WG2: High-energy quantum gravity experiment

What you always wanted to know about our field but were afraid to ask

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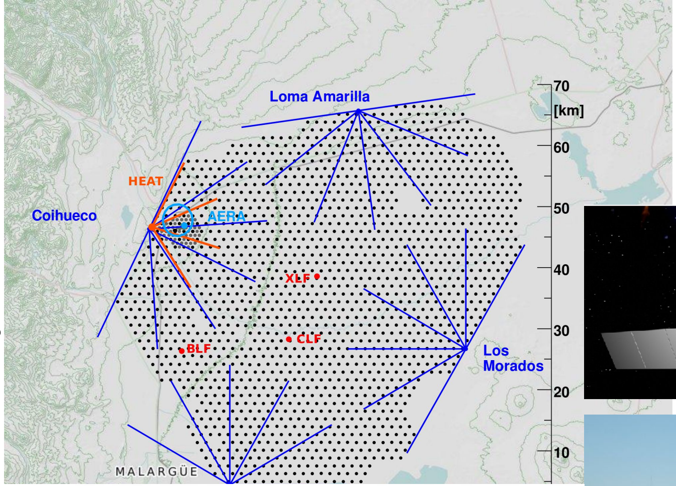
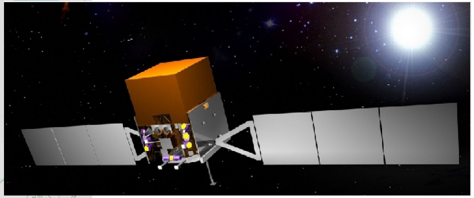
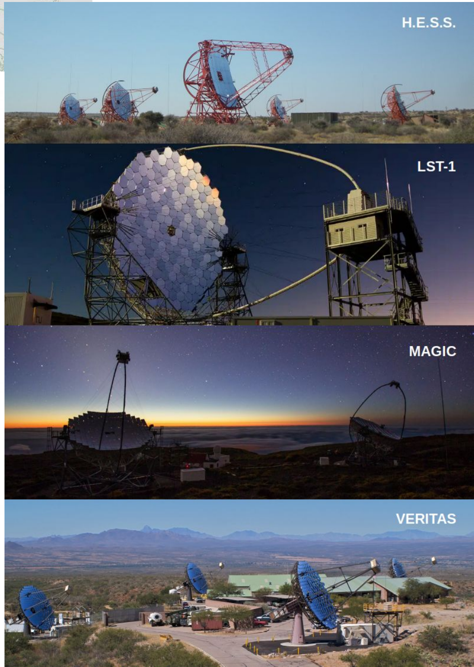
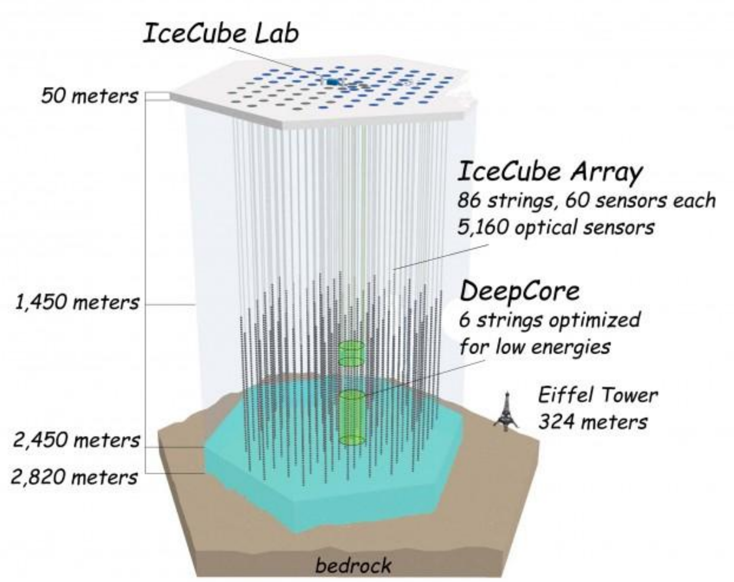
BridgeQG – WG2

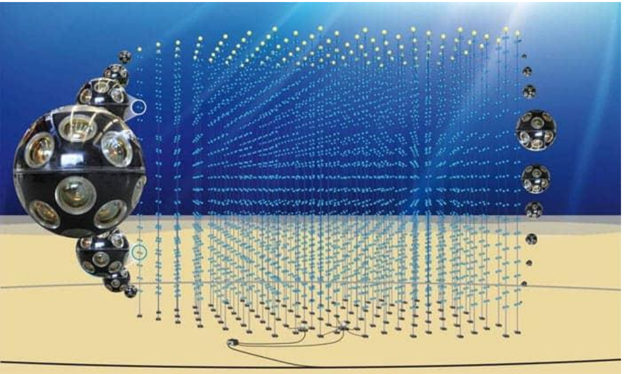
- Focus on the experimental tests of QG models and properties at high energies
- Experiments in:
    - Cosmic rays
    - Gamma rays
    - Neutrinos
    - Gravitational waves











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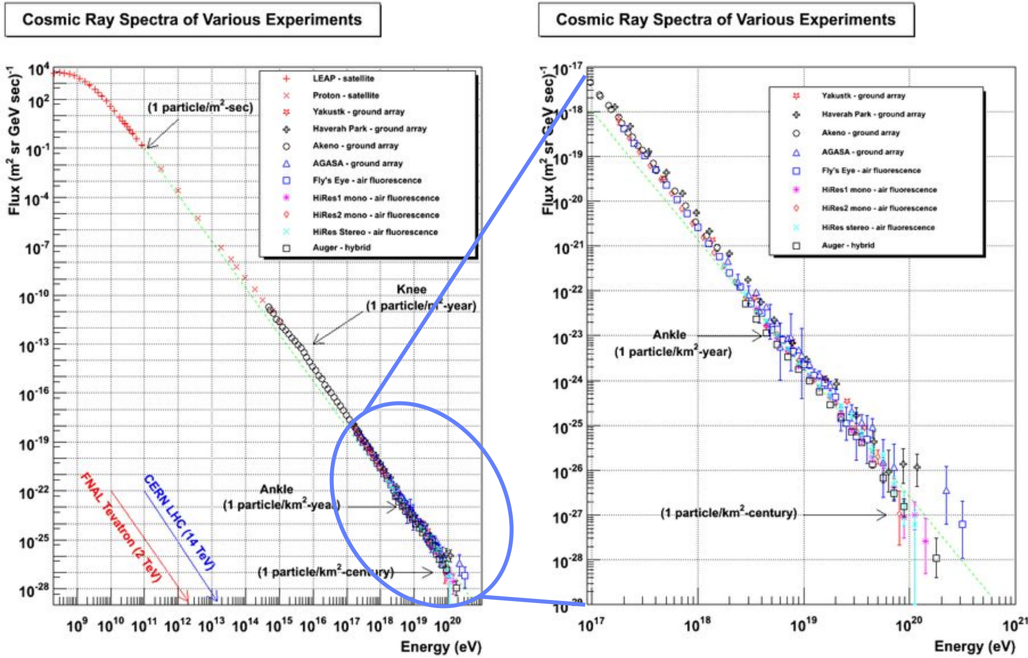
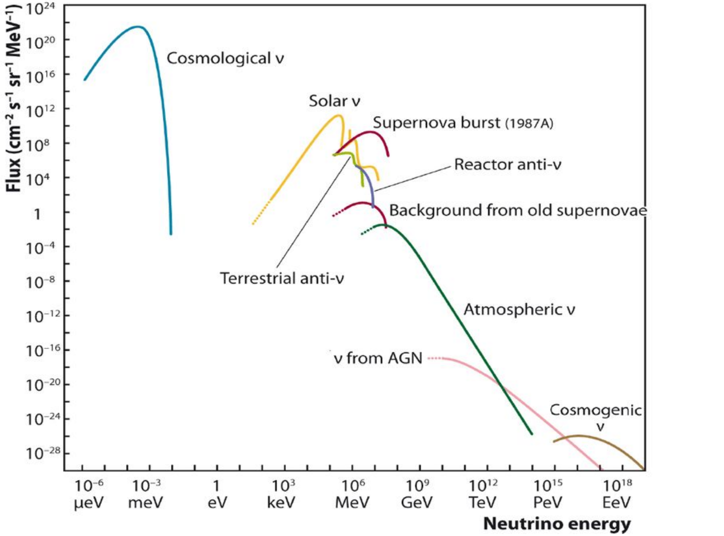
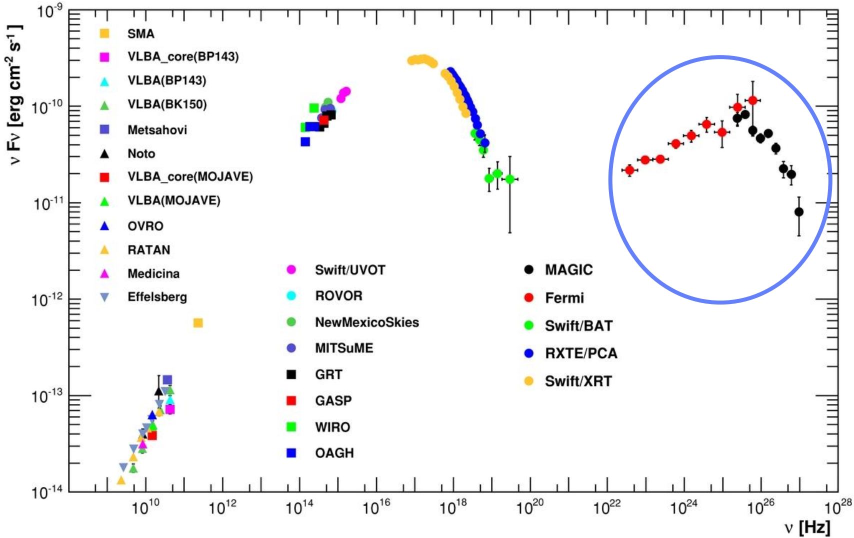
- Experiments in: **Cosmic rays, Gamma rays, Neutrinos**

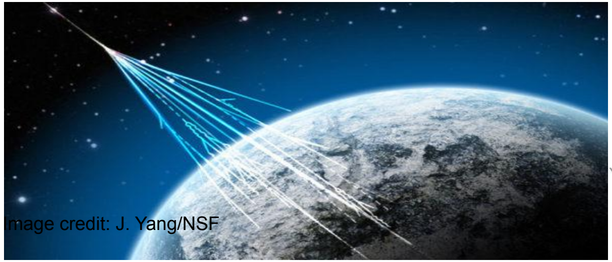






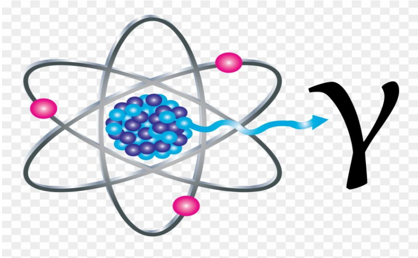
Motivation

- Planck energy – expected energy scale of QG
- How does one measure effects at the scale of 10^{28} eV?
- Take the most energetic particles you can find in nature



Cosmic rays: $E_{max} \sim 3.2 \times 10^{20}$ eV

Neutrinos: $E_{max} \sim 2.2 \times 10^{17}$ eV

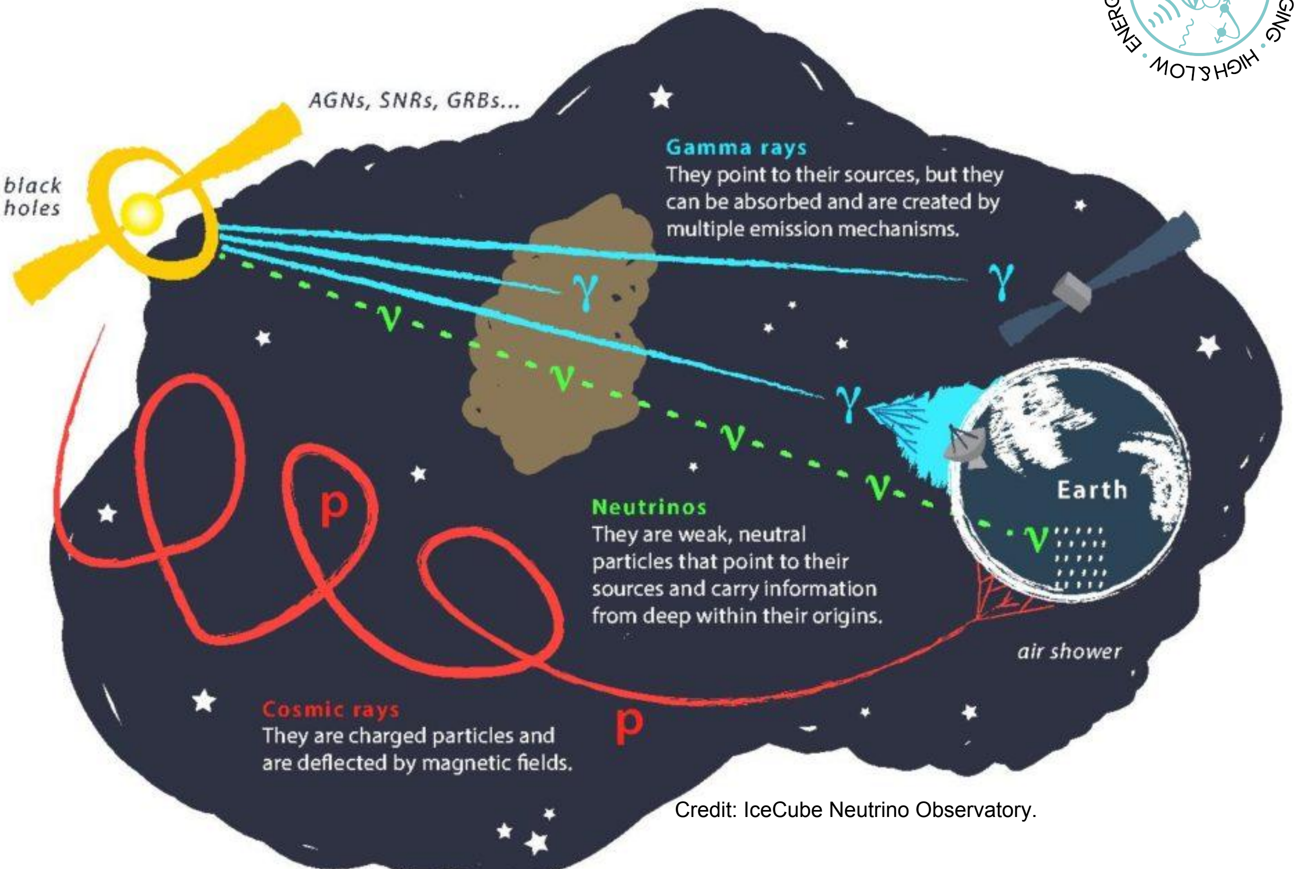


Gamma rays: $E_{max} \sim 1.4 \times 10^{15}$ eV

- Still orders of magnitude below E_{Pl}

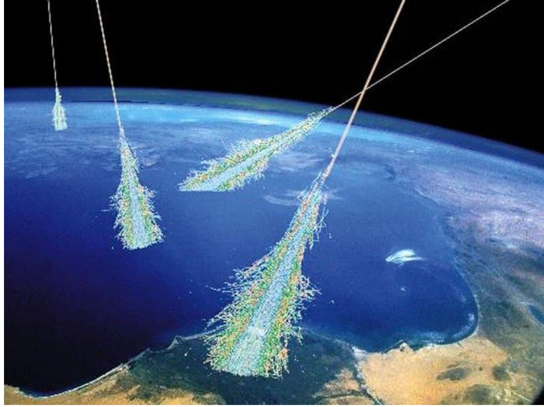
Motivation

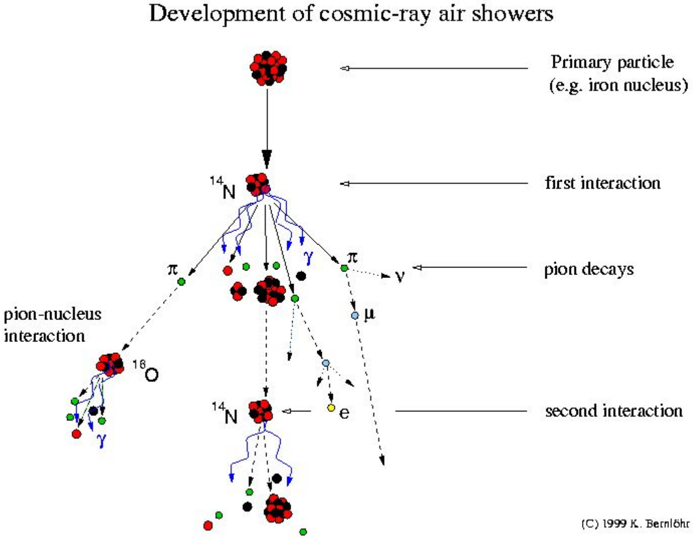
- **Ultra-high energies** (although still orders of magnitude below E_{Pl})
- Accumulation of effects on **Gyear** time scale

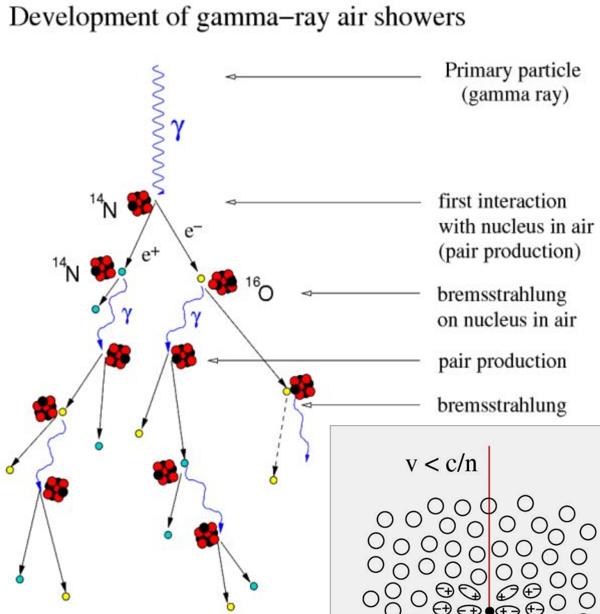


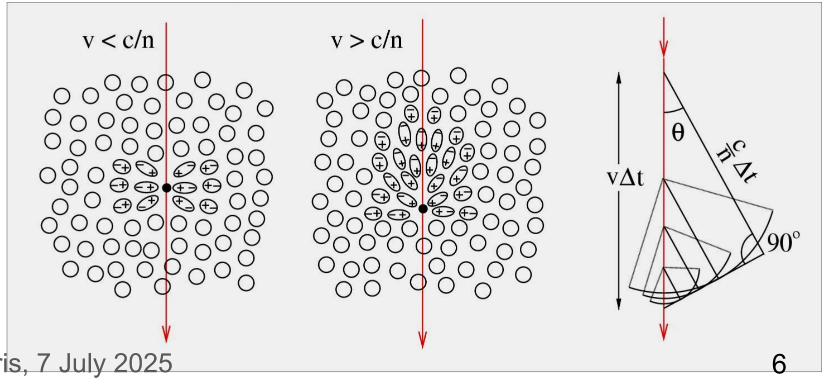
Credit: IceCube Neutrino Observatory.

WG2: Detection principle









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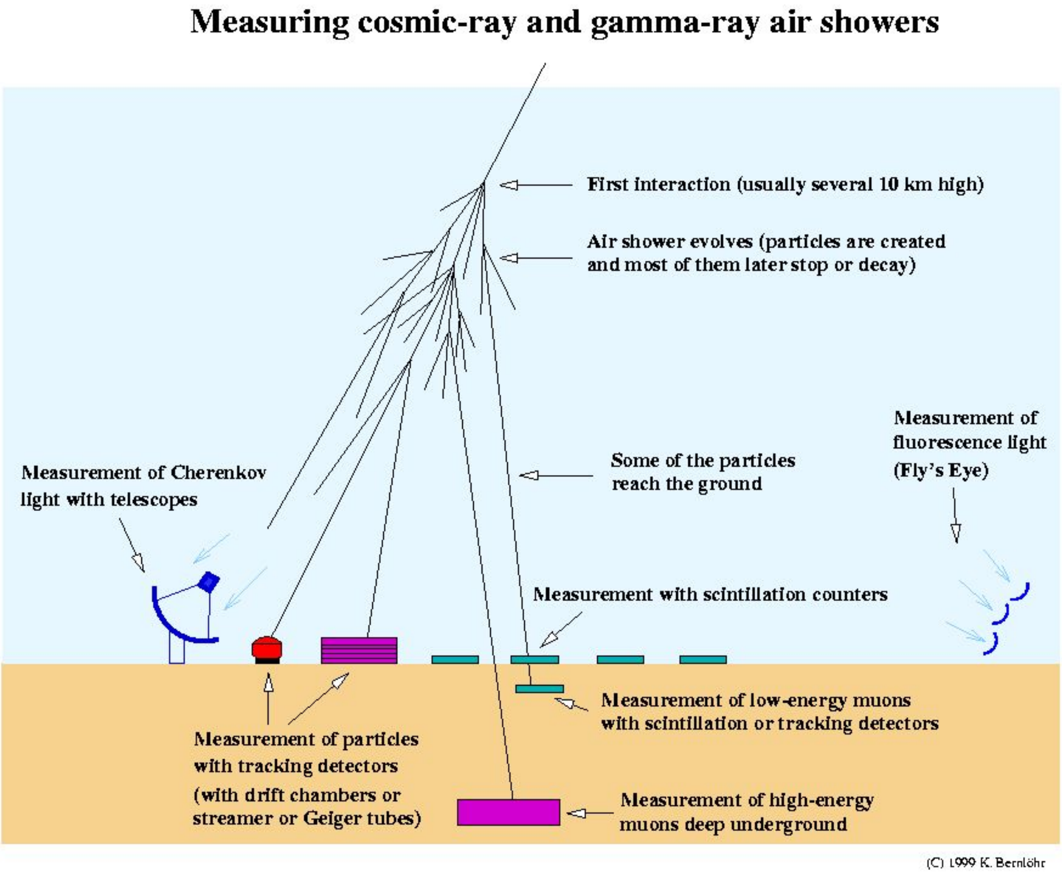
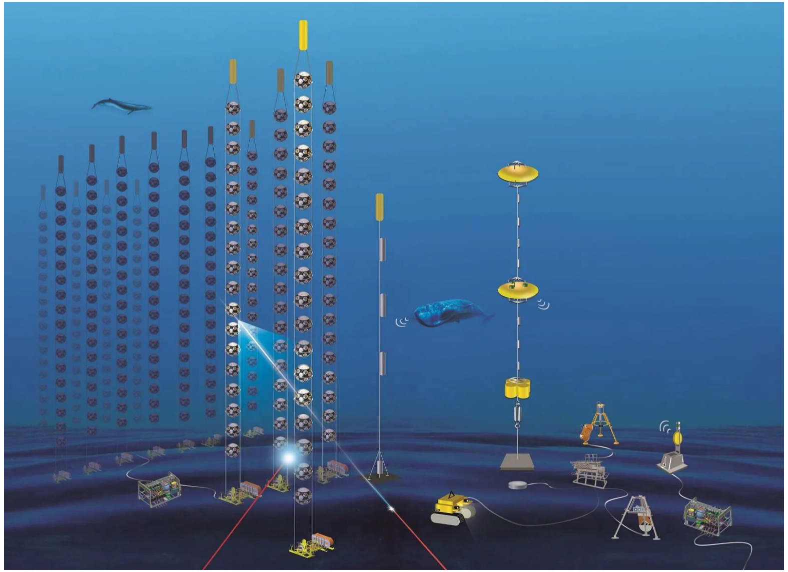
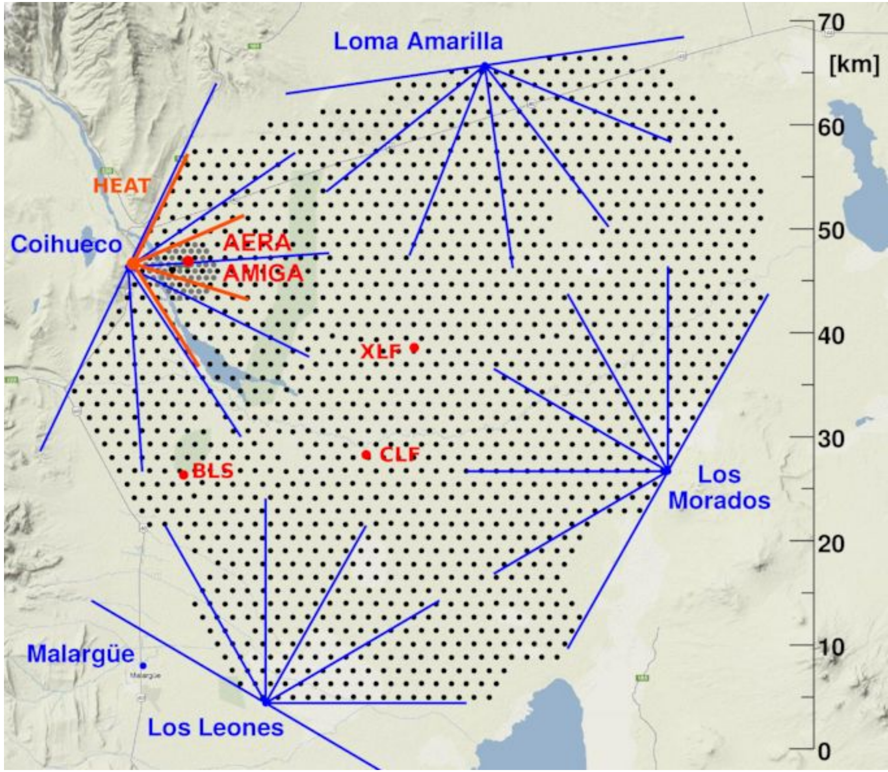




WG2 experiments: The Pierre Auger Observatory

- **Largest cosmic ray detector array in the world**
- Location: Mendoza Province, Argentina
  35.2° S, 69.2° W, 1 400 m a.s.l. (≈ 880 g/cm 2)
- Energy range: ~ 10^{17} – 10^{21} eV
- Main array for UHE operating since 01 Jan 2004:
  - **Surface Detectors:** 1600 water Cherenkov detectors over 3000 km^2 triangular grid (1.5 km spacing)
  - **Fluorescence Detectors:** 24 telescopes on 4 sites on edge of SD array
- Low-energy extension (HEAT and AMIGA):
  - 3 extra FD telescopes at higher elevation
  - 73 extra SDs with 750 m and 433 m spacing



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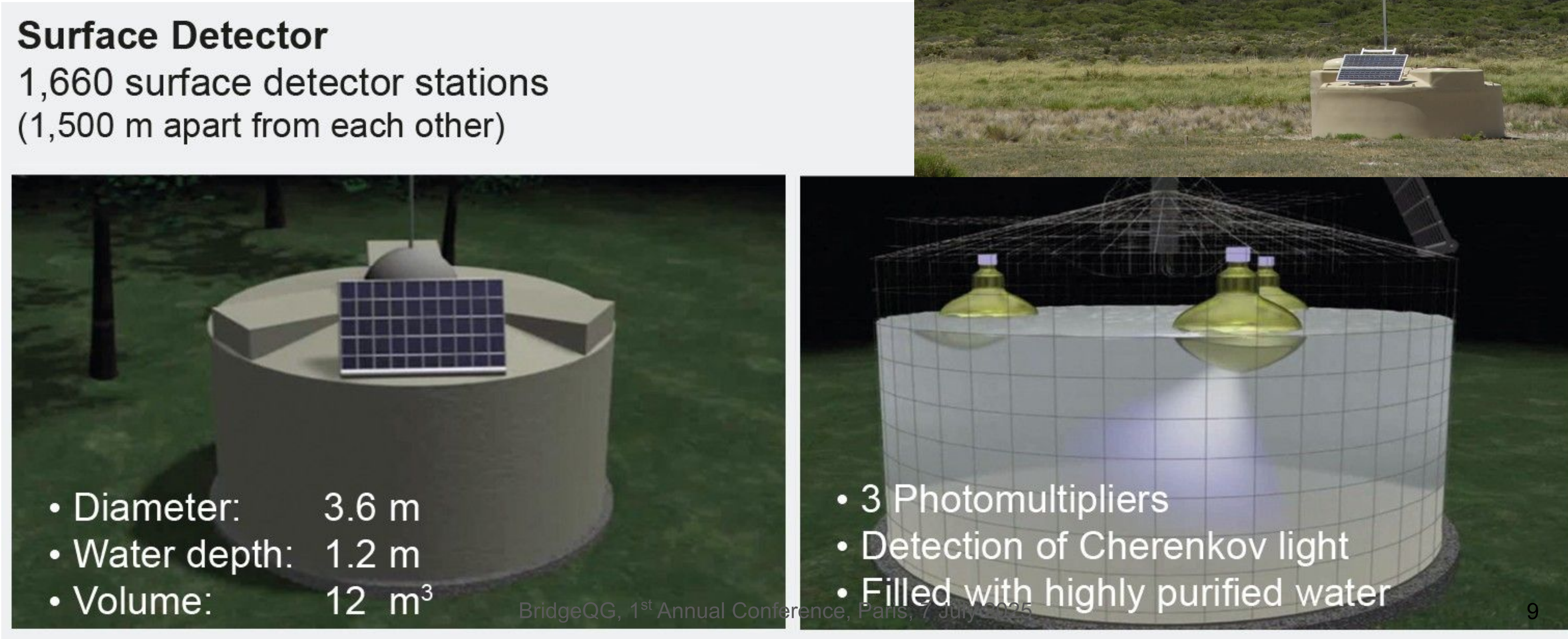

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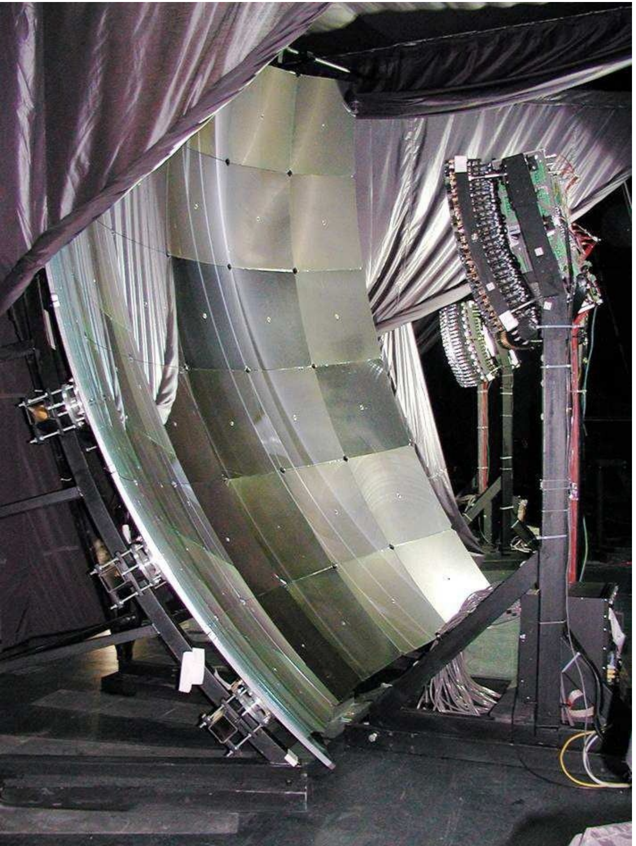
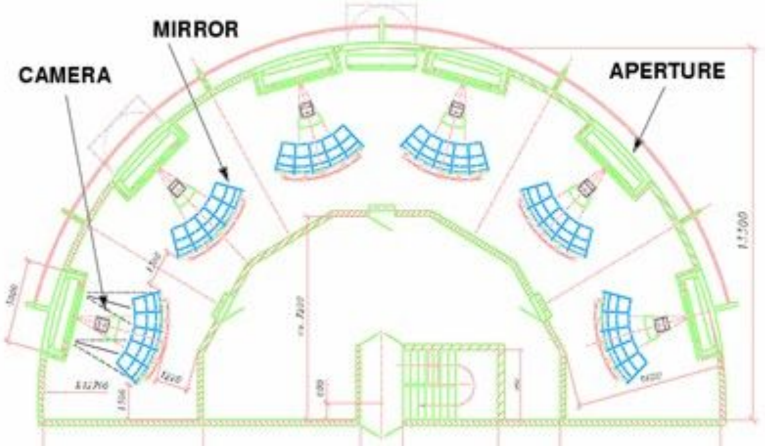
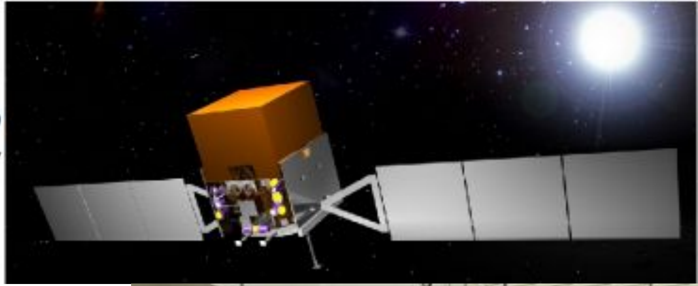


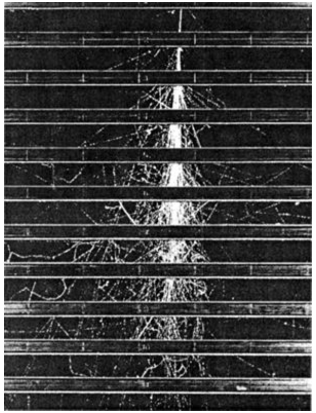
- 440 Photomultipliers
- Detection of fluorescence light
- Duty cycle: ~ 10 %

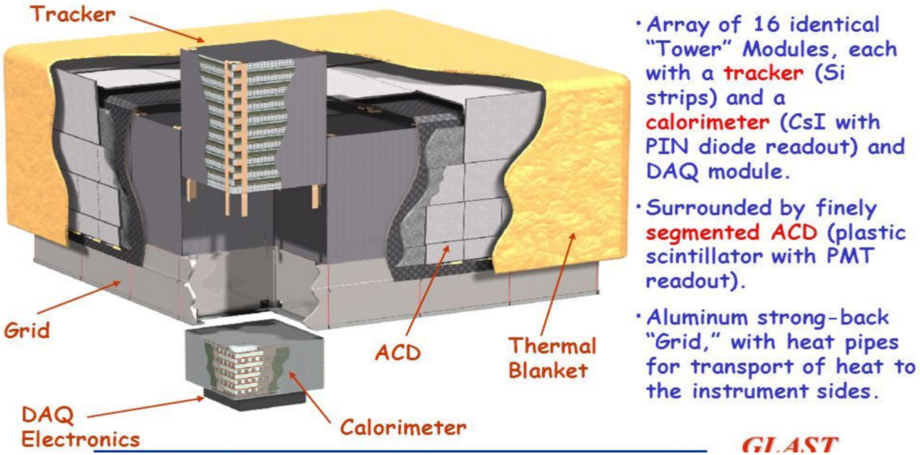


WG2 experiments:



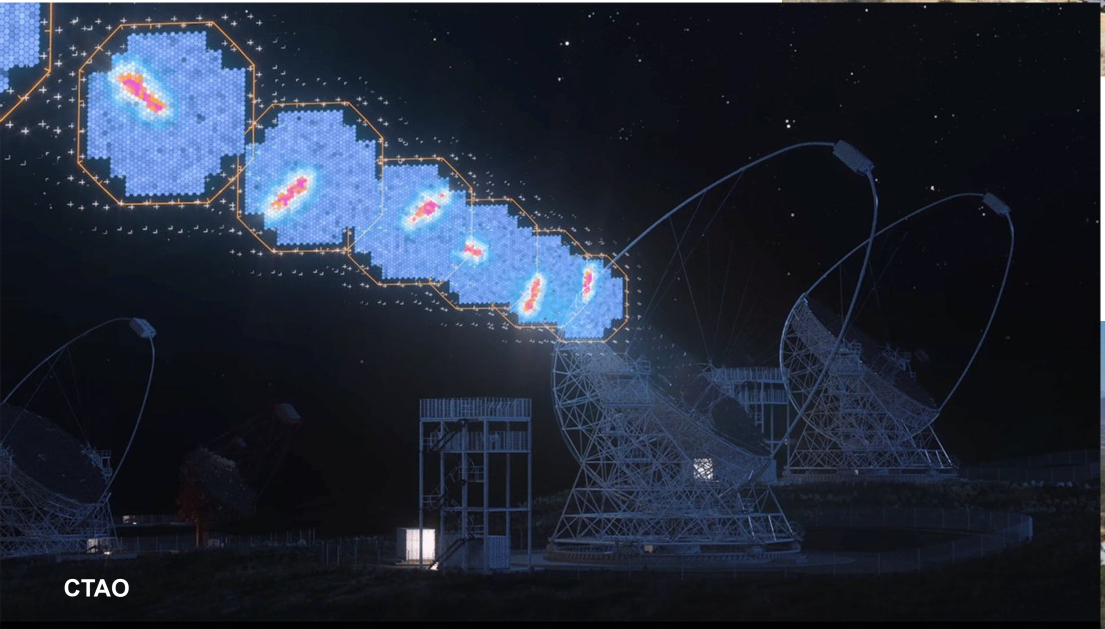
- **Major gamma-ray satellite observatory**
- Gamma-ray Burst Monitor (GBM)
- Large Area Telescope (LAT)
    - Energy range: 20 MeV < E < 300 GeV
    - FoV: 2,4 sr (~⅕ 4π) → Full sky survey every 3 hours
    - Every point in the the sky continuously observed for 30 mins
    - Duty cycle: ~ 100 %





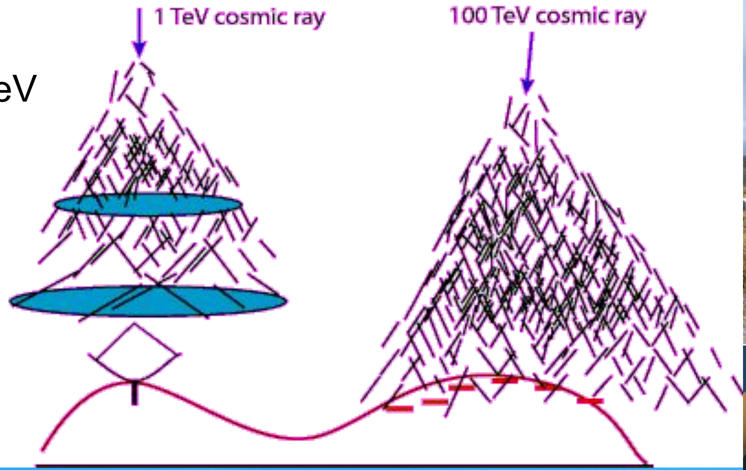
WG2 experiments: Imaging Atmospheric Čerenkov telescopes

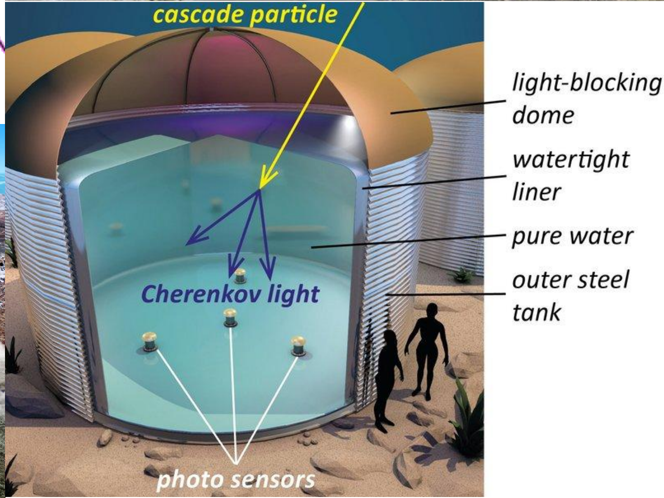
- Energy range: ~30 GeV – ~ 100 TeV
- Field of View: ~ 5 deg
- Duty cycle: ~ 10%

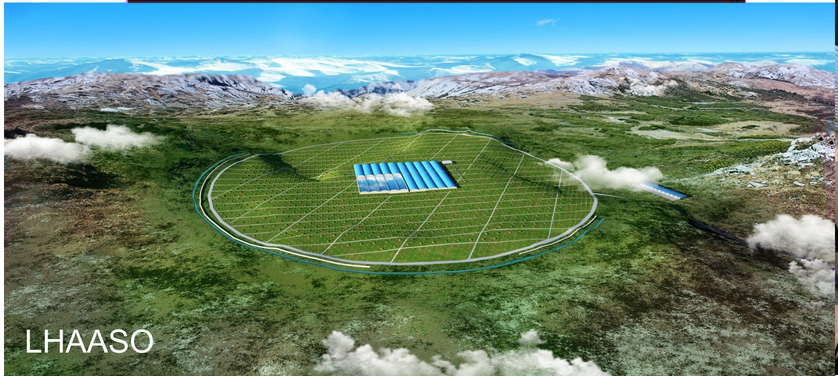


WG2 experiments: Water and Hybrid detectors

- Energy range:
  ~100 GeV – ~ 100 TeV
- Field of View:
  ~ 15 % of the sky
- Duty cycle: > 90%

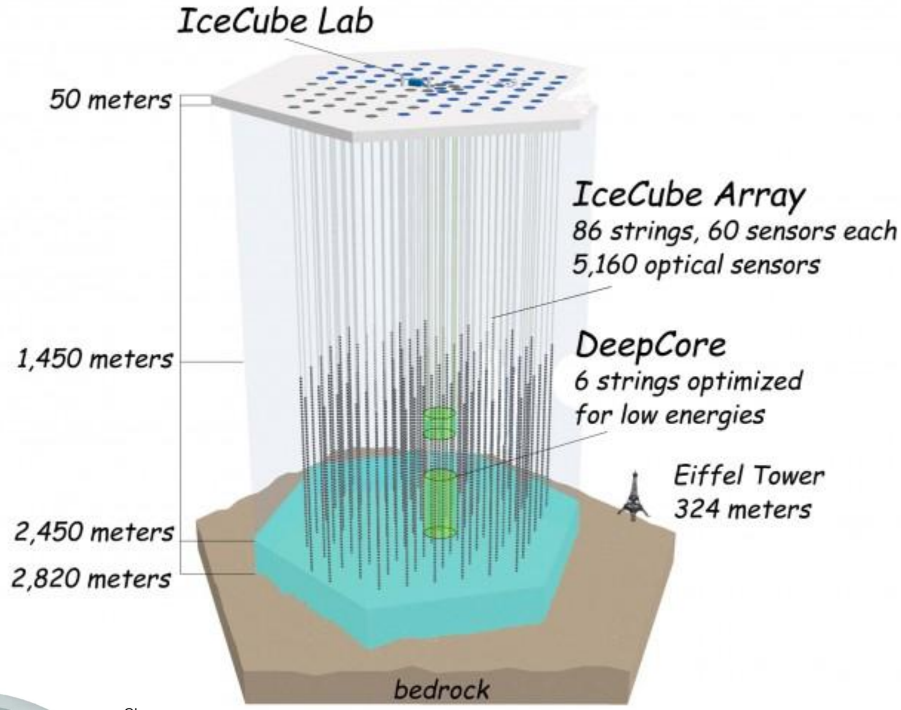


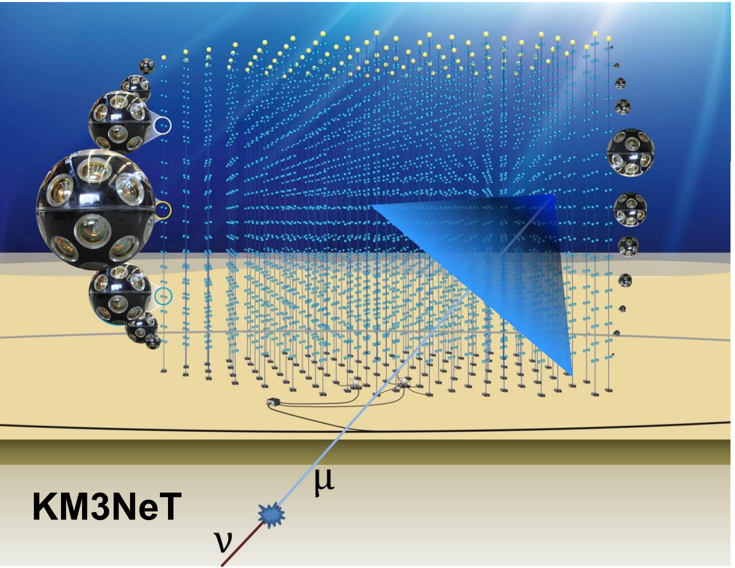


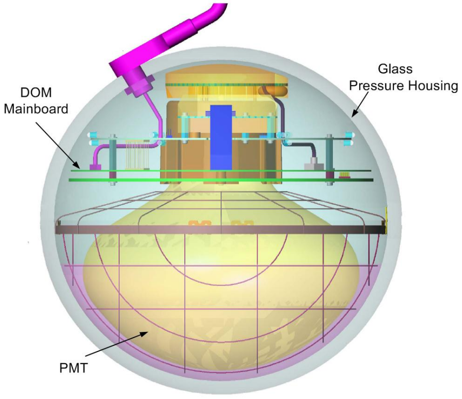


WG2 experiments: Neutrino detectors

- 3D arrays of photomultipliers
- IceCube — South pole (ice)
- KM3NeT — Mediterranean sea
- Energy range: ~ 1 – 10^9 GeV







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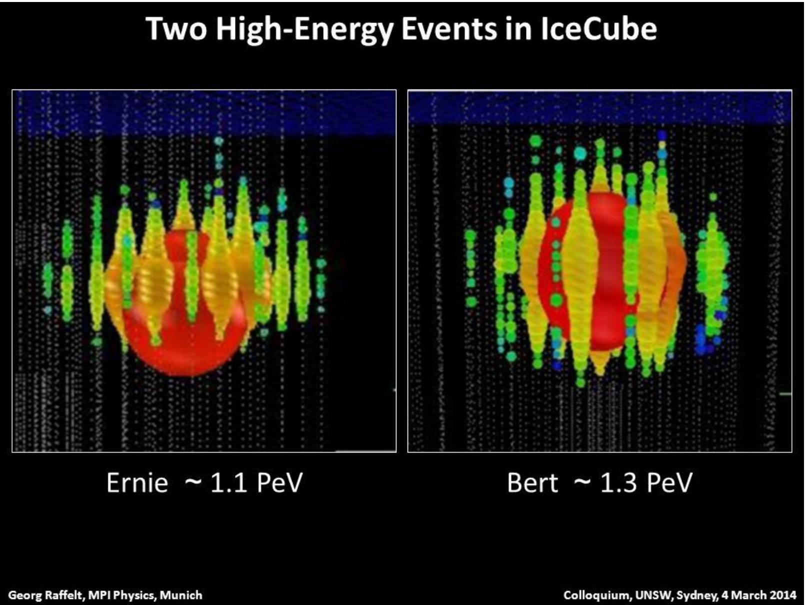
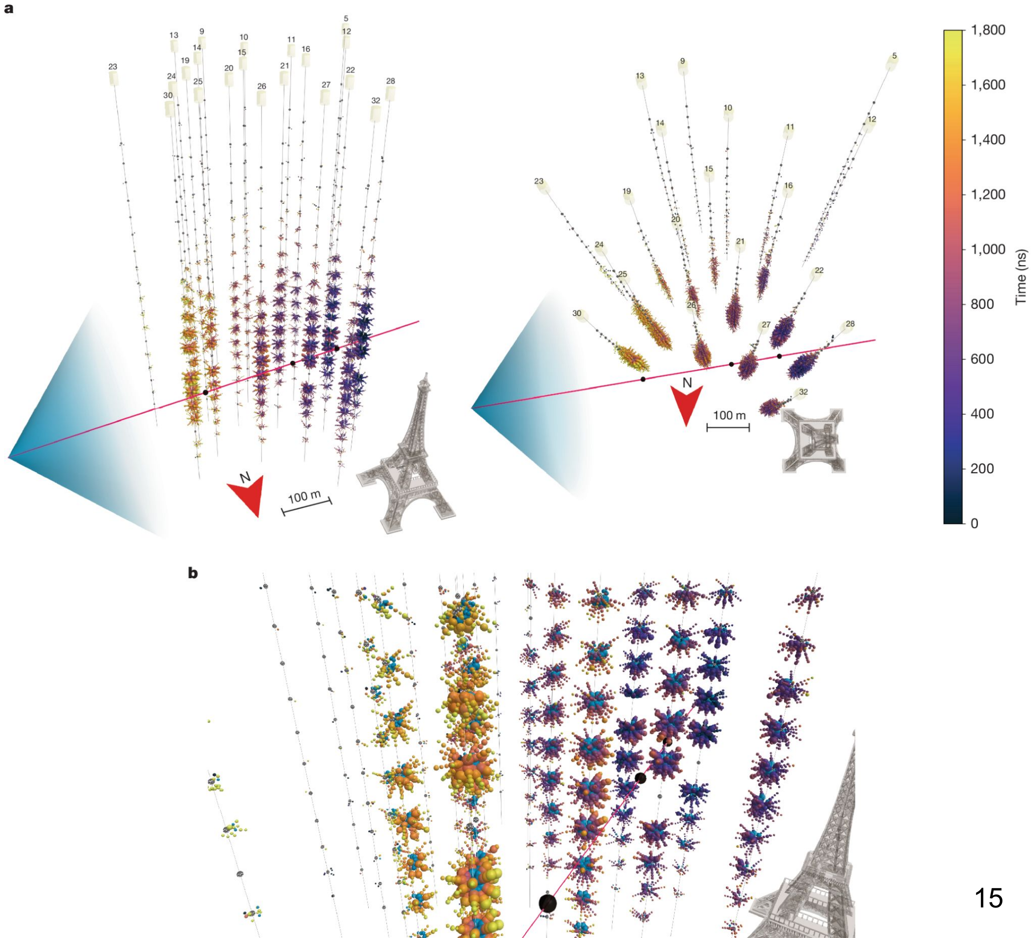
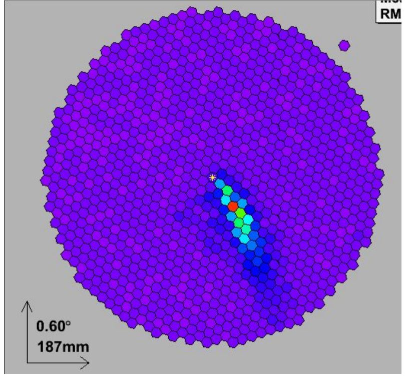
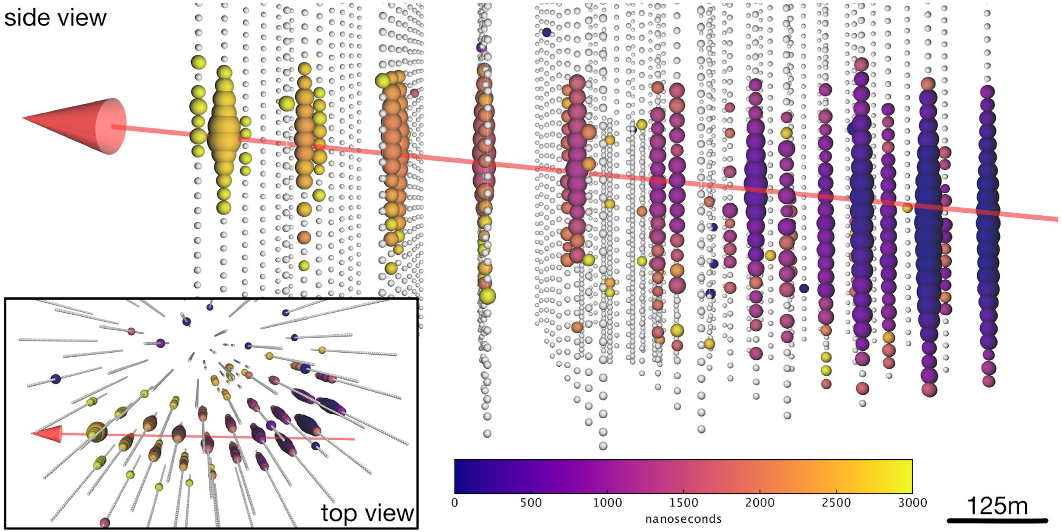


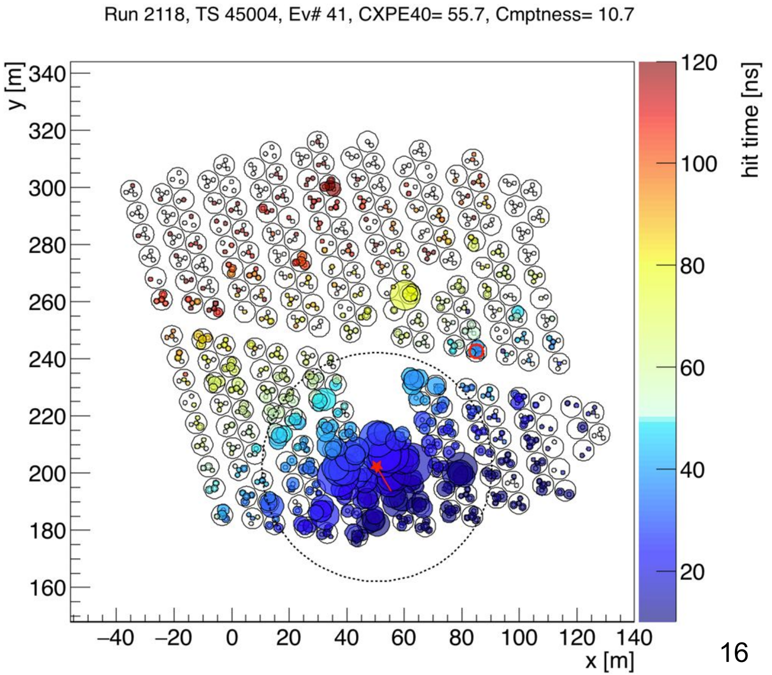


WG2 experiments: What we measure



- Measured quantities:
  - Time, photomultiplier output
- Reconstructed observables: everything else
  - Particle energy, direction, type…
  - Expressed as **Probability distribution functions**





WG2 experiments: Analysis results

- Observables:
  - Individual events:
    - Primary particle energy, direction, detection time
    - Primary particle type:
      proton, heavy nucleus, gamma ray, neutrino type, etc.
  - Data sample:
    - Chemical composition
    - Spectral distribution
    - Temporal distribution (light curve)
    - Flavour ratio

- IMPORTANT: Each measured value comes with an uncertainty.
  Observable value is NOT a number, but a probability distribution function.

Astroparticle tests of QG

- Testing for consequences of Lorentz symmetry breaking or deformation
  - Time delays
  - Modified reaction thresholds
  - Modified reaction dynamics
  - Vacuum birefringence
  - Impact on neutrino oscillations
- Decoherence tests
  - Neutrino oscillations as an open quantum system in a QG environment

$$E_{\mathrm{i}}^2 = m_{\mathrm{i}}^2 c^4 + p_{\mathrm{i}}^2 c^2 \left[1 + \sum_{n=1}^{\infty} \eta_n^{(\mathrm{i})} \left(\frac{p_{\mathrm{i}} c}{E_{\mathrm{QG},n}^{(\mathrm{i})}} \right)^n \right]$$

Modified dispersion relation - the usual starting point for LIV tests

Check: Addazi et al. 2022 (arXiv: 2111.05659) for a comprehensive review of QG models and tests with cosmic messengers

See: QG-MM Catalogue for a census of measurement results

Time delays

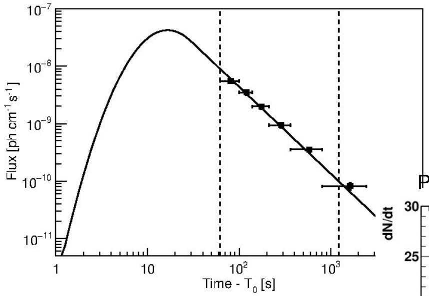
$$v_\gamma = \frac{\partial E}{\partial p} \simeq \left[1 - \sum_{n=1}^{\infty} S \frac{n+1}{2} \left(\frac{E}{E_{\mathrm{QG,n}}}\right)^n\right]$$

$$S = \begin{cases} +1, \text{ subluminal} \\ -1, \text{ superluminal} \end{cases}$$

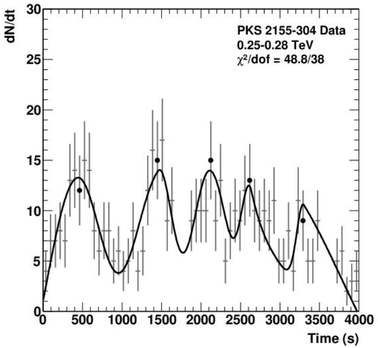
- Based on gamma rays time of flight
- Challenges:
  - Estimating emission time →highly variable sources
  - Disentangling LIV from source-intrinsic effects → multi-source (multi-instrument)

$$\Delta t = t \cdot \Delta v_\gamma \simeq S \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{\mathrm{QG,n}}^n} \times D_n(z)$$

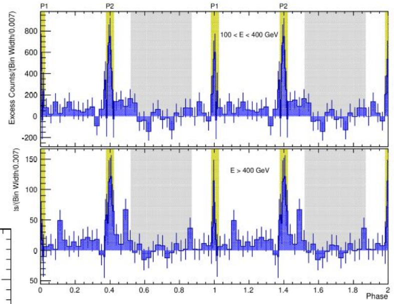
GRB 190114C (MAGIC Coll. 2020)



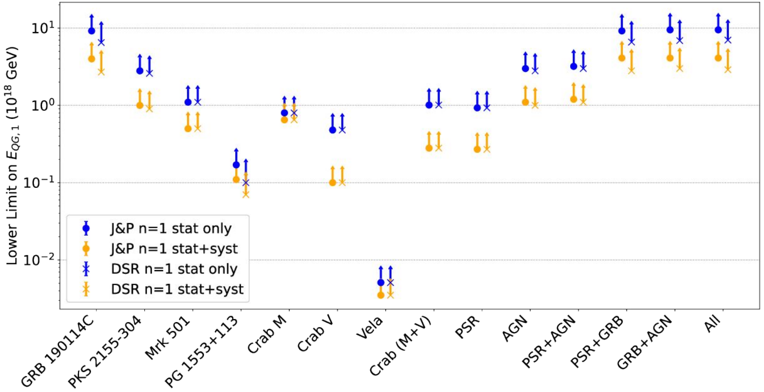
PKS 2155 (H.E.S.S. Coll. 2011)



Crab pulsar (MAGIC Coll. 2016)



Bolmont+ 2022



Time delays

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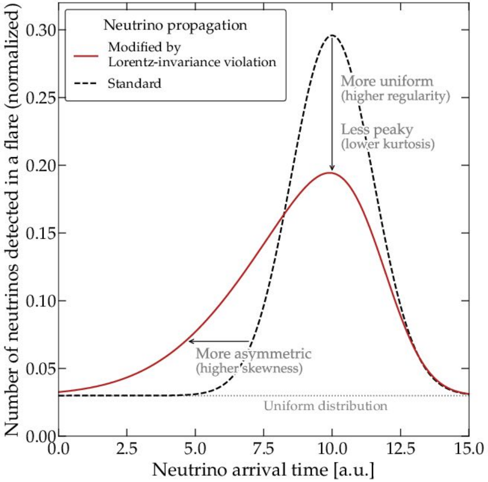
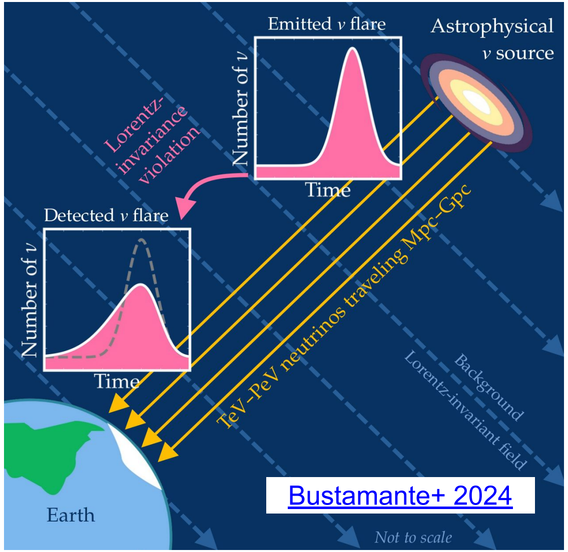
$$\Delta t = t \cdot \Delta v_\gamma \simeq S \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{\mathrm{QG,n}}^n} \times D_n(z)$$

- Based on astrophysical neutrinos time of flight
- Challenges:
  - Very low statistics
  - Difficult association with sources → multi-messenger observations
    - Very rare and unreliable
  - Disentangling LIV from source-intrinsic effects
  - Energy reconstruction for most energetic events





Bustamante+ 2024

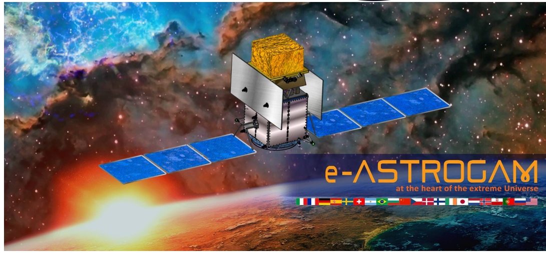
Birefringence

- Based on gamma rays and/or neutrinos
- Energy-dependent rotation of the polarization vector of linearly polarized photons

$$\Delta\psi = (E_1^2 - E_2^2) L_z^{(5)} \sum_{\substack{j=0\ldots3 \\ m=-j\ldots j}} Y_{jm}(\theta_k, \varphi_k) k^{(5)}_{(V)jm}$$

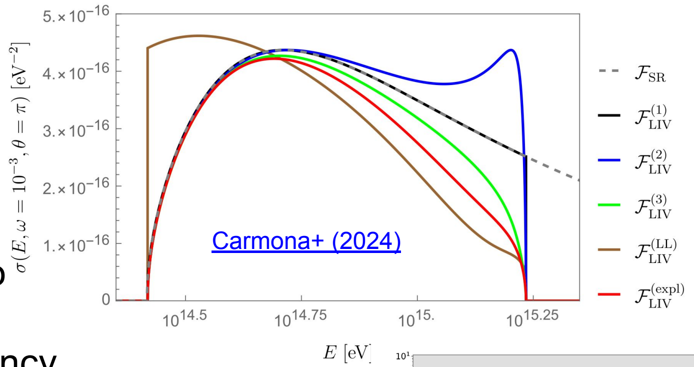
see e.g. [Kislat & Krawczynski (2017)]

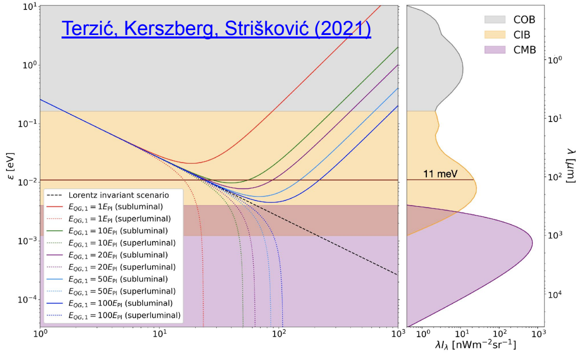
- Manifested as:
  - Depolarization of signal from astrophysical sources
  - Super/sub luminal behaviour dependent on polarization
- Very sensitive effect
- Measured on radio – soft gamma rays
  We cannot measure polarization of VHE gamma rays



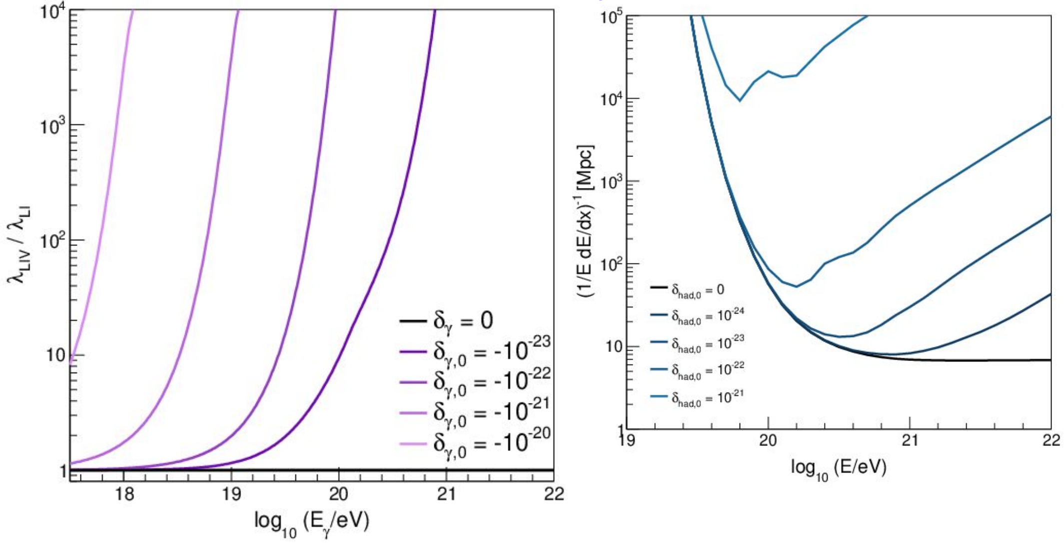
Modified reactions

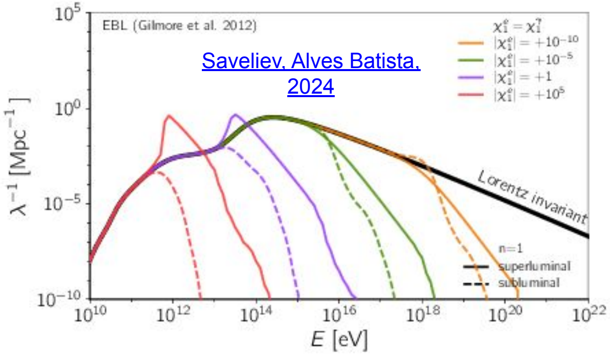
- Based on cosmic ray, gamma ray, and neutrino interactions and stability
  - Increased/decreased universe transparency
  - Superluminal massless particle decay
  - Vacuum Čerenkov emission





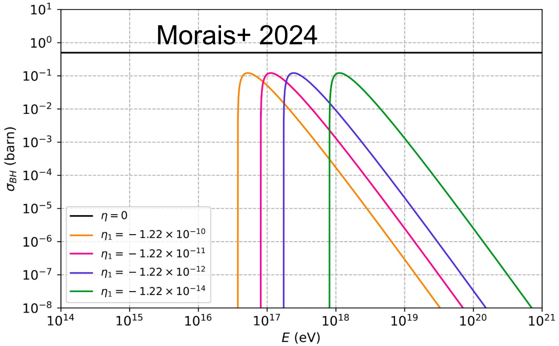
Pierre Auger Collab. 2022

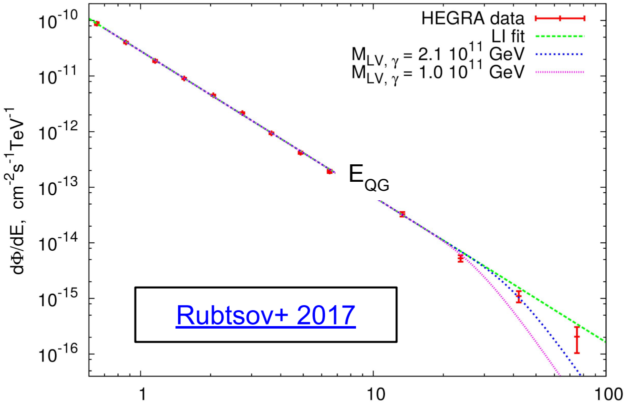


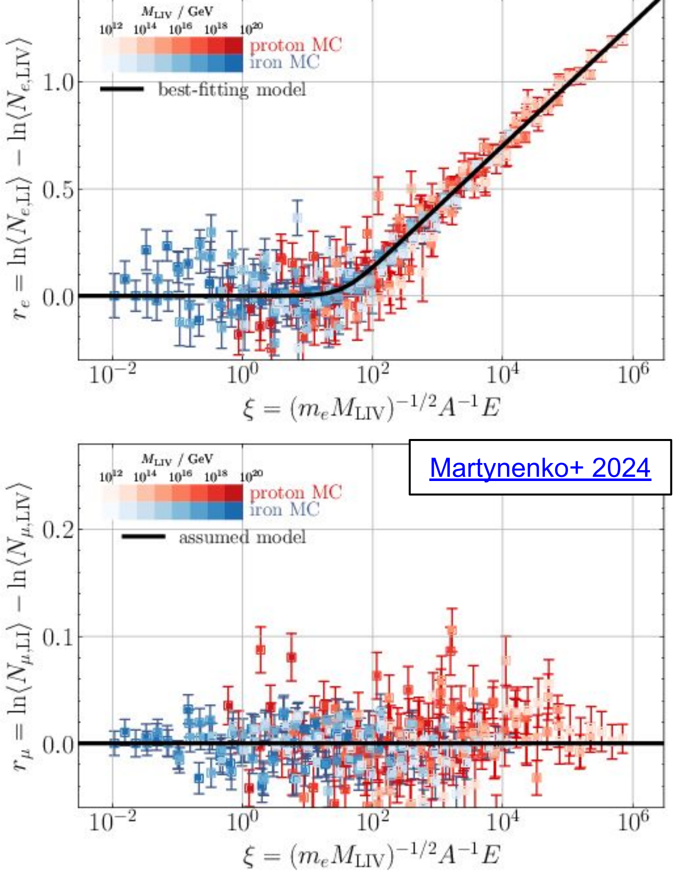


Modified reactions

- Based on cosmic ray, gamma ray, and neutrino interactions and stability
  - Modified particle shower development — one thing in common for all detectors (!)

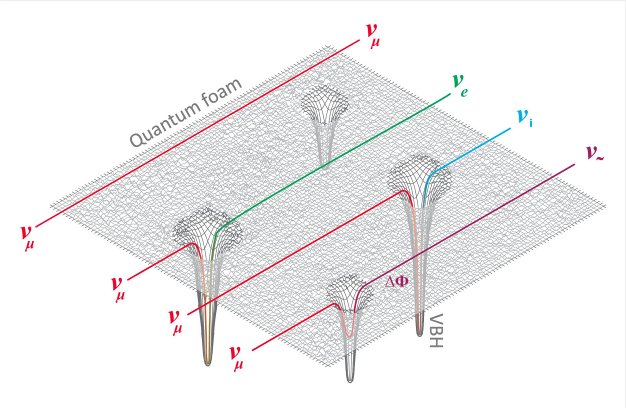




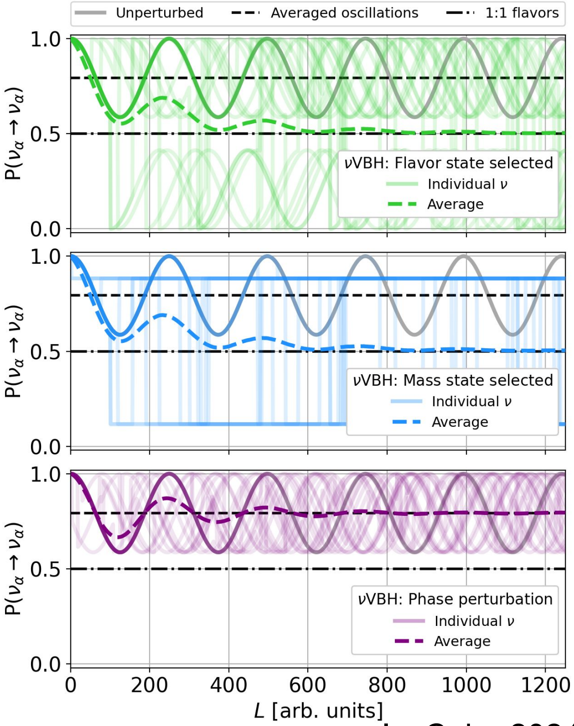


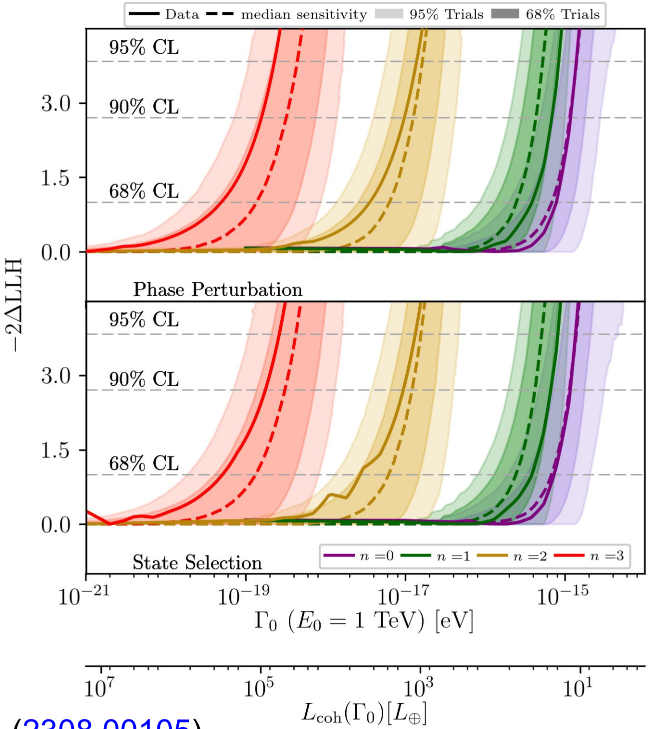
Decoherence tests

- Based on atmospheric neutrino flavour oscillations



$$\Gamma(E_\nu) = \Gamma_0 \left(\frac{E_\nu}{E_0} \right)^n$$





IceCube 2024 (2308.00105)

n	Phase Perturbation Γ_{90}	State Selection Γ_{90}
0	$1.18 \cdot 10^{-15}$ eV	$1.17 \cdot 10^{-15}$ eV
1	$6.89 \cdot 10^{-16}$ eV	$6.67 \cdot 10^{-16}$ eV
2	$9.80 \cdot 10^{-18}$ eV	$9.48 \cdot 10^{-18}$ eV
3	$1.58 \cdot 10^{-19}$ eV	$1.77 \cdot 10^{-19}$ eV

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All tests performed on single messenger type

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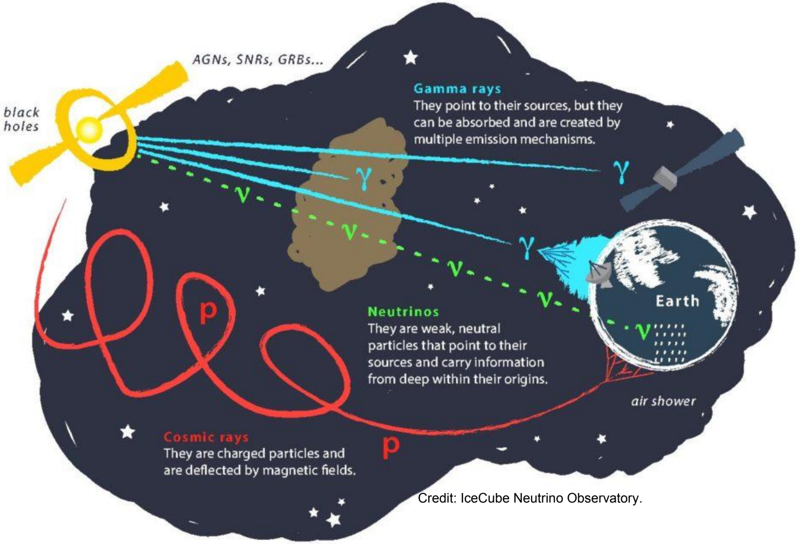
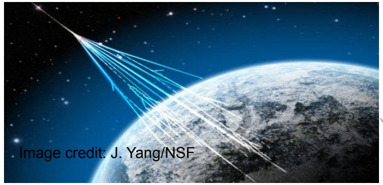
See: QG-MM Catalogue for a census of measurement results

Messenger pros & cons

- Cosmic rays
  - Highest energies
  - Highest fluxes
  - Charged →trajectories deflected by magnetic fields
- Gamma rays
  - Straight propagation from the source
  - Easily detectable
  - Lowest energies
- Neutrinos
  - Straight propagation from the source
  - Probe interiors of sources
  - Notoriously difficult to detect
  - Poor angular resolution

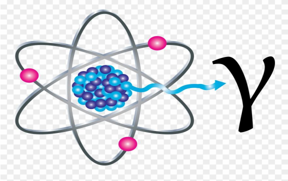


Credit: IceCube Neutrino Observatory.



Cosmic rays: $E_{max} \sim 3.2 \times 10^{20}$ eV

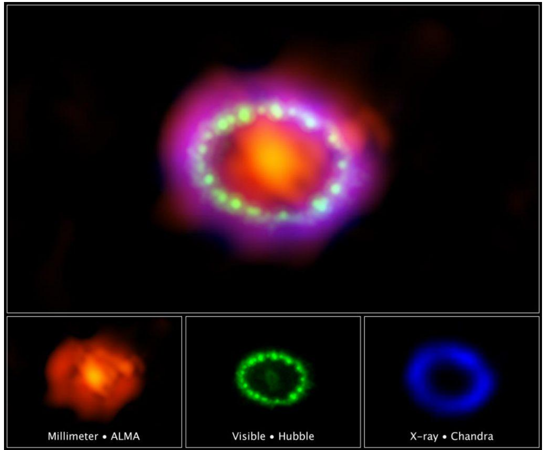
Neutrinos: $E_{max} \sim 2.2 \times 10^{17}$ eV



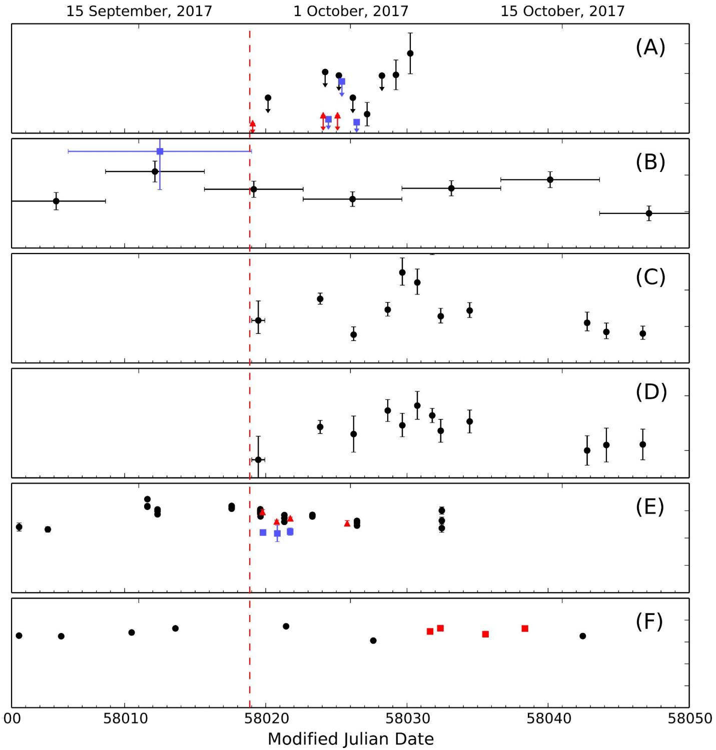
Gamma rays: $E_{max} \sim 1.4 \times 10^{15}$ eV

Multi-messenger observations

- Very hot topic in astrophysics
- Extremely rare:
  - SN1987A — Supernova in LMC
    25 ν detected within 13 sec
  - TXS 0506+056 — first AGN with quasi-simultaneous detection in EM and neutrino sector



Detection: Ice Cube Coll. et al. (2018)
Emission modelling: MAGIC Coll. (2018)



WG2 - Who is Who

Group ID	Research topics	Location / Affiliation	Group members	Additional info (contactt, webpage, ...)
UNIRI-Wrinkle	LIV and DSR with VHE gamma rays, involved in CTAO-LST, MAGIC, SWGO experiments.	University of Rijeka, Croatia & J. J. Strossmayer University of Osijek, Croatia	Filip Reščić, Jelena Strišković, Tomislav Terzić	https://wrinkle.uniri.hr
Paris-SU	Energy-dependent time delays with VHE gamma-ray sources, including LIV/DSR + Source intrinsic delays modeling in blazar flares. CR propagation. HESS, CTAO, GRAND experiments.	Sorbonne Université, Paris, France CNRS	Rafael Alves Batista, Julien Bolmont, Daniel Kerszberg, Ugo Pensec	
Lodz	LIV with VHE gamma rays (LST, but also MAGIC). Source intrinsic effects	University of Lodz, Poland	Julian Sitarek, Alberto Rosales de Leon, Grzegorz Borkowski	
Kings	LIV and other QG-motivated physics tests with astrophysical messengers	King's College London	TPPC: Nick Mavromatos, Mairi Sakellariadou EPAP: Teppei Katori	Theoretical Particle Physics and Cosmology (TP https://www.kcl.ac.uk/research/theoretical-particl Experimental Particle and Astroparticle Physics (https://www.kcl.ac.uk/research/experimental-pa
ECAP-FAU	QD and LIV with neutrinos	Erlangen Centre for Astroparticle Physics - Friedrich-Alexander-Universität Erlangen-Nürnberg	Alba Domi, Lukas Hennig, Rodrigo Guedes Lang	
NBI	Tests of LIV with high-energy neutrinos	Niels Bohr Institute, University of Copenhagen	Mauricio Bustamante, Bernanda Telalovic	https://mbustamante.net/
LAPP	LIV with VHE gamma rays - CTAO-LST and combination in gammaLIV-WG	Laboratoire d'Annecy de physique des particules, Annecy, France CNRS	Sami Caroff, Cyann Plard	
DCU	Broadband studies of gamma-ray binaries and other systems with extreme accelerators.	School of Physical Sciences, Dublin City University, Ireland	Masha Chernyakova, Iuliia Shebalkova (PhD student), Aoife Kiera Finn Gallagher (Ms student)	
UnivAQ & GSSI	LIV in CR and photon propagation in extragalactic space and in the development of showers in the Earth atmosphere	University of L'Aquila and Gran Sasso Science Institute	Denise Boncioli, Francesco Salamida, Caterina Trimarelli	denise.boncioli@univaq.it, francesco.salamida@
QuGraPheno	Beyond Special Relativity (DSR and LIV): theory and phenomenology	University of Zaragoza, Spain University of Burgos, Spain	José Manuel Carmona, José Luis Cortés, Maykoll Reyes, José Javier Relancio, Justo López, Filip Reščić	https://qugraphenozaragoza.wordpress.com/

Check WG2 session: Tuesday AL

				12:40 - 14:00
14:00	**When astroparticles arrive at Earth - new ways for investigating LIV**	*Denise Boncioli*	*Amphithéâtre Charpak, LPNHE*	14:00 - 14:40
	New constraints on Lorentz invariance violations from H.E.S.S. observations of the blazar PKS 2155-304 flaring period ...	*Ugo Pensec*		
15:00	**Assessing SWGO Sensitivity to Lorentz Invariance Violation through Transparency Studies**	*Filip Reščić*	*Amphithéâtre Charpak, LPNHE*	15:00 - 15:20
	Neutrino oscillations and decoherence: insights from microscopic models	*Renata Ferrero*	*Amphithéâtre Charpak, LPNHE*	15:20 - 15:40
	Advancing superluminal neutrino constraints with UHE events	*José Manuel Carmona*	*Amphithéâtre Charpak, LPNHE*	15:40 - 16:00
16:00	**Testing in-vacuo dispersion with GRB neutrinos**	*Domenico Frattulillo*	*Amphithéâtre Charpak, LPNHE*	16:00 - 16:20
	Coffee Break			

BridgeQG – WG2 – Tasks

- Tasks (see CA23130 MoU):
  - To establish standards for data analysis in astrophysical searches for effects of QG,
  - To develop a base for multi-messenger data analysis for searches for signatures of QG,
  - To search for signatures of QG expected in both regimes (close collaboration with WG4 and WG5),
  - To establish and maintain close contacts with the relevant experimental collaborations.

BridgeQG – WG2 – Opportunities

1) **Within WG2**
   - Develop and improve strategies for MM observations
     - Not much room for improvement
   - Develop analysis procedures to be ready in case of another MM observation.
     - E.g. LIVelihood for gamma rays
   - Find common ground for testing using different messengers.
     - E.g. Each experimental technique is based on particle shower development
   - Combine data from different experiments to mitigate systematic uncertainties unique to each (e.g. IceCube & KM3NeT; γ-ray LIV WG)
     - Future online WG2 meetings: discussion on the main sources of uncertainties in individual QG tests
       Can these be mitigated by combining QG tests through different QG effects or even messengers?

BridgeQG – WG2 – Opportunities

2) **In collaboration with WG1 understand the following**
   - Experimental searches often rely on phenomenological models: how can results constrain theoretical QG models?
   - Are there additional possible effects of QG that could be tested using our data (other than the ones already tested)?
   - Is there a way of combining results from different experiments and tests to test a single specific model or framework?
   - What are the expected consequences of LIV (or other models/frameworks)
     - E.g. Do we expect the ν flavour ratio to change at emission?
     - Would that affect the γ ray emission at the same time?
     - What about secondary ν and γ from UHECR interaction with background fields?
   - Can a single QG effect produce multiple outcomes, e.g., LIV affecting both neutrino propagation speed and oscillations, or a combination of LIV + QD?
   - See talk by D. Mattingly in WG2 online meeting from 24/04/2025

BridgeQG – WG2 – Opportunities

3) **In collaboration with WG4 and WG5**
   - Identify signatures of QG expected in both regimes (high and low energy)
   - Develop a way to combine results of experiments in different regimes.