European Strategy for Particle Physics

Plenary Session / **Neutrinos and Cosmic Messengers**

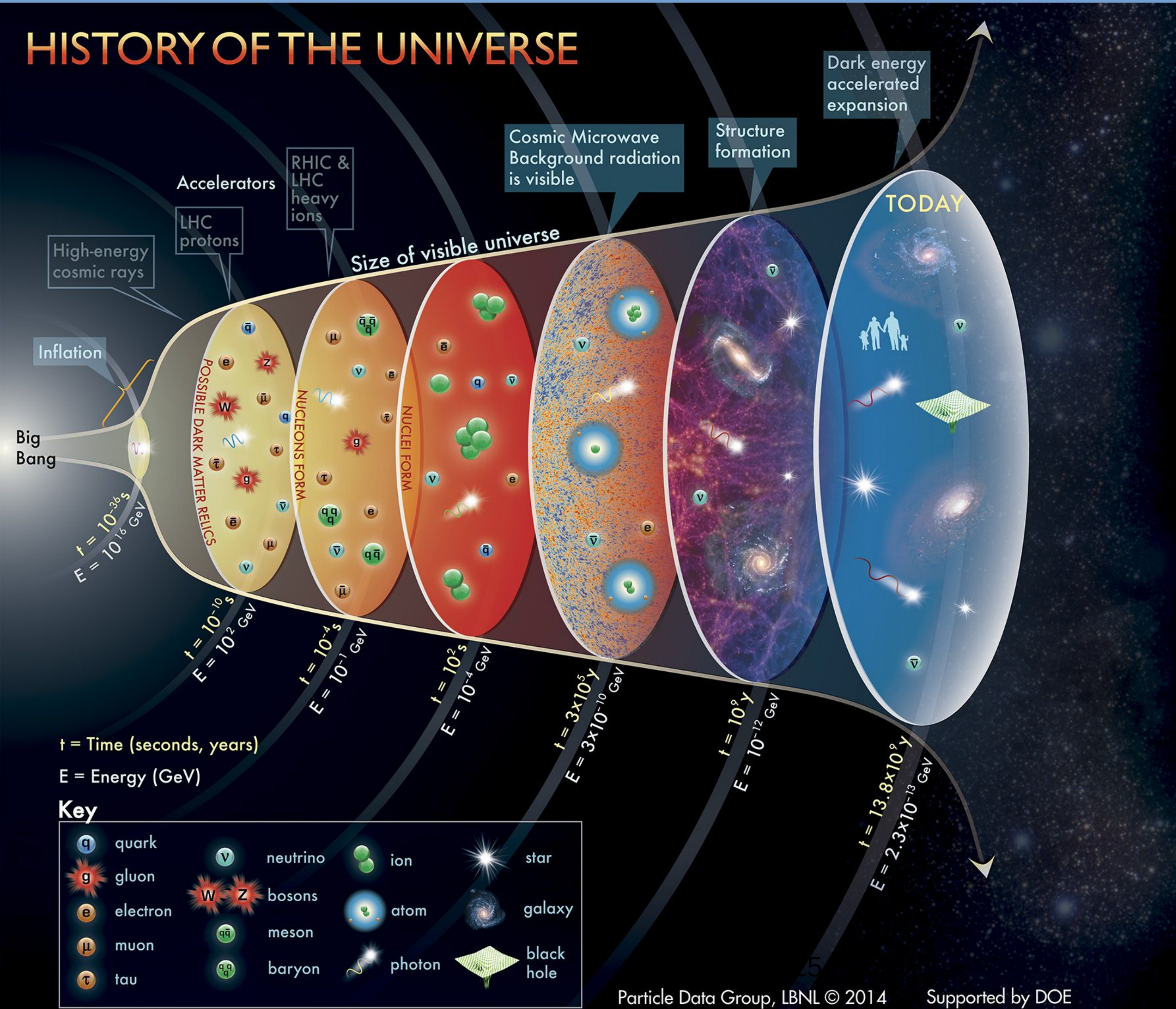
Cosmic Messengers for Particle Physics

Valerie Domcke (CERN)

On behalf of the Neutrinos and Cosmic Messengers Working Group

Based on inputs from
IceCube #236, KM3NeT #249, P-One #53, TAMBO #272, Pierre Auger #201,
LIGO-Virgo-KAGRA #122, LISA #164, Einstein Telescope #198, TVLBAI #37,
Quantum Sensing #260, CMB #252, XSCRC #89, APPEC #276, EuCAPT #215

Cosmic Relics



Cosmic Relics

Messengers of our cosmic history:

Matter:

- Light element abundances from Big Bang Nucleosynthesis (BBN)
- Matter-antimatter asymmetry from baryogenesis
- Large scale structure (LSS)
- Dark matter (DM)

Radiation:

- Cosmic microwave background (CMB) from photon decoupling
- Cosmic neutrino background (CνB) from neutrino decoupling (N_{eff})
- Gravitational Waves (GWs)
- Magnetic fields? BSM relics?

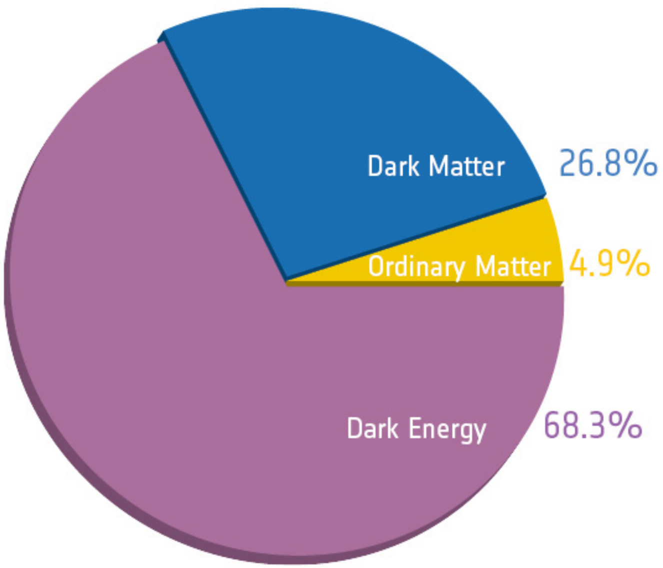
Production and evolution governed by laws of particle physics and gravity at high energies

Present day properties allow to infer information on BSM scenarios

Status ΛCDM

The cosmological concordance „standard“ model:

SM + GR = ΛCDM



- Phenomenologically very successful
- We have reached the level of precision test *at different scales* → true test of ΛCDM
- Some tensions (H_0, σ_8, Ω_m) and challenges (systematics, …)
- Sensitive to neutrino mass scale (testing neutrino mass ordering), extra radiation,...
- More data coming !

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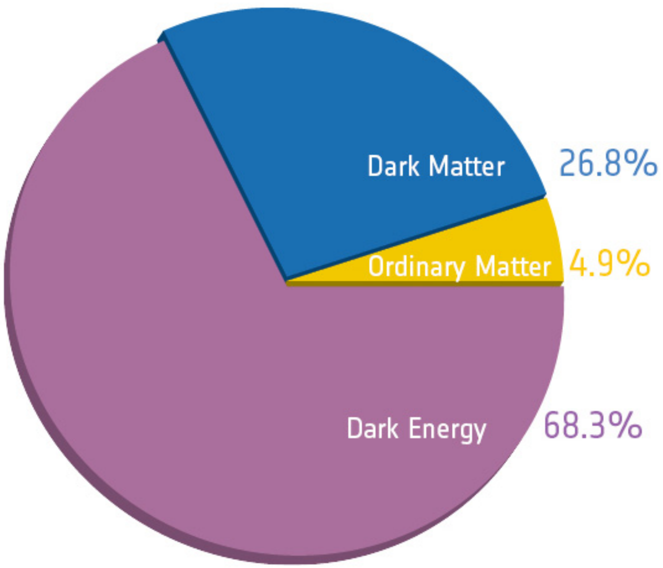

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Astrophysical messengers

Astrophysical environments as laboratories
for fundamental physics:

- Cosmic rays (CRs)
- Neutrinos
- Electromagnetic (EM) radiation
- Gravitational Waves (GWs)

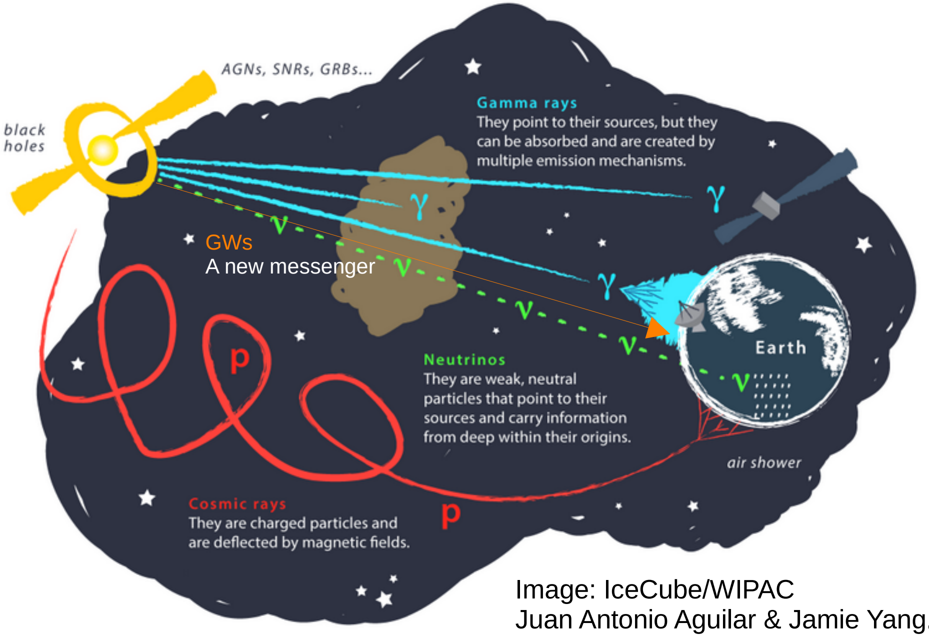

Image: IceCube/WIPAC
Juan Antonio Aguilar & Jamie Yang.

- Probes of extreme environments in and around stars and their remnants
- Products of cosmic accelerators
- Probes of galactic and extragalactic environments (propagation)
- Travel over large length- and time scales: sensitive to rare processes

Probes of particle physics at high energies and/or low event rates
(with challenges from astrophysical modeling)

Outline

Astrophysical messengers

- Electromagnetic Radiation
- Neutrinos
- (Charged) Cosmic Rays
- Gravitational Waves

Cosmic relics

- Cosmic Microwave Background
- Large Scale Structure

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Astrophysical messengers

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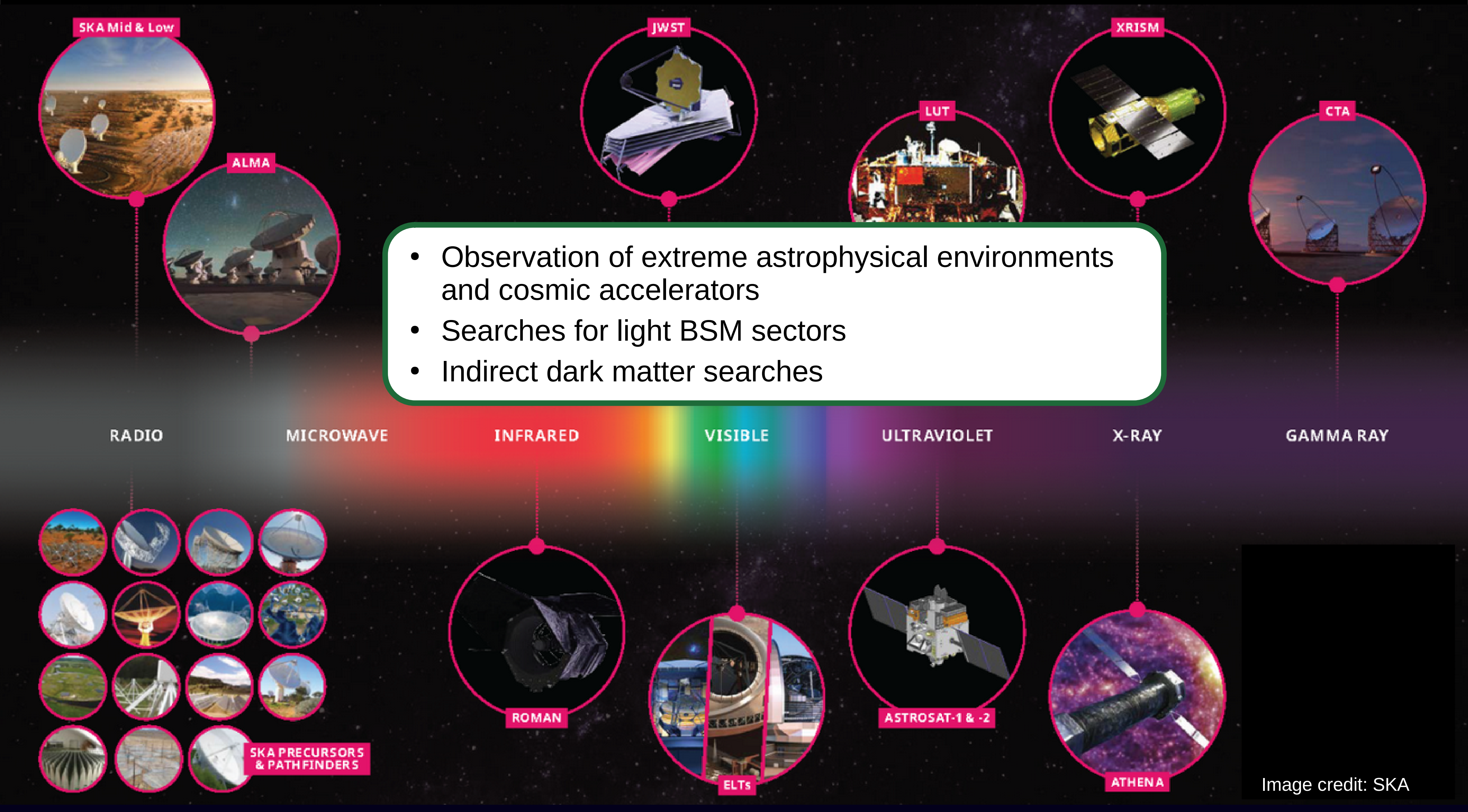
Electromagnetic radiation



- Observation of extreme astrophysical environments and cosmic accelerators
- Searches for light BSM sectors
- Indirect dark matter searches

Image credit: SKA

A multimessenger view of our galaxy

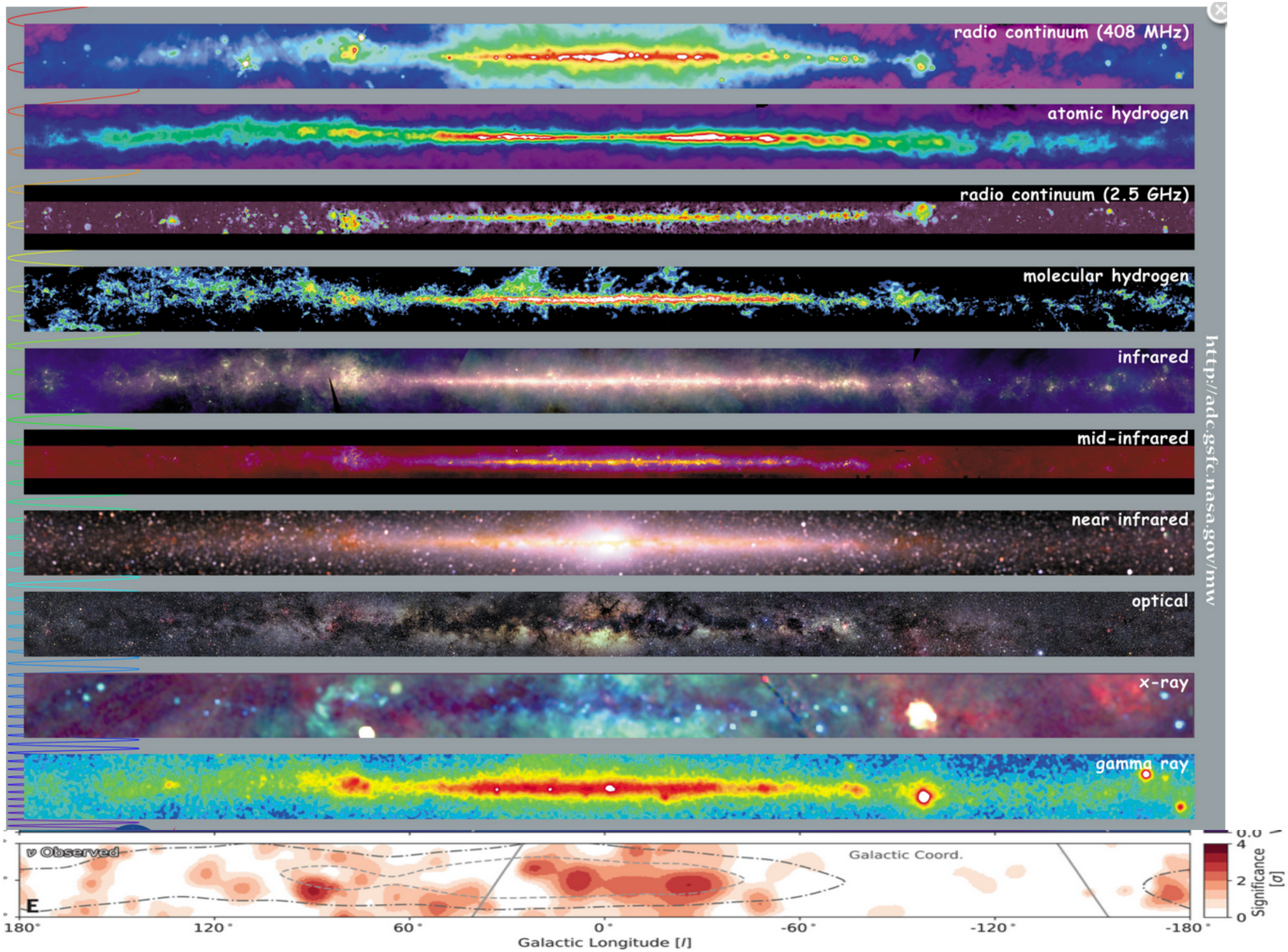
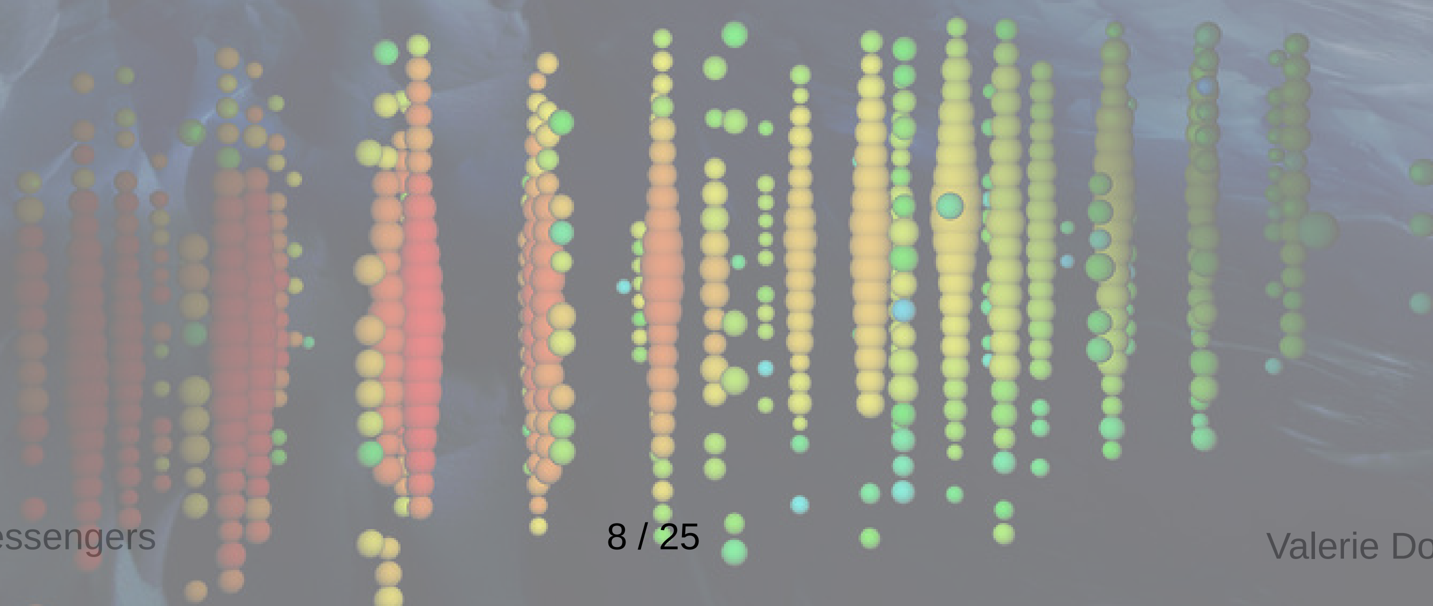


Image credit:
NASA/CSFC
IceCube

High-energy neutrinos

- Galactic, cosmic, supernova neutrinos, AGNs, Blazars,..
- Detect high-energy neutrinos to study extreme cosmic accelerators, origin of cosmic rays.
- Sub-degree angular resolution → multimessenger astronomy
- New physics searches: DM, ν-interactions, Lorenz invariance violation (LIV), …



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Current water-Cherenkov telescopes @ GeV to PeV (Global Neutrino Network):

- IceCube (South Pole, 7-string in-fill upgrade to be completed by 2026)
- KM3Net ORCA/ARCA (Mediterranean Sea, 20/30% deployed, full deployment by 2030)
- GVD (Baikal lake, Russia, 0.5 km^3 deployed and growing)

Proposed water-Cherenkov telescopes :

- IceCube Gen2 (10 x IceCube volume, construction could begin 2027/28)
- P-ONE (Pacific Ocean Neutrino Experiment, first stage under construction)
- TRIDENT/HUNT/NEON (next generation)

Other (proposed) detection concepts @ PeV – EeV:

Radio, optical Cherenkov, fluorescence, particle showers, radar

Synergies:

- Forward neutrino detectors at LHC (FASER, SND) : x-section for neutrino production
- Instrumentation, trigger and data acquisition systems, simulation and reconstruction software

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arxiv: 2203.05591

Experiments	Phase & Online Date	Energy Range	Site	Flavor: Tau	Flavor: All Flavor	Technique: Optical / UV	Technique: Radio	Technique: Showers	Neutrino Target: H_2O	Neutrino Target: Atmosphere	Neutrino Target: Earth's limb	Neutrino Target: Topography	Neutrino Target: Lunar Regolith	Geometry: Embedded	Geometry: Planar Arrays	Geometry: Valley	Geometry: Mountains	Geometry: Balloon	Geometry: Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediteranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

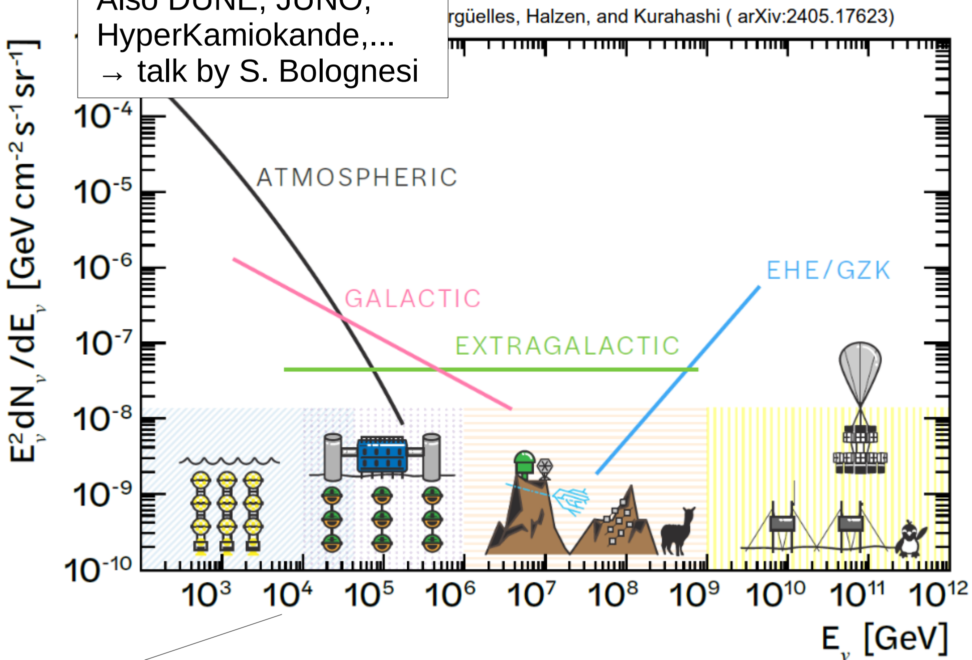
Operational	Date full operations began
Prototype	Date protoype operations began or begin
Planning	Projected full operations

Synergies:

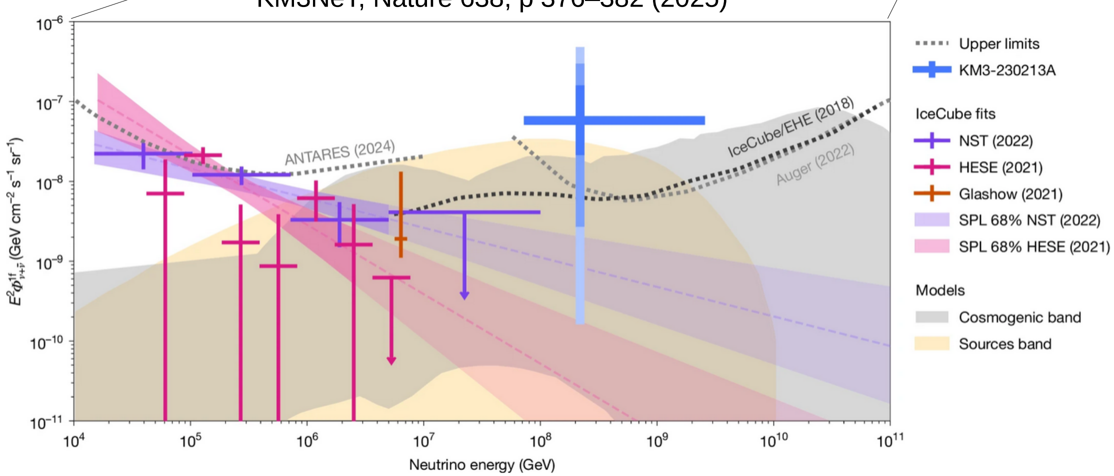
- Forward neutrino detectors at LHC (FASER, SND) : x-section for neutrino production
- Instrumentation, trigger and data acquisition systems, simulation and reconstruction software

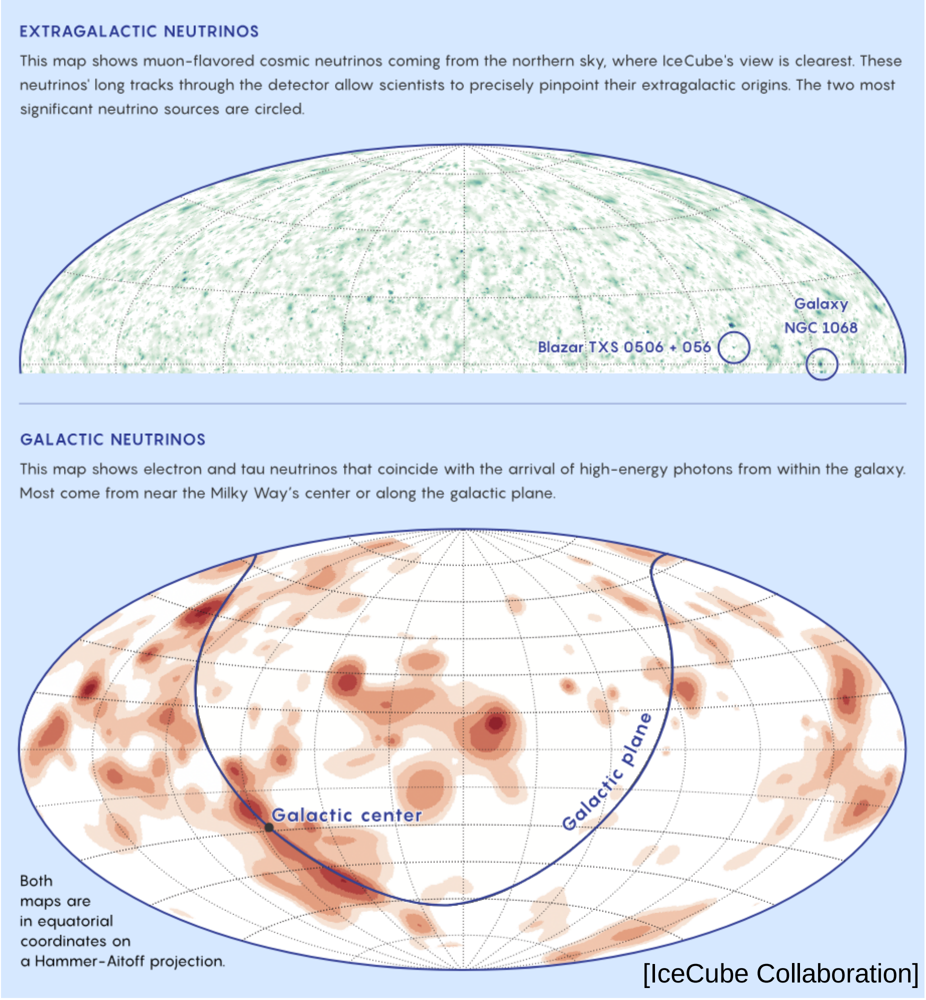
The sky in neutrinos

Also DUNE, JUNO, HyperKamiokande,...
→ talk by S. Bolognesi



KM3NeT, Nature 638, p 376–382 (2025)



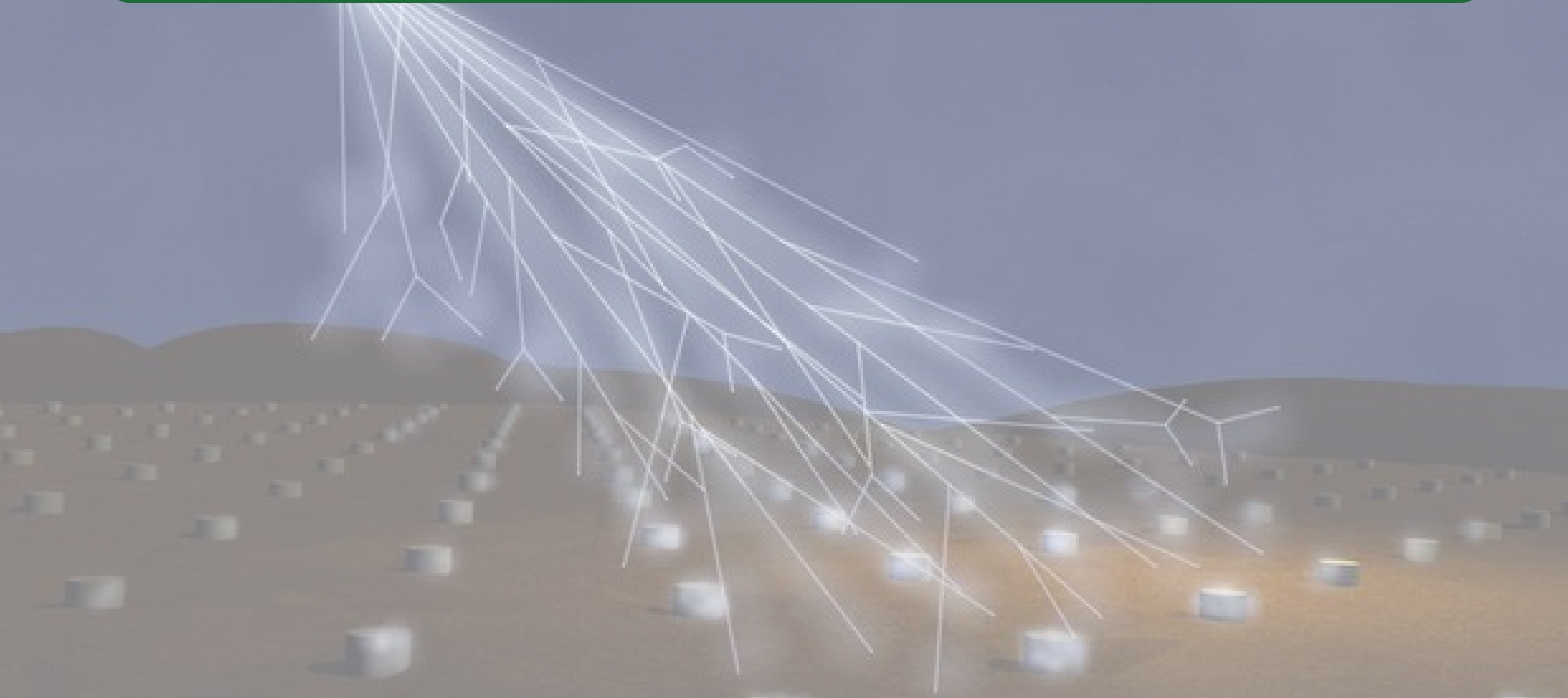


Cosmic Rays

Probe of extreme environments

→ probe of galactic and extragalactic astrophysical sources, interaction with interstellar medium

→ particle physics at very high energies & rare processes



Cosmic Rays

Probe of extreme environments
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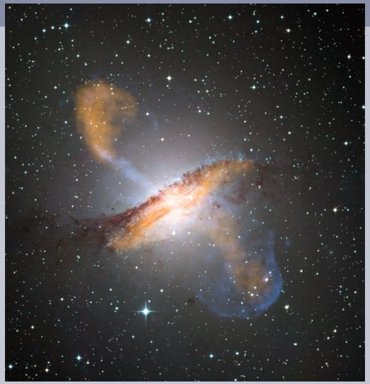
→ particle physics at very high energies & rare processes

Current instruments:

- Direct detection (DD) of galactic CRs (< 10^6 GeV) taking data until 2030: AMS, CALET (ISS), DAMPE (satellite), HELIX, GAPS (balloon)
- Indirect detection (ID) of extragalactic CRs (> 10^6 GeV): Pierre Auger Observatory (Argentina), Telescope Array (USA)



ESO: Centaurus A (AGN)

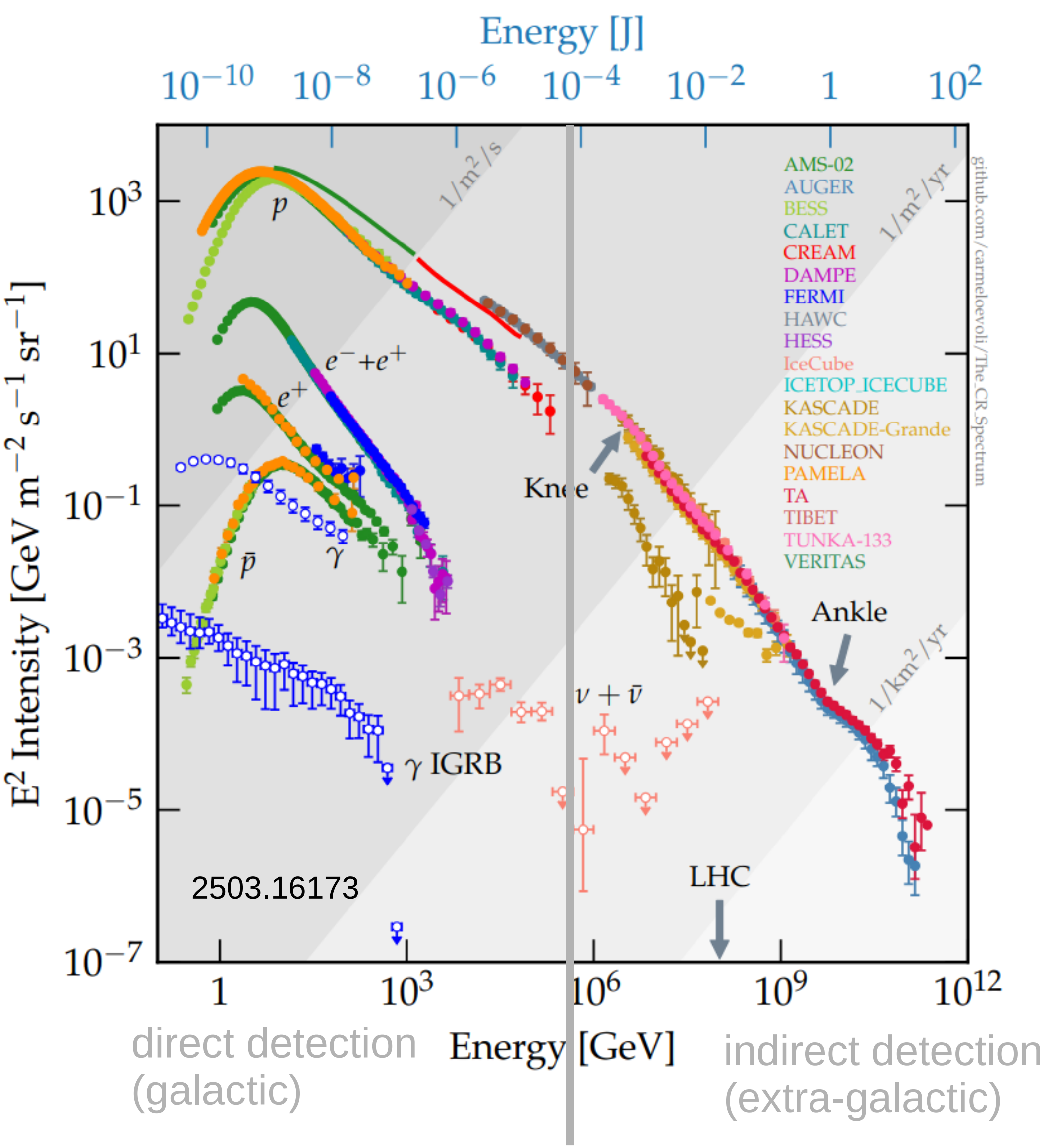
Future instruments:

- DD (from 2027-2028): HERD (China Space Station), TIGER-ISS
- ID (2030+): Giant Radio array for Neutrino Detection (GRAND), Global cosmic ray observatory (GCOS)

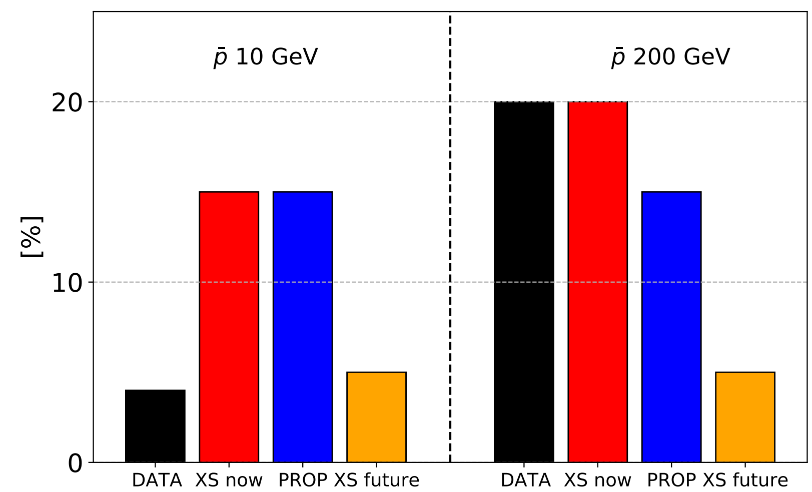
Synergies:

- Indirect DM searches: antimatter particle fluxes in CRs
- DD: Fixed target experiments (e.g. LHCb-SMOG, AMBER (COMPASS), NA61/SHINE (NA49), n-TOF) provided key input to reduce cross-section uncertainties in galactic CR propagation (spallation)
- ID: Accelerator data (TOTEM, FASER, SND, Forward Physics Facility) for hadronic interactions in air showers, light ion runs (p-O) at LHC, Monte-Carlo simulations

Cosmic Rays



X-sections as the limiting factor
(e.g. antiproton production, AMS):



Particle	Reaction	Measurement	$\sqrt{s}$	Sought precision
$\bar{\mathrm{p}}$	$\mathrm{p}+\mathrm{p}\to\bar{\mathrm{p}}+\mathrm{X}$	σ_{inv}	5 to 100 GeV	$<3\%$
	$\mathrm{p}+\mathrm{He}\to\bar{\mathrm{p}}+\mathrm{X}$			$<5\%$
	$\mathrm{p}+\mathrm{p}\to\bar{\Lambda}+\mathrm{X}$			$<10\%$
	$\mathrm{p}+\mathrm{He}\to\bar{\Lambda}+\mathrm{X}$			$<10\%$
	$\mathrm{p}+\mathrm{p}\to\bar{\mathrm{n}}+\mathrm{X}$			$<5\%$
	$\mathrm{p}+\mathrm{n}\to\bar{\mathrm{p}}+\mathrm{X}$			$<5\%$

sought precision to match current %-level measurements

Gravitational waves

- Strong-field tests of gravity and cosmology
- Test early universe and TeV-scale particle physics via SGWBs
  (first order EWPT, topological defects in GUTs,…)
- Nuclear physics from neutron star mergers (QCD phase diagram..)

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Current instruments:

- LIGO/Virgo/Kagra network ~ 100 Hz (First detection 2015, currently in run O4b, O5 to start 2028)
- Pulsar timing arrays ~ nHz: EPTA+InPTA, NanoGrav, PPTA, CPTA, Meerkat (First evidence for SGWB)

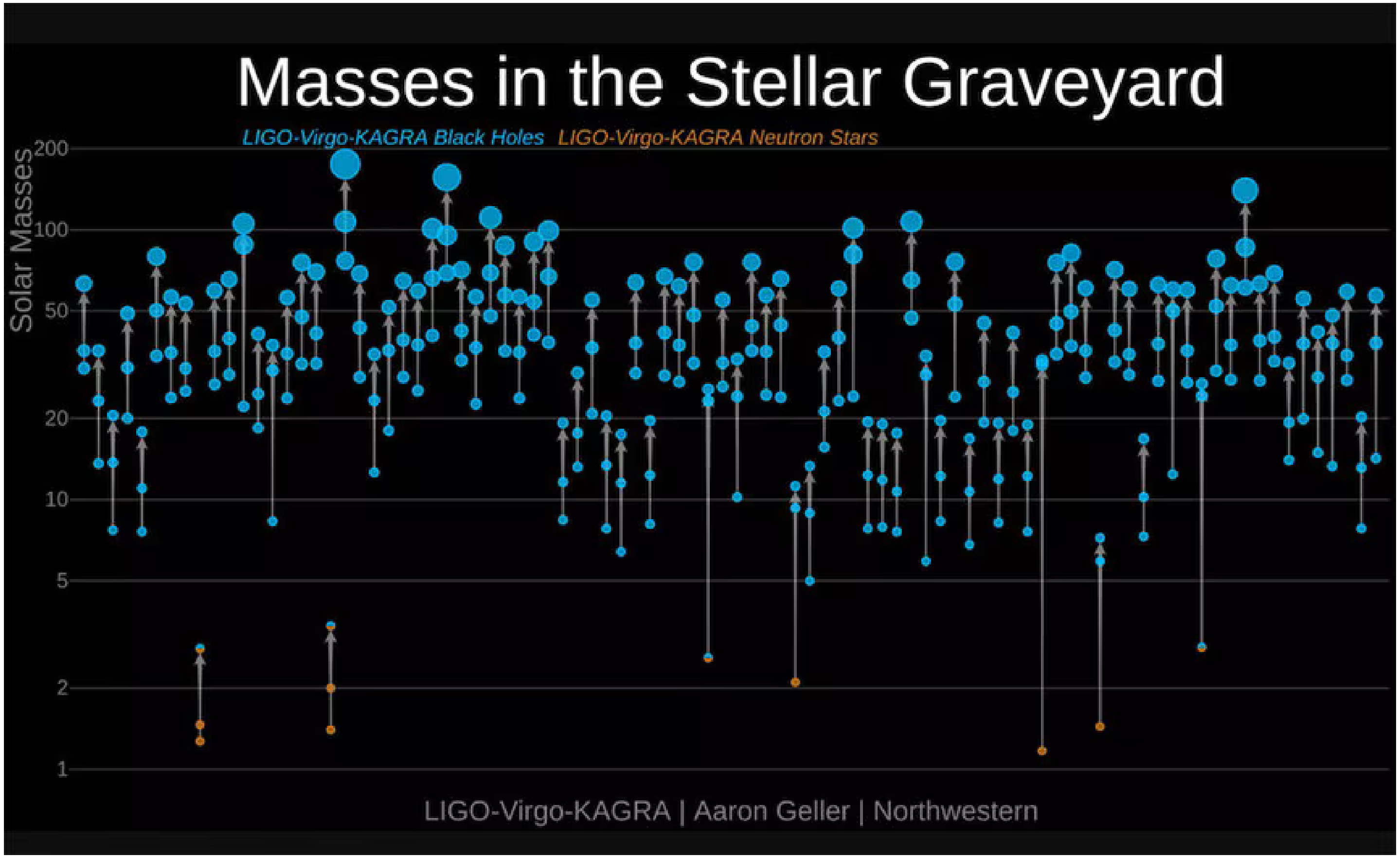
Future/Proposed instruments:

- Continuous upgrades of PTAs, in particular SKA
- ESA mission LISA, launch 2030s, ~ mHz
- Einstein Telescope (Europe), Cosmic Explorer (US) ~ 100 Hz
- Extending spectral coverage: Astrometry, atom interferometers, R&D for high frequency GW searches,..

Synergies:

- Probe of particle physics at extremely high energies (SGWBs)
- Complementary probe of the weak scale (LISA)
- Vacuum system, civil and technological infrastructures (ET)
- Computing and data analysis, theoretical tools from PP applied to GW waveform computations

Gravitational waves



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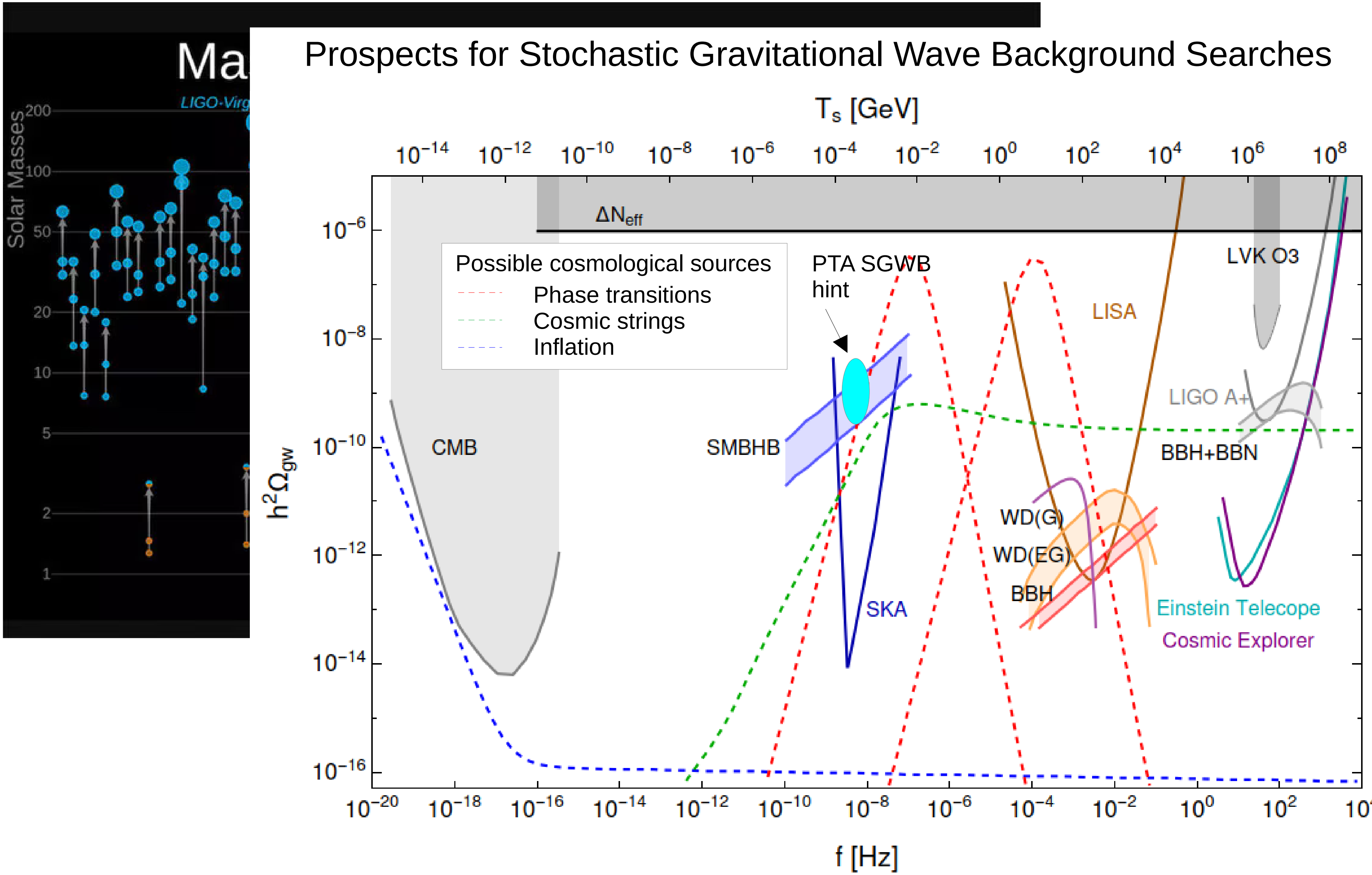

Cosmic microwave background

- Probe ΛCDM and the dark universe (dark matter, dark energy, synergies with LSS surveys)
- Probe cosmic inflation (B-modes)
- Probe light relics (cosmological plasma, propagation since last scattering surface)
- Probe neutrino mass scale

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Current instruments:

- ESA satellite Planck (completed)
- Ground-based: ACT, SPT, Bicep/Keck, Simons Observatory
- Balloon: SPIDER, LSPE (completed)

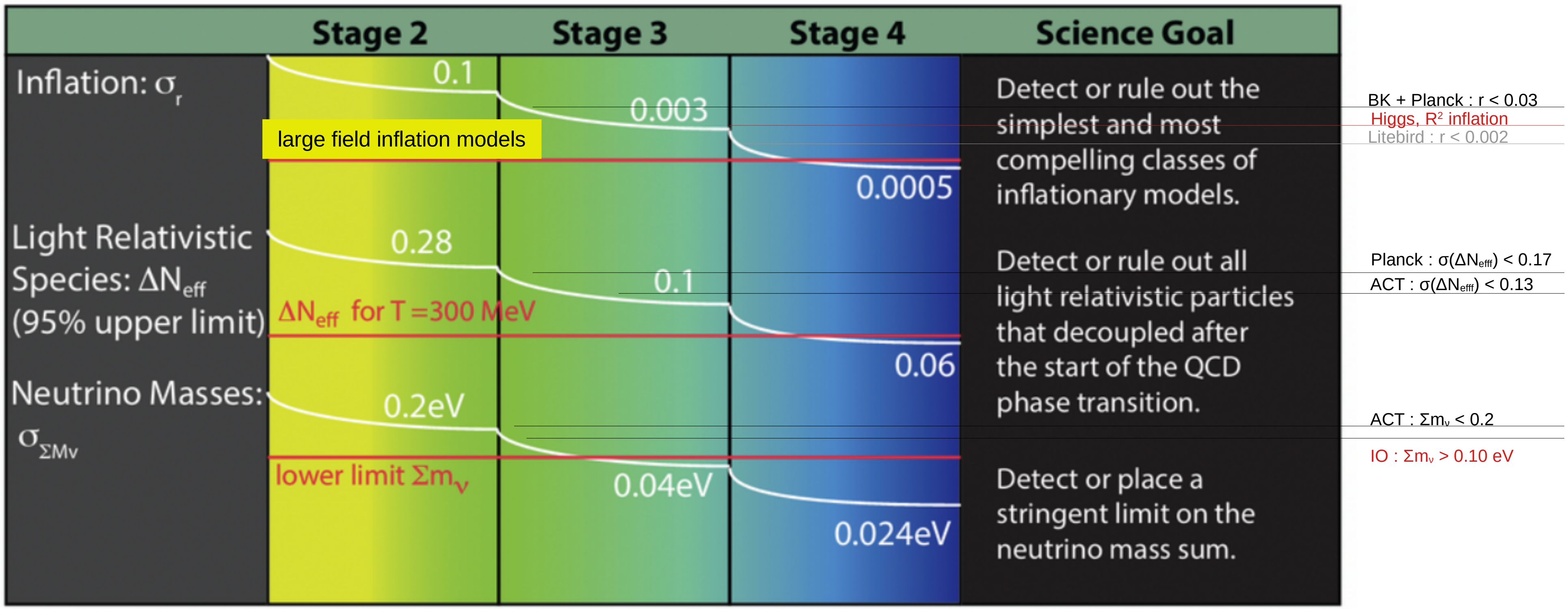
Future instruments (next decade):

- JAXA satellite mission LiteBIRD
- Ground-based: CMB S4
- *COBE-FIRAS successor overdue (proposals: COSMO, BISOU, TMS, PIXIE, FOSSIL,..)*

Synergies:

- Sensor and readout development (ECFA DRD5 initiative, low temperature detectors + electronics R&D)
- Design and development of large cryogenic platforms/infrastructures, for deployment & detector tests
- Radiation-hardness assurance utilizing CERN's accelerator facilities and expertise

Cosmic microwave background



see Kevork Abazajian et al. CMB-S4 Science Case, Reference Design, and Project Plan. 2019

You are here

Large scale structure

Test of cosmic inflation paradigm
Test of ΛCDM (eg dark energy, dark matter, neutrino mass)
Cross-correlation with CMB (and GWs)

Euclid, 2025

Current instruments (galaxy cluster counts):

- DESI (Arizona US, deep field, spectroscopic, ongoing: DR2 released 2025)
- Euclid (ESA mission, all-sky, photometric, launched 2023, DR1 expected 2026)
- SPHEREx (NASA mission, all-sky, spectroscopic, targeting f_{NL} at large scales, launched 2025)

Upcoming instruments (galaxy cluster counts):

- Vera Rubin Observatory (Chile, deep field, photometric, first light expected July 2025)
- Roman Telescope (NASA mission, all-sky + deep field, spectroscopic, to be launched 2027)

Plus several other tracers:

- Lyman-α (HETDEX), 21 cm (HERA/Meerkat → SKA), Supernovea (DES), weak lensing of galaxies (HSC → Euclid, Vera Rubin) + Distance ladder H_0 measurements (complementary to CMB)

Synergies:

- Theoretical tools (EFTs)
- Complementary searches for new physics

Outlook

Rich observational program in the next few years. Full science exploitation requires

- Multimessenger analyses, synergies between observatories and particle physics
- Dialog between astroparticle and particle physics: Theory and R&D

Complementarity and synergies with particle physics, e.g:

- Sensor R&D for particle and astroparticle detectors. Desire for stronger European coordination, centralized technical support.
- Infrastructure and management of large facilities: cyrogenic platforms, vacuum systems, detector testing, radiation hardness testing,...
- Many interdisciplinary physics cases: neutron stars, x-sections for cosmic rays, dark matter searches, probing the early universe

Complementary ways to probe particle physics at high energies and small couplings

Backup

High energy gamma rays : instruments

- Observation of extreme astrophysical environments
- Indirect dark matter searches

Current instruments:

- Fermi-LAT satellite (20 MeV – 300 GeV)
- Water Cherenkov Telescope HAWC (100 GeV – 50 TeV)
- Atmospheric Cherenkov Telescopes HESS, MAGIC, VERITAS (20 GeV – 100 TeV)
- LHAASO (> 100 TeV)

Proposed instruments:

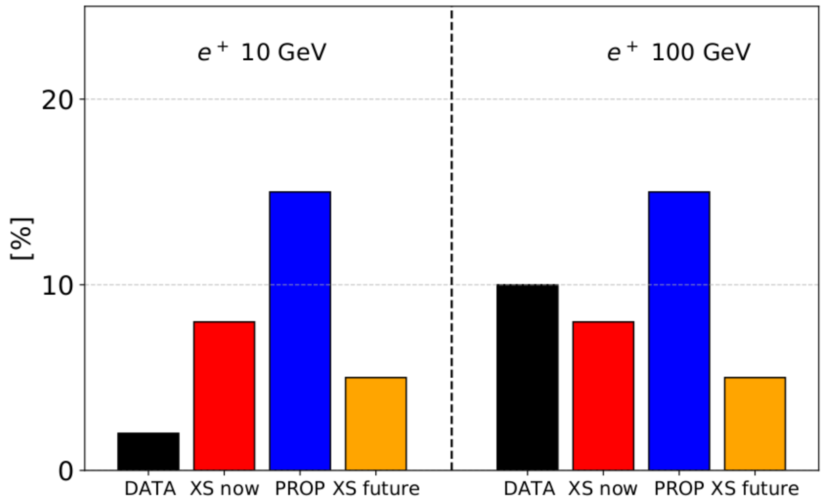
- HERD (GeV – 100 TeV)
- Atmospheric Cherenkov Telescope CTAO (10 GeV – 300 TeV)
- SWGO (100 GeV - PeV)
- THESEUS satellite (proposal for M7 ESA mission)
- Compton Spectrometer and Imager (COSI) (0.2 – 5 MeV) (NASA, to be launched 2027)

Synergies and strategic importance:

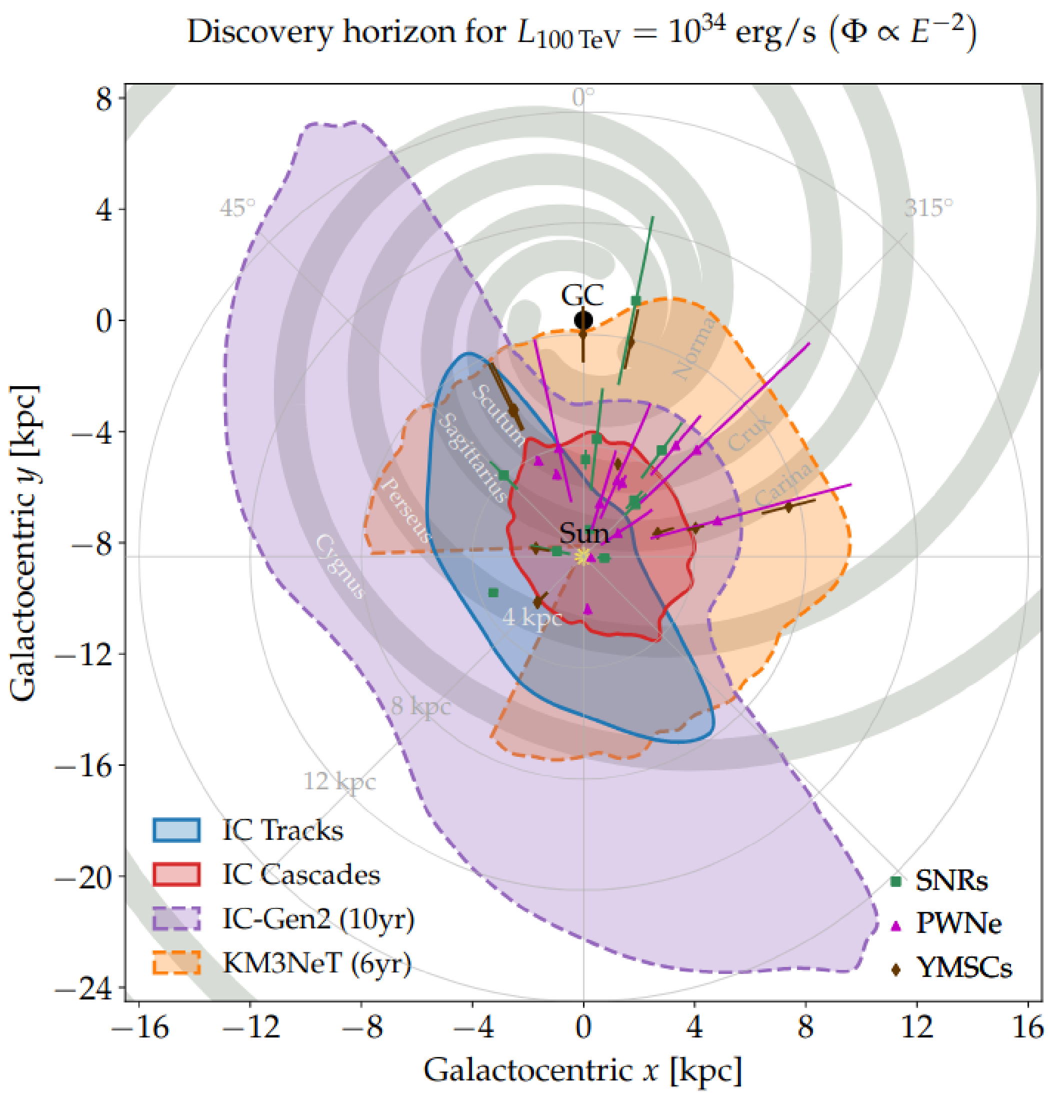
- Synergies with particle physics detectors (Fermi, AMS,..)

Cosmic rays : Xsection challenge (DD)

Particle	Reaction	Measurement	$\sqrt{s}$	Sought precision
$\bar{\mathrm{p}}$	$\mathrm{p}+\mathrm{p}\to\bar{\mathrm{p}}+\mathrm{X}$ $\mathrm{p}+\mathrm{He}\to\bar{\mathrm{p}}+\mathrm{X}$ $\mathrm{p}+\mathrm{p}\to\bar{\Lambda}+\mathrm{X}$ $\mathrm{p}+\mathrm{He}\to\bar{\Lambda}+\mathrm{X}$ $\mathrm{p}+\mathrm{p}\to\bar{\mathrm{n}}+\mathrm{X}$ $\mathrm{p}+\mathrm{n}\to\bar{\mathrm{p}}+\mathrm{X}$	σ_{inv}	5 to 100 GeV	$<3\%$ $<5\%$ $<10\%$ $<10\%$ $<5\%$ $<5\%$
$\bar{\mathrm{d}}$	$\mathrm{p}+\mathrm{p}\to\bar{\mathrm{d}}+\mathrm{X}$ $\mathrm{p}+\mathrm{He}\to\bar{\mathrm{d}}+\mathrm{X}$ $\bar{\mathrm{p}}+\mathrm{p}\to\bar{\mathrm{d}}+\mathrm{X}$	$\sigma_{\mathrm{inv}}/n_{\mathrm{tot}}$ $\sigma_{\mathrm{inv}}/n_{\mathrm{tot}}$ σ_{inv}	5 to 100 GeV 5 to 100 GeV 2 to 10 GeV	(any data) (any data) (any data)
$\overline{\mathrm{He}}$	$\mathrm{p}+\mathrm{p}\to\overline{\mathrm{He}}+\mathrm{X}$	$\sigma_{\mathrm{inv}}/n_{\mathrm{tot}}$	5 to 100 GeV	(any data)
$e^{\pm}$	$\mathrm{p}+\mathrm{He}\to\pi^{\pm}+\mathrm{X}$ $\mathrm{p}+\mathrm{He}\to K^{\pm}+\mathrm{X}$	σ_{inv}	5 to 100 GeV	$<5\%$ $<5\%$
γ	$\mathrm{p}+\mathrm{p}\to\pi^{0}+\mathrm{X}$ $\mathrm{p}+\mathrm{He}\to\pi^{0}+\mathrm{X}$	σ_{inv}	5 to 1000 GeV	$<5\%$ $<5\%$



Sky coverage of neutrino telescopes



Ambrosone et al,
arxiv:2306.17285

FIG. 1. IceCube's detection horizon for Galactic neutrino sources with an E^{-2} emission spectrum ("IC Tracks" [13] and "IC Cascades" [14]) and the expected reach of KM3NeT [15] and the proposed IceCube-Gen2 facility [16, 17] assuming a monochromatic neutrino luminosity $L_{100\,\mathrm{TeV}} = 10^{34}$ erg/s. We indicate the location of Galactic arms [18] and nearby candidate neutrino sources. See main text for details.

Searching for neutrinos at the highest energies

The highest energies ν

Method	Energy range	Principle	Experiments Past present and future
Ground-based air shower	10 PeV – EeV	ν_τ interact in earth or mountain, detect τ air shower	Auger, TA, GRAND, Trinity, TAMBO, BEACON
Radar in ice	10 PeV – EeV	Bounce radar off cascade ionization trail in ice	RET
Radio in ice	100 PeV – EeV+	Detect radio signal from cascades in Ice.	ARA, ARIANA, RNO-G, IceCube-gen2 radio
Space-based air showers	EeV+	Look from for optical or radio from air showers with satellites or balloons	ANITA, PUEO, EUSO-SPB2, POEMNA
Lunar detection	EeV-ZeV	Moon is target; detect radio signal	NuMoon, LUNASKA, RESUN, SKA

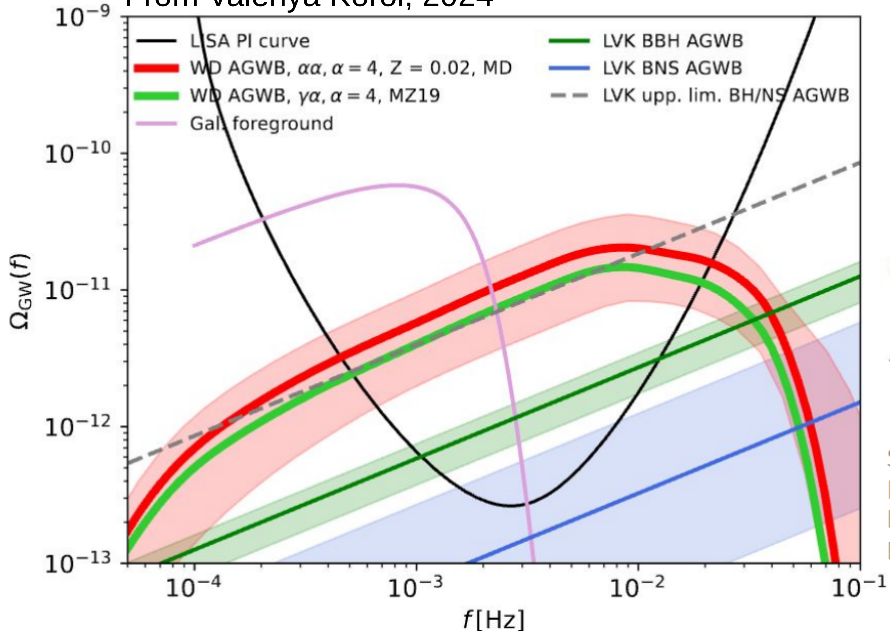
Adapted from 'Discovering the neutrino sky', Lu Lu, Cern courier

PAST, RUNNING, PROPOSED

Aart Heijboer – 22-6-2025 - COSMIC MESSENGERS

GW foregrounds

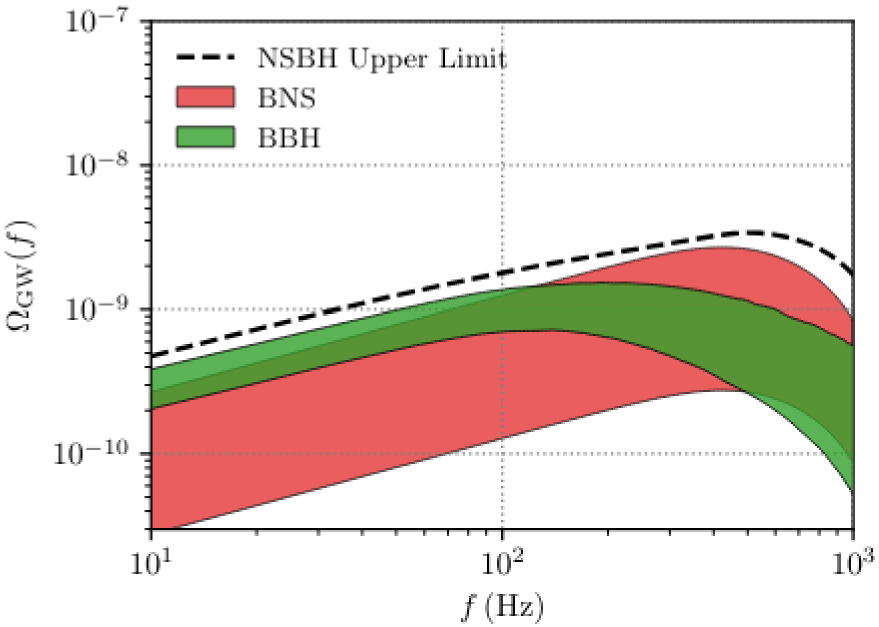
From Valeriya Korol, 2024

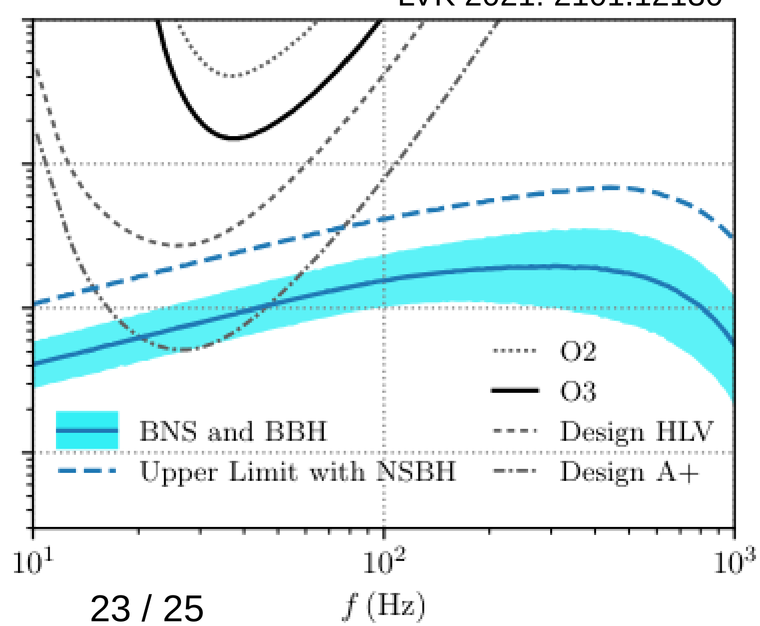


Staelens & Nelemans 2023, arXiv:2310.19448
Hofman & Nelemans 2024, arXiv:2407.10642
Boileau et al. in prep
Based on Farmer and Phinney 2003

Astrophysical foregrounds depend on frequency and detector sensitivity

LVK 2021: 2101.12130





Complementary probes of the weak scale: GWs and HL LHC

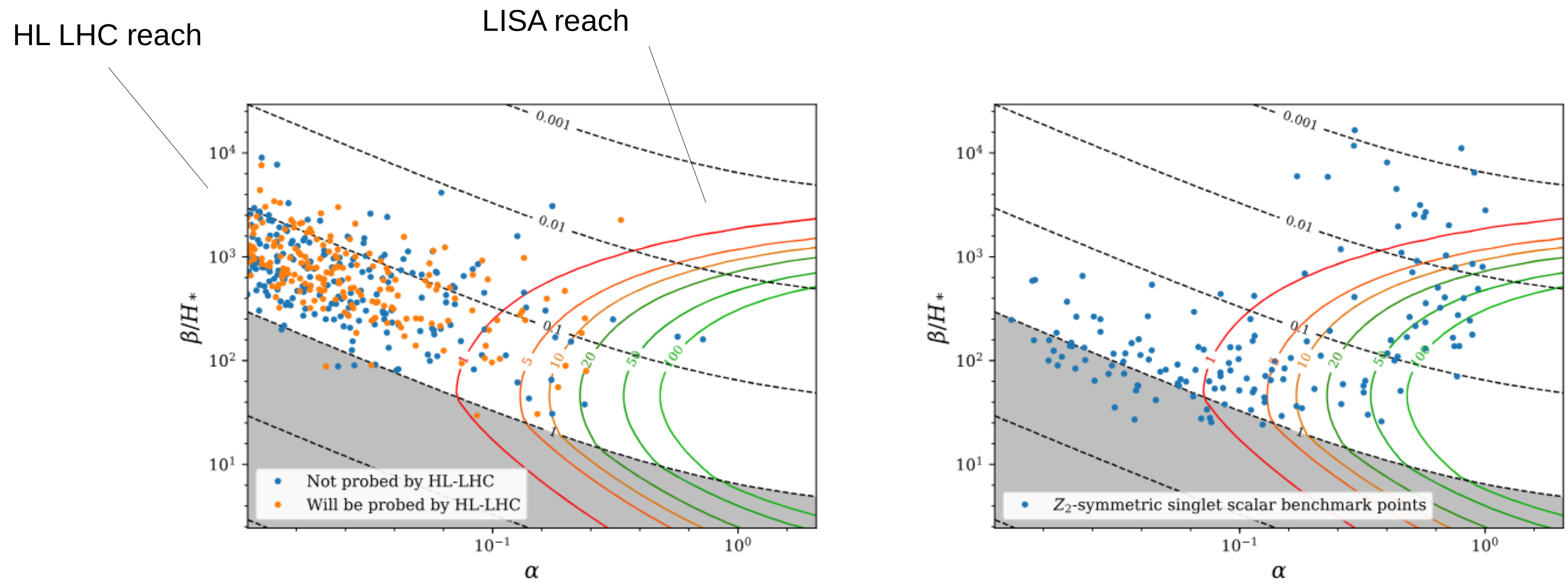
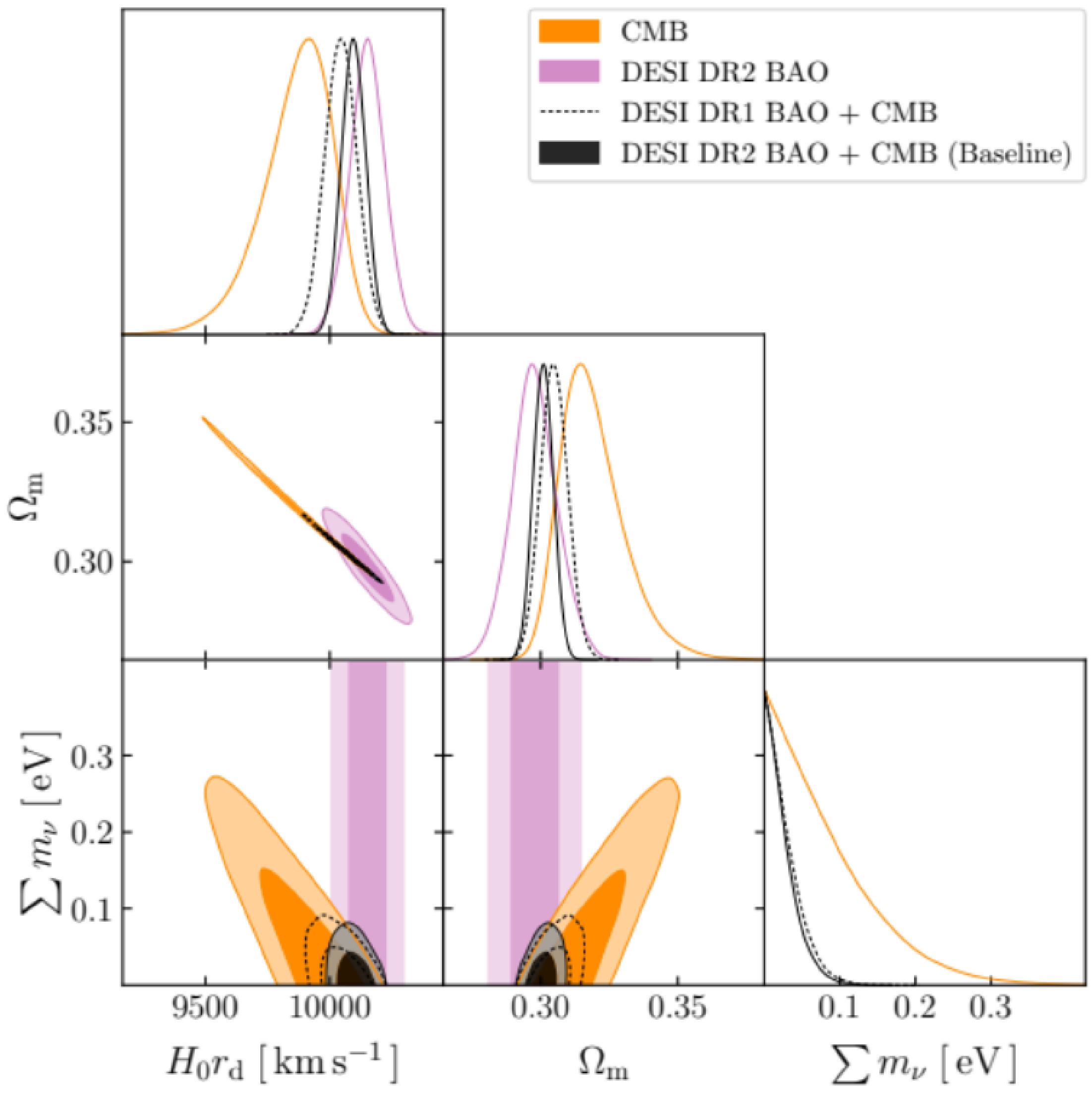


Figure 4: LEFT: Predicted values of α and β/H for $m_2 = 170$ GeV and 240 GeV (combined in one plot) in the general singlet model obtained by linearly varying the free parameters of the model and imposing requirements as described in the text. The mixing angles considered were $\sin\theta = 0.01$ (blue points) and 0.1 (orange points). The models in blue (orange) are unlikely (likely) to be probed by the high-luminosity LHC. The expected LISA sensitivities correspond to $T_* = 50$ GeV. RIGHT: Sensitivity curve for the Z_2 symmetric singlet extension. In both the left and right panels we have taken $v_w = 1$.

Caprini et al, 1910.13125

Example cosmological parameter constraints: BAO + CMB



Minimal neutrino mass from oscillations:

$$\sum m_\nu > 0.1 \text{ eV} \quad (IO)$$

$$\sum m_\nu > 0.06 \text{ eV} \quad (NO)$$