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Dipartimento di Fisica E.R. Caianiello

Overview on neutrino astronomy

Marcell Grossman 17, Pescara
July 7$^{\text{th}}$-12$^{\text{th}}$ 2024

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INFN-NA Gruppo collegato di Salerno

Outline

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1. Neutrino astronomy
2. Neutrino telescopes
3. Recent results

Hadronic emission

Cosmic protons/nuclei can interact with the medium

$$p + p \to \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}, p, n, \ldots \tag{1}$$

Astrophysical beam dump

or with ambient radiation

$$p + \gamma_{\mathcal{E}} \to \Delta^{+} \to \pi^{0} + p \tag{2}$$

$$\to \pi^{+} + n \tag{3}$$

Photoproduction via Δ resonance

Hadronic emission

Astrophysical beam dump (pp process)

$$p + p \to \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}, p, n, \ldots$$

$$\begin{aligned} \pi^{+} &\to \nu_{\mu} + \mu^{+} \\ &\hookrightarrow \mu^{+} \to \bar{\nu}_{\mu} + \nu_{e} + e^{+} \end{aligned} \tag{4}$$

$$\begin{aligned} \pi^{-} &\to \bar{\nu}_{\mu} + \mu^{-} \\ &\hookrightarrow \mu^{-} \to \nu_{\mu} + \bar{\nu}_{e} + e^{-} \end{aligned} \tag{5}$$

Hadronic emission

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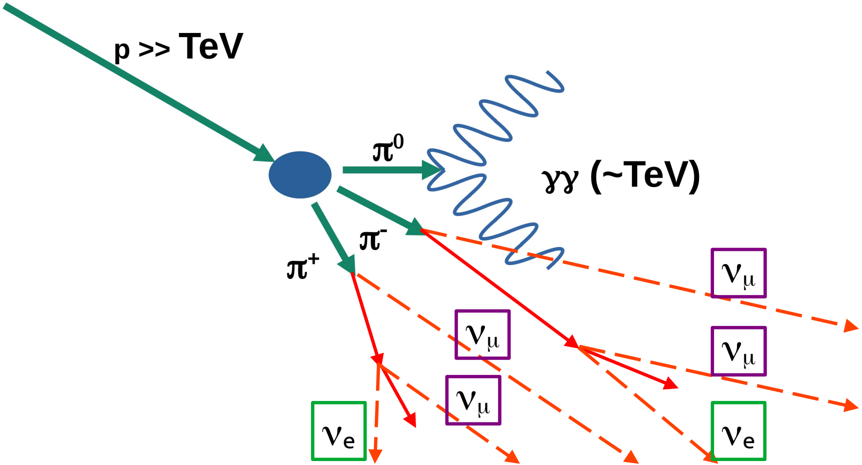

Hadronic emission

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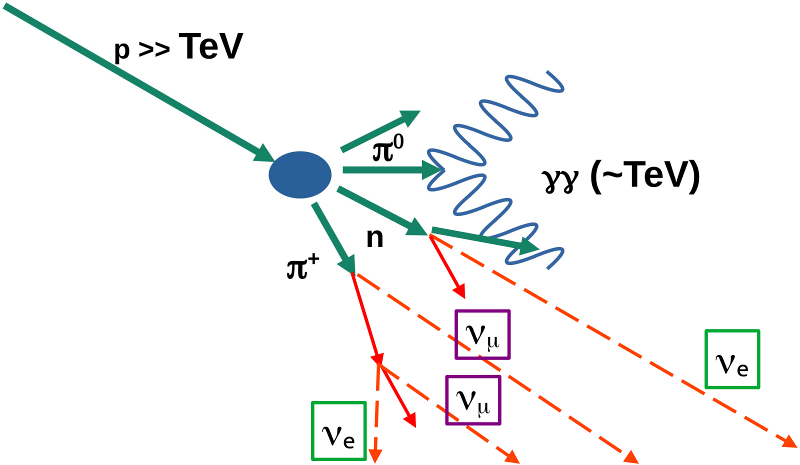
Photoproduction via Δ resonance ($p\gamma$ process)

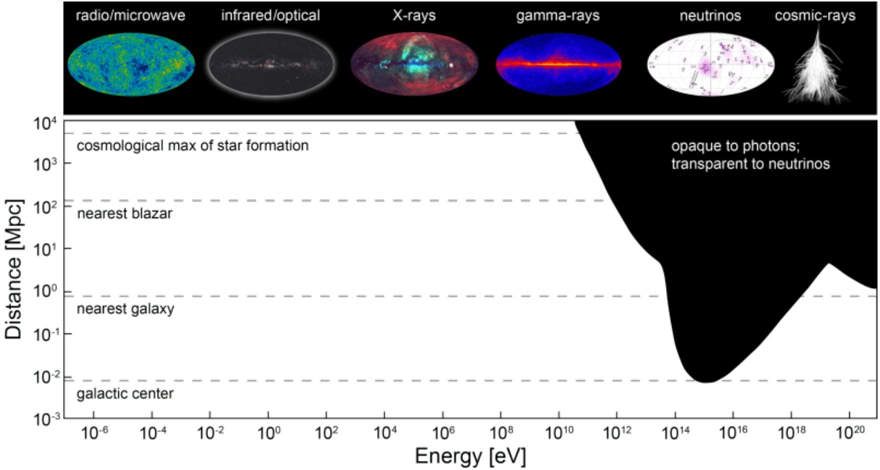
$$
\begin{aligned}
p + \gamma_{\varepsilon} \to \Delta^{+} &\to \pi^{0} + p \\
&\to \pi^{+} + n
\end{aligned}
$$

$$
\begin{aligned}
\pi^{+} &\to \nu_{\mu} + \mu^{+} \\
&\hookrightarrow \mu^{+} \to \bar{\nu}_{\mu} + \nu_{e} + e^{+} \qquad (6) \\
n &\to p + e^{-} + \nu_{e} \qquad (7)
\end{aligned}
$$

Hadronic emission



Why neutrinos?



Neutrinos from sources

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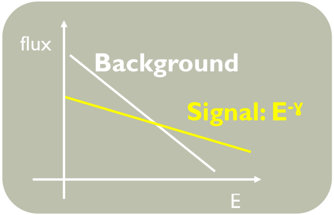
- In *pp* emission
  - Neutrinos will follow the same spectrum as the primary CR
  - Neutrinos will carry about 1/2 of the energy of photons ($\sim$5% of the primary)
  - Neutrinos will be roughly 2 times more abundant than photons
- For the $p\gamma$ processes, the outcome will be more dependent on the nature of the radiation field.

Neutrino sources search

- When we search for a neutrino signal, this is buried under background events
- Different strategies to search for it:
  - Direction
  - Energy
  - Time



Diffuse fluxes

- The ensemble of all sources which are too faint to be detected individually will produce a diffuse background (see γ- and X-ray backgrounds)
- We know this is a guaranteed flux, since high-energy CRs will interact somewhere
- Of particular interest in our Galaxy

Diffuse flux searches

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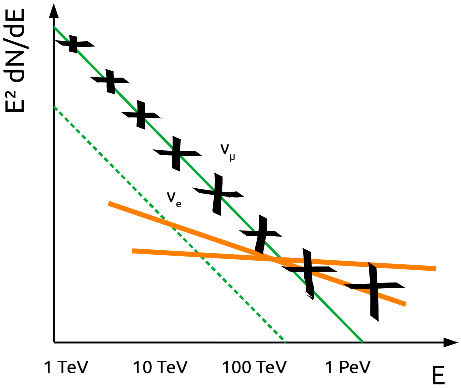
- Cosmic signal will pop out at the highest energies
- Many possibile underlying sources
- Energy estimation is crucial



How to?

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- High-energy cosmic neutrino fluxes will be low
- Neutrino cross section with matter is very low

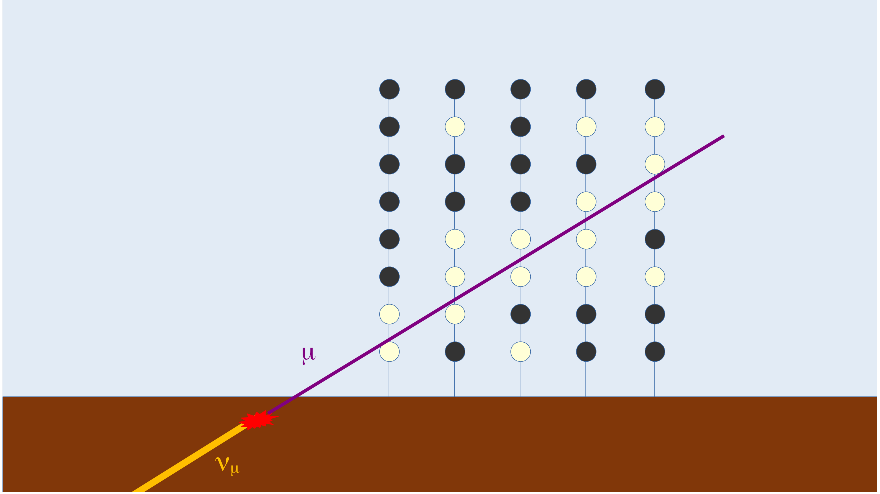
$\Rightarrow$ Detection will be difficult

And we want to measure their direction and energy accurately

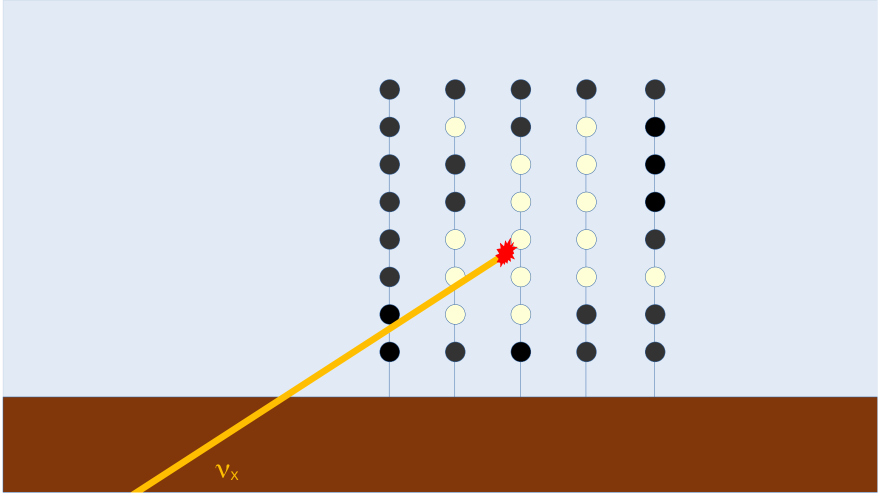
How to?

- Collect Cherenkov photons from particles coming out of the neutrino interaction
- km^3 volumes of transparent media
- At large depth (2–3 km)

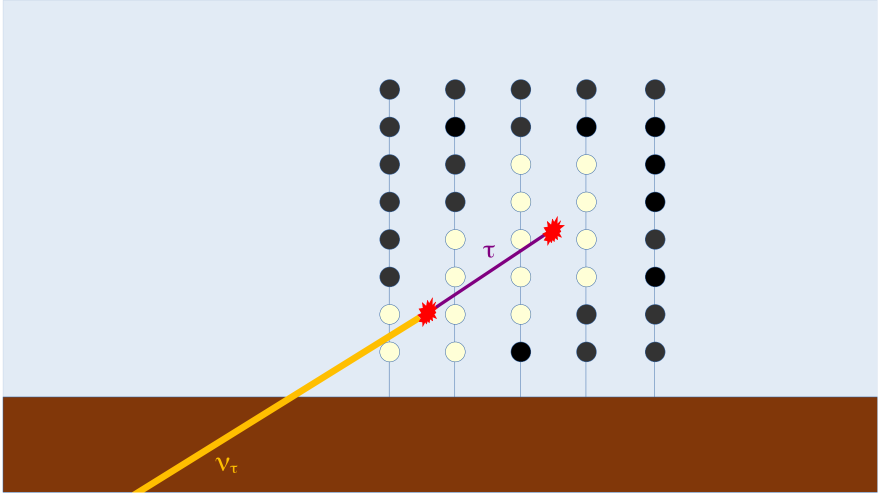
How to?



How to?



How to?



How to?

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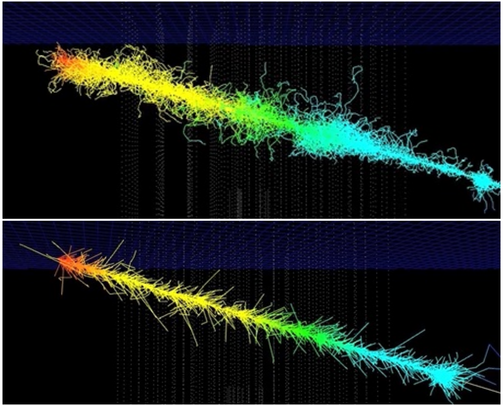
- Ice is more transparent but light scatters a lot
- Water absorbs more but light is almost always direct



The early days – DUMAND

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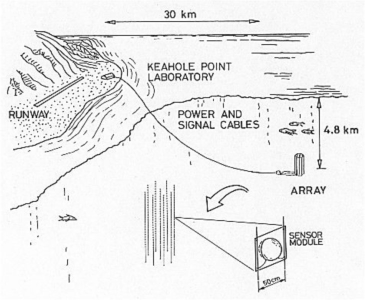
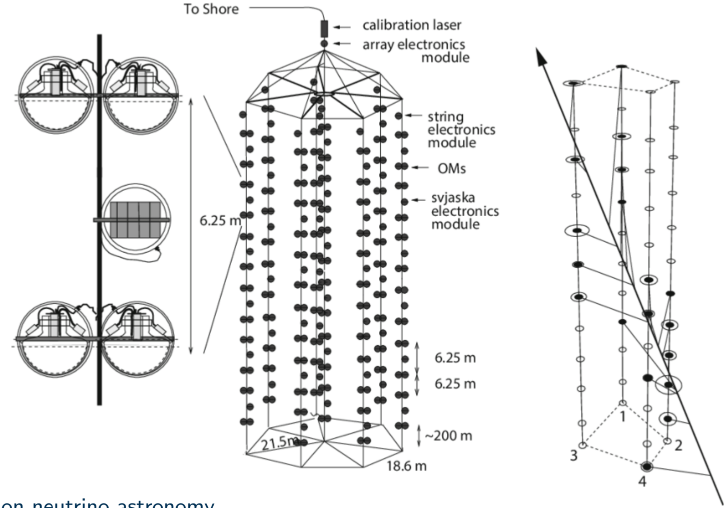
4800 m depth at Hawaii shore



The early days – Baikal



The early days – AMANDA

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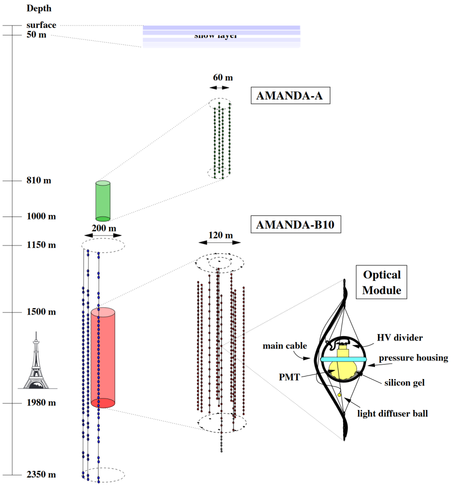

The early days – In the Mediterranean

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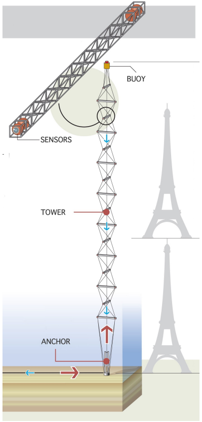
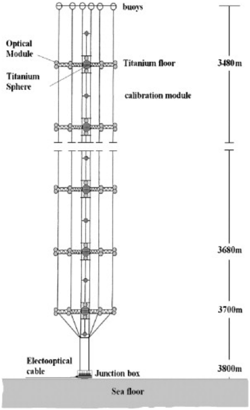


NEMO



NESTOR

IceCube (2006 – ongoing)

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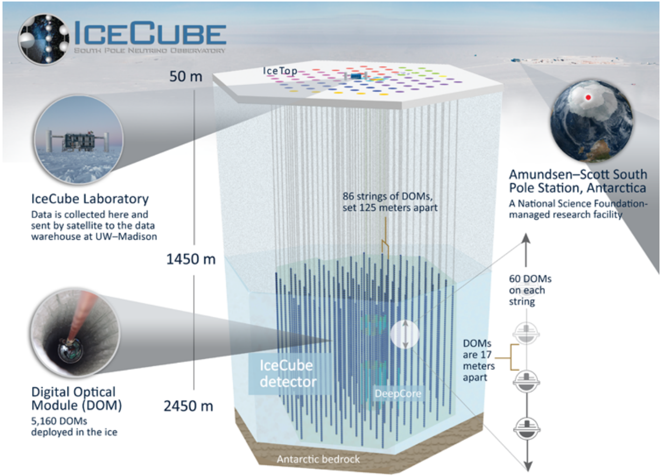

ANTARES (2007 – 2022)

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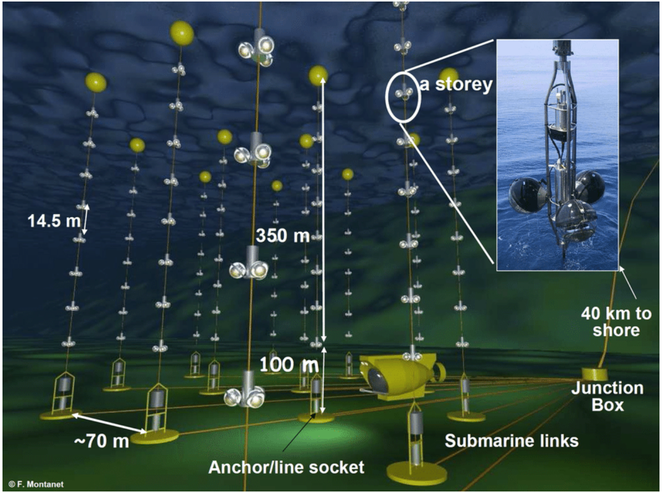
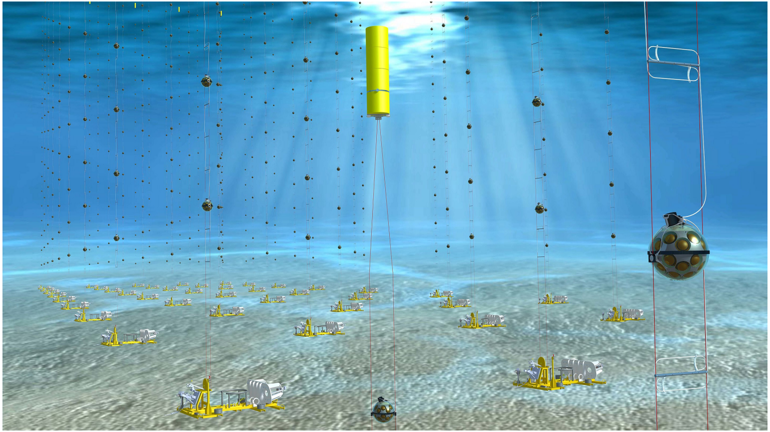
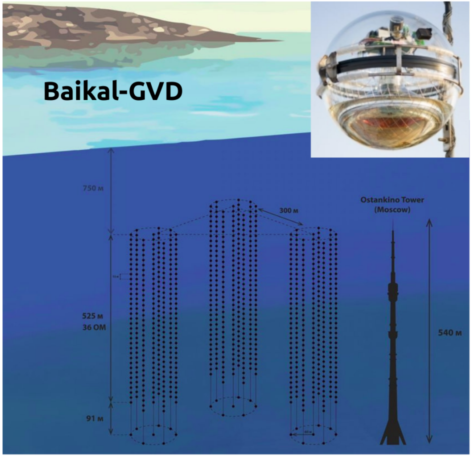
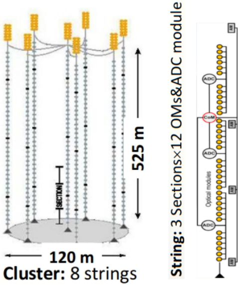


KM3NeT (2016 – ongoing)



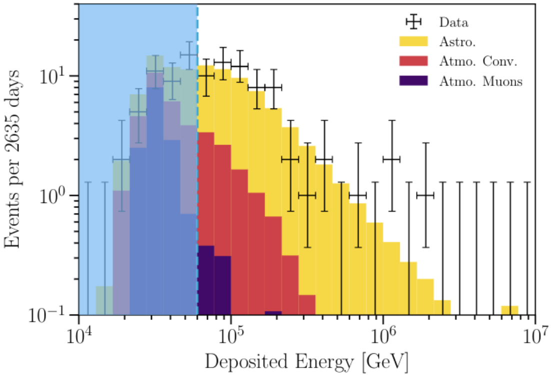
GVD (2017 – ongoing)

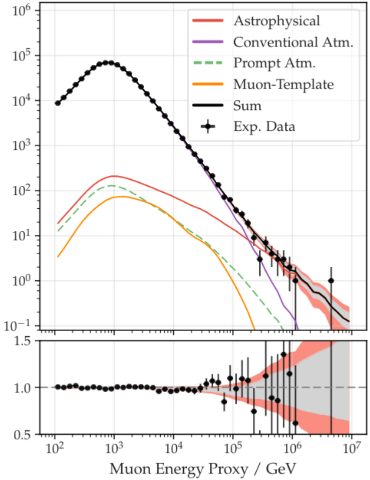




7 clusters working now,
more to come
$V_{inst} \sim 0.3 km^3$

Diffuse fluxes





Diffuse fluxes

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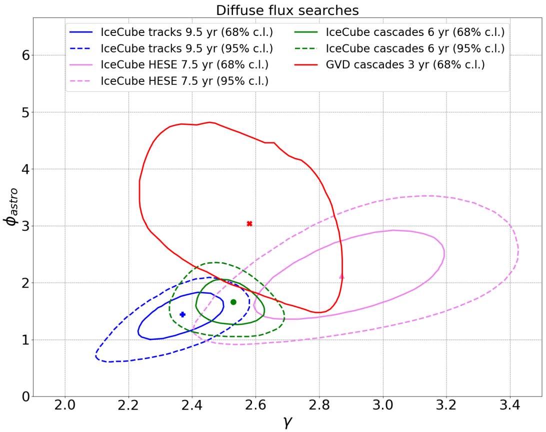
- Comparing the constrained parameter space
- How to interpret these tensions?



Milky Way

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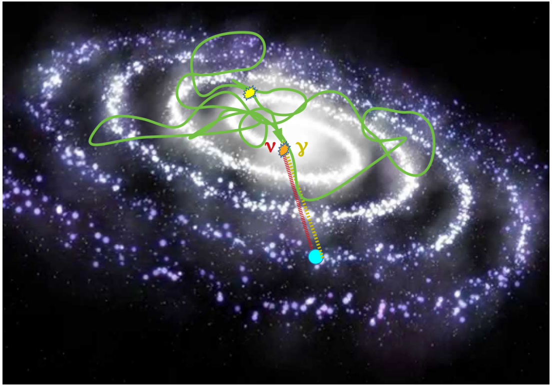
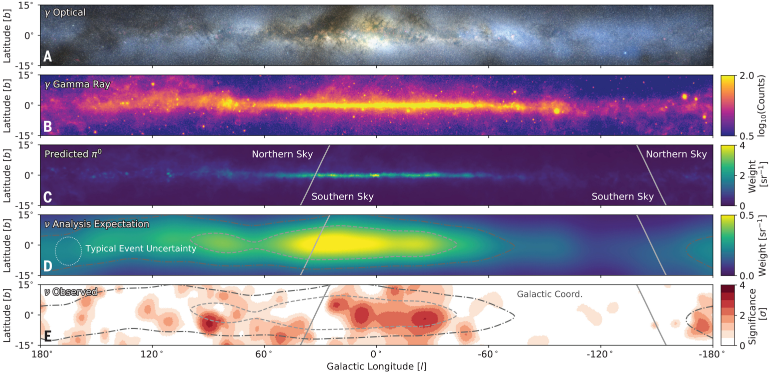
- CRs fill the Galaxy
- ISM fills the Galaxy
  $\rightarrow$ CR collisions will produce γs and νs

We have a guaranteed component of neutrinos in the Southern Sky from the presence of the Galactic Plane

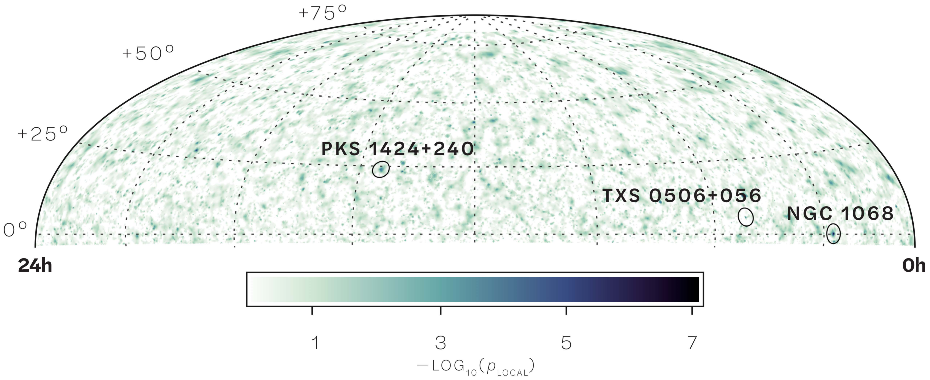


Milky Way

- June 29$^{\text{th}}$ 2023: IceCube announced the detection of neutrinos from the Milky Way
- Selected cascade events using machine learning techniques to improve the purity of the sample



Point sources



Point sources

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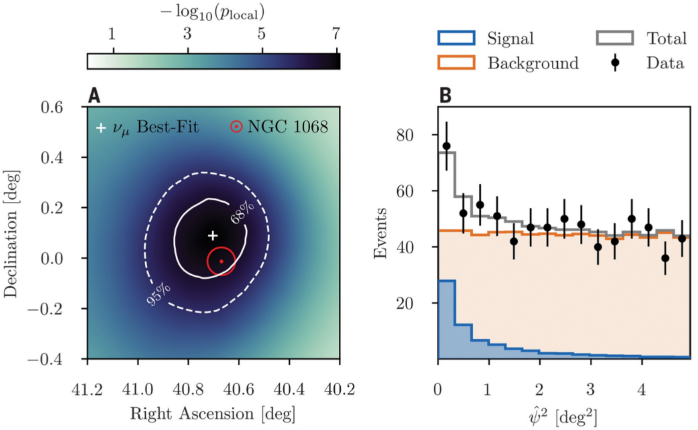

Multi-messenger

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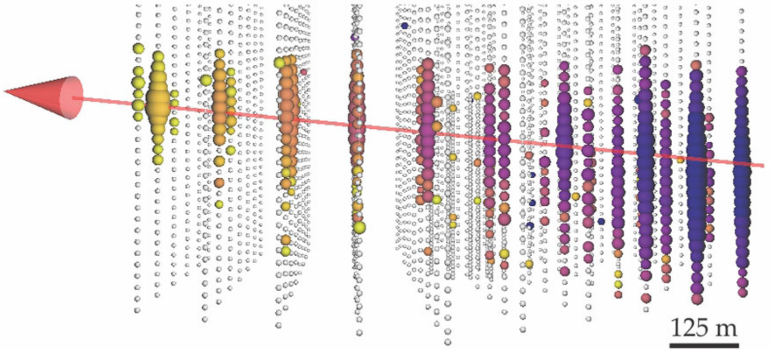
IceCube detected a 270 TeV muon on September 22, 2017 at 20:54:30.43 UTC



Multi-messenger

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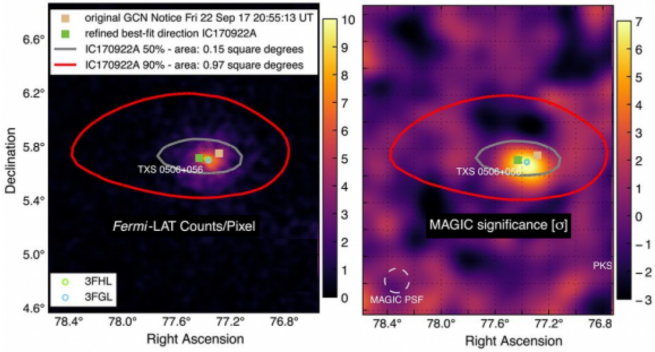
Fermi-LAT and MAGIC reported high-energy emissions in coincidence with the Blazar



And much more

- This is only a partial overview, there's a lot of stuff going on
  - Not only astronomy and astrophysics, but also beyond standard model physics, cosmic rays, environmental science
- The role of ANTARES in this history will be covered in detail in the next talks

Backup slides

Diffuse fluxes

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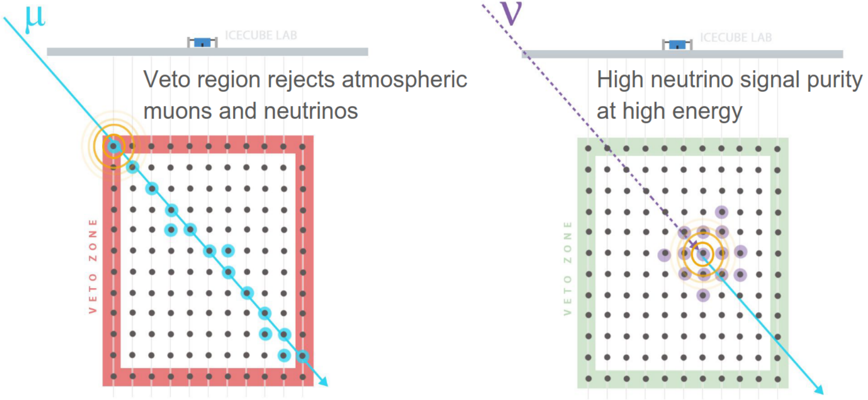

Diffuse fluxes

- Once the veto is applied, select high-energy events
- As they "start" inside the detector, with no signal outside, these are called High Energy Starting Events (HESE)
- These are mainly showering events $\rightarrow$ Above 30-50 TeV

First discovery of cosmic neutrinos, in 2013, by IceCube

Diffuse fluxes

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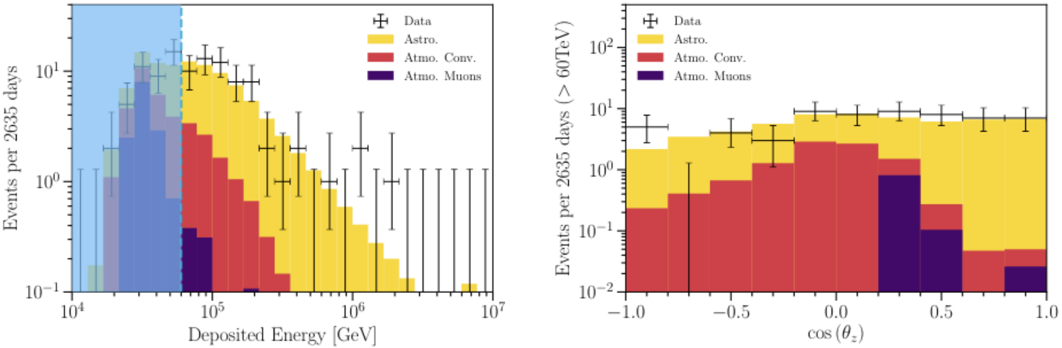


IceCube, 7.5 years of data, HESE sample

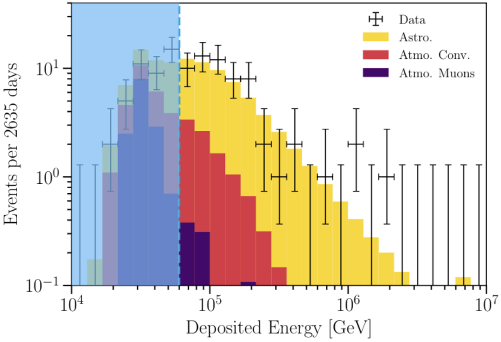
Diffuse fluxes

- IceCube HESE analysis
- Mainly electron neutrinos from the Southern Sky

Flux parameters:

γ_{fit}	$\Phi_{\text{fit}}(100\ \text{TeV})$ 10^{-18}[d.f.u]
2.87 ± 0.2	1.89 ± 0.52

d.f.u = diffuse flux units: $(\text{GeV cm}^2\ \text{s sr})^{-1}$

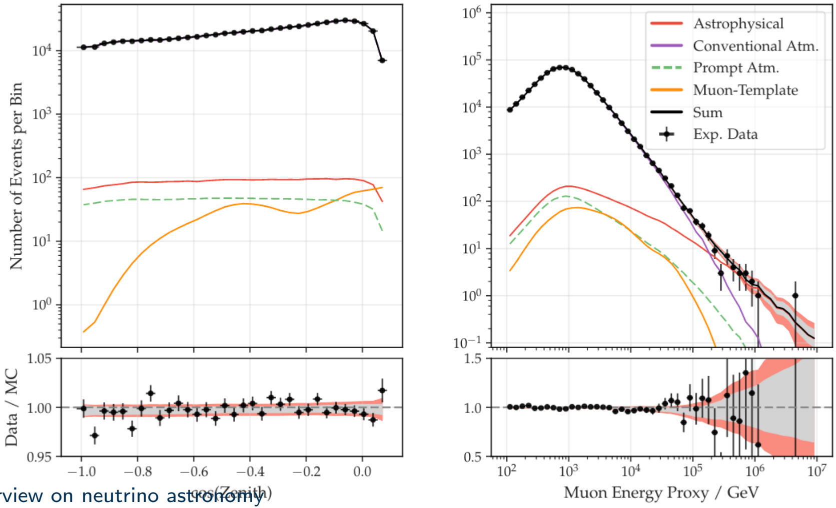


Diffuse fluxes

To complement the HESE, a more standard search from IceCube looks at upward-going tracks

- Events from the Northern Sky
- At higher energies than the HESE events ($>$ 100-200 TeV)

Diffuse fluxes



Diffuse fluxes

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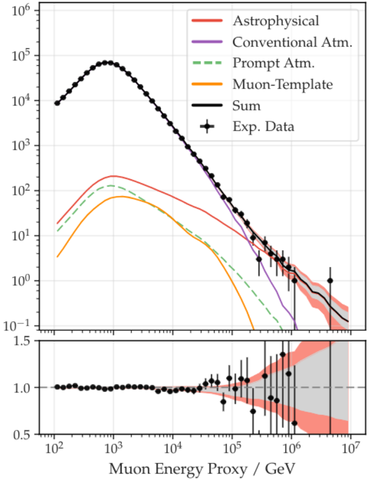
- IceCube upgoing tracks analysis
- Mainly muons from the Northern Sky

Flux parameters:

γ_{fit}	$\Phi_{\mathrm{fit}}(100\ \mathrm{TeV})$ 10^{-18}[d.f.u]
2.37 ± 0.09	1.44 ± 0.25

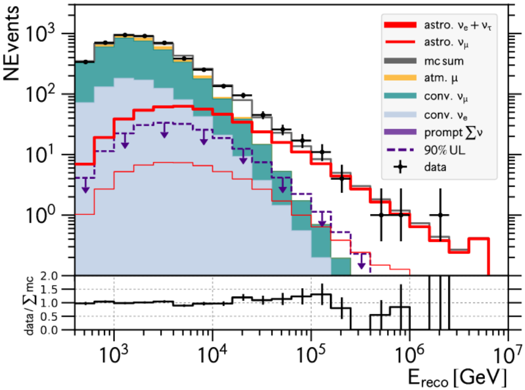


Diffuse fluxes

- IceCube cascades analysis
- Mainly electron and tau neutrinos

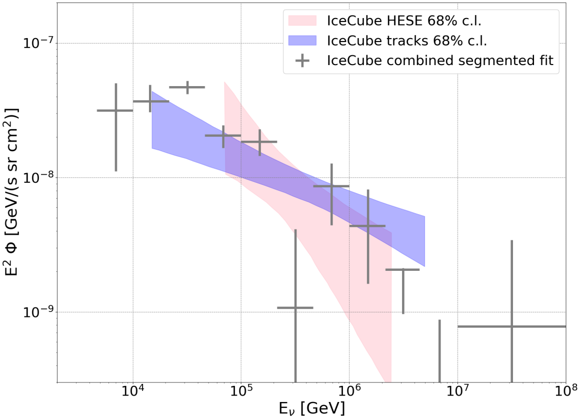
Flux parameters:

γ_{fit}	$\Phi_{\text{fit}}(100\text{ TeV})$ 10^{-18}[d.f.u]
2.58 ± 0.07	1.66 ± 0.25

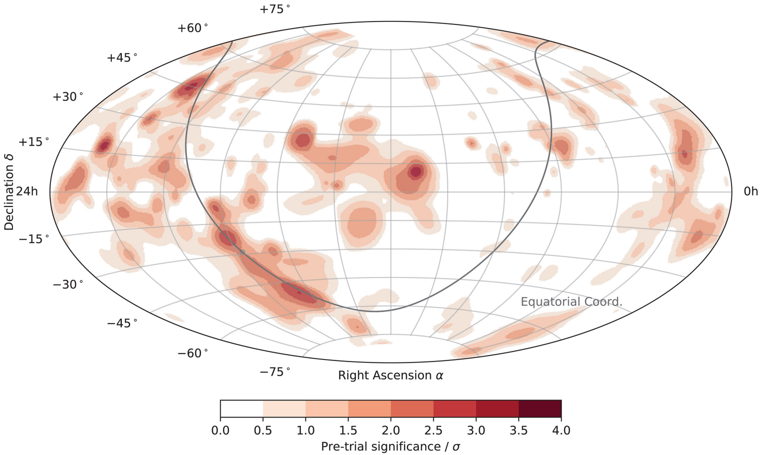


Diffuse fluxes

- Spectral features?

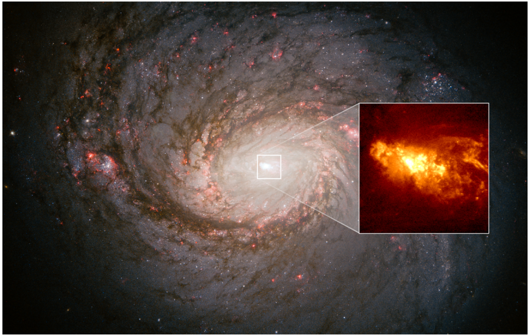


Milky Way



+75°
+60°
+45°
+30°
+15°
24h
0h
−15°
−30°
−45°
−60°
−75°
Declination δ
Right Ascension α
Equatorial Coord.
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
Pre-trial significance / σ

Neutrino sources



NGC 1068 (M77) is the brightest and one of the closest and best-studied type 2 Seyfert galaxies

AGN + intense starburst activity

KM3NeT (2016 – ongoing)

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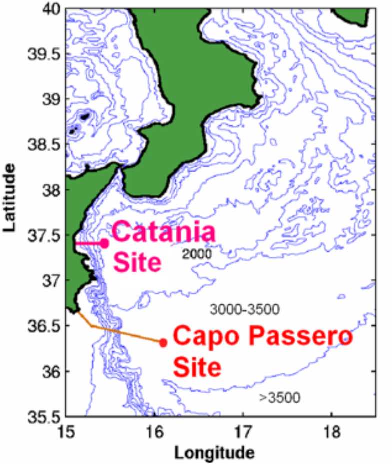
KM3NeT-ARCA

- Off-shore Sicily, 3.5 km depth
- Target: neutrino astronomy
  → high-energy neutrinos
- 90 m DU horizontal spacing,
  36 m DOM vertical spacing
- 230 DUs target, for 1 km^3
- Currently: 28 DUs working



KM3NeT (2016 – ongoing)

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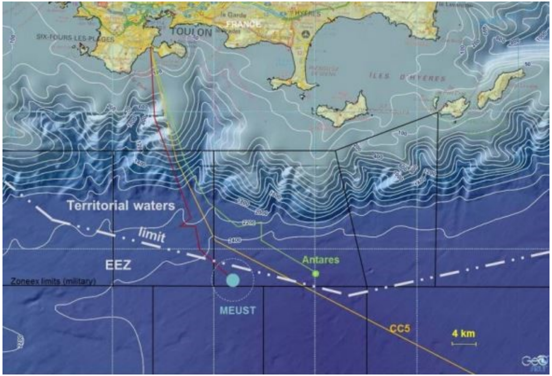

KM3NeT-ORCA

- Close to the ANTARES site
- Target: neutrino oscillations $\rightarrow$ low energy threshold
- 20 m DU horizontal spacing, 9 m DOM vertical spacing
- 115 DUs target, for 0.0067 km^3
- Currently: 21 DUs working