PARALLEL 3 / NEUTRINOS AND COSMIC MESSENGERS

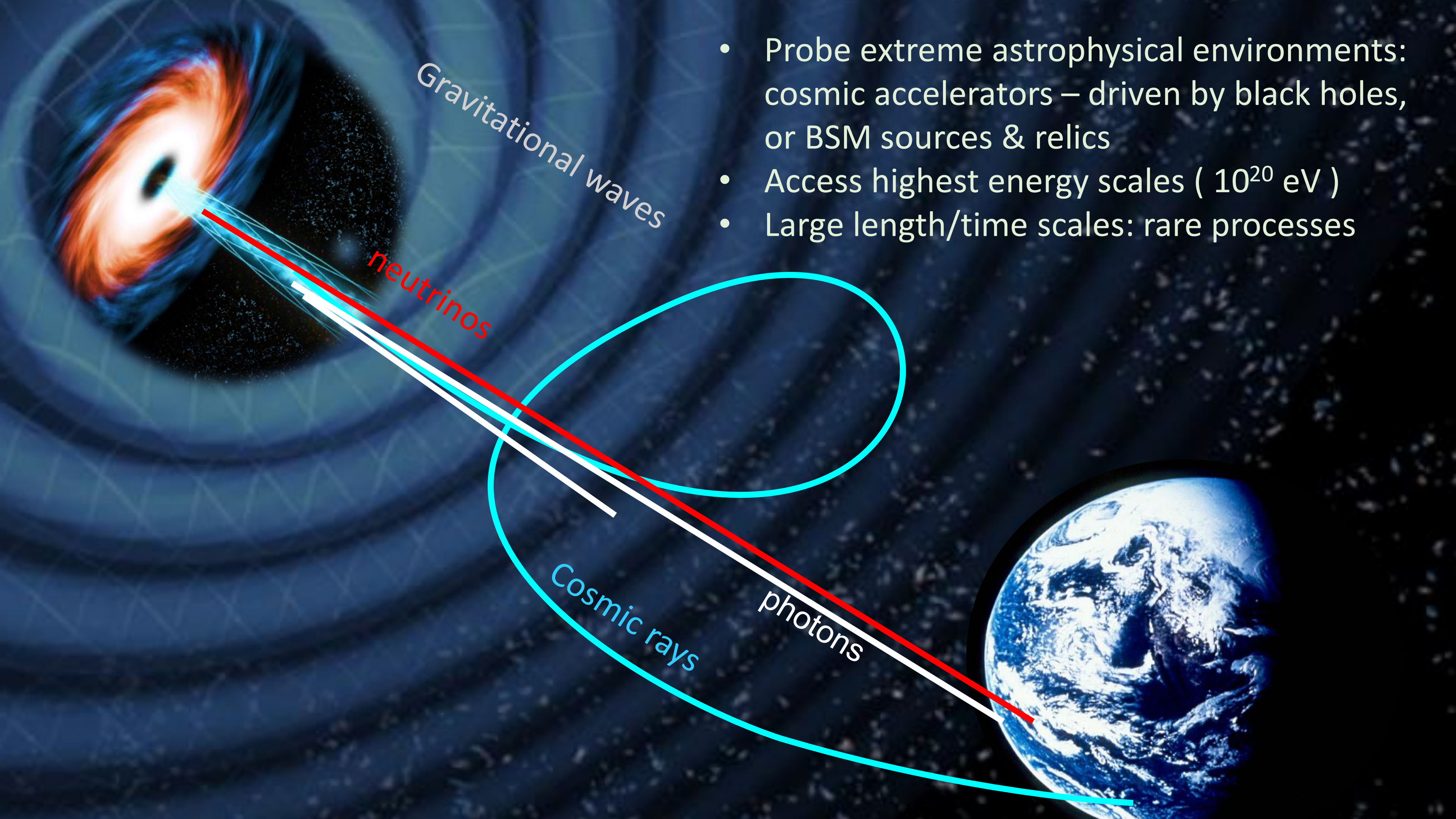
Cosmic Messengers

Aart Heijboer (Nikhef)
On behalf of the working group

Input from:
P-One #53, Icecube+Gen2 #236, KM3NeT #249, TAMBO #272, Pierre Auger Observatory #201, Ligo-Virgo-Kagra #122, Lisa #164, Atom Interferometry #37, Einstein Telescope #198
Precision cross-sections for advancing cosmic-ray physics #89, Astroparticle Physics European Consortium #276

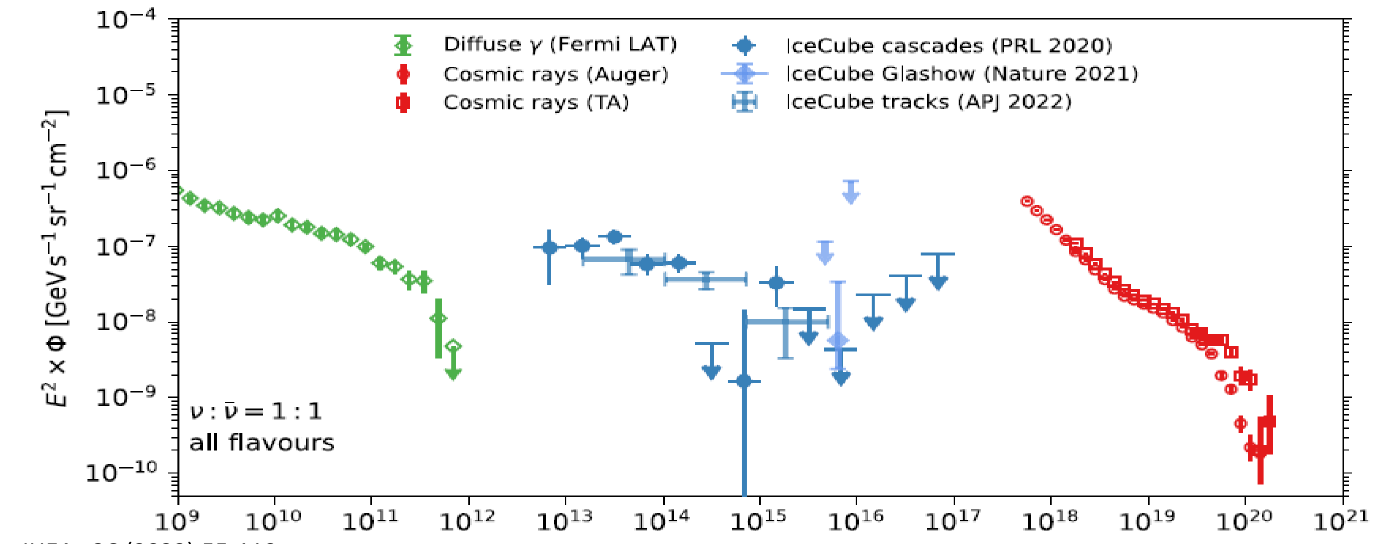
Discussed Elsewhere:
- Dark Matter
- Atmospheric Neutrinos
- CMB/Cosmology

- Probe extreme astrophysical environments: cosmic accelerators – driven by black holes, or BSM sources & relics
- Access highest energy scales (10^{20} eV)
- Large length/time scales: rare processes

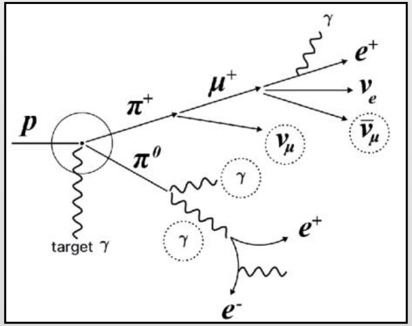


Introduction: messengers and connections

Diffuse extragalactic fluxes



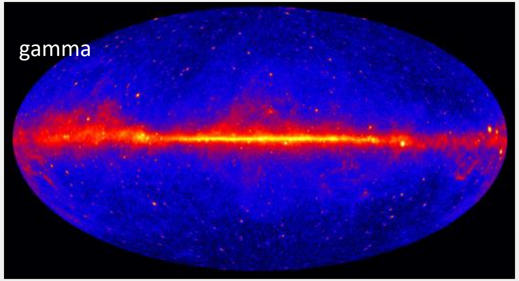
JHEAp 36 (2022) 55-110

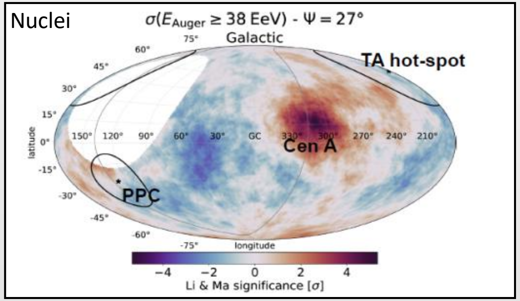


- Field started with cosmic rays, now measured up to 10^{20} eV
- Since 2013: diffuse cosmic neutrino flux
- Connection expected and suggested by same energy in flux
- Same sources?

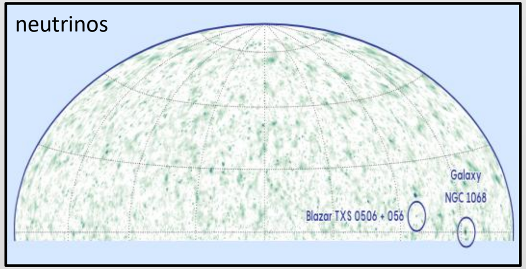
Introduction: Known sources..

- GW: many events detected; conjunction with other messengers is rare
- Gamma rays: many sources (Fermi, HESS, LHAASO)
  EM/hadronic origin
- CR: 4σ sigma (post trial) for excess from Cen A at
  E> 2.8 10^{19} eV
- Neutrinos: *most 'IceCube' neutrinos unassociated*
  first exceptions: Blazar TXS 0506+056, Galaxy NGC 1068, Galactic plane





(Astrophysical Journal, 935:170, 2022, update ICRC 2023)



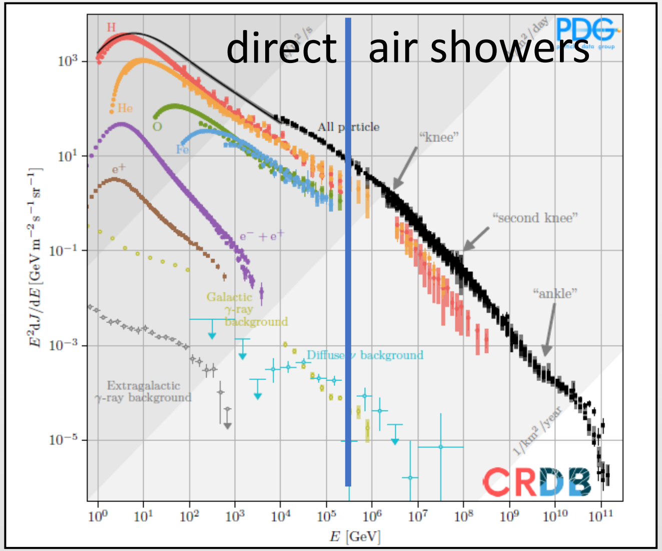
Many (common) sources still to be found.
Much astro- and particle- physics to be done

(charged) Cosmic Rays

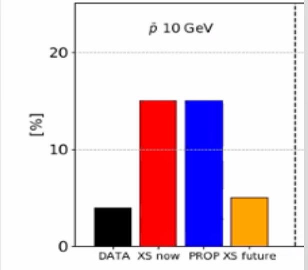
Cosmic rays

Below ~PeV: Direct detection from space.

- Understand particle abundances, in particular anti-matter
  - From dark-matter decay
  - Primordial
- AMS, CALET (ISS), DAMPE (satellite), HELIX, GAPS (balloon)
- Future: HERD (China Space Station), TIGER-ISS
- Direct connection to collider physics:
  XSCRC community #89:
  Understanding the data requires precise cross-section measurements: LHCb-SMOG, Alice, LHCf, AMBER (COMPASS), NA61/SHINE(#171) (NA49), n-TOF



Example: anti-protons in AMS



Particle	Reaction
$\overline{\mathrm{p}}$	$\mathrm{p}+\mathrm{p}\rightarrow\overline{\mathrm{p}}+\mathrm{X}$
	$\mathrm{p}+\mathrm{He}\rightarrow\overline{\mathrm{p}}+\mathrm{X}$
	$\mathrm{p}+\mathrm{p}\rightarrow\overline{\Lambda}+\mathrm{X}$
	$\mathrm{p}+\mathrm{He}\rightarrow\overline{\Lambda}+\mathrm{X}$
	$\mathrm{p}+\mathrm{p}\rightarrow\overline{\mathrm{n}}+\mathrm{X}$
	$\mathrm{p}+\mathrm{n}\rightarrow\overline{\mathrm{p}}+\mathrm{X}$

Cosmic rays

Highest energies:

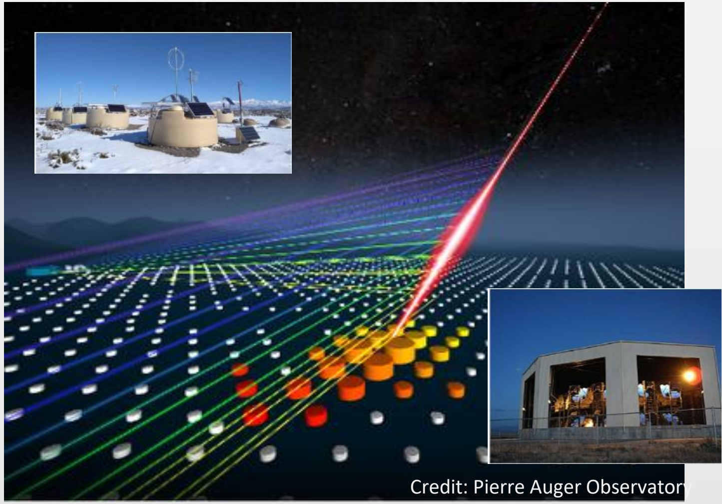
- Observe airs-shower by surface detectors, fluorescence and radio.
- Telescope Array & Pierre Auger Observatory [#201]
  (Large European component)
- Future: Global cosmic ray observatory (GCOS) & GRAND

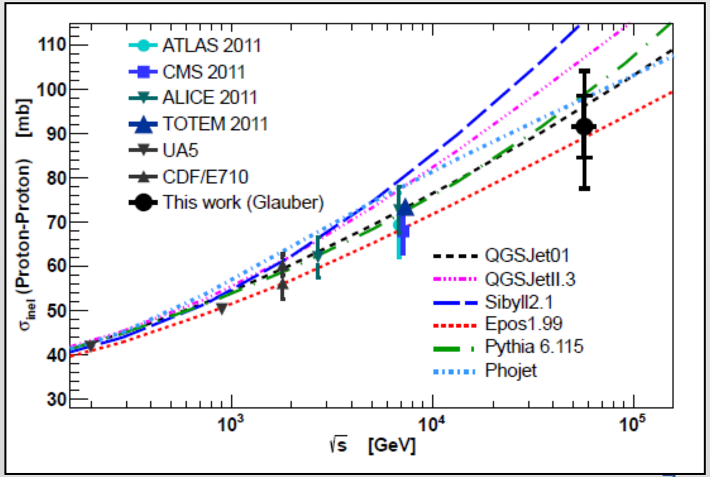
Goals:

- Probe cosmic accelerators at the highest energies
- pp cross-section at √s=50 TeV.
- Understand composition / GZK cutoff → neutrinos?
- Experiments also sensitive to UHE neutrinos and gamma's

Physics of Air Showers :

- Modeling hadron-air and nucleus-air interactions (muon puzzle)
- Crucial link to LHC: TOTEM, Faser, SND, FPF, #19,#23,#63
  and fixed target: (e.g. NA61/SNINE , n-TOF).
- Benefit from LHC run with light ions, such as p-O; see also strong interactions WG

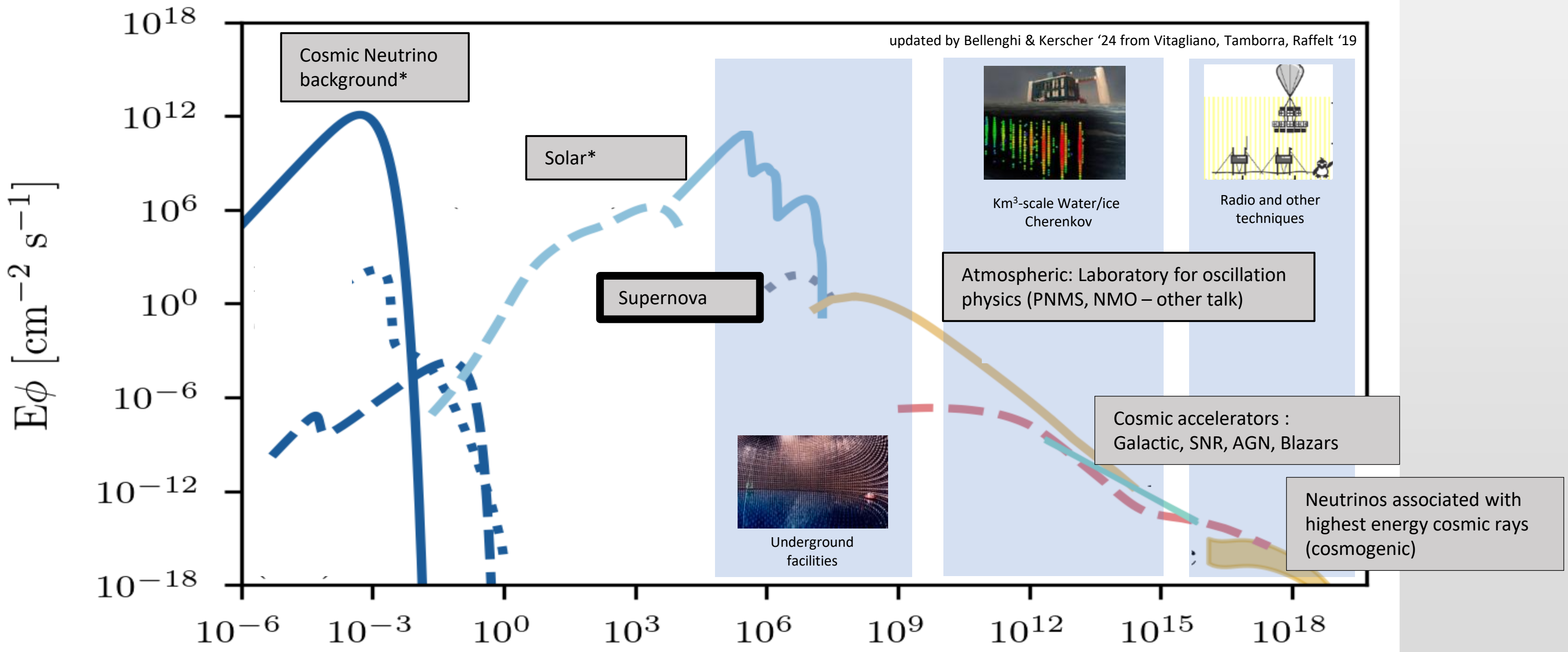




Neutrinos

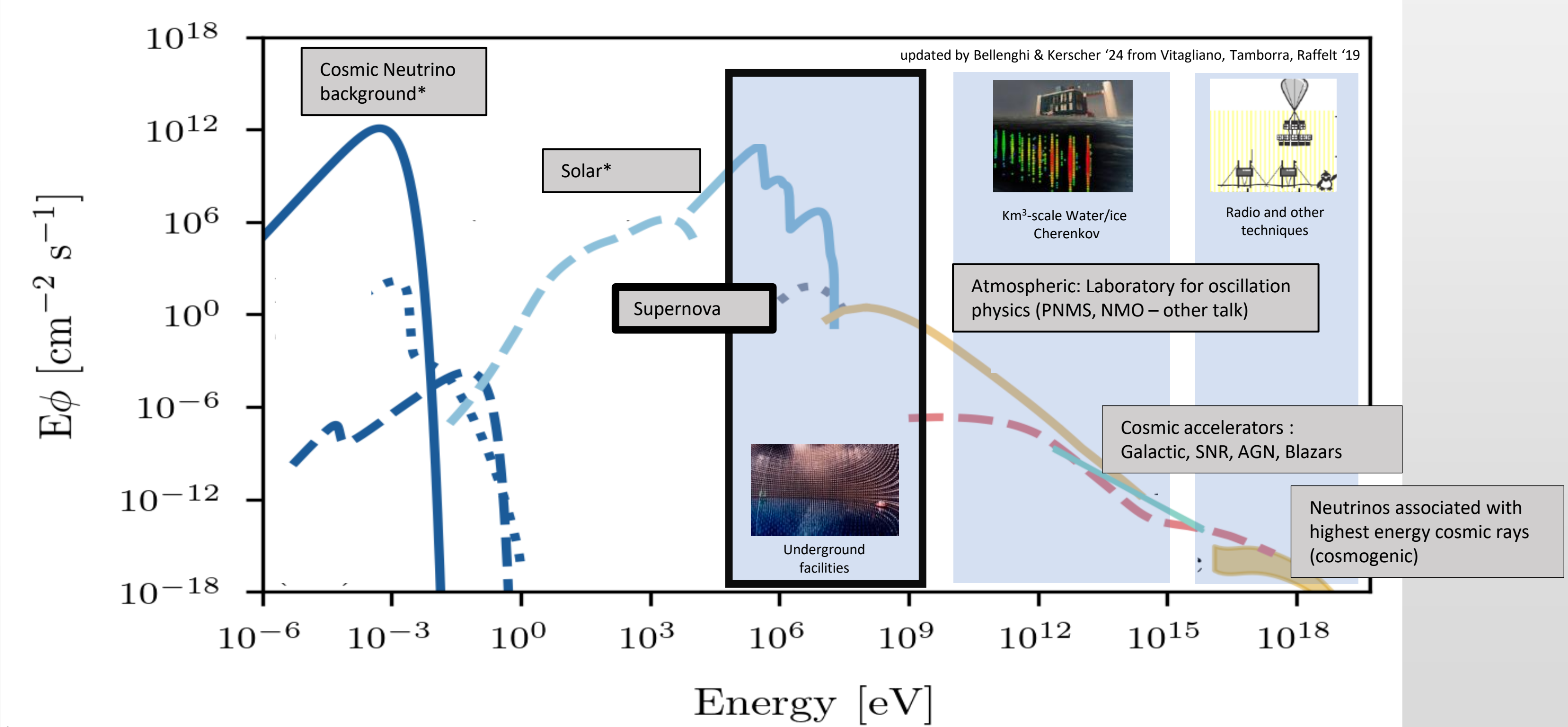
Cosmic Neutrinos

- Straight line : identify source
- Smoking gun of CR acceleration (>GeV)
- Unabsorbed: probe inside dense objects



* Not discussed in this talk

Cosmic Neutrinos



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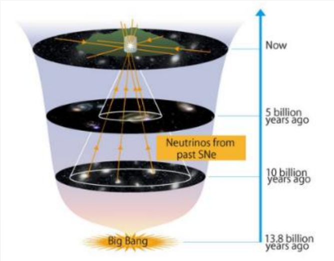
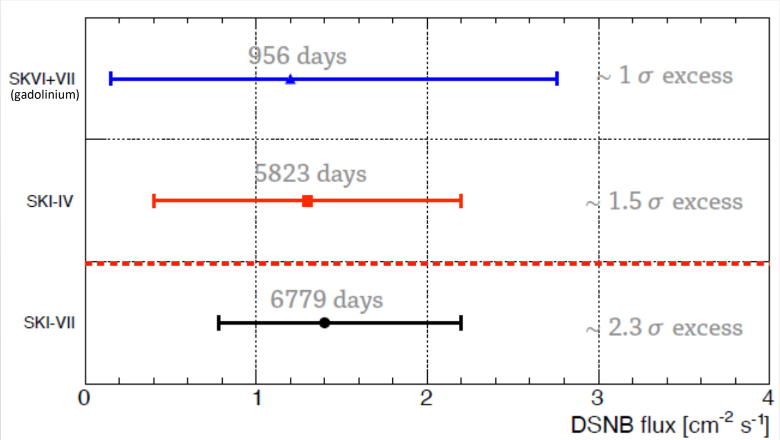
Supernova neutrinos

If Supernova in our (or nearby) Galaxy:

- Large signals in Hyper-Kamiokande, Dune, Juno
- HK:@ 10 kPc
    - 55-90k events in HK
    - ~degree localization
- Additional detections IceCube, KM3NeT and others.
- Additional pointing via timing of networked detectors (SNEWS network)

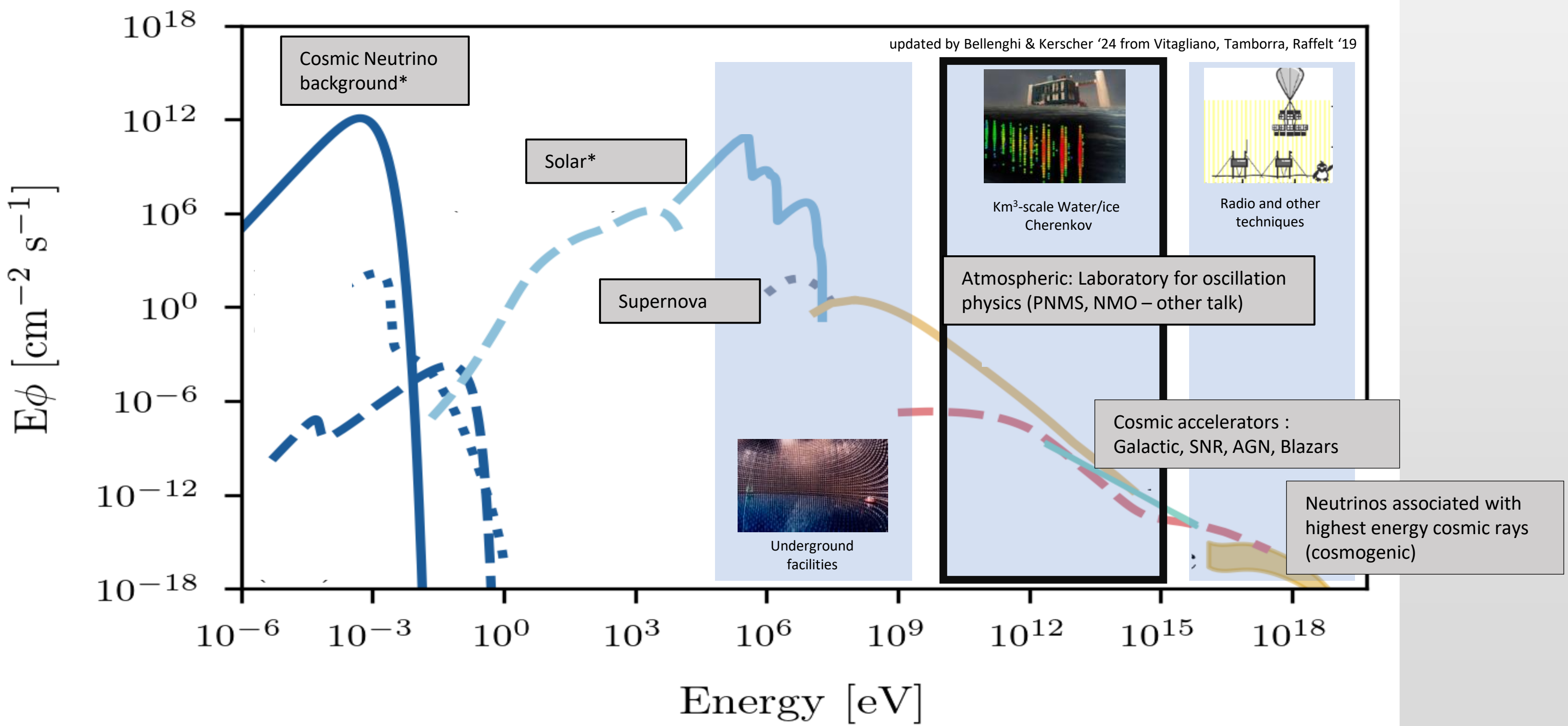


Diffuse supernova neutrino background is messenger of star formation history and (astro) physics.



- 2.3 sigma hint in Super-Kamiokande ~20 MeV
- Looking forward to discovery of DSNB in the next decade (HK, Juno)

Cosmic Neutrinos



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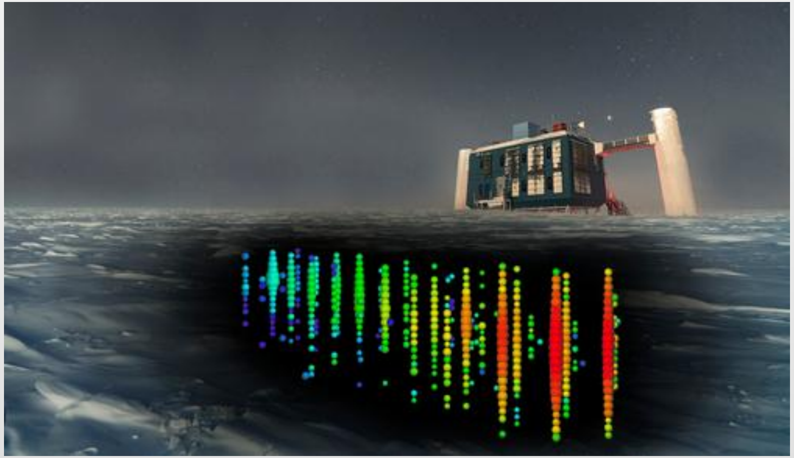
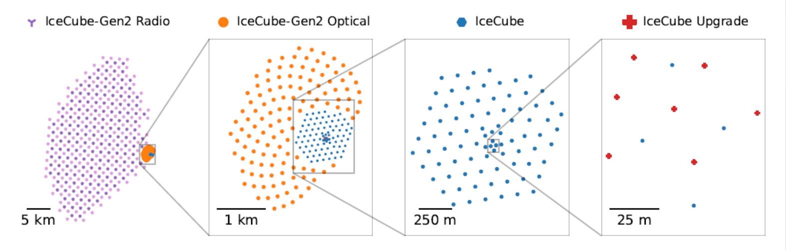
IceCube (#236)

- Main observatory now and over past decade with strong European involvement.
  - Discovery of Cosmic Neutrino's 2013,
  - First Multi-messenger Blazar
  - First steady point source: Active Galaxy NGC 1068
  - Glashow resonance neutrino
  - Galactic contribution.

- Next : Upgrade (Jan '26)
  - Lower Energy threshold to ~1 GeV: oscillations
  - Recalibration to retroactively improve the data!

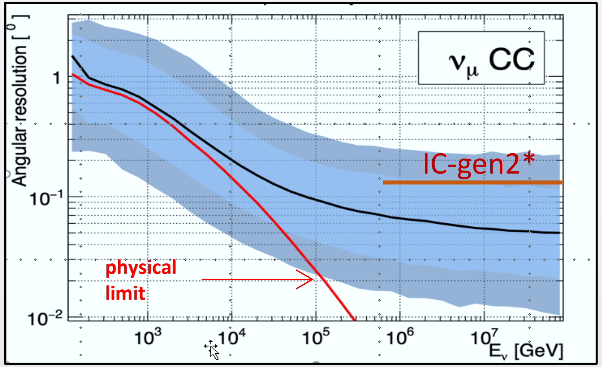
- Vision for future: Gen-II
  - x 10 volume at high E
  - Extend energy range with radio array for Ultra-high E.



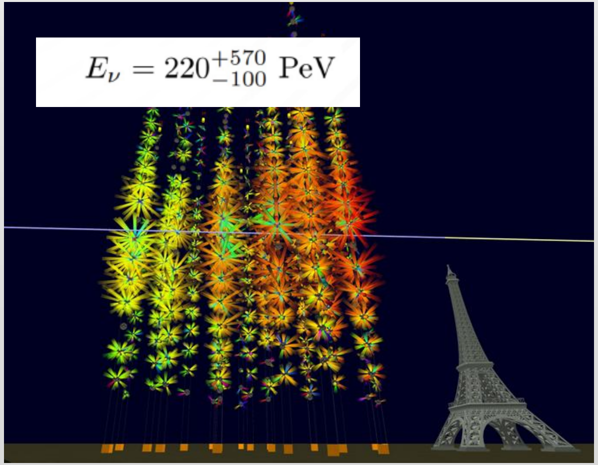


KM3NeT (#249)

- European Collaboration with 2 observatories
  - ORCA : Oscillations in GeV regime
    - France, 7 Mt, Neutrino mass ordering (not this talk)
  - ARCA: Astronomy TeV-PeV (and above),
    - Italy, 1 Gton; (same as IceCube; better angular precision)
    - Excellent view of galactic center at relevant energies.
    - Recent discovery: Highest energy neutrino
- Under construction: 20% of total; producing science
- Completion of the two detectors around 2030

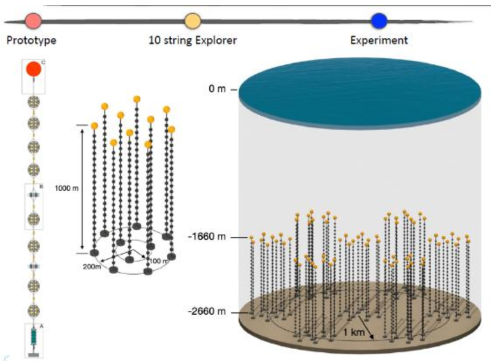


* 2008.04323v1 10 arcmin (0.16deg)

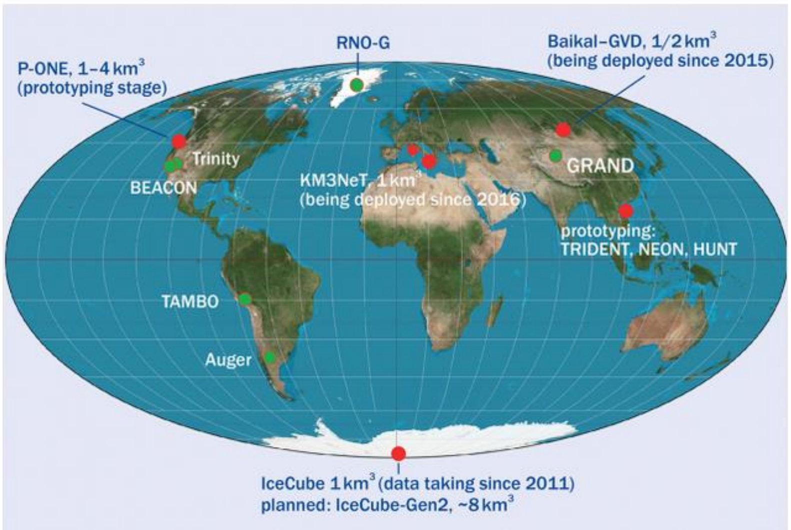


Global neutrino telescopes

P-One (#53)

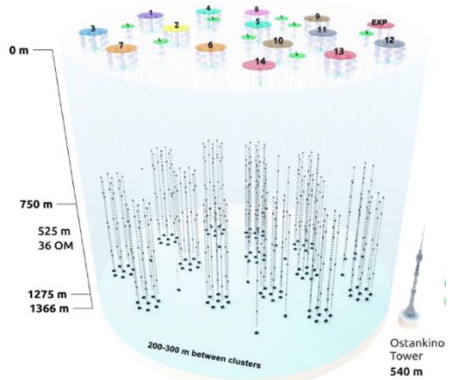


- Use Canadian deep sea network
- Aim for multi-km^3
- Explorer under construction



- R&D for 3 Chinese projects
- Hunt, Trident, Neon
- 7.5 – 30 km3 / 21-55k Modules

GVD @ lake Baikal

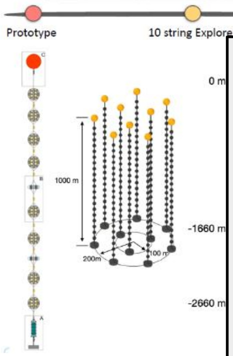


- 0.5 km^3 and growing, running
- Confirms Cosmic IceCube flux

(25 up-going cascades over bg=6)

Global neutrino telescopes

P-One (#53)



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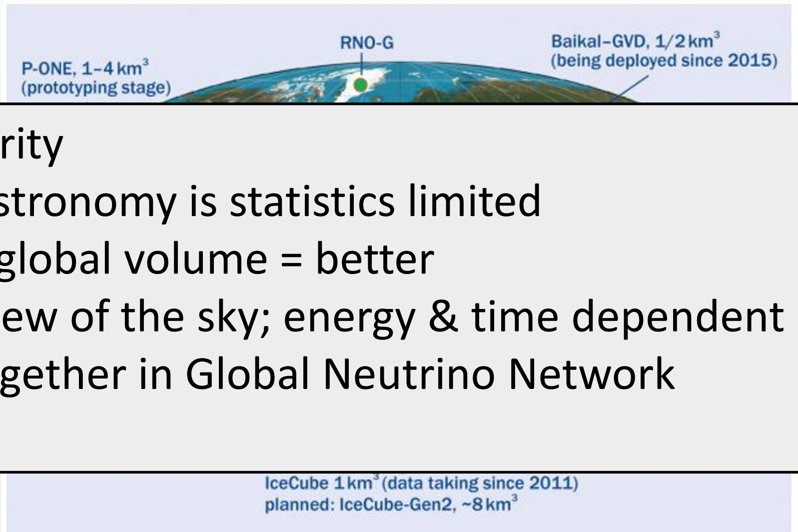

Complementarity

- Neutrino astronomy is statistics limited
  - more global volume = better
- Different view of the sky; energy & time dependent
- Working together in Global Neutrino Network

- R&D for 3 Chinese projects
- Hunt, Trident, Neon
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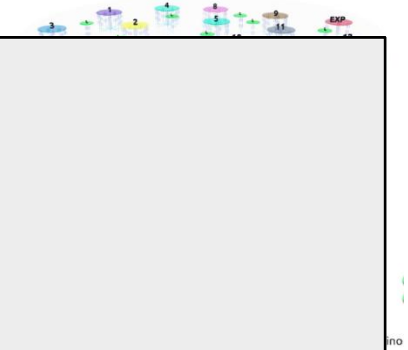
GVD @ laike Baikal



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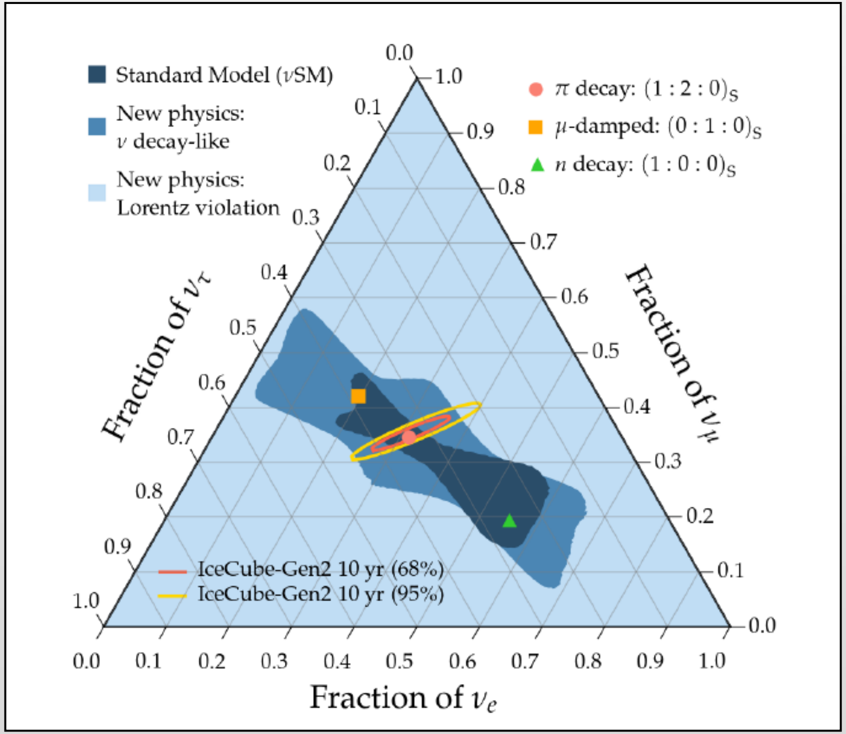
particle physics cosmic neutrinos

... one example for IceCube gen-II



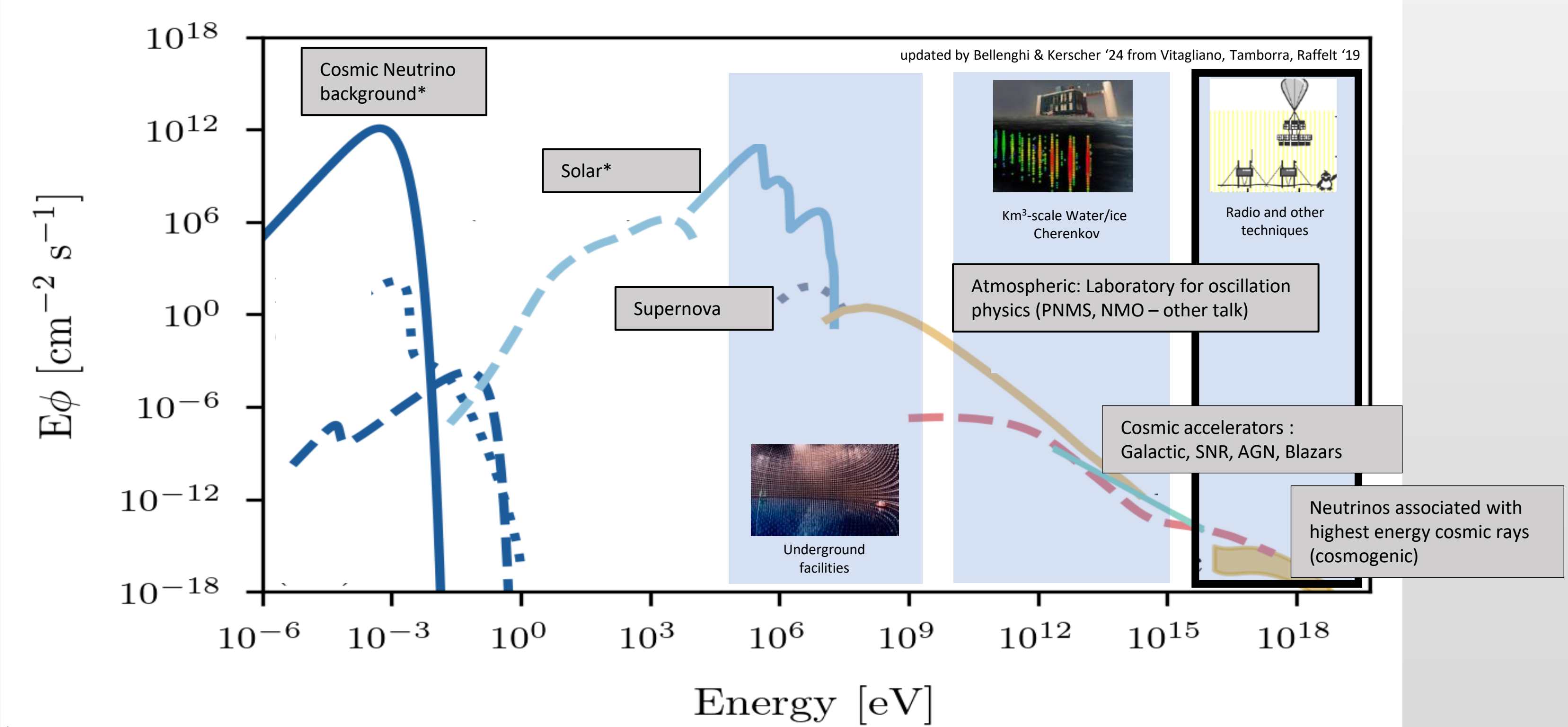
Flavour ratio of neutrinos

- Caries information on source production mechanism…
- And is sensitive to rare BSM processes during propagation.

Other science with neutrinos includes

- Indirect Dark matter searches
- Cross-sections up to sqrt(s) ~ FCC

Cosmic Neutrinos



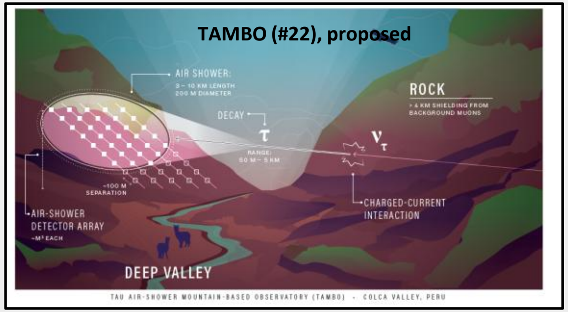
* Not discussed in this talk

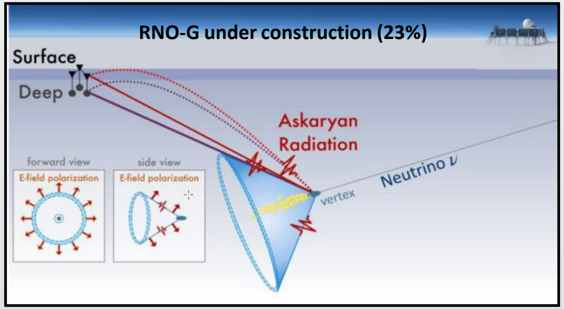
The highest energies ν

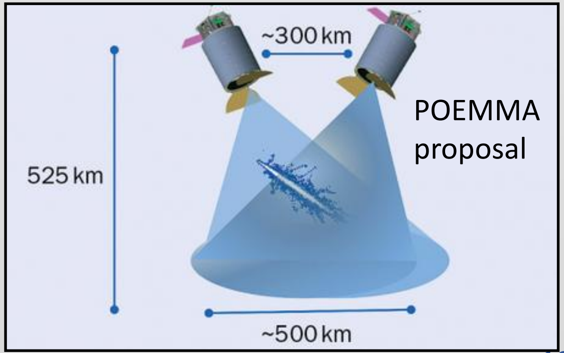
Method	Energy range	Principle	Experiments Past present and future
Ground-based air shower	10 PeV – EeV	ν_τ interact in earth or mountain, detect τ air shower	Auger, TA, GRAND, Trinity, TAMBO, BEACON
Radar in ice	10 PeV – EeV	Bounce radar off cascade ionization trail in ice	RET
Radio in ice	100 PeV – 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





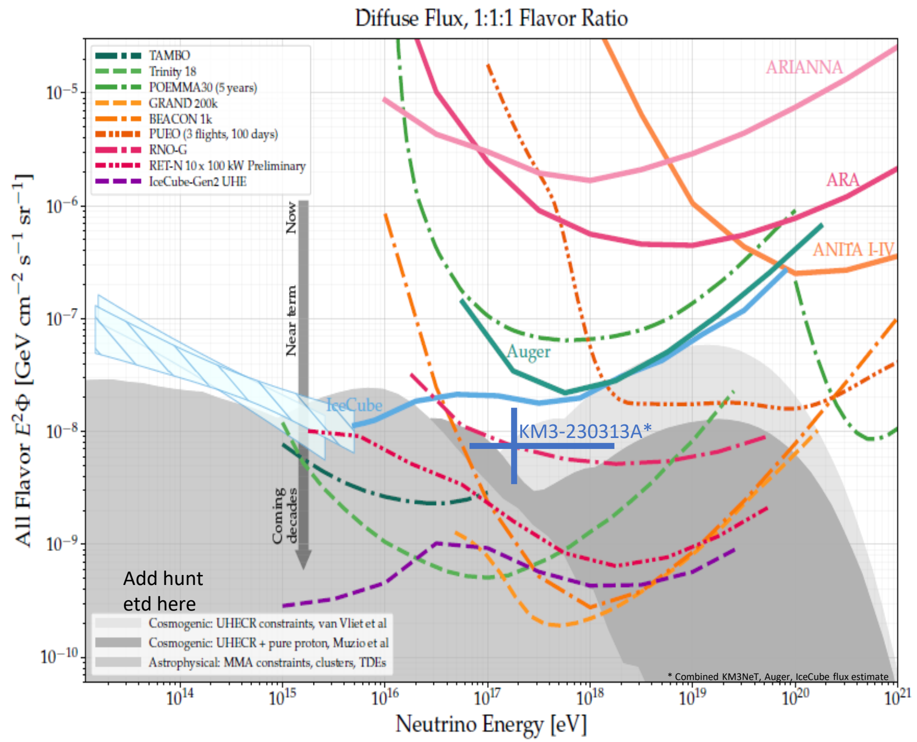


The highest energy ν: projects

- Current best limits from IceCube & Auger
- One neutrino from KM3NeT
- Next: RNO-G & PUEO

Further future

- Proposals to improve current sensitivity by 2 orders of mag.
- ~guaranteed to see neutrinos
- *cosmogenic* neutrinos very likely

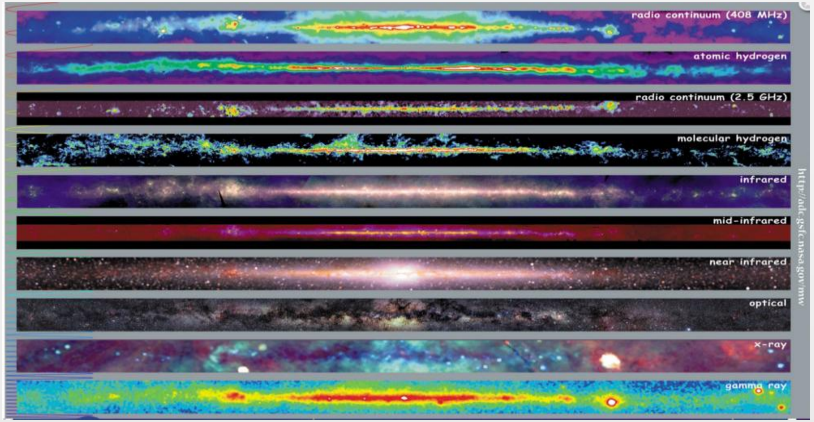


* Joint flux with PAO&IC

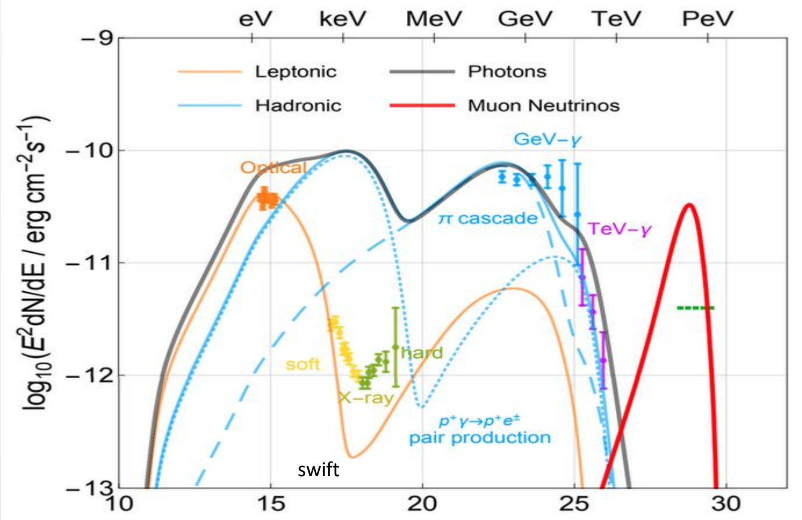
Photons

Photons

- Many observatories from radio to gamma-ray and a lot of data coming in the next years.
- Indirect Dark Matter detection
- Directly related to cosmic accelerators : Gamma
  - Cosmic accelerators HAWK Lhaaso, Hess, Magic, Veritas, soon: CTA
  - Galactic sources up to PeV energies; hadronic origin?
- Photon spectrum at *all wavelengths* is crucial for multi-messenger modeling of cosmic accelerators
- Rely crucially gamma and x-ray satellites now: Fermi, Swift, 2027 : HERD, Cosi



Example: Modeling TXS- 0506+056



S. Gao, A. Fedynitch, W. Winter, and M. Pohl
Nature Astronomy **3** no. 1, (Nov, 2018) 88–92.

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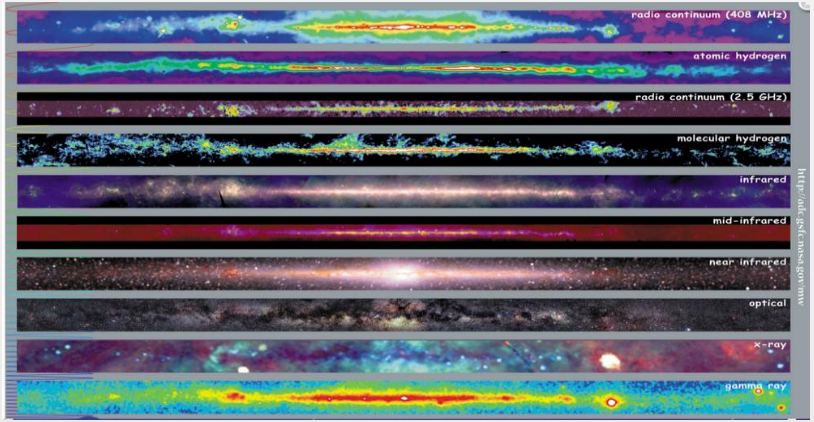

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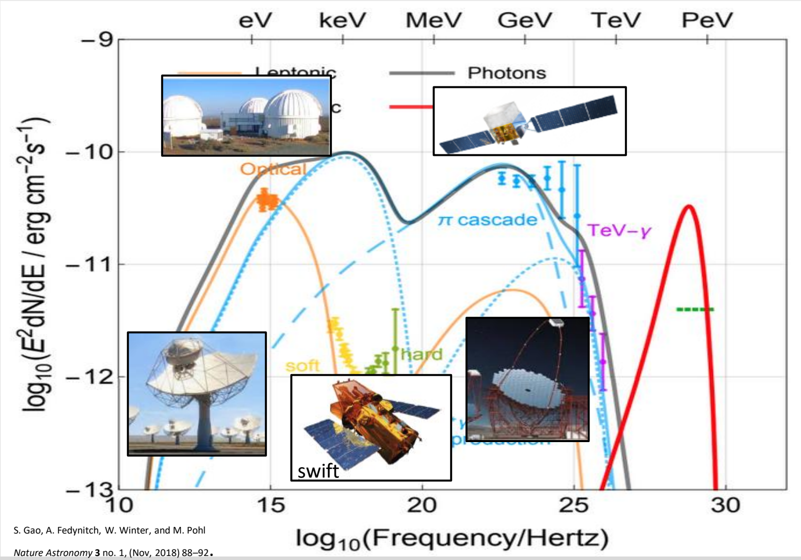

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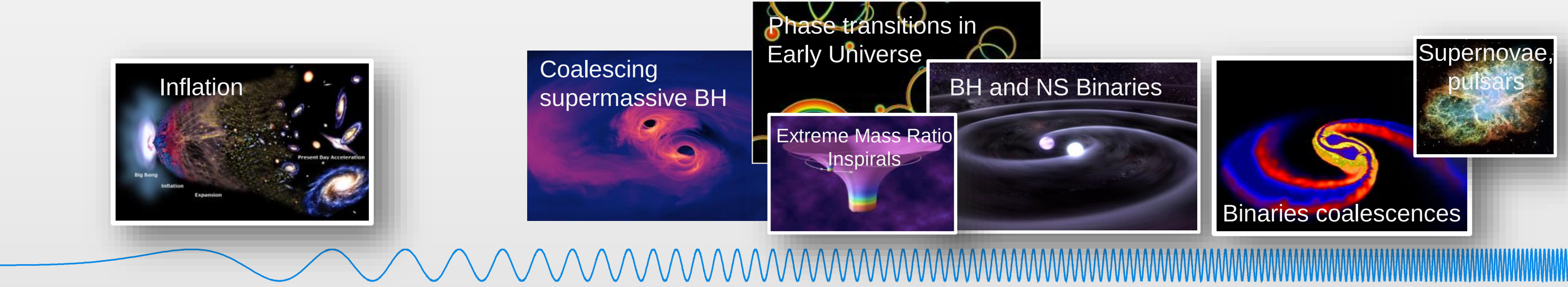
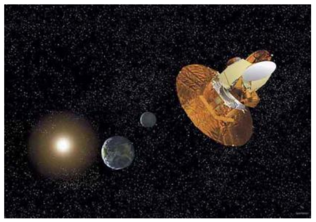
Gravitational waves

Gravitational waves



10^{-16} Hz *10^{-9} Hz* *10^{-4} Hz* *10^{0} Hz* *10^{3} Hz*

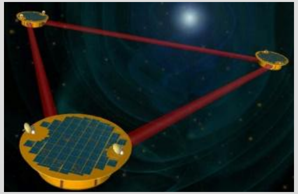
CMB probes



Pulsar timing

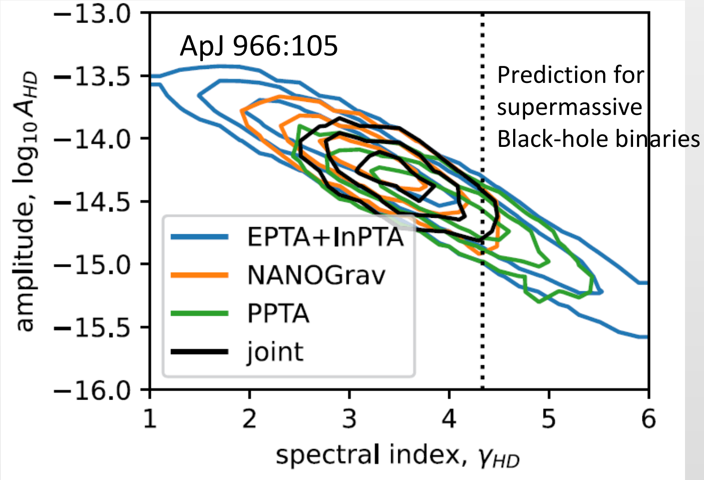
Space atomic Ground

interferometry



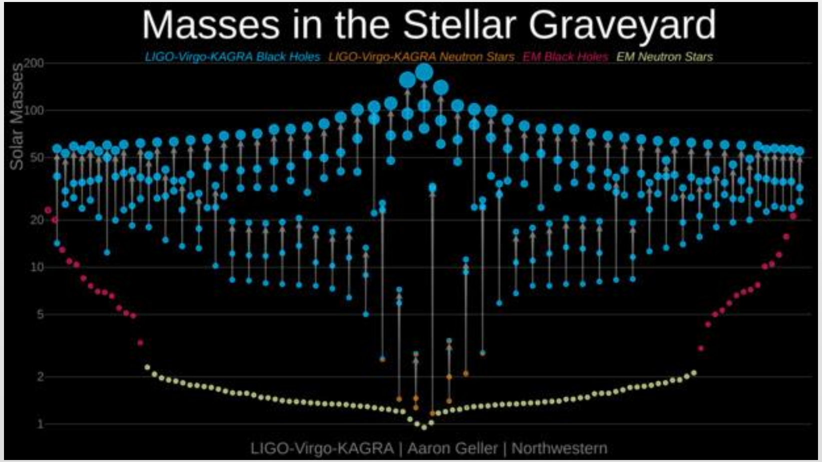
Detections so far

Pulsar timing arrays



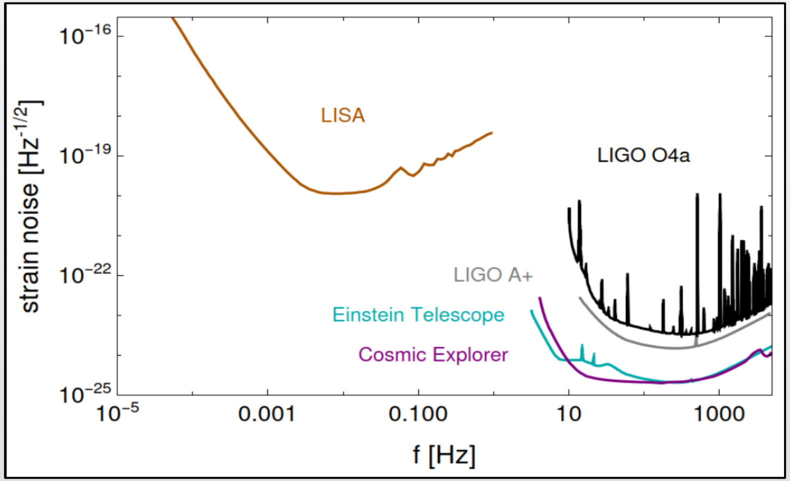
- Evidence of nHz stochastic background in multiple experiments
- Compatible with SMBHBs.. or from primordial universe.
- Future upgrades expected, SKA.

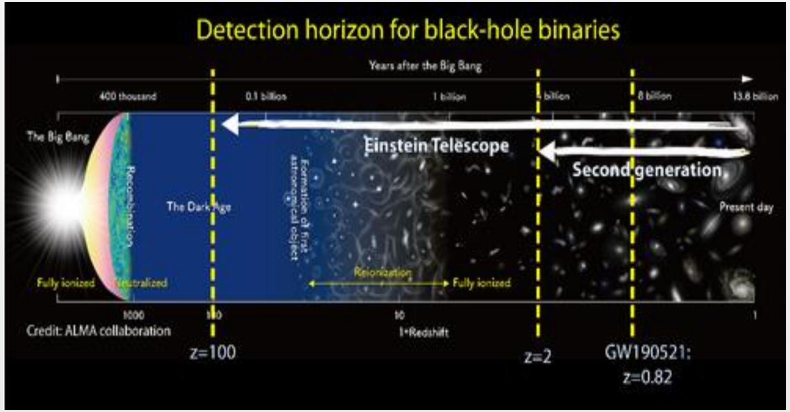
Ligo-Virgo-Kagra

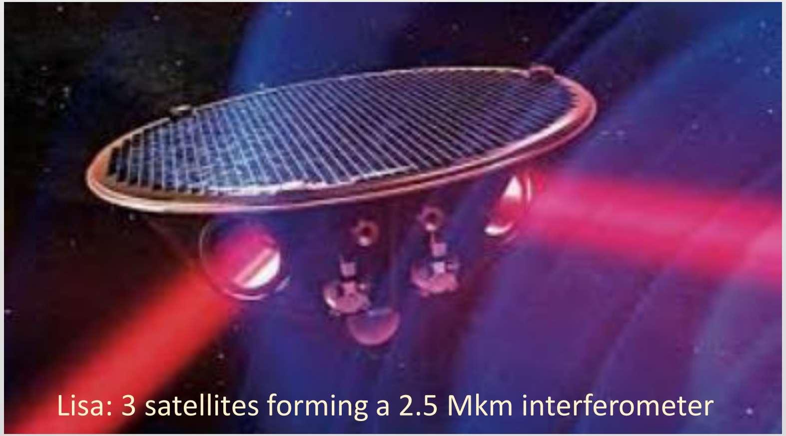


- Detectors working as one collaboration
- Since 2015: Hundreds of mergers of NS and BH
- Science includes: Strong-field tests of General relativity, discovery 20 Msun Black holes.
- O4 ongong, O5 in 2028

2035 and beyond

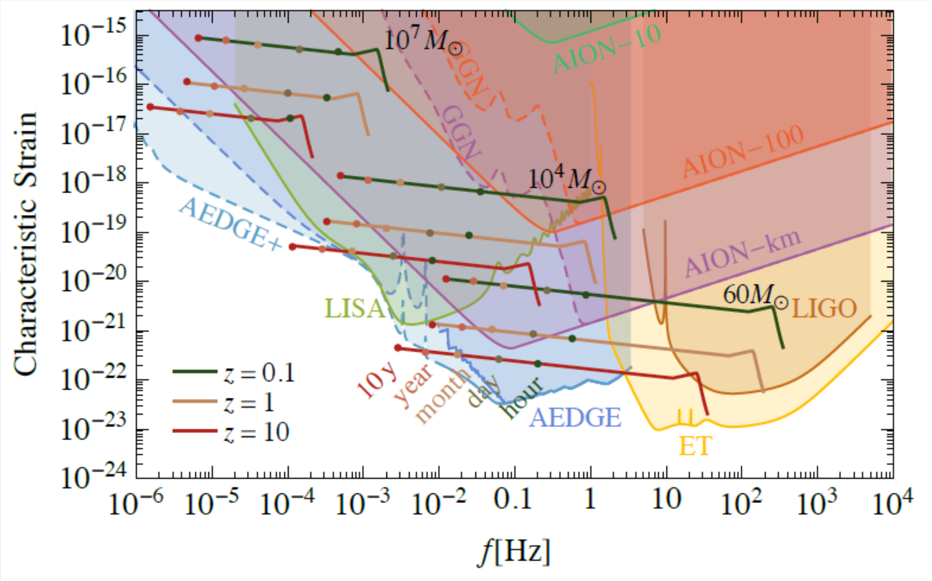






- Next Generation: cryogenic interferometers: order of magnitude improvement in 100 Hz range.
- For Europe next-generation means Einstein telescope; expected 2nd half the next decade.
- Ligo & Virgo have upgrade possibility in the meantime (Ligo A♯, Virgo_nEXT)
- 2035, Lisa will be launched, opening up the mHZ regime.

Atom interferometers



- Multi-purpose instruments (low-mass DM + GW); strong synergy with particle physics.
- Fill the gap between Lisa and ET. ~ 0.1 Hz
- Network 100 m instruments under construction with European participation (e.g. MIGA in France, PX46 LHC shaft at CERN).
- Vision: 1 km instrument operating by 2035. in conjunction with Lisa & ET (AION-km)
- Future: space-based (AEDGE)

Observe same objects subsequently in Multiple detectors.

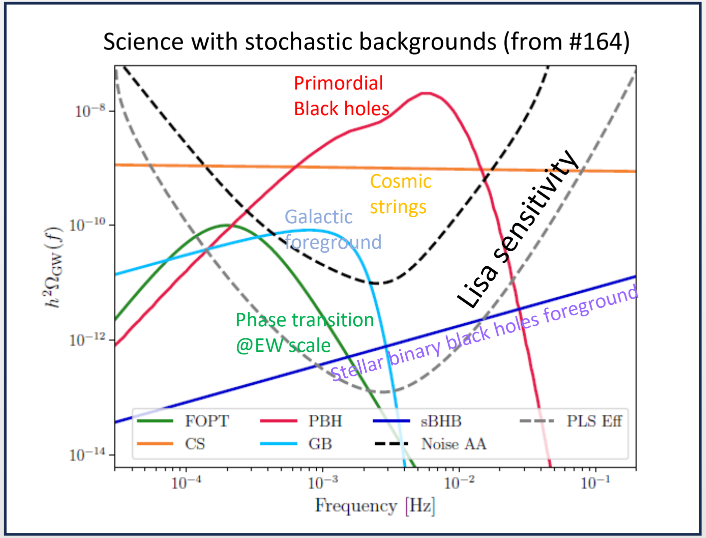
GW Science reach

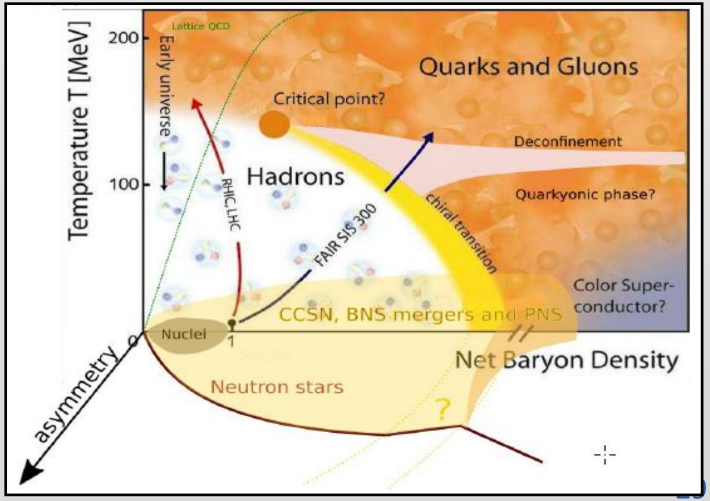
a selection

- Multi-messenger Astronomy
- Search for (exotic) compact objects
- Strong-field tests of gravity
- Cosmology; Cosmic strings, primordial black holes

Particle physics related

- Phase transitions in the early Universe
  Lisa probes EW-scale.
- Nuclear physics (QCD phase diagram..)
- Dark matter (e.g. affecting the GW in the source region)



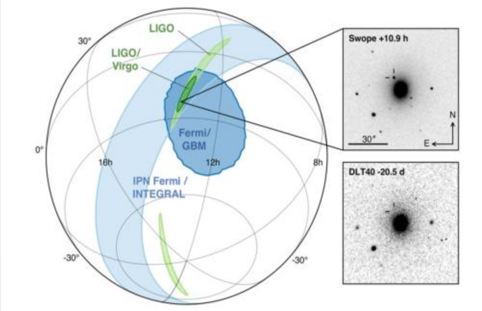


Multi Messenger

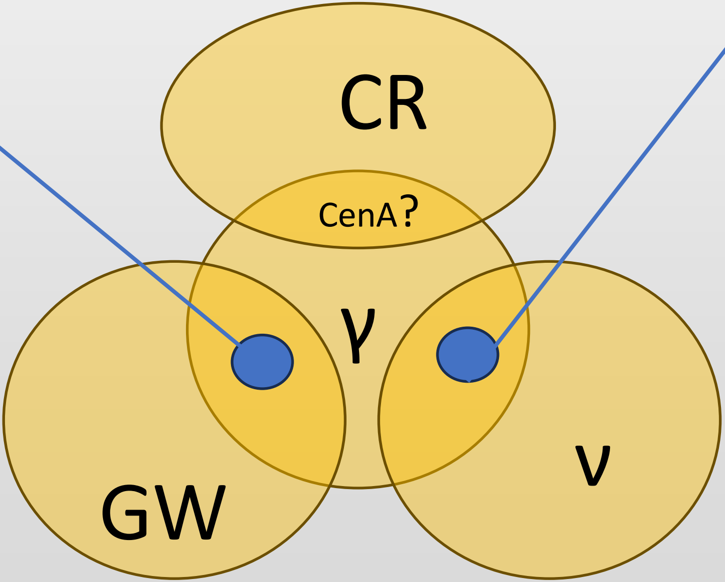
Multi messenger

- Most powerful: combination of many messengers
- Only a couple of real multi-messenger events so far

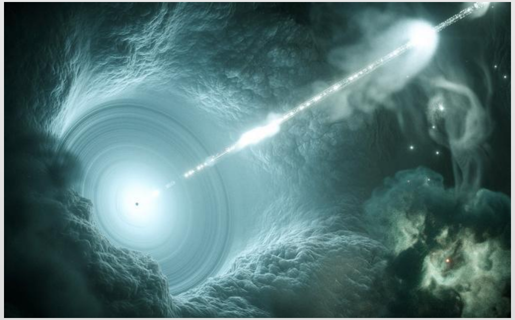
GW170817,
First binary neutron star
Detected in GW and EM
Allowed to measure speed of GW



Astrophys.J. 848 (2017) no.2, L12
(70 observatories)



TXS 0506+056
IceCube alert sent within 1 min
Fast follow up (Fermi, Magic,
many others)

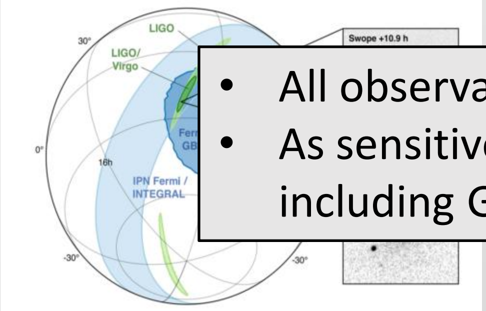


Science, 361 (2018)
18 observatories

Multi messenger

- Most powerful: combination of many messengers
- Only a couple of real multi-messenger events so far

GW170817,
First binary neutron star
Detected in GW and EM
Allowed to measure speed of GW



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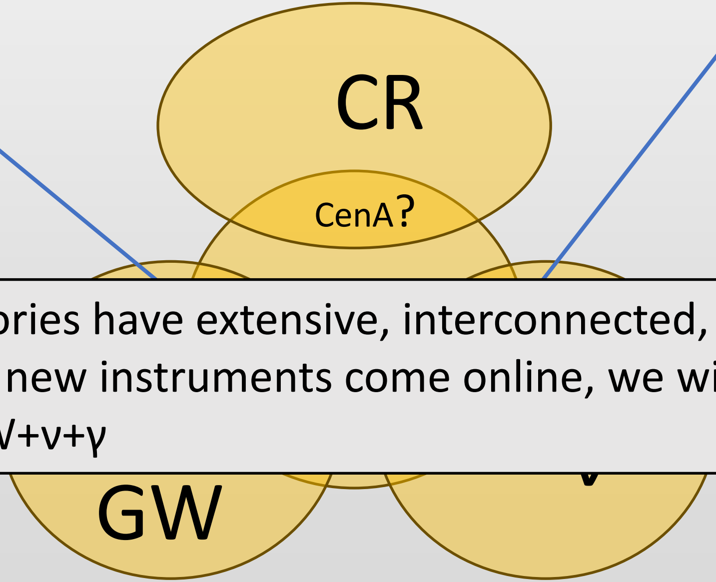

- All observatories have extensive, interconnected, alert programs
- As sensitive new instruments come online, we will see more, including GW+ν+γ

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conclusions

- Cosmic messengers of:
  - Extreme astrophysical environments
  - The highest energies
  - Possible new physics
- New observatories on the horizon with wealth of new science
  (SN background, new TeV neutrino sources, cosmogenic neutrinos, many (mHz) GW sources)
- Networks for Multi-messenger science drastically increases the science reach
- Strongly interconnected, and connected to (other) particle physics
  - Many interdisciplinary physics cases: neutron stars, x-sections for cosmic rays, dark matter searches, probing the early universe...
  - Desire & need for strong European collaboration: theory, computing, coordination & support