The future of neutrino astronomy

Gwen W De Wasseige

https://agenda.irmp.ucl.ac.be/event/468

Pwd: neutrinos

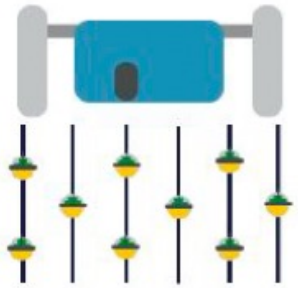
UCLouvain

Francqui Foundation

Neutrinos in the Multi-Messenger Era

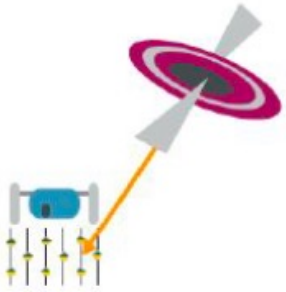
20 talks last week

10 talks summarized in this contribution

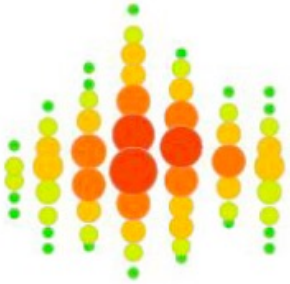


IceCube completion

Diffuse astro flux



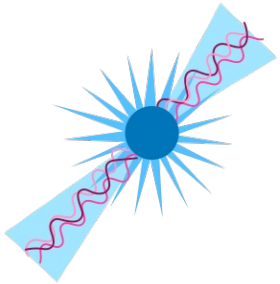
TXS0506+056



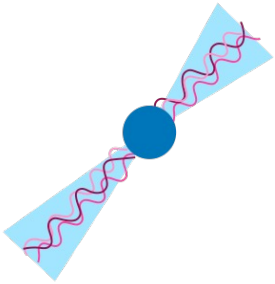
Glashow event

NGC1068

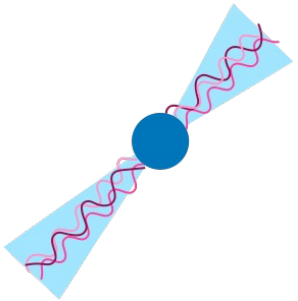
GW150914



GW170817



IACT's GRBs



GRB221009A

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022

Master

PhD study

Postdoc

Professor


Neutrino
astronomy


Neutrino
astronomy
110


Neutrino
astronomy
110

Summary

APPEC

- Astroparticle Physics is a booming and blooming field
- In search of the wonders of the cosmos
- Going to understand the fundamental law of Nature
- Plenty of opportunities for young scientists
- APP RI are central for the forthcoming Multi-Messenger Era

APPEC:

- Publication of Roadmap Update in 2022
- Coordination of European Astroparticle Physics strategy…
- …in cooperation with neighboring fields
- APPEC Newsletter: https://www.appec.org/latest-news/newsletters

…and further foster and coordinate the European Astroparticle Physics!

Andreas Haungs

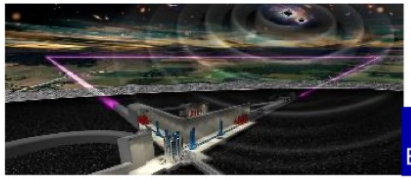
APPEC Flagship Research Infrastructures

This is not a closed, but dynamic list…

[construction KM3NeT 2020-2026; IceCube-Gen2]

ESFRI

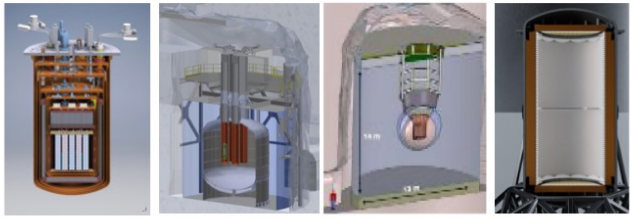
HE Neutrinos



ESFRI

[construction Einstein Telescope 2026-]

Gravitational Waves



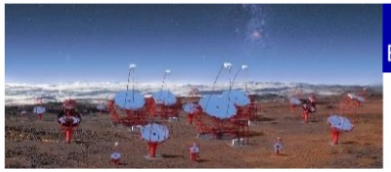
[construction LEGEND-1000 / nEXO 2023- ; …]

Neutrino Properties

[construction AugerPrime 2019-2023]

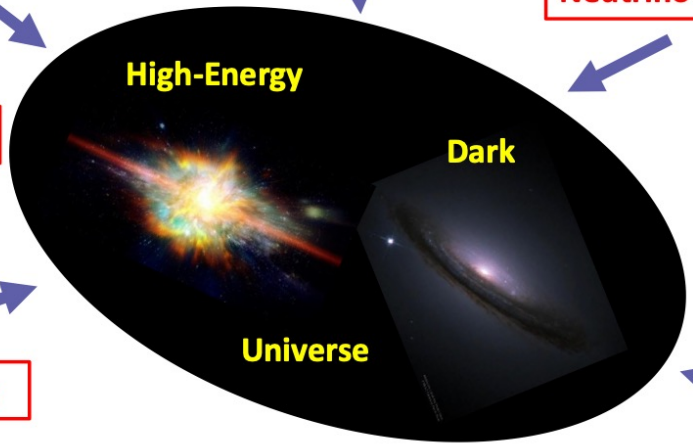
HE Cosmic Rays

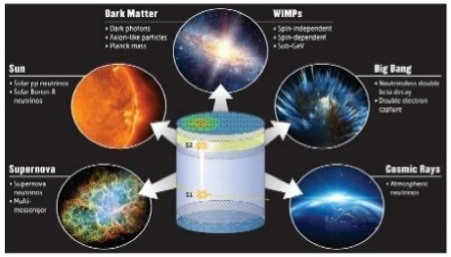
[construction CTA 2021-]



ESFRI

HE Gamma Rays





[construction DARWIN 2024- ; XLZD, ARGO, …]

Dark Matter

Andreas Haungs

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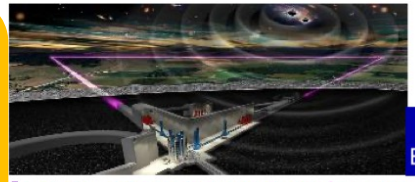

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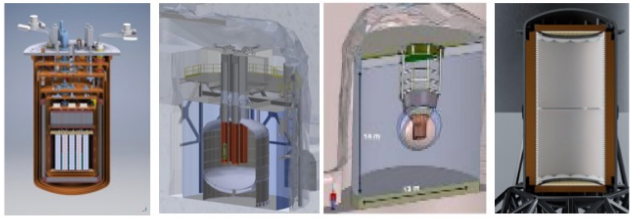

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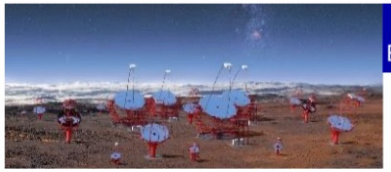
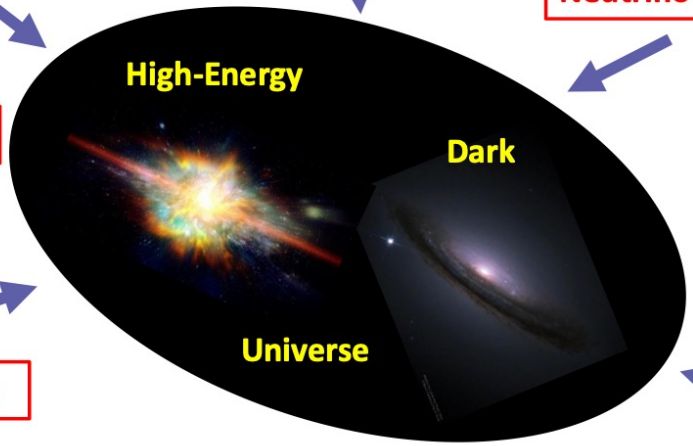
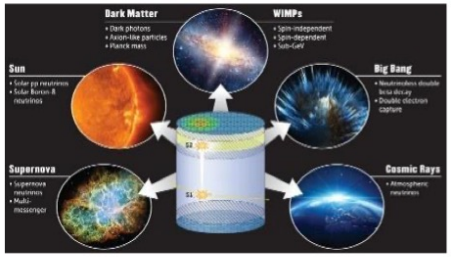


ESFRI

HE Gamma Rays





[construction DARWIN 2024- ; XLZD, ARGO, …]

Dark Matter

Andreas Haungs

Why neutrinos?

Multi-messenger synergies

Optical telescopes: TAROT, GRANDMA, MASTER, LCOGT, ZTF, LSST…
- Easy access follow-up of large error box
- Characteristation of the potential counterpart with spectroscopy (nature, redshift…)

X-ray telescopes: Swift, INTEGRAL, SVOM, ATHENA…
- Very clean sky
- Provide transient triggers (GRB, AGN, Novae…)
- ToO program (not so easy access)

γ-ray telescopes: Fermi-LAT
- All-sky complete monitoring
- Provide transient triggers (GRB, AGN…)

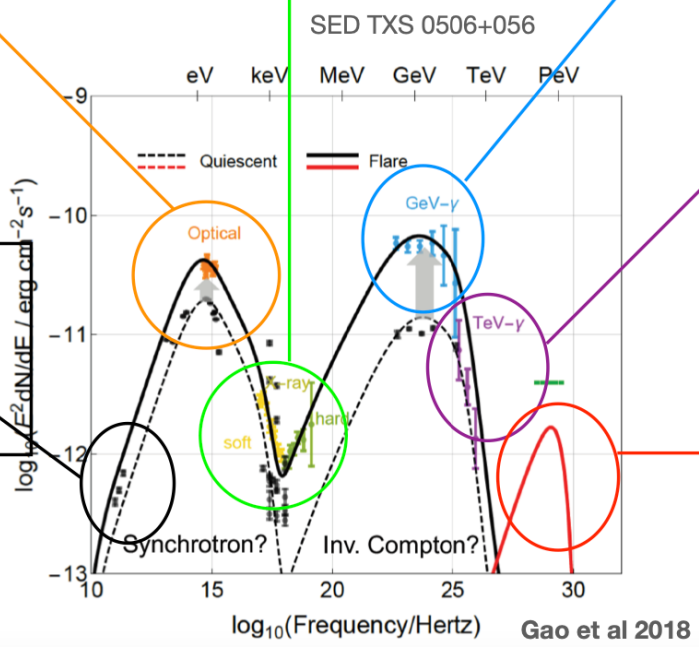
VHE γ-ray telescopes: HESS, MAGIC, CTA…
- Most natural common science case
- Follow-up (not easy access)

VHE γ-ray telescopes: HAWC, LHAASO…
- All-sky monitoring
- Provide triggers

Neutrino telescopes: ANTARES, IceCube, KM3NeT, GVD…
- Mutual follow-up
- Confirmation of sources, improve significance

Radio telescopes: Parkes, MWA, Lofar, Nenufar, ASKAP, SKA, VLBI…
- Provide triggers (FRB…)
- Follow-up

+ link with LIGO/VIRGO
+ SK, SNEWS



Why neutrinos?

New-physics menu

1. Neutrino-matter cross section
2. Unstable neutrinos
3. New neutrino interactions
   (If time allows)
4. Neutrinos & dark matter
5. Flavor composition
6. Physics with individual sources
7. ANITA mystery events

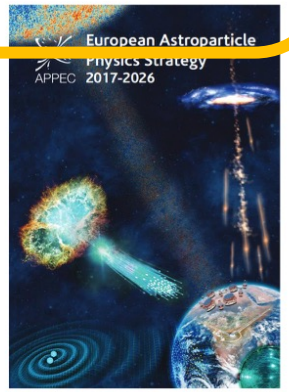
APPEC organisational & societal issues

Organisational:

- European and global collaboration and coordination
- Neighboring communities
- European Commission
- Unique infrastructures
- Interdisciplinary opportunities

Societal:

- Diversity
- Education and outreach
- Open Science and Citizen Science
- Transfer Knowledge
- Connection to industry
- Ecological impact



JENAA
Joint ECFA-NuPECC-APPEC Activities

https://indico.cern.ch/e/JENAS2022

Horizon Europe
THE NEXT EU RESEARCH & INNOVATION PROGRAMME (2021–2027)

Andreas Haungs

REINFORCE

REsearch INfrastructures FOR Citizens in Europe

https://docs.google.com/forms/d/e/1FAIpQLSfIRYiYJN_jb7dtPVi_J5QdYiOUP27ugtXObn7G-gGFGFRHkA/viewform?usp=sf_link

Speeding up

Cascades vs tracks	Cascades + Tracks + Double cascades
Upgoing track searches	All-sky all-flavour searches
1 km^3 detector	At least 3 km^3 detectors around the globe
Seeing the diffuse flux	Resolving sources

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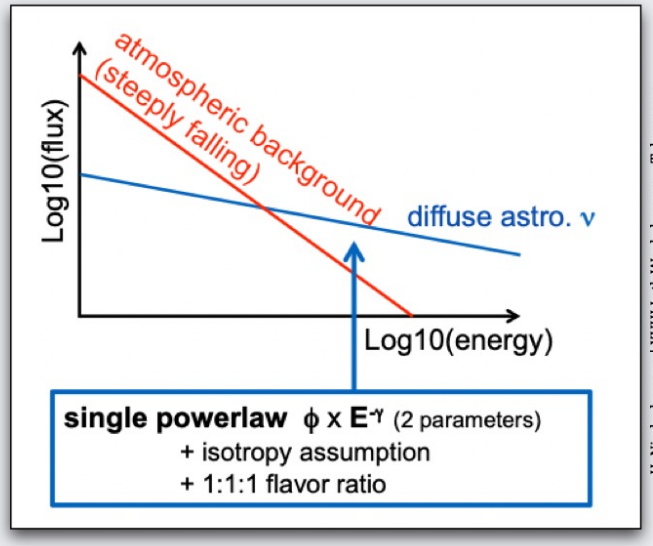
Cascades + Tracks + Double cascades

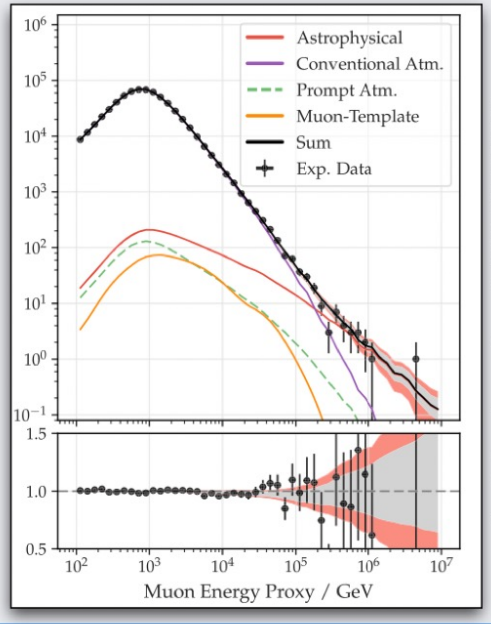
Introduction

- Diffuse ν^{astro}: excess at high E_ν
- Give insights into acceleration and propagation of high-E cosmic rays



H. Niederhausen | XVIII Intl. Workshop on ν Telescopes

- Possible sample slices: Contained, Upgoing, Track-like, Cascade-like, Tau-like
- Possible sources: AGNs, choked GRBs, TDEs, Starburst galaxies…

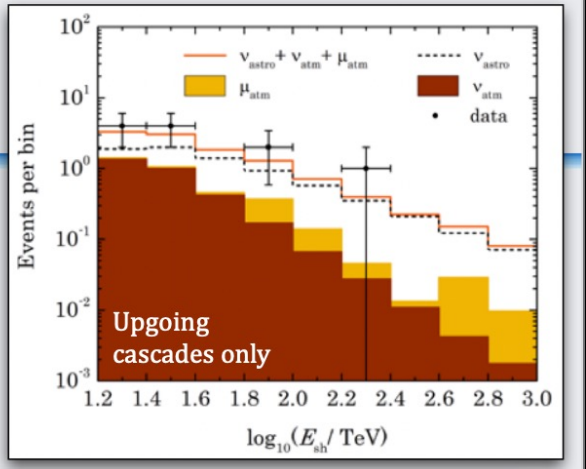


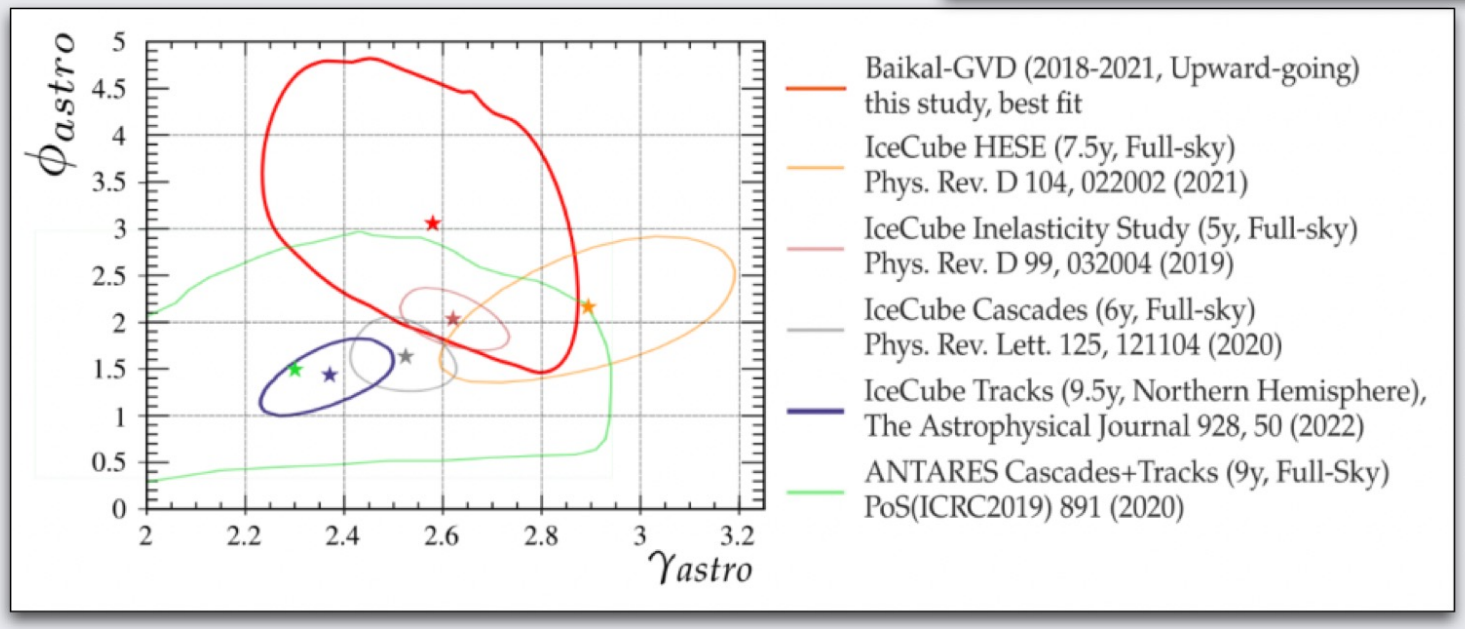
IceCube, Astrophys. J. 928, 50 (2022)

Cascades + Tracks + Double cascades

New Results: GVD

- Based on cascade-like events
  - Consistent with other msmts.





https://arxiv.org/pdf/2211.09447.pdf

Cascades + Tracks + Double cascades

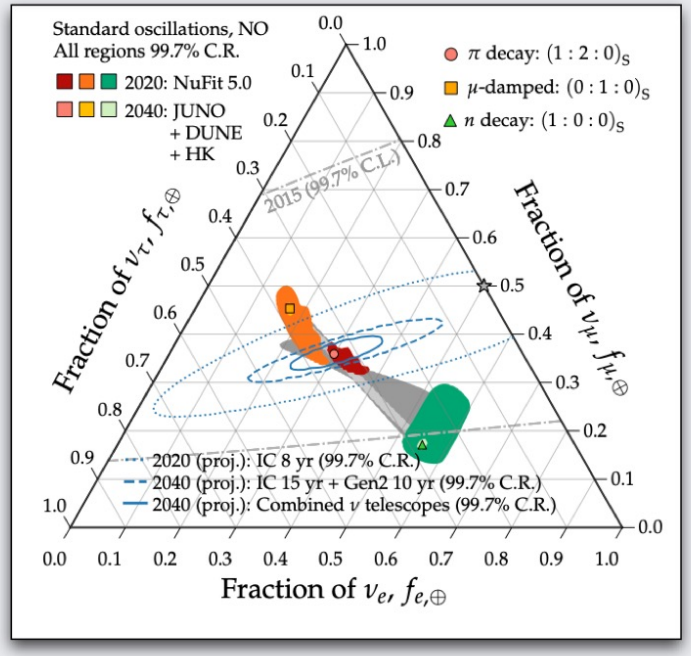
ν_τ^{astro}: A New (Multi-)Messenger?

- Detection of ν_τ^{astro} is very challenging. Why bother?
  - Can help pin down flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ at sources
    - More insight into acceleration environment
  - Improves access to cosmic baseline ν oscillations
    - Strong deviations from 1:1:1 at detector→new physics?

Cascades + Tracks + Double cascades

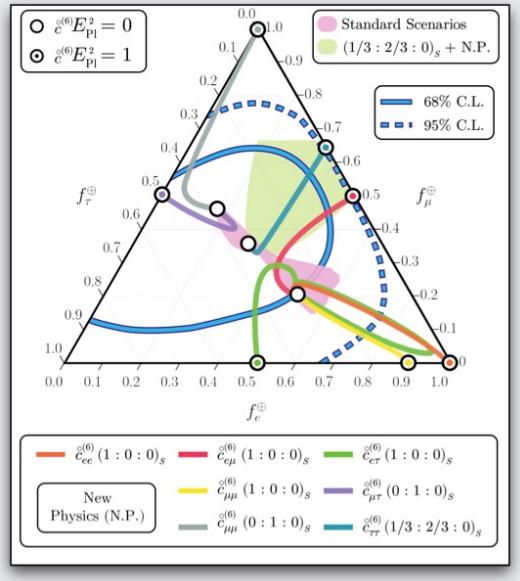
Importance of Flavor ID for ν^{astro}

At Earth, $\nu_e : \nu_\mu : \nu_\tau$ could tell us about the source…



https://arxiv.org/abs/2012.12893

…while strong deviations from 1:1:1 could mean new physics.



https://arxiv.org/abs/2111.04654v1

Example: Effect of quantum gravity.

For more examples, see Refs. 22-59 in IceCube, PRD 104, 022002 (2021).

Doug Cowen

See also Carlos Argüelles' talk

Cascades + Tracks + Double cascades

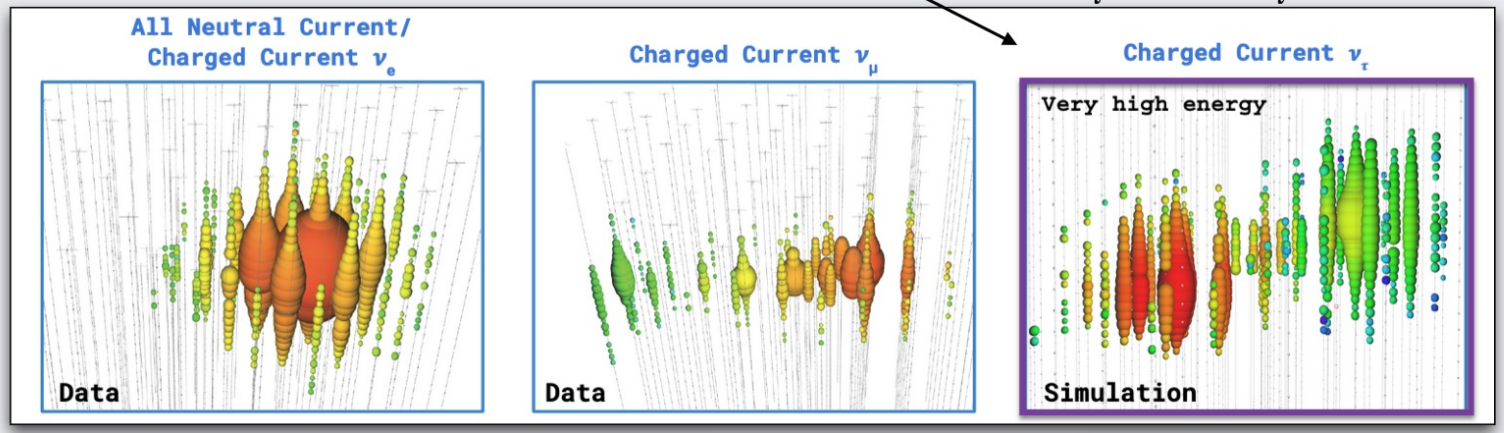
ν_τ^{astro}: Signatures

Spheres: DOMs
White: recorded no light
Color: recorded light
Size: light collected

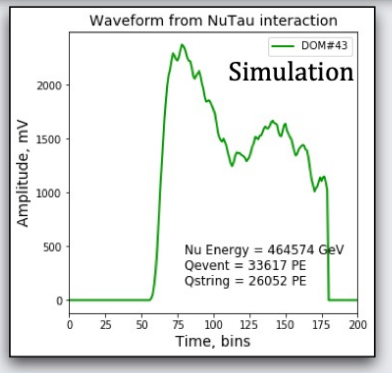
Color shows time information:
Early — Late

At high energies: "Double Bang."
Unfortunately, very rare.

$L_\tau \simeq 50\text{m} \cdot E_\tau\ /\text{PeV}$



More flux at lower energies!
Look for subtler signature(s) in one or more modules.



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Cascades + Tracks + Double cascades

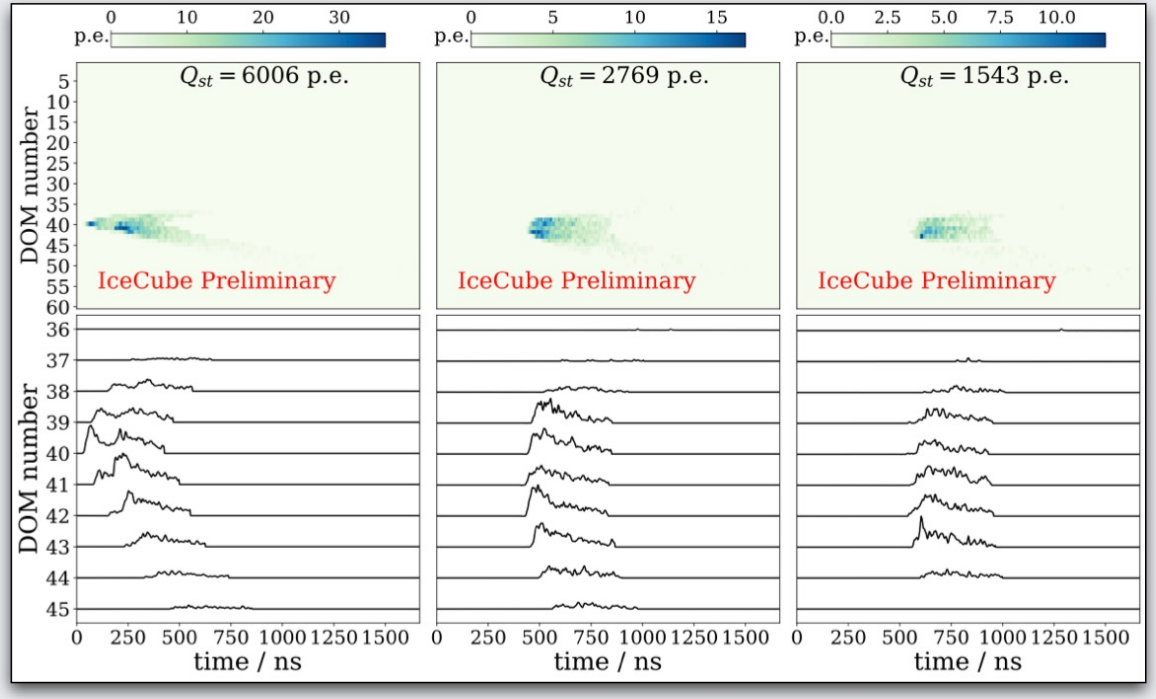
ν_τ^{astro}: Results

- Saw 7 candidate ν_τ^{astro} events
  - ~0.5 events estimated total background
  - 4 of 7 candidates not selected by previous analyses
  - 3 of 7 candidates previously selected
    - 1 of which was identified as a ν_τ candidate
  - $\Phi(\nu_\tau^{\text{astro}})$ consistent with measured $\Phi(\nu^{\text{astro}})$ from published analyses
    - $(\phi_0, \gamma) = [(2.23, 2.5), (1.36, 2.37), (2.12, 2.87), (2.04, 2.62)]$ (GlobalFit, Diffuse, HESE and Inelasticity, respectively)
- Exclusion of $\Phi(\nu_\tau^{\text{astro}}) = 0$ will be reported soon.
  - Pre-unblinding, predicted ~50% chance of ~5σ result.

Cascades + Tracks + Double cascades

ν_τ^{astro} Candidate Event Pics

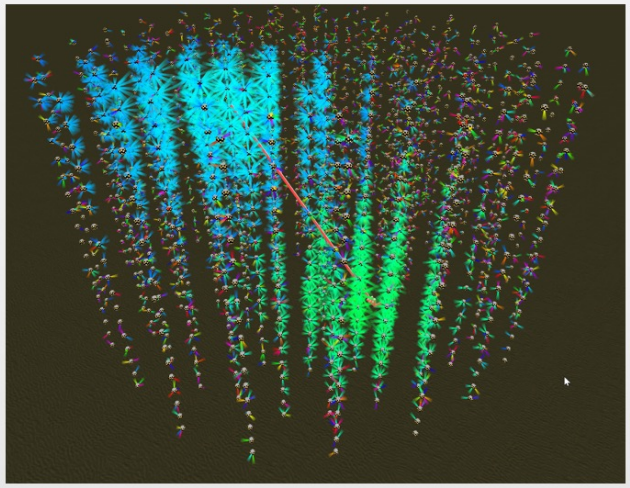
Here's "Scarlet Macaw," a new event:

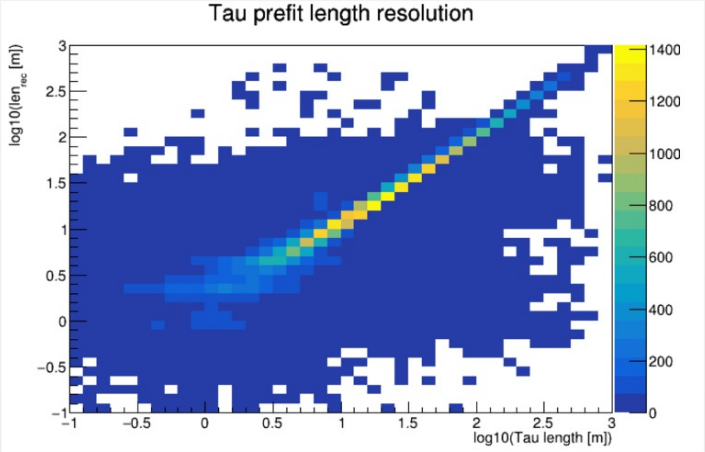


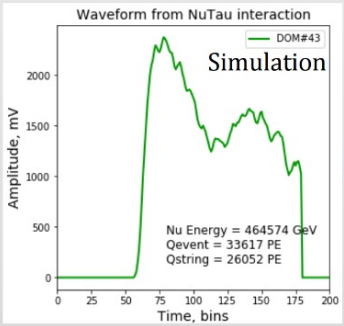
Clear ν_τ signature. Detected in 2019 (too recent for previous analyses to have seen).

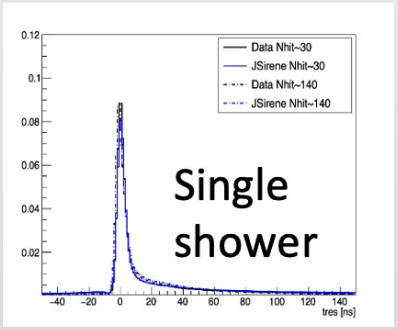
Cascades + Tracks + Double cascades

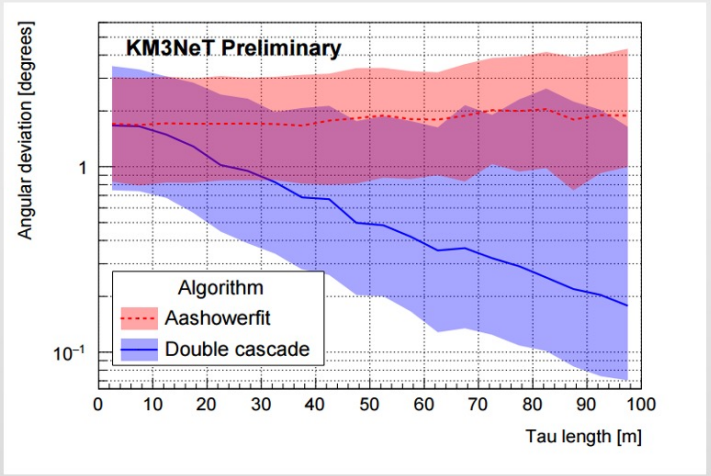
Tau neutrinos @ KM3NeT











See Aart Heijboer' talk

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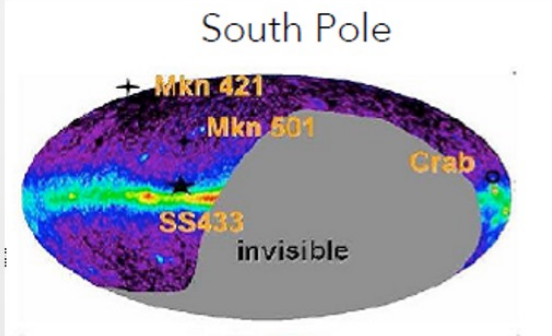
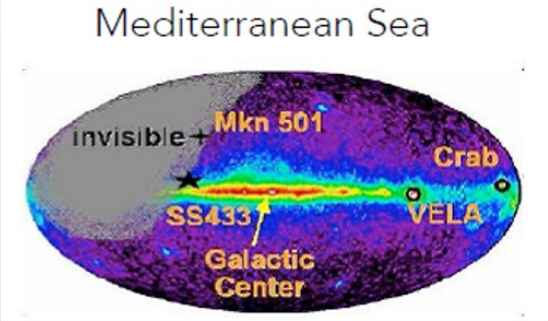
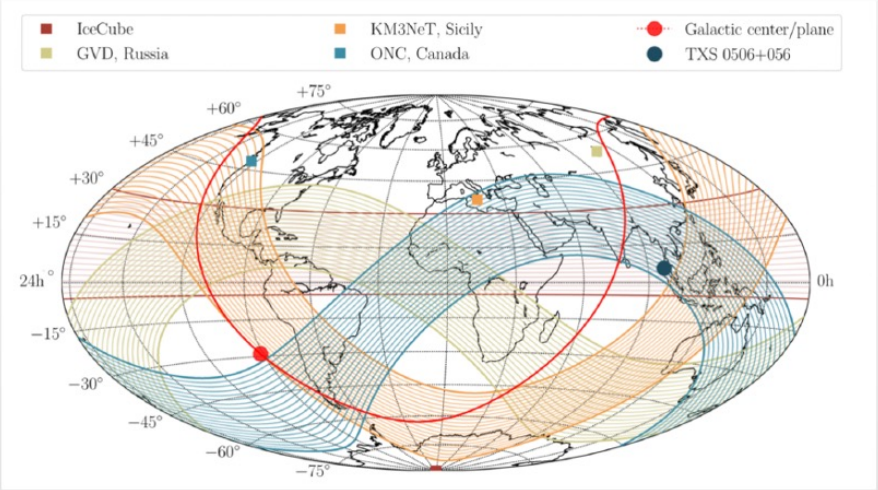




Galactic sources expected at 1-10 TeV energies.

Field of view with horizontal tracks



At highest energies : neutrinos don't make it through the Earth: horizontal tracks are golden channel. Instantaneous field of view complementary.

All-sky all-flavour searches

Lessons from the ANTARES follow-up

Key points to be improved:

- Important to have all-flavor neutrino reconstruction and classifier
- Reduce the systematics on the angular direction of the alerts (good control of the pointing accuracy)
- Private / public neutrino alerts (how to optimize the follow-up)
- Uniformise the alert format: only VO event

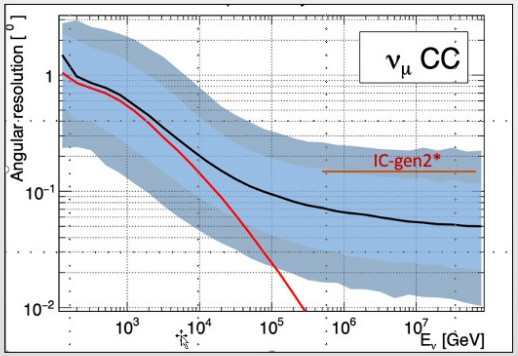
- Increase the scientific interest of the neutrino alerts (provide more astro content)
- Automatize the astro counterpart search directly at the alert level (crossmatch catalogs, LC…)

- Automatize the real-time correlation analyses as much as possible
- Have a real organized team to manage the online analyses, not only a few persons. Reinforce the MWL follow-up expertise in the collaboration. Provide some centralized tools for the shifters

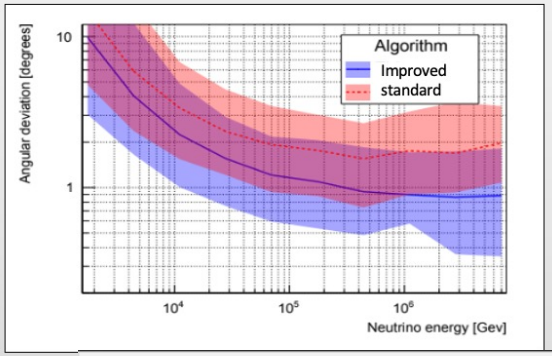
All-sky all-flavour searches

KM3NeT Resolutions

Tracks



Cascades

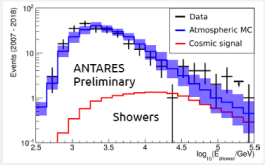


* 10 arcmin is quoted in 2008.04323v1

Aart Heijboer

Zhan Dzhilkibaev

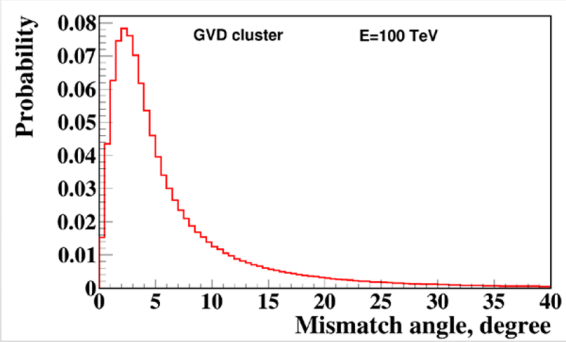
Baikal-GVD performance showers

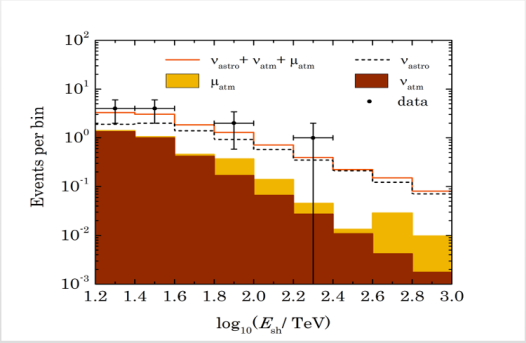


Directional resolution for cascades:
median mismatch angle ~ 4.5°

Energy resolution : δE/E ~ 30%

P-value = 0.0024 (3.05σ)





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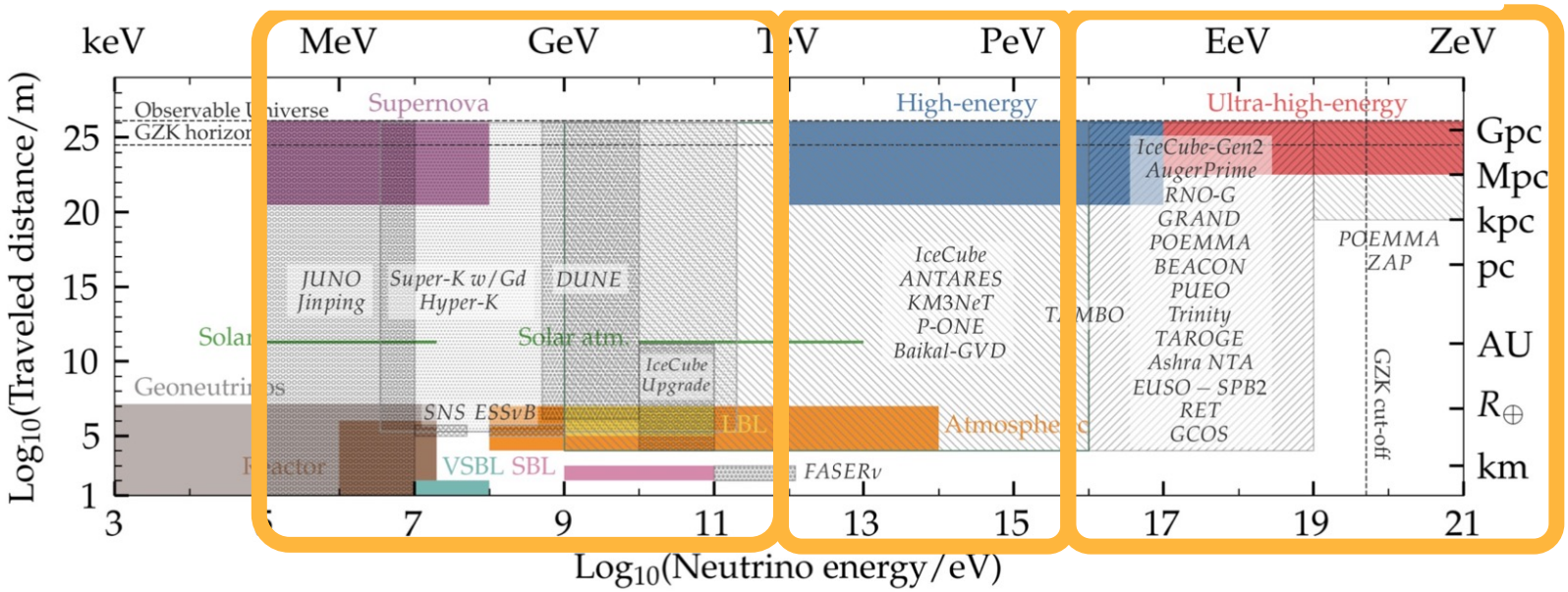
Seeing the diffuse flux	Resolving sources



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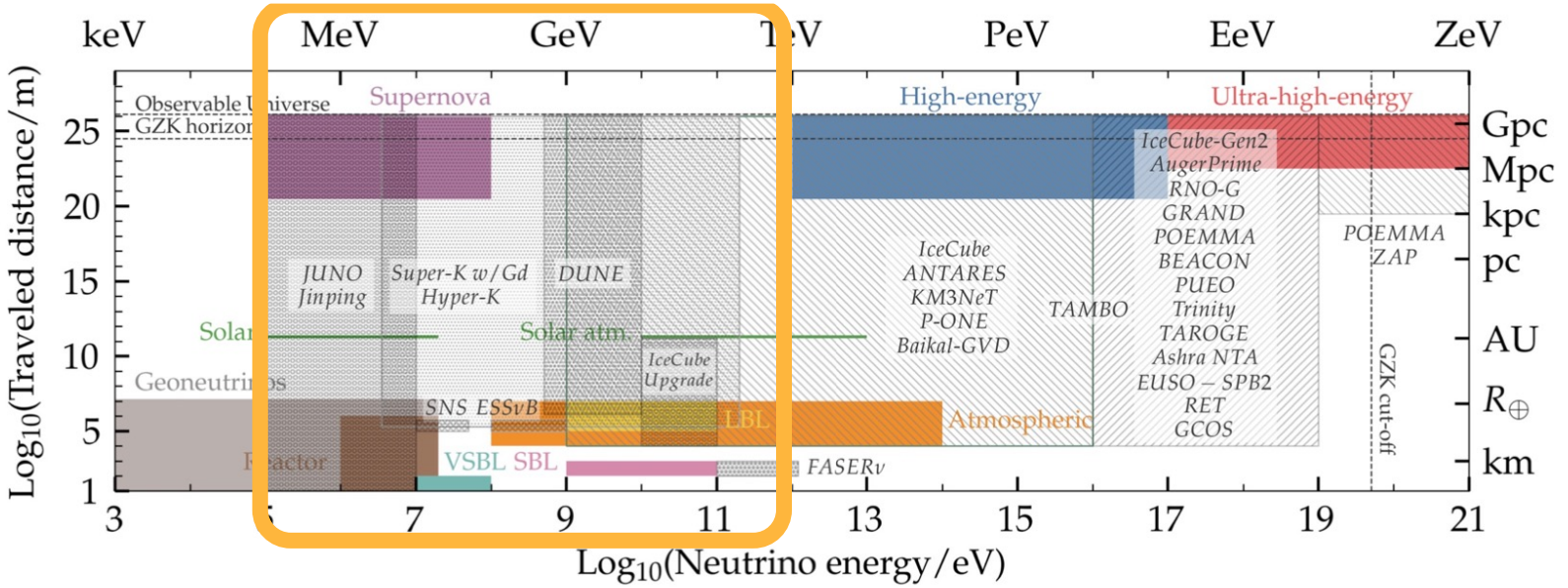

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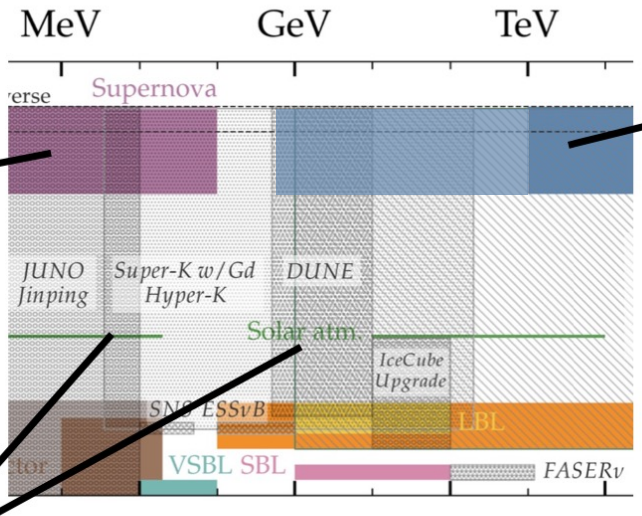
Neutrino sources in the MeV-TeV energy range

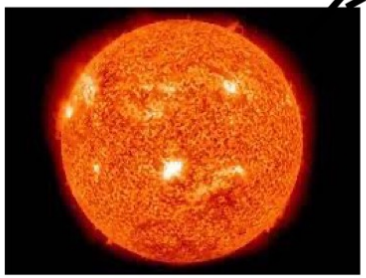
Supernova

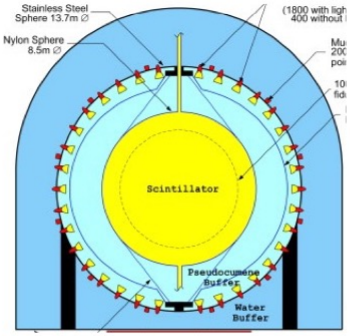


Low energy (GeV-TeV) cosmic sources

GRBs
Novae
Solar flares

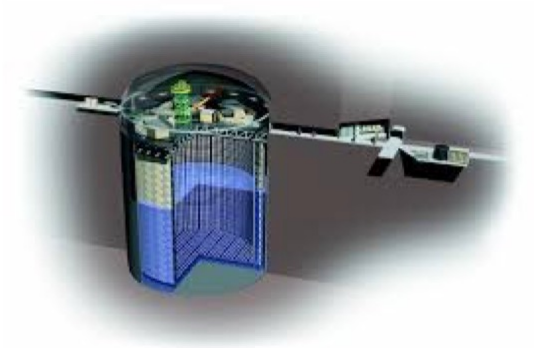
Solar





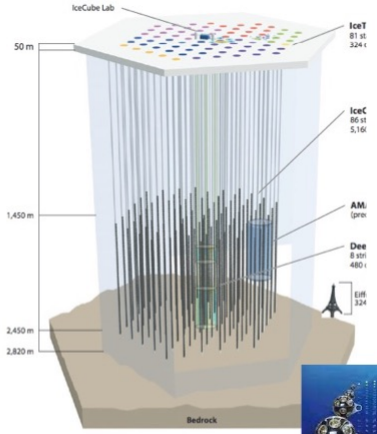
Borexino (finished)

100 Ton



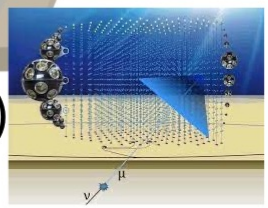
Super-Kamiokande (current)

50 kTon



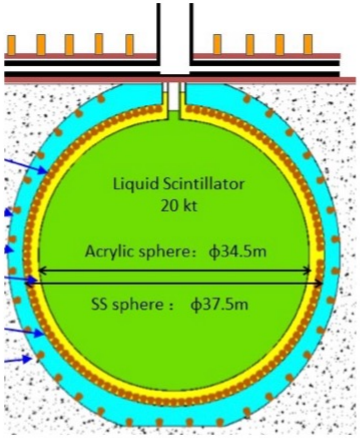
IceCube (current)

1 GTon



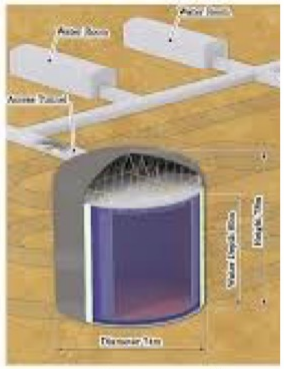
KM3Net

(coming online)



JUNO (future)

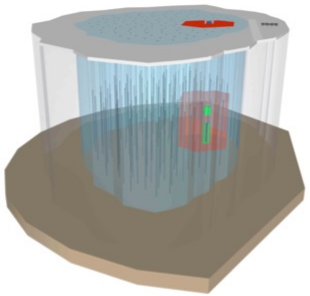
20 kTon



Hyper-Kamiokande

(future)

250 kTon

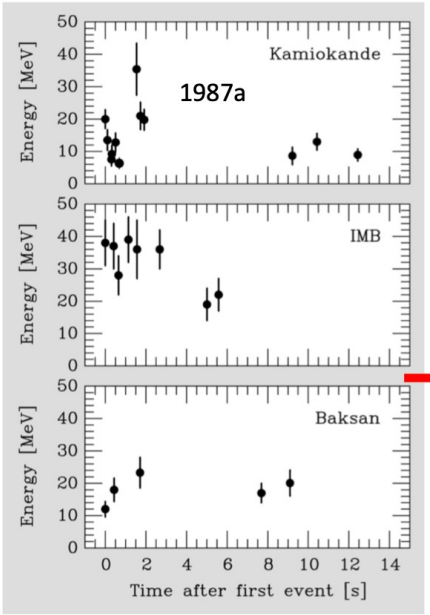


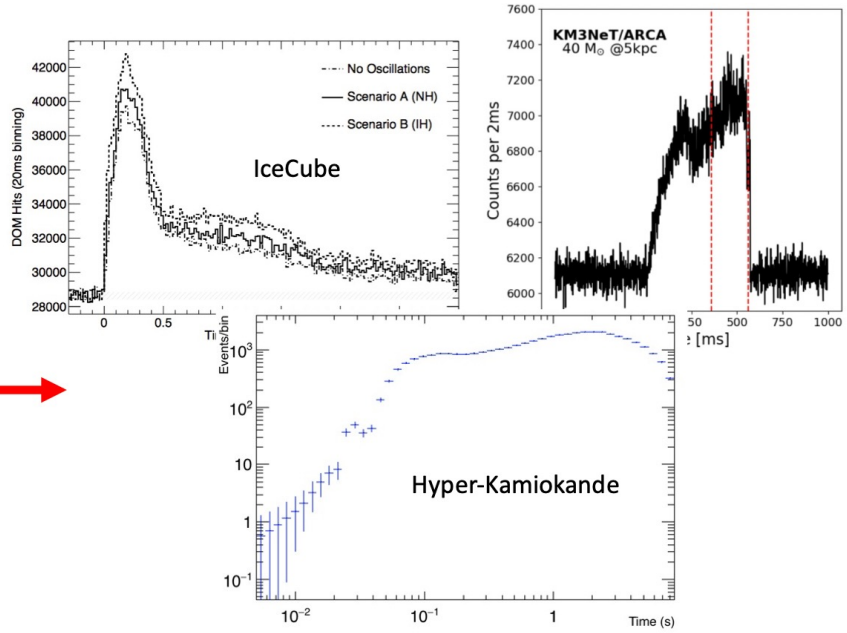
IceCube-Gen2 (future)

10 GTon

BAIKAL-GVD

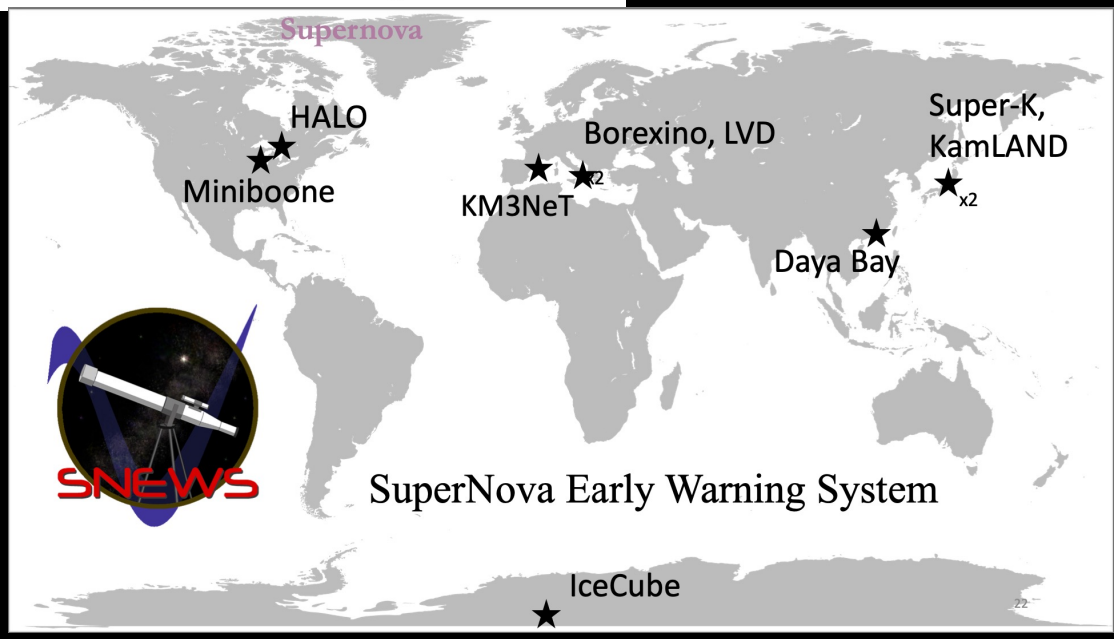
Supernova light curve in neutrinos





+ GW counterpart!

Supernova



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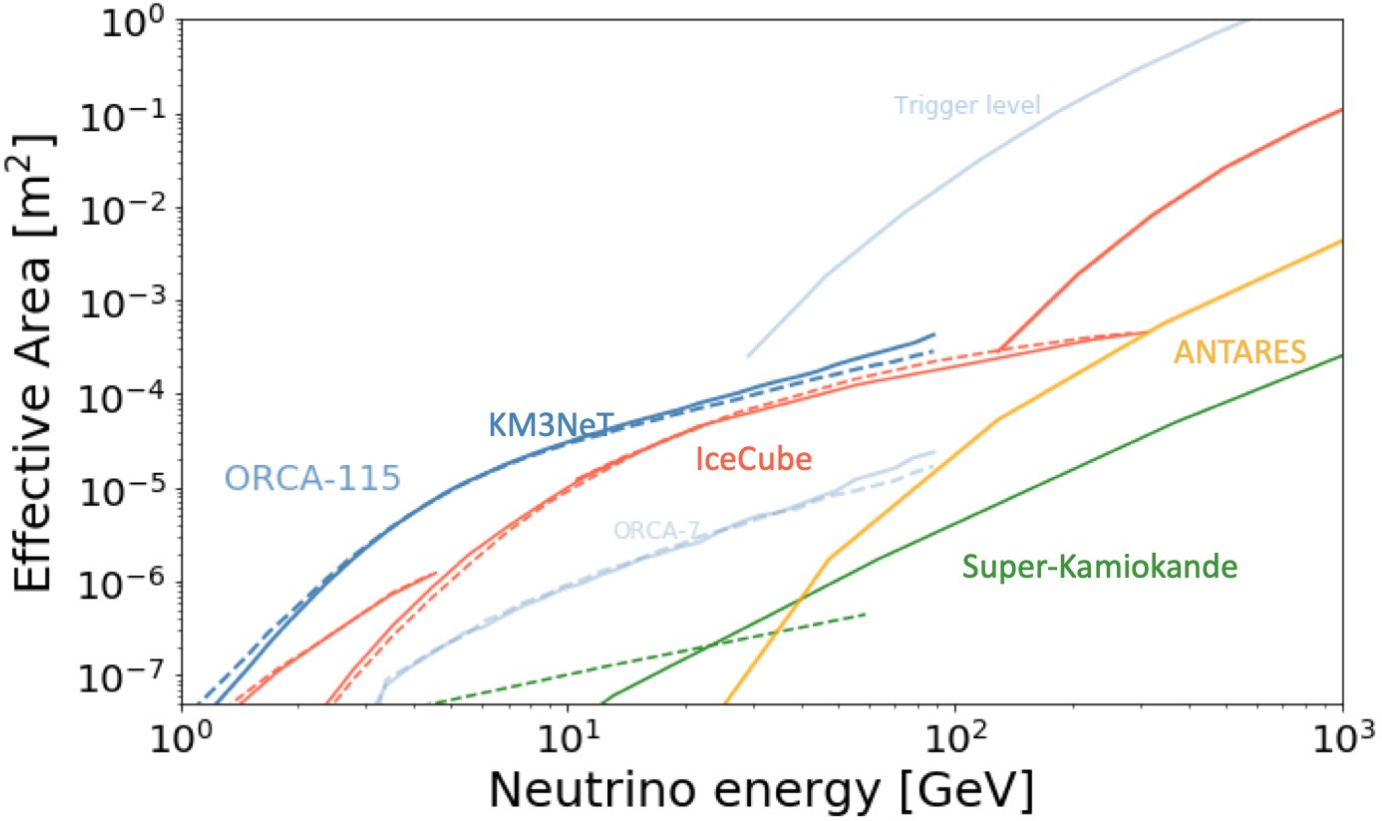
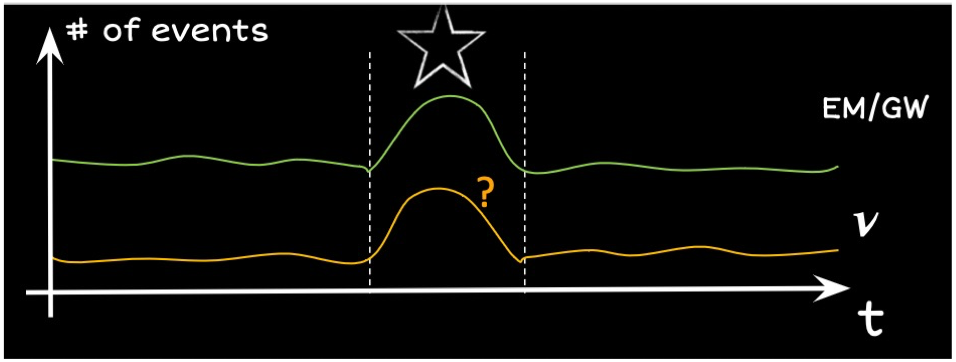
Thanks, Gwen!

GeV-TeV transients:
How do we capitalize on our full energy range?

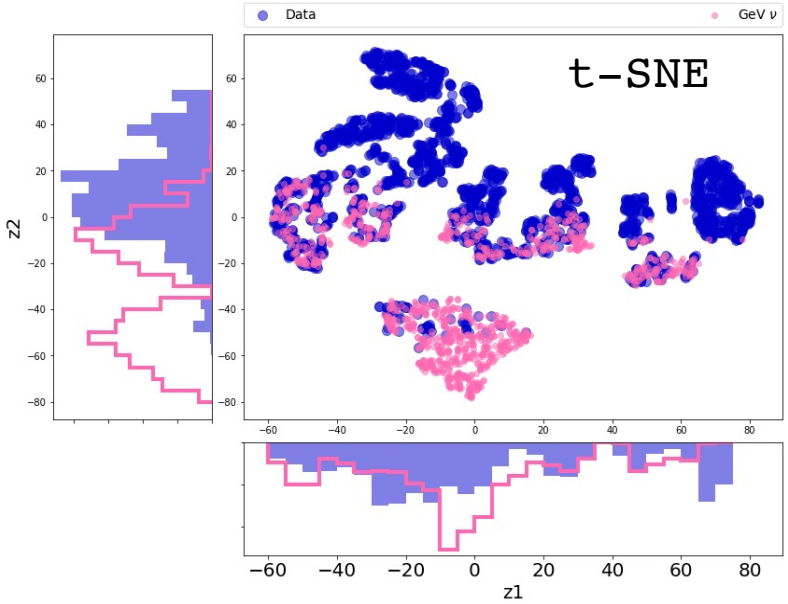


Thanks, Gwen!

Low energy (GeV-TeV) cosmic sources



Tight timing coincidence with transients
– suppress the (huge) atmospheric background



Weak and hard to reconstruct events
- Big benefit with machine learning

Motivation for low-energy neutrino searches

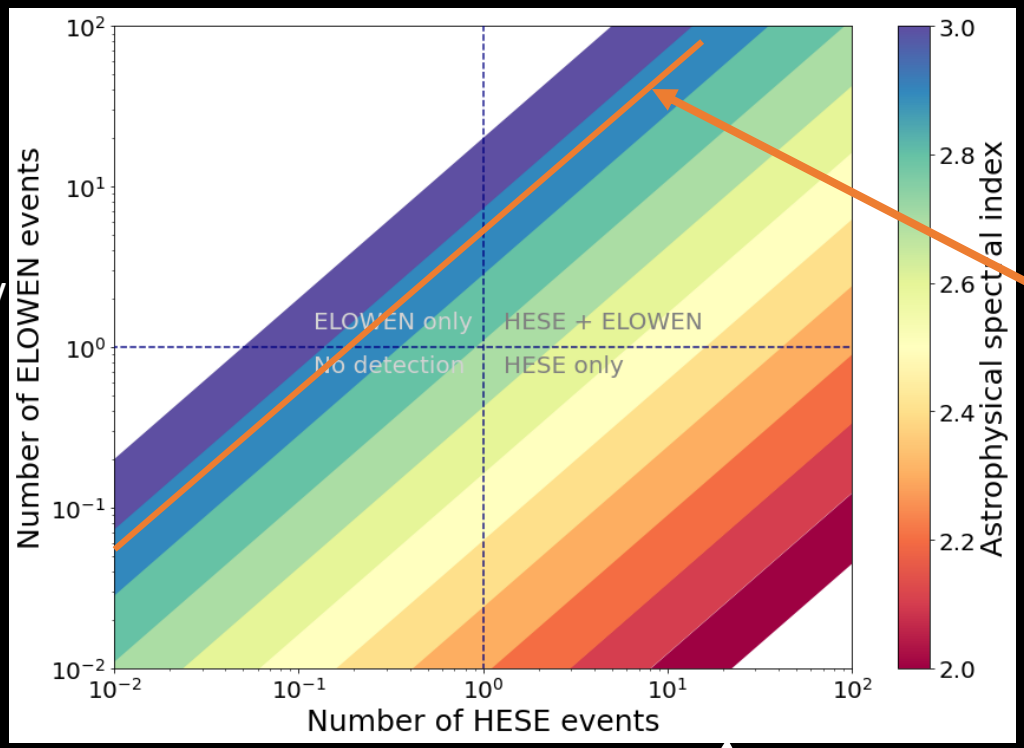
$$N_{events} = \int dE \quad A_{eff} \times \Phi$$

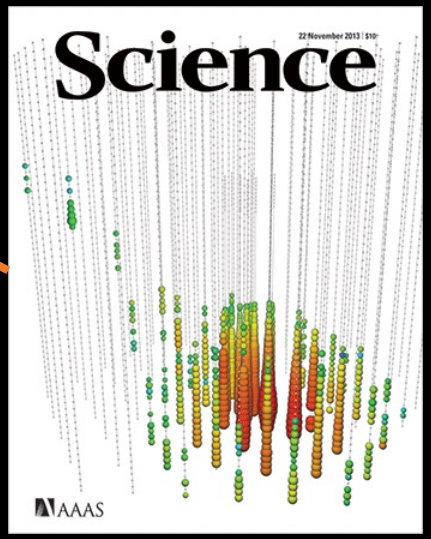
$$= \int dE \quad (A \times E^{b}) \times (C \times E^{-d})$$

We know:
- A_{eff} of HESE selection
- A_{eff} of low-energy selection

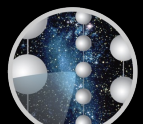
2 steps:
1- What is the flux producing 1 high-energy event
2- What is the number of low-energy events produced by this flux

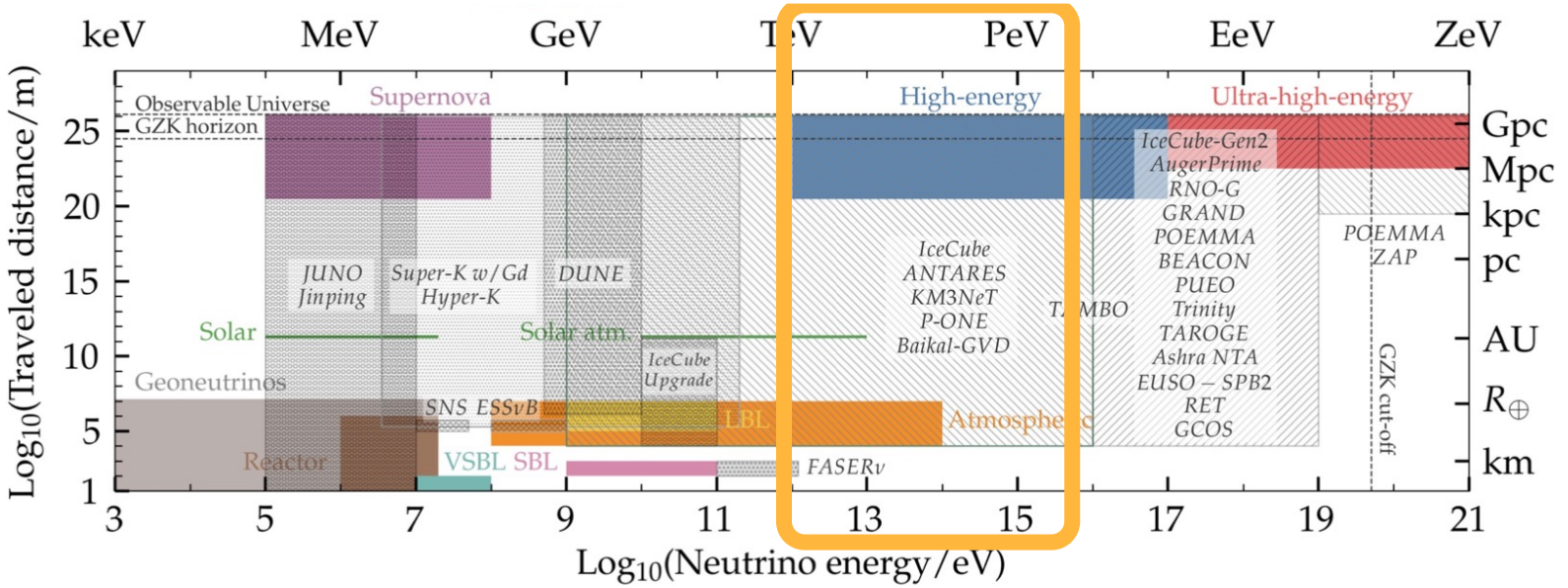
0.5-5 GeV





TeV-PeV scale





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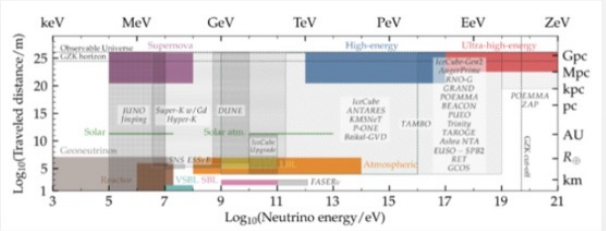
Rich landscape



Instruments

- P-One
- IceCube Gen-II
- KM3NET ORCA + ARCA
- IceCube + deepcore + upgrade
- GVD

sources

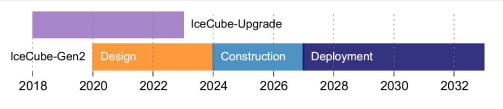
- Galactic SNR
- Tidal disruption events
- AGN, Blazars
- Atmospheric (NMO++)
- Diffuse (?) cosmic flux
- Dark Matter
- Galactic plane
- HE ?
- cosmogenic
- GRB

GeV TeV PeV EeV

guaranteed signals | speculative

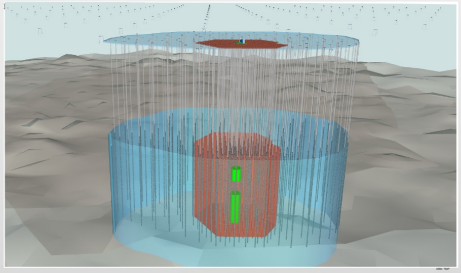
Very near future

IceCube gen-II

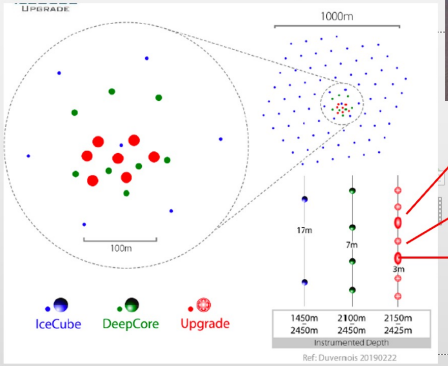


- Gen-II : current design emphasizes high energies.
- Deployment: possibly after 2027
- Not yet funded

- In short term: Upgrade!



IceCube + upgrade



Key features »

2024-25
2025-26

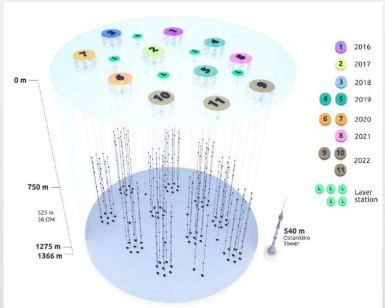
13

KM3NeT: Technology

Digital Optical Module (DOM)
- Multi-PMT : 31 x 3" PMTs
- Gbit/s on optical fiber
- Positioning & timing

18

Baikal GVD



10 clusters + 1 special string (laser+36 OM)
+ 2 experimental strings + 4 laser stations

Deployment schedule

Year	Number of clusters	Number of strings	Number of OMs
2016	1	8	288
2017	2	16	576
2018	3	24	864
2019	5	40	1440
2020	7	56	2016
2021	8	64	2304
2022	**10**	**80 + 3**	**2880 + 84**
2023	12	96	3456
2024	14	112	4032

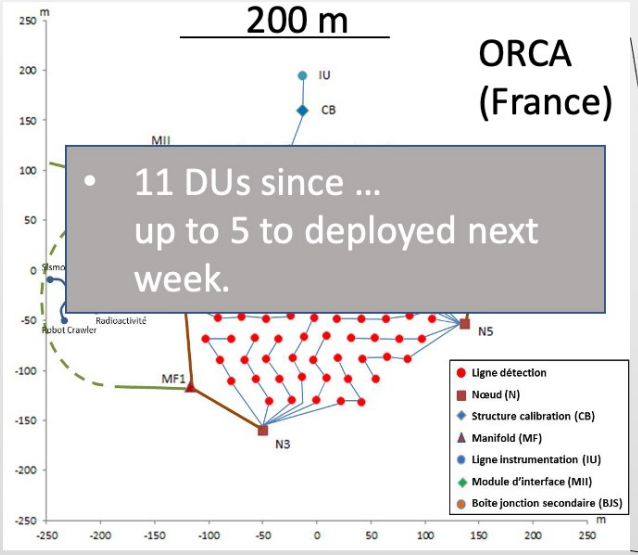
Large volume instrumented.
0.5 km^3 for cascades above 100 TeV

Multi-cluster ν_μ events in progress

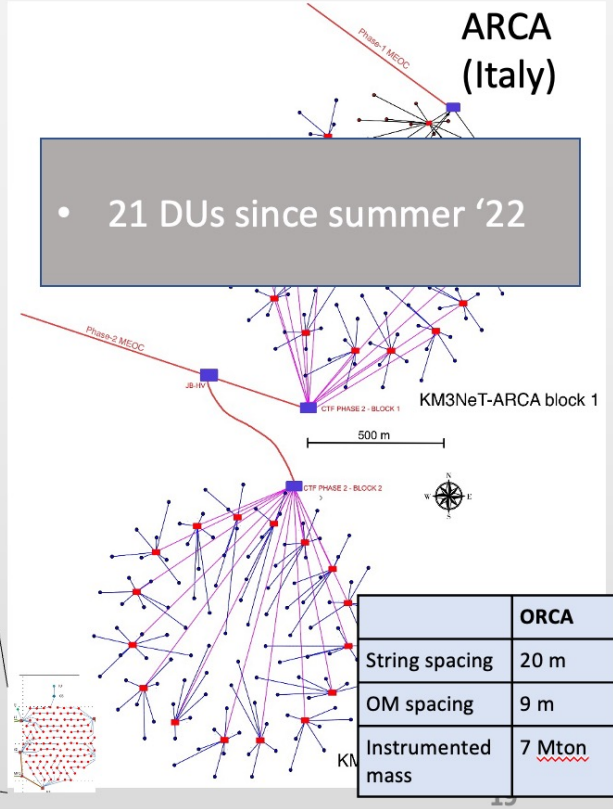
8

Very near future

Building blocks



- 11 DUs since …
  up to 5 to deployed next week.



- 21 DUs since summer ‘22

	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Instrumented mass	7 Mton	500*2 Mton

10 clusters + 1 special string (laser+36 OM)
+ 2 experimental strings + 4 laser stations

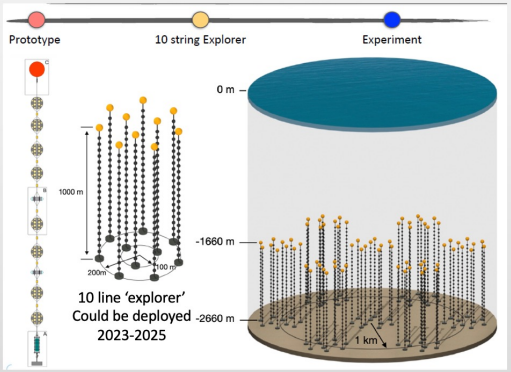
0.5 km³ for cascades above 100 TeV

Multi-cluster ν_μ events in progress

Aart Heijboer

Planned

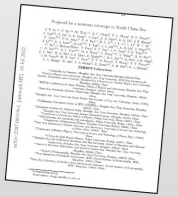
P-one

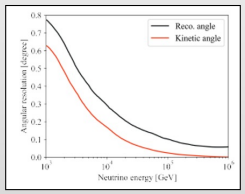


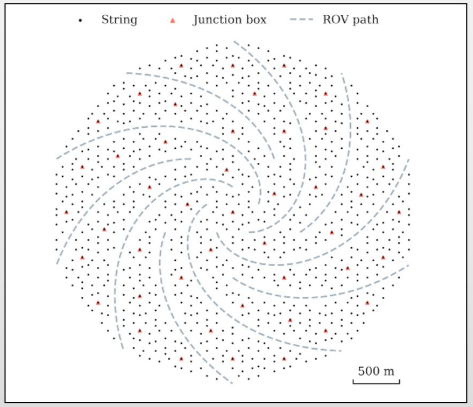
- Hosted within the oceanographic infrastructure of Ocean Networks Canada.
- Goal: neutrino astronomy from the TeV to the PeV
- To be optimised for optimal acceptance, volume and resolutions
- To be optimised for maximal complementarity with other telescopes

Trident

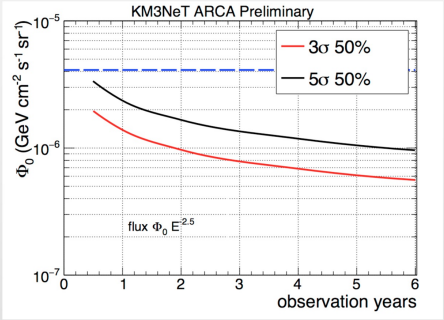
- arXiv:2207.04519
- Proposal for a neutrino telescope in South China sea.
- 1211 strings x 20 DOMs
- ~ 7.5 km3, 1211 strings

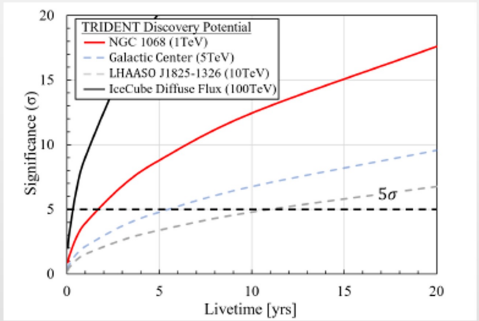






(sources of) Diffuse neutrinos



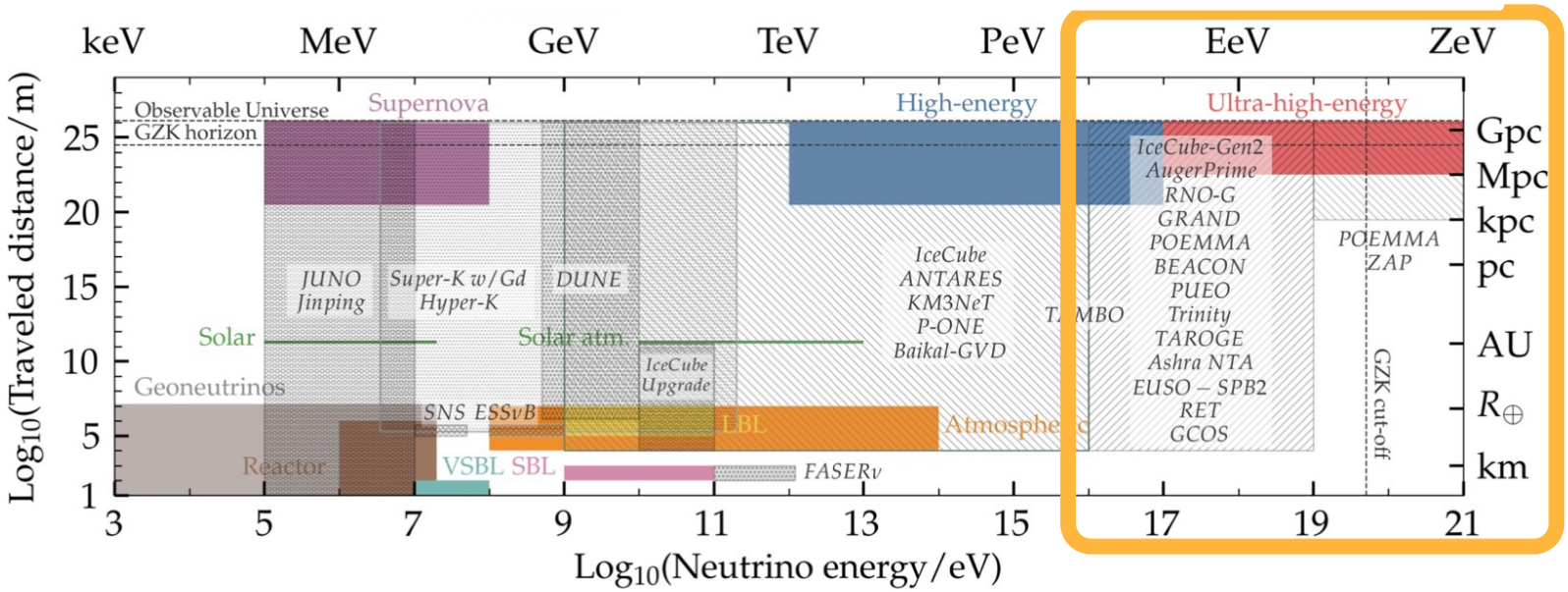


Already seen in GVD, ANTARES. KM3NeT will quickly "rediscover."
Then we'll have catalog searches with 0.1/1 degree resolutions.

Conclusions

- Interesting times!
  - ‘Many’ discovered or guarranteed signals!
  - New generation coming online and starting to produce science
  - New initiatives
    - Optimisation will be key (TeV or PeV?)

- GVD: volume for cascades, looking forward to tracks
- KM3NeT: great resolution, will grow in next years.
- IC Upgrade : may (greatly) enhance all data already on tape
- IC Gen-II & P-one: … let’s hope for funding (&KM3NeT)



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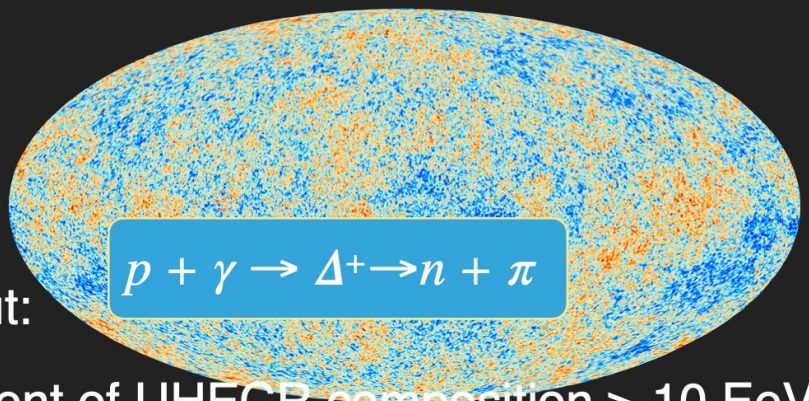
The neutrino sky: what are we hunting?

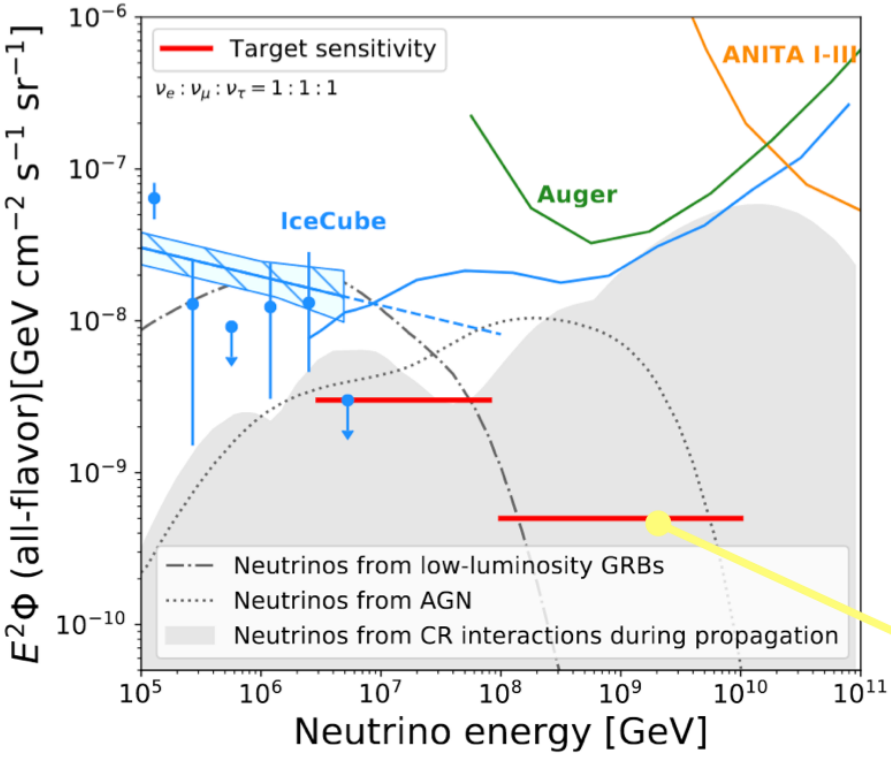
Astrophysical > 10 PeV | Cosmogenic (GZK) > EeV



UHE neutrinos can give information about:

- Cosmogenic flux serves as measurement of UHECR composition > 10 EeV. Direct link to highest energy CRs (carry 5% of primary energy)
- Astrophysical neutrino sources (transient multi-messenger astronomy is a powerful tool with low statistics).
- Fundamental physics at energies not accessible at Earth (covered by Mauricio and Carlos this morning)

Science goal: target sensitivity of new experiments



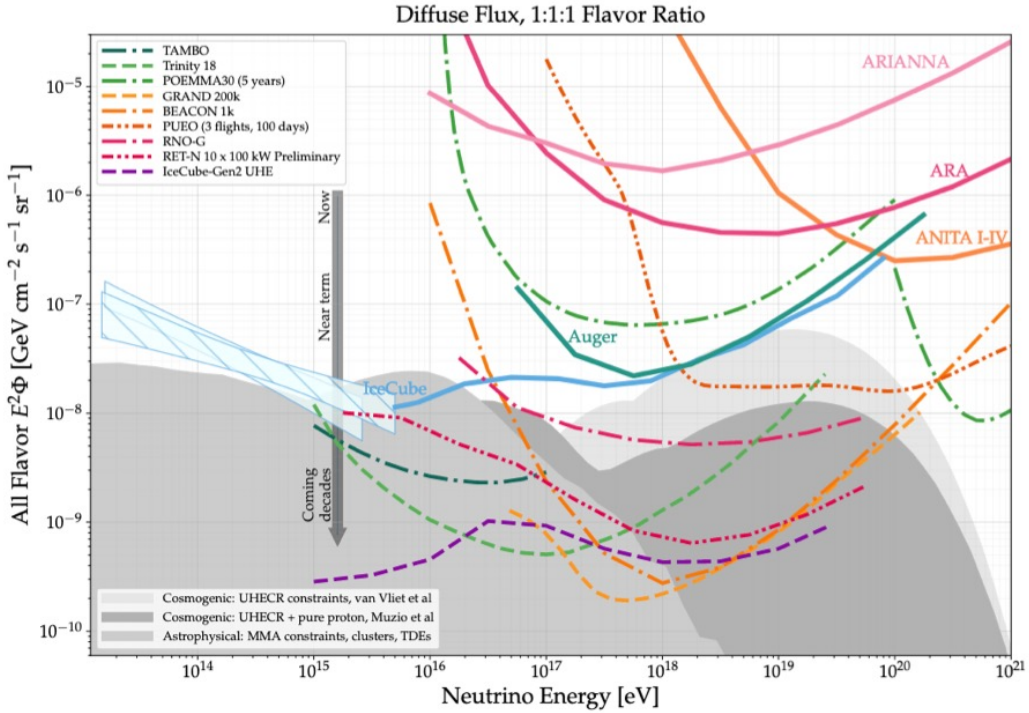
[Ackerman et al., Astro2020 White Paper, arXiv:1903.04334.pdf]

- Very large effective volumes (Teraton) needed.
- E > 10 PeV is an uncovered territory.

Study of the source evolution and propagation mechanism needs ~2 orders of magnitude improvement in sensitivity (to reach more pessimistic scenarios).

The experimental landscape: diffuse neutrino flux

UHE neutrinos Snowmass White Paper: arxiv.org/pdf/2203.08096.pdf



Particle detectors

Optical Cherenkov and fluorescence

Earth-Skimming in-air radio

In-ice radio

Optical Cherenkov

IceCube, Auger, and ANITA experiments already constrain the cosmogenic neutrino parameter space.
Major goal for next-generation observatories is detection (reaching pessimistic predictions: flux sensitivity near 10^{-10} GeV cm^{-2} s^{-1} sr^{-1} @ 1 EeV.

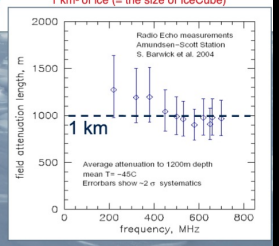
COMMON FEATURE: INSTRUMENTING HUGE EFFECTIVE VOLUMES TO REACH EXTREMELY LOW FLUX

IN-ICE RADIO DETECTION OF NEUTRINOS

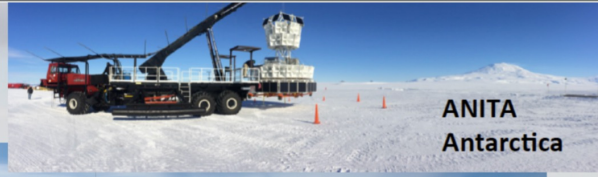
BIG EFFECTIVE VOLUME WITH SMALL NUMBER OF DETECTION UNIT (λ_{att} ~1 km)

CHEAPEST OPTION (BOTH IN HARDWARE AND DEPLOYMENT)

One radio station can typically monitor 1 km³ of ice (= the size of IceCube)



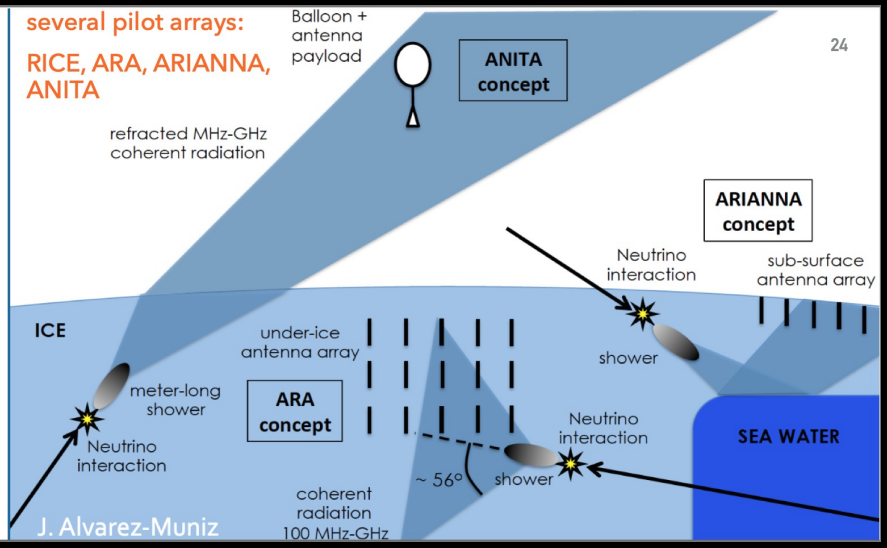
CURRENT DETECTORS: pilot radio arrays



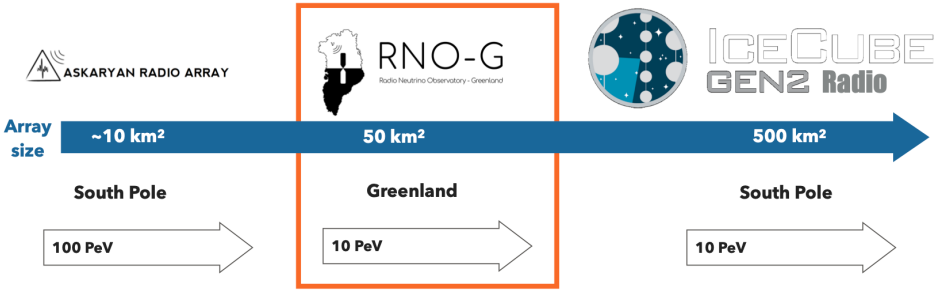
ARA
South Pole

In-ice Radio detection

several pilot arrays:
RICE, ARA, ARIANNA, ANITA

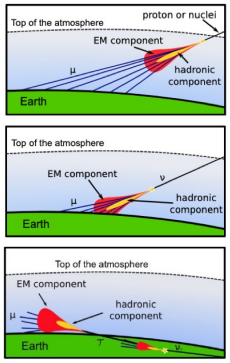


RNO-G: the road towards Gen2-Radio

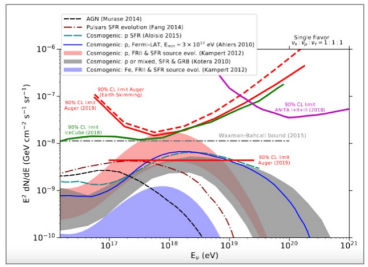


- RNO-G is a middle-scale **discovery** instrument
- RNO-G **design will inform** IceCube-Gen2 Radio design (now preparing for TDR).

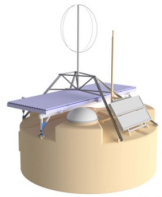
Neutrino detection at the Pierre Auger Observatory



- Mostly Earth-skimming but also very inclined down-going (dominated)
- Looking for young showers (rich in electromagnetic component).
- Strong limits constraining already several cosmogenic and astrophysical scenarios.



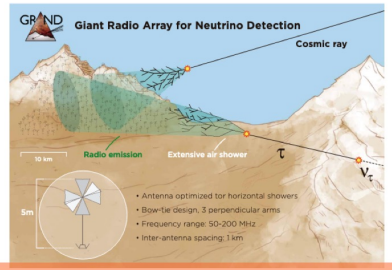
AugerPrime
completed in ~2023



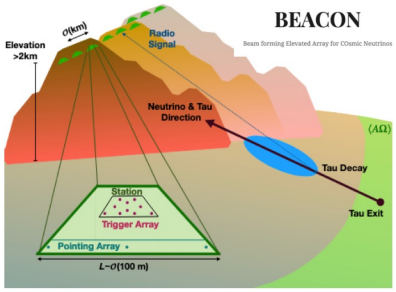
Impression of the upgraded SD

Air-shower radio detection: Earth-Skimming neutrinos

- 200k radio antennas over 200k km² : ~ 20 hotspots of 10k antennas at various favorable sites around the world
- Phased approach:
  - prototype GRANDProto300 - hardware developed, but site search delayed (COVID)
  - GRAND 10k (> 2025) - 1 sub-array
  - GRAND 200k (> 203x) - 20 sub-arrays

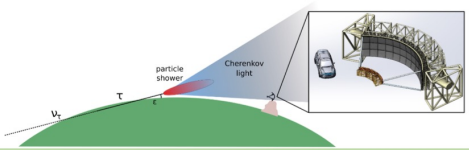


- 100-1000 stations with ~10 antennas each, viewing shower from top of mountain.
- Interferometer concept: clustered phased-array for triggering, and long-baselines for pointing.
- Prototype: 4 dual-polarized dipole already searching for CR signals (California).



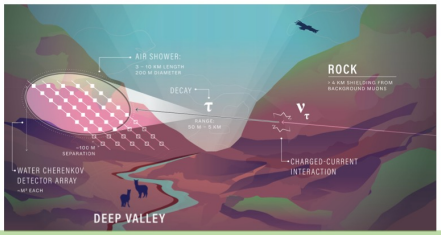
Trinity

- 8 air-shower Cherenkov telescopes optimized for detecting Earth-Skimming neutrinos in 10-1000 PeV range.
- Wide-FoV (60deg)
- Located at 2-3 km altitude
- 20% duty cycle compensated by detection of very distant showers (as far as 200 km)

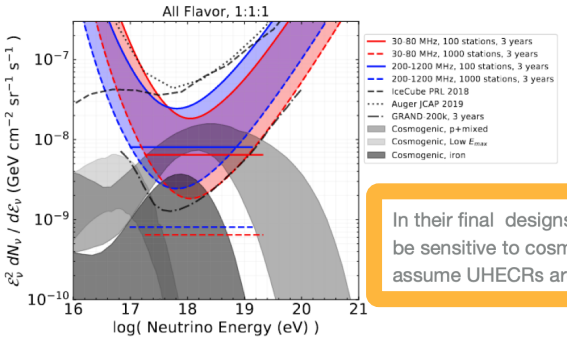


TAMBO

- 22k water tanks deployed in slope
- characterization of astrophysical neutrino flux in 1-10 PeV range (ν_τ component)
- small tank separation: low-energy threshold



Air-shower radio detection: Earth-Skimming neutrinos

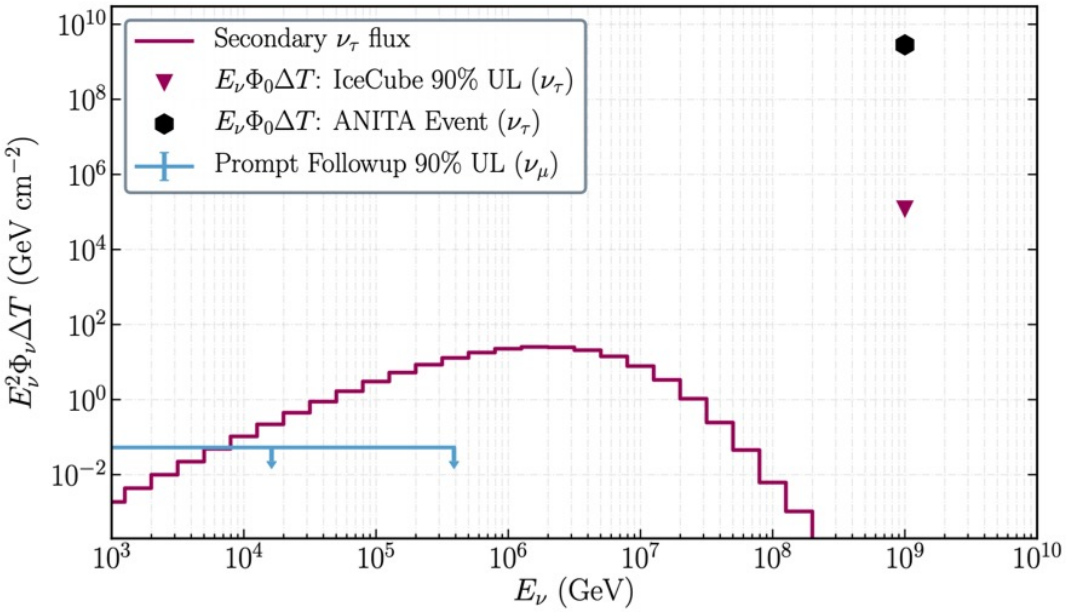


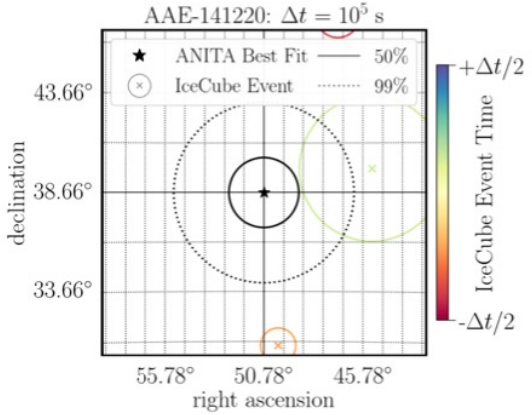
In their final designs BEACON and GRAND will be sensitive to cosmogenic neutrino models which assume UHECRs are iron only

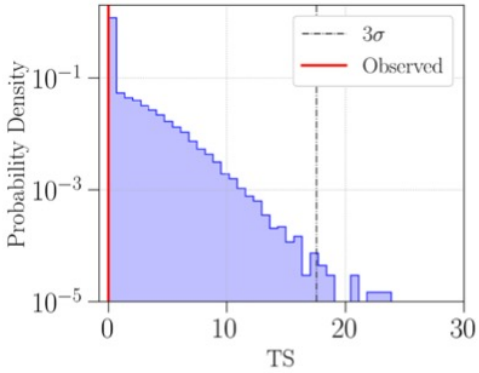
[S. Wissel et al. JCAP 11 (2020) 065]

Simona Toscano

Ruling out ANITA Neutrino Interpretation







IceCube Collaboration arXiv:2001.01737

Speeding up

Cascades vs tracks	Cascades + Tracks + Double cascades
Upgoing track searches	All-sky all-flavour searches
1 km^3 detector	At least 3 km^3 detectors around the globe
Seeing the diffuse flux	Resolving sources

We may have pass
the point of using catalogs.
Sources may/will start popping up.

Chad Finley

Neutrino astronomy is
at the same point
as Cosmology in the 90's

Mauricio Bustamante

Towards Multi-Detector and Multi-Energy
neutrino astronomy
in the Multi-Messenger Era!