MSCA

Marie Skłodowska-Curie Actions

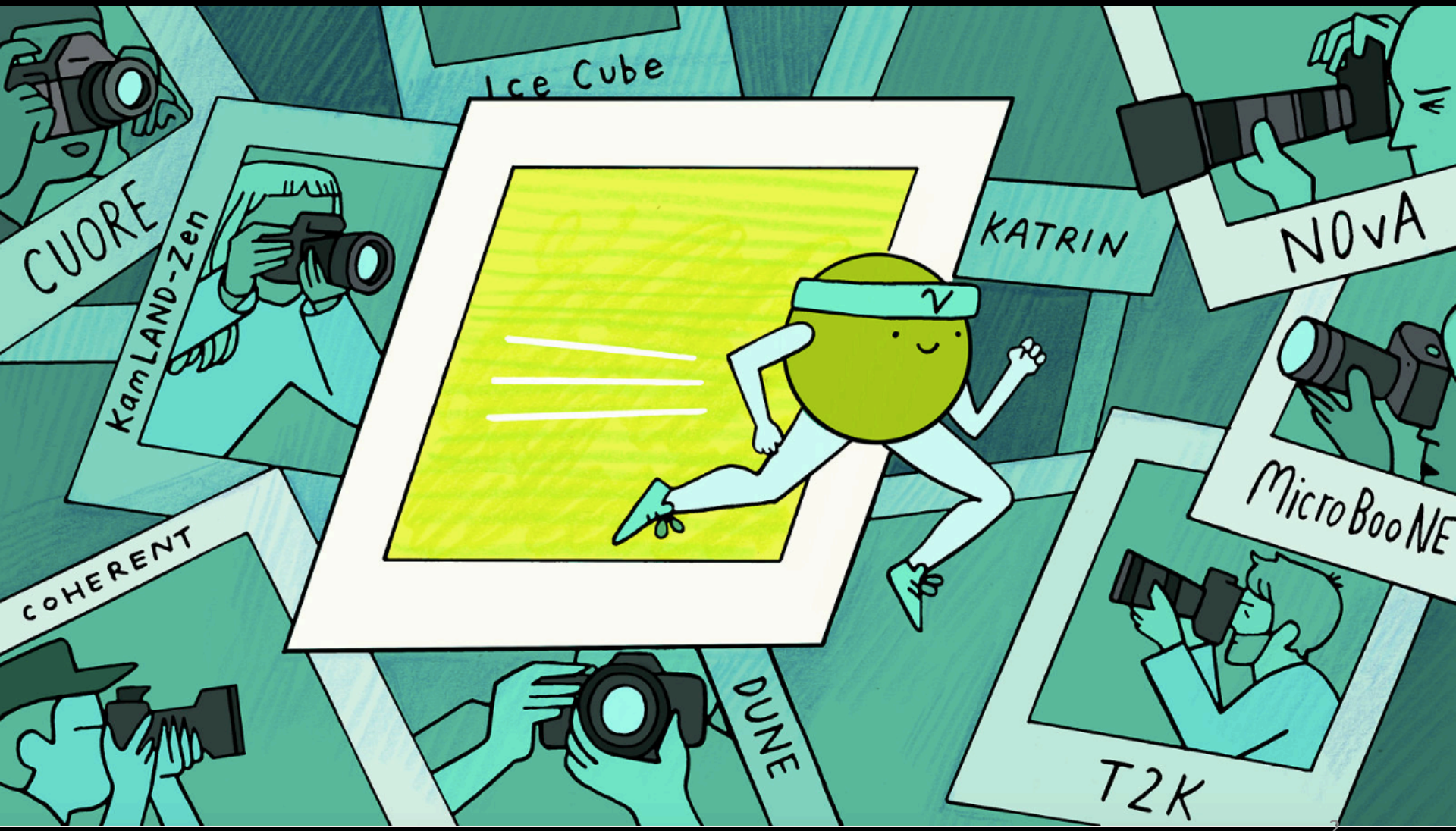
Labex UnivEarthS

High-Energy Neutrino Astronomy: Current Status and Prospects

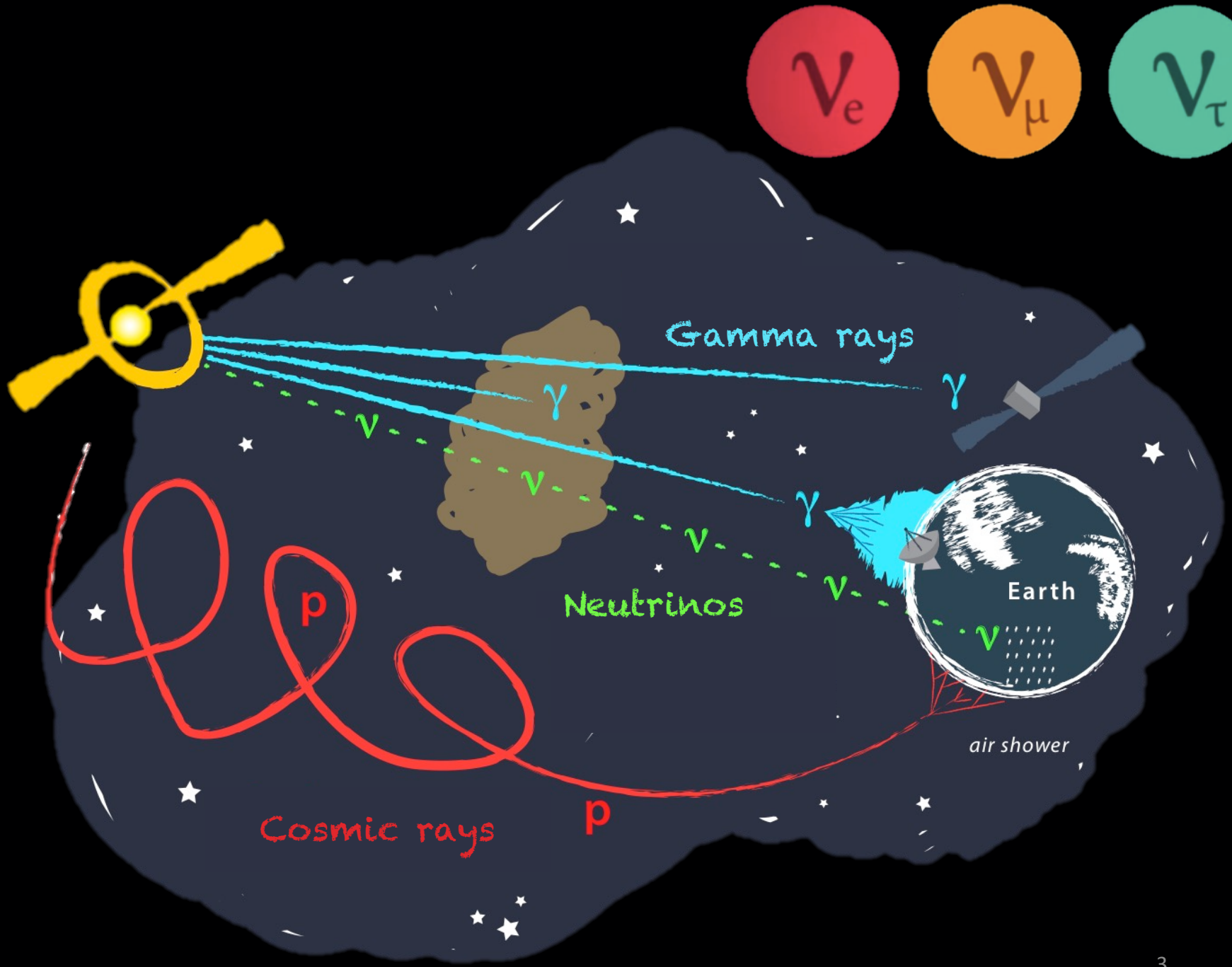
IceCube

APC, CNRS, FRANCE

Gwenhaël de Wasseige



Symmetry magazine

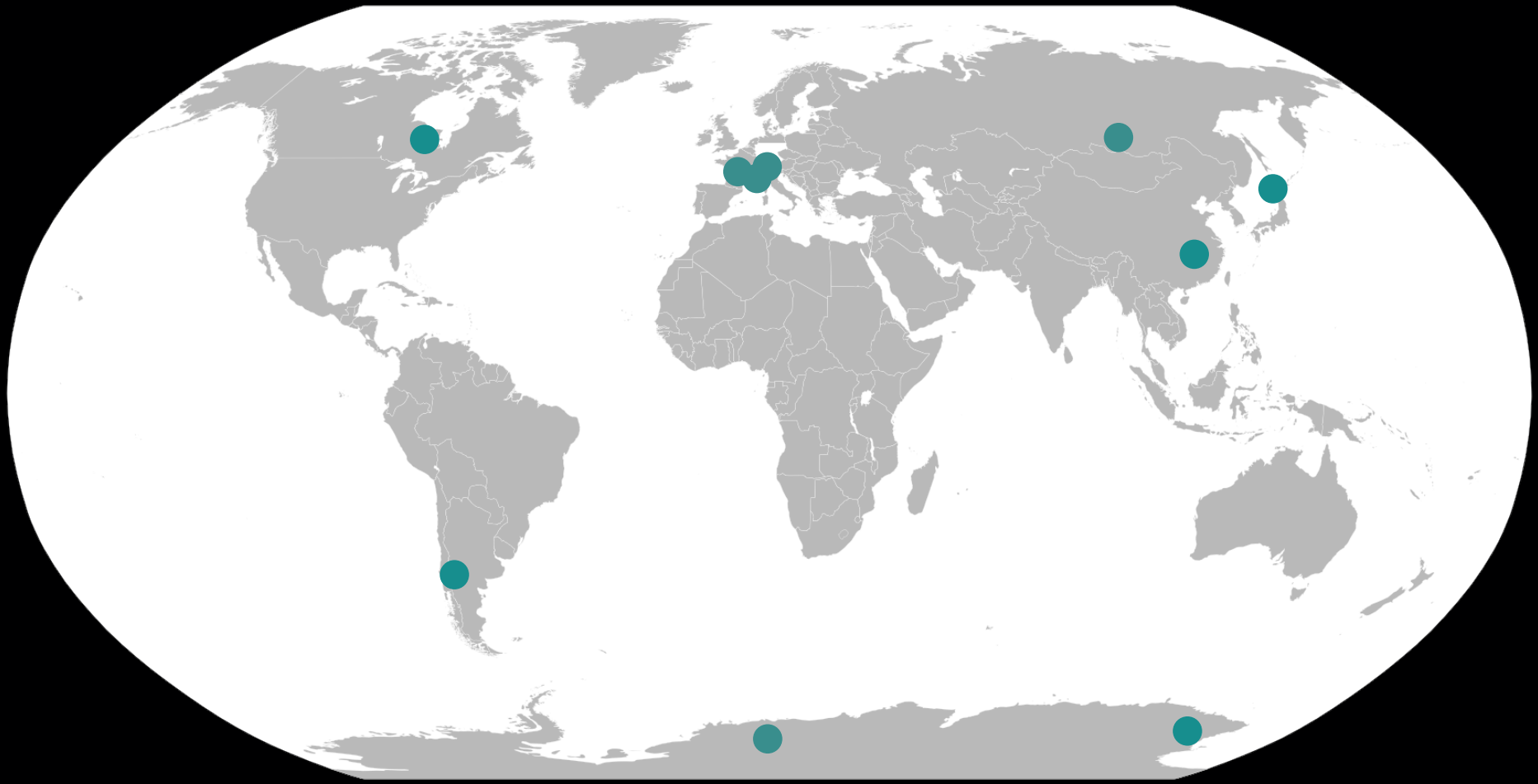

ν_e
ν_μ
ν_τ
Gamma rays
γ
γ
γ
ν
ν
ν
ν
ν
Neutrinos
Earth
p
p
Cosmic rays
air shower

Where are high-energy astrophysical neutrinos coming from?

Can we identify cosmic hadronic accelerators ?

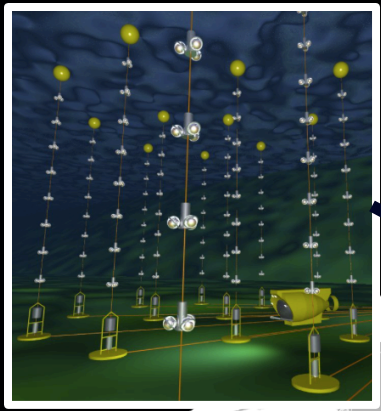
What are the properties of these accelerators?

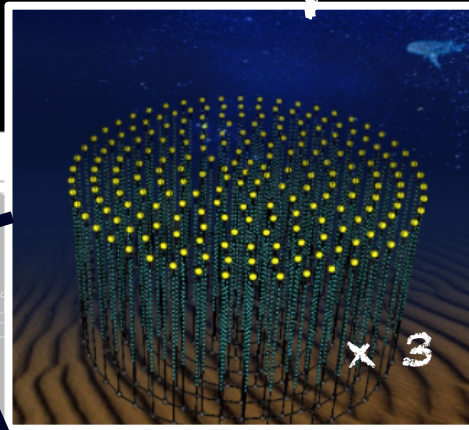
Neutrino telescopes

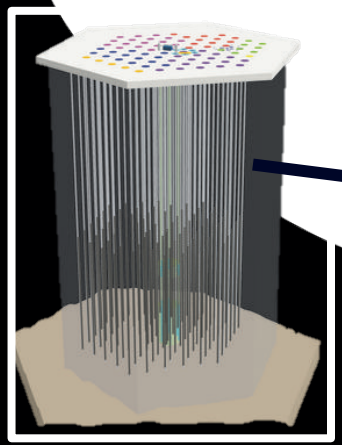


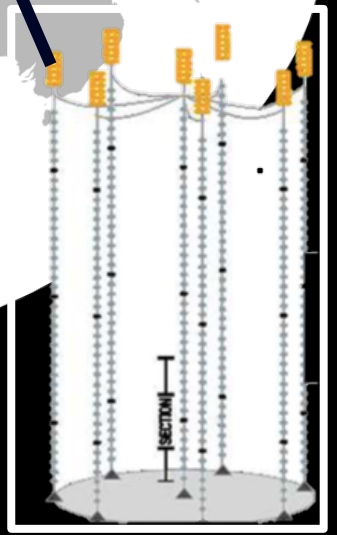
Non-exhaustive list

Neutrino telescopes





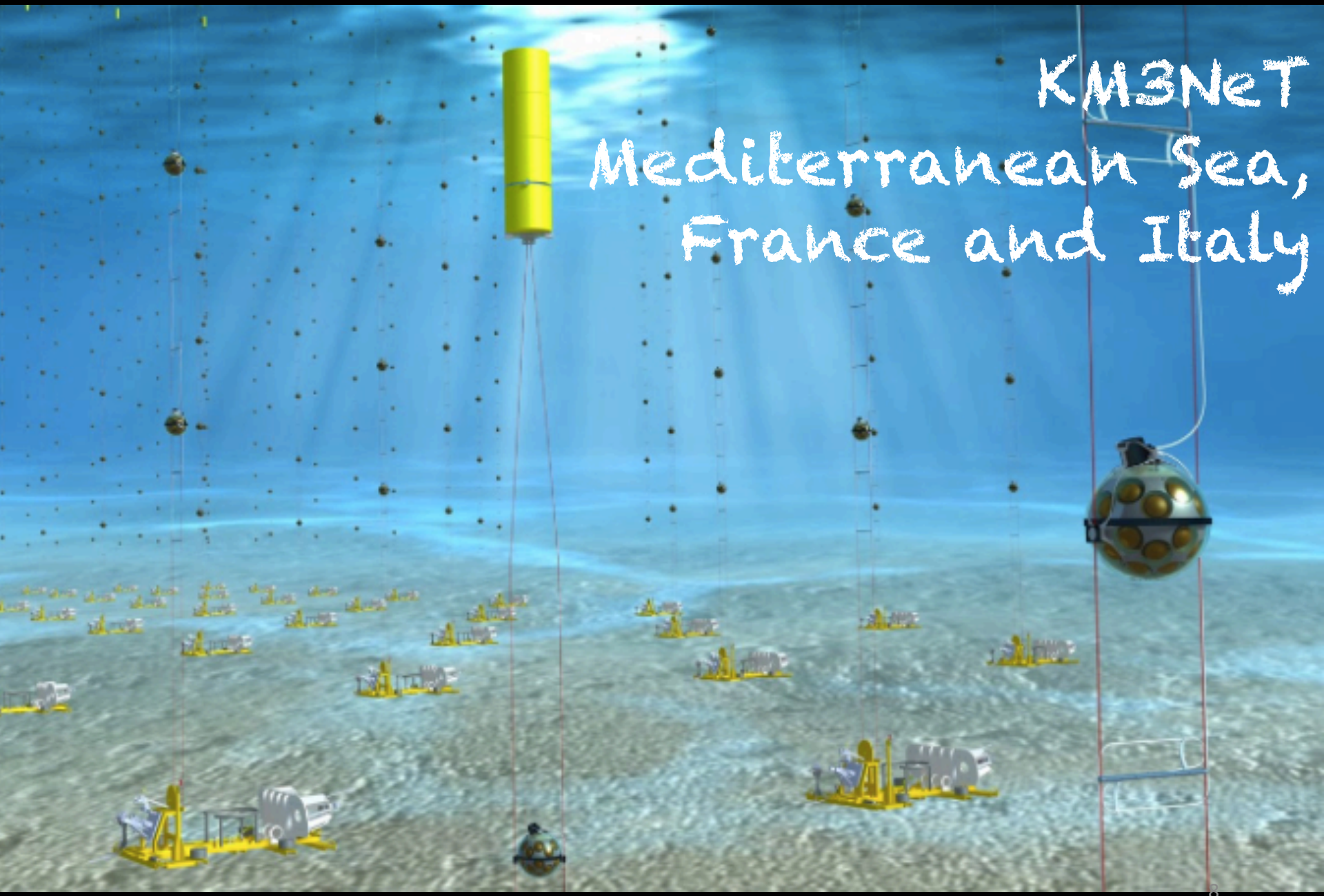




GNN
The Global Neutrino Network

x 8

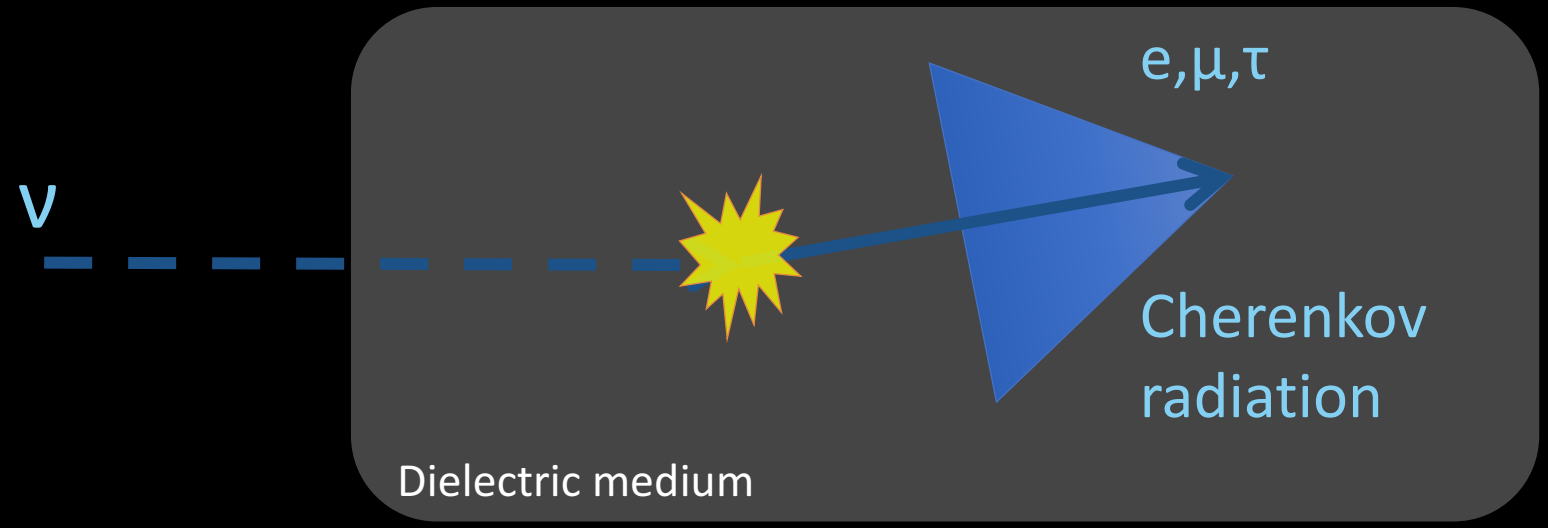

ANTARES
Mediterranean Sea,
France
nautile

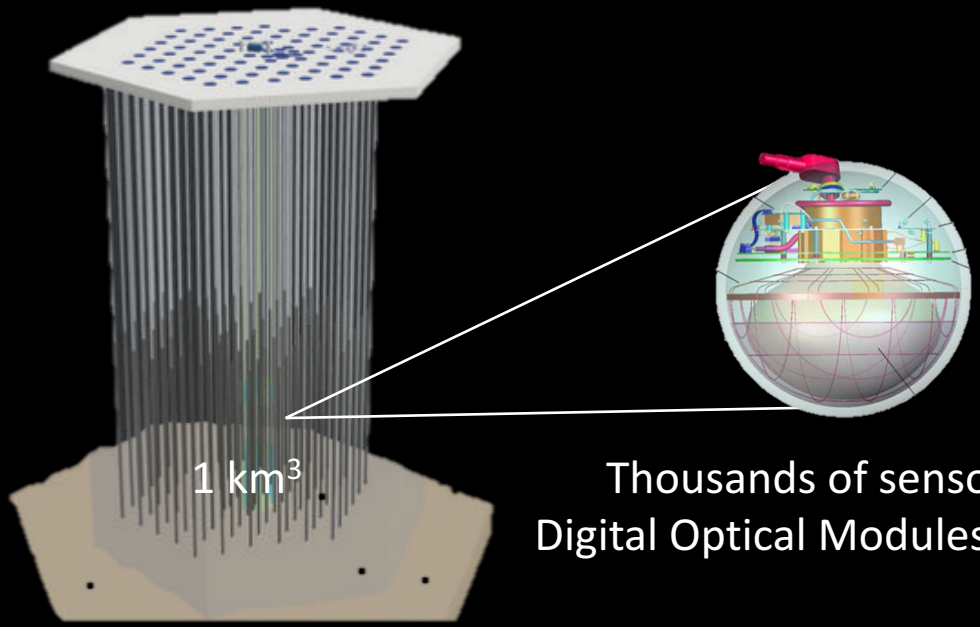

KM3NeT
Mediterranean Sea,
France and Italy


GVD
Baikal Lake,
Russia


IceCube
South Pole,
Antarctica

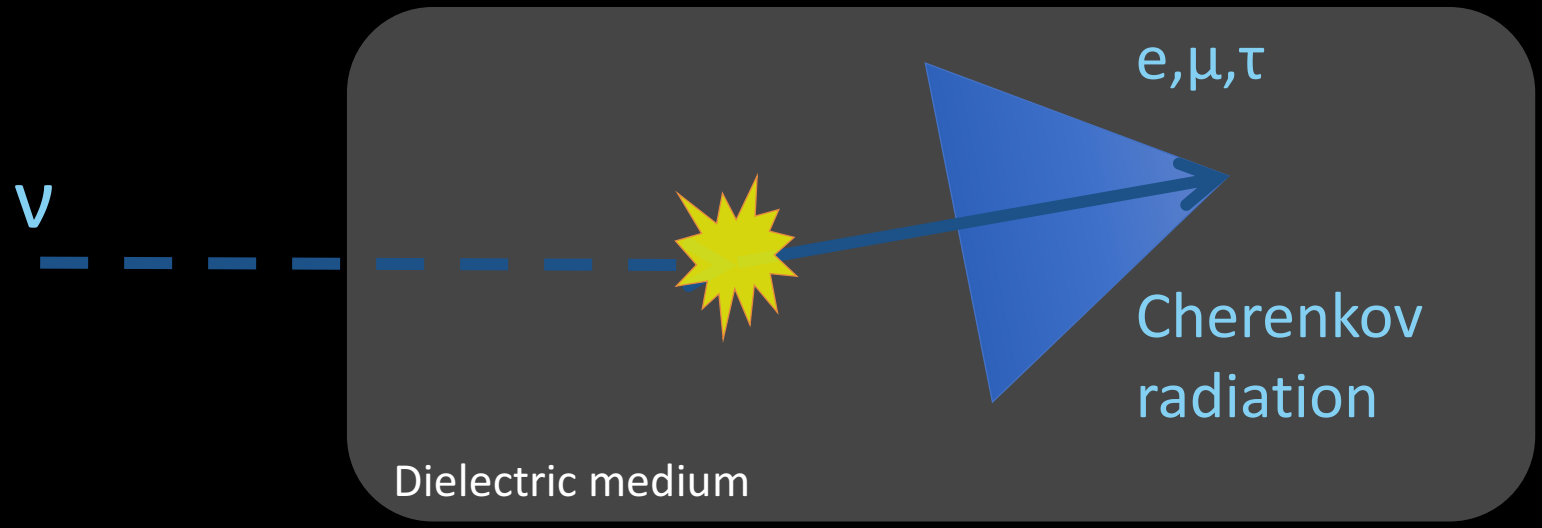
How to detect high-energy neutrinos?

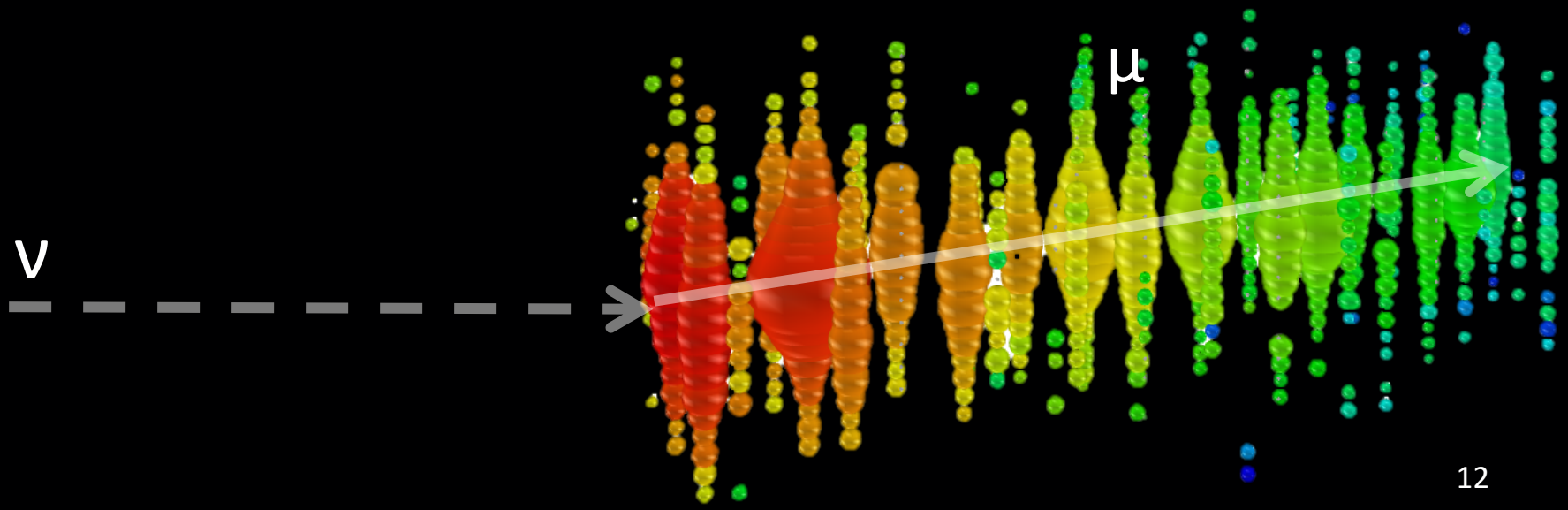




Thousands of sensors or
Digital Optical Modules (DOMs)

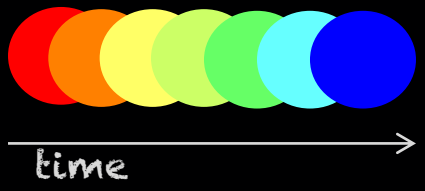
How to detect high-energy neutrinos?

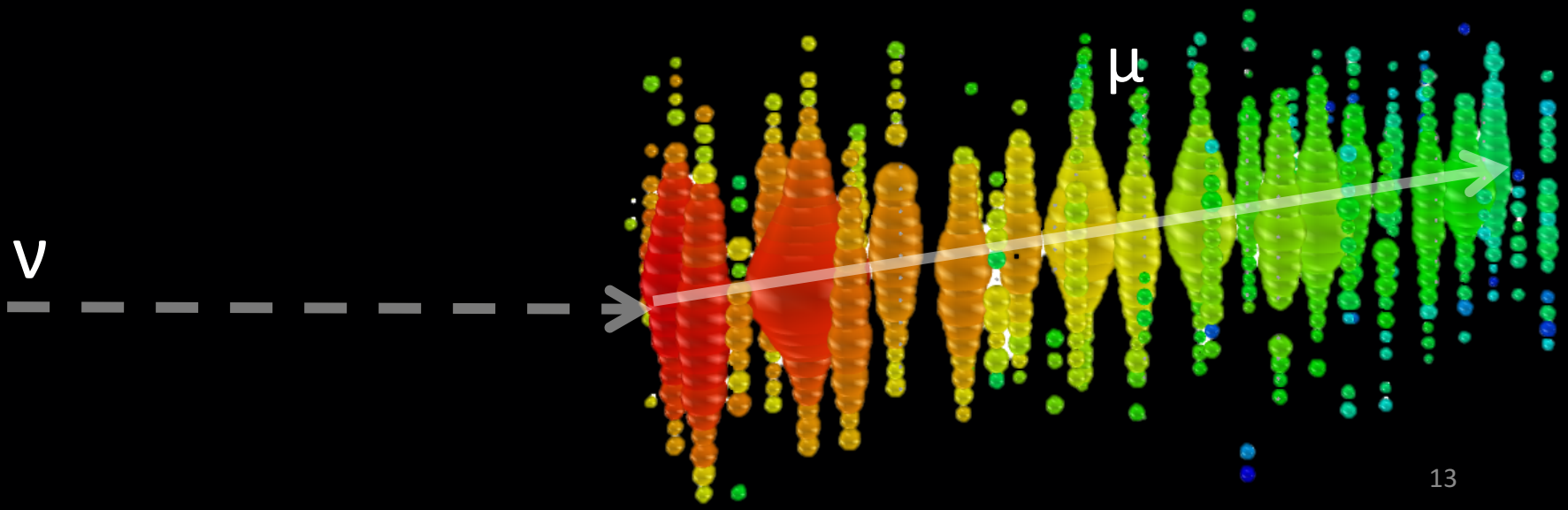




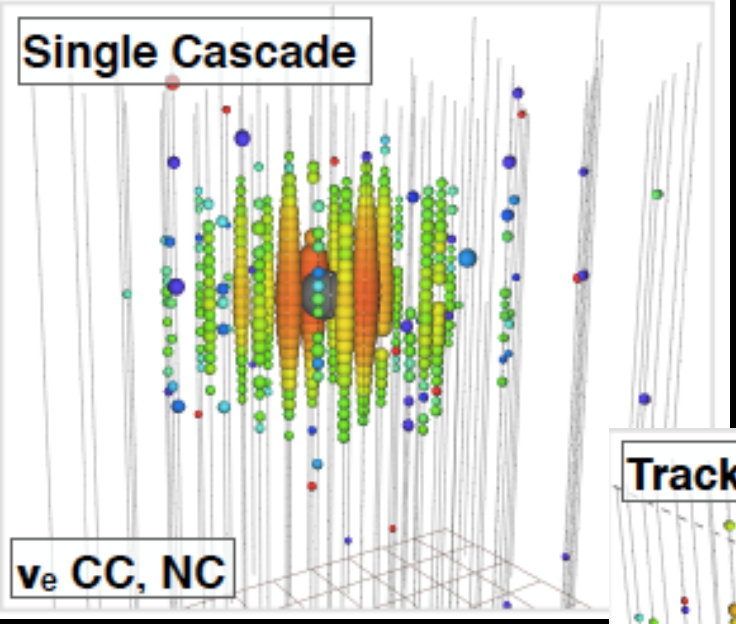
Which information can we get?

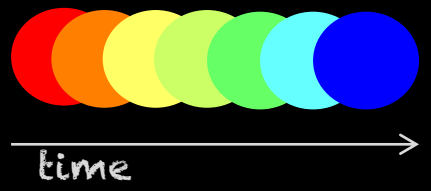
- Amount of light -> Energy
- Timing -> Direction
- Topology -> Flavour



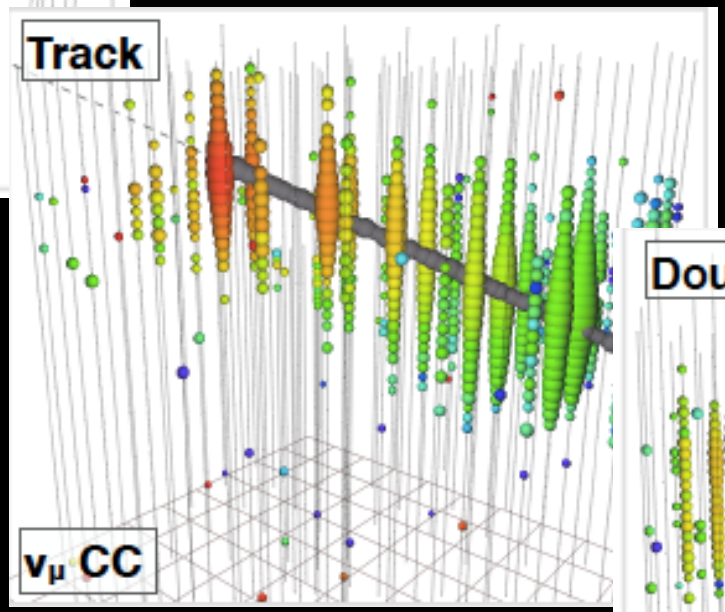


Event topology

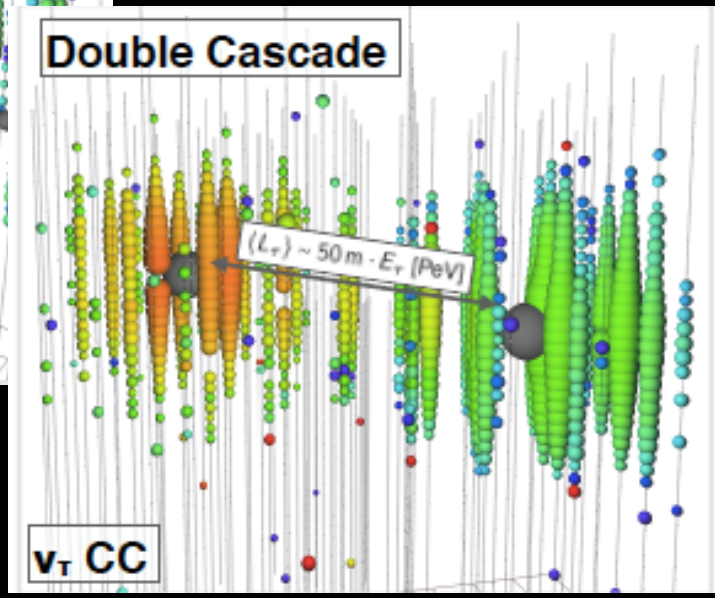




- Good E resolution
- Bad angular resolution

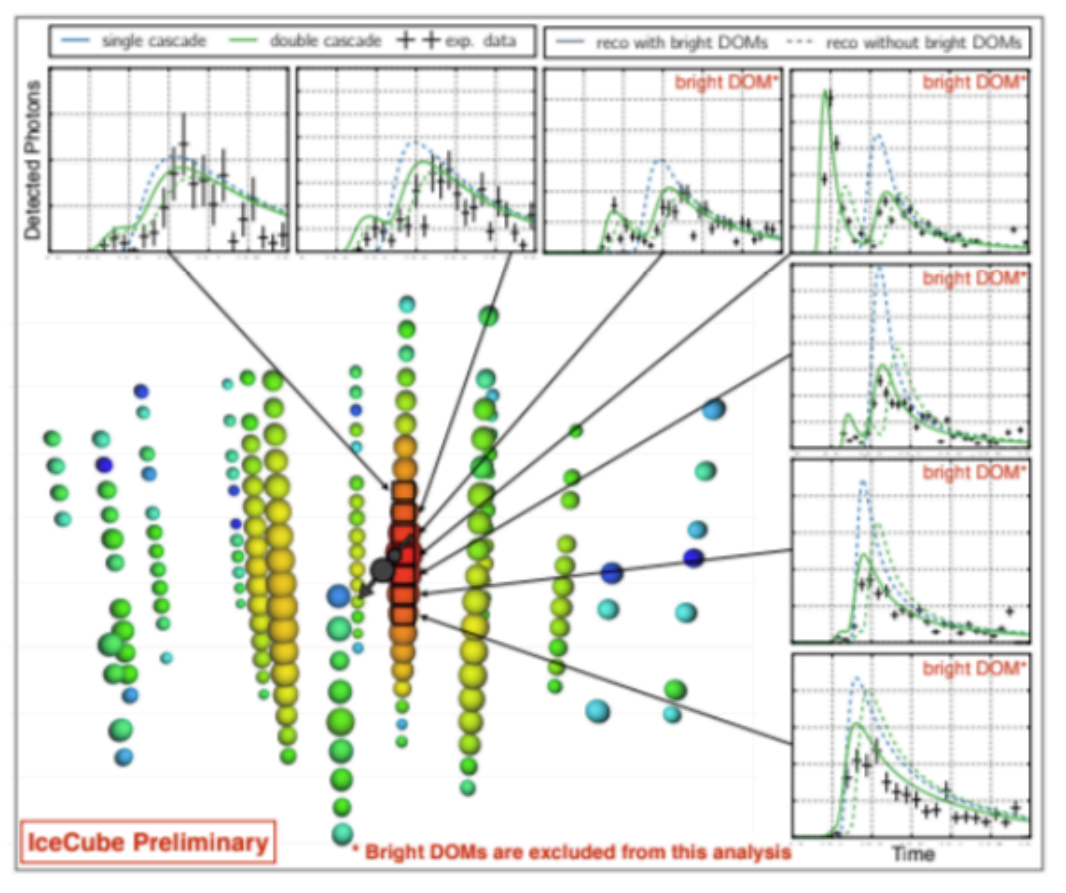


- Bad energy resolution
- Good angular resolution

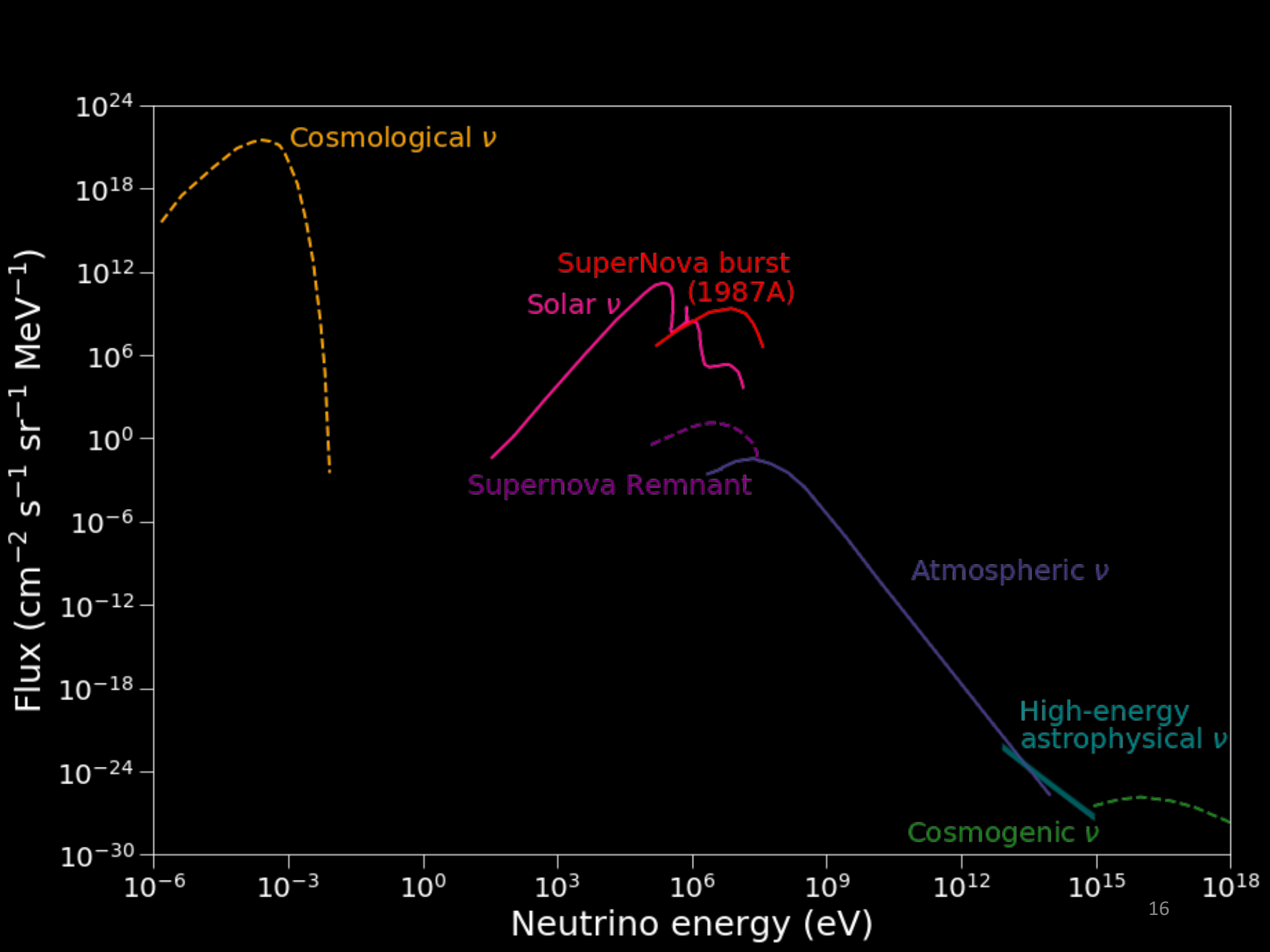


- Good E resolution
- Better angular resolution than single cascade

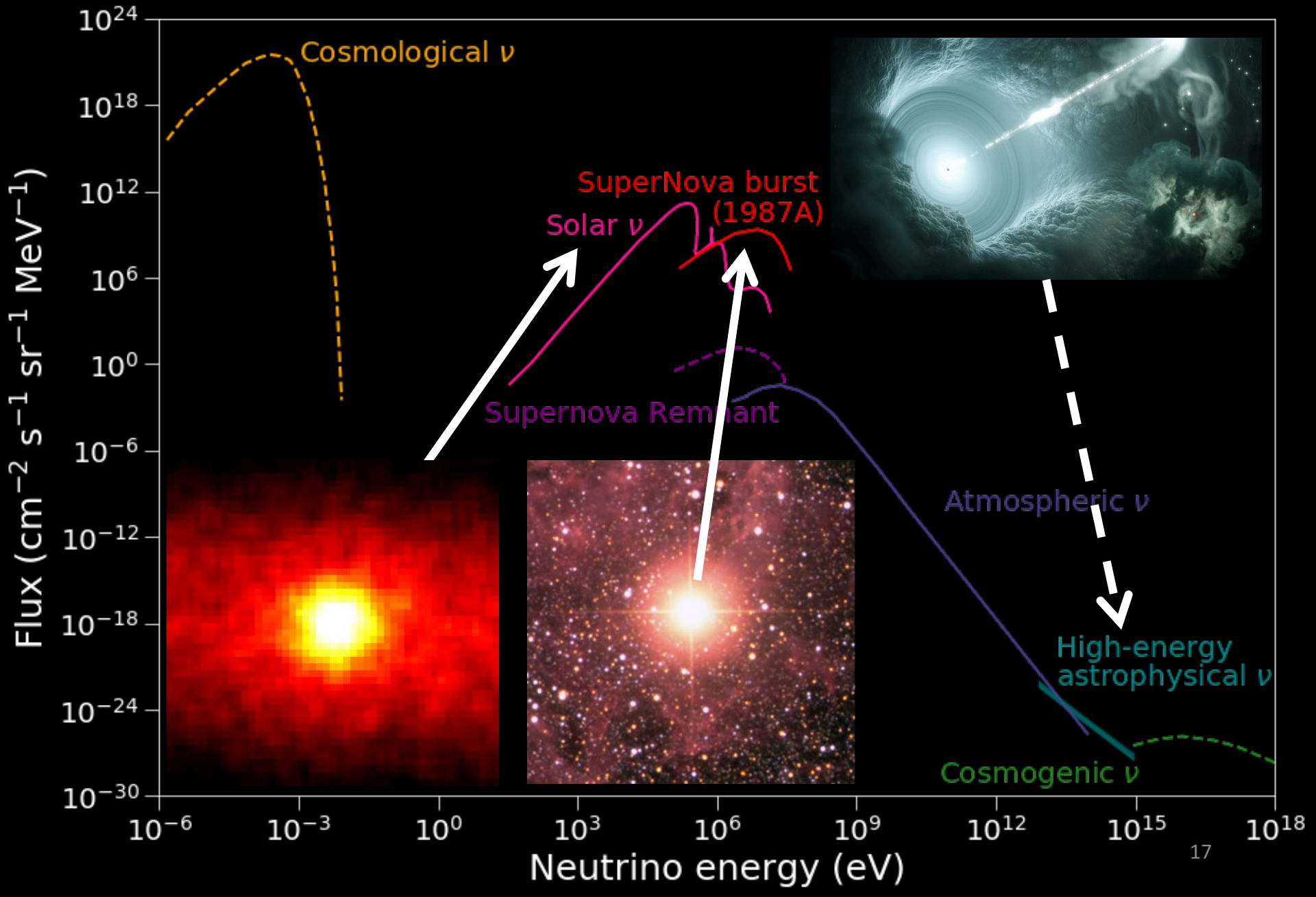
Double Double



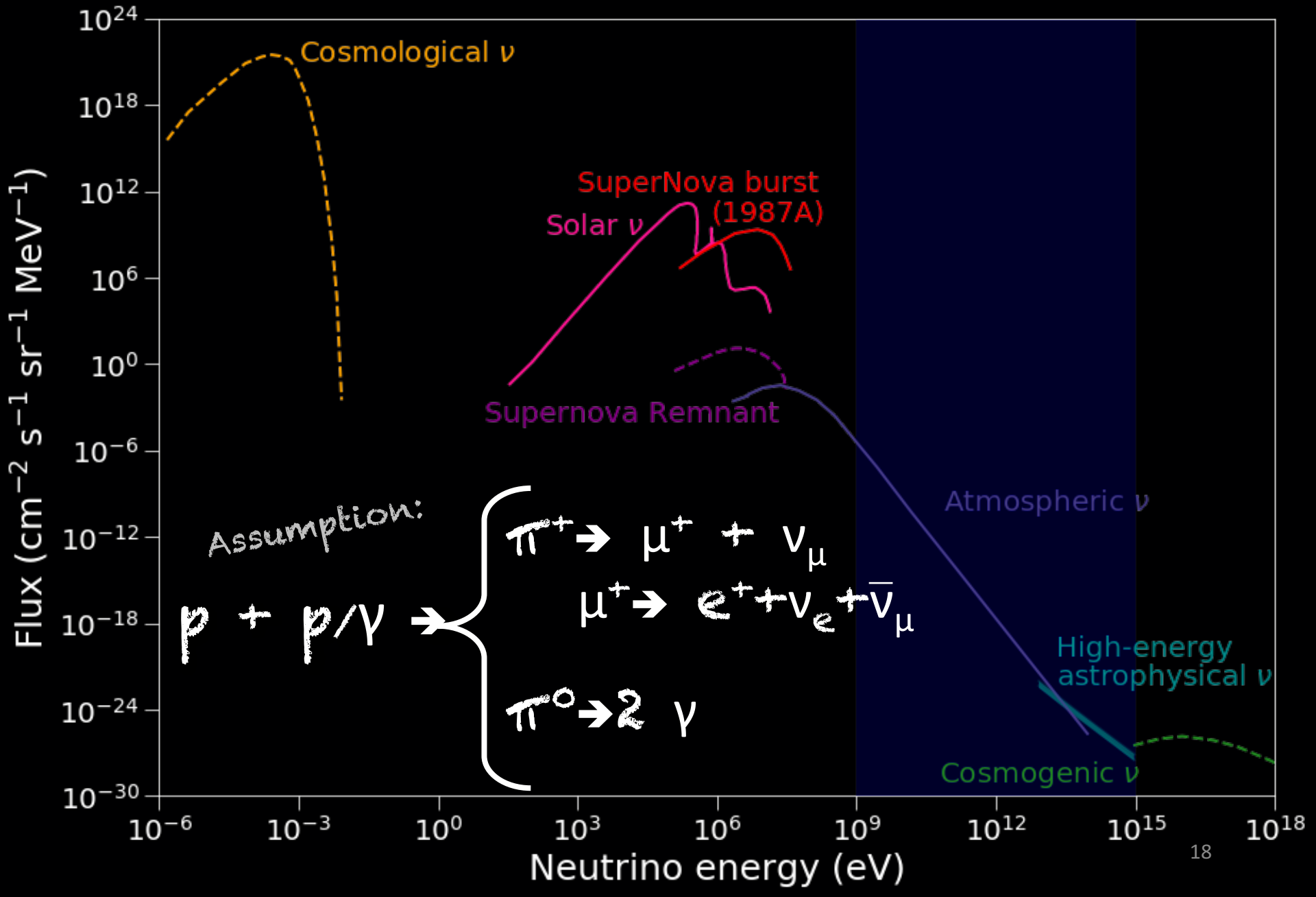
- Energy of the cascades = 9 TeV and 80 TeV
- Separation = 17m
- Observed in 2014
- Observed light arrival pattern clearly favors double cascade


Cosmological ν
SuperNova burst
(1987A)
Solar ν
Supernova Remnant
Atmospheric ν
High-energy
astrophysical ν
Cosmogenic ν
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Neutrino energy (eV)
10²⁴
10¹⁸
10¹²
10⁶
10⁰
10⁻⁶
10⁻¹²
10⁻¹⁸
10⁻²⁴
10⁻³⁰
10⁻⁶
10⁻³
10⁰
10³
10⁶
10⁹
10¹²
10¹⁵
10¹⁸

Figures not to scale



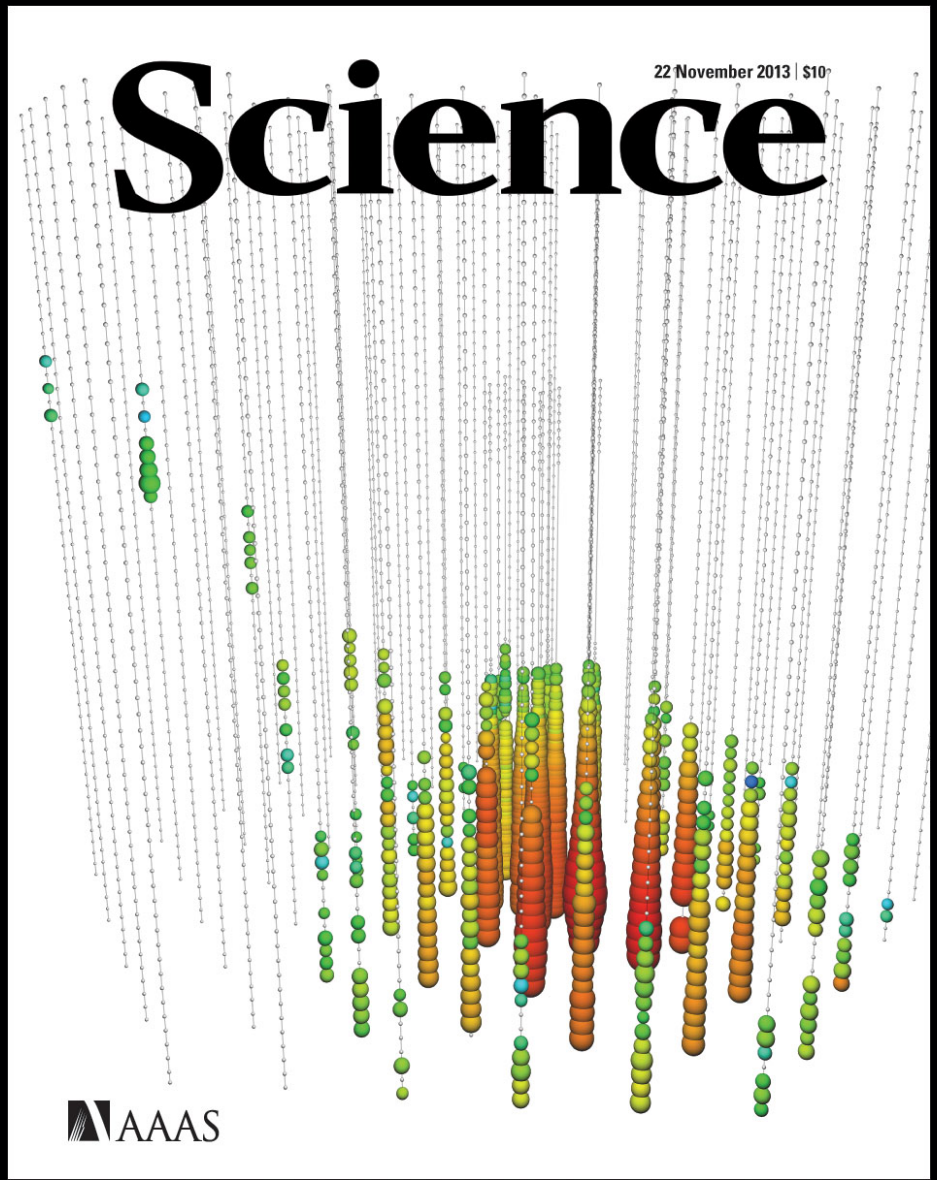
What do we learn from HE neutrinos?



Outline

1. What did we discover?
2. What's new? / What else?
3. What's next?

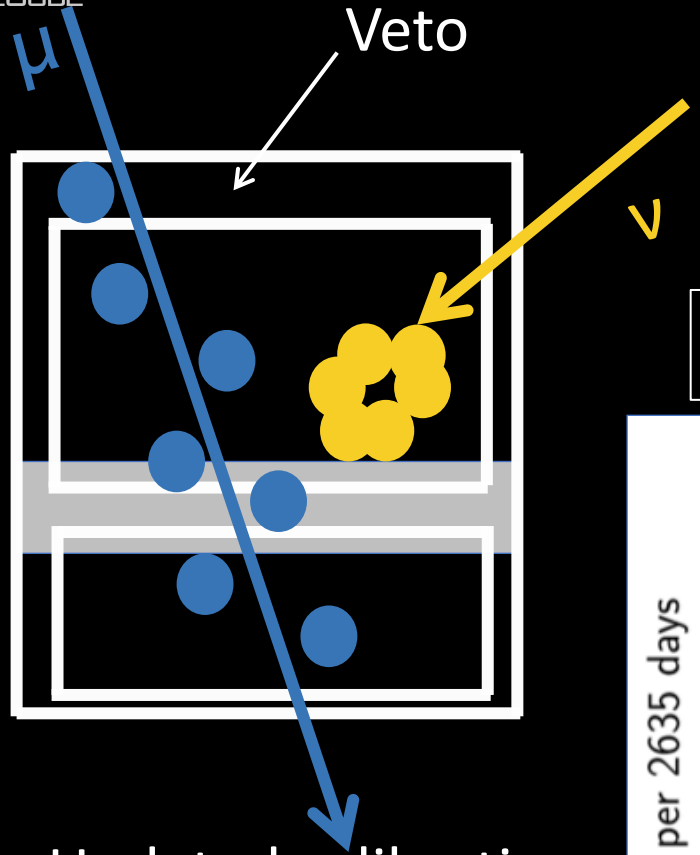
1. What did we discover?



Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

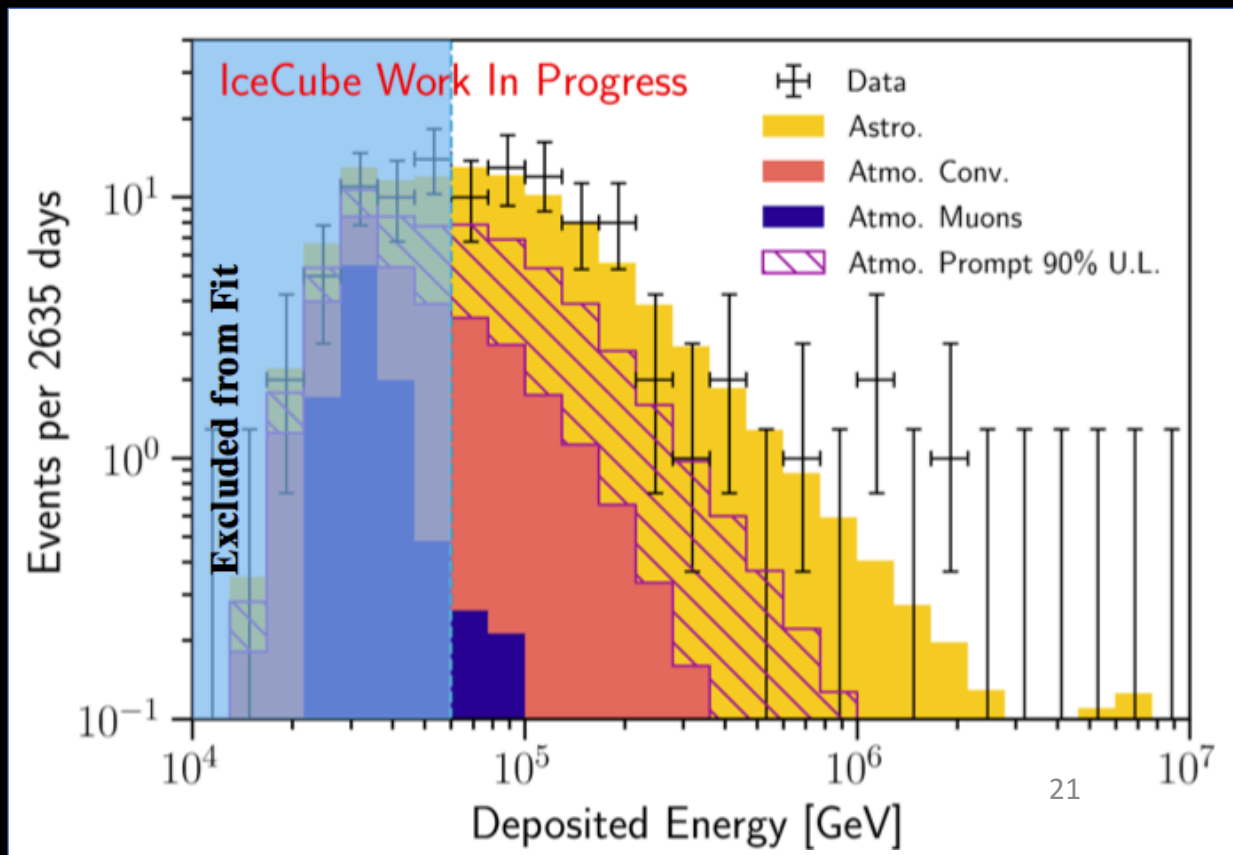
22 Nov. 2013

Diffuse neutrino flux 7.5 year

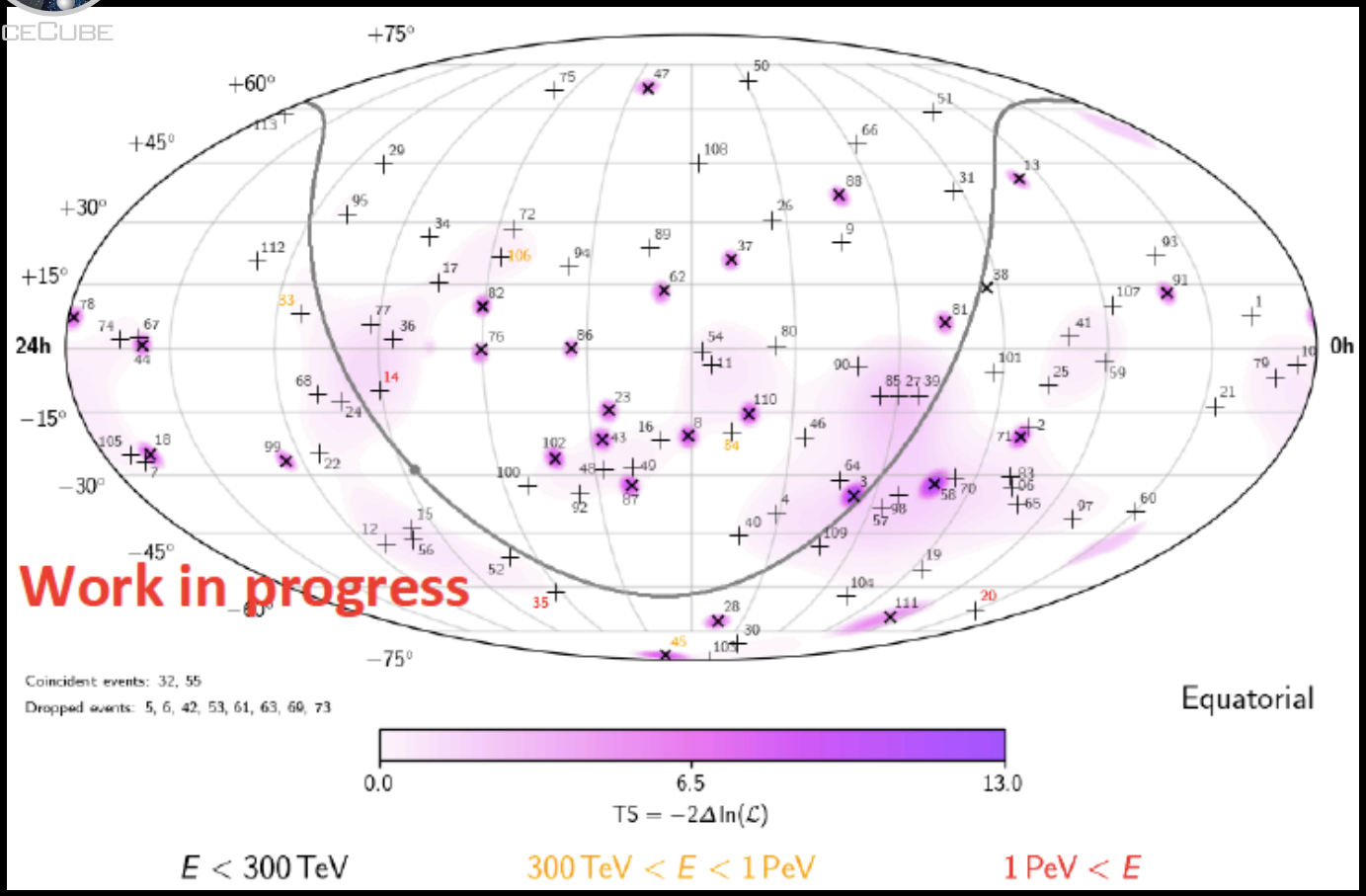


103 events, with 60 events > 60 TeV

- Updated calibration and ice model
- Changes to RA, Dec, energy



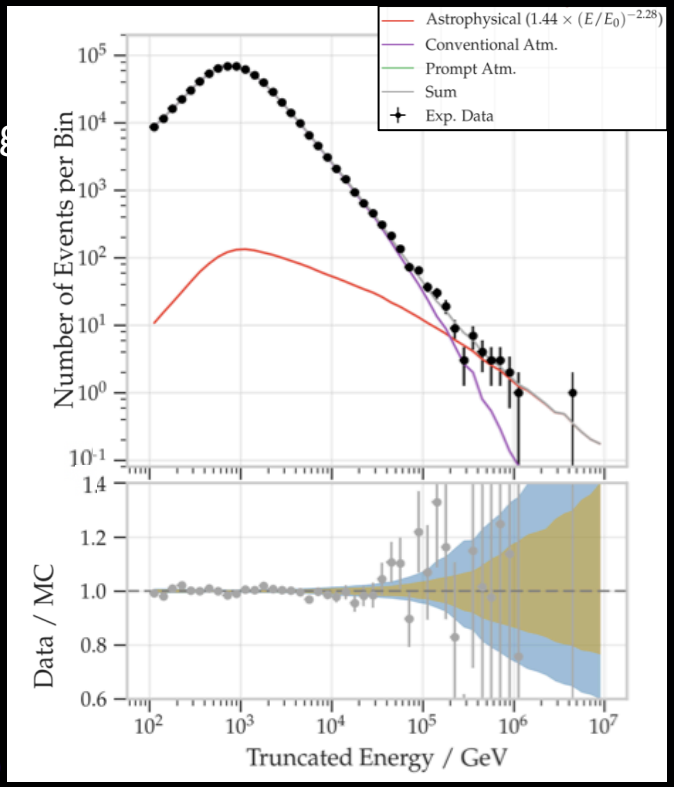
Diffuse neutrino flux 7.5 year



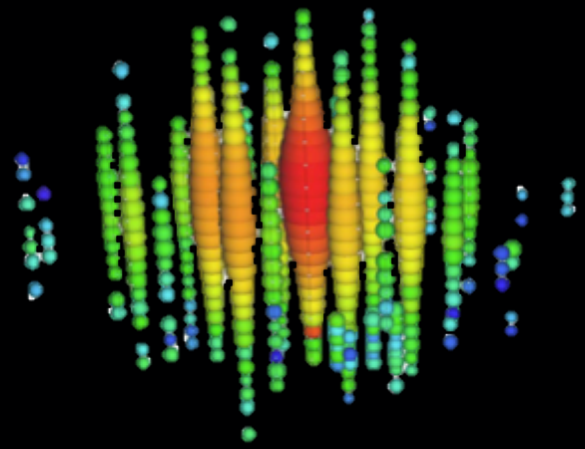
- No evidence for point sources
- No correlation with the galactic plane
- Best fit: Single power law with spectral index $\gamma = 2.89^{+0.20}_{-0.19}$ all-flavor flux normalization $\Phi = 6.45^{+1.46}_{-0.46} \times 10^{-18}$ GeV^{-1}cm^{-2}s^{-1}sr^{-1}
- Data does not prefer a broken power law model

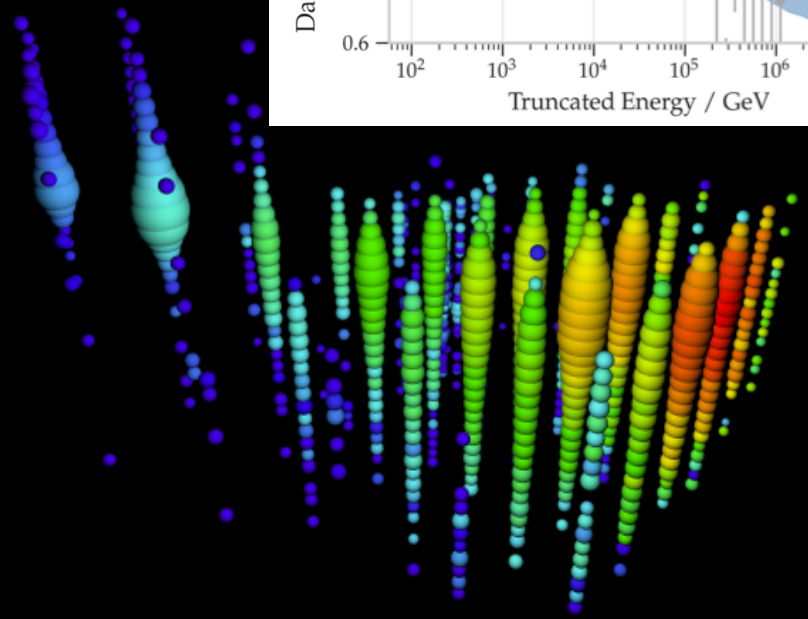
Diffuse neutrino flux

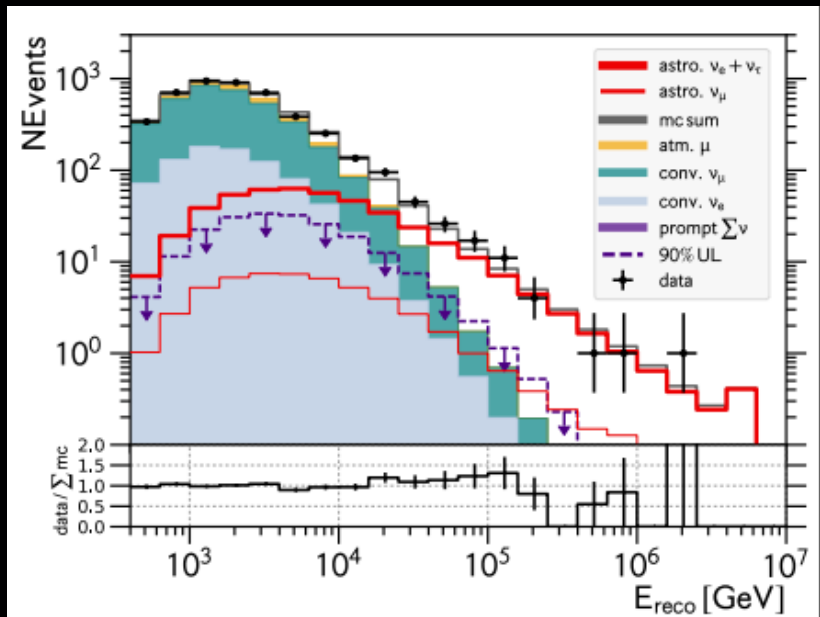
Through-going tracks



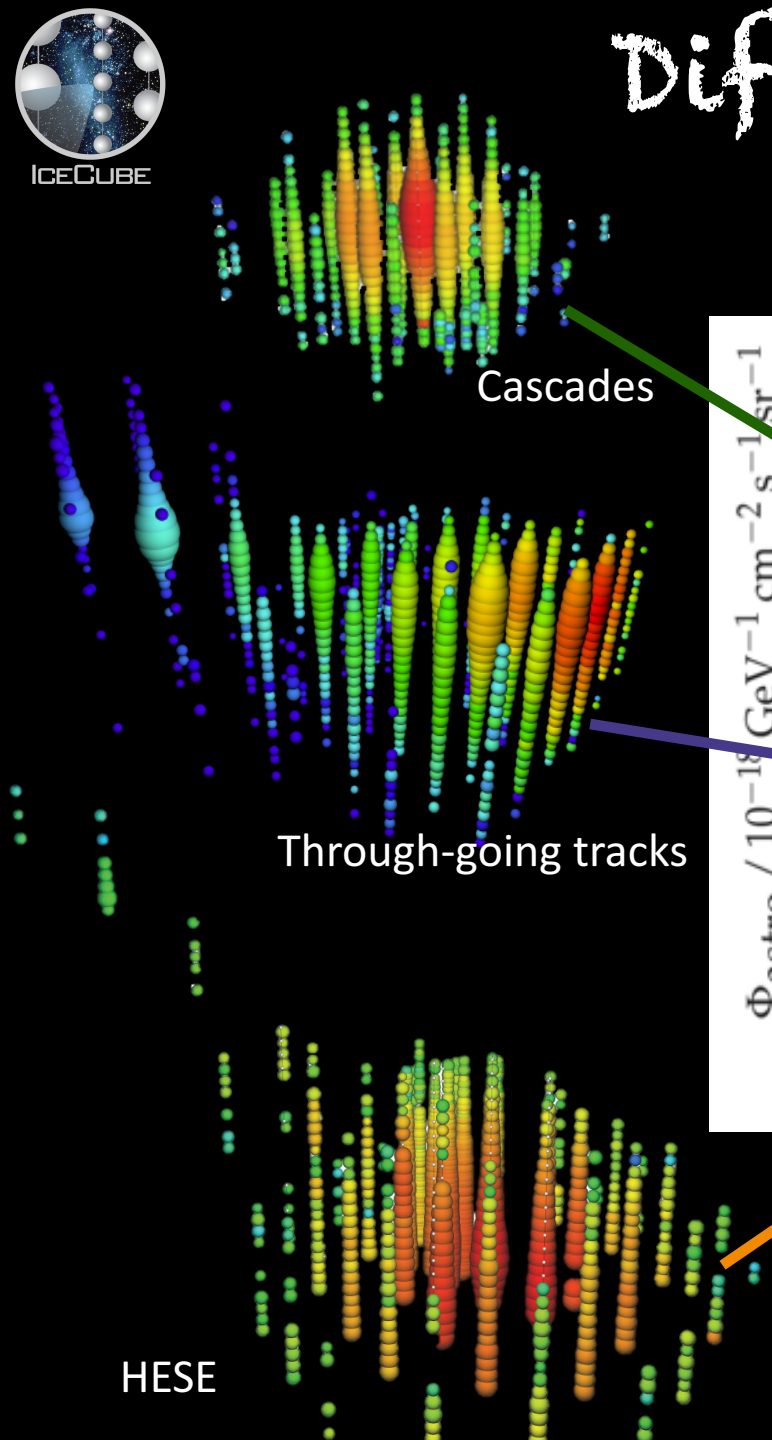
Cascades

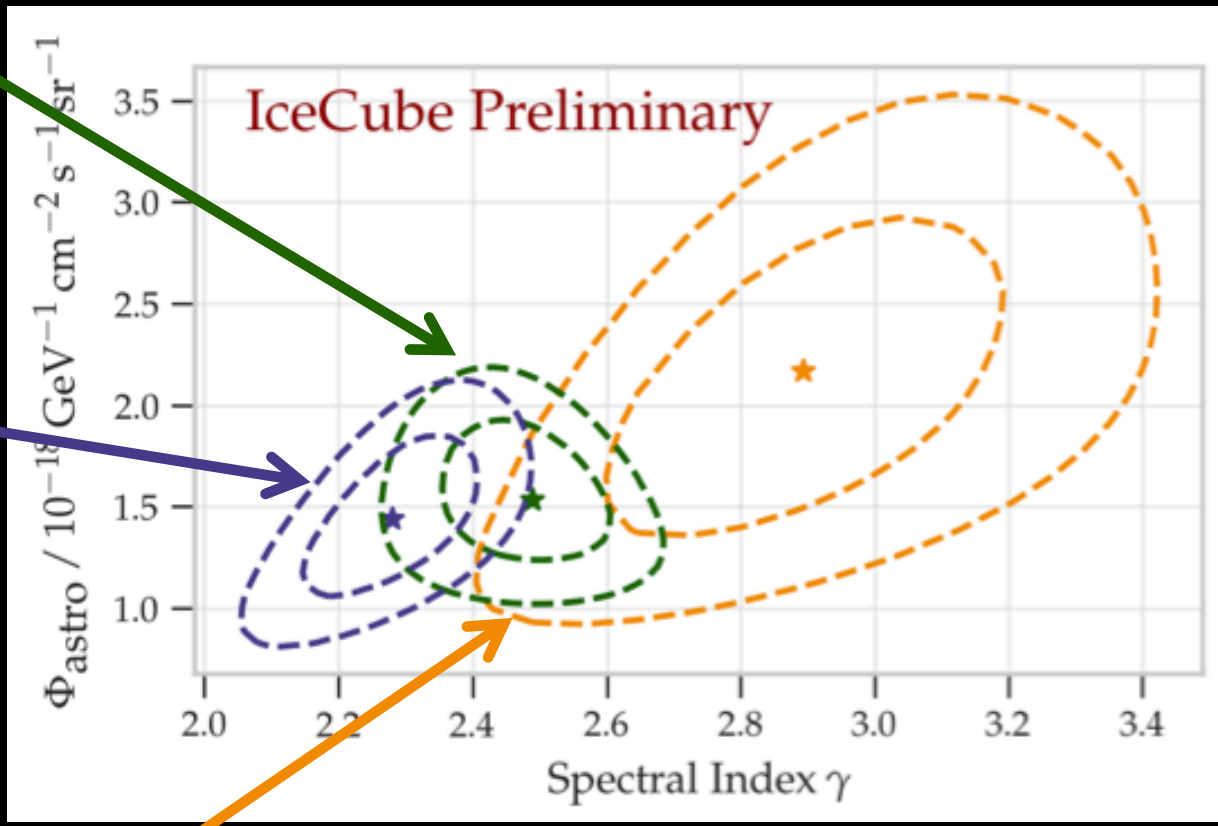






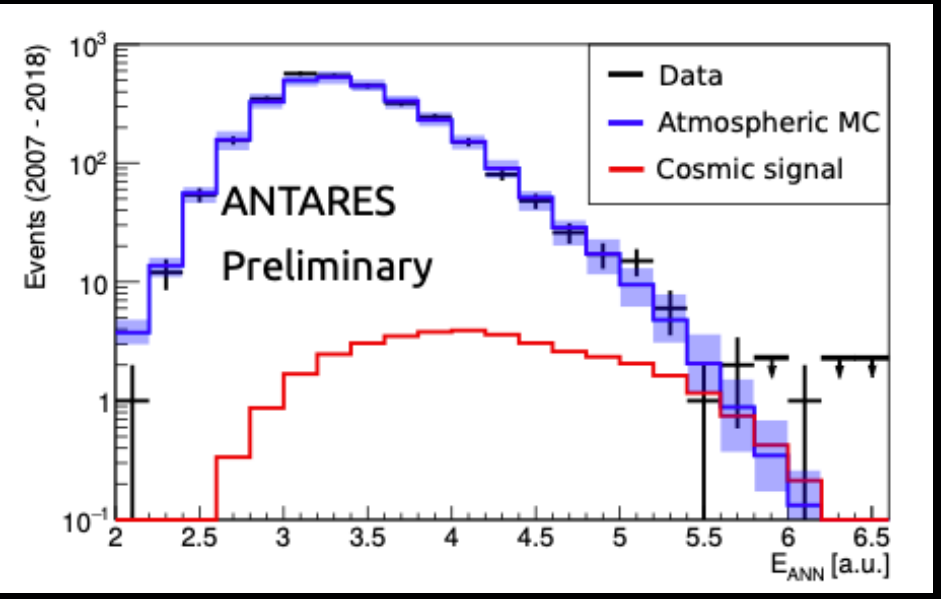
Diffuse neutrino flux





Astrophysical flux = ϕ_{astro} x $E^{-\gamma}$

Diffuse neutrino flux 11 year



Data: 50 events

Expected background: 36.1 ± 8.7

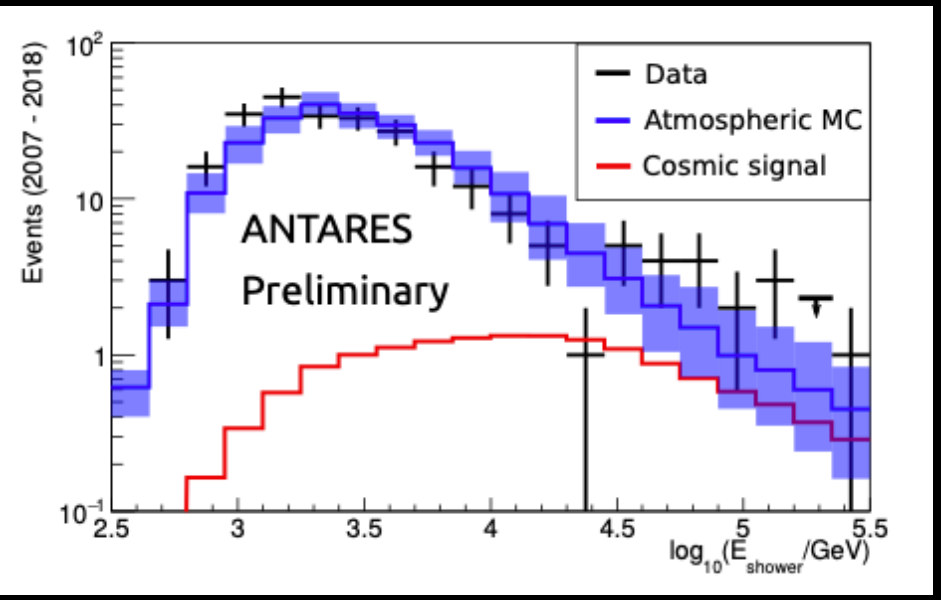
Best fit:

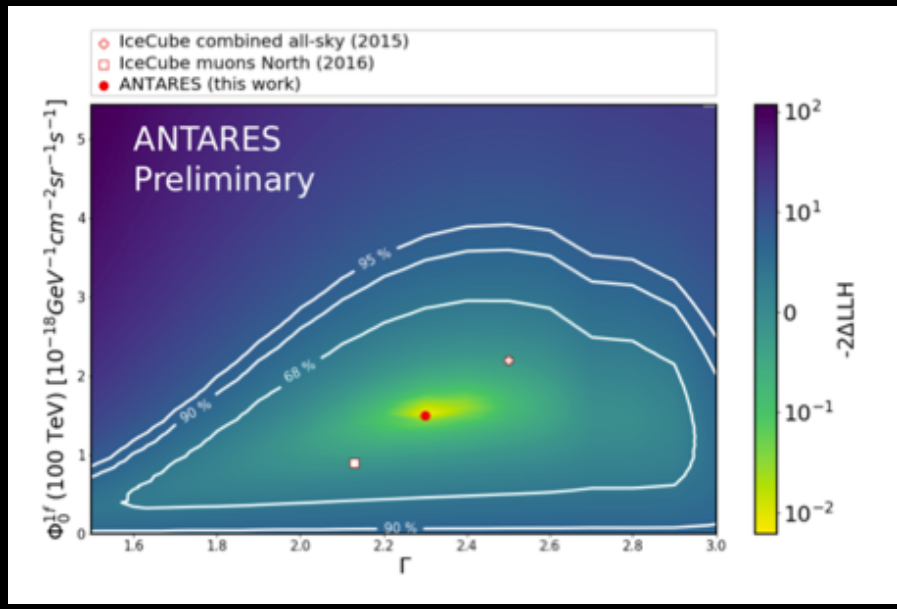
$\phi = 1.5 \pm 1 \times 10^{-18}$ GeV^{-1}cm^{-2} sr^{-1} s^{-1}

$\gamma = 2.3 \pm 0.4$

1.8 σ excess

(increased w.r.t. the 9 year analysis)





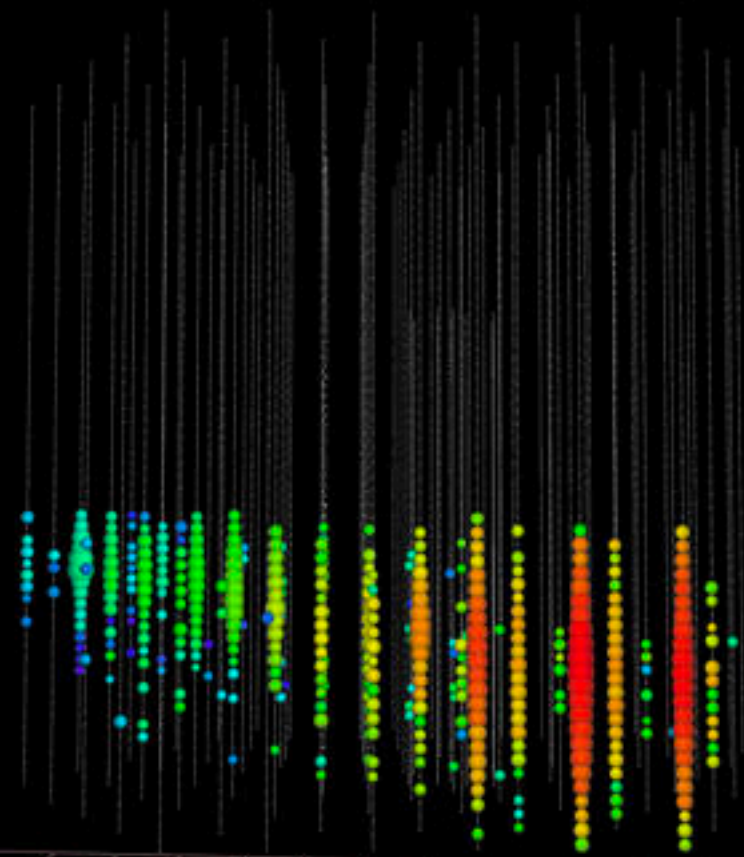
1. What did we discover?

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

13 Jul. 2018

22 September 2017
IceCube-170922A

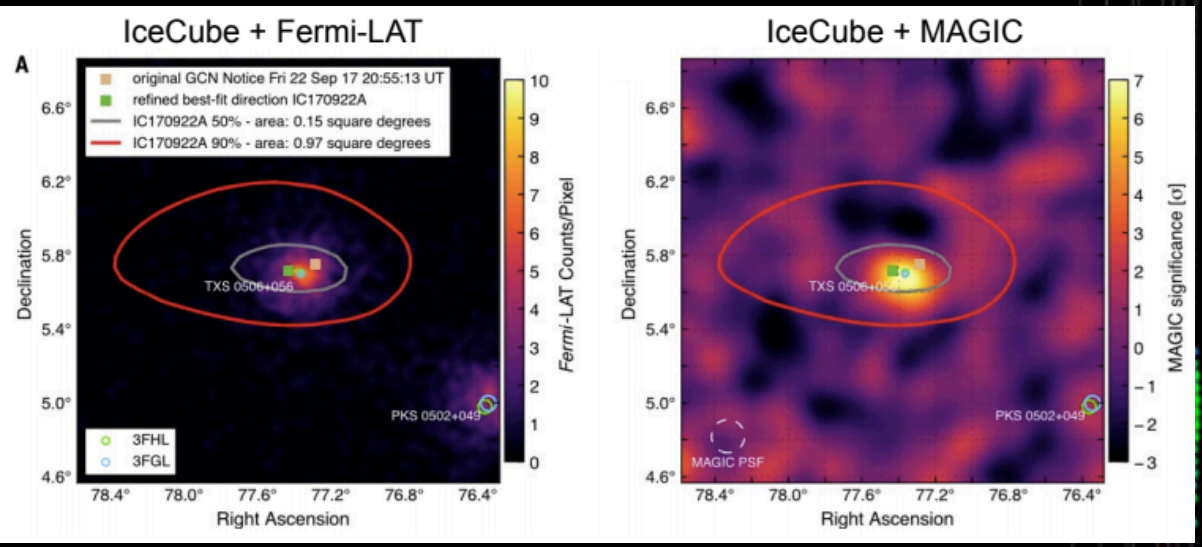


Neutrino Energy: 290 TeV (>180 TeV, 90% CL)
RA: 77.43° (-0.65°/+0.95° 90% CL)
Dec: 5.72° (-0.30°/+0.50° 90% CL)

22 September 2017
IceCube-170922A

- Fermi observations of a known blazar TXS 0506+056, in a state of enhanced gamma-ray emission

- MAGIC detection of > 400 GeV gamma rays from the blazar

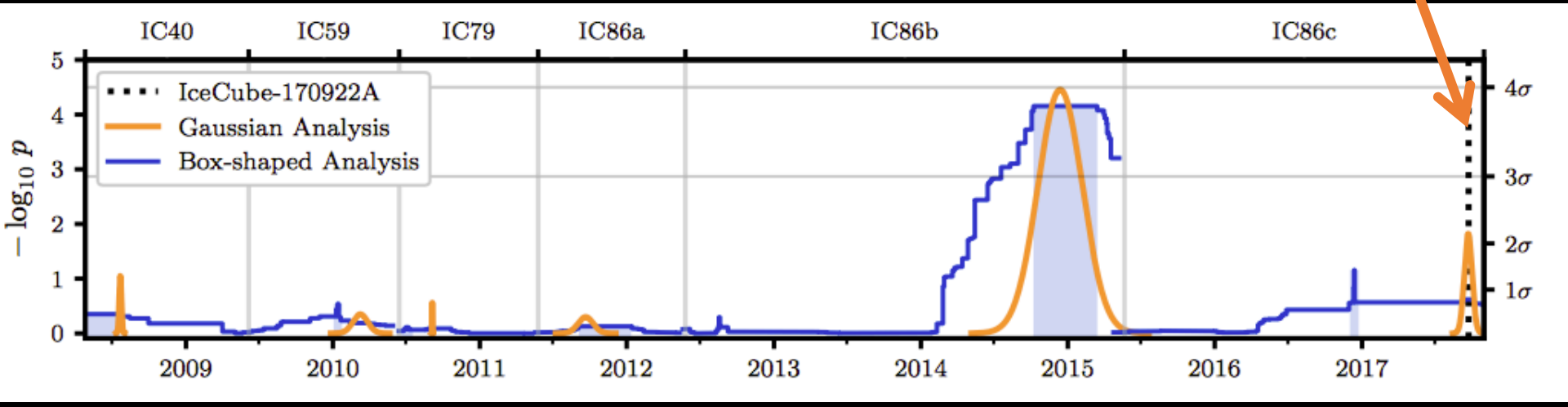


Significance for the overlap: 3σ

Neutrino Energy: 290 TeV (>180 TeV, 90% CL)
RA: 77.43° (-0.65°/+0.95° 90% CL)
Dec: 5.72° (-0.30°/+0.50° 90% CL)

Archival data search

IceCube170922A



- Time-dependent point source search at location of TXS blazar
- 13 ± 5 neutrino excess in 2014-2015 over 110 days
- Significance defined using identical searches using randomized event directions: 3.5σ

2. What's new? / What else?

- Neutrino point source searches

- Neutrinos in the multi-messenger era

2. What's new? / What else?

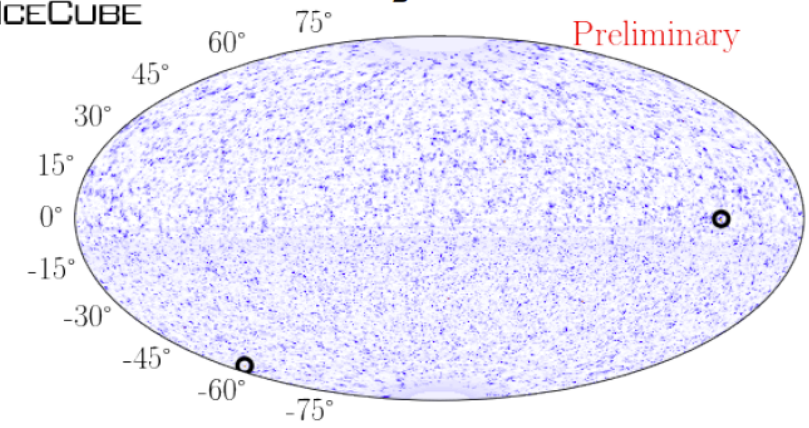
- Neutrino point source searches

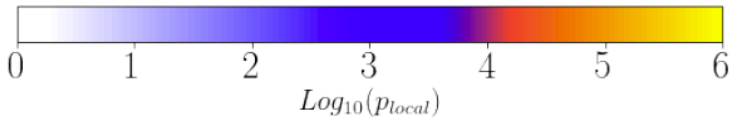
- Neutrinos in the multi-messenger era

2. What's new? What else?

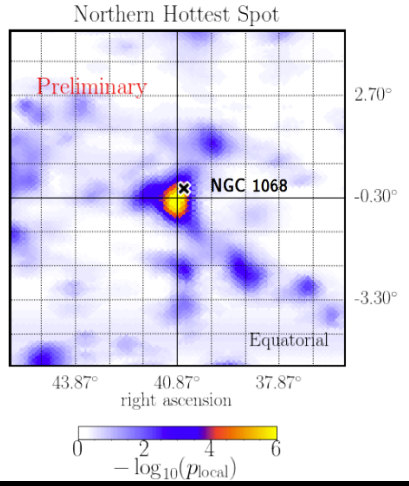
T. Carver and T. Montaruli, ICRC 2019

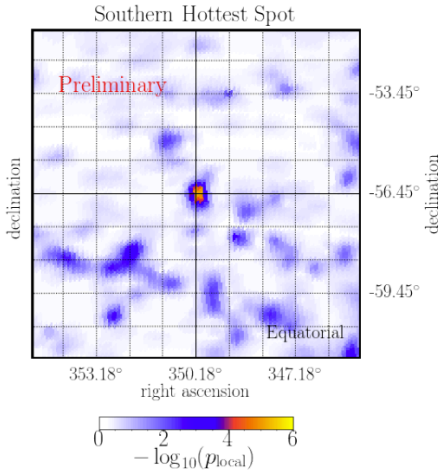
10 year All-Sky Scan Results





- Evaluate likelihood of signal over background for grid over entire sky.
- **Hottest point** = position with smallest p-value in each hemisphere.





Hottest Point in Northern Hemisphere : δ ≥ -5°

RA = 40.87° , Dec = -0.30°

n_{signal} = 61.45 , γ= 3.411

Pval = 6.45, TS = 25.34 ⇒ 9.9 % post-trial

2.9σ post-trial

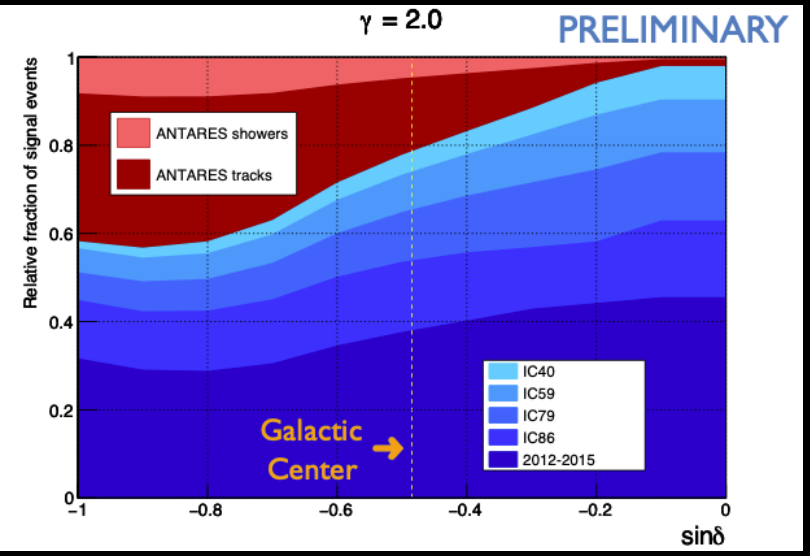
Hottest Point in Southern Hemisphere : δ< -5°

Ra = 350.18° , dec -56.45°

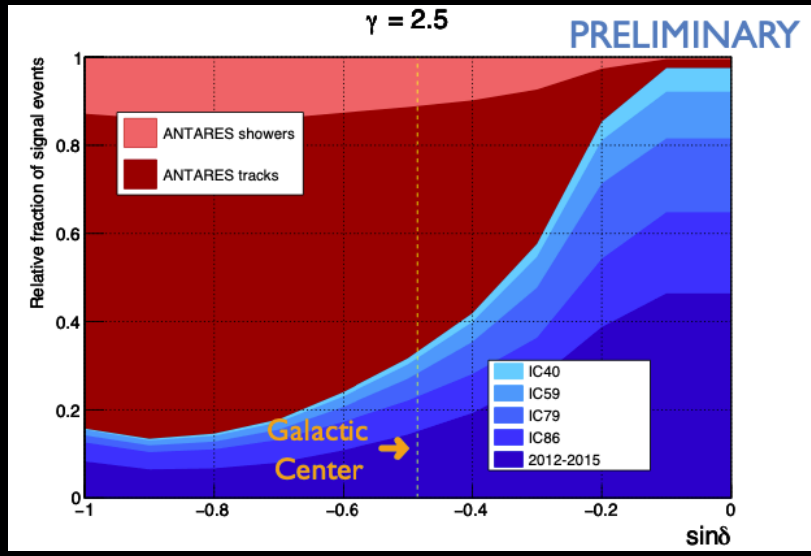
n_{signal} =17.75, γ = 3.34

Pval =5.37, TS= 19.95 ⇒ 75 % post-trial

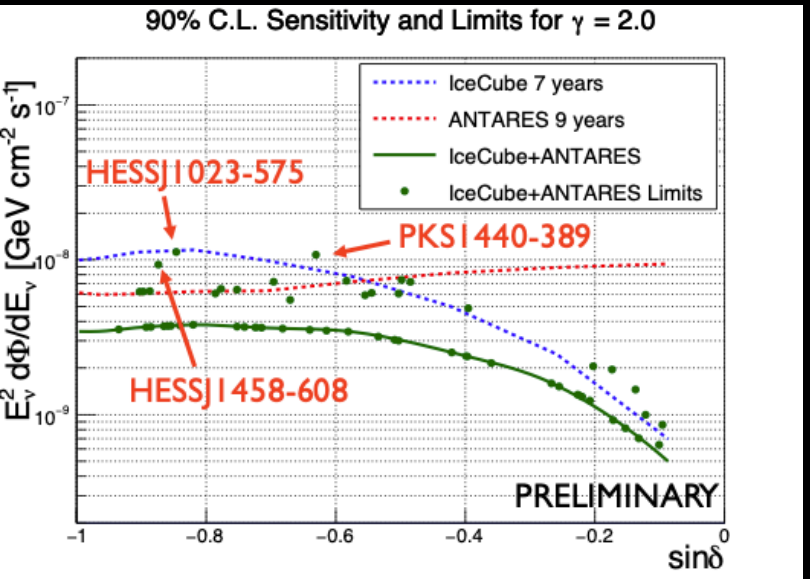
What's new? What else?

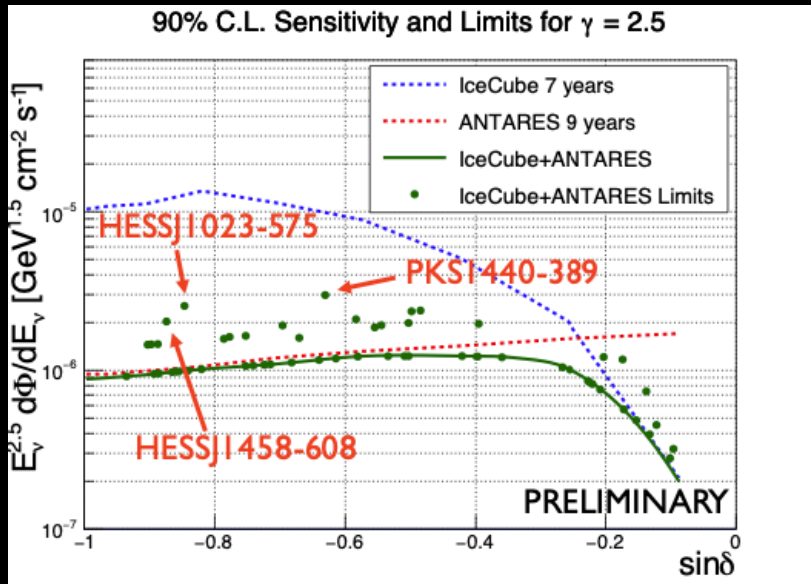


9/7 year combination



Highest excess: HESSJ1023-575 0.2 σ post-trial significance



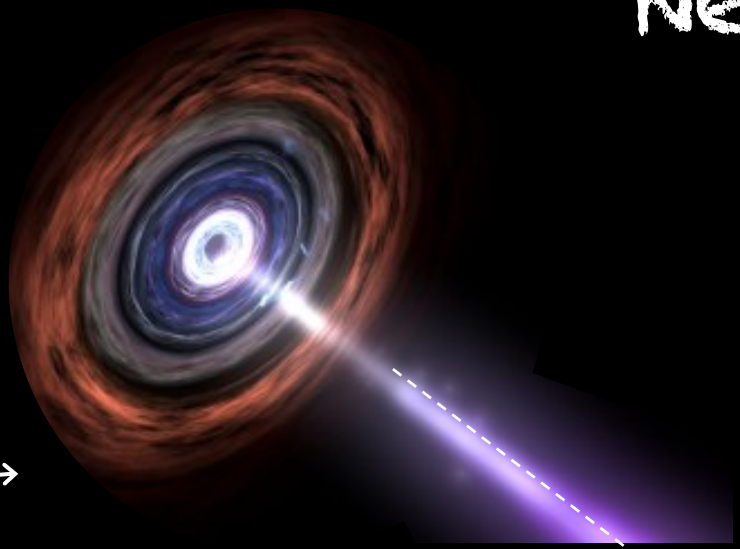


2. What's new? / What else?

- Neutrino point source searches

- Neutrinos in the multi-messenger era

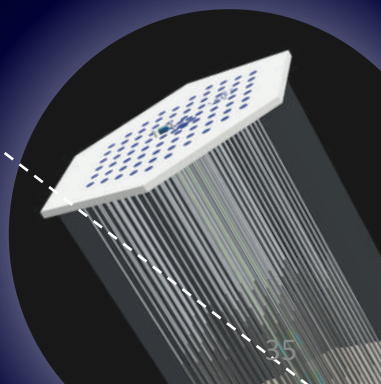
Neutrino search from known sources



Potential high-energy ν emitter

ν

Neutrino telescope



<u>Goal</u>: Identifying hadronic accelerators in the Universe

Neutrino search from known sources

	Contribution to the HE ν flux
Blazars (Fermi 2LAC catalog)	< 27%
Gamma-ray burst	< 1%
Galactic plane	< 14%

What can we do to find sources?

Real-time multi-messenger astronomy

Multi-messenger partners

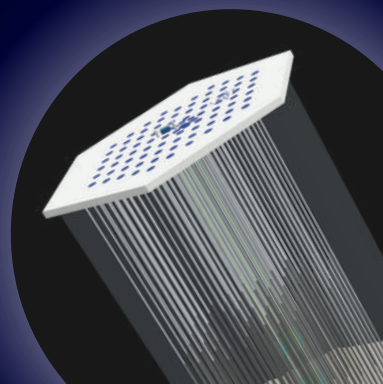
IACTs
Gamma-ray satellites

Ground based observatories
Satellites

Neutrino telescopes

Interferometers

IceCube
ANTARES



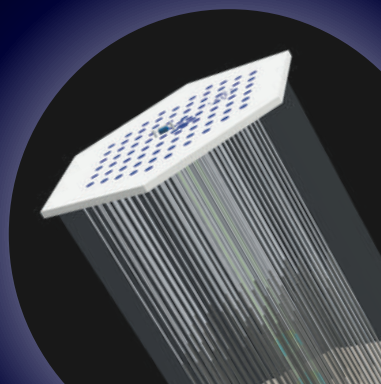
Real-time multi-messenger astronomy

Multi-messenger partners

IceCube170922A!

IceCube ANTARES

- New IceCube alert categories since June 2019
  - Gold = 50% signal probability ~ 12 evt/yr
  - Bronze = 30% signal probability ~ 16 evt/yr
- ANTARES alerts:
  - Single neutrino with direction close to local galaxies (1 TeV): ~ 10 evt/yr.
  - Single HE neutrinos (7 TeV): ~ 15 evt/yr
  - VHE neutrinos (30 TeV): ~ 3-4 evt/yr



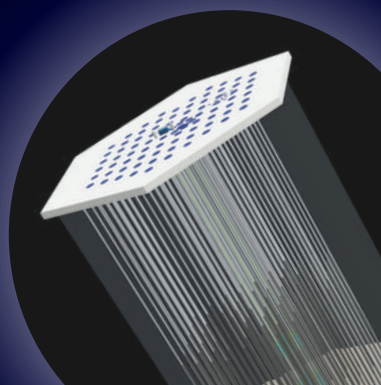
Real-time multi-messenger astronomy

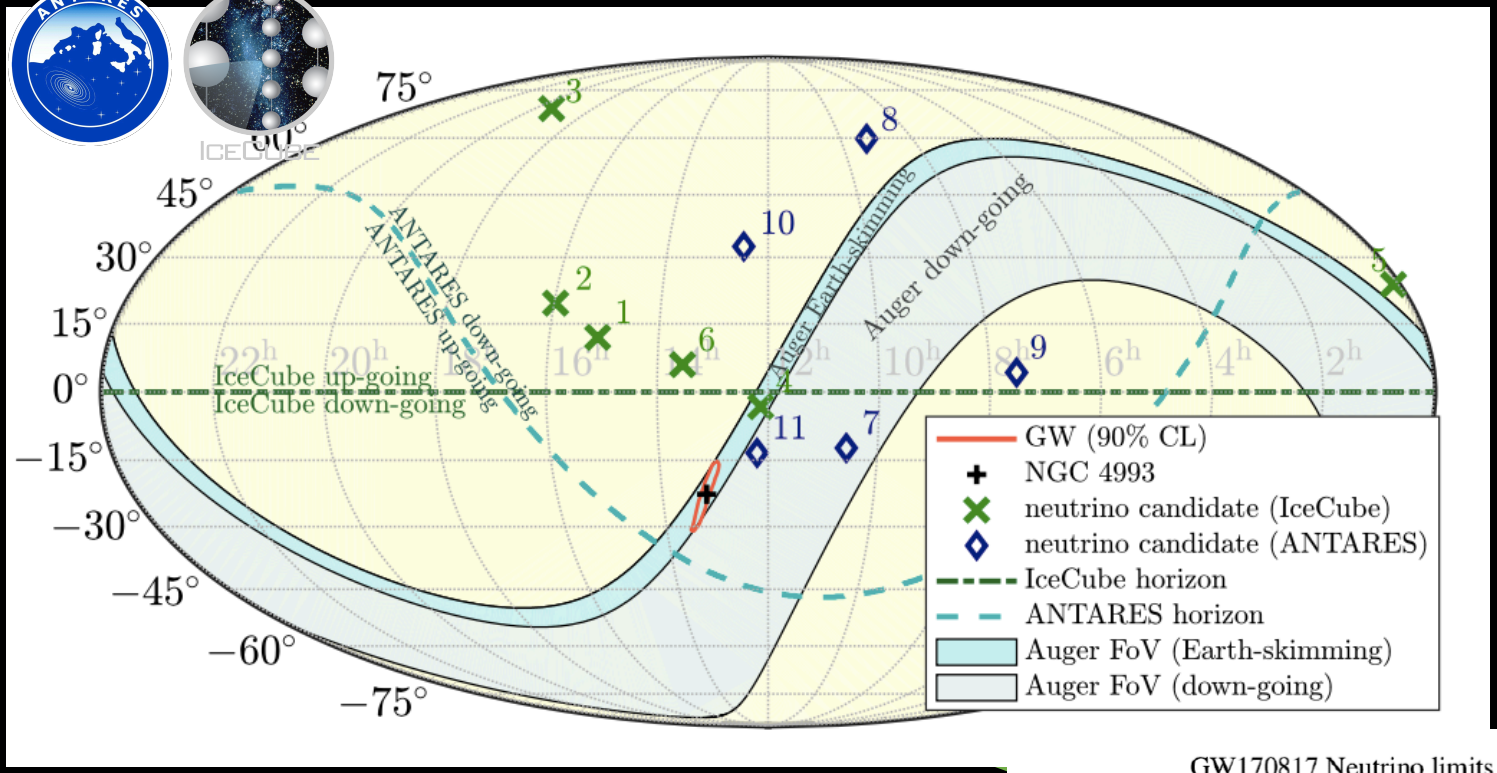
Multi-messenger partners

- Fast-response analysis for interesting events, such as flares from the Crab Nebula or unknown bright transients in IceCube

IceCube

- Systematic follow-up of GW events in both IceCube and ANTARES

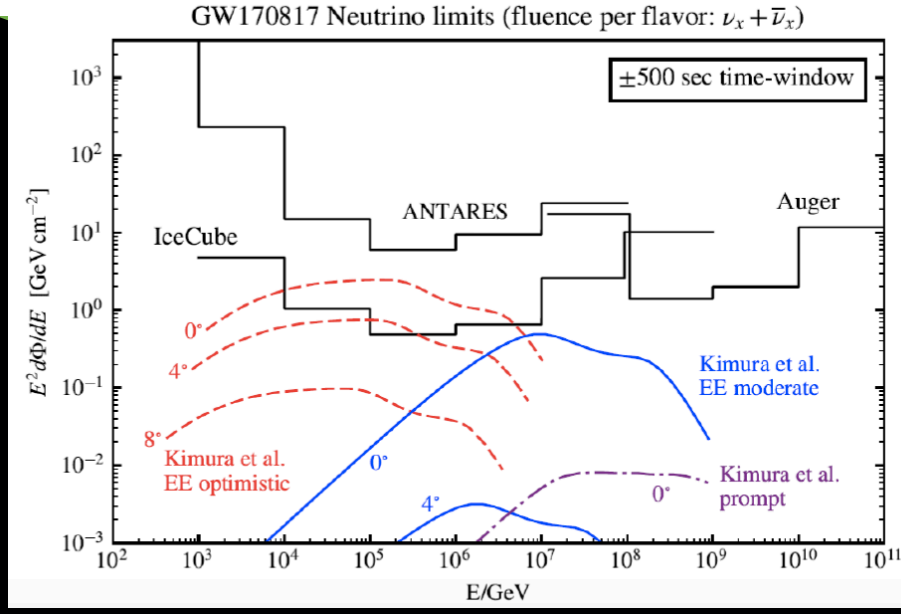


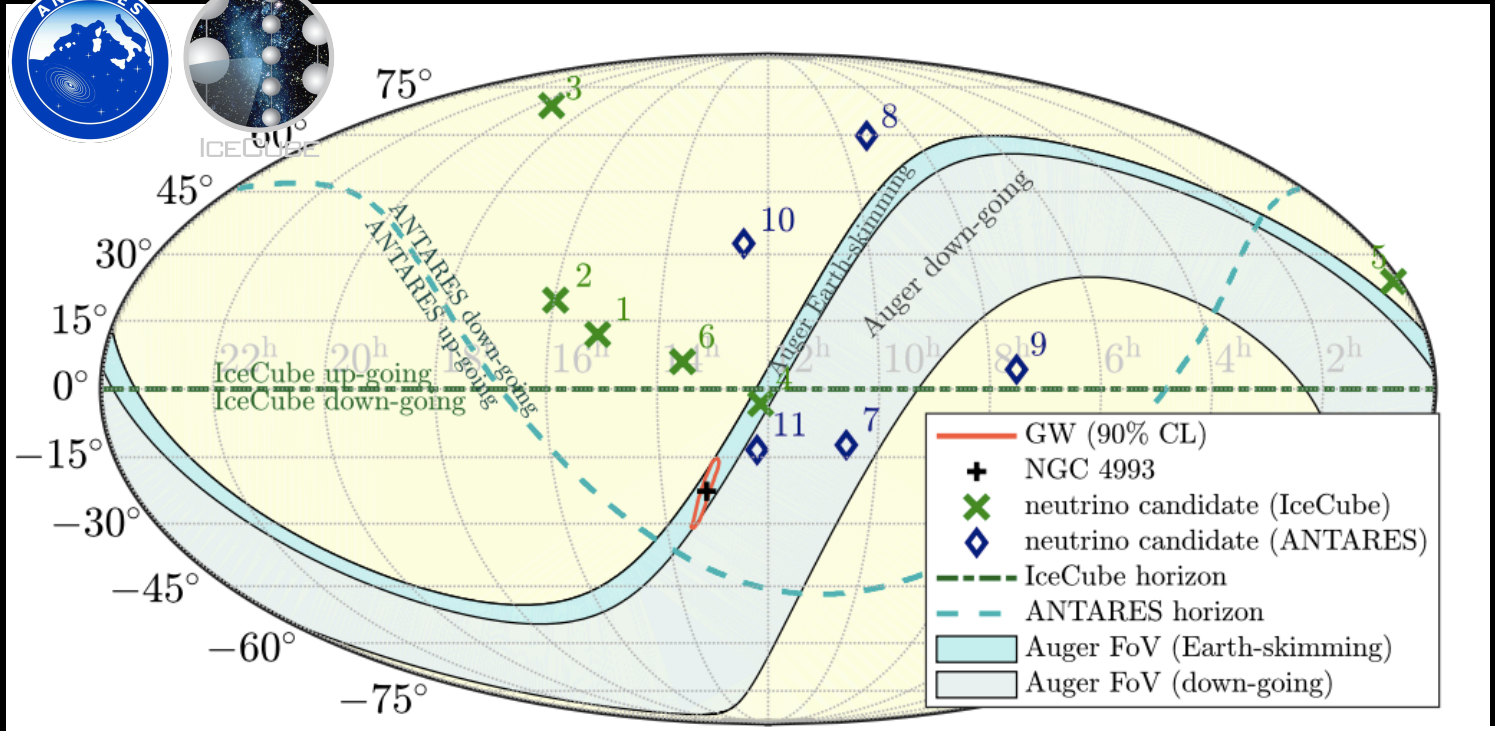


GW170817
[-500s , +500s]

- So far in O3:
  - > 30 BBH candidates
  - 8 BNS candidates
  - 6 NS-BH candidates
  - 3 Mass Gap candidates
  - 2 unmodeled transient candidates

- 3 coincident IceCube candidates





GW170817
[-500s , +500s]

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  - > 30 BBH candidates
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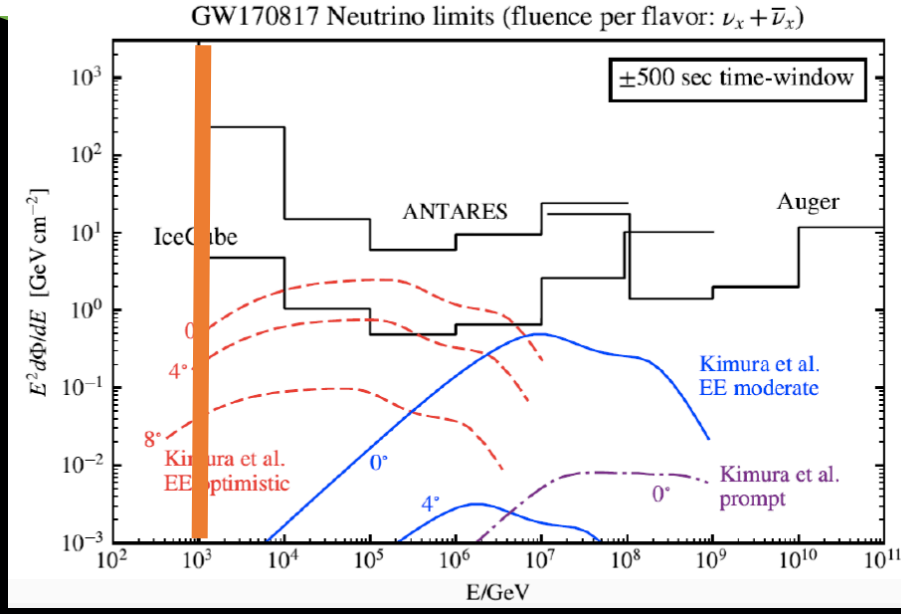
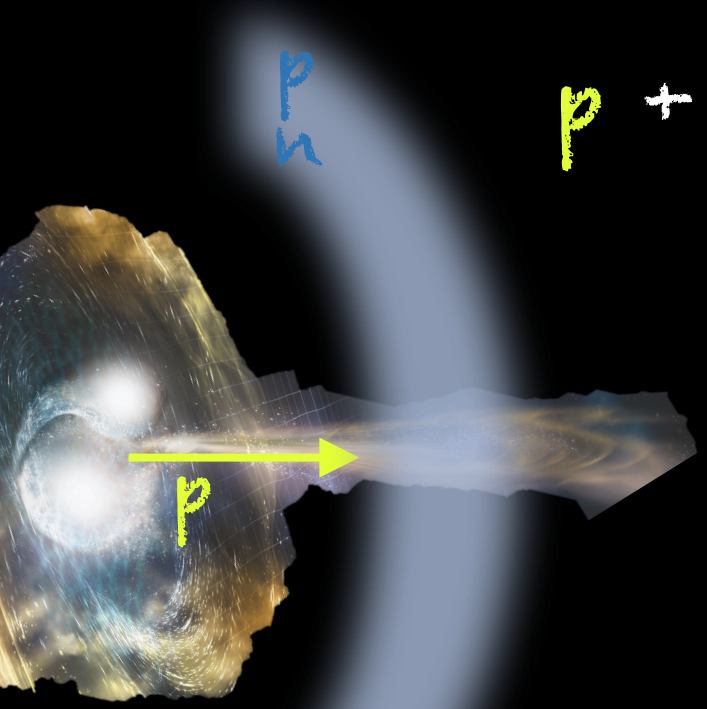


Limits above 1 TeV

Why exploring the sub-TeV sky



$p + p, n \rightarrow$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$\pi^0 \rightarrow 2\,\gamma$

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

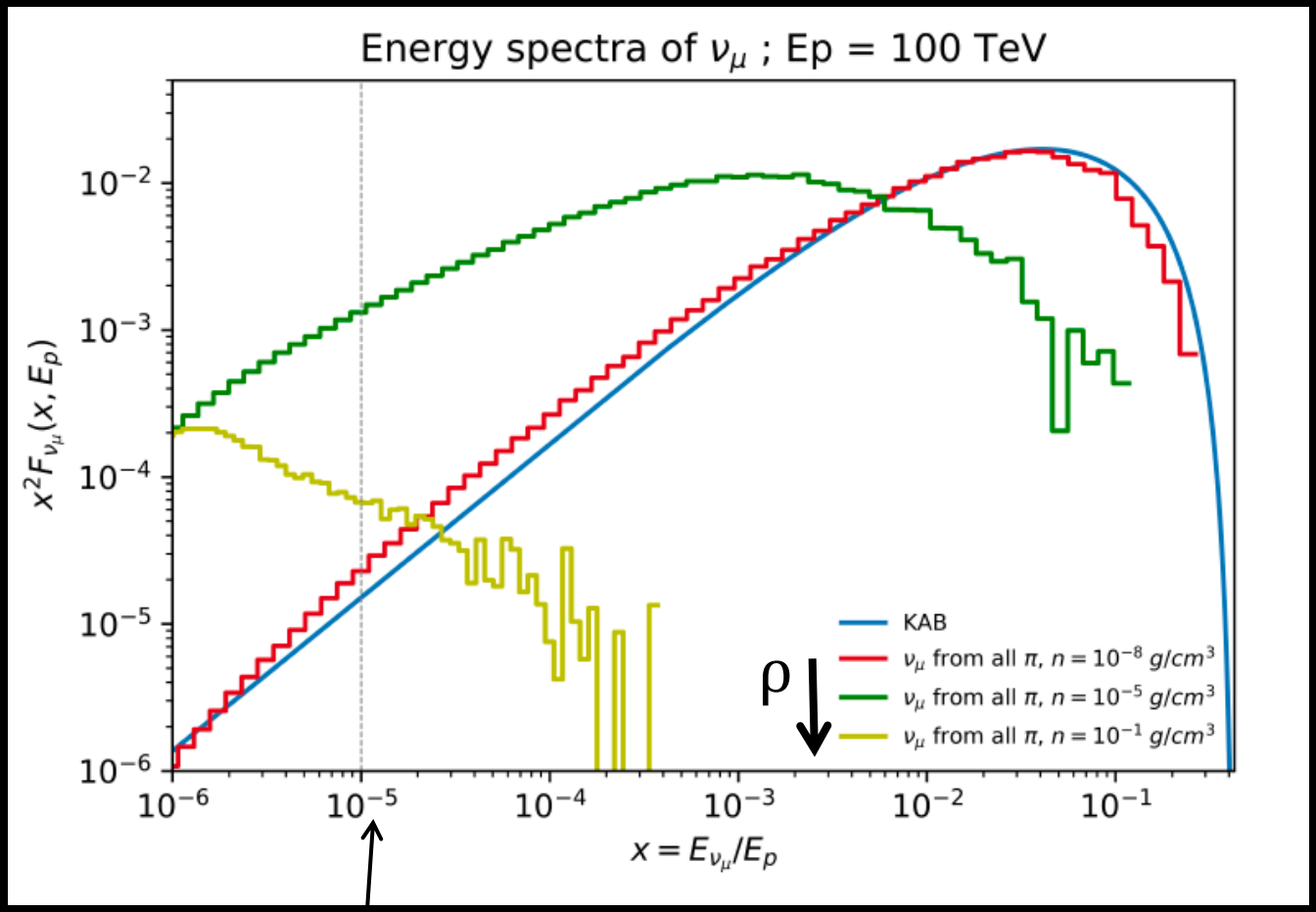
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Give extra information on source environment

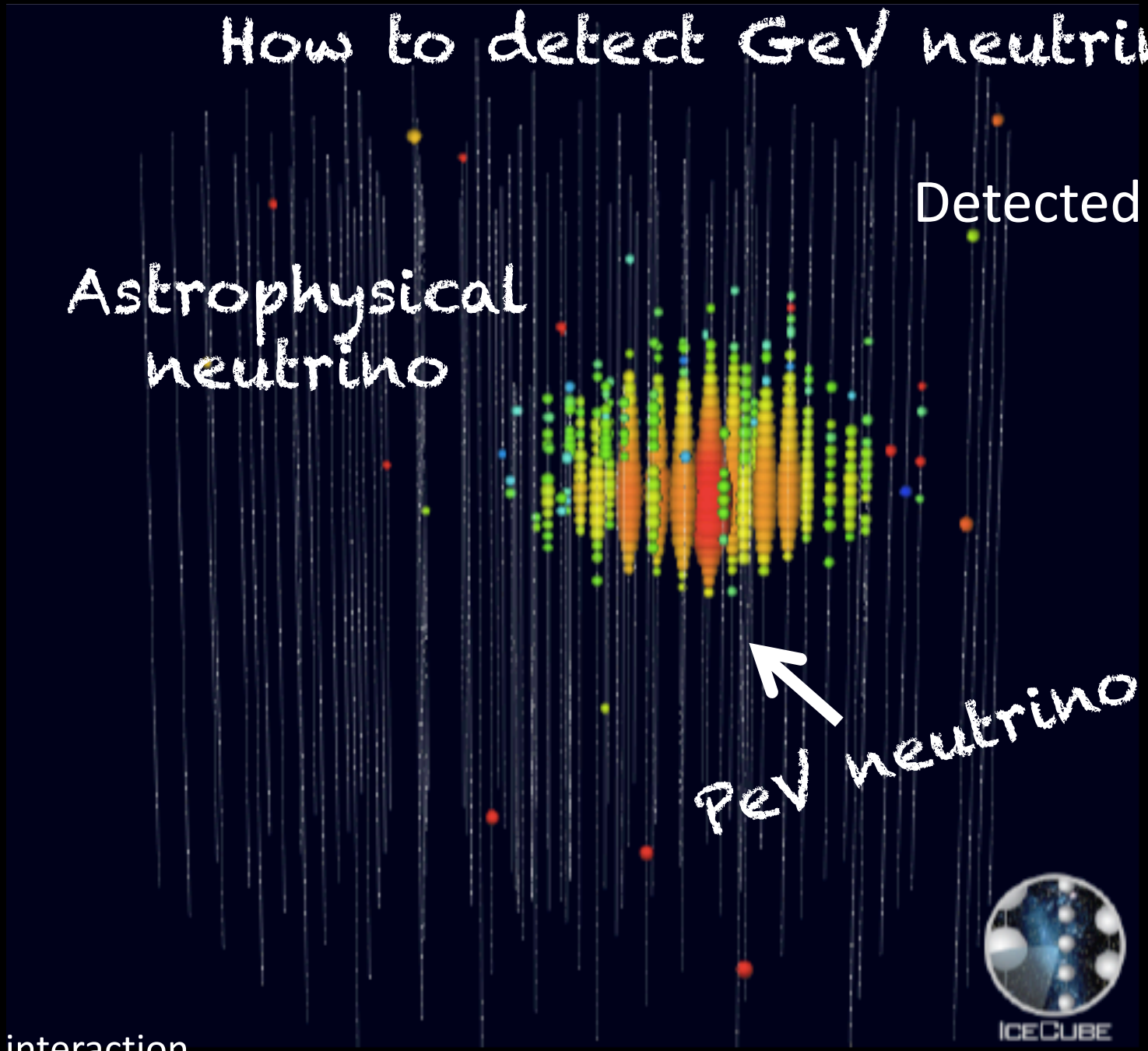
Murase *et al.,* Phys.Rev.Lett. 111 (2013) 131102
Bartos *et al.*, Phys.Rev.Lett. 110 (2013) 241101
Maouloud, GDW, Ahlers, Bustamante, van Elewyck, PoS(ICRC2019)1023

Why exploring the sub-TeV sky

Monoenergetic flux of protons
on a fixed proton target in Geant4

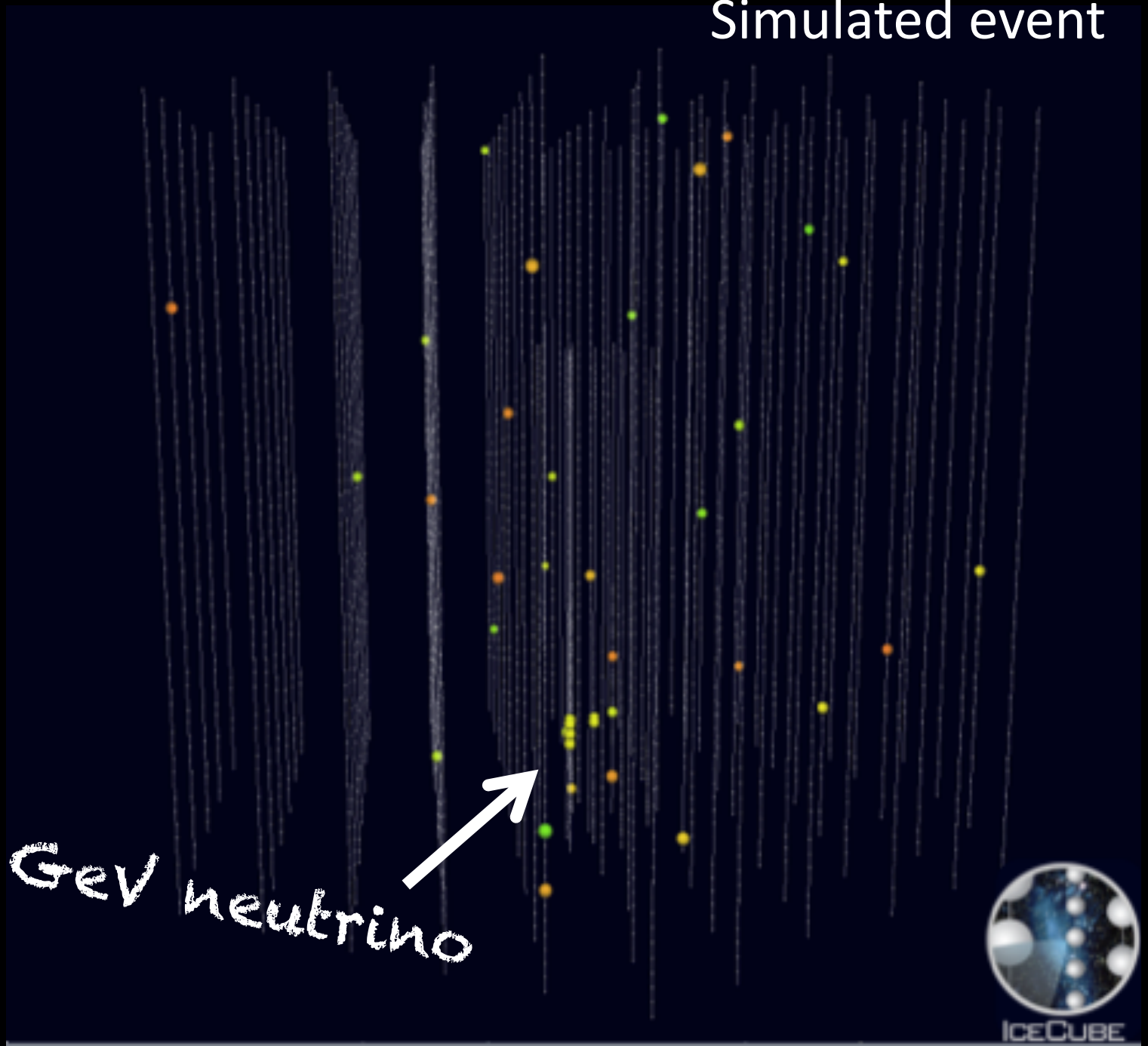


Maouloud, GDW, Ahlers, Bustamante, van Elewyck, PoS(ICRC2019)1023

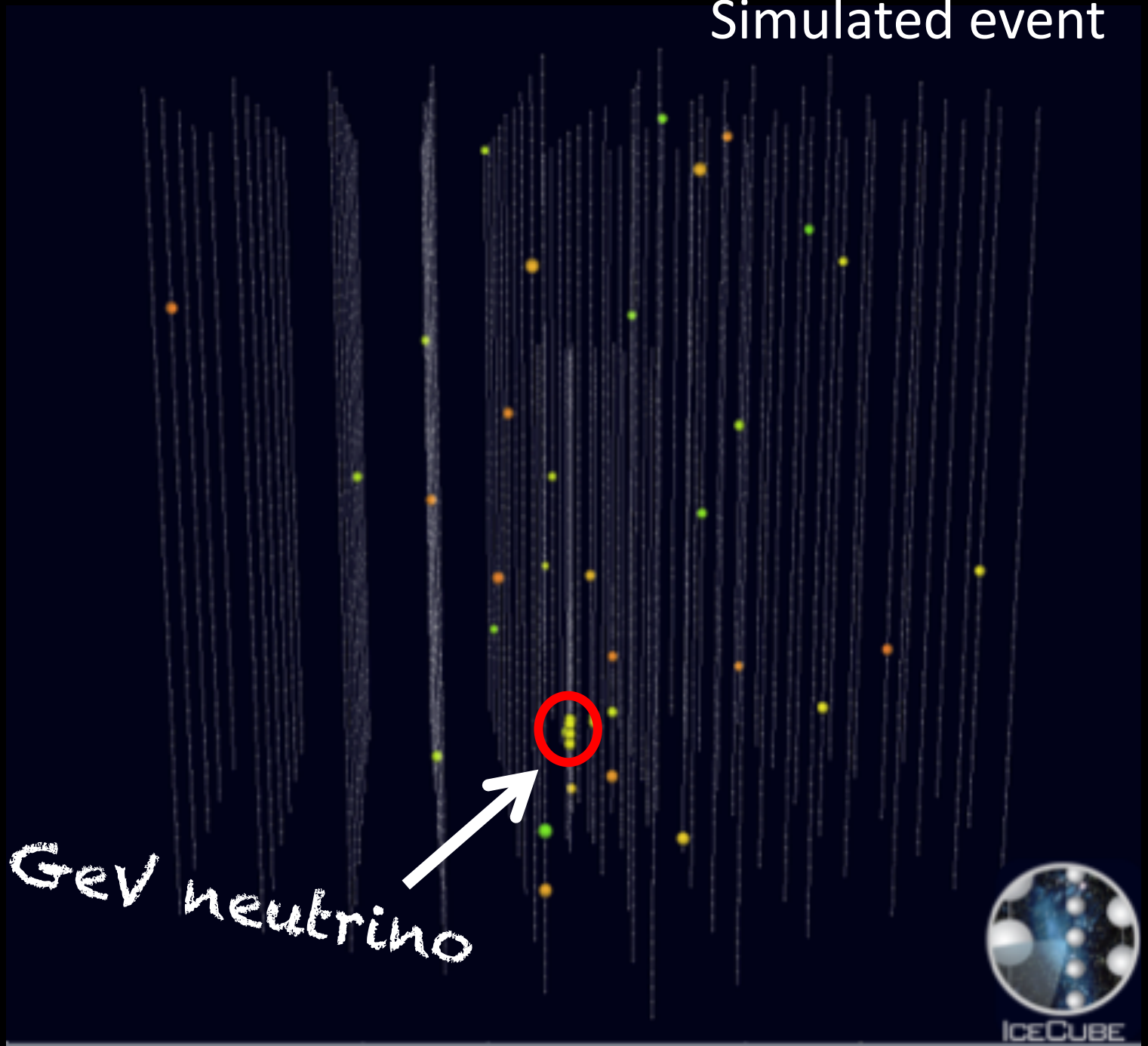


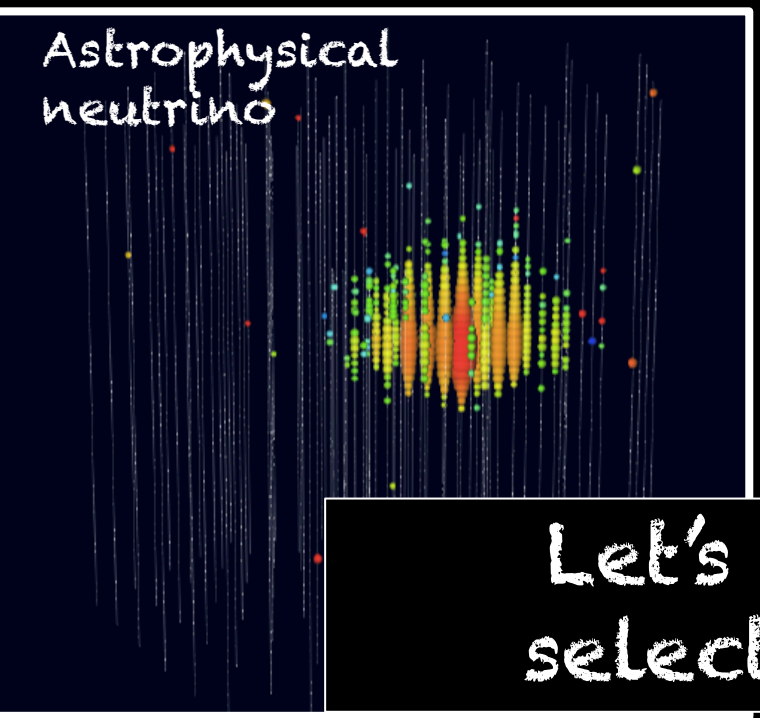
Not ν_μ CC interaction

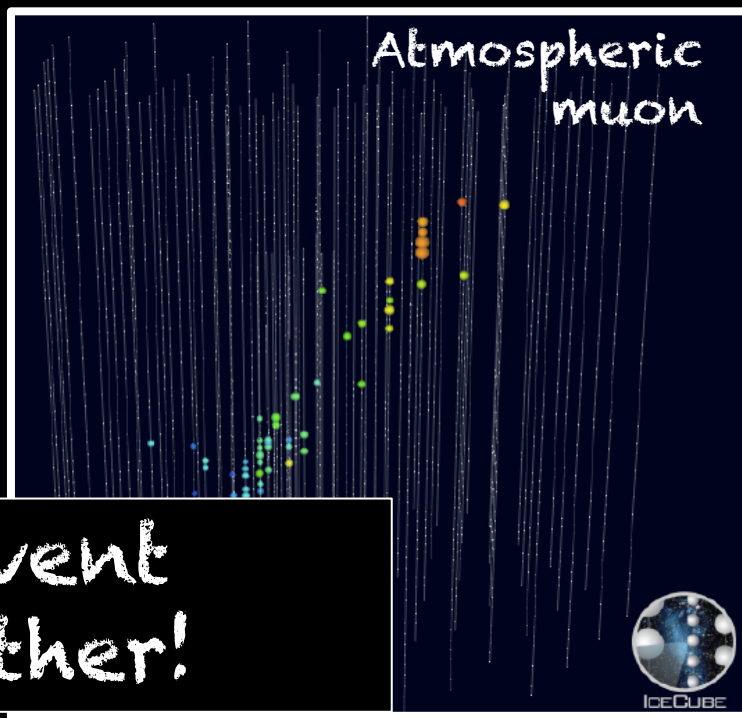
Simulated event



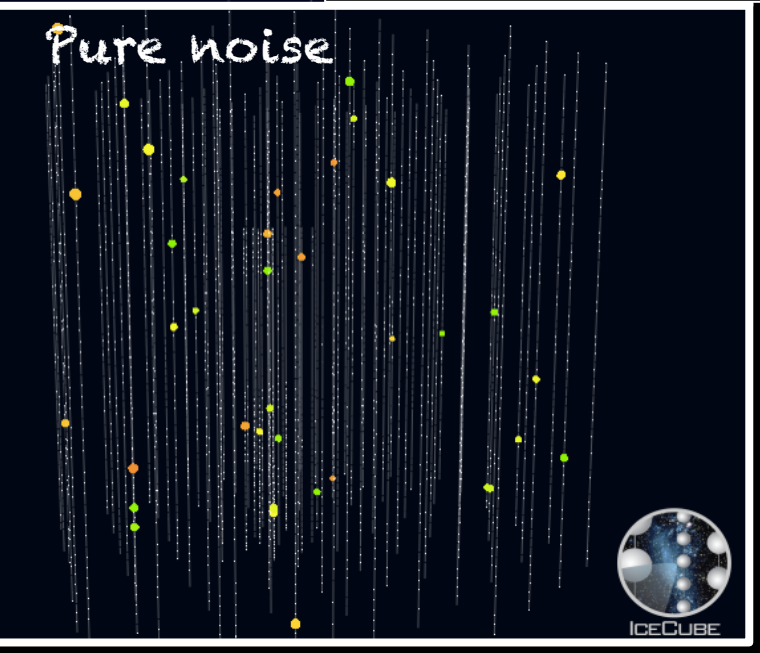
Simulated event

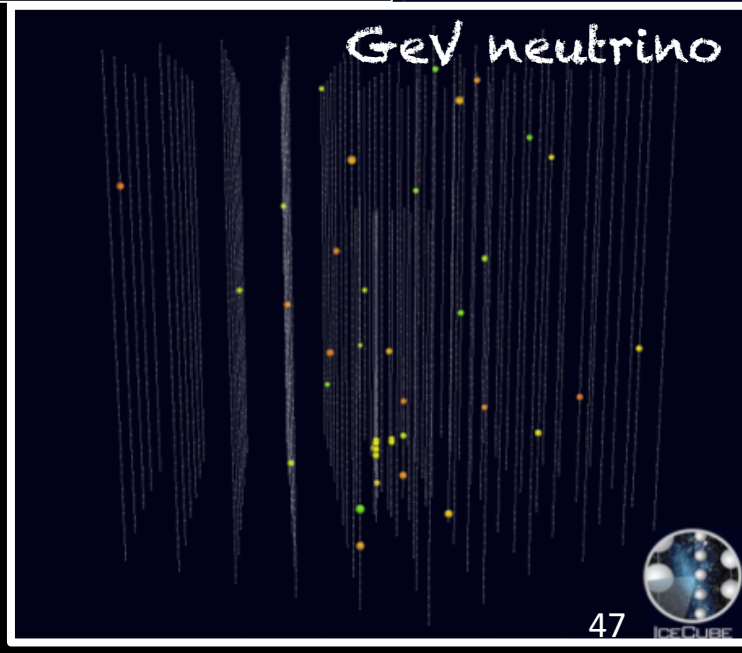


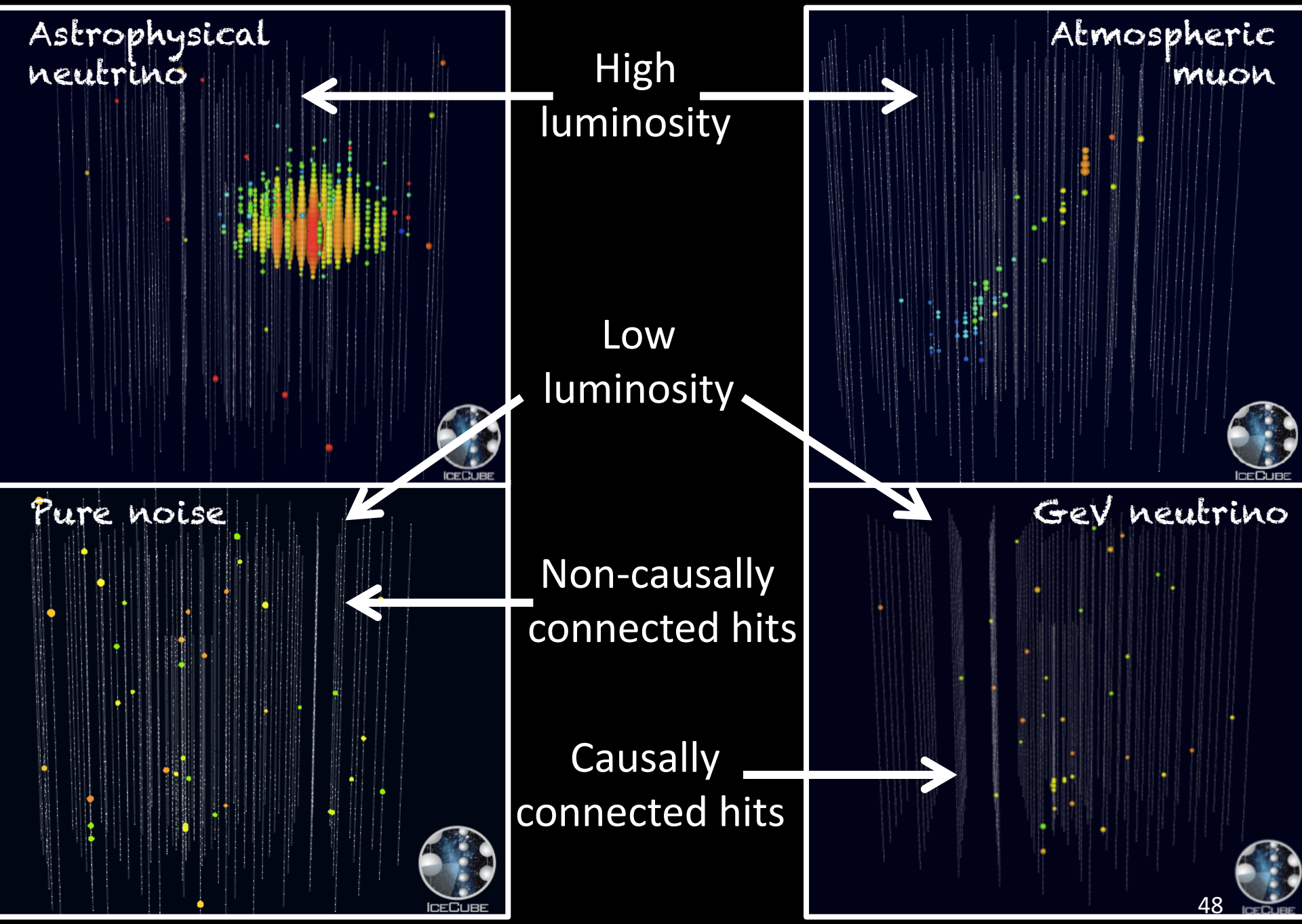


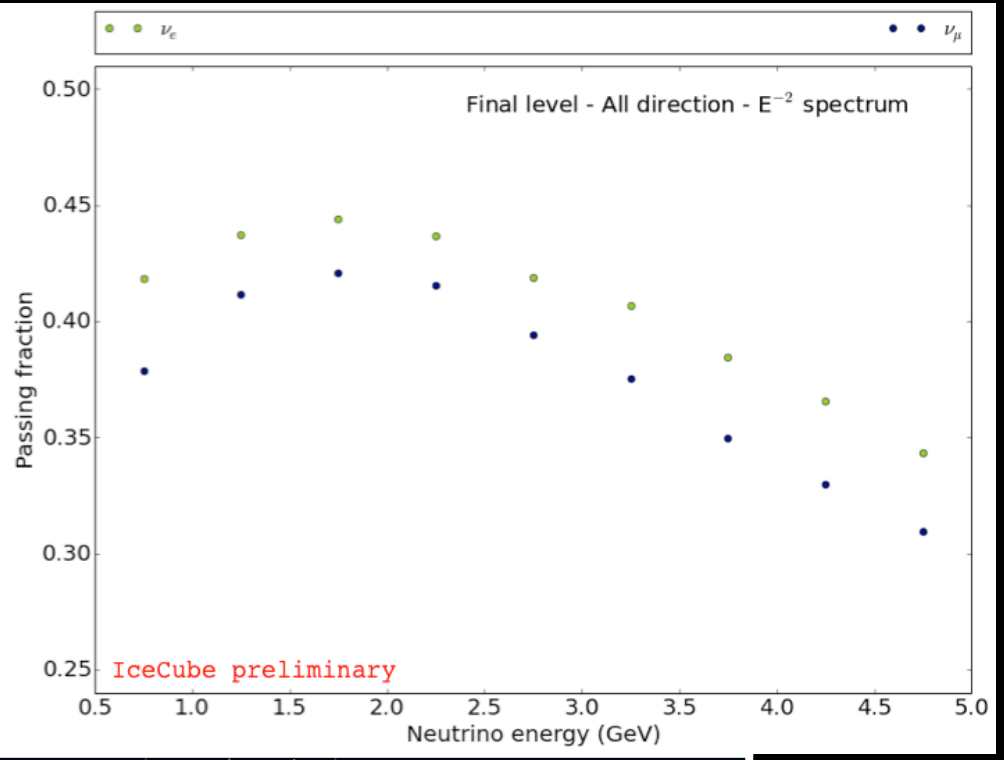


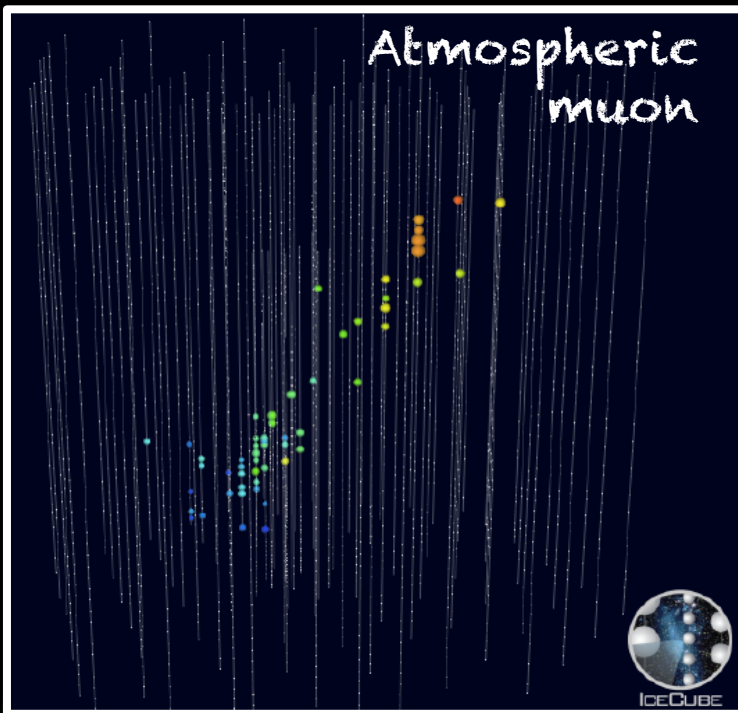
Let's do the event selection together!

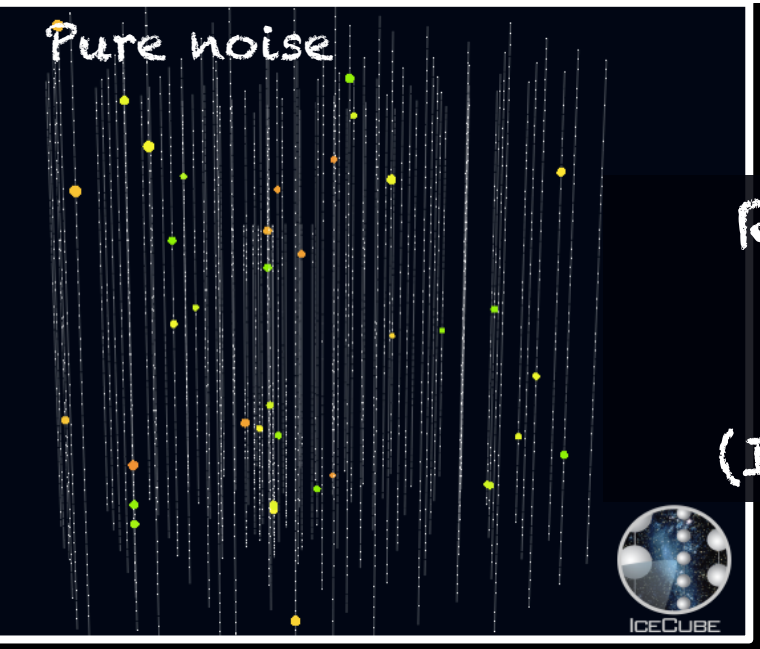





Astrophysical neutrino
High luminosity
Atmospheric muon
Low luminosity
Pure noise
Non-causally connected hits
GeV neutrino
Causally connected hits
IceCube
IceCube
IceCube
IceCube

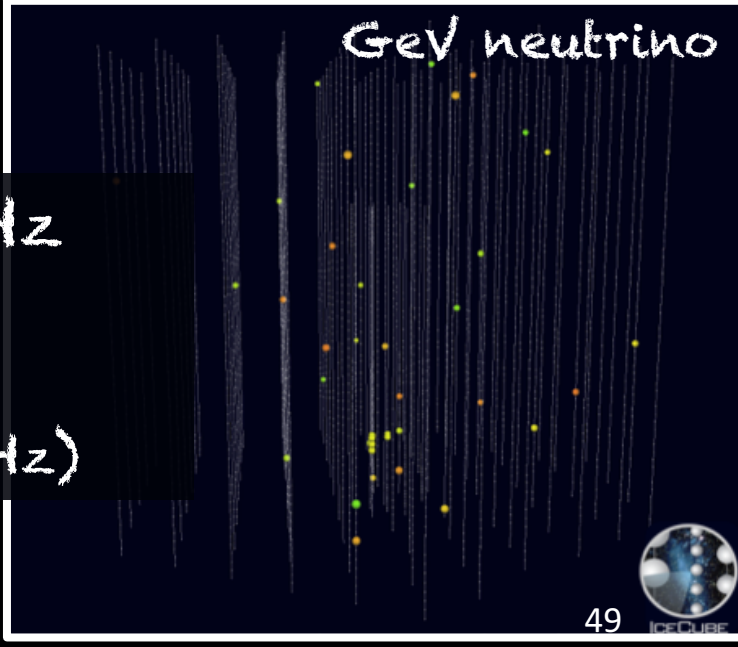




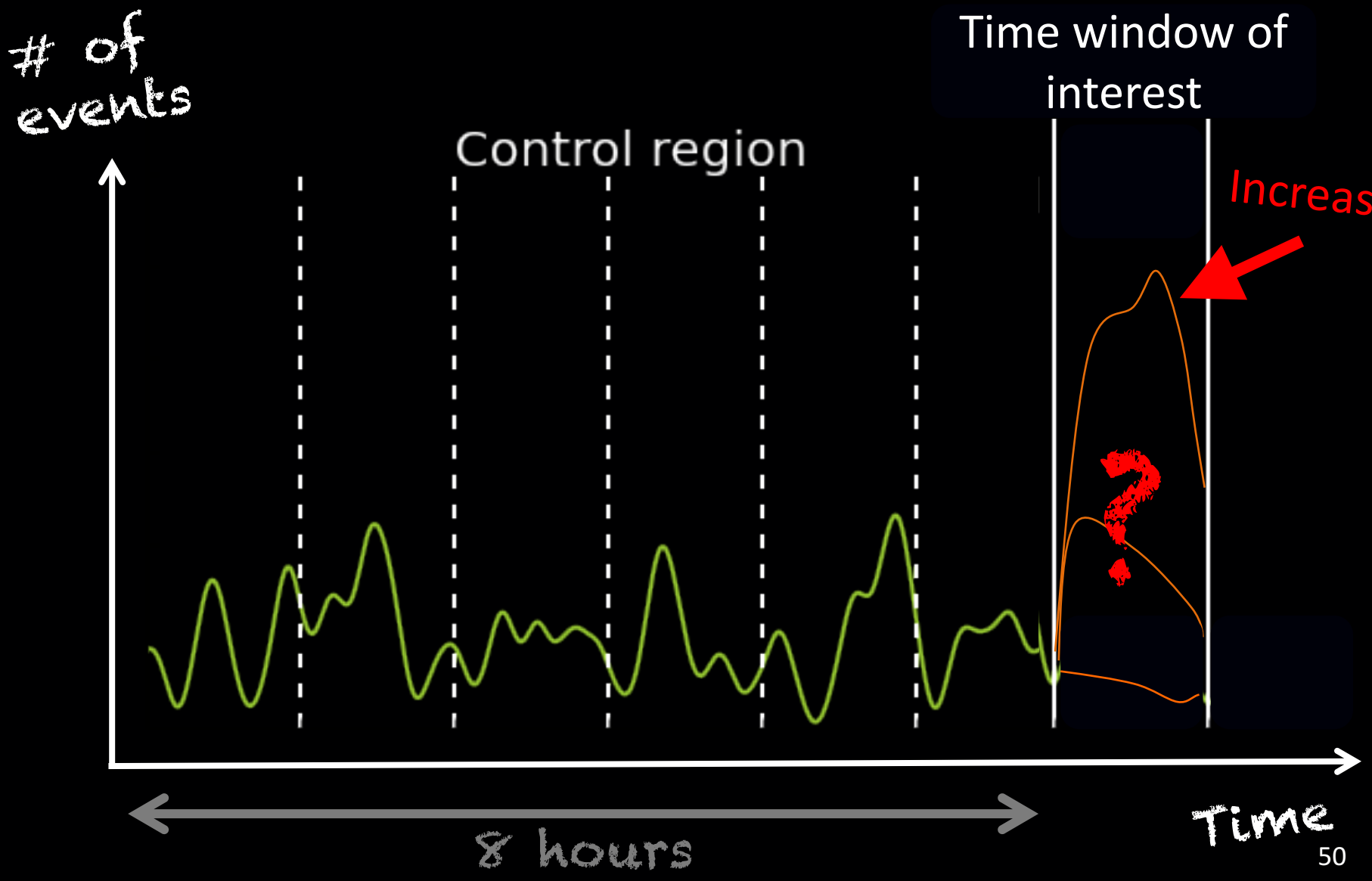


Rate = 0.02Hz

(Initial rate: kHz)

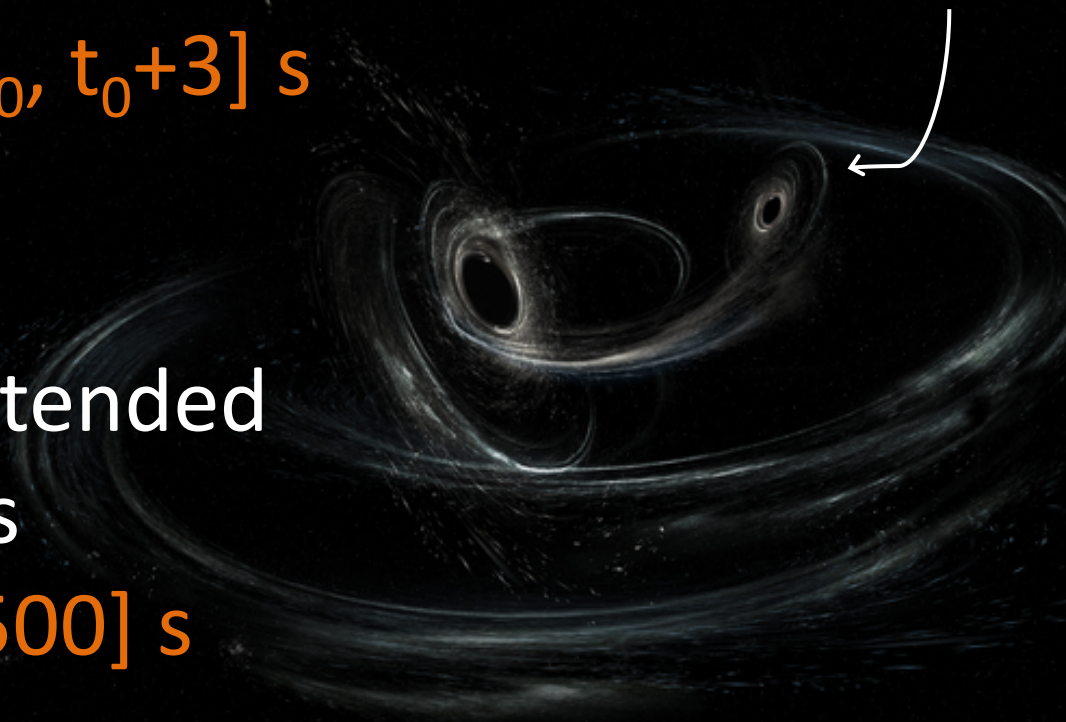


How to detect a GeV neutrino signal?



Did we find GeV neutrinos?

"Spiraling Black Holes"
(Artist's conception)



- 3 BNS + 1NSBH mergers
  Search for a prompt signal
  $[t_0, t_0+3]$ s

- 6 BBH mergers
  Search in an extended time windows
  $[t_0-500, t_0+500]$ s

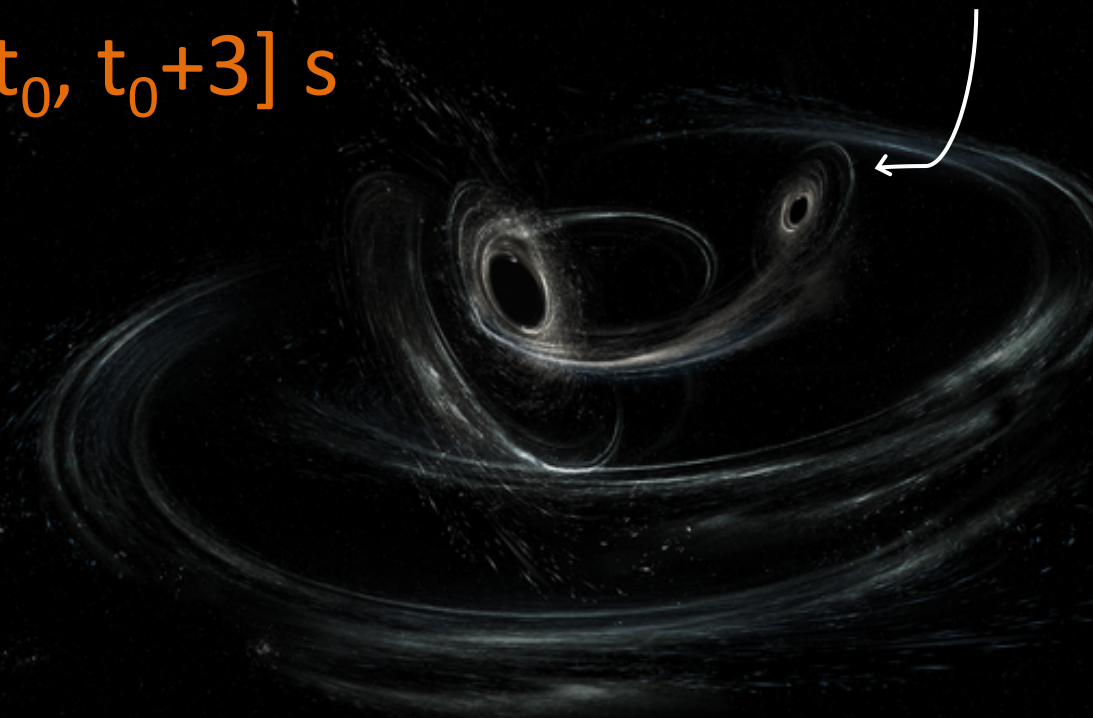
Did we find GeV neutrinos?

- 3 BNS + 1NSBH mergers

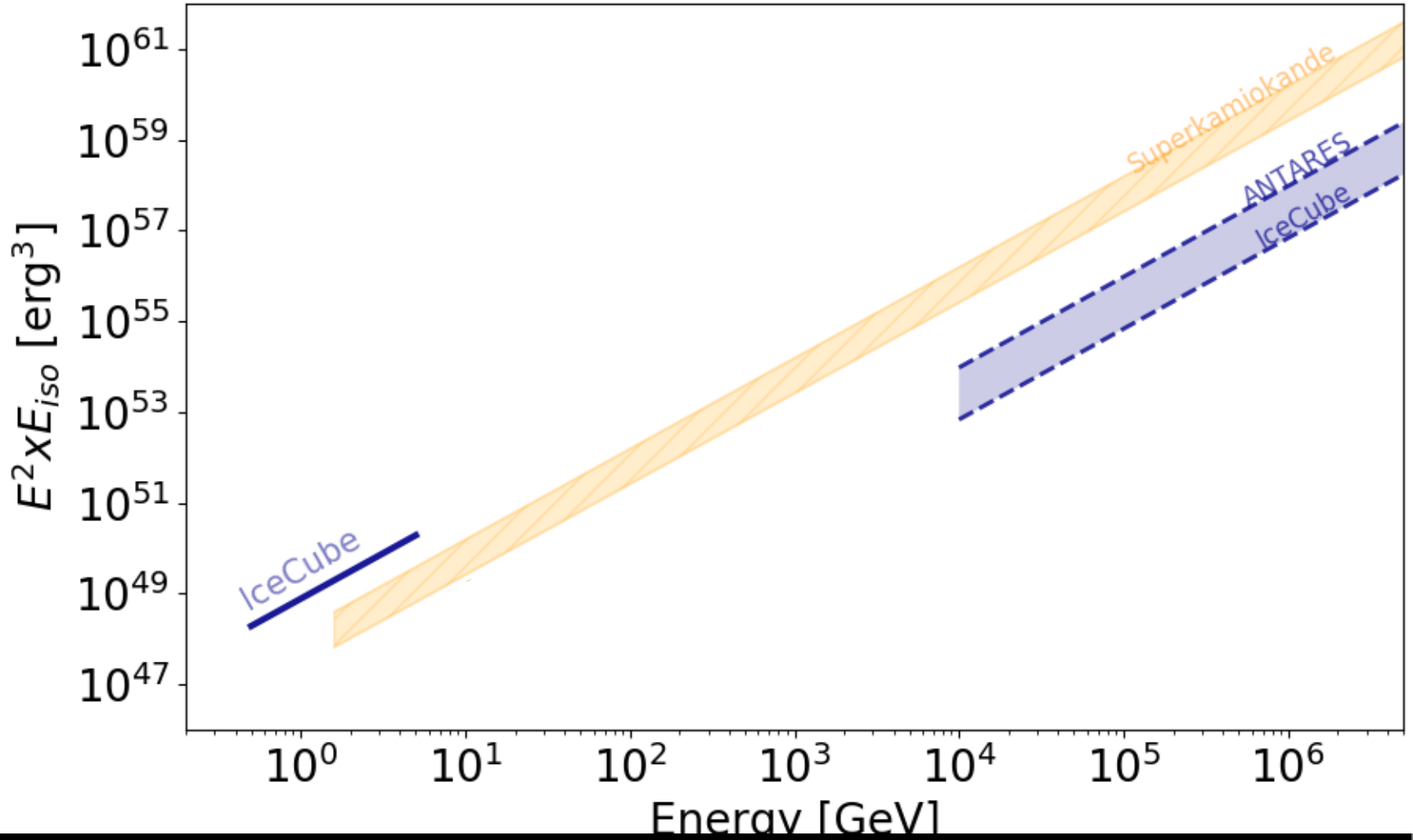
  Search for a prompt signal

  $[t_0, t_0+3]$ s

"Spiraling Black Holes"
(Artist's conception)



Comparison with other neutrino searches



Did we find GeV neutrinos?

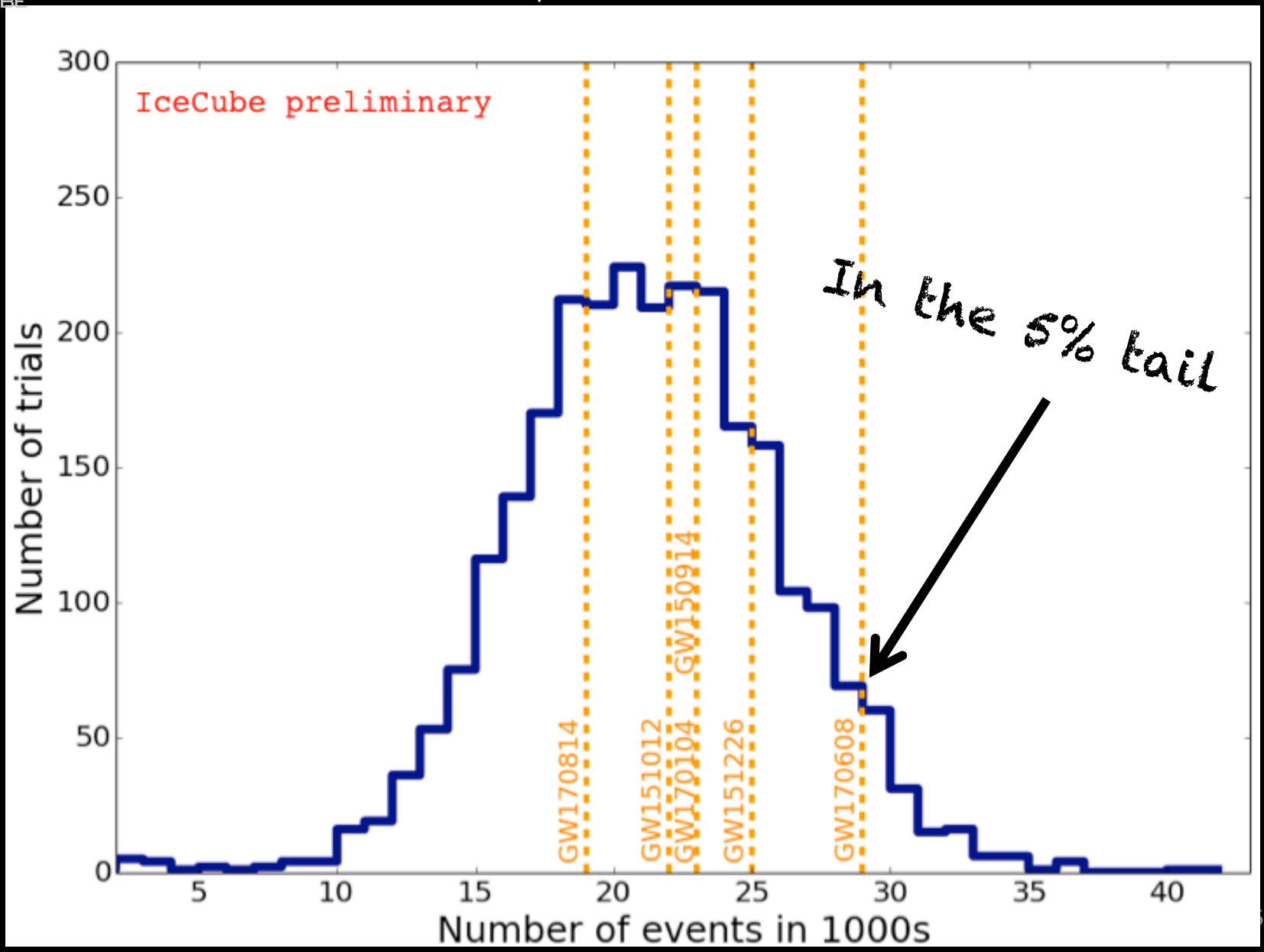
"Spiraling Black Holes"
(Artist's conception)

- 6 BBH mergers

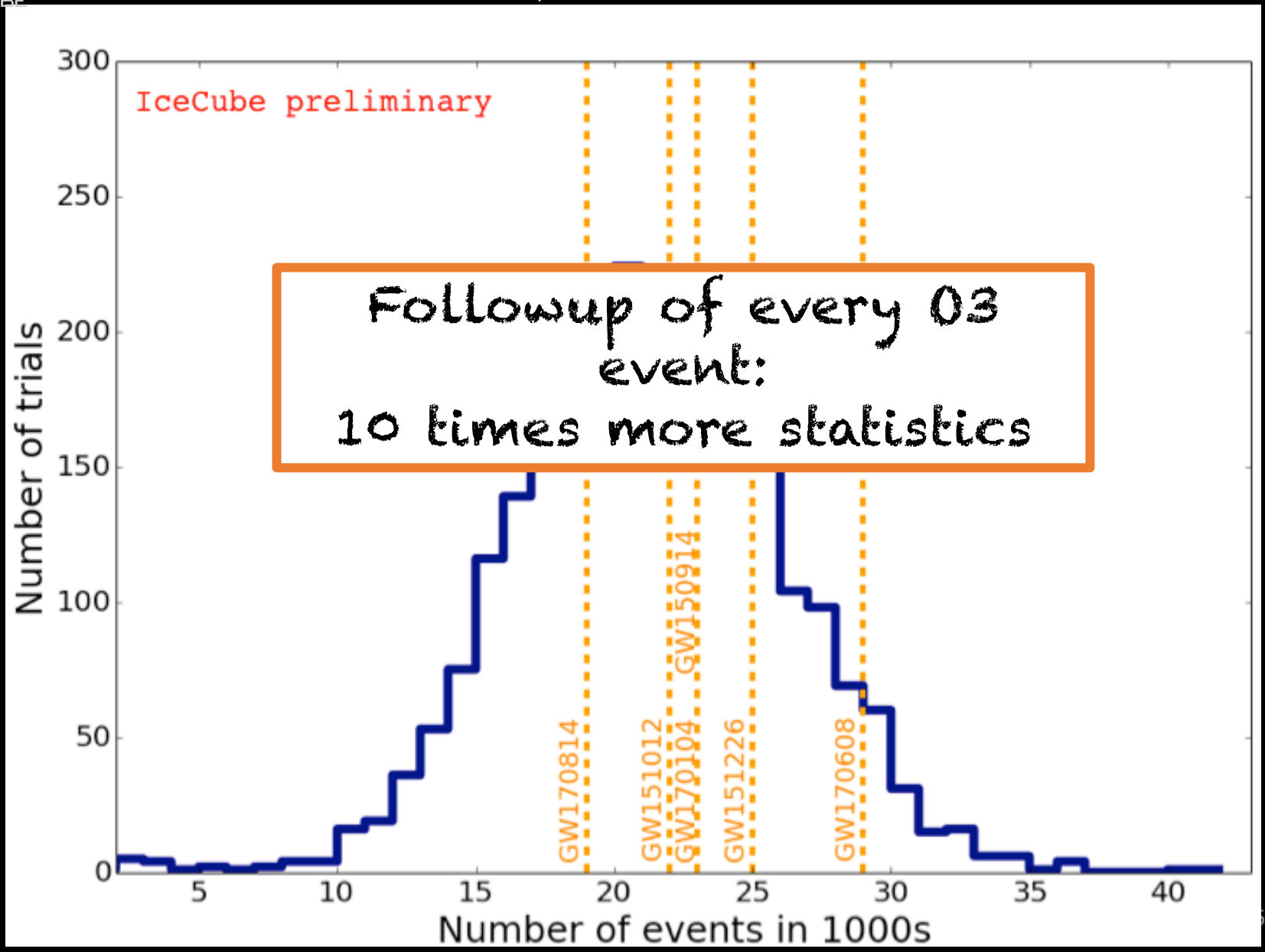
  Search in an extended time windows

  $[t_0\text{-}500, t_0\text{+}500]$ s

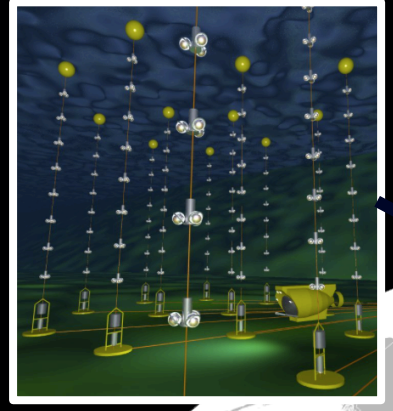
Did we find GeV neutrinos?

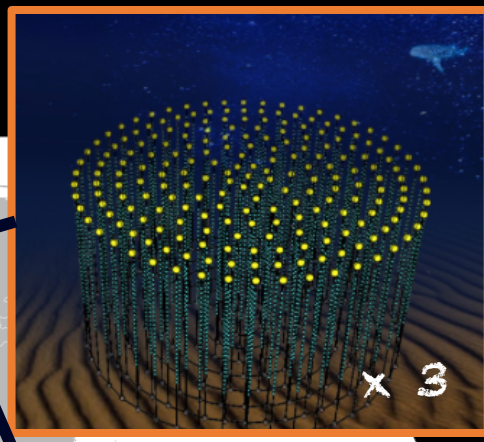


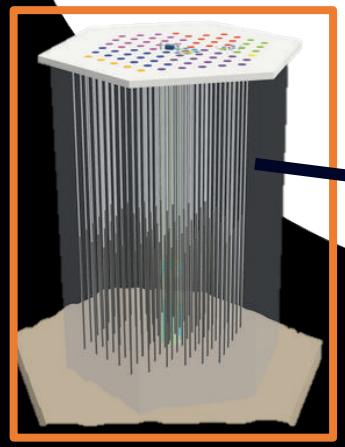
Did we find GeV neutrinos?

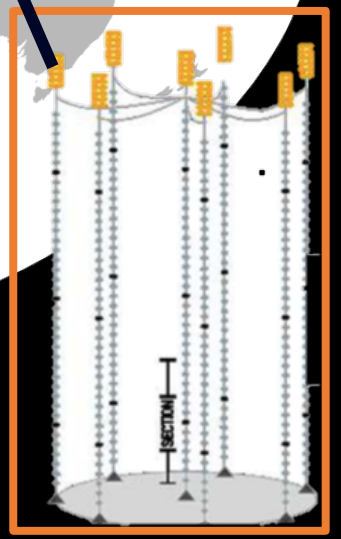


3. What's next?







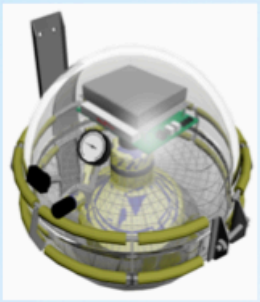


GNN
The Global Neutrino Network

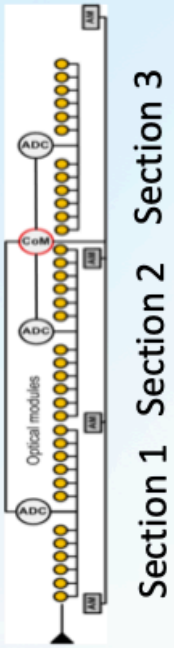
x 8

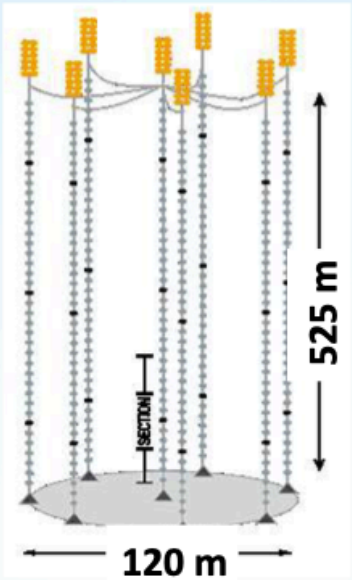
Non-exhaustive list

Baikal-GVD: phase 1 (2020-2021)

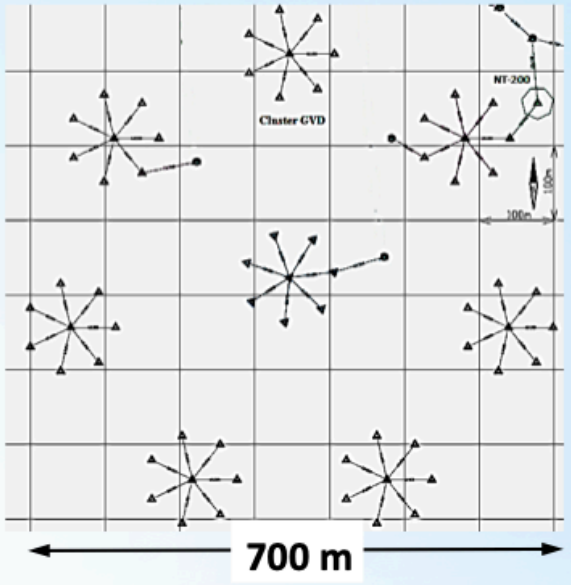


Optical module
PMT: R7081-100





Cluster: 8 strings



GVD-1: 8 clusters

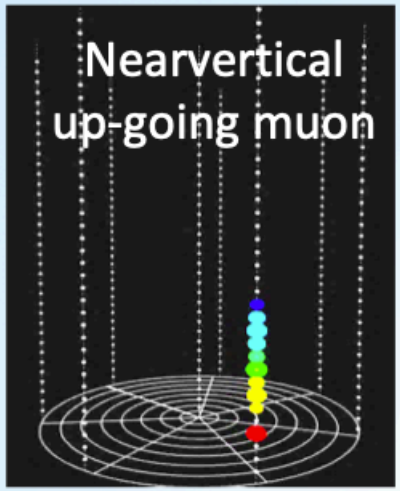
GVD-1	
OMs	2304
Clusters (8 Strings)	8
Depths, m	750 – 1275
Eff. Volume	0.4 km^3

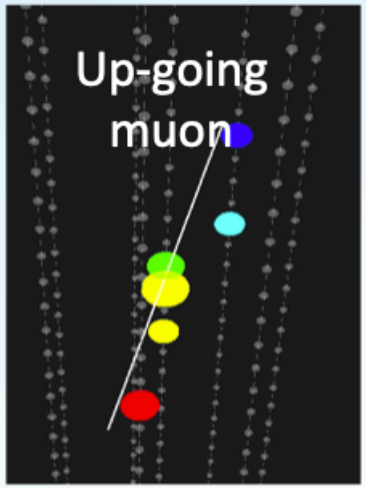
Directional resolution	Energy resolution
Cascades: 4.5°	$\delta(E/E_{sh}) \sim 0.30$
Muons: 0.25° - 0.5°	$\delta(\lg E) \sim 0.4$

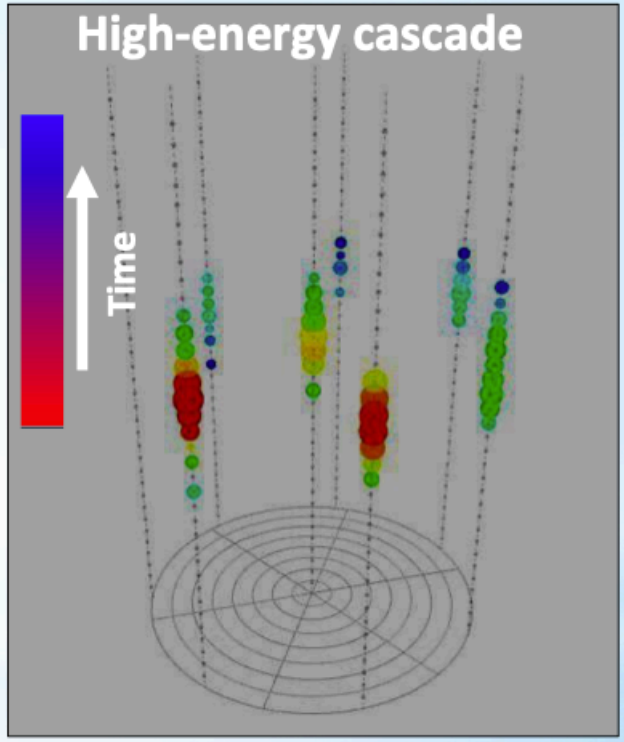
Detector response

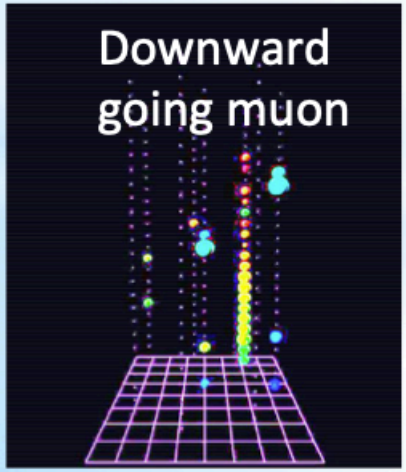
Neutrino signals

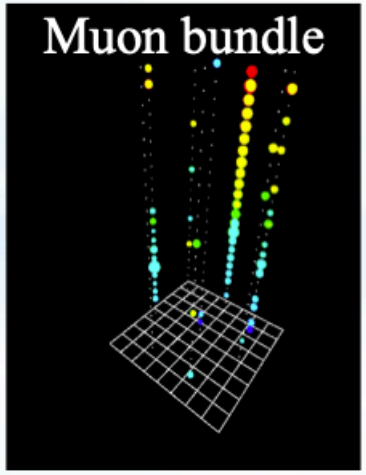
Background









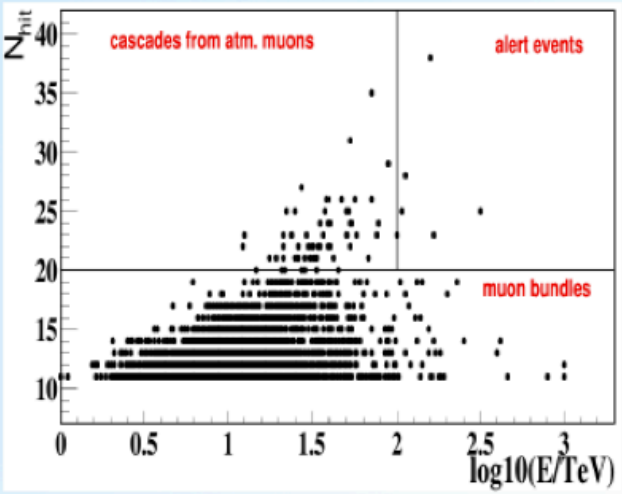


O. Suvorova, Town Hall KM3NeT meeting

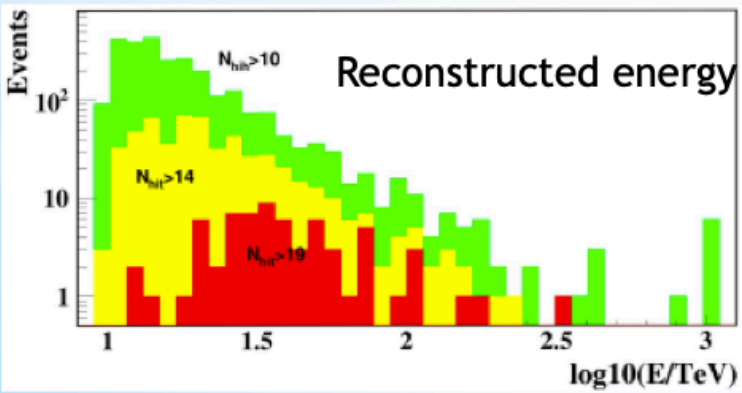
Selected cascades induced in GVD: 2016, 2018, 2019

(Preliminary)

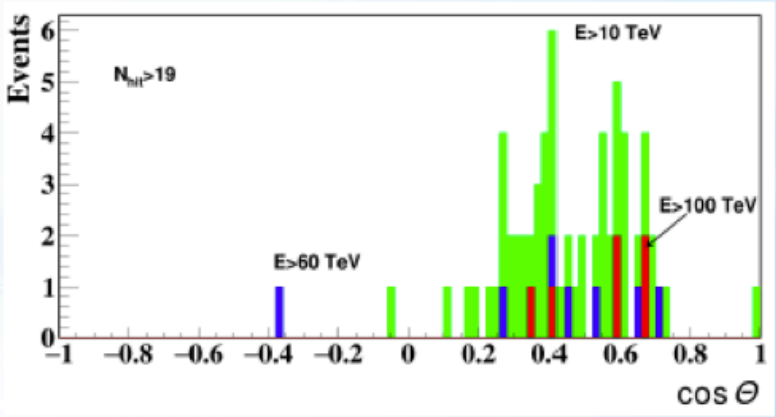
2704 selected cascades with Nhit>10&&E>10TeV:



	> 10 TeV	> 60 TeV	> 100 TeV
> 10 OM	2704	547	66
> 14 OM	111	36	13
> 19 OM	50	16	6



Zenith angle distribution **Nhit>19**



up-going down-going

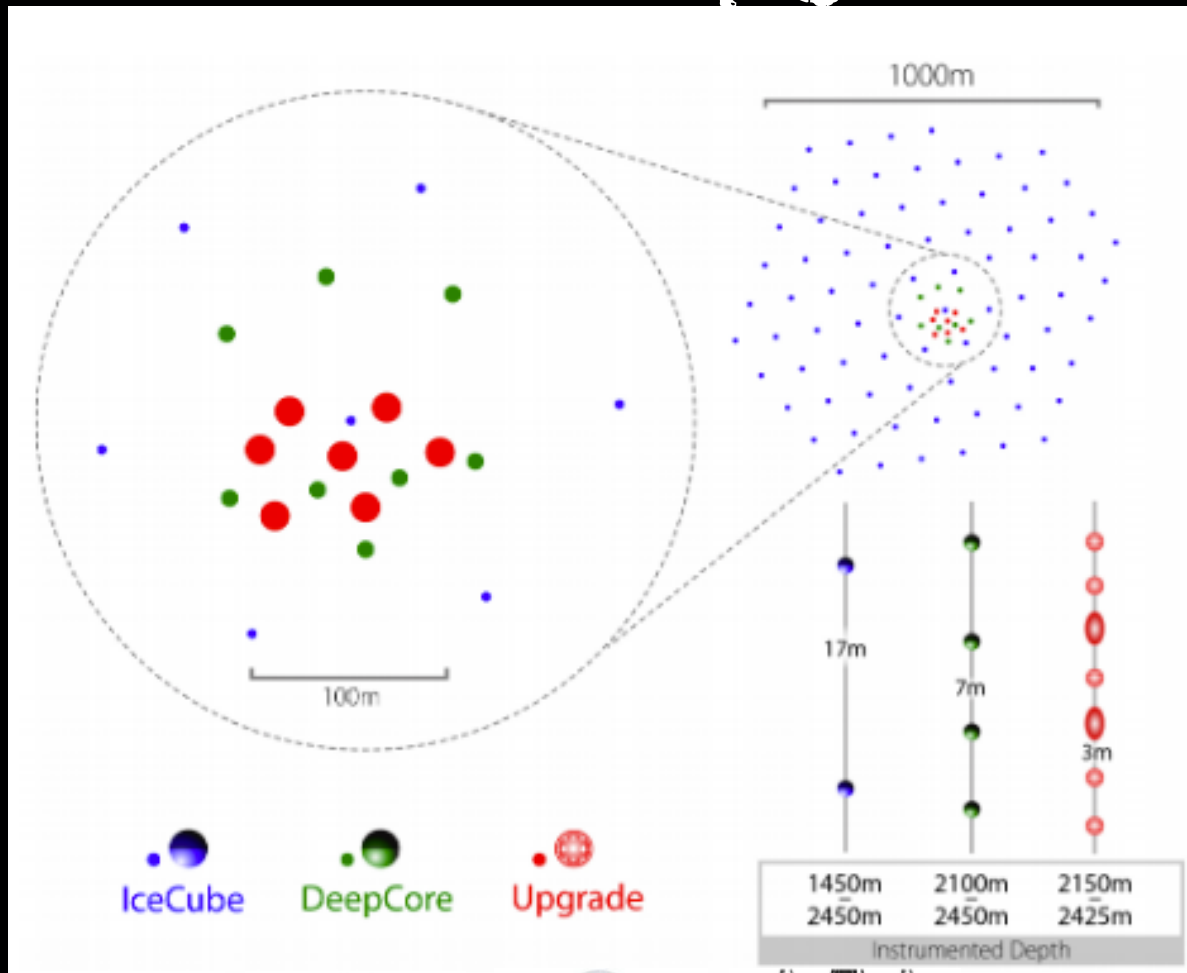
The Upgrade

- 7 new strings of modules
  - Interstring spacing 20m (DC 70m)
  - InterDOM spacing 2.4m (DC 7m)

- Neutrino physics:
  - oscillations
  - atmospheric tau neutrino appearance

- Astrophysics:

precise calibration of ice optical properties and DOM response -> apply to 10-years of existing data



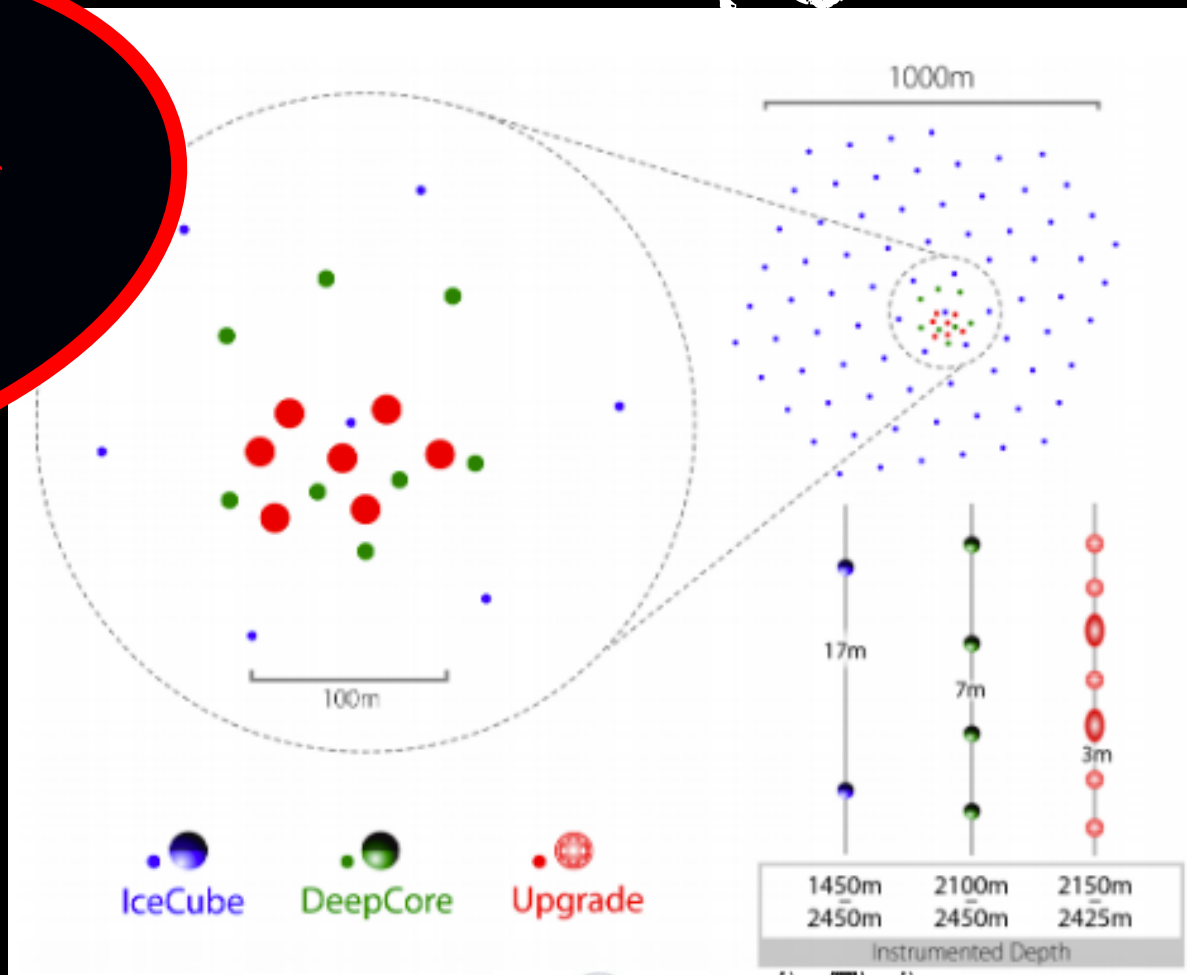
The Upgrade

- Deployment planned for 2022– 2023

- Neutrino physics:
  - oscillations
  - atmospheric tau neutrino appearance

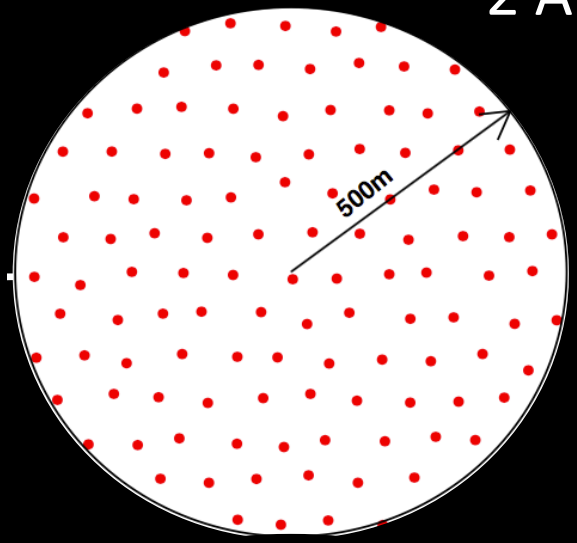
- Astrophysics:

precise calibration of ice optical properties and DOM response -> apply to 10-years of existing data

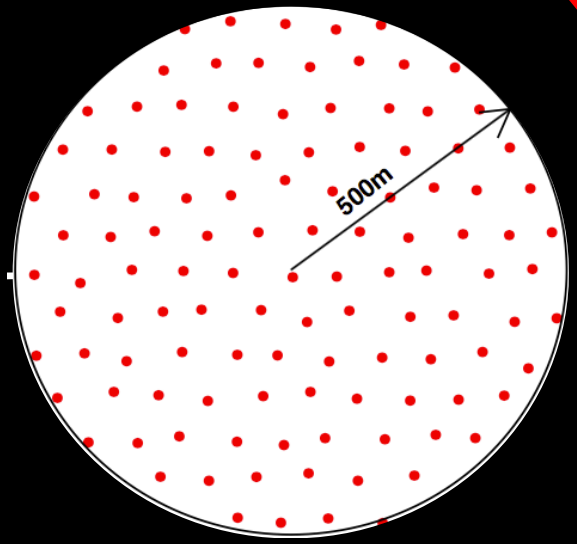


KM3NeT

2 ARCA blocks
+ ORCA



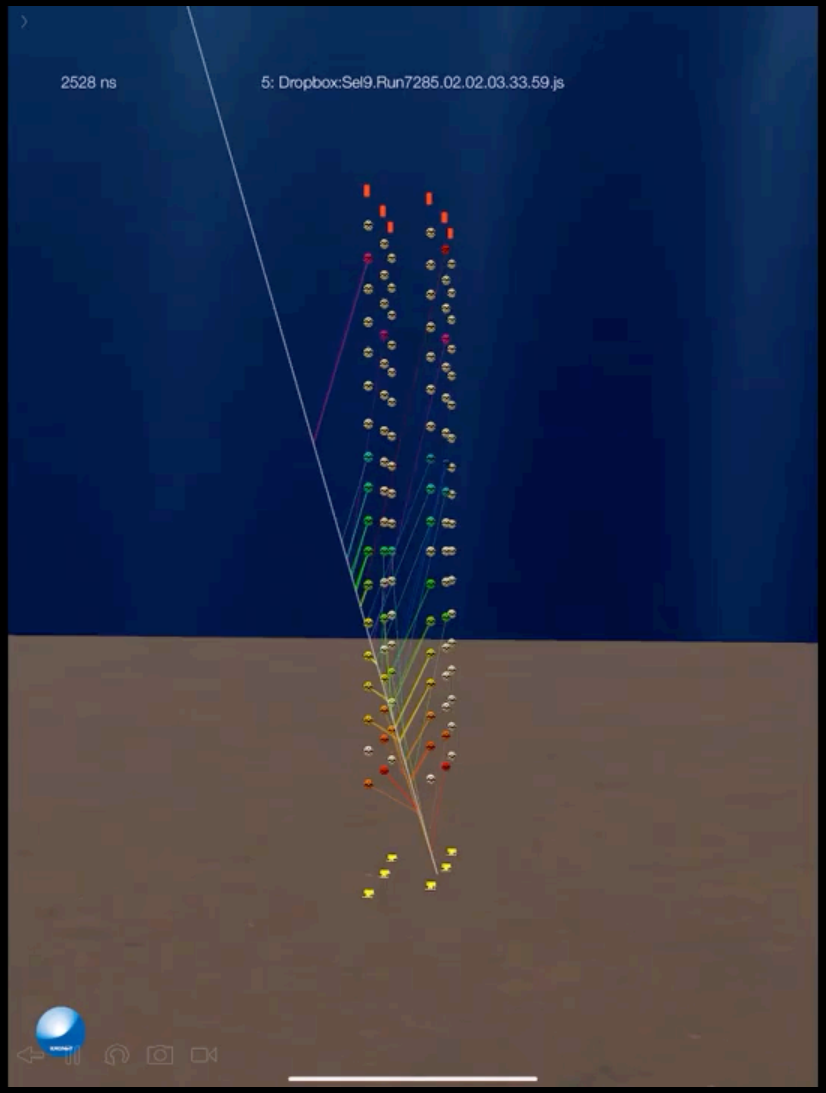
Astroparticle Research with
Cosmics in the Abyss



- 3 x 115 Detector Units
  InterDU spacing: 20m or 90m
- 18 DOMs
  Interdom spacing: 9m or 36m

Currently 1 ARCA + 6 ORCA DUs taking data

KM3NeT



ORCA - 6 DUs

Neutrino candidates

Real data!

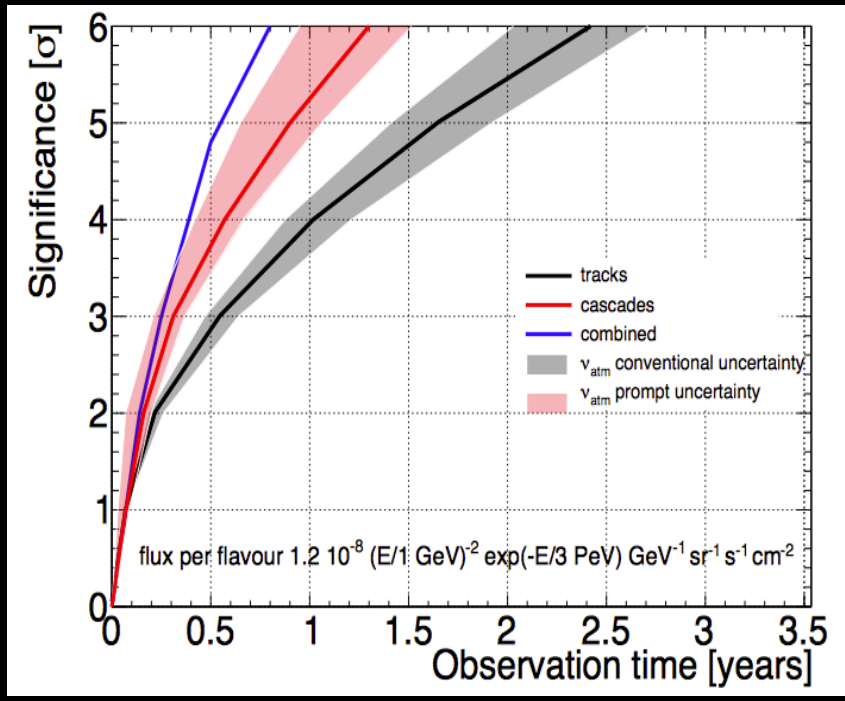
KM3NeT

ARCA:

- ν_μ angular resolution < 0.1° for E_ν> 100 TeV
- ν_e angular resolution < 2° and energy resolution ~ 5%

- Diffuse flux combining
  tracks and cascades

-> IceCube flux equivalent at 5σ in 6 months

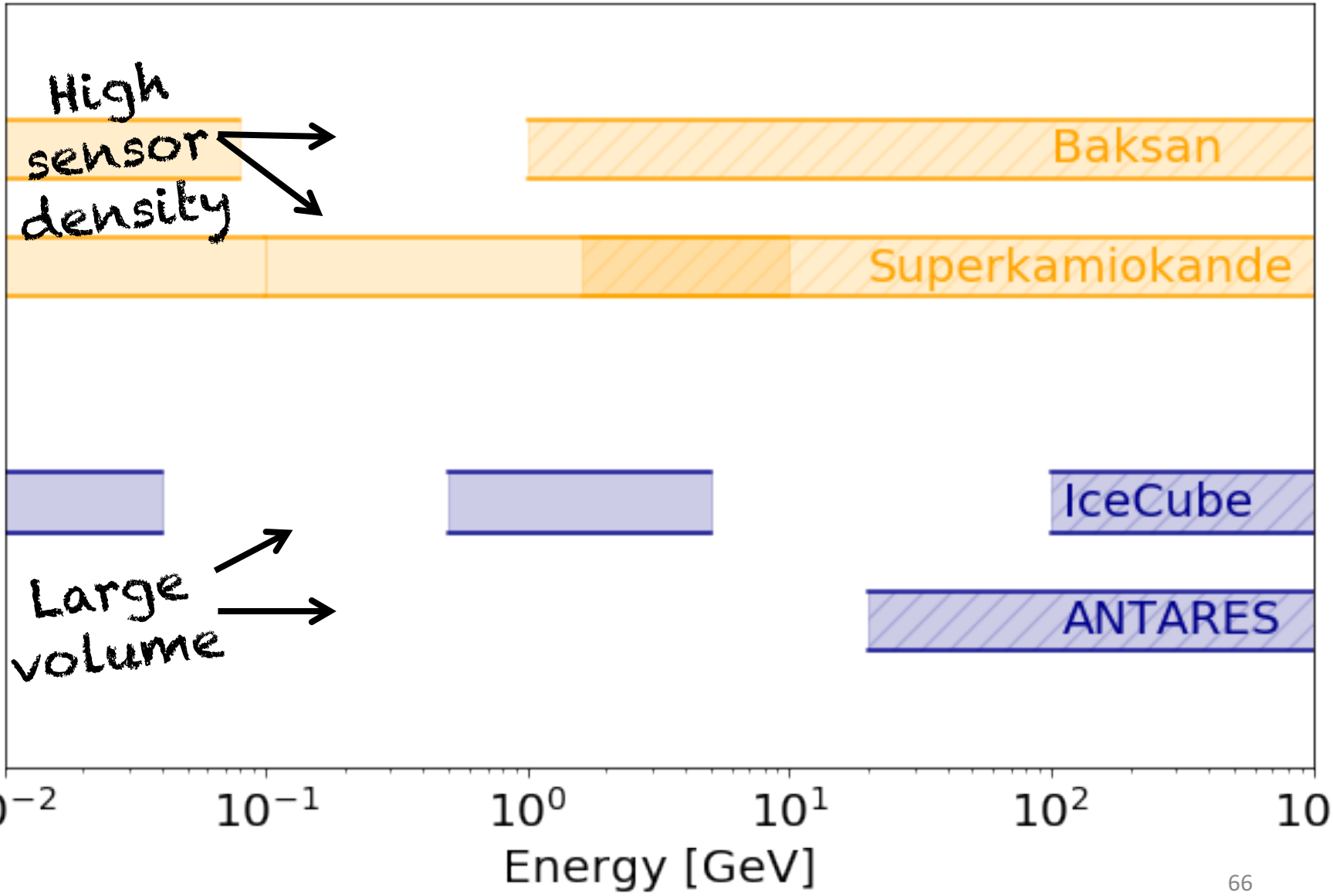


ORCA:

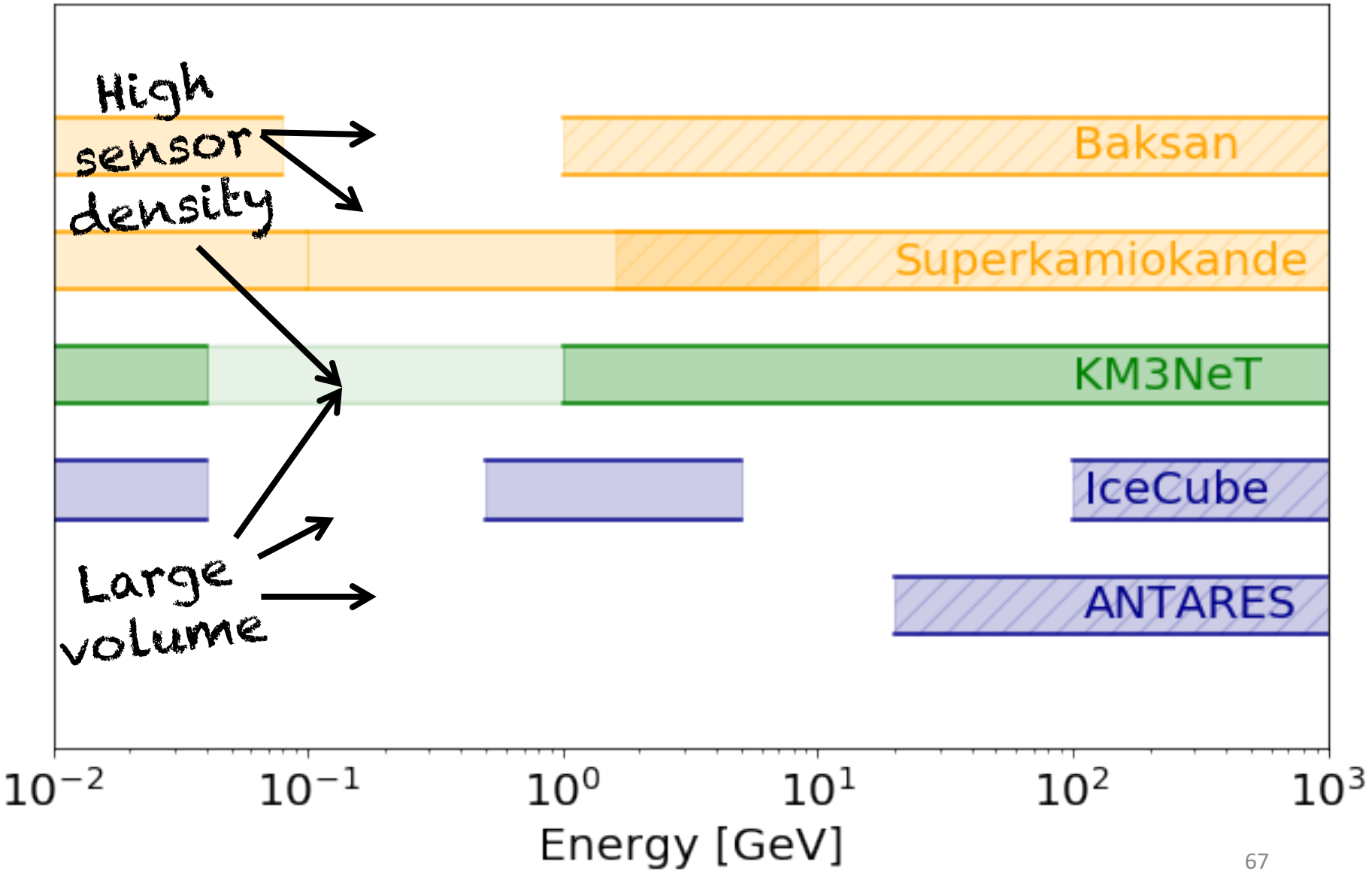
- Multi-messenger astronomy down to 1 GeV

State of the Art

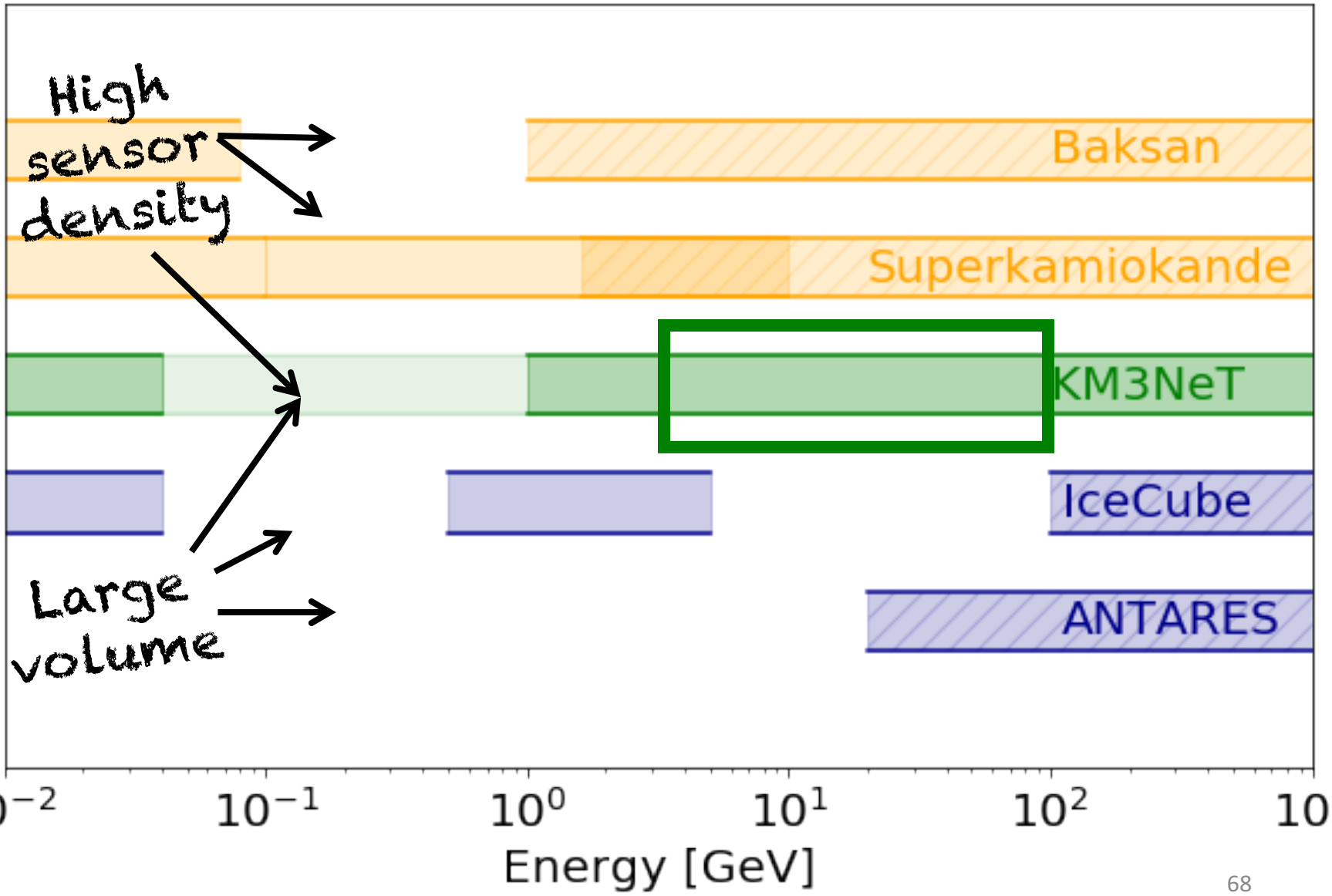
Follow up of GW170817



State of the Art



State of the Art



Existing event selection between 3-100 GeV

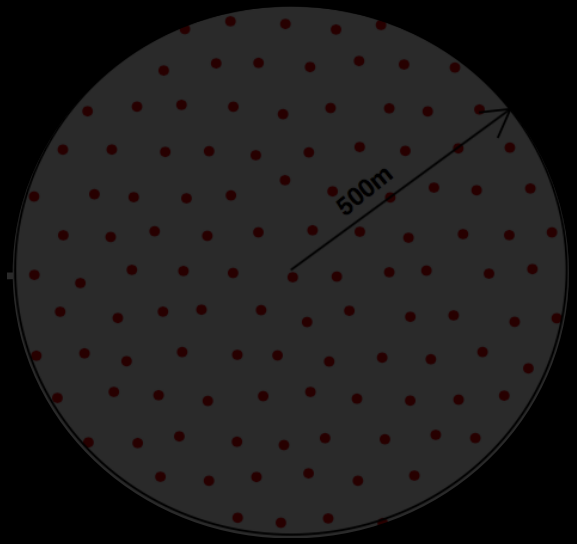
Step 1: Events are required to

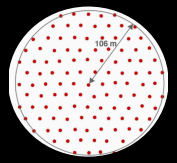
(a) pass a pre-selection based on reconstruction quality

(b) have a reconstructed vertex contained inside or close to the instrumented volume

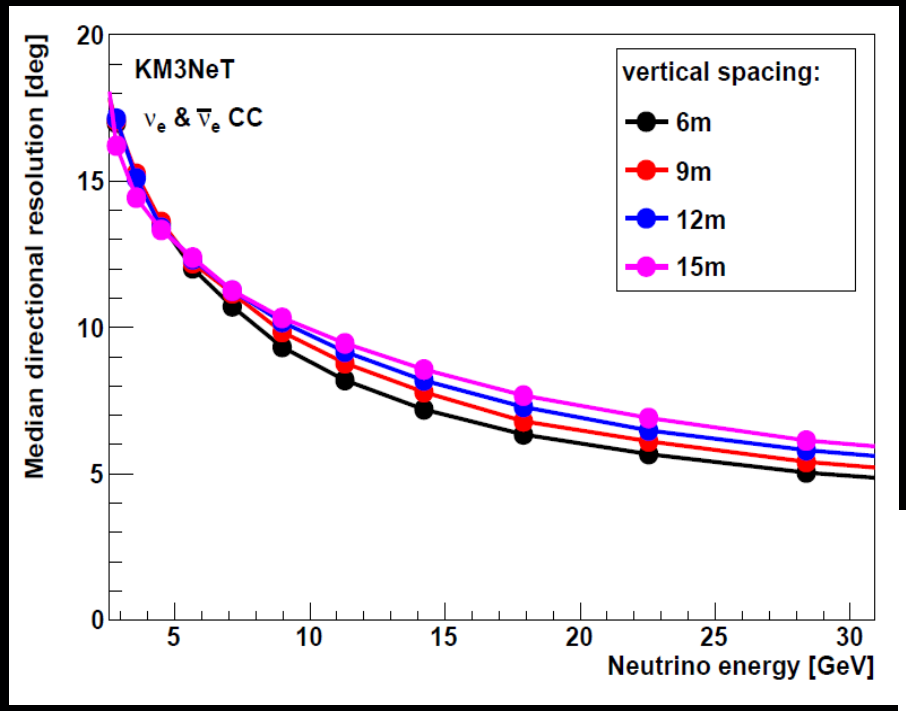
(c) be reconstructed as upward traveling in the detector

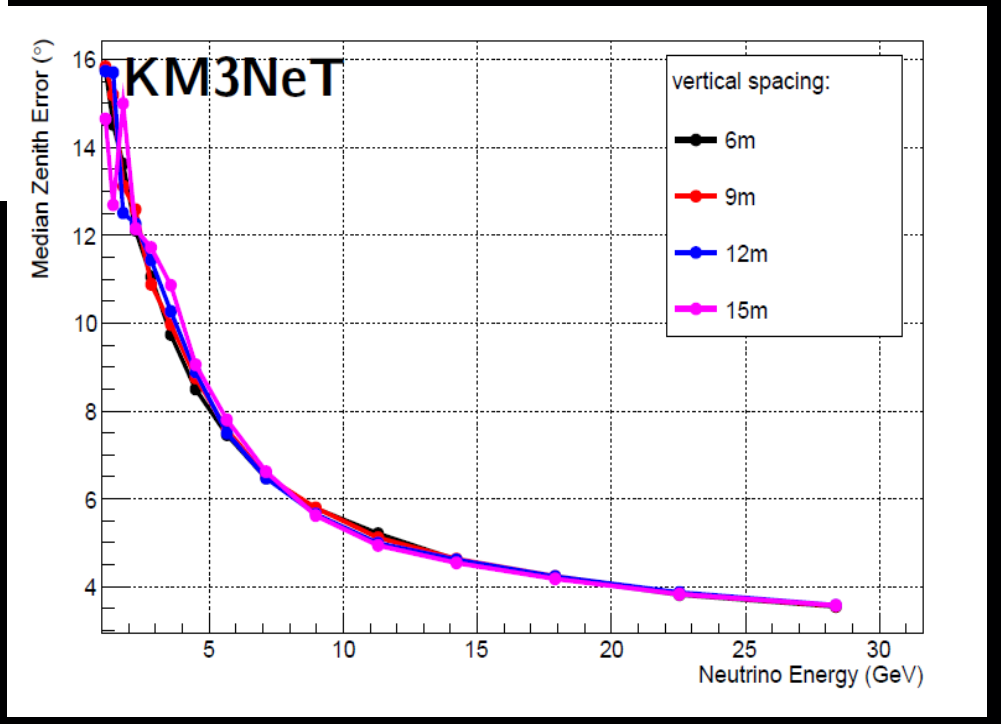
Good reconstruction performance + suppression of part of atmospheric muons and pure noise events





Which resolution?





Existing event selection between 3-100 GeV

Step 1: Events are required to

(a) pass a pre-selection based on reconstruction quality

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Good reconstruction performance + suppression of part of atmospheric muons and pure noise events

Step 2: PID Optimization for an E^{-2} flux

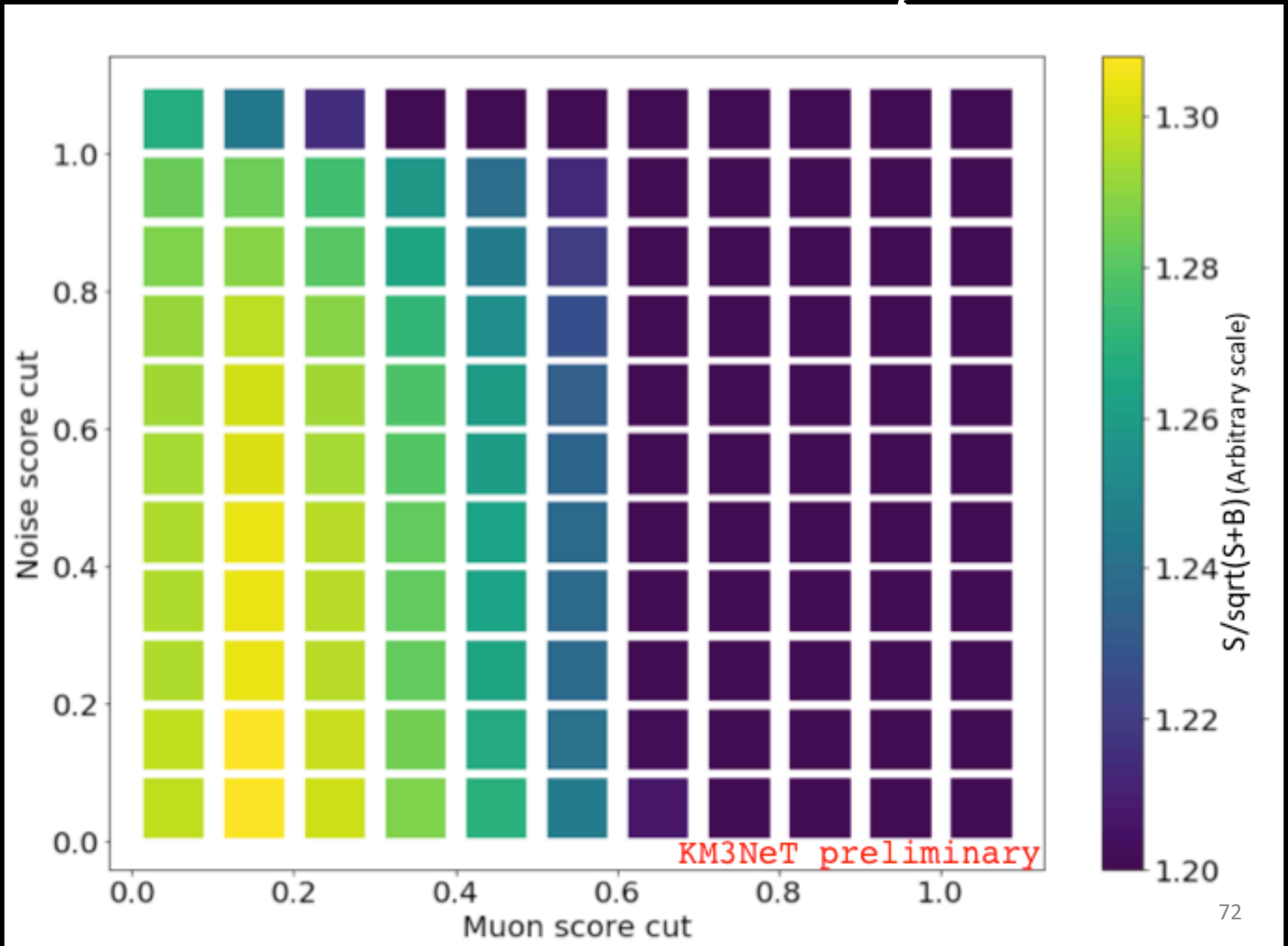
3 different scores, with values between 0 and 1:

(a) A track-score used to differentiate tracks from showers

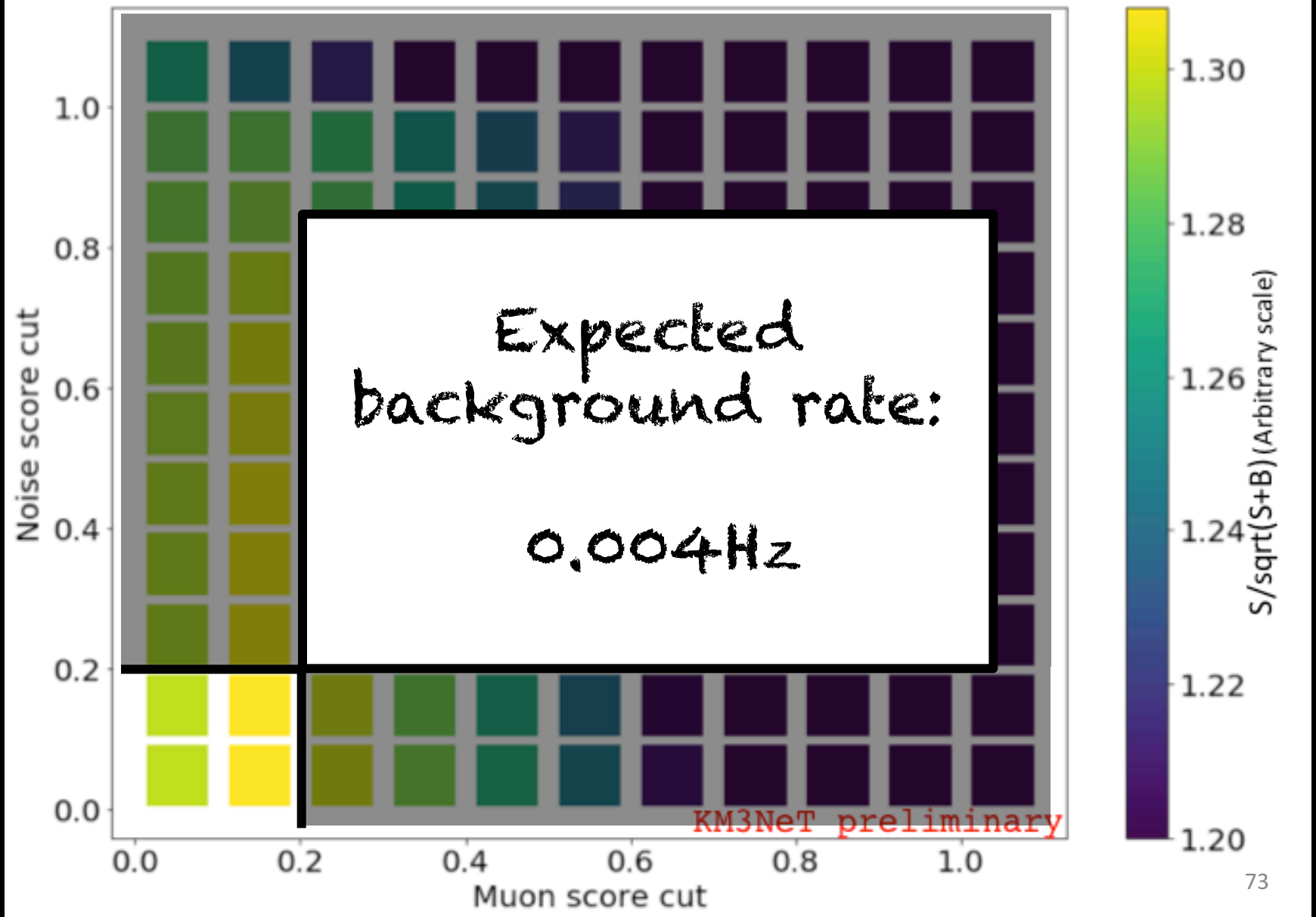
(b) A muon-score, dedicated to tag atmospheric muon candidates

(c) A noise-score, which helps reducing the pure noise event

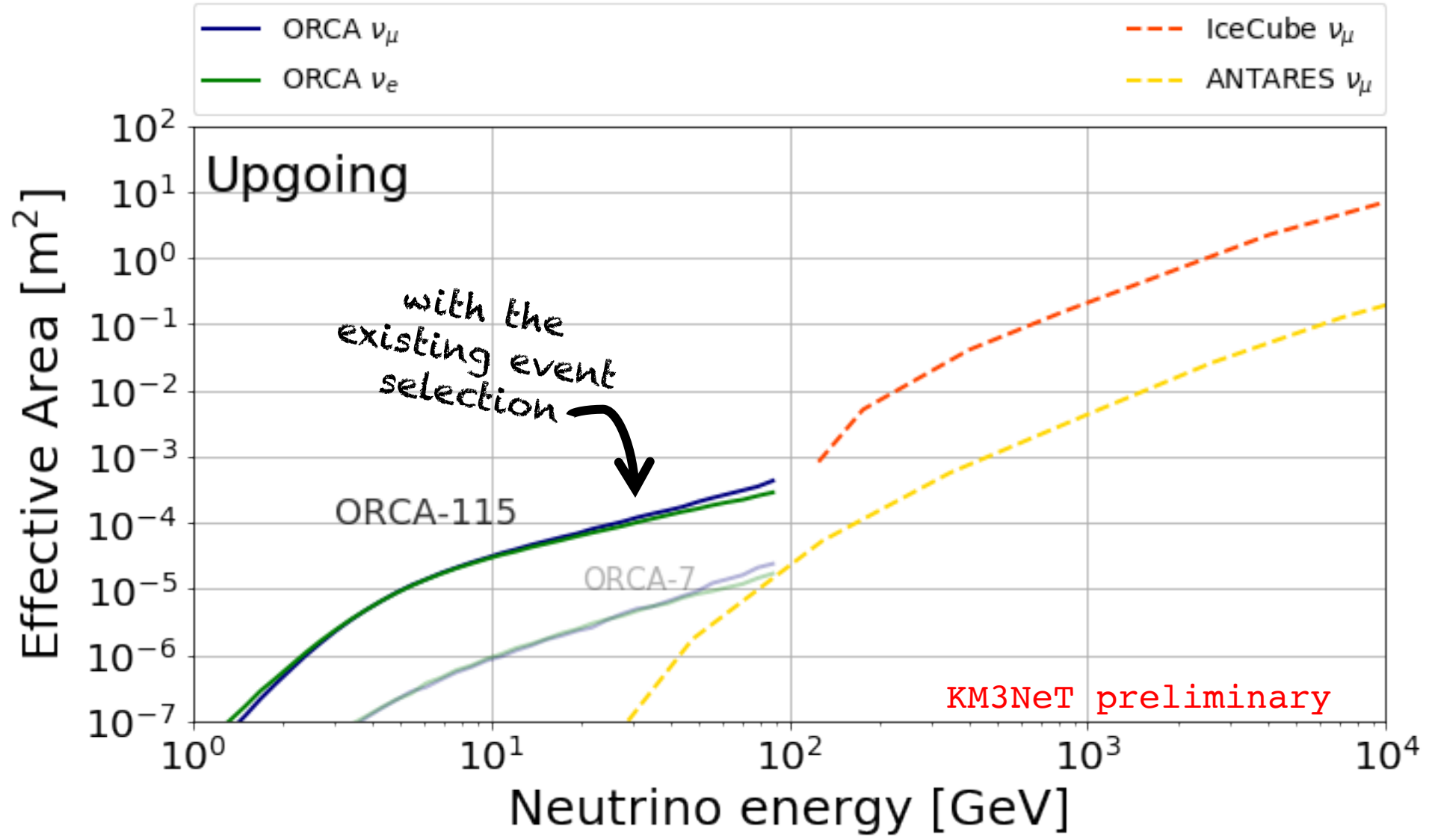
PID optimization



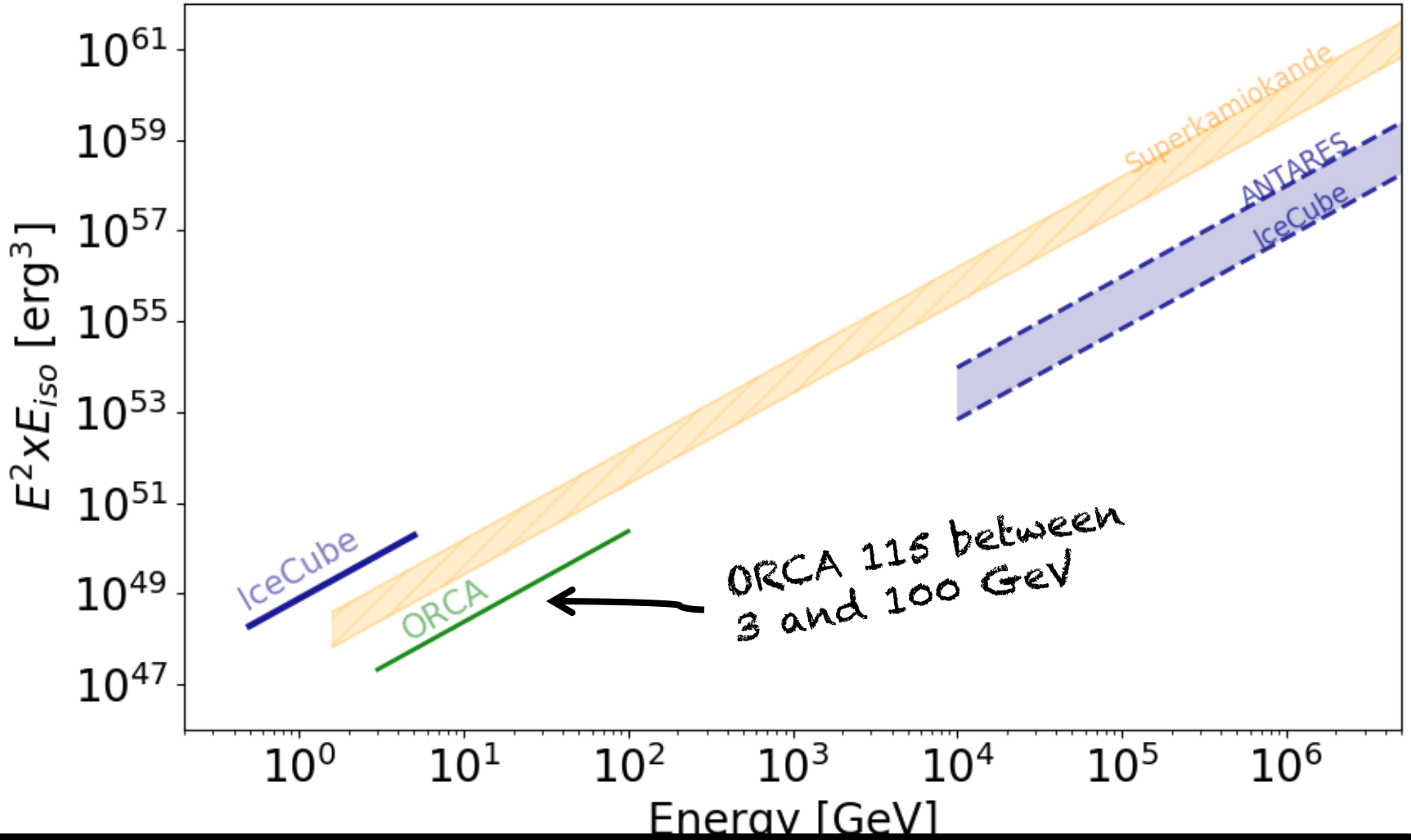
PID optimization



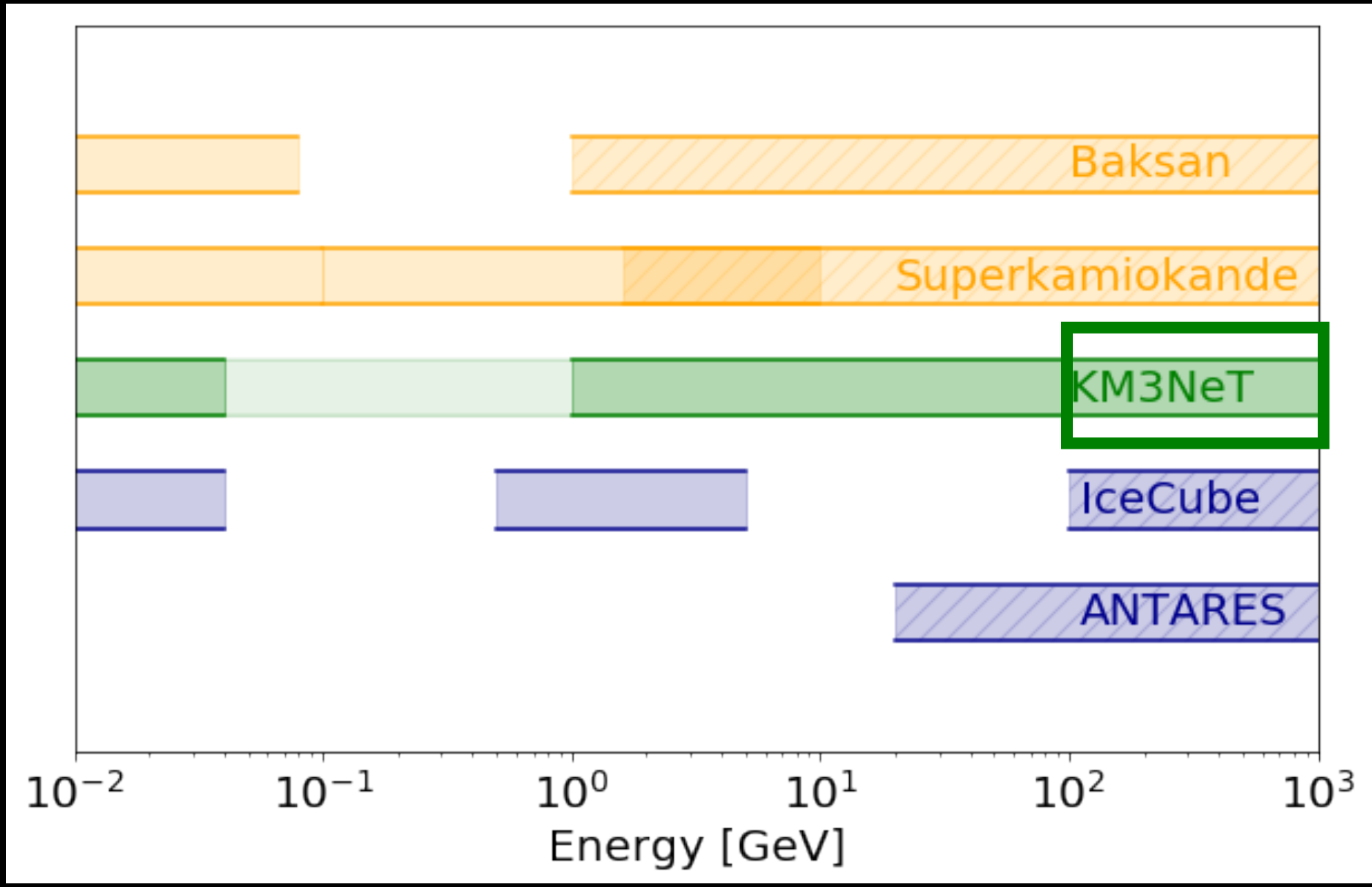
Effective area comparison



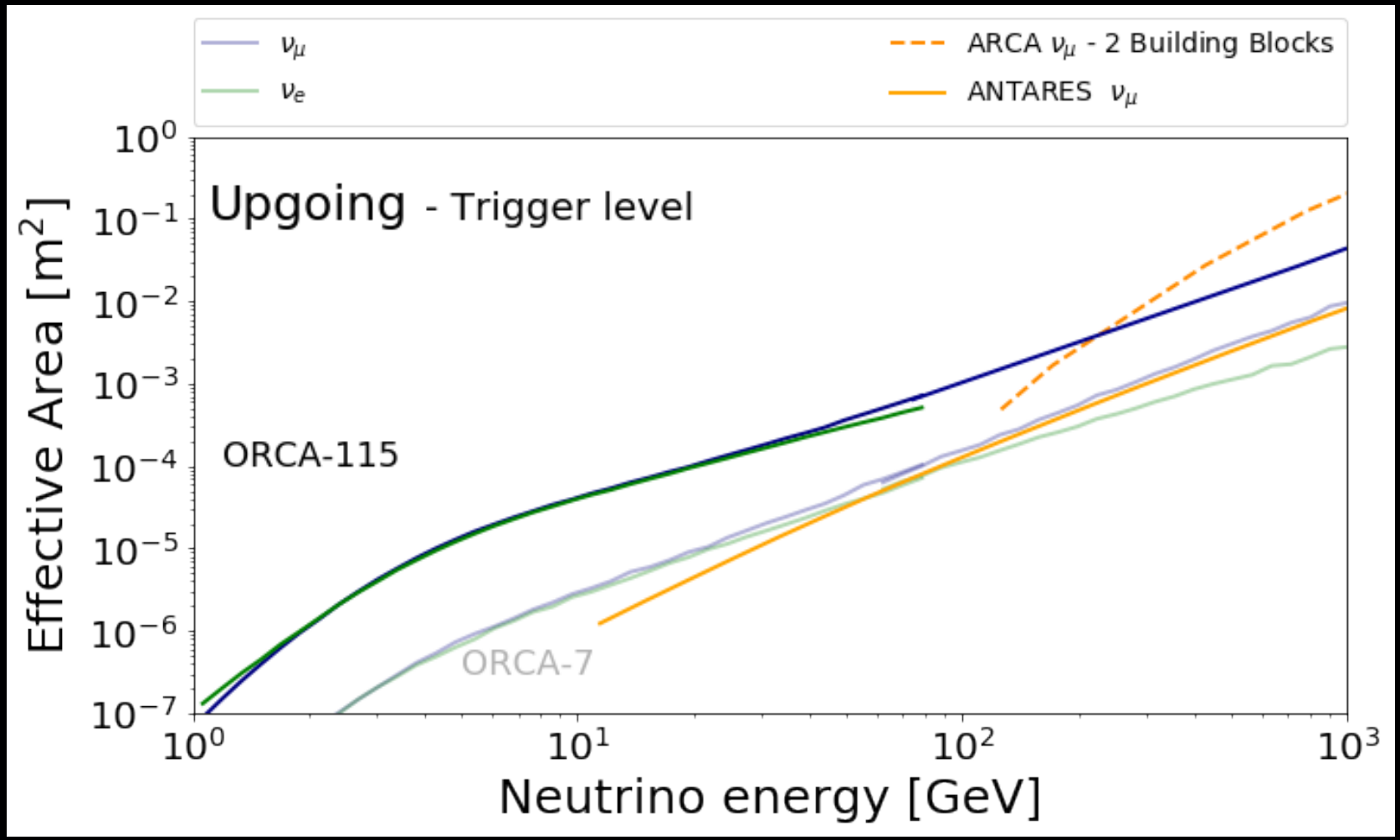
Sensitivity to GW170817



Can we do (even) better?



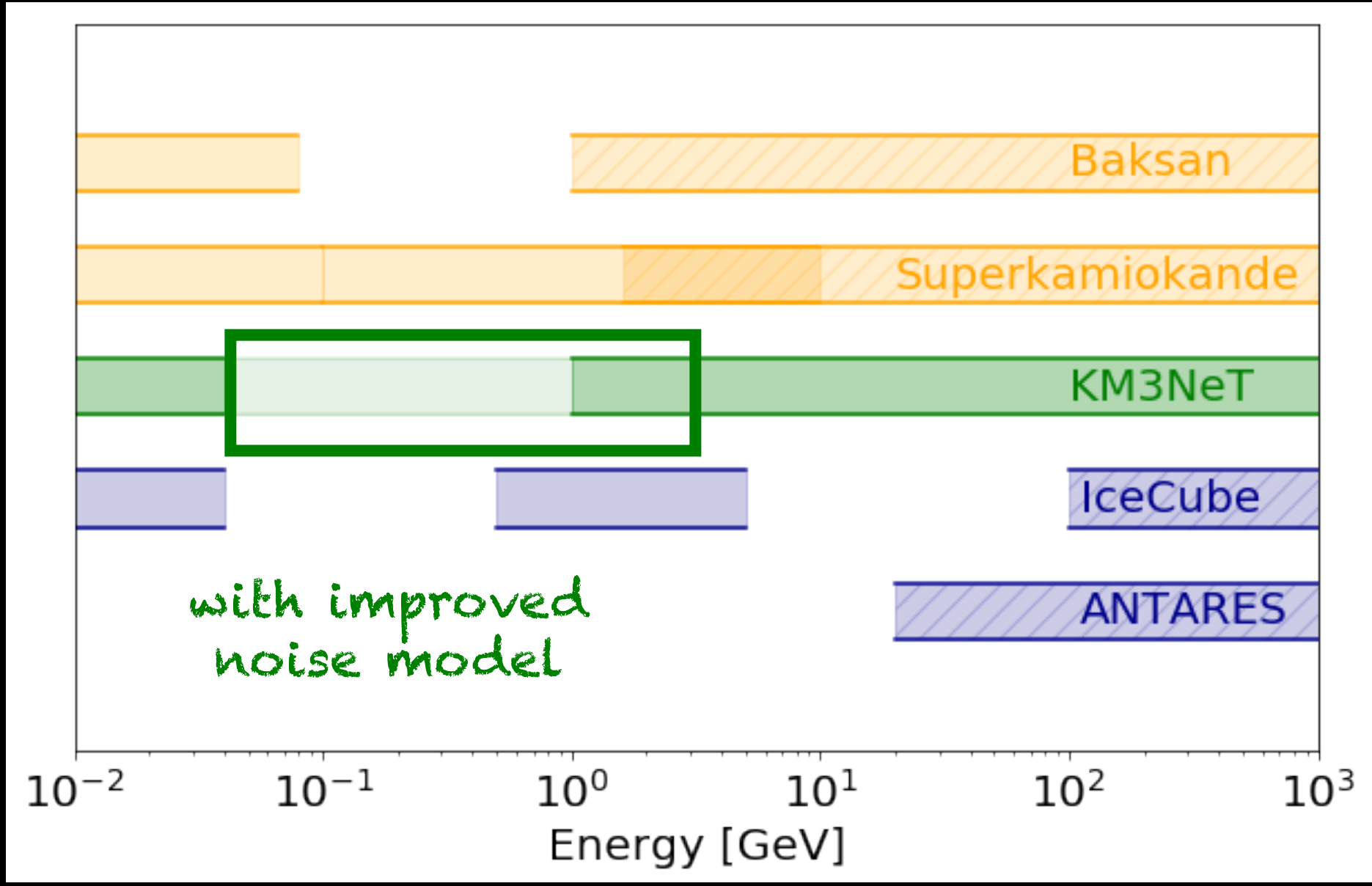
KM3NeT



ORCA:

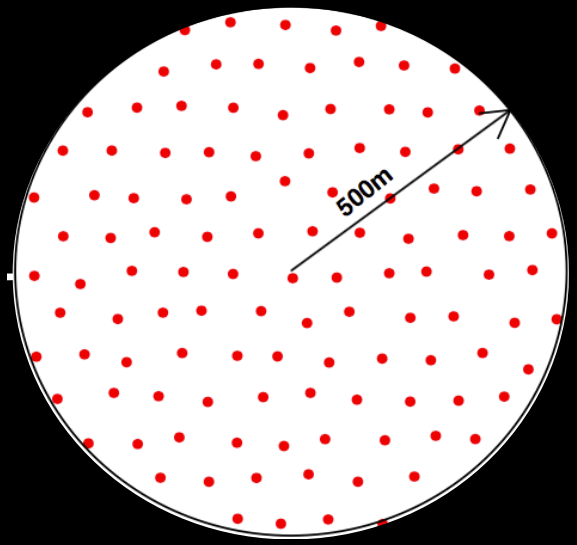
- Multi-messenger astronomy down to 1 GeV
- Opportunity of e.g., GW follow-up with reduced configuration

Can we do (even) better?

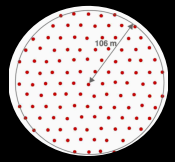


Single-DOM based analysis

with improved noise model developed using unsupervised ML



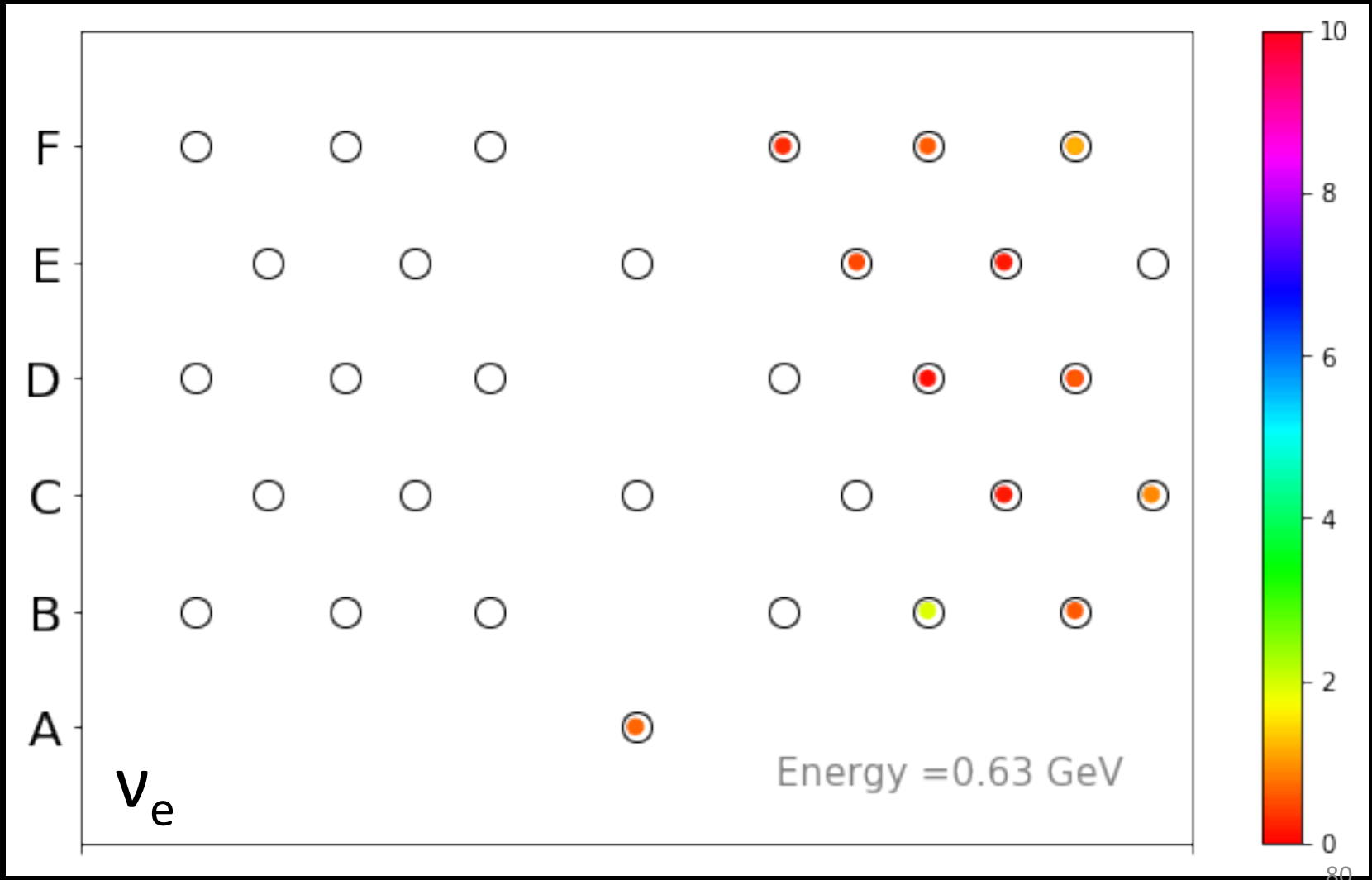
ARCA



ORCA

Single-DOM based analysis

Search for an increase in the event rate



Take-home message

- High-energy neutrino astronomy is a young field of research but already it counts already several breakthroughs
- Promising future with the next generation being deployed
- The sub-TeV range will bring complementary information for source identification/characterization
- KM3NeT will become a leader in the sub-TeV range

Draw me a neutrino

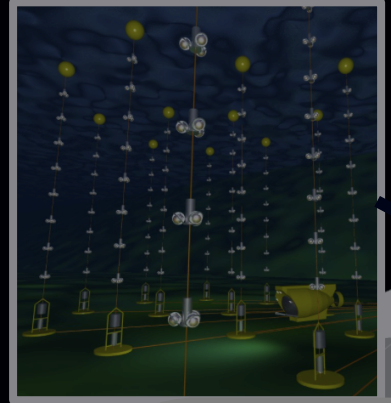
- **When?**
  - Deadline to send the drawings: March 15th
  - Announcement of the winners: April-May 2020
  - Exhibition at the Naples National Archeological Museum: May 2020
- Do not hesitate to participate!

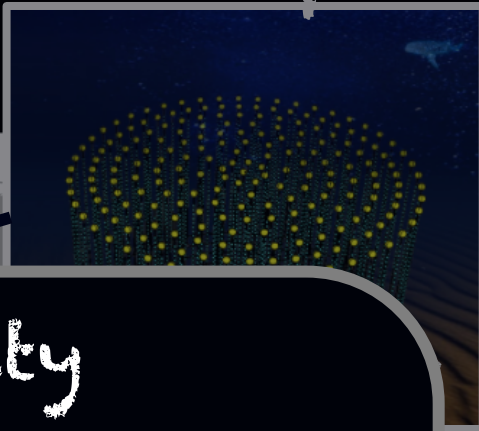
NEW: World contest open to participants worldwide!

http://wos.ba.infn.it

Thanks!

Neutrino telescopes



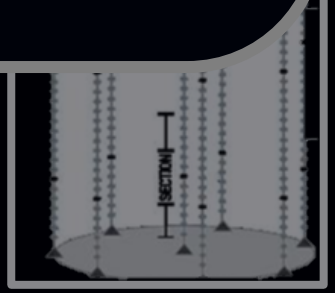


Instrumentation density

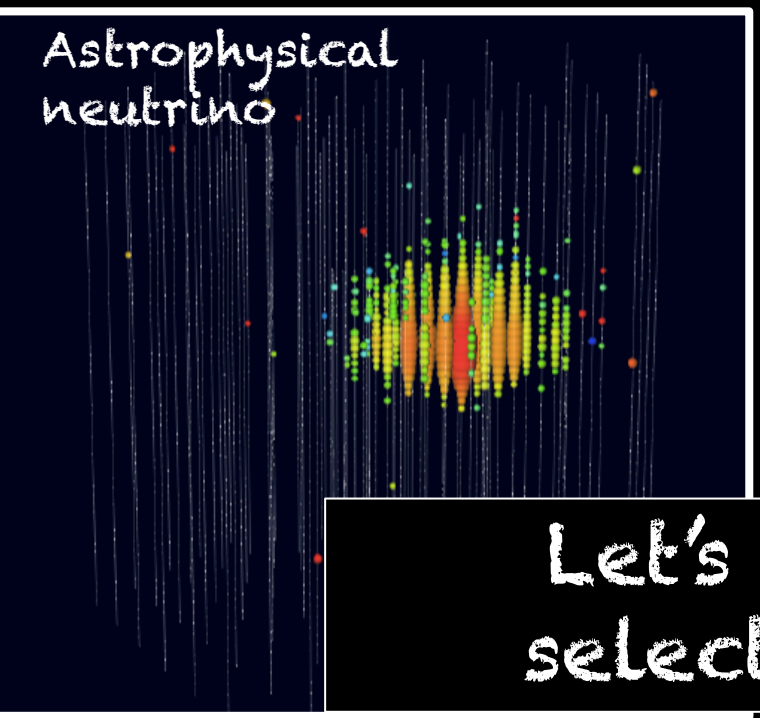
Particle detectors (e.g., pixel detector in CMS)	~ 1k modules/m^2
HE neutrino detectors (e.g., IceCube)	~ 5k sensors/km^3

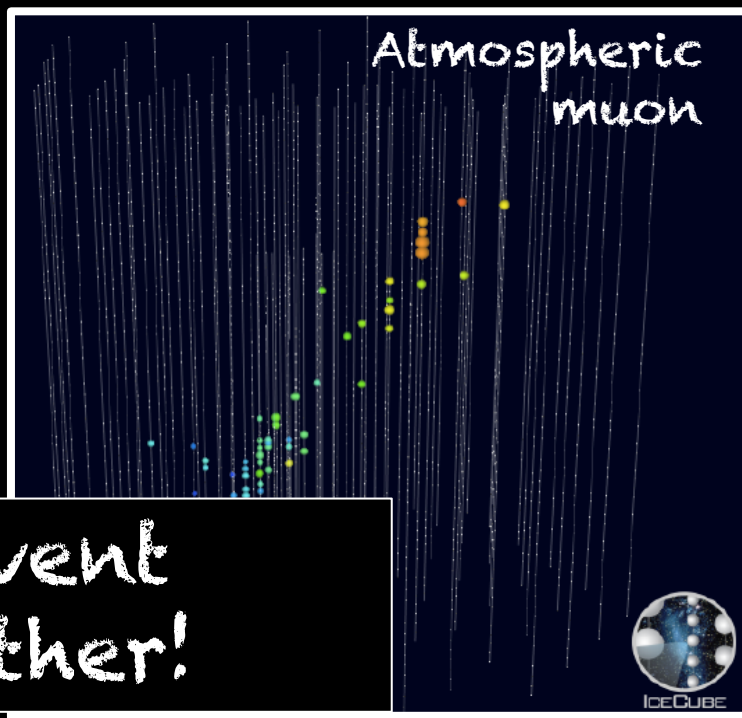
GNN
The Global Neutrino Network

x 8

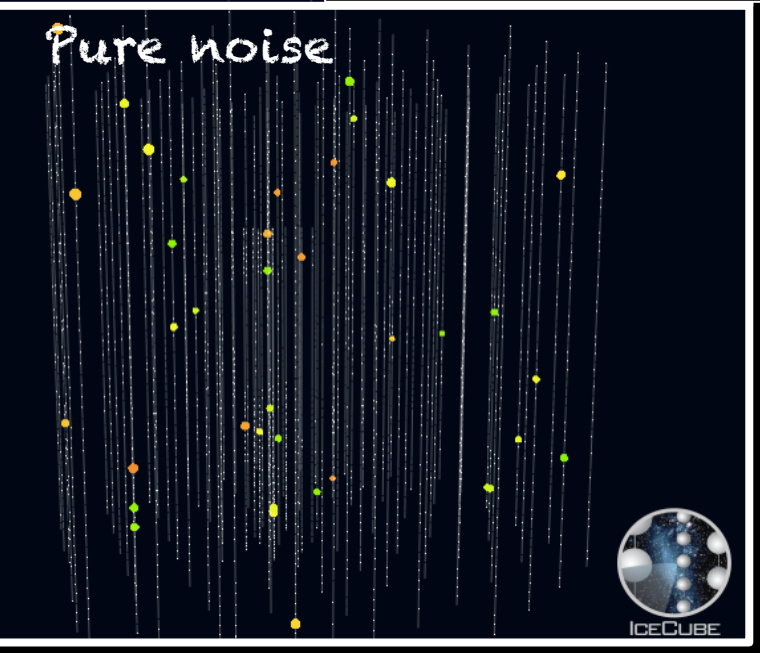


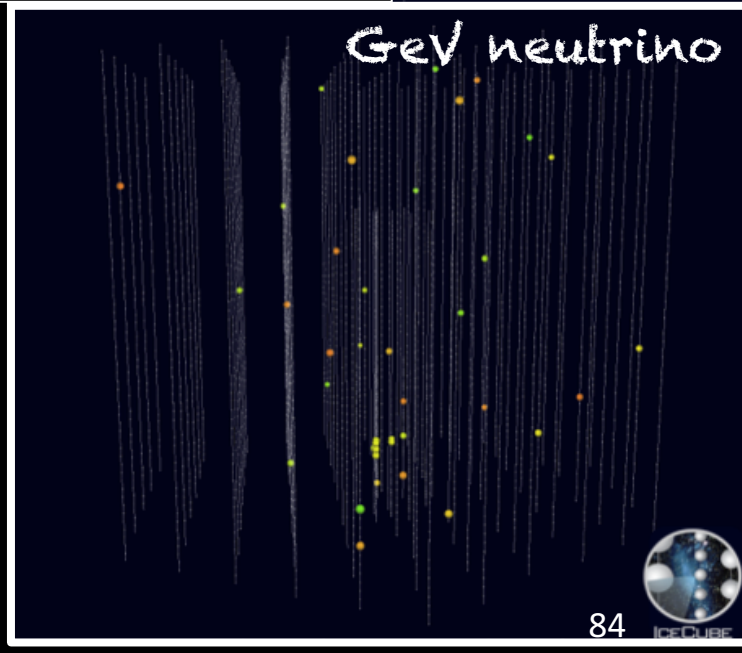
Non-exhaustive list

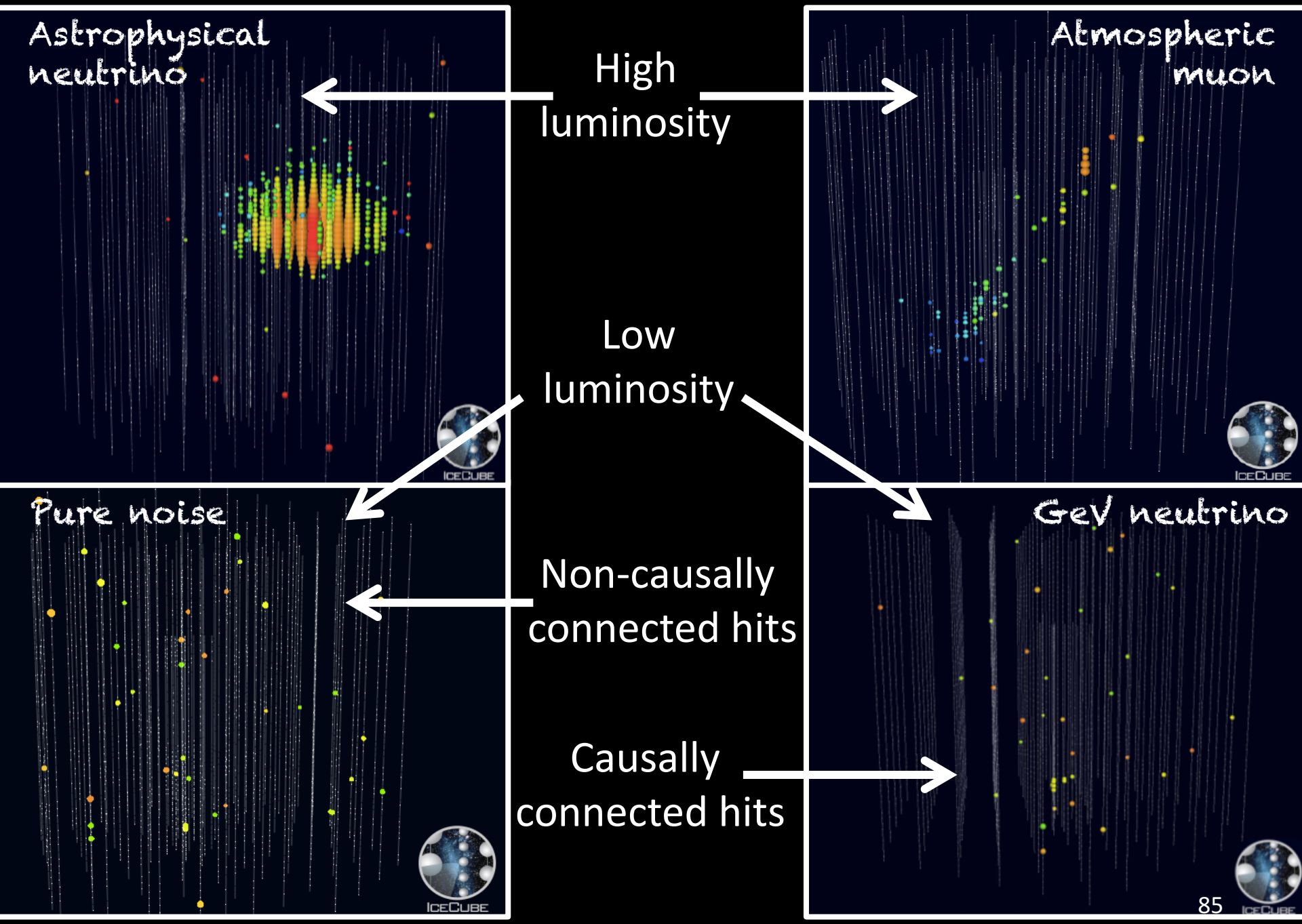


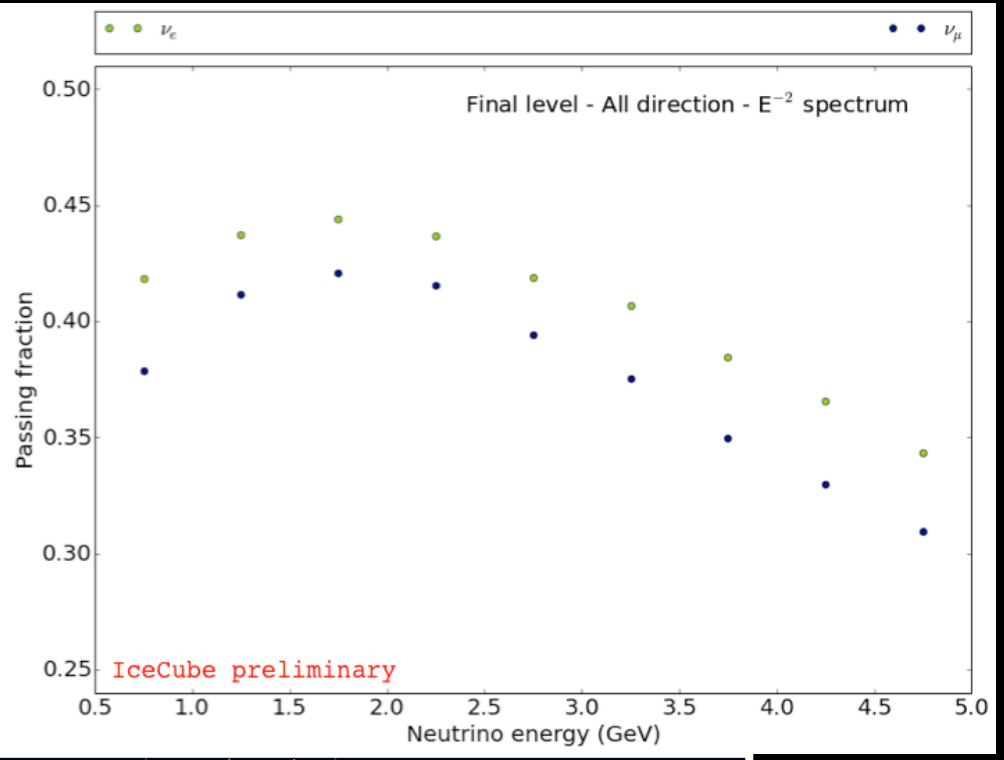


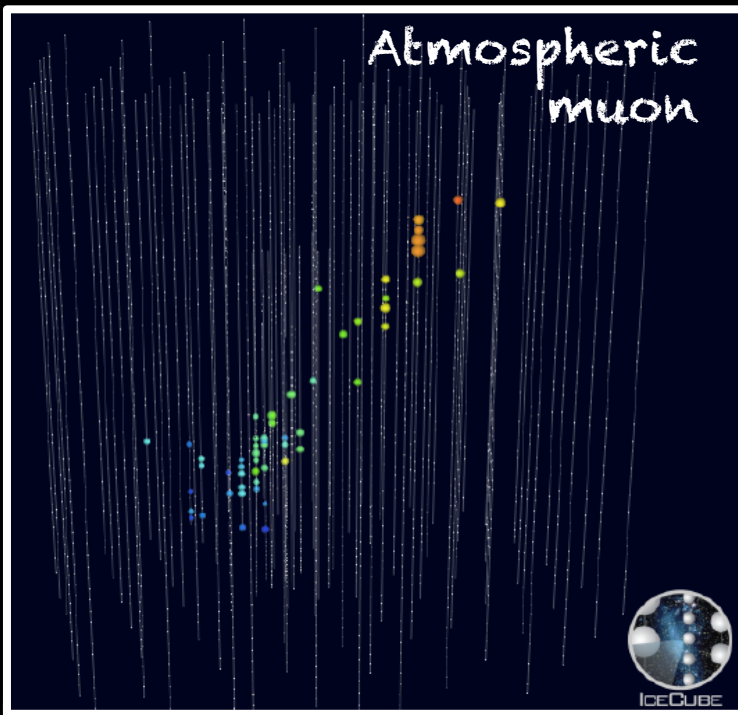
Let's do the event selection together!

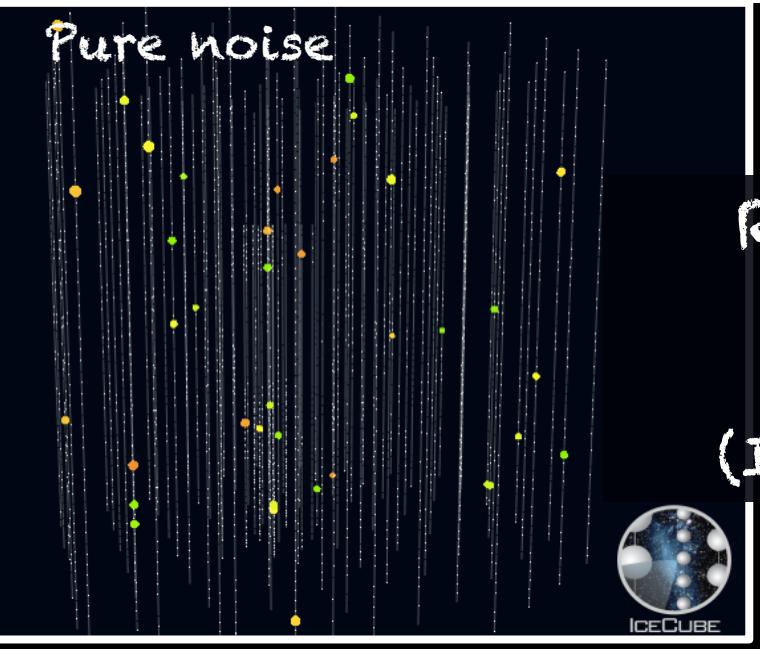





Astrophysical neutrino
High luminosity
Atmospheric muon
Low luminosity
Pure noise
Non-causally connected hits
GeV neutrino
Causally connected hits
IceCube
IceCube
IceCube
IceCube

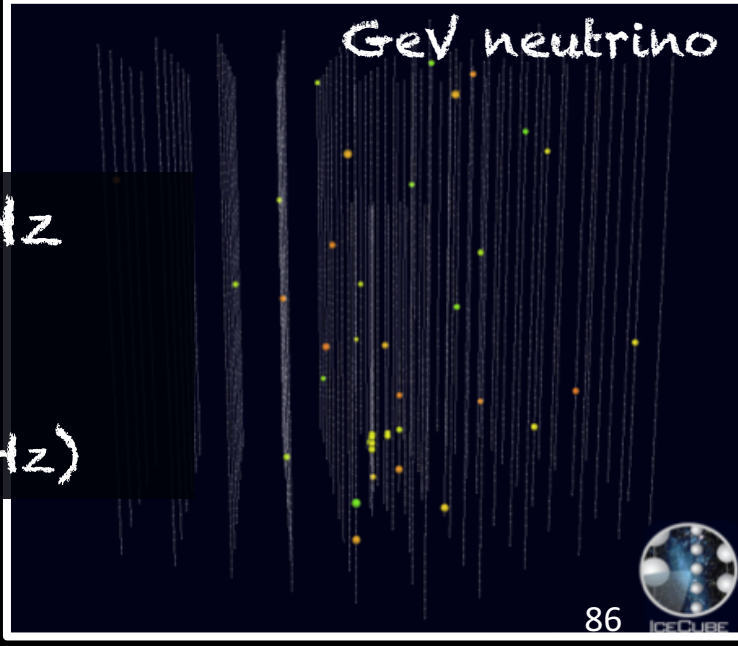






Rate = 0.02Hz

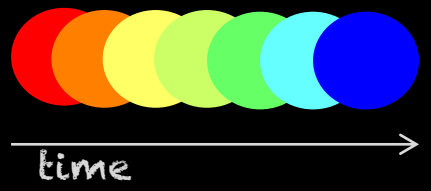
(Initial rate: kHz)

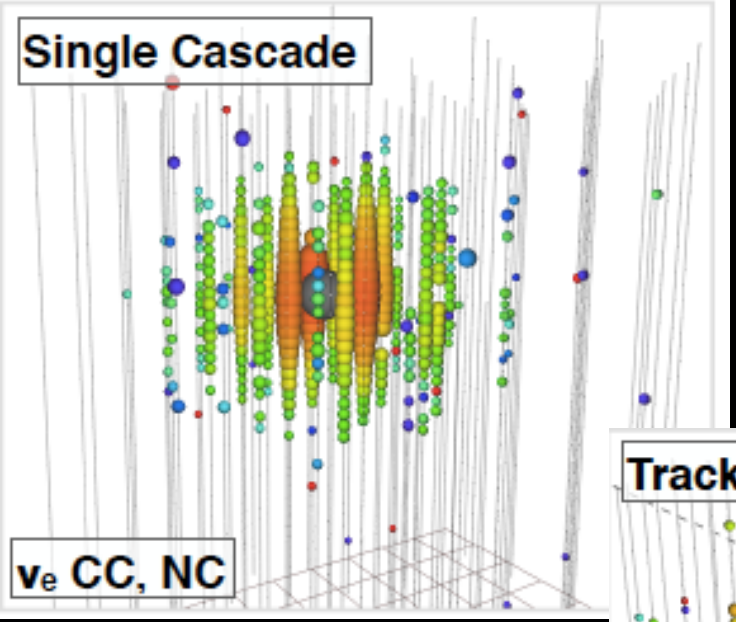


2. What's new? / What else?

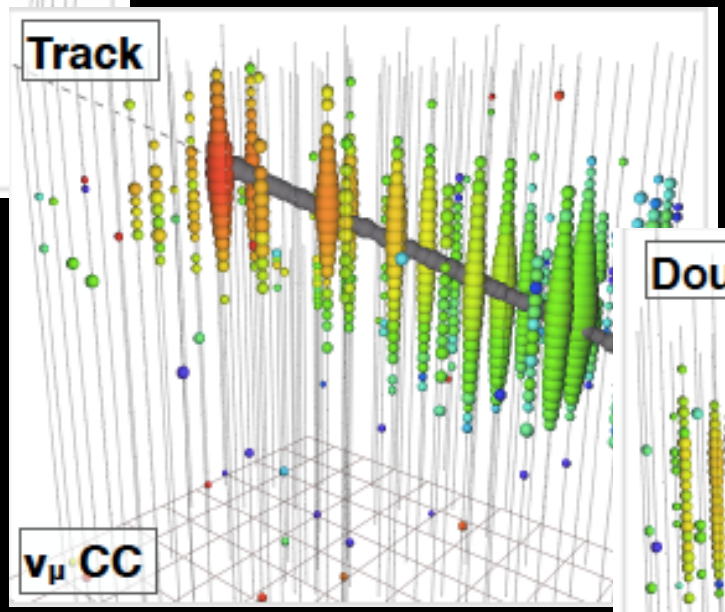
- Flavor ratio and tau neutrinos

Event topology



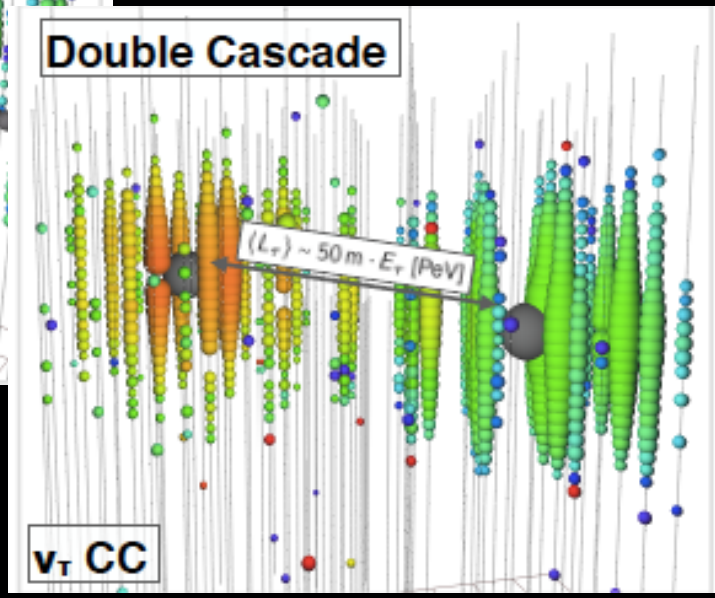


- Good E resolution
- Bad angular resolution



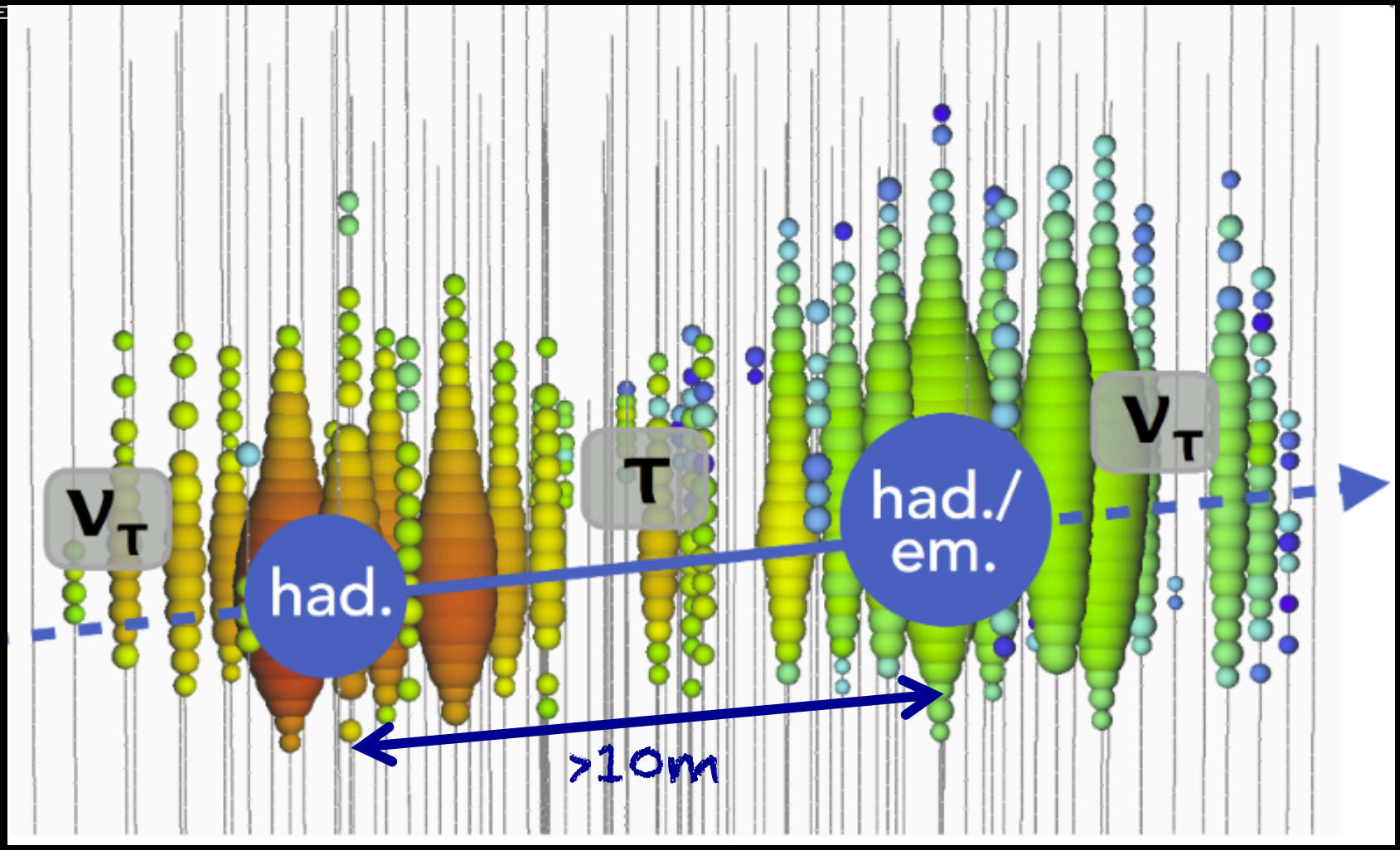
- Bad energy resolution
- Good angular resolution

+ Starting track!



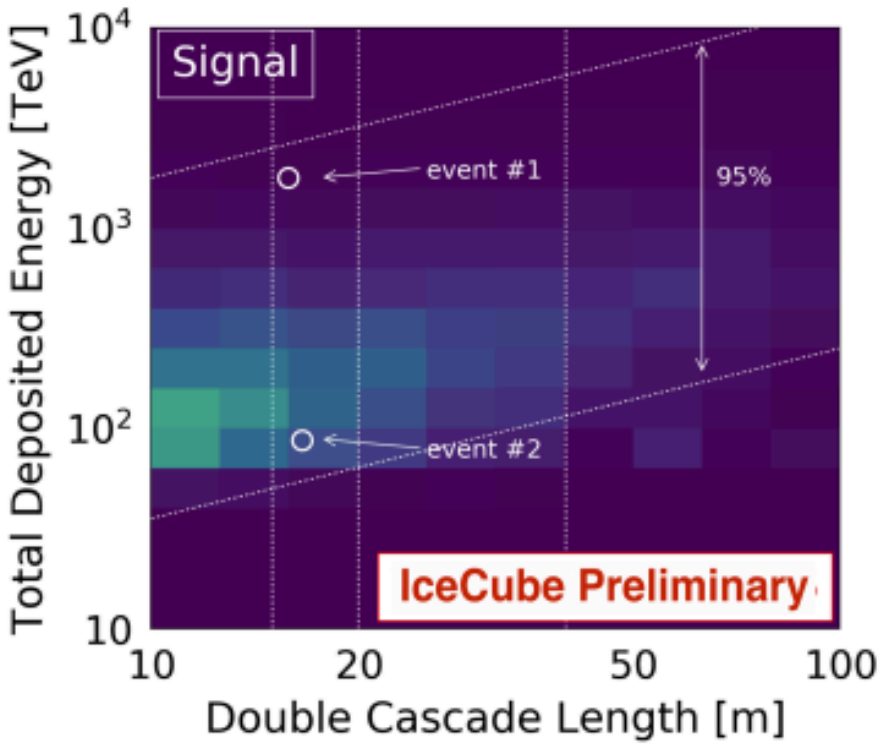
- Good E resolution
- Better angular resolution than single cascade

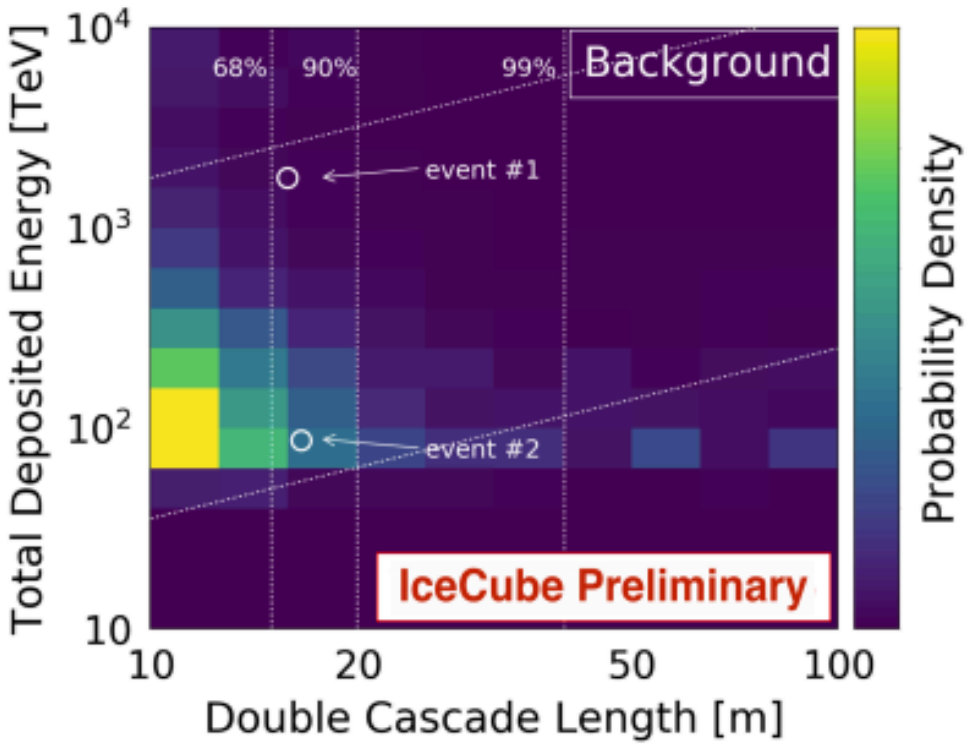
Double cascade



- Both cascades with E > 1 TeV
- Separation distance > 10 m

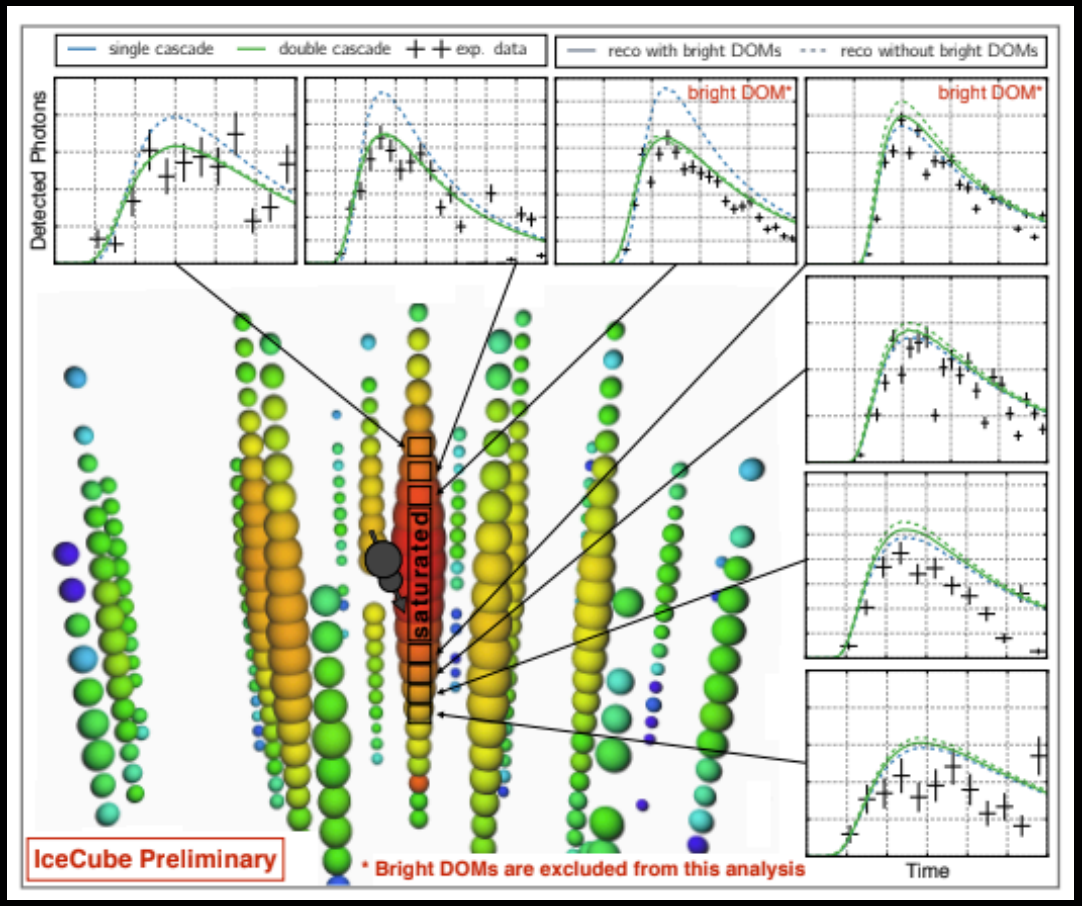
Double cascade





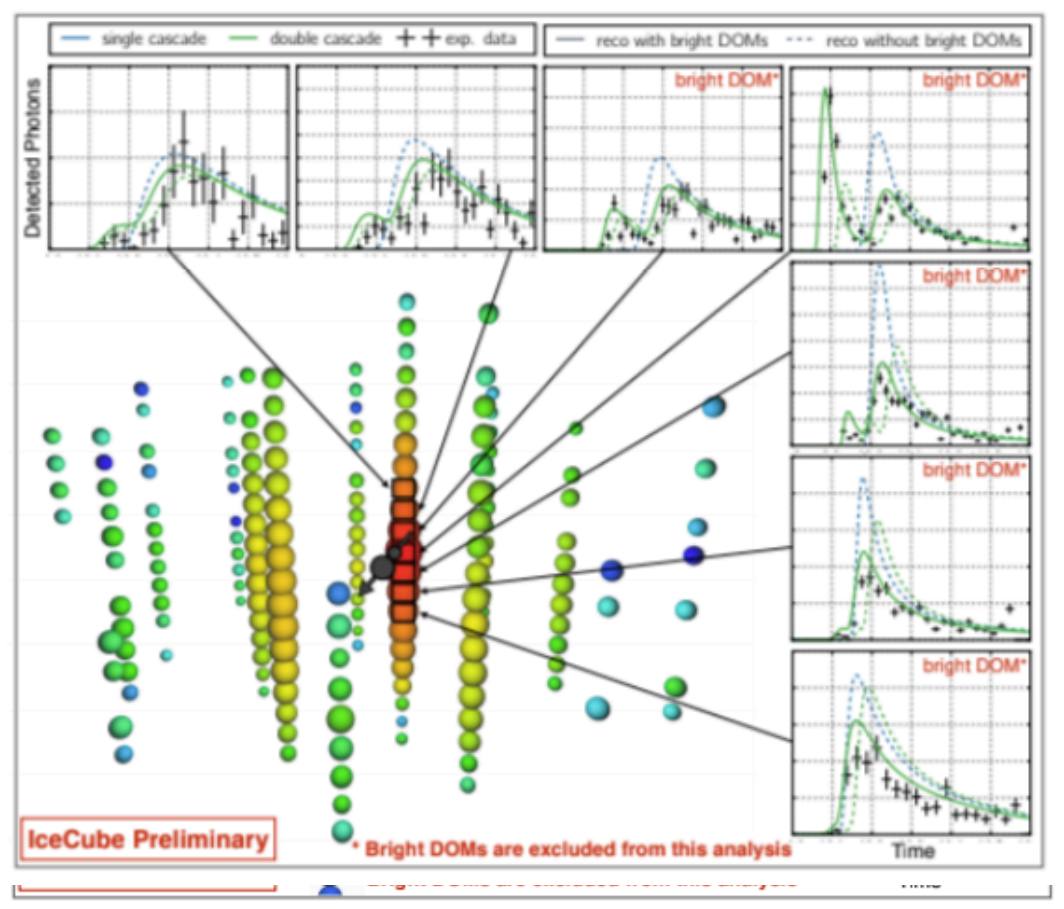
- Ternary-PID of cascades, tracks and double-cascades
- 2 double-cascade candidates
- ν_τ or mis-identified background

Event 1: Big Bird



- Energy of the cascades = 1.2 PeV and 0.6 PeV
- Separation = 16m
- Observed in 2012
- No clear preference between a single cascade and double-cascade

Event 2: Double Double



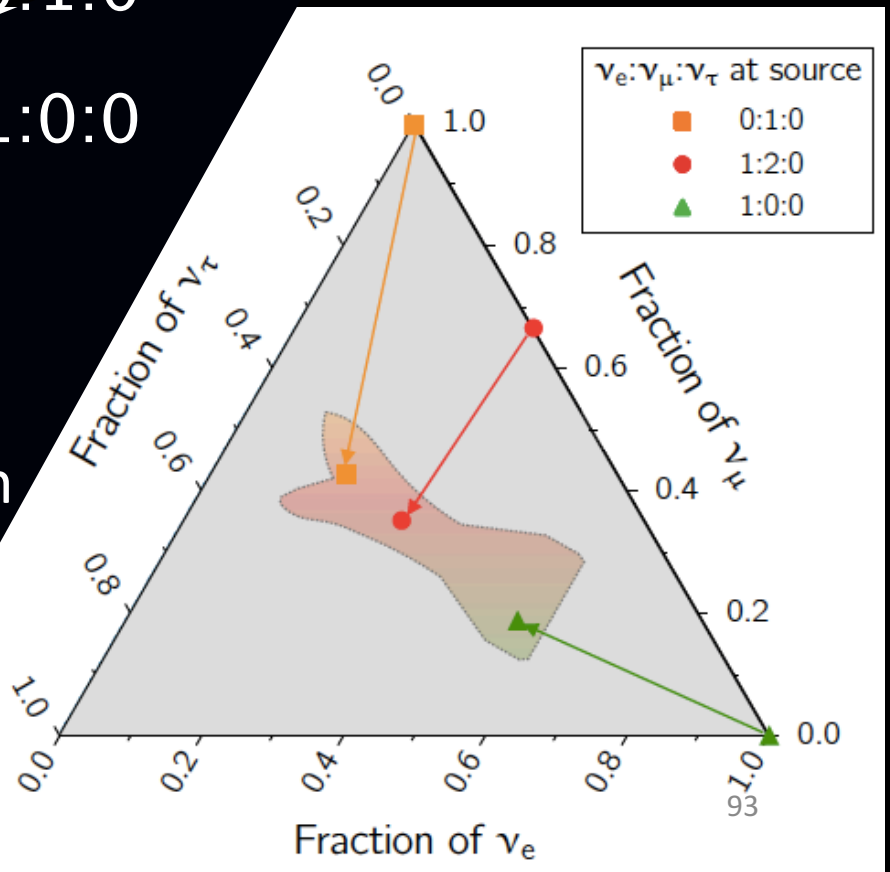
- Energy of the cascades = 9 TeV and 80 TeV
- Separation = 17m
- Observed in 2014
- Observed light arrival pattern clearly favors double cascade

Flavor composition

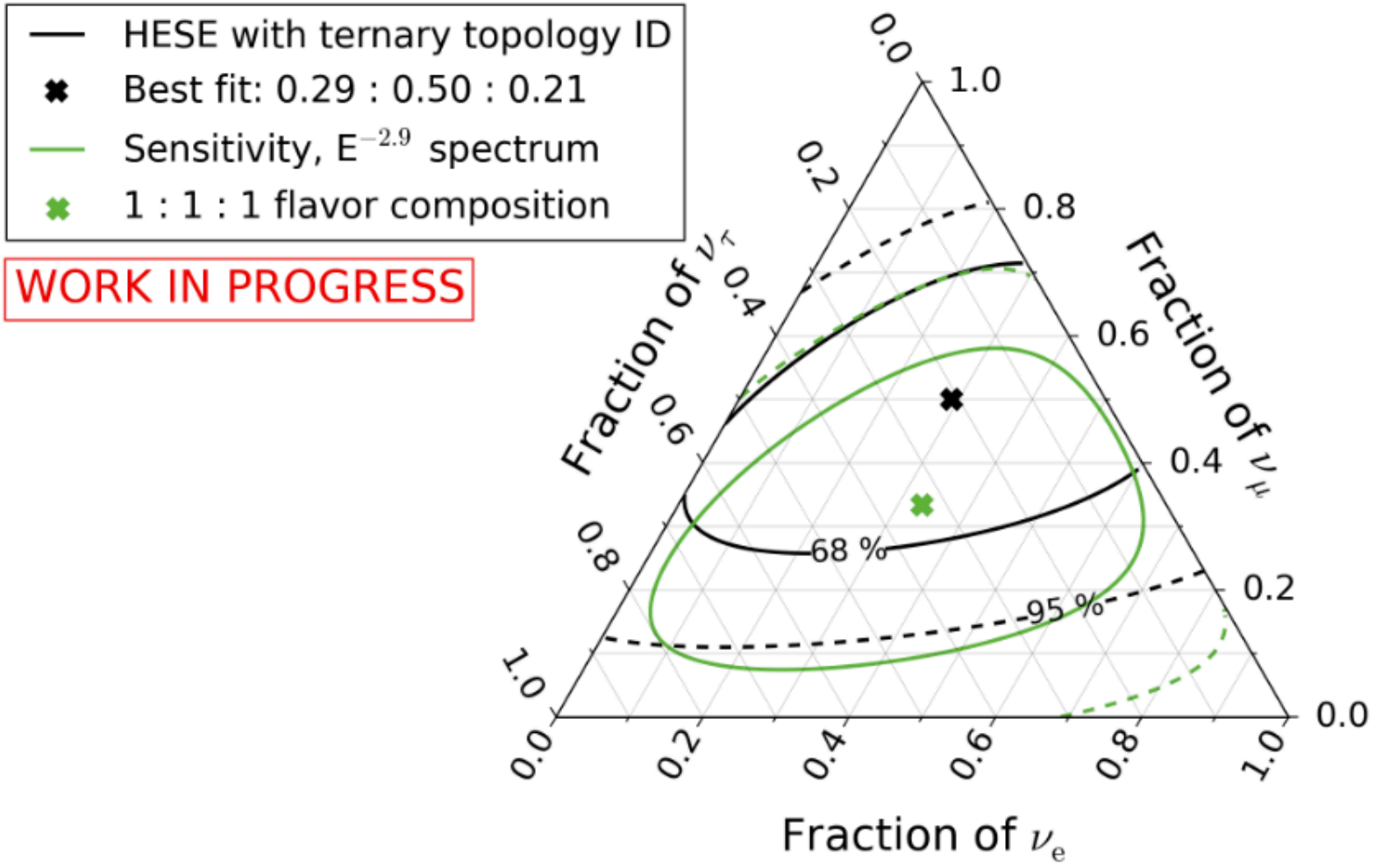
Cosmic particle accelerator	$\nu_e:\nu_\mu:\nu_\tau$
Pion decay	1:2:0
Muon- damped	0:1:0
Neutron decay	1:0:0

+ others

- Study of the composition at Earth
- Oscillation back to the source
- Information on the emission mechanism



Flavor composition



- Non-zero best-fit for ν_τ
- Zero ν_τ flux not excluded