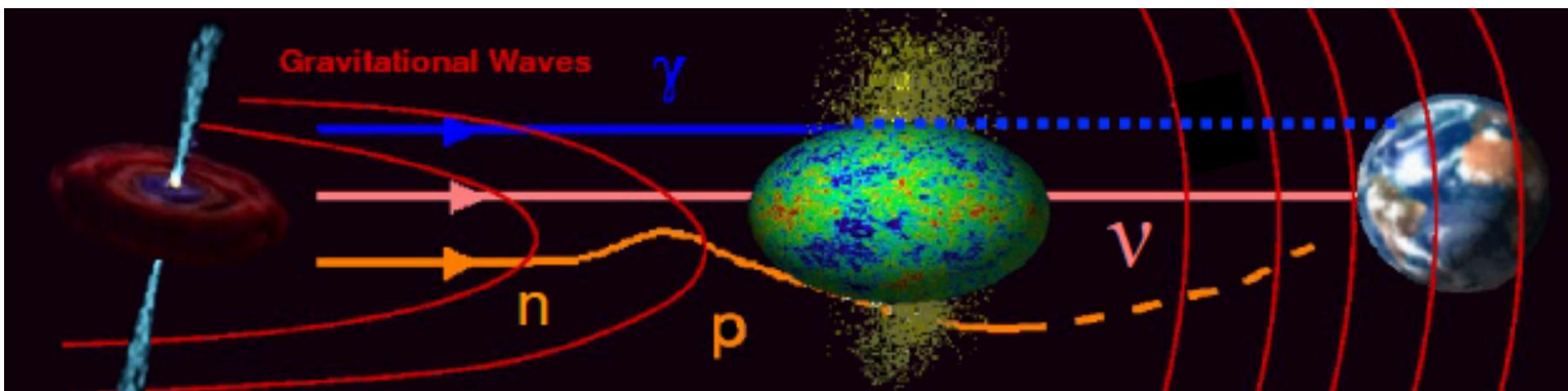




(high-energy) Neutrino astronomy: Motivations, Techniques and Observations

Véronique Van Elewyck
(APC & Université Paris Diderot)

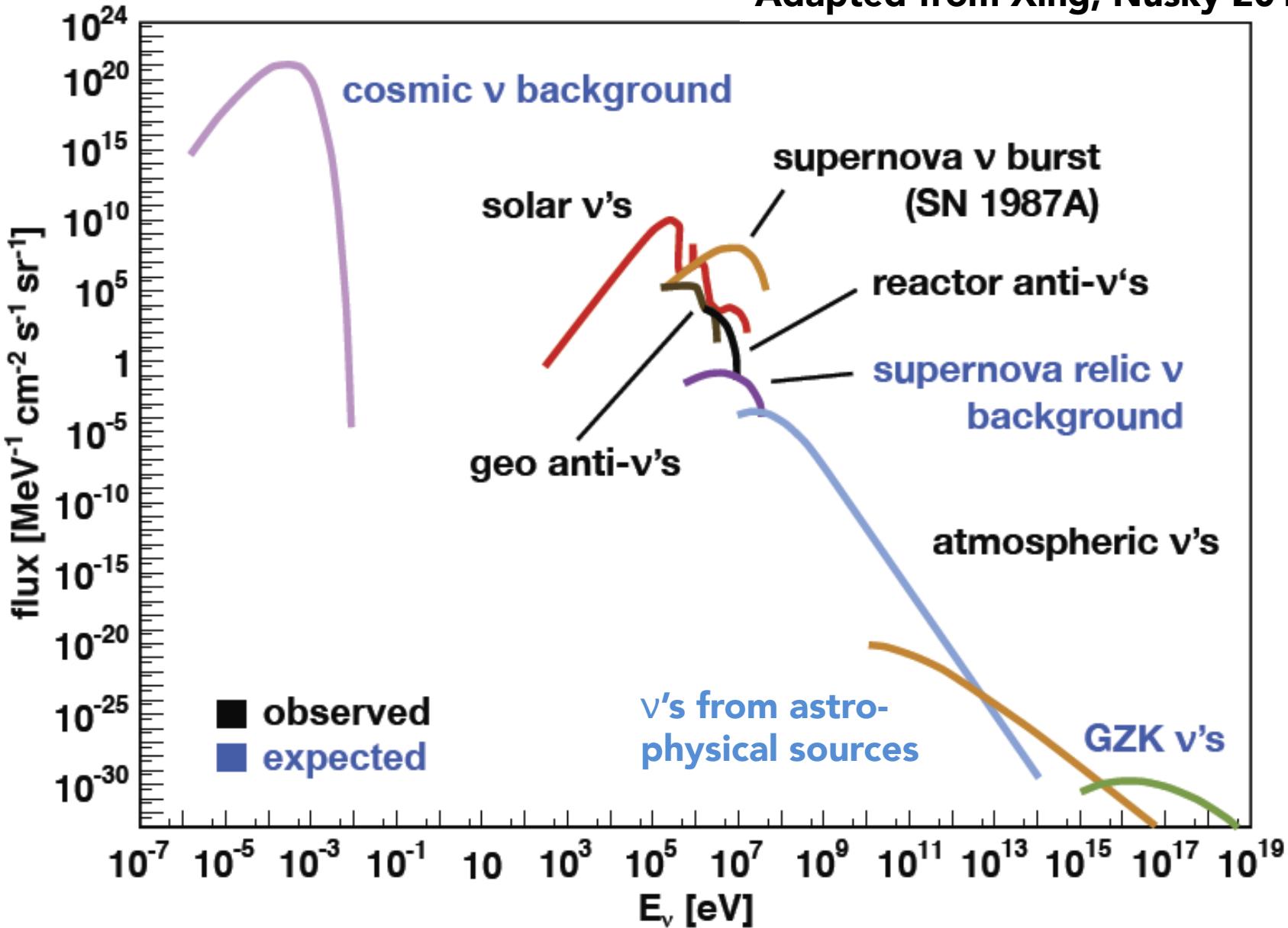
Neutrino astronomy



- ❖ Neutrinos: neutral, stable, weakly interacting
 - not absorbed by background light → access to full energy range
 - not absorbed by matter → access to dense environments
 - not deviated by magnetic fields → astronomy over cosmological distances
- ❖ Correlated in time/direction with electromagnetic and gravitational waves
- ❖ ‘Smoking gun’ signature for hadronic processes
 - trace cosmic ray production/acceleration/interaction sites
- ... But difficult to detect: small fluxes, small cross-section
 - Instrument naturally abundant, transparent media: ice, water

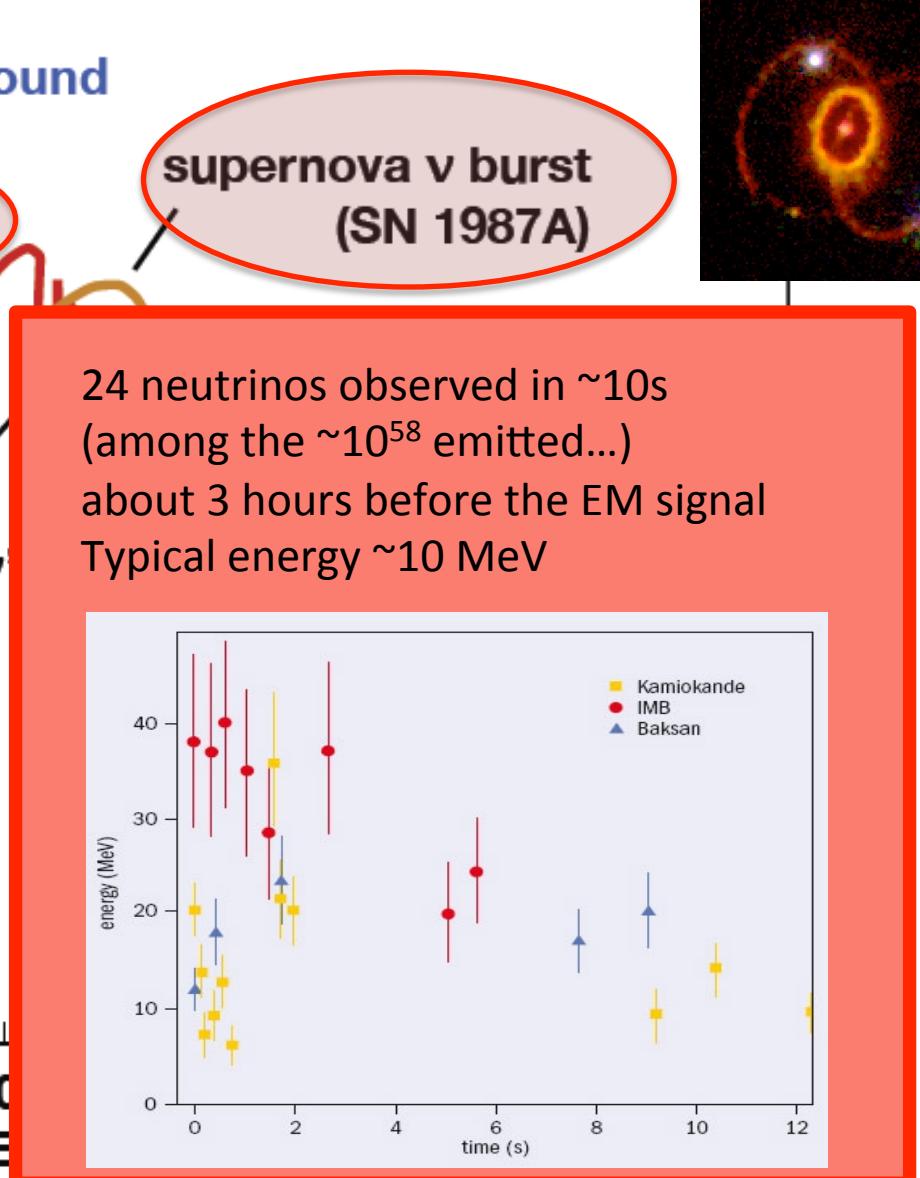
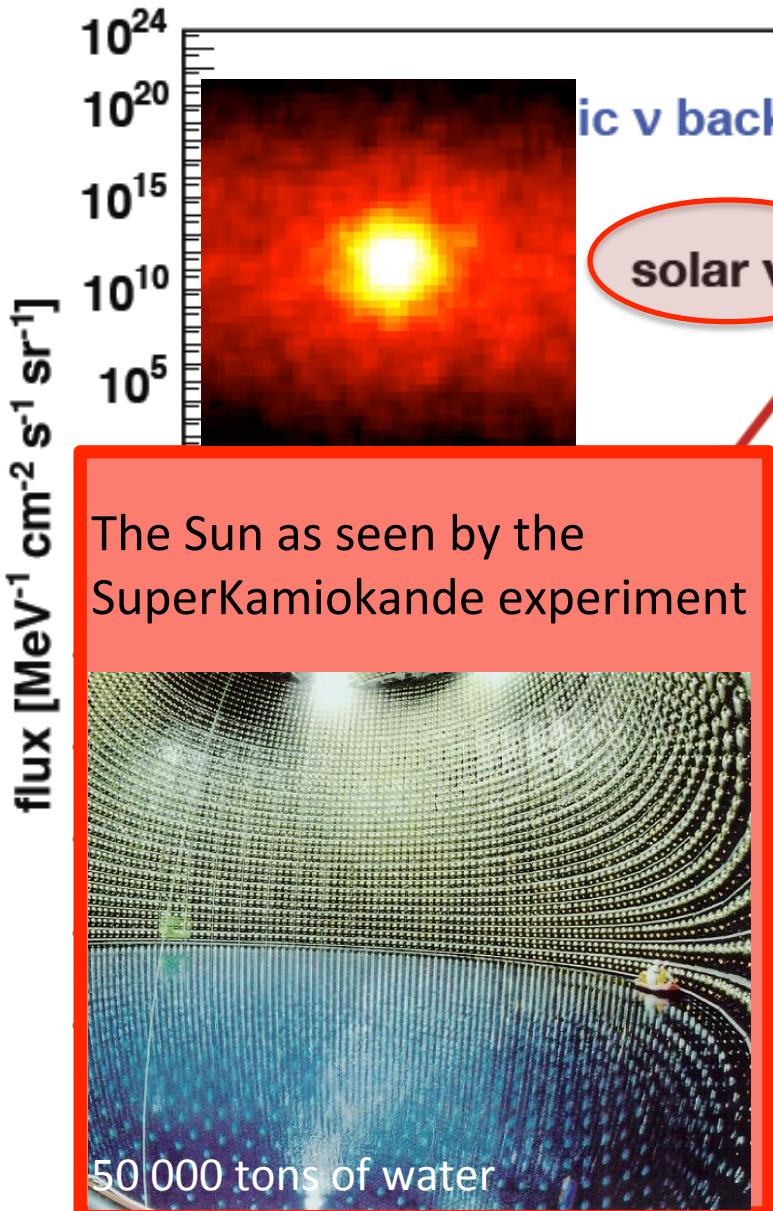
The sources of neutrinos

Adapted from Xing, Nusky 2011



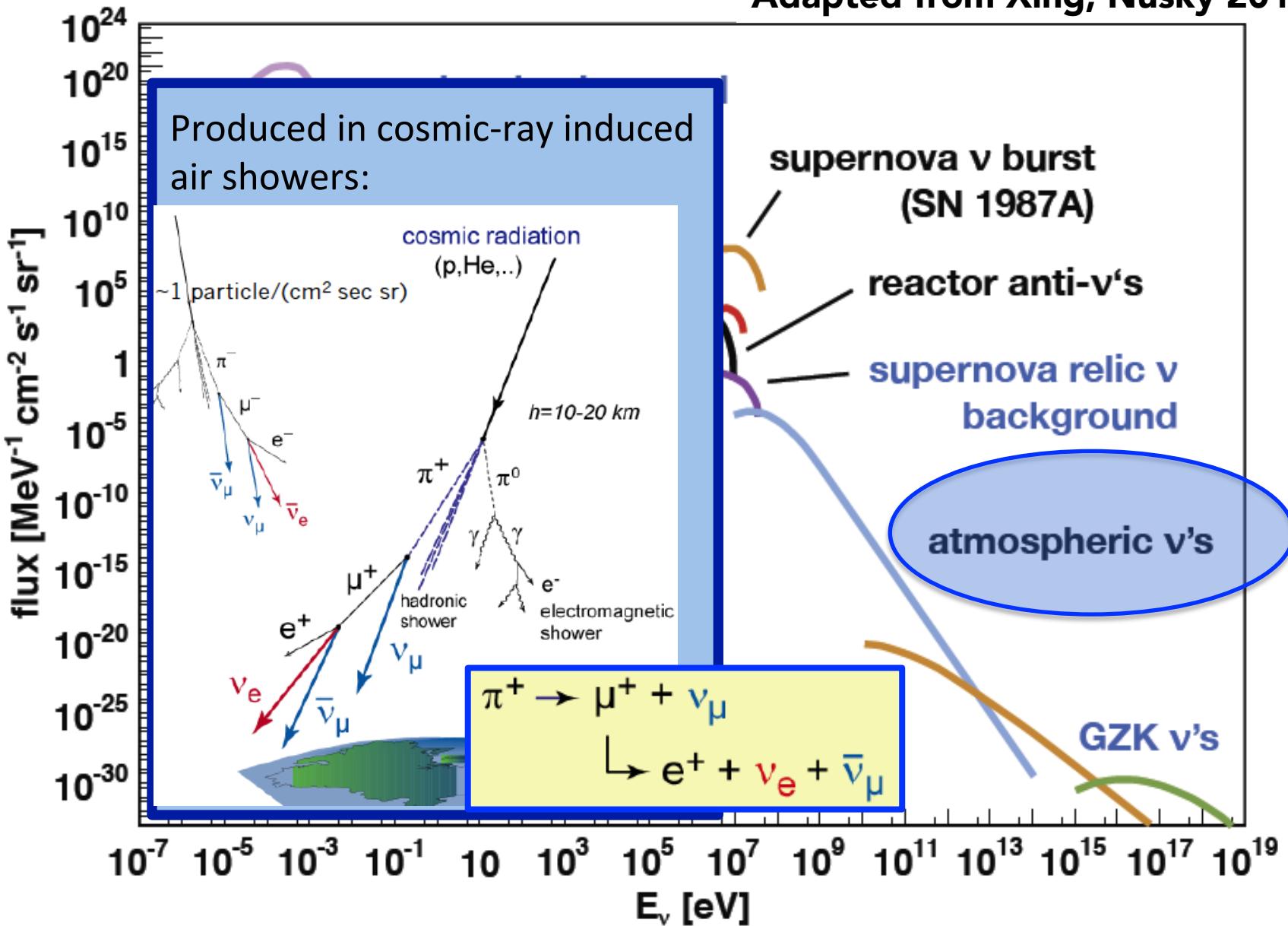
The sources of neutrinos

Adapted from Xing, Nusky 2011



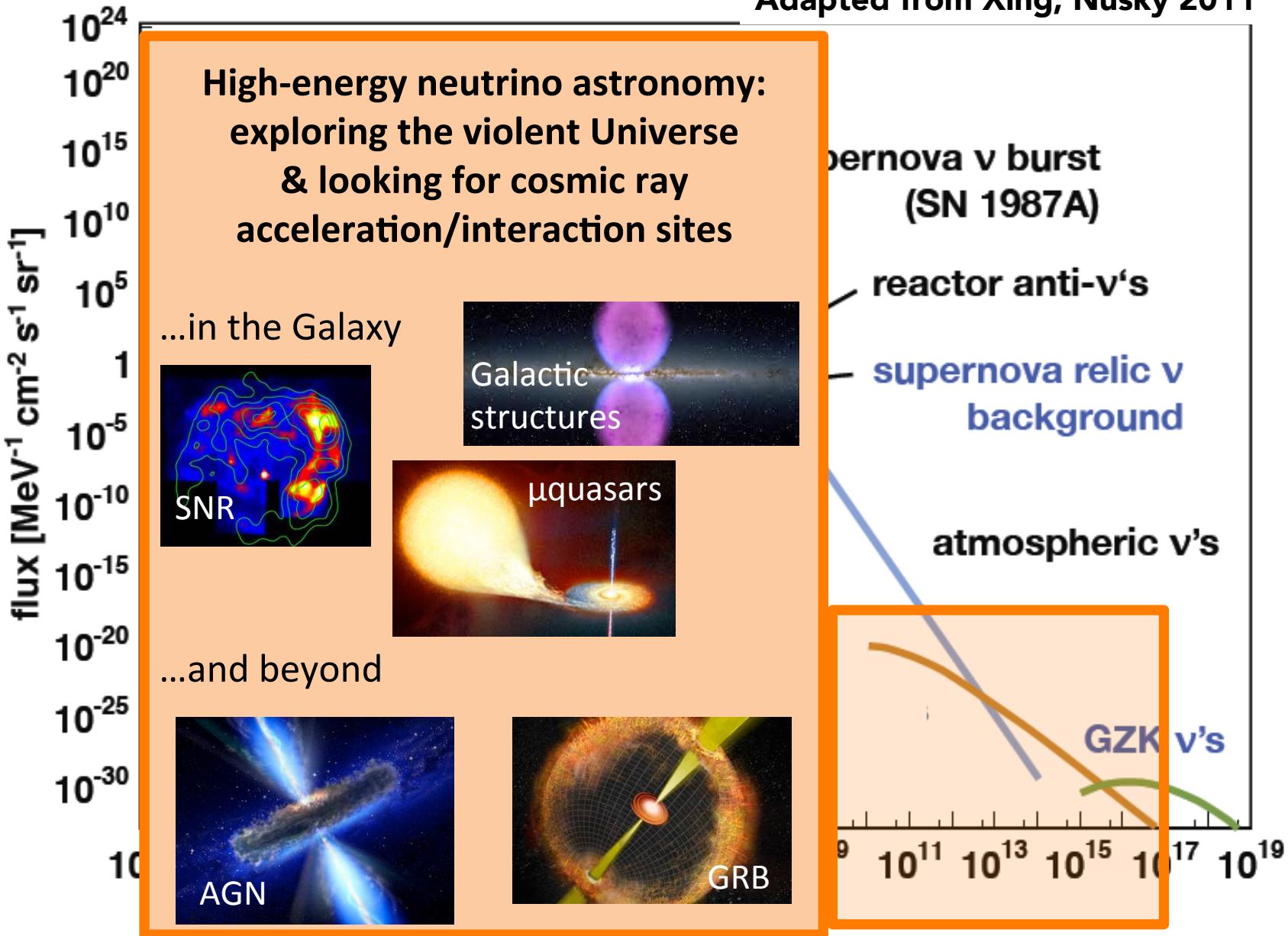
The sources of neutrinos

Adapted from Xing, Nusky 2011

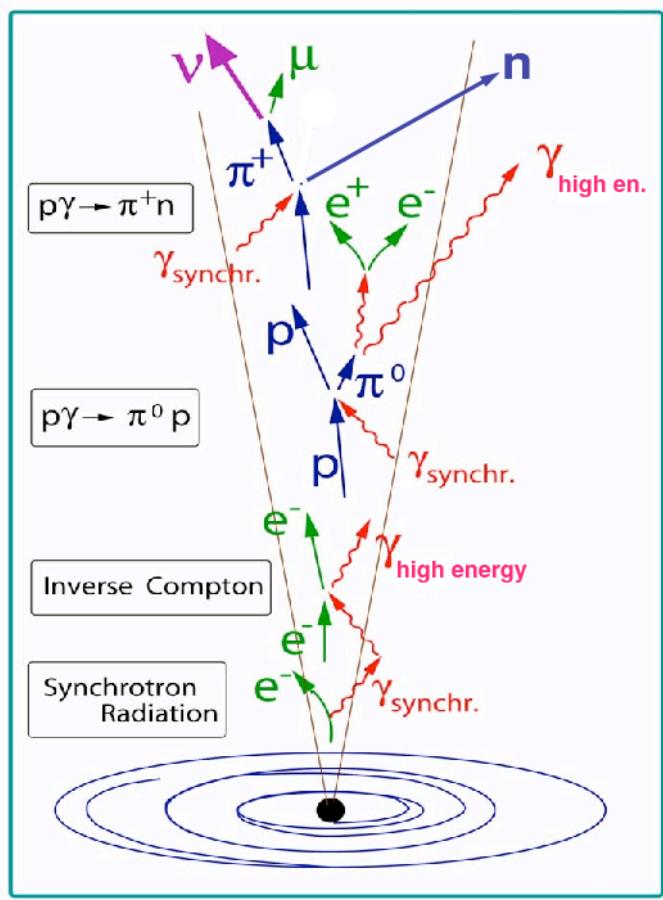


The sources of neutrinos

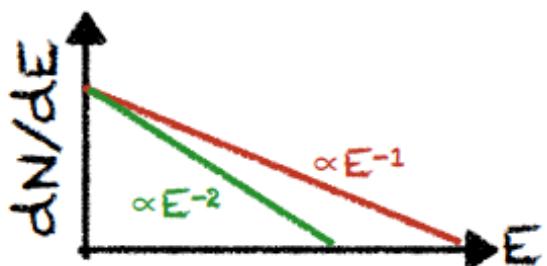
Adapted from Xing, Nusky 2011



High-energy neutrino production mechanisms

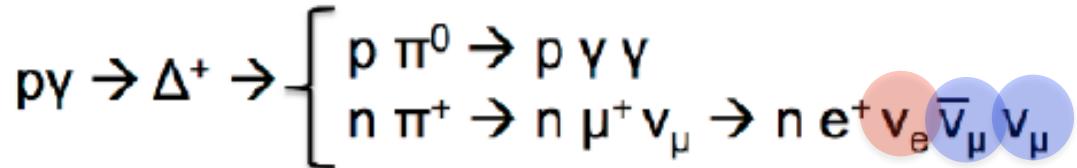


credits: U. Katz



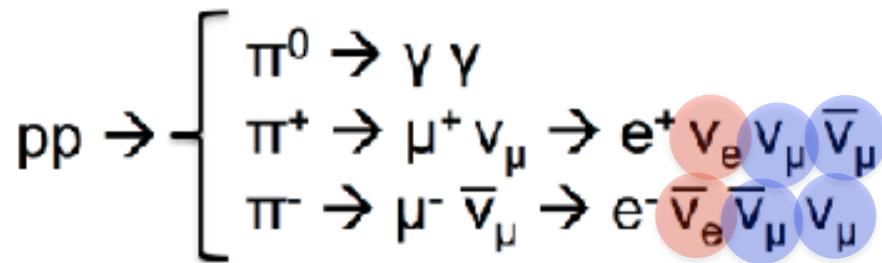
❖ Photohadronic processes

(e.g. gamma-ray bursts, AGN, microquasars,...)



❖ Hadronuclear processes

(e.g. starburst galaxies, galaxy clusters, galactic cosmic rays)



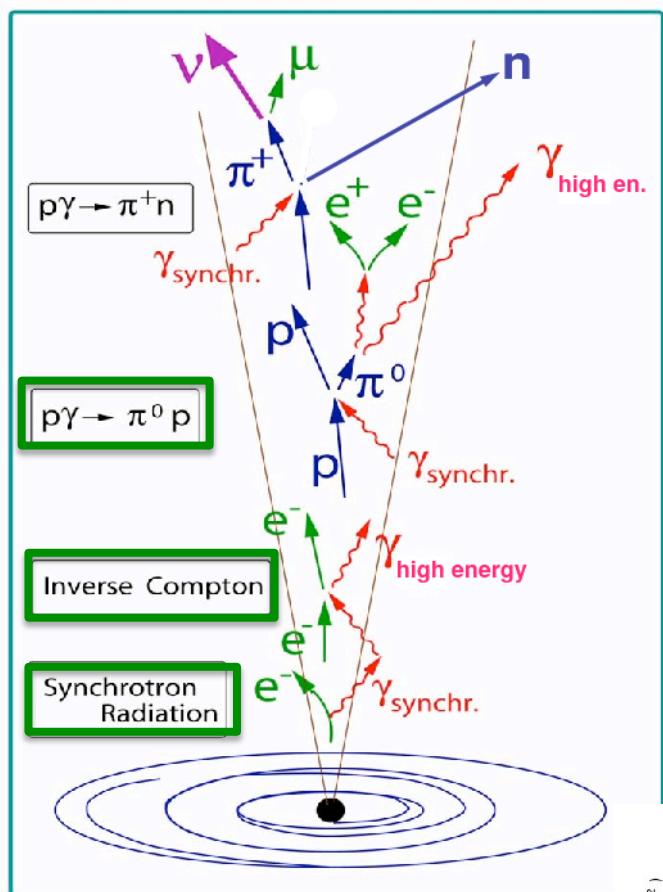
Expected spectral index $\approx 1 - 2$

Expected flavour ratio:

$$\nu_e : \nu_\mu : \nu_\tau = 1:2:0 \xrightarrow{\text{oscillations}} \nu_e : \nu_\mu : \nu_\tau = 1:1:1 \text{ at Earth}$$

ν carries $\sim 3\text{-}5\%$ of proton energy:
TeV-PeV ν 's produced by protons with PeV – 100 PeV

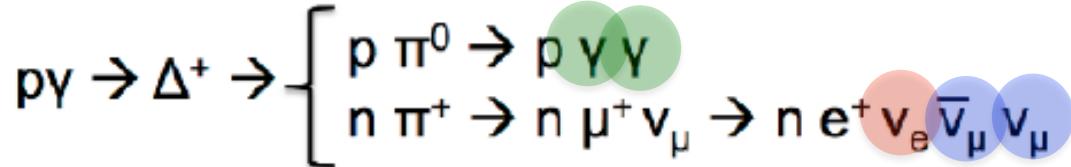
High-energy neutrino production mechanisms



Neutrinos needed to unambiguously confirm a hadronic component !

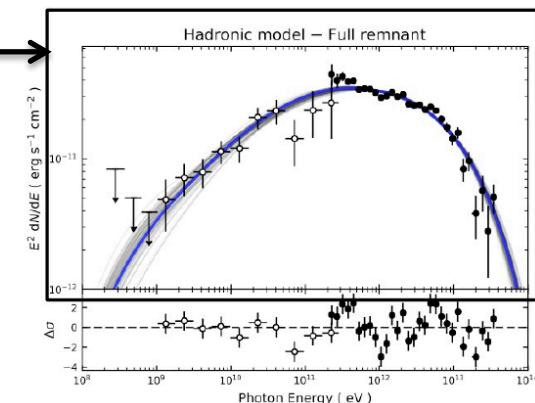
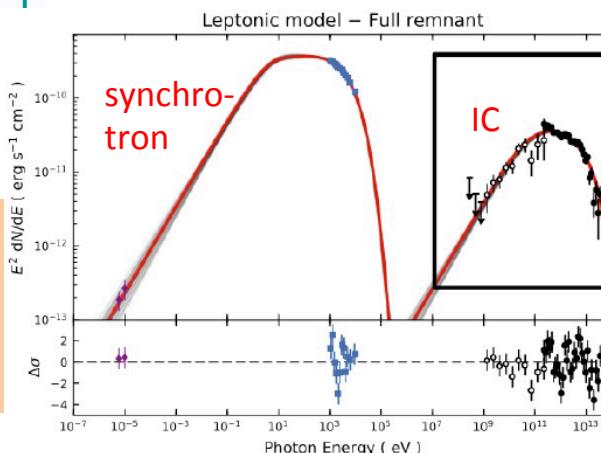
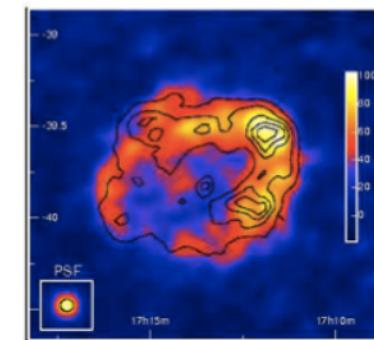
❖ Photohadronic processes

(e.g. gamma-ray bursts, AGN, microquasars,...)



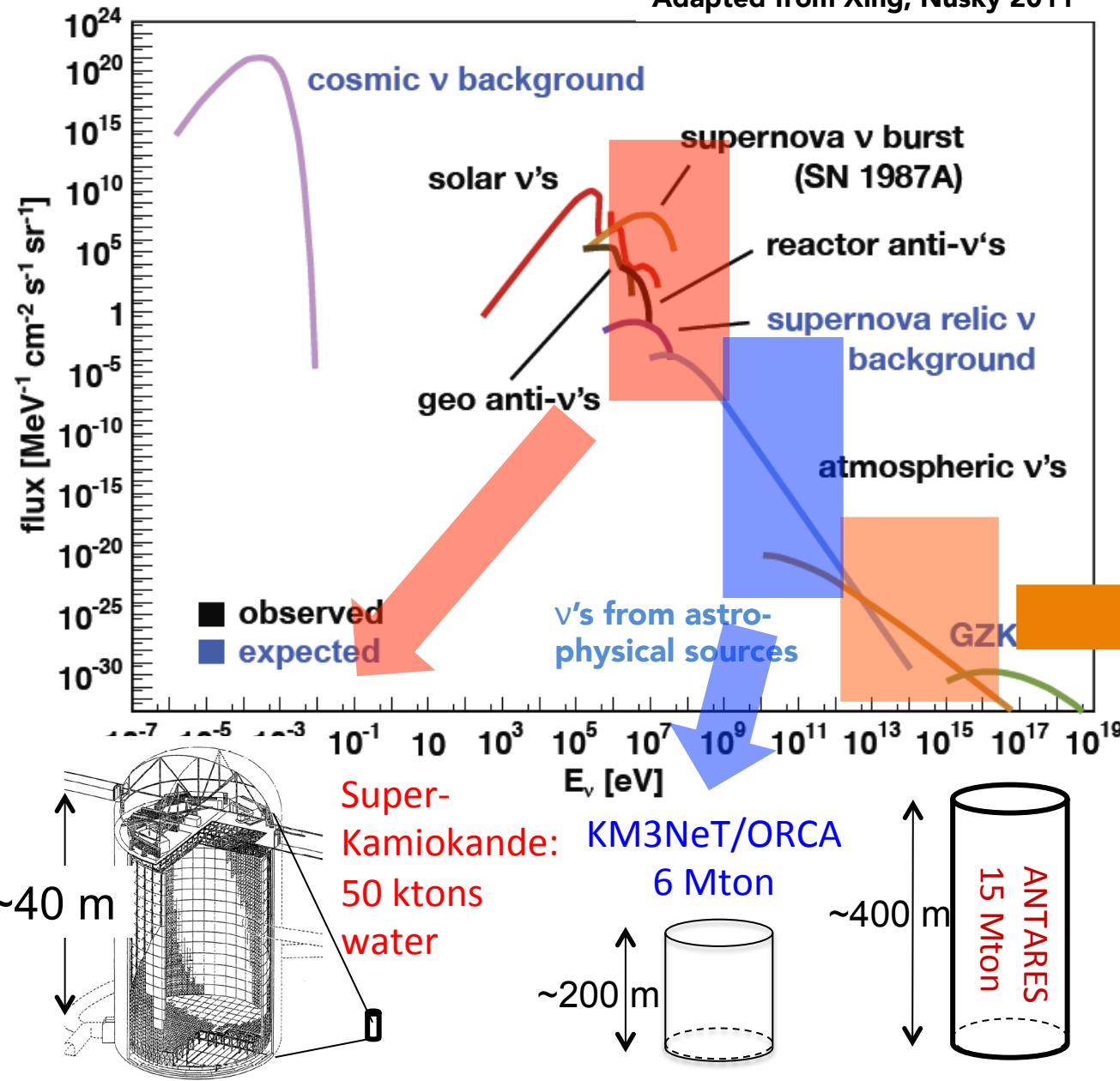
Photons can be produced either by hadronic or leptonic processes:

Ex. SNR RXJ1713:
gamma-ray observations from
Fermi, H.E.S.S. can be accommodated
by either model:

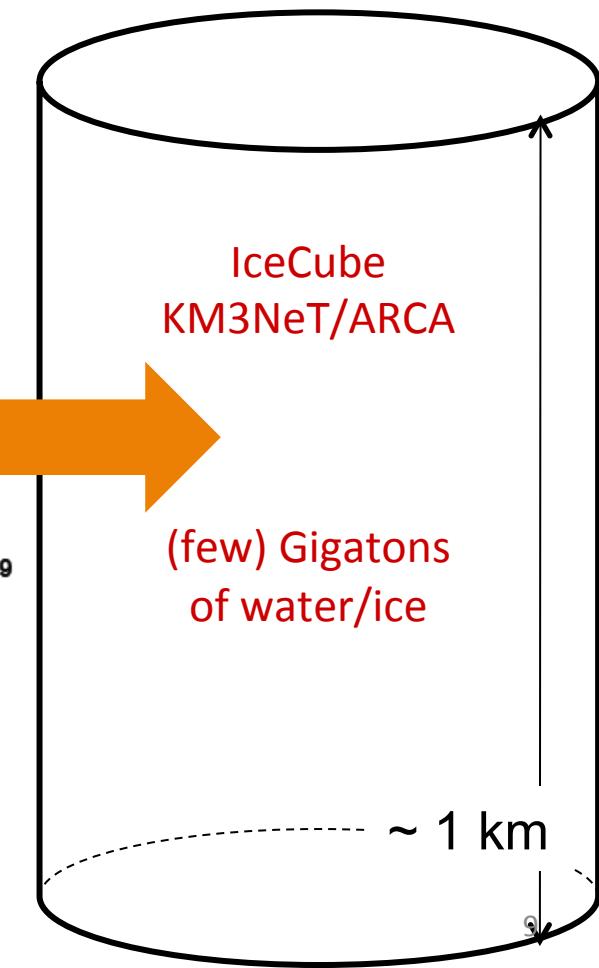


Neutrino detectors: size matters...

Adapted from Xing, Nusky 2011



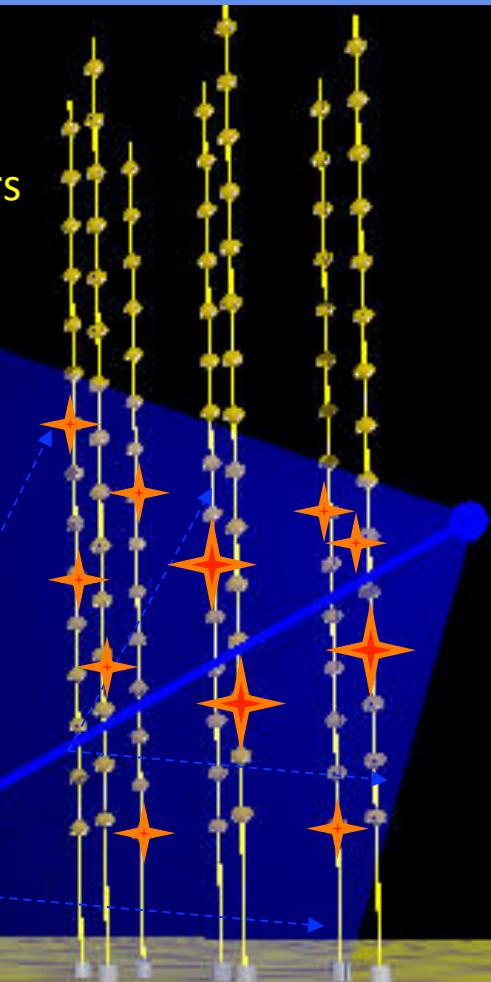
High-energy neutrino astronomy requires km³-scale detectors !



Detection principle

"We propose getting up an apparatus in an underground lake or deep in the ocean in order to determine the location of charged particles with the help of Cherenkov radiation" *M. Markov, 1960*

Detector:
3D array of
photomultipliers



**Detection
medium:**
WATER/ICE

Earth's crust

ν_μ
interaction

time, position & amplitude of hits

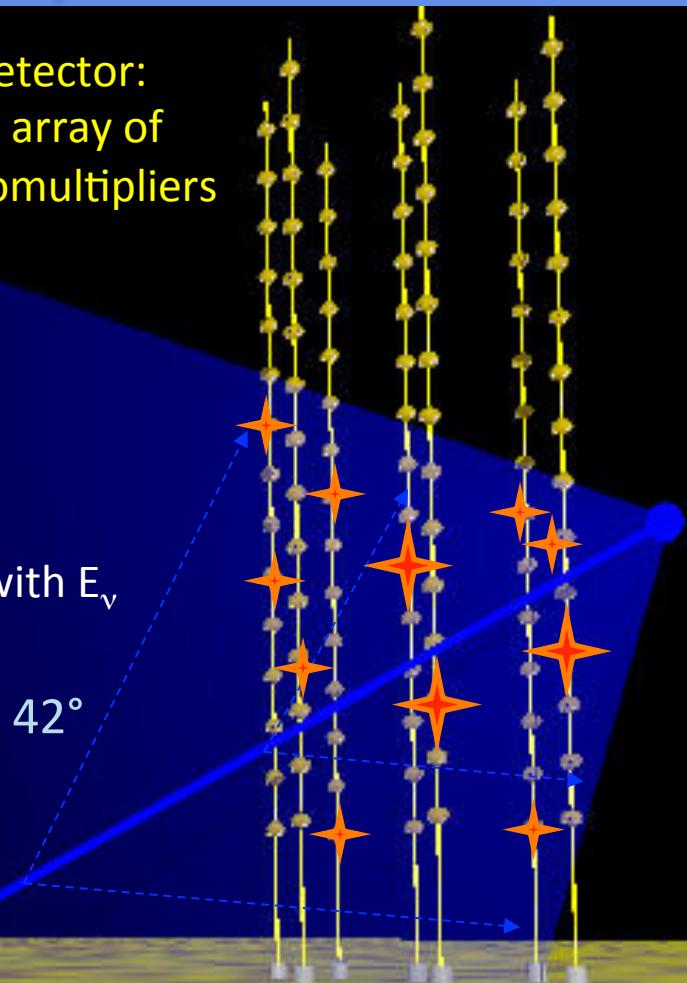


energy & arrival direction of ν

Detection principle

"We propose getting up an apparatus in an underground lake or deep in the ocean in order to determine the location of charged particles with the help of Cherenkov radiation" *M. Markov, 1960*

Detector:
3D array of
photomultipliers

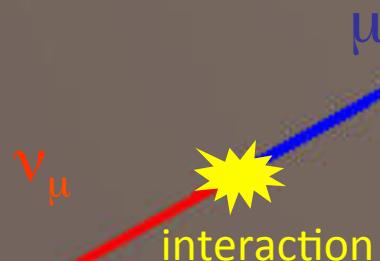


MUON (TRACK) TOPOLOGY:
Golden channel for astronomy

- Detection effective volume increases with E_ν
- Good angular resolution:
 $0.5^\circ/0.1^\circ$ for ice/water 1km^3

**Detection
medium:
WATER/ICE**

Earth's crust

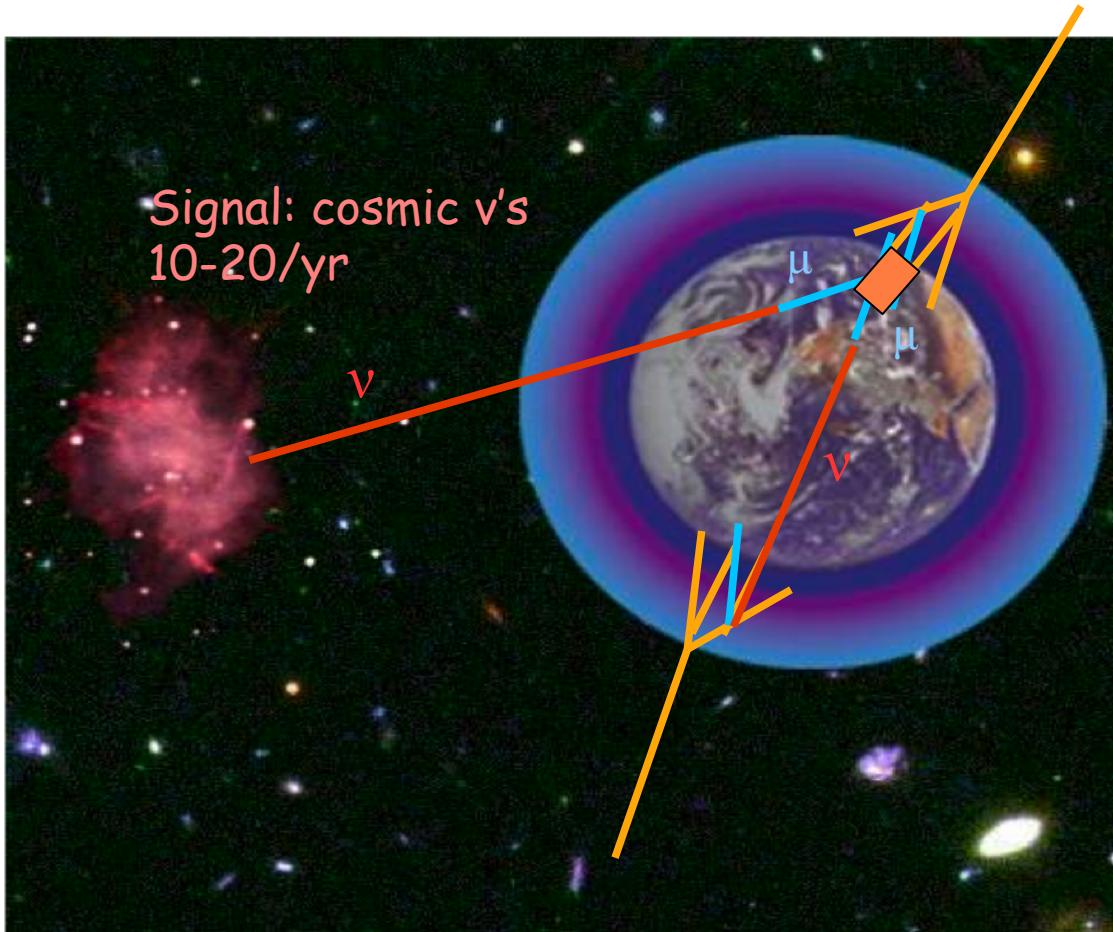


time, position & amplitude of hits



energy & arrival direction of ν

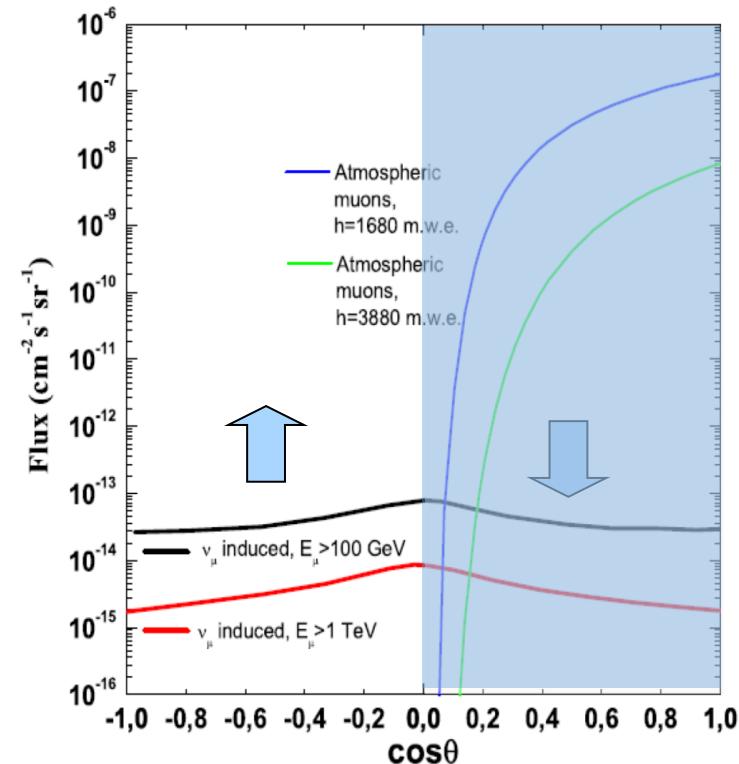
Detection principle



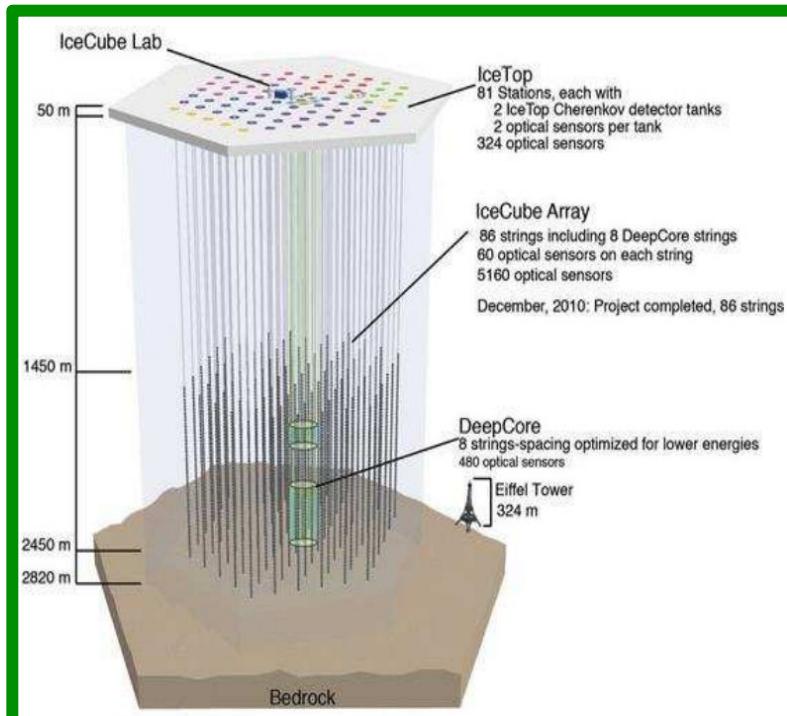
- Detectors buried deep
- Optimised for upward-going signals
- use veto (« starting events »)

Physical background:
Cosmic-ray induced air showers

- atmospheric muons: μ_{atm}
 $\sim 10^{10}/\text{yr}$ in km^3 detector
- atmospheric neutrinos: ν_{atm}
 $\sim 10^5/\text{yr}$ in km^3 detector



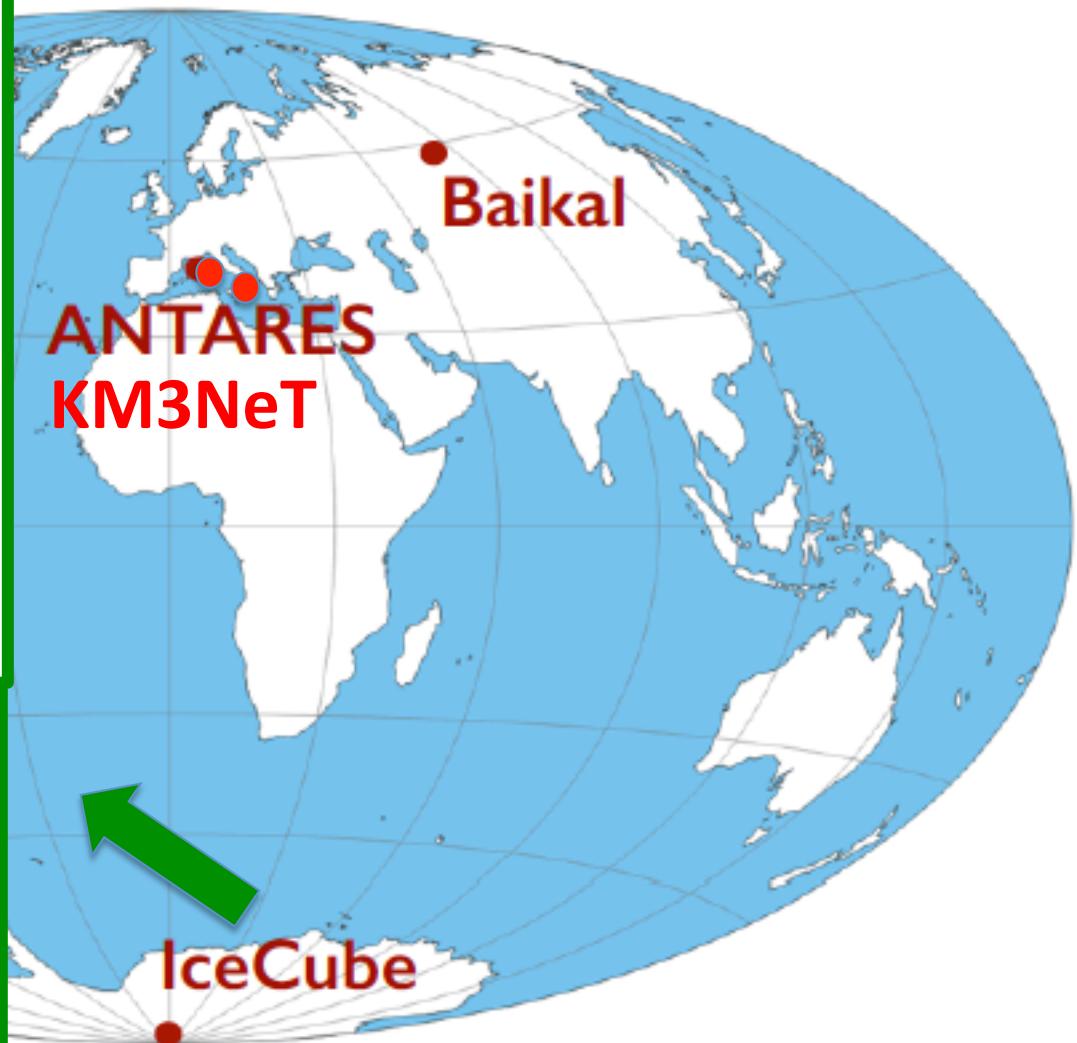
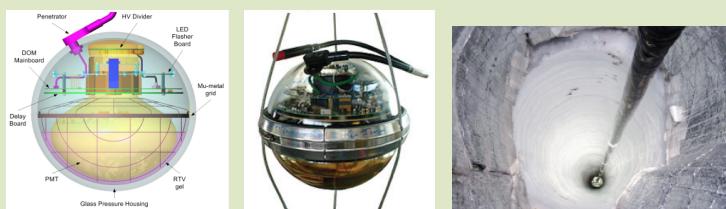
Neutrino telescopes



InIce: 86 lines, completed 2010
~ 1 km³ instrumented volume

DeepCore: 8 lines, dense infill

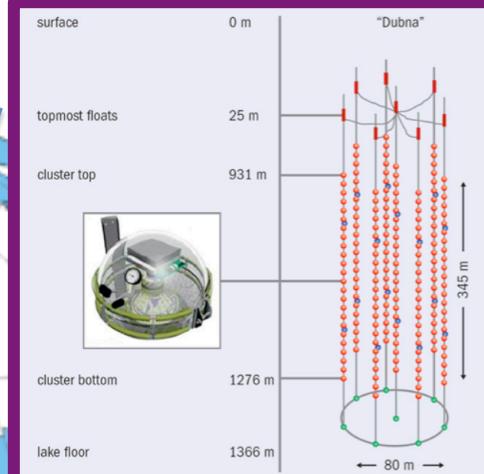
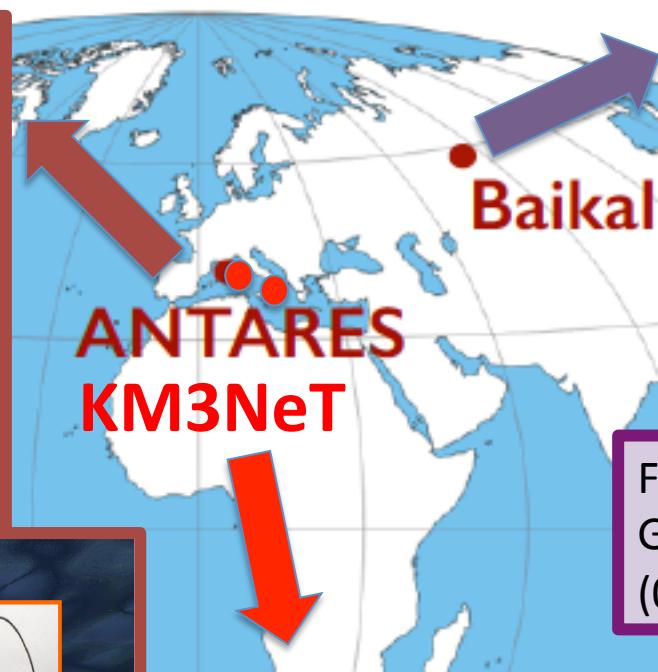
IceTop: air shower array



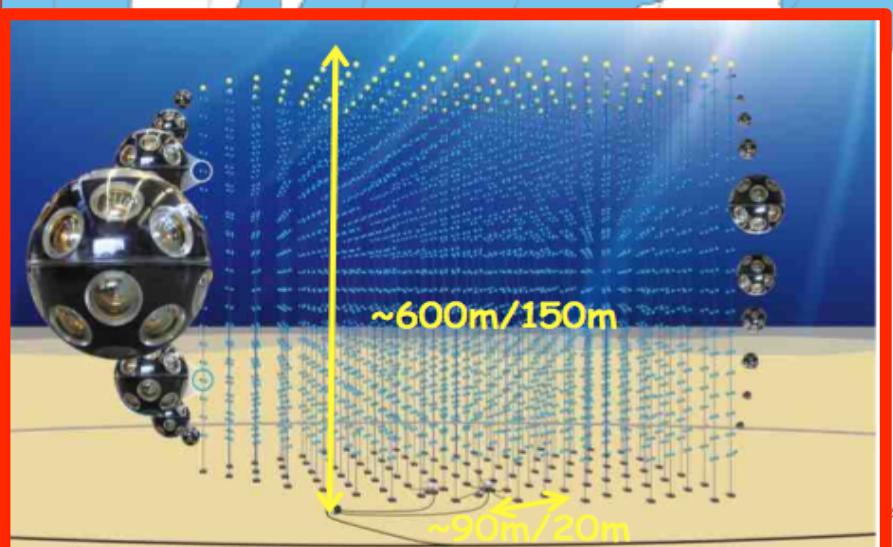
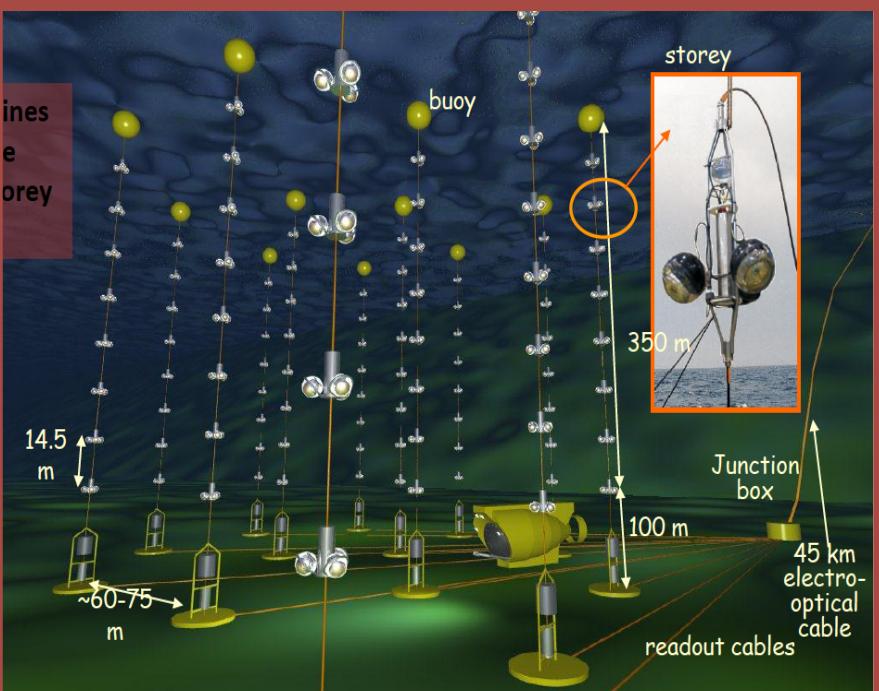
Neutrino telescopes

12 lines, completed 2008
~ 0,02 km³ instrumented volume

Prototype for a km³-sized detector in the Mediterranean:
KM3NeT (ARCA & ORCA)
under construction with new technology (multi-PMT optical module)



First cluster of Gigaton Volume Detector (0.4 km³) being deployed



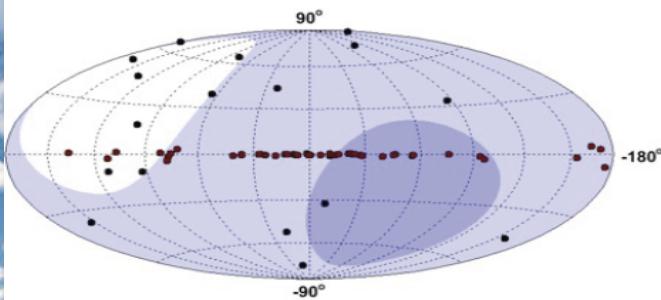
Water vs ice



Water vs ice

Visibility Mediterranean (Antares)

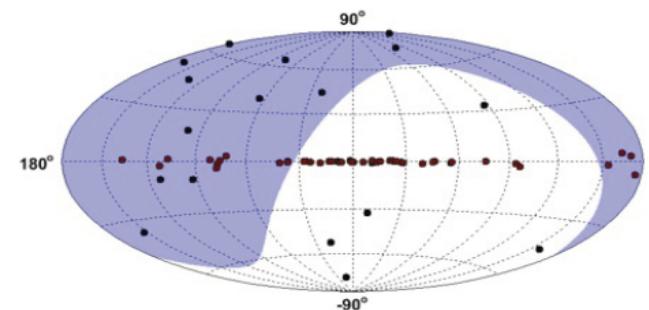
- > 75%
- 25% – 75%
- < 25%



Complementary
fields of view
(below 100 TeV)

Visibility South Pole (IceCube)

- 100%
- 0%

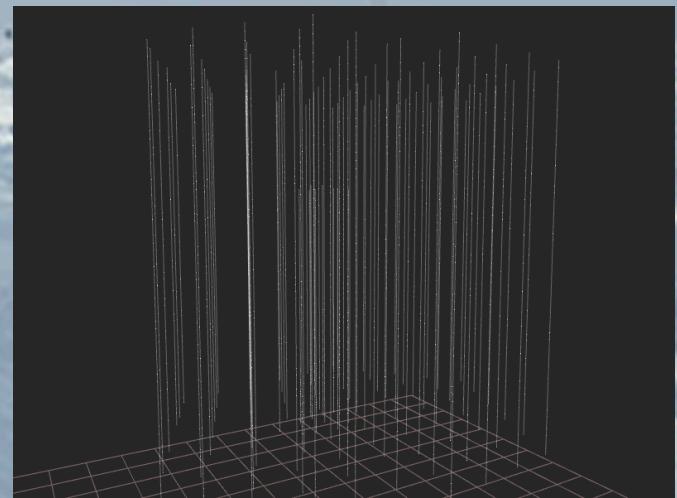
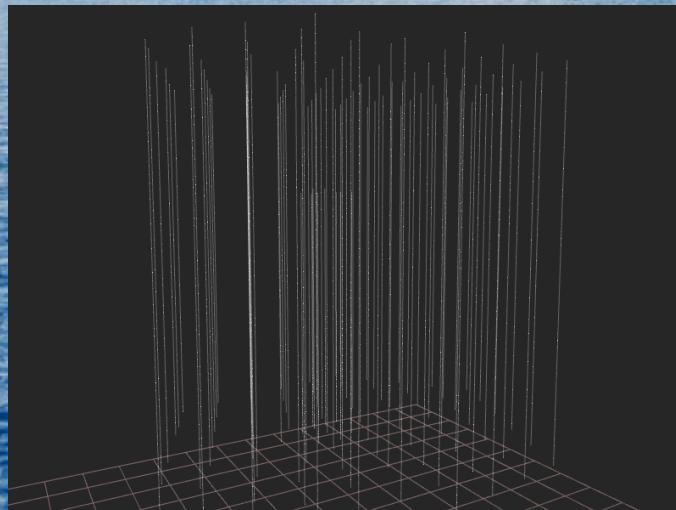


Mediterranean: logically attractive
Optical noise/ ^{40}K (use for calibration)

Water: better tracker!

Different
environments

Quiet environment, low noise
Ice: better calorimeter!



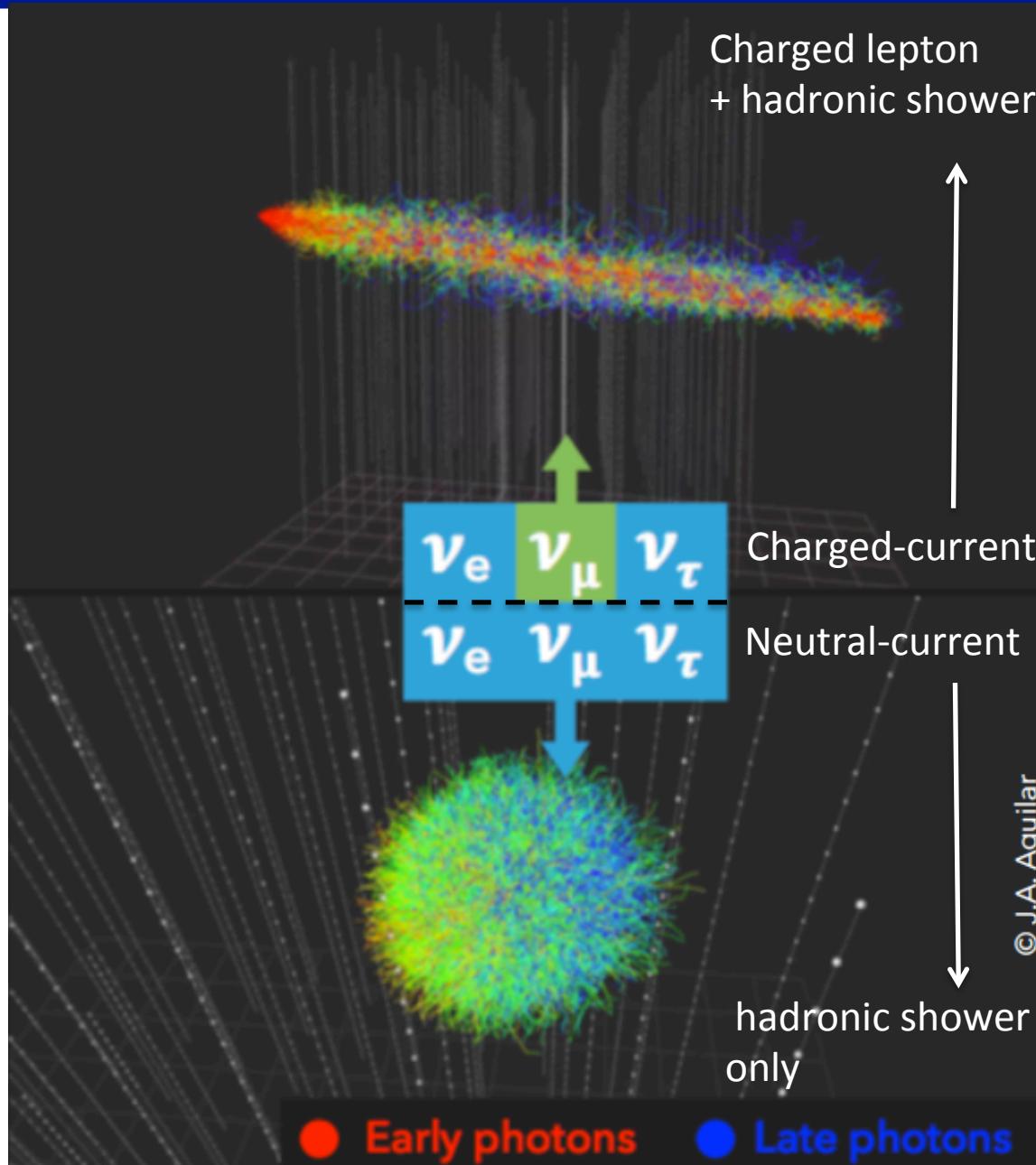
Event topologies

TRACKS:

- Only for ν_μ – induced muons
- Good angular resolution:
 - < 0.1° - 0.4° in water
 - < 1° in ice
- interaction vertex can be outside of the detector:
→ increased effective volume

SHOWERS (or CASCADES):

- Sensitive to ν_e , ν_τ flavours
(and neutral-current interactions)
- Mostly contained events,
quasi-spherical topology
→ Limited angular resolution
 - ~ 1° - 3° in water
 - ~ 10° in ice
- Good energy resolution (~5 %)



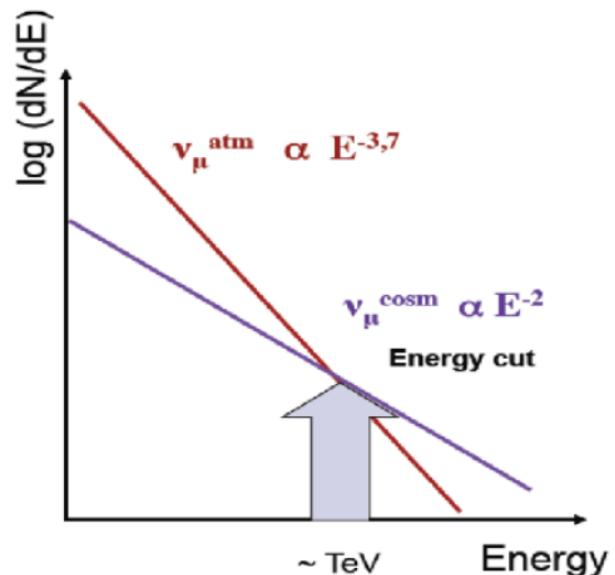
Analysis principle

- ❖ Looking for excess at high energies

→ diffuse flux analyses

Focus at high energies where the astrophysical neutrino flux is expected to dominate over the atmospheric one

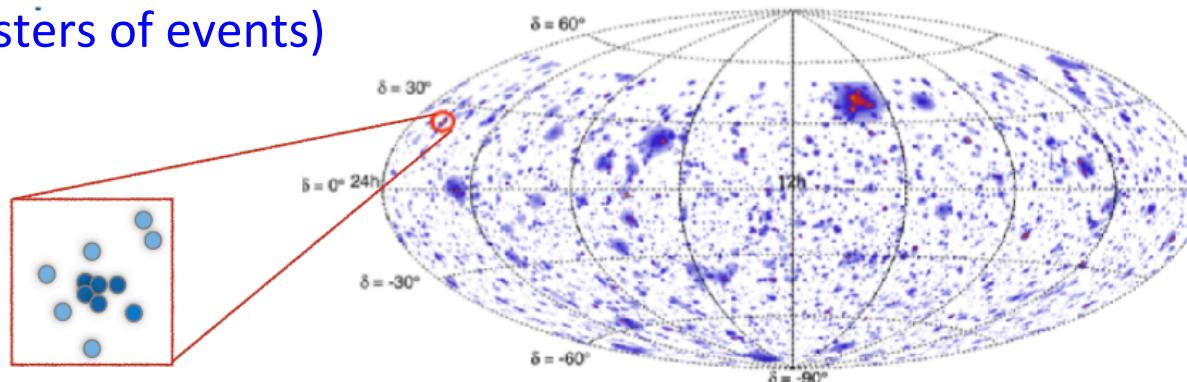
- Requires good energy resolution
- useful for unresolved, non localized source populations (e.g. extragalactic sources) or large regions of the sky (Galactic Plane, Fermi bubbles...)



- ❖ Looking for anisotropies (clusters of events) in the sky

→ Point-source searches

- Requires good angular resolution



- ❖ Looking for coincidences with other astrophysical signals

→ Multi-messenger searches

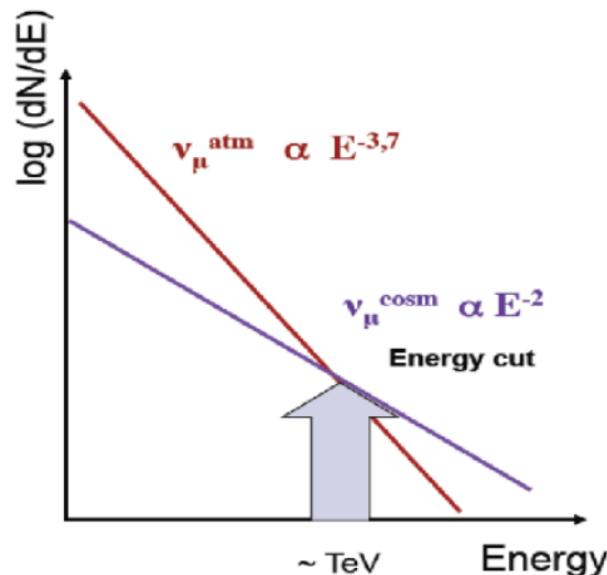
- Requires spatio-temporal coincidence with other probes (cosmic rays, photons, grav. waves)

Analysis principle

- ❖ Looking for excess at high energies
→ diffuse flux analyses

Focus at high energies where the astrophysical flux is expected to dominate over the atmospheric flux.

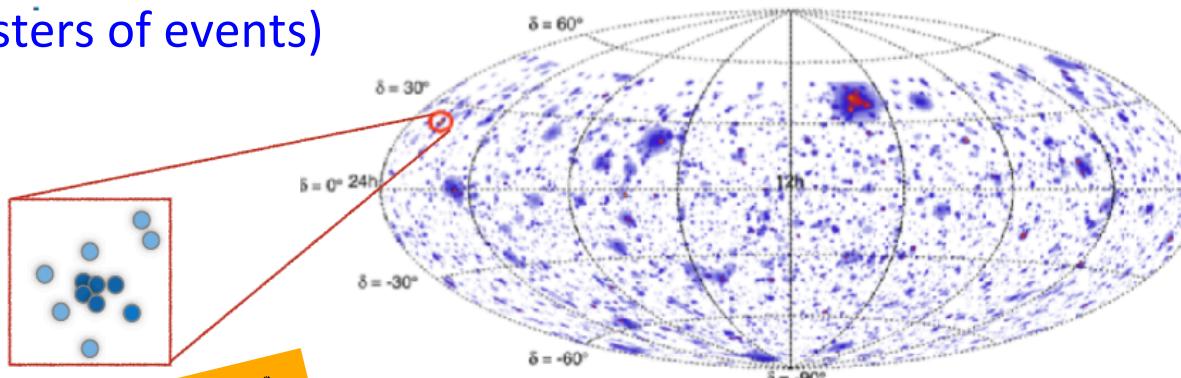
- Requires good energy resolution
- useful for studying unlocalized source populations (e.g. extragalactic point sources) or large regions of the sky (Galactic Plane, Fermi bubbles...)



- ❖ Looking for anisotropies (clusters of events) in the sky

→ Point-source searches

- Requires good angular resolution



- ❖ Looking for coincidences with other signals

→ Multi-messenger

- Requires spatial coincidence with other probes (cosmic rays, photons, grav. waves)

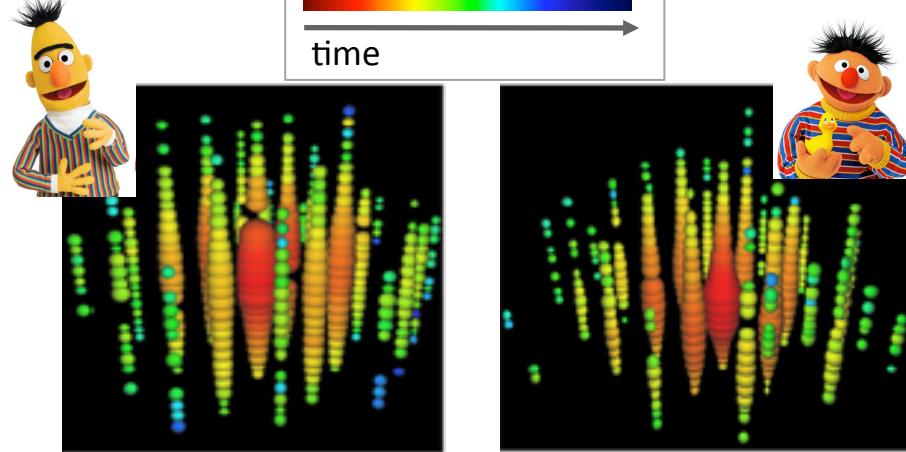
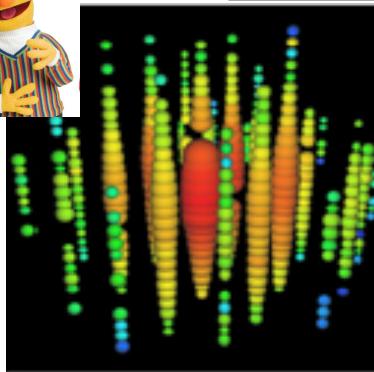
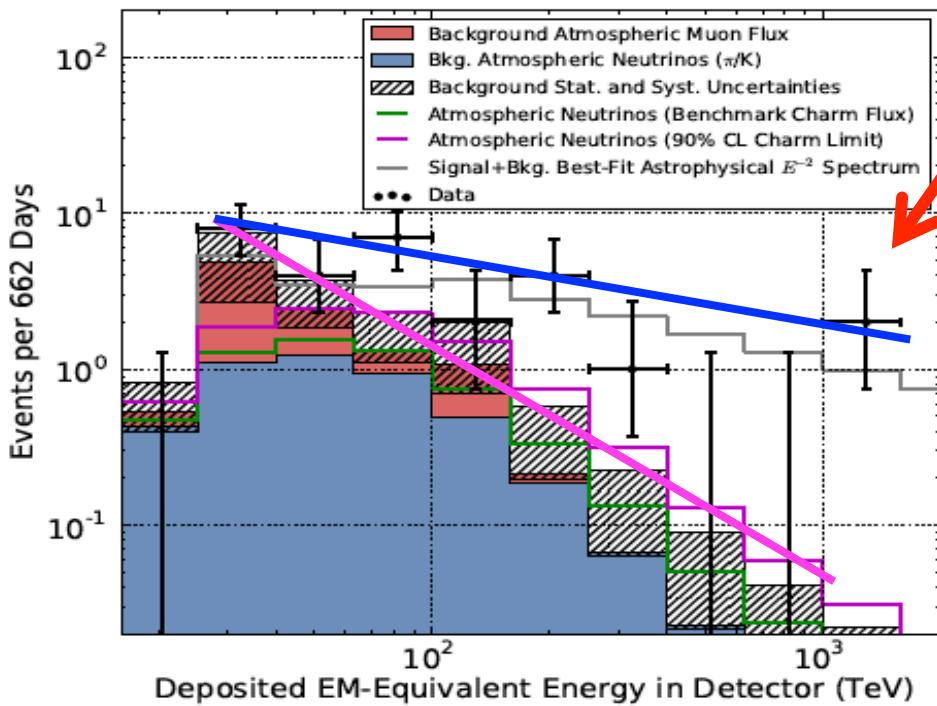
2017: IceCube first event with EM counterpart!

HE neutrino astronomy: the debuts

2013

First detection of HE cosmic neutrinos by IceCube!

- ❖ 2 shower events at PeV: Ernie & Bert
- ❖ Analysis reoptimized to select high-energy starting events (HESE):
energy threshold ~ 30 TeV
+ veto against μ_{atm} & ν_{atm}



1.0 +/- 0.2 PeV

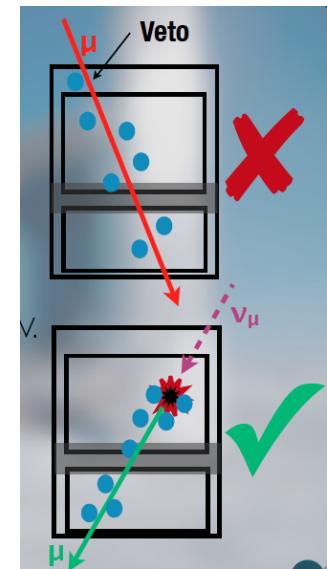
1.1 +/- 0.2 PeV

2 years data:

28 observed events
(7 tracks & 21 cascades)

11 background events
expected (μ_{atm} & ν_{atm})

Significance 4.1σ



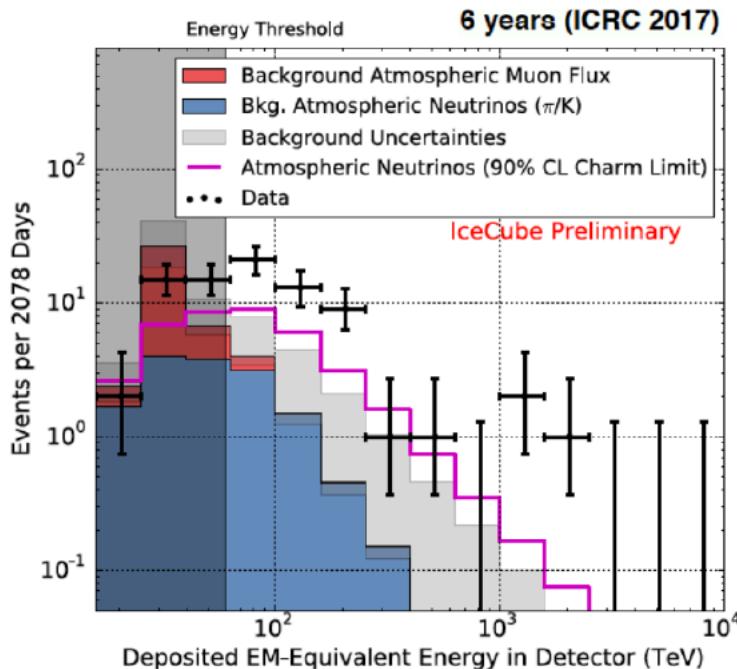
The IceCube signal(s) today

6 years HESE analysis (ICRC2017)

80 (+2) events

Northern & Southern hemispheres

Threshold energy 60 TeV



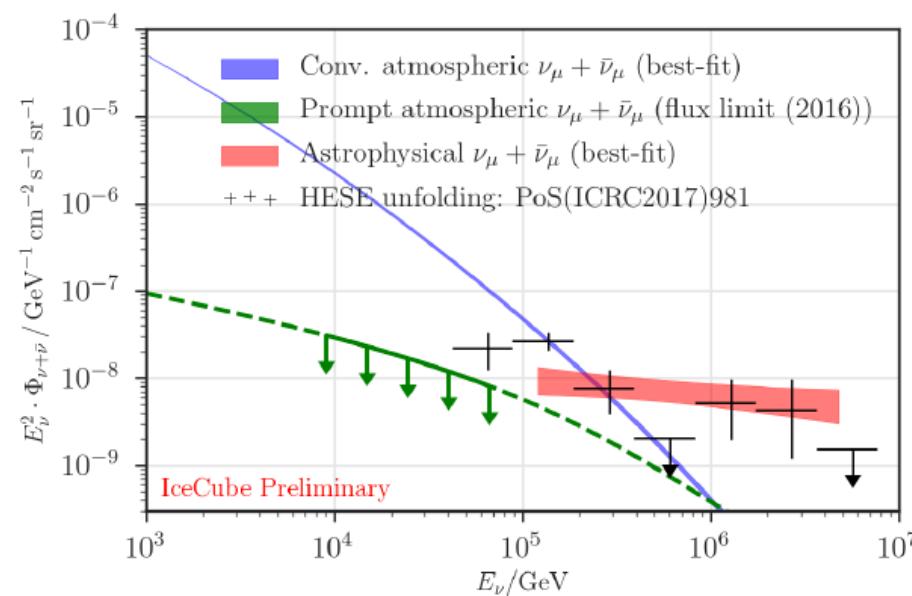
Significance: 6.5σ
Spectrum fit: $\sim E^{-2.92(+0.33 -0.29)}$

8 year upgoing muon sample (ICRC2017)

36 events

Northern hemisphere only

Energy range 200 TeV – 10 PeV



Significance: 6.7σ
Spectrum fit: $\sim E^{-2.19(\pm 0.10)}$

- Indication of a break/hardening in the spectrum ? (different energy thresholds)
- Indication of galactic and extra-galactic components ? (different hemispheres)

ANTARES results

Diffuse flux searches

9-years sample

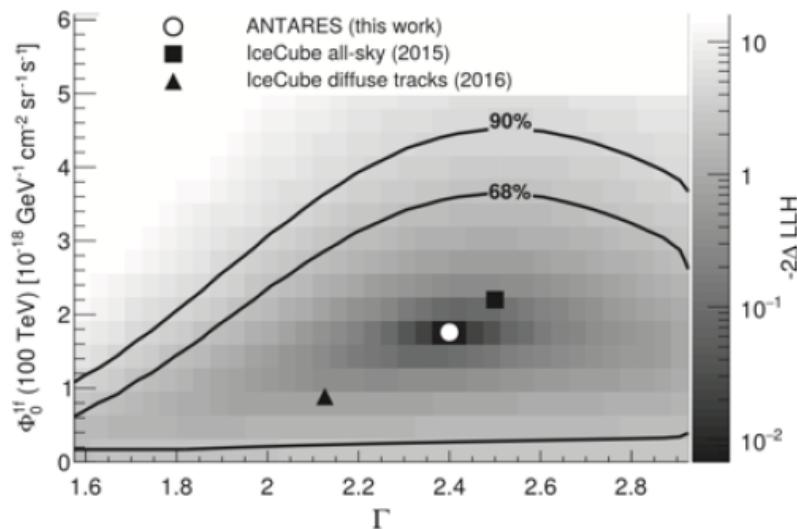
All-sky / all-flavour search

Tracks + Cascades

	Bkg expectation	Signal expectation	Nb events measured
Track	13.5 ± 4	3-3.5	19
Shower	10.5 ± 4	3-3.5	14

...first hints of a signal ?

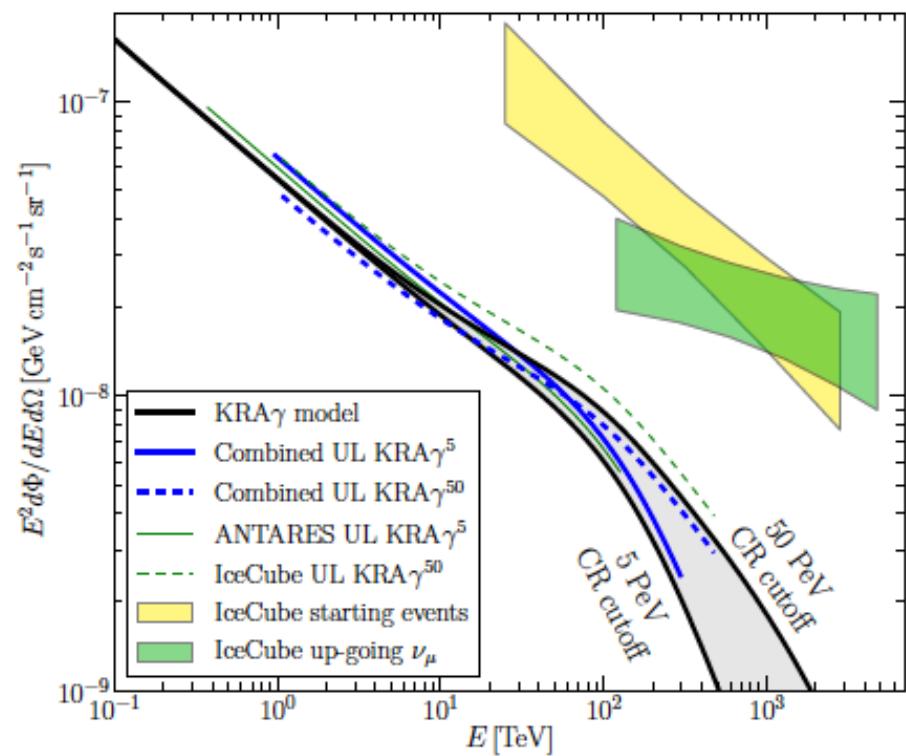
Hypothesis of null cosmic flux
excluded at 1.6σ ...



Galactic diffuse neutrino emission

Combined analysis ANTARES+IceCube

Test of KRAγ model: cosmic ray diffusion in the Galaxy (Gaggero et al.)

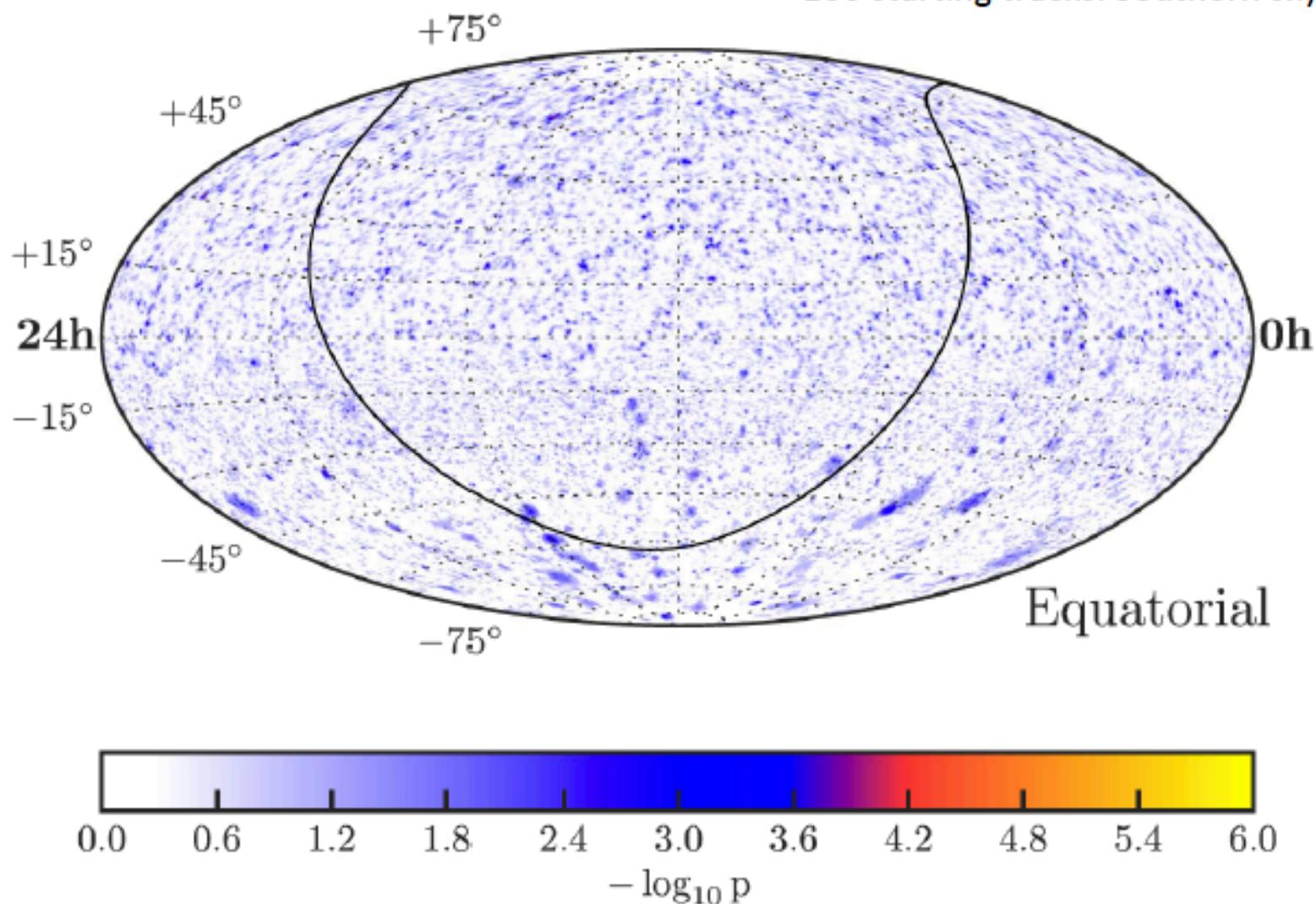


50 PeV CR cutoff disfavoured
diffuse Galactic contribution
to IceCube flux limited to < 8.5%

Searches for neutrino point sources

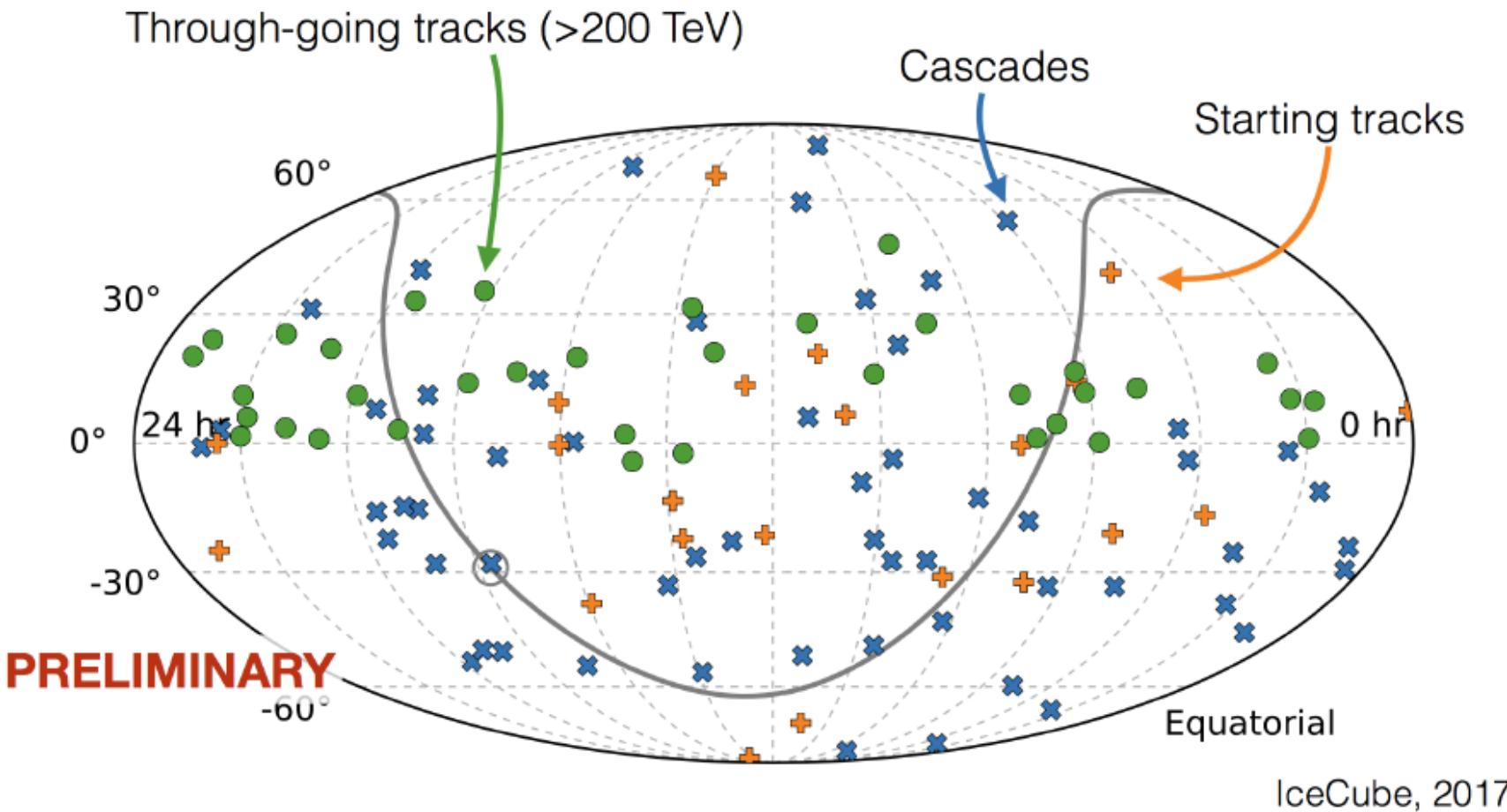
IceCube skymap with 7 years of data:
mostly background!

Most recent data periods:
~80k northern hemisphere evt/yr (atm ν)
~35k southern hemispher evt/yr (atm μ)
~200 starting tracks. Southern sky



Searches for neutrino point sources

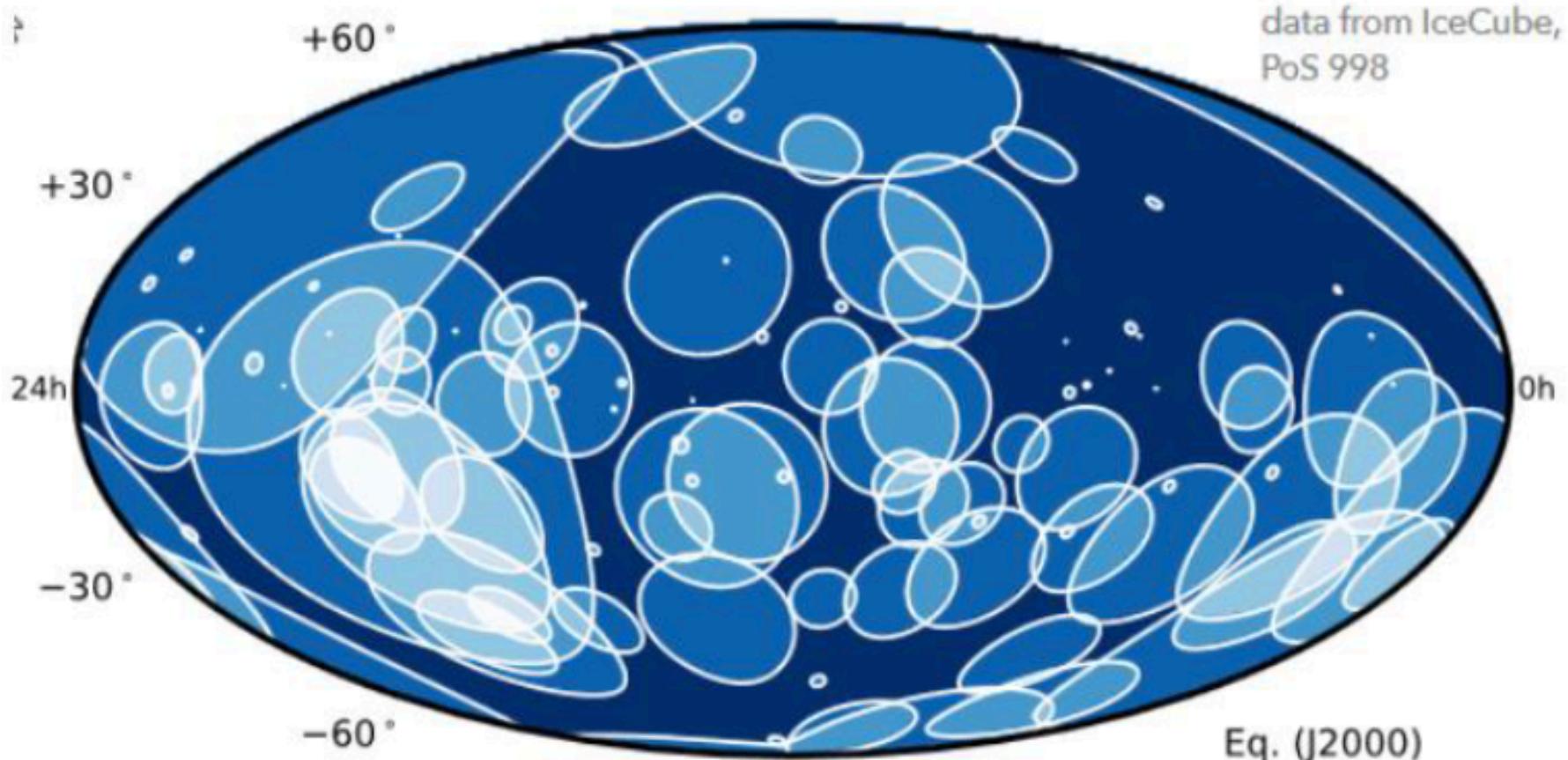
After selection of candidate cosmic neutrinos:



No evidence of clustering in high-energy neutrino directions
mostly isotropic \Rightarrow neutrinos of extragalactic origin

Searches for neutrino point sources

...but limited angular resolution, especially for cascade events...



Better performance for
cascade reconstruction
in water:

Resolution for ν_e	
ANTARES	○
KM3NeT	○

Multi-messenger programs



Gamma rays
GeV-TeV



Searches for neutrinos in coincidence with GRBs, blazars, microquasars, X-ray binaries,...
Correlations with astrophysical catalogues...
EM follow-up (Fermi, MAGIC,...)

Ultra-high energy Cosmic Rays



Searches for spatial correlations with Auger and TA UHECR events

HE Neutrinos

Optical /
X-rays

Target of Opportunity programs
EM follow-up: optical/X-ray
(TAROT, ROTSE, Swift...)

- ❖ Increase in sensitivity (independant datasets, time constraint)
- ❖ Better understanding of astrophysical processes at play in the sources
- ❖ Huge effort in the development of real-time alert programs

Gravitational waves



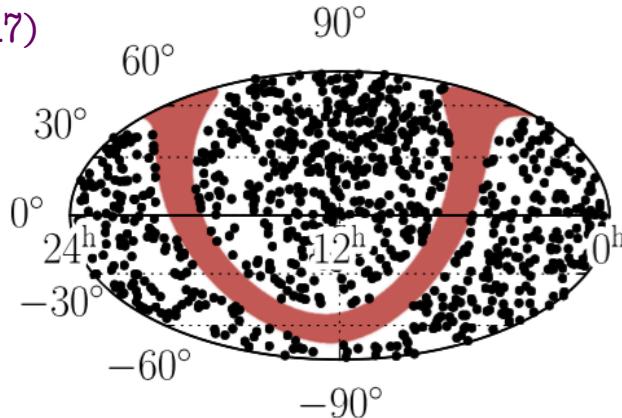
GWEN: joint searches of HE Neutrinos and gravitational waves:
ANTARES+IceCube +LIGO+Virgo



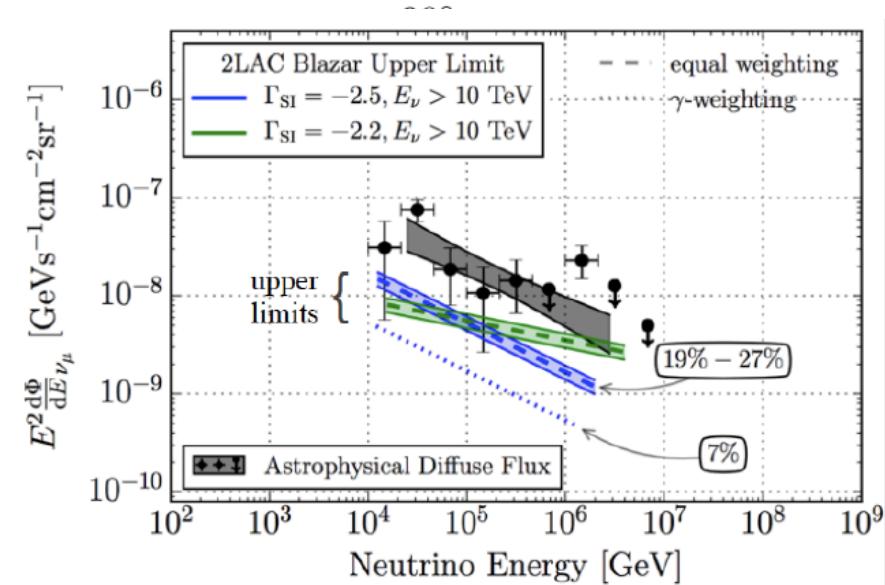
Neutrino - EM connection: examples

❖ IceCube stacked search for neutrinos from Fermi-LAT Blazars (2LAC catalogue)

ApJ 835 (2017)



Blazars contribute less than 30% to observed diffuse neutrino flux



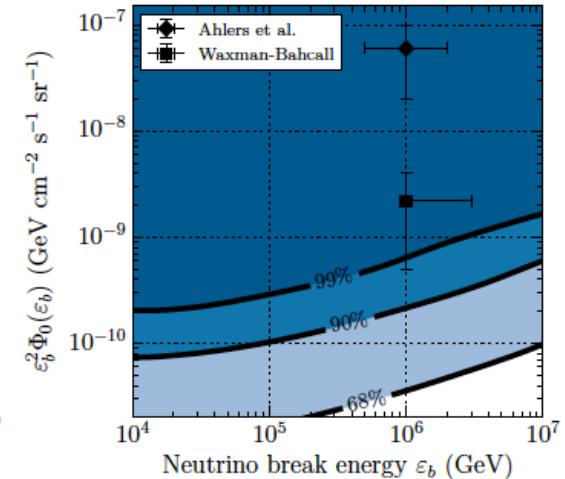
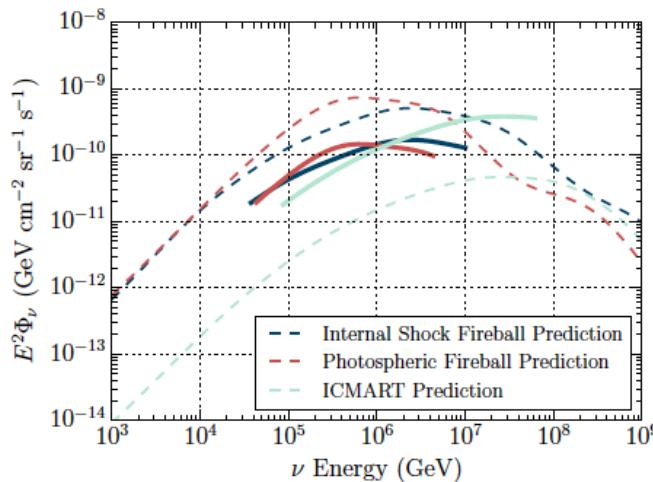
❖ IceCube searches for prompt neutrinos in coincidence with Gamma-ray bursts

All-sky, tracks & cascades

1172 GRBs correlated

GRBs contribute <1% to observed diffuse neutrino flux

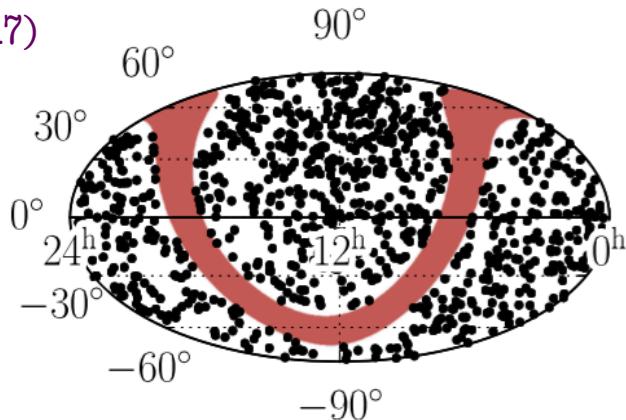
Disfavours GRBs as main source of UHECR ?



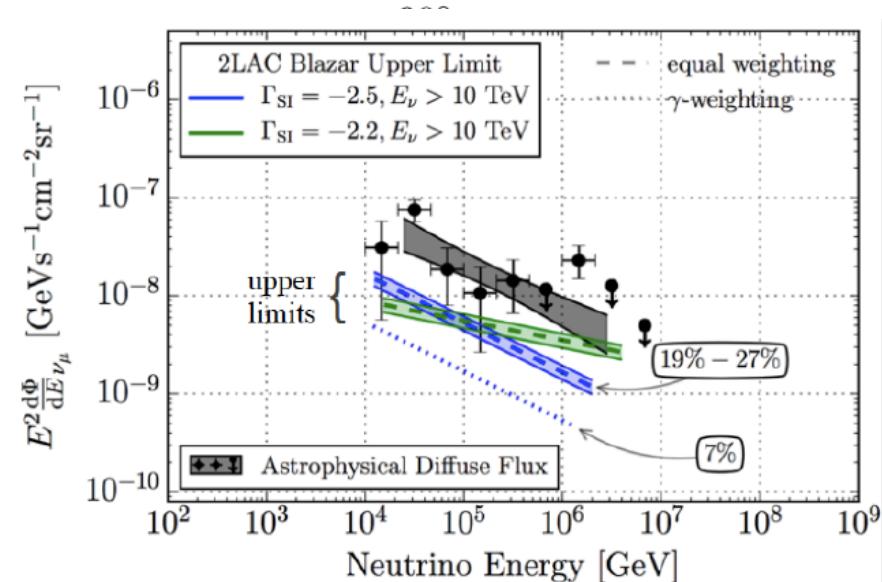
Neutrino - EM connection: examples

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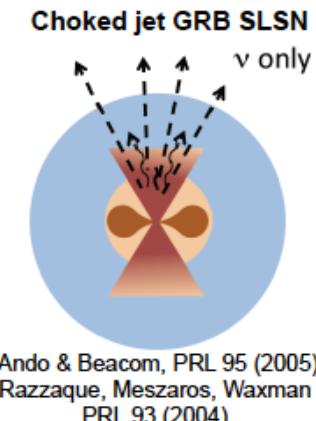
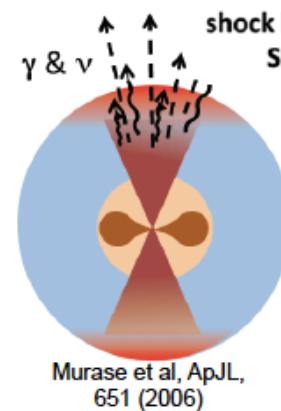
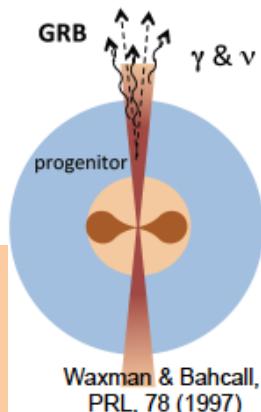
Blazars contribute less than 30% to
Observed diffuse neutrino flux



❖ IceCube searches for prompt neutrinos in coincidence with Gamma-ray bursts

...CAVEAT: potentially large population of low-luminosity/
choked GRBs not constrained !

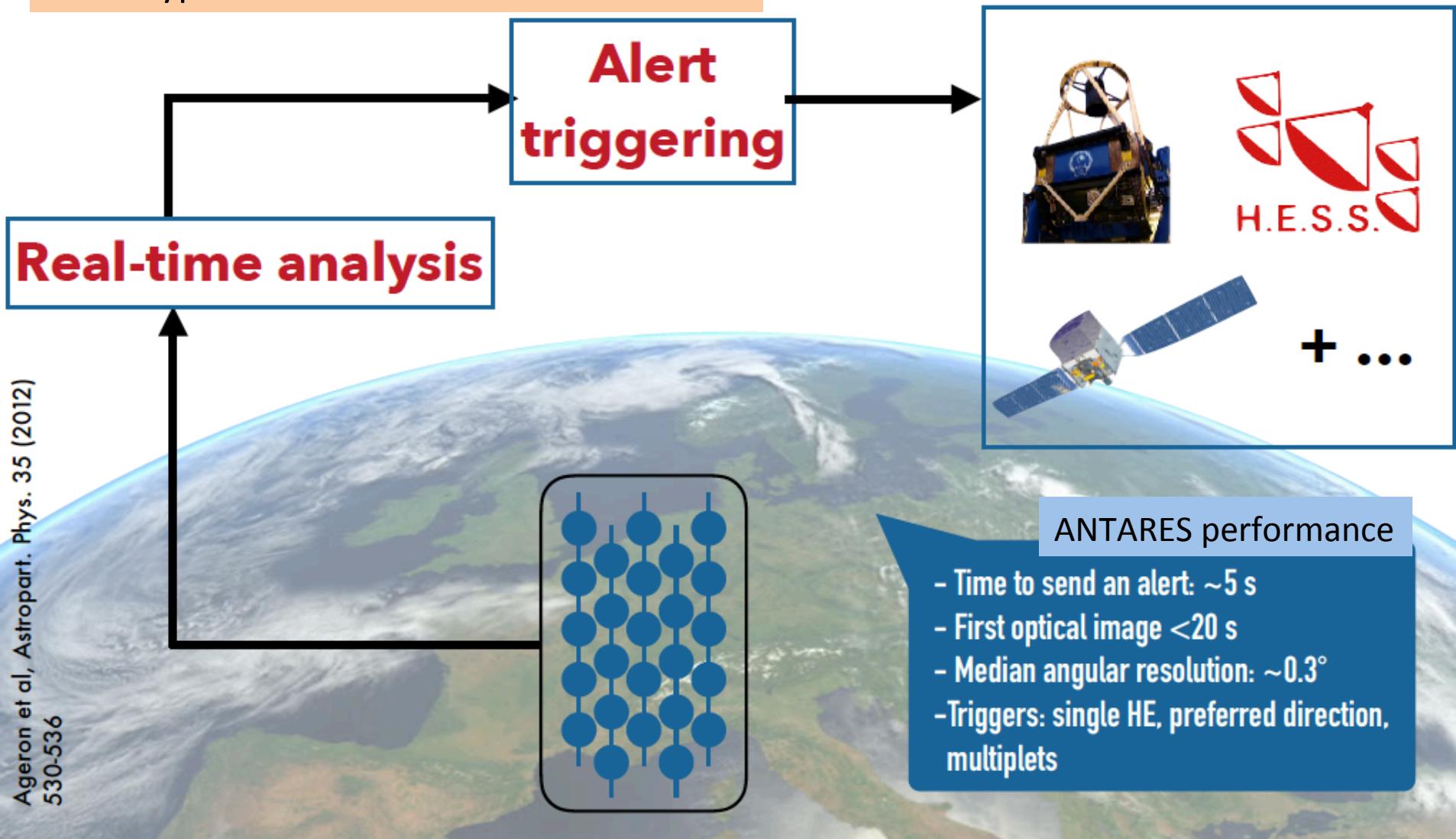
Look for association with SN
→ Trigger EM follow-up of neutrino
events: Target of Opportunity programs



Credit: A. Franckowiak

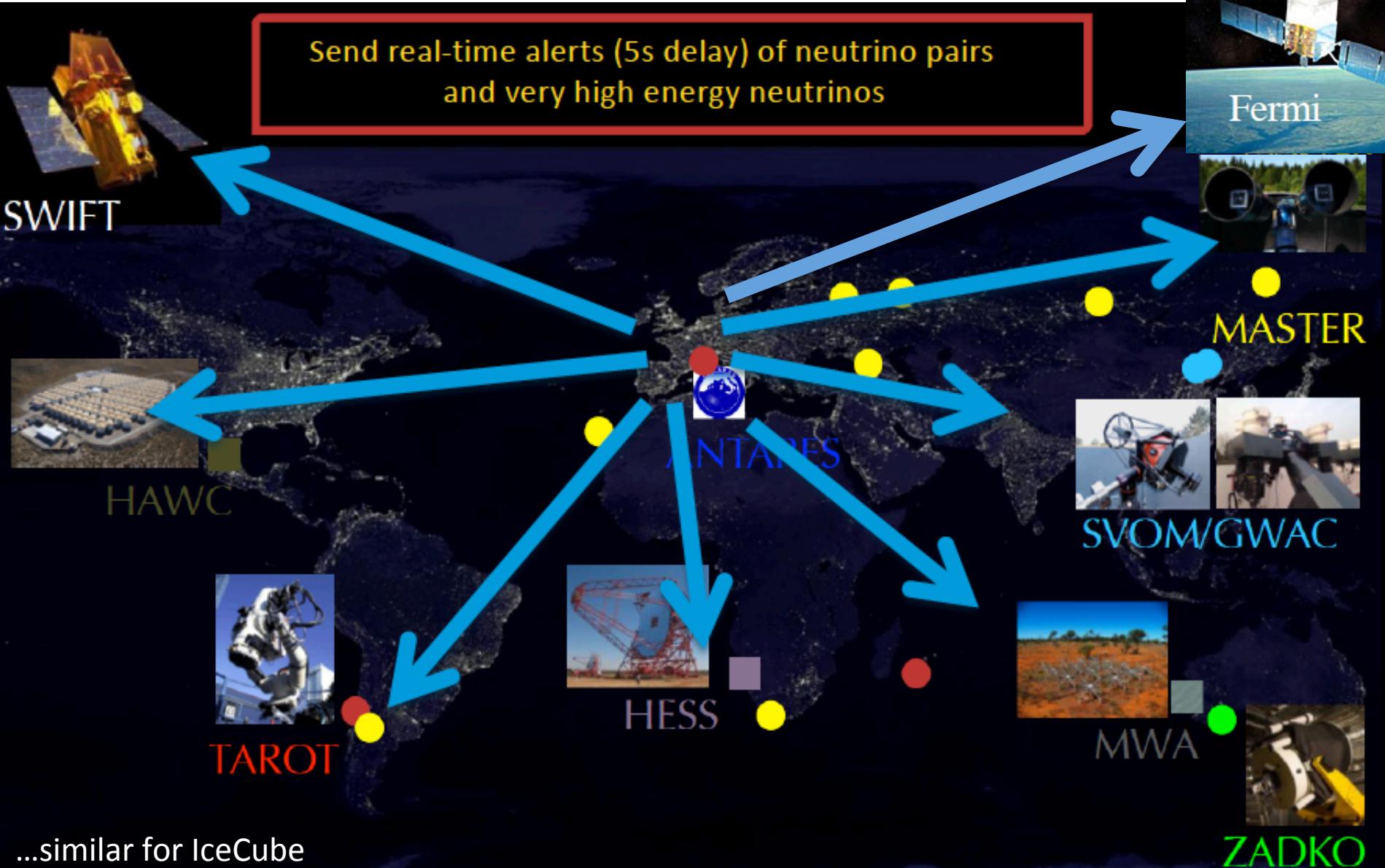
EM follow-up of neutrino events

- extended sky coverage, high duty cycle
- no hypothesis on the nature of sources



EM follow-up of neutrino events

Multi-wavelength observatories linked to ANTARES for real-time analysis:



The Supernovae Early Warning System

The detection of even a single neutrino in association with a nearby supernova would reduce the uncertainty on the start time from ~ 1 day to ~ 10 seconds, which would help for GW searches for instance.

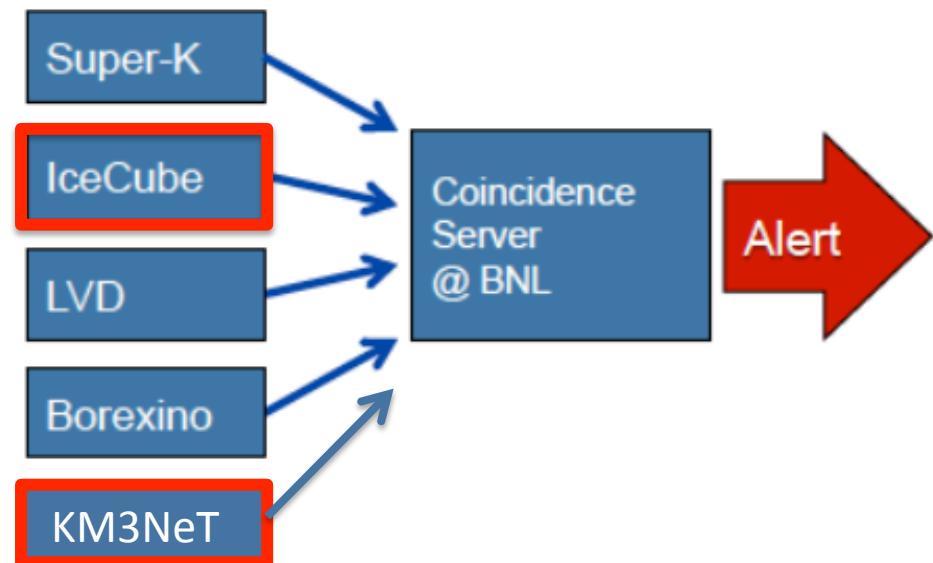
+ trigger of EM observations



<http://snews.bnl.gov>

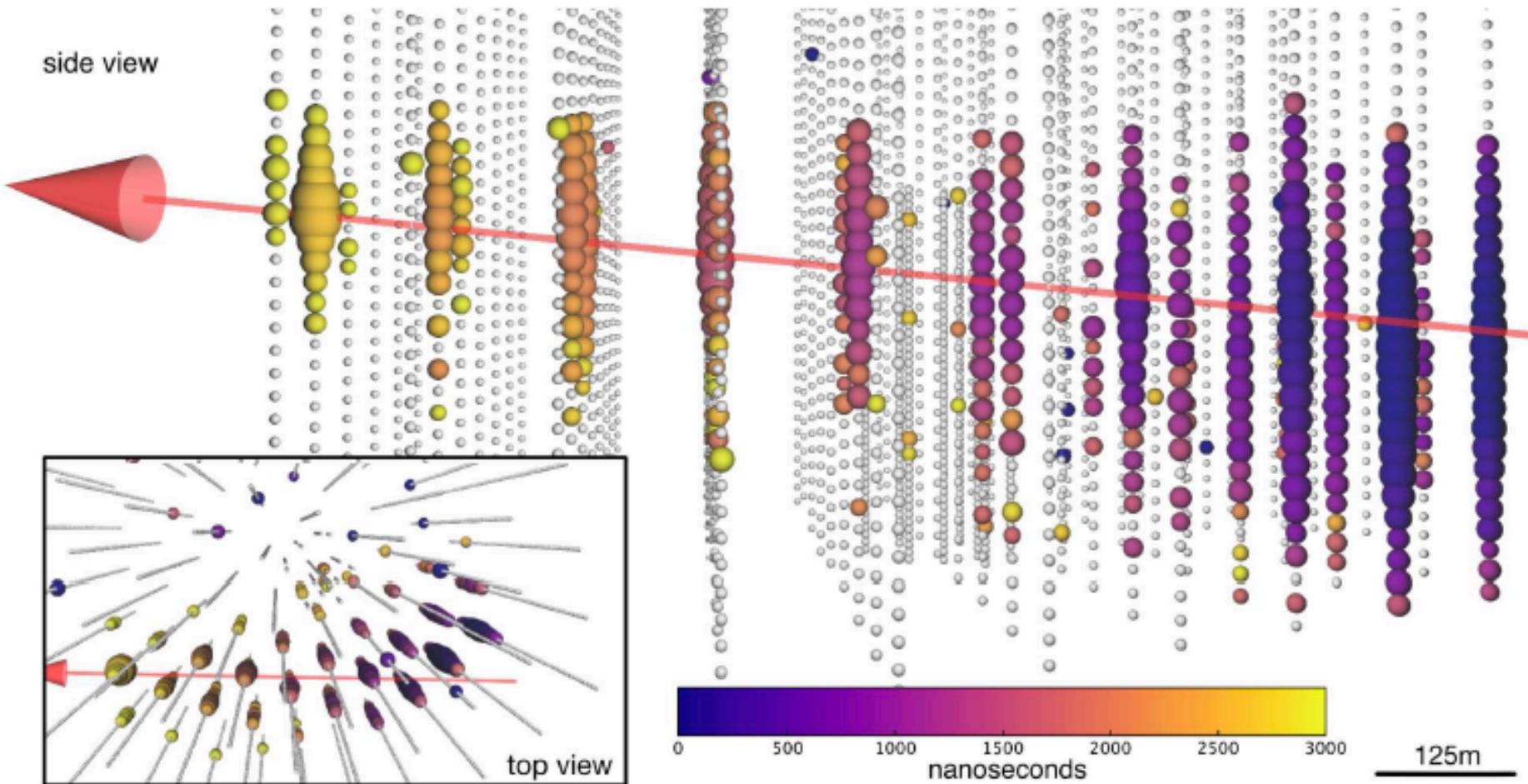
- Neutrinos arrive several hours before photons
- Can alert astronomers several hours in advance

...neutrino telescopes are sensitive to MeV transients, too!



First neutrino-EM correlation: TXS0506+056

An IceCube Extremely High Energy Event occurred on 22d September 2017 20:54:30 UTC



Most probable energy: 290 TeV

First neutrino-EM correlation: TXS0506+056

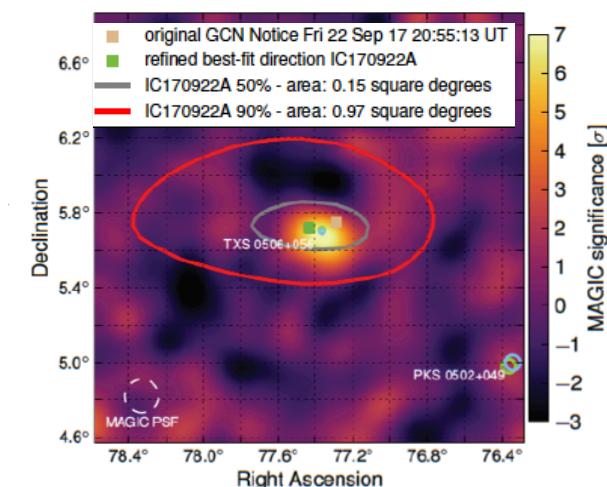
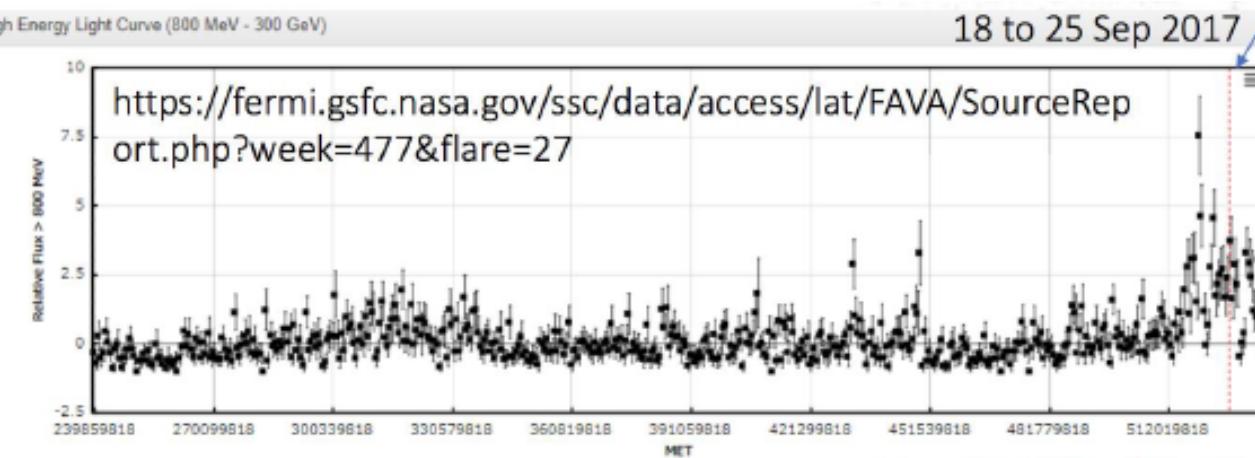
Event occurred: September 22d, 2017 20:54:30 UTC

↳ First GCN notice sent 43s later

↳ Revised coordinates sent 4 hours later

Follow-up responses:

- GCN 21917 – INTEGRAL : no detection
- Atel 10971 – Fermi: increased gamma-ray activity of TXS0506+056 (RA 77.36° , Dec $+5.69^\circ$) Blazar, among the 50 brightest sources of 3LAC sources
- ATel 10817 – MAGIC: First-time detection of VHE gamma-rays (up to 400 GeV)



- ...and observations/reports by many more:

"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A," The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, 2018

First neutrino-EM correlation: TXS0506+056

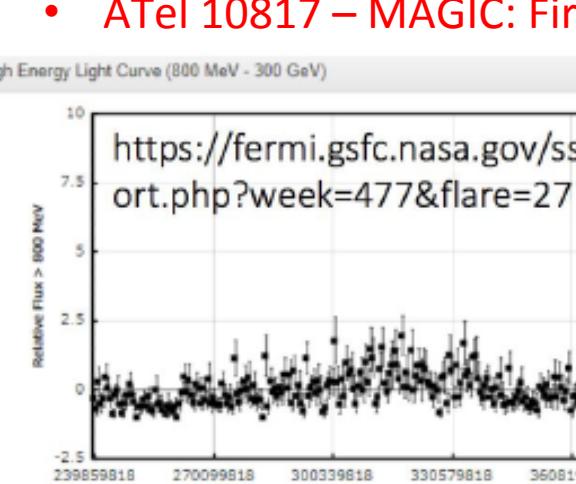
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Follow-up responses:

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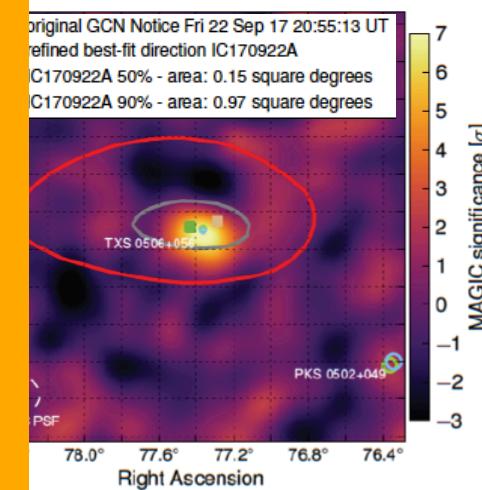


Chance probability of neutrino-gamma association:

Pre-trials p-value: 4.10

Post-trials p-value: 3.00
(10 alerts, 41 archival events)

→ Random coincidence excluded at 99.73% C.L.



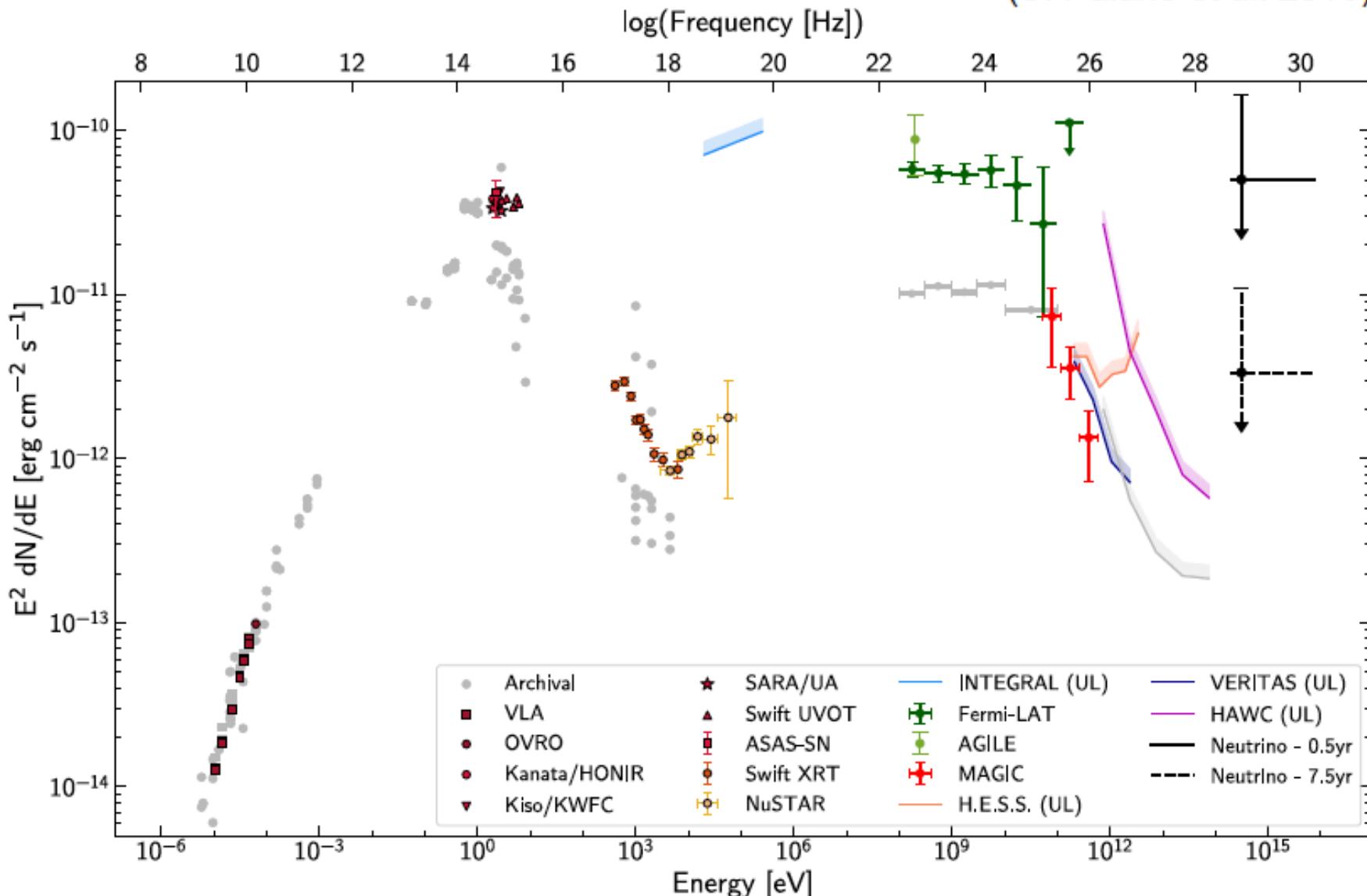
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GWHEN: neutrinos and gravitational waves

...The first multi-messenger SED of a blazar ☺

Redshift 0.3365 ± 0.0010
(S. Paiano et al. 2018)



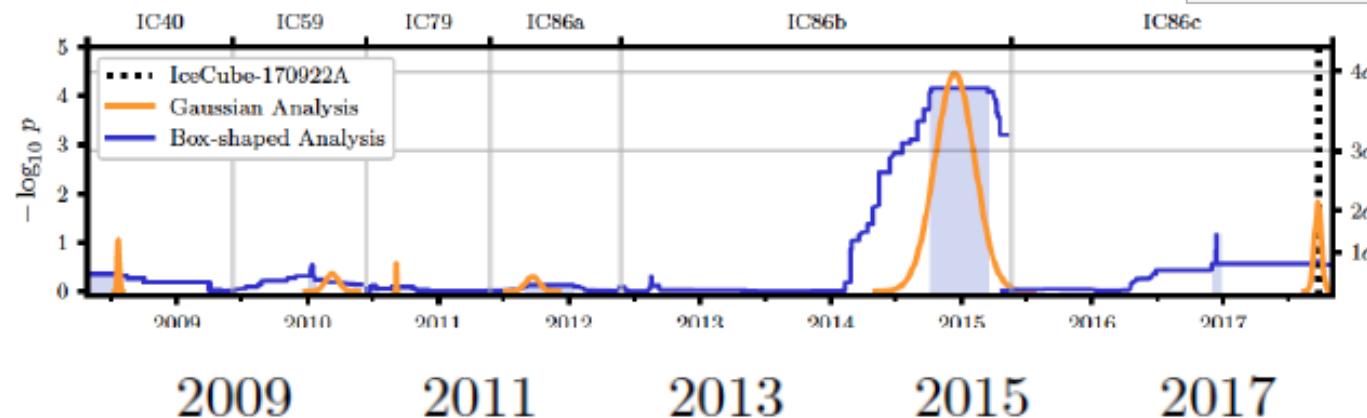
First neutrino-EM correlation: TXS0506+056

+ search for more neutrino flares

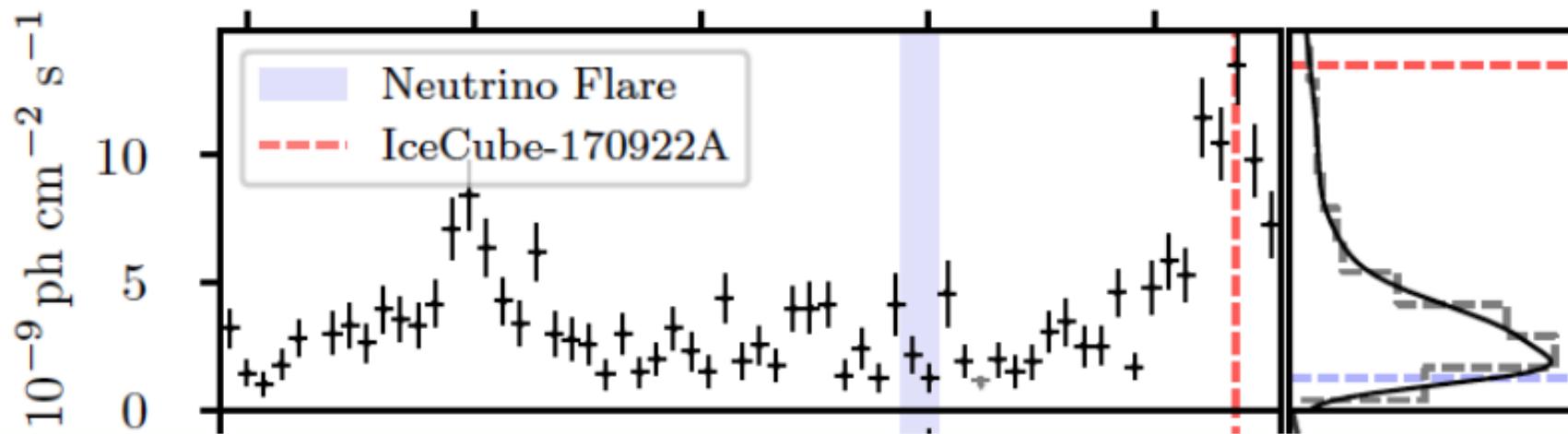
in archival data:

Excess found both with Gaussian-shaped and
box-shaped sliding time window

Best-fit values	Gaussian	Box
Central Date	2014 Dec. 13	2014 Dec. 26
Width	110 days (-1 σ to +1 σ)	158 days
$\nu_\mu + \bar{\nu}_\mu$ fluence	2.1×10^{-4} TeV cm $^{-2}$	2.2×10^{-4} TeV cm $^{-2}$
spectral index	2.1	2.2



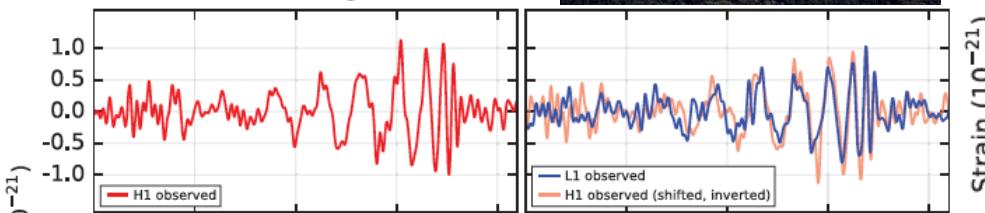
...but no associated flare in Fermi data...?



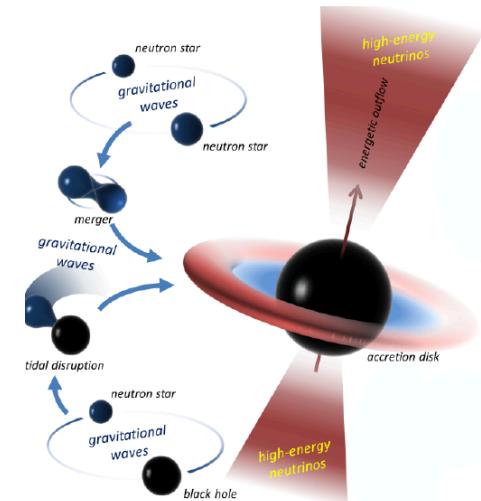
GWHEN: neutrinos and gravitational waves

2015

First detection of gravitational wave event:
GW150914



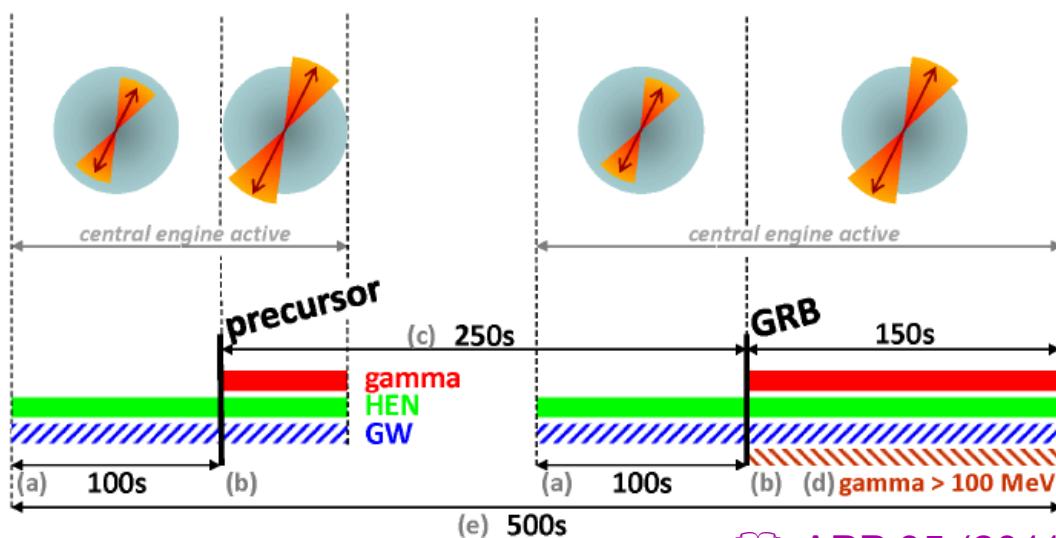
BH – BH merger:
plausible (short)
GRB progenitor



No EM counterpart detected

Neutrino emission expected
if hadronic content in the jet

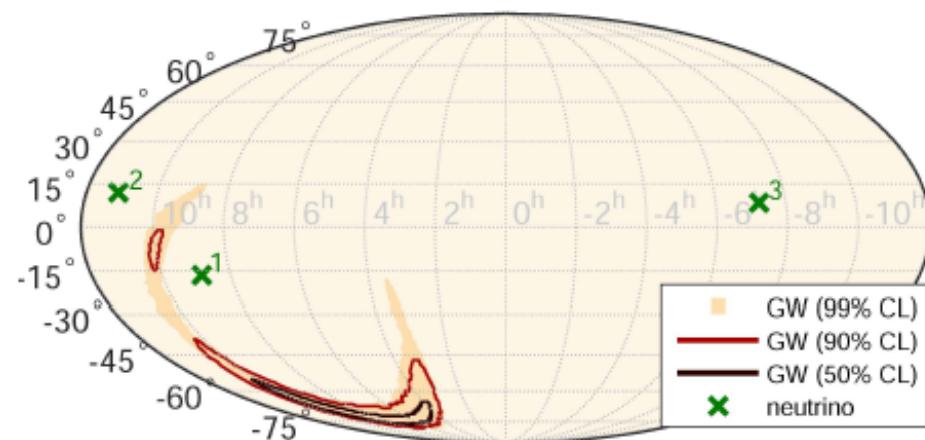
Conservative time window for
neutrino searches (based on long
GRBs): **±500s around GW trigger**



Neutrino follow-up of GW150914

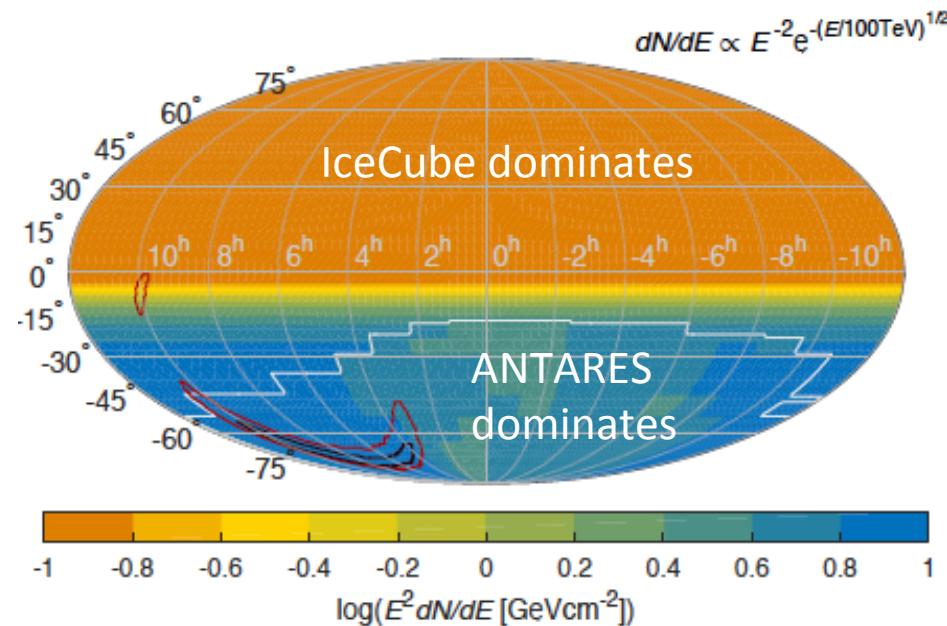
Combined limits IceCube + ANTARES on the neutrino fluence (spectrum E^{-2})

PRD 93 (2016)



3 neutrino candidates IceCube
0 ANTARES

Upper limit on the integrated fluence:
[100 GeV – 100 PeV] or
[100 GeV – 100 TeV]:



$$E_{\nu, \text{tot}}^{\text{ul}} \sim 10^{52} - 10^{54} \left(\frac{D_{\text{gw}}}{410 \text{ Mpc}} \right)^2 \text{ erg}$$

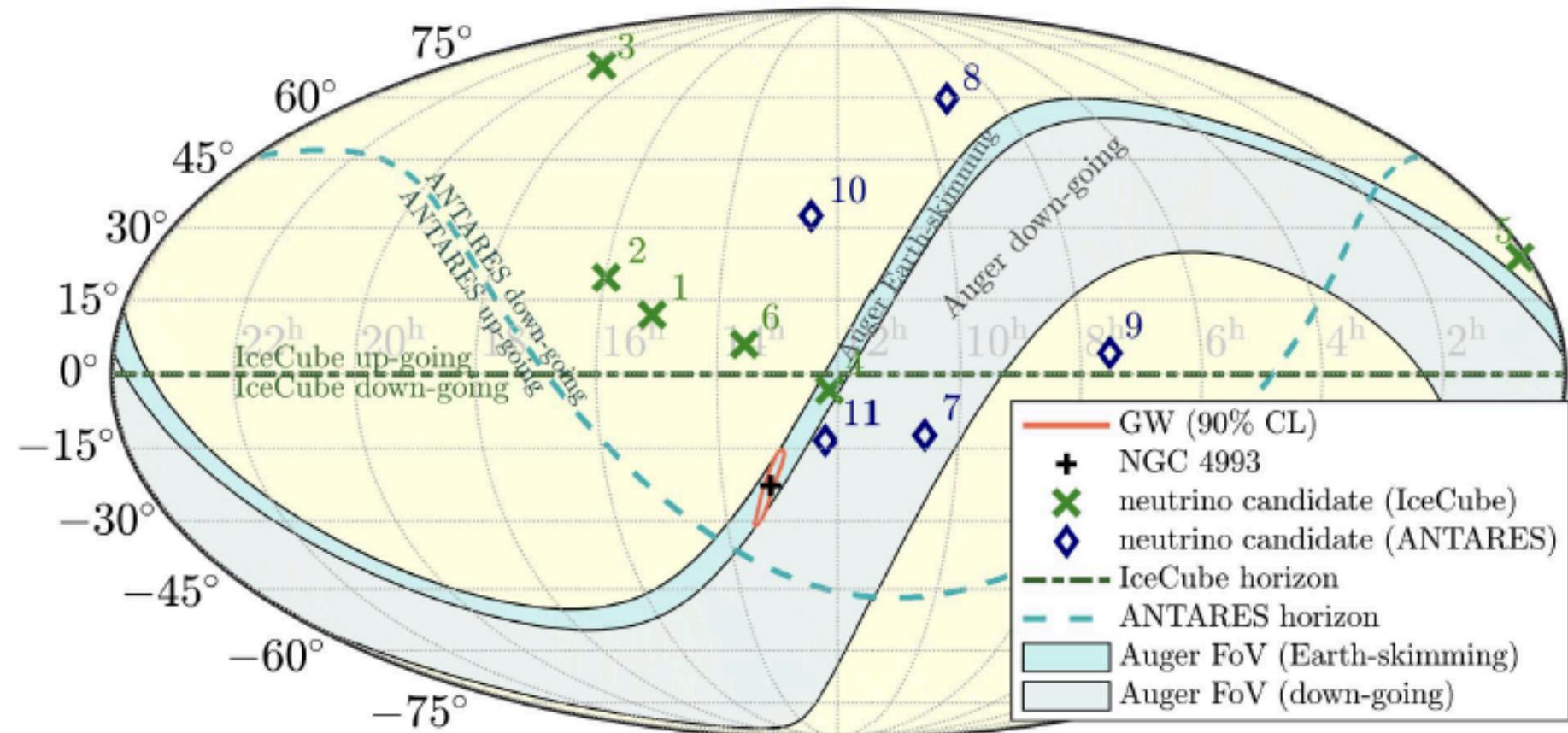
- IceCube & ANTARES provide complementary constraints below ~ 100 TeV
- fast observation of a neutrino counterpart can reduce error box for EM follow-up error for GW150914 : $590 \text{ deg}^2 \leftrightarrow$ ANTARES resolution: : $< 0.5 \text{ deg}^2$
- ...neutrino telescopes part of the online alert network of LIGO/Virgo since O2

GWHEN: neutrinos and gravitational waves

2017

First detection of gravitational wave event with EM counterpart:
GW170817/GRB170817 (see N. Leroy's talk)

Joint study ANTARES – IceCube - Pierre Auger Observatory
No candidate neutrino found within [-500s,+500s] of GW event



The future: KM3NeT & IceCube Gen2

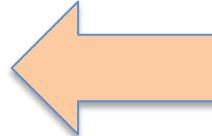
Exciting times for multimessenger astronomy: first cosmic neutrinos 2013

first gravitational waves 2016

first association GW-EM 2017

first association neutrino-EM 2017

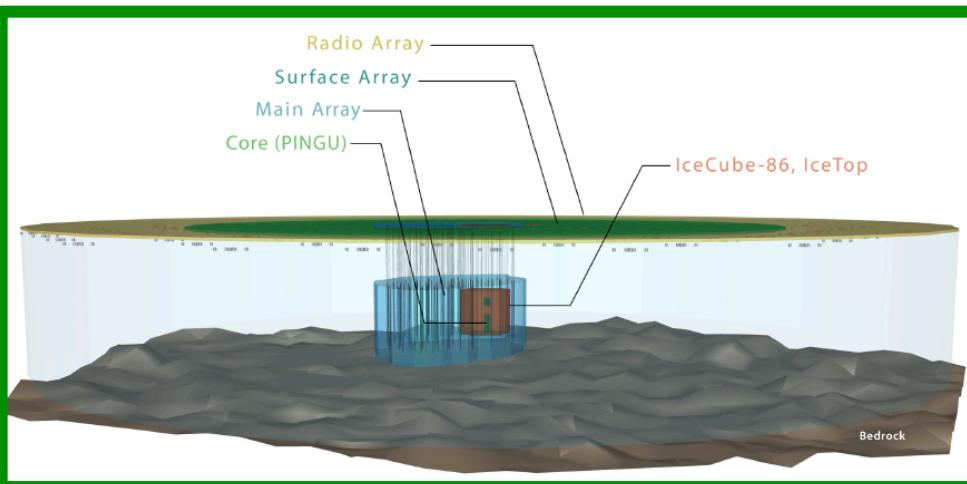
...We need more than
one of each kind!



- more neutrino sources detected/resolved
- possible identification of Galactic vs extragalactic components ?
- performant multi-messenger programs to increase sensitivity
- high-statistics (few km³-scale), all-flavour neutrino astronomy

IceCube Gen2

Phase-1: 7-line prototype
(dense array + calibration)



KM3NeT (ARCA+ORCA)
under construction

