Physics Highlights and Challenges

Astroparticle Physics Towards a New Roadmap

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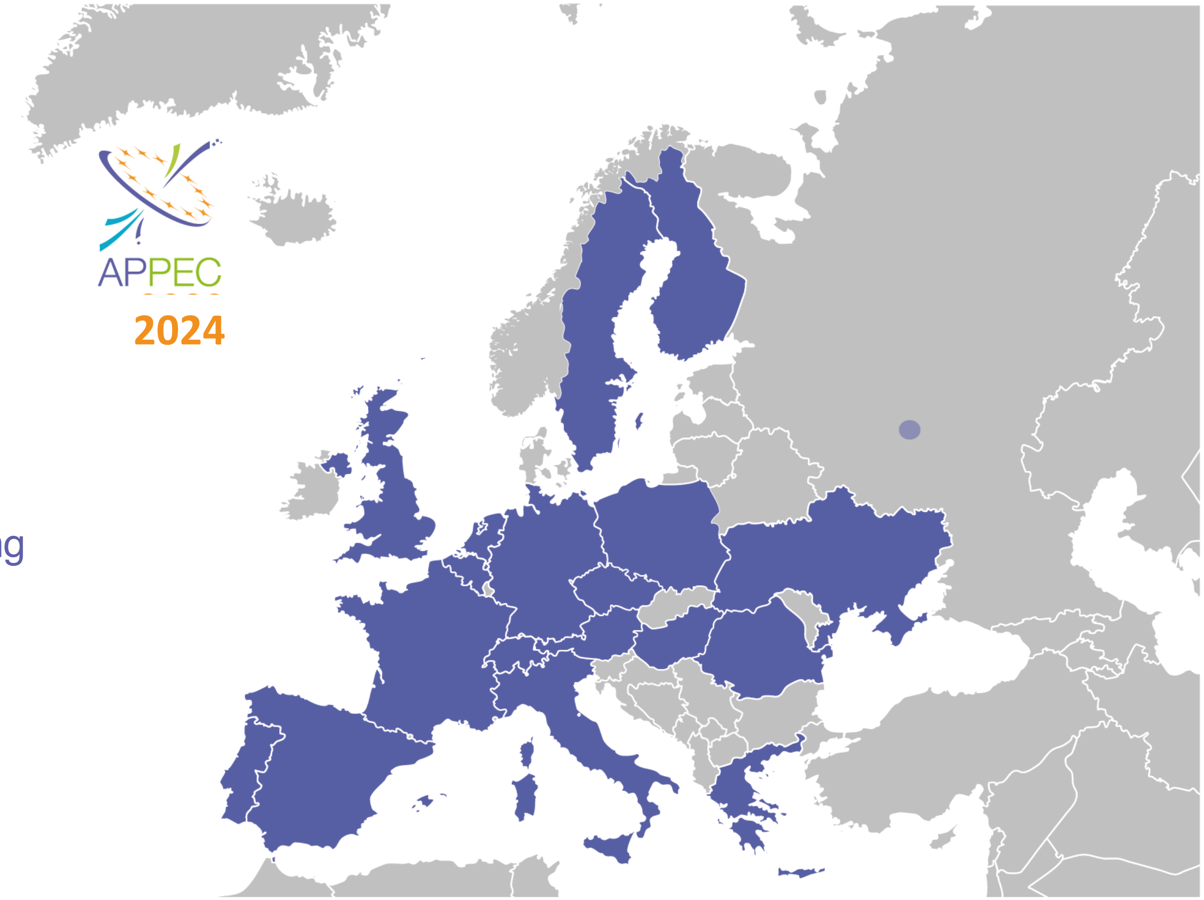
INFN Gran Sasso Laboratory

ISAPP 2025 Lecce, June 20th 2025

APPEC: what is it?

www.appec.org



AstroParticle Physics European Consortium

- An international coordinating structure, founded in 2001 to facilitate EU network in Astroparticle
  - ✓ European Strategy for Astroparticle Physics published in 2008
  - ✓ First roadmap with priorities in 2011
- Based on MoU by all partners and an APPEC Common Fund of order 70k€/year
- 18 (+1 suspended) member countries with 22 funding agencies
  - In discussion with Denmark and Norway
- 3 bodies:
  - **General Assembly** with Observers
  - **Scientific Advisory Committee**
  - **Joint Secretariat**

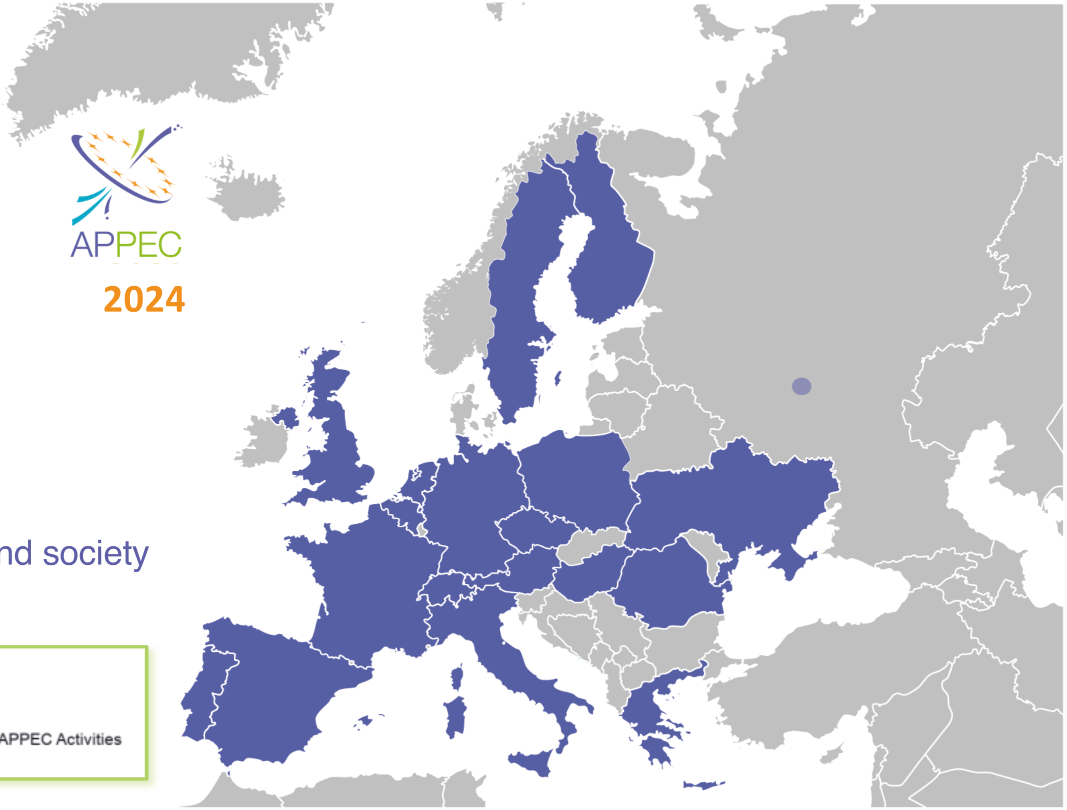
APPEC Bodies

APPEC

- **General Assembly**
  - Strategic, decision making and supervisory body
  - Representatives of funding agencies
  - Chair: **Carlos Peña-Garay** (LSC, Spain) 2025-2026
  - Vice-Chair: **Antoine Kouchner** (APC, France)
- **Scientific Advisory Committee**
  - Advisory body
  - Chair: **Aldo Ianni** (INFN-LNGS) since June 2024;
  - Vice-Chair: **Mathieu de Naurois** (CNRS) since June 2024
- **Joint Secretariat (distributed office)**
  - Executive body chaired by the General Secretary
  - General Secretary: **Julie Epas** (APC) since June 2024
- **Connections**
  - Nuclear, particle, and astroparticle physics communities (NuPECC, ECFA, APPEC, ESFRI) joining efforts for science and society
  - ESO (Andy Williams)
  - EPS-HEPP (Ramon Miquel)
  - EU Consortium for Astroparticle Physics Theory (EuCAPT, Silvia Pascoli)

JENAA
Joint ECFA-NuPECC-APPEC Activities

www.appec.org



APPEC
2024

Outcome: APPEC roadmaps

https://www.appec.org/roadmap

APPEC

2008

2011

2017 + 2023 midterm update

APPEC roadmap – scientific/technical topics

- Cosmic rays
- High-energy neutrinos
- High-energy photons
- Gravitational waves
- WIMP Dark Matter
- Non-WIMP Dark Matter
- Neutrino properties
- Cosmic Microwave Background
- Dark Energy
- Multi-messenger astroparticle physics
- Astroparticle theory
- Instrumentations and technology
- Computing and data policies

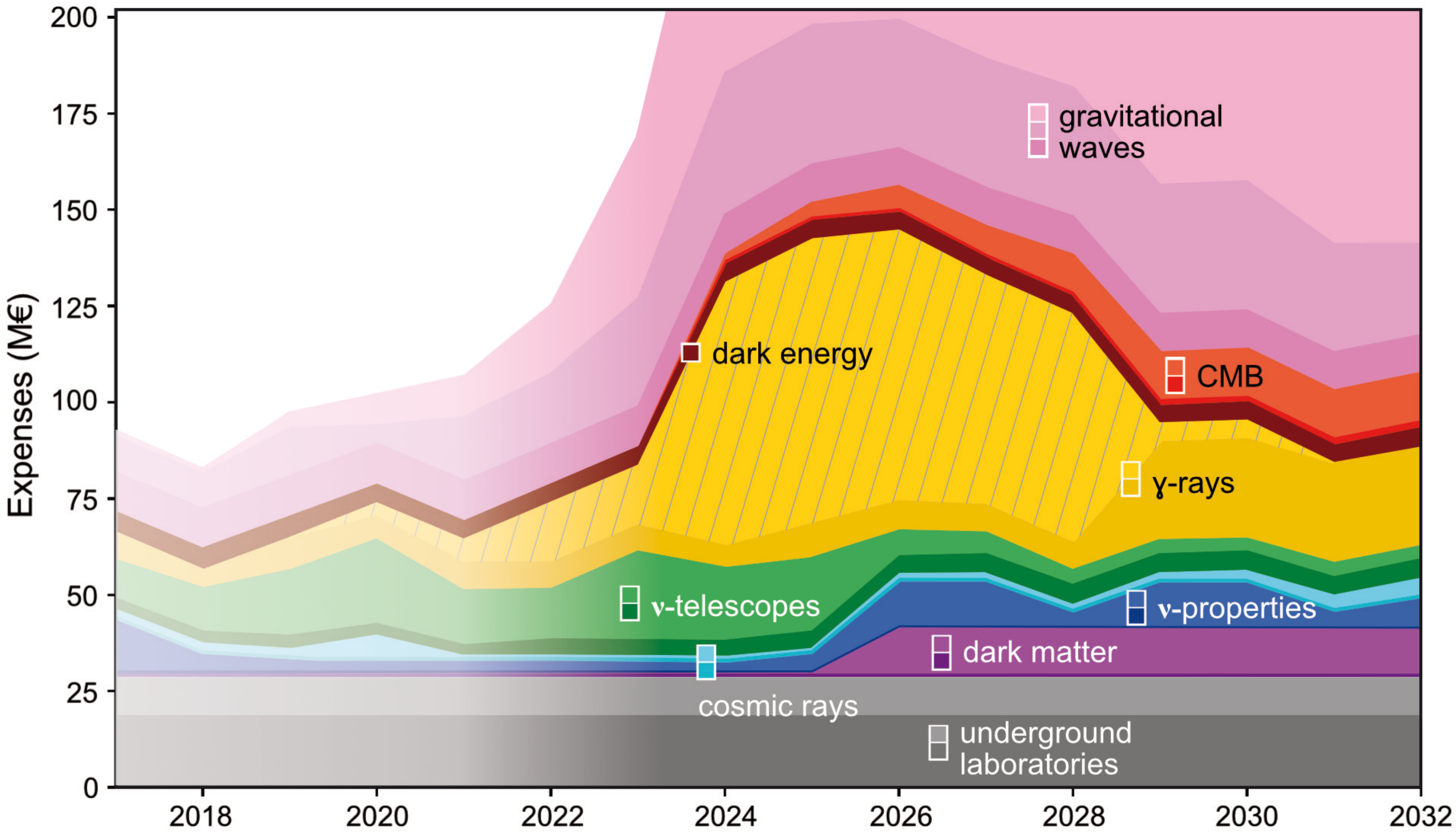
- Ecological Impact
- Societal Impact
- Open Science and Citizen Science
- Human Talent Management
- Central Infrastructures
- European and Global Cooperation
- Interdisciplinary Opportunities

Recommendations are given for each topic

Resources updated: survey from major experiments/projects

A resource aware roadmap
(darker colors show M&O of RI)

Roadmap Update 2023: projected annual capital investment

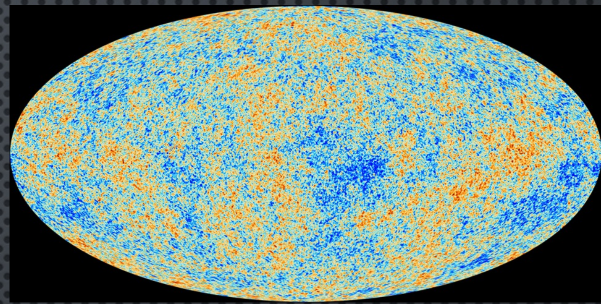


THE BIG QUESTIONS IN ASTROPARTICLE PHYSICS
(FROM APPEC SAC)

- What is Dark Matter ?
- What is Dark Energy ?
- What is the origin of a matter and not anti-matter dominated universe ?
- Can we prove deeper into the earliest phases of the Universe ?
- What are the properties of neutrinos ?
- Can we identify source of high-energy neutrinos ?
- What is the origin of cosmic rays ?
- Do proton decay ?
- What do gravitational waves tell us about general relativity and cosmology ?
- What will multi-messenger astronomy teach us ?

OUR UNIVERSE AS A LABORATORY

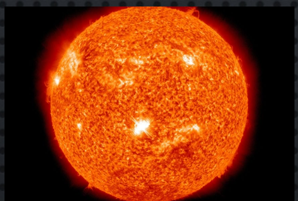
CMB



Large Magellanic Cloud 50kpc
Host remnant of SN1987A

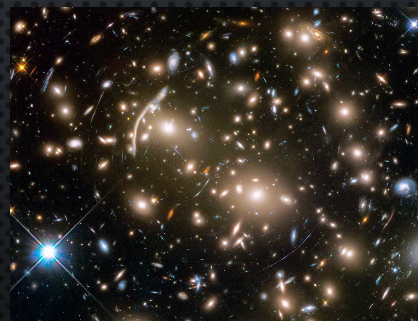
Betelgeuse180pc

Sun



Milky Way

Galaxy cluster 4Gpc

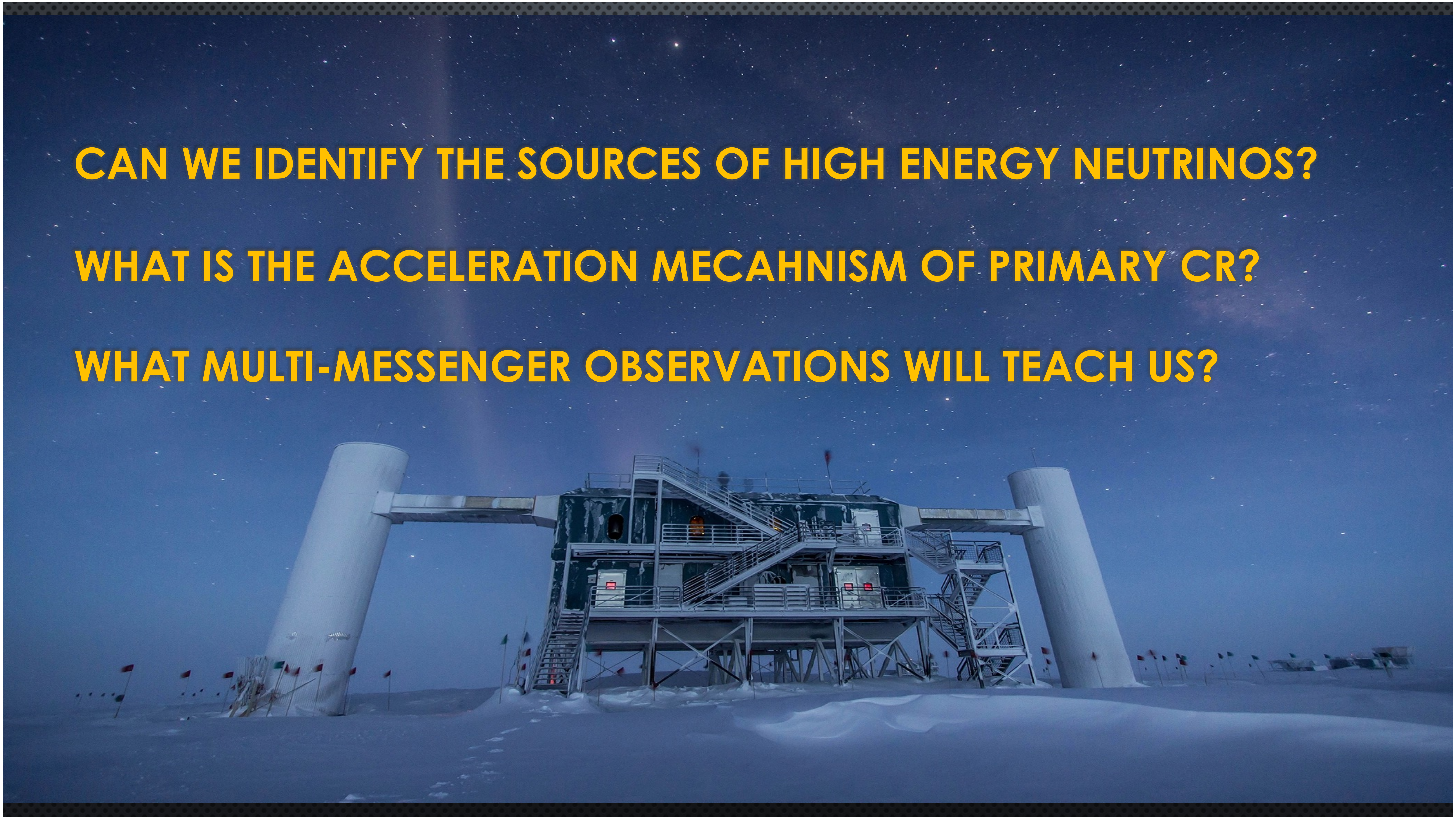


ASTROPARTICLE PHYSICS MODALITY

- Satellite-based experiments
- Ground-based experiments (telescopes, reactors, accelerators)
- Underground experiments: ice, water or rock overburden

ABOUT THIS TALK

- Selection of highlights
  - ➢ Astroparticle has many projects over wide topics
- Not covered
  - ➢ Neutrino oscillations
  - ➢ Solar, SN neutrinos, and proton decay
  - ➢ Nuclear astrophysics in underground laboratories
- Next APPEC roadmap


CAN WE IDENTIFY THE SOURCES OF HIGH ENERGY NEUTRINOS?
WHAT IS THE ACCELERATION MECAHNISM OF PRIMARY CR?
WHAT MULTI-MESSENGER OBSERVATIONS WILL TEACH US?

NEUTRINO ASTRONOMY

- **NEUTRINOS FROM ASTROPHYSICAL SOURCES ARE IDEAL PROBES TO UNDERSTAND THE ORIGIN OF COSMIC RAYS**

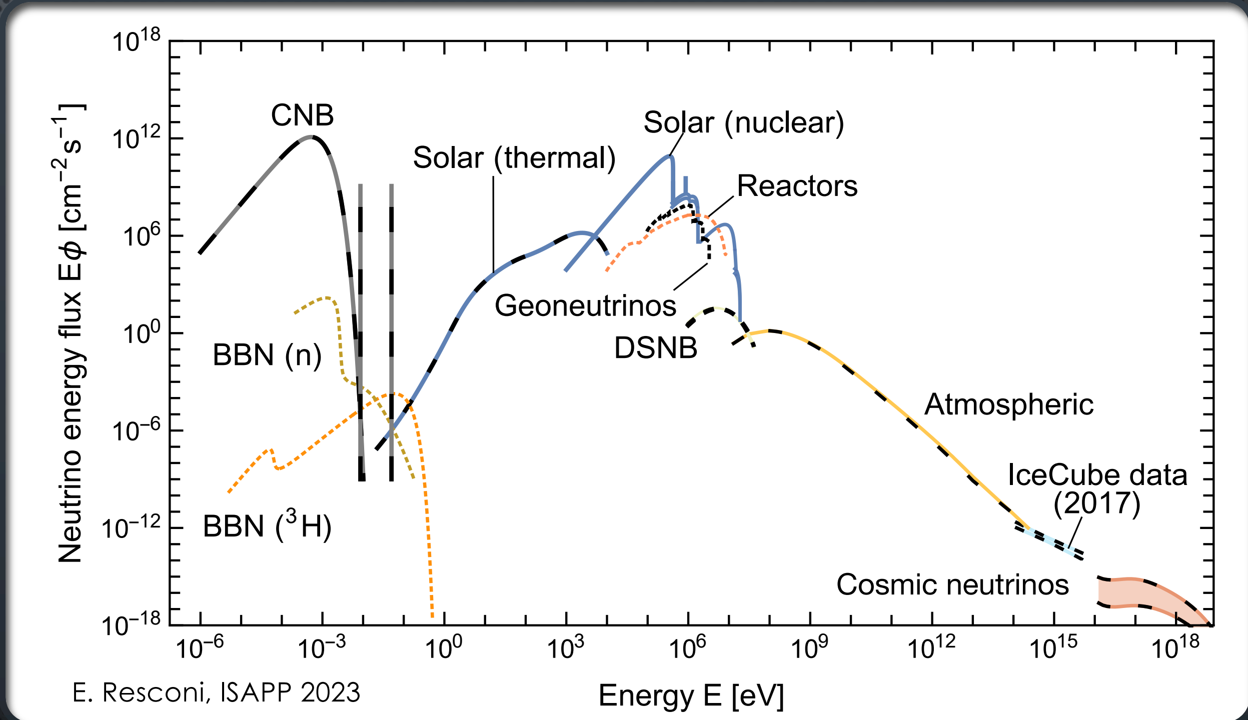
(no magnetic deflection, no decay attenuation, weak interaction in the source)

- Universe opaque to PeV photons

due to pair-production off CMB photons

- Gamma-rays emission can be hidden in the source

Unified Neutrino Spectrum

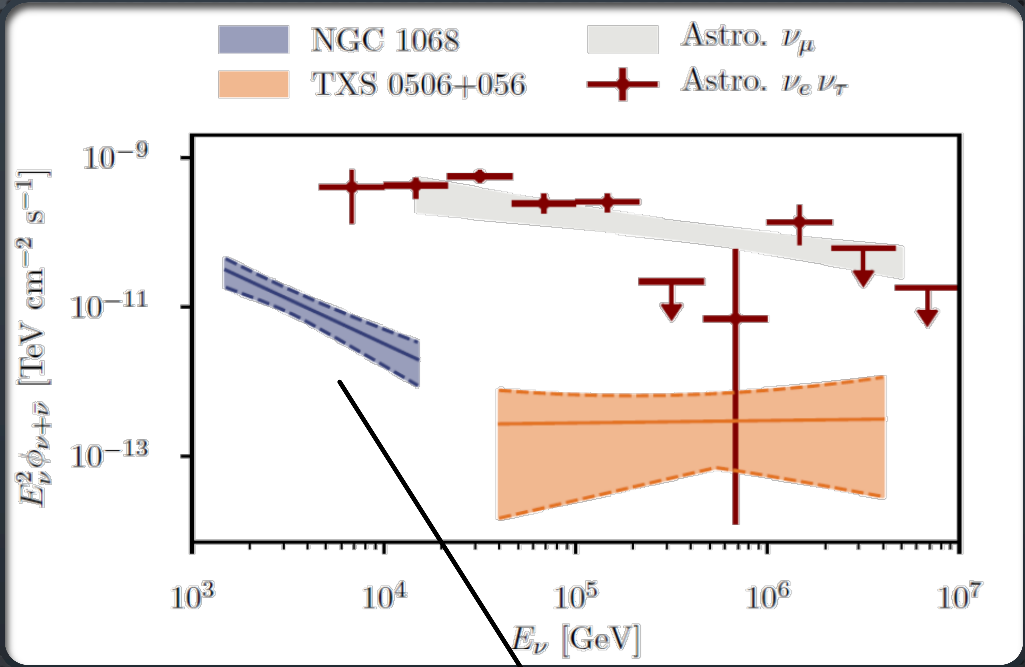


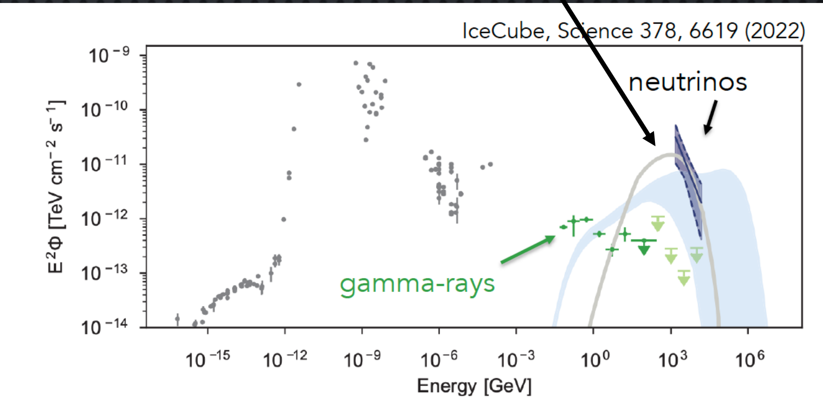
A CASE STUDY: ICECUBE

Identified a diffused high energy neutrino signal
(since 2013)

Identified neutrino sources:
NGC 1068 (M77) spiral galaxy at 10±2 Mpc
TXS 0506+056 Blazar at ~1.8 Gpc

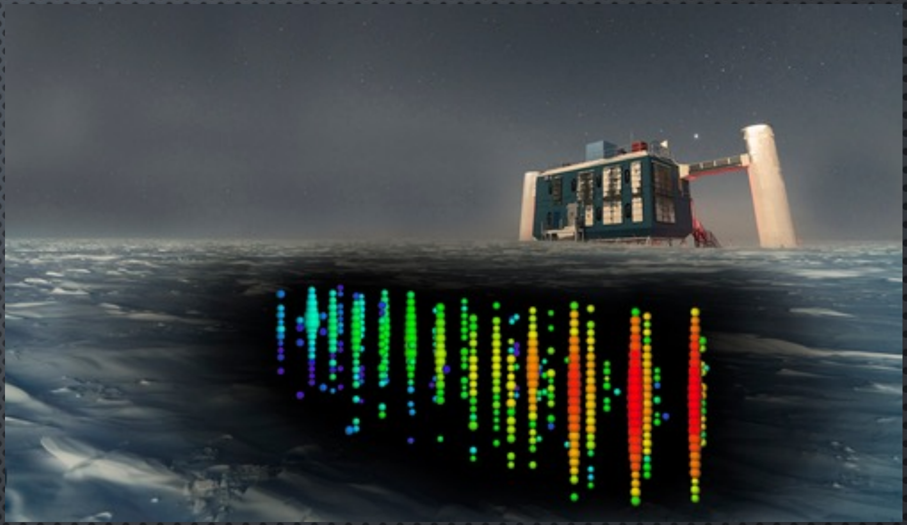
From data source mechanism unclear:
1. at least two populations of sources
2. TXS 0506+056 correlation with gamma-rays observations in 2017 (Fermi-LAT and MAGIC)
3. TXS 0506+056 neutrino burst in 2015 with no EM correlation
4. NGC 1068: brightest extragalactic neutrino source; neutrino flux exceed gamma-ray fluxes and upper limits from Fermi, MAGIC: gamma-ray obscured source?

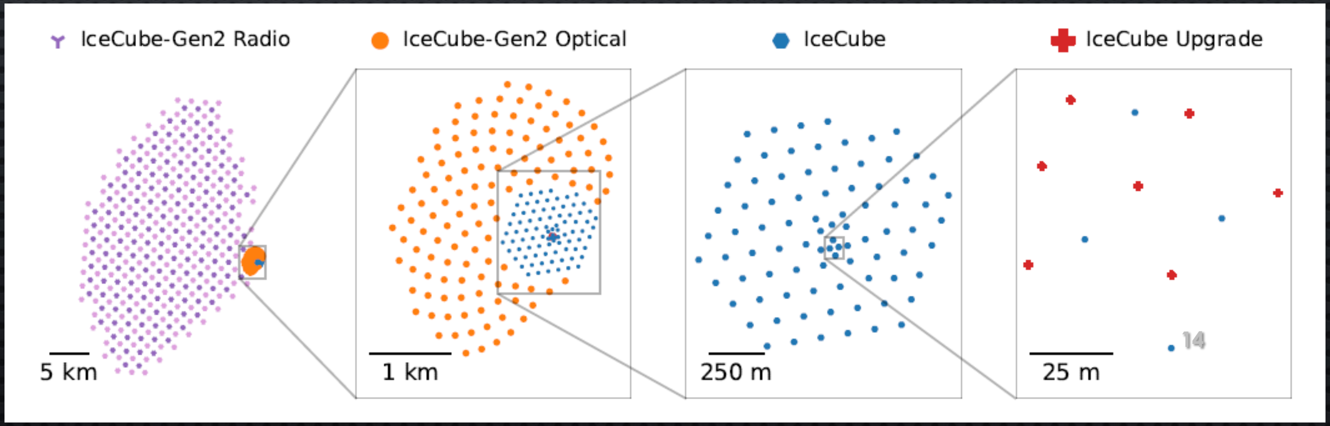




ICECUBE

- Main observatory now and over past decade with strong European involvement.
  - Discovery of Cosmic Neutrino's 2013
- Next : Upgrade (Jan '26)
  - Lower Energy threshold to ~1 GeV : oscillations
  - Recalibration -> retroactively improve the data!
- Vision for future: Gen-II
  - x 10 volume at high E
  - Extend energy range with radio array for Ultra-high E.





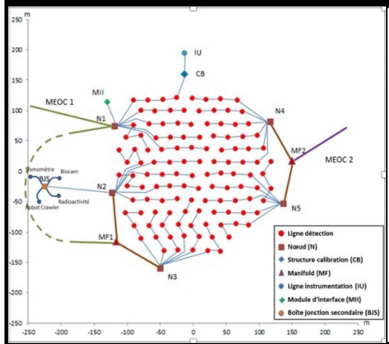
KM3NeT is a research infrastructure in the Mediterranean Sea hosting two neutrino detectors

KM3NeT/ORCA: Study of the physical properties of the neutrino – neutrino mass ordering
KM3NeT/ARCA: Discovery and observation of cosmic neutrino source

Two different detectors based on the same technology and operated by the same collaboration

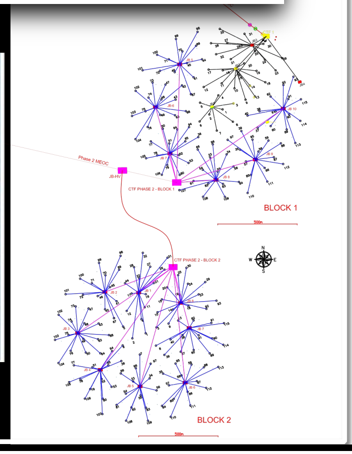
ORCA (Oscillation Research with Cosmic in the Abyss)

- block of 115 Detection Units
- Average distance between Detection Units ~20 m
- Average vertical distance between DOMs ~9 m
- Volume ≈ 7 Mton



ARCA (Astroparticle Research with Cosmic in the Abyss)

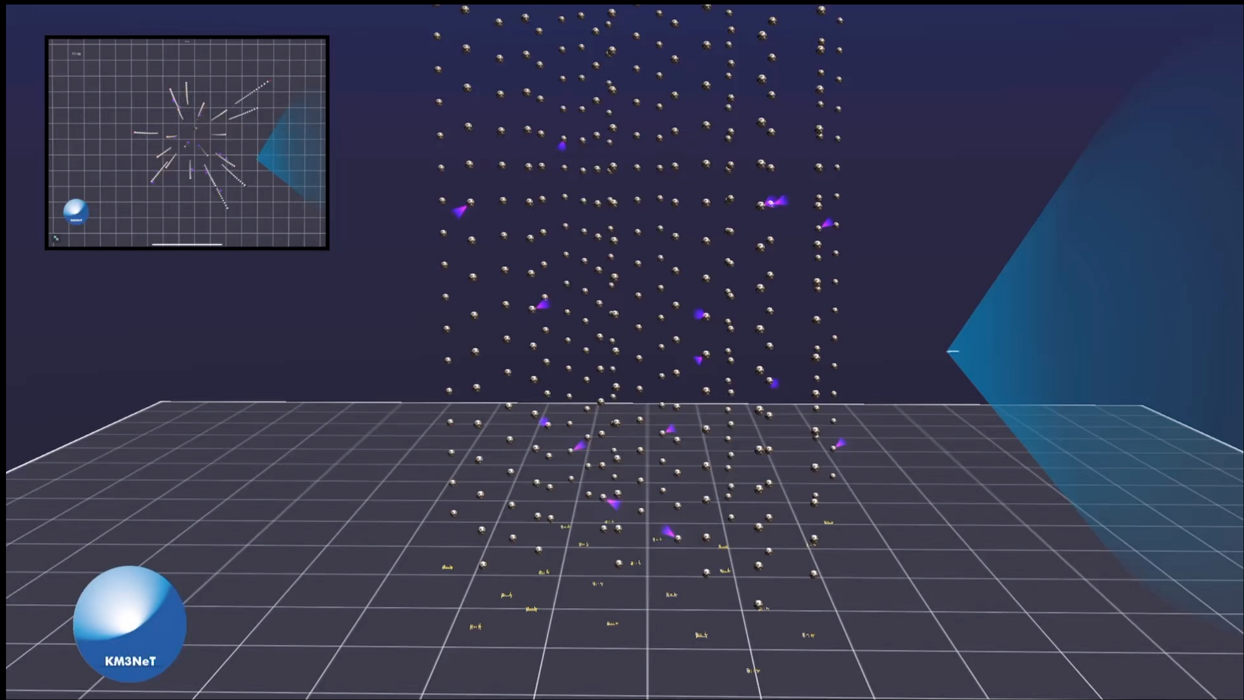
- Two blocks of 115 Detection Units each
- Average distance between Detection Units ~90 m
- Vertical distance between DOMs ~36 m
- Volume (0.5 × 2) km^3 ≈1 Gton



THE UHE KM3NET EVENT: KM3-230213A

February 13 2023 a neutrino event with the highest energy ever detected with ARCA

Huge amount of light detected: 35% of the total number of PMTs were triggered

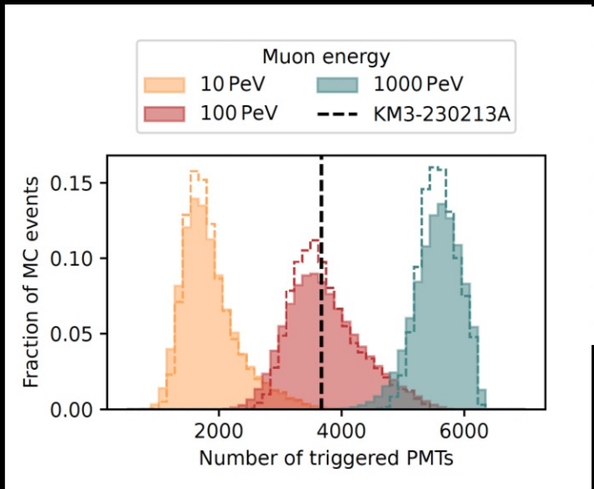


Nature 638, 376–382 (2025)

THE UHE KM3NET EVENT: KM3-230213A, A COSMIC NEUTRINO

- It is not an atmospheric neutrino or atmospheric muon background
  - ✓ Given the detected energy and direction the expected rate of atmospheric muon is « 10^{-10} per year.
- Horizontal track event (0.6° above the horizon) traversing ~140km of rock&water
  - ✓ At this energy a muon has an attenuation lenght of 20km
- It is a neutrino which has produced a muon near the detector

12 AGN sources found in region of 3° (@99%) around the estimated direction



- **Energy is measured from the amount of light:**

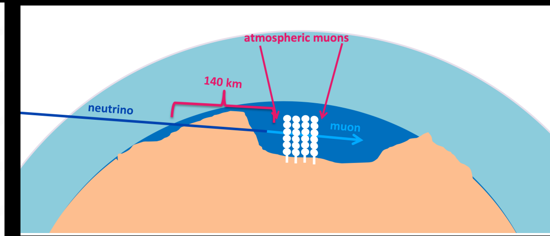
$$E_\mu = 120^{+110}_{-60}\ \mathrm{PeV}$$

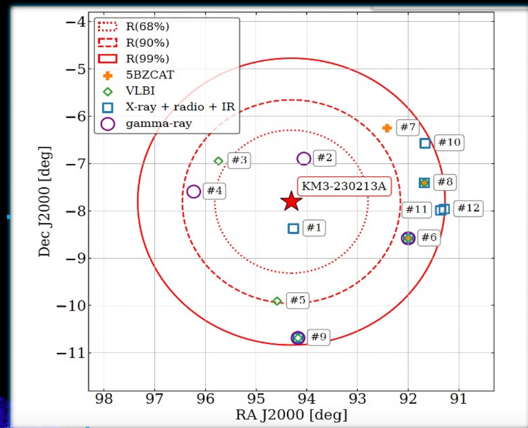
(10 000 times the energy of the LHC)

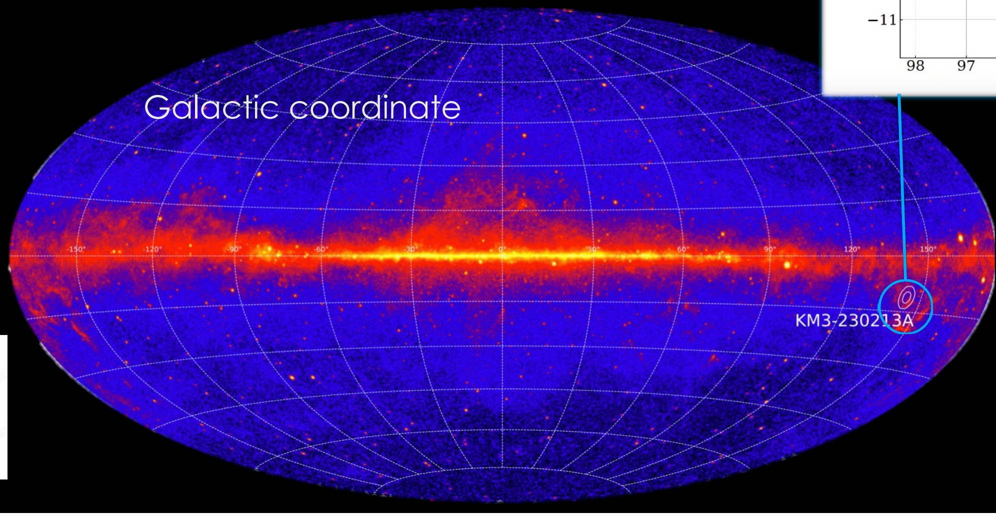
- **The neutrino Energy is higher:**

$$E_\nu = 220^{+570}_{-100}\ \mathrm{PeV}$$

(assuming an E^{-2} source spectrum)





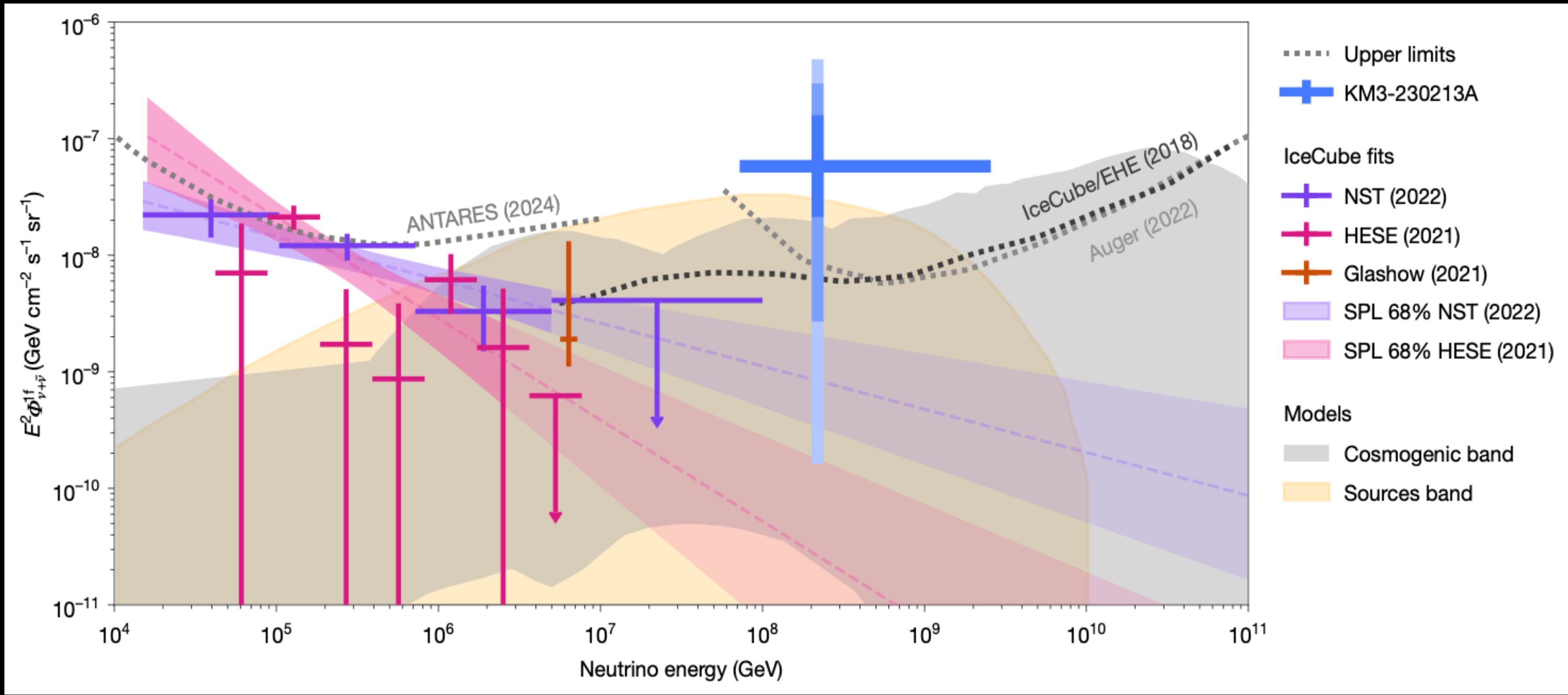


- Celestial coordinate

Equatorial coordinate

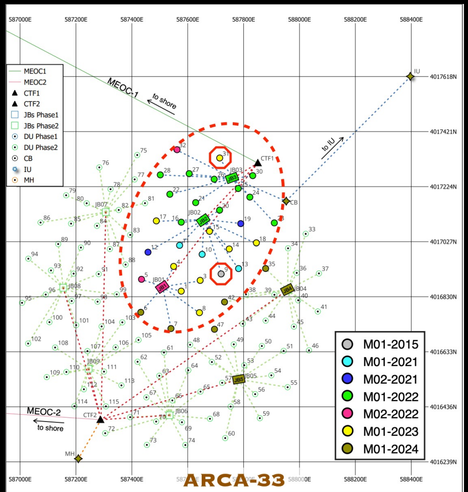
- **Approximate celestial origin:**

$$RA = 94.3°,\ Dec = -7.8°$$
with 1.5° error circle



Upper limits
KM3-230213A
IceCube fits
NST (2022)
HESE (2021)
Glashow (2021)
SPL 68% NST (2022)
SPL 68% HESE (2021)
Models
Cosmogenic band
Sources band
ANTARES (2024)
IceCube/EHE (2018)
Auger (2022)
$E^2\Phi^{1f}_{\nu+\bar{\nu}}$ (GeV cm^{-2} s^{-1} sr^{-1})
Neutrino energy (GeV)

ARCA

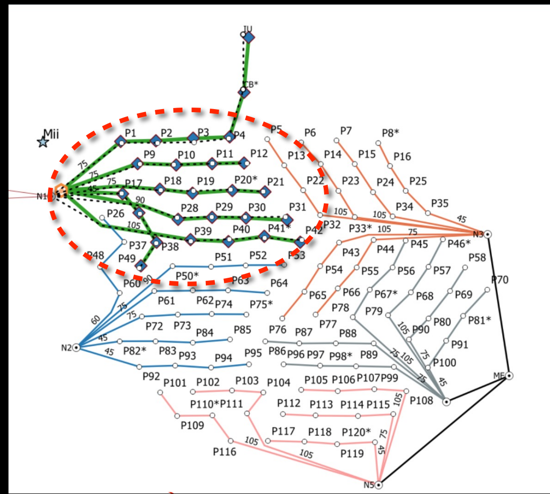


Status

KM3NeT detectors under construction present status

- ARCA 33 DUs (30% of one building block)
- ORCA 24 DUs (20% of the full detector)

ORCA

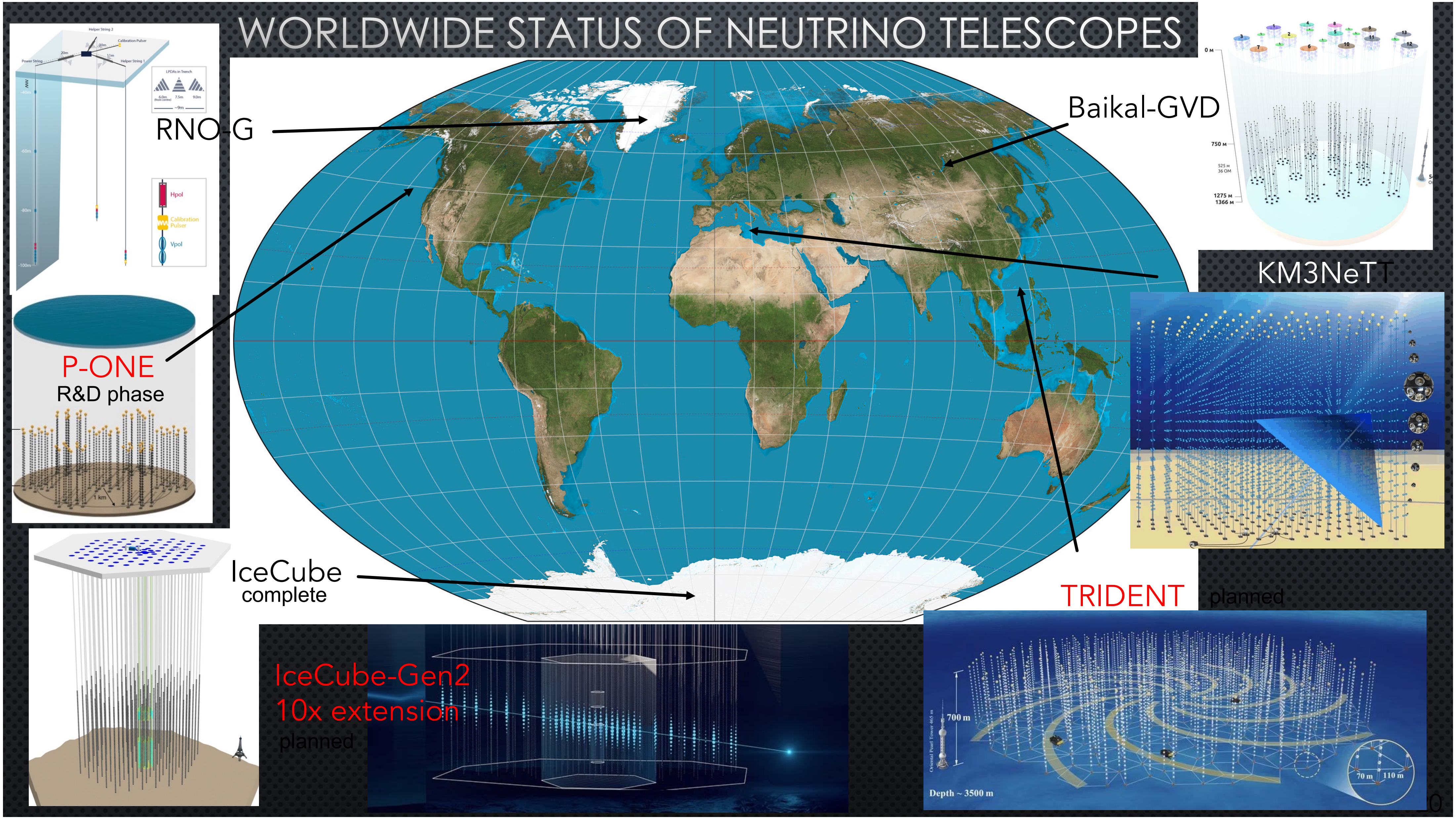


Challenges

- Have the detectors completed around 2030
  - Funds availabilities
  - Availabilities of components

  } International political context important

- Improve the present systematic uncertainties on
  - angular resolution ➡️ precision measurement of the absolute detector position (~1m)


WORLDWIDE STATUS OF NEUTRINO TELESCOPES
RNO-G
Hpol
Calibration Pulser
Vpol
P-ONE
R&D phase
1 km
IceCube
complete
IceCube-Gen2
10x extension
planned
Baikal-GVD
0 м
750 м
1275 м
1366 м
KM3NeT
TRIDENT
planned
700 m
Depth ~ 3500 m
70 m
110 m

APPEC MID-TERM ROADMAP UPGRADE

NEUTRINO ASTROPHYSICS

- APPEC fully endorses the goal of the KM3NeT collaboration to completer the construction ot the large-volume telescope optimised for high-energy neutrino astronomy **ARCA**, and the dedicated detector to resolve the neutrino mass hierarchy ORCA. APPEC strongly supports the construction of the IceCUbe Upgrade, and the ambition to build **IceCube-Gen2** in the following decade
- The Global Neutrino Network (IceCube, KM3NeT, Baikal-GVD) will boost neutrino astrophysics
- **The Radio Neutrino Observatory** (RNO-G) is under construction on top of Greenland ice sheet (23% of stations deployed) will exploit a new technology cost-effective for neutrino astrophysics in view of IceCube-Gen2 (>2030)
- P-ONE demonstrator (EU + Canada) + TRIDENT (8 km^3 in China)


WHAT DO GRAVITATIONAL WAVES TELL US ABOUT GENERAL RELATIVITY AND COSMOLOGY ?
WHAT WILL MULTI-MESSENGER ASTRONOMY TEACH US ?

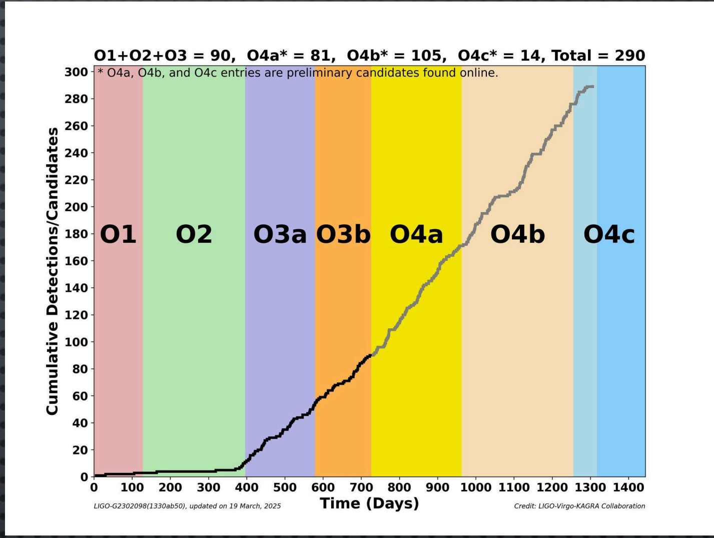
GRAVITATIONAL WAVES

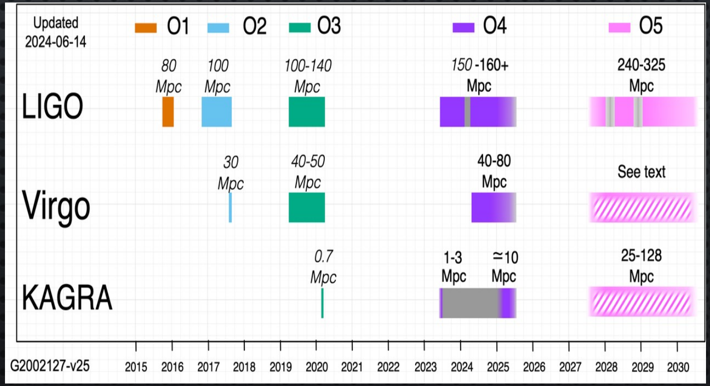
- Gravitational astronomy is a new emerging field with a strong impact on fundamental physics and astrophysics
- After first detection of GW in 2015 (GW150914)
  - ✓ Binary stellar-mass black holes (BBHs) exist
  - ✓ BBHs can merge producing GWs
  - ✓ BHs with a mass > 20 $M_\odot$ exist

LIGO, Virgo and KAGRA network

- Currently 4 runs since 2015
  - ✓ O1, O2, O3
  - ✓ O4 in progress
- In O2 merging of two neutron stars (BNS) with EM signal correlation (GW 170817 @ 40Mpc)
- In O3 BNS w/o EM signal (GW 190425)
  - ✓ Total mass 5σ > than the mean fo galactic BNS
- In O3 NSBH merging w/o EM signal (GW 200115, GW 200105)
- O1+O2+O3 with 90 observations, most BBH
  - ✓ population study: mass, spin
- O4 with increase of sensitivity
- **Almost 300 detected mergers of compact object binaries**
- **The large majority are binary black-holes**

O1, O2, O3 runs completed and O4 in progress

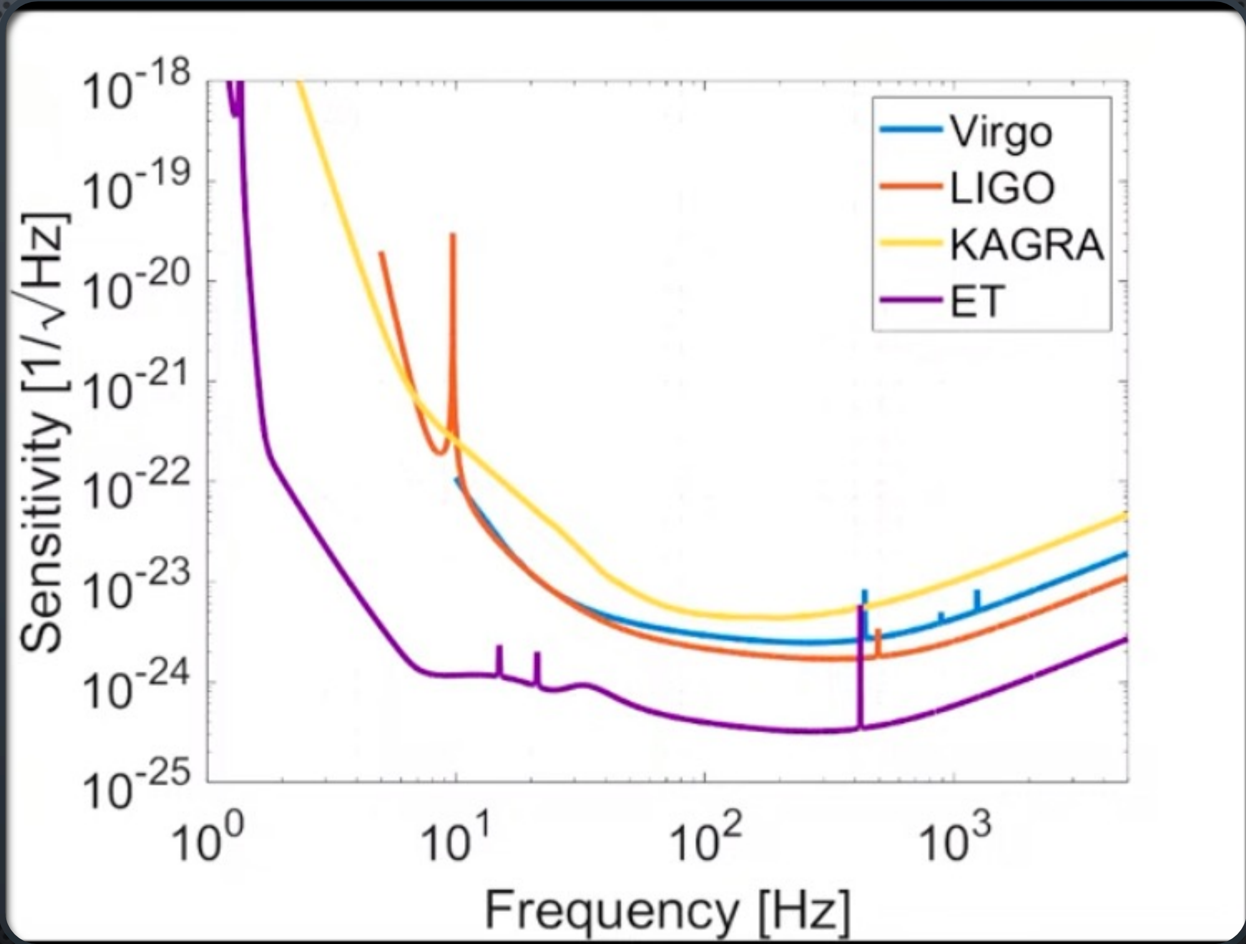




- ➢ Keep improving Virgo with the Advanced Virgo+ (2025-2029 x2 sensitivity) and Virgo-NEXT programme (>2031 x2 sensitivity)
- ➢ critical building the bridge between second and third-generation detectors to maintain European expertise and leadership in the field

FUTURE: EINSTEIN TELESCOPE EXPECTED SENSITIVITY

- 10^5 BNS detections per year
- 10^5 BBH detections per year
- Sensitivity to 100 $M_\odot$
- EM from massive BBH
- Priomordial BHs
  - ✓ For z>10, freq. < 10 Hz
- Enlarge volume of probed universe (Ligo < 200 Mpc)



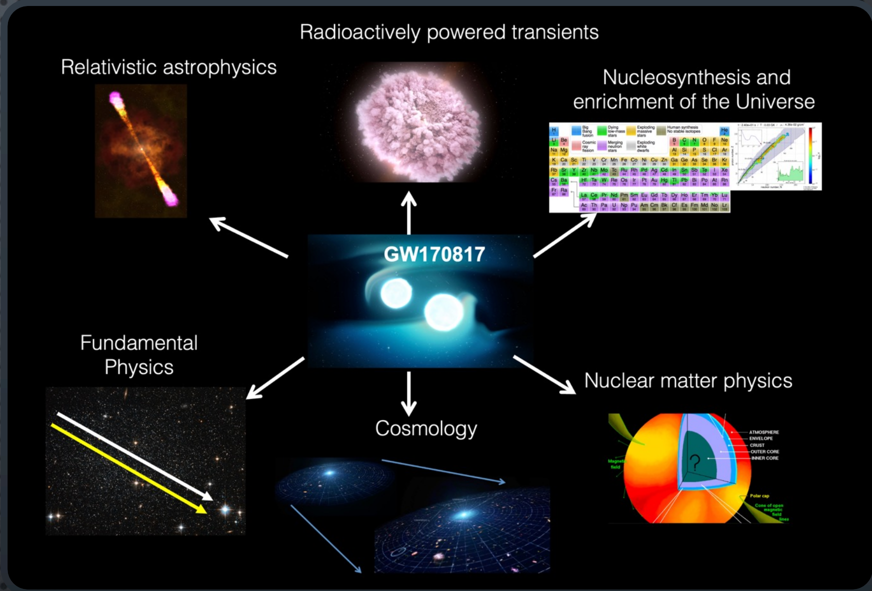
APPEC MID-TERM ROADMAP UPGRADE
GRAVITATIONAL WAVES

- APPEC strongly suppports actions to enlarge European countries' participation in ET, acquire funds for ET construction and operations, and develop the ET scientific community.
- Challenges: low vibration cryogenics for GW detectors; more efficient seismic filtering; advancement in surface science polishing, cleaning , preservation; use of AI for low noise control; cost of vacuum systems production
- The Cosmic Explorer is the US contribution to next-generation GW detectors with two facilities with 40 km and 20 km L-shaped interferometers
  - ✓ Future network: ET, CE, LISA

MULTI-MESSENGER ASTRONOMY

- Multiple signals from the same source
- Merging neutron stars:
  - ✓ **GW 170817** from LIGO&Virgo in GW and Fermi&Integral in gamma-rays (short GRB)
  - ✓ Gamma-ray emission observation after merging shows an increase of the flux within first 150 days
  - ✓ Optical emission after merging shows that these events (BNS) are the forge of heavy elements
  - ✓ Probe equation-of-state of neutron stars
  - ✓ Probe H_0 from GW infer distance and use redshift
  - ✓ Fundamental physics: measure speed of GW from time delay between gravitational and EM signals
- Ongoing plan: search for GW signal in coincidence with GRBs, SNs, HE neutrinos
- With ET and CTA a scientific-based selection required to optimize collected data
- To maximize scientific output wide-field telescope in operation with ET (e.g. Vera Rubin) + gamma-ray and X-ray detectors (e.g. THESEUS, ELT)

GW170817 and multi-messenger astronomy



APPEC MID-TERM ROADMAP UPGRADE

MULTI-MESSENGERS

- APPEC supports the further development and coordination of optimised multi-messenger observational strategies, common tools and data formats. Optimising future observatories for multi-messenger observation among theorists, experimentalists, and experts in data analysis and computing from different communities.

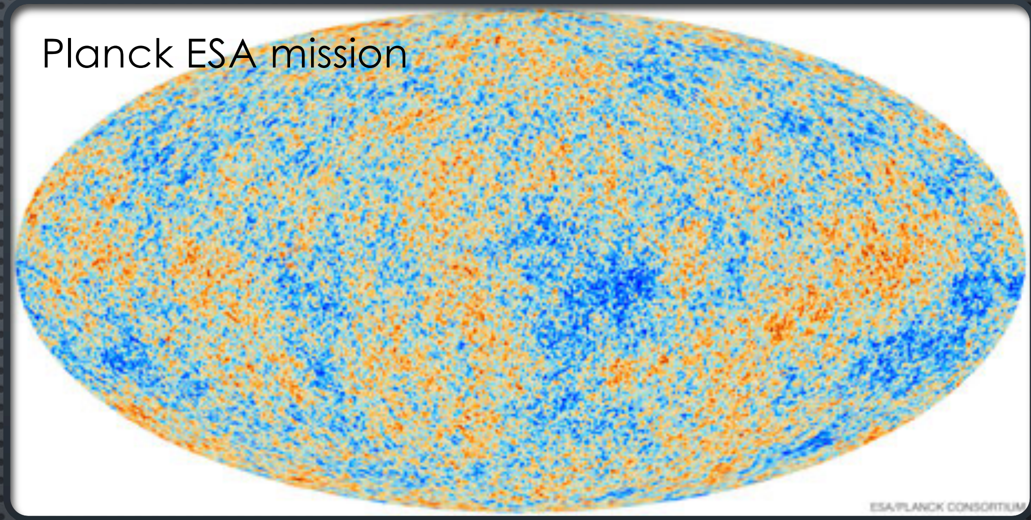
WHAT IS DARK ENERGY?

WHAT IS DARK MATTER?

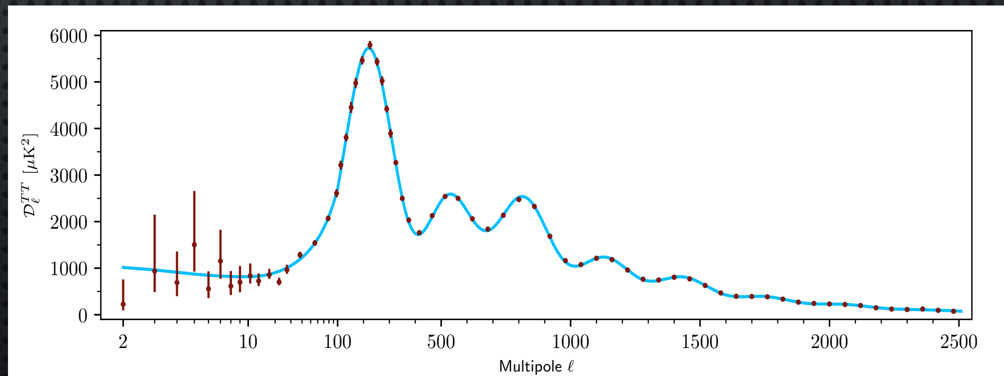
CAN WE PROVE DEEPER INTO THE EARLIEST PHASES OF THE UNIVERSE ?

WHAT DO GRAVITATIONAL WAVES TELL US ABOUT GENERAL RELATIVITY AND COSMOLOGY ?

CMB: THE HOLY GRAIL



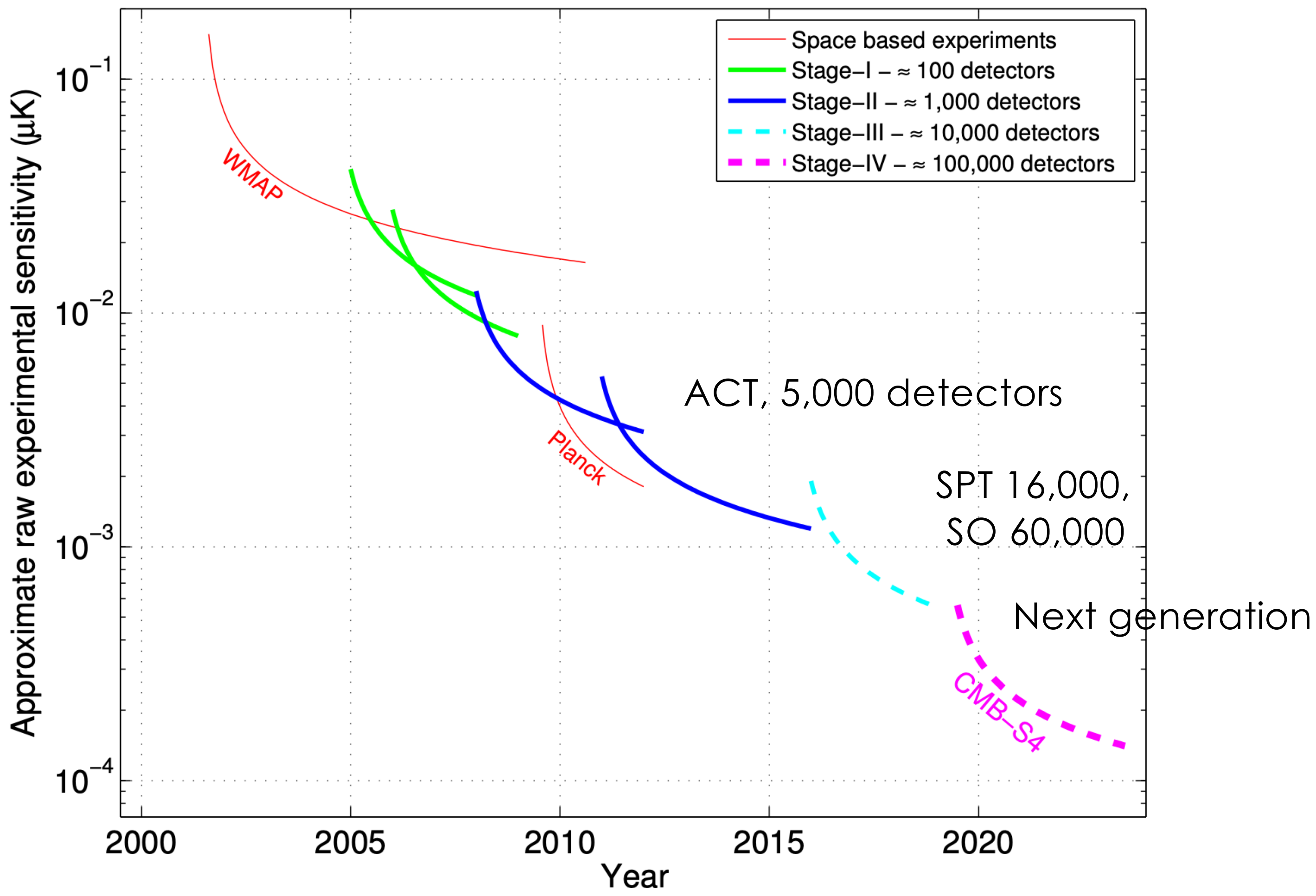
- Snapshop of priomordial sound waves at photons decoupling. Different modes (k) decouple at different moments and have different amplitudes
- Observations of CMB have been crucial in establishing the “standard” cosmological model , providing evidence of primordial fluctuations from a period of inflation
- Intensity of CMB reflects density perturbations when the universe was about 380.000 years old.
- A remarkable agreement between theory and data



Standard cosmology in 6 parameters:
$\{A_s, n_s, \Omega_b, \Omega_m, \Omega_\Lambda, \tau\}$
Assumed SM and power spectrum for initial perturbations

Outstanding effort in CMB observation

- COBE Cosmic Background Explorer launched by NASA in 1989
- WMAP Wilkinson Microwave Anisotropy Probe launched by NASA in 2001
- Planck L-class CMB mission launched by ESA in 2009
- Litebird Next generation CMB mission planned by JAXA
- PICO Ambitious future CMB mission concept in the US
- PIXIE CMB spectrometer concept first discussed in 2011
- PRISM CMB imager and spectrometer concept proposed to ESA for the L2 and L3 call in 2013
- FOSSIL CMB spectrometer concept proposed to ESA for the M7 call in 2022
- Voyage 2050 Long-term programmatic planning of ESA's future space program
- ACT Atacama Cosmology Telescope
- SPT South Pole Telescope
- SO The Simons Observatory
- AliCPT in Thibet/China
- CMB-S4 Stage IV CMB experiment
- TMS Tenerife Microwave Spectrometer
- BISOU CMB spectrometer balloon supported by CNES
- QUBIC bolometric interferometer for CMB



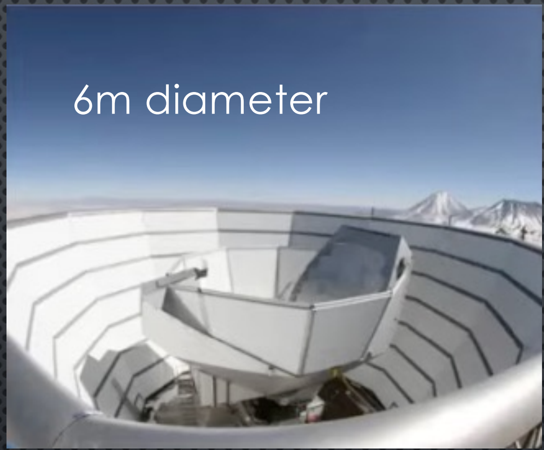
Space based experiments
Stage–I – ≈ 100 detectors
Stage–II – ≈ 1,000 detectors
Stage–III – ≈ 10,000 detectors
Stage–IV – ≈ 100,000 detectors
WMAP
Planck
CMB–S4
ACT, 5,000 detectors
SPT 16,000,
SO 60,000
Next generation
Approximate raw experimental sensitivity (μK)
Year

BUILDING ON PLANCK LEGACY

Planck

2009-2013
Final data 2018
100% coverage
0.35-10mm (9 bands)
5-33' resolution

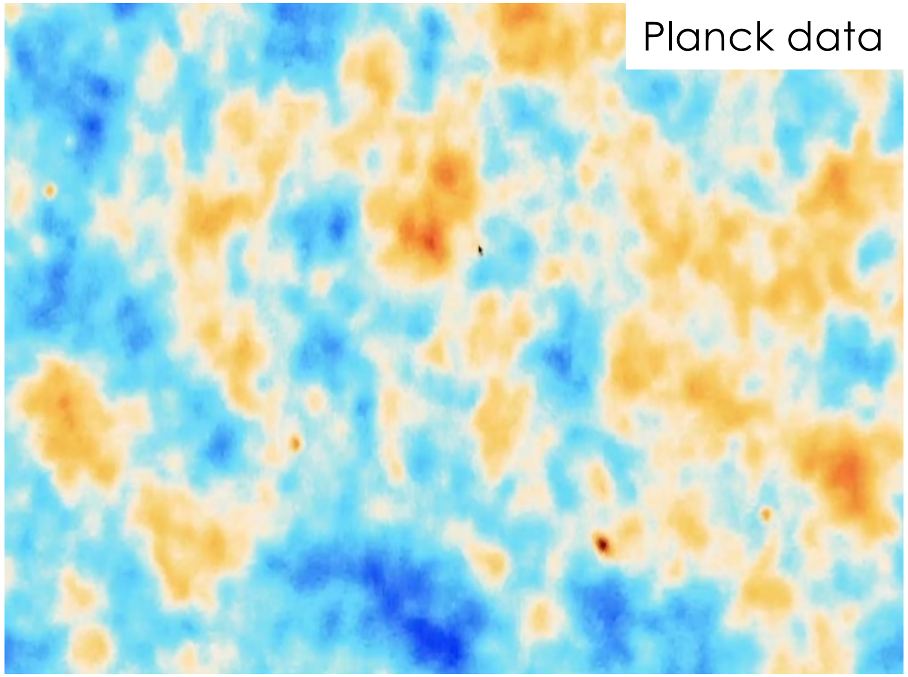
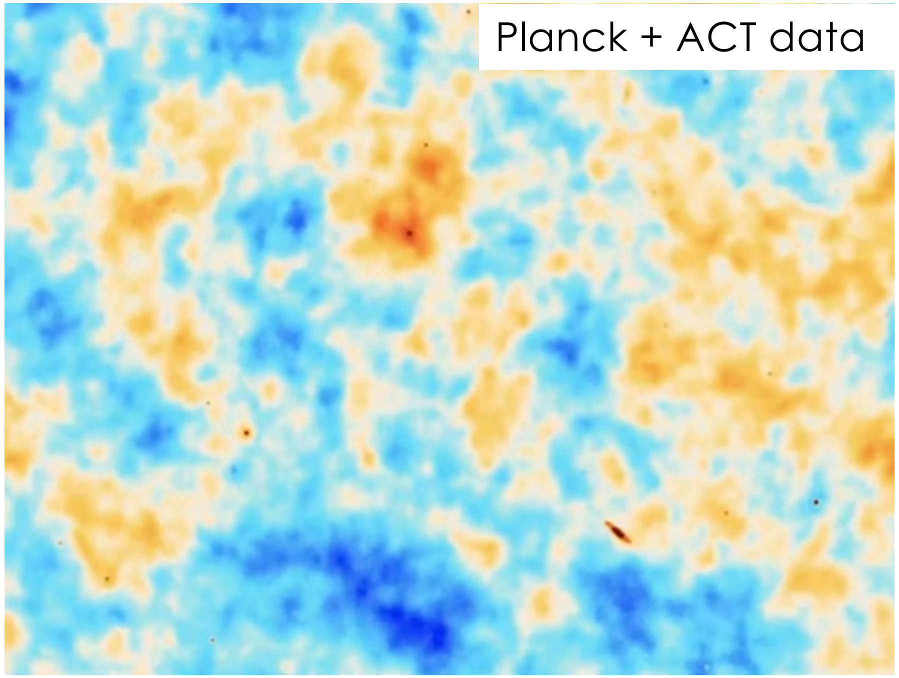
ACT

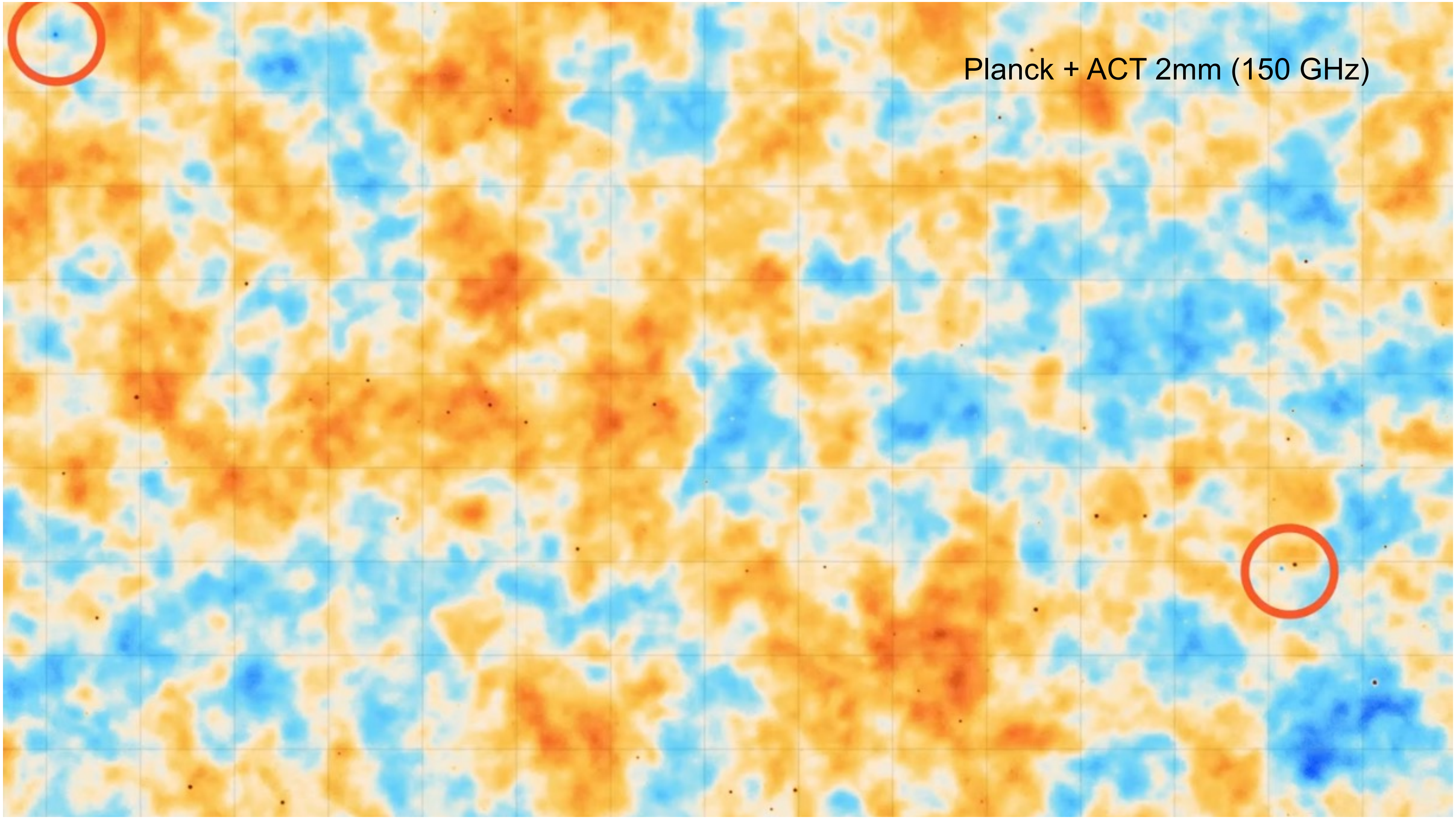


Observations ended 2022
Last data release 2025
40% coverage
Noise < 3x Planck
1.4-10mm (5 bands)
1-7' resolution

SO

Since 2025
40% coverage
Noise < 3x ACT
1-10mm (6 bands)
1-7' resolution


Planck data

Planck + ACT data


Planck + ACT 2mm (150 GHz)

OPPORTUNITY TO GO BEYOND STANDARD COSMOLOGY WITH CMB

Improve measurements of intensity and polarization to:

- probe relativistic species with small-scale anisotropies
  - ✓ accurate measurement of small scales anisotropies
- probe existence of B modes induced by GWs
  - ✓ current experiments (BICEP, SPTpol, Polarbear) not sensitive (scalar-to-tensor ratio < 0.035)
  - ✓ detected lensing B modes
- probe inflation through initial conditions detecting B modes
  - ✓ inflation predicts primordial GWs through tensor fluctuations with amplitude related to the expansion rate and a power law spectrum

Improve synergy between ground-based and satellite-based experiments:

- Satellite-based higher sensitivity to large scales ($2<l<30$), thermal stability and wide sky coverage
- provide foreground information for ground-based from satellite-based
- improve satellite-based with high resolution ground-based
- ground-based longer time integration, high resolution, detector accessibility and upgrade
- technological development of cryogenic sensors

A GLIMPSE INTO THE FUTURE FOR CMB

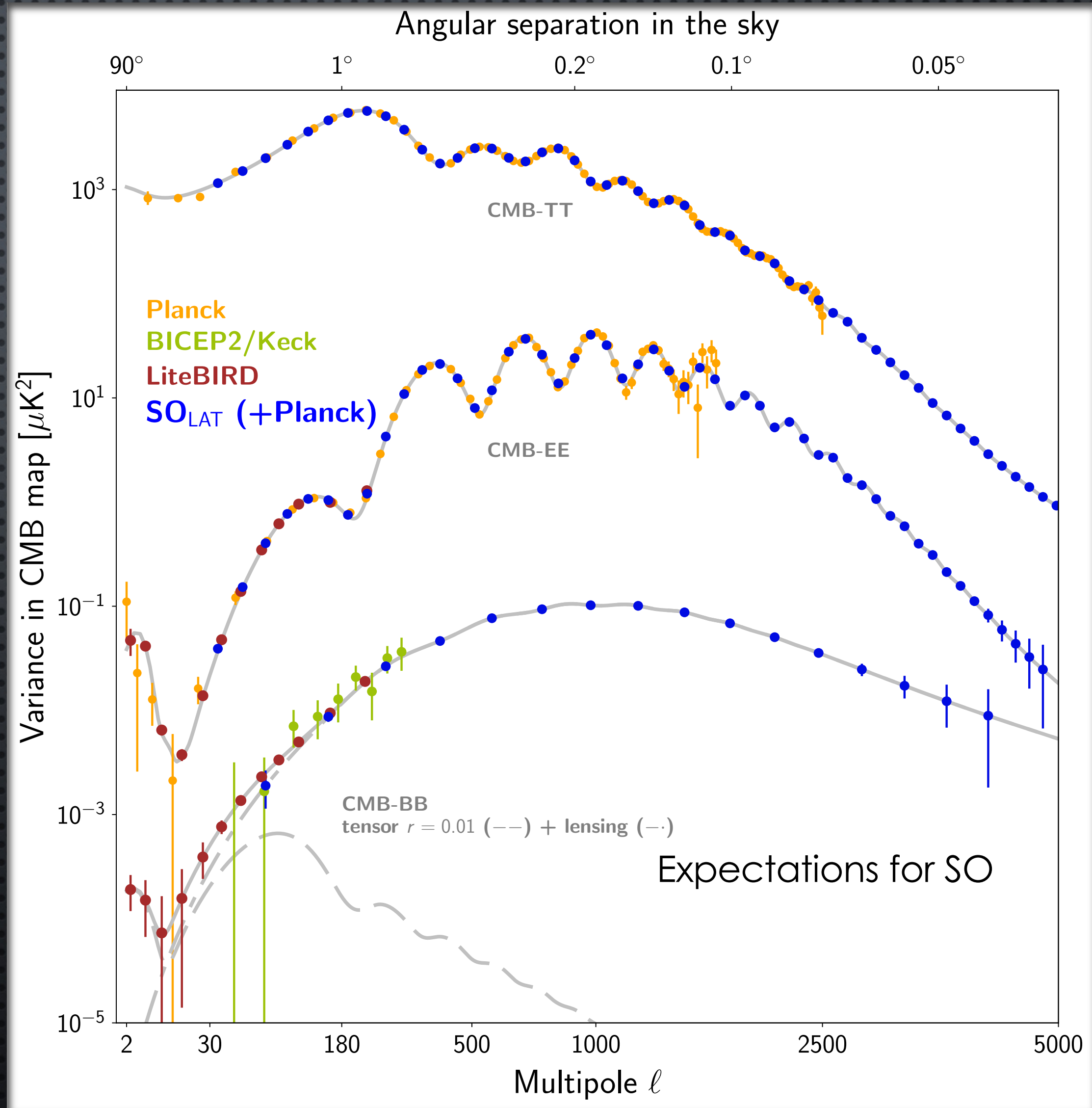
CMB-S4 (2030+)

- Measurement of the scalar-to-tensor ratio (probe inflation)
    - ✓ $r<0.001$ @95%CL if $r=0$
- Relic particles
    - ✓ $\Delta N_{eff} < 0.06$ @ 95%CL
- Connection with LSS
- Site selection: South Pole, Atacama desert (Chile)
- Challenges:
    - ✓ exploit technology from Simons Observatory (SO; need 10x detectors deployment, ~500k TES detectors)
    - ✓ major challenge is production on the required scale, high performance computing and cryogenics read-out
    - ✓ QUBIC outcome as technological input

LiteBIRD (2032)

- JAXA strategic mission (2032) for 3-year survey from sun-earth Lagrangian point L2
- Full sky
- Improve measurements of polarization and spectrum (distorsions)
- Probe large scale E modes (reionization optical depth)
- Probe inflation paradigm by measuring B modes induced by primordial GWs
- Probe relativist species with
- Probe sum of neutrino masses

CURRENT AND FUTURE IN CMB MEASUREMENTS



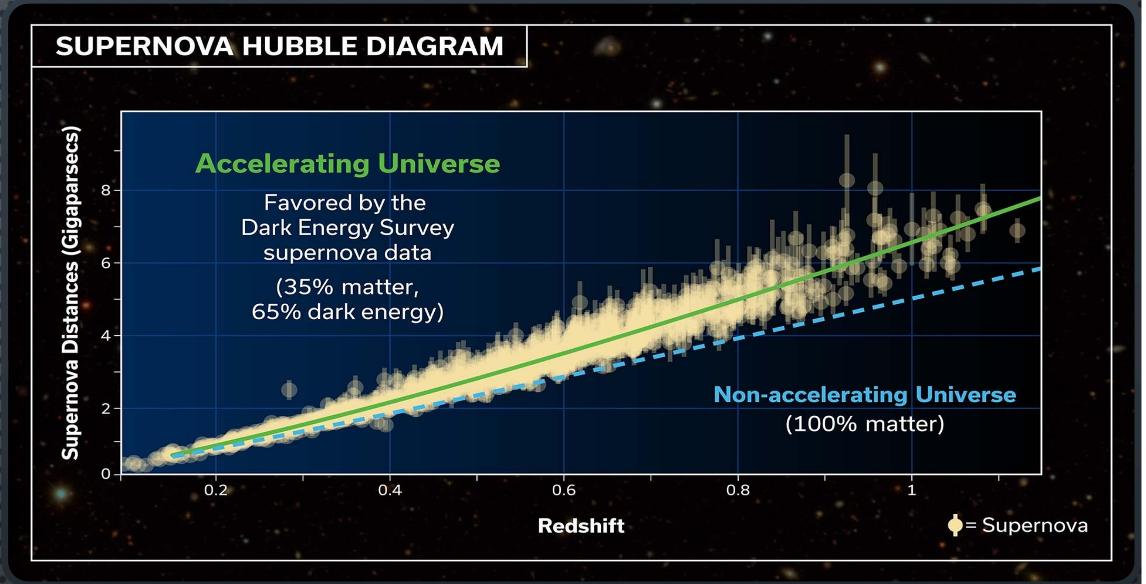
Small-scale anisotropies
E-modes
CMB lensing

APPEC MID-TERM ROADMAP UPGRADE
COSMIC MICROWAVE BACKGROUND

- APPEC encourages European contribution to the LiteBIRD mission as well as R&D for further space-based CMB studies, such as a possible successor of COBE/FIRAS. APPEC encourages contributions to CMB Stage 4 and R&D towards other, next-generation, ground-based experiments.

DARK ENERGY

- SN Ia candles show an accelerating universe
- Measuring clustering of galaxies with BAO one can add another way to probe this observation
  - ✓ 2PCF in bins of z



- Standard cosmology contains a significant amount of dark energy

The equation of state of dark energy seems to be that of a cosmological constant, $w_0 = -1$

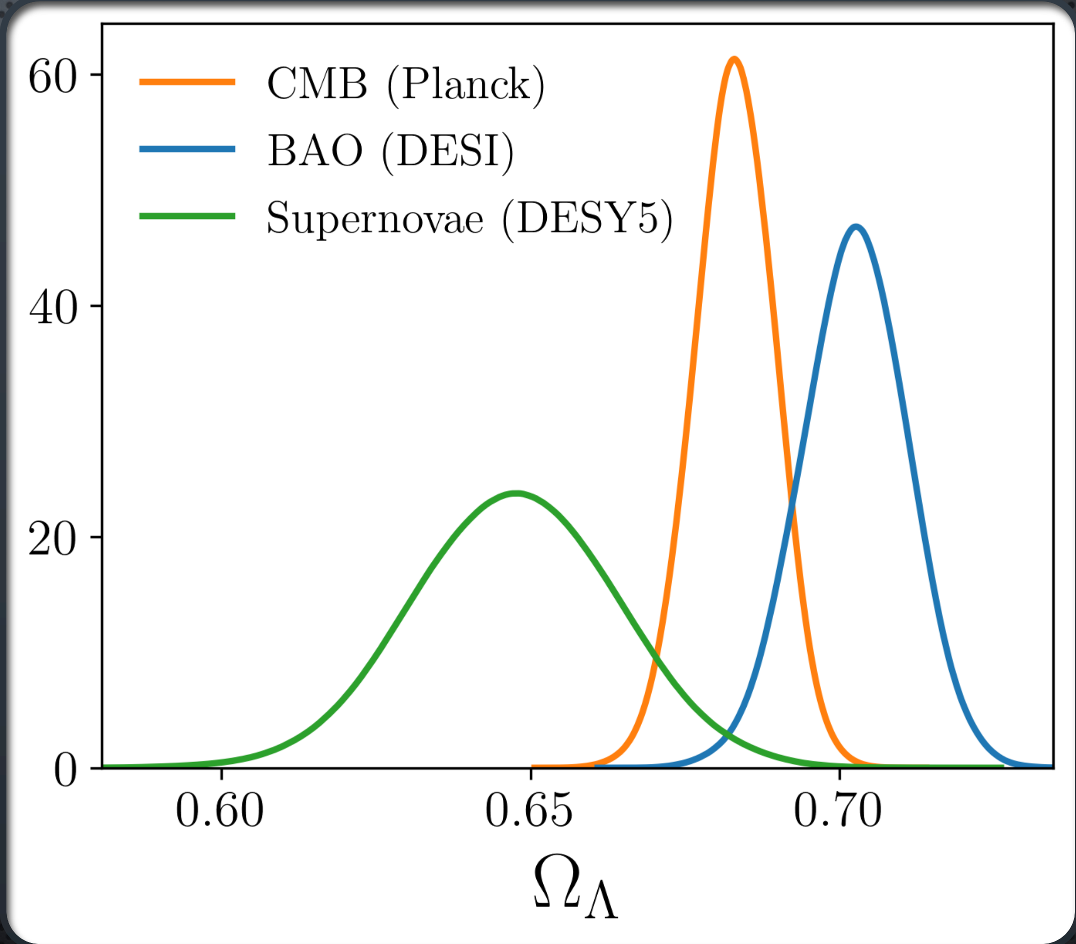
- Non standard scenario (WCDM): $w(a) = w_0+(1-a)w_a = w_0 + w_a\, z/(1+z)$

The accelerating expansion of the universe is a cosmological constant or modified gravity or …?

HINTS FROM DIFFERENT DATA SET

- Combining different data set at different redshifts shows DE might not be constant
- Non standard scenario:

$w(a) = w_0+(1-a)w_a = w_0 + w_a\, z/(1+z)$



DARK ENERGY SPECTROSCOPIC INSTRUMENT

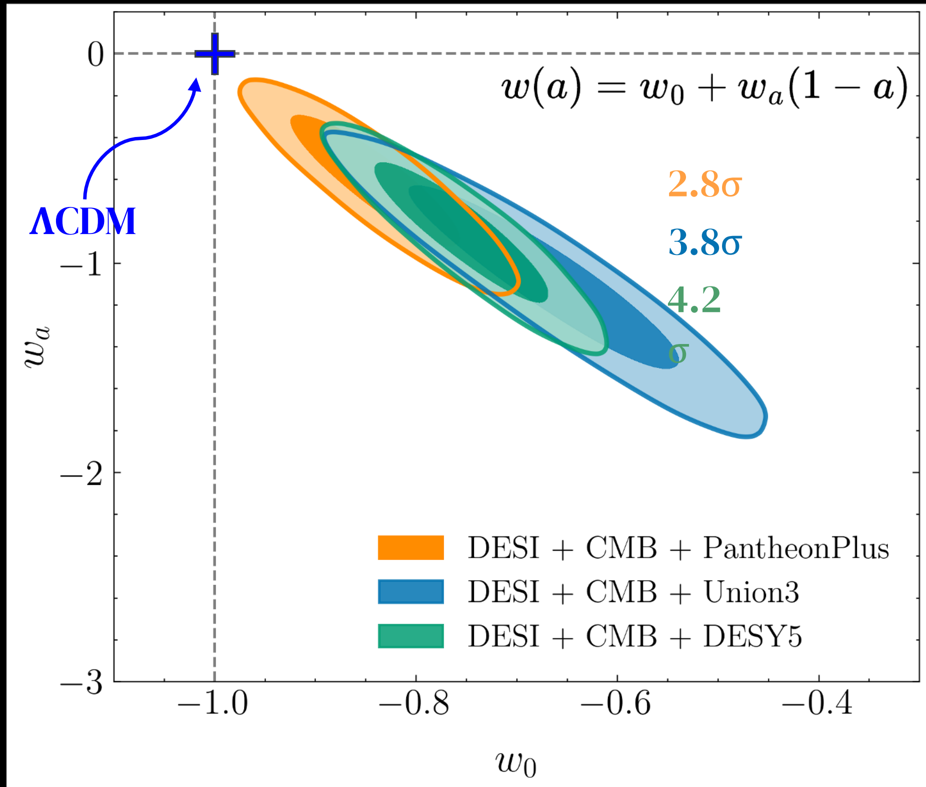
U.S. Department of Energy Office of Science

DYNAMICS OF DARK ENERGY

- Dark Energy Spectroscopic Instrument (DESI)
- DESI goal: survey 40 milion redshifts in 5 years

- DESI DR2 BAO in combination with CMB and SNe Ia provide tightest constraints on dynamics of DE.
- Disfavors Λ by **2.8 - 4.2σ.**

(depending on SN data used)

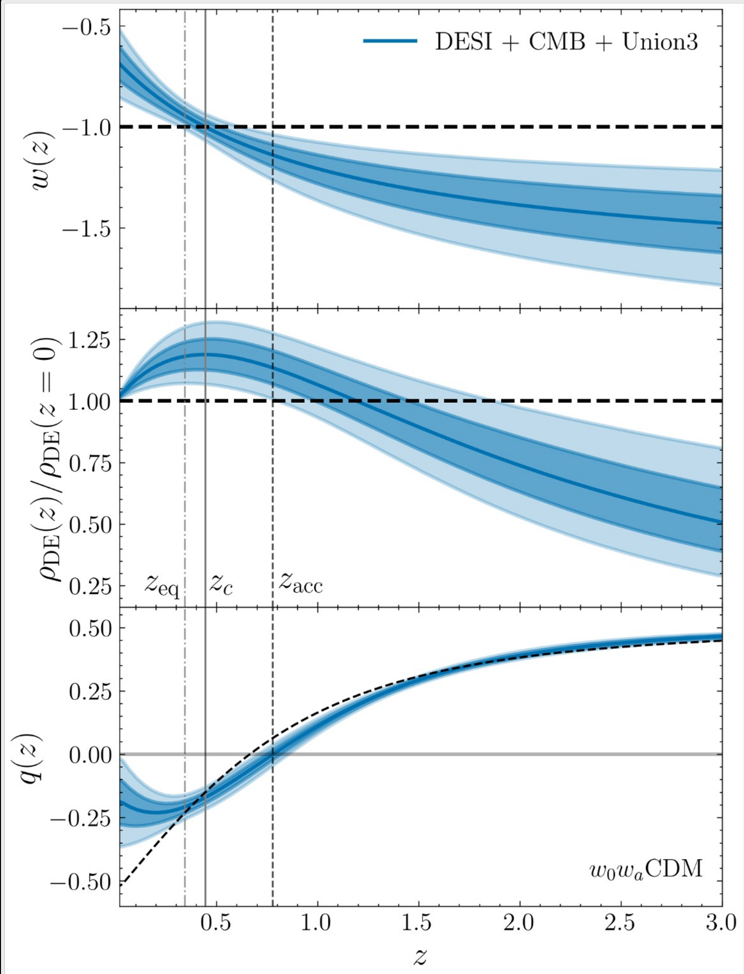


Ref: DESI DR2 Results II

Courtesy DESI coll.

DYNAMICS OF DARK ENERGY

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science



$$w(z) = w_0 + w_a \frac{z}{(1+z)}$$

Acceleration starts earlier than predicted by ΛCDM
Slow down effect of cosmic acceleration prediced
We expect q(0) ~ -0.5

Goal: To test robustness of this deviation using different parametric and non-parametric methods (change parametrization and number of parameters)

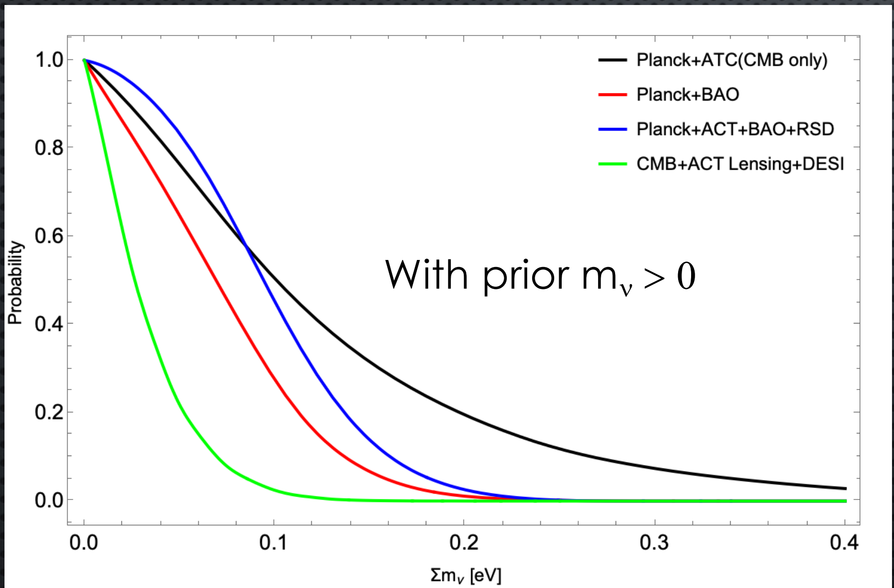
In the absence of unknown systematics, the results suggest a more richer dark energy sector than expected, potentially giving clues to new fundamental physics.

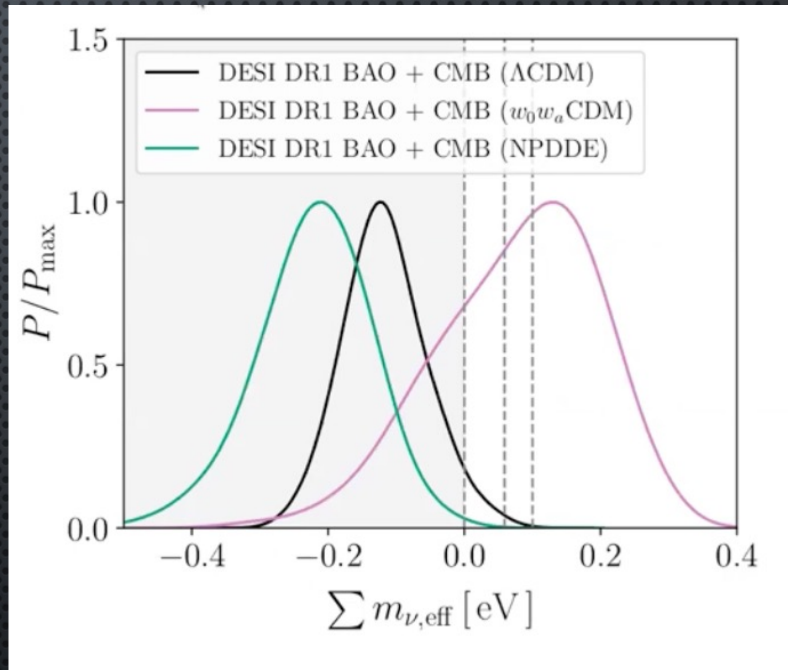
Courtesy DESI coll.

NEUTRINO MASS FROM INCLUDING DESI DATA

DESI 2025 With ΛCDM < 0.064 eV (95% CL)

H(z) given as a function of Ω_ν, Ω_γ, Ω_m, Ω_{DE}, Ω_κ



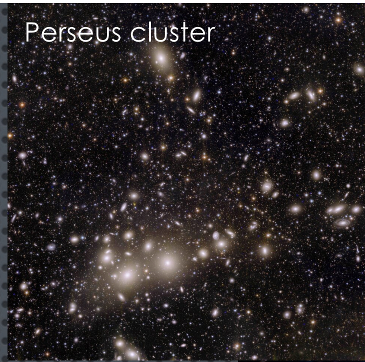


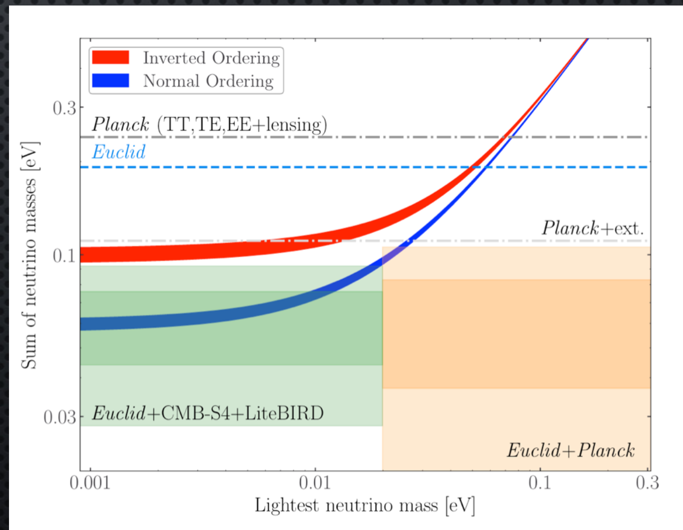
Ma Yin-Zhe and Xin Tang

6 standard cosmological parameters + 1 free neutrino mass parameter + 2 dark energy equation of state parameters in the case of w_0w_aCDM + 9 nuisance parameters associated with CMB calibration and foregrounds. Hence, the total is 16 or 18 parameters.

EUCLID ESA MISSION

- At the Lagrangian L2 since August 2023
- 6-year mission
- 1.2 m diameter telescope in the payload module
  - ✓ Visible and near IR
- November 2023 1st images
- Spacecraft and instruments performing well
- Public DR1 expected in 2026 and final in 2030
- Designed for
  - ✓ Dark Energy and Dark Matter
  - ✓ Probe expansion of the universe
  - ✓ Probe gravity at cosmological scale





APPEC MID-TERM ROADMAP UPGRADE
DARK ENERGY

- APPEC supports the forthcoming ESA Euclid satellite mission, which will establish European leadership in space-based Dark Energy research. APPEC encourages continued participation in next-generation ground-based research projects, e.g. Rubin-LSST and spectroscopic surveys such as DESI and proposed successors.

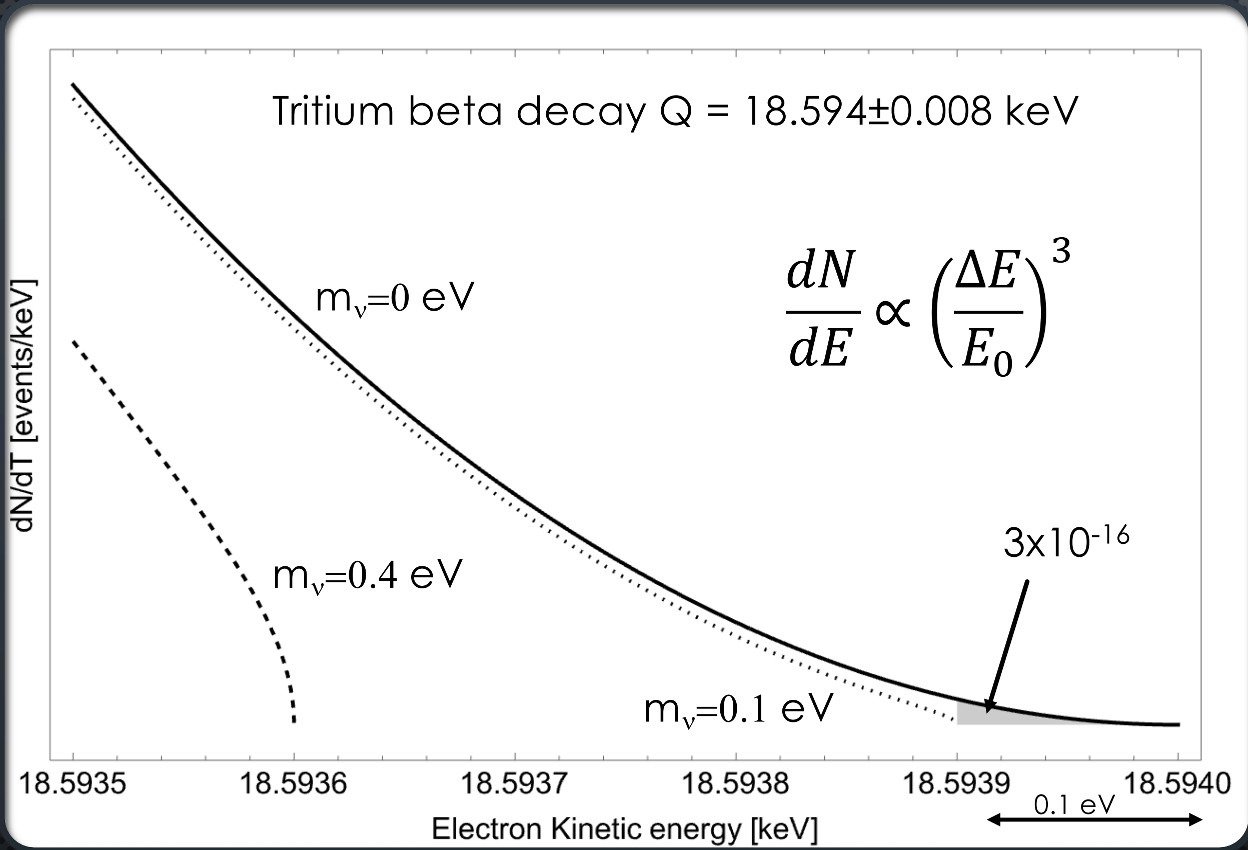

WHAT IS THE NEUTRINO MASS?
IS NEUTRINO A MAJORANA PARTICLE?
WHAT ARE THE NEUTRINO PROPERTIES?

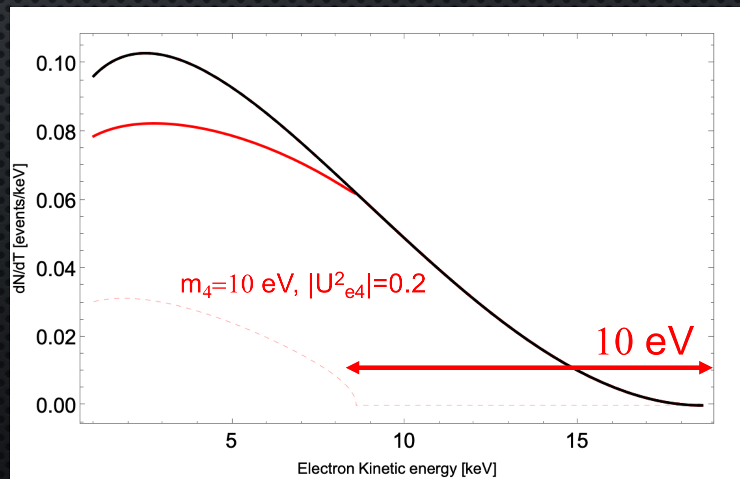
NEUTRINO PROPERTIES

Crucial questions after discovery of neutrino oscillations

- Neutrino mass scale
- Mass ordering for neutrinos: NO vs IO
- CP violation in neutrino sector
- Neutrino nature: are neutrinos their own antiparticle?
- Are there sterile neutrinos?

NEUTRINO MASS FROM BETA DECAY





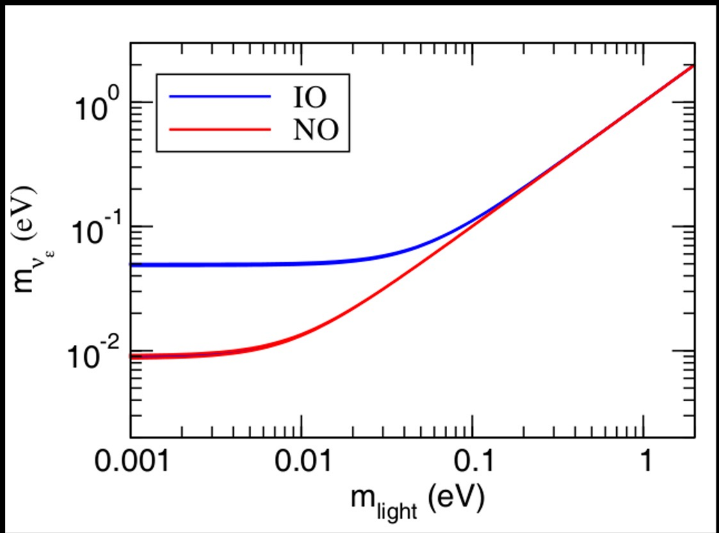
NEUTRINO MASS FROM THE β-SPECTRUM END-POINT

$$\frac{dN}{dE} \simeq R(E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - (m_{\nu_e}^{\mathrm{eff}})^2}\,,$$

$$(m_{\nu_e}^{\mathrm{eff}})^2 = \frac{\sum_i m_i^2 |U_{ei}|^2}{\sum_i |U_{ei}|^2} = \sum_i m_i^2 |U_{ei}|^2\,,$$

Oscillation bounds:
m_ν > 10 meV (N.O.)
m_ν > 60 meV (I.O.)

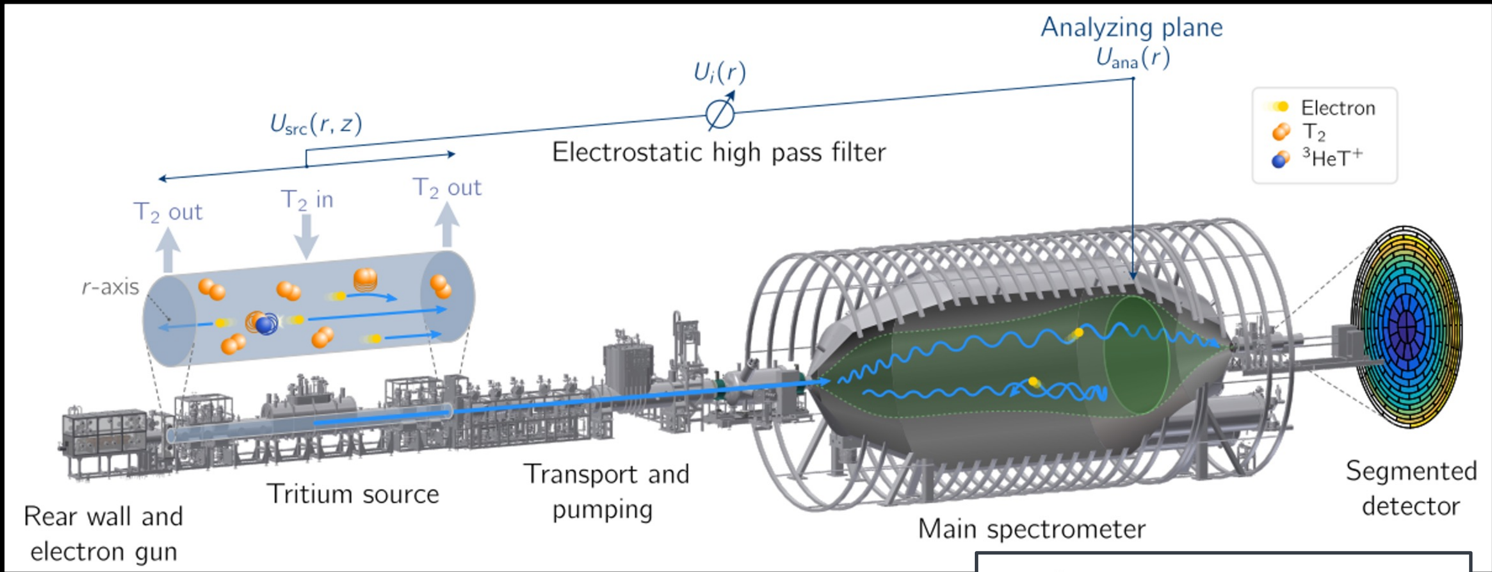
Cosmology bounds:
$\Sigma\, m_\nu$ < 250 meV (CMB)



Depends on the ordering

Experimental Requirements:
- low Q-value
- reasonable half-life
- simple nuclear structure
- sizeable source
- high rate handling
- energy resolution ≤ 1 eV

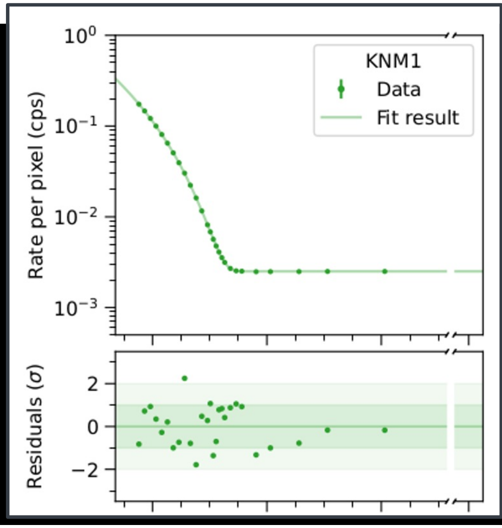
KATRIN - MOLECULAR TRITIUM (T_2)



KATRIN KNM1 to KNM5 campaigns:

m_ν < 0.45 eV (90% CL) (Lokhov-Tkachov)
m_ν < 0.31 eV (90% CL) (Feldman-Cousins)
Q-val = 18575.0 ± 0.3 eV

140 nuisance parameters and 4 physics parameters (amplitude of the beta spectrum, end point energy, background rate, and the mass of the neutrino)



KATRIN at KIT:

10^{11} Bq T_2 source with an high acceptance and eV-resolution integrating spectrometer

Energy resolution ~ 1 eV
Ultimate sensitivity 300 meV

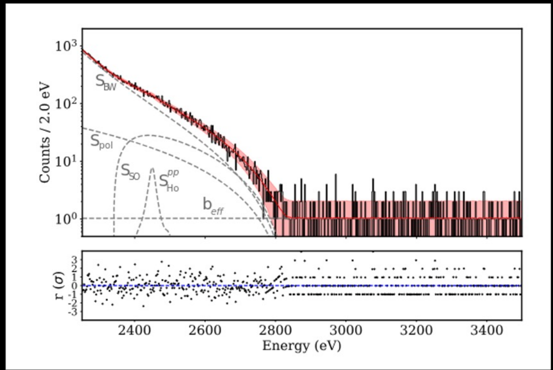
End of data taking 2025

Far future upgrade (sensitivity 50 meV)

KATRIN++
- Atomic tritium
- Reuse of the KATRIN infrastructure

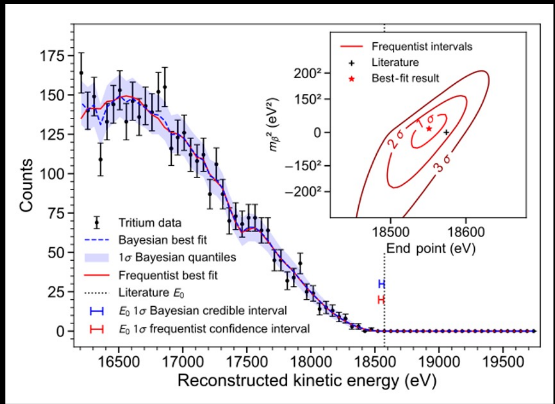
OTHER PROJECTS

ELECTRON CAPTURE WITH ^{163}HO (Q~3 KEV) **CRYOGENIC** BOLOMETERS:
(ECHO AND HOLMES)



HOLMES
[ARXIV:2503.19920]
7 X 10^7 EVENTS IN ROI
M_ν < 27 EV (90% CL)
ENERGY RESOLUTION 6 EV

CYCLOTRON RADIATION EMISSION SPECTROSCOPY (CRES):



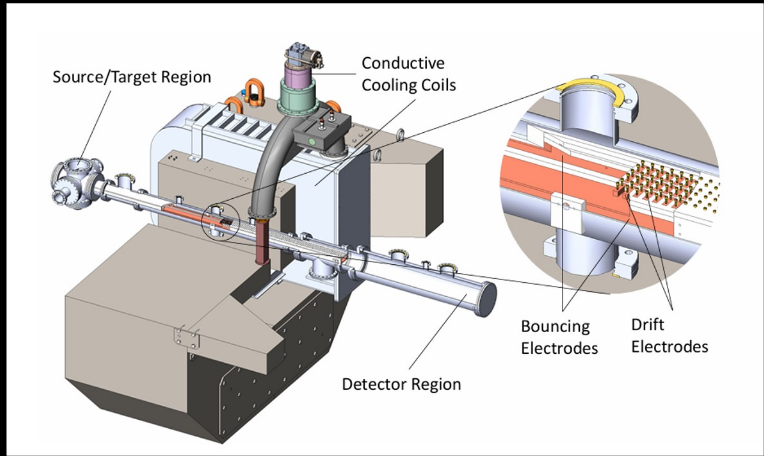
PROJECT 8
[PRL 131, 102502 (2023)]
3800 EVENTS IN ROI
M_ν < 155 EV (90% CL)
ENERGY RESOLUTION 1.7 EV

QTNM, A R&D CRES WITH QUANTUM SENSORS

PTOLEMY

Full-scale: detection of cosmic neutrino background via capture on tritium bound on graphene layers:
Monochromatic peak at Q_β + $m_{\nu e}$

- compact source
- small-size transverse dynamic filter
- ultra-high energy resolution goal (50 meV)



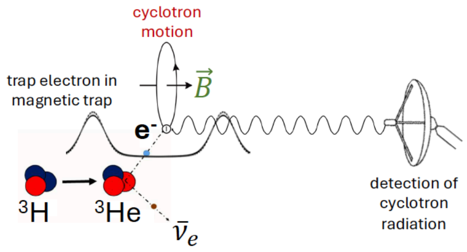
Demonstrator (LNGS): filter prototype with superconducting magnet. Sensitivity lower than 200 meV with a few μg's of tritium on graphene, exposed for 1 years.

Cyclotron Radiation Emission Spectroscopy (CRES)

- A new technique to measure electron energy from cyclotron emission from radiating electrons.

- Pioneered by the Project 8 Collaboration.
  - Also being persued by the QTNM Collaboration (UK)

- <u>Advantages</u>:
  - Frequency measurement, high precision
  - Differential measurement
  - Reduced backgrounds (Metric: 3×10^{-10}cps/eV)
  - Amenable to using an atomic tritium source.
  - Demonstrated technique



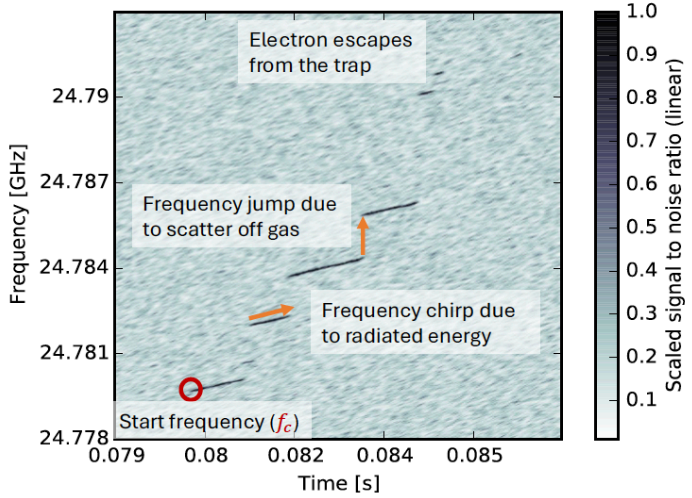
to measure

average magnetic field experienced by electron

$$f_c = \frac{1}{2\pi}\frac{e\,\langle B\rangle}{m_e + E_{kin}/c^2}$$

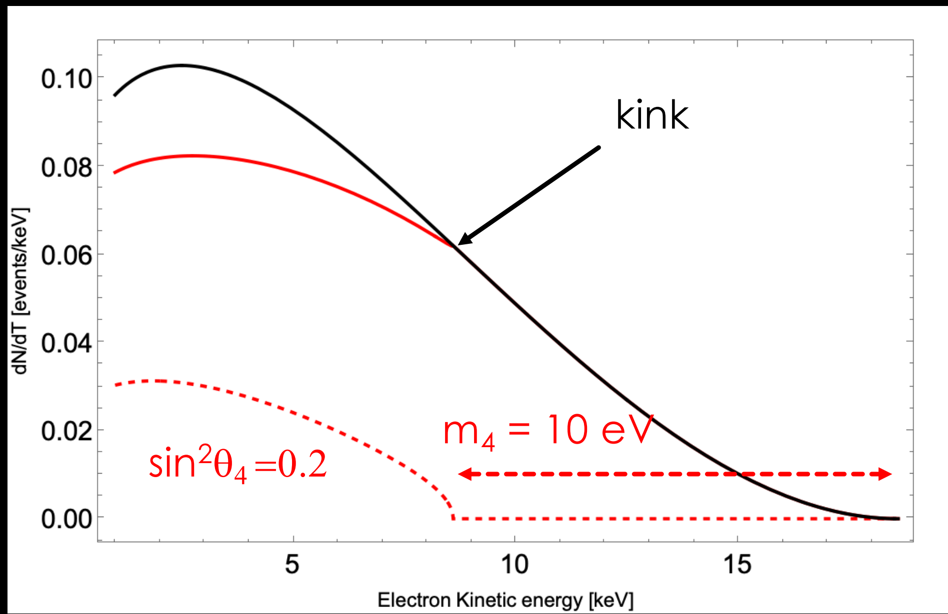
cyclotron frequency

kinetic energy



KATRIN++

- KATRIN will conclude its program with one year sterile neutrino search with TRISTAN
- GOAL: 50 meV with 0.2 eV sensitivity and atomic Tritium
- Atomic Tritium requires use of a new technology.
- Switch to differential spectrum measurement



NEUTRINOLESS DOUBLE BETA DECAY

$(A,Z) \rightarrow (A,Z-2) + 2e^-$

Gateway to BSM physics

Majorana nature of neutrino + $\Delta L \neq 0$

Probe neutrino mass scale

Isotope	Daughter	$Q_{\beta\beta}$ [a] [keV]	f_{nat} [b] [%]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)

M. Agostini, et al., (2023) Rev. Mod. Phys. 95, 025002

Isotope choice:

High $Q_{\beta\beta}$ for low background

High BR for lower cost

Detector technology:

Liquid or gas Xenon (nEXO, XLZD, NEXT

Semiconductor (LEGEND)

Liquid scintillator (SNO+, Kamland-Zen)

Cryogenic bolometer (CUPID, AMORE)

Tracking caloremeter (SuperNEMO)

Energy resolution

Low background

Scalability

Current experiments:

$m_{\beta\beta} \gtrsim 40 - 100$ meV ($T_{1/2} \sim 10^{27}$ yr)

Next-generation experiments:

$m_{\beta\beta} \gtrsim 8 - 20$ meV ($T_{1/2} \sim 10^{28}$ yr)

<0.1 cts/FWHM/ton/yr ~ 10^{-5} cts/keV/kg/yr

^{130}Te, no enrichment, bolometer and LS

Experiment	Isotope	Mass Isotope [kg]	Technology	Status or expected start	lab	$T_{1/2}$ [years]	$\Delta E@Q_{\beta\beta}$ FWHM [keV]	B [cts/keV/kg/y]	$m_{\beta\beta}$ [meV]	Notes and/or challenges
CUORE	^{130}Te	202	Bolometer 988 TeO_2 crystals	running	LNGS	$>2.8\times10^{25}$	8	10^{-2}	70-240	Running till 3 ton x year in early 2026
SNO+ Phase-I	^{130}Te	1330	Liquid scintillator	2025	SNOLAB	$>2\times10^{26}$	230	10^{-4}	28-240	0.5% loading by mass
SNO+ Phase-II	^{130}Te	3990	Liquid scintillator	planned	SNOLAB	$>7\times10^{26}$	230	10^{-4}	17-73	Funding 1.5% loading by mass

^{76}Ge and ^{100}Mo, enrichment, HPGe and bolometer

Experiment	Isotope	Mass Isotope [kg]	Technology	Status or expected start	lab	$T_{1/2}$ [years]	$\Delta E@Q_{\beta\beta}$ FWHM [keV]	B [cts/keV/kg/y]	$m_{\beta\beta}$ [meV]	Notes and/or challenges
GERDA+Majorana	^{76}Ge	40.7+26	HPGe	stopped	LNGS / SURF	$>1.9\times10^{26}$	2	5.2×10^{-4}	77-175	
LEGEND-200	^{76}Ge	128-190	HPGe	running	LNGS	$\gtrsim2.8\times10^{26}$	2	5×10^{-4}	75-200	
LEGEND-1000	^{76}Ge	900	HPGe	2031-2035	LNGS	$\gtrsim10^{28}$	2	**10^{-5}**	9-25	Funding driven schedule Underground Ar
AMoRE	^{100}Mo	100	Scintillating bolometer 360 LMO crystals	90 LMO 2026 360 LMO 2027	Yemilab	$>4.5\times10^{26}$	8	**10^{-4}**	17-50	background index
CUPID	^{100}Mo	240	Scintillating bolometer 1596 LMO crystals	Stage I (80kg) 2030 Stage II 2034	LNGS	$\gtrsim10^{27}$	8	**10^{-4}**	12-21	background index Use of CUORE infrastructure

^{136}Xe, no enrichment/enrichment, liquid or gas single and double phase TPC

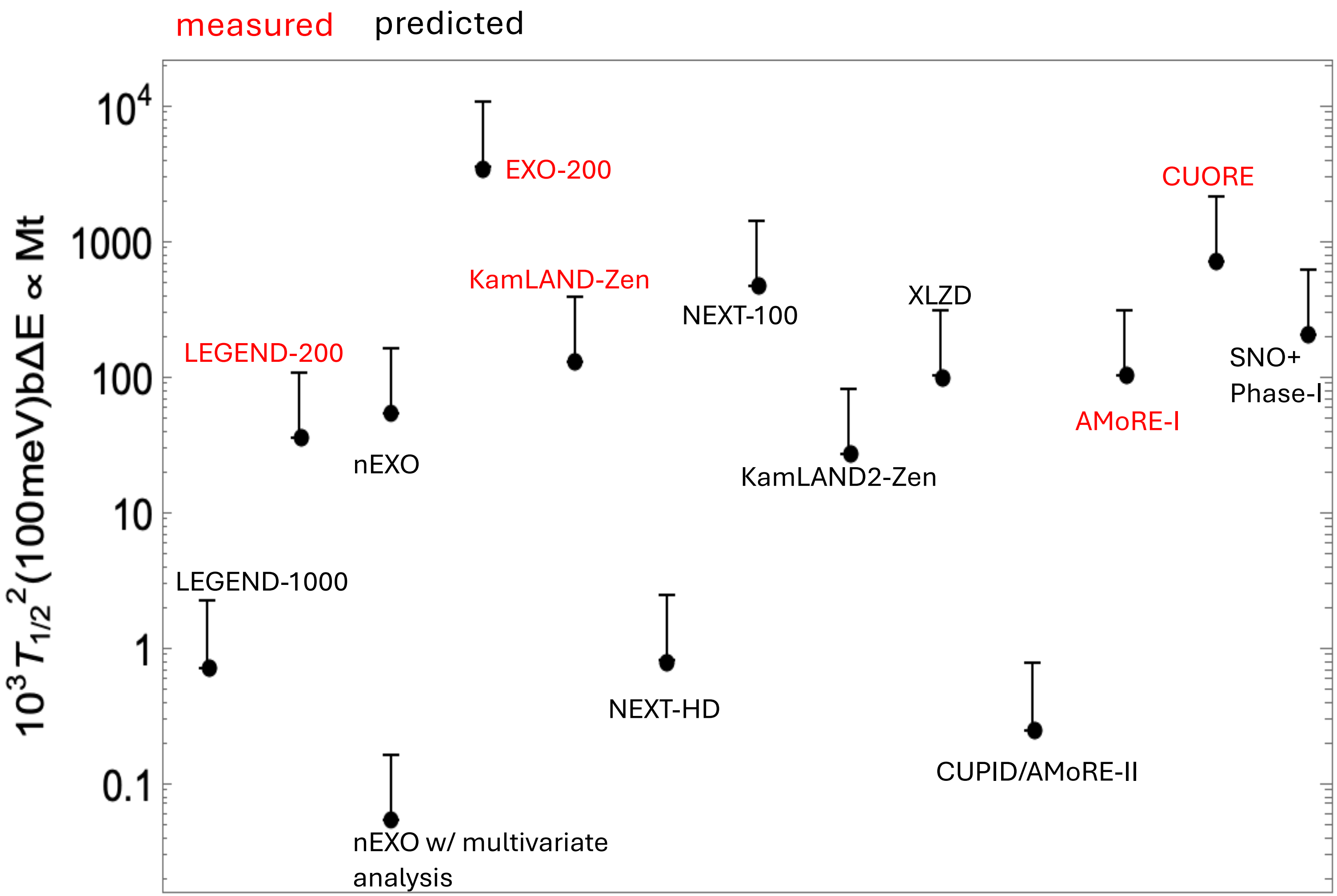
Experiment	Isotope	Mass Isotope [kg]	Technology	Status or expected start	lab	$T_{1/2}$ [years]	$\Delta E@Q_{\beta\beta}$ FWHM [keV]	B [cts/keV /kg/y]	$m_{\beta\beta}$ [meV]	Notes and/or challenges
Kamland-Zen	^{136}Xe	670	Liquid scintillator	stopped	Kamioka	$>4x10^{26}$	240	$1.5x10^{-4}$	28-122	
Kamland2-Zen	^{136}Xe	8001	Liquid scintillator	2027	Kamioka	$>1x10^{27}$	120	$1.7x10^{-5}$	>20	Low background vessel production
NEXT-100	^{136}Xe	87	High pressure gas TPC	running	LSC	$\gtrsim 10^{26}$	24.5	$4x10^{-4}$	_	Rn background
NEXT-HD	^{136}Xe	900	High pressure gas TPC	2032	LSC	$>10^{27}$	15-20	**$4x10^{-5}$**	_	scalability
EXO-200	^{136}Xe	80	LXe TPC Single phase	stopped	WIPP	$>3.5x10^{25}$	66.5	**$4x10^{-3}$**	93-286	
nEXO	^{136}Xe	430	LXe TPC Single phase	2034	SNOLAB	$>4x10^{26}$	58	**$7x10^{-5}$**		Funding Phase 1 no enrichment
nEXO	^{136}Xe	4500	LXe TPC Single phase	2036+	SNOLAB	10^{28}	58	**$7x10^{-5}$**	6-27	Funding Phase 2 enrichment
XLZD	^{136}Xe	5340	LXe TPC Double phase	2035+	Selection in 2026	$2x10^{27}$	38	**$2x10^{-4}$**	_	No enrichment

Detectors technology

- Liquid or gas Xenon (nEXO, XLZD, NEXT)
- Semiconductor (GERDA, LEGEND)
- Liquid scintillator (SNO+, Kamland-Zen)
- Cryogenic bolometer (CUORE, CUPID, AMORE)
- Tracking caloremeter (SuperNEMO)

$$\boldsymbol{T^{0\nu}_{1/2}} \propto \begin{cases} a\, M\, \varepsilon\, t, & background\ free \\ a\, \varepsilon \sqrt{\dfrac{\boldsymbol{M\, t}}{\mathrm{b}\, \boldsymbol{\Delta E}}}\ , & with\ background \end{cases}$$

$$\frac{\boldsymbol{S}}{\boldsymbol{B}} \propto \left(\frac{\boldsymbol{Q_{\beta\beta}}}{\boldsymbol{\Delta E}}\right)^{6} \frac{\boldsymbol{T^{2\nu}_{1/2}}}{\boldsymbol{T^{0\nu}_{1/2}}}$$



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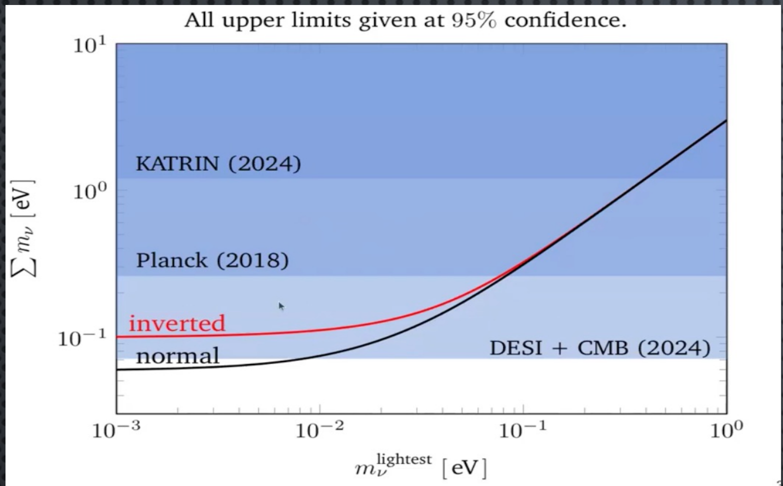
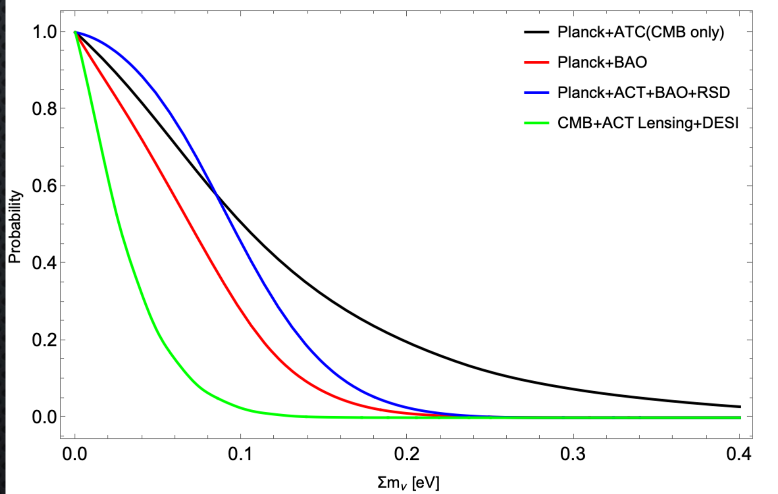
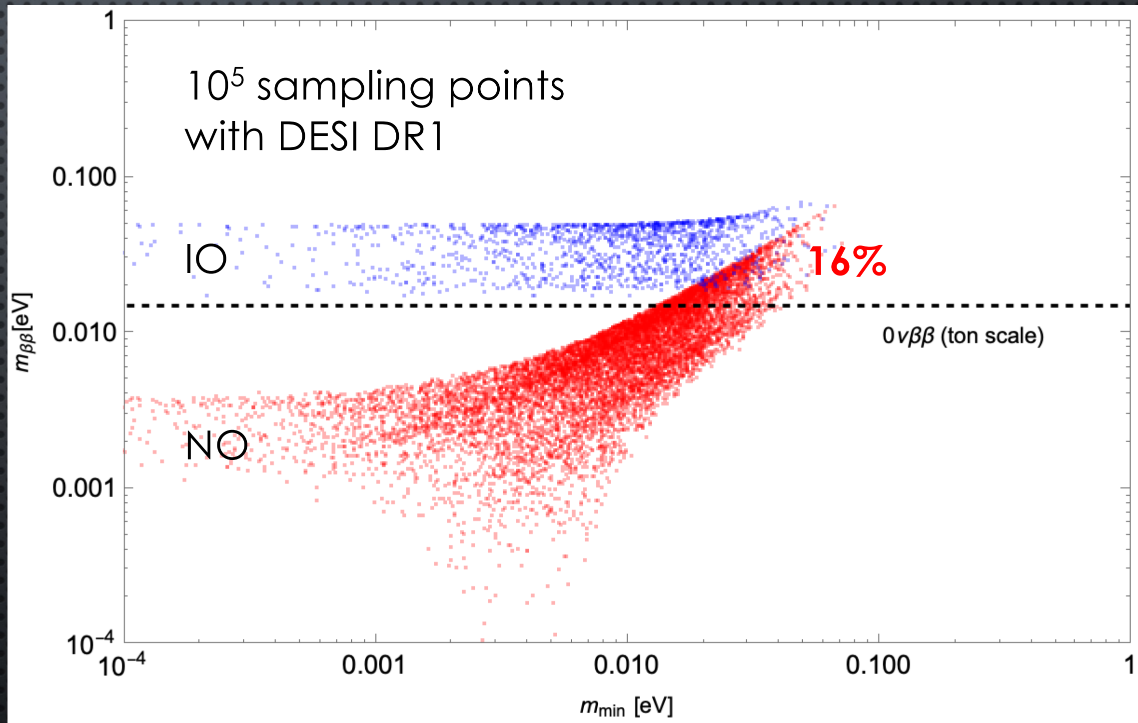
https://arxiv.org/pdf/2106.16243
D. Leonard, 1° Yemilab Workshop 2024
KamLAND2-Zen:
Itaru Shimizu,
International Conference on the Physics of the two Ininities, 2023
AMoRE: document submitted to ESPPU
SNO+: document submitted to ESPPU
CUPID: slides submitted to ESPPU
LEGEND: slides submitted to ESPPU
XLZD: M. Schumann, 3rd Summit on DBD 2025

$M_{\beta\beta}$ PROBABILITY IN PARAMETER SPACE

$$m_{\beta\beta}^2 = \left|\sum_k U_{ek}^2 m_k\right|$$







AI, Ma Yin-Zhe, N. Rossi, Xin Tang, A. Razeto, work in preparation

CURRENT PROJECTS

CUORE
- ^{130}Te 741 kg TeO_2 (206 ^{130}Te)
- Cryogenic bolometer
- Location: LNGS
- Status: running

LEGEND-200
- ^{76}Ge 200 kg
- Arrays of semiconductor in active LAAr veto
- Location: LNGS
- Status: running

AMORE
- 100 kg of ^{100}Mo
- Cryogenic bolometer
- Location: Yemilab
- Status:
  - ✓ 90 crystals 2025-2026; 360 crystals 2026-2030

SuperNEMO
- ^{82}Se 100kg
- Tracking caloremeter
- Location: LSM
- Status: commissioning

SNO+
- ^{130}Te 3.9 ton
- Liquid scintillator
- Locqtion: SNOLAB
- Status: commissioning

NEXT-100
- ^{136}Xe 100 kg
- Gas TPC
- Location: LSC
- Status: commissioning

Kamland-Zen
^{136}Xe 745 kg
Liquid scintillator
Location: Kamioka
$> 3.8\times10^{26}$ yr
Status: upgrading untill 2027
New target: >20 meV

XENONnT
^{136}Xe 5.9 ton
LXe TPC
Location: LNGS
Status: running

PANDA-X
^{136}Xe 3.7 ton
LXe TPC
Location: CJPL
Status: running

FUTURE PROJECTS

CUPID

- ^{100}Mo 500 kg
- Cryogenic scintillating bolometer with particle identification
- Location: LNGS

LEGEND-1000

- ^{76}Ge 1 ton
- Arrays of semiconductor in active LUAr veto
- 20x improvement of BI w.r.t. LEGEND-200
- Expected sensitivity 10^{28} yr
- BI $<10^{-5}$cts/keV/kg/yr
- Location: LNGS

CDEX

- ^{76}Ge
- Arrays of semiconductor in active LUAr veto
- Location: CJPL

nEXO

- ^{136}Xe 5ton
- LXe
- Expected sensitivity 10^{28} yr
- Location: SNOLAB ???

NEXT-HD / NEXT-BOLD

- ^{136}Xe 1 ton
- GXe 1ton / with Ba tagging
- Location: LSC

FUTURE OPPORTUNITIES AND CHALLENGES

Opportunity

- JUNO/THEIAS: take advantage on current technology with SNO+

- XLZD: take advantage on current technology with direct dark matter experiments

Challenges

- Huge effort on material screening

(sensitivty and number of samples) asks for work load sharing in screening facilities worlwide

- Crucial procurement of underground argon

- Geo-political situation for funding

Community merging in technical and economical effort for ton-scale experiments while considering new technologies for future projects

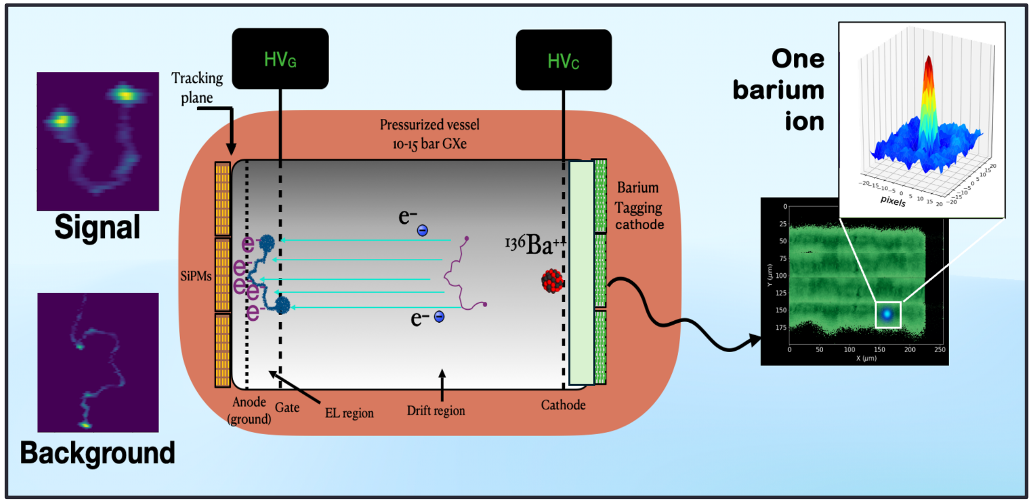
FUTURE OPPORTUNITIES AND CHALLENGES: BARIUM TAGGING

Identify this Ba2+ ion within one ton of xenon for a potentially background-free experiment.

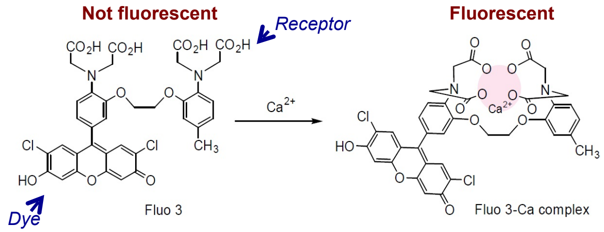
Fluorescence imaging of Ba2+ atoms

For 10^{28} yr 50% efficiency order
1-2 events 10 ton-year

$^{136}Xe \rightarrow\ ^{136}Ba + e + e$



Barium ions are imaged through single molecule fluorescence imaging.



Courtesy NEXT collaboration

Rapid technical progress on molecules, microscopes, and ion manipulation for Ba^{2+} tagging aims to provide a path toward background-free ton- to beyond-ton-scale searches.

APPEC MID-TERM ROADMAP UPGRADE
NEUTRINO MASS AND NATURE

- APPEC strongly supports the CUPID and LEGEND-1000 double-beta decay experiments selected in the US-European process and endorses the development of NEXT. APPEC strongly supports fully exploiting the potential of the KATRIN direct neutrino mass measurement and the development of a new generation of experiments beyond KATRIN.

WHAT IS DARK MATTER?

WIMP SEARCH

In the last 30 years the most studied hypothesis

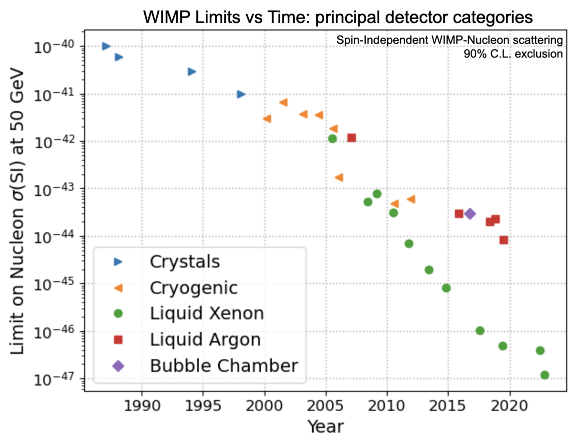
- Liquid Xenon is leading the sensitivity since 2007
- Background reduction by 3×10^4 and fiducial mass increased by ~900x

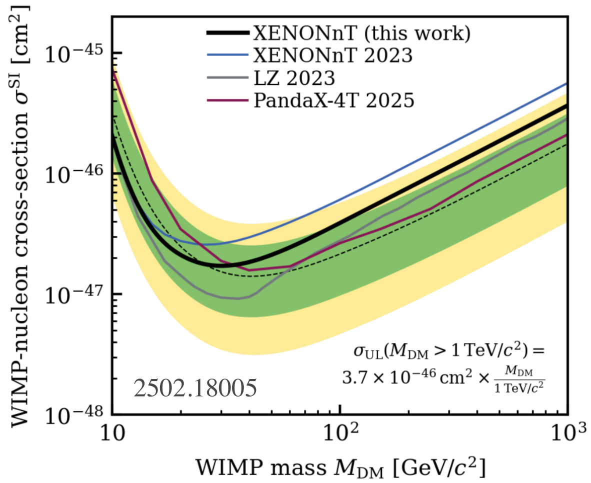
Current experiments:

- **XENONnT** at LNGS 2-phase TPC with 5.9t
  - ✓ Active neutron veto with Gd in water
- **LZ** at SURF 2-phase TPC with 7t
  - ✓ Active neutron veto with Gd in liquid scintillator
- **PandaX-4T** at CJPL 2-phase TPC with 3.7t

Future opportunity (ultimate option???):

- **Xenon, LZ, DARWIN (XLZD):** active mass 60-80 t multi-purpose detector
  - ✓ solar and SN neutrinos, DBD (~6×10^{27} yr)
- Sensitivity for SI at 40 GeV/c^2 ~10^{-49} cm^2



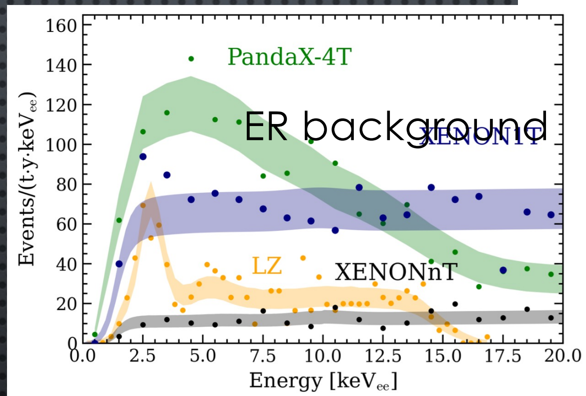


E. Aprile UCLA DM 2025

SOLAR NEUTRINOS WITH DM DETECTORS

Low backgrund achieved in current WIMP DM experiment opens new opportunities:

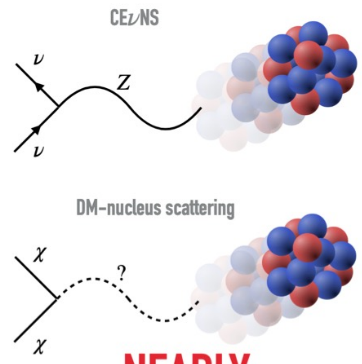
- Coherent Elastic Neutrino-Nucleus Scattering can be detected through Nuclear Recoil techniques



Solar neutrinos:

- ^{8}B solar neutrinos <15 MeV good candidate in LXe
- First step into the neutrino floor
- Low energy calibration: ^{88}YBe with 152keV neutron
- Background only hypothesis disfavoured at 2.73σ

(PANDA-X also mesured 8B solar neutrinos)



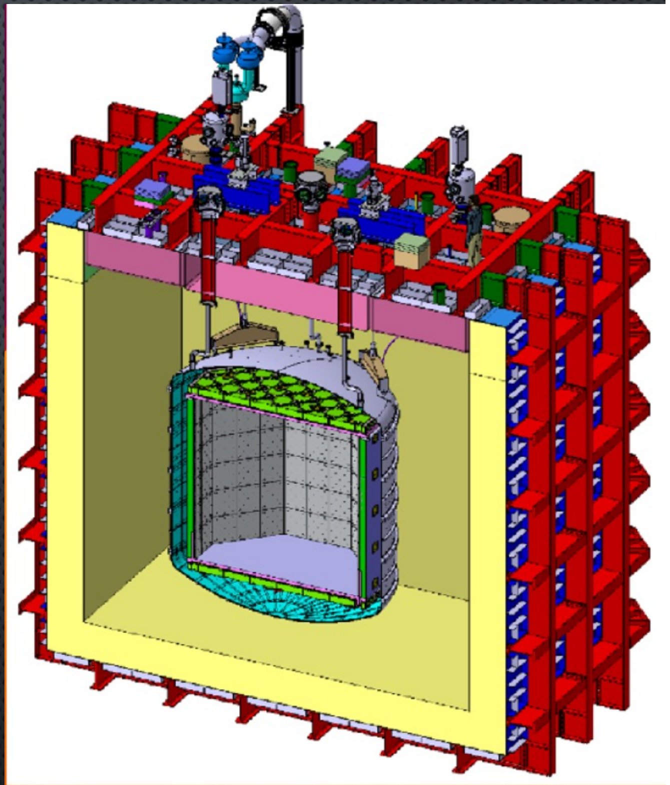
NEARLY INDISTINGUISHABLE

Component	Expectation	Best-fit
AC (SR0)	7.5 ± 0.7	7.4 ± 0.7
AC (SR1)	17.8 ± 1.0	17.9 ± 1.0
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3
Total background	$26.4^{+1.4}_{-1.3}$	26.3 ± 1.4
^{8}B	$11.9^{+4.5}_{-4.2}$	$\boxed{10.7^{+3.7}_{-4.2}}$
Observed	37	

PRL 133(2024) 19, 191002

LIQUID ARGON FOR DARK MATTER SEARCH

DarkSide-20k with 50(TPC)+32(veto) tons of UAr



LAr:

- Excellent scintillator
- 8-10 orders of magnitude suppression of ER with PSD
- Challenge: required underground argon w/o ^{39}Ar; 20m^2 SiPM instrumented detection surface

The Global Argon Dark Matter Collaboration (GADMC):

- DEAP-3600, DarkSide-50, MiniCLEAN, ArDM, DarkSide-20k
  - ✓ UAr extraction rate expected to be 250-330 kg/day
- DEAP-3600 upgrade completed; expected data taking summer 2025
- DarkSide-20k under construction; commissioning and data 2028

Next-generation:

- ARGO with 300 t FM @ SNOLAB or SURF(2nd option)

COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING (CEνNS)

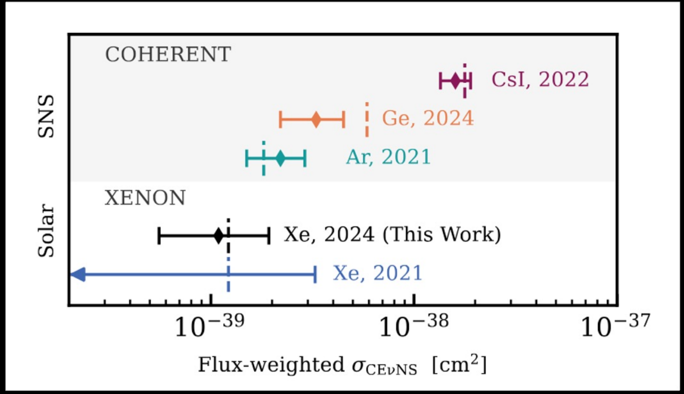
WHY important for DM search?

- Well predicted by SM
- Validation of NR detection techniques
- Benchmark for DM detector sensitivity

Crucial for upcoming DM detectors:

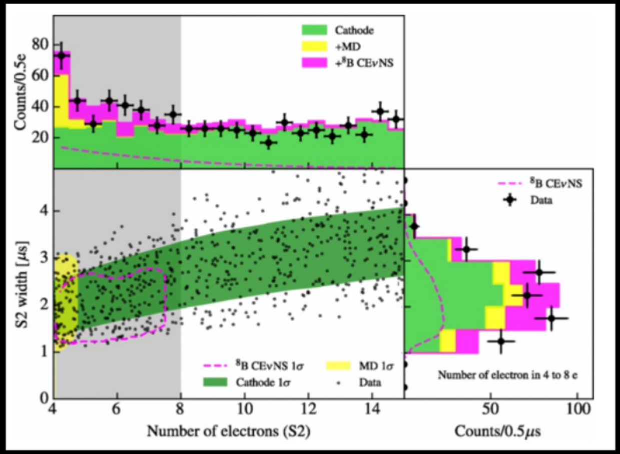
- **Background (neutrino floor)**
- **New physics beyond SM**

Synergy with direct CEνNS measurements (e.g. COHERENT, NUCLEUS, CONUS, etc)



Two "first Indication" of Solar 8B Neutrinos

XENON-nT, 2.7σ
[Phys. Rev. Lett. 133, 191002]

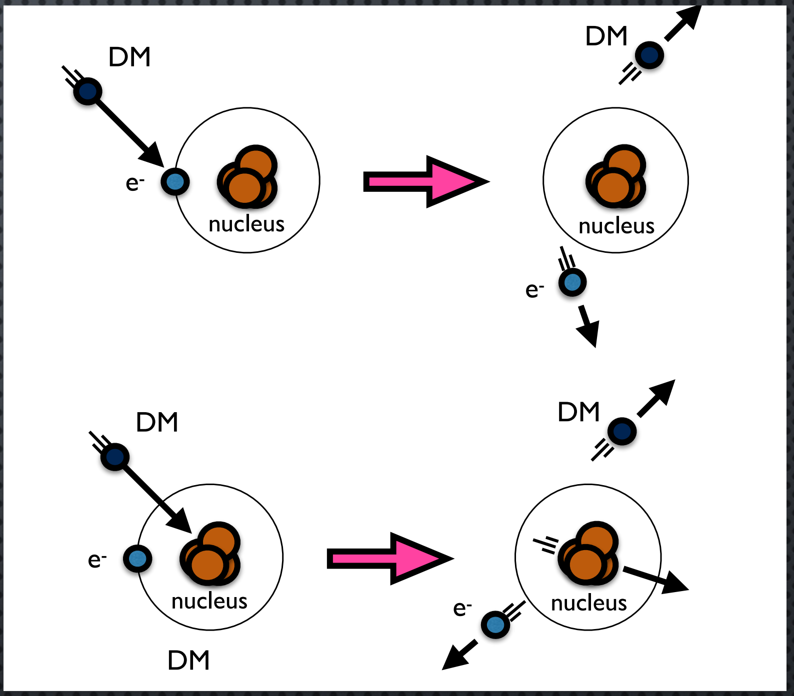


PandaX-4T, 2.6σ

[Phys. Rev. Lett. **133**, 191001]

BEYOND WIMPS

Rouven Essig UCLA DM 2025



Crucial to understand the particle nature of DM

There is a wide range of possible DM candidates.

Hidden dark sector (Ultra-light DM, e.g. QCD axions)

This motivate exploiting different techniques.

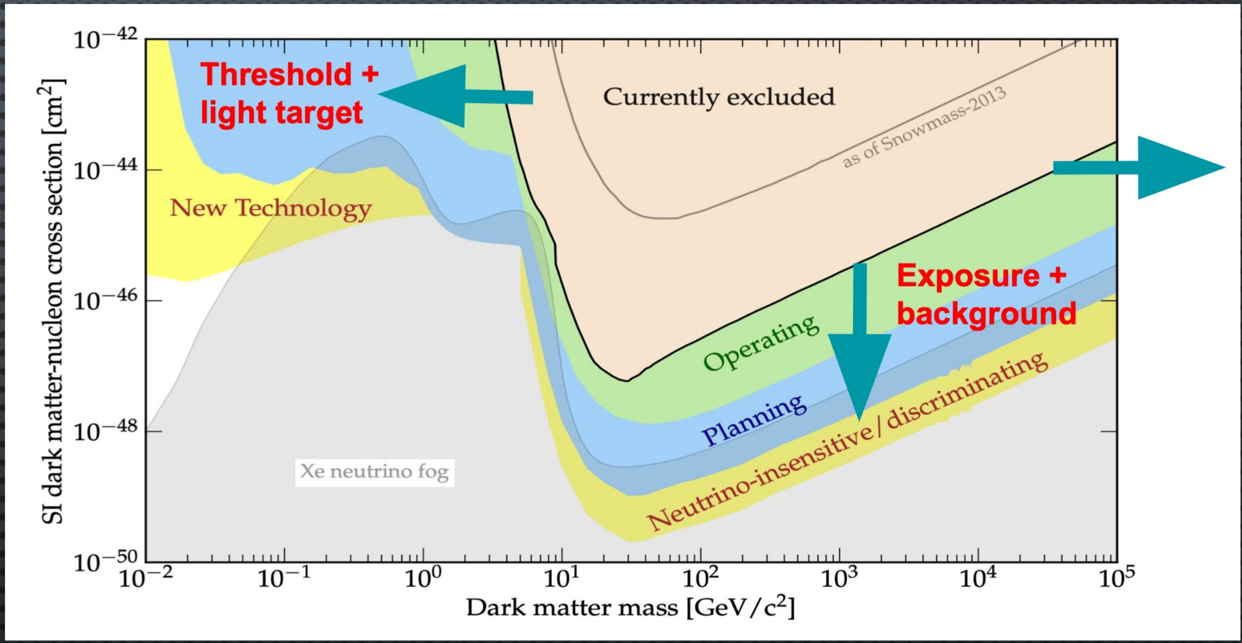
Multi-experiment program

Probe parameter space through:

DM – e scattering
DM – nucleus scattering with Migdal effect

DM WIMP/WIMP-like/low mass detectors (non-exhaustive list)

- XENONnT, LZ, Panda-X, DarkSide-20k, DEAP-3600, PICO-40L, PICO-500, XLZD, ARGO
- CRESST, DELight, TESSERACT, SENSEI, DAMIC-M, DarkNESS, CrystalLiZe, SuperCDMS
- TRISTAN
- CYGNO, CYGNUS (network), MIMAC, TREX-DM, NEWS-G, NEWAGE, NEWSdm
- ANAIS, COSINE, SABRE, COSINUS
- PADME



Indirect DM search

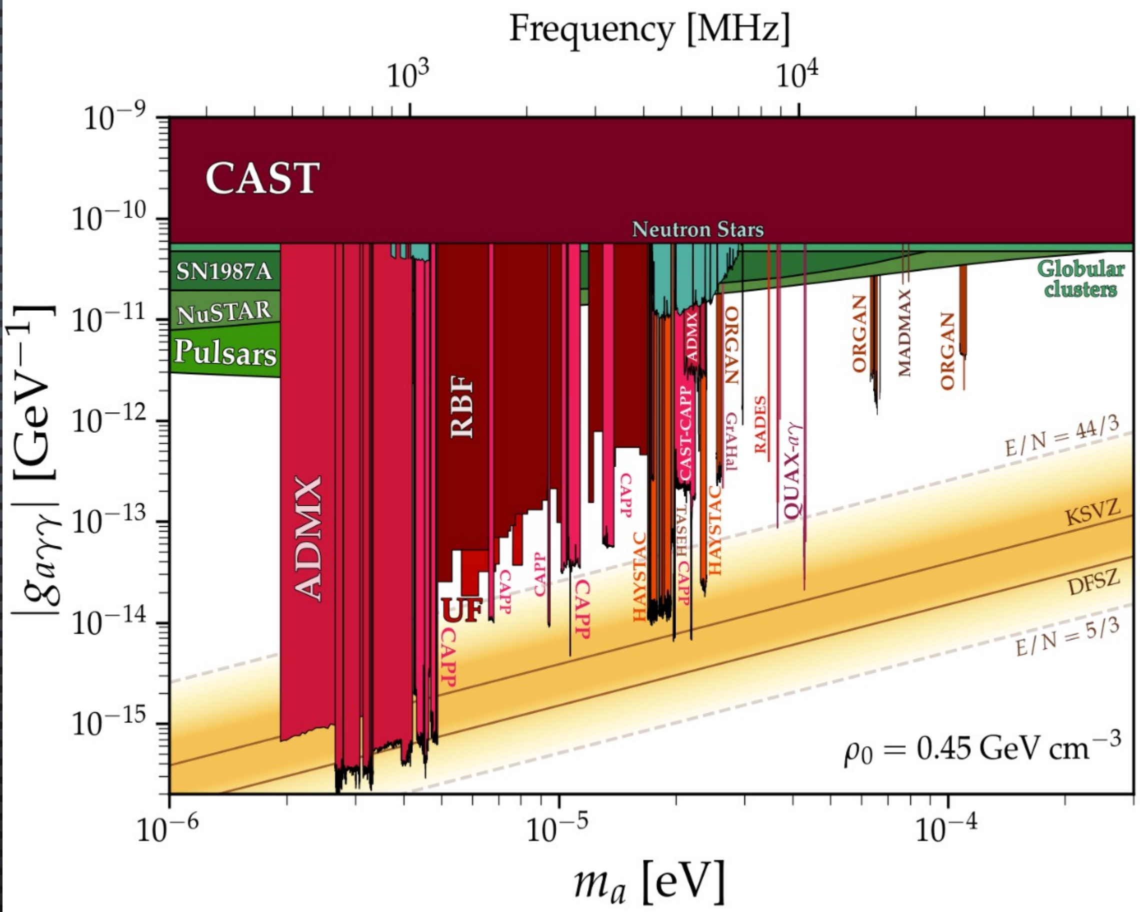
- **Basic idea**: look at the center of the galaxy assuming WIMP-like particles decay or annihilation into SM particles
- Several multi-purpose instruments: AMS, FERMI, MAGIC, CTA, HAWC, IceCube, KM3NeT, …
- Search for
  - Gamma ray lines
  - Neutrino lines
  - Continuu, gamma emission (excess of gamma rays in the galaxy center)
- Dwarf galaxies
  - Expected high DM concent
- Positrons excess
  - Clear excess wrt secondary positron flux (AMS-02, Pamela)
  - Explained by electrons accelerated in a pulsar's magnetic field radiating and producing $e^- + e^+$
  - Still options for ad-hoc DM models to be tested by AMS-0
- Huge impact from direct search and no conclusive evidence of DM signal. Anomalies explained by systematics, models

QCD AXIONS

- Motivated by the strong CP QCD problem
- QCD axions can be a cold DM candidate
- QCD axions can interact with SM particles
- QCD axions can account for some or most of the DM

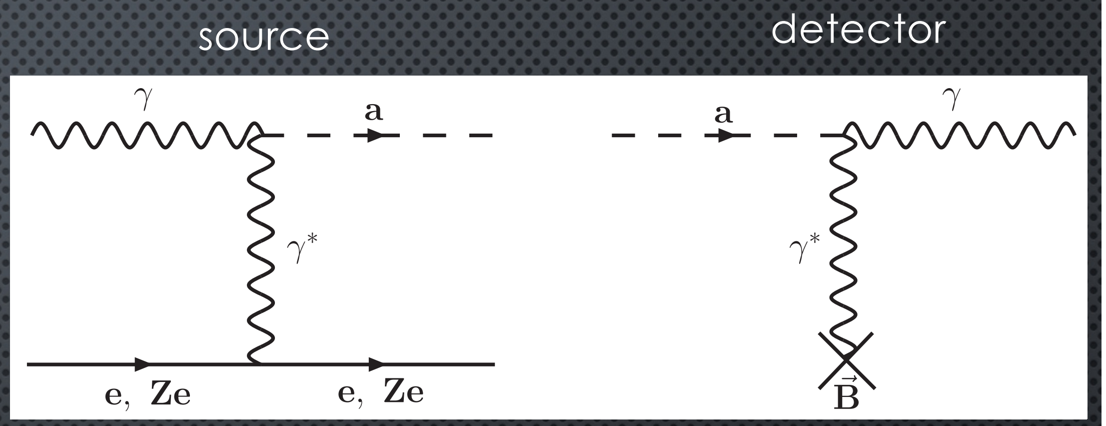
- Huge parameter space: 10^{-12} – 1 eV

- ADMX paved the way for an Haloscope with a resonant cavity
  - ✓ Exploiting axion-photon conversion ($g_{a\gamma\gamma}$)



AXION-LIKE PARTICLES (ALPS)

- Solar axion experiments: Helioscopes
- Space-satellite:
  - ✓ NuSTAR
- DM-axions converting into photons in sun spots detected by low frequency radio telescopes (sensitivity to μeV)
- Ground-based:
  - ✓ CAST (stopped), BabyIAXO, IAXO



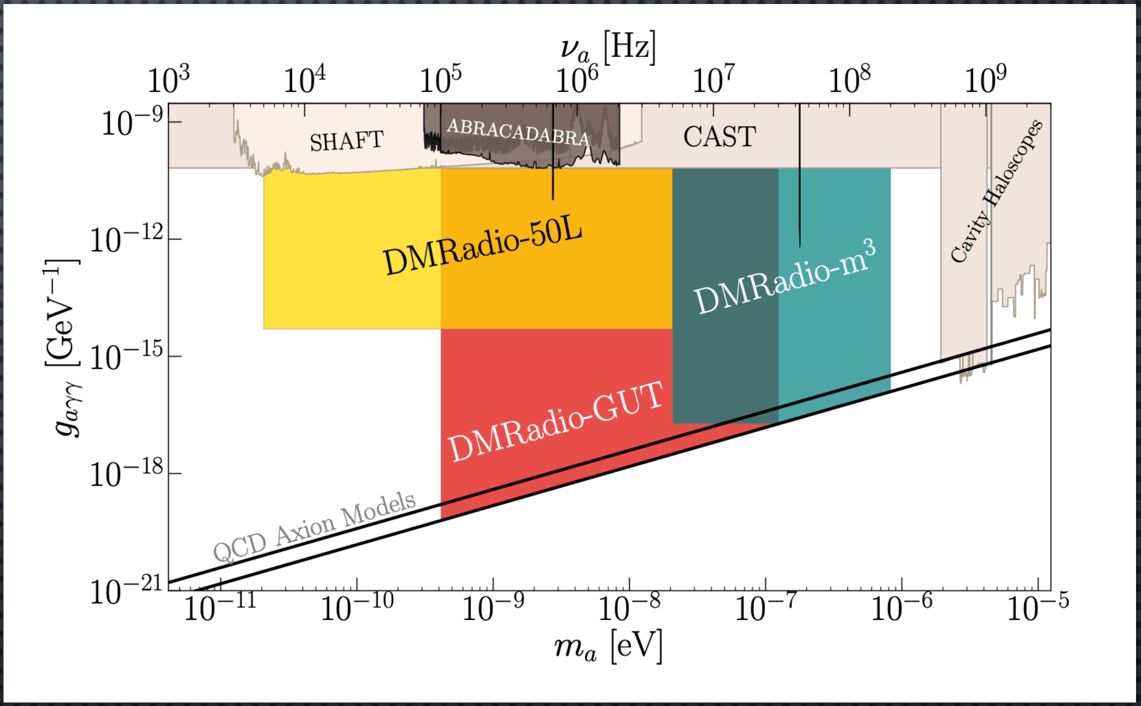
QCD Axion and ALP detectors (non-exhaustive list)

IAXO and BabyIAXO
ADMX
HAYSTAC
NuSTAR
DMRadio
PXS
ABRACADABRA
RADES

QUAX
PADME
MADMAX
LUXE
ALPS II
CADEx
RADES
Multipurpose experiments: CUORE, …

DMRadio

- Tuning the detector on the basis of the axion wavelength relative to the size of the cavity (radio tuning idea)
- DMRadio-50L under construction

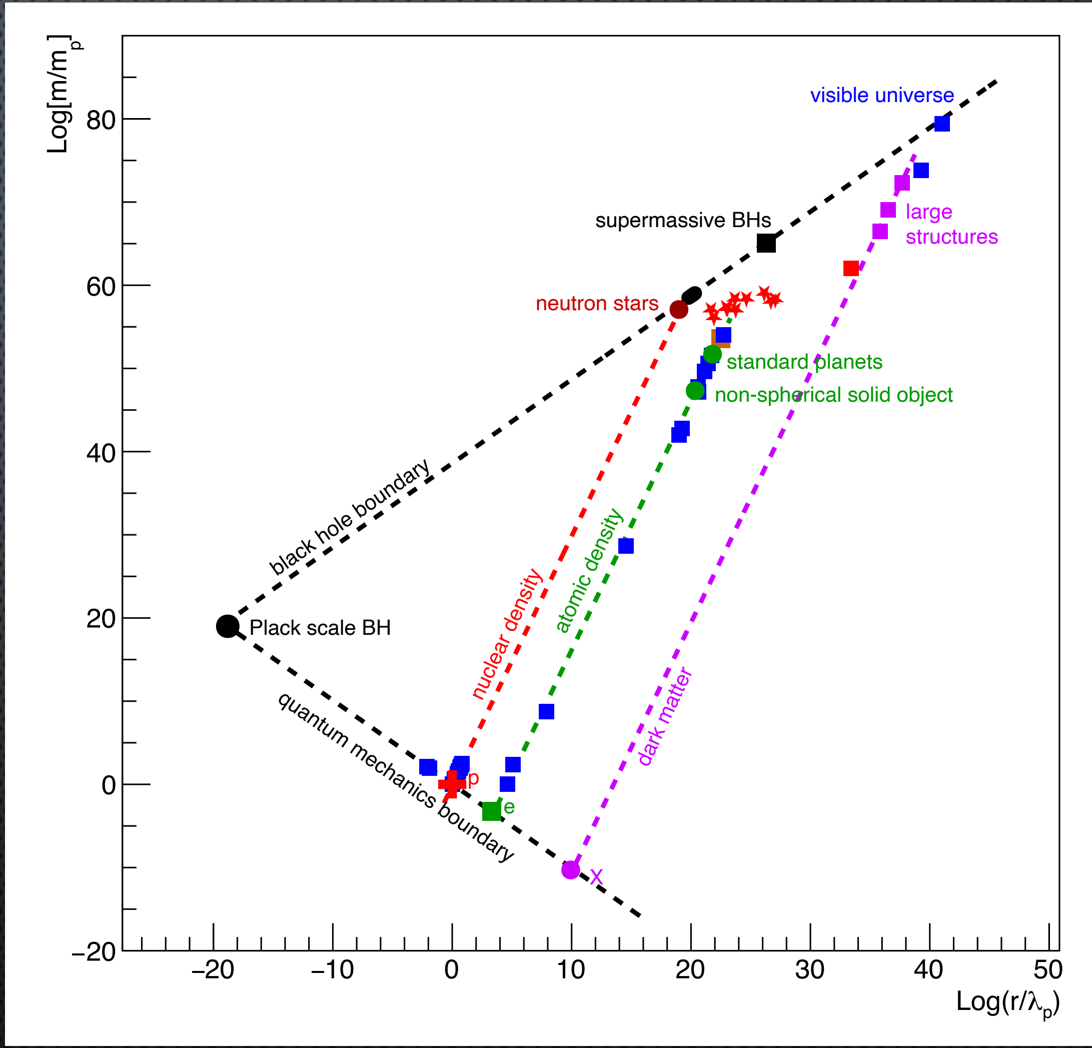


Mass-Radius distribution of all structures in the universe

Understand nature of DM from observations at all scales

Synergy between different fields in Astroparticle

Example: mass-radius distribution extrapolation SIDM mass ~ 10 meV



AI, M. Mannarelli, N. Rossi, Results in Physics, 38 (2022), 105

APPEC MID-TERM ROADMAP UPGRADE
DARK MATTER

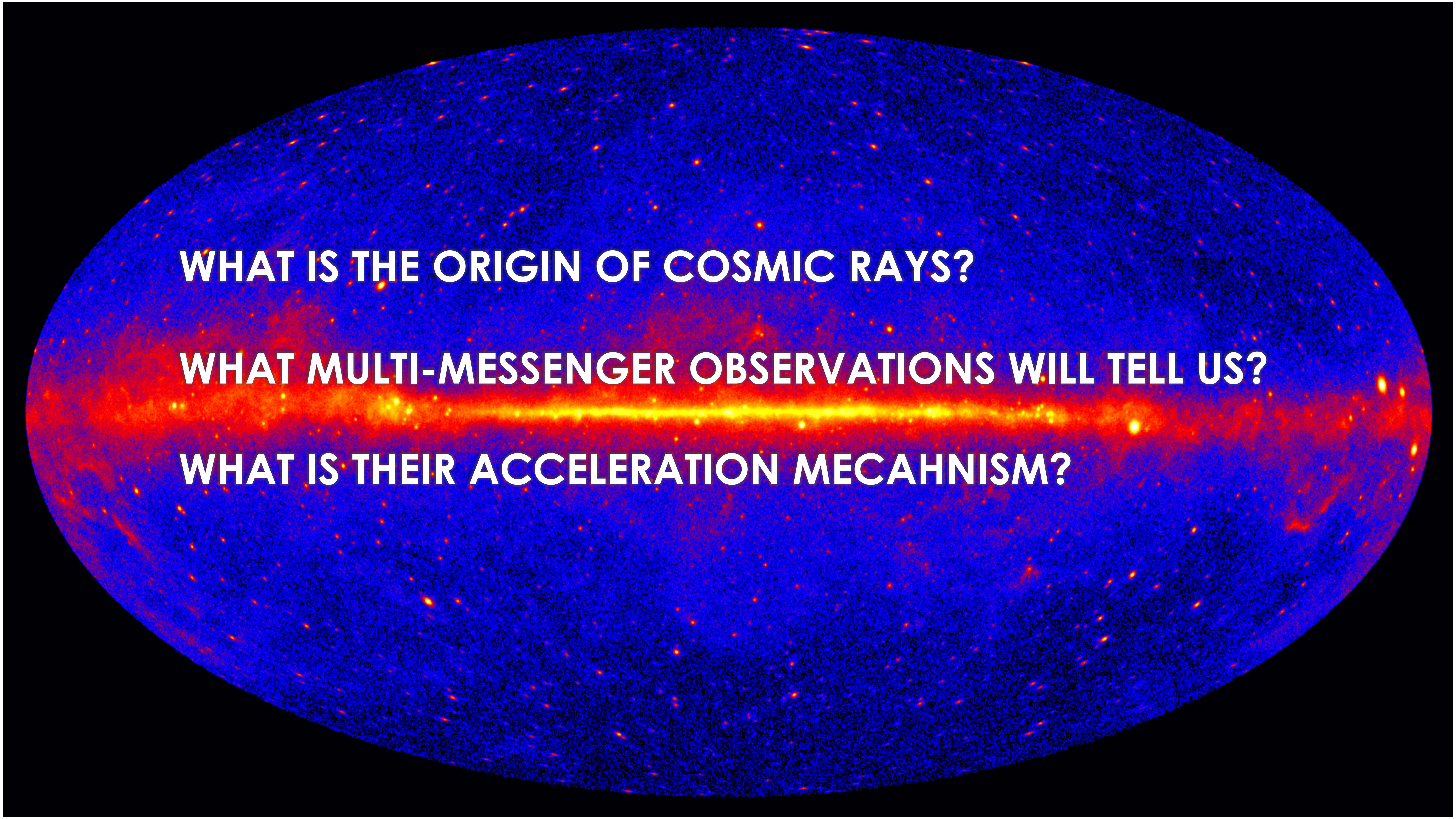
- APPEC strongly supports the European leadership role in the Dark Matter direct detection, underpinned by the pioneering LNGS programme, to realise at the least one next-generation xenon (order 50 tons) and one argon (order 300 tons) detector, respectively, of which at least one sshould be situated in Europe. APPEC strongly encourages detector R&D to reach down to the neutrino floor on the shortest possible time scale for WIMP searches for the widest possible mass range.

- APPEC supports the unique European-led efforts for axions and ALPs detection in mass ranges complementary to the established cavity approach. APPEC encourages R&D efforts to improve experimental sensitivity and extend the accessible mass range.

Next generation WIMP experiments require global coordination

Huge parameter space requires a strategy for small scale projects and technology developments

Crucial synergy with collider phyiscs, astrophysics and cosmology


WHAT IS THE ORIGIN OF COSMIC RAYS?
WHAT MULTI-MESSENGER OBSERVATIONS WILL TELL US?
WHAT IS THEIR ACCELERATION MECAHNISM?

HIGH ENERGY GAMMA RAY ASTROPHYSICAL AND POLITICAL CONTEXT

Emergence of multi-messenger astronomy

- Growing evidence that AGN are also sources of neutrinos
- Synergies with GWs

Rather complete wavelength coverage (from radio to TeV)

- MeV gap (last mission was Comptel, 1996)
- Very important to maintain a GeV mission (Fermi-LAT)

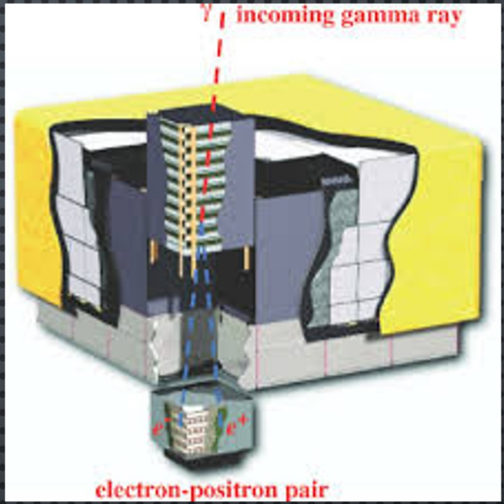
Political context

- Competition from China: LHAASO, HERD, LACT
- Possible threat on existing (VERITAS, IceCube) and proposed (SWGO) projects

EXISTING INSTRUMENTS

Fermi-LAT

- Large field of view pair-creation telescope
- Energy range 20 MeV – 300 GeV
- Launched June 2008
- Still in operation
- Solar array drive failure in 2018, degraded operation mode
- > 7000 sources detected



tracker

veto

calorimeter

Integral – International Gamma-ray astrophysics laboratory

- Large field of view (imager + spectrometer)
- Energy range 15 keV – 10 MeV
- Launched October 2002
- Mission ended 2025 after 22 years

EXISTING INSTRUMENTS

Atmospheric Cherenkov Telescopes

- 3 arrays in operations: HESS (Namibia), MAGIC (Canary Island)

and VERITAS

- Energy range 20 GeV – 100 TeV
- Operation extended to 2028 (CTAO will take over)

Large High Altitute Air Shower Observatory (LHAASO)

- At 4,410 a.s.l. in China, in operation since 2019
- Focusing on > 100 TeV
- 43 UHE gamma sources detected
- Hybrid design with three sub-arrays: Water Cherenkov Detector Array (WCDA), Kilometer Square Array (KM2A), Wide Field-of-view Cherenkov Telescope Array (WFCTA)
- WCDA: 78,000 m^2 equipped with 3,120 water Cherenkov detectors with 1 PMT
- KM2A: 1 km^2 equipped with 5,195 1m^2 scintillators and 1,188 36 m^2 water Cherenkov for muons

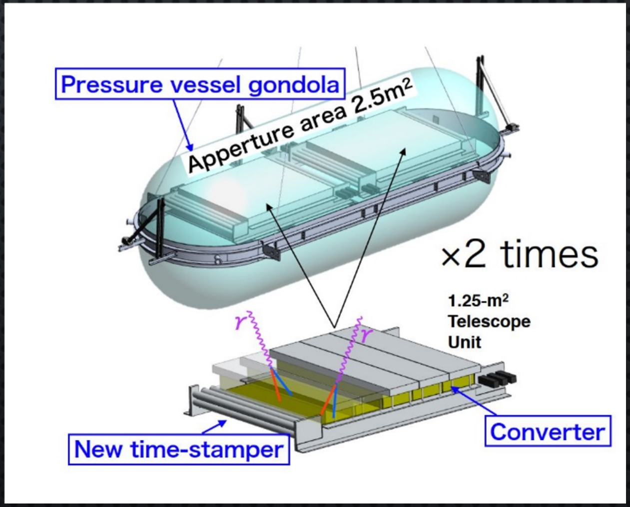
EXISTING INSTRUMENTS

High Altitude Water Cherenkov (HAWC)

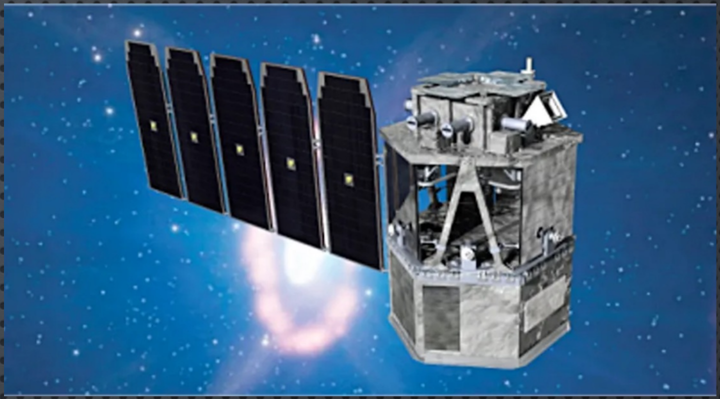
- At 4,100 a.s.l. in Sierra Negra (Mexico), in operation since 2015
- Energy range 100 GeV – 50 TeV
- 20,000 m^2 array with 300 WCD 7.5 m diameter + 350 out tanks 1.5 m diameter

Gamma-Ray Astro-Imager with Nuclear Emulsions (GRAINE)

- Baloon-born mission
- Based on emulsion plates with polarization capabilities
- Low exposure
- Energy range 10 MeV-100 GeV
- Last flight April 2023

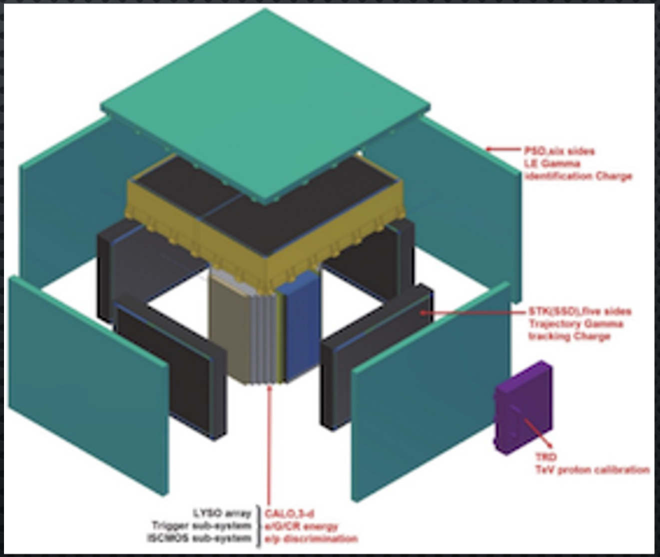


PLANNED PROJECTS



Compton Spectrometer and Imager (COSI)

- Selected in 2021 by NASA as its next small Explorer (SMEX) astrophysics mission
- Energy range 0.2 – 5 MeV
- Launch scheduled in 2027



High Energy cosmic-Radiation Detector (HERD)

- Hodoscopic Calorimeter + Transition Radiation
- Energy range 0.5 GeV - 100 TeV
- Operation from 2027 for 10 years

PLANNED PROJECTS

Cherenkov Telescope Array Observatory (CTAO)

- Successor of HESS, MAGIC, Veritas
- Two Imaging Atmospheric Cherenkov Telescopes (IACTs) in the northern and southern hemispheres
- Energy range 10 GeV – 300 TeV
- Wide scientific programs from gamma-ray astronomy to cosmology and fundamental physics
- Three classes of telescopes: LST (Large Sized Telescopes), MST, and SST
- CTAO: 4 LST in north site in operation 2026; south site construction soon and operations in 2028+
- Challenges:

From APPEC survey: ERIC signed in 2015 but very delayed

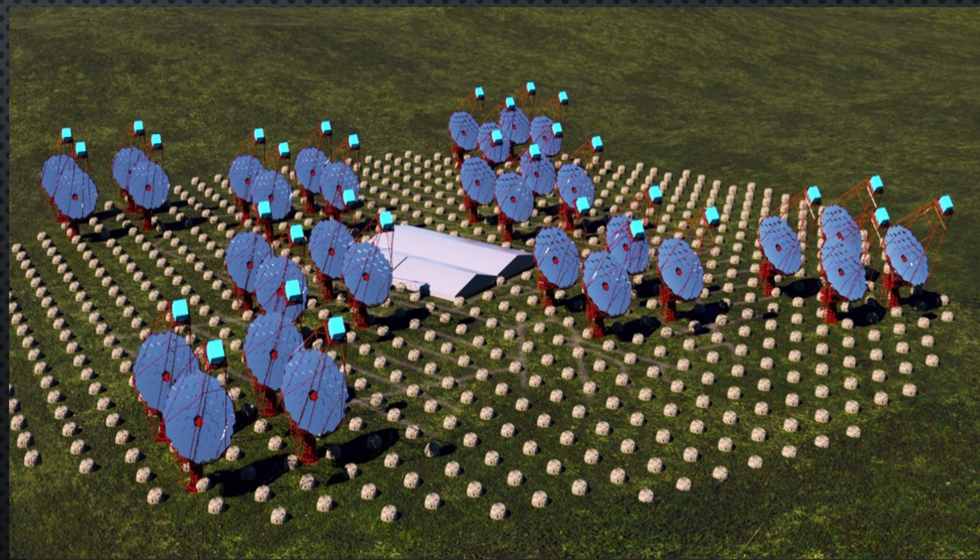
north site in advanced stage than south site.

Artistic Rendering of CTAO-South

PLANNED PROJECTS

Large Array of Cherenkov Telescope (LACT)

- Next generation Image Atmospheric Cherenkov Telescope
- Array of 32 IACTs to be deployed in LHAASO site
- Photodetector type: SiPM
- Energy range 1 TeV - 1 PeV
- Resolution 0.05° 6x LHAASO
- Prototype being built and full array expected in 2025
- Second telescope in 2026
- Full array by 2028



PROPOSED PROJECTS

Southern Wide-field Gamma-ray Observatory (SWGO)

- Site selected in 2024 in Atacama Astronomical Park (above 4400 a.s.l.)
- Currently down-selecting design and funding applications for construction
- Aiming start construction in 2027; challenge: funding approval

Transient High-Energy Sky and Early universe Surveyor (THESEUS)

- ESA mission as candidate M7 for a launch in 2037
- combination of X-/gamma-ray monitors
- Designed to provide a breakthrough in early universe cosmology and multi-messenger astrophysics through Gamma-Ray Burst and other classes of high-energy transients

PROPOSED PROJECTS

e-Astrogram

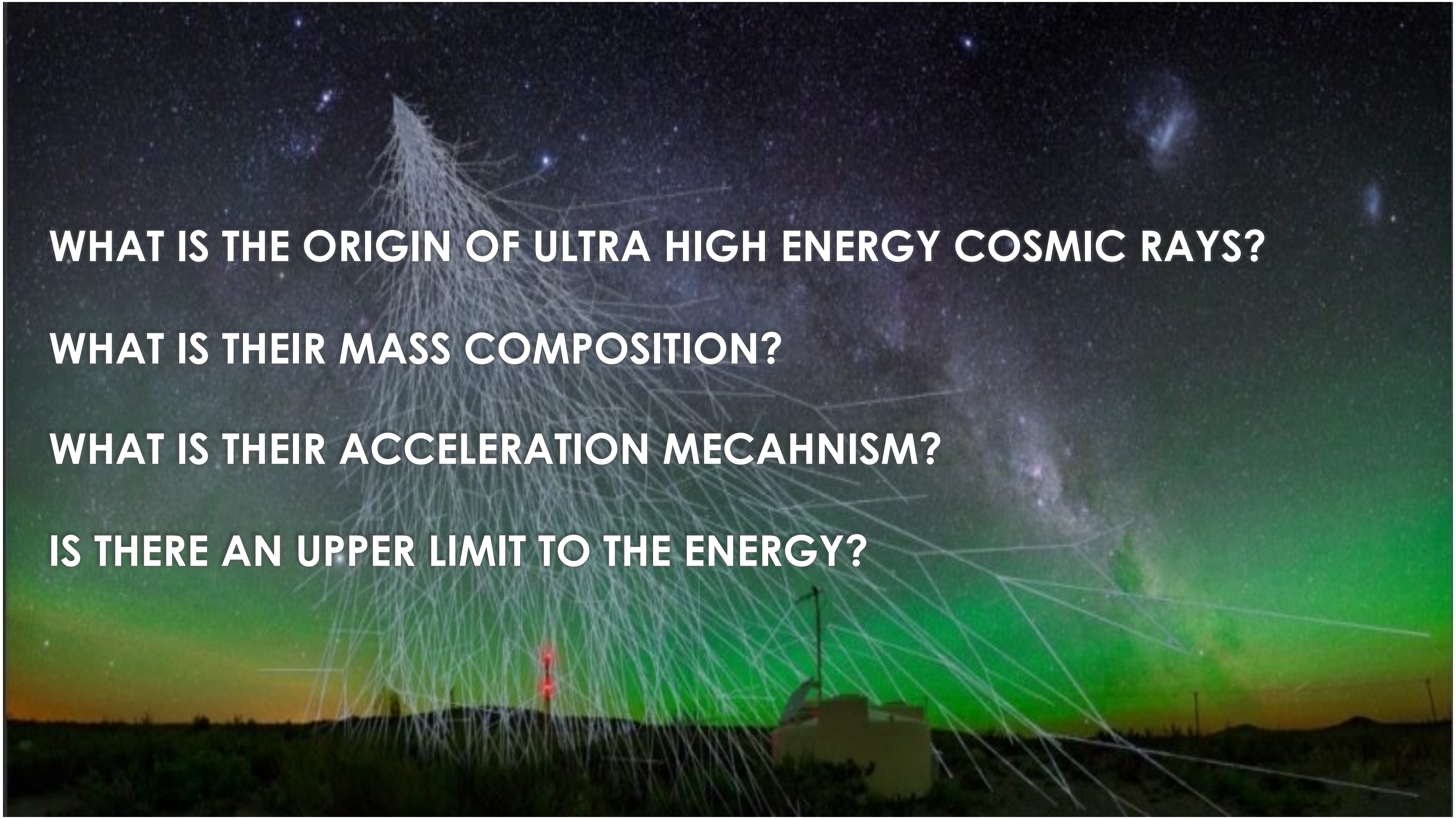
- Space-based project
- Compton and pair-creation telescope (silicon tracker + calorimeter)
- Energy range: 0.3 MeV – 3 GeV
- Proposed at ESA M5 mission in 2017 and M7 in 2022
- Not selected in M7; new proposal for M8 (2041)

AMEGO-X (All –sky Medium-Energy Gamma-ray Observatory eXplorer)

- Space-based project
- Compton and pair-creation telescope (silicon tracker + CsI calorimeter)
- Energy range: 100 keV – 1 MeV
- Proposed in 2021, to be launched no later than 2028

APPEC MID-TERM ROADMAP UPGRADE
HIGH ENERGY GAMMA RAYS

- APPEC fully endorses the construction and subsequent long-term operation of CTA in bot the northern and southern hemispheres APPEC supports work towards the selection of the mission concept THESEUS and the construction of SWGO. It urges the community to consider a replacement for the Fermi telescope.


WHAT IS THE ORIGIN OF ULTRA HIGH ENERGY COSMIC RAYS?
WHAT IS THEIR MASS COMPOSITION?
WHAT IS THEIR ACCELERATION MECAHNISM?
IS THERE AN UPPER LIMIT TO THE ENERGY?

ULTRA HIGH ENERGY COSMIC RAYS ($E > 10^{18}$ EV): EXISTING INSTRUMENTS

Pierre AugerPrime Observatory:

- South hemisphere, Argentina
- 1660 surface detectors (SD) stations (WCD+SSD) in 3000 km^2
- 27 fluorescence detectors (FD) stations
- Upgrade completed
- Upgrade of UMD ongoing

Telescope Array (TA):

- North hemisphere
- In Utah, USA at 1,400 m a.s.l.
- 680 km^2 with 507 SD
- 3 FD stations

Pierre Auger Observatory

Telescope Array

FD determines the lateral shower extension: $X_{max}(Fe) < X_{max}(p)$
Inferred mass composition depends on hadronic interaction models

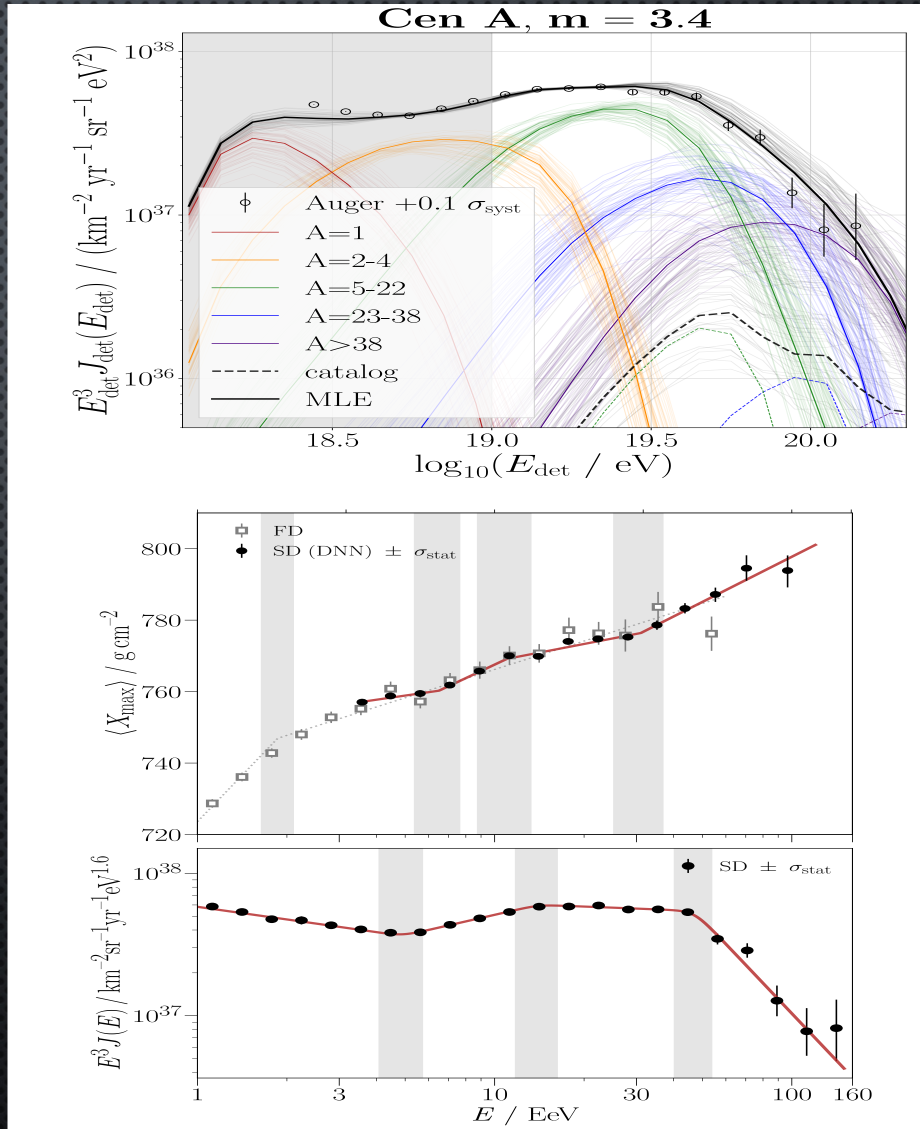
HIGHLIGHTS

E > 10^{20} eV ~ 10^{-3} particle/km²/yr
~ 1/km²/century

Use large natural media (polar ice sheet, atmosphere, ocean, earth)

UHECR flux from 3.4 source evolution scaling.
- Large exposure > 20 years
- New feature above 10^{19} eV
- Established presence of intermediate-mass nuclei at highest energies
- Test hadronic interactions at > 14 TeV in CoM

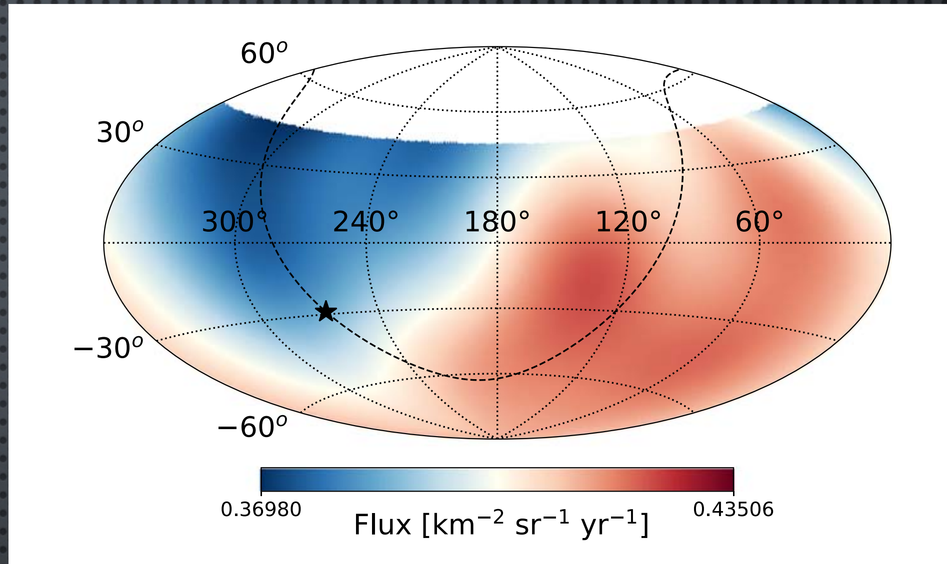
1st high statistic measurement of Xmax with SD using neural network which shows similar features as from the energy spectrum



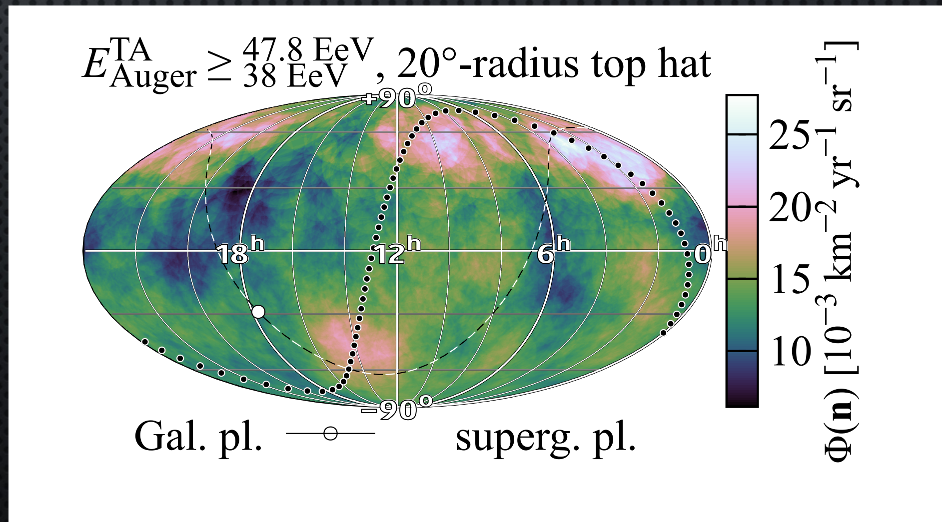
HIGHLIGHTS

UHECR flux in equatorial coordinates

- Dashed line is galactic plane with center at the star
- Maximum of flux outside the galactic plane
- Evidence of extragalactic origin of UHECR
- Evidence of dipole structure (>6.8σ)



Combined TA and Auger above $4x10^{19}$ eV
Hotspots visible, lower one is Centaurus A
Correlation with supergalactic plane under investigation by joined WG



FUTURE DIRECTIONS

AugerPrime fully deployed > 2035 and in operations for 10 years

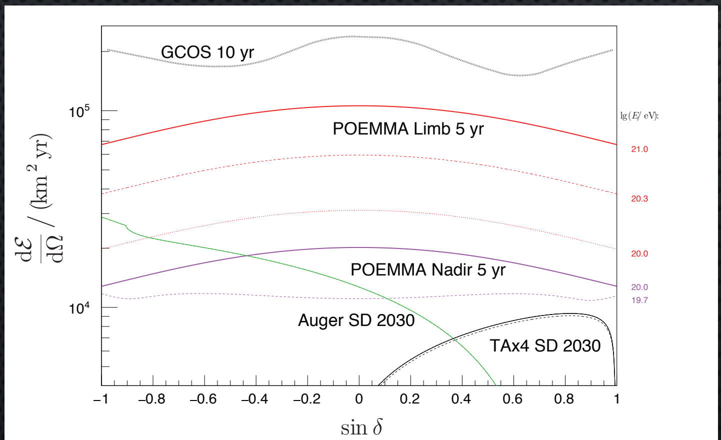
Next-generation:

Space: POEMMA (Stereo Fluorescence Observatory from Space)

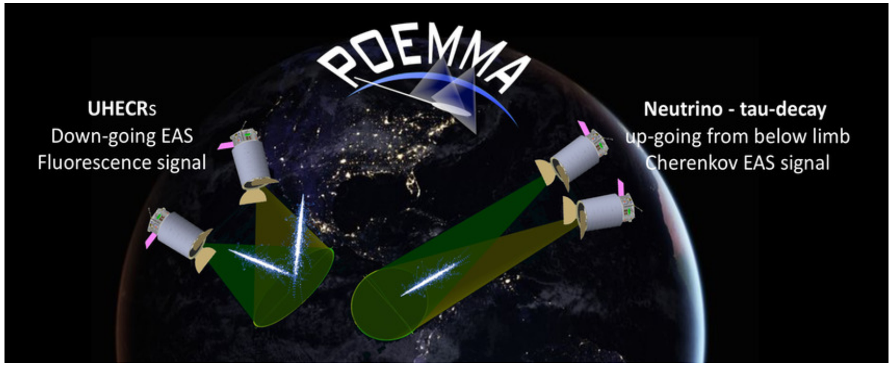
Funding secured to relaunch a baloon

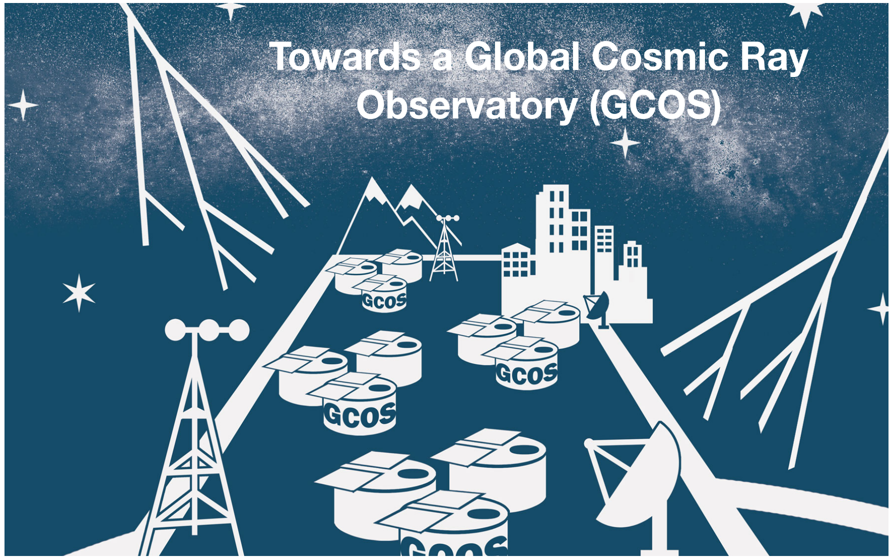
Surface: Global Cosmic Ray Observatory (GCOS) in conceptual stage with multiple sites (N and S) and a surface of order 60,000 km^2

Combination of surface, fluorescence, and radio detectors



exposure





FUTURE DIRECTIONS

Giant Radio Assay for Neutrino Detection (GRAND)

- Surface radio detection of EAS induced by UHE particles
- 200,000 km^2
- Antennas operate in 60-200 MHz band to avoid noise at low frequencies
- Complementarity with IceCube-Gen2 radio, GRAND has a better angular resolution and narrower field of view
- First prototype deployed in 2023 in 2 sites (46 antennas in the Gobi desert in China and 10 antennas in the Auger site), currently under commissioning
- Next steps:
  - ✓ Extension of stations in China to 300
- Challenge: funding for full deployment

APPEC MID-TERM ROADMAP UPGRADE

HIGH ENERGY COSMIC RAYS

- APPEC fully endorses the completion of AugerPrime and strongly supports the exploitation of the combined Auger and TA full sky coverage by joint working groups. APPEC encourages continued R&D on new cost-effective detector technologies for next-generation observatory. APPEC encourages theory efforts to understand air shower physics, cosmic rays sources and propagation.

PATH TO THE NEXT APPEC ROADMAP 2027-2036

- Community survey: November 2024 – January 2025
  - ✓ 250 responses
  - ✓ 40 responses from collaboration
- SAC divided into 16 WGs (including AI, computing, open science, social impact)
- TOWN MEETING in Zaragoza 23-24 Septempber

APPEC
TOWN MEETING
ZARAGOZA 2025

https://indico.cern.ch/event/1516919/

Town Meeting Agenda

Time	Sept 23rd
9:00-9:25	Introduction by APPEC chair C. Pena-Garay
9:25-9:50	APPEC SAC A. Ianni
9:50-10:15	ACME overview A. Kouchner
10:15-10:45	Summary from ESG (focus Astroparticle) E. Previtali
10:45-11:10	ASTRONET, M. Giard
11:10-11:30	break
11:30-12:00	Summary from P5 (focus Astroparticle) Karsten Heeger
12:00-12:30	EuCAPT S. Pascoli
12:30-13:00	ESO overview, Xavier Barcons
13:00-13:30	JWST overview, Frederic.Courbin
13:30-15:00	Lunch break
15:00-18:30	Round tables
20:30-22:30	dinner

CONCLUSIONS: THE APPEC ROADMAP

- Astroparticle is an incredibly rich field with great opportunities to contribute to science advancement and BSM physics
- Pleanty of projects require a «good» strategy and roadmap
- Next-generation projects ask global coordination (strategy crucial)
- It is understood that AI will lead to substantial advancements (trigger algorithms, …)
- It is required a network of European supercomputers for advanced data analysis for astroparticle physics
- Crucial synergy with astronomy, astrophysics, collider physics and nuclear physics to tackle the DM conundrum

CONCLUSIONS: ASTROPARTICLE OPPORTUNITIES

- Crucial synergy with astronomy, astrophysics, collider physics and nuclear physics to tackle the DM conundrum
- Crucial advancement in DBD research: an incredible opportunity for BSM physics
- Crucial advancement in neutrino mass direct determination
- Understanding UHECRs origin
- Crucial advancement for next-generation GW detectors


APPEC
TOWN MEETING
ZARAGOZA 2025
CAPA
Universidad Zaragoza
Input for the Strategic Roadmap 2027-2036
23-24 Sept 2025
Local Organizing Committee
Susana Cebrián
Iván Coarasa
Theopisti Dafni (co-chair)
Igor García Irastorza
Maurizio Giannotti
Héctor Gómez
Gloria Luzón
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