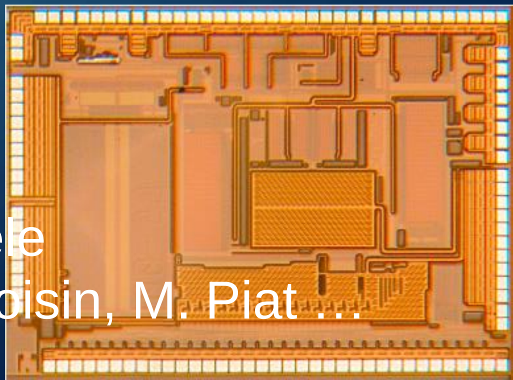
Besoins en microélectronique des astroparticules

S. Loucatos (APC, Irfu)

Apports de E. Delagnes, D. Prêle
Ch de la Taille, F. Druillole, F. Voisin, M. Piat …



Prospectives

CERN (physique et R&D), Insu, CNES, OdP, APPEC

Table 11.1: Summary of promising technologies and their possible specific detector applications to address experimental challenges of approved and future projects.

	Technologies				
	Solid state	Gas	Scintillator	Noble liquid	Cherenkov
Vertex / Tracker	**Challenges**: high spatial resolution, high rate/occupancy, fast/precise timing, radiation hardness, low mass, 4D tracking.				
	Planar, 3D, (D)MAPS [1], LGAD [2], (HV-HR) CMOS [3]	TPC [4], DC [5]	SciFi [6] + SiPM [7]		
Calorimeter	**Challenges**: high granularity, radiation hardness, large volume, excellent hit timing, PFA/dual-readout capability, 5D imaging.				
	Si sensors sampling	RPC [8] or MPGD [9] sampling	Tile/fibers + SiPM sampl., homogeneous crystals (e.g. LYSO)	LAr sampling	Quartz fibers sampling in dual-readout
Muon detector	**Challenges**: large area, low cost, spatial resolution, high rate.				
		MPGD, RPC, DT [9] MWPC [10]	Scint+ WLS fibers + SiPM		
PID / TOF	**Challenges**: high photon detection efficiency, large area photodetectors, thinner radiator, timing resolution ≤ 10 ps, radiation hardness.				
	LGAD (timing)	TPC, DC, MRPC [11] (timing)			RICH [12], TOF [13], TOP [14], DIRC [15]
Neutrino / Dark Matter	**Challenges**: high photon detection efficiency, very large volume,radio purity, cryogenic temperature, large area photodetectors.				
	Si, Ge	TPC	liquid scint., scint. tiles / bars	single/dual-phase TPC	water/ice + mPMT [16]

1. (Depleted) Monolithic Active Pixel Sensor
2. Low Gain Avalanche Detector
3. (High Voltage - High Resistivity) CMOS
4. Time Projection Chamber
5. Drift Chamber
6. Scintillating Fiber tracker
7. Silicon Photomultiplier
8. Resistive Plate Chamber
9. MicroPattern Gaseous Detector
9. Drift Tube
10. Multi-Wire Proportional Chamber
11. Multi-gap Resistive Plate Chamber
12. Ring-Imaging Cherenkov detector
13. Time-Of-Flight detector
14. Time-Of-Propagation counter
15. Detection of Internally Reflected Cherenkov
16. multi-anode Photo-Multiplier Tube

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

APPEC Strategy Recommendations summary

https://www.appec.org/implementation/recommendations

- Large-scale multi-messenger infrastructures
- These messengers include gamma rays, neutrinos, cosmic rays and gravitational waves. European coordination is essential to ensuring timely implementation of such infrastructures and enabling Europe to retain its scientific leadership in this field.

1. High-energy gamma rays

- The next-generation European-led, ESFRI-listed global project will be the Cherenkov Telescope Array (CTA), which has excellent discovery potential ranging from astrophysics to fundamental physics. The CTA is expected to start full operation as an observatory in 2023. both northern and southern hemispheres.

2. High-energy neutrinos

- .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.

3. High-energy cosmic rays

- The Auger collaboration will install additional particle detectors (AugerPrime) to measure simultaneously the electron and muon content of air showers, in order to help determine the mass of primary cosmic rays. This upgrade will also deepen understanding of hadronic showers and interactions at centre-of-mass energies above those accessible at the LHC. APPEC strongly supports the Auger collaboration's installation of AugerPrime by 2019. At the same time, APPEC urges the community to continue R&D on alternative technologies that are cost-effective and provide a 100% (day and night) duty cycle so that, ultimately, the full sky can be observed using very large observatories.

4. Gravitational waves

- In this field, the laboratories that host gravitational-wave antennas play a crucial role by developing new technologies to increase detection efficiencies further. 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 ?eld of space-based interferometry, APPEC strongly supports the European LISA proposal.
- Medium-scale Dark Matter and neutrino experiments
- APPEC considers as its core assets the diverse, often ultra-precise and invariably ingenious suite of medium-scale laboratory experiments targeted at the discovery of extremely rare processes. These include experiments to detect the scattering of Dark Matter particles and neutrino-less double-beta decay, and direct measurement of neutrino mass using single-beta decay. Collectively, these searches must be pursued to the level of discovery, unless prevented by an irreducible background or an unrealistically high demand for capital investment.

5. Dark Matter

- A suite of smaller-scale experiments is exploring, in particular, low-mass WIMPs and other Dark Matter hypotheses such as those based on dark photons and axions. 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.

6. Neutrino mass and nature

- Among the various experiments worldwide searching for neutrino-less double-beta decay, European experiments such as GERDA (focusing on germanium), CUORE (tellurium) and NEXT (xenon) are some of the most competitive.
- APPEC strongly supports the present range of direct neutrino-mass measurements and searches for neutrino-less double-beta decay. Guided by the results of experiments currently in operation and in consultation with its global partners, APPEC intends to converge on a roadmap for the next generation of experiments into neutrino mass and nature by 2020.

Plus:

- 7. Oscillations de neutrinos émis de réacteurs
- 8. Cosmologie: CMB et énergie noire
- 9. X et gamma sur satellite
- 10. Radiotélescopes

Techniques en astroparticules

Des techniques de détection variées.

dapnia
cea
saclay

- Environnements variés souvent extrêmes:
  spatial, ballon, terrestre, sous terrain, sous-marin..
- Des méthodes de détection souvent indirectes et astucieuses.
- Souvent basées sur la photodétection:
  - photon particule secondaire.
  - photodétecteurs rapides et à timing précis.
  - photodétecteurs fiables, compacts et faciles à mettre en œuvre.
- Observation d'interactions rares => grandes surfaces détectrices.
- Nombres de canaux de qq 1000 à qq 10000.
- Détecteurs à géométrie distribuée sur de grands « territoires ».
- Techniques en perpétuelle évolution.

Et les ASICs là dedans ??.

- Technique de physique des particules « exportées ».
- Utilisés en astroparticules dès 1995 (cf SNO)
- Les gains apportés:

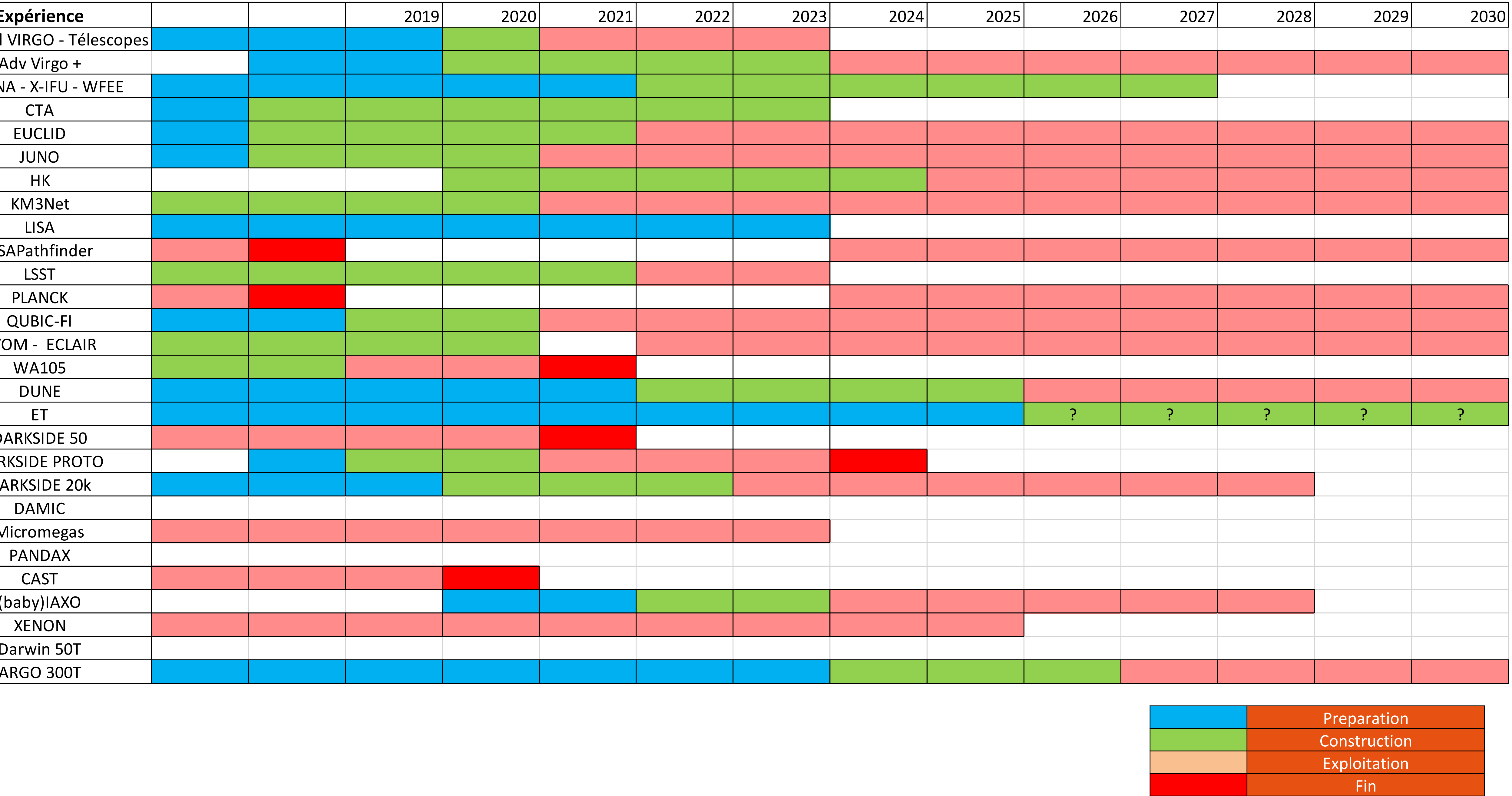
  Les mêmes qu'en HEP mais dans un ordre différent:

  - Fiabilité.
  - Intégration (permettent des géométries plus compactes).
  - Diminution de puissance.
  - Performances ?!?
  - Coût.
- Parfois, clef de la faisabilité de l'expérience (INTEGRAL).

- Pas ou peu d'expérience de design d'ASIC dans le monde de l'astrophysique.

Meilleurs performances en AP

- dt, DT, dE, miniaturisation, imagerie-nombre de canaux, durcissement spatial…
- Technique: multiplexage : comme pour le marché des appareils photo numériques, la résolution montant vers les "mégapixels", tous les imageurs scientifiques et high-tech (quelle que soit la longueur d’onde - de la radio à Rayons X) tend également à toujours augmenter le nombre de pixels -> multiplexages TDM, FDM, CDM, ThermalM


Expérience
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
l VIRGO - Télescopes
Adv Virgo +
NA - X-IFU - WFEE
CTA
EUCLID
JUNO
HK
KM3Net
LISA
SAPathfinder
LSST
PLANCK
QUBIC-FI
TOM - ECLAIR
WA105
DUNE
ET
?
?
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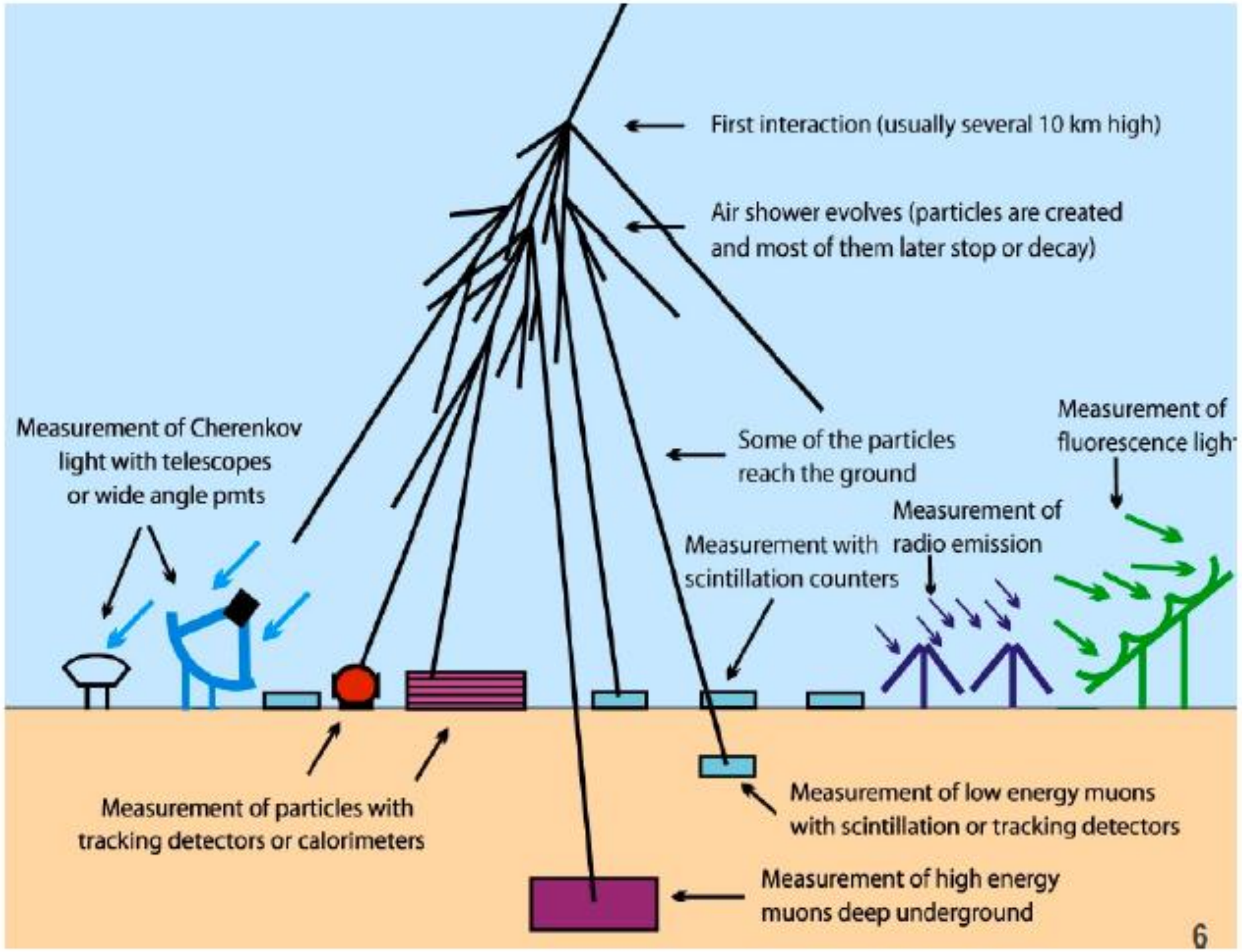
?
?
DARKSIDE 50
RKSIDE PROTO
ARKSIDE 20k
DAMIC
Micromegas
PANDAX
CAST
(baby)IAXO
XENON
Darwin 50T
ARGO 300T
Preparation
Construction
Exploitation
Fin

Light in astro-particle physics

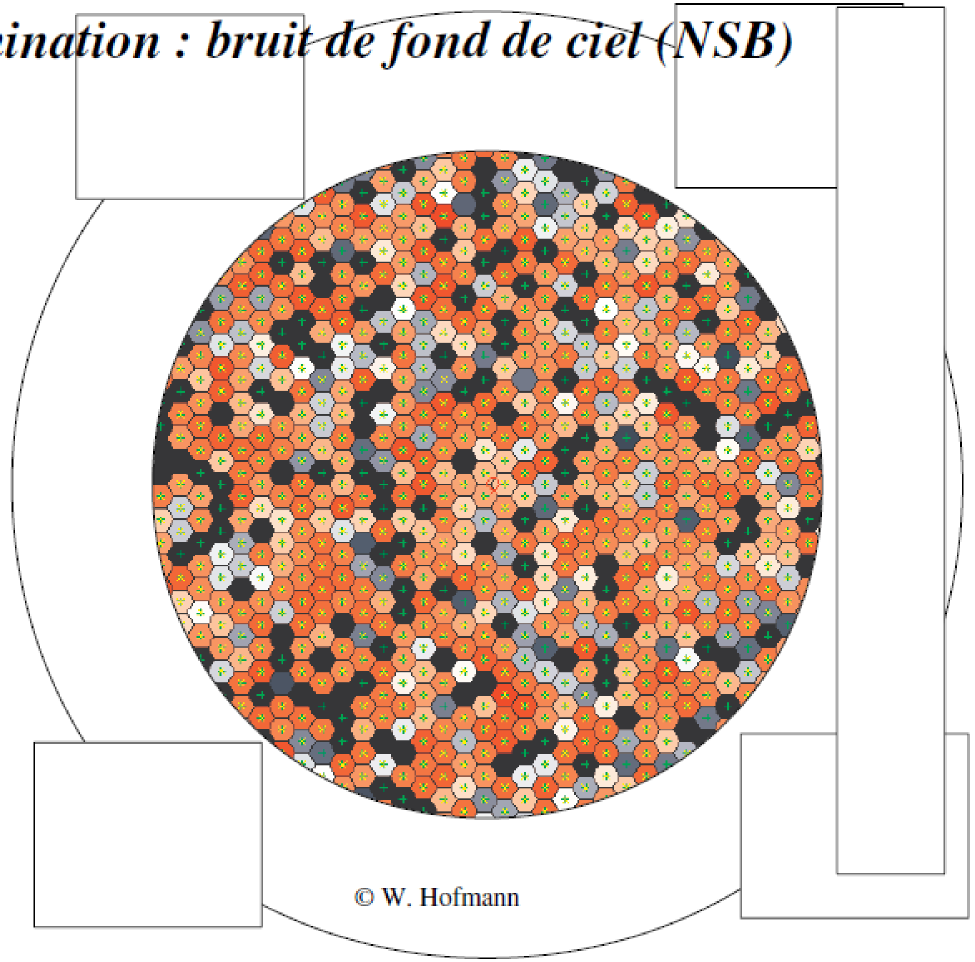
- Low energies (charged particles $<10^{14}$ eV & gamma rays $<10^{10}$ eV)
  - Particle detectors in space or on balloons
- For high energies (charged particles $>10^{14}$ eV & gamma rays $>10^{10}$ eV)
  - Atmosphere as calorimeter
    - Imaging Atmospheric Cherenkov Telescopes
    - Fluorescence Telescopes
    - Detectors on the ground
- Neutrino Telescopes:
  - use atmosphere, water, ice, earth crust, or dedicated large detector volumes.
- Dark Matter experiments

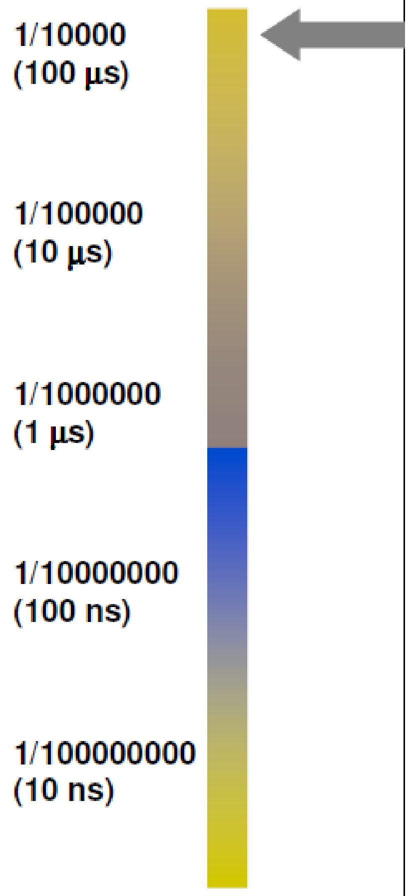


Gammas de HE: télescopes imageurs Cherenkov

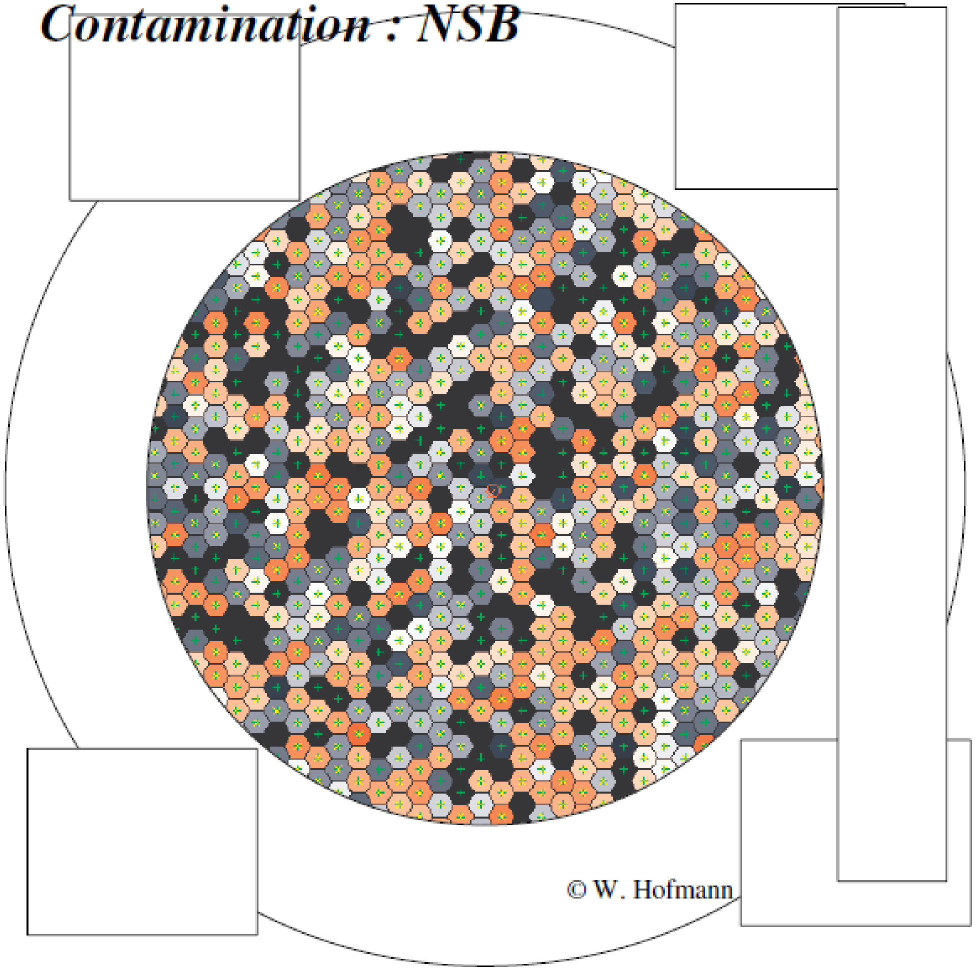
Imaging Atmospheric (or Air) Cherenkov Telescopes

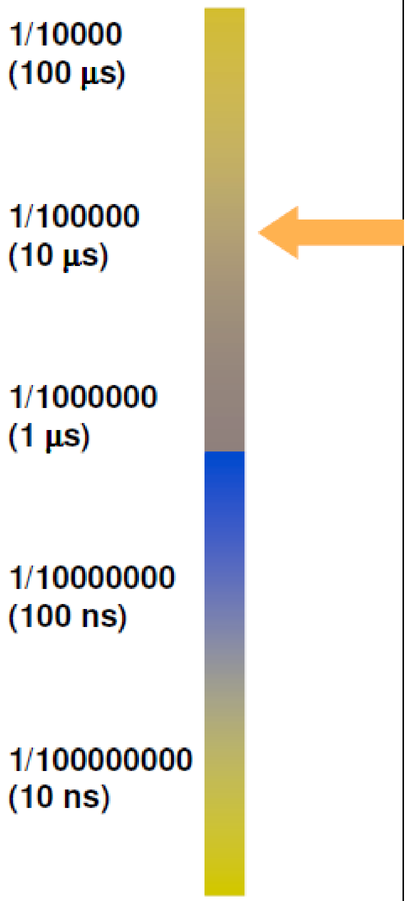
Contamination : bruit de fond de ciel (NSB)



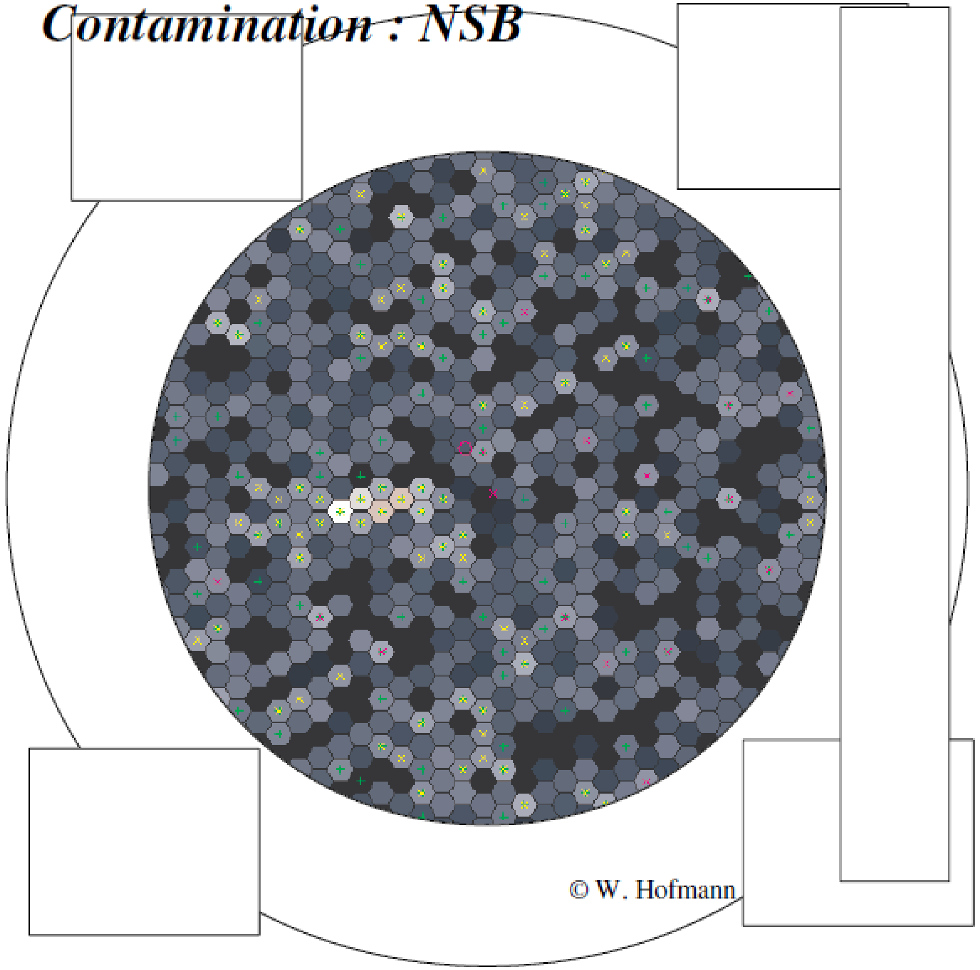


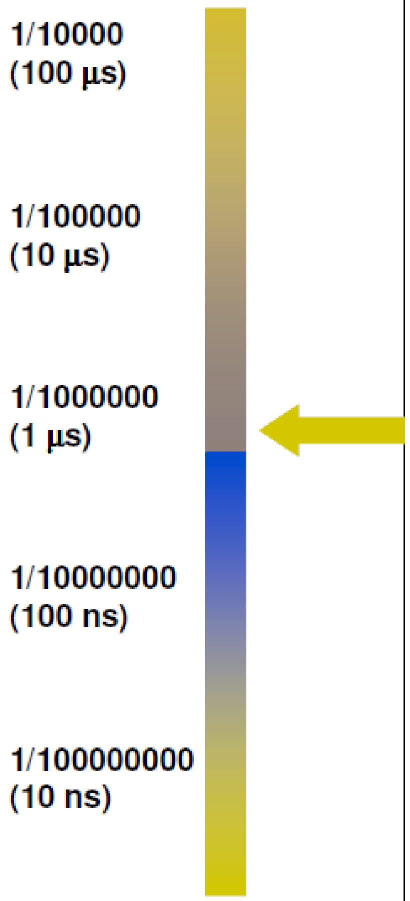
Contamination : NSB

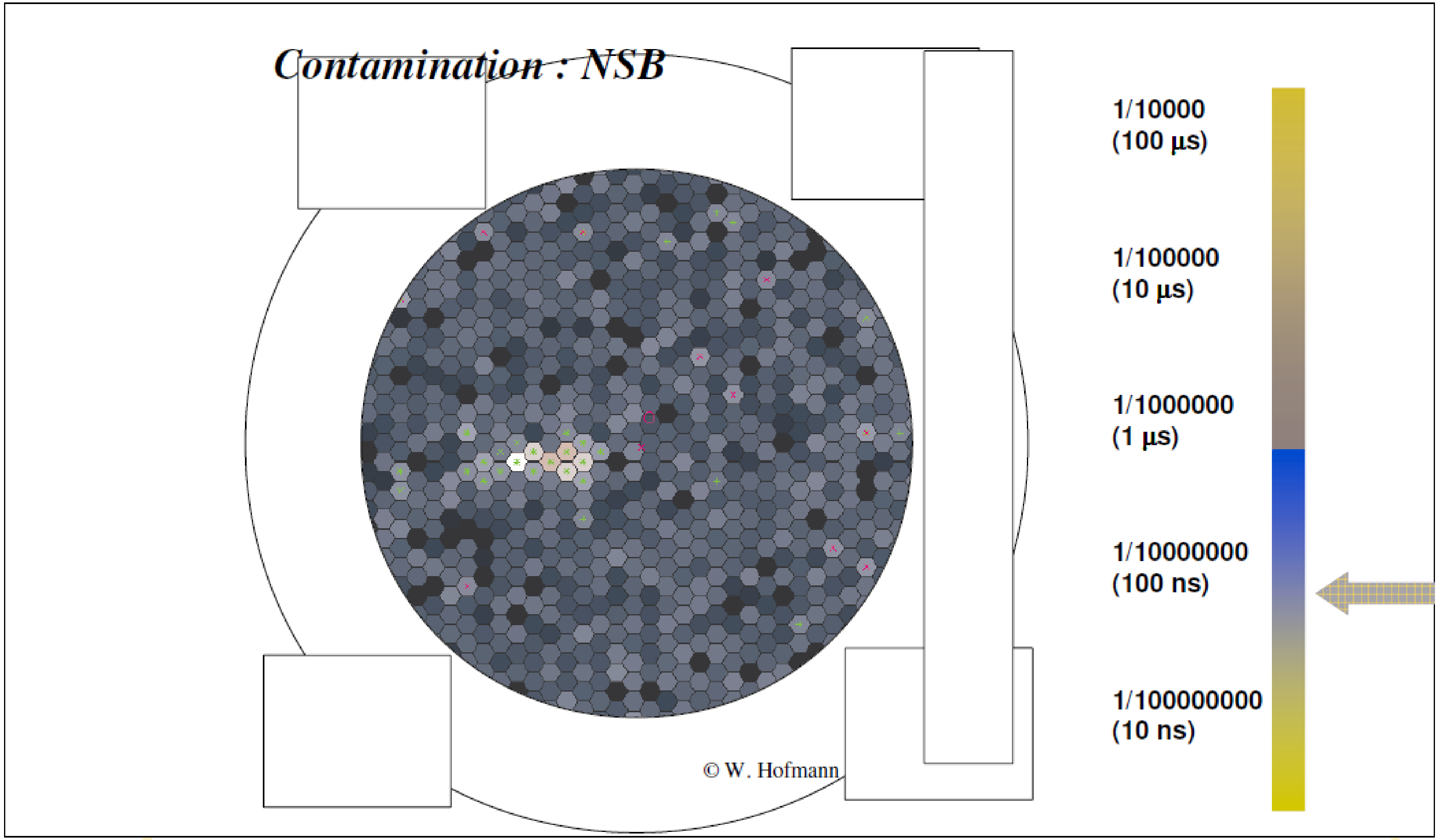




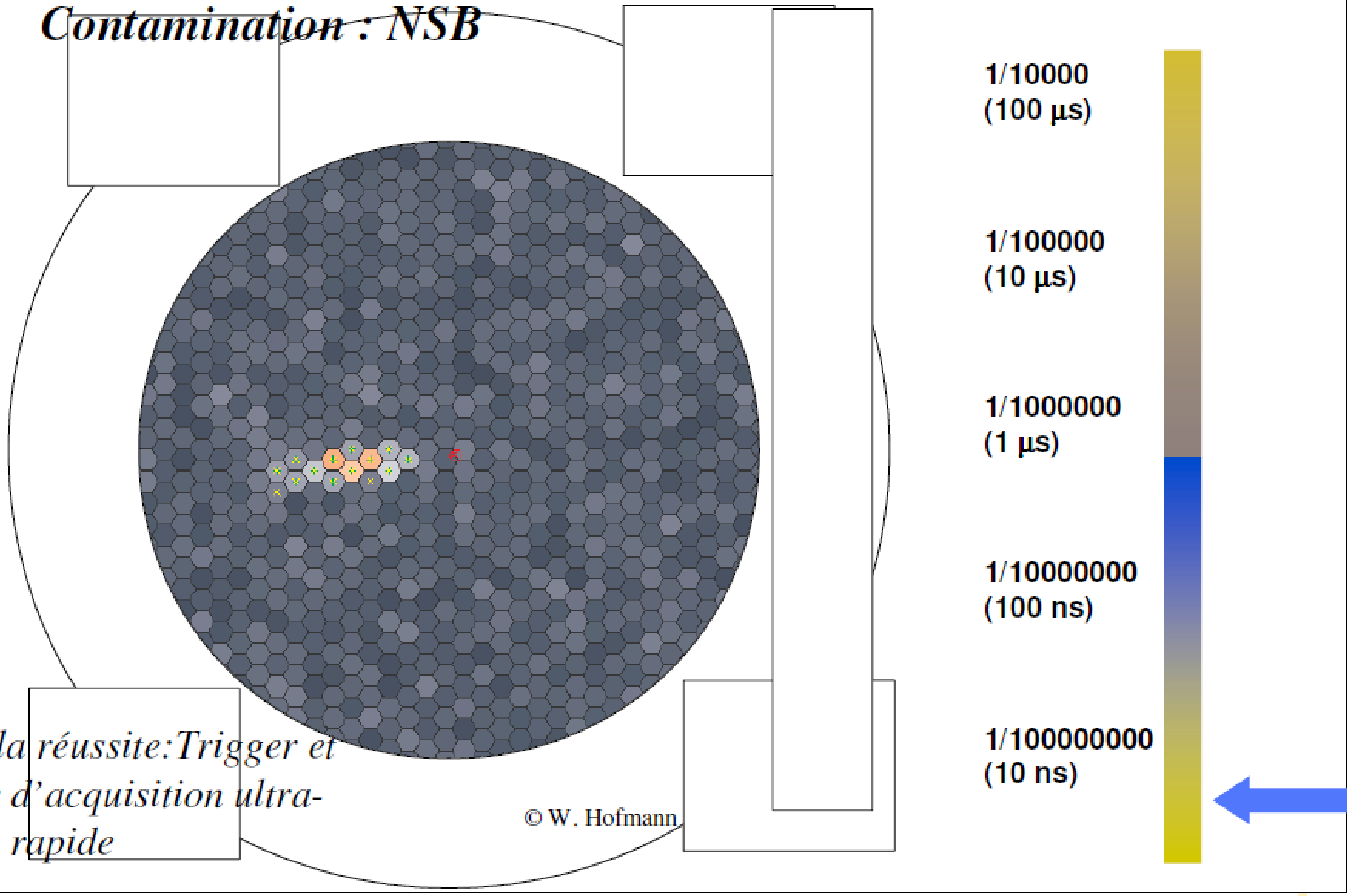
Contamination : NSB






Contamination : NSB
© W. Hofmann
1/10000
(100 µs)
1/100000
(10 µs)
1/1000000
(1 µs)
1/10000000
(100 ns)
1/100000000
(10 ns)

Contamination : NSB



Les Clefs de la réussite:Trigger et électronique d'acquisition ultra-rapide

Microélectronique CTA

- Lecture des PMTs:
- ASICS dans Nectarcam et Flashcam
- Asic Nectar au site nord ou les 2. Nouvelle version actuelle de Nectar avec moindre temps mort.

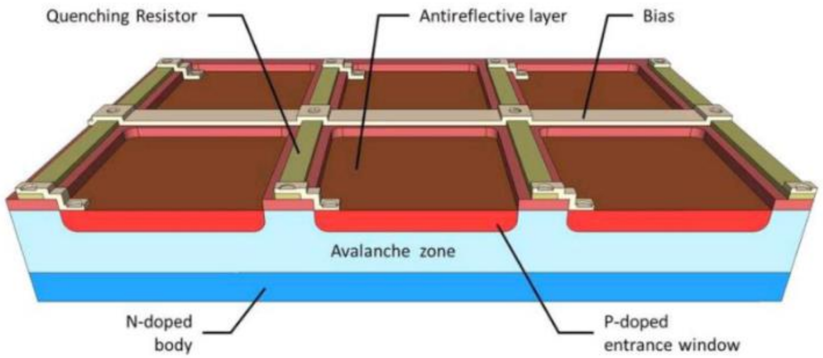
TRIGGER

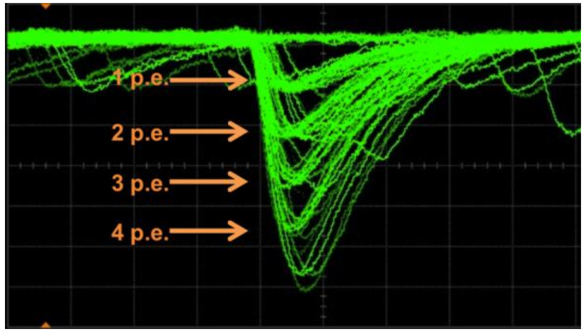
- En général en circuits discrets ou en numérique. Niveau L0 dans CTA, mais calibration laborieuse.

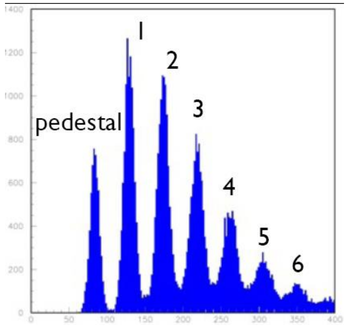
Frank Hartmann
JENAS Orsay '19

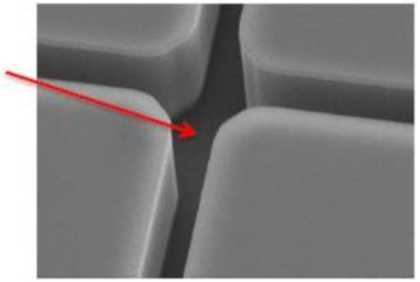
SiPM Silicon Photomultiplier

- Gamma-ray cameras, PET scanners, X-Ray detection, calorimetry, LIDAR, neutrino detection, DUNE, radiation monitoring, space application (EUSO, AMS), SHiP, SiFi (LHCb), nEXO, timing@LHC (up to $3*10^{14}\ n_{eq}/cm^2$), telescope (e.g. MAGIC), Darkside, etc.
  - Limit on radiation tolerance due to DCR (cooling helps)
- High gain, High PDE, accurate photopeak resolution, good time resolution, compact and robust, low bias voltage, insensitive to magnetic field, tolerate fast acceleration
- Single photon detection
- Further interests:
  - Operating at cryo temperatures (Darkside, DUNE)
  - Fill factor (tiny cells, microcells)

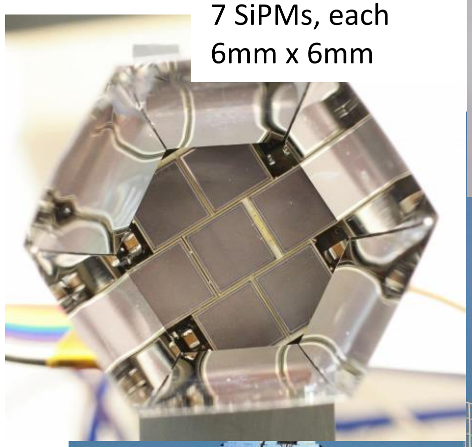


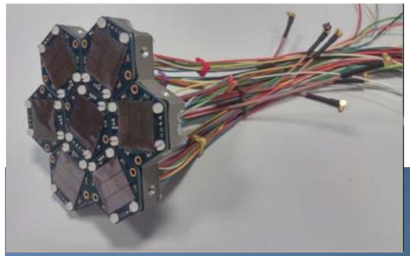






7 SiPMs, each 6mm x 6mm





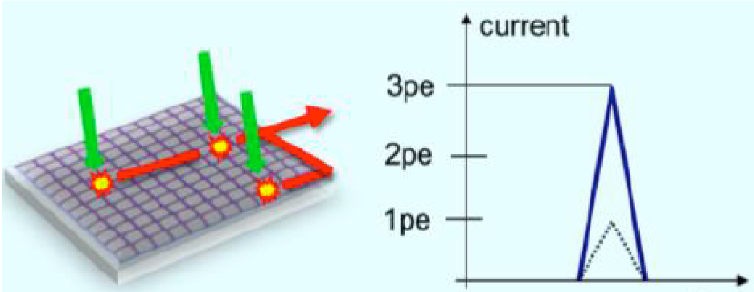
SHiP: **S**earch for **Hi**dden **P**article: Dark matter search behind SPS beam dump facility 10^{20} Protons on Target (PoT) (3500 SiPMs)
EUSO Extreme Universe Space Observatory
nEXO = (next) Enriched Xenon Observatory (digital SiPMs - **3DdSiPM**)

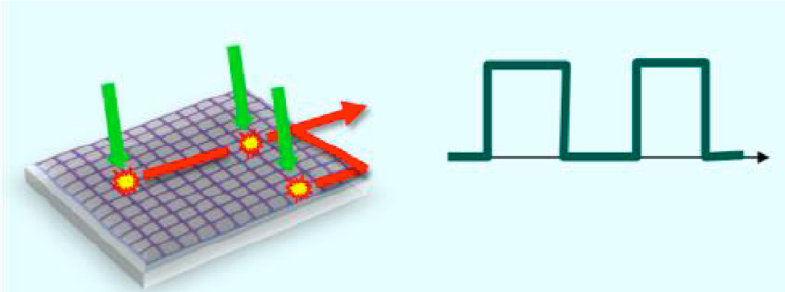
SiPM

- Array of compact independent Avalanche Diodes (SPAD), with integrated quenching circuit, operating in Geiger mode outputting the sum of cell signal (analog sum or digital sum)
- Great progress in the last 15 years

- ANALOG
- SPADs connected in parallel through a decoupling resistor, which is also used for quenching avalanche
  - Amplitude of output signal $\propto$ n(photons)
  - Custom technology (or CMOS) optimized SPAD performance.

- DIGITAL
  - SPAD signal digitized at pixel level.
  - Integrated digital architecture allows data processing on the sensor.
  - CMOS technology with active quenching via a transistor
  - Optimized signal treatment, quenching/reset and processing





SiPMs testés sur la caméra FACT: 1440 SiPM x 3660 SPADs chacun installée près du télescope MAGIC sur l'île de La Palma en 2011, Mesurant du spectre gamma de la nébuleuse du Crabe

Silicon-Photo-Multipliers are arrays of hundreds to ten thousands of Single-Photon-Avalanche-Photodiodes operated in quenched Geiger mode above the break-down voltage. Given their excellent performance, they now replace Vacuum-Photo-Multipliers in many applications. Their photon-detection efficiency can exceed 50 % in a wide wavelength interval, they count single photons with a time resolution in the 20 ps (FWHM) range, operate at voltages of a few tens of volts, are insensitive to magnetic fields, are robust and do not deteriorate, even if exposed to strong light. However, their size is limited to about 10 cm^2 , their dynamic range is limited by the number of cells, and they have dark-count rates of tens to hundreds of kHz/mm^2 at room temperature. Their photon-counting resolution is influenced by optical cross-talk and afterpulsing. Developments in the last years resulted in major performance improvements and further progress is expected.

SiPM


Philips
KETEK
MPI-HLL
CPTA
MePhi/
Pulsar
SensL
Zecotek
RMD
Excelitas
AdvanSiD
NDL
NanoFab
Korea
Hamamatsu

SiPMs in CTA

CTA SSTs are using SiPM

Small size telescopes

SST 1M

ASTRI

GCT

Science drivers
Highest energies (> 5 TeV)
Galactic science, PeVatrons

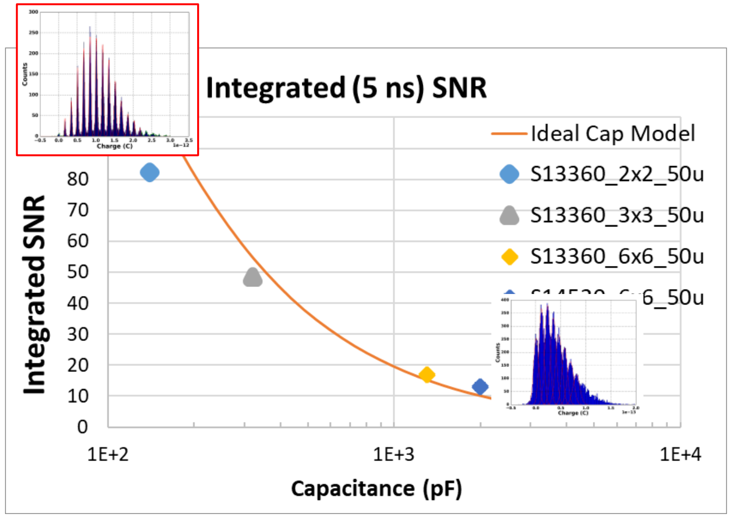
Array layout
South site: 70 SST
North site: -

- Smaller areas (SiPM <1cm^2), hence higher pixel angular resolution
- Higher photo-detection efficiency at UV wavelengths (c.a. 50%)
- Fast response O(1-10) ns
- Not damaged by moonlight, can be operated during bright Moon nights enhancing the DAQ duty cycles
- Can be operated with bias voltages <100V
- Low power consumption (μW)
- Light-weight
- Noisy, dark count rates O(10-100) KHz/mm^2 at room temperature, but below the expected average night sky background.

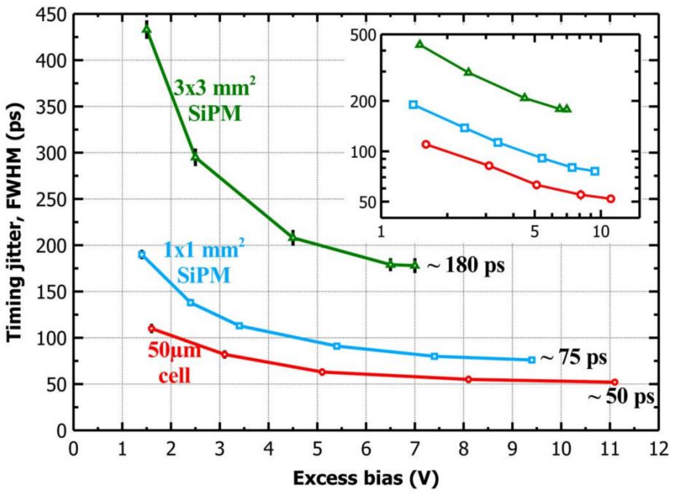
Large Area SiPMs and SENSE
Ultimate Low Light-Level Sensor Development

- Small SiPMs & large area = large channel count & high cost
- But (a) photopeak resolution and (b) time resolution get worse with large cells (>1cm^2)
  - as signal ~ Cap^{-1} ~ A^{-1} & total charge constant but delayed with large C
  - also X-talk increases with size
- Combine small sensors – Active Summation
  - Noise about same, signal higher.   E.g. MUSIC chip
- Future: Towards a picosecond hybrid single photon sensor
- ➔ Digital SiPM (TDC/pixel - in-pixel electronics ...)
  - overcomes Capacitance limitation

(a)



(b)



F. Acerbi *et al.*, "Characterization of Single-Photon Time Resolution: From Single SPAD to Silicon Photomultiplier," in *IEEE Transactions on Nuclear Science*, vol. 61, no. 5, pp. 2678-2686, Oct. 2014.

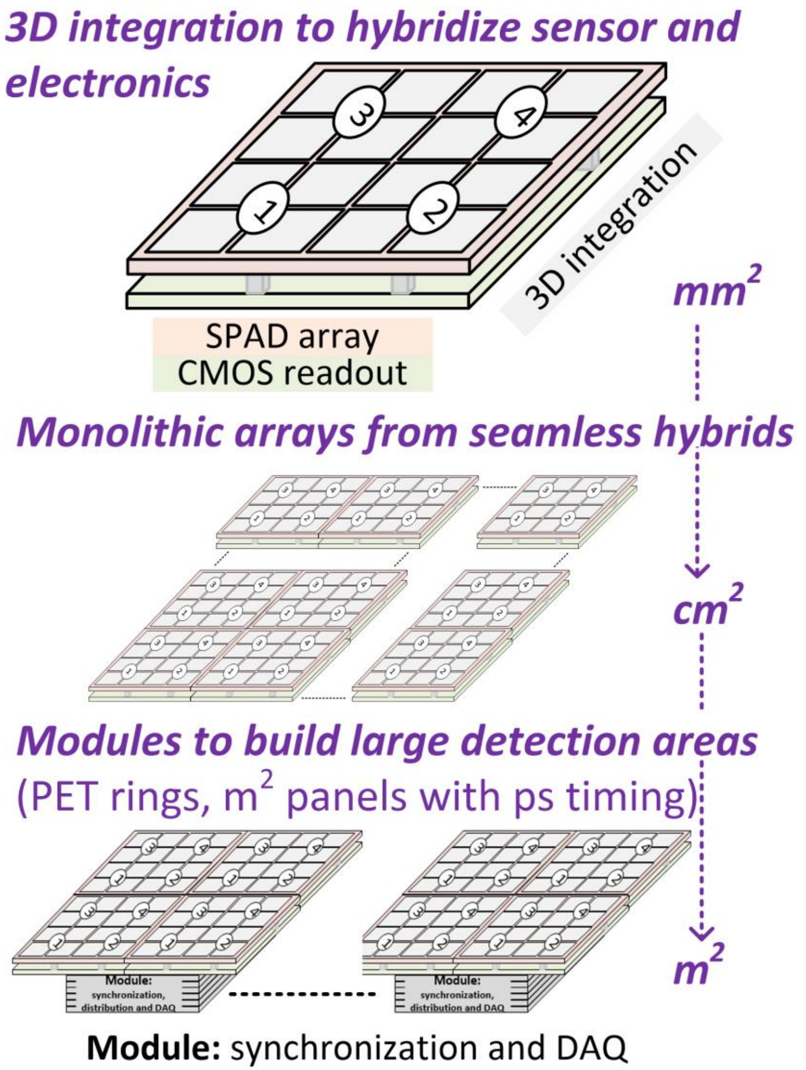
Towards a picosecond hybrid single photon sensor

- Combine actively
  - *signal of small micropixel sub-arrays o*f the *best* single photon *sensor*
  - *ultrafast readout* electronics (≤ 65 nm) using *3D integration*

- **Unprecedented time resolution** for large sensitive areas
  - Active summation and combination of small groups of SPADs which show a ***capacitance two orders of magnitude lower than a large SiPM***

- **Scalability**:
  - the architecture and the 3D integration approach (see HAPS) allow to build arbitrarily large arrays

- **Low cost** for mass production
  - Will be based on mass production CMOS processes



TSV: Through Silicon Via

Applications des SiPM

- The combination of Magnetic Resonance Imaging (MRI), which provides exquisite anatomical information, with Positron Emission Tomography (PET) giving functional information, is a major step forward in medical instrumentation. Given the high magnetic fields required for MRI, solid state photo-detectors, which are immune to magnetic fields, are ideal to realise MRI/PET systems. In addition, the precise time measurement can be used to suppress backgrounds.

- Innovative TRIMAGE project: Electro-Encephalography is added to a PET/MRI scanner as a tri-modality imaging tool for schizophrenia

- Excellent timing resolution and high photon sensitivity make SiPMs prime candidates for LIDAR applications, including automatic driving.

R. Klanner, Europhysics News 50/4, 2019, p. 17-20

A. Del Guerra et al., Eur. Psychiatry 50, 7 (2018)

J. Riu et al., Optics Letters 37, 7, 1229(2012).

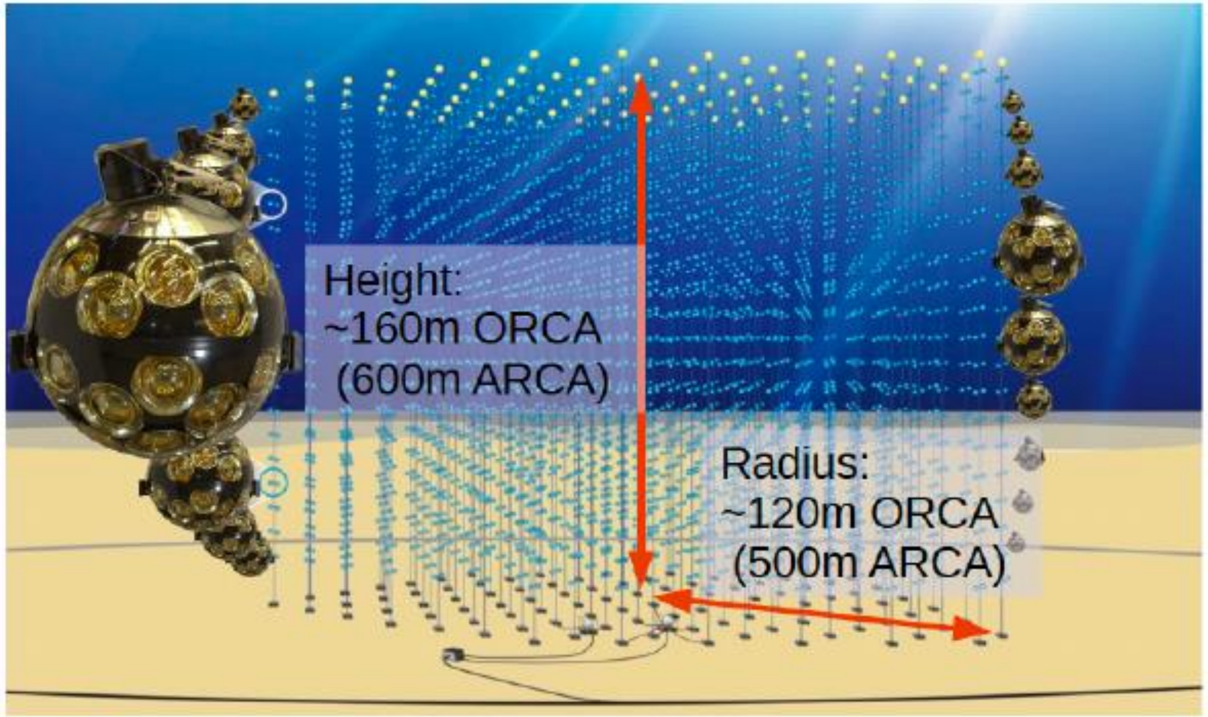
Neutrinos cosmiques de haute énergie

KM3NET

ORCA will consist of one dense **KM3NeT Building Block:**

115 detection lines
Total: 64k * 3" PMTs

	ORCA	ARCA
String spacing	23 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	1x 8 Mton	2x 0.6 Gton



Directional information

Will also be used for the ICECUBE Telescope Upgrade

Km3net neutrinos cosmiques

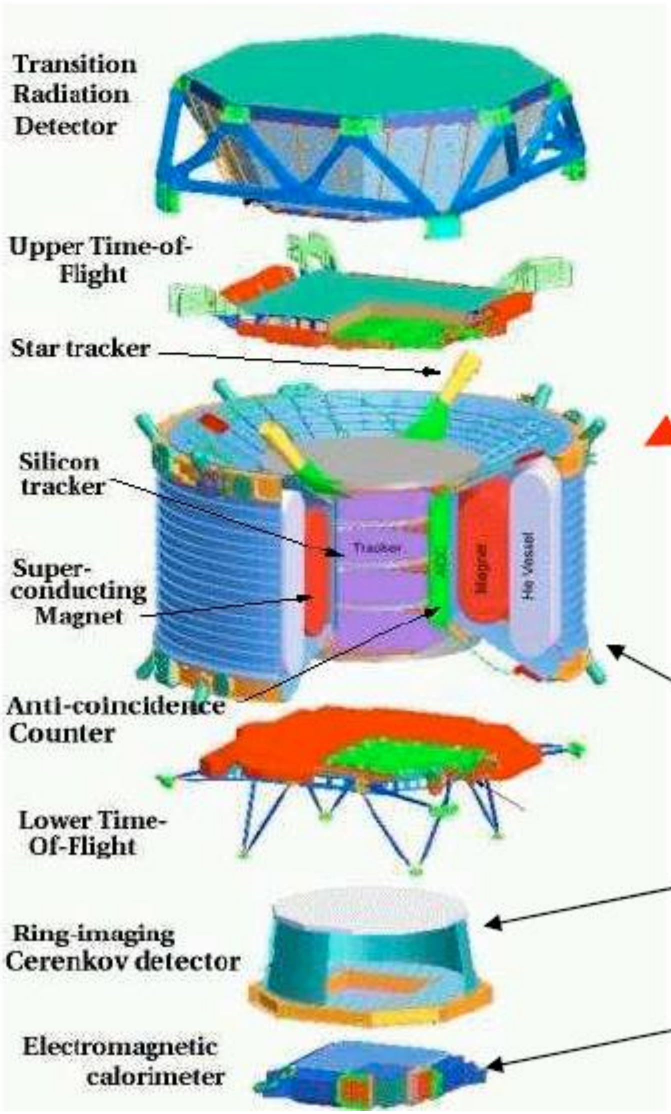
- ASICS Promis, COCO par Valencia, NIKHEF
- Nouvelle version en préparation, nouvelle techn.
- Asic Maroc d’Omega utilisé aux tests de PMTs dans une cuve à l’APC, dispositif pour Memphys avant (aide de Sylvie Blin).

Rayons cosmiques

AUGER

- Il n'y a pas d'ASIC dans AUGER.
- Quelques tentatives pour AUGER Nord:
  - Circuit multi-gain pour couvrir les 16bits de gamme dynamique du PM.
  - Suivi d'un ADC (LAL) ?

AMS-02 (passager de l'ISS)



70000canaux
?

160000 canaux lus par 1000 MAPMT
ASIC ISN Grenoble

Calo Pb-Fibres scintillantes
1296 canaux lus par 324 PM multianode.
ASIC LAPP

Ondes gravitationnelles

VIRGO, LISA

LISA n’a pas vraiment de besoin en micro-électronique, au moins jusqu’à maintenant. Récemment, il a été proposé que les électroniques de proximité des photodiodes soient implémentés sur des ASICs (jusqu’à présent on utilise des électroniques discrètes).

Le phasemètre quant à lui est basé sur des FPGA aujourd’hui et ce sera a priori la même chose pour le modèle de vol.

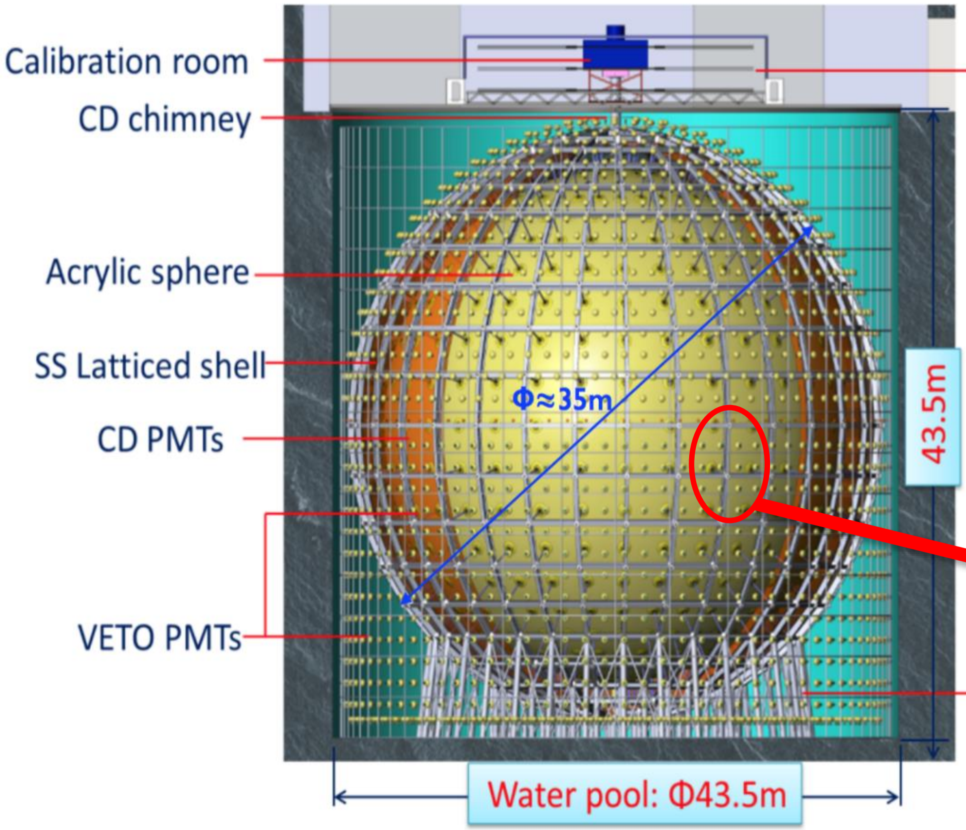
Echantillonneur à 80MHz du phasemètre, qui doit échantillonner 5Mhz, la différence entre 2 lasers. Les photodiodes sont des Avalanche PD. échantillonneur durci pour CMS, du LHC

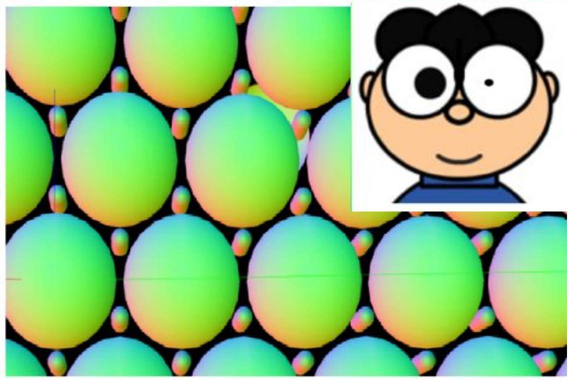
Tous les composants de vol durcis.

Neutrinos de réacteurs

JUNO (Jiangmen Underground Neutrino Observatory)

A multipurpose **neutrino experiment** designed to determine neutrino mass hierarchy with a **20,000 tons liquid scintillator detector** at 700-meter deep underground

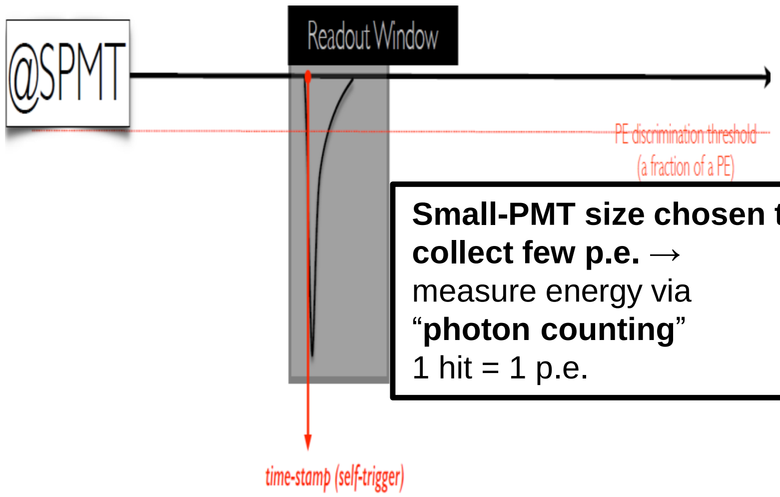




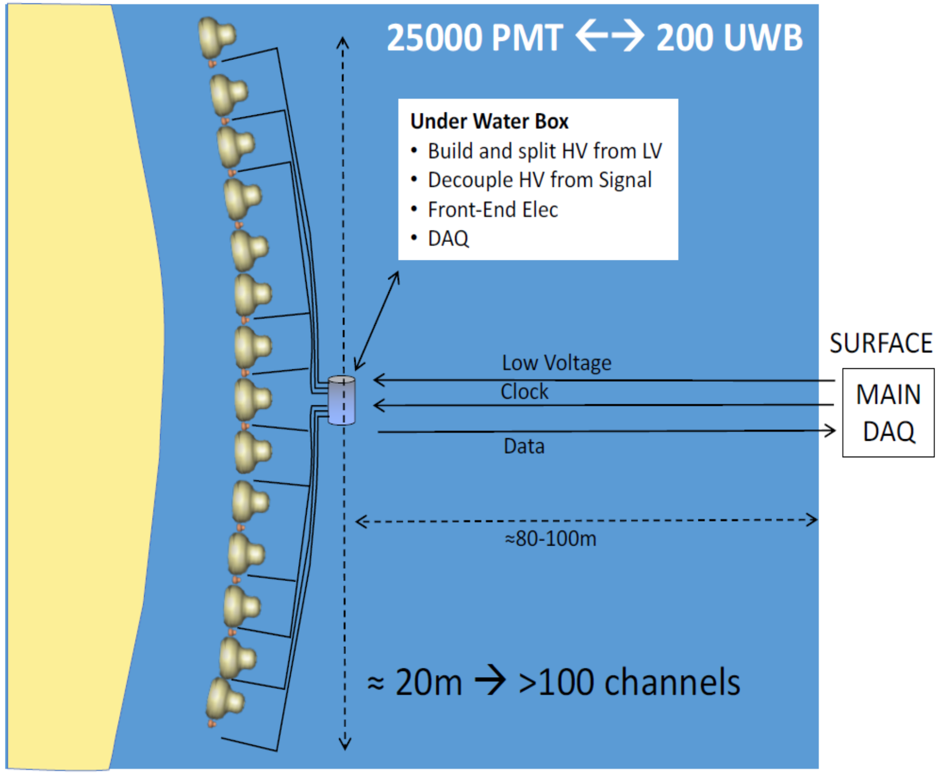
~ 18,000 PMTs (20” diameter) → Large-PMT system (LPMT) → **75 % of the inner surface**
~ 25,000 PMTs (3” diameter) → Small-PMT system (SPMT) →

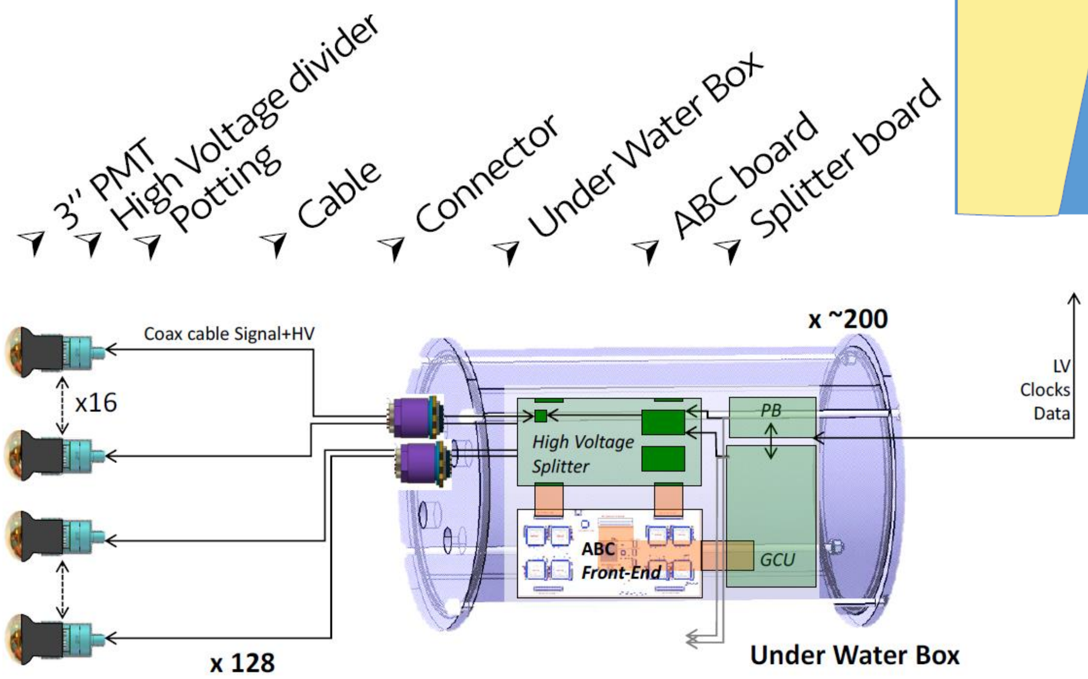
- Increase coverage of the surface → Improve energy reconstruction
- Cross calibration

Small PMT (SPMT) system



Small-PMT size chosen to collect few p.e. → measure energy via "**photon counting**"
1 hit = 1 p.e.



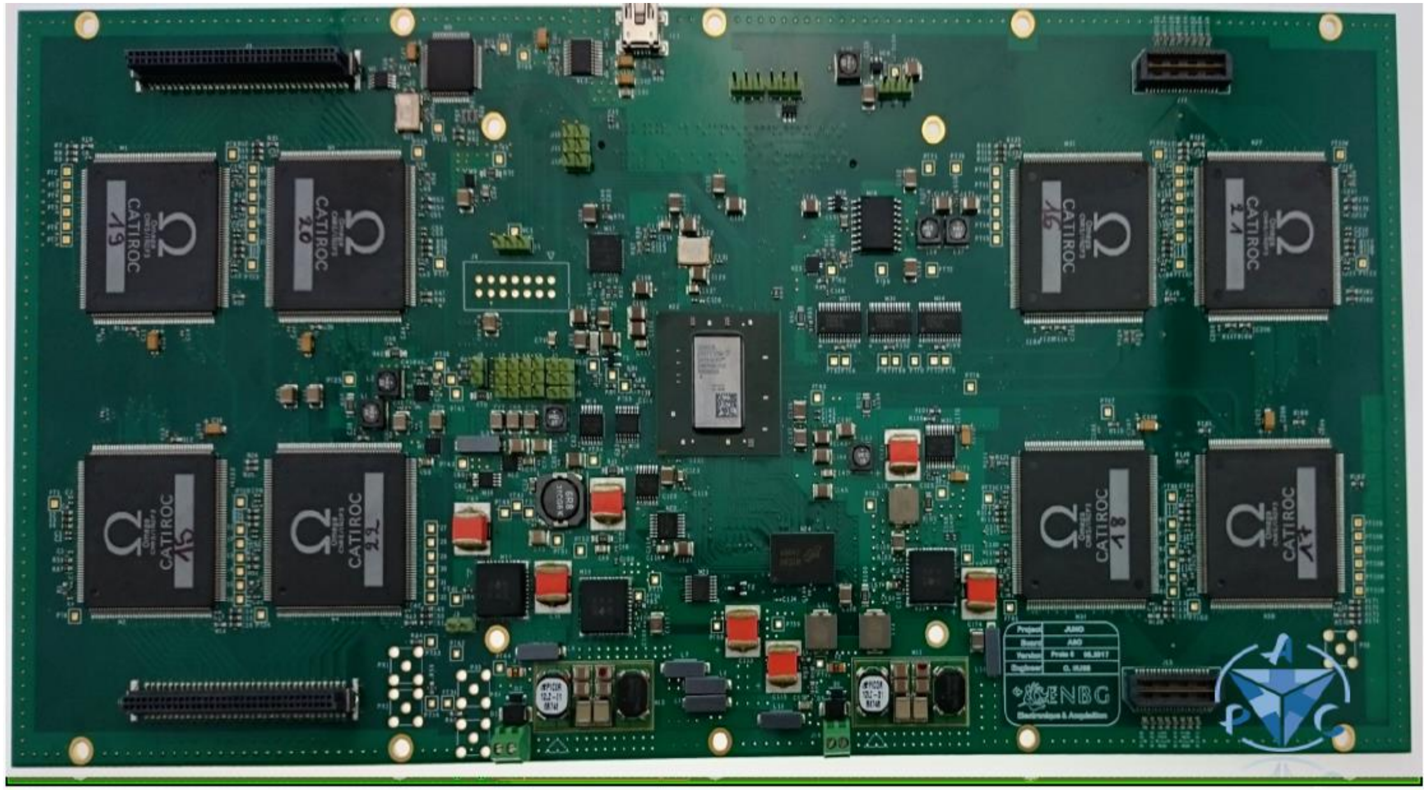


- **128 Small PMTs** with a read-out system:
  the Under Water Box (UWB)
- A dedicated FEB based on **CATIROC**

Small PMT front-end board

SPMT

- SPMT front-end with **8 ASIC CATIROC** each of 16 channels
- **FPGA** (Kindex 7 425-T)+ 2GB DDR3 **RAM memory** (large storage and processing on board)
- **4 connector (2 ERNI, 2 SAMTEC)** x 32 signals (CATIROC inputs)
- Power supply for ASIC and FPGA
- Low cost concept (**one board/ 128 PMTs/** one under water cable to send out data)



CATIROC for JUNO

A complex System on Chip (SoC). Technology: 0.35 µm SiGe AMS

CATIROC general features	Application to JUNO
16 independent channels	**Reduce the number of electronic** board (only 200 boards for 25,000 SPMTs)
Analog F.E. with **16 trigger outputs** + **charge and time digitization**	**Photon counting** + **charge and time measurements**. Resolutions very good
Autotrigger mode: all the PMTs signals above the threshold (1/3 p.e.) generate a trigger and are converted in digital data	Simplify online-DAQ
100% trigger efficiency @ 1/3 p.e.	**Good 1 p.e. detection** photon counting mode
Dual gain front-end: HG and LG channel Charge dynamic range 0 to 400p.e. (at PMT gain 10^6)	Only **HG** actually used (only few p.e. expected)
Time stamping (resolution ~ 170 ps rms)	< **1ns required**
Each channel has a **variable gain**	**To compensate gain vs HV spread** for the 16 PMTs
One output for **DATA**	**Less number of cables to the surface**
Hit rate 100 kHz/ch (all channels hit) **50 bits of data / hit channel**	**Very "light" data output** (compared to a FADC waveform)

Conclusions

Omega

- CatiROC performance fits very well for JUNO-SPMT:
  - 100% trigger efficiency @ **1/3 p.e.** (50 fC @ PMT gain 10^6)
  - Charge resolution (**only HG used**) : 1.5 ADCu ~ **15 fC** (50 fC @ PMT gain 10^6)
  - Time resolution= **167 ps rms**
- Tests with the HZC 3" PMT shows
  - **Good p.e. spectrum**
  - Some features (ping/pong and wiggles) that have not significant effects on the data taking
- To do:
  - **Tests with the ABC board V0 → Ongoing**
  - **ABC V0 Board and a module of 128 PMTs → Test bench in China**
  - **ABC V1 board→ Ongoing (December 2018)**

- **2000 ASICs** CATIROC production at the end of 2018

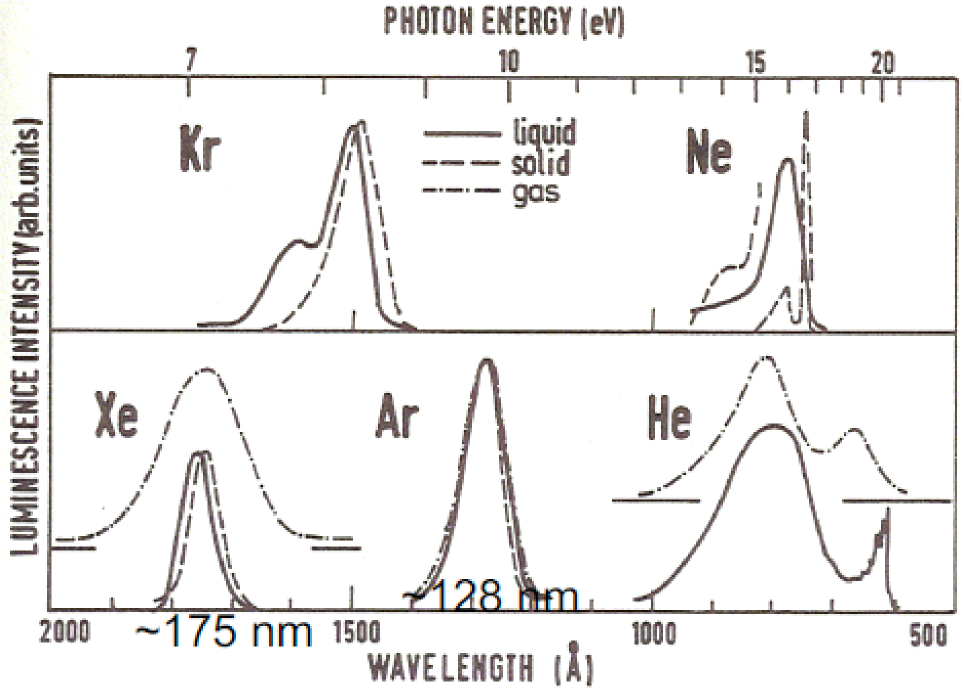
Matière noire

A suite of smaller-scale experiments is exploring, in particular, low-mass WIMPs and other Dark Matter hypotheses such as those based on dark photons and axions.

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.

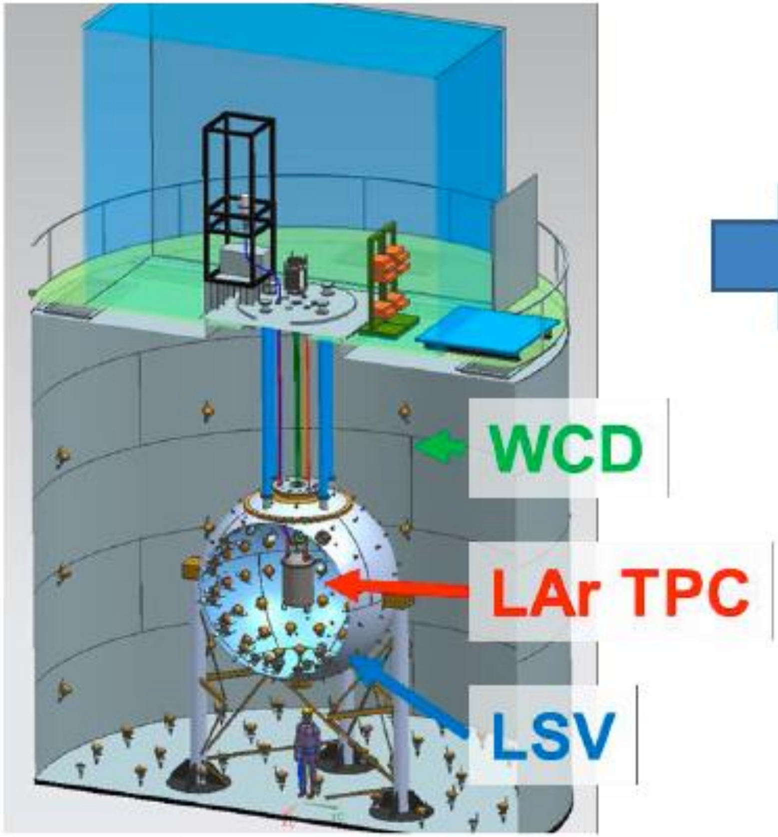
Cryogenic operation of SiPMs

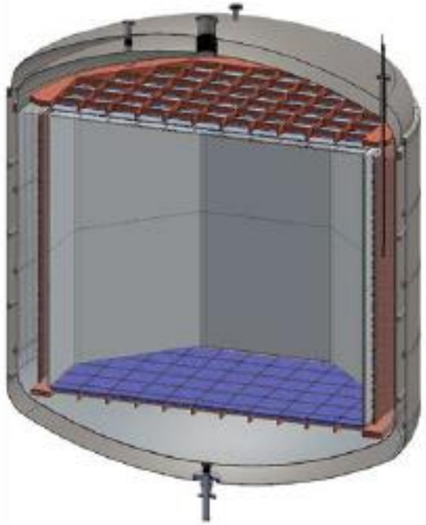
- Several particle detectors use liquified noble gasses as target:
  - Xe = 165 K, LAr = 87 , LNe = 27 K
  - Liquified noble gasses show:
    - Very high light yield O(10 pe/keV)
    - Very high electron lifetime O(10 ms)
- Beam experiments
  - Neutrino Long and Short baseline experiments at FNAL: DUNE/ICARUS
  - MEG/MEG-II
- Low Background experiments
  - Dark Matter detectors: DarkSide-20k, Xenon-nT
  - Double beta detectors: NEXO



- VUV light detection challenges
- Thermal issues
- Low radioactivity content

SiPMs in Dark Side





~ 23t of UAr

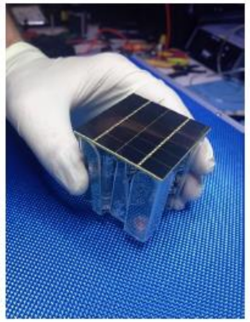
LAr (λ=128nm)
↓
TPB WLS:
emission 400–450 nm

2 light readout planes: 15 m^2

SiPM tiles

DarkSide-50
PMT-based TPC

DarkSide-20k
SiPM-based TPC



- Higher photo-detection
- efficiency
- Better single photon resolution
- Lower background
- Lower cost
- High dark rate
- Requires electronic development to combine SiPMs and reduced preamps etc

Transfert de techo entre FBK et LFOUNDRY

Calendrier DarkSide

50 kg a pris des données, amplis froids.

Proto 1T avec SiPM en construction, commissionning ‘20 au CERN, en ‘21 au Gran Sasso.

« 20k » en ‘23: 15m^2 de SiPM = 8000 canaux, chacun 25 pixels 5x5 cm^2

Expérience			2019	2020	2021	2022	2023	2024	2025	2026
DARKSIDE 50										
ARKSIDE PROTO										
DARKSIDE 20k										

DAMIC

CCDs pour la matière noire. Circuit intégré (CABAC pour Clocks And Biases ASIC for CCDs) développé par le LAL et le LPNHE, capable de fournir toutes les horloges (4 parallèles et 4 séries) et les tensions de polarisation nécessaires au bon fonctionnement des CCDs. Utilisé dans DAMIC où la qualité des horloges est essentielle pour minimiser le bruit de lecture

Circuit intégré ASPIC développé (CROC) DSI

MicroMegas

Sphère pour DM et DBD. Recherche d'Axions: CAST, IAXO.

Asics: GET/DREAM et VMM3 (pour ATLAS-NSW) et dans un futur NTOF.

Axions

CAST est plutôt vers la fin de sa vie. IAXO a été accepté au PRC à DESY
Premiere phase BABYIAXO est de 4 ans : 2023 mise en route (commissioning) avec l'aimant et 2024 prise de données.

Double désintégration β

Among the various experiments worldwide searching for neutrino-less double-beta decay, European experiments such as GERDA (focusing on germanium), CUORE (tellurium) and NEXT (xenon) are some of the most competitive.

^{130}TE: Cryogenic Underground Observatory for Rare Events (CUORE)

~1000 TeO_2 bollometers ~ 206 kg ^{130}Te

https://cuore.lngs.infn.it

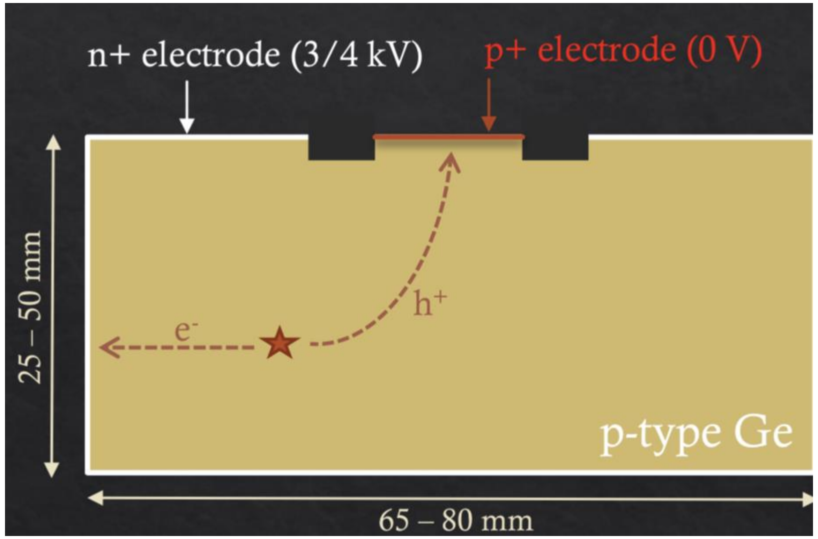
→ Later CUPID (CUORE Upgrade with Particle Identification) – cryo SiPMs

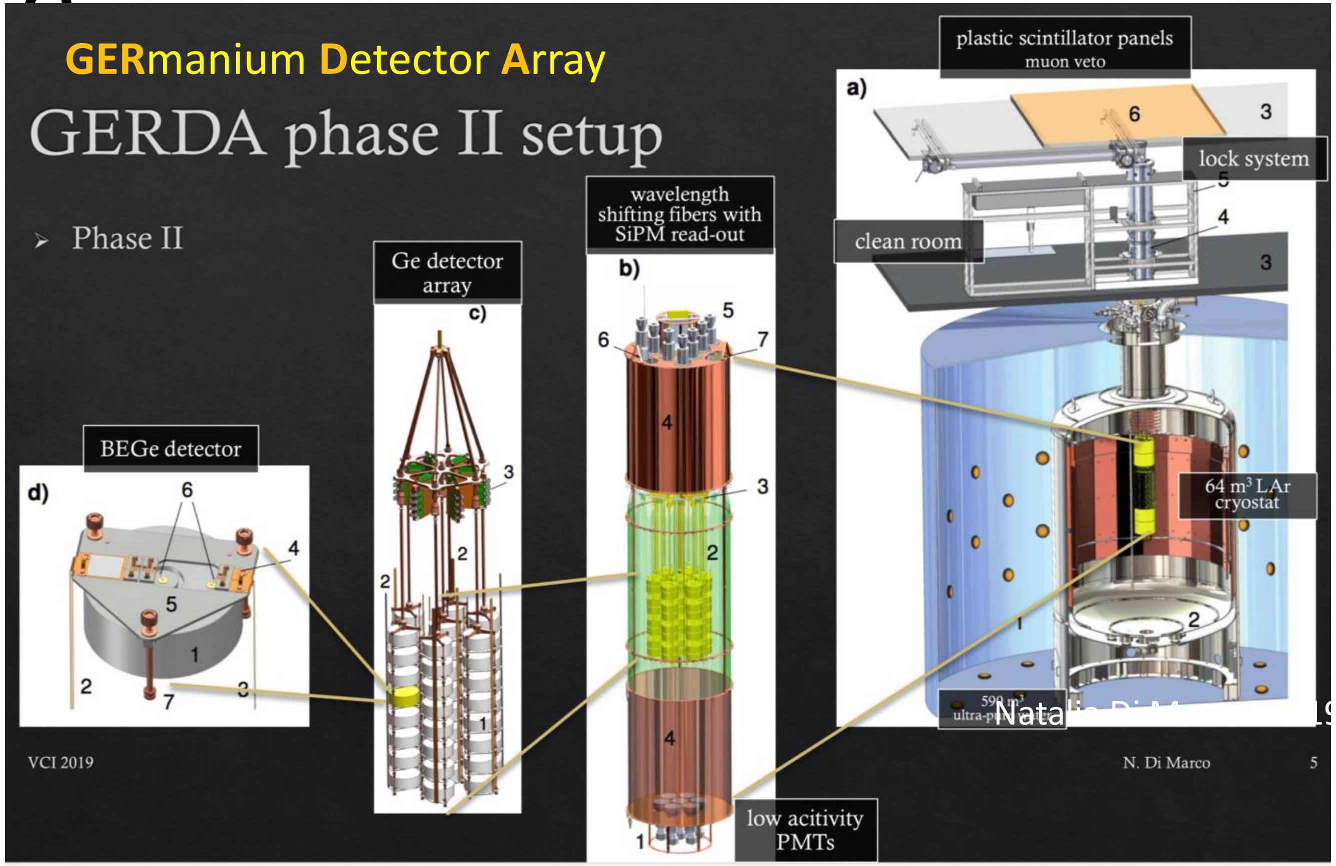
PandaX

$0\nu2\beta$ decay with solid state devices - Ge and Te

$^{76}Ge \rightarrow {}^{76}Se + 2e$ (38kg)

- Source = detector → high efficiency
- Radio-pure – no intrinsic background
- High density semiconductor - diode





GERDA, to be followed by LEGEND-200 kg and LEGEND-1000 kg

PandaX

TPC Micromégas dans Xe sous pression

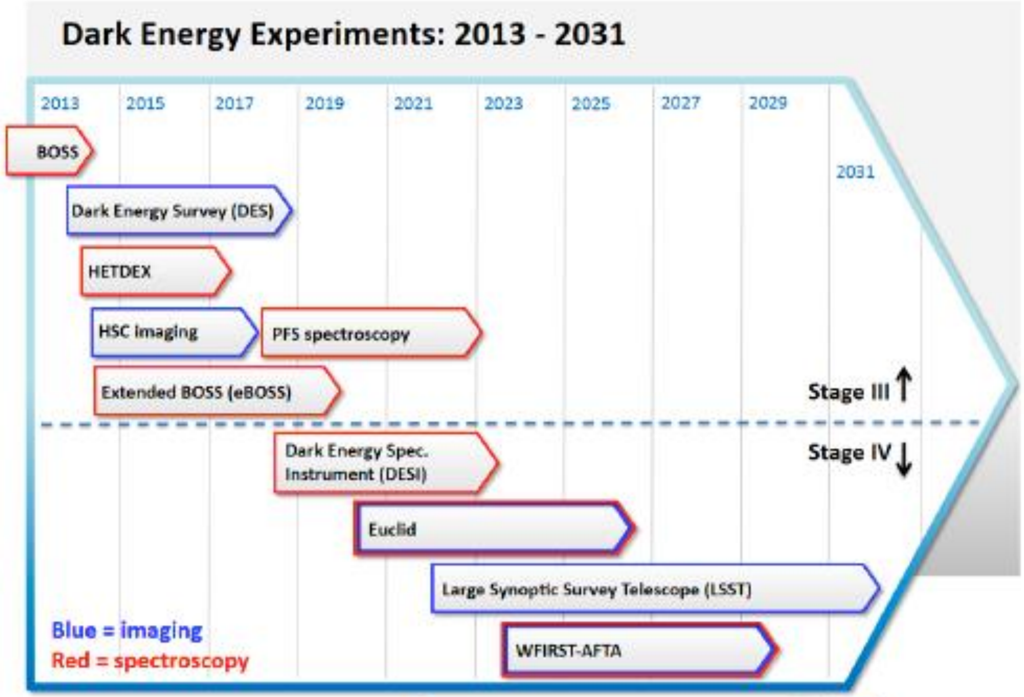
Asics GET

Cosmologie

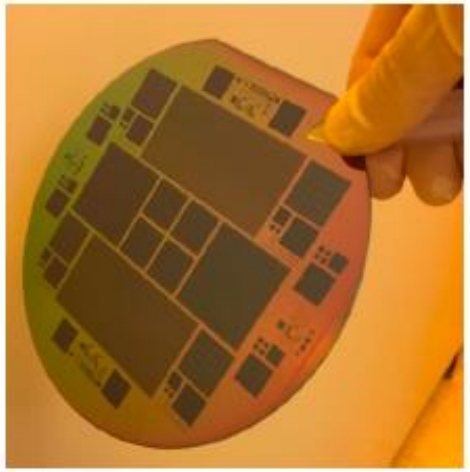
CMB and Dark Energy experiments

- Transition Edge Sensor
  - Widely used in stage-2 and stage-3 CMB experiments

- Microwave Kinetic Inductance Detectors



CCDs



Readout for **TES**

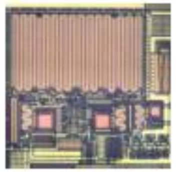
- TES is currently readout using SQUID as a first stage. ASIC can be developed both for **cryogenic** and **room temperature** operation.

  -> Time and frequency domain multiplexing topology

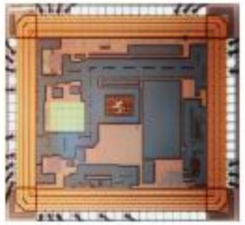
  - **Low noise amplification** (both TDM and FDM)
  - **SQUID biasing** (both TDM and FDM)
  - **Clocked SQUID biasing and/or amplification** (TDM)
  - **Buffering the TES biasing** (FDM)

Current development done for QUBIC and Athena X-IFU in the MHz readout range, both for TDM and FDM uses SiGe BiCMOS tech.

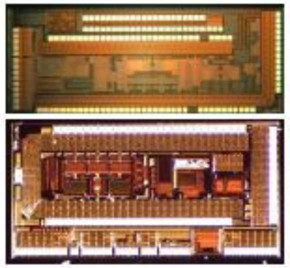
cryoLNA4HEB
1 nV/$\sqrt{Hz}$ 1 GHz 77K



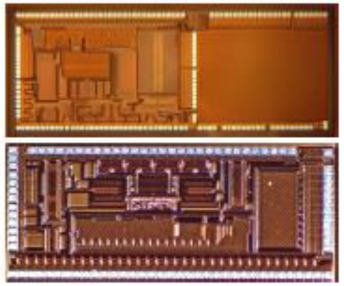
SQMUX8 2x4 TDM
.2 nV/$\sqrt{Hz}$ 5 MHz 4K



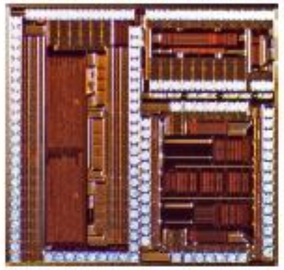
SQMUX24 3x8 TDM
.2 nV/$\sqrt{Hz}$ 5 MHz 4K



SQMUX128 4x32 TDM
.2 nV/$\sqrt{Hz}$ 5 MHz 4K



AwaXe_v1 FDM
.8 nV/$\sqrt{Hz}$ 10 MHz 300K

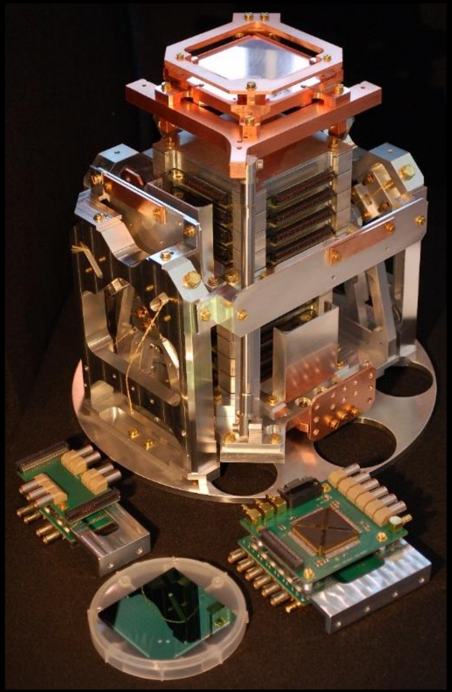


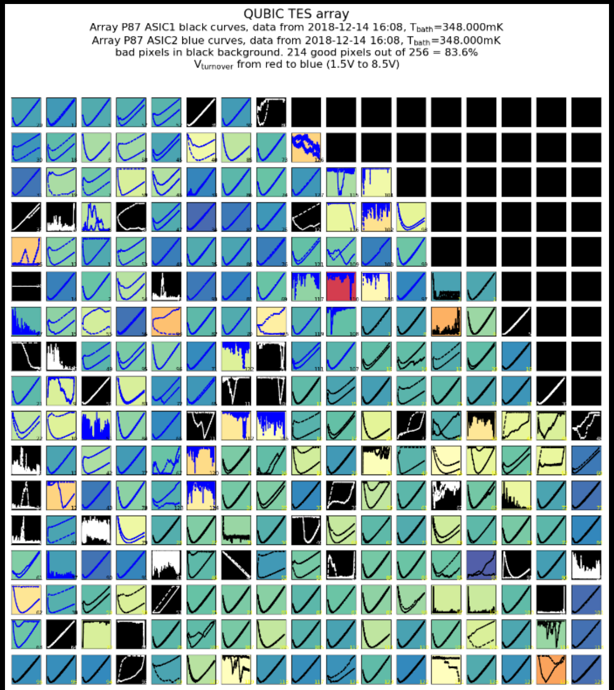
LNA design using BiCMOS SiGe technology

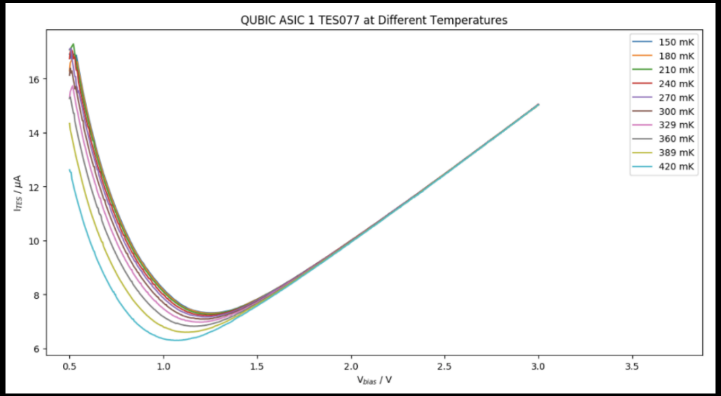
*SQmux*128, cryogenic ASIC for the TDM of QUBIC

AwaXe, Warm Front End Electronics for the FDM of ATHENA X-IFU

TES Detector Array



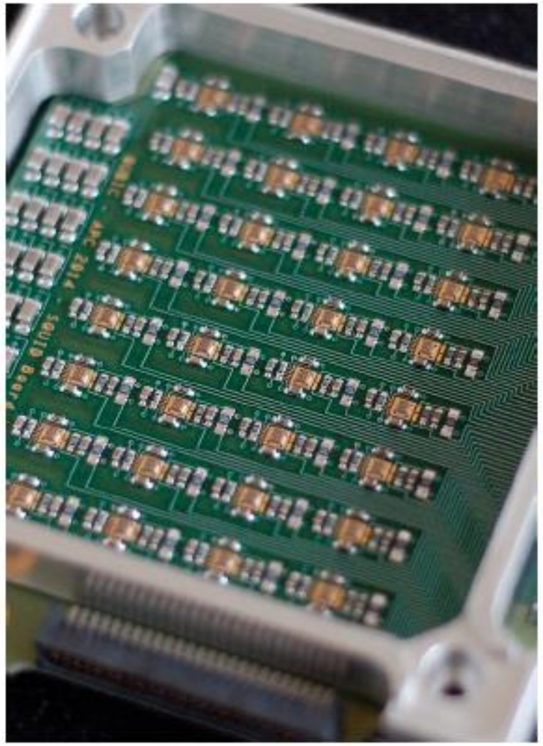


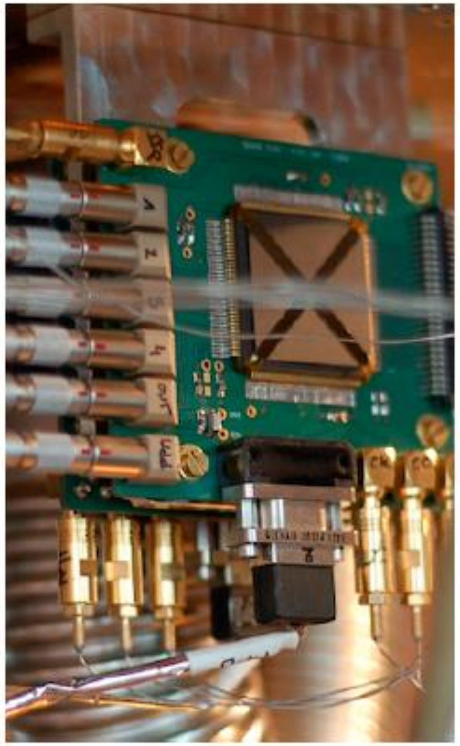


TES fabrication: CSNSM
Readout electronics: APC & IRAP

Cryogenic TES time domain multiplexer - QUBIC

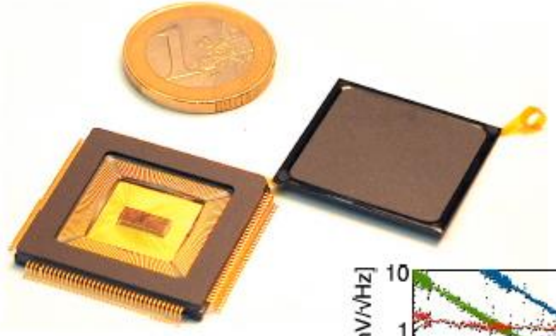
QUBIC readout chaine : TES (300 mK) + SQUID (1K) + ASIC (77K)

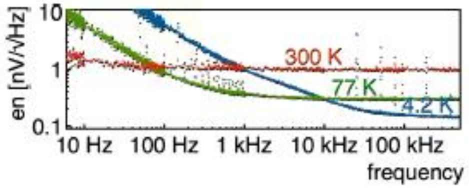


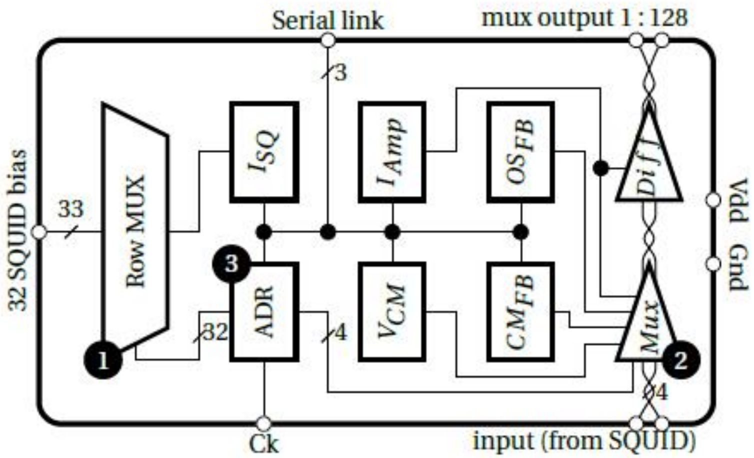


Correlated sampling on blind thermometers to remove 1/f noise

SiGe ASIC for cryogenic 1:128 TD SQUID M



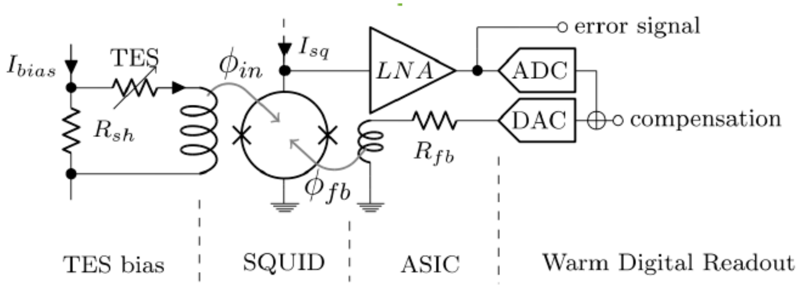




BiCMOS SiGe ASIC

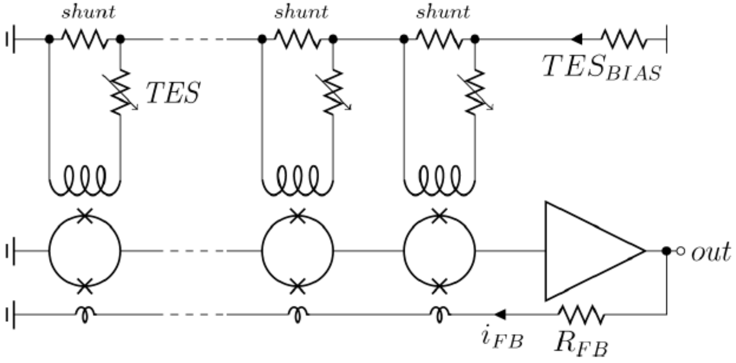
$350nm$ AMS technology

1. SQUID rows addressing: Biasing through capacitors with AC multiplexed current sources (1 : 32)
2. Low noise amplifier with multiplexed inputs: FLL preamplifier column mux. (1 : 4)
3. Digital addressing circuit controlled by external Ck



Multiplexage temporel à SQUID - 1D

Plusieurs SQUIDs sont connectés en série et polarisés 1 à 1.



Le signal de chacun des TES est lu successivement au rythme de la polarisation des SQUIDs

Besoins, futur

Réduction du bruit.

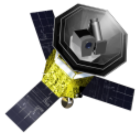
$5\ 10^{-17}$ W.Hz$^{-1/2}$

Ou 0.2 nV .Hz$^{-1/2}$

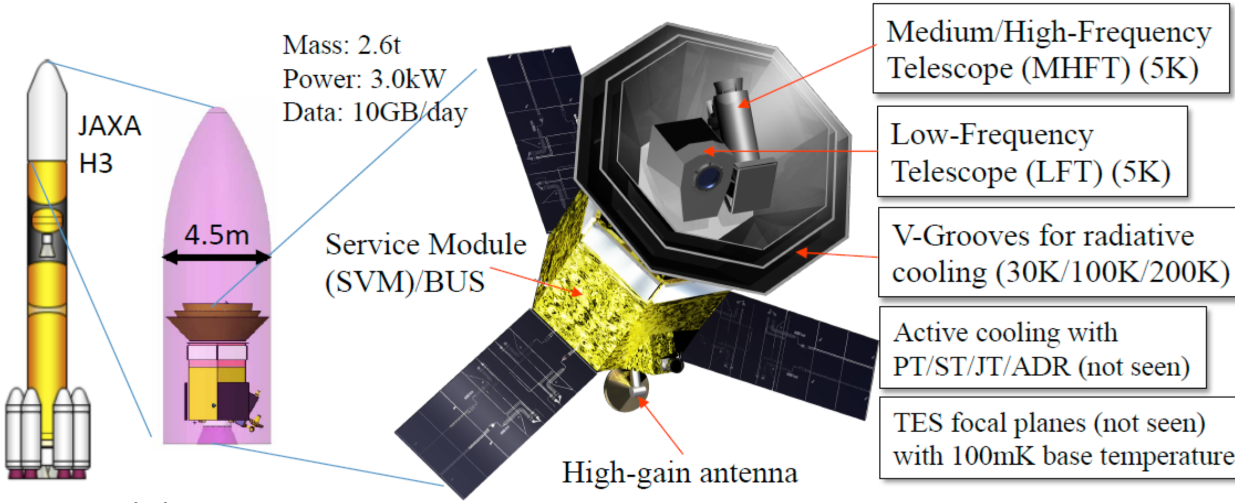
Pour l'aliasing (repliement de fréquence): augmentation de la fréquence d'échantillonnage pour TDM.

LiteBird

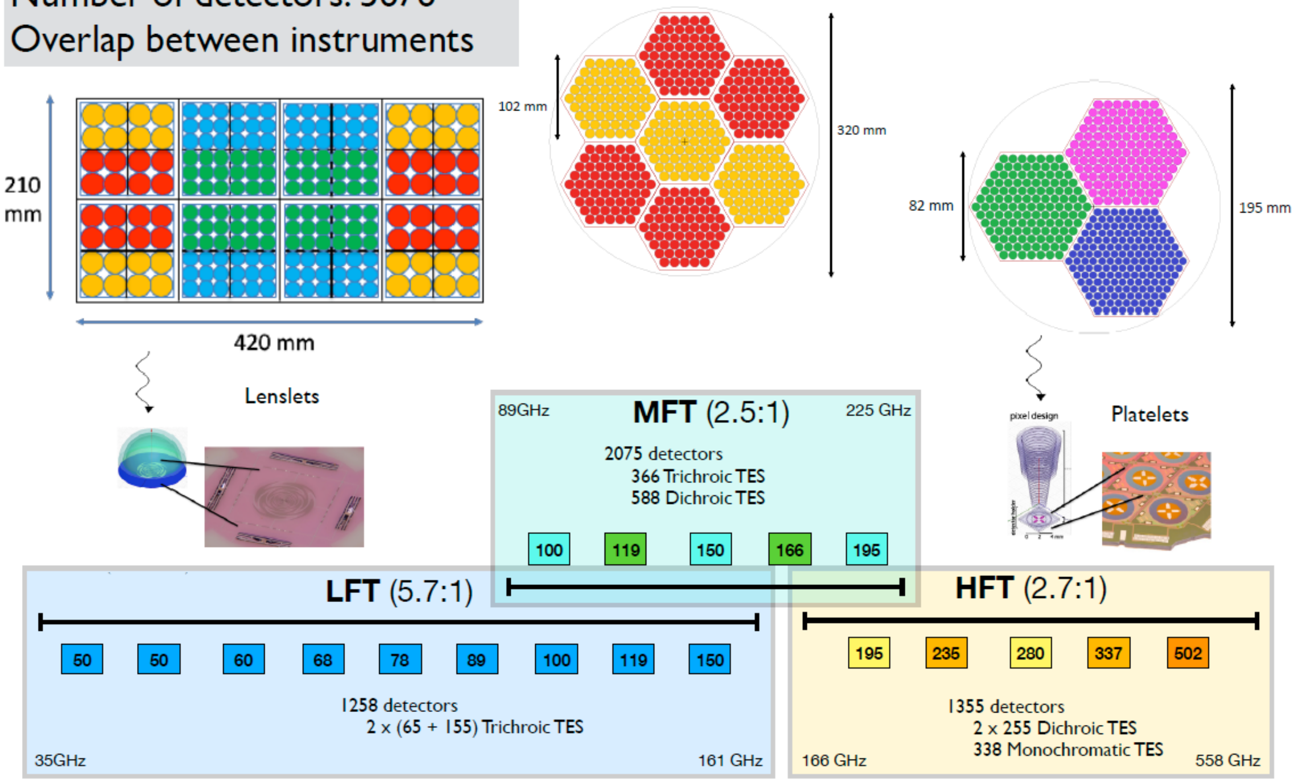
LiteBIRD - the basics



- JAXA's L-class mission (selected in May 2019)
- Expected launch in 2027 with JAXA's H3 rocket.
- Observations for 3 years (baseline) around Sun-Earth Lagrangian point L2.
- Millimeter-wave all sky surveys (34–448 GHz, 15 bands) at 70–20 arcmin.



APC, 09/12/19 European CMB coordination workshop 2019 7



R. Stompor, L. Montier
S. Henrot-Versillé

Technologies

Notre prospective In2p3 – Irfu 2012:

- La compatibilité de la technologie AMS 0.35 SiGe avec les très basses températures ouvre de nouvelles opportunités pour l'instrumentation qui demande un effort conséquent. Même si la pérennité de la technologie 0.35µm est encore assurée pour quelques années, une transition progressive vers de nouvelles technologies est nécessaire. Le choix est plus compliqué que dans le passé et il se porte non plus vers une, mais plusieurs technologies cibles. Les technologies 0.13µm ou 65 nm, sur lesquelles le CERN mise, semblent incontournables pour les applications LHC nécessitant un fort durcissement (trackers). L'offre TOWER 0.18µm est particulièrement attractive pour les pixels monolithiques actifs, car incluant des modules spécifiques, mais reste coûteuse pour les autres designs. Le noeud technologique SiGe 0.18µm Instrumentation semble être le successeur naturel du 0.35µm pour les applications visant une grande dynamique et des besoins de faible offset et grande précision (calorimètres et TPC).
- Les technologies 3D paraissent très attractives, cependant la faiblesse de l'offre commerciale et le récent retour d'expérience sur le run Tezzaron/Globalfoundry démontrent clairement qu'elles ne sont pas matures et engagent à la prudence et à réfléchir à des noeuds technologiques plus fins.

- En 2012 beaucoup de laboratoires tiraient profit du savoir faire sur la techno AMS 0.35. Fin de cette technologie fin 2020. C’est un défit, ou pour le moins un gros changement, à envisager pour de très nombreux groupes (Omega, IRFU, … APC). Ce virage a déjà été pris par plusieurs labos (LPSC Clermont, IPNL, LPSC Grenoble, Omega) avec le démarrage de la « Collaboration/Projet BB130 » qui vise a organiser un usage commun de la technologie TSMC130nm. (pour remplacer la techno AMS0.35?) …
- La nouvelle technologie TSMC n’a pas de Bipolaire SiGe (composants indispensables pour les applications Cryo et/ou large-bande et bas bruit. A l’APC, on essaie de remplacer l’AMS0.35 par une technologie qui elle bénéficie de Bipolaire SiGe (la ST130nm)

  - (extraits de commentaires de D Prêle)

CMB suite: CORE

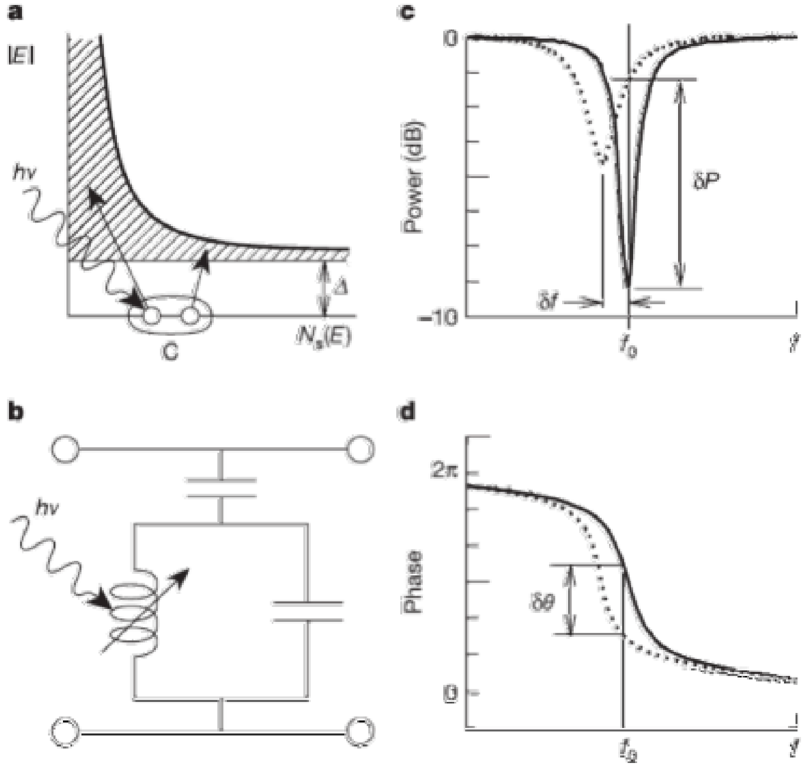
Satellite CMB refusé par l'ESA. Projet après LiteBird, plus grand télescope, résolution angulaire, périmètre scientifique plus large.

TES ou KIDs.

KIDs

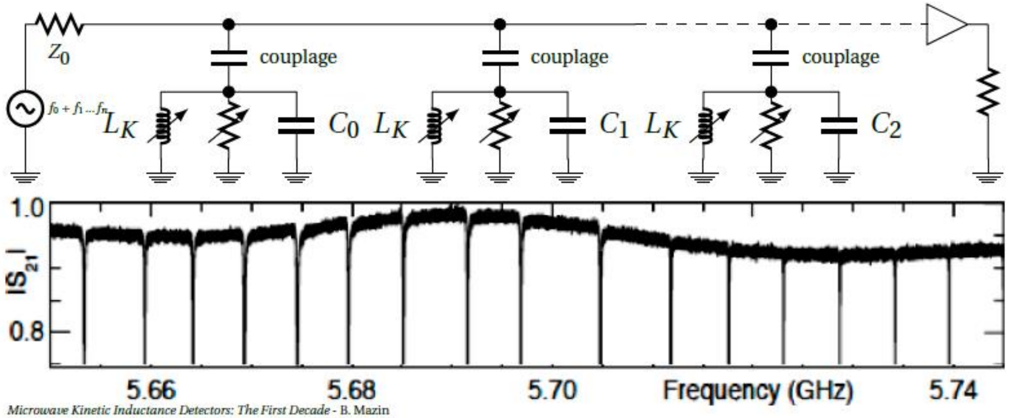
Kinetic Inductance Detectors (KIDs)

- Effect of photon absorption in a superconductor:
  - **If hν>2Δ**: Cooper pair breaking
  - Change of kinetic inductance and ohmic losses
- **In a resonant circuit: change of resonance**
  - **Shift in resonant frequency:** $1/\sqrt{C(L_m+L_k)}$
  - **Decrease of the quality factor**
- Detection technique used
  - In the mm/sub-mm wavelength range
  - In the visible/NIR: low spectral resolution photon counting

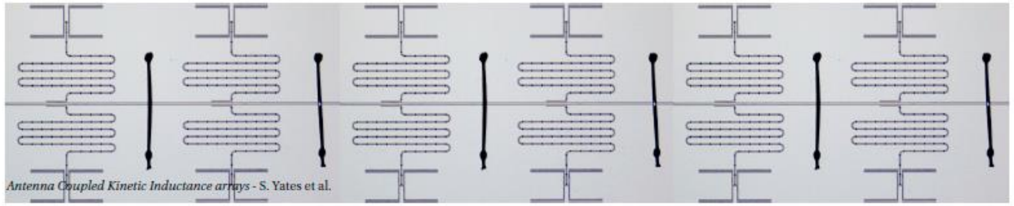


P.Day et al. Nature 2003

KID multiplexing

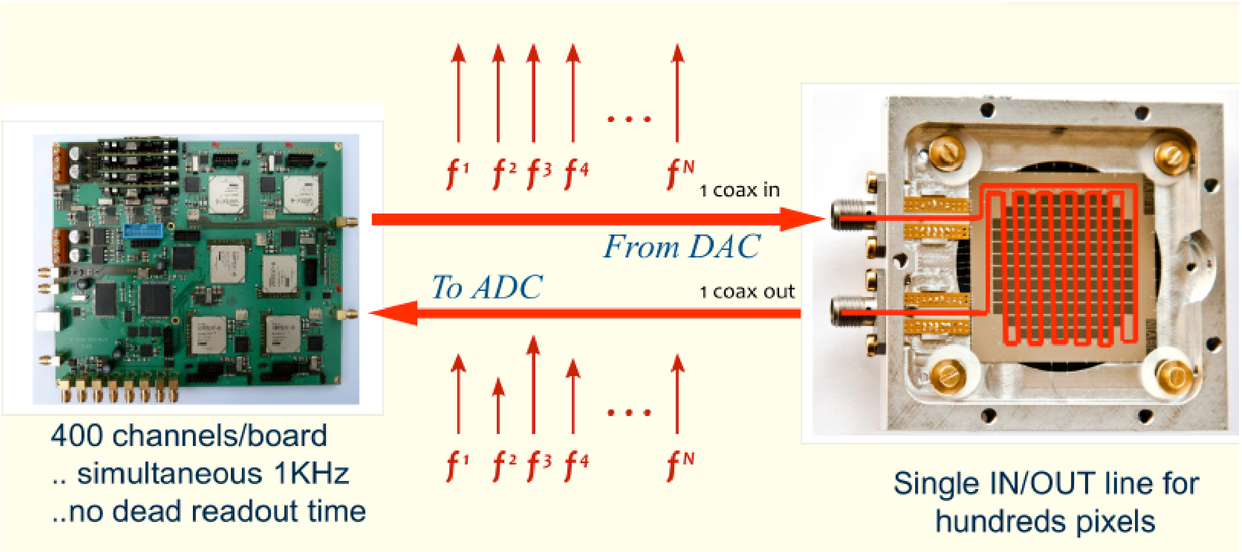


Microwave Kinetic Inductance Detectors: The First Decade - B. Mazin



Antenna Coupled Kinetic Inductance arrays - S. Yates et al.

KID/FDM by NEEL



Journal of Instrumentation 7, Issue 07, 7014 (2012)
Journal of Instrumentation 8, Issue 12, C12006 (2013)
Journal of Instrumentation, submitted, arXiv:1602.01288

NIKA and NIKA2: from the pathfinder KID camera to the ultimate mm-wave imaging/polarimetry at the 30-meters Pico Veleta telescope - A. Monfardini - 2017

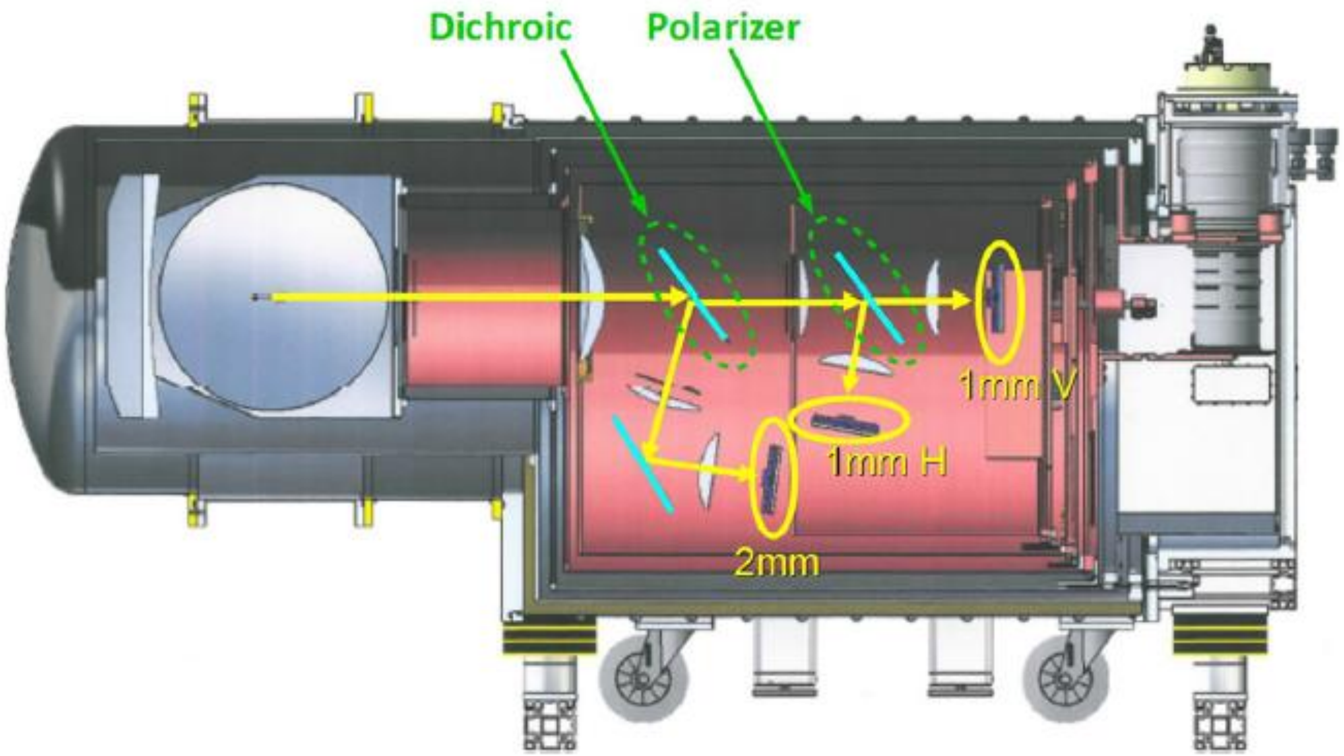
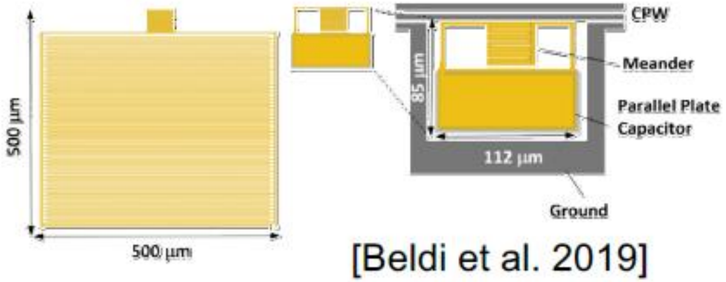


Fig. 1 Schematic representation of the NIKA2 cryostat, with the optical path to the three arrays in evidence. The cryostat is 2.3 m long and weighs more than 1 ton (Color figure online)

Pas de microélec dans le système de lecture des KIDs de Grenoble. Système numérique: on passe dans un ADC rapide puis tout est fait dans un FPGA avec aussi un DAC rapide.

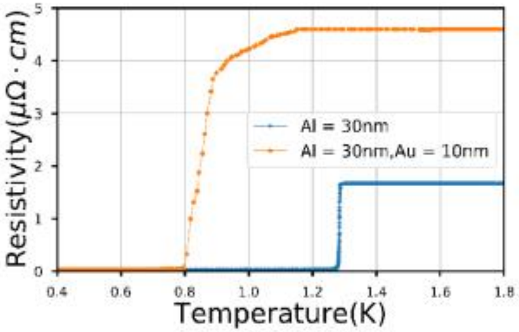
NGKIDs: Work packages

- **WP1: Optical/NIR KIDs fabrication**
  - Fabrication of optical/IR KIDs array of 1000 pixels
  - Use of TiN



[Beldi et al. 2019]

- **WP2: Novel KIDs devices**
  - New material
  - Proximity effect (Al/Au)
  - KIDs tuning



[Hu et al. 2019]

- **WP3: Readout system**
  - Use of commercial board (HTG-ZRF8 from Hitech Global)

Lecture par FPGA. Développement: un ASIC pour l’ amplificateur analogique

LSST

Le plan focal comprend 189 CCDs (Charge-Coupled Device ou Dispositif à Transfert de Charges) de 4096x4096 pixels chacun. Chaque CCD sera lu en parallèle à travers 16 canaux de sortie correspondant chacun à 2048x512 pixels par un circuit intégré ASPIC

Analog Signal Processing ASIC dedicated to the analog processing
of the CCD outputs. ASPIC, 8 channel DSI, AMS 0.35 "m chip. Clocks And Bias: discrete component (COTS)

Euclid

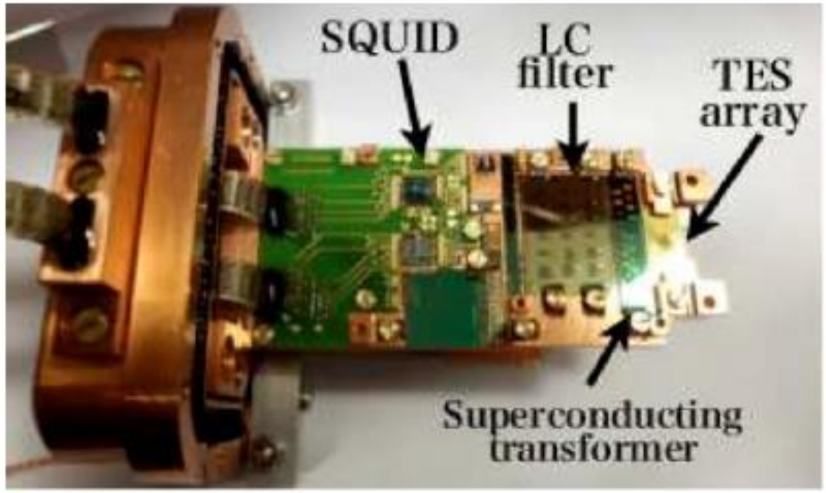
CCDs, Asics de lecture Teledyne?

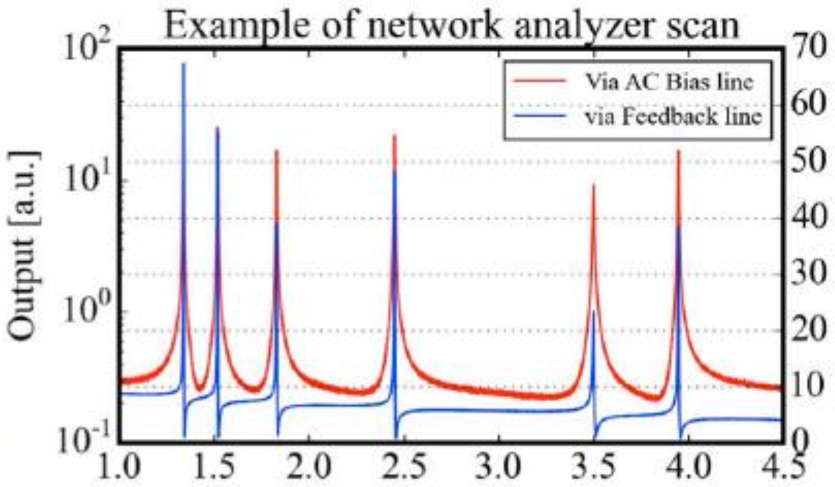
IR, X et gamma sur satellite

SVOM

Détecteurs CdTe, Si. Asics JFET, lisent comme un CCD, DepFet

FDM by SRON 1D ATHENA X-IFU demonstrator



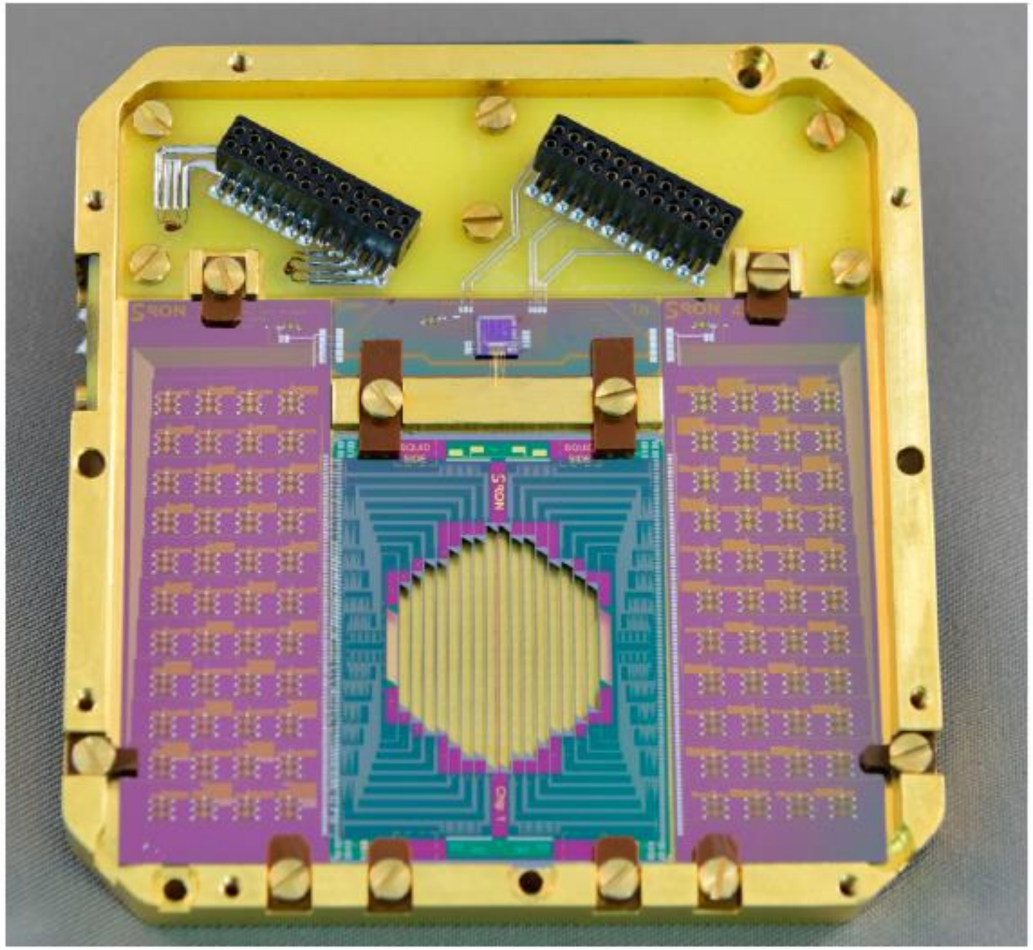


Development of FDM for the X-ray Integral Field Unit (X-IFU) on the Athena - H. Akamatsu et al. - 2016

A35S18_2 AWAXE_V2DOT5

is an upgrade ASIC developed for the Warm Front End Electronics (WFEE) of the future X-ray space telescope ATHENA. This 2.5 version integrates an ultra-low gain-drift LNA (Low Noise Amplifier), a buffer and 8 configurable current sources developed for a breadboard version (Phase A) of the X-IFU (X-ray Integral Field Unit) readout chaine - ATHENA space observatory. This ASIC also includes series bus RS485/I2C for slow control using RadHard by Design digital library and a differential thermometer for high common-mode noise rejection HK (HouseKeepig and Telemetry). This ASIC is one of the AwaXe and SQmux ASIC families developed at APC for the SQUID/TES readout. This development is funded by CNES and CNRS. This chip is developed to demonstrate the readout of one cryogenic multiplexer (Frequency domain SQUID multiplexer in the 1-6 MHz) for the X-IFU instrument.

FDM by SRON 1D for the far-infrared satellite mission SPICA



Détecteurs radio

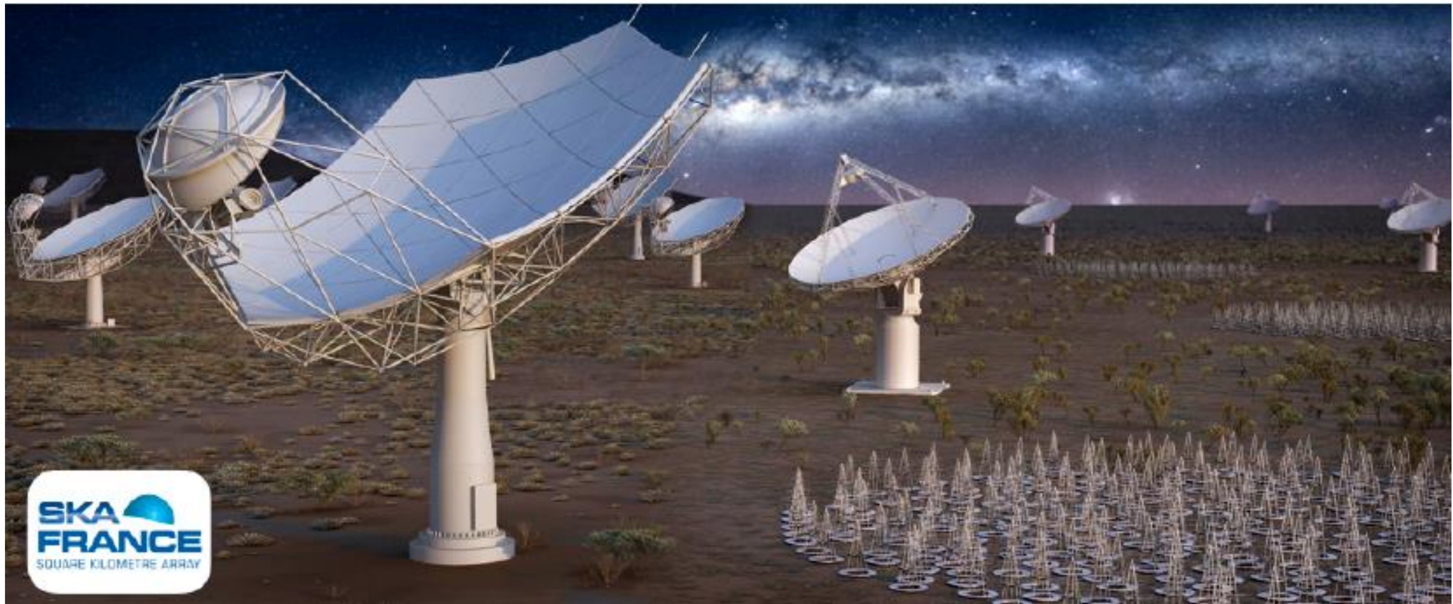
SKA

Several interferometric arrays to observe metric and centimetric wavelengths. The deployment of the SKA in two sites, in South Africa and Australia, and in two phases separated in time:

Phase 1, estimated cost of €674 million, the start of construction planned for 2020 and of commissioning by 2024+, consists of installing approximately 10% of the nal arrays. It will include about 200 dishes in South Africa and slightly more than 130,000 low-frequency simple antennas organised in phased arrays in Western Australia. In this configuration, SKA1 will represent a huge qualitative leap with respect to existing instruments, and will allow decisive advances in all the domains of modern astrophysics and physics, such as cosmology, the origin of cosmic magnetic fields, the physics of the interstellar medium, the formation of stars at different epochs of the universe, the detection of gravitational waves, . . .

Phase 2 is envisaged for 2030+.

(Livre Blanc SKA France 2019)



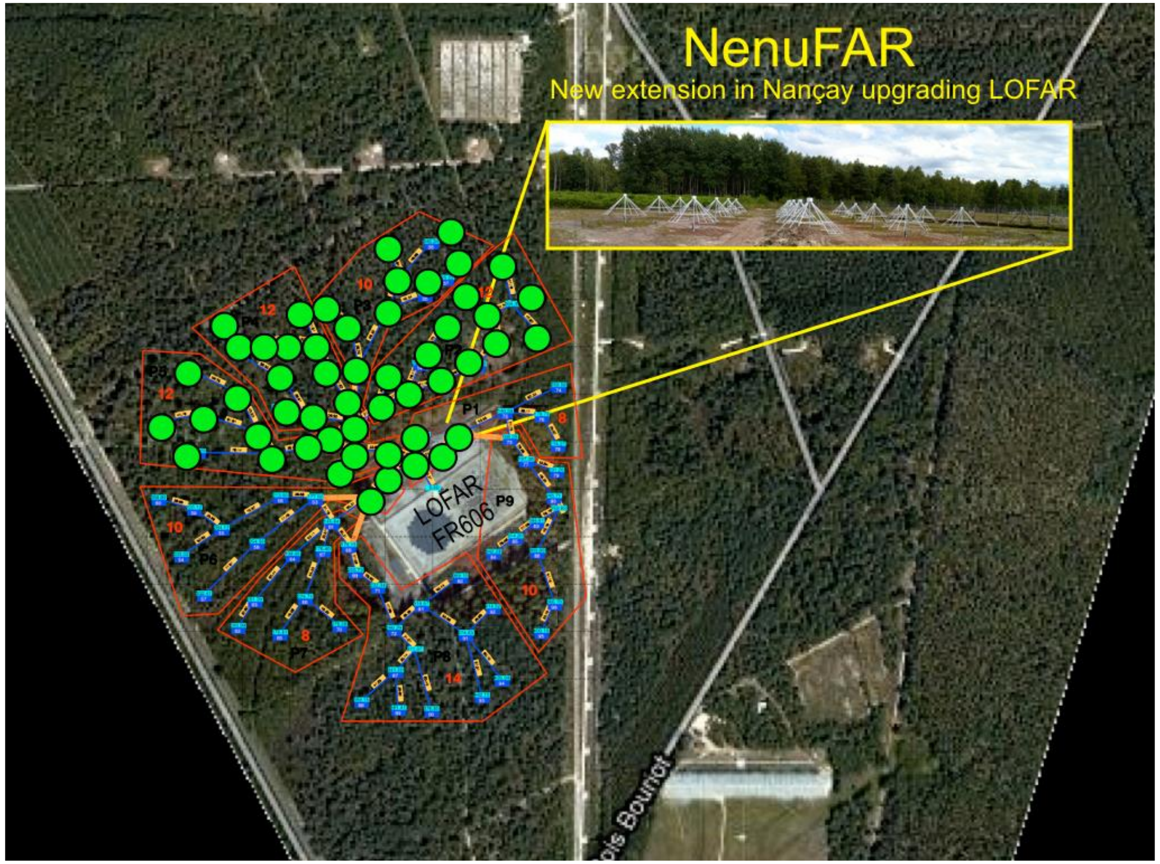
Fréquences: Low (Lofar-NenuFar), Medium (Embrace), High

Low (50 to 350 MHz): hundreds of thousands of simple antenna elements (e.g. dipoles or log{periodic elements), which will be arranged in hundreds of stations of a few metres in diameters. The signal of all elements within one station will be combined numerically and all the stations will work together forming a so called aperture array. The station separation will go from a few tens of meters in a central core area, to several tens (up to hundreds) of km in the outer distribution, which will include a few spiral arms. This low-frequency part of the telescope is going to be built in the Murchison desert of Western Australia.

High (above 350 MHz): hundreds of 15 m diameter dishes, to be initially distributed within the Karoo desert (about 500 km North of Cape Town) and subsequently extending to different states in central up to northern Africa, going from maximum baselines of hundreds to thousands of km.

Intermediate frequencies: Further technical developments are planned, also with dense aperture arrays.

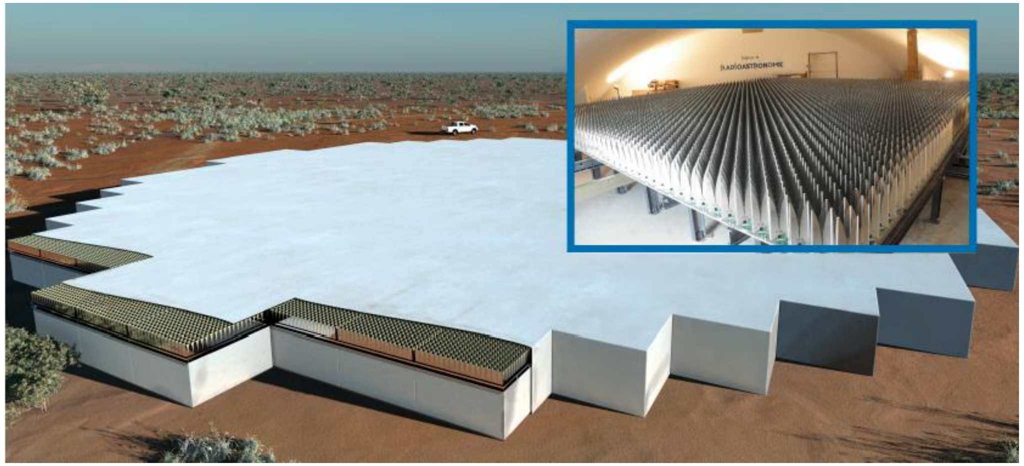
LOFAR et NenuFAR à Nançay



The antennas contain each an ASIC preamplifier, whose design (made in France) ensures a very at response over the whole (10-85 MHz) frequency range with a noise 10 dB below the sky noise level (Girard et al. 2012).

Suite sur SKA? D Charrier Subatech.

Moyennes fréquences



Artist's conception of a single station of a mid-frequency aperture array instrument proposed
for the Square Km Array (SKA). Over two hundred stations will be required for the full SKA. The inset shows the currently operational EMBRACE array at the Nançay composed of 4608 Vivaldi antenna elements separated from each other by 12.5 cm, making it a dense array for frequencies above 1200 MHz. EMBRACE@Nançay measures 8.42 m 8.42 m for a total area of 70.8 m2.

Aperture arrays are composed of many small antennas with signals combined together to form the equivalent of a telescope with large collecting area. Digital combination. The Observatoire de Paris developped the analogue integrated circuit responsible for the first stage of beam forming (Bosse et al. 2010)

Electronique similaire à PP et AP? Distances entre antenne et lecture -> amplis de tension (ou P) et pas I,Q

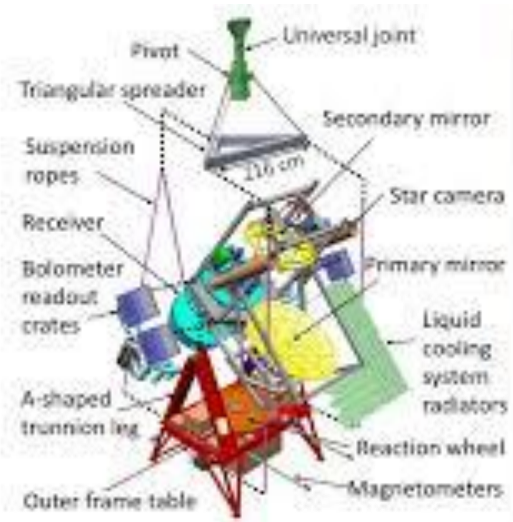
-OMEGA
-Timepix
- SoC
- HyperKamiokande

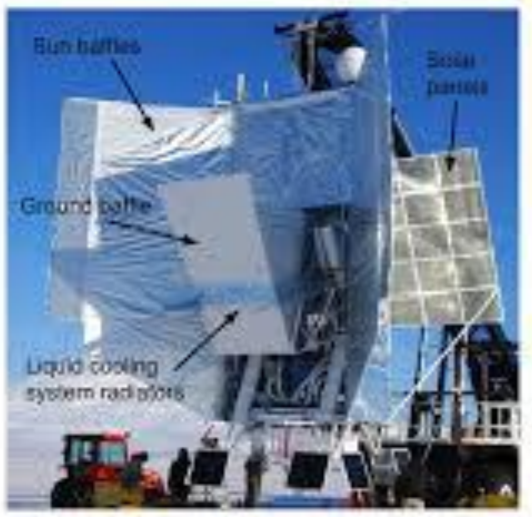
Choix: analogique-numérique et discret-monolithique

Notre prospective In2p3 – Irfu 2012:
La numérisation des signaux se fait de plus en plus tôt : les circuits mixtes discrets intègrent des préamplificateurs « maison » directement suivis par des ADC rapides du commerce pour échantillonner les signaux et les envoyer vers des FPGA. Le traitement numérique du signal de plus en plus puissant permet de traiter à la fois les informations charge et temps et de mémoriser la forme des signaux.

Choix: FPGA <-> Asics

Proposé en 2015 pour la lecture des TES sur le plan focal du Ballon Ebex-10K pour le CMB par J. Delabrouille et Omega. Ballon ou spatial





IA –apprentissage machine embarqué

- Téléphones
- Reconnaissance de formes
- Conduite automatique
- Appareils domestiques…

Can we use analog/mixed-signal circuits to improve the efficiency of "edge" machine learning systems?

Mixed-Signal Techniques for Embedded Machine Learning Systems Boris Murmann

https://tinymlsummit.org/meetups/bay-area-murmann-20190926.pptx

https://murmann-group.stanford.edu/mediawiki/index.php/Main_Page

CMOS circuits for Applications in Quantum Engineering

Loick LE GUEVEL CEA-Leti/IRIG

Quantum bits consisting of single electron or hole spins are realized at CEA-Grenoble on 300mm-wafer industrially compatible CMOS technology.

Their spin state can be manipulated and read-out to build, one-day, a quantum processor. While semiconductor technologies might allow the fabrication of the required thousands of quantum-bits, it also opens valuable possibilities for integrated electronics along with the quantum processor, allowing for better qubit control and higher speed.

Cryogenic circuits are designed and tested at CEA-LETI/IRIG using the newly-developed Fully Depleted Silicon-On-Insulator 28nm CMOS technology at temperatures as low as 50mK.

Sources et documents

- Prospective 2012 In2p3-Irfu: http://journeesprospective-in2p3-irfu.in2p3.fr/ , Document synthèse, GT14
- MultiplexageCryo_PRELE_DRTBT2018_presJourJ
- Cours E Delagnes 2009

Merci de votre attention