Astronomy and physics with cosmic neutrinos

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Physics Colloquium, TU Chemnitz
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FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

The plan for the next hour

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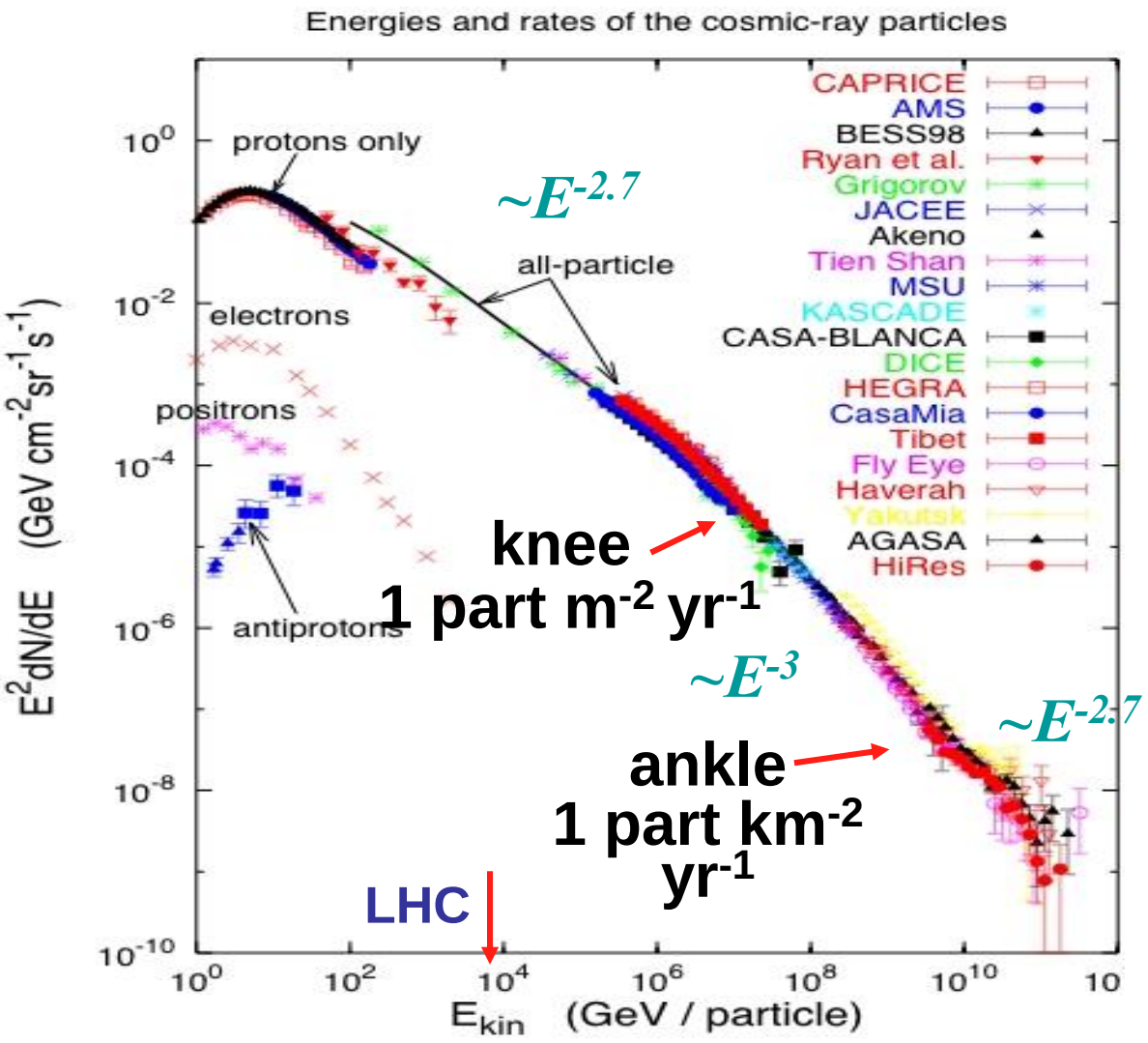
- Introduction to neutrino astronomy
- First detection of cosmic neutrinos with IceCube
- Neutrino astronomy in the Mediterranean Sea
- Particle physics with neutrino telescopes
- Summary and outlook

Neutrino astronomy

The mysterious cosmic rays



- Particles impinging on Earth from outer space carry energies up to 10^{21} eV (the kinetic energy of a tennis ball at ~200km/h.)
- The acceleration mechanisms are unknown.
- Cosmic rays carry a significant fraction of the energy of the universe – cosmologically relevant!
- Neutrinos play a key role in studying the origin of cosmic rays.

Neutrino production mechanism

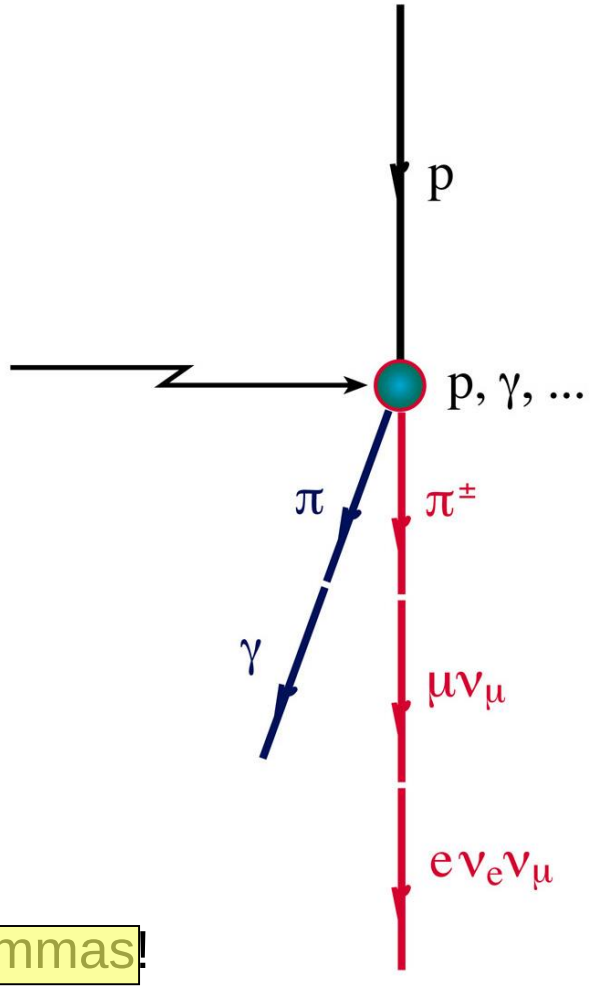
- Neutrinos are produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \rightarrow \pi^{\pm}(K^{\pm}...) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

$$\downarrow$$

$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$

Cosmic rays



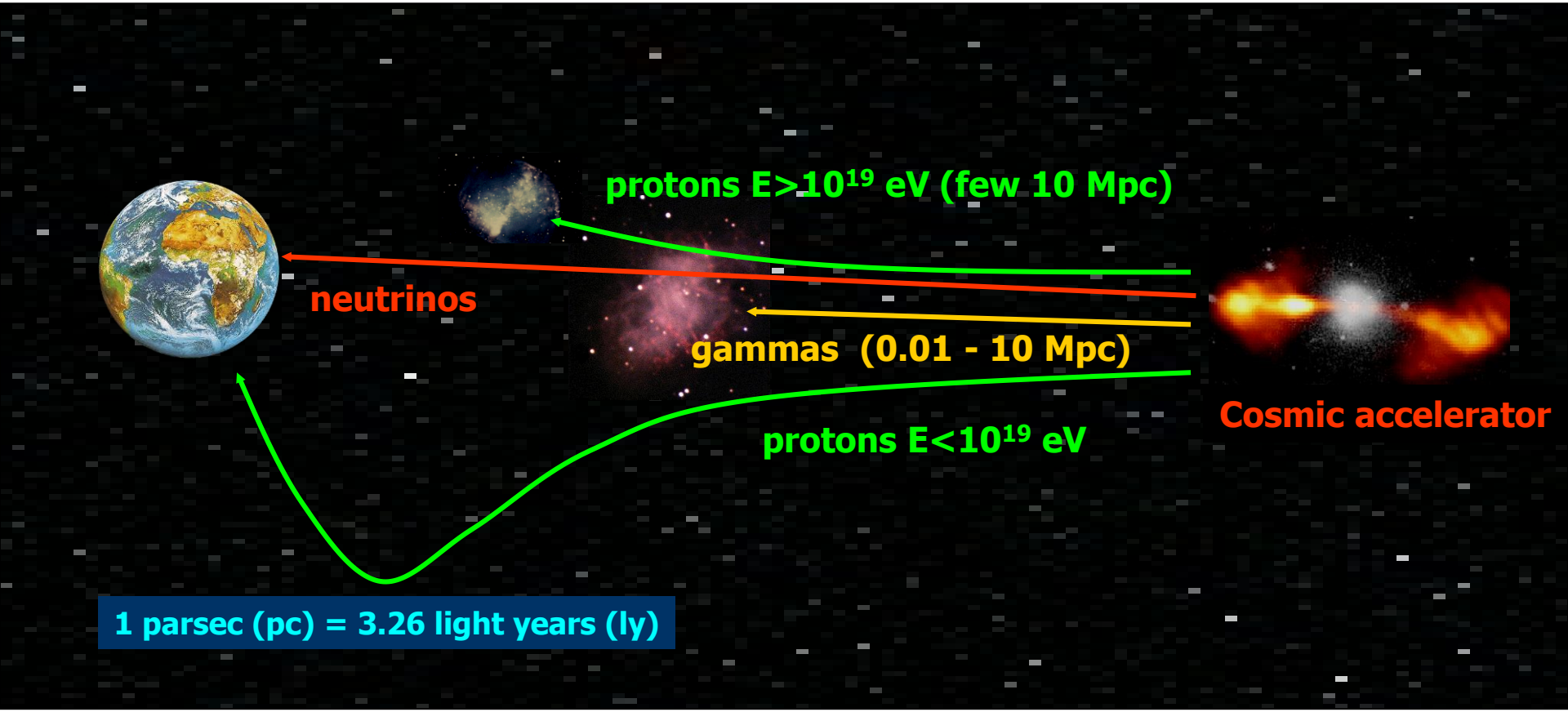
- Simultaneously, gamma production takes place:

$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\ \gamma + Y$$

Cosmic rays

- Cosmic ray acceleration yields neutrinos and gammas!
- … but gammas also from purely leptonic processes

Particle propagation in the Universe



Photons: absorbed on dust and radiation;
Protons/nuclei: deviated by magnetic fields, reactions with radiation (CMB)

How does a neutrino telescope work?

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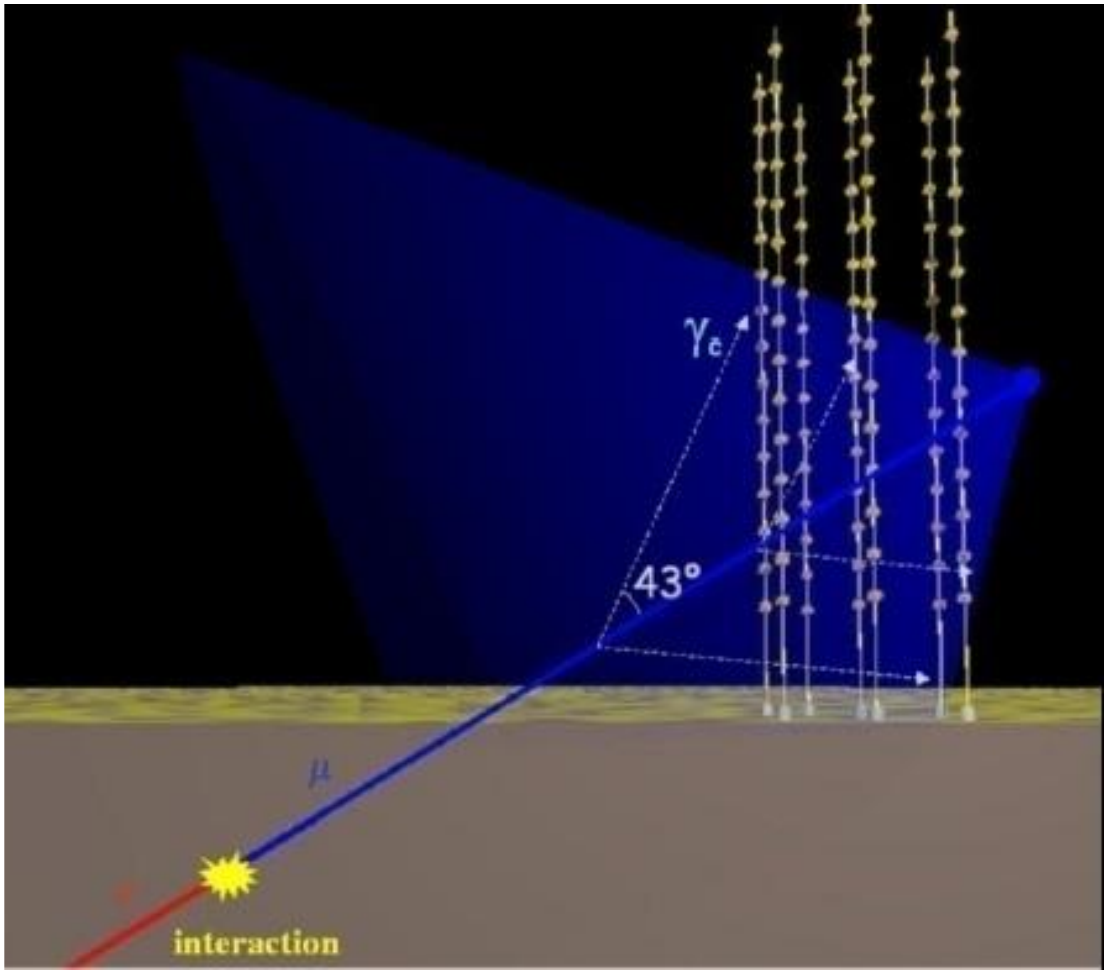
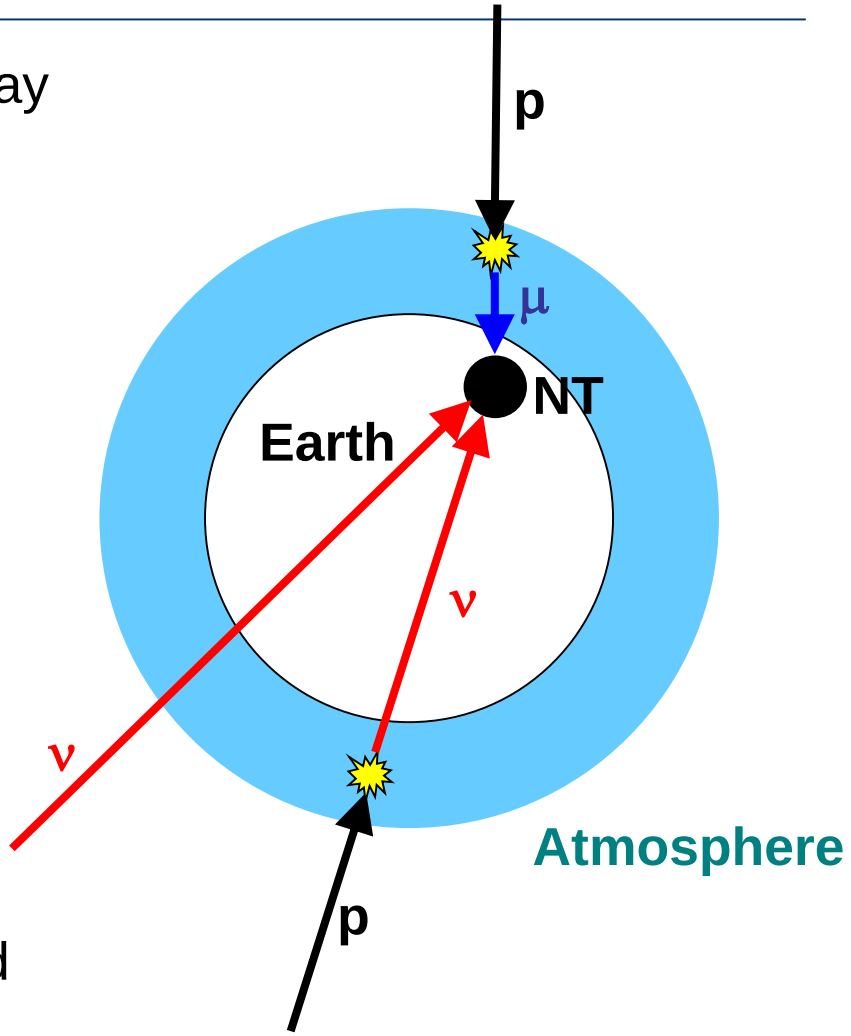
- Neutrino interacts in the (vicinity of the) telescope
- Charged secondaries cross the detector volume (water or ice) and stimulate Cherenkov emission
- Recorded by a 3D-array of photo-sensors
- “Traditional” channel:
  $\nu_\mu + N \rightarrow \mu + X$
- Energy range :
  10(0) GeV – some PeV

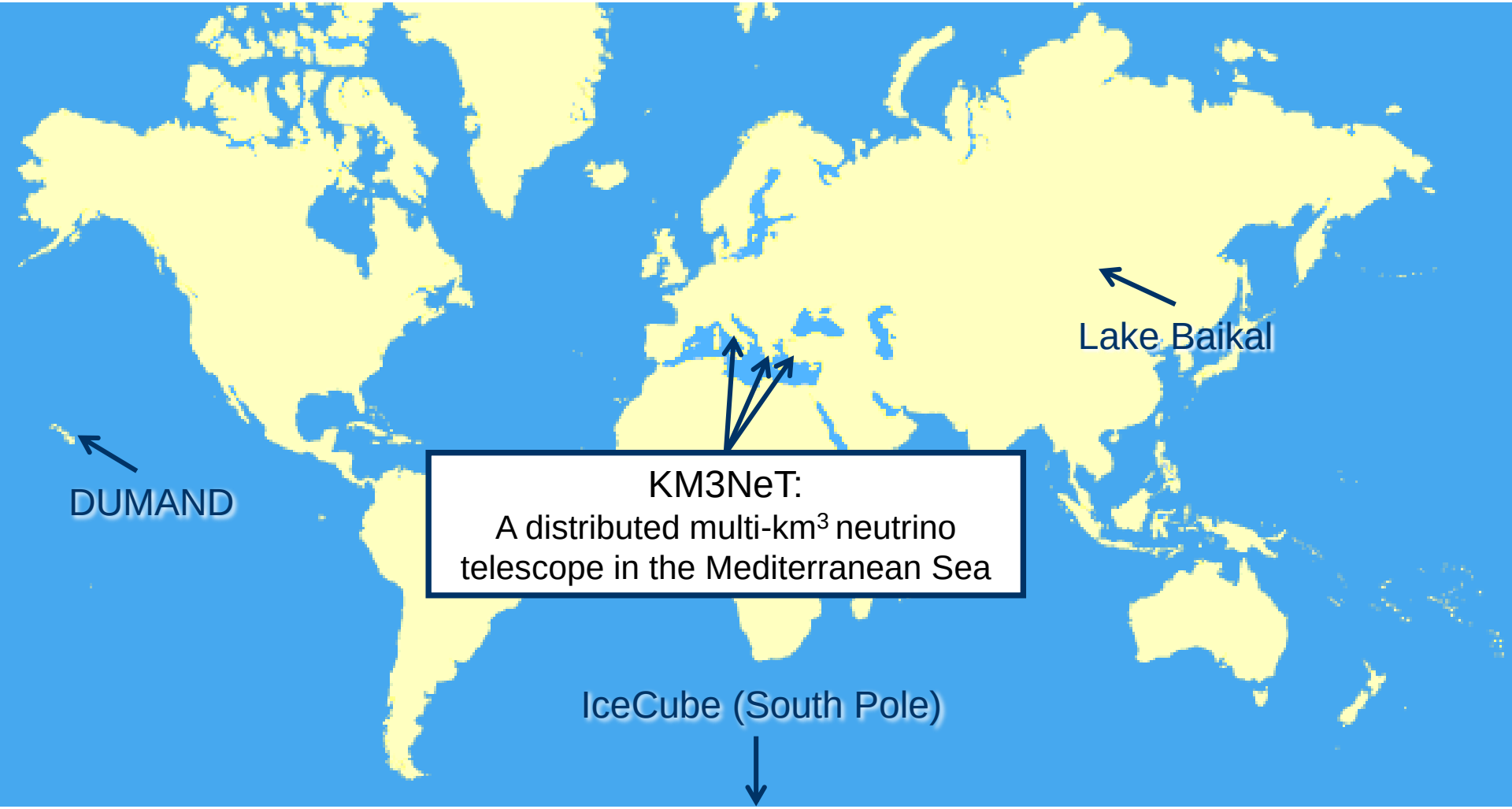


Backgrounds, or maybe not

- Atmospheric neutrinos from cosmic-ray interactions in atmosphere
  - irreducible
  - important calibration source
  - allow for oscillation studies
- Atmospheric muons from cosmic-ray interactions in atmosphere above NT
  - penetrate to NT
  - exceed neutrino event rate by several orders of magnitude
- Sea water: light from K40 decays and bioluminescence

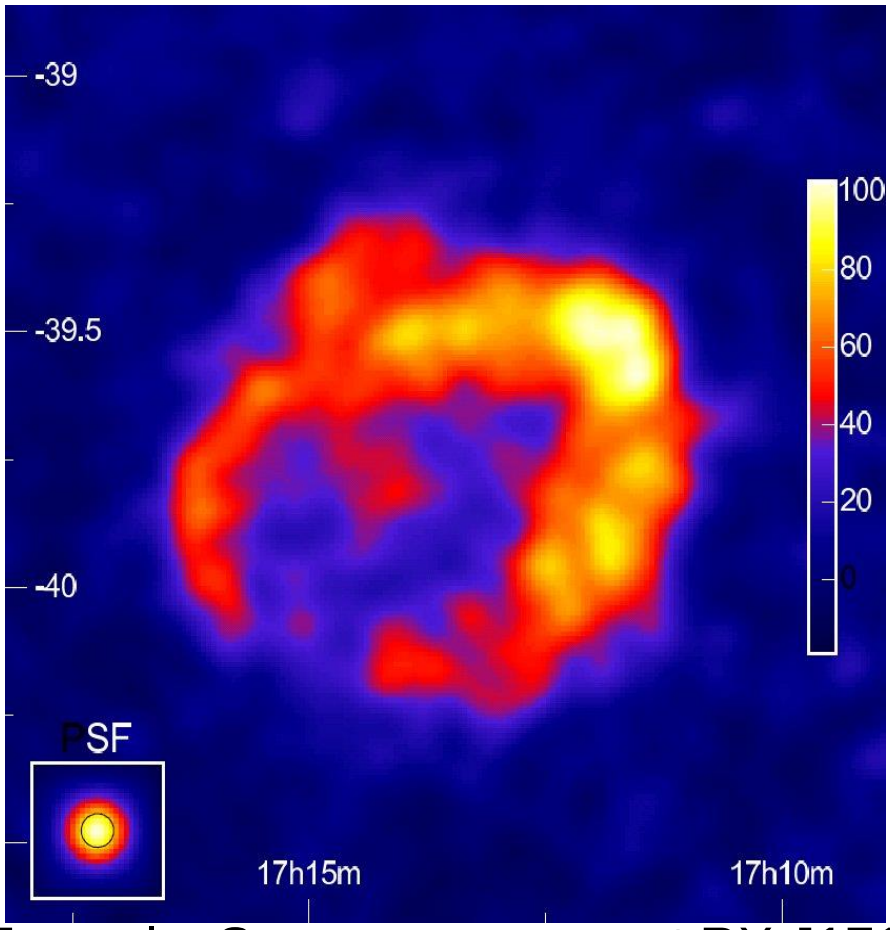


The ν telescope world map



Example targets of ν astronomy

- Galactic neutrino sources



Example: Supernova remnant RX J1713
Gamma observation by H.E.S.S.

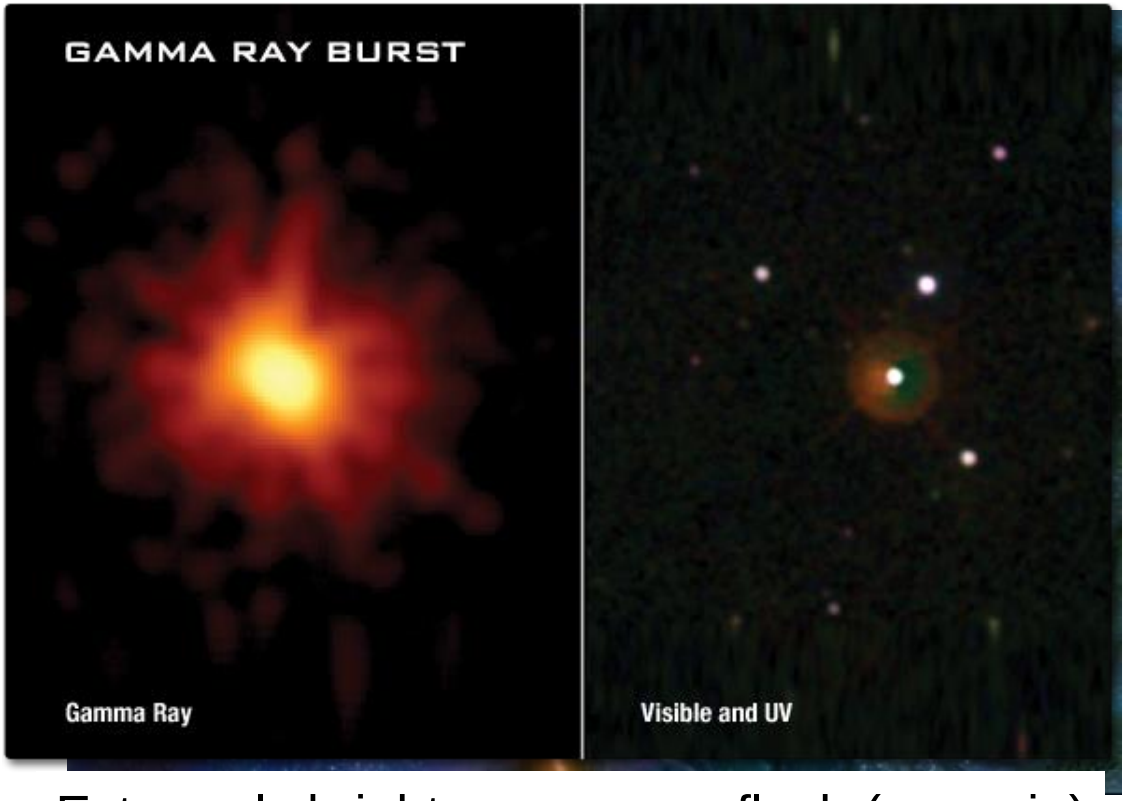
Example targets of ν astronomy

- Galactic neutrino sources
- Extragalactic sources

Active Galactic Nuclei (AGN):
Super-massive black hole in centre of galaxy with accretion disk and jet emission

Example targets of ν astronomy

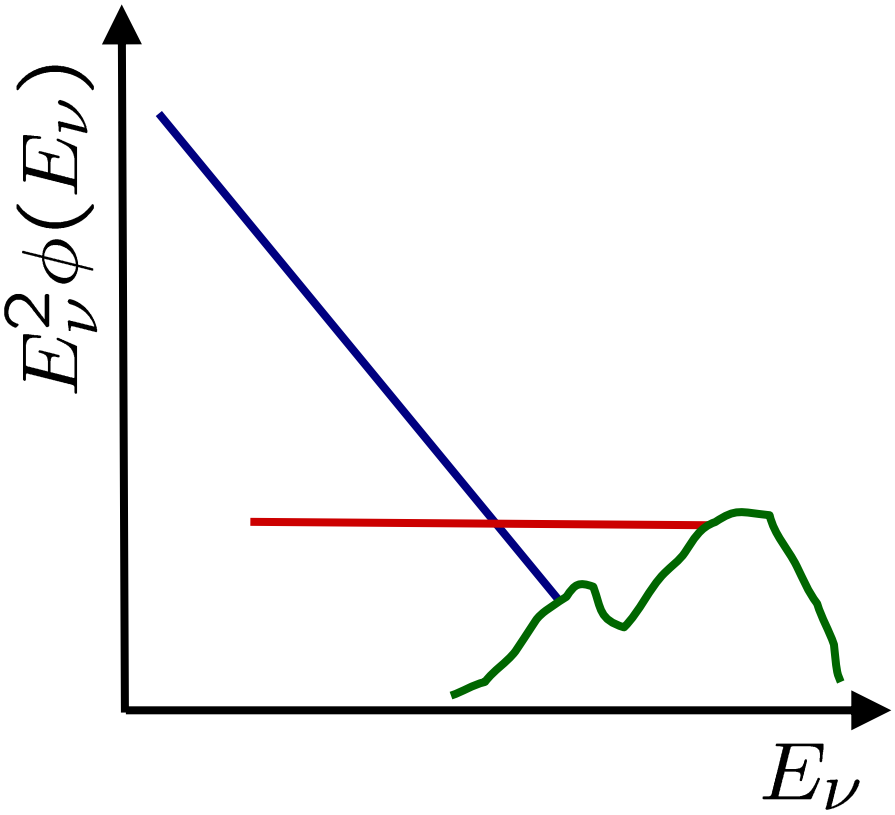
- Galactic neutrino sources
- Extragalactic sources
- Transient sources



Extremely bright gamma ray flash (sec-min) from hypernovae or BH/NS mergers or …
Isotropic distribution → extragalactic

Example targets of ν astronomy

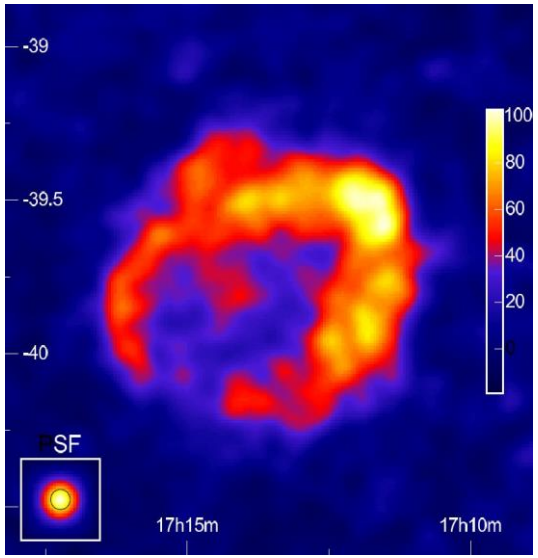
- Galactic neutrino sources
- Extragalactic sources
- Transient sources
- Diffuse neutrino flux

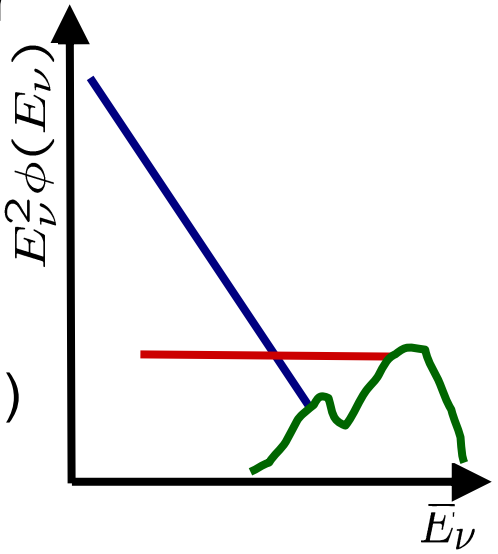


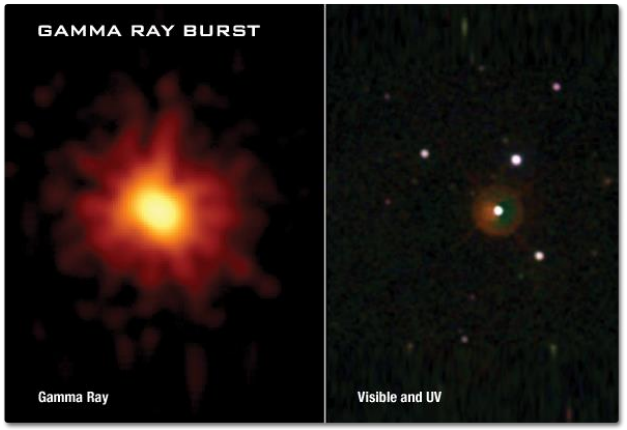
Isotropic high-energy neutrino flux
above atmospheric neutrino background
from unresolved astrophysical sources
or of cosmogenic origin (GZK)

Example targets of ν astronomy

- Galactic neutrino sources
- Extragalactic sources
- Transient sources
- Diffuse neutrino flux
- Neutrinos from Dark Matter annihilations
- Particle physics with atmospheric neutrinos
- Search for exotics (monopoles, nuclearites,…)







South Pole and Mediterranean Fields of View

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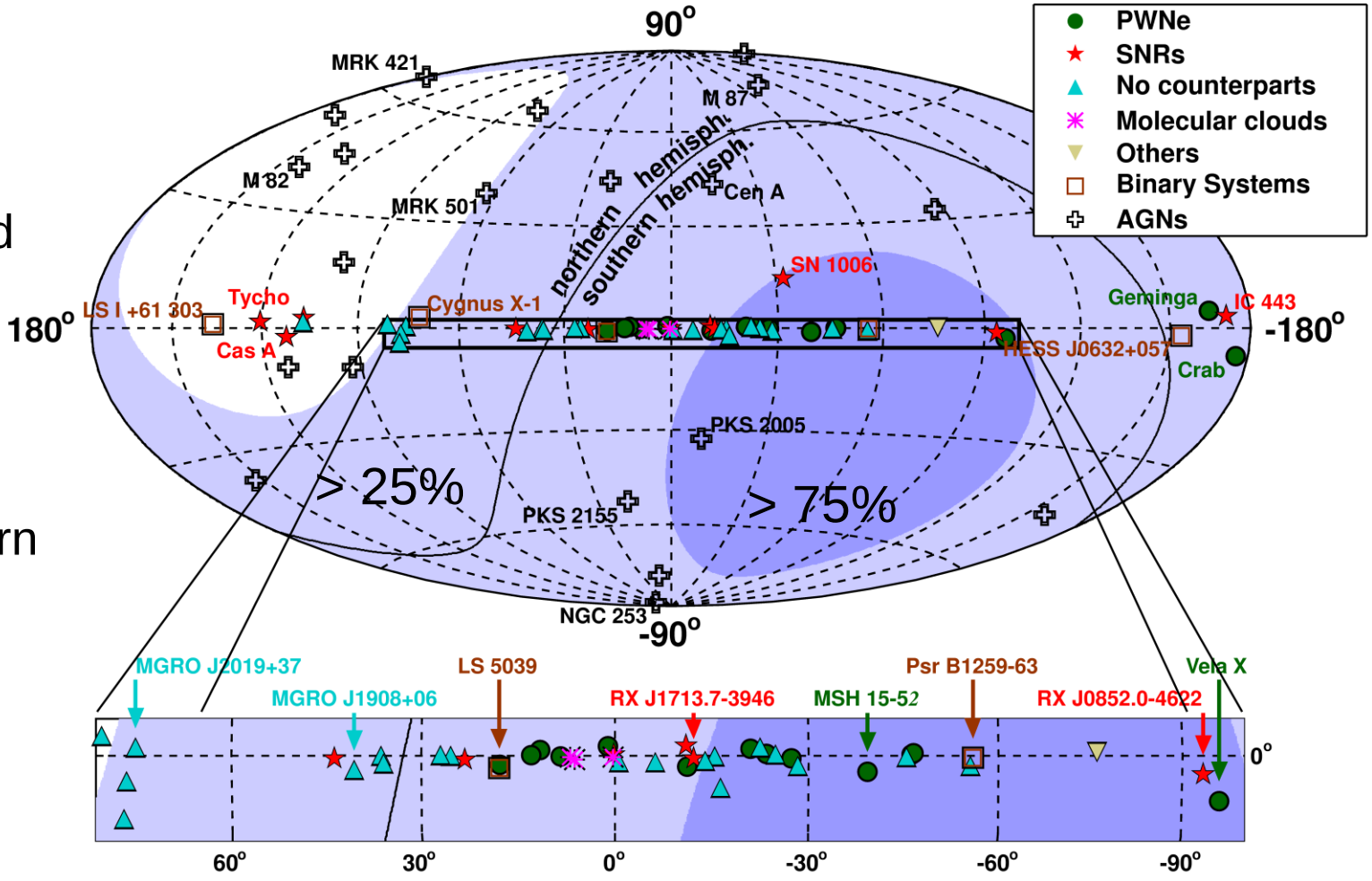
Galactic coordinates

2π downward sensitivity assumed

IceCube @ South Pole: Sees Northern hemisphere



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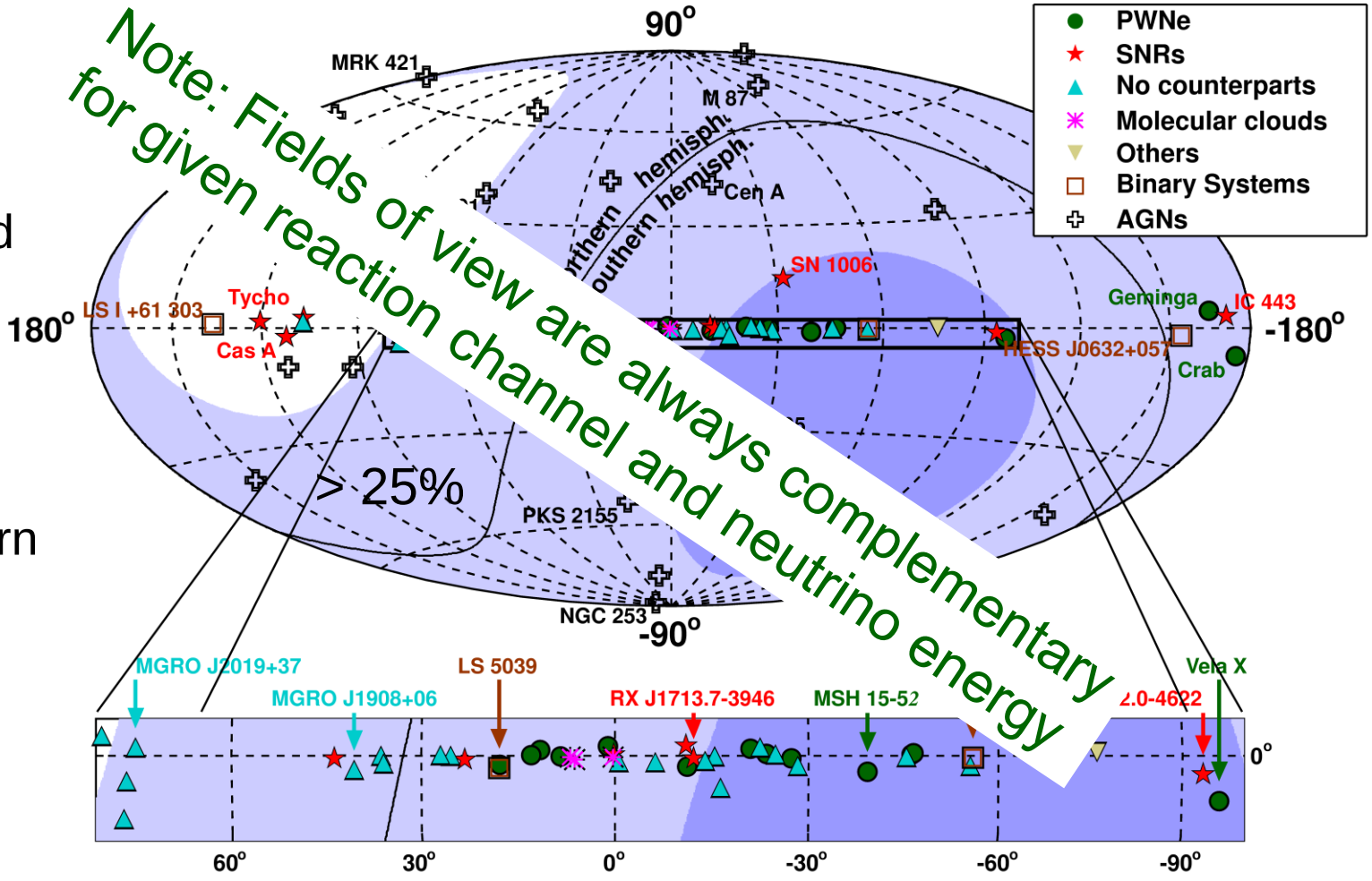

IceCube and the first detection of cosmic neutrinos

Several slides adapted from:
F. Halzen: “IceCube: the discovery of cosmic neutrinos”, VHEPA 2016
K. Hanson: “IceCube Gen2”, VHEPA 2016

IceCube: A km^3 detector in the Antarctic ice

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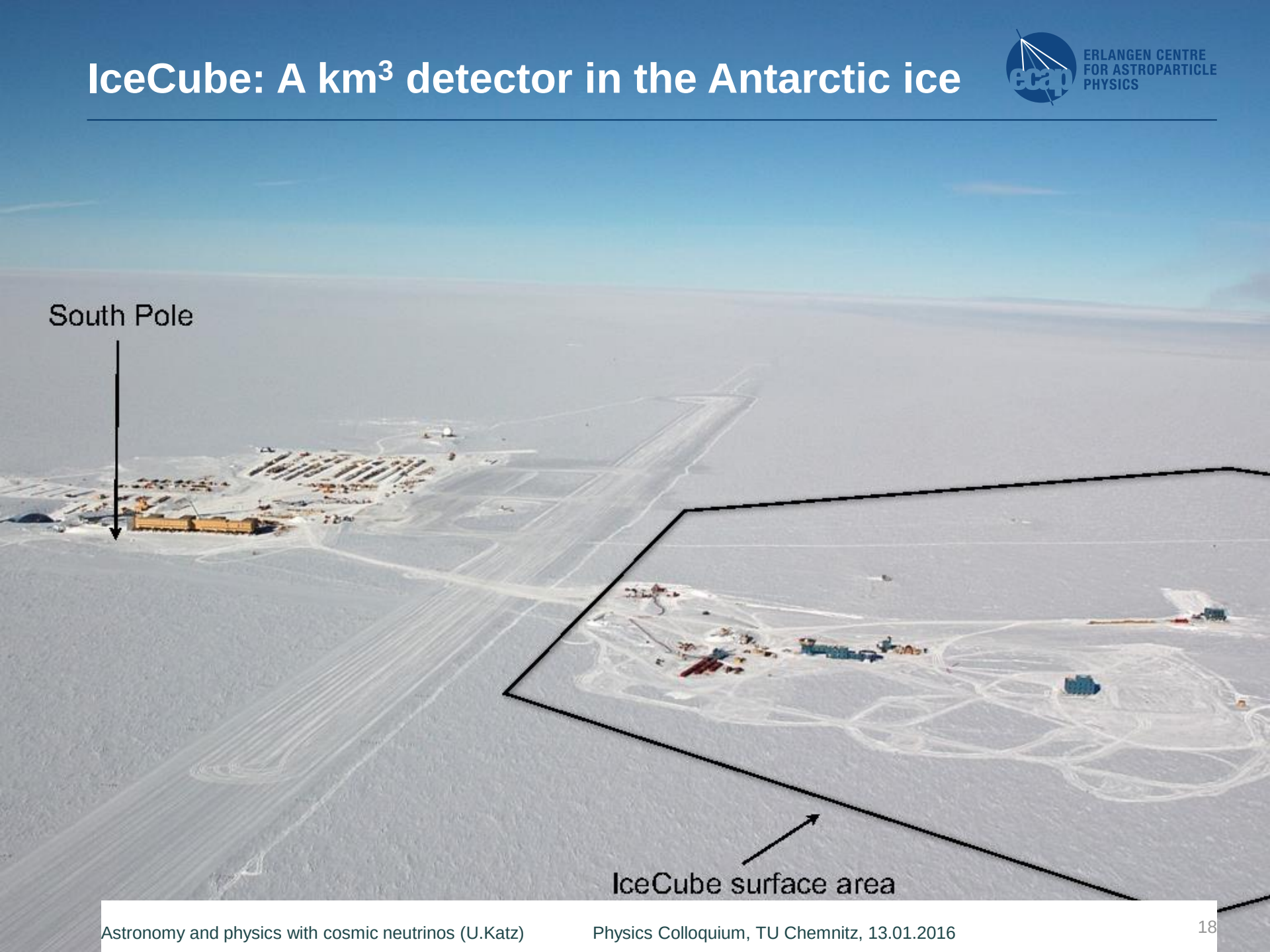
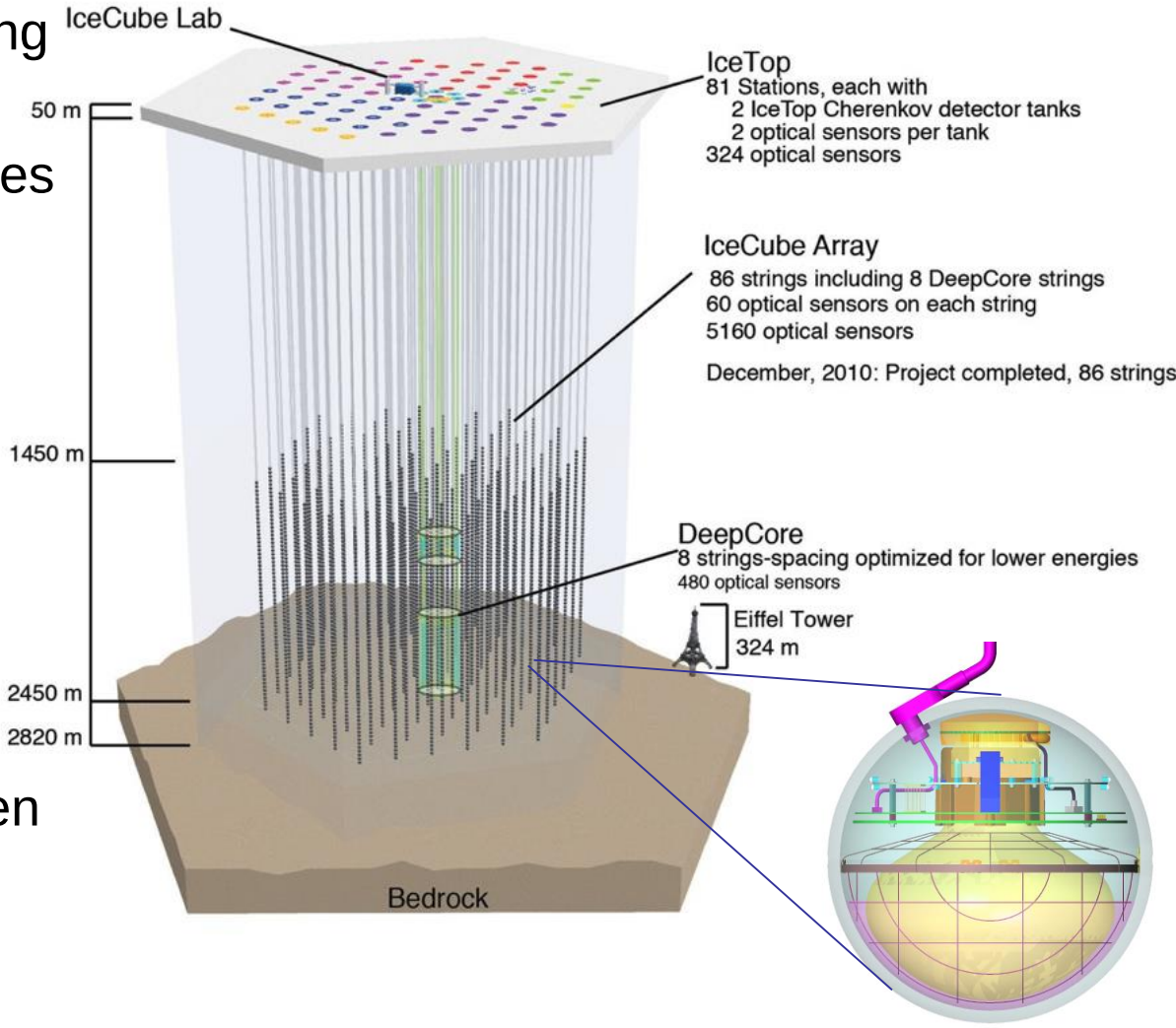
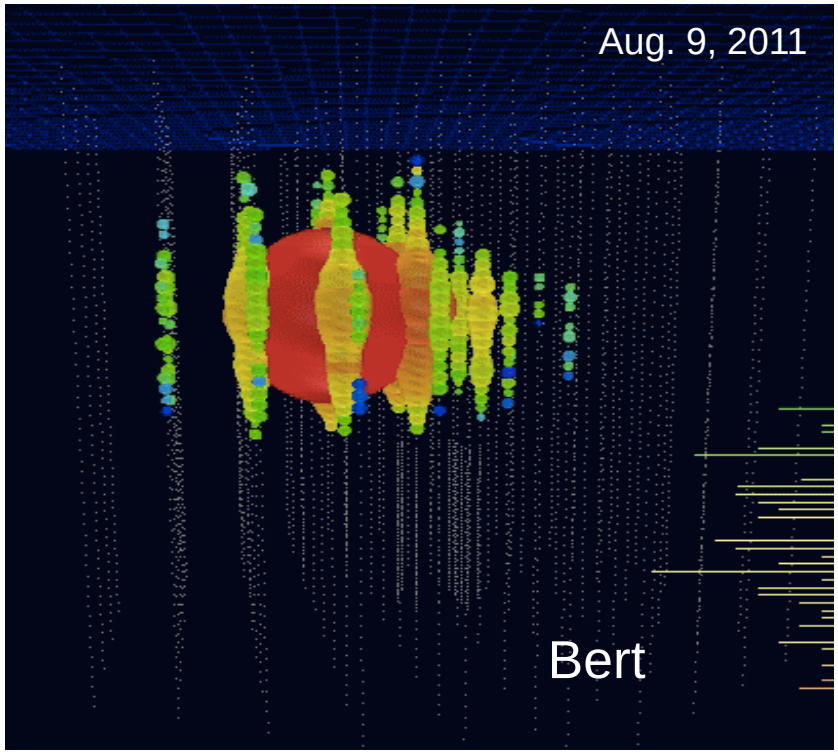


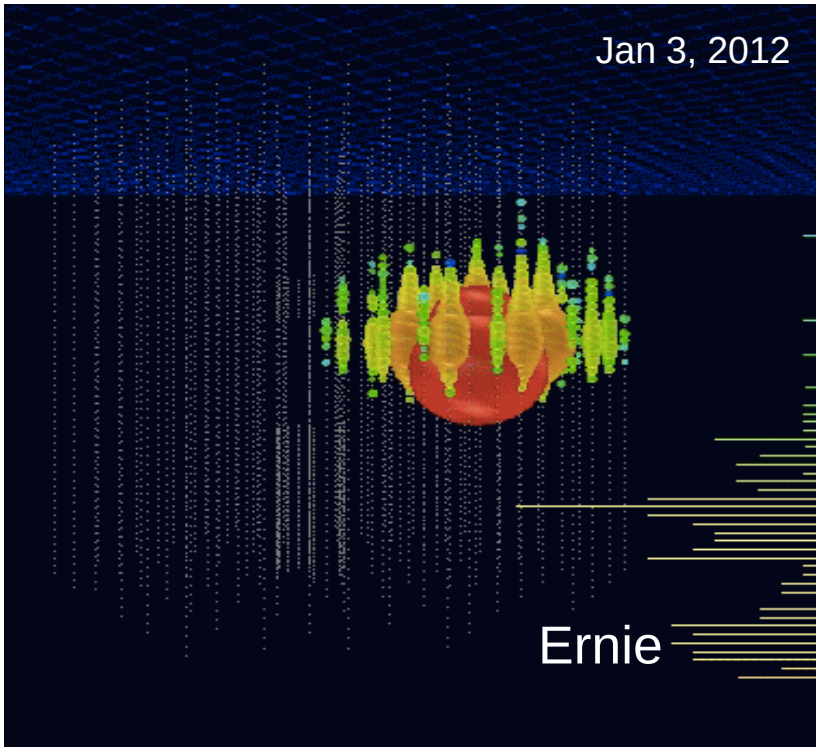
The IceCube detector

- 86 strings altogether
  - 125 m horizontal spacing
  - 17 m vertical distance between Optical Modules
  - 1 km^3 instrumented volume, depth 2450m
- Deep Core
  - densely instrumented region in clearest ice
- Completed in Dec. 2010
- Extremely stable and efficient operation since then

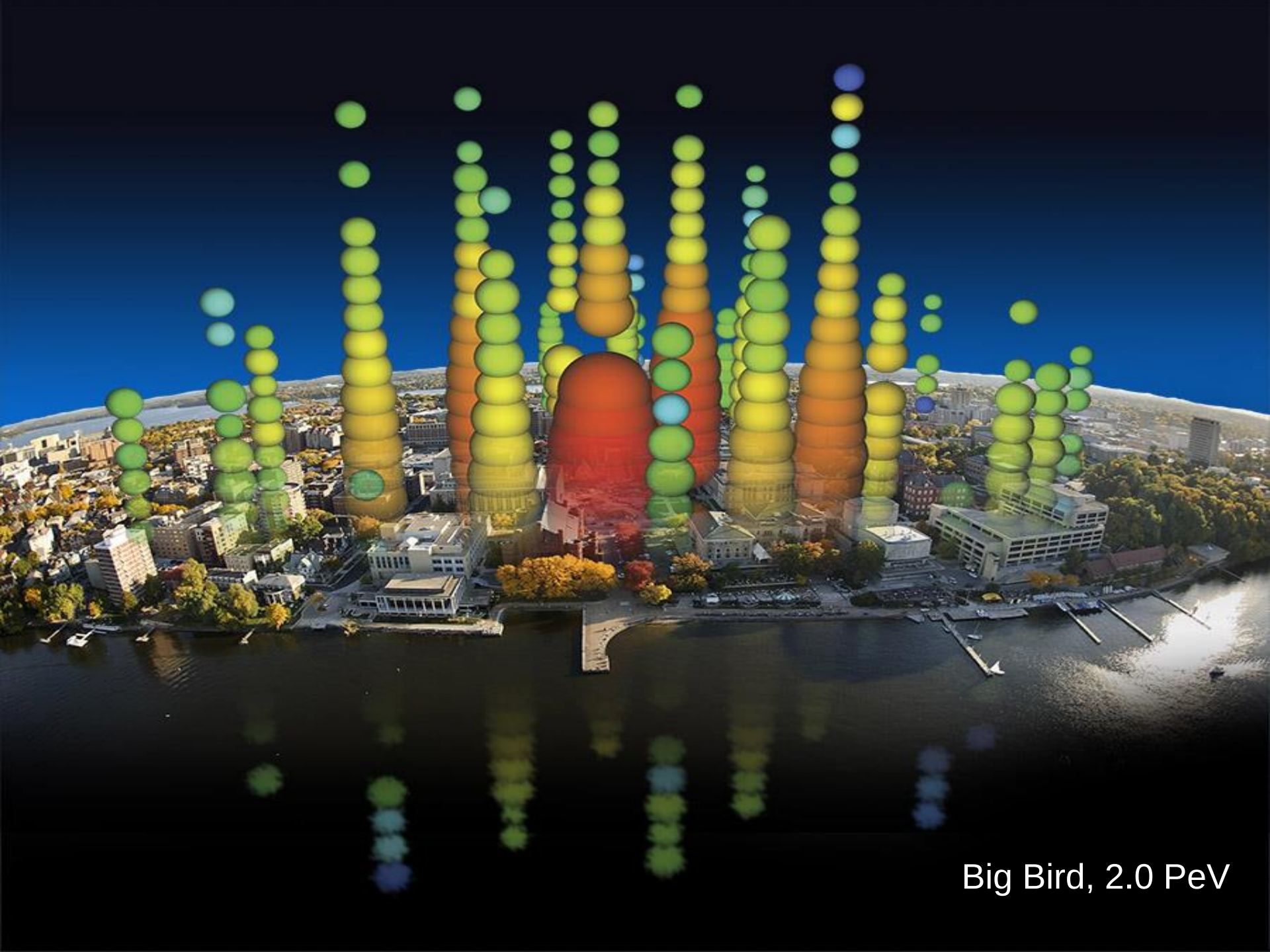


A first glimpse at cosmic ν's



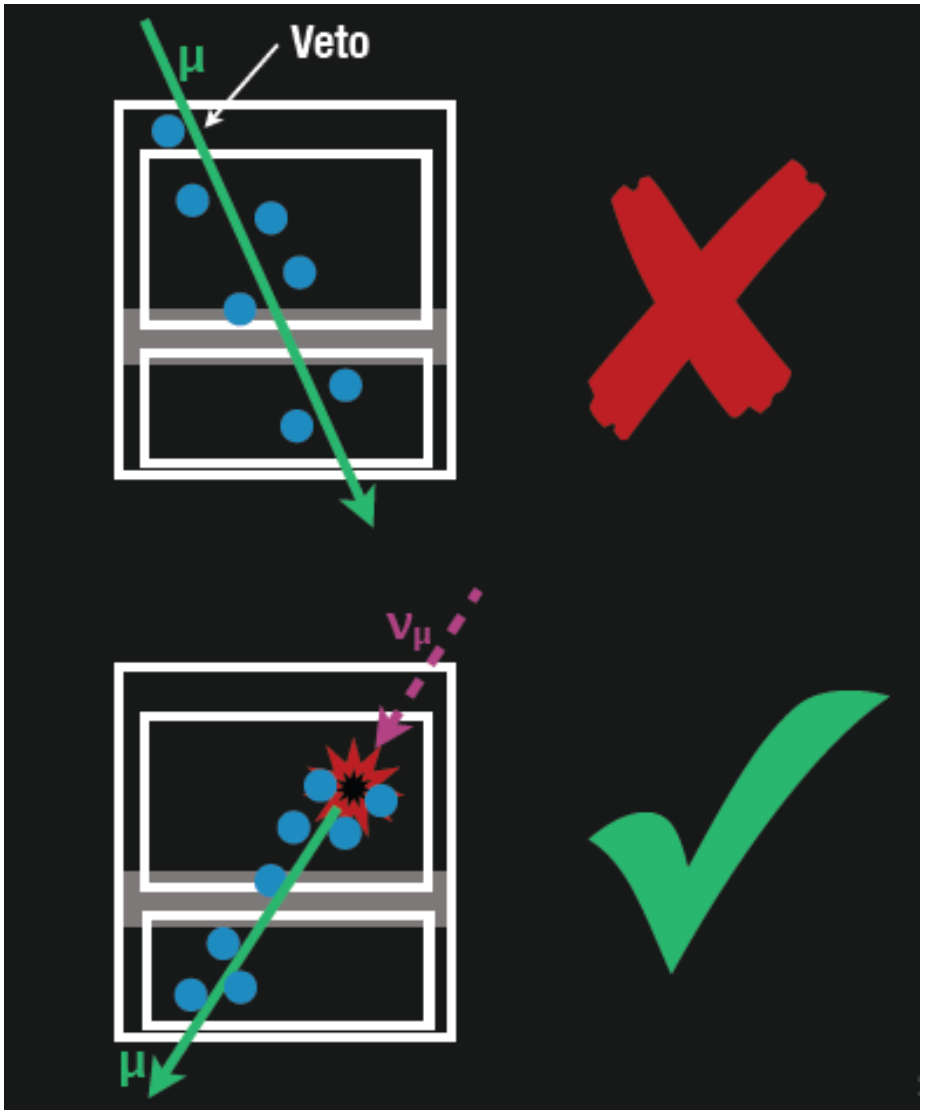


- First PeV events found in 2011/12 (deposited energy > 10^{15} eV)
- Hardly consistent with atmospheric neutrino background
- Note: Cascade events without muon tracks

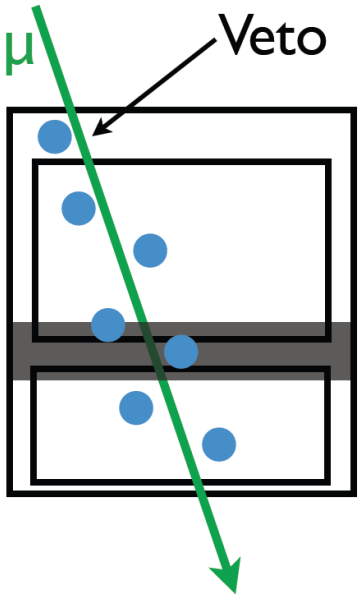

Big Bird, 2.0 PeV

Systematic search for such events …

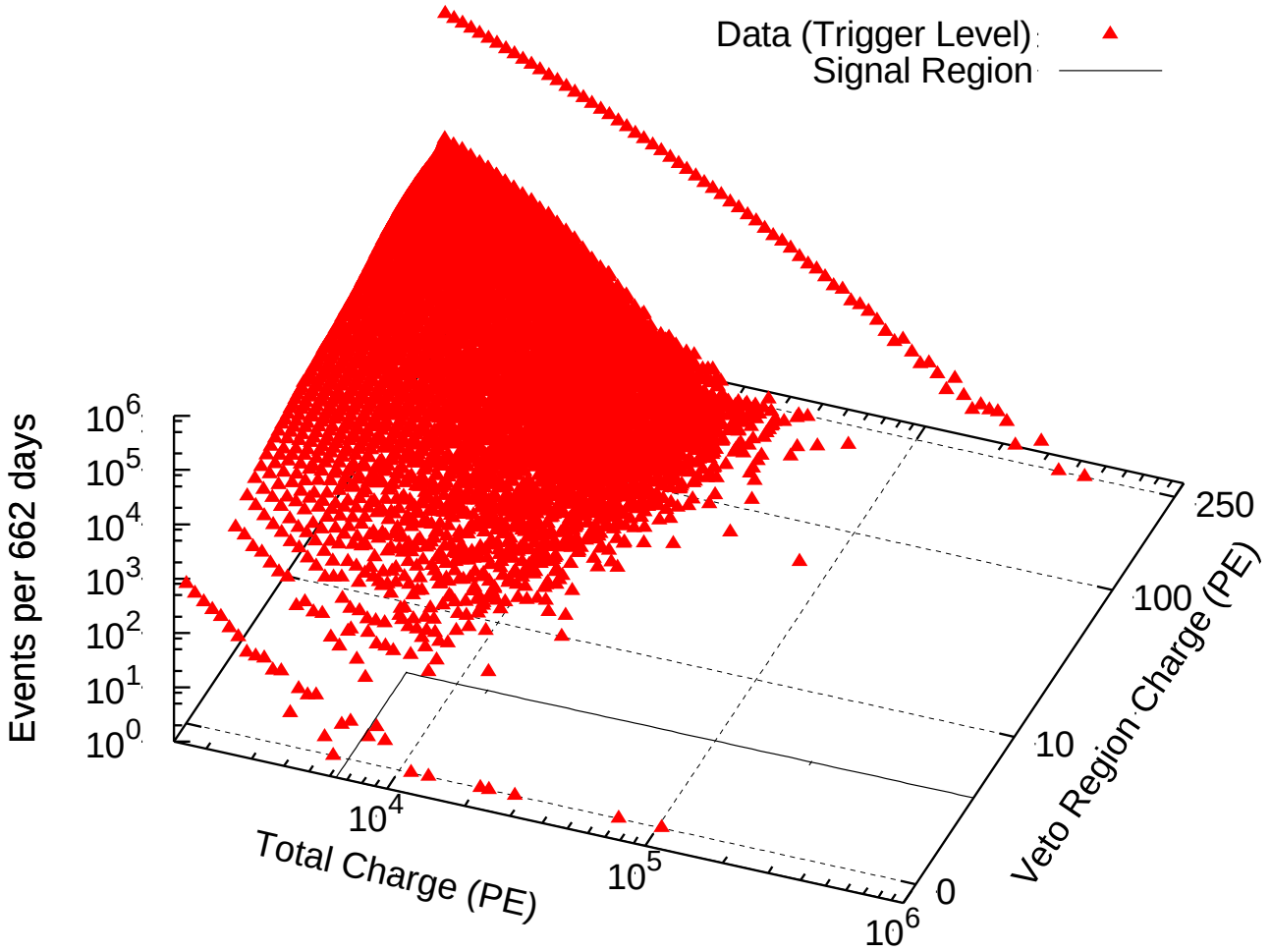
- Select events interacting inside the detector only
- No light in the veto region
- Veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- Energy measurement: total absorption calorimetry
- → “High-energy starting events” (HESE)



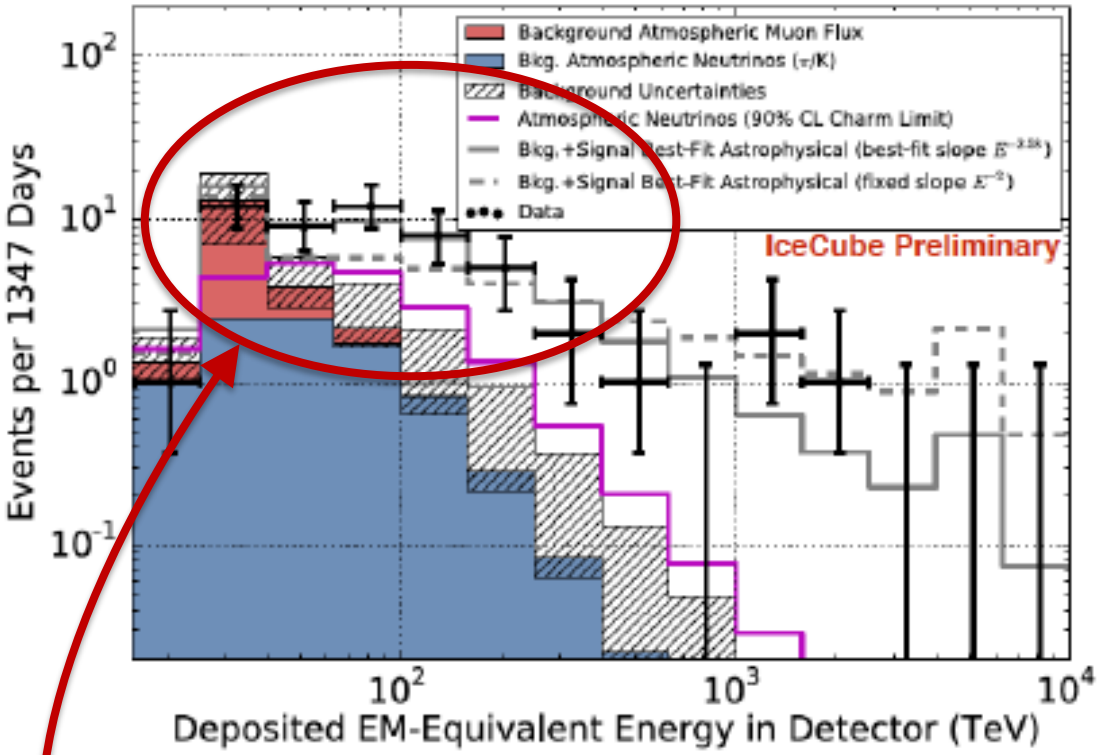
… success!



26 events in one year of data!

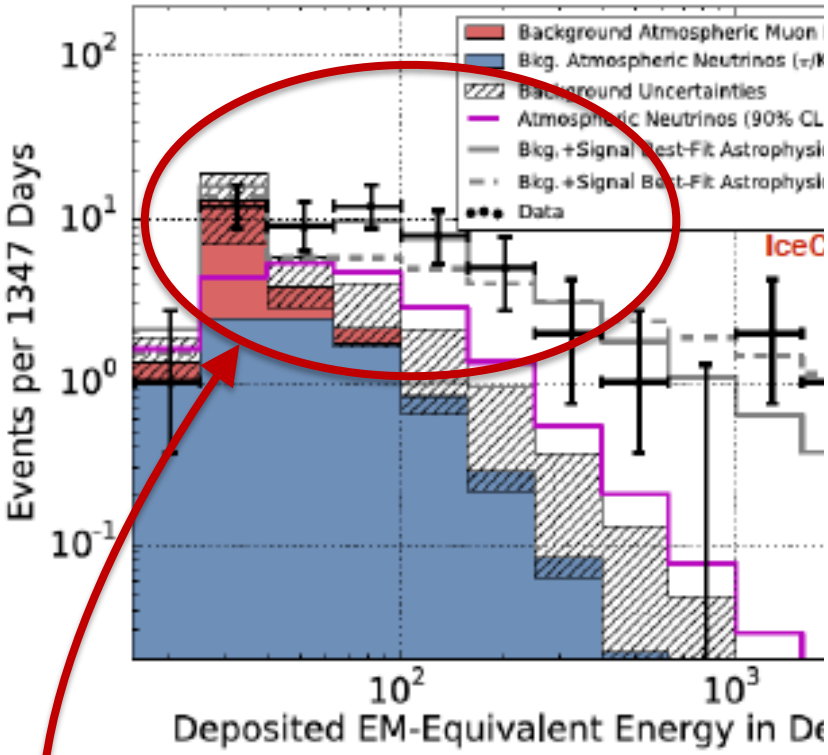


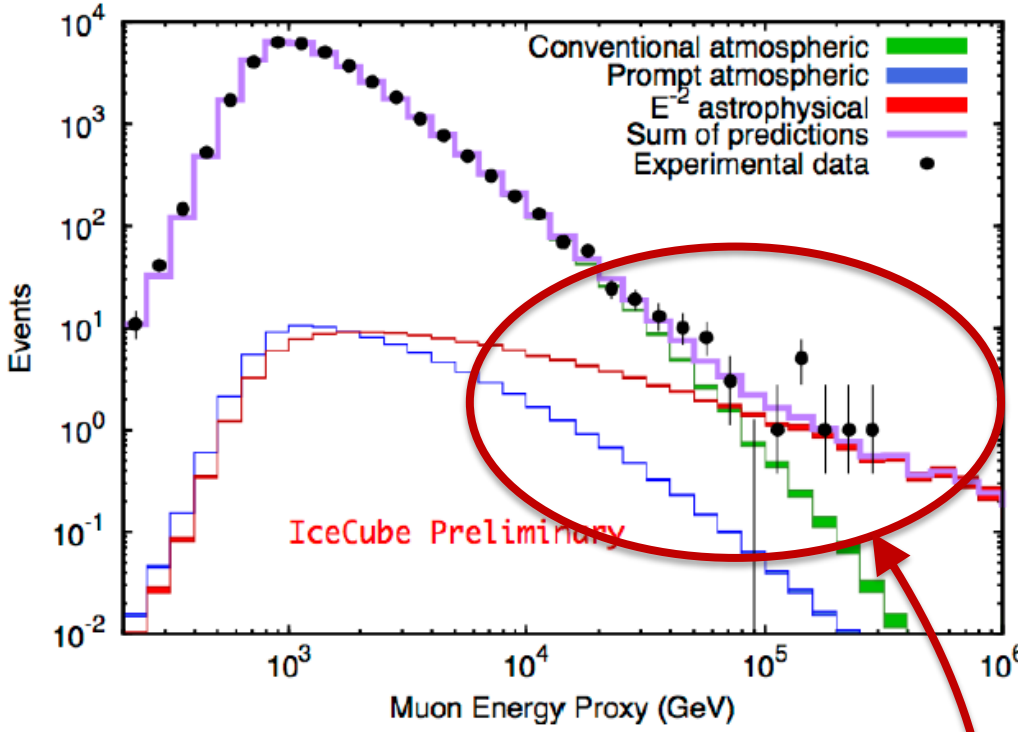
After 4 years:



7σ excess of neutrinos of all flavours over background expectations

After 4 years:





7σ excess of neutrinos of all flavours over background expectations

6σ excess of muon neutrinos over background expectations

Where do they come from?

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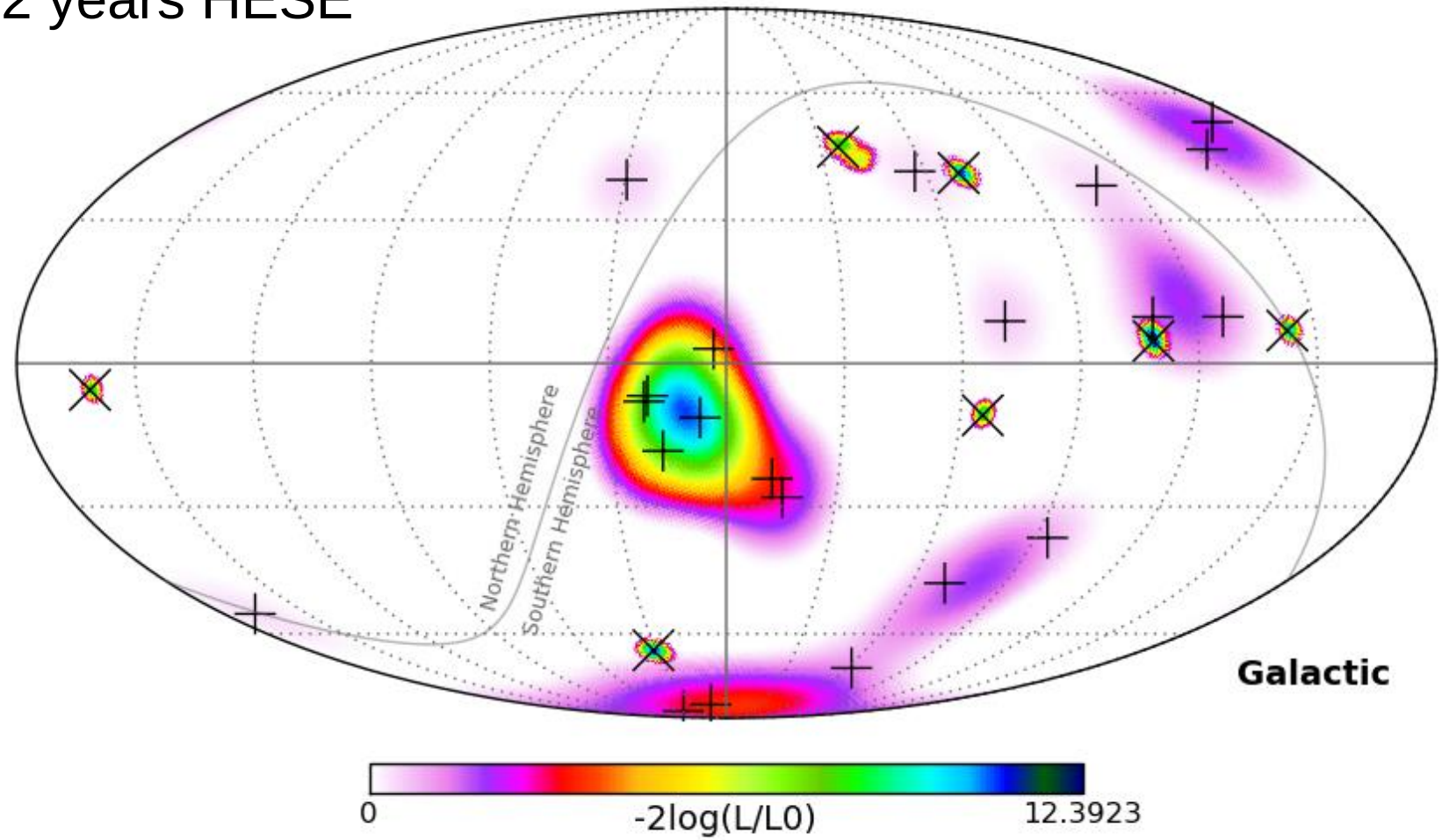
2 years HESE



Where do they come from?

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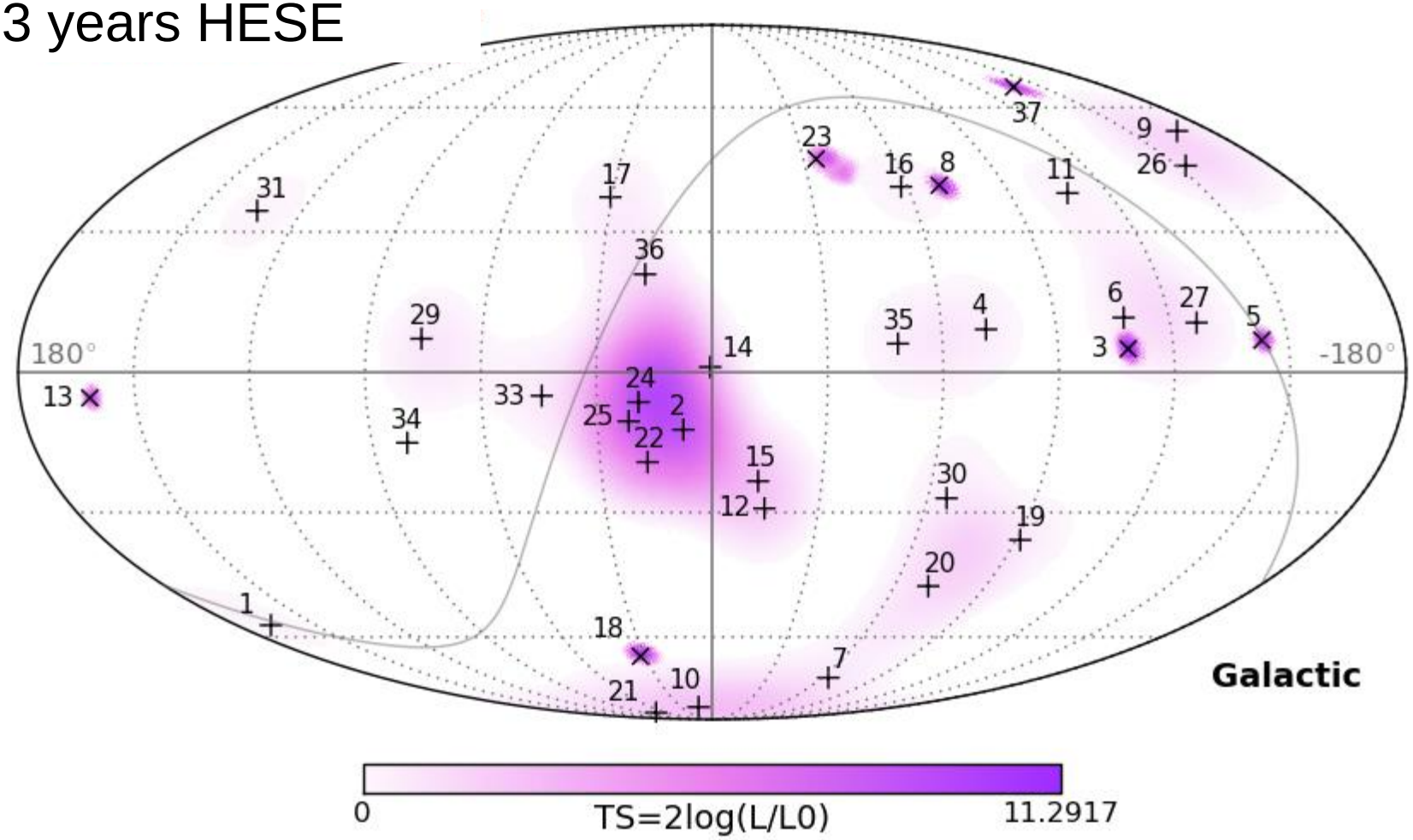
3 years HESE



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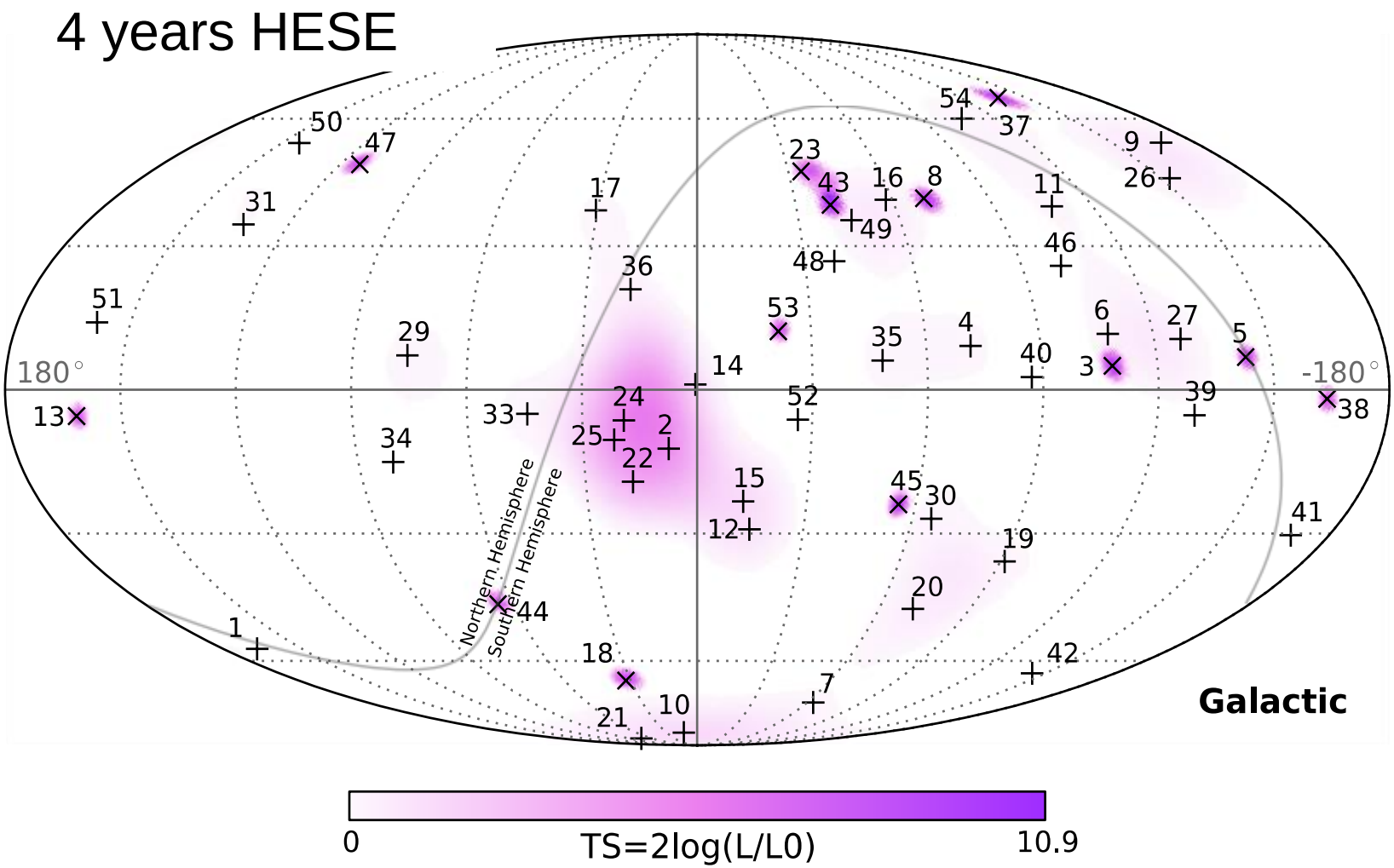
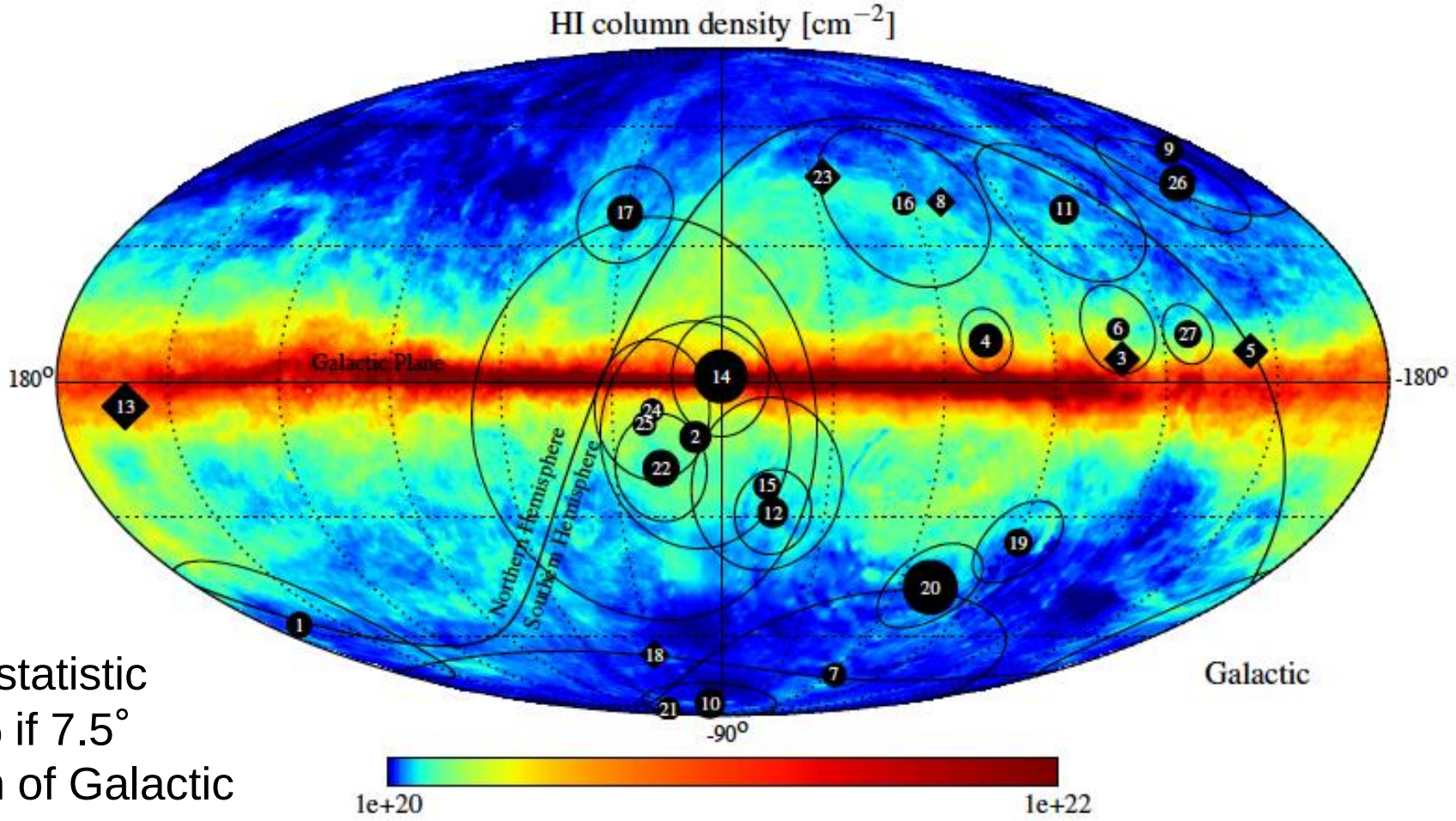


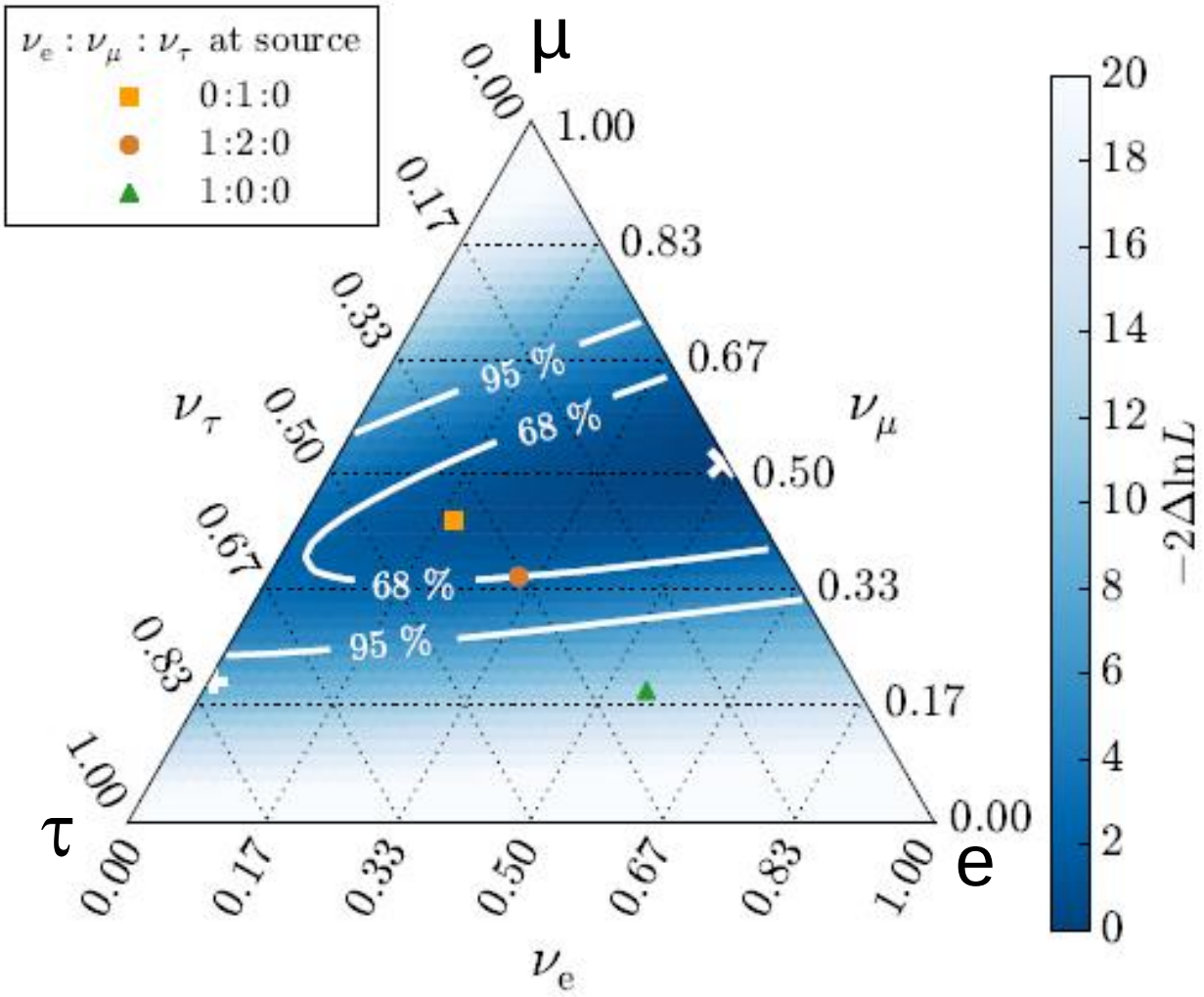
Correlation with Galactic plane?



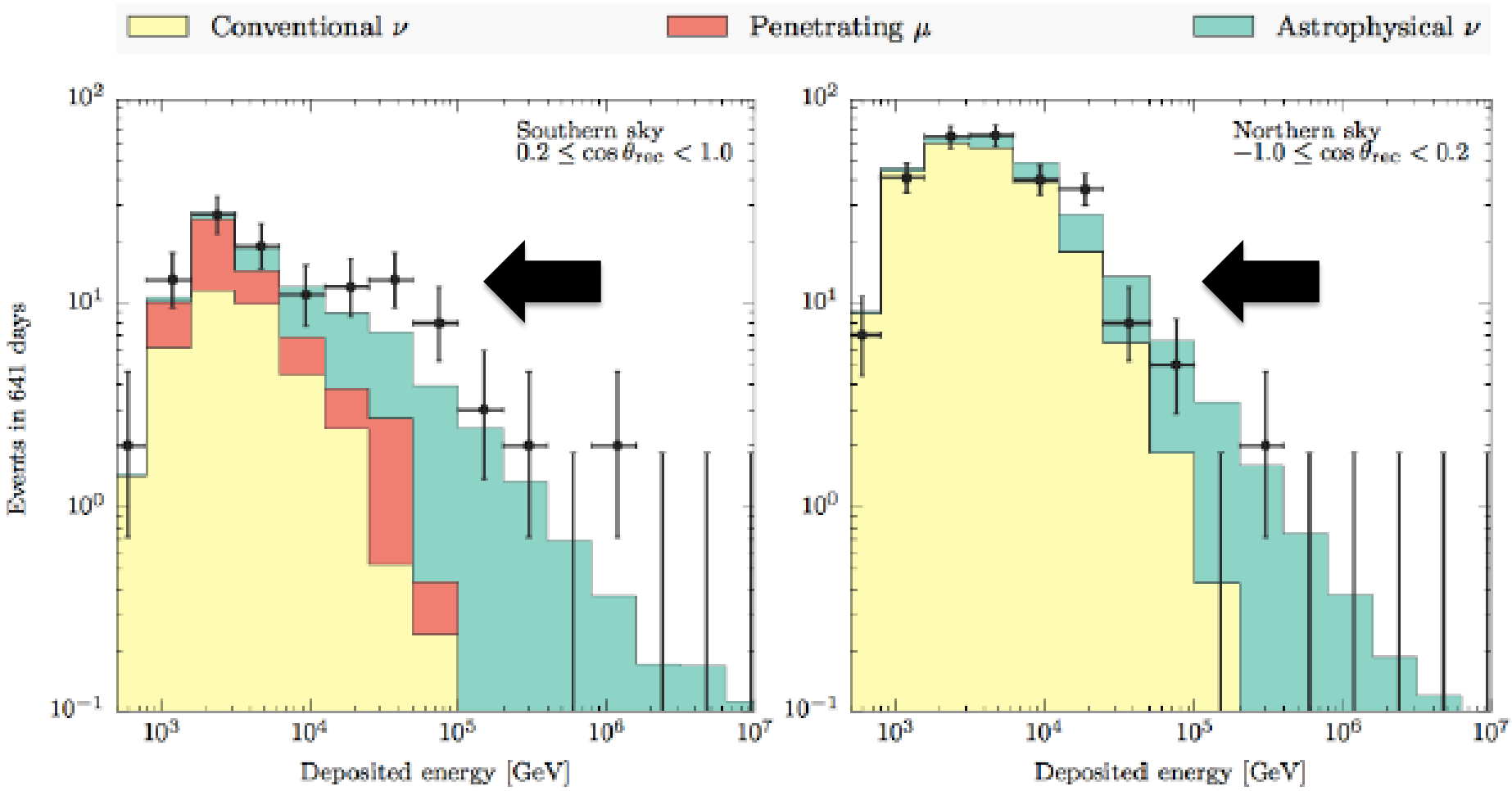
Test statistic
2.5% if 7.5˚
width of Galactic
plane assumed

Neutrino flavor composition?

- Neutrinos from p/K decays oscillate to e:μ:τ = 1:1:1 over cosmic distances
- IceCube measures mostly μ:(e+τ)
- Result consistent with expectation



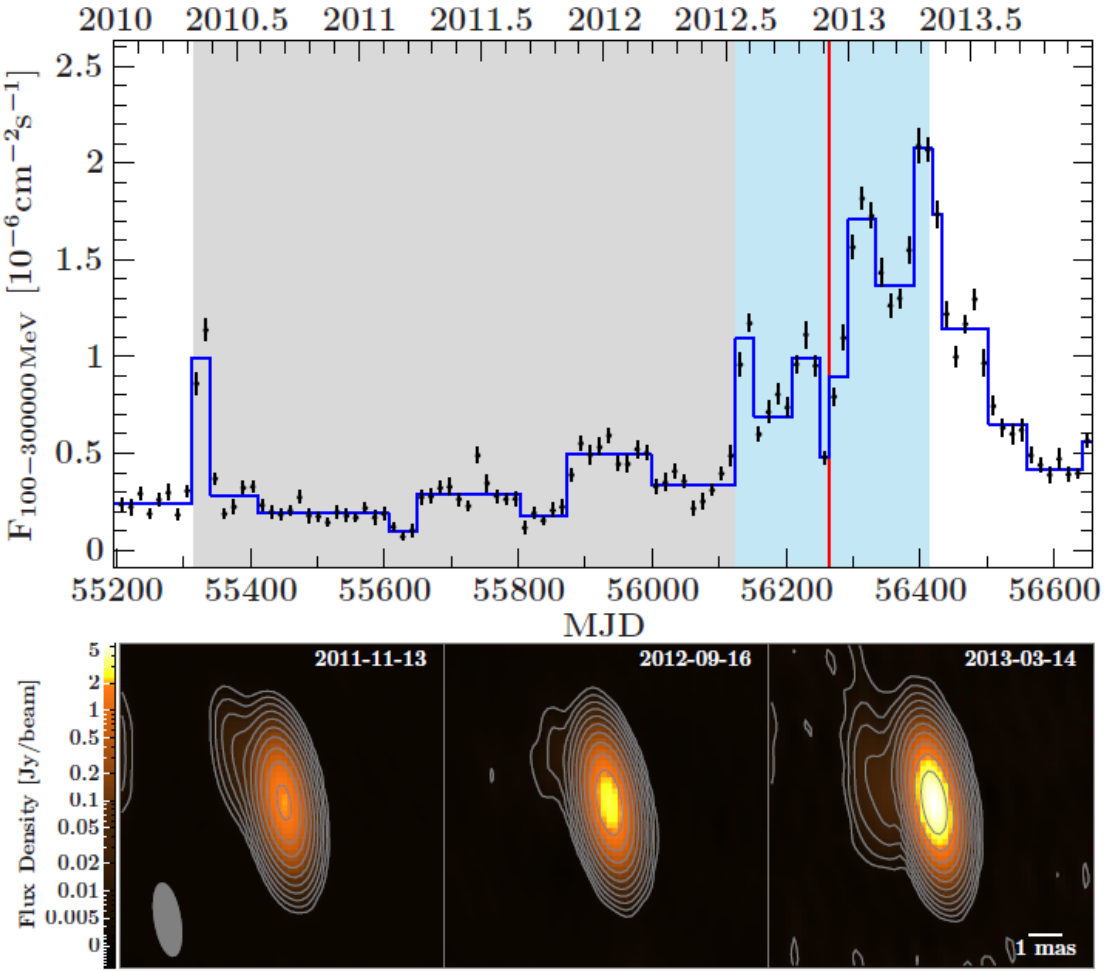
Questions, no answers (yet)



- A non-power-law component? Different source classes?
- Attention: Neutrinos are absorbed in Earth above ~100 TeV

IceCube events from blazars?

- Multi-messenger analysis using Fermi-LAT and radio data
- Candidate source for Big Bird: “Flat-spectrum radio quasar (FSRQ)” B1424-418 – temporally and spatially coincident
- Consistent with astrophysical modelling
- Probability for random association 5%



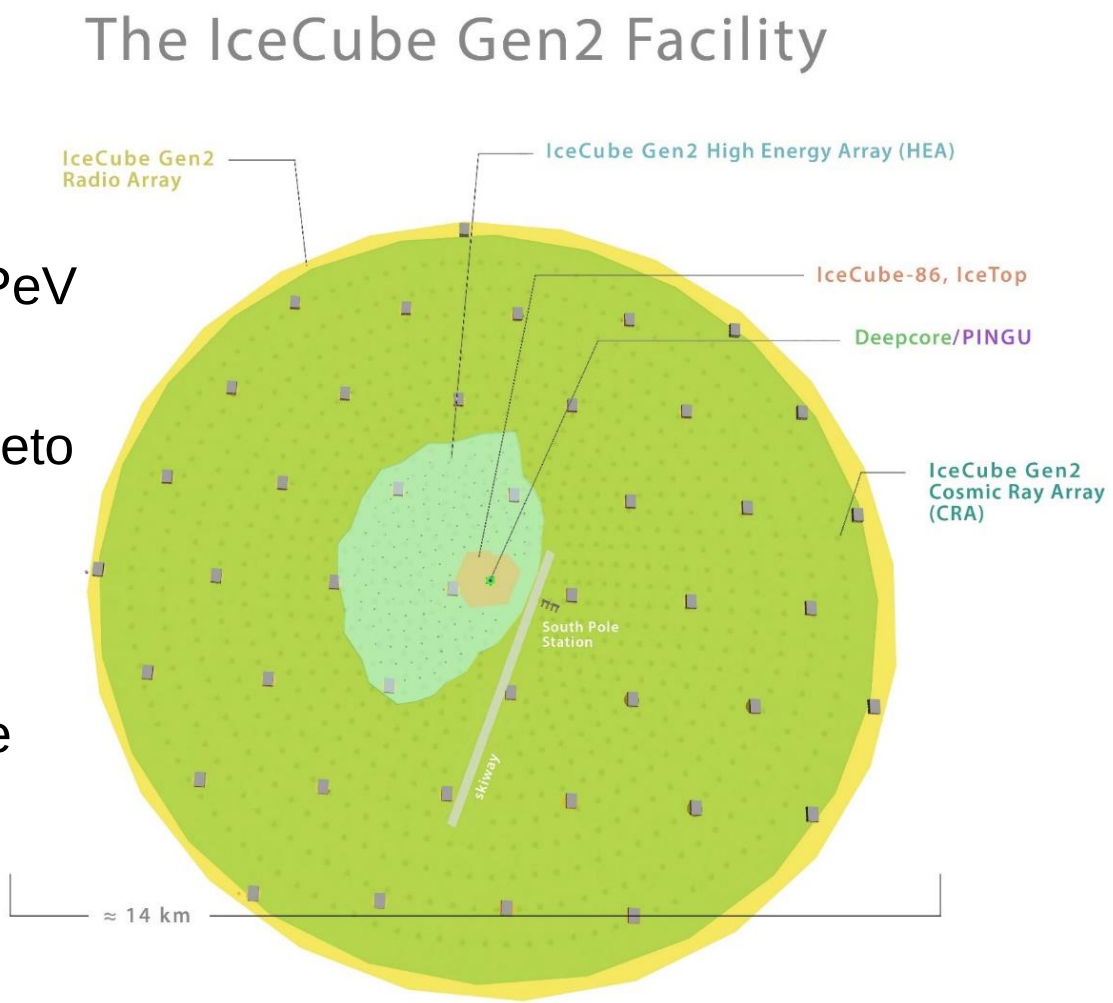
The IceCube signal

- Confirmed with high significance in cascade and muon channels
- Consistent with being fully isotropic
- Flavour composition consistent with π/K decay origin
- Possible structure in energy spectrum around 100 TeV?
- Origin is still unclear!

→ More data needed to draw firm conclusions!

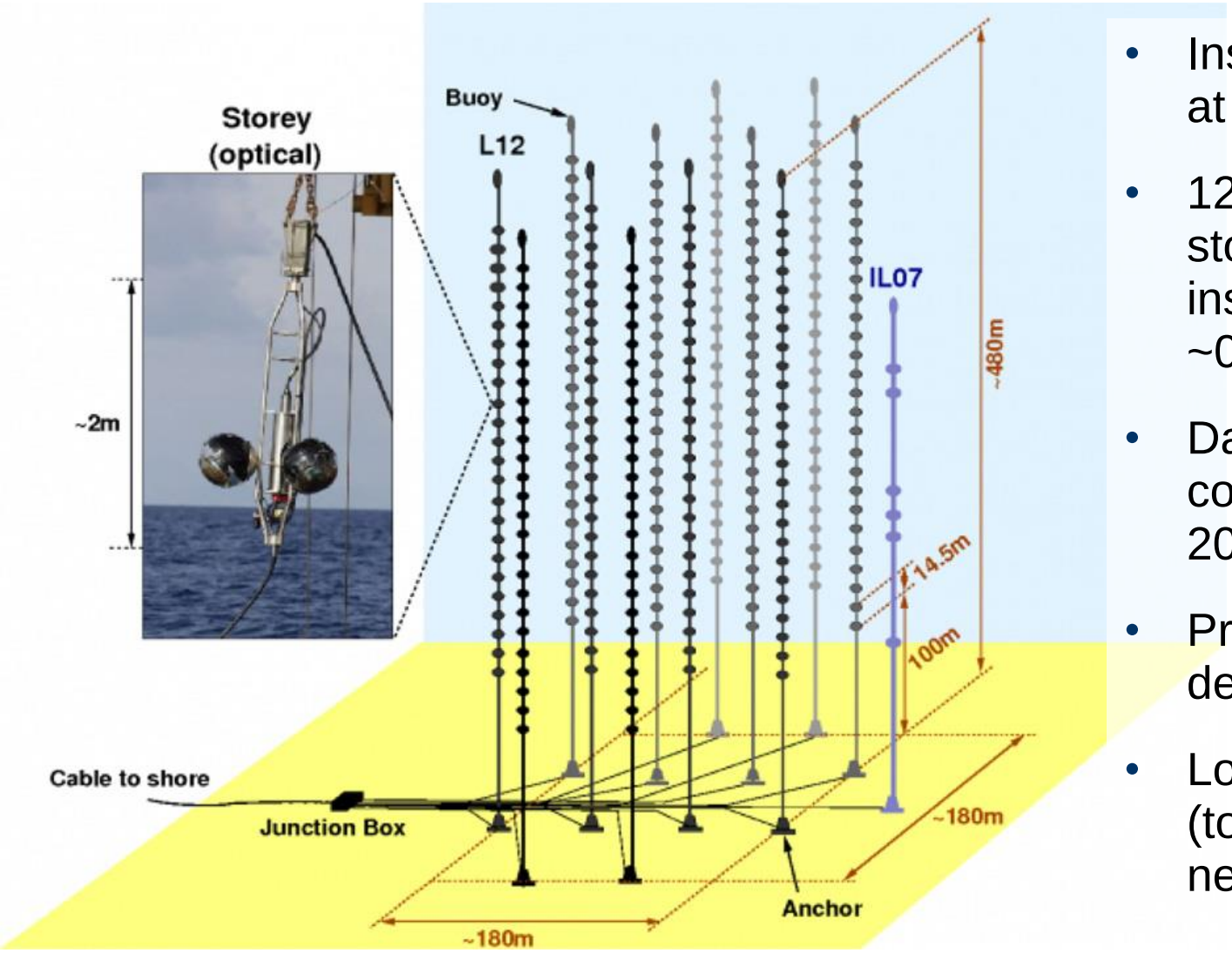
Future plans: IceCube Gen2

- PINGU:
  low energy, mass hierarchy
- High Energy Array (HEA): PeV scale neutrinos
- Cosmic Ray Array (CRA): veto array for HEA,
  cosmic ray physics
- Radio Array (RA):
  array of RF power envelope detectors



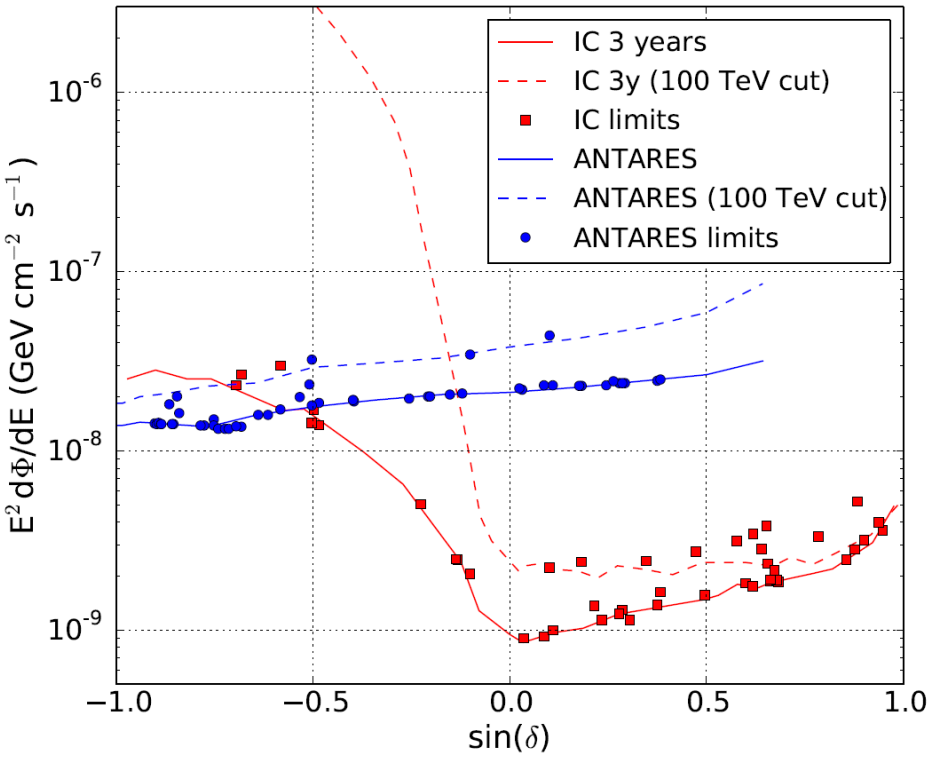
Neutrino astronomy in the Mediterranean Sea: ANTARES and KM3NeT

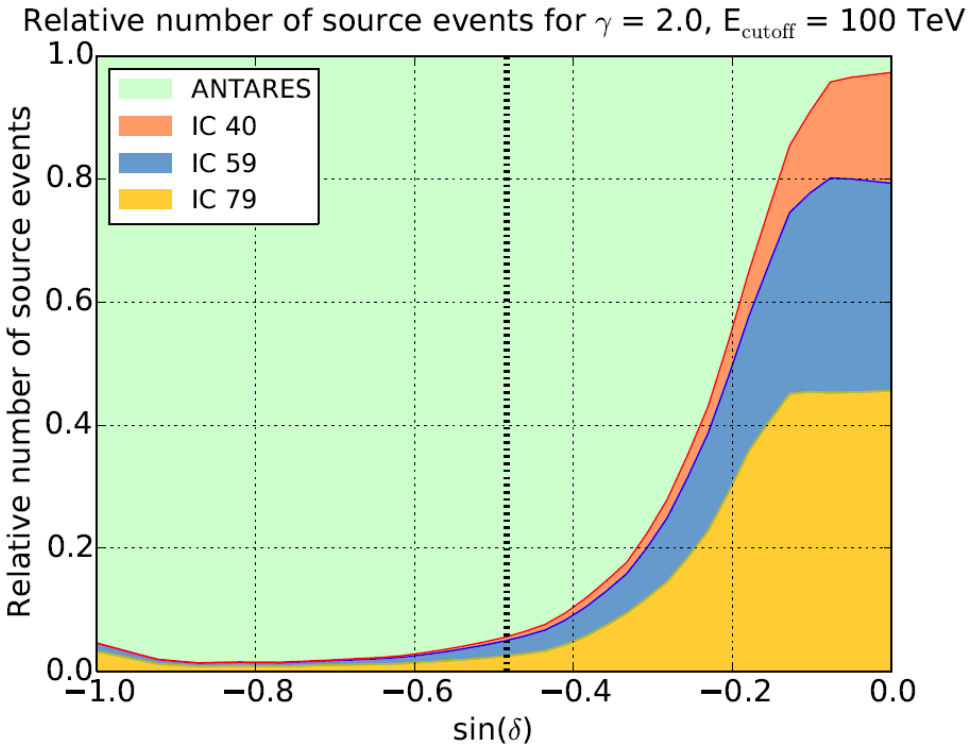
ANTARES: The first deep-sea ν telescope



- Installed near Toulon at a depth of 2475m
- 12 strings with 25 storeys each, instrumented volume ~0.01km^3
- Data taking in full configuration since 2008
- Proof of principle of deep-sea ν telescope
- Lots of results – but (too) small for cosmic neutrinos

ANTARES and IceCube: Combined analysis





- Common analysis of ANTARES and IceCube data
- Search for point-like neutrino sources, spectrum ~ $E^{-\gamma}$ * cutoff(E_{cutoff})
- Substantial contribution from ANTARES for spectra with E_{cutoff} ~ 100 TeV

The KM3NeT concept

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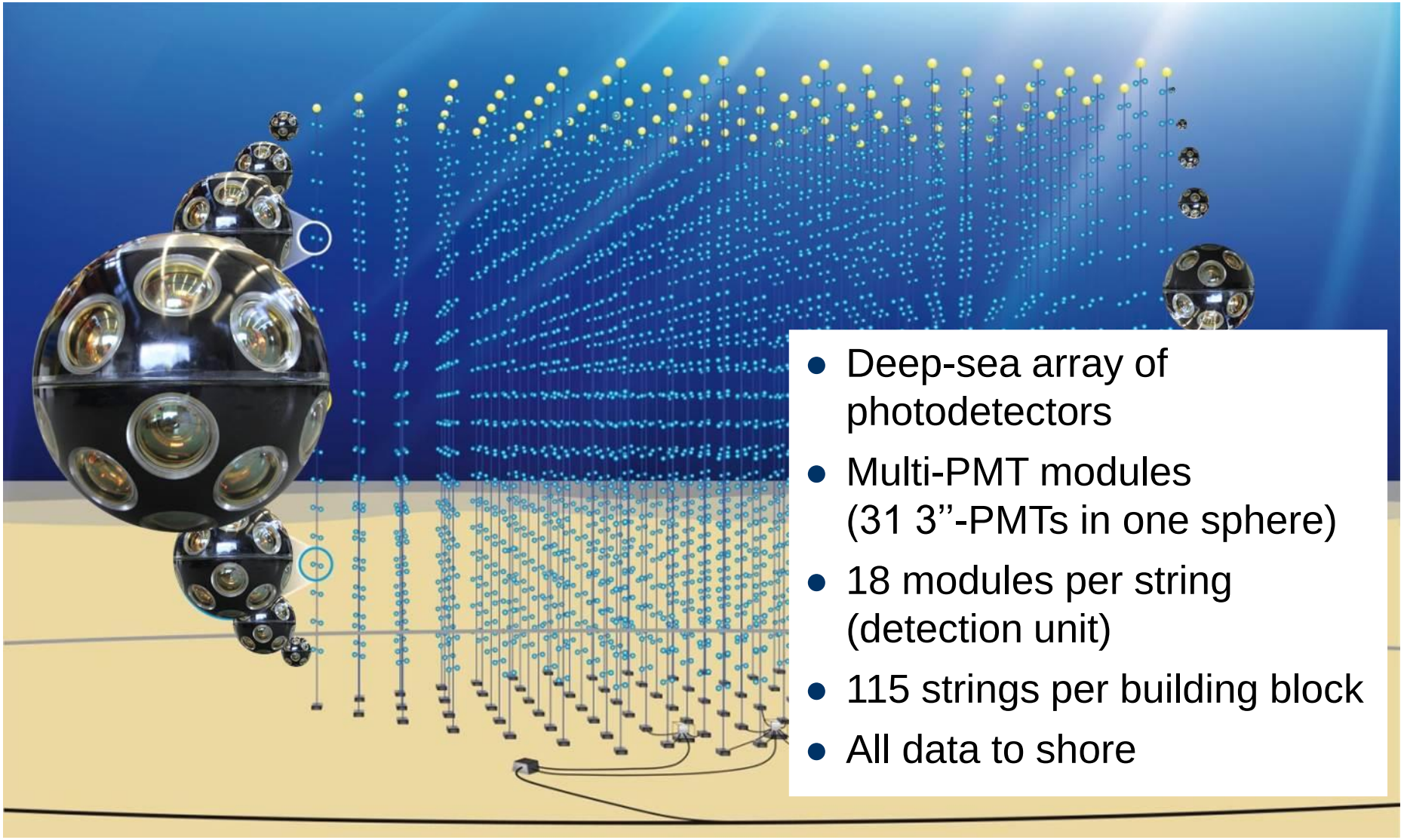
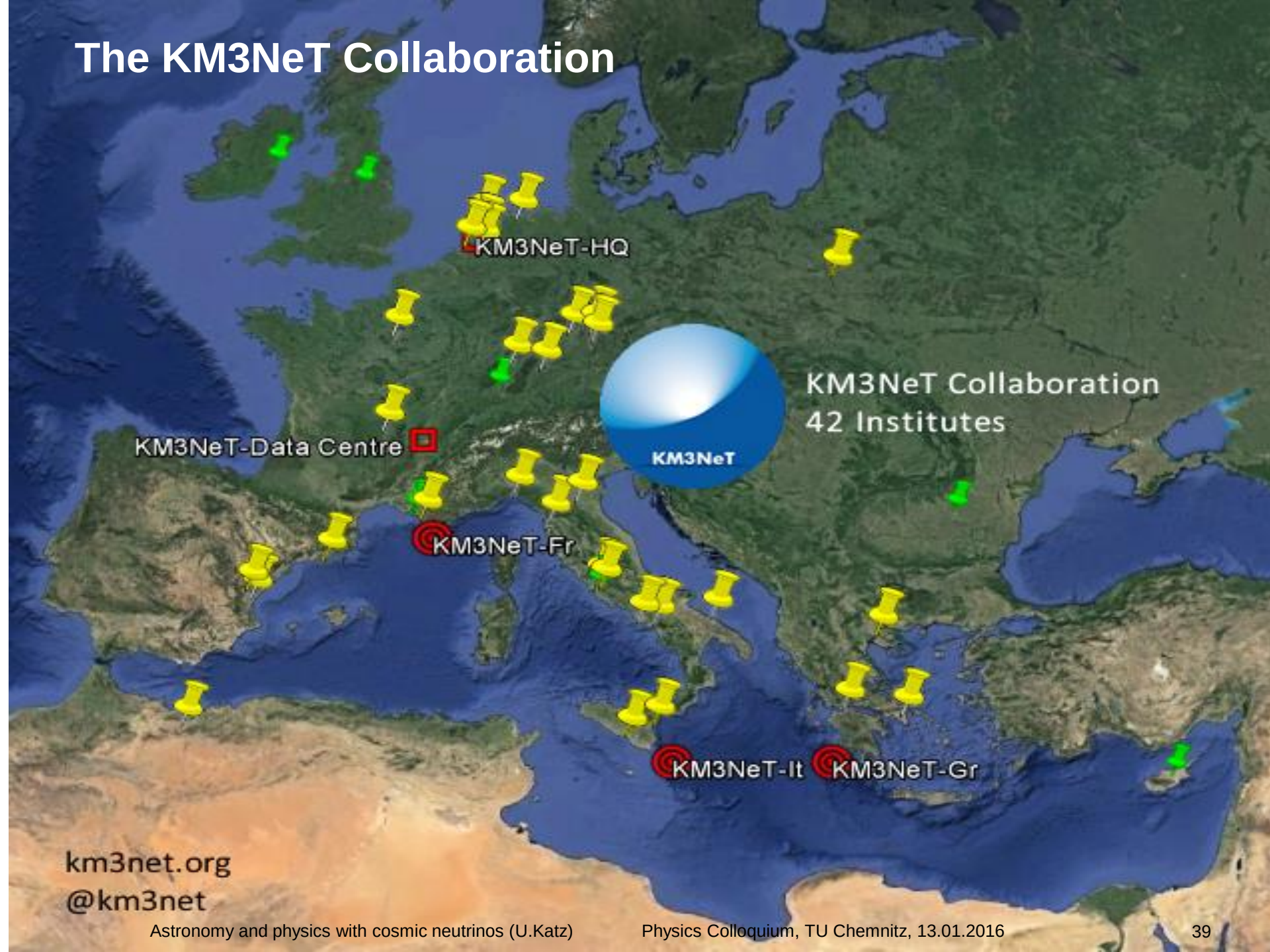


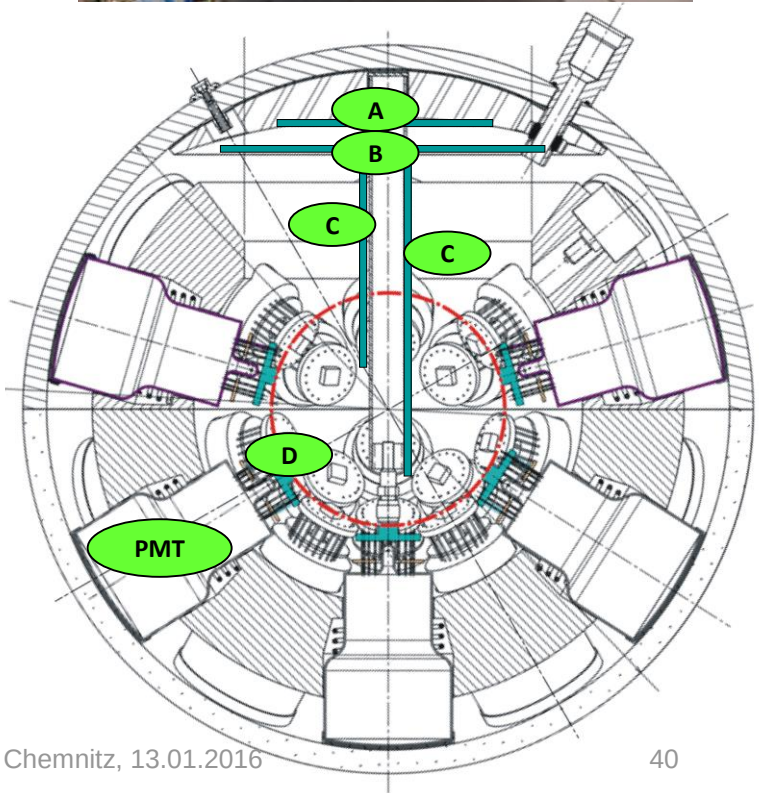
- Deep-sea array of photodetectors
- Multi-PMT modules (31 3”-PMTs in one sphere)
- 18 modules per string (detection unit)
- 115 strings per building block
- All data to shore

The KM3NeT Collaboration



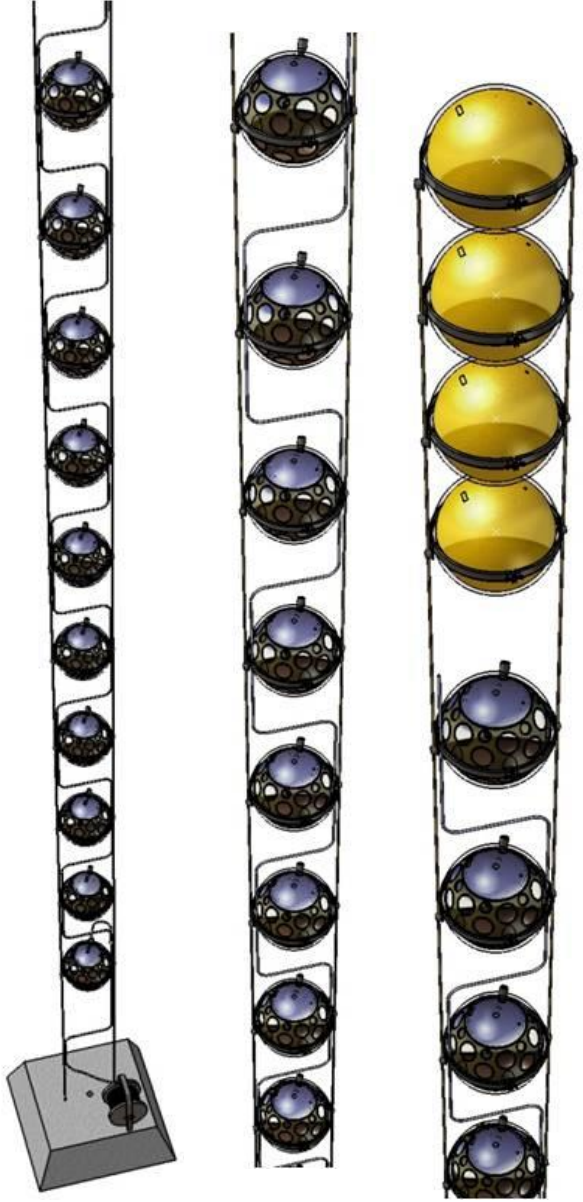
The KM3NeT Digital Optical Module

- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10-inch PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by plastic structure
- 31 PMT bases (total ~140 mW) (D)
- Front-end electronics (B,C)
- Al cooling shield and stem (A)
- Single penetrator
- Advantages:
  - Increased photocathode area
  - 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - Directionality
  - Cost / photocathode area
  - Minimal number of penetrations → reduced risk

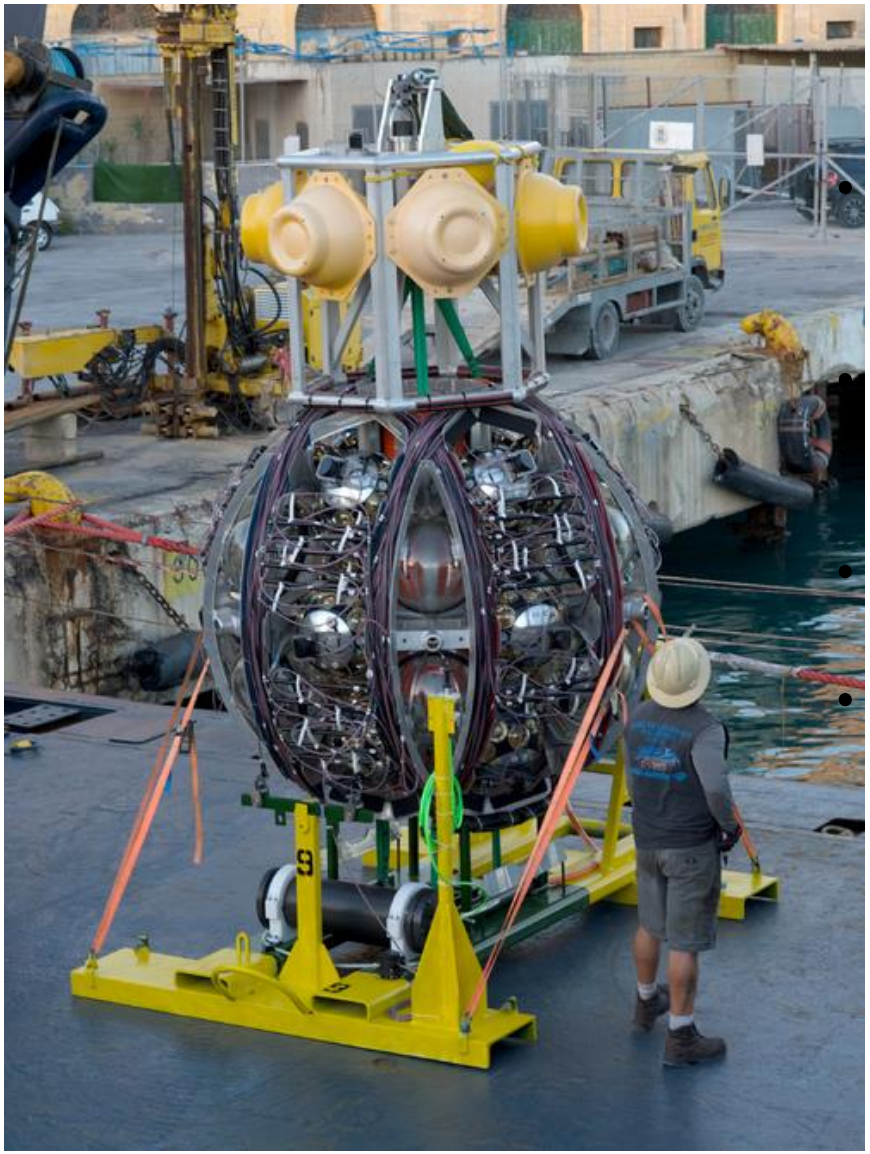


The KM3NeT detection unit (DU)

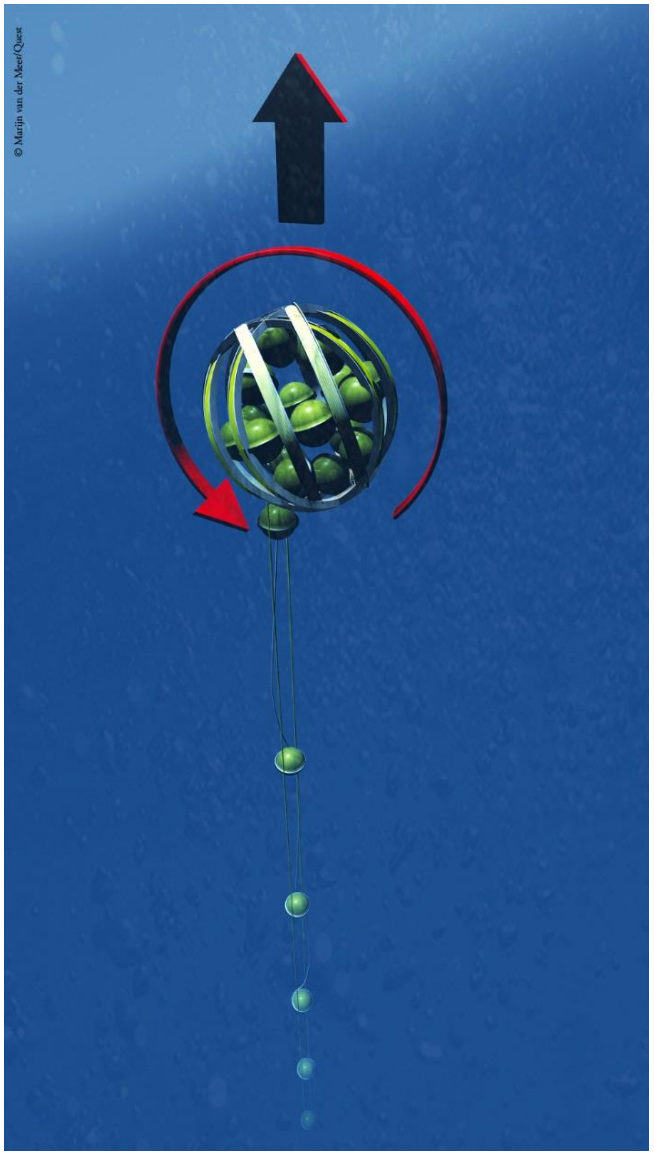
- Mooring line:
  - Buoy (syntactic foam or empty spheres)
  - 2 pre-stretched Dyneema© ropes (4 mm diameter)
  - 18 storeys (one DOM each)
- Electro-optical backbone (VEOC):
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - Optical fibres and copper wires
  - At each storey: Break-out box for connection to 1 fibre + 2 wires (one single pressure transition)



Deployment



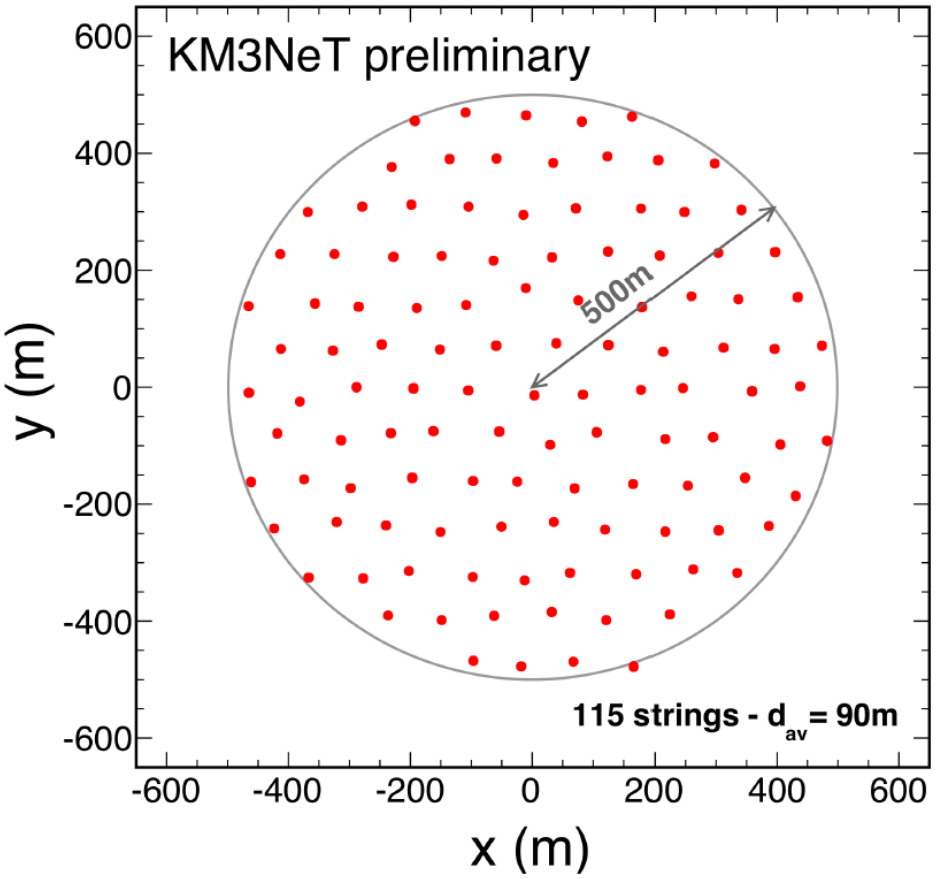
- ← Deploy to sea bed
- Acoustic release
- Unfurl →
- Collect frame



The building block concept

- Building block:
  - 115 detection units
  - Segmentation enforced by technical reasons
- Large block (neutrino astronomy)
  - Sensitivity per string for muons independent of block size above ~75 strings
  - One block ~ half IceCube
- Small block (neutrino oscillations)
  - Precision measurement of atmospheric neutrinos
  - One block ~ 6 Mtons
- Allows for staged, block-wise, multi-site installation

DU distance adjusted to scientific objective:
90-120 m for neutrino astronomy /
20 m for oscillation research



KM3NeT development

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Phase	Blocks/ strings	Primary deliverables / site(s)	Funding Construction
1	0.2/31	Proof of feasibility and first science results; KM3NeT-Fr + KM3NeT-It sites	Fully funded 2015-17
2.0	2/230	Measurement of neutrino signal reported by IceCube; All-flavor neutrino astronomy; KM3NeT-It site	Applications pending 2017-2020
	1/115	Neutrino mass hierarchy; KM3NeT-Fr site	
3	6+1/805	Neutrino astronomy including Galactic sources; Multiple sites	t.b.d. ?

KM3NeT Phase-1 = 31 DUs

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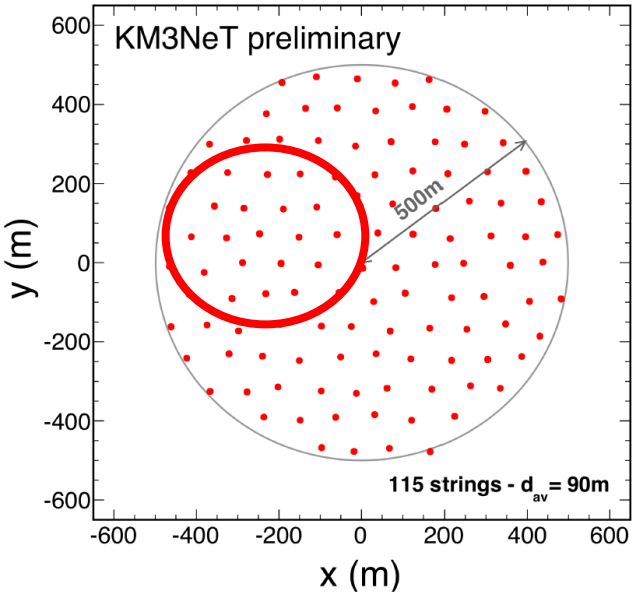
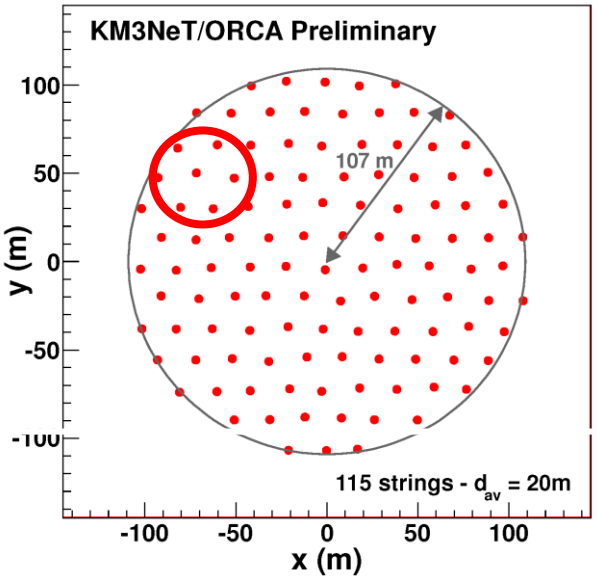
ARCA =

Astroparticle Research with Cosmics in the Abyss



Vertical OM distance = 36 m
→ 3 times ANTARES

ORCA =
Oscillation Research with Cosmics in the Abyss



Vertical OM distance = 9 m

KM3NeT 2.0 = ARCA and ORCA

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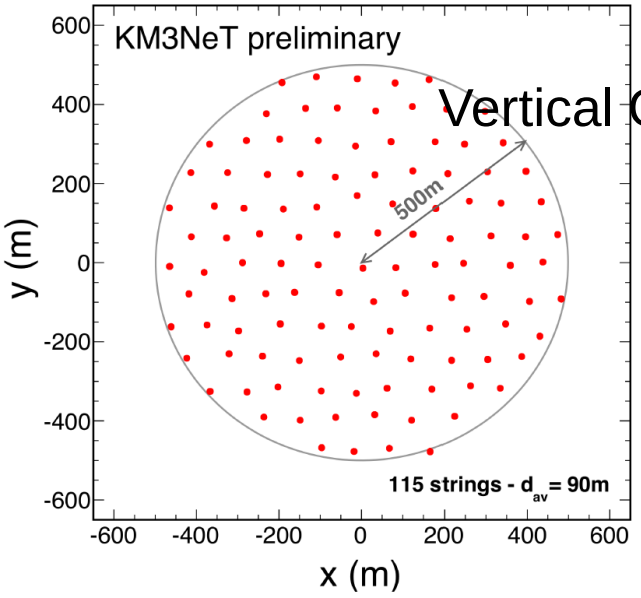
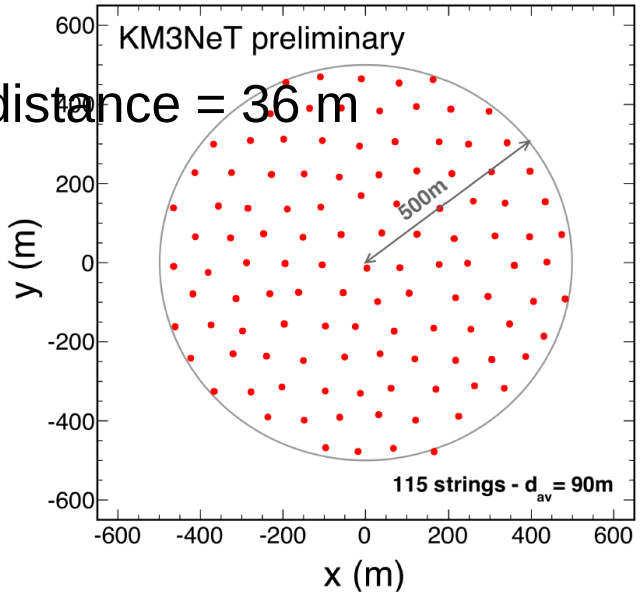
ARCA =

Astroparticle Research with Cosmics in the Abyss



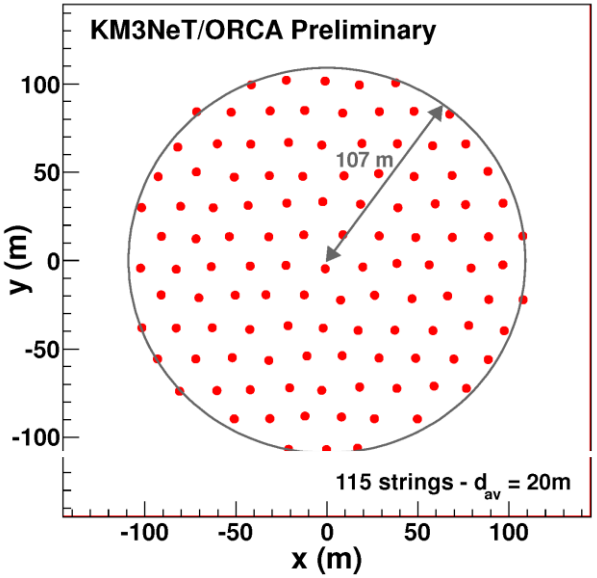
Vertical OM distance = 36 m

+



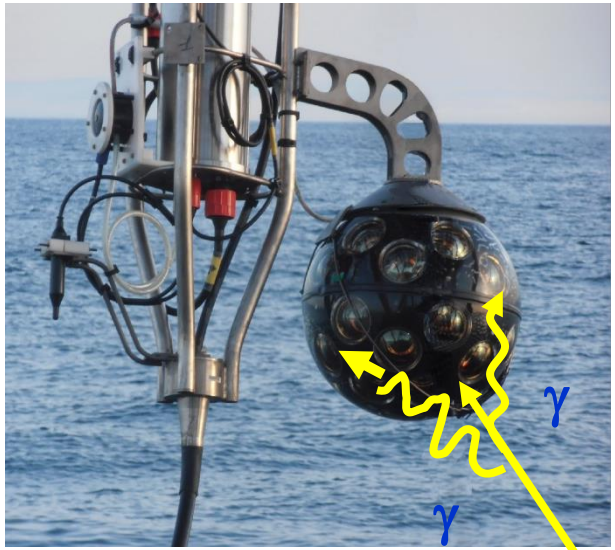
ORCA =

Oscillation Research with Cosmics in the Abyss



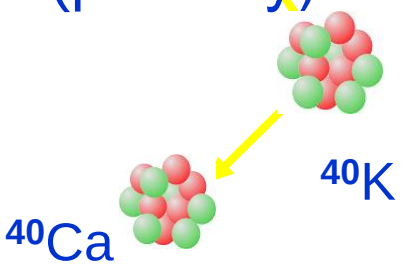
Vertical OM distance = 9 m

DOM prototype (PPM-DOM)

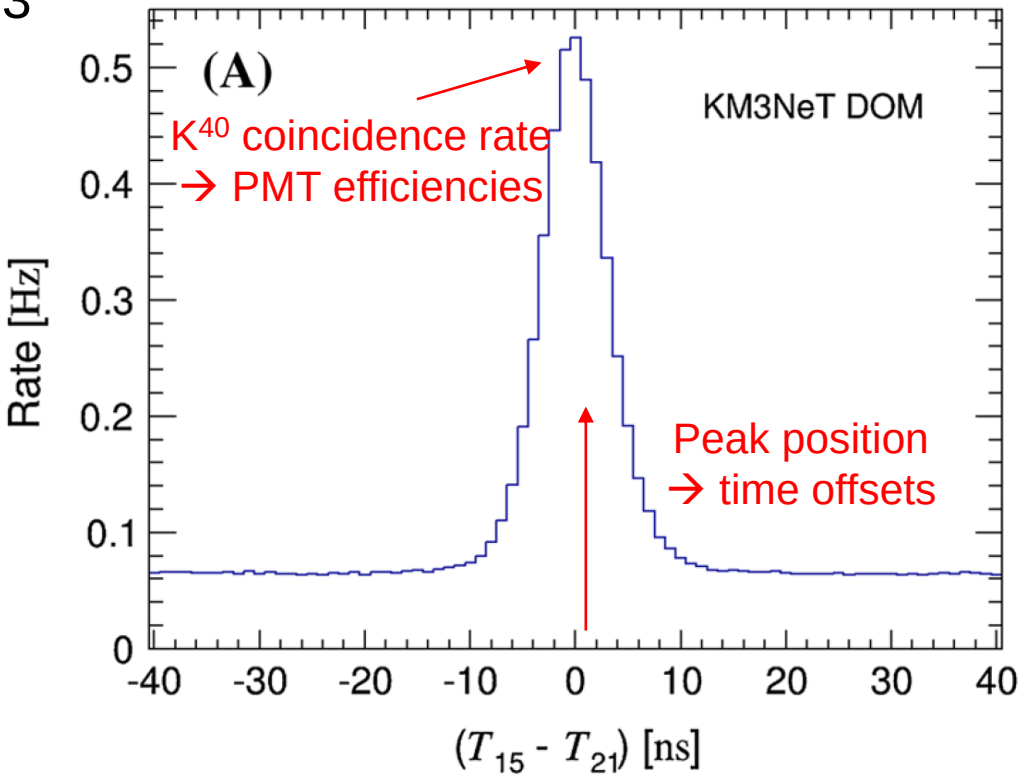


Deployed at ANTARES in April 2013

Up to 150 Cherenkov photons per decay



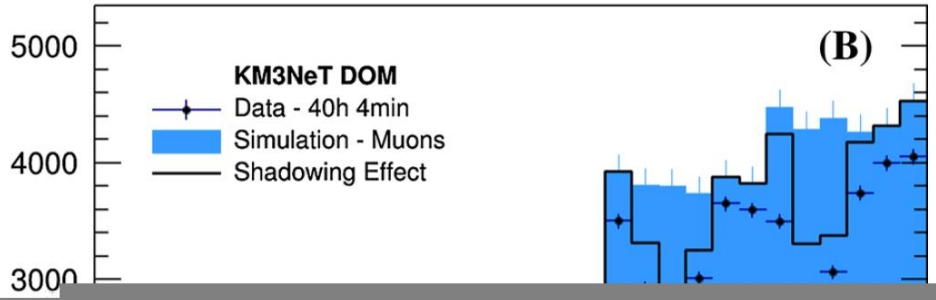
Coincidence rate on 2 adjacent PMTs (33° angular separation)



Eur.Phys.J. C74 (2014) 3056

Concentration of ^{40}K is stable
(coincidence rate ~5 Hz on adjacent PMTs)

PPM-DOM: Atmospheric muons



Eur.Phys.J. C74 (2014) 3056

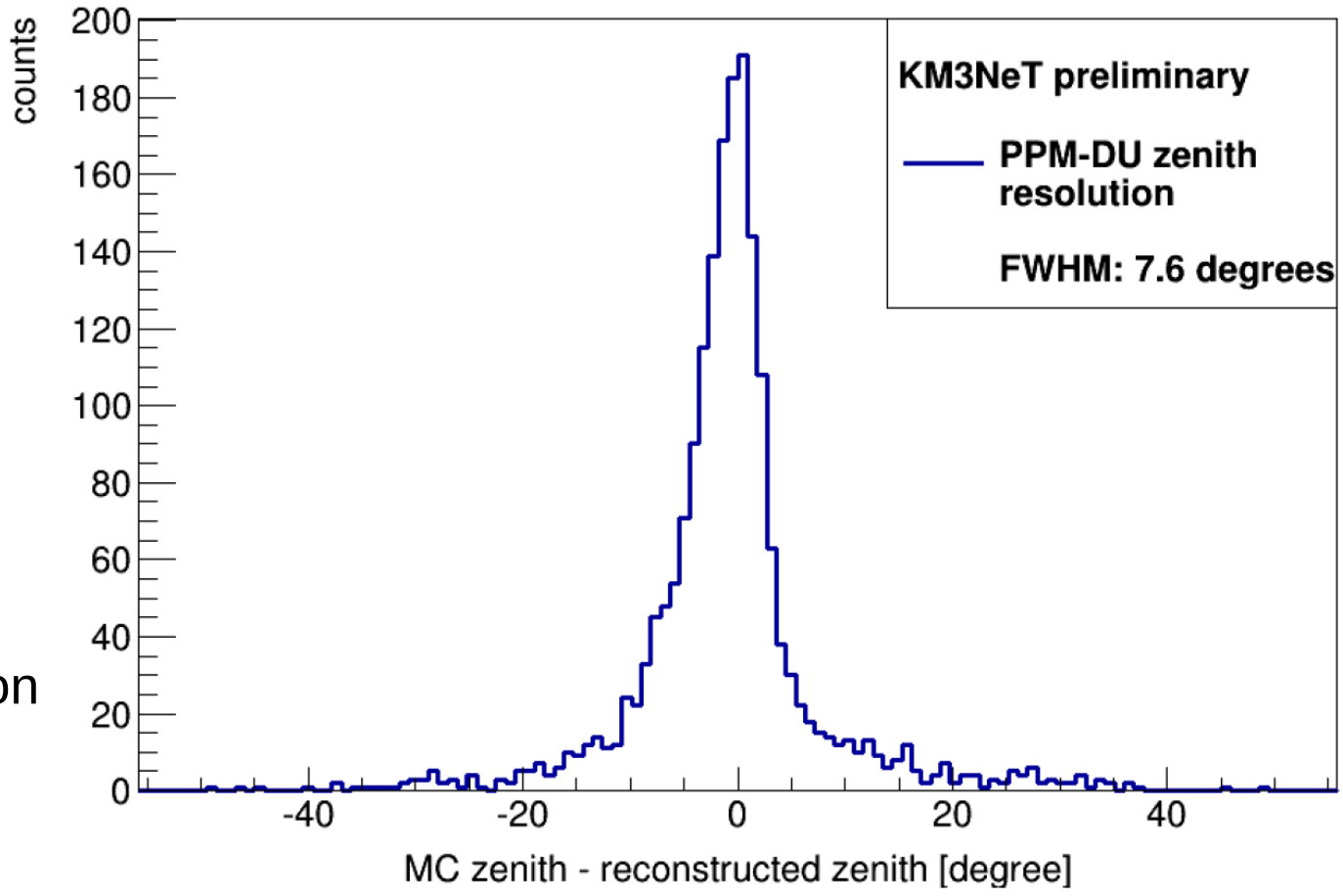
Number of coincident hits in a DOM

Zenith angle of hit PMTs in events with more than 7 coincident hits

- >5 coincidences within 20ns
  - reduced K40 contribution, dominated by atmospheric muons
- More upper PMTs in multi-hit events
  - directional information from single storey

PPM-DU: Muon reconstruction

- Reconstruct muon trajectory from hits on 3 DOMs
- Ambiguities can be reduced by cuts on time differences
- 7° FWHM resolution achieved



First string deployed on 3 Dec 2015

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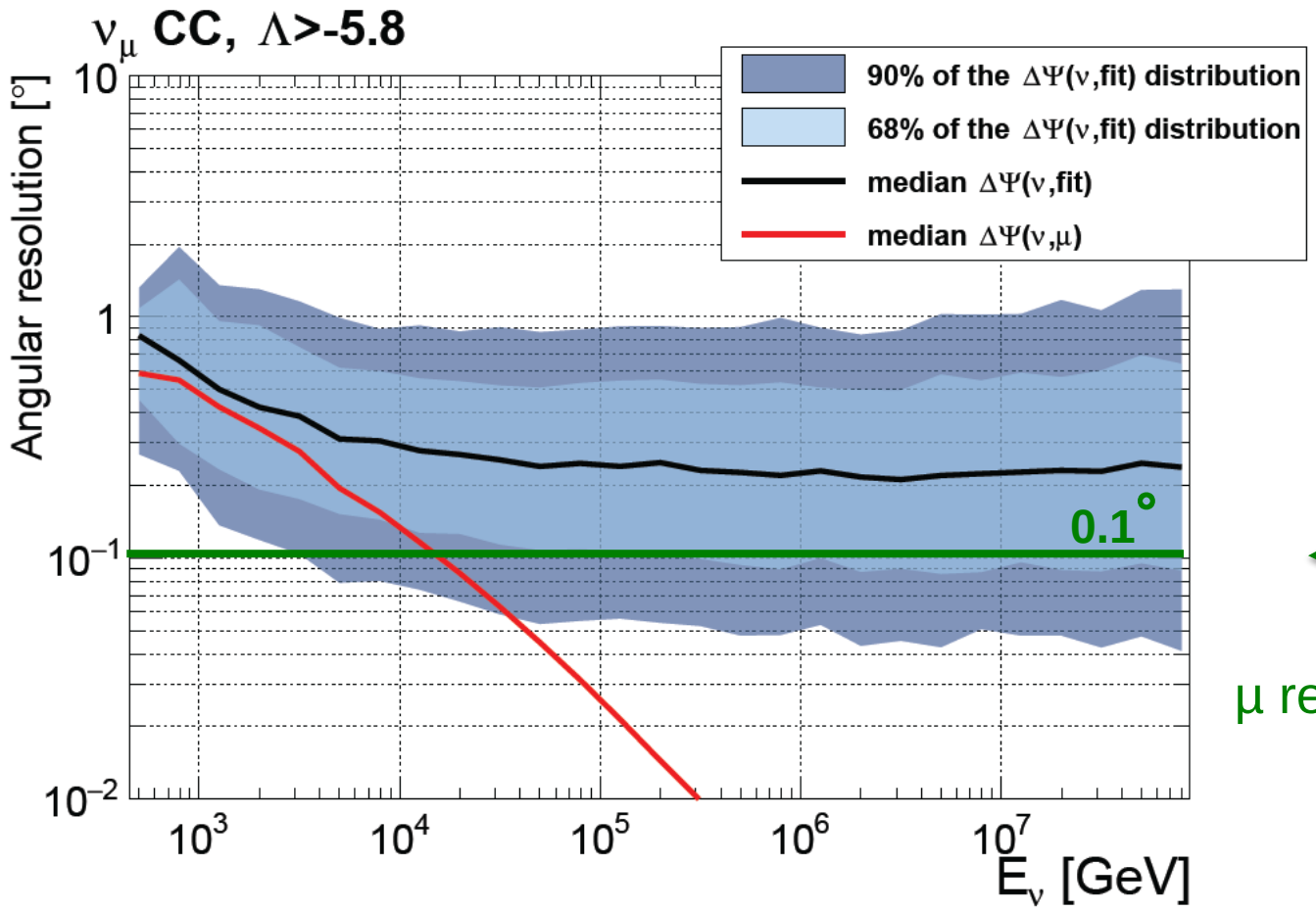
- Smooth operation
- All 18 DOMs alive and functional
- First muons reconstructed within hours after switch-on
- Data taking in progress

Muon angular reconstruction

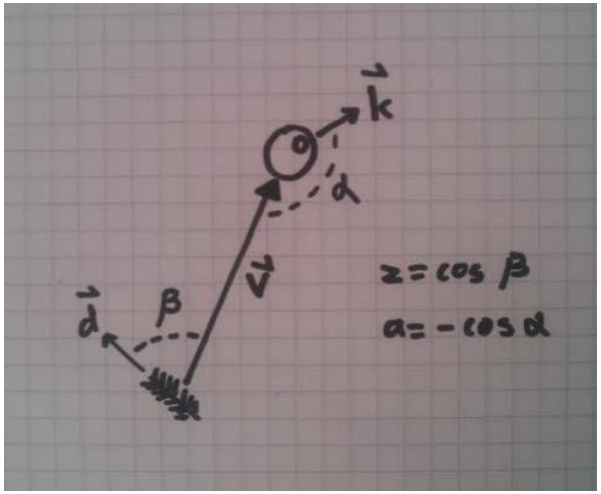
Reconstruction using new PMT response simulation:
Median of angle $\Delta\Omega$ between reconstructed μ and true ν direction

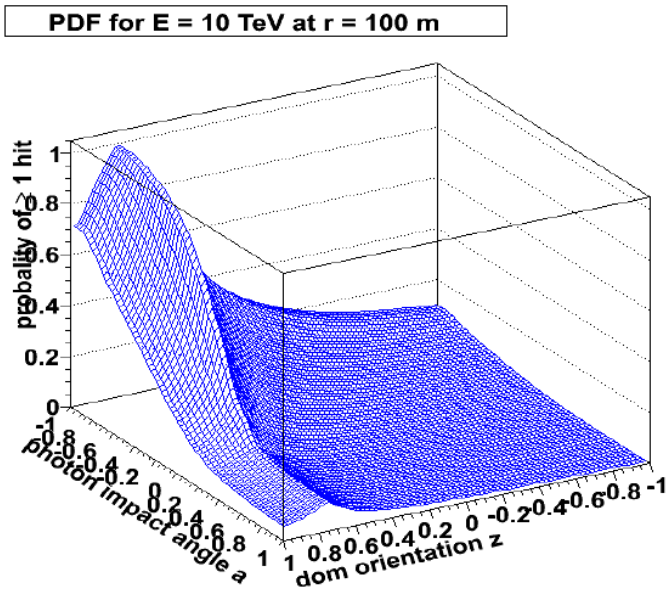


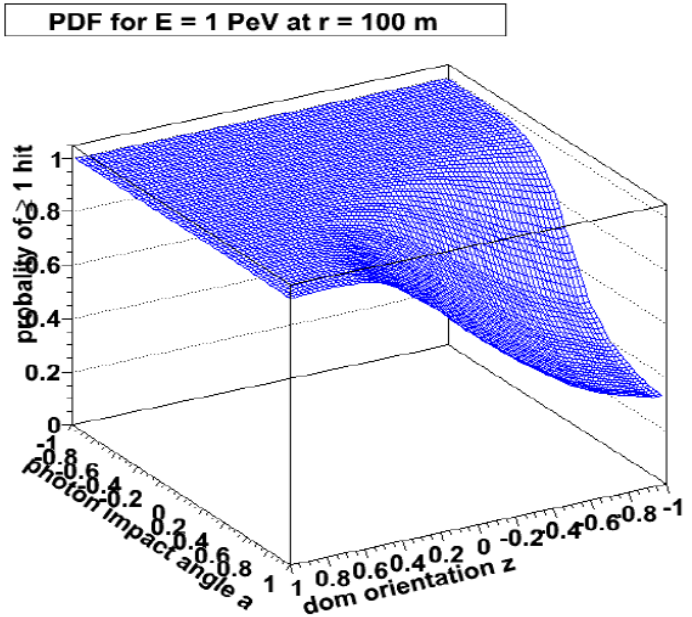
Expected
μ reconstruction
precision

Shower reconstruction: Method

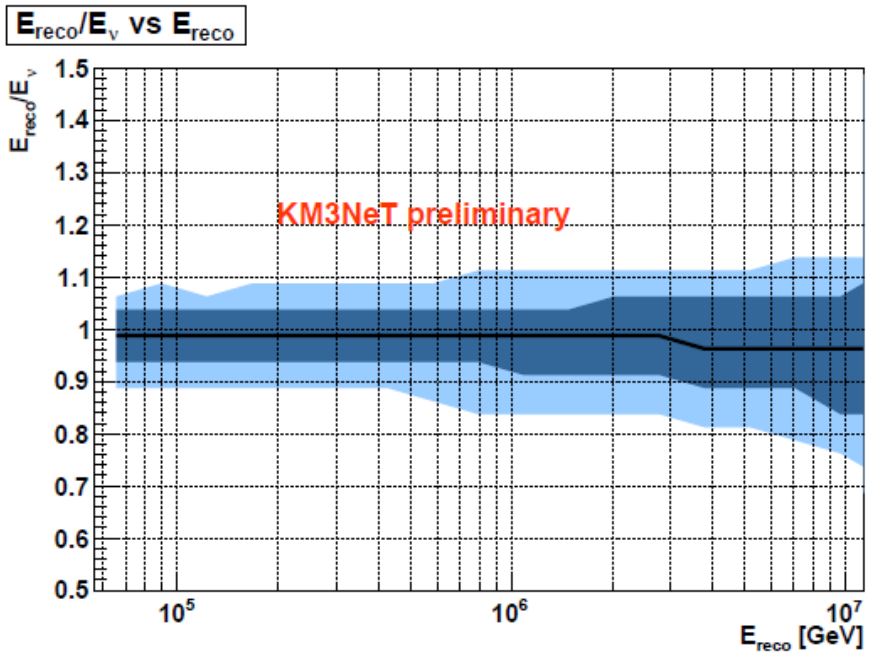
- Vertex fit: Suitable hit selection, fit uses timing; result used for containment requirement
- Direction and energy: Uses PDF depending on
  - Distance vertex – DOM
  - Angle between shower direction and DOM
  - Orientation of PMTs
- Hit information used: yes/no

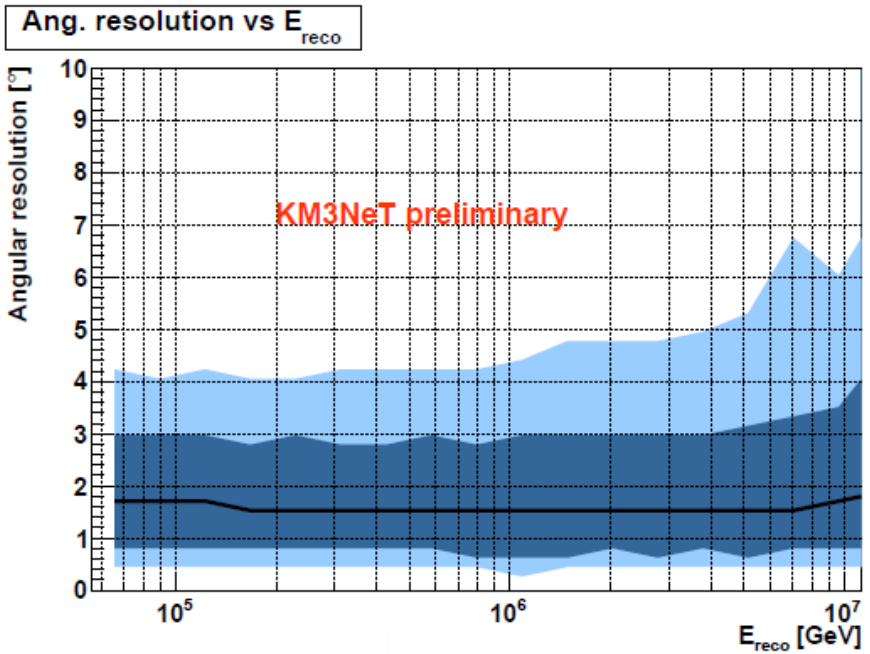






Shower reconstruction: θ, E





- For contained ν_e CC events
- Event sample after selection cuts
- ~10% in E, better than 2° in direction

Diffuse extragalactic neutrino flux

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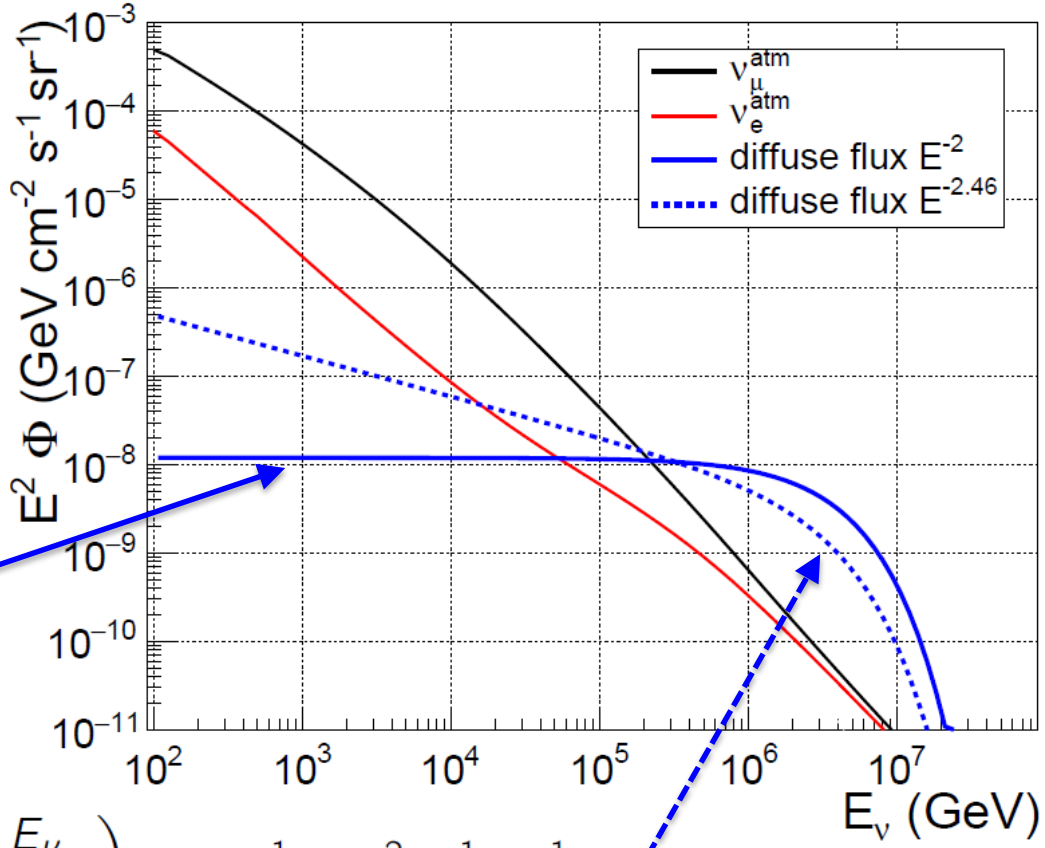
Assumptions:

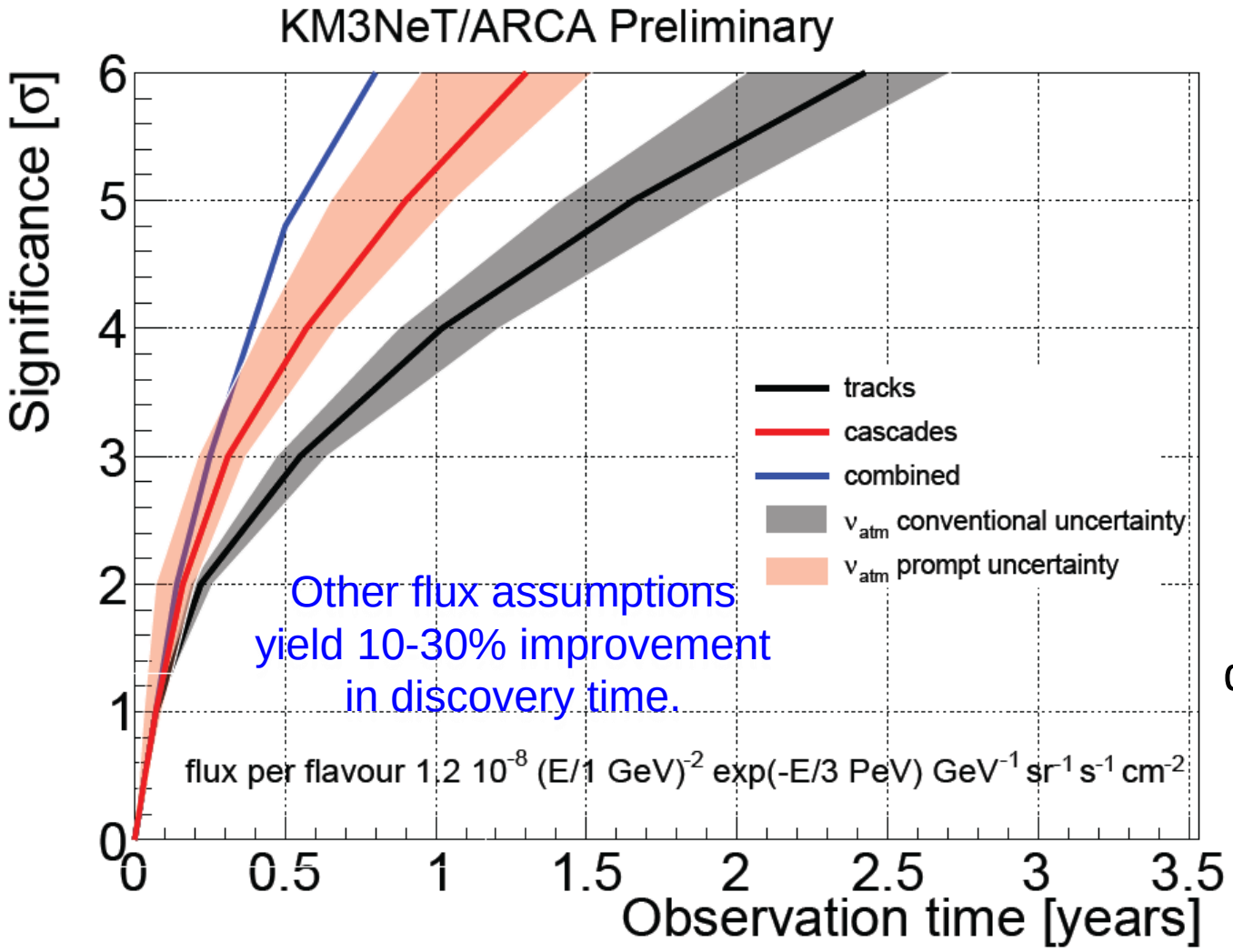
1. Flavour-symmetric
2. Isotropic
3. Energy spectrum consistent with IceCube findings



$$\Phi(E_\nu) = 1.2 \times 10^{-8} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2} \cdot \exp\left(-\frac{E_\nu}{3\,\mathrm{PeV}}\right) \quad \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

$$\Phi(E_\nu) = 4.11 \times 10^{-6} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2.46} \cdot \exp\left(-\frac{E_\nu}{3\,\mathrm{PeV}}\right) \quad \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

Diffuse flux results (max. liklihood)



Event numbers (cut&count):

16/9 cascades

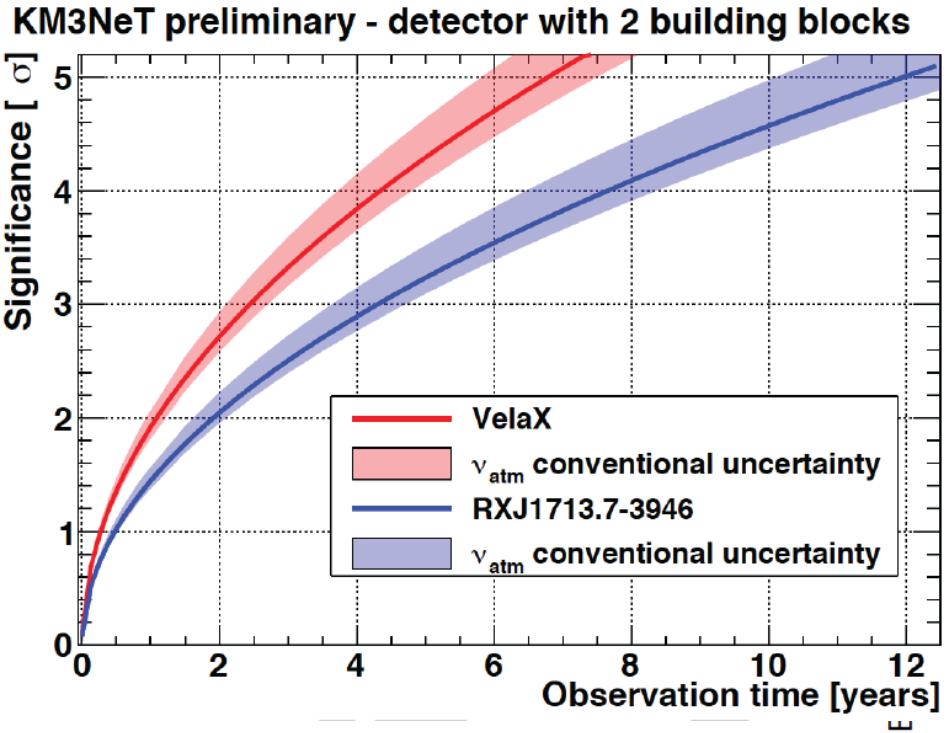
7.5/5 track-like

(signal/background per ARCA year)

Note:

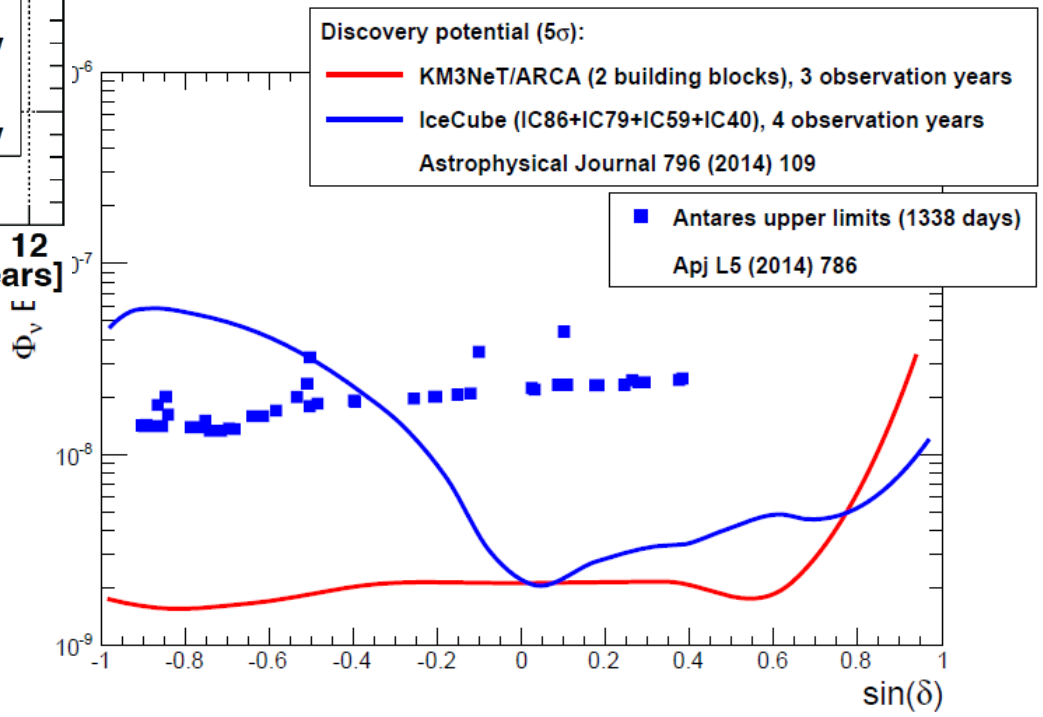
For each energy, direction and flavour, KM3NeT is complementary to IceCube

Point-source results

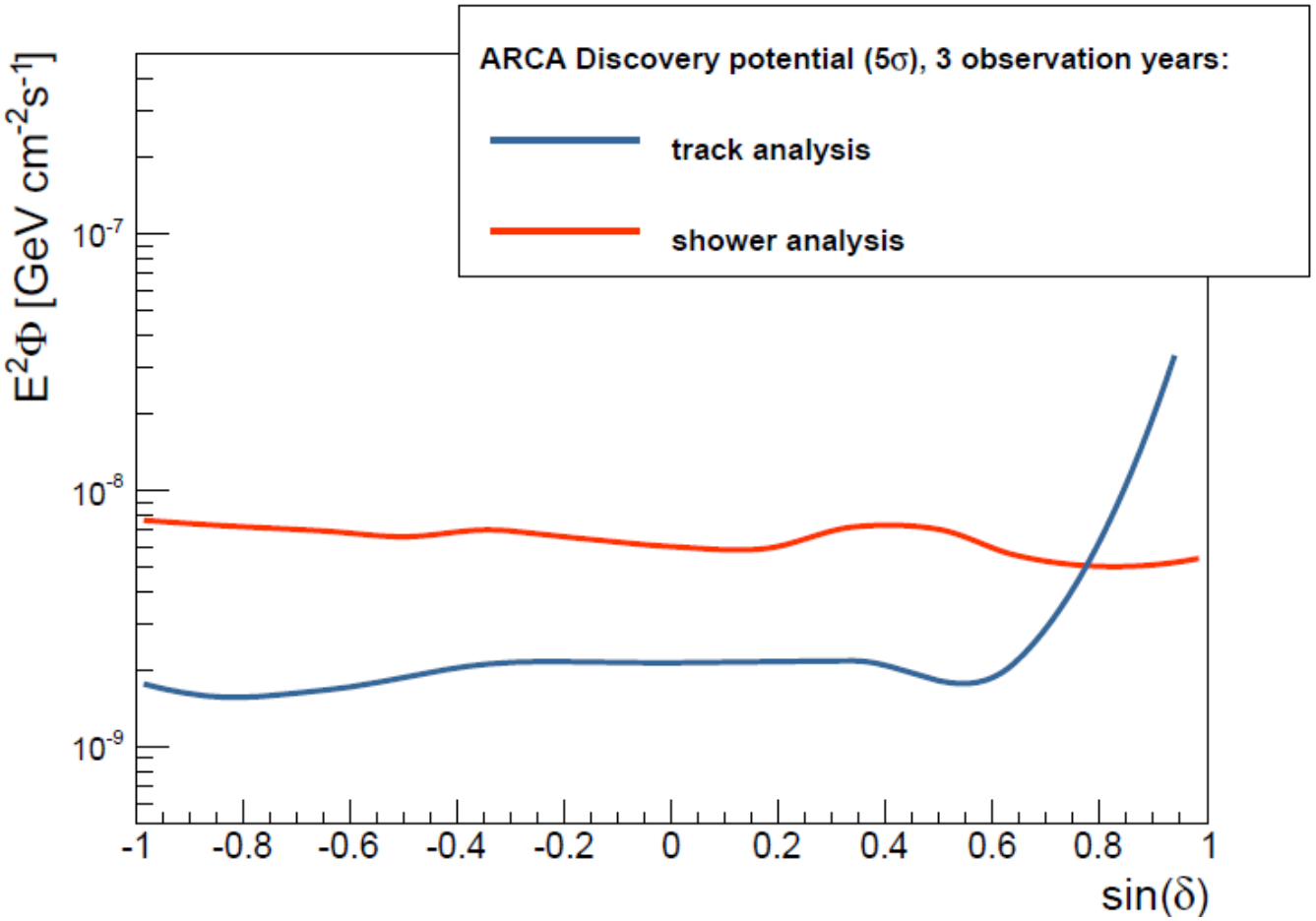


- Galactic sources in reach

- Significant discovery potential for extragalactic sources



Point-source search with cascades

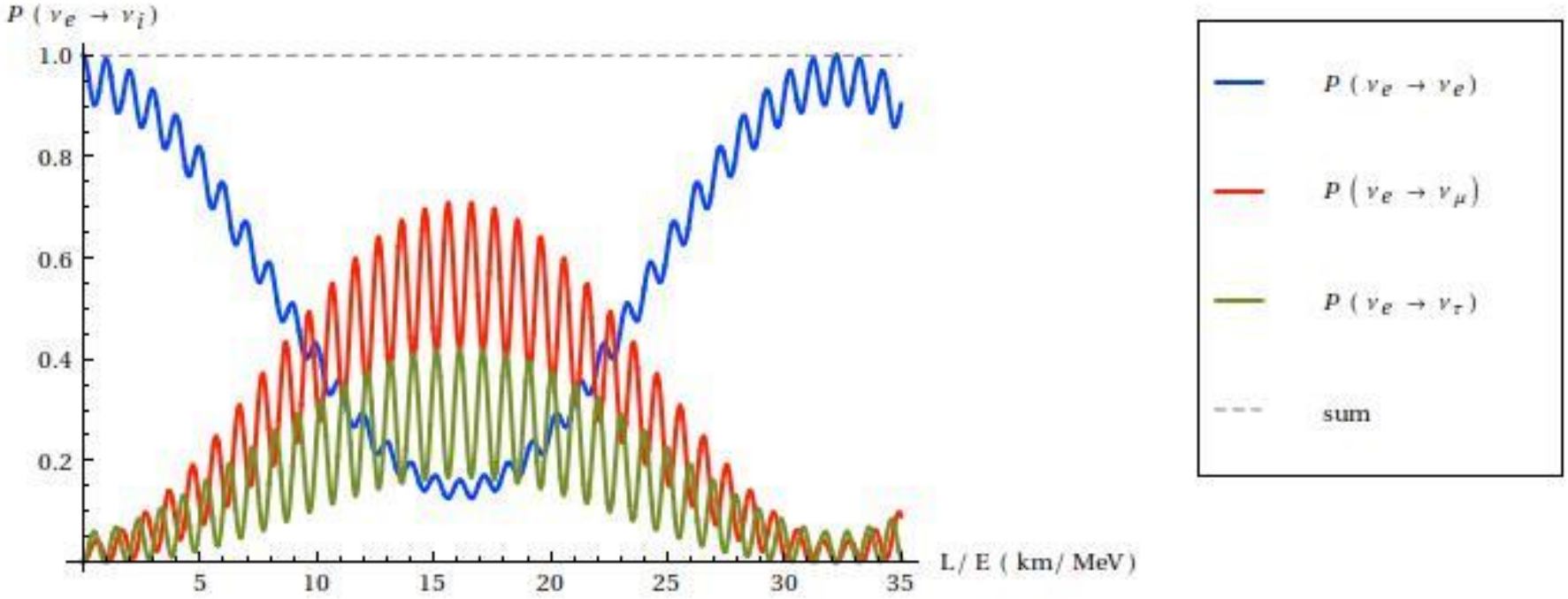


- Results are “rather preliminary”
- Important: Provides cascade event sample for source candidates
- Closes visibility gap

Particle physics with neutrino telescopes

Oscillations of atmospheric neutrinos

- Neutrino telescopes observe large numbers of atmospheric neutrinos
- Path length through Earth depends on zenith angle (0–12.000 km)
- Can we use them to study neutrino physics? … Yes!



Neutrino oscillations in vacuum

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- Neutrino flavour and mass eigenstates are not the same:

$$\underset{\text{(propagation)}}{[\text{mass}] \rightarrow} \quad |\nu_i\rangle = \sum_{\alpha=1}^{3} U_{i\alpha}|\nu_\alpha\rangle \quad \underset{\text{(production)}}{\leftarrow [\text{flavour}]}$$

- Consequence: Neutrino oscillations
  Very simplified case: 2 flavours, vacuum

$$P_{\alpha\rightarrow\beta} = \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2/\text{eV}^2 \cdot L/\text{km}}{E_\nu/\text{GeV}}\right)$$

- No information on sign of Δm^2

- In the above units:

$L/E \ll 1/\Delta m^2 \quad \rightarrow$ no effect
$L/E \sim 1/\Delta m^2 \quad \rightarrow$ observe oscillations
$L/E \gg 1/\Delta m^2 \quad \rightarrow$ observe averaged oscillations

The 3-flavour case

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- Parameterisation of mixing matrix
  (up to Majorana phases that are not discussed here):

$$U_{\mathrm{PNMS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \cdot \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \cdot \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

  with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

- Neutrino oscillation parameters (only central values given):

$\sin^2(2\theta_{23}) = 0.97; \quad |\Delta m^2_{23}| = 2.35 \times 10^{-3}\,\mathrm{eV}^2$ atmos. + acc.

$\sin^2(2\theta_{12}) = 0.86; \quad \Delta m^2_{12} = 7.58 \times 10^{-5}\,\mathrm{eV}^2$ solar + reactor

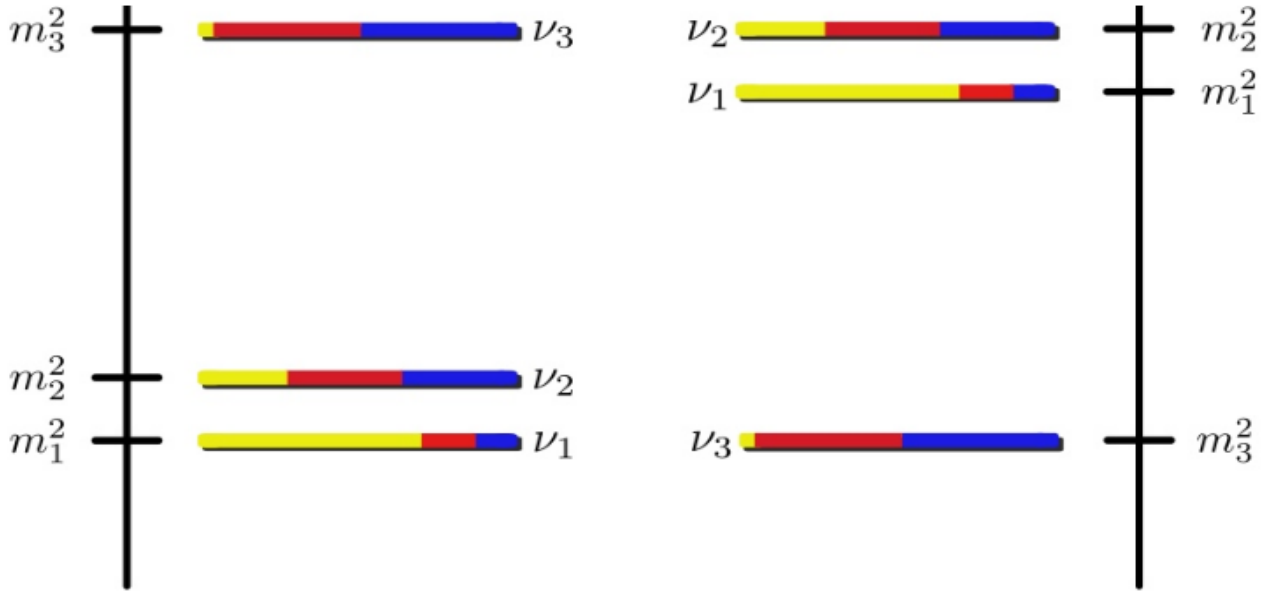
$\sin^2(2\theta_{13}) = 0.096;$ reactor (2012)

- Unknown: sign of Δm^2_{23}
  CP-violating phase δ

The neutrino mass hierarchy

- Depending on sign of Δm^2_{23} :

"normal hierarchy" (NH) or "inverted hierarchy" (IH)



- A fundamental parameter of particle physics!
  → Knowledge required to investigate neutrino CP violation

Neutrino oscillations in matter

- Neutrino propagation in matter different for ν_e and $\nu_{\mu,\tau}$

  $\nu_e e^- \rightarrow \nu_e e^-$ and $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$ W and Z exchange

  $\nu_{\mu,\tau} e^- \rightarrow \nu_{\mu,\tau} e^-$ and $\overline{\nu}_{\mu,\tau} e^- \rightarrow \overline{\nu}_{\mu,\tau} e^-$ Z exchange only

  Result: Modification of oscillation pattern

- Dominant cause of solar neutrino oscillations (MSW effect)
- For atmospheric ν_μ and $\overline{\nu}_\mu$:
  Matter effect depends on sign of Δm^2_{13}
  Same effect for $\Delta m^2_{13} < 0, \overline{\nu}_\mu$ and $\Delta m^2_{13} > 0, \nu_\mu$
- Atmospheric neutrinos offer just the right $L \lesssim 2R_E$
  and $E = \mathcal{O}(\text{a few GeV})$ to measure the effect.
- In neutrino telescope: ν_μ and $\overline{\nu}_\mu$ cannot be distinguished,
  but net effect since $\sigma(\nu_\mu N) \approx 2\sigma(\overline{\nu}_\mu N)$

Oscillations of atmospheric neutrinos

- Determining the sign of Δm^2_{23} requires matter effect. Oscillation of ν_e and/or $\overline{\nu}_e$must be involved.
- 3-flavour oscillations of $\nu_e \leftrightarrow \nu_\mu$ in matter:

$$P_{e\to\mu} \approx P_{\mu\to e} \approx \sin^2\theta_{23}\sin^2(2\theta^{\text{eff}}_{13})\sin^2\left(\frac{\Delta^{\text{eff}}_{13}L}{2}\right)$$

$$\Delta_{13} = \frac{\Delta m^2_{13}}{2E_\nu} \qquad \sin^2(2\theta^{\text{eff}}_{13}) = \frac{\Delta^2_{13}\sin^2(2\theta_{13})}{\left(\Delta^{\text{eff}}_{13}\right)^2}$$

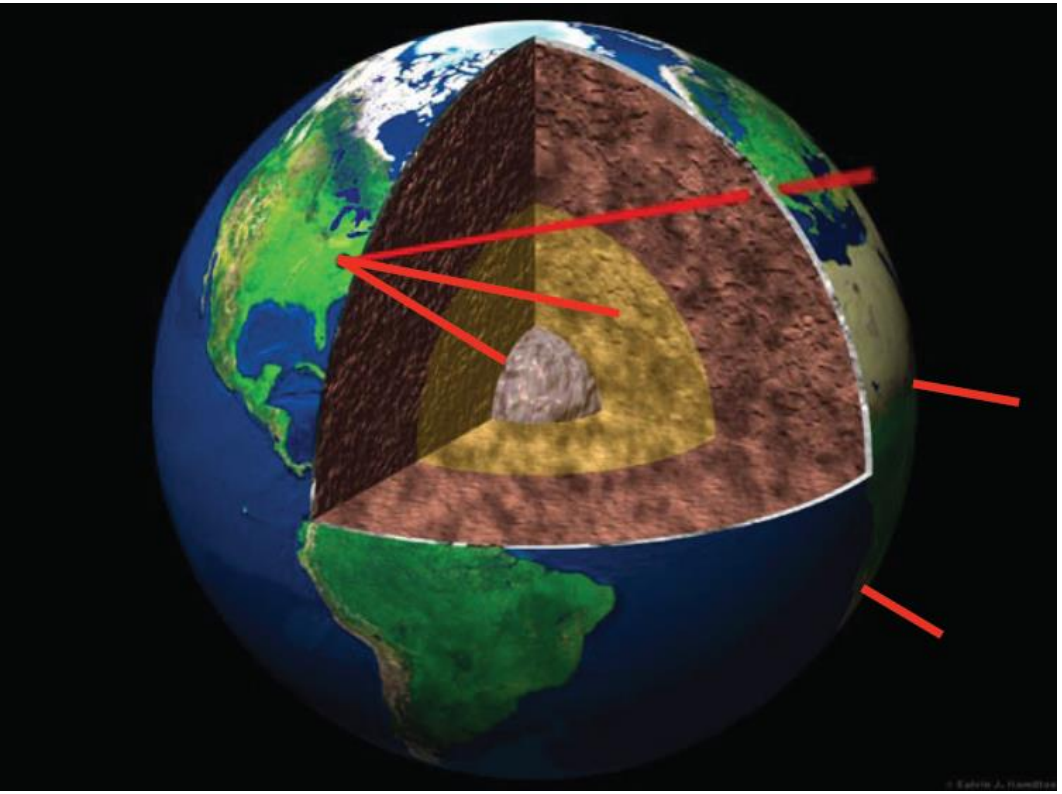
$$\Delta^{\text{eff}}_{13} = \sqrt{[\Delta_{13}\cos(2\theta_{13}) - A]^2 + \Delta^2_{13}\sin^2(2\theta_{13})}$$

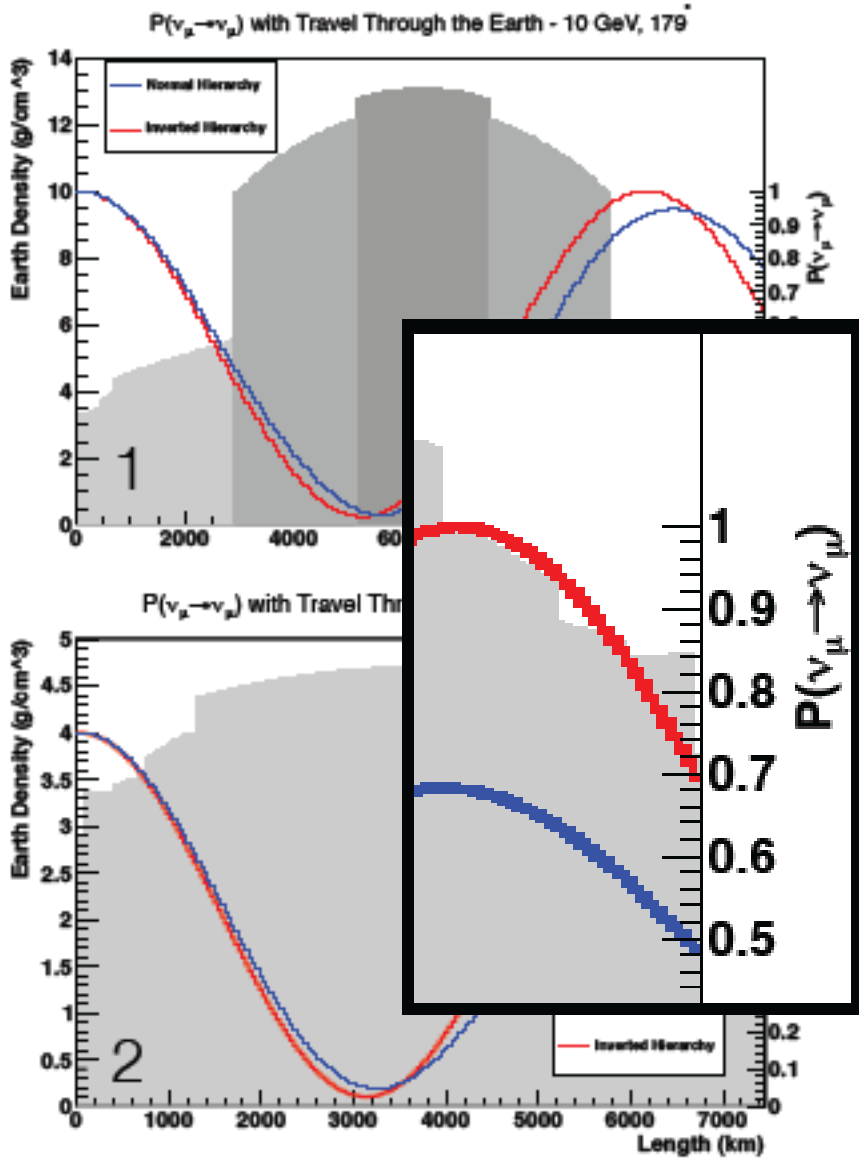
$$A = \sqrt{2}G_F N_e \text{ for } \nu \text{ and } A = -\sqrt{2}G_F N_e \text{ for } \overline{\nu}$$

- "Matter resonance" for $A = \Delta_{13}\cos(2\theta_{23})$ (maximal mixing, minimal oscillation frequency). This is the case for $E_\nu \approx 30\,\text{GeV}/\rho[\text{g cm}^{-3}]$

Neutrino oscillations in the Earth

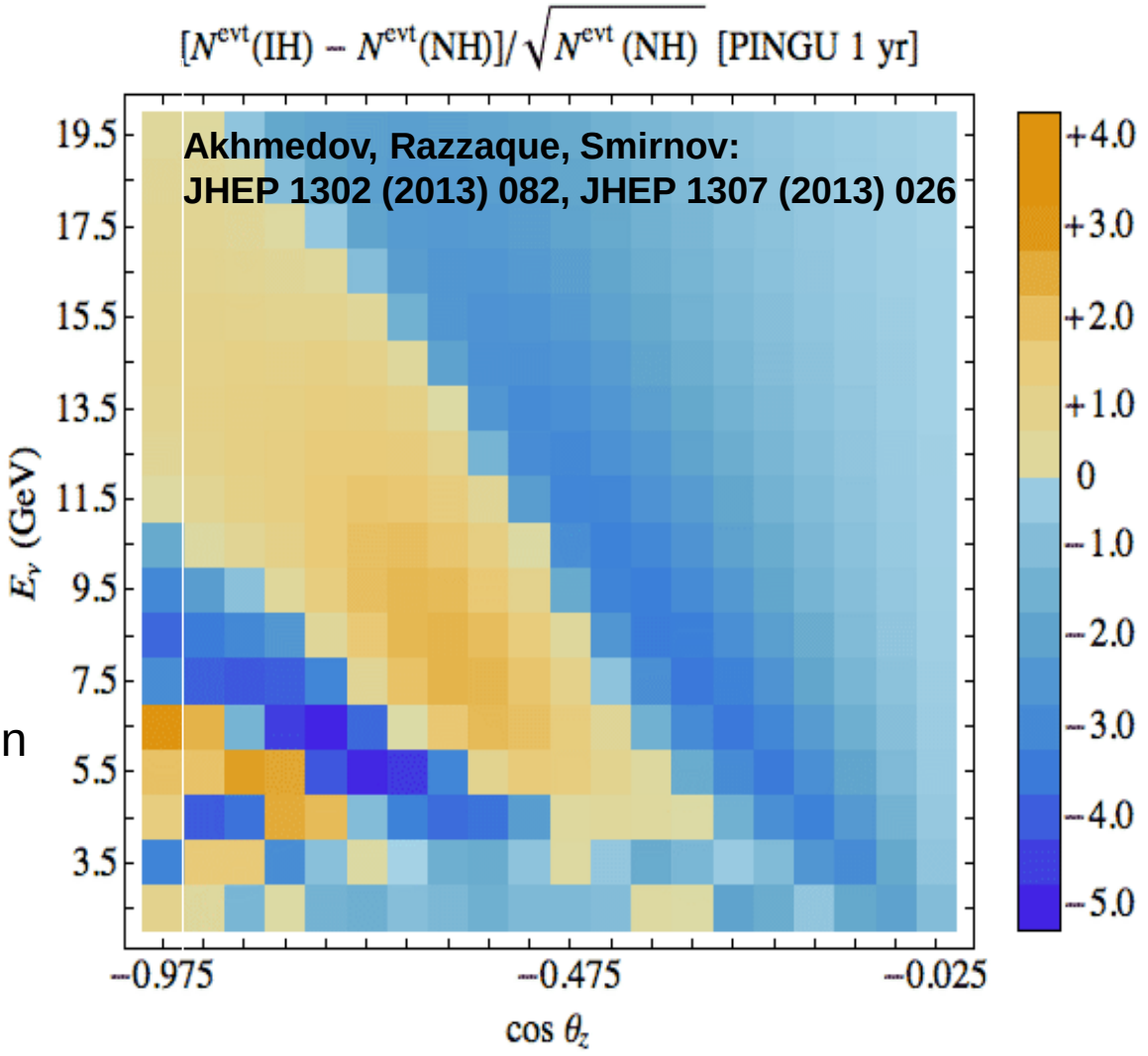
- Earth density 4-13 g/cm^3
- Relevant: $E_\nu \sim 3\text{–}10\,\mathrm{GeV}$



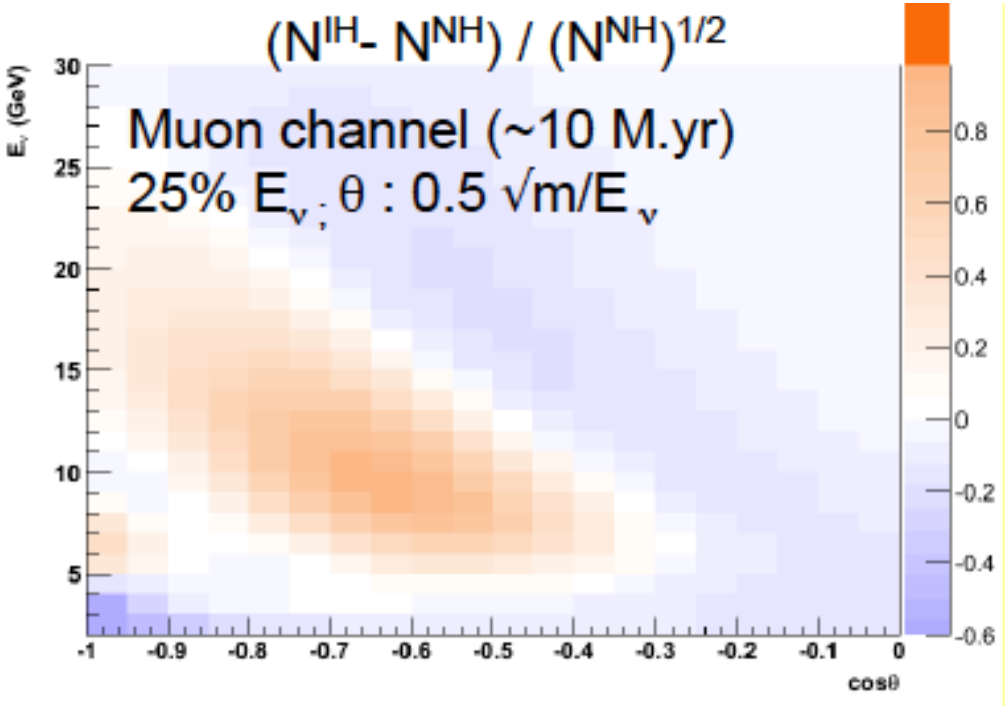


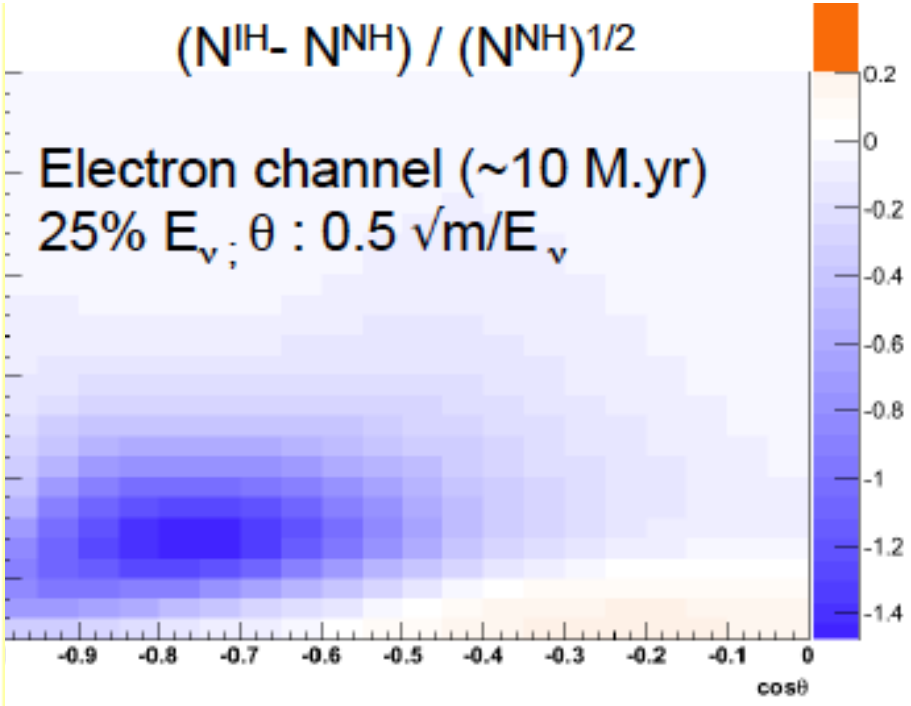
Mass hierarchy “oscillogram”

- Expected signal significance in energy vs. zenith w/o experimental effects
- Need to assess neutrino reactions at 3–20 GeV
- Required:
  - Good angular and energy resolution
  - Flavour separation



… and in the real world

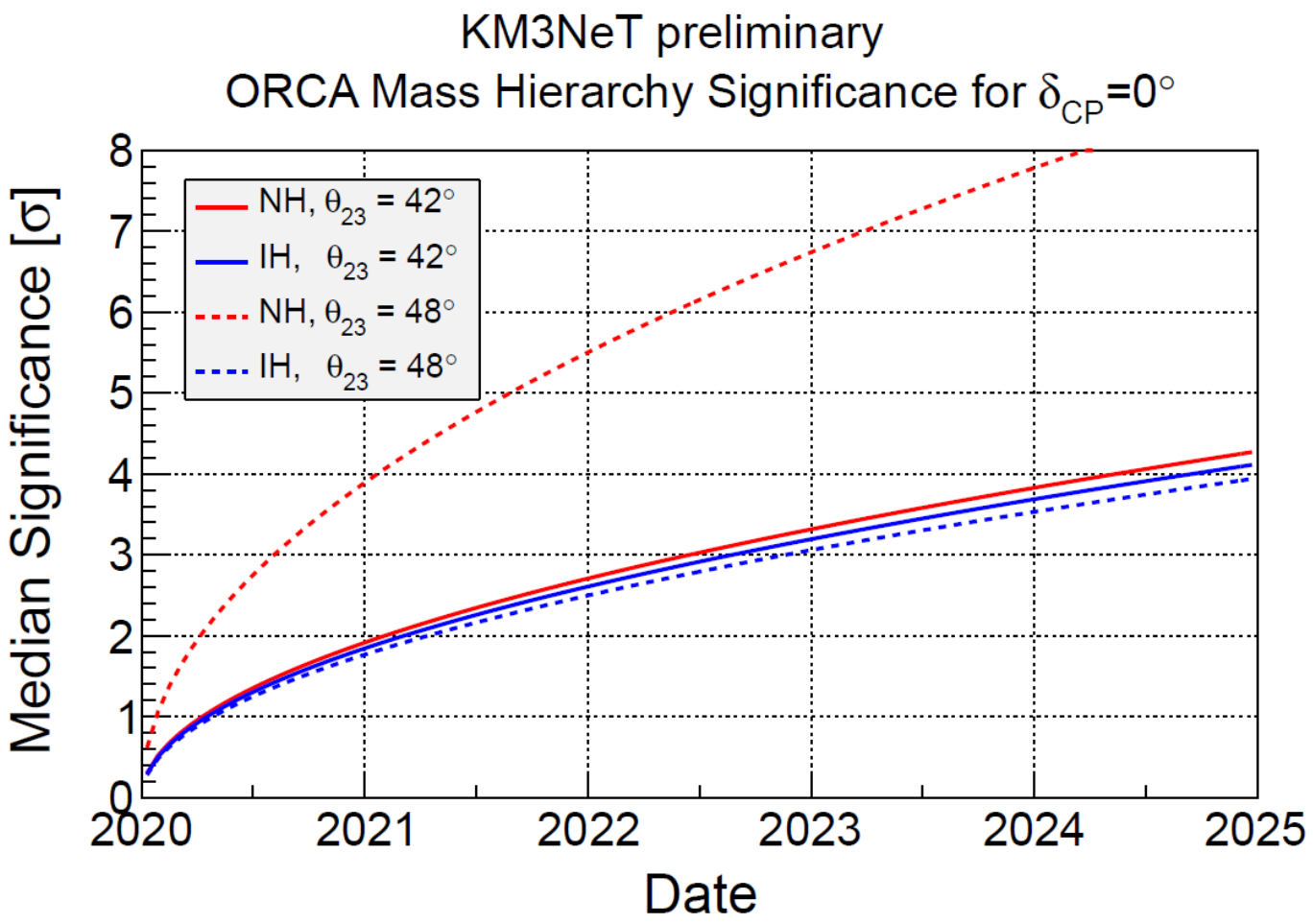




- Both muon (ν_μ survival) and electron channel ($\nu_\mu \rightarrow \nu_e$ conversion) contribute
- Removal of atmospheric muon background essential
- Major effort to control systematics
- But: Measurement in reach

Measuring the mass hierarchy

- Sensitivity depends on true value of θ_{23} (“the octant”)
- 3σ in 3 years for most unfavourable situation
- Similar result for PINGU, but later starting date



… concluding

Summary and outlook

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Neutrino astronomy has become mature – transition from searches to observation
- Addressing fundamental questions of particle and astrophysics, and of cosmology
- Cubic-kilometre detectors required
- Full sky coverage by IceCube and KM3NeT, complementary environments and sensitivities
- Addressing central questions of neutrino physics

Stay tuned!