JENAS-2022

2nd Joint ECFA-NuPECC-APPEC Symposium

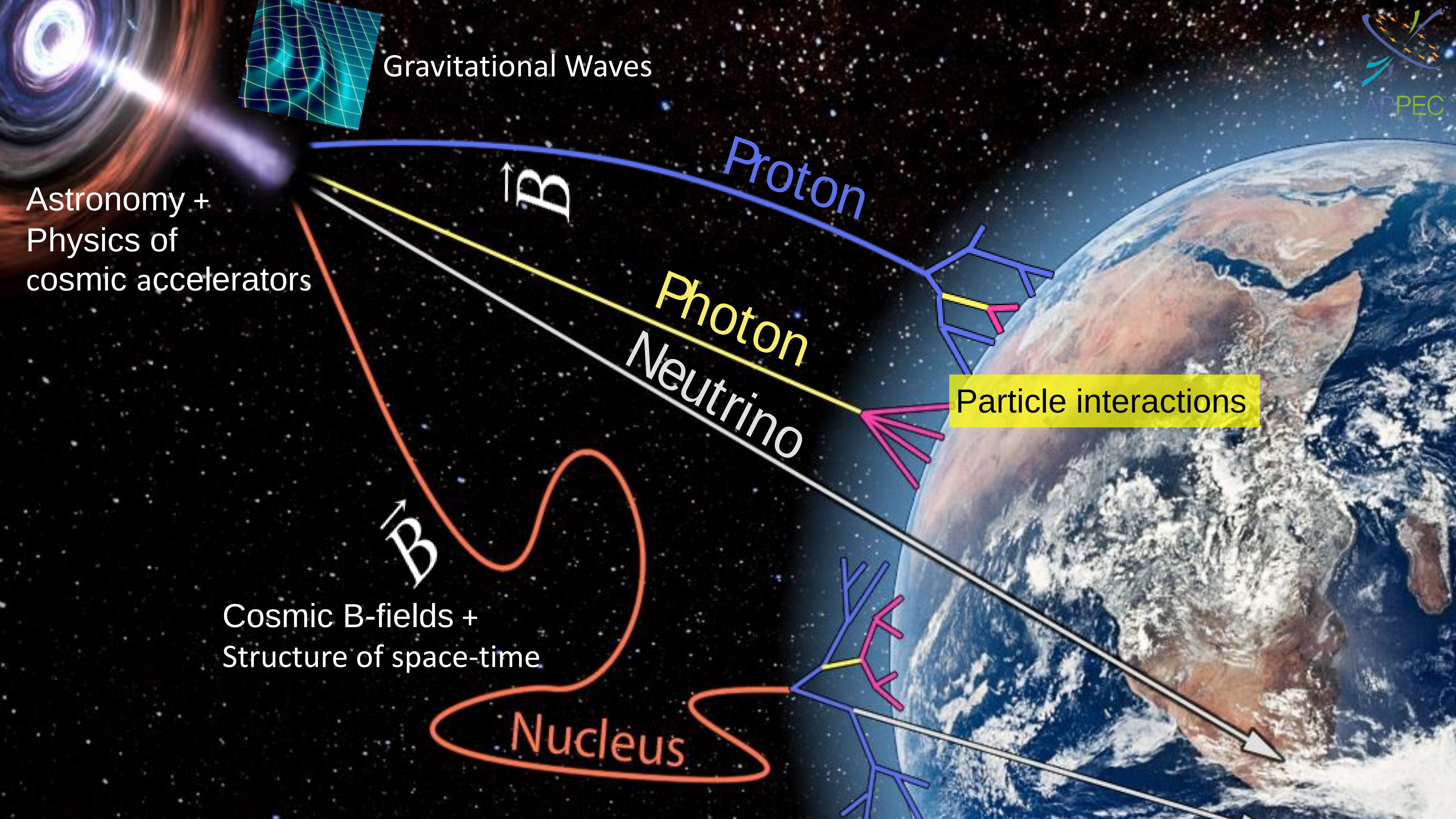
Recent highlights in AstroParticle Physics

Sijbrand de Jong (APPEC SAC chair)

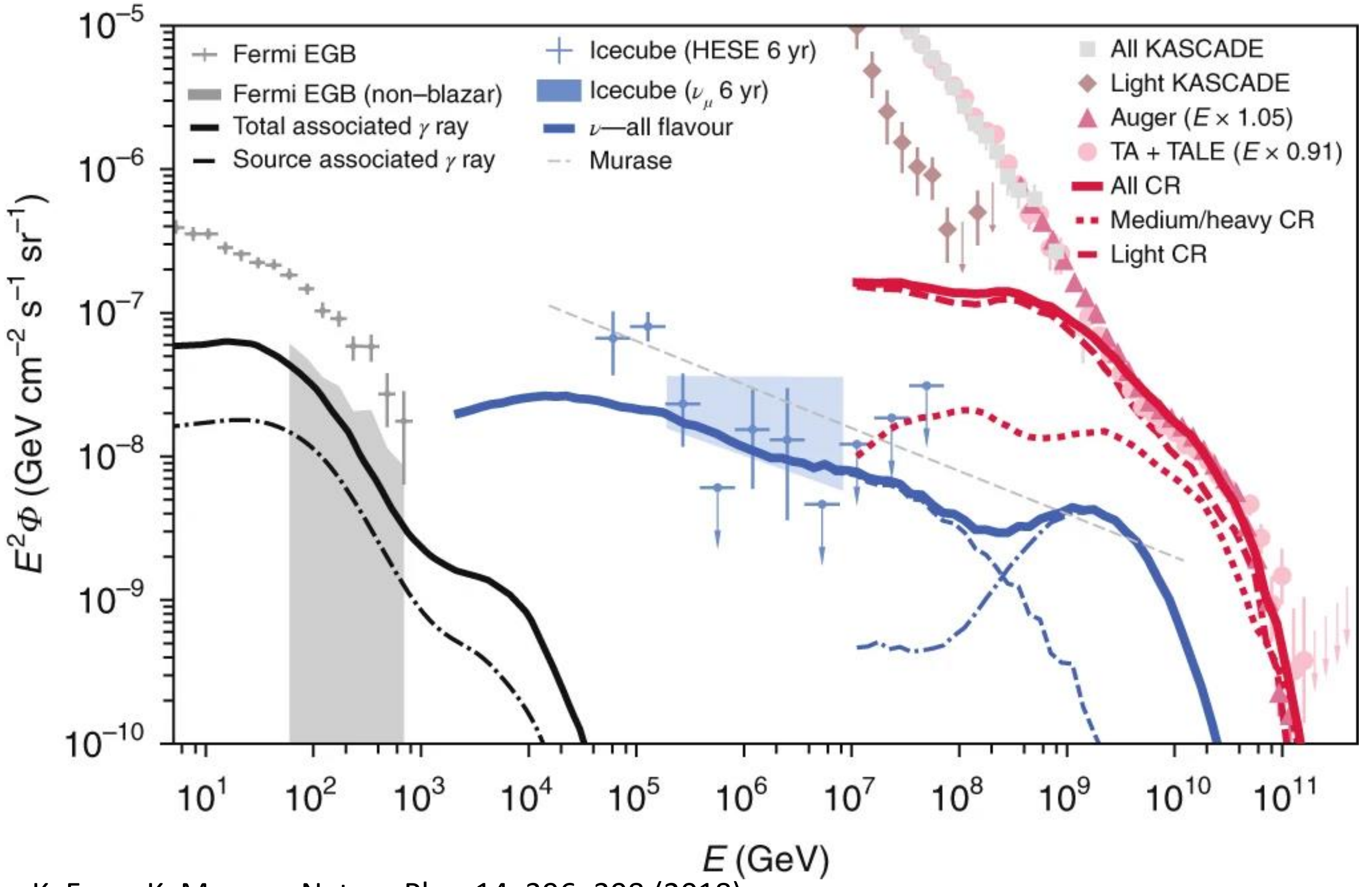
Many thanks to the APPEC SAC members, in particular Ken Ganga, Jocylin Monroe, Manfred Lindner, Silvia Pascoli, and to Andreas Haungs, Paris Sphicas, Ian Shipsey, for interfacing and to Antoine Kouchner, Harm Schoorlemmer and Charles Timmermans

Overview

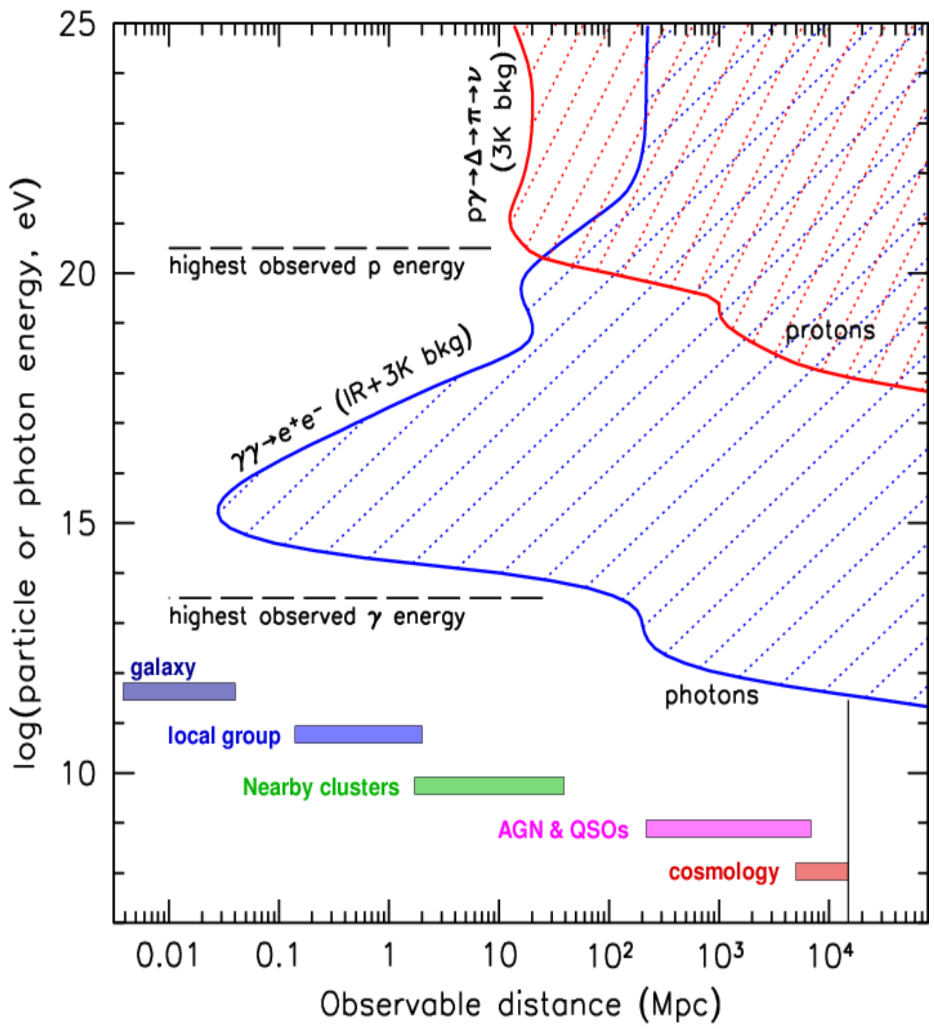
- AstroParticle Physics field of study and methods
- Particles and waves from and fields in the Universe
  - Detection technologies
  - Astronomical Objects (including nuclear physics)
  - Evolution of the Universe (including nucleosynthesis)
  - Particle Properties
  - Space-time Properties
- Non-accelerator experiments
  - Neutrino properties
  - EuCAPT
- Ecological footprint
- Conclusion


Gravitational Waves
APPEC
Astronomy +
Physics of
cosmic accelerators
Proton
B
Photon
Neutrino
Particle interactions
B
Cosmic B-fields +
Structure of space-time
Nucleus

Cosmic particle energy spectra and horizons

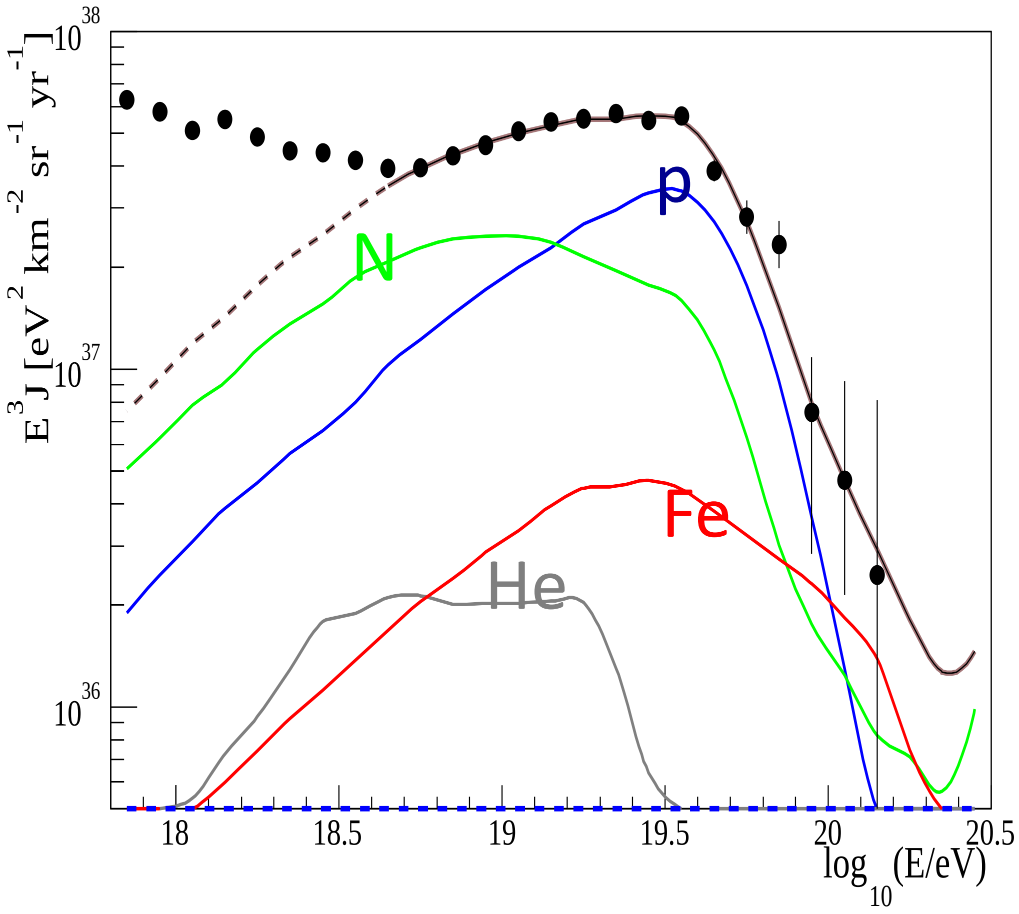


K. Fang, K. Murase, Nature Phys 14, 396–398 (2018).

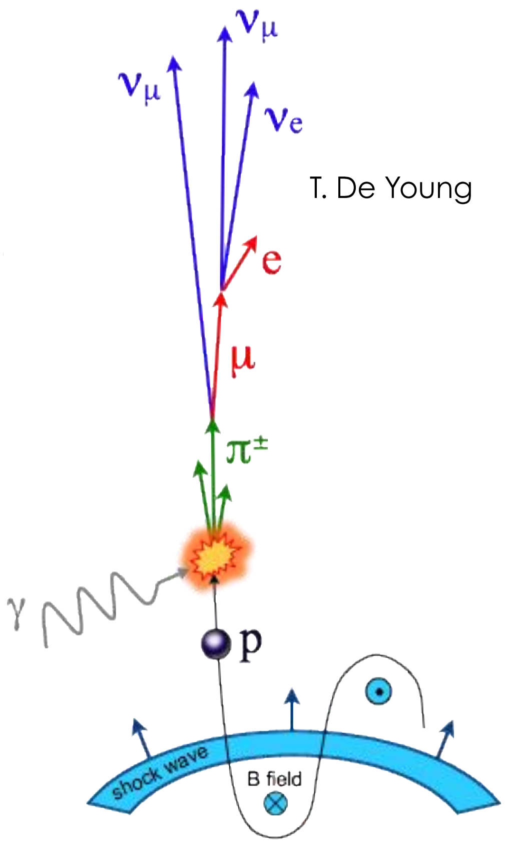


Cosmic particle type spectrum

Proton & Nuclei



Point sources



Cosmogenic sources

$p+\gamma_{CMB} \rightarrow p+\pi^0$

$\pi^0 \rightarrow \gamma + \gamma \qquad E_\gamma \approx E_p/10$

$p+\gamma_{CMB} \rightarrow n+\pi^+$

$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad E_\nu \approx E_p/20$

$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e \qquad E_\nu \approx E_p/1000$

$A+\gamma_{CMB} \rightarrow A'+p$

$p+\gamma_{CMB} \rightarrow \nu\text{'s} \qquad E_\nu \approx E_A/A/20$

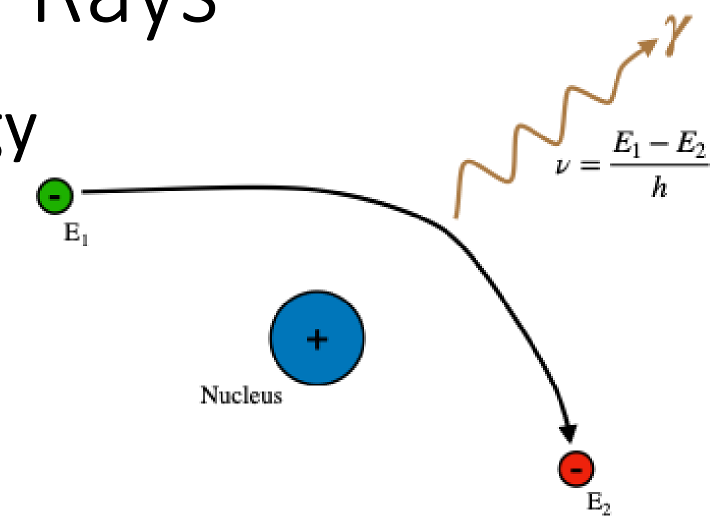
$p+\gamma_{CMB} \rightarrow \gamma\text{'s} \qquad E_\gamma \approx E_A/A/10$

High Energy Gamma Rays

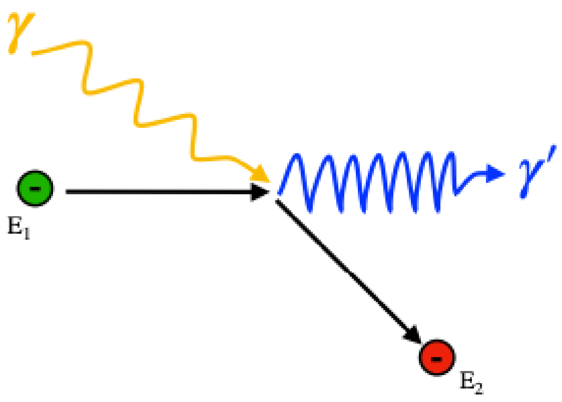
Practical upper limit in energy from cosmic horizon

$E_\gamma \approx E_A/A/10$

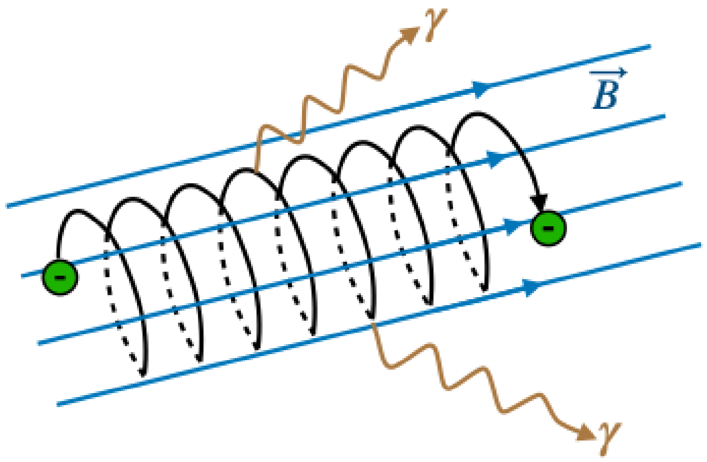
Inverse Compton at highest energies: leptonic of hadronic origin



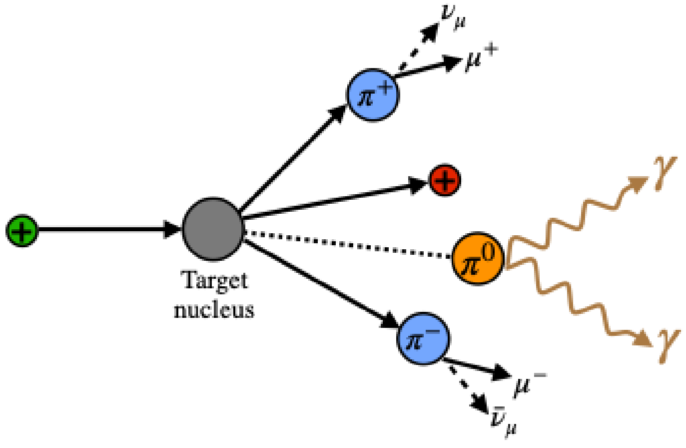
Bremsstrahlung



Inverse Compton



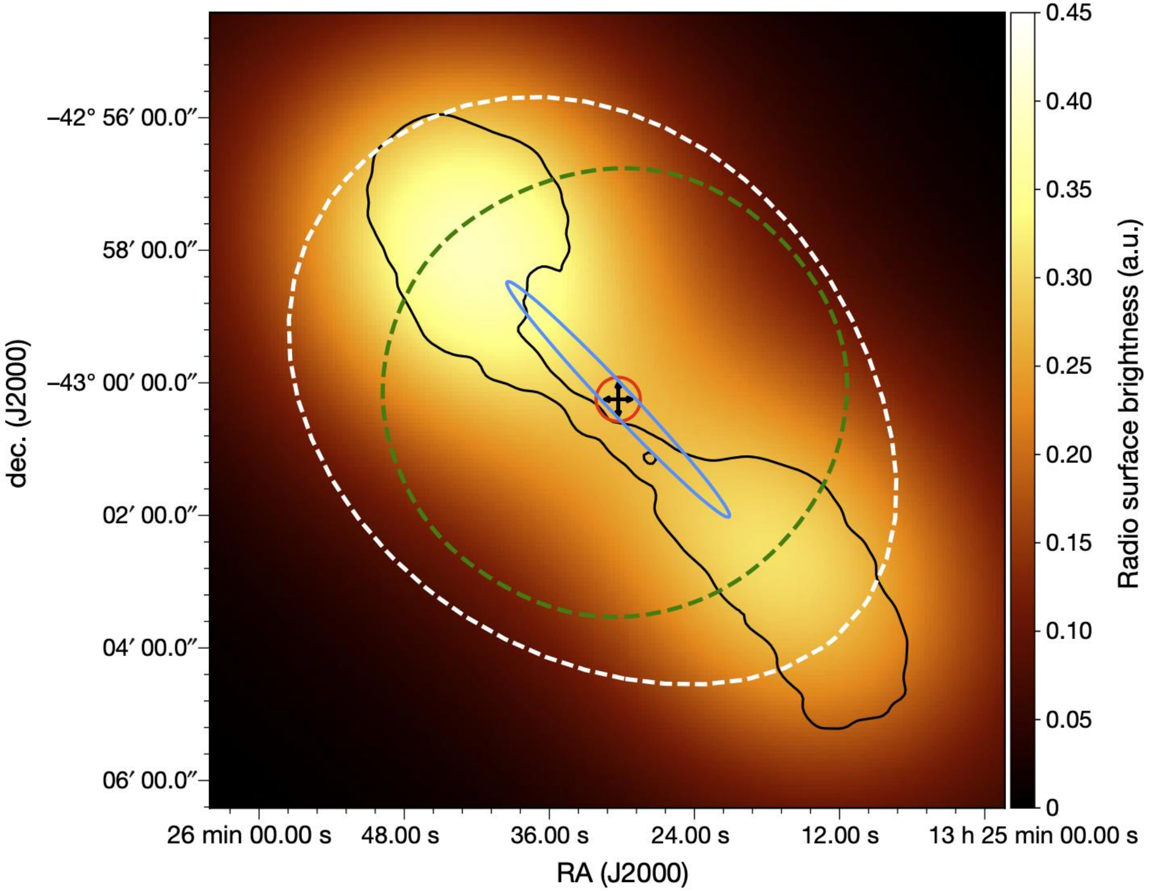
Synchrotron

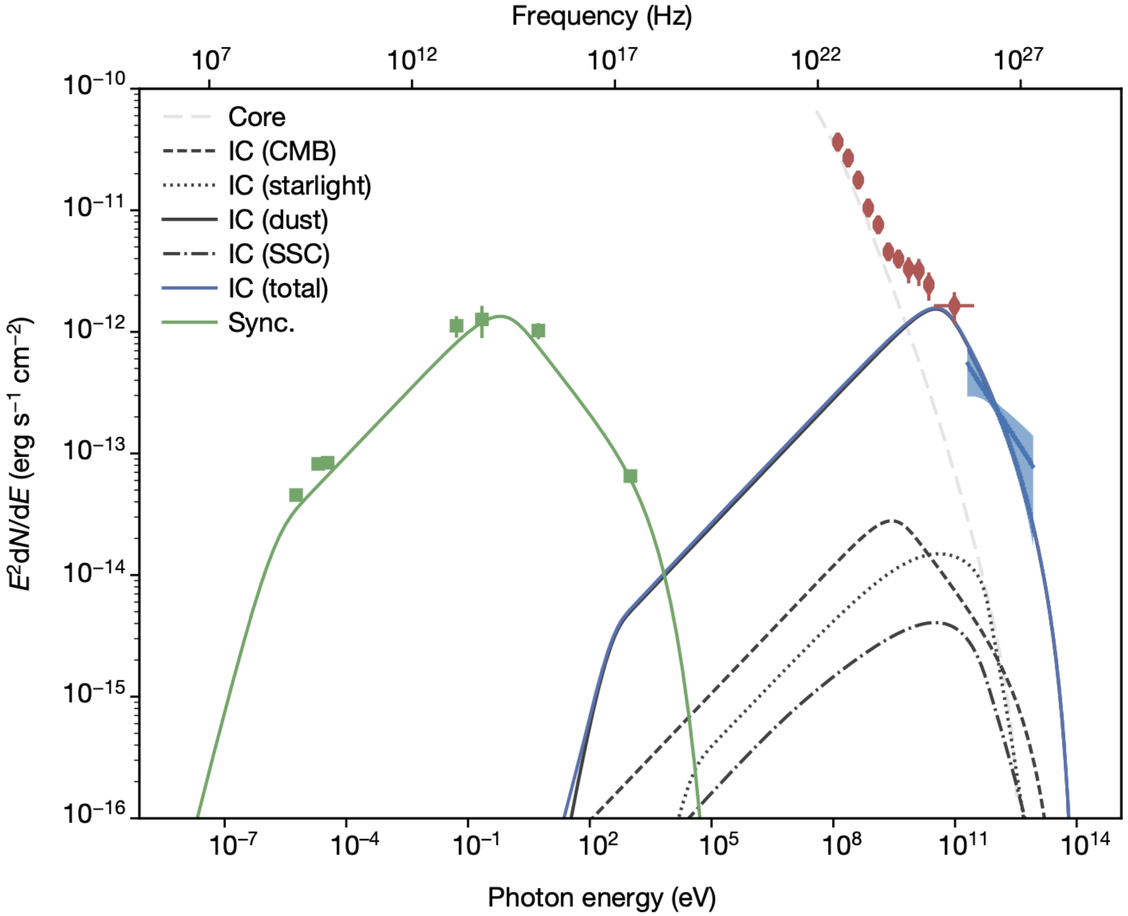


Pion decay

High Energy Gamma Rays

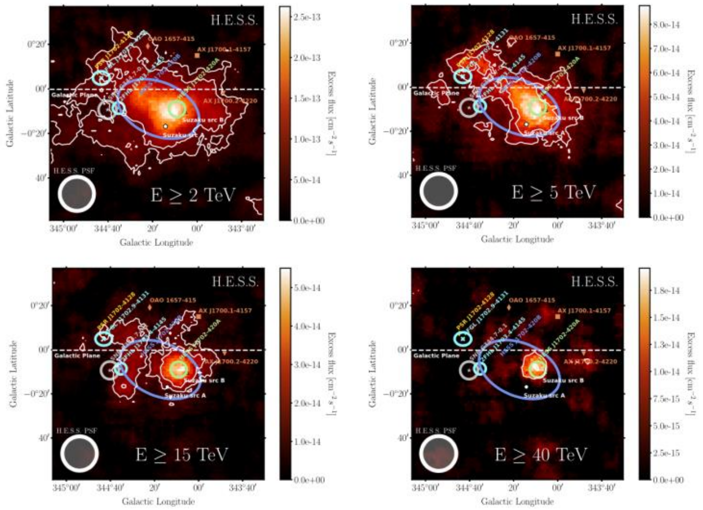
Particle acceleration along the jet of Centaurus A



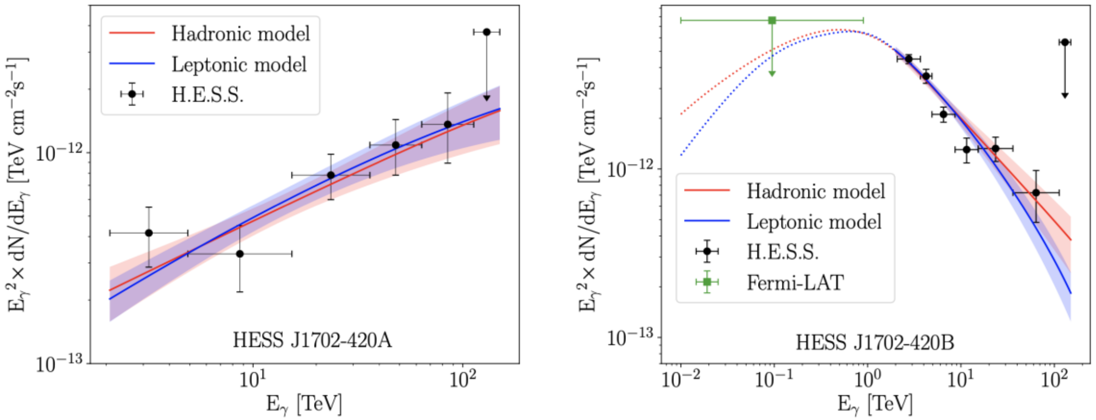


H.E.S.S. Collaboration, Nature volume 582, pages 356–359 (2020)

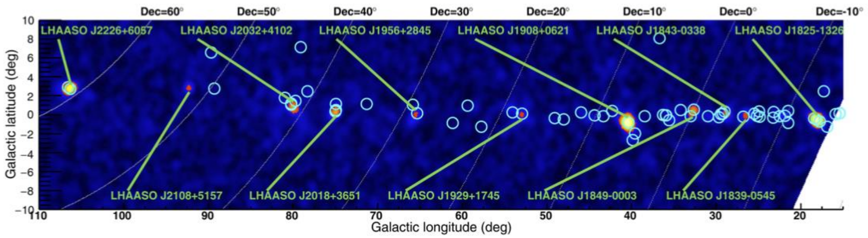
High Energy Gamma Rays: PeV sources in Milky Way



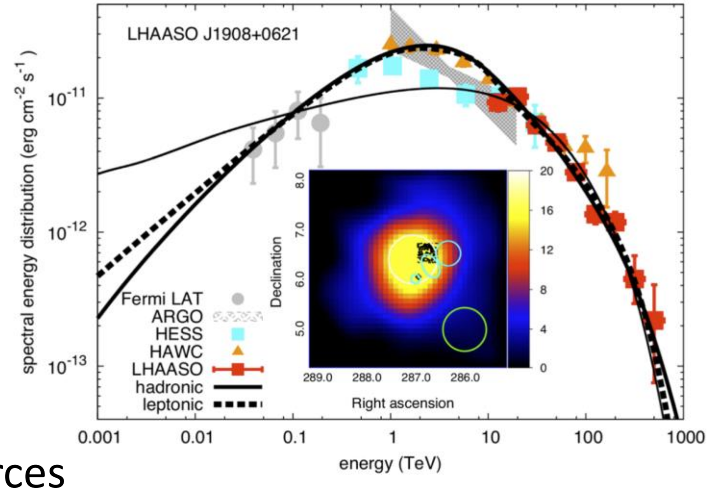
H.E.S.S. Collaboration, A&A 653, A152 (2021)
Evidence of 100 TeV γ-ray emission from HESS J1702-420

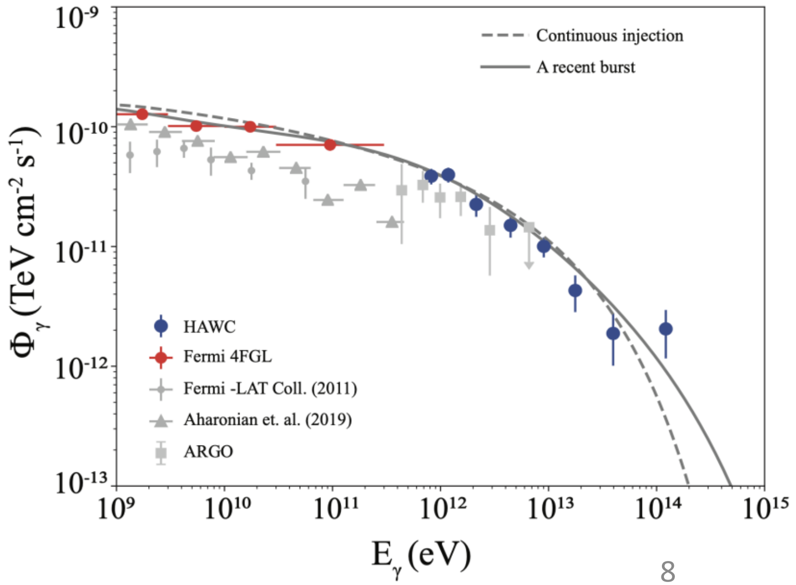


HAWC Collaboration, arXiv.org/2103.06820, HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon



LHAASO Collaboration, Nature volume 594 (2021) 33–36,
Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

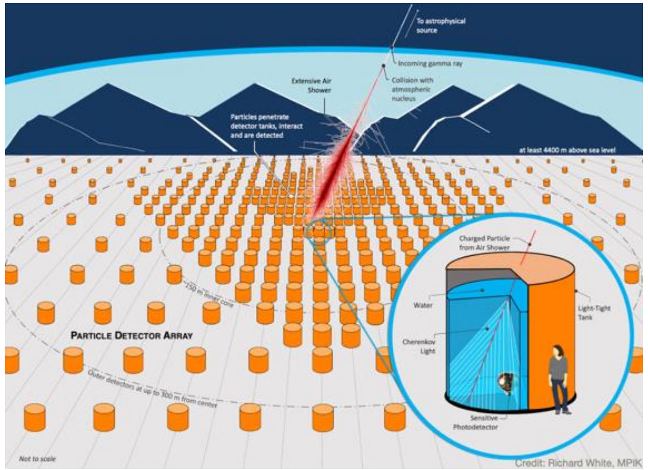




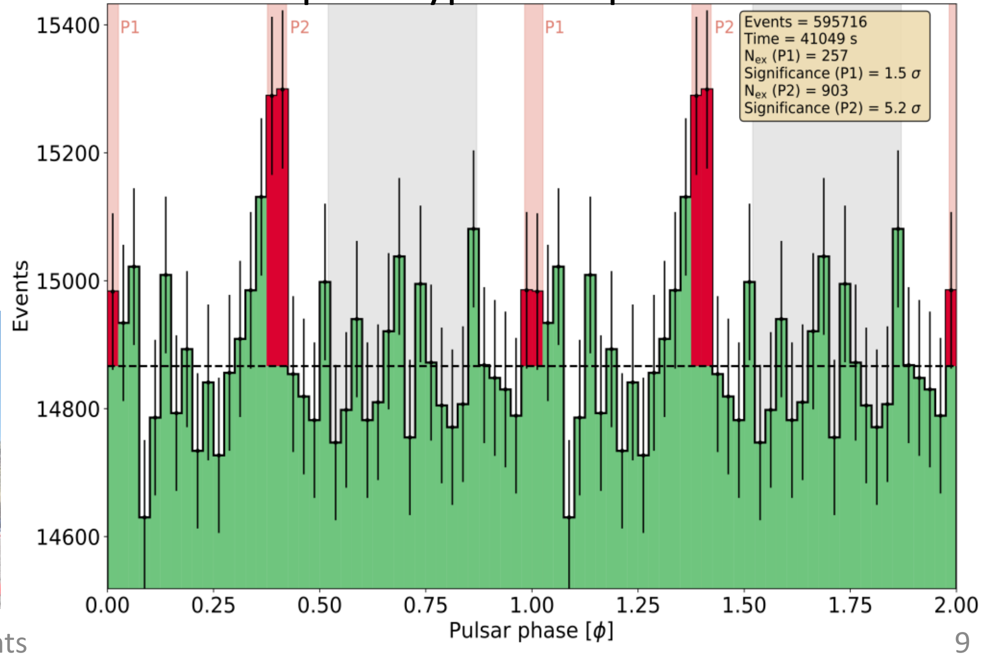
High Energy Gamma Rays / Future

CTA

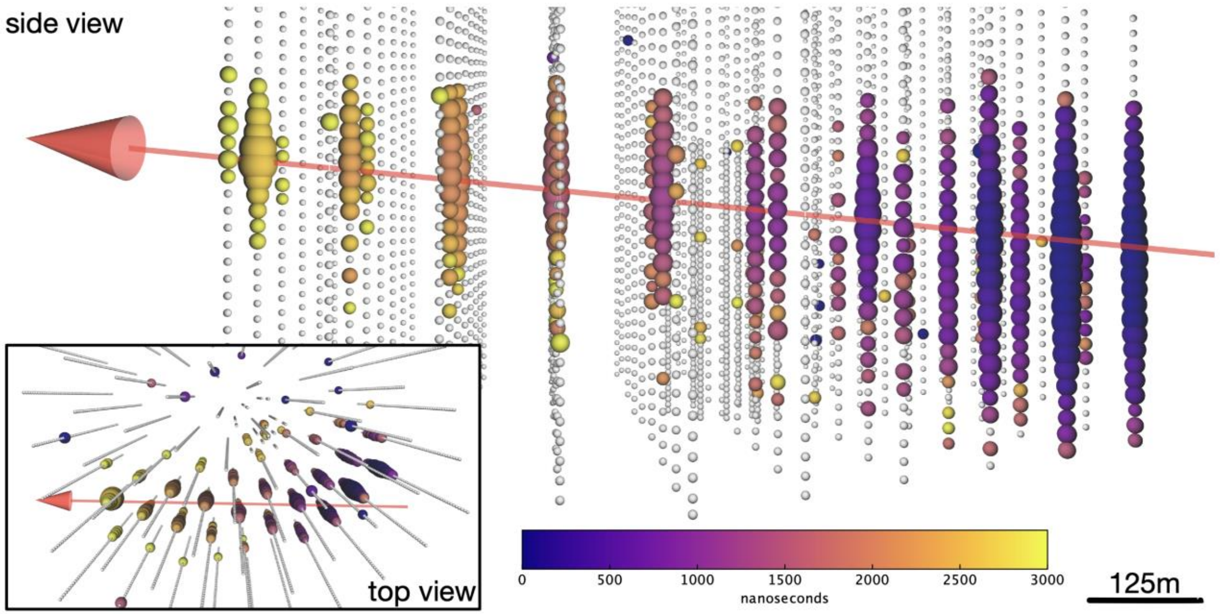
SWGO



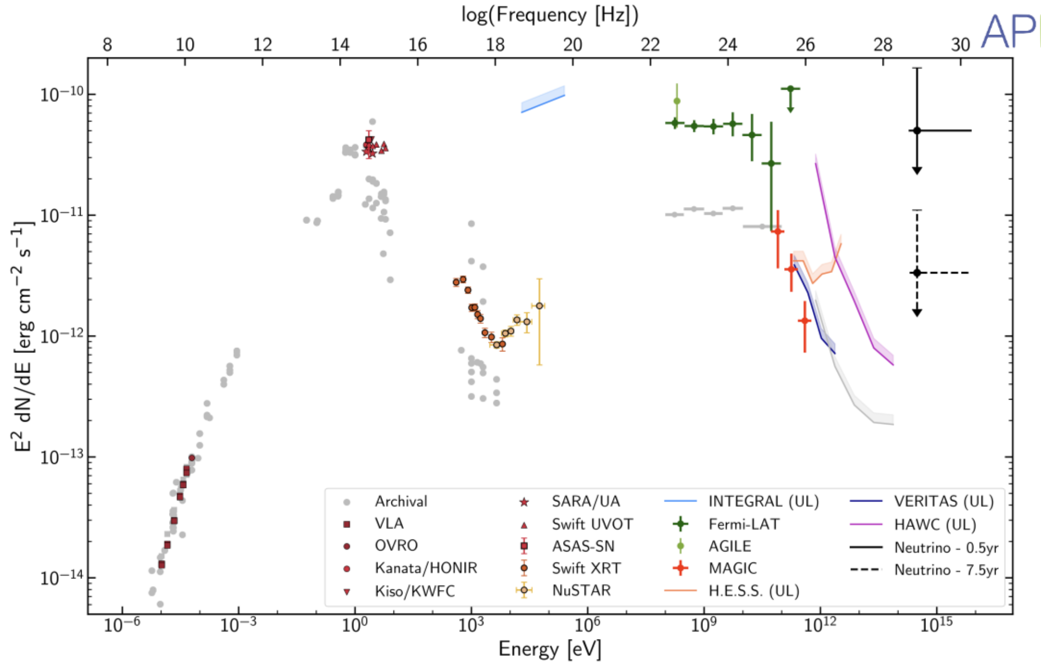
CTA LST-1 prototype Crab pulsar observation



High Energy Neutrinos: TXS 0506+056

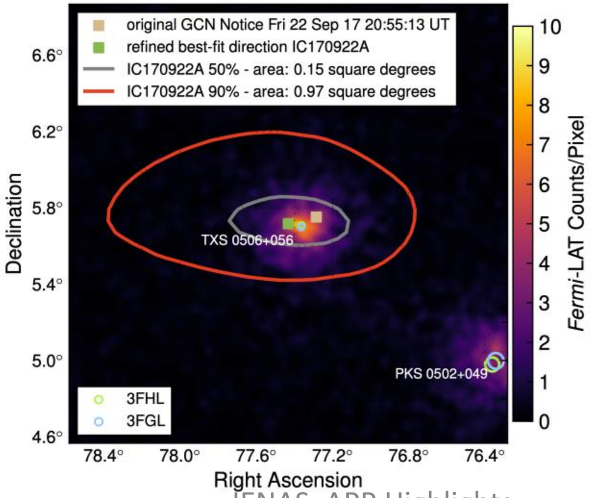


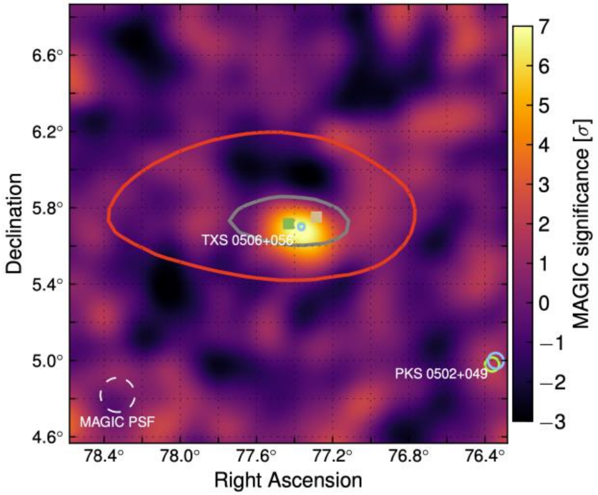
(A)



(B)

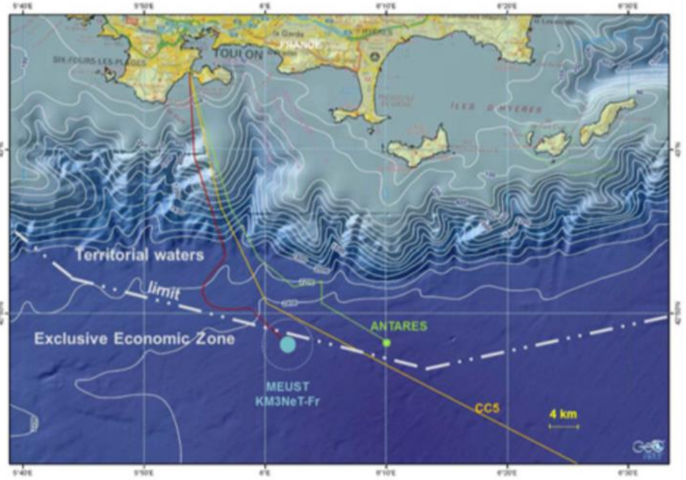
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., Integral, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, VLA/17B-403 Teams,
Science 361, eaat1378 (2018)
Multi-messenger observations of a flaring Blazar coincident with high-energy neutrino IceCube-170922A

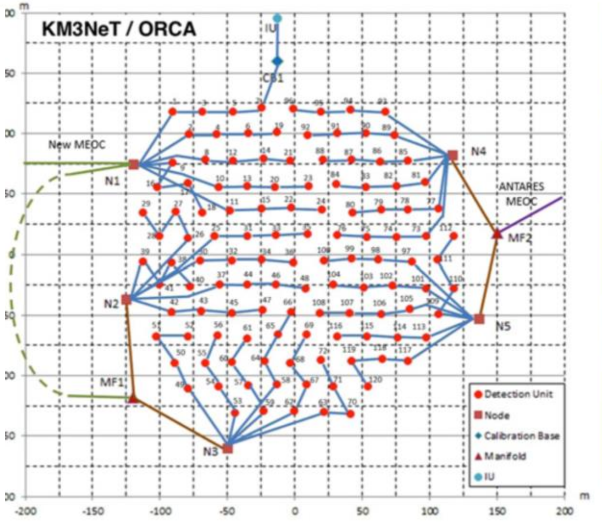




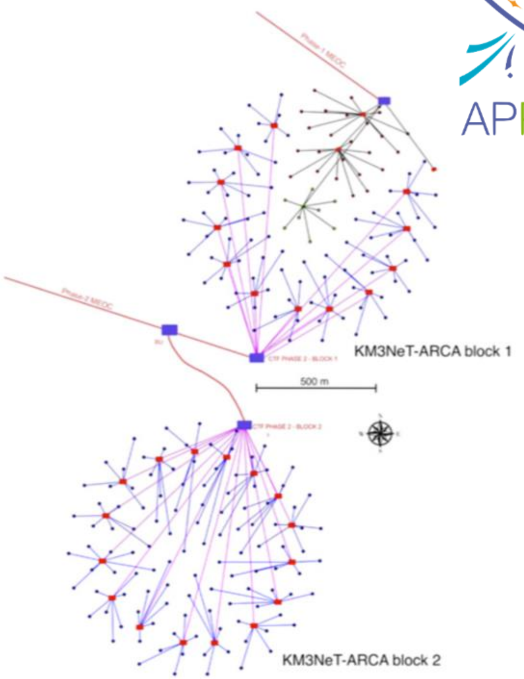
High Energy Neutrinos

KM3NeT ORCA



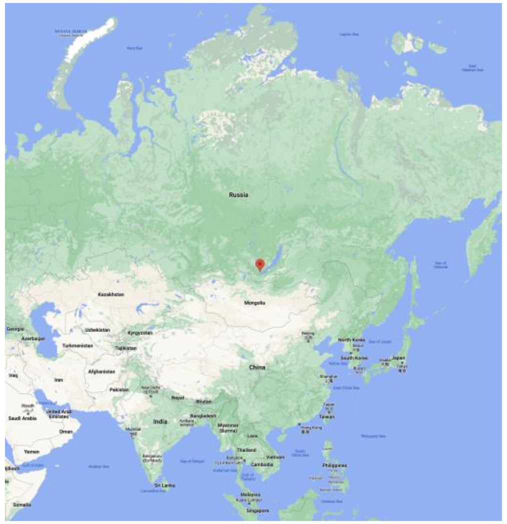


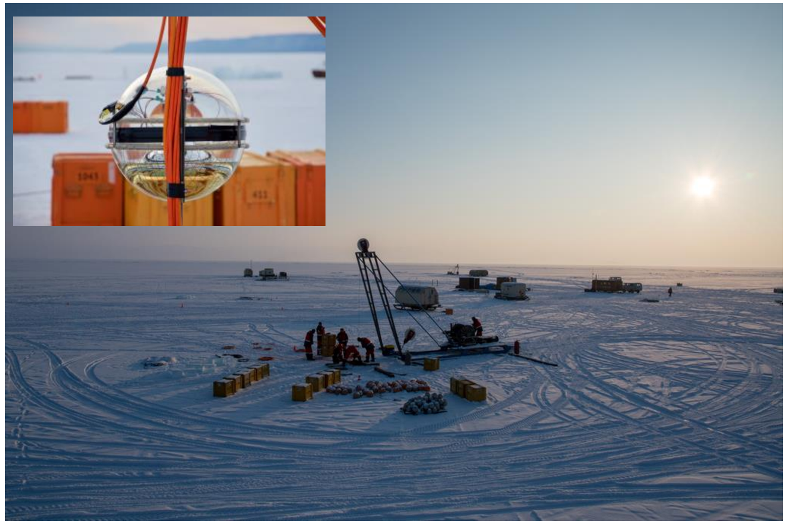
ARCA



Antares ends

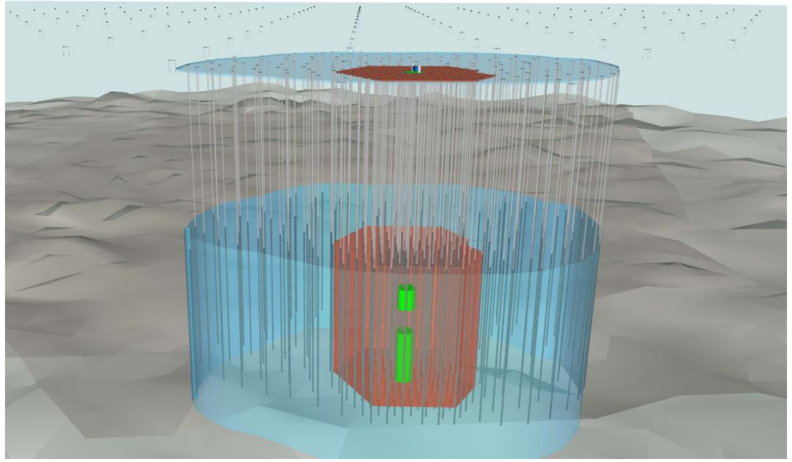
Baikal-GVD

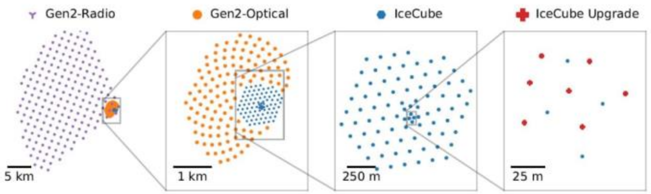




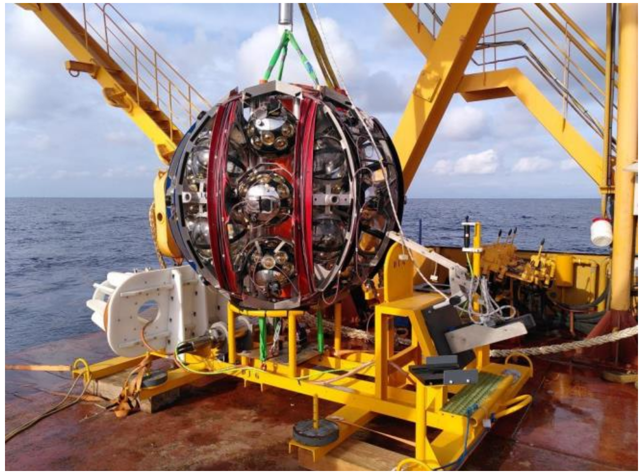
High Energy Neutrinos / Future

IceCube-Gen2

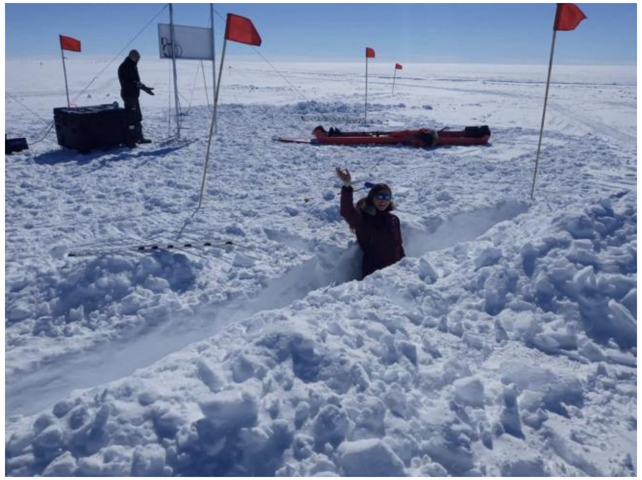




KM3NeT



RNO-G



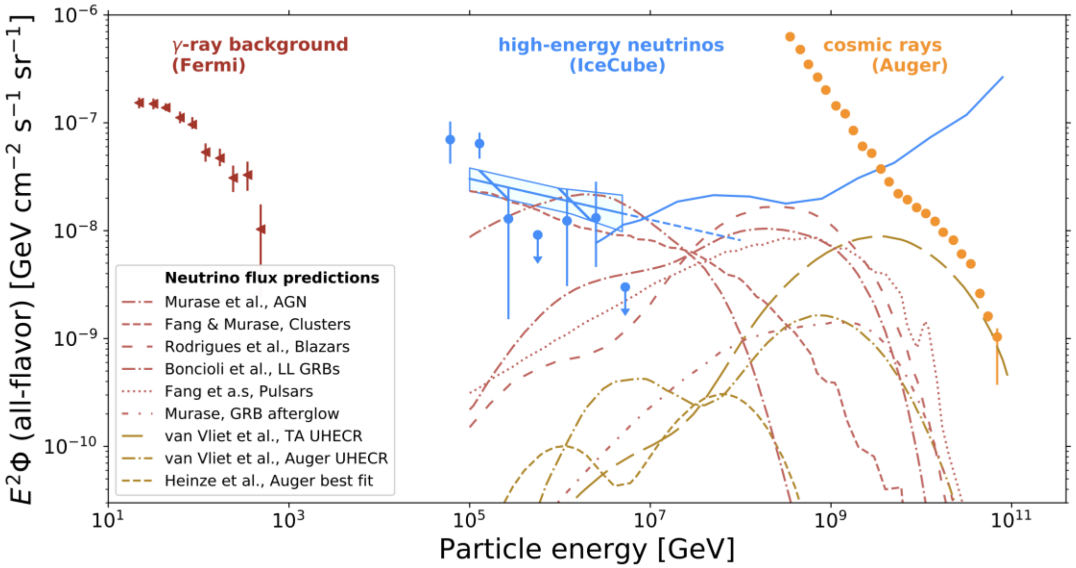
Neutrino astronomy, also (SN) bursts

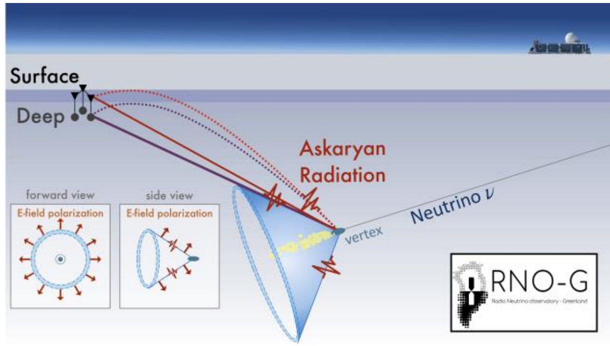
Neutrino properties

Cosmic rays

Study of ice and sea

…

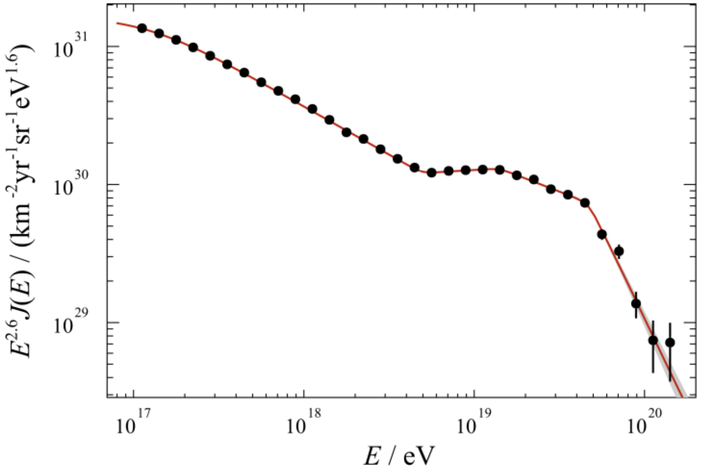


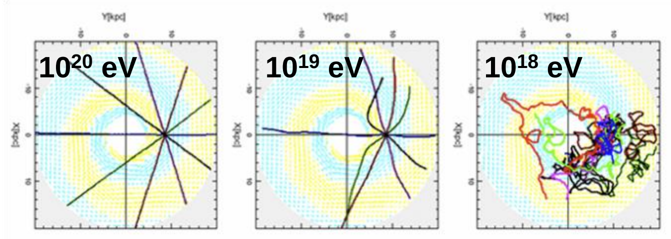


GNN
The Global Neutrino Network

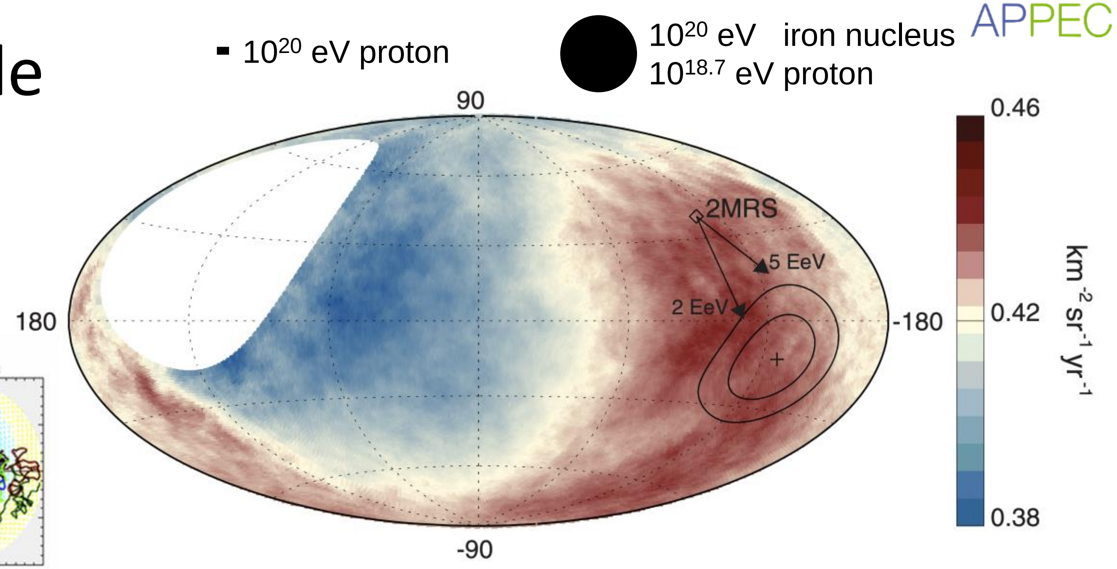
Ultra High Energy Cosmic Rays

Energy spectrum

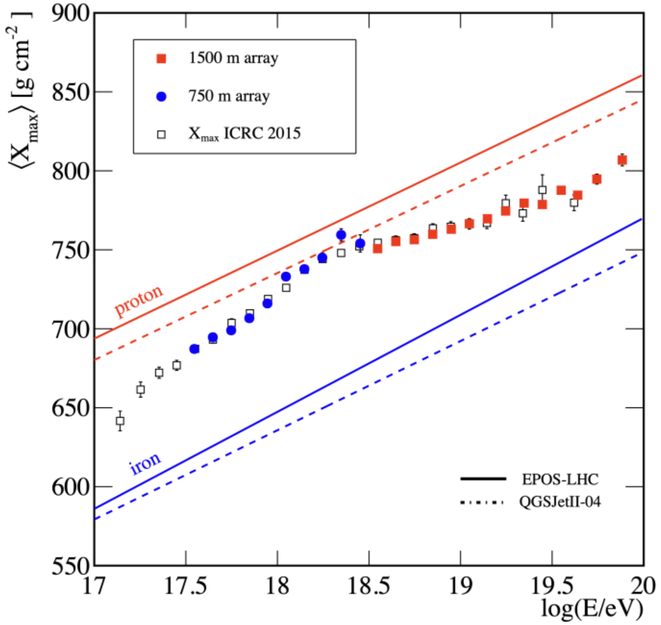




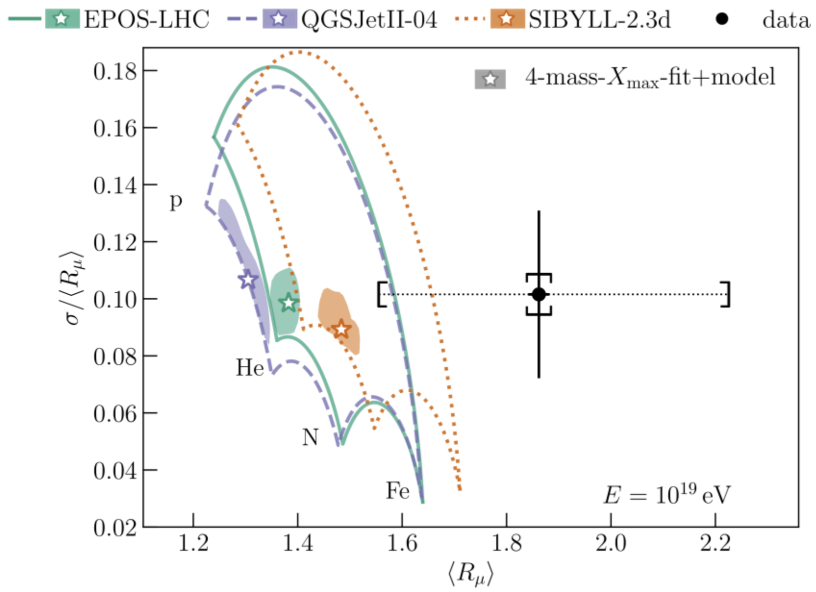
Dipole



Composition

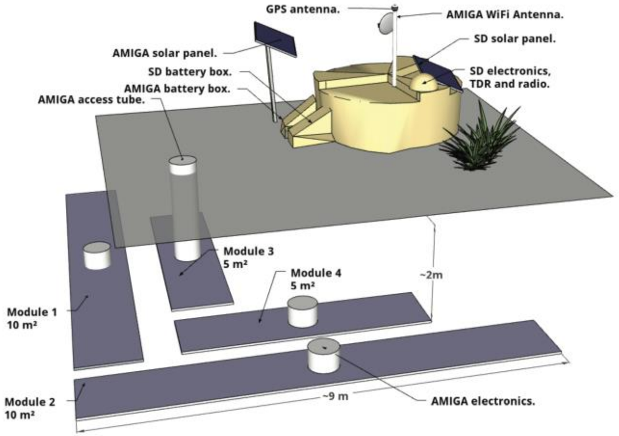


Muon excess



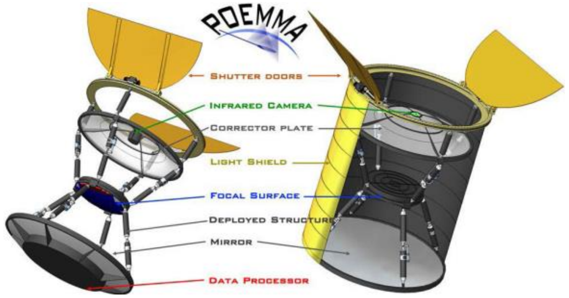
Ultra High Energy Cosmic Rays / Future

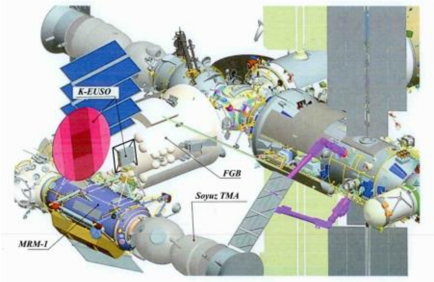
Auger upgrade



TA upgrade/extension

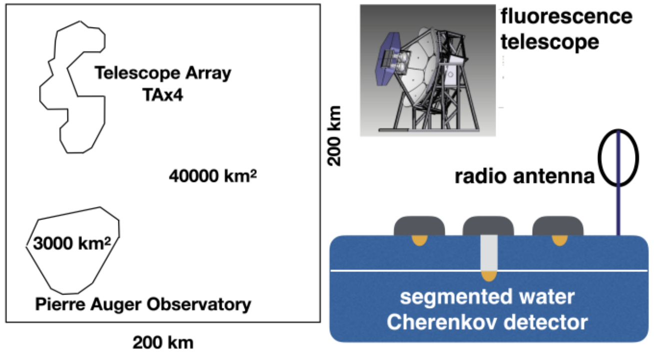
Satellite experiments



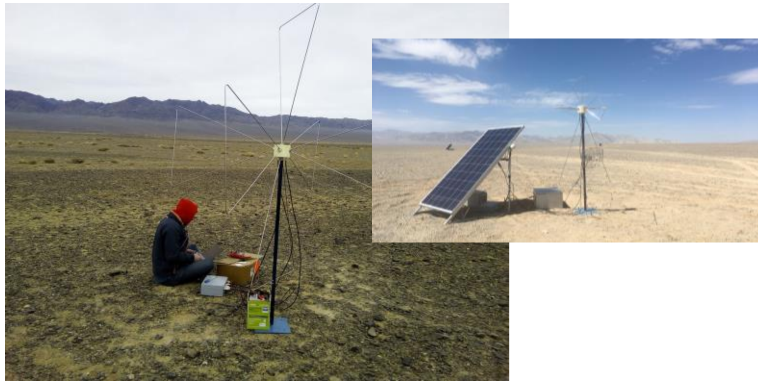


Huge ground based experiments

GCOS



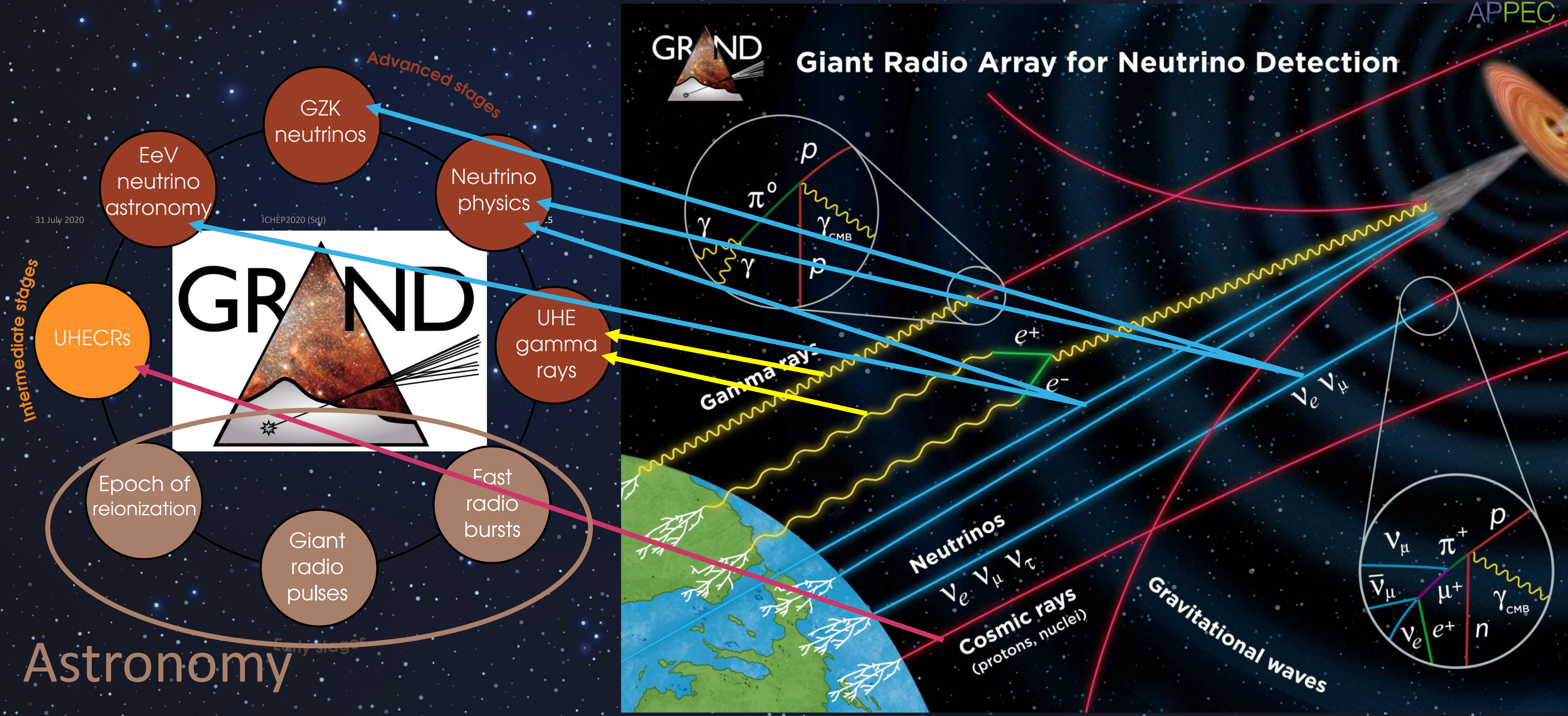
GRAND



Technical challenge: need to cover huge area with cheap, reliable, easy to deploy detector stations

Key is energy consumption

GRAND multi-messenger observatory

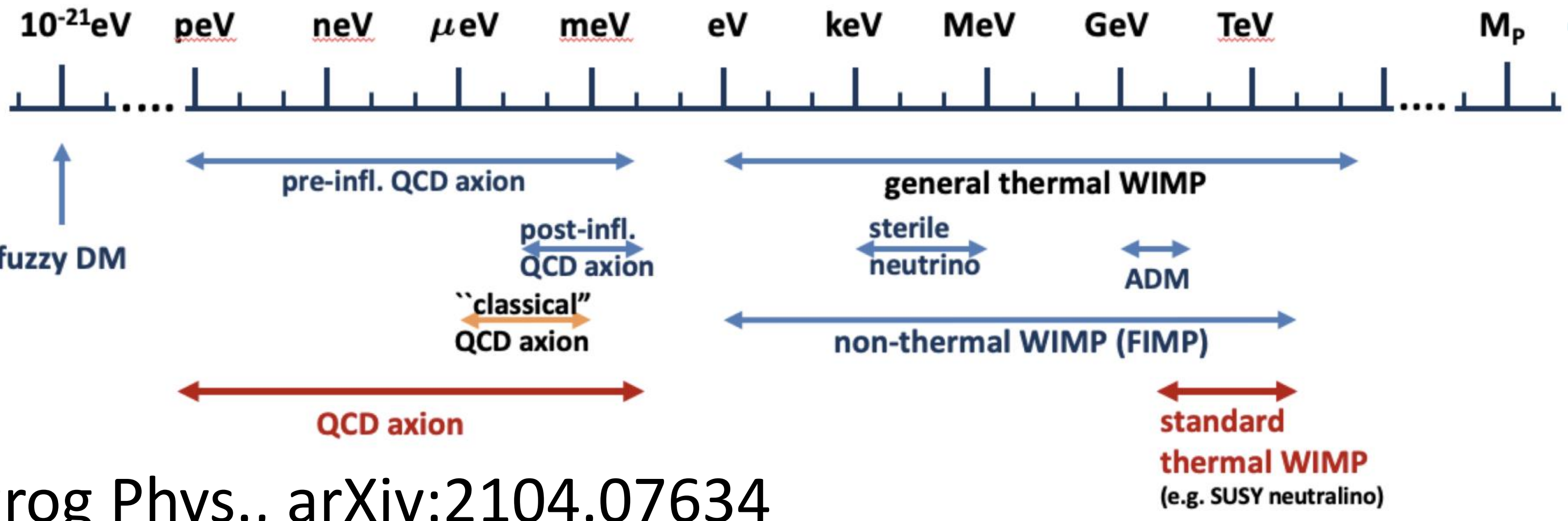


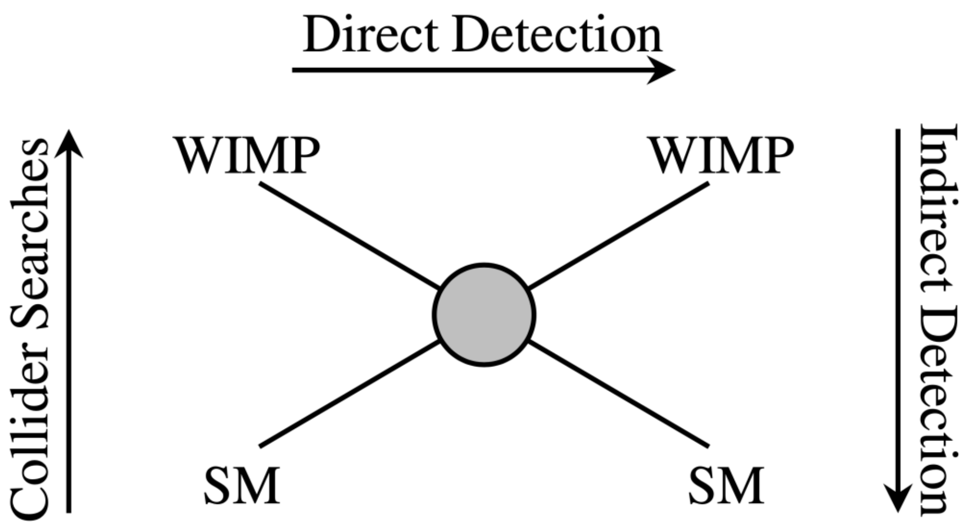
Dark Matter

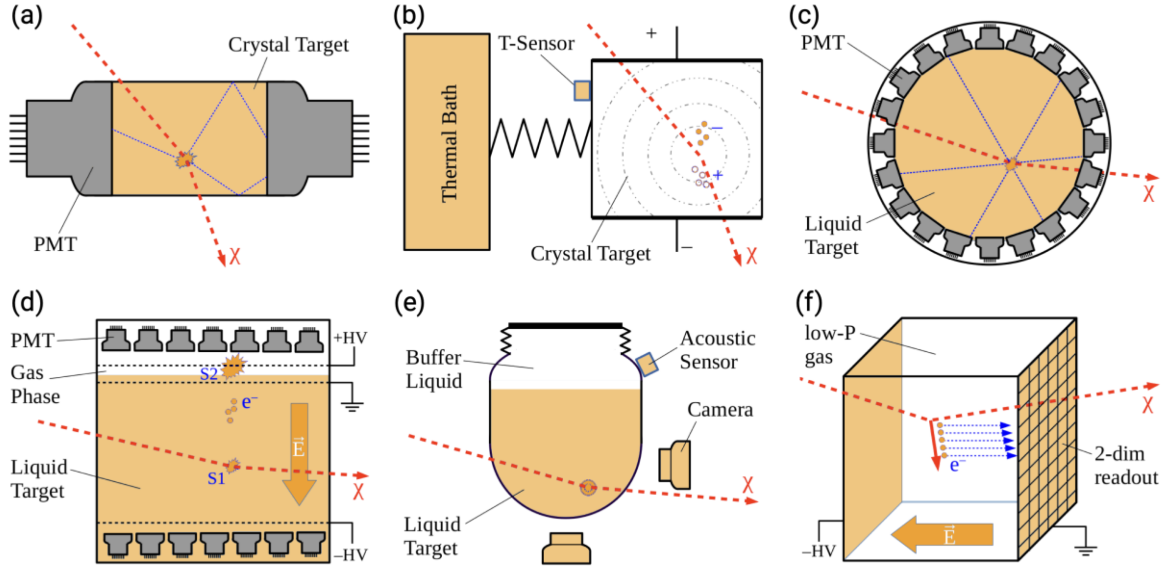
Direct Dark Matter Detection APPEC report:

J. Billard, et al.,

Accepted by Rep Prog Phys., arXiv:2104.07634

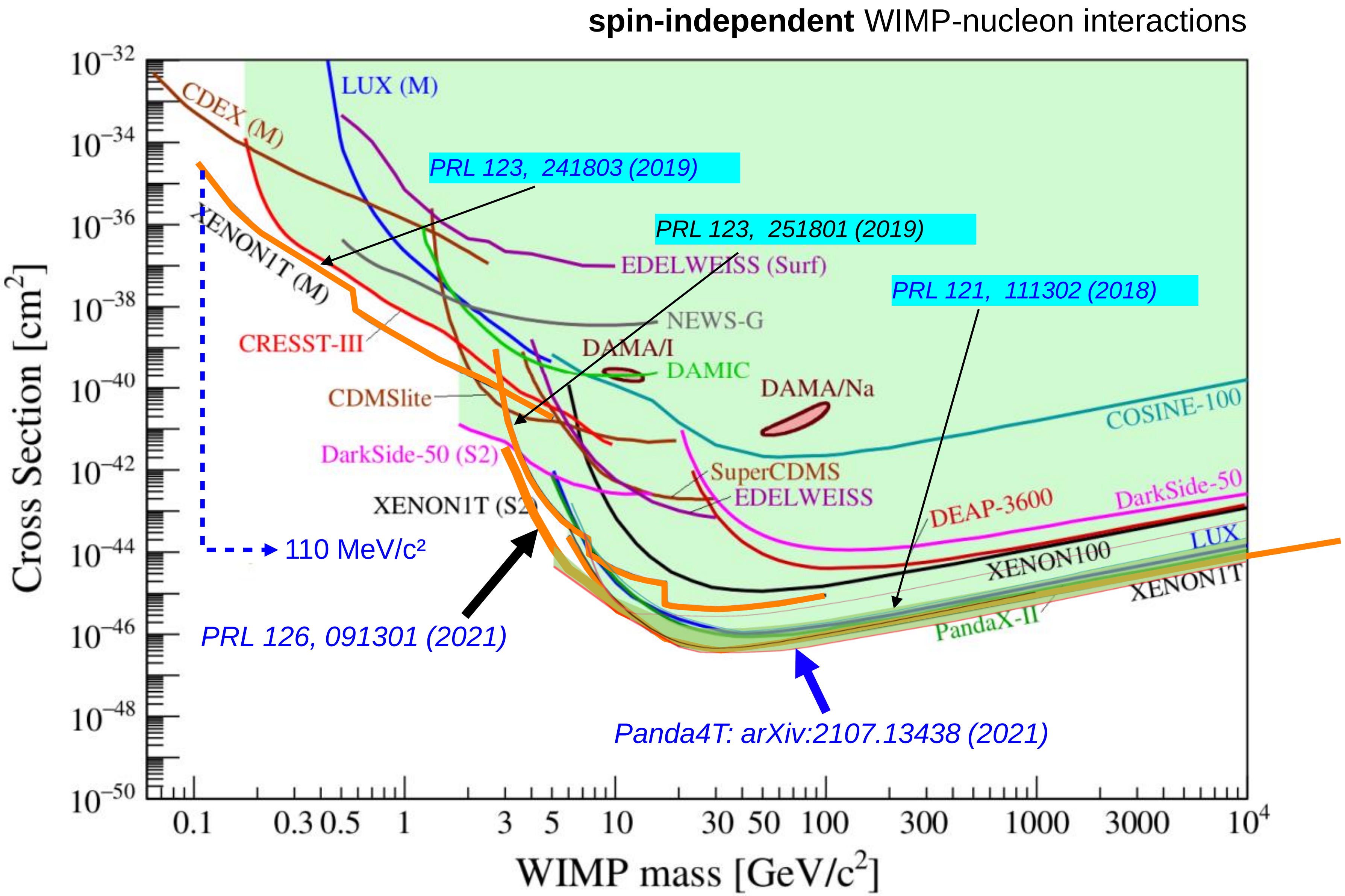






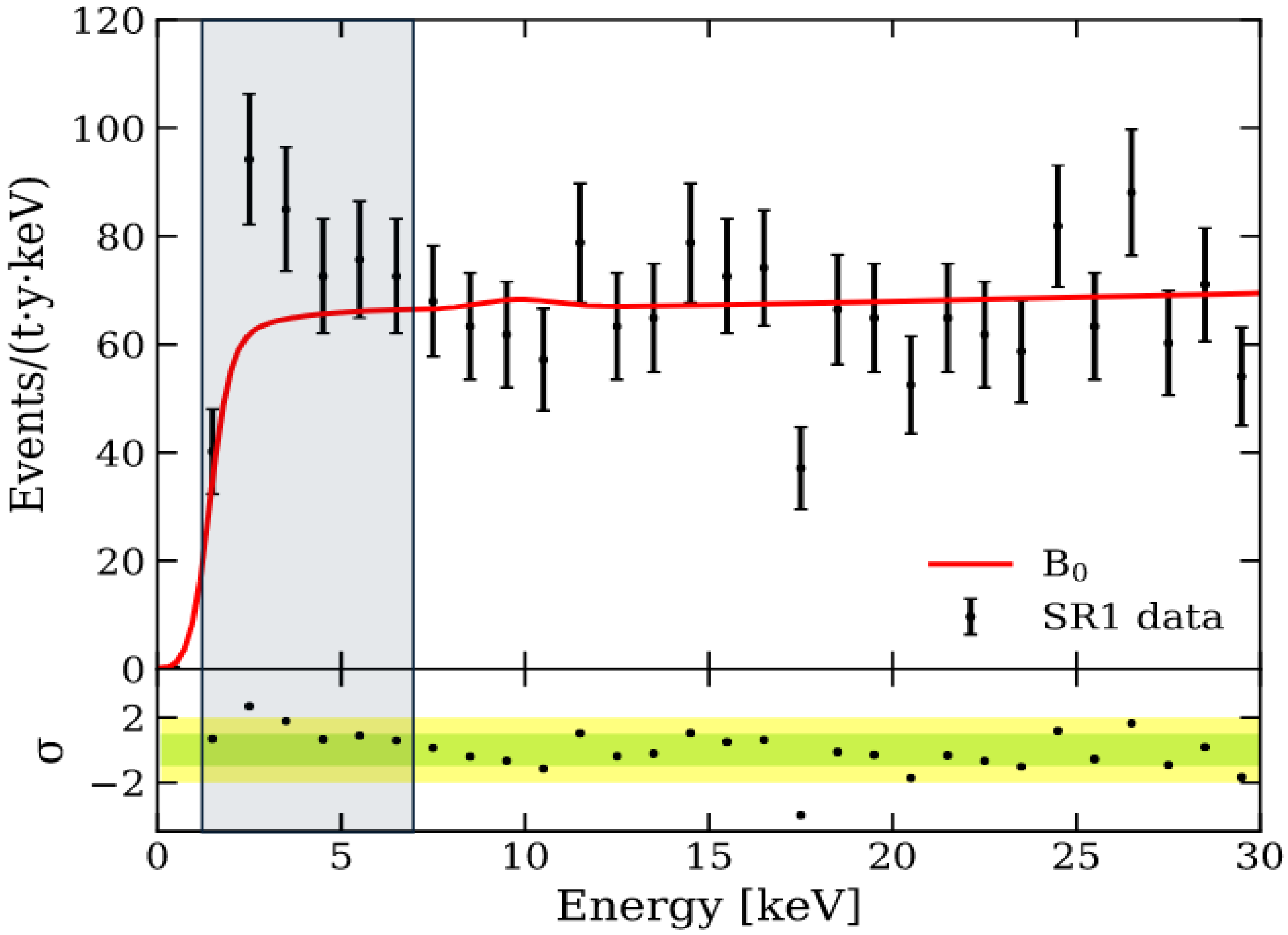
Dark Matter

Direct Dark Matter Detection



Dark Matter

Xenon1T low E_R excess



- **excess in 1-7 keV range of electronic recoils (ER)**
  285 evts observed vs
  (232 ± 15) expected from
  detailed background model
  → **(naive) 3.3σ fluctuation**
- WIMPs are expected to produce nuclear recoils!

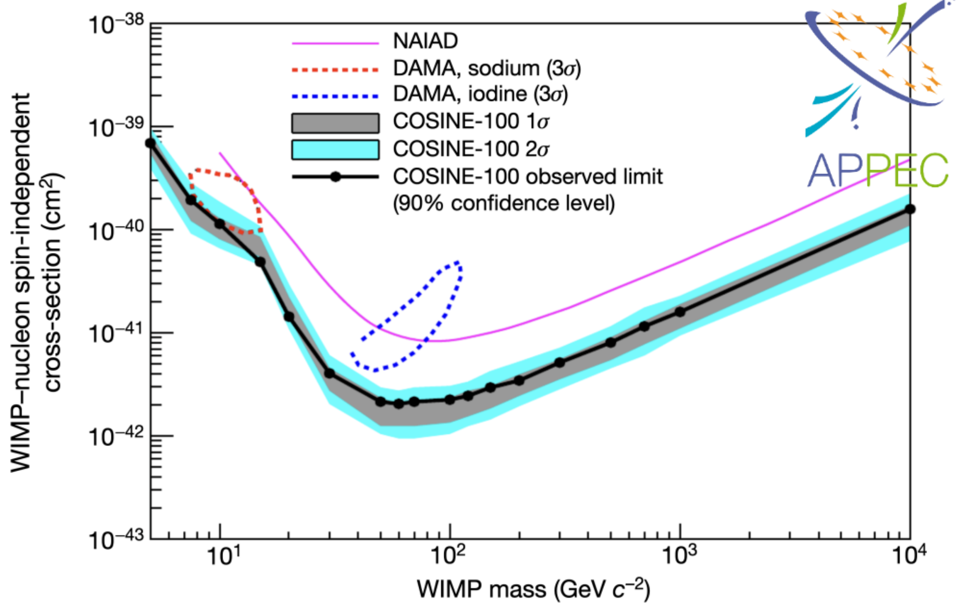
Possible Explanations

- Solar axions: 3.4σ
  but tension with astrophysical contraints
- Bosonic ALPs: 3.0σ
- Neutrino Magn. Moment: 3.2σ
  but tension with astrophysical contraints
- many other explanations proposed >400 citations so far
- Also possible: new background Tritium: 3.2σ

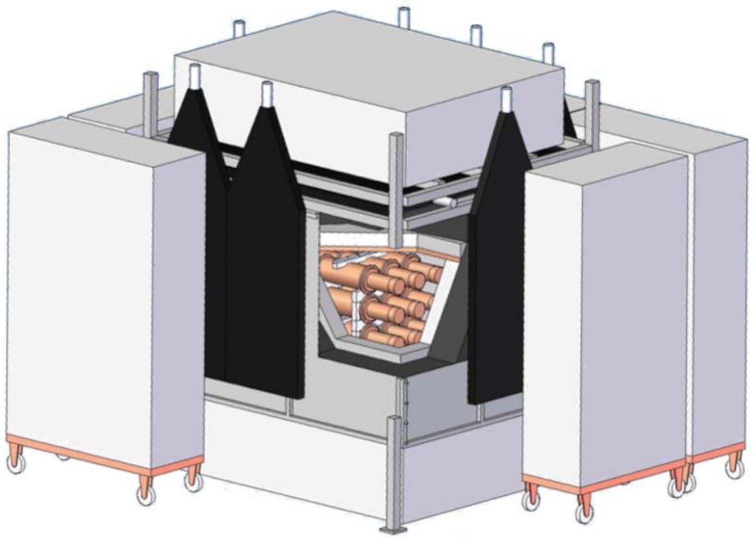
→ to be tested with XENONnT

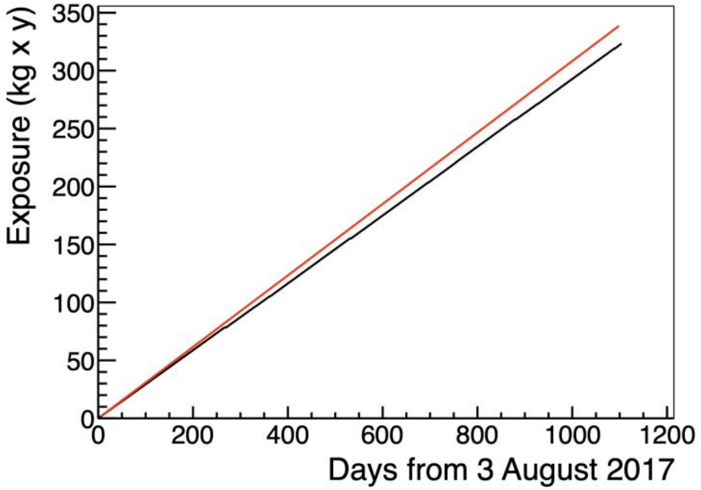
Dark Matter / Annual modulation

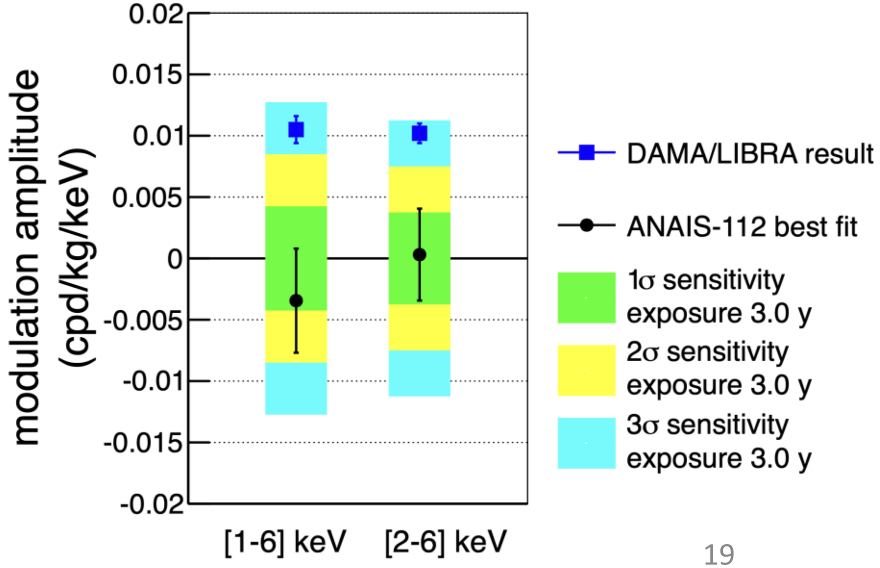
COSINE-100 Collaboration, Nature 564 (2018) 83, An experiment to search for dark-matter interactions using sodium iodide detectors



ANAIS 3-year result on annual modulation, Phys. Rev. D 103, 102005 (2021), Annual modulation results from three-year exposure of ANAIS-112







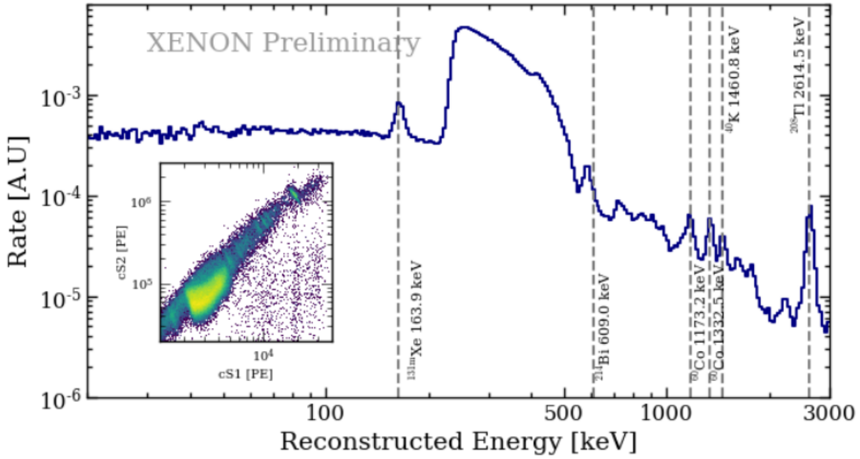
Dark Matter / XENONnT progress

- Dark Matter TPC with
- 5.9t LXe target
- operating @ LNGS
- strong European role

Recent Highlights

- 1st science run completed end of 2021
- Analysis ongoing
- Goal: new DM result and test of XENON1T excess

TPC works very well

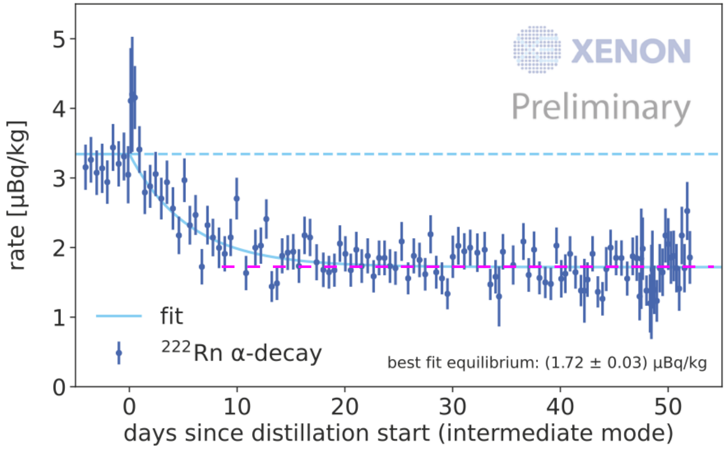


example: ^{220}Rn calibration of ER signals

Panda 4T

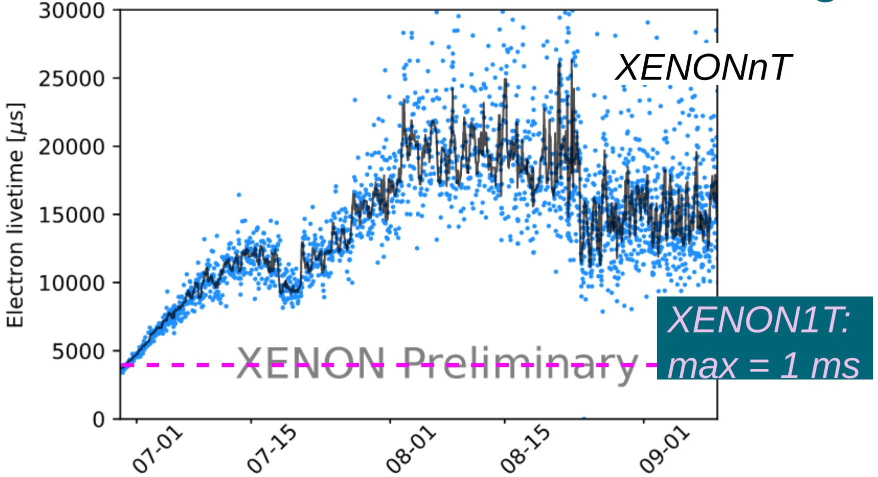
LZ

Rn Distillation: Reduce main background



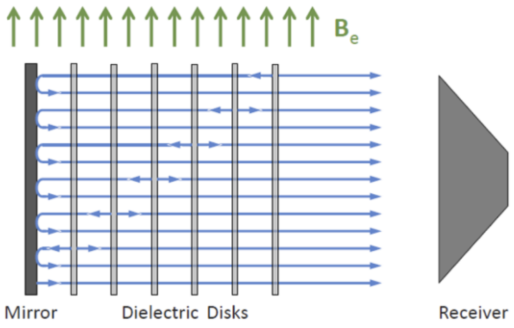
Lowest ^{222}Rn Concentration in LXe DM detectors.

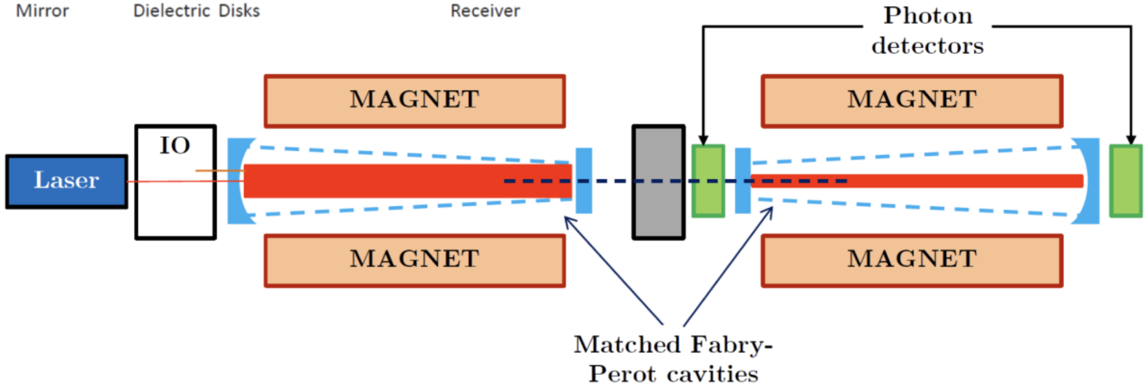
LXe Purification: Increase Charge Signal

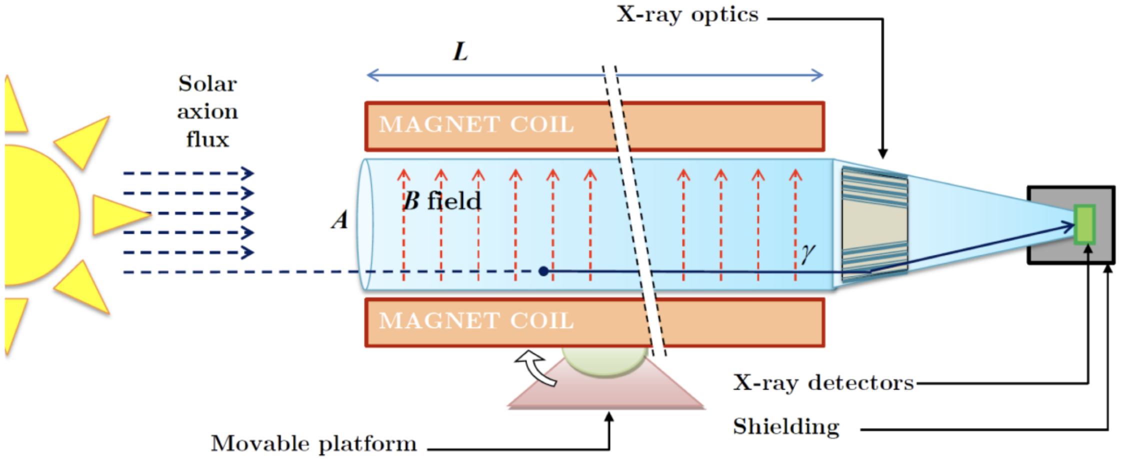


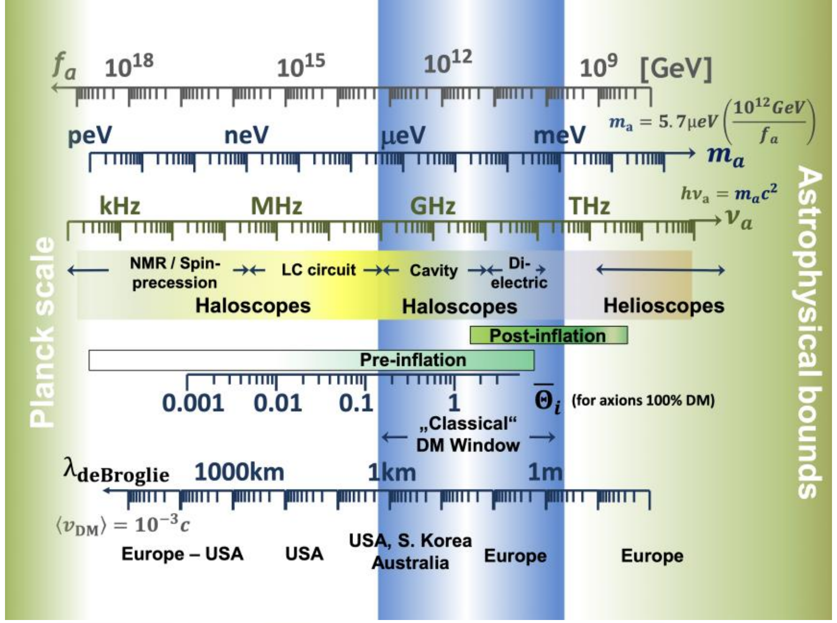
Best LXe Purity ever reached in LXe DM detectors

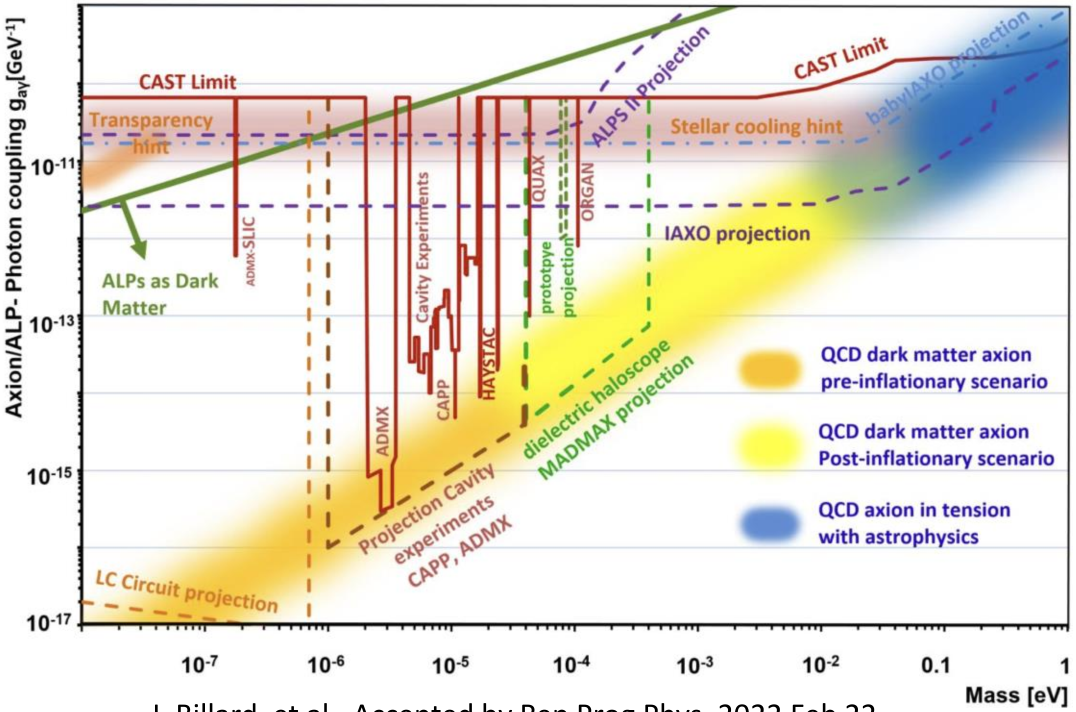
Dark Matter / ALPs









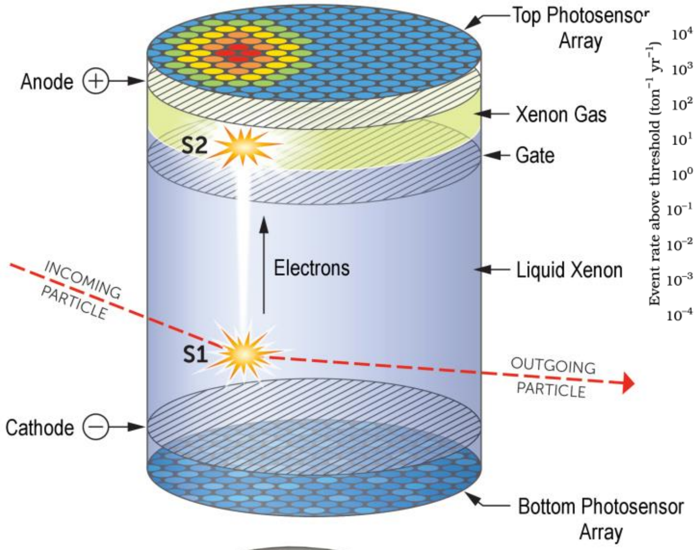


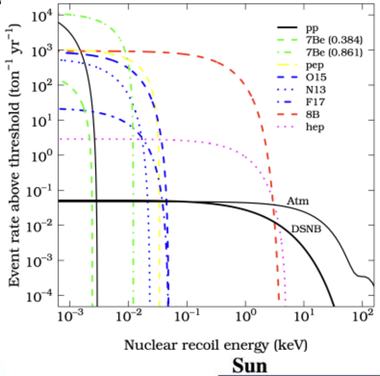
J. Billard, et al., Accepted by Rep Prog Phys. 2022 Feb 22
Direct Detection of Dark Matter – APPEC Committee Report

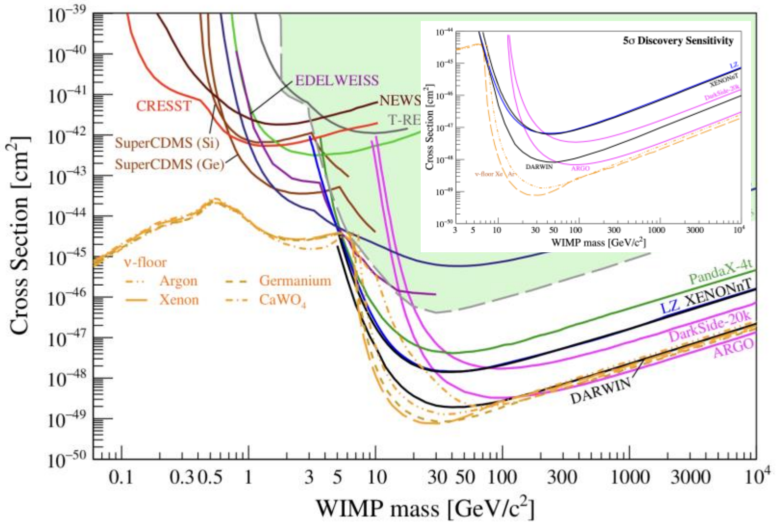
Dark Matter

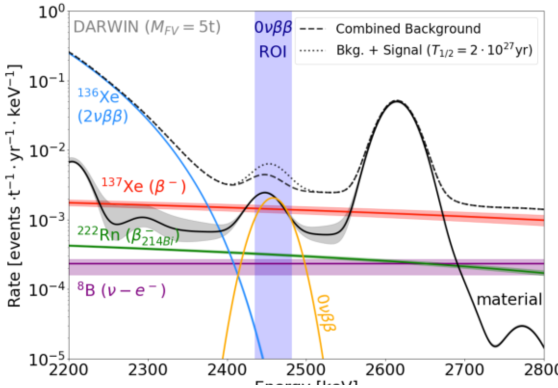
LXe white paper DARWIN/G3

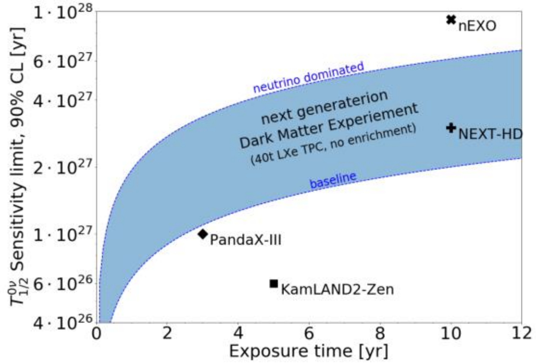
A Next-Generation Liquid Xenon Observatory
for Dark Matter and Neutrino Physics
https://arxiv.org/pdf/2203.02309

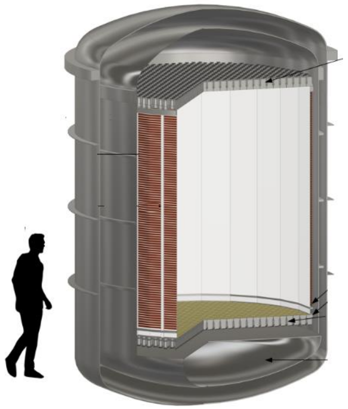




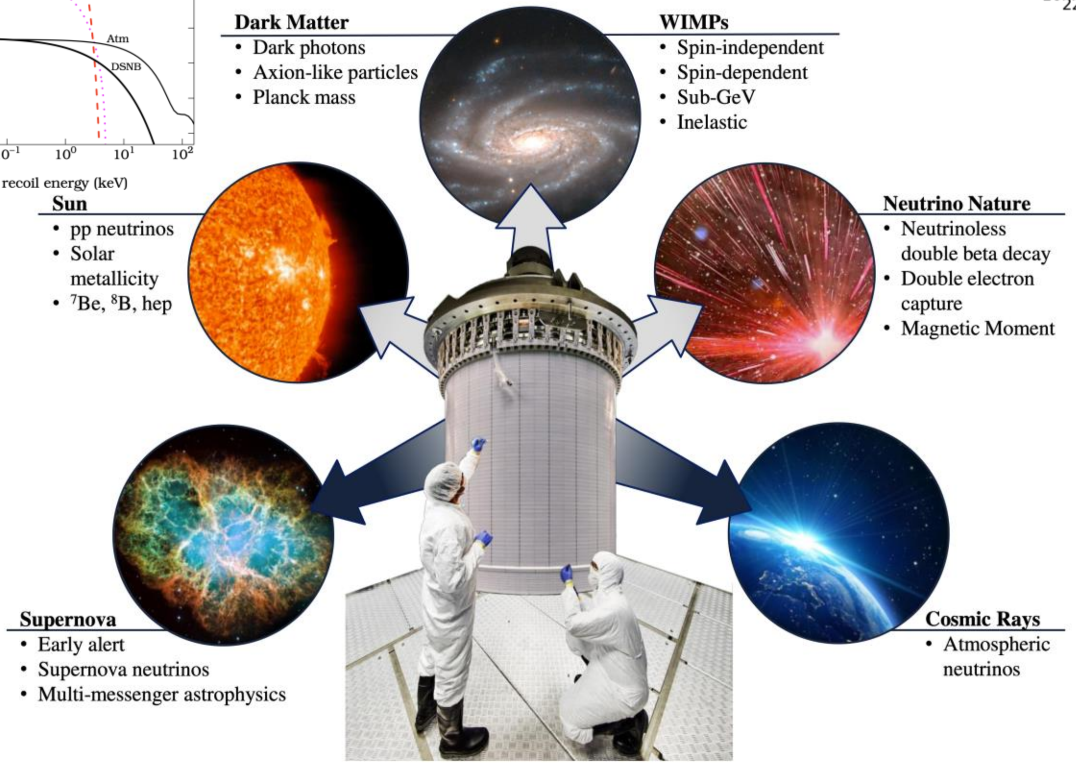


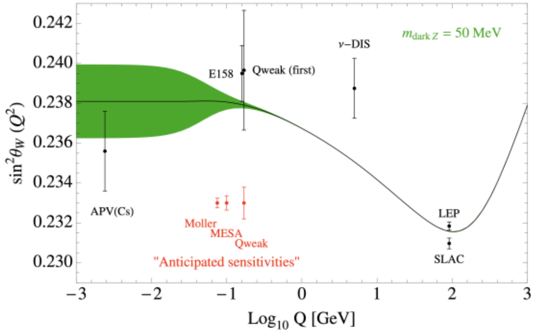






DARWIN
~50t total LXe mass
~40 t LXe TPC

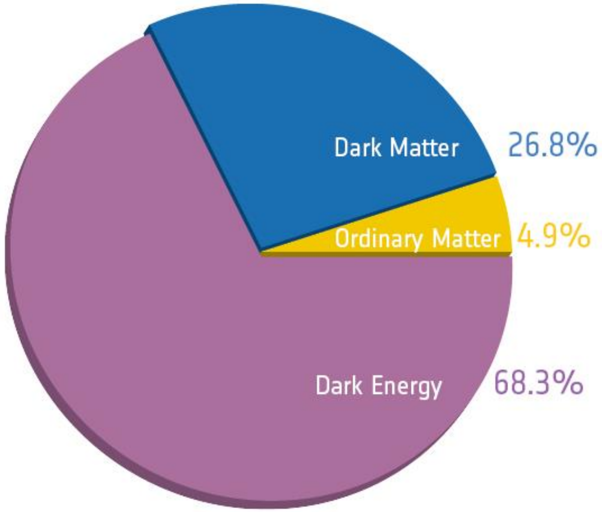


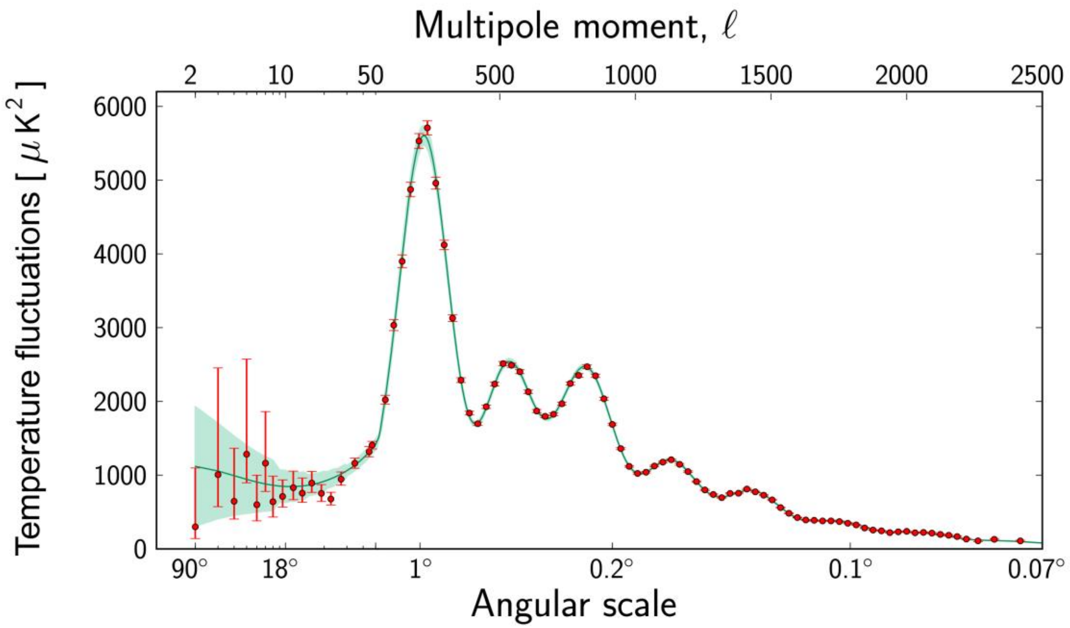


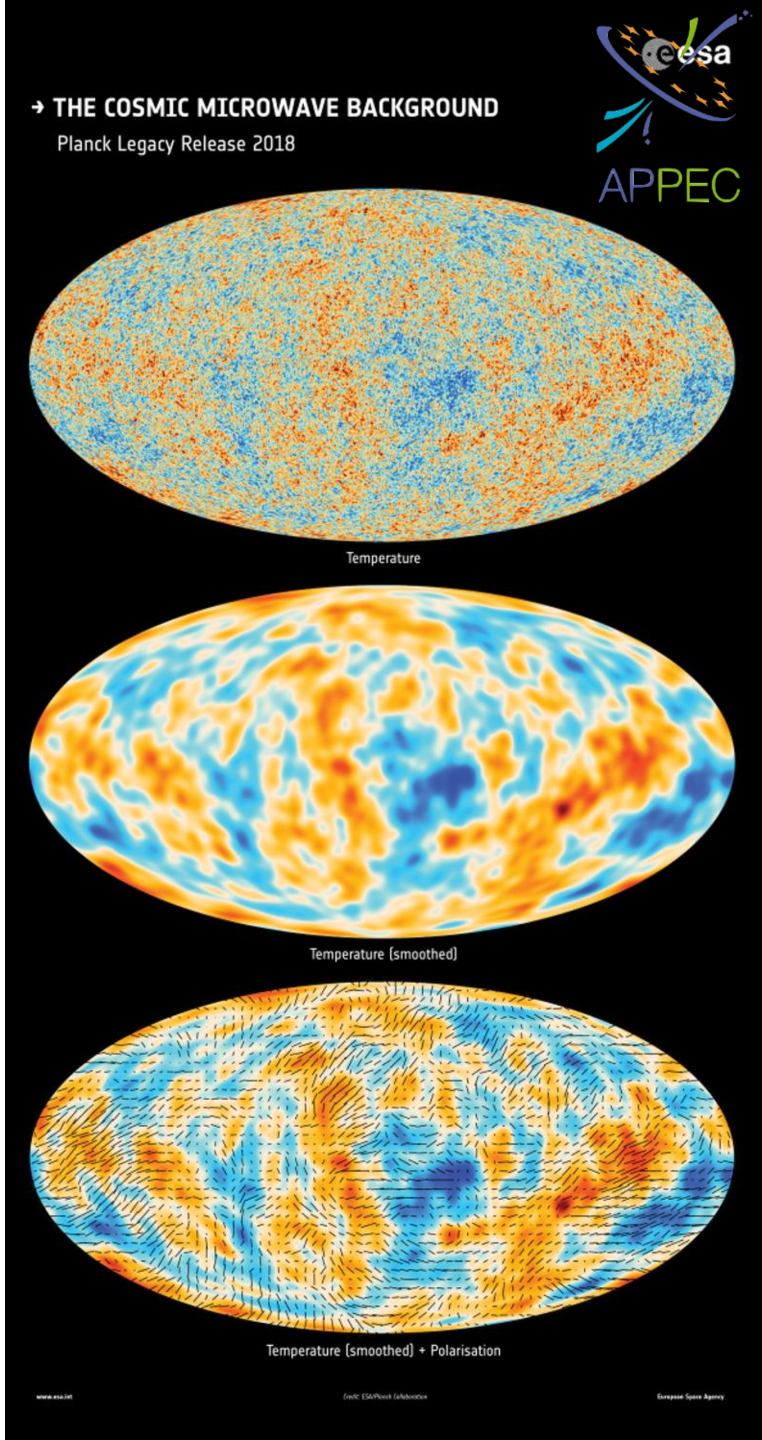
Cosmic Microwave Background

- Remember: the CMB measurement are a large part of the believe with many of you in dark matter and dark energy

Baryon Acoustic Oscillation







Cosmic Microwave Background / Future

LiteBIRD

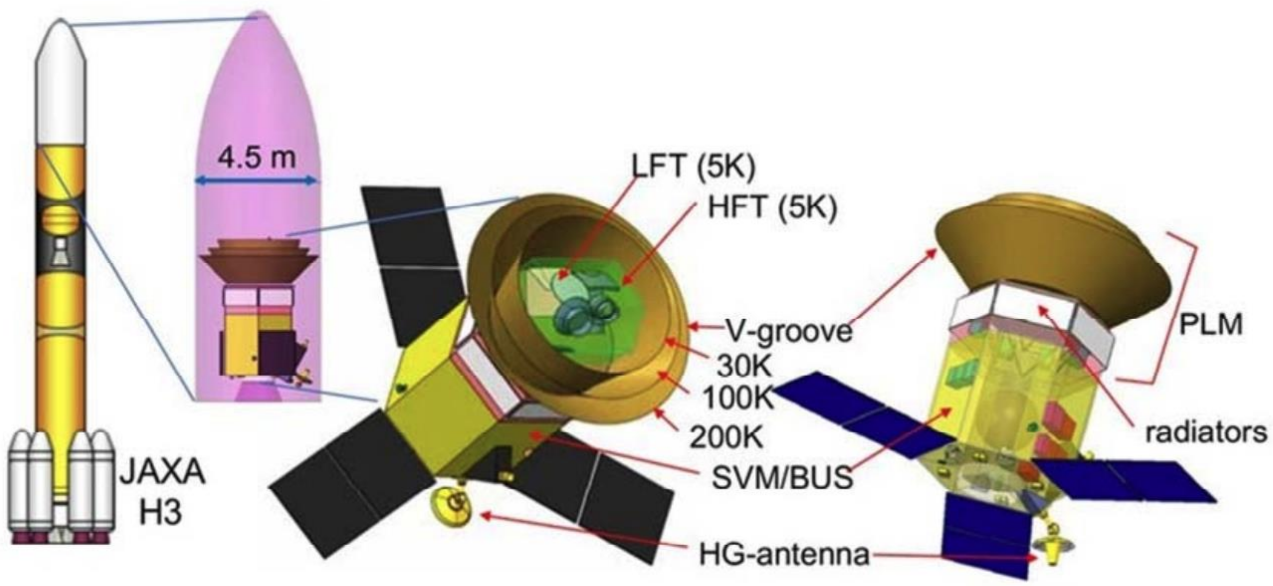


FIGURE 1-1 - OVERALL DESIGN OF THE LITEBIRD SPACECRAFT
(courtesy JAXA)

CMB-S4

B polarisation is the holy grail for now

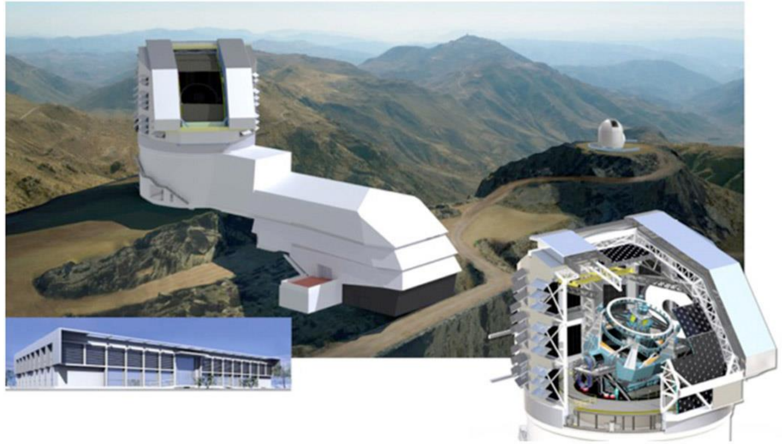
Dark Energy / Future

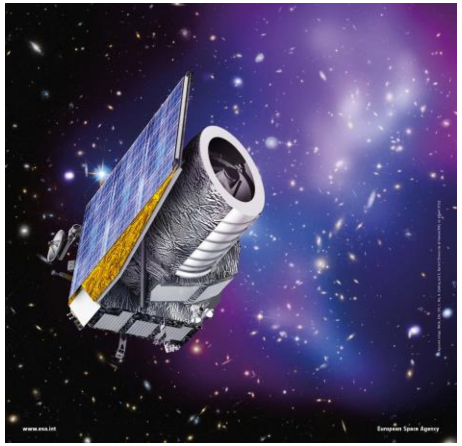
- Observations:
  - SN1a: Super Nova type Ia
  - BAO: Baryon Acoustic Oscillation
  - WL: Weak Lensing
  - GCE: Galaxy Cluster Evolution

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right]$$

non-rel matter, rel, curvature, Λ, $w=P/\rho$

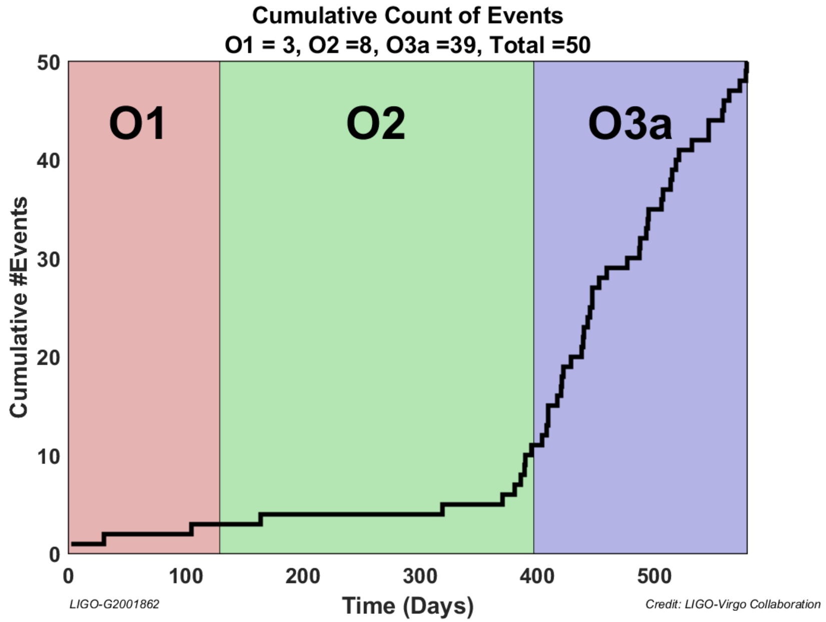
DESI	Rubin LSST	Euclid	Nancy Grace Roman (WFIRST)
BAO+GCE	SN1a+BAO+WL	WL	SN1a+BAO

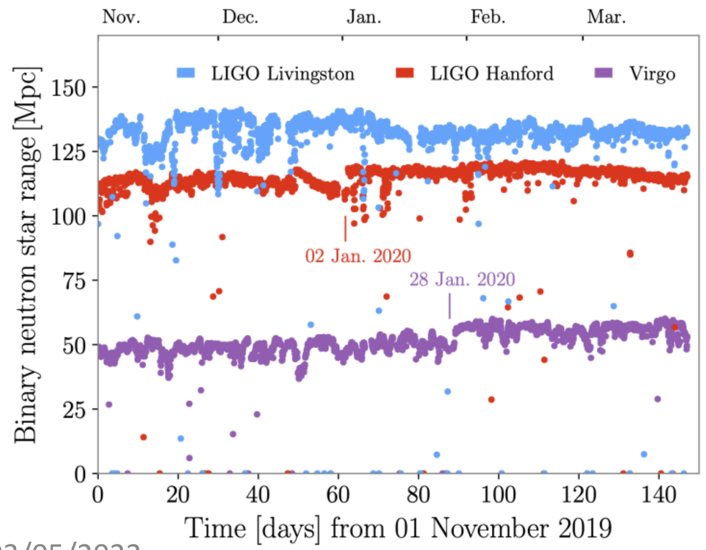


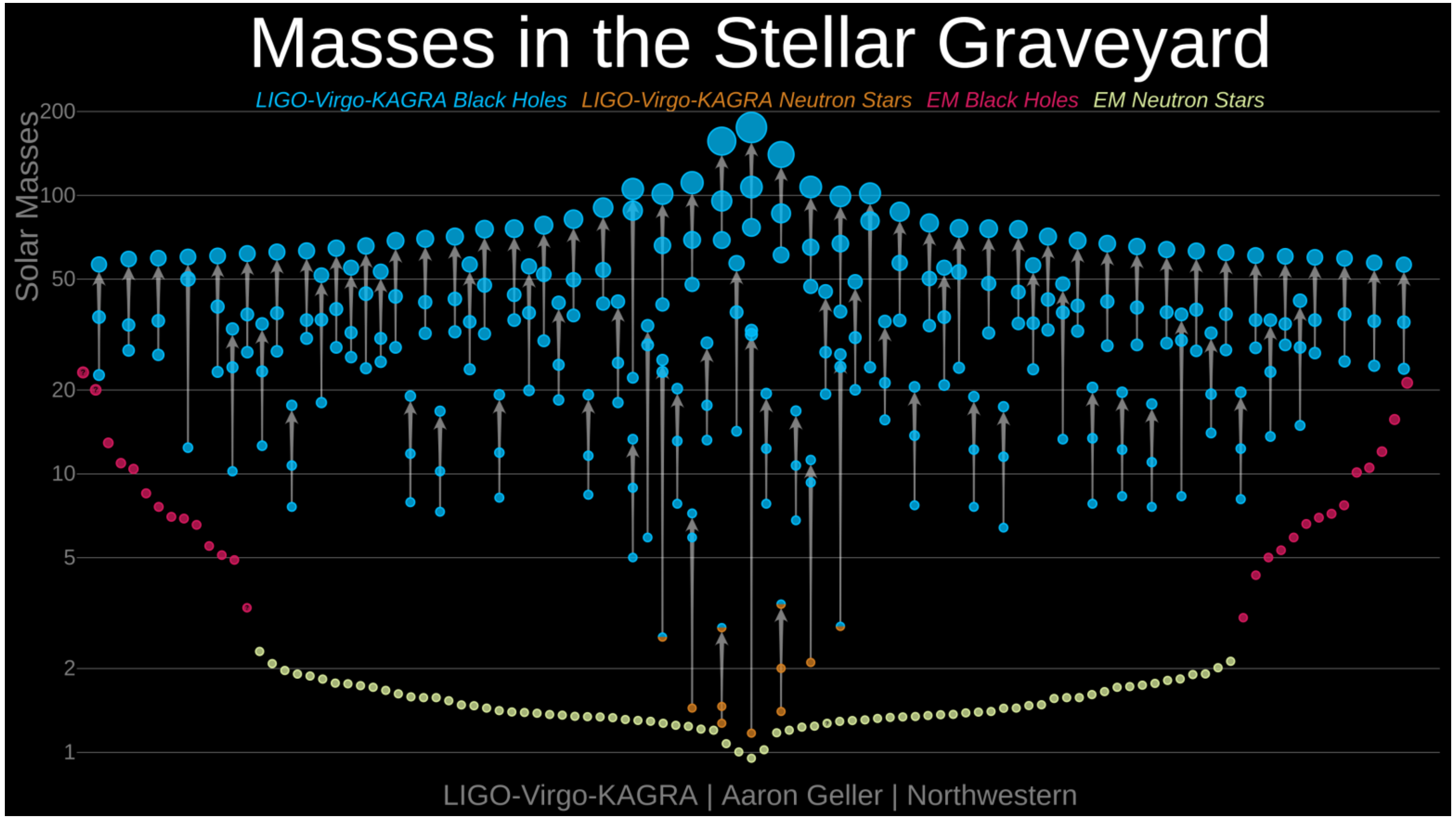


Gravitational Waves LIGO-Virgo-KAGRA

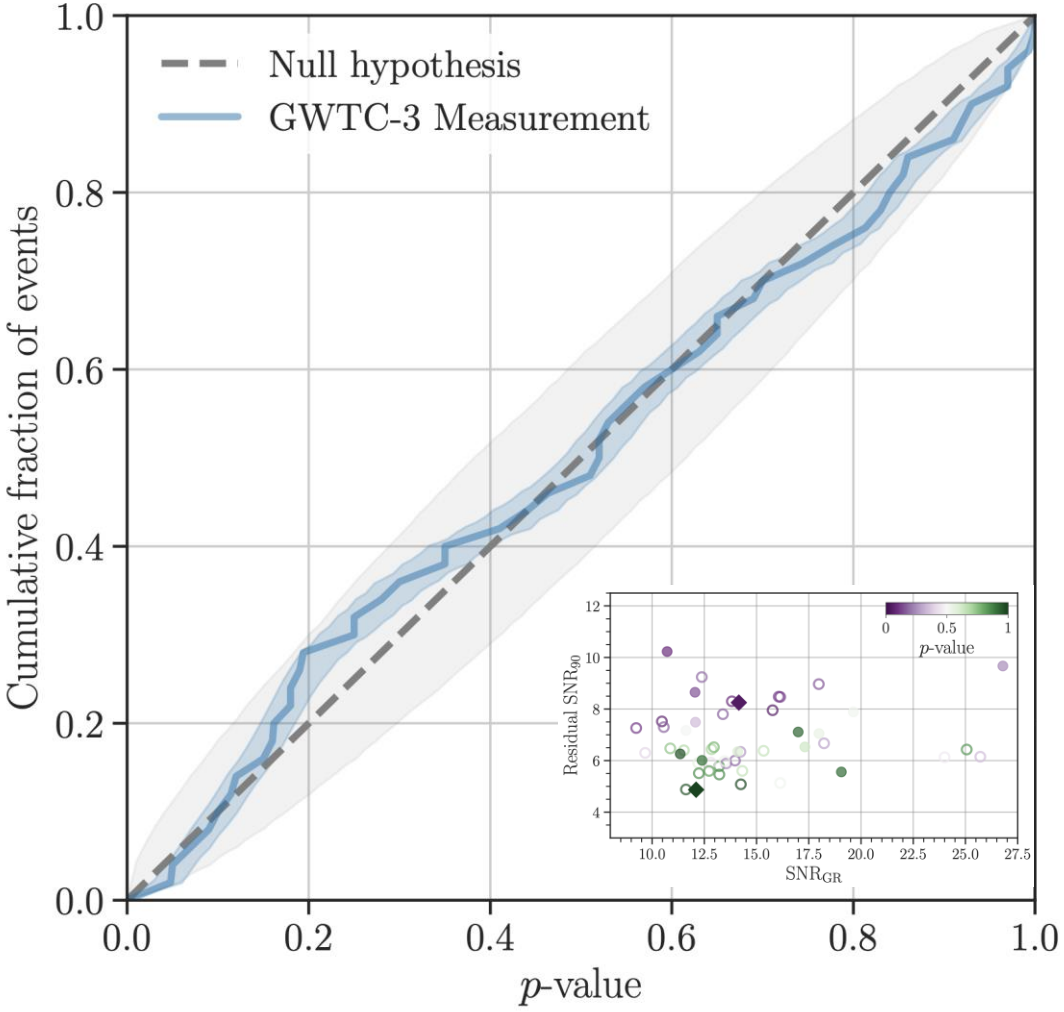
from single events to ensemble studies







Gravitational Waves / GR tests



LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration
Tests of General Relativity with GWTC-3, arXiv:2112.06861
From the abstract:
"…we find all the post-Newtonian deformation coefficients to be consistent with the predictions from GR, ….
We also find that the spin-induced quadrupole moments of the binary black hole constituents are consistent with those of Kerr black holes in GR.
We find no evidence for dispersion of gravitational waves, non-GR modes of polarization, or post-merger echoes in the events that were analyzed.
We update the bound on the mass of the graviton, at 90% credibility, to $m_g \leq 1.27 \times 10^{-23}$ eV/c^2. …"

Gravtitational Waves / Multi-Probe

APPEC

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OPEN ACCESS

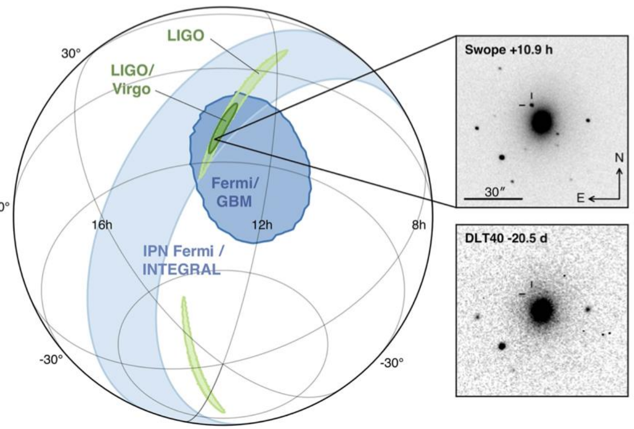
CrossMark

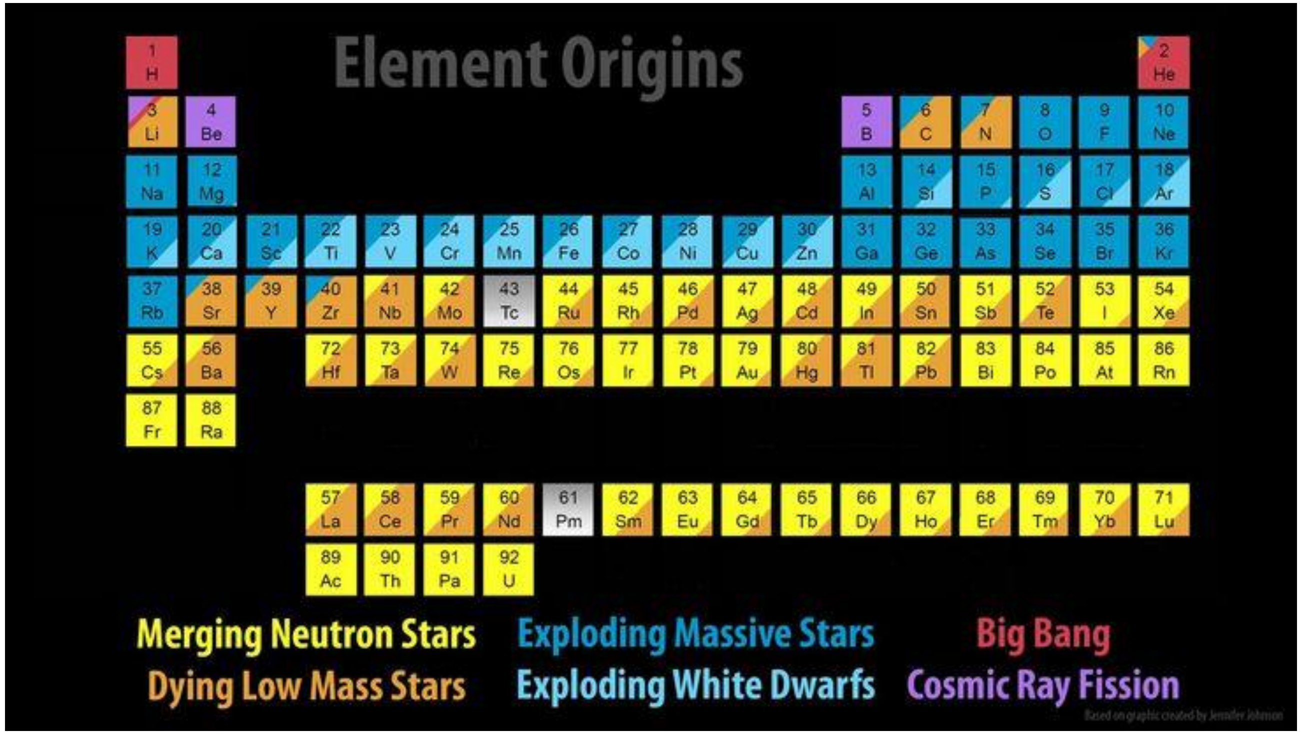
Multi-messenger Observations of a Binary Neutron Star Merger*

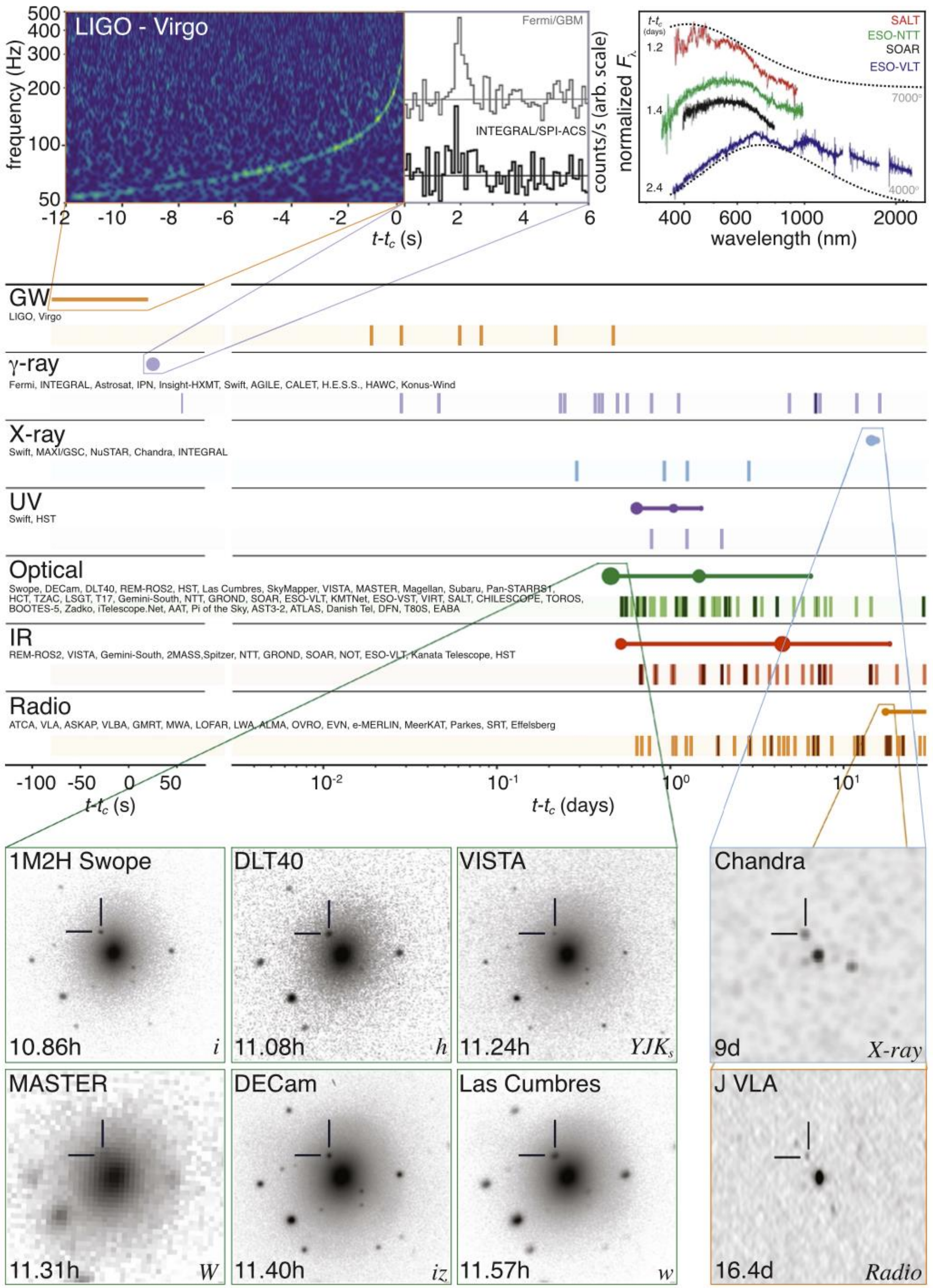
LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-HXMT Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Gravitational Waves / Multi-Probe

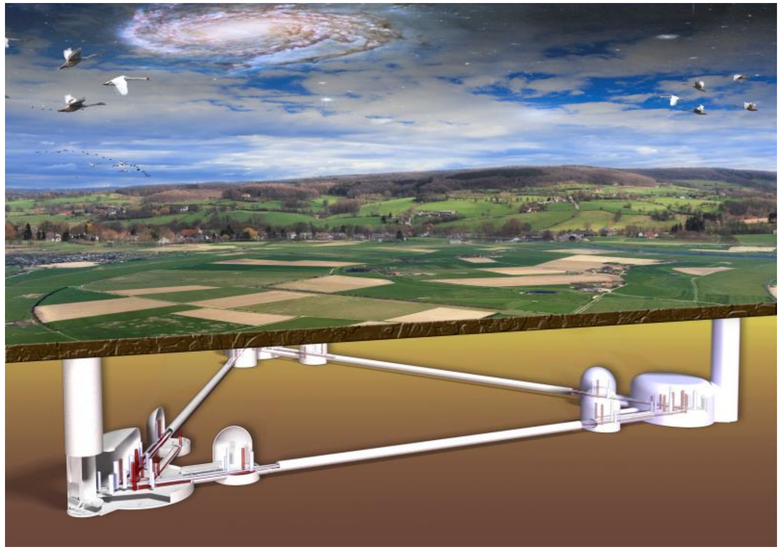




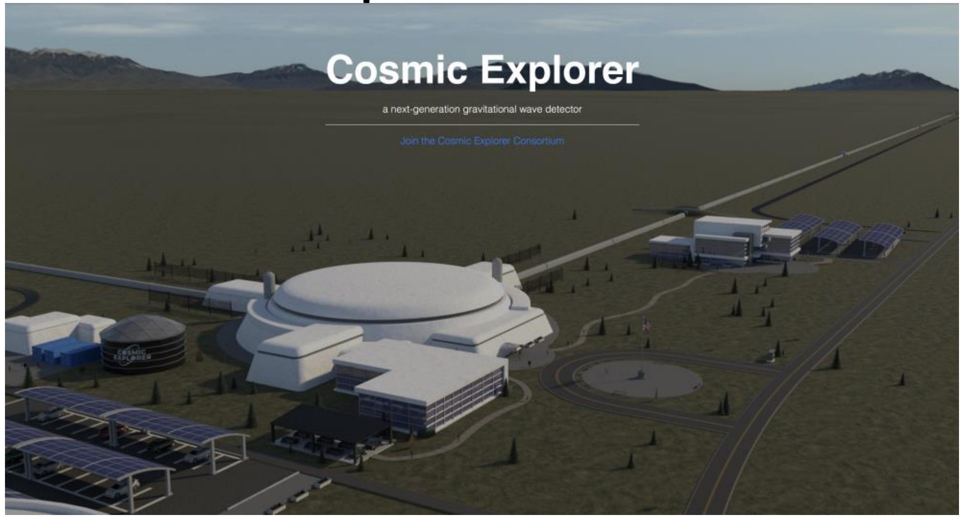


Gravitational Waves / Future

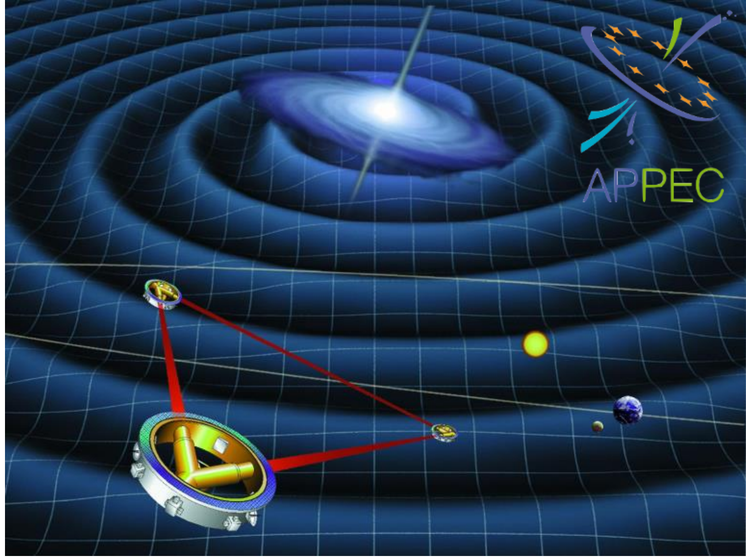
ET



Cosmic Explorer



LISA



Technology: Laser power and squeezed states, Newtonian noise, arm's length,, digging long tunnels

- ET Pathfinder

- ET Groeifonds

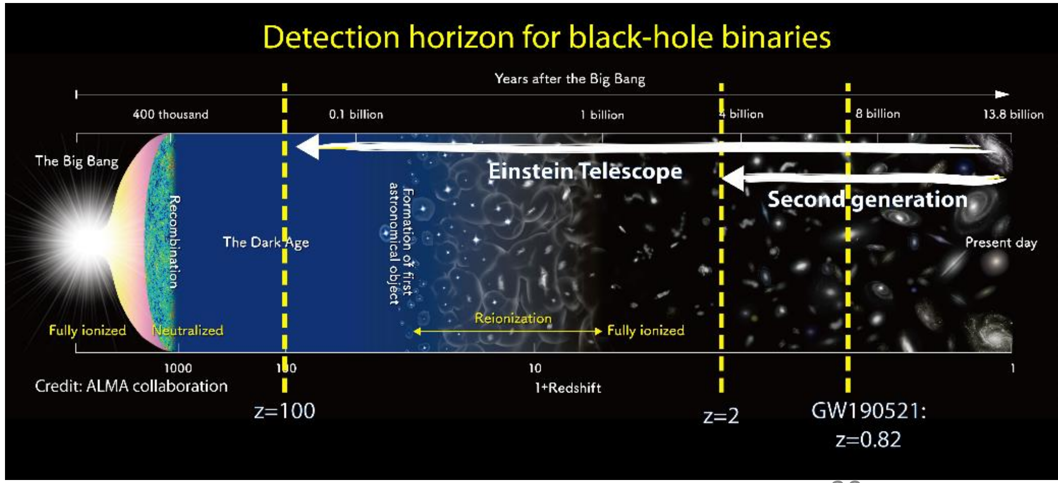
42 M€ site preparation

870 M€ when built in NL

ET Italian Consortium

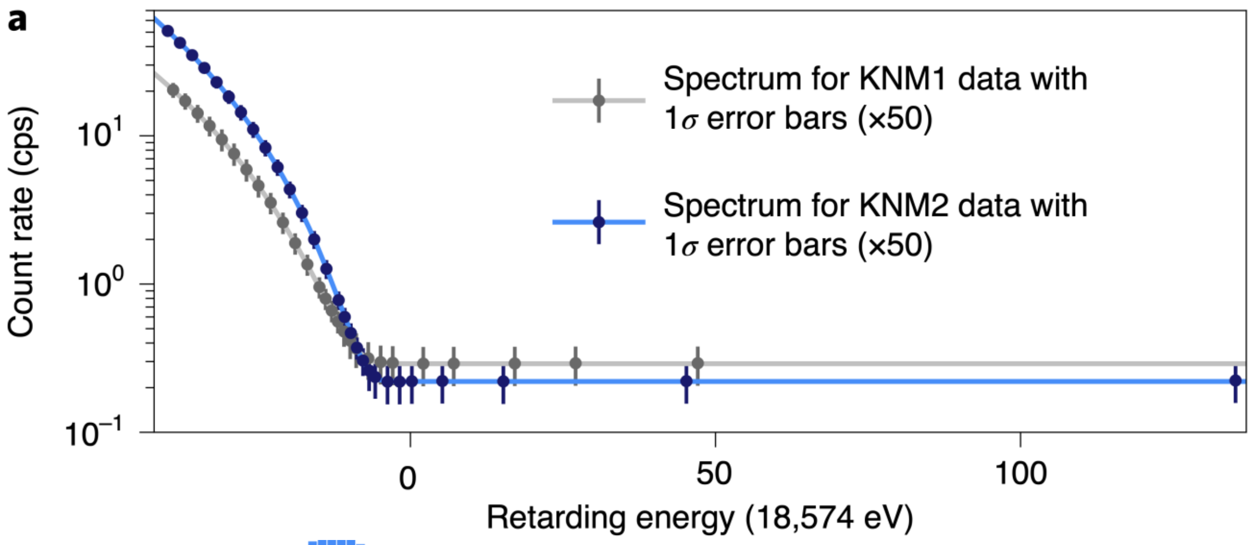
100 M€ site preparation

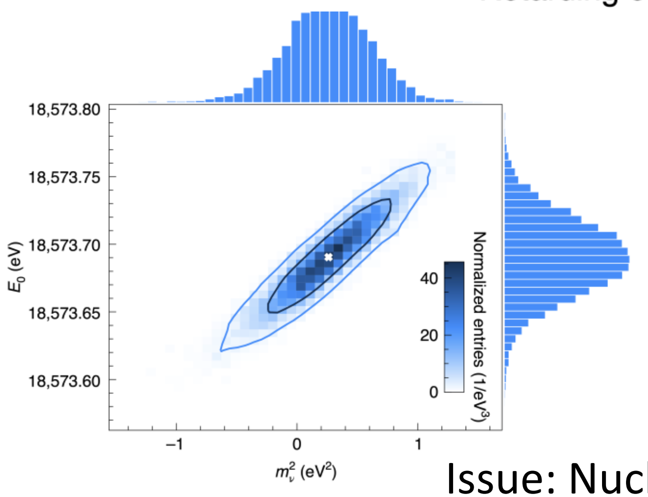
IT resilient fund 900 M€



Neutrino Properties / mass / Dirac-Majorana

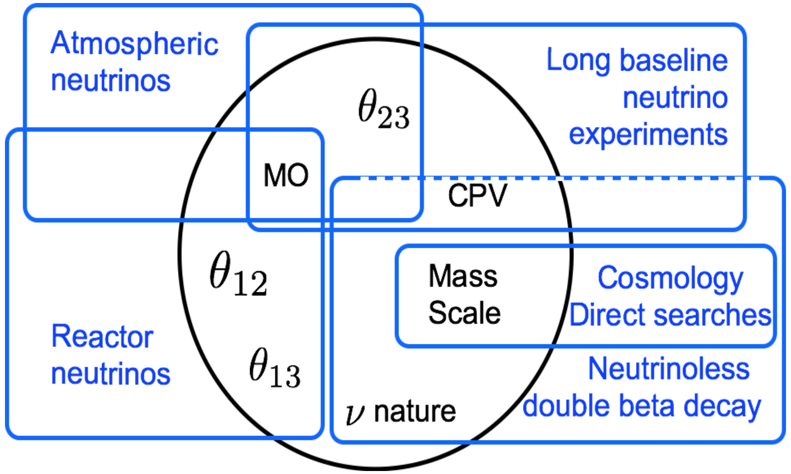
KATRIN

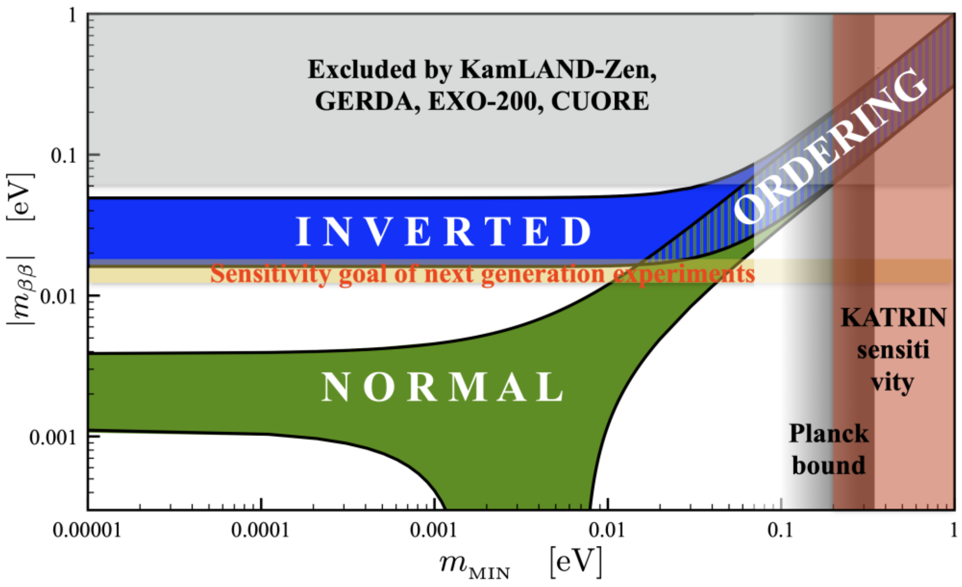




$m_\nu < 0.8$ eV c–2 at 90% CL

Issue: Nuclear Matrix Element calculations





Neutrinos Properties / mixing

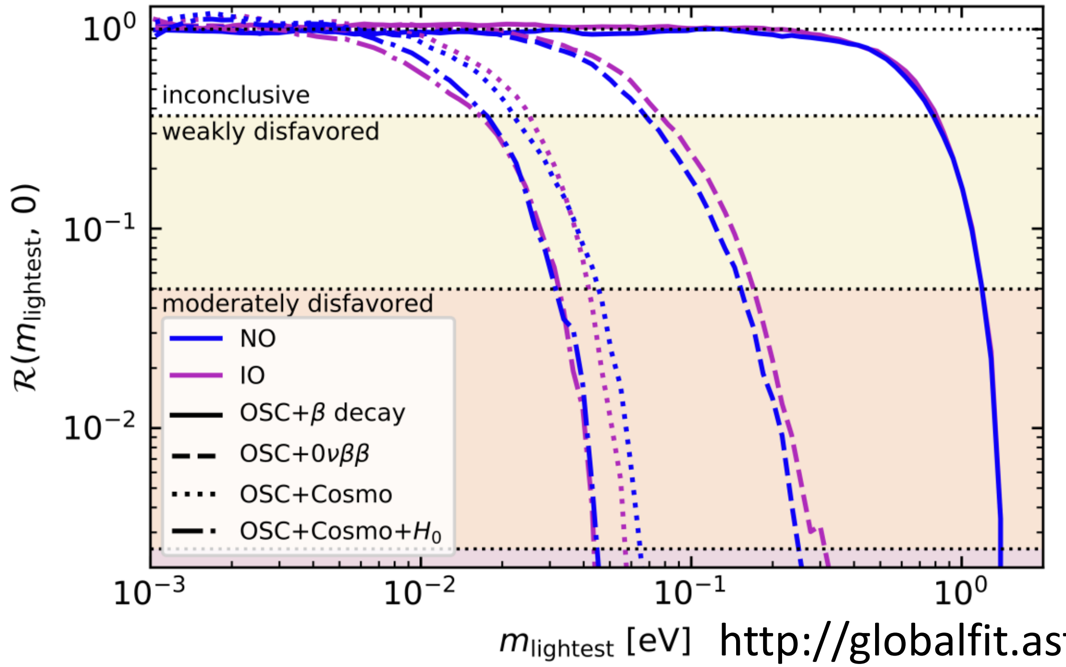
- New oscillation measurements from Atmospheric: IceCube, SuperK, Long Baseline: T2K, NOvA, Reactor: DayaBay, RENO, DoubleChOOZ

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79	47.37–50.71	41.20–51.33
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$	47.35–50.67	41.16–51.25
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$	8.27–8.79	8.13–8.92
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$	8.30–8.83	8.17–8.96
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/^\circ$ (NO)	194^{+24}_{-22}	152–255	128–359
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96
$\delta/^\circ$ (IO)	284^{+26}_{-28}	226–332	200–353

$$U^{\mathrm{NO}} = \begin{pmatrix} 0.7838 \to 0.8442 & 0.5135 \to 0.6004 & (-0.1568 \to 0.1489) + i(-0.1182 \to 0.1520) \\ (-0.4831 \to -0.2394) + i(-0.0749 \to 0.0962) & (0.4636 \to 0.6749) + i(-0.0521 \to 0.0668) & 0.6499 \to 0.7719 \\ (0.3068 \to 0.5391) + i(-0.0643 \to 0.0933) & (-0.6897 \to -0.4821) + i(-0.0446 \to 0.0644) & 0.6161 \to 0.7434 \end{pmatrix}$$

while for inverted ordering:

$$U^{\mathrm{IO}} = \begin{pmatrix} 0.7835 \to 0.8440 & 0.5133 \to 0.6005 & (-0.1423 \to 0.1490) + i(0.0191 \to 0.1553) \\ (-0.4802 \to -0.2682) + i(0.0114 \to 0.0990) & (0.4549 \to 0.6395) + i(0.0074 \to 0.0695) & 0.6493 \to 0.7711 \\ (0.3106 \to 0.5133) + i(0.0094 \to 0.0947) & (-0.6956 \to -0.5248) + i(0.0057 \to 0.0654) & 0.6171 \to 0.7434 \end{pmatrix}$$



http://globalfit.astroparticles.es/

Neutrinos Properties / Future

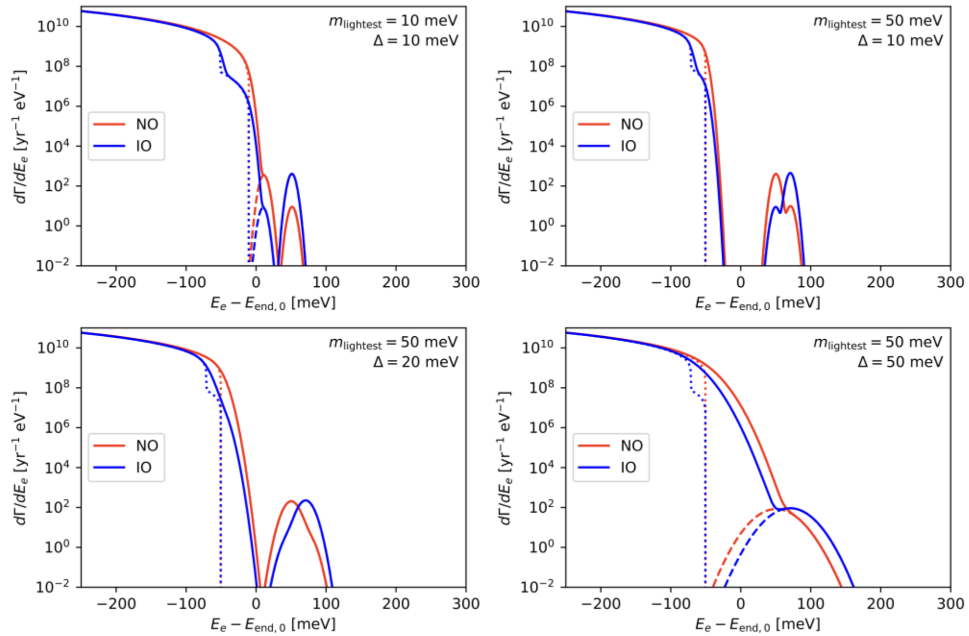
0νββ and more: LEGEND, CUPID (CUORE), NEXT-BOLD/HD/100, nEXO

Current experiments	Iso	M_{iso} [kg]	σ [keV]	ROI [σ]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{kg_{iso}yr}{yr}\right]$	$\mathcal{B}_{ROI}$ $\left[\frac{cts}{kg_{iso}yr}\right]$	Sens./Lim. (90%C.L.) $T_{1/2}$ [yr]	$\lvert m_{\beta\beta}\rvert$ [meV]
GERDA	^{76}Ge	31	1.4	(-2.0, + 2.0)	60	19	$6 \cdot 10^{-3}$	$1.1/0.9 \cdot 10^{26}$	102-213
CUORE	^{130}Te	206	3.4	$-1, 4, +1, 4$	67	138	$6.7 \cdot 10^{-1}$	$2.3 \cdot 10^{25}$	90-420
Current demonstrator	**Iso**	**M_{iso} [kg]**	**σ [keV]**	**ROI [σ]**	**ϵ_{sig} [%]**	**$\mathcal{E}$ $\left[\frac{kg_{iso}yr}{yr}\right]$**	**$\mathcal{B}_{ROI}$ $\left[\frac{cts}{kg_{iso}yr}\right]$**		
CUPID-0	^{82}Se	4,65	8.5	$-2.0, +2.0$	70	3.3	$2.2 \cdot 10^{-1}$	$3.5 \cdot 10^{24}$	311-638
CUPID-Mo	^{100}Mo	2.26	2.3	$-2.0, +2.0$	64	1.44	-	-	-
NEXT-White	^{136}Xe	91	10	$-1.0, +1.9$	26	-	-	-	-
Funded experiments	**Iso**	**M_{iso} [kg]**	**σ [keV]**	**ROI [σ]**	**ϵ_{sig} [%]**	**$\mathcal{E}$ $\left[\frac{kg_{iso}yr}{yr}\right]$**	**$\mathcal{B}_{ROI}$ $\left[\frac{cts}{kg_{iso}yr}\right]$**	**3σ disc. sens. $T_{1/2}$ [yr]**	**$m_{\beta\beta}$ [meV]**
LEGEND-200	^{76}Ge	177	1.1	$-2.0, +2.0$	70	123	$1 \cdot 10^{-3}$	$9.4 \cdot 10^{26}$	35–73
NEXT-100	^{136}Xe	87	10.4	$-1.0, +1.8$	26	23	$4 \cdot 10^{-2}$	$7.0 \cdot 10^{25}$	65–281
Future experiments	**Iso**	**M_{iso} [kg]**	**σ [keV]**	**ROI [σ]**	**ϵ_{sig} [%]**	**$\mathcal{E}$ $\left[\frac{kg_{iso}yr}{yr}\right]$**	**$\mathcal{B}_{ROI}$ $\left[\frac{cts}{kg_{iso}yr}\right]$**	**3σ disc. sens. $T_{1/2}$ [yr]**	**$m_{\beta\beta}$ [meV]**
LEGEND-1000	^{76}Ge	883	1.1	$-2.0, +2.0$	70	614	$7 \cdot 10^{-5}$	$1.2 \cdot 10^{28}$	10–20
CUPID	^{100}Mo	253	2.1	$-2.0, +2.0$	68	172	$2 \cdot 10^{-3}$	$1.1 \cdot 10^{27}$	12–20
NEXT-HD	^{136}Xe	991	7.7	$-1.3, +2.5$	32	317	$9 \cdot 10^{-4}$	$1.7 \cdot 10^{27}$	13–57

Many open questions:

- leptonic CPV?
- neutrino mass ordering?
- precise oscillation parameters? (JUNO !)
- beyond 3-neutrino mixing (SNB,
  very short baseline programme)

Ptolemy



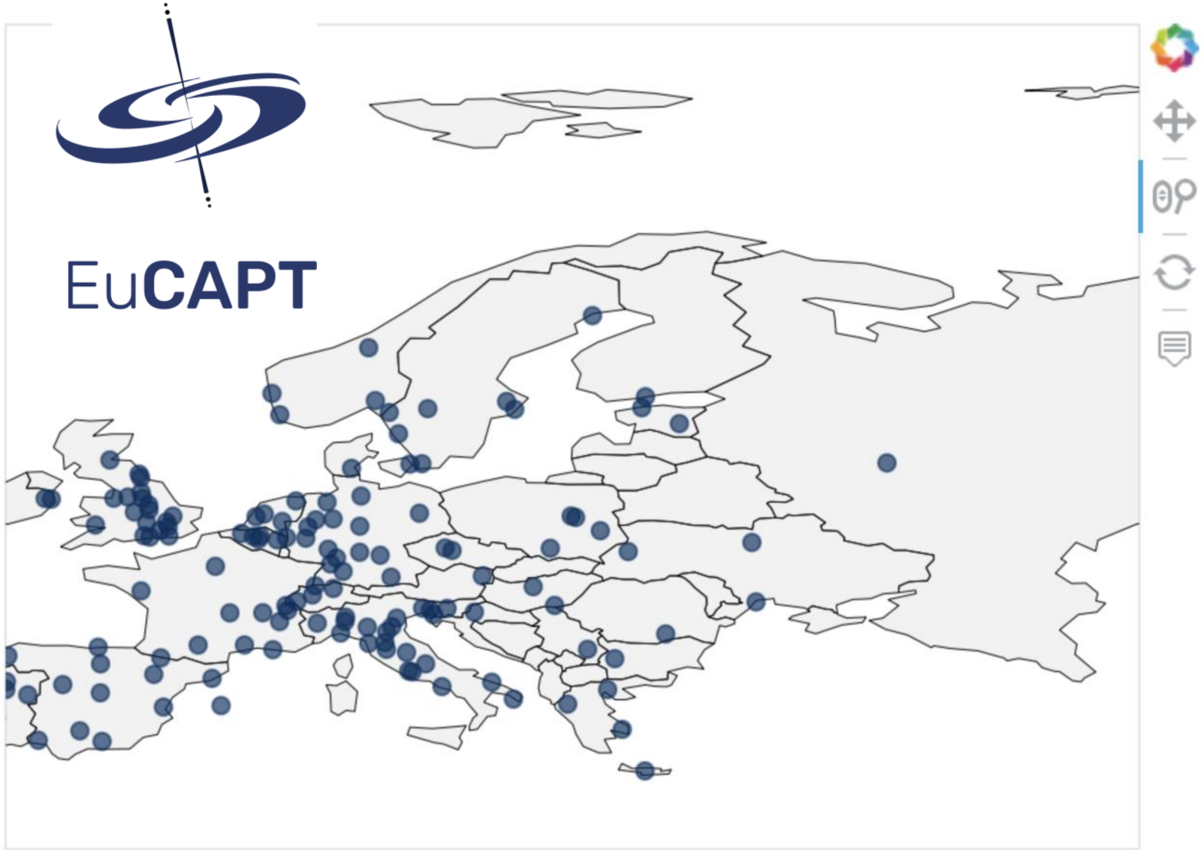
Detector R&D:

The right and sufficient isotopes, radiopurity, energy resolution

binding Tritium in a controlled way, …

EuCAPT Progress in Theory

Census in 2019, interactively available at https://www.eucapt.org:



Design&Code: Niko Sarcevic (twitter.com/NikoSarcevic)

White paper arXiv:2110.10074

Many (virtual) colloquia

Annual symposia: 5-7 May 2021

23-25 May 2022

Workshop 11-13 November 2019

Ecological footprint

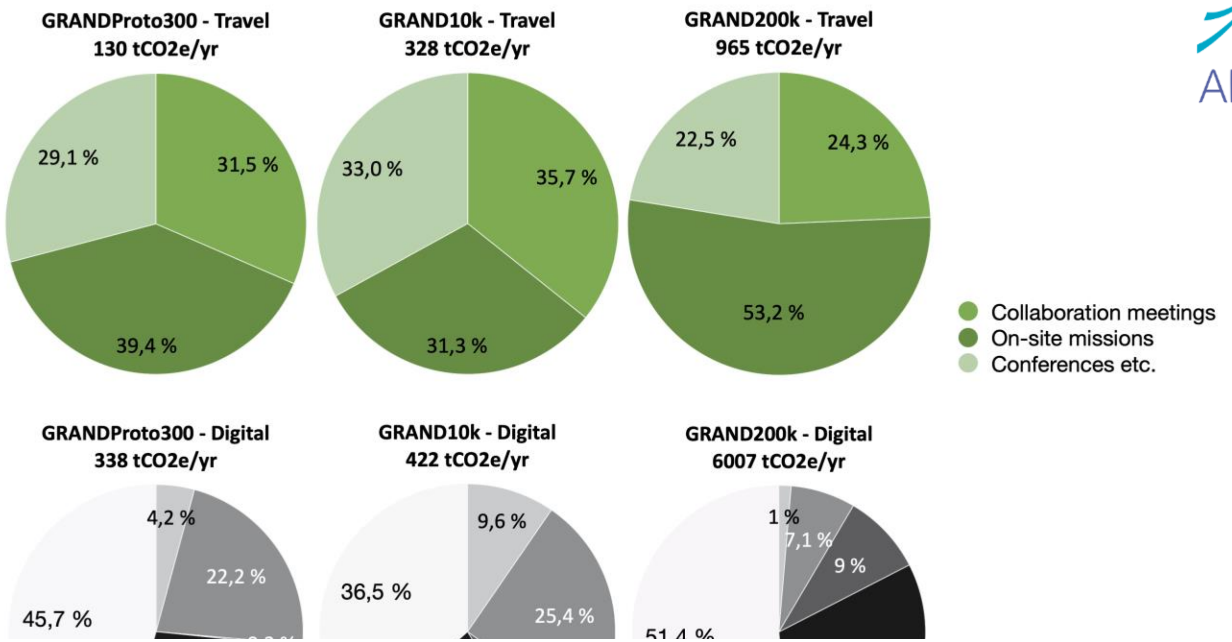
GRAND Carbon footprint study

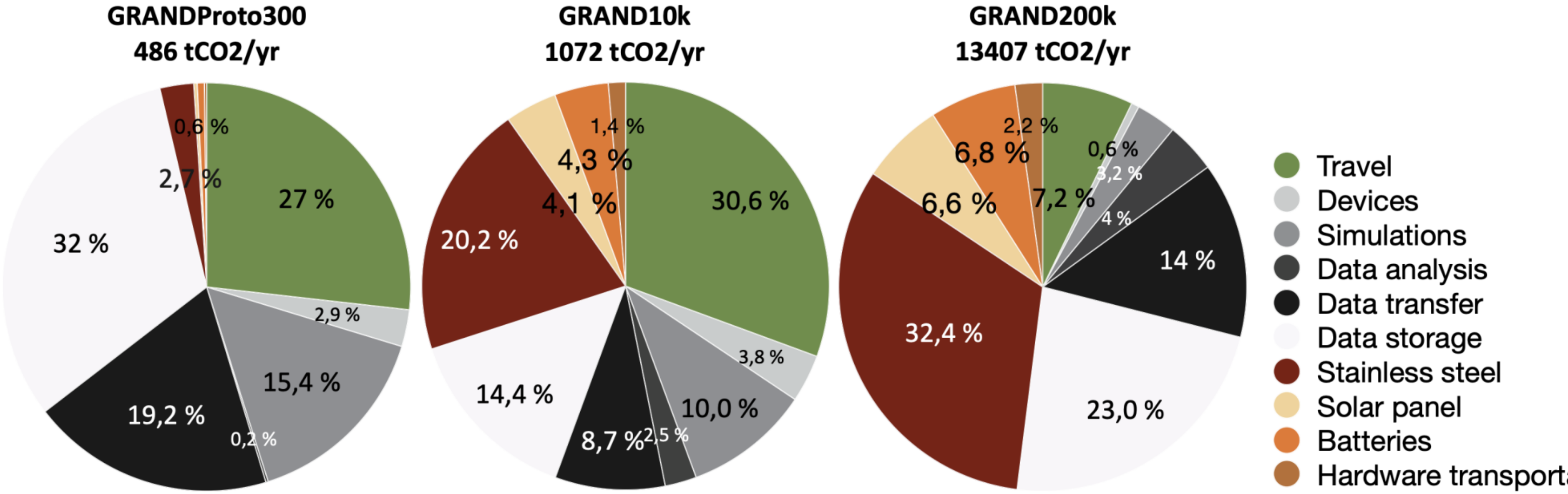
Challenge/Mitigation:

On-site work by locals

Data reduction/smarter analysis?

Detector design/materials





Summary and Outlook

- Many observatories/experiments => many results
- Theory/Phenomenology key in linking the results
- Ready for many next-generation detectors:
  - many multi-purpose and/or multi-probe
  - many require more R&D
  - all requiring substantial funding
- A variety of observatories ⇒ multi-messenger ⇒ much enhanced science
- Most overlap with particle physics and astronomy,
  but also significant overlap with nuclear physics