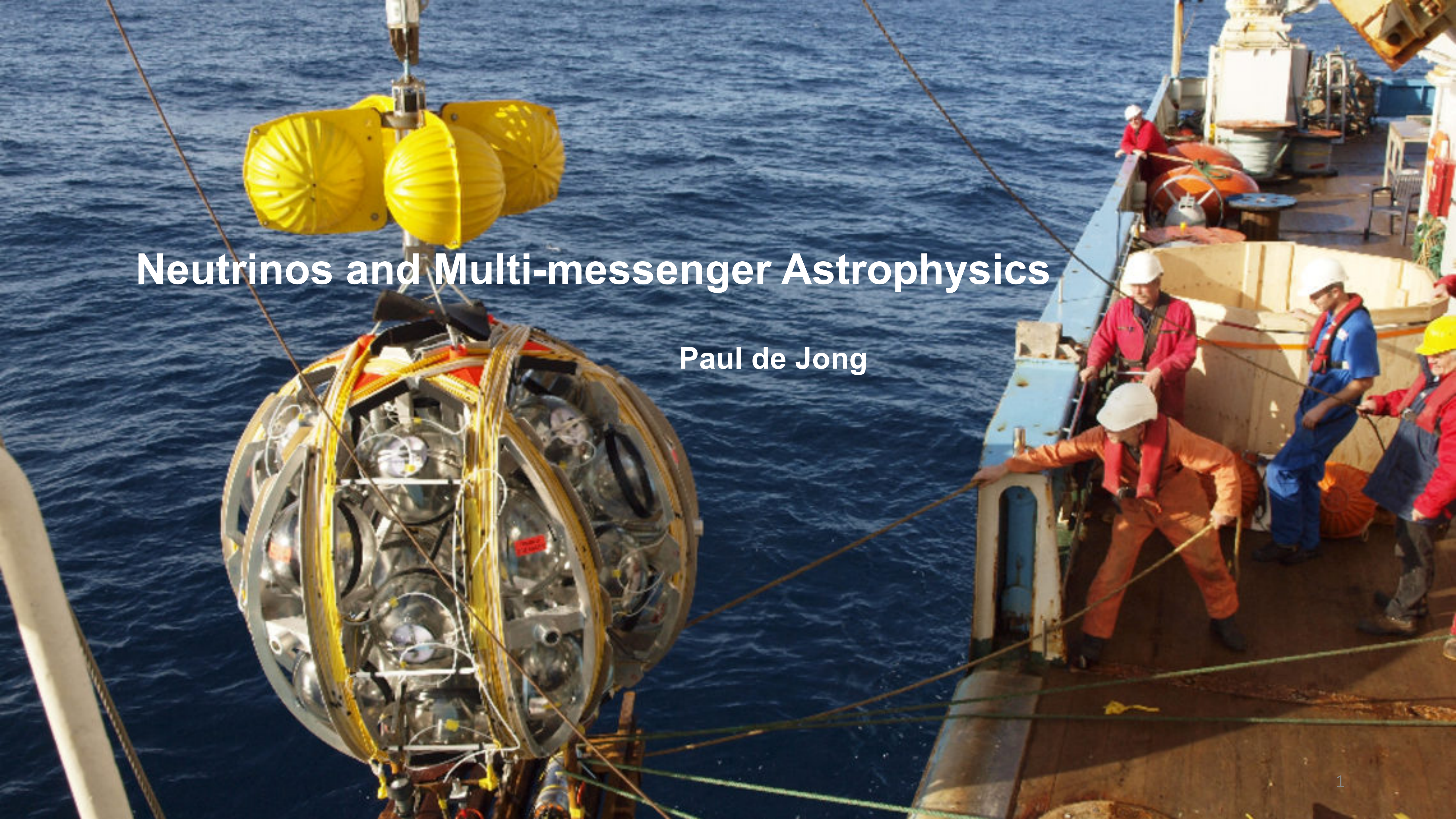
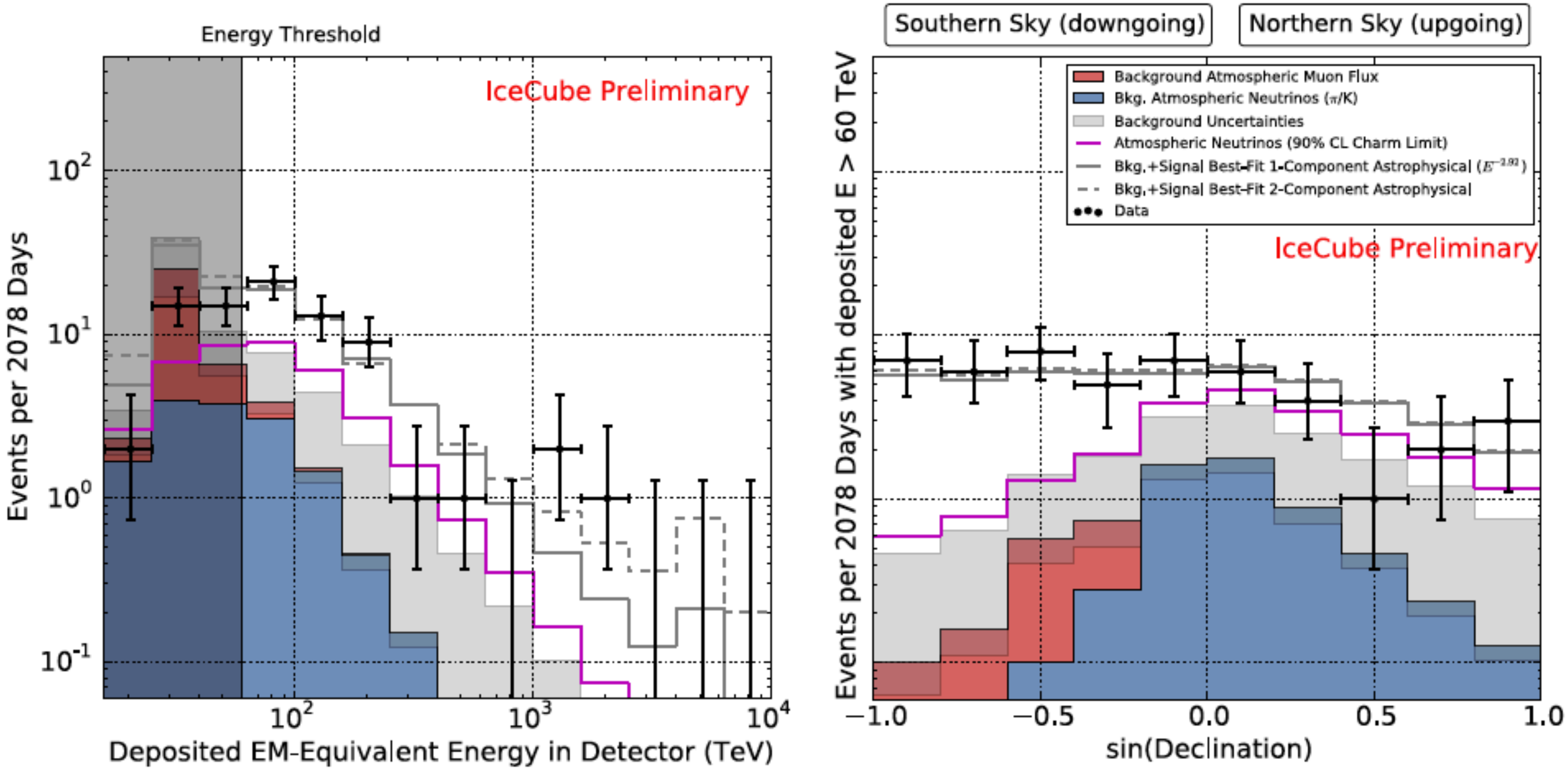


Neutrinos and Multi-messenger Astrophysics

Paul de Jong

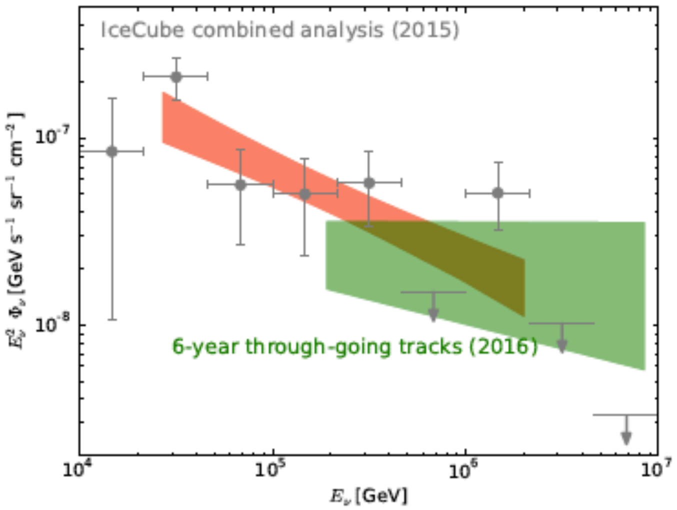
After solar neutrinos and SN1987A, we now finally have a signal for high-energy extraterrestrial neutrinos:

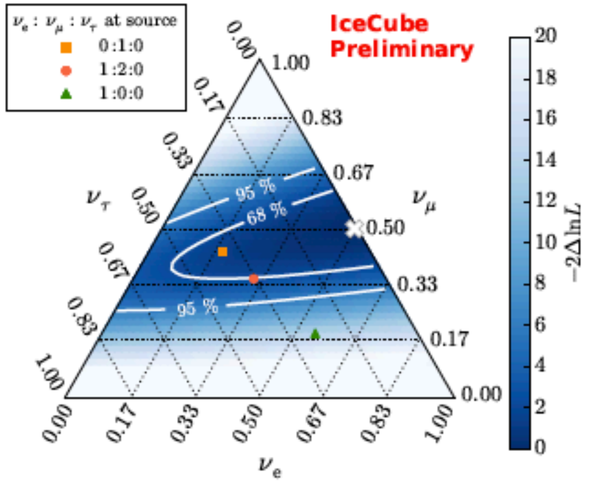


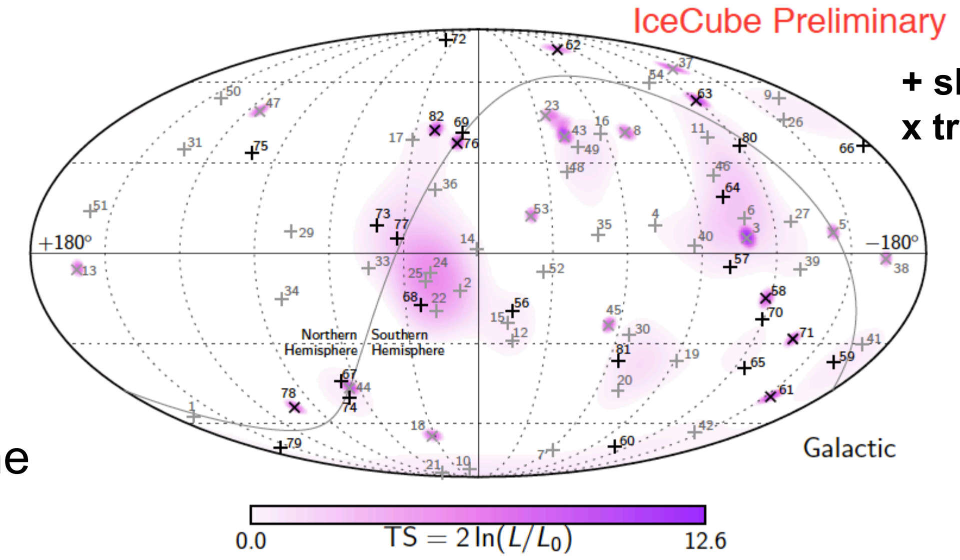
(a) deposited energies (b) arrival directions

IceCube signal: High Energy Starting Events (tracks and showers) + throughgoing muons

Perhaps 2 different spectral indices?







+ showers
x tracks

No sign of clustering
Isotropic
No correlation with galactic plane

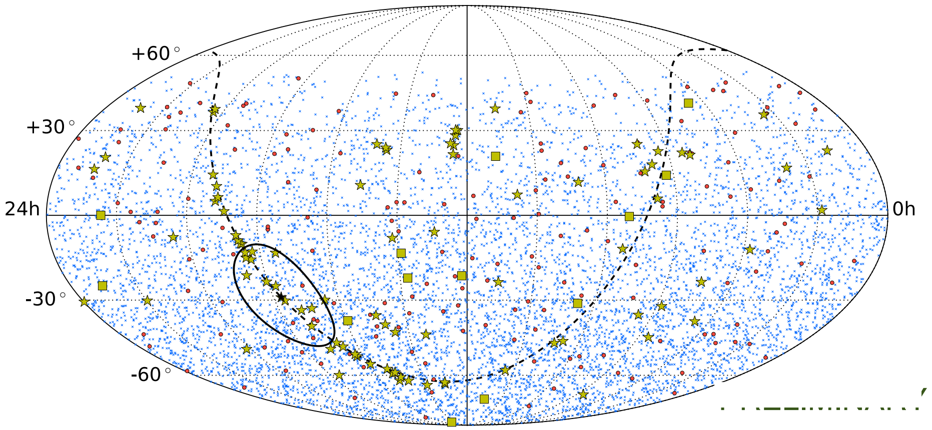
Antares All-flavour neutrino point source search

‘Can we find sources of neutrinos in the sky?’

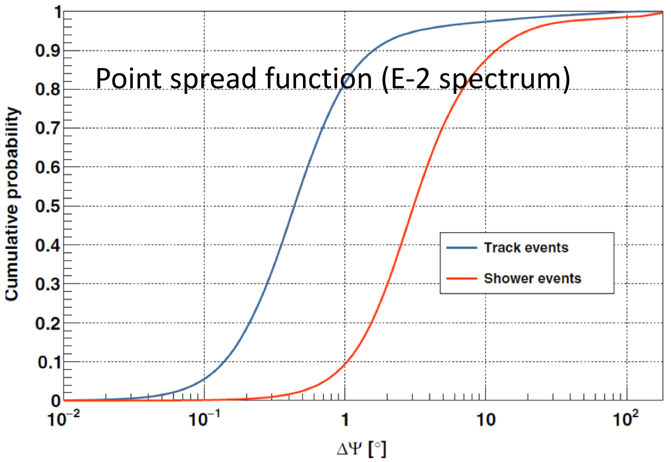
Strategies:
- Grid scan of sky-positions 1x1 degree
- GC region scan
- Sagittarius A* (Extended source: Gaussian profiles)
- Coordinates of interest
    - Candidate list of 106 (pulsars, SNRs)
    - IceCube events (13 HESE)

Ingredients :

Dataset:
- o 2007 - 2015
- o 2424 days lifetime
- o All-flavour analysis:
  - 7622 tracks
  - 180 showers



X : track ● : shower

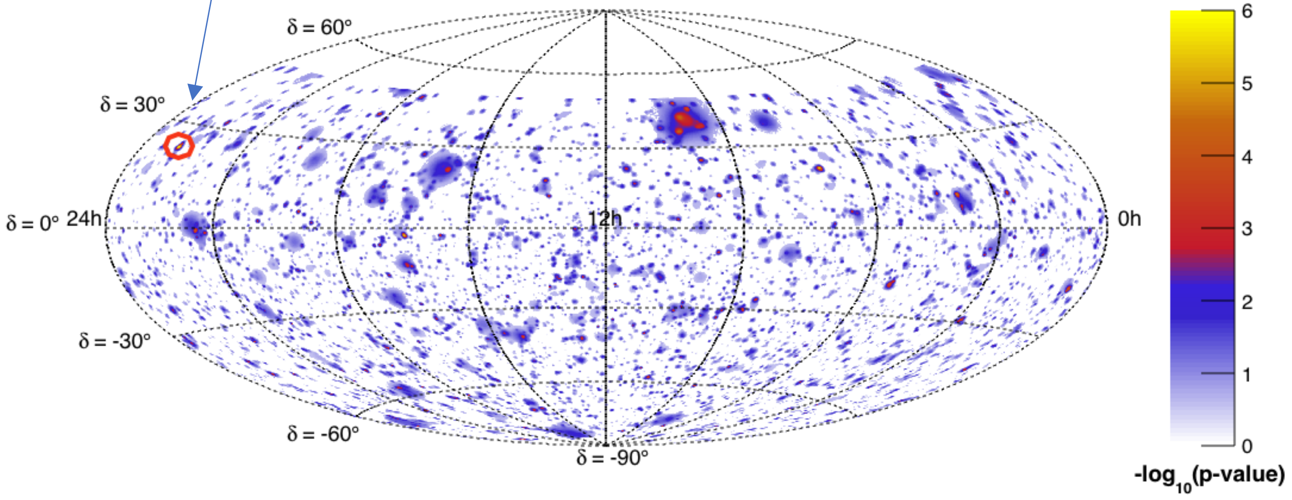


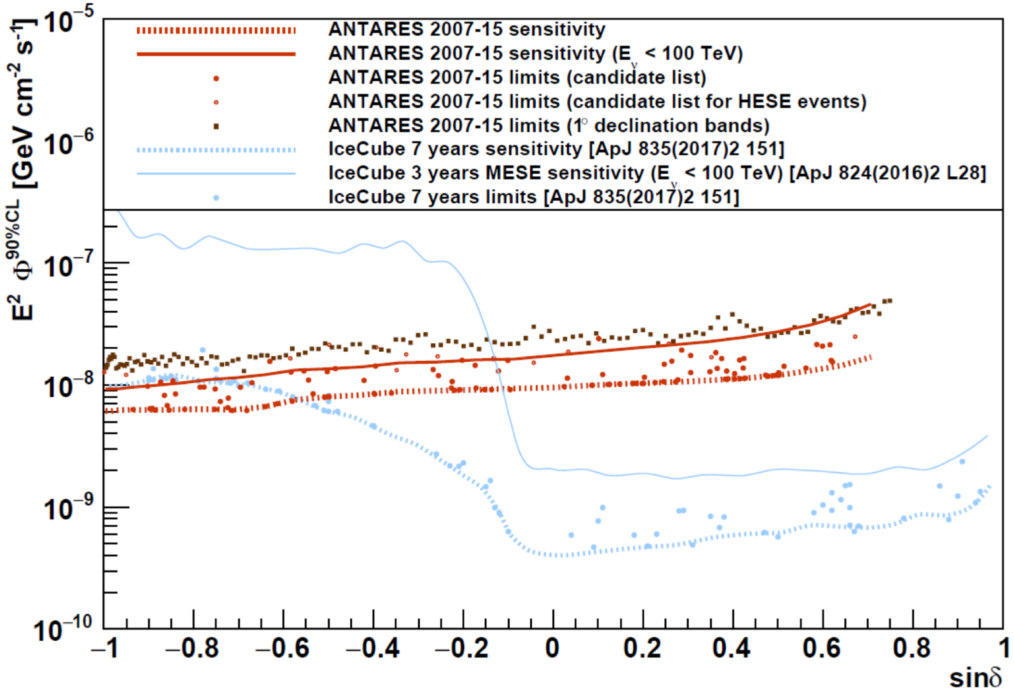
Background Simulation (Atmospheric Neutrinos and Muons)

Likelihood ratio based test statistic

Antares Point Source Searches

Most significant cluster : 1.9 σ



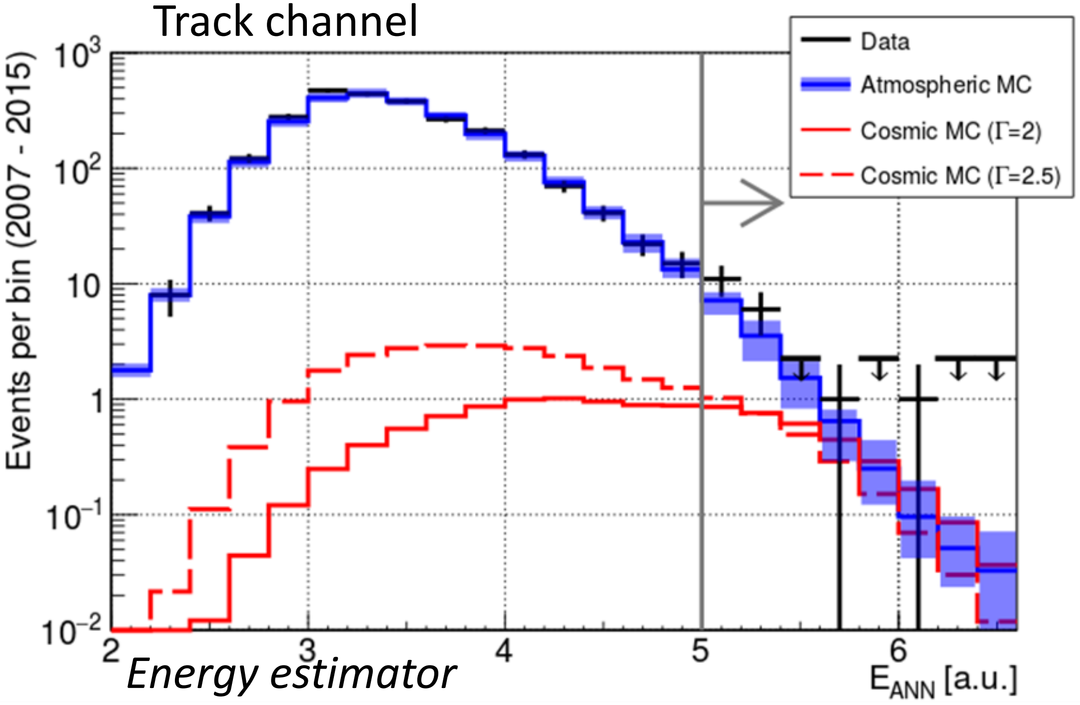


Most sensitive upper limit in fraction of the sky in particular at low energies (< 100 TeV)

Antares Diffuse flux

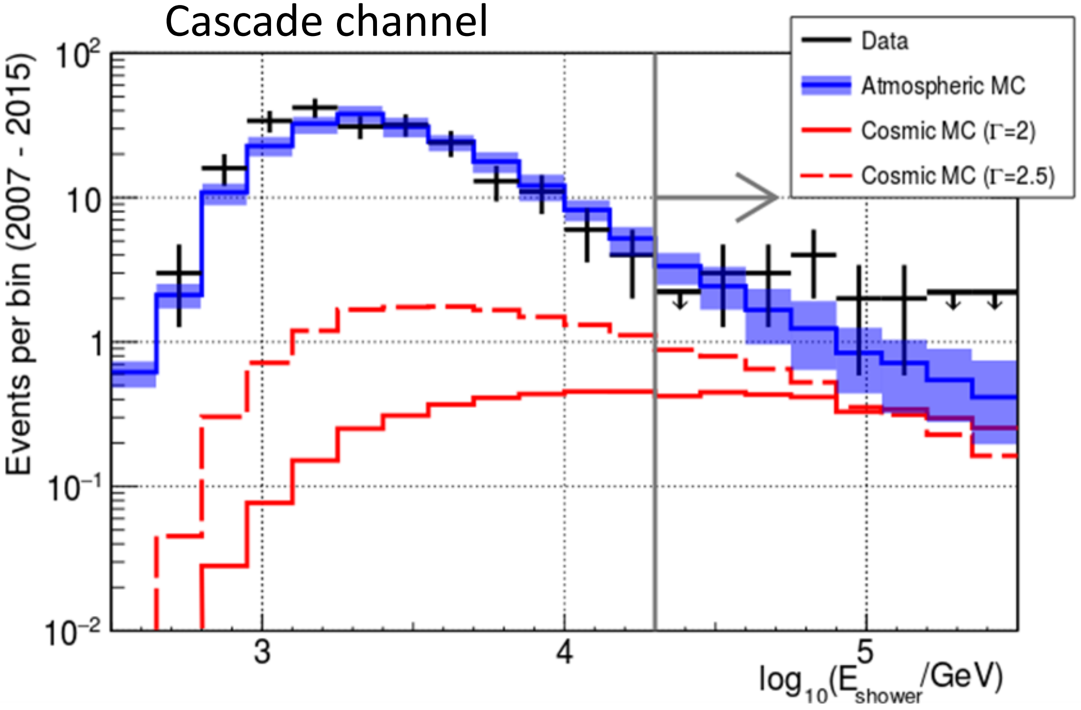
‘Is there a neutrino flux resulting from unresolved sources? (on top of background)’

Track channel



Energy estimator

Cascade channel



MC uncertainty bands include
Honda +- 25 %
Enberg high/low
Detector systematics

Antares Diffuse Flux : upper limits and best fit

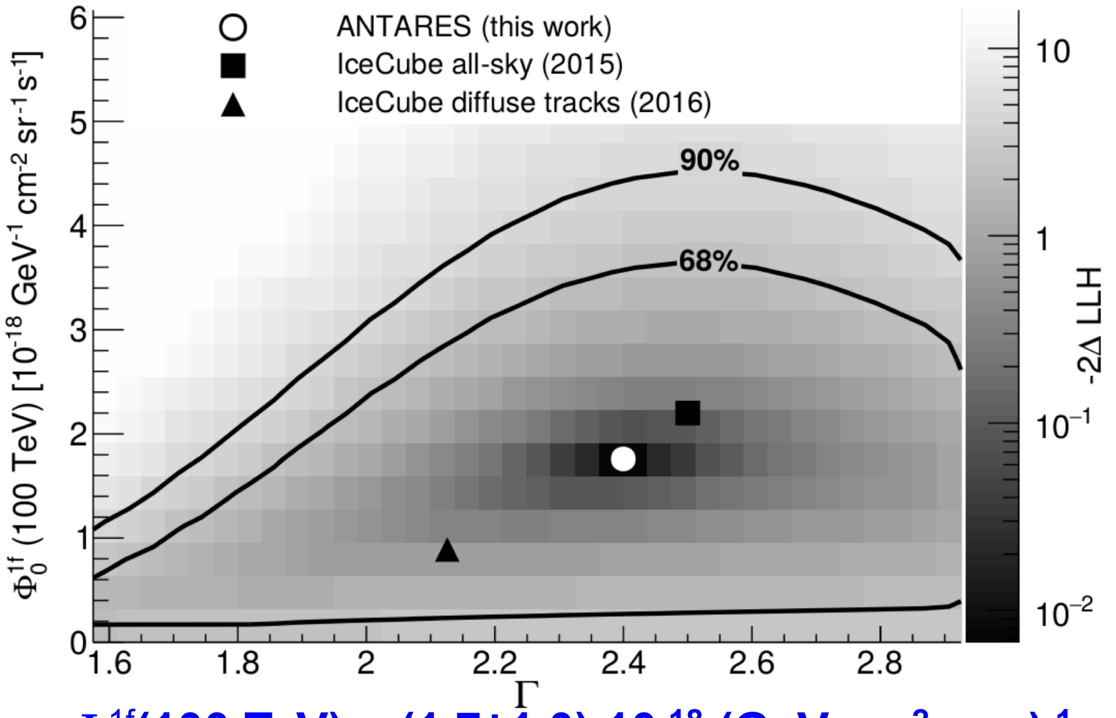
Results :

33 events (**19** tracks + **14** showers) in **data**
24 ± 7 (stat.+syst.) events from **background MC**

1.6σ excess, null cosmic rejected at 85% CL

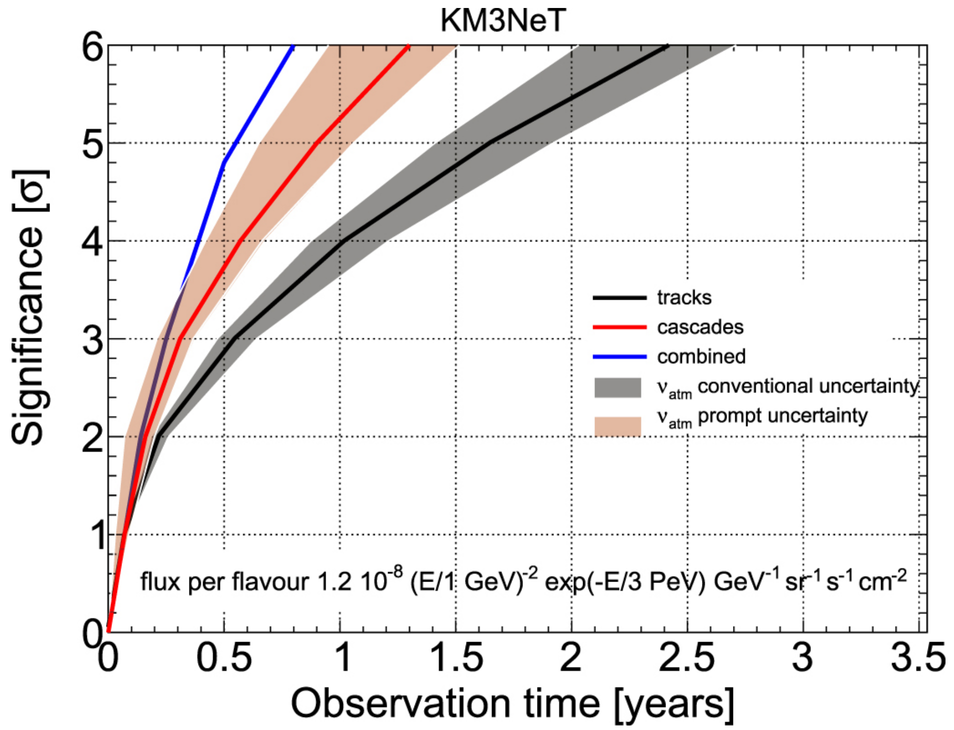
Limits on 1-flavour flux normalization (100 TeV)

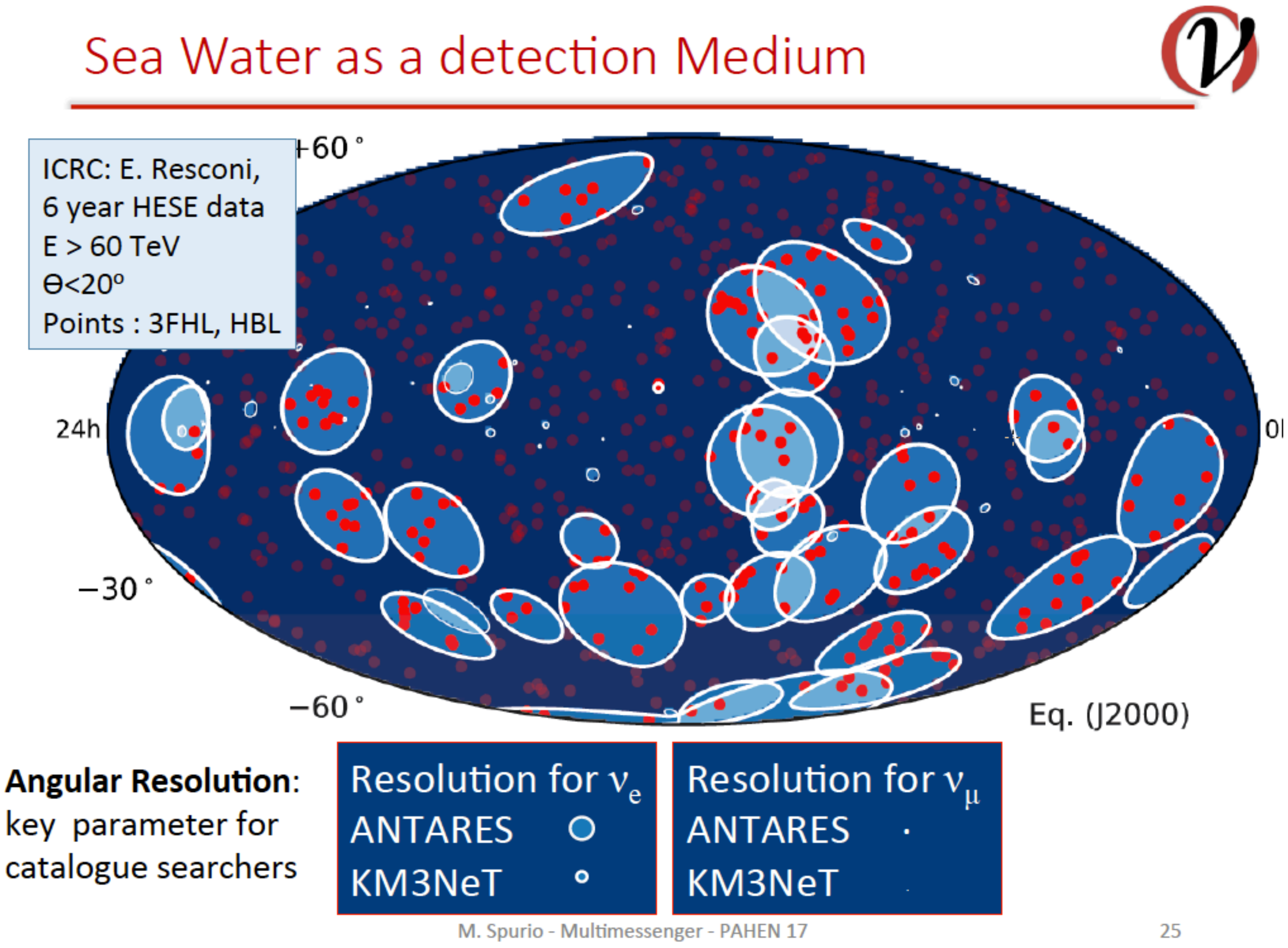
	$\Gamma = 2.0$	$\Gamma = 2.5$
$\Phi_0^{1f,90\%\mathrm{Sens.}}$ (100 TeV)	1.2×10^{-18}	2.0×10^{-18}
$\Phi_0^{1f,90\%\mathrm{U.L.}}$(100 TeV)	4.0×10^{-18}	6.8×10^{-18}
$\Phi_0^{1f,68\%\mathrm{C.I.}}$(100 TeV)	$(0.29–2.9) \times 10^{-18}$	$(0.5–5.0) \times 10^{-18}$



Φ^{1f}**(100 TeV) ~ (1.7±1.0) 10^{-18} (GeV cm^2 s sr)$^{-1}$**
Γ **~ 2.4$^{+0.5}_{-0.4}$**

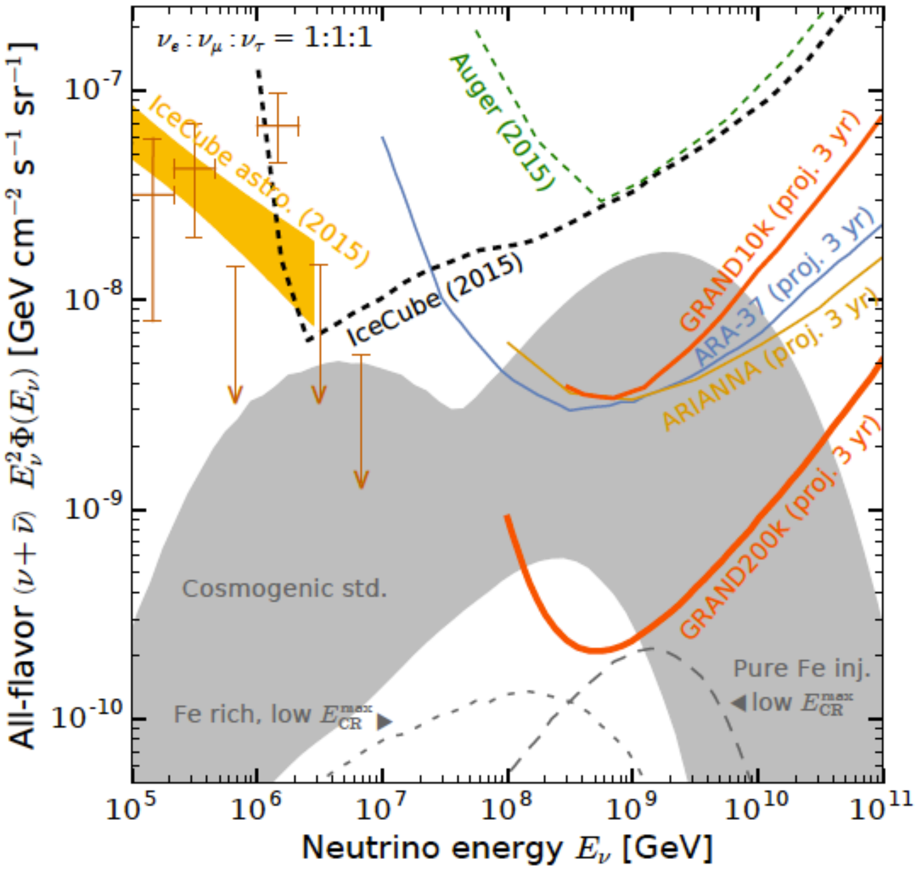
Under construction: KM3NeT

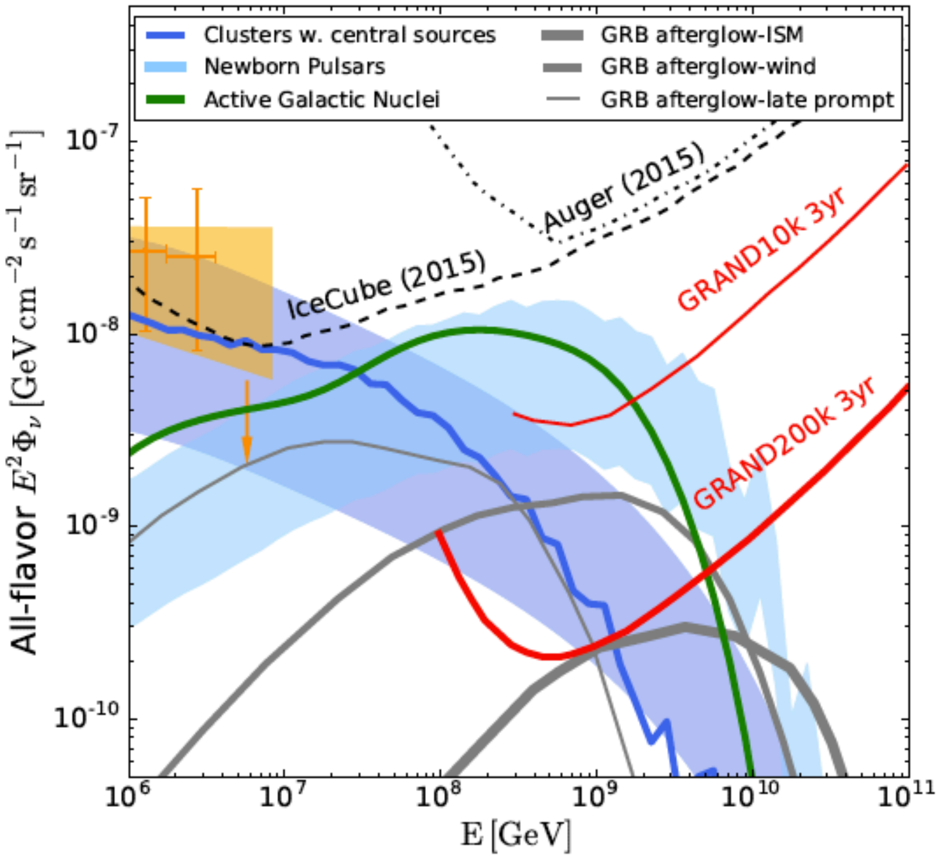




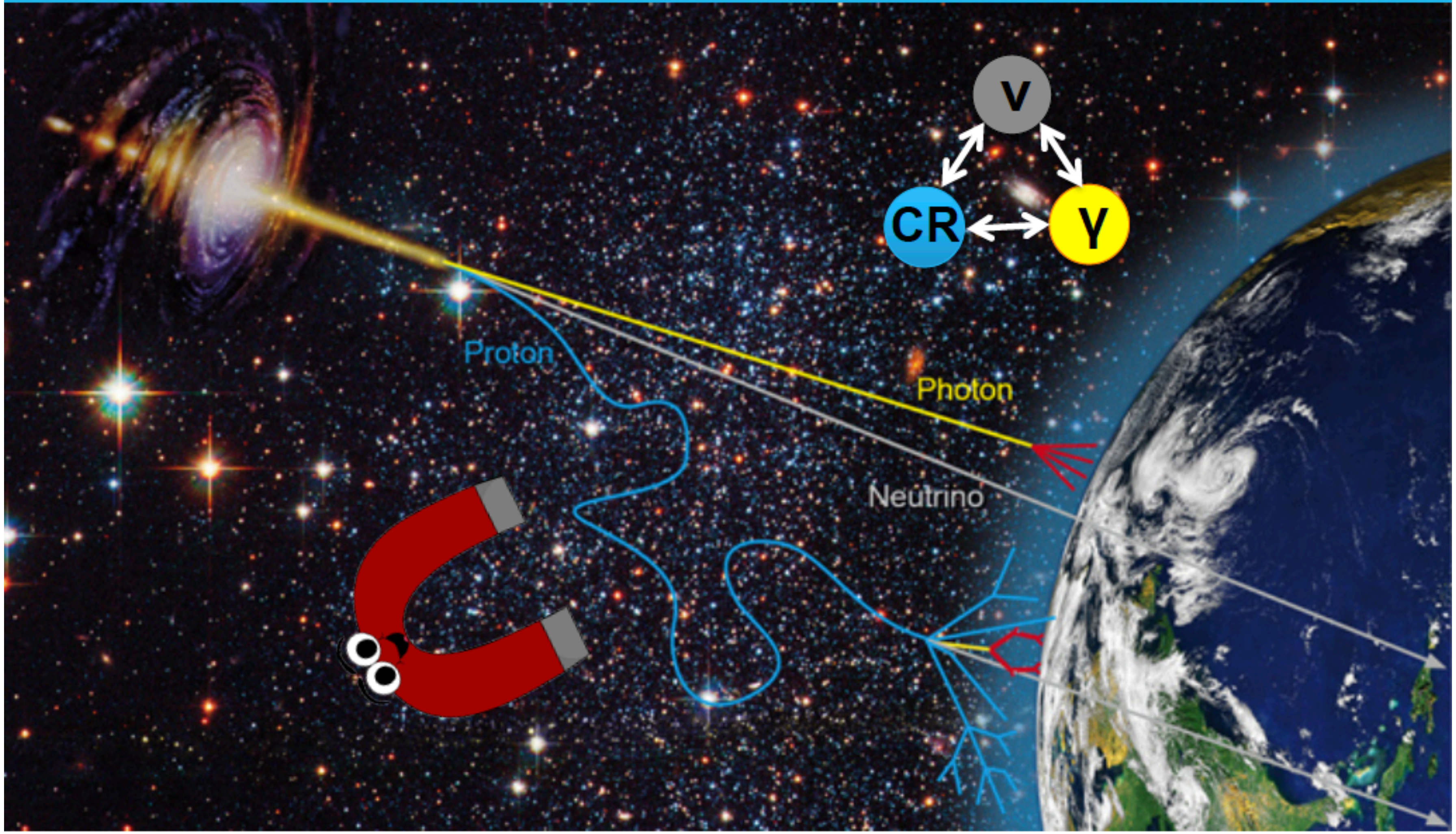
Better angular resolution than IceCube

Very high energy neutrinos: air showers: Auger, GRAND





The Neutrino Cosmic-Ray Connection



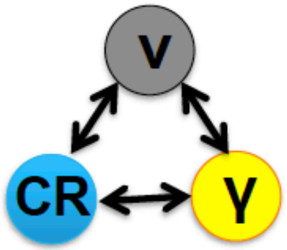
The IceCube flux is about as high as could be optimistically expected! (Waxman-Bahcall)

Close relation between neutrinos, cosmic rays and gamma rays

Neutrino Production Processes

Hadronuclear (e.g. star burst galaxies and galaxy clusters)

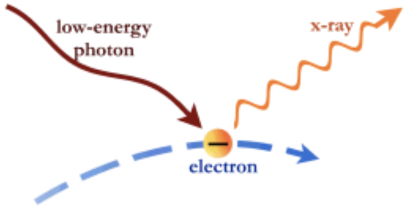
$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

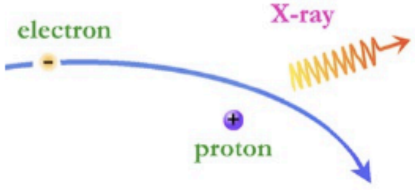


Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

Gamma-rays are not exclusively produced in hadronic processes

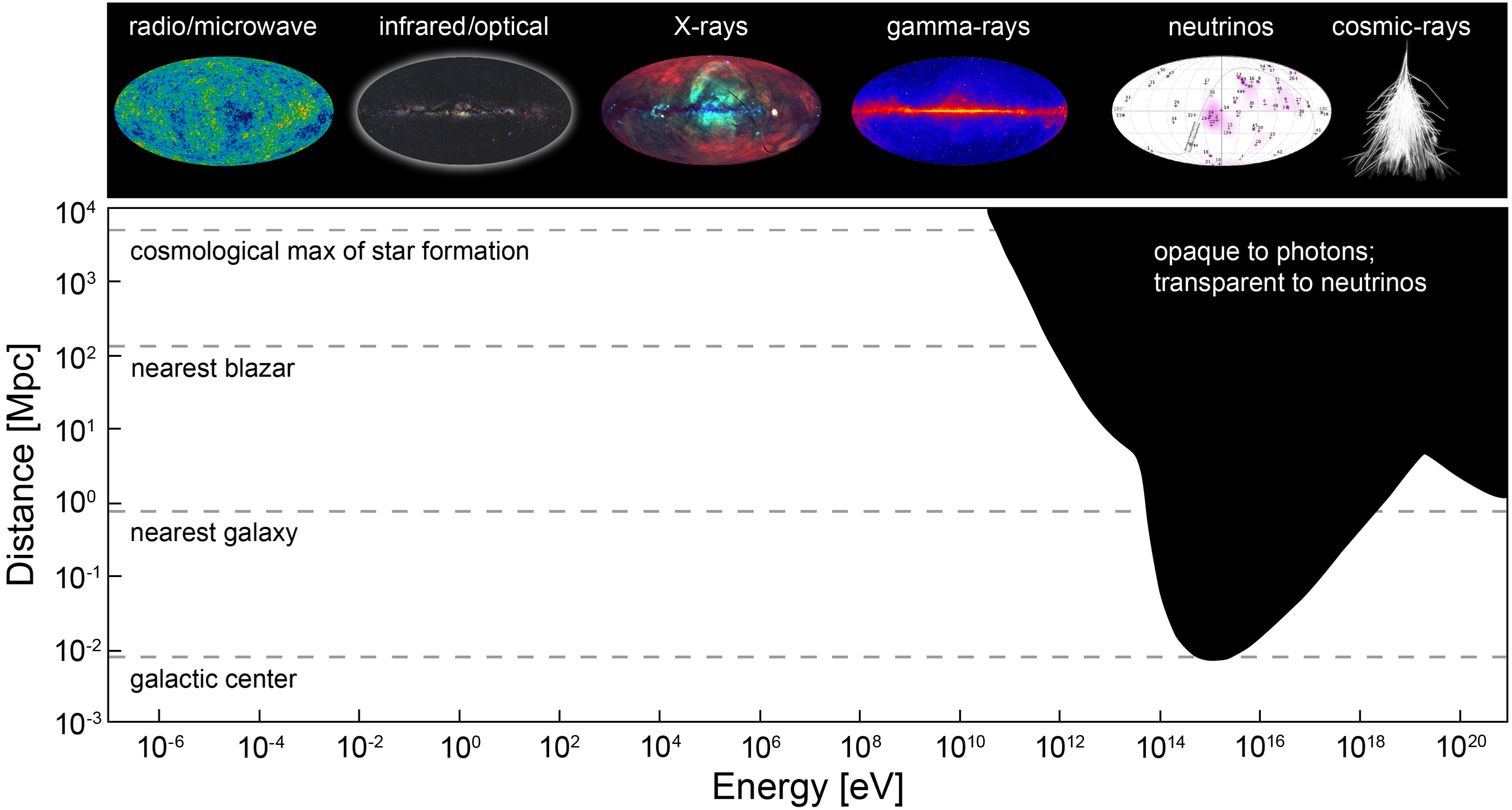




Page 4

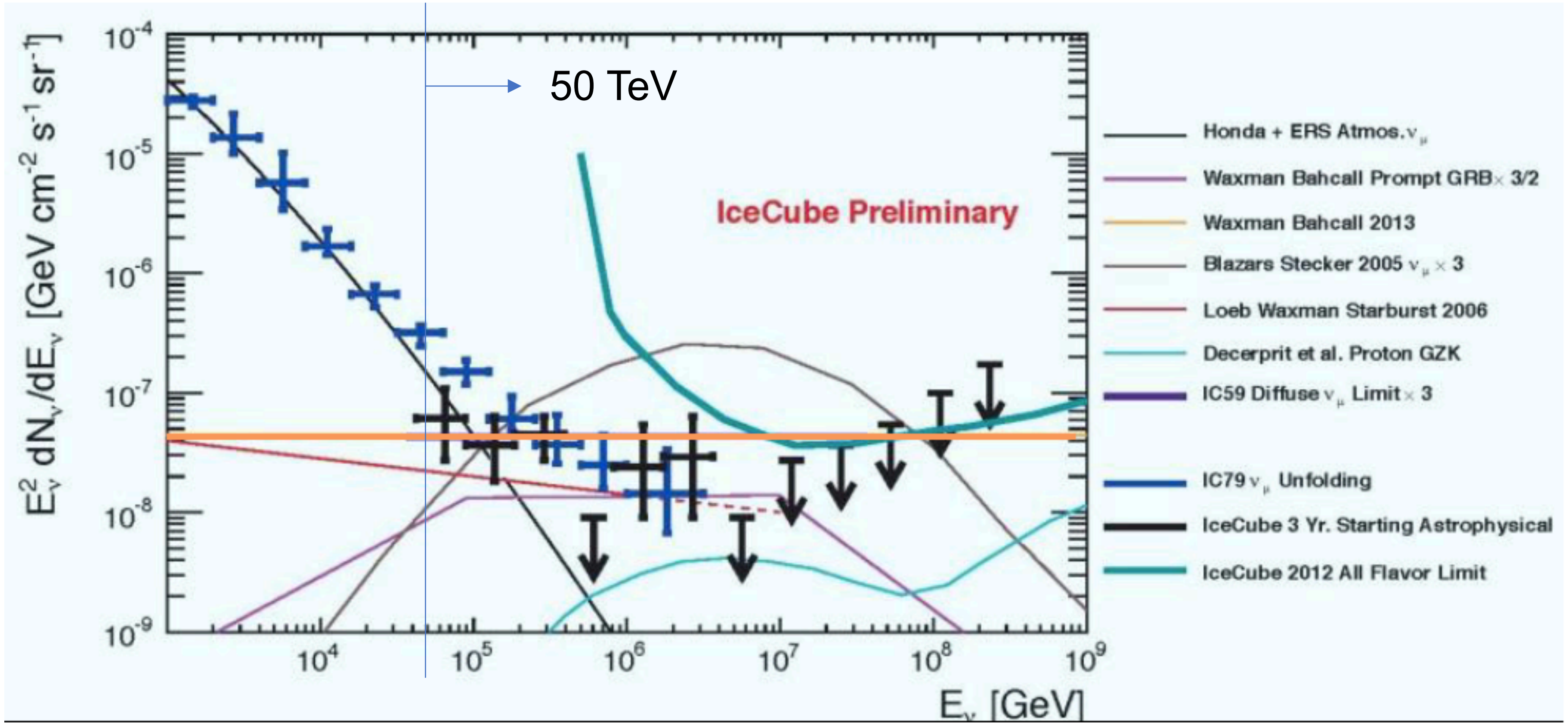
Advantages of neutrino telescopes

- Very high **duty cycle** (almost 100%)
- Large observation **solid angle** (2π or 4π: different resolutions)
- **Complementary f.o.v.** for Mediterranean and South Pole detectors
- Adequate **angular resolution**, depending on the ν direction, medium and track/shower (0.1° → 10°)
- **Online analysis**, fast response (few seconds), immediate alert
- (Neutrinos): no **significantly attenuated**, no **deflected**, during propagation
- (Neutrinos): not significantly absorbed by Earth for E_ν<100 TeV

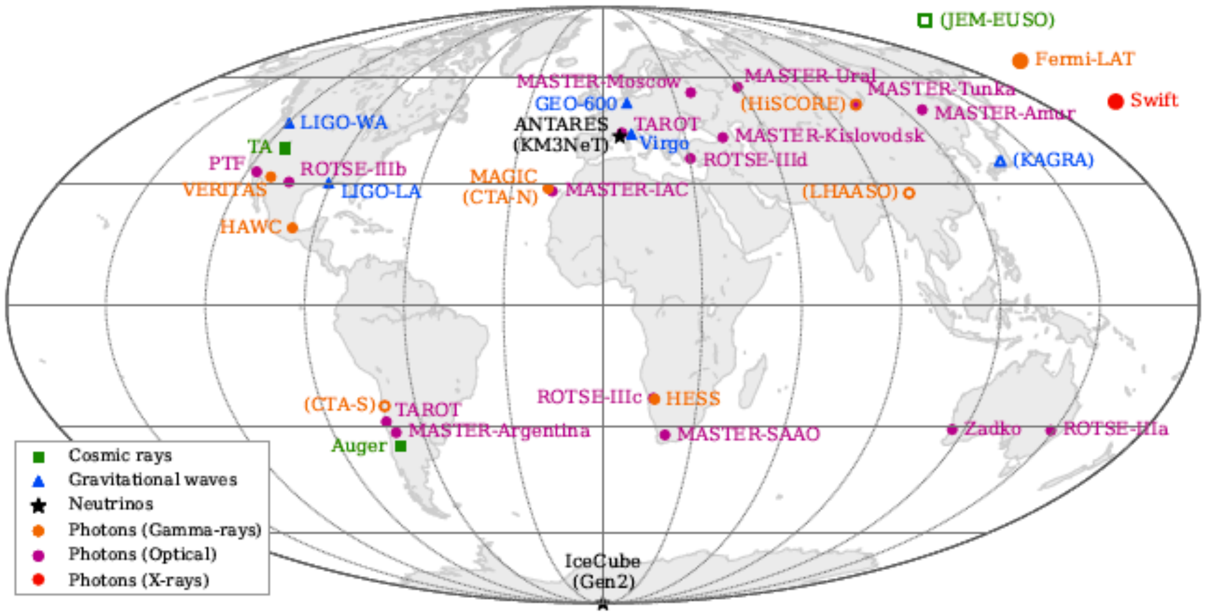

radio/microwave
infrared/optical
X-rays
gamma-rays
neutrinos
cosmic-rays
cosmological max of star formation
nearest blazar
nearest galaxy
galactic center
opaque to photons;
transparent to neutrinos
Distance [Mpc]
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}
Energy [eV]

And the disadvantages

- Low cross sections, huge detectors
- Difficult operating environment (South Pole, Deep Sea)
- Backgrounds: cosmic ray muons, atmospheric neutrinos



Multi-messenger: Neutrinos and γ/X rays/optical



Offline: look for correlations in directions (and perhaps time) with a list of known γ/X ray sources

Transients: quasi-real-time alert system

neutrino telescope triggers something else (ν telescope wide field of view)

something else triggers neutrino telescope

Correlation with a priori catalogue (IceCube)

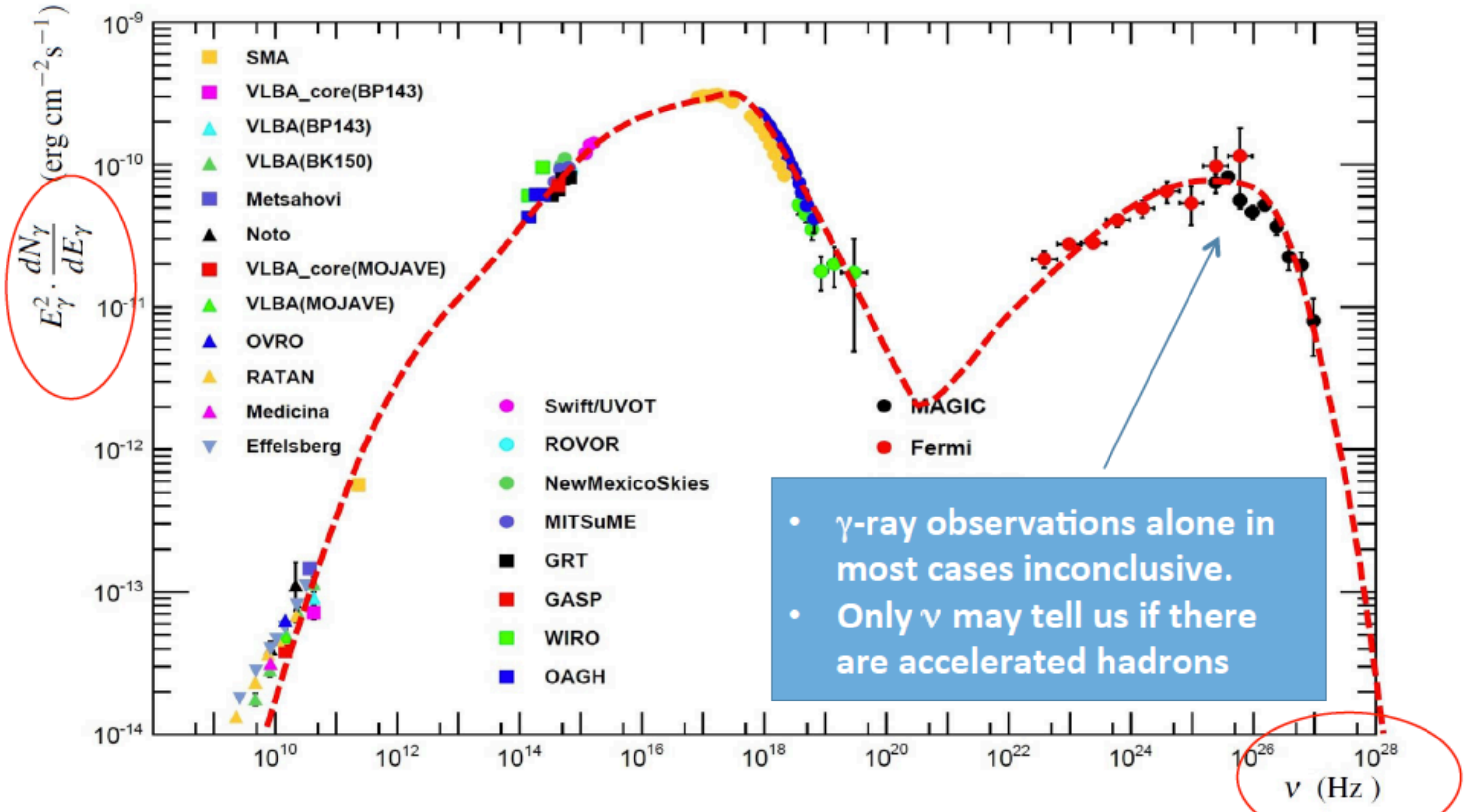
Starburst/radio galaxy
Quasars
Pulsar Wind Nebulae
BL Lac Blazars
X-ray binaries
Supernova remnant

Highest correlation with MGRO J1908+06
Post-trial p-value 10%

Source	Type	α [deg]	δ [deg]	p-value	TS	n_s	Φ_0 [TeV cm^{-2} s^{-1}]
MGRO J1908+06	NI	286.99	6.27	0.0032	6.284	3.28	$1.13{\cdot}10^{-12}$
Cyg A	SRG	299.87	40.73	0.0049	6.335	4.30	$1.78{\cdot}10^{-12}$
4C 38.41	FSRQ	248.81	38.13	0.0055	5.686	6.62	$1.72{\cdot}10^{-12}$
3C454.3	FSRQ	343.50	16.15	0.0072	5.503	5.98	$1.26{\cdot}10^{-12}$
Crab Nebula	PWN	83.63	22.01	0.1188	0.709	4.32	$8.65{\cdot}10^{-13}$
Cas A	SNR	350.85	58.81	0.2069	0.033	0.88	$1.05{\cdot}10^{-12}$
1ES 1959+650	BL Lac	300.00	65.15	0.2069	0.124	1.69	$1.17{\cdot}10^{-12}$
PKS 1502+106	FSRQ	226.10	10.52	0.2322	-0.000	0.00	$5.98{\cdot}10^{-13}$
Mrk 421	BL Lac	166.11	38.21	0.2433	0.029	0.48	$8.68{\cdot}10^{-13}$
NGC 1275	SRG	49.95	41.51	0.2582	0.007	0.25	$8.31{\cdot}10^{-13}$
LSI 303	XB/mqso	40.13	61.23	0.2843	0.001	0.17	$1.01{\cdot}10^{-12}$
PKS 0528+134	FSRQ	82.73	13.53	0.2870	-0.002	0.00	$5.74{\cdot}10^{-13}$
Cyg OB2	SFR	308.09	41.23	0.3174	-0.002	0.00	$7.53{\cdot}10^{-13}$
Cyg X-3	XB/mqso	308.11	40.96	0.3230	-0.003	0.00	$7.28{\cdot}10^{-13}$
3C66A	BL Lac	35.67	43.04	0.3306	-0.001	0.00	$7.50{\cdot}10^{-13}$
3C 273	FSRQ	187.28	2.05	0.3807	-0.014	0.00	$4.42{\cdot}10^{-13}$
W Comae	BL Lac	185.38	28.23	0.4420	-0.055	0.00	$5.37{\cdot}10^{-13}$
TYCHO	SNR	6.36	64.18	0.4471	-0.019	0.00	$8.14{\cdot}10^{-13}$
1ES 0229+200	BL Lac	38.20	20.29	0.4762	-0.059	0.00	$4.47{\cdot}10^{-13}$
BL Lac	BL Lac	330.68	42.28	0.5104	-0.028	0.00	$5.58{\cdot}10^{-13}$
Cyg X-1	XB/mqso	299.59	35.20	0.5422	-0.106	0.00	$4.93{\cdot}10^{-13}$
M87	SRG	187.71	12.39	0.6711	-0.256	0.00	$2.85{\cdot}10^{-13}$
Mrk 501	BL Lac	253.47	39.76	0.6847	-0.172	0.00	$3.51{\cdot}10^{-13}$
S5 0716+71	BL Lac	110.47	71.34	0.7230	-0.380	0.00	$3.84{\cdot}10^{-13}$
PKS 0235+164	BL Lac	39.66	16.62	0.7355	-0.400	0.00	$2.04{\cdot}10^{-13}$
H 1426+428	BL Lac	217.14	42.67	0.7890	-0.243	0.00	$1.96{\cdot}10^{-13}$
IC443	SNR	94.18	22.53	0.8153	-0.457	0.00	$1.22{\cdot}10^{-13}$
HESS J0632+057	XB/mqso	98.24	5.81	0.8359	-0.917	0.00	$1.01{\cdot}10^{-13}$
SS433	XB/mqso	287.96	4.98	0.8738	-1.085	0.00	$1.01{\cdot}10^{-13}$
M82	SRG	148.97	69.68	0.8887	-0.888	0.00	$1.83{\cdot}10^{-13}$
3C 123.0	SRG	69.27	29.67	0.9055	-0.747	0.00	$1.30{\cdot}10^{-13}$
1ES 2344+514	BL Lac	356.77	51.70	0.9264	-0.808	0.00	$1.58{\cdot}10^{-13}$
Geminga	PWN	98.48	17.77	0.9754	-2.424	0.00	$1.16{\cdot}10^{-13}$
MGRO J2019+37	PWN	305.22	36.83	0.9884	-3.191	0.00	$1.39{\cdot}10^{-13}$
	Hottest spot of the unbiased scan on the Northern hemisphere						
—	—	170.16	27.87	$10^{-5.14}$	17.271	10.28	—

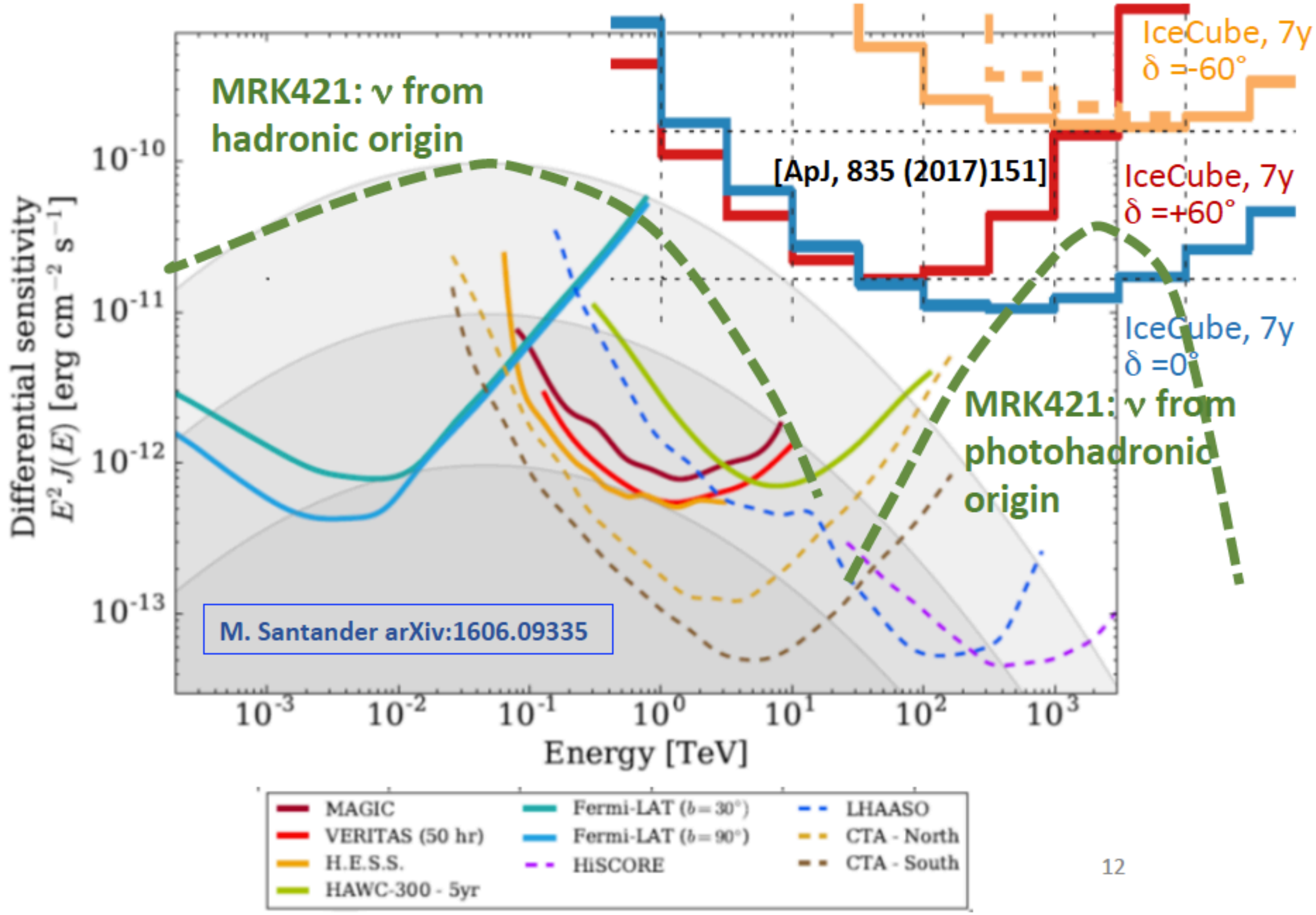
Bright Blazar Mrk 421: how much hadronic contribution?

Multi-wavelength observation: Mrk421



Extensive multi-wavelength measurements showing the spectral energy distribution ***(SED) of Markarian 421 from*** *observations made in 2009. The dashed line is a fit of the data with a leptonic model. Abdo et al. ApJ 736(2011) 131 for the references to the data*

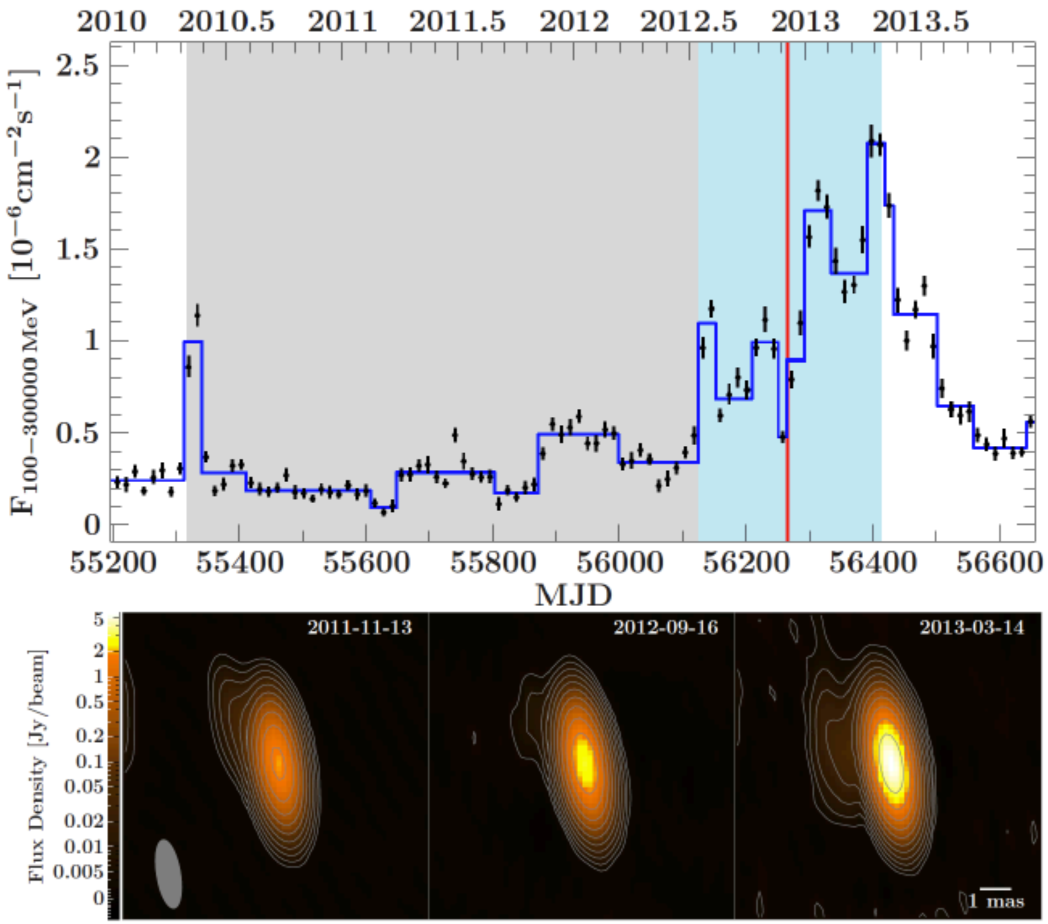
γ and ν discovery potential



3rd IceCube High Energy Neutrino: coincidence with a blazar?

M. Kadler *et al.*,
"Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event,"
Nature Phys. **12**, no. 8, 807 (2016)
[arXiv:1602.02012 [astro-ph.HE]].

γ-ray light curve of PKS B1424−418.



"Intriguing" Coincidence

in time

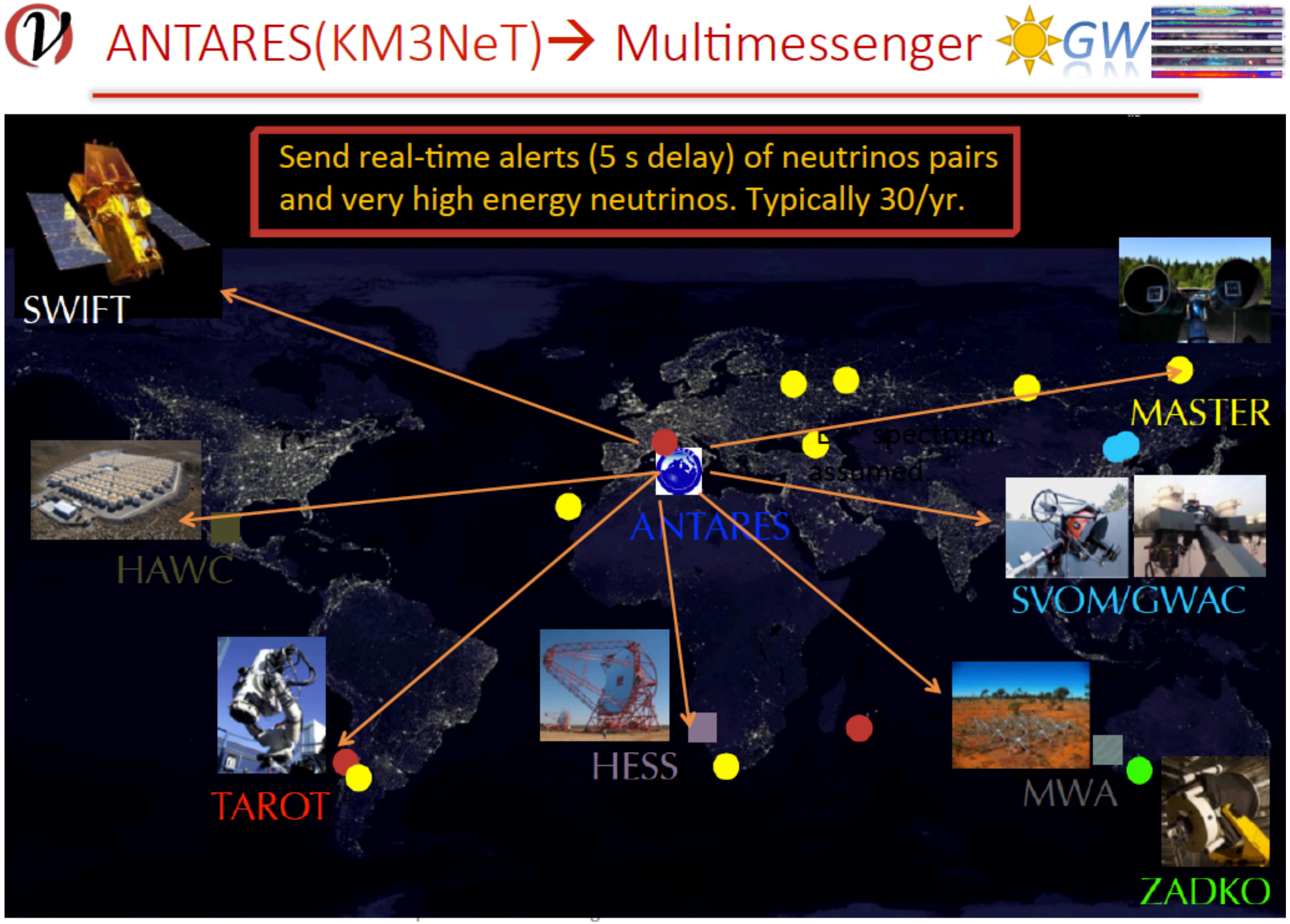
and direction
[error 15 degrees]

Probability for accidental overlap estimated at 5% ?

Recently: a second coincidence between an IceCube track and a blazar

Coincidence in space AND time for transient sources

Real-time alert sent by Antares to observatories for EM observations



Real-time follow-up (TAToO)

- APP 35 (2012) 530 (method)
- JCAP 02 (2016) 062 (optical)
- AJ 820 (2016) L24 (radio)

ANTARES trigger

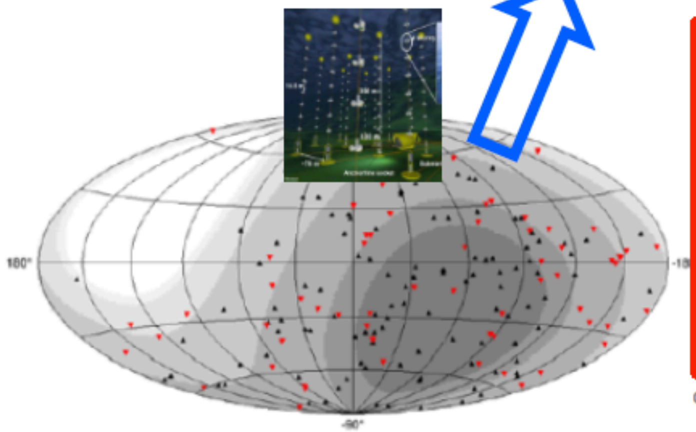
- doublet of ν's (~0.04/yr)
- single HE ν (~7 TeV) (~15/yr)
- single ν (~1 TeV) correlated to local galaxies for SNe (~10/yr)

External server

TAROT
ZADKO
MASTER
GWAC
SWIFT
MWA
HESS
HAWC

GCN

Mail
SMS



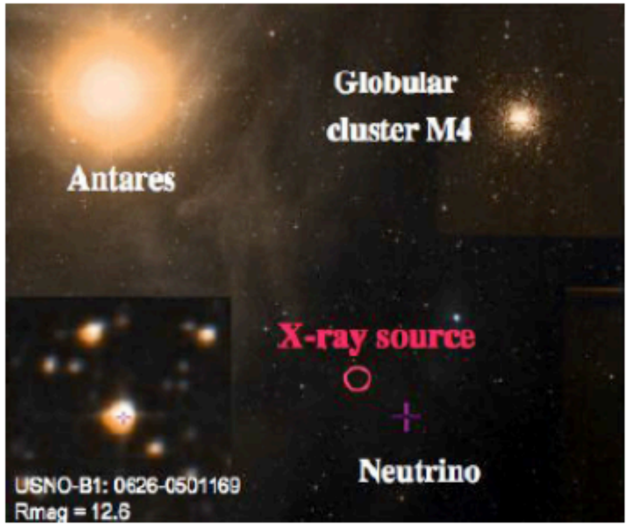
Performances:

- **Time to send an alert: ~ 5 s**
- **Median angular resolution: 0.3° - 0.4°**
- First image of the follow-up: <20 s
- Dedicated optical image analysis

A particular event: ANT150901

Alert **VHE (Sept. 1, 2015)**
E ~ 50-100 TeV
RA=246.306°; dec=-27.468°
Uncertainty: ~18 arcmin (radius, 50%)

Sent after 10 s to MASTER, Swift-XRT
Follow-up with **Swift-XRT after 9h**
Follow-up with **MASTER after 10h**



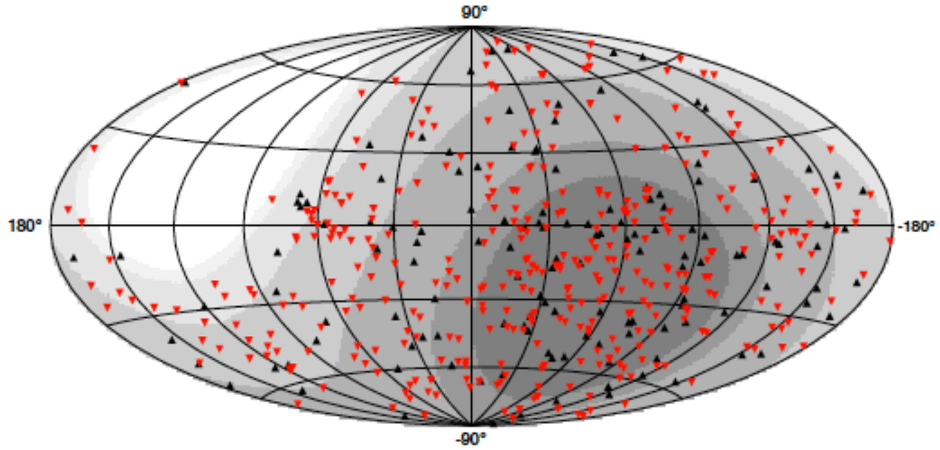
Multifrequency observations:
16 ATEL + 6 GCN

- Neutrinos
  - IceCube: ATel 8097
- Optical
  - Pan-STARRS: ATel 7992, 8027
  - SALT: ATel 7993
  - NOT: ATel 7994 GCN18236
  - WiFeS: ATel 7996
  - CAHA: ATel 7998, GCN18241
  - MASTER: ATel 8000 GCN18240
  - LSGT: ATel 8002
  - NIC: ATel 8006
  - ANU: GCN18242
  - GCM: GCN18239
  - VLT/X-shooter
- X-rays
  - Integral: ATel 7995
  - MAXI: ATel 8003
  - Swift: ATel 8124, GCN18231
- Radio
  - Jansky VLA: ATel 7999, 8034
- Gamma-rays
  - MAGIC: ATel 8203
  - Fermi-GBM: GCN18352
  - HAWC
  - HESS

GCN CIRCULAR NUMBER: 18236
(Optical + NIR spectroscopy from NOT)
..All this points to USNO-B1.0 0626-0501169 being a young accreting G-K star, undergoing a flaring episode that produced the X-ray emission. We also note that this object is close to the nearby Rho Ophiuchi star forming region, being probably associated with it.

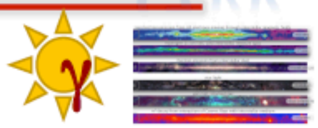
Alerts sent to Antares:

- Gravitational Waves triggers from LIGO/VIRGO
- HESE, and all events > 1 PeV from IceCube
- GRBs from Swift/Fermi
- Fast Radio Bursts (FRB) from Parkes Radio Telescope



Typically triggers dedicated analyses

ANTARES Multimessenger program



- **A way to better understand the related physics mechanisms**
- **A way to increase the detector sensitivities**

Up to July 2017:

→ 256 alerts sent
→ 13
→ 2
→ 20

Real-time (follow-up of the selected neutrino events):

- optical telescopes [TAROT, ROTSE, ZADKO, MASTER]
- X-ray telescope [Swift/XRT]
- GeV-TeV γ-ray telescopes [HESS, HAWC]
- radio telescope [MWA]
- Online search of fast transient sources [GCN, Parkes]

Multi-messenger correlation with:

- Gravitational wave [Virgo/Ligo]
- UHE events [Auger]

Time-dependent searches:

- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Gamma-ray binaries [Fermi/LAT, IACT]
- Blazars [Fermi/LAT, IACT, TANAMI…]
- Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]
- Fast radio burst [radio telescopes]

What do we know about the IceCube sources ?

Neutrino astronomy with IceCube and beyond

To cite this article: Marek Kowalski and IceCube Collaboration 2017 *J. Phys.: Conf. Ser.* **888** 012007

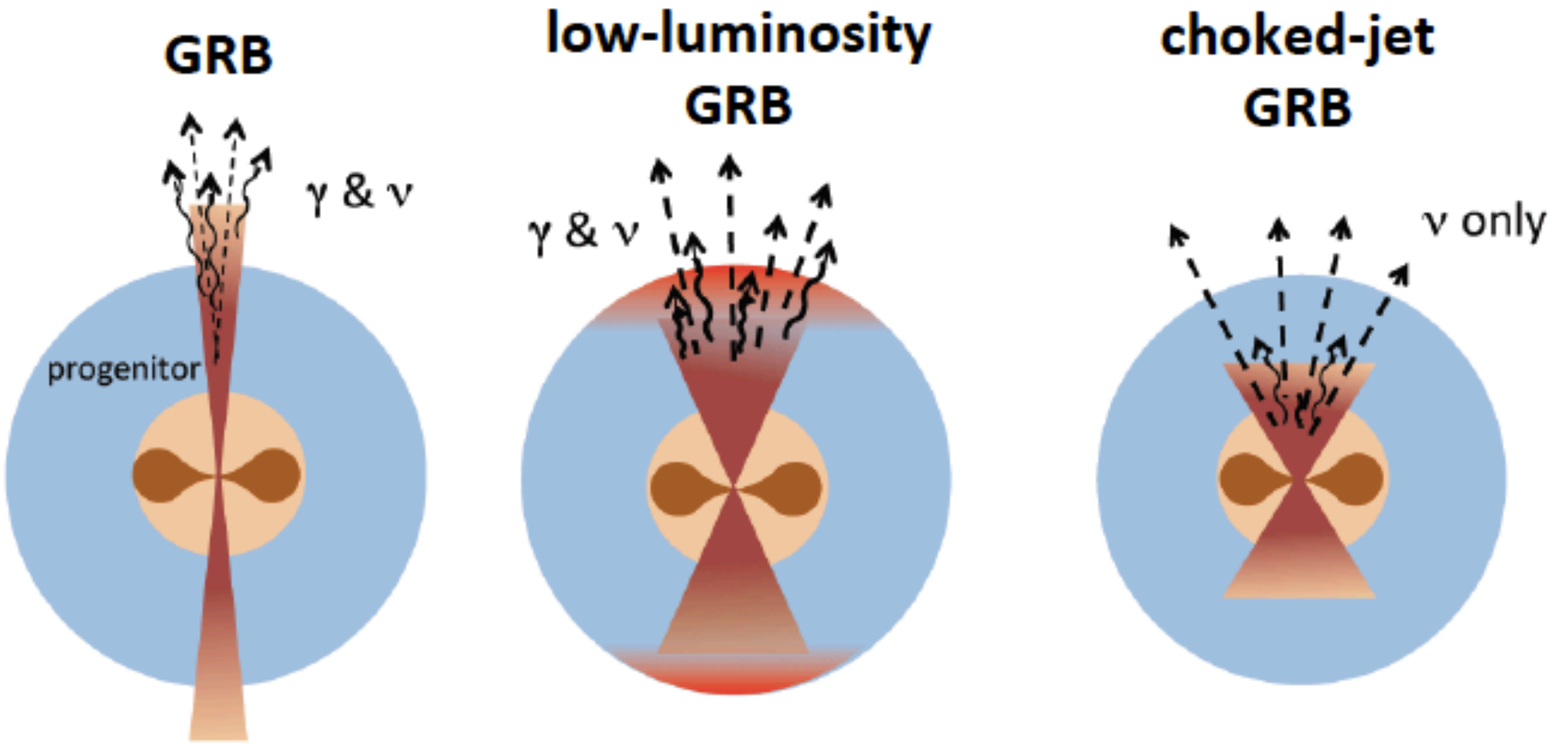
- High-luminosity GRB contribution <= 1%

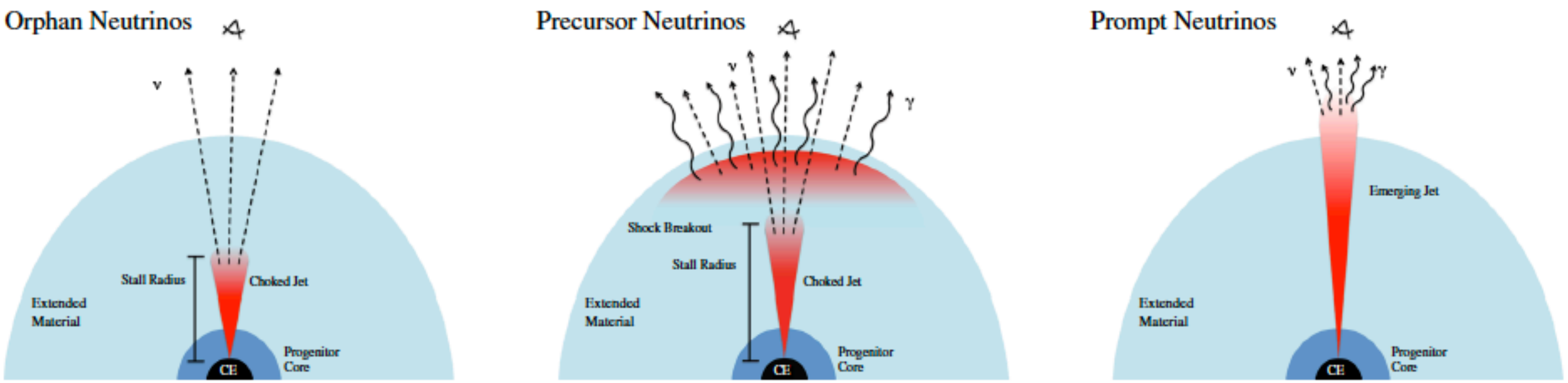
- Blazar contribution <= 27% (but perhaps more at high E)

- Starburst galaxies seem to produce too few gamma rays

"*Dark sources*" are still allowed:

- Core collapse supernovae with stellar envelope, or thick circumstellar medium
- Low-luminosity or choked GRBs
- Core regions of AGNs
- Tidal disruption events

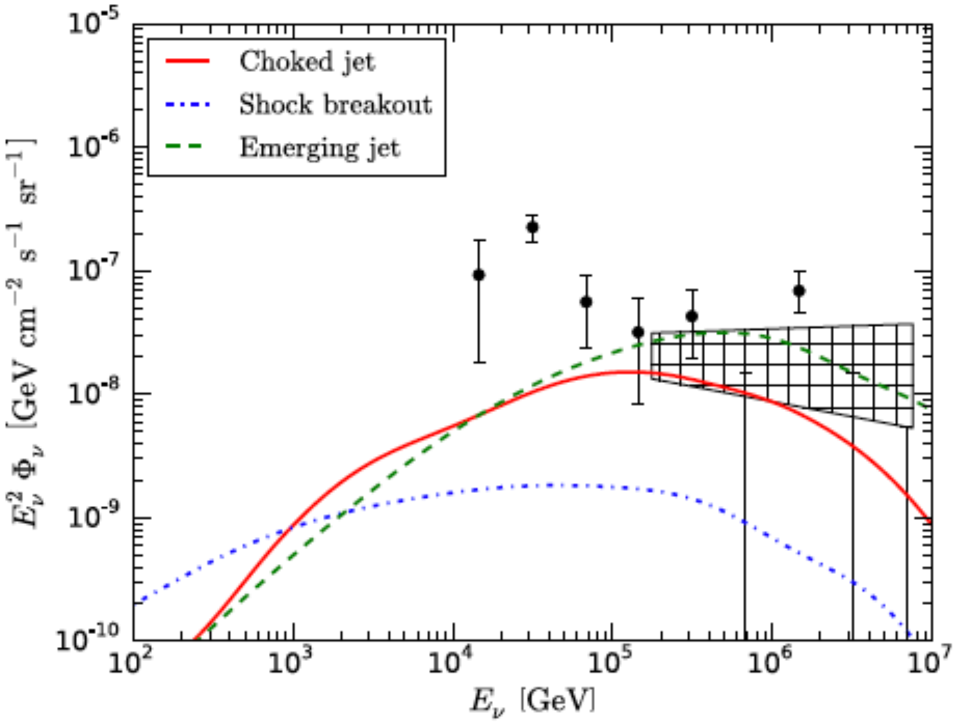

GRB
γ & ν
progenitor
low-luminosity GRB
γ & ν
choked-jet GRB
ν only



PHYSICAL REVIEW D **93**, 083003 (2016)

Choked jets and low-luminosity gamma-ray bursts as hidden neutrino sources

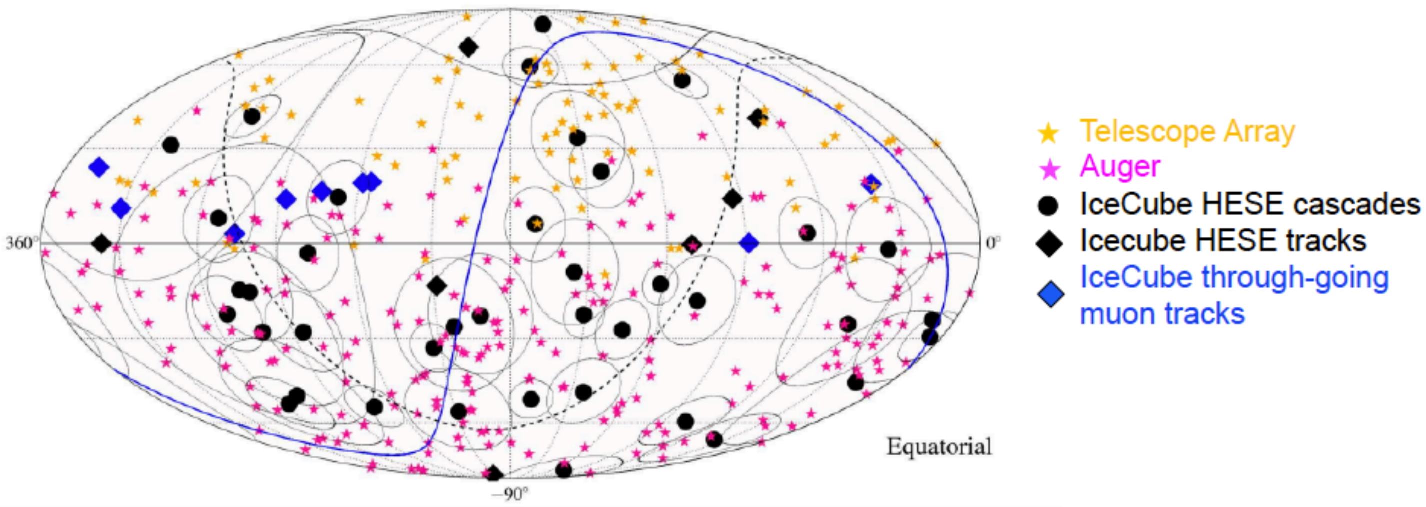
Nicholas Senno, Kohta Murase, and Peter Mészáros



Neutrinos and charged cosmic rays

Neutrinos and UHE Cosmic-Rays

> Correlation of IceCube neutrinos with UHE cosmic-rays (E>50 EeV) from Auger and Telescope Array



GZK horizon ~200 Mpc

Neutrino horizon 4 Gpc

No significant correlation found

IceCube Coll. JCAP01 (2016) 037

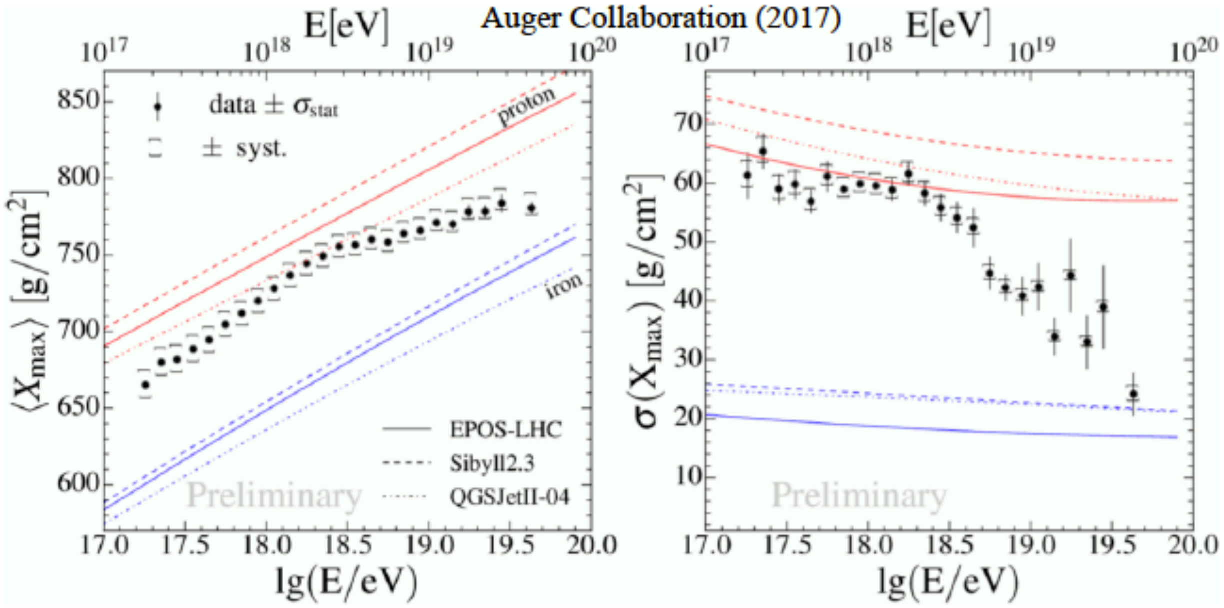
Cosmogenic neutrinos: produced by CR interacting with CMB/EBL

CR + $\gamma_{CMB} \rightarrow X + \pi$, pions decaying to neutrinos

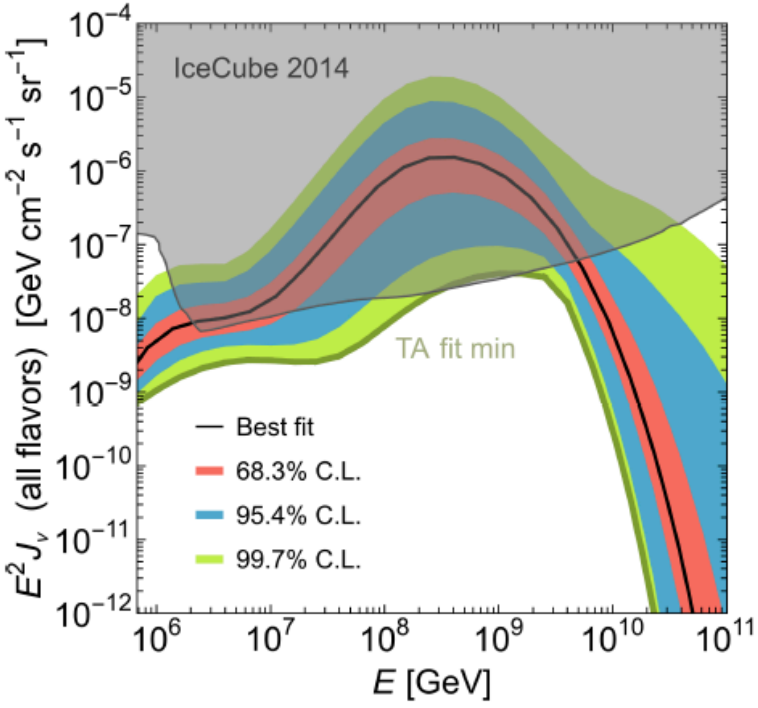
COSMOGENIC NEUTRINOS CHALLENGE THE COSMIC RAY PROTON DIP MODEL

JONAS HEINZE[1], DENISE BONCIOLI[1], MAURICIO BUSTAMANTE[2,3], & WALTER WINTER[1]

Astrophys.J. 825 (2016) no.2, 122



UHECR composition: discrepancy between Auger and TA



IceCube limits seem to disfavor the higher flux associated with protons

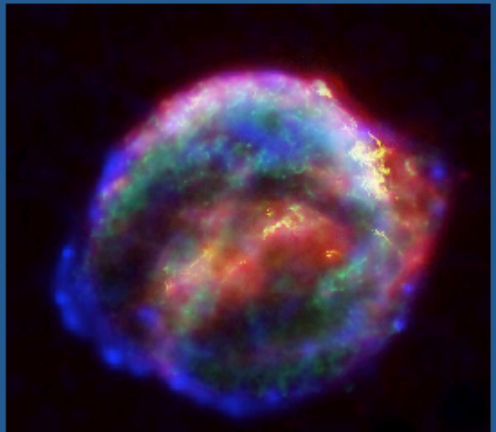
Neutrinos and gravitational waves

The Astrophysical Gravitational-Wave Source Catalog

Credit: Bohn, Hébert, Throwe, SXS

Coalescing Binary Systems

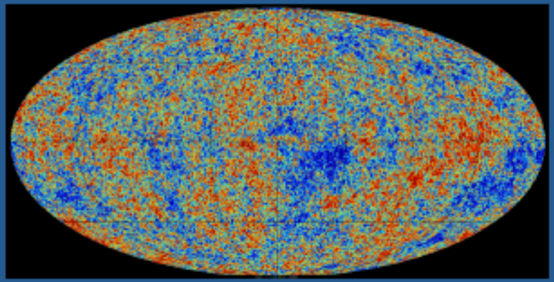
- Black hole – black hole
- Black hole – neutron star
- Neutron star – neutron star
- modeled waveform



Credit: Chandra X-ray Observatory

Transient 'Burst' Sources

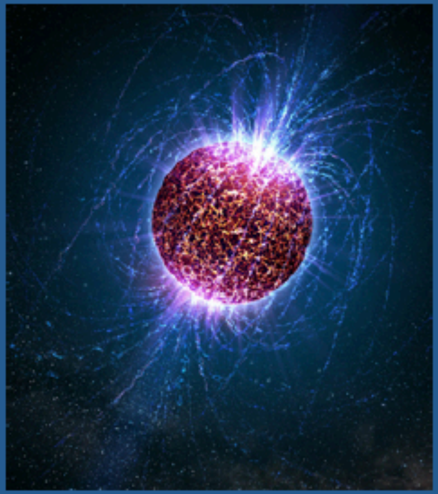
- asymmetric core collapse supernovae
- cosmic strings
- ???
- Unmodeled waveform



Credit: Planck Collaboration

Cosmic GW Background

- residue of the Big Bang
- probes back to < 10^{-15} s
- stochastic, incoherent background
- Difficult (impossible?) for LIGO-Virgo to detect

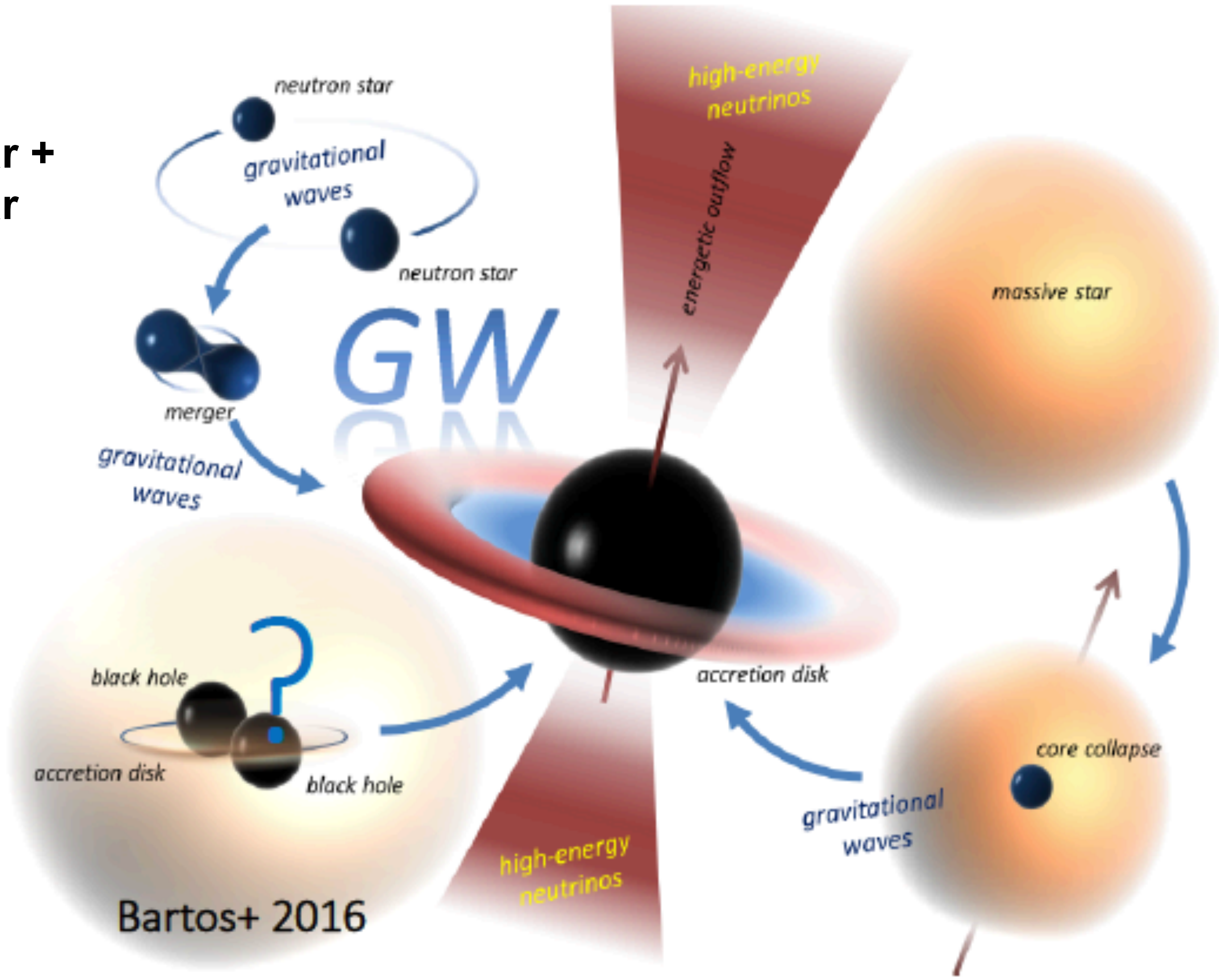


Credit: Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars
- monotone waveform

Neutron star +
Neutron star



Asymmetric
core collapse

Black hole +
Black hole

Perhaps if there is
an accretion disk

Binary black hole mergers:

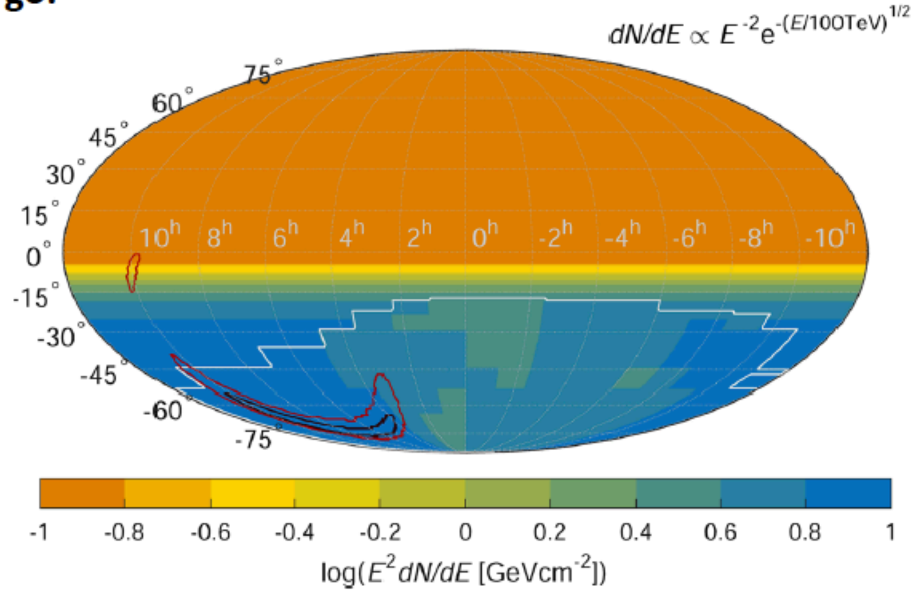
Neutrino follow-up of GW150914

Joint ANTARES/IceCube/LigoSC/Virgo.

- Phys.Rev. D93 (2016), 122010
- Phys.Rev. D96 (2017) 022005

TABLE II. Upper limits on neutrino spectral fluence ($\nu_\mu + \bar{\nu}_\mu$) from GW150914, separately for different spectral ranges, at Dec = −70°. We assume $dN/dE \propto E^{-2}$ within each energy band.

Energy range	Limit [GeV cm^{-2}]
100 GeV–1 TeV	150
1 TeV–10 TeV	18
10 TeV–100 TeV	5.1
100 TeV–1 PeV	5.5
1 PeV–10 PeV	2.8
10 PeV–100 PeV	6.5
100 PeV–1 EeV	28



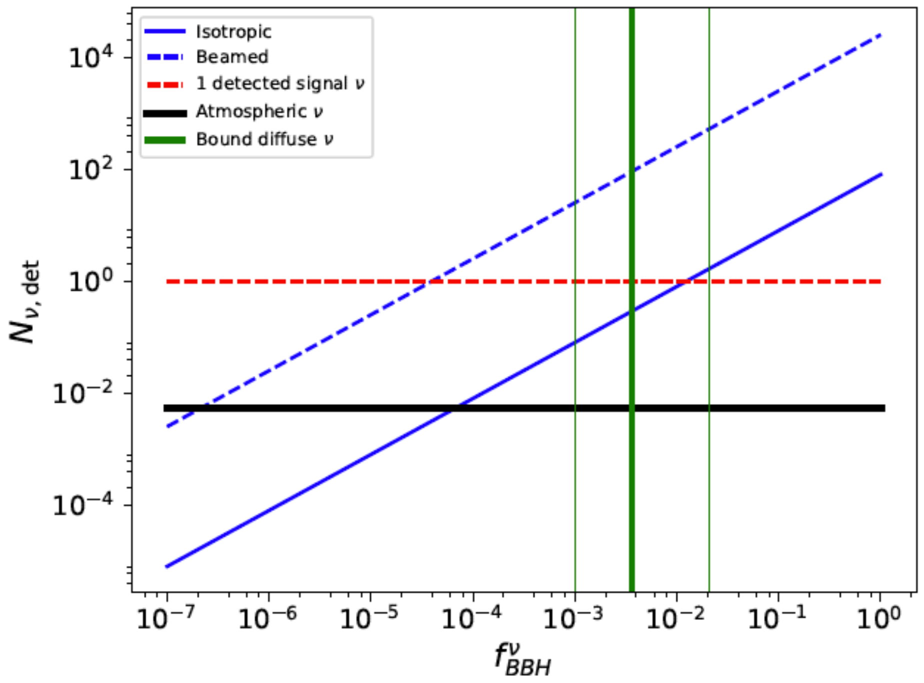
- No IC/ANTARES events in ±500 s from the GW time (0.015 expected)
  - Limits from ANTARES dominates for E_ν < 100 TeV
  - Limits from IC dominated for E_ν >100 TeV
- Size of GW150914 : 590 deg^2 ANTARES resolution: <0.5 deg^2
- Limits on total energy radiated in neutrinos: <10% GW
- Future: Receive / send alerts in real time

K. De Vries et al., arXiv:1709.04880 (ICRC 2017)

Binary black hole merger:

No neutrinos/gamma rays expected if regions around black holes devoid of matter
But: perhaps possibility for emission if there is an accretion disk

$f^{\nu}_{\mathrm{BBH}} = \frac{E_{\nu}}{E_{\mathrm{GW}}}$ = fraction of energy in neutrinos

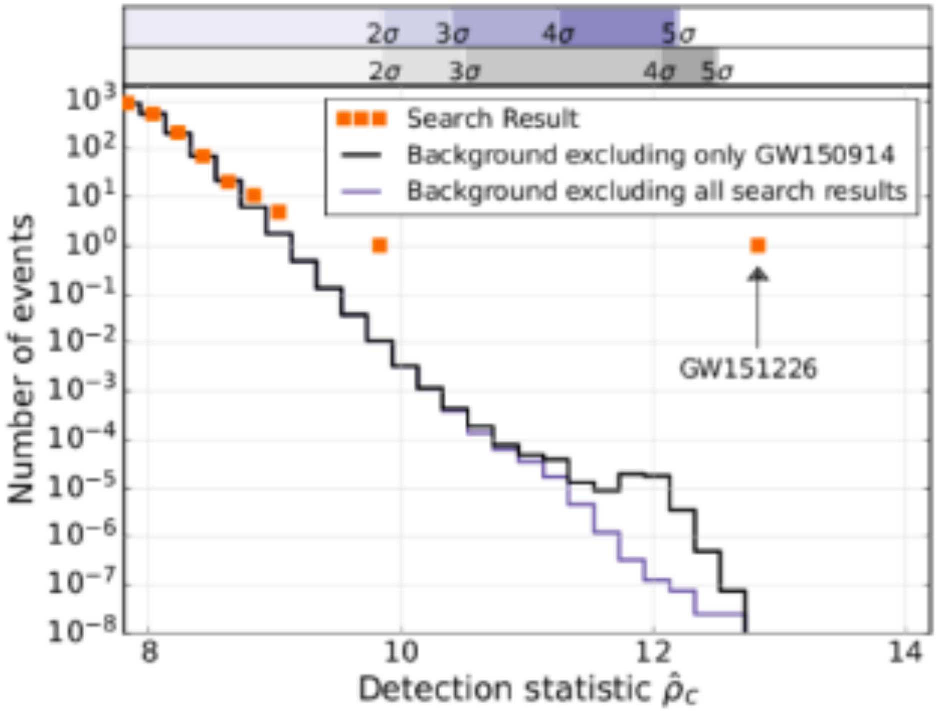


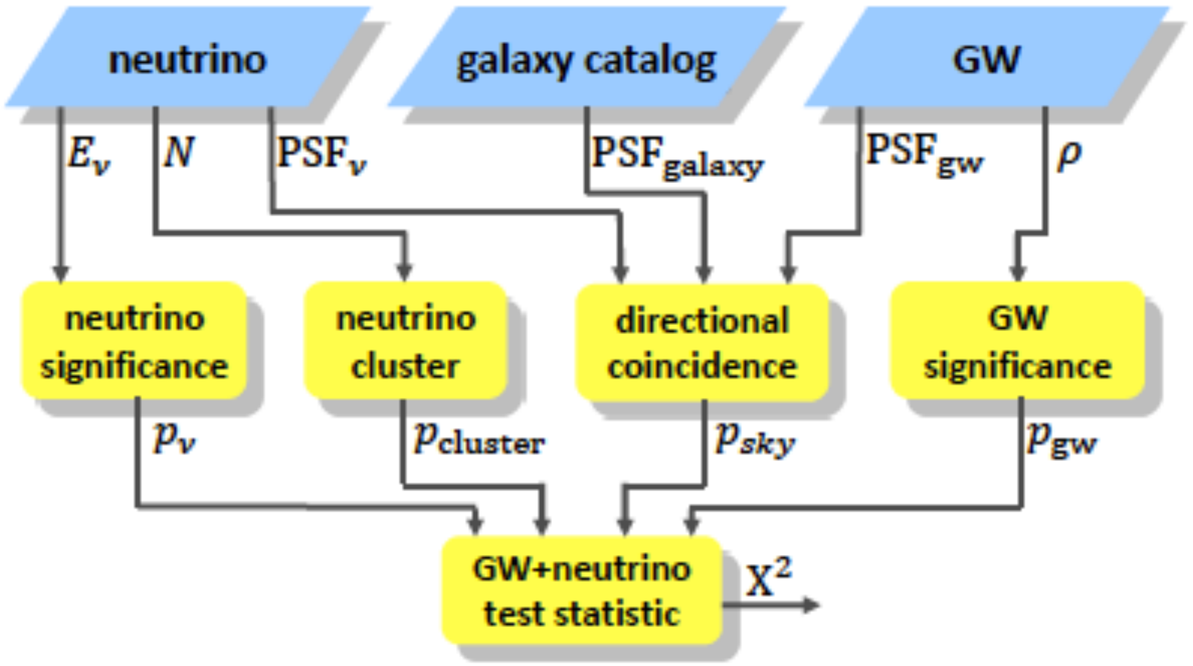
$$f^{\nu}_{\mathrm{BBH}} = f_{\mathrm{matter}} \times f_{\mathrm{engine}} \times \varepsilon_{\mathrm{p,acc}} \times \varepsilon_{\nu}$$

Matter around BH (in terms of GW energy)

$$f^{GW150914}_{\mathrm{matter}} \lesssim 7.9 \times 10^{-2} \times \frac{\Delta\Omega}{0.2 \times 0.2}$$

Multi-messenger approach: with a list of neutrino events, one can do a GW sub-threshold analysis: include events with low signal/noise





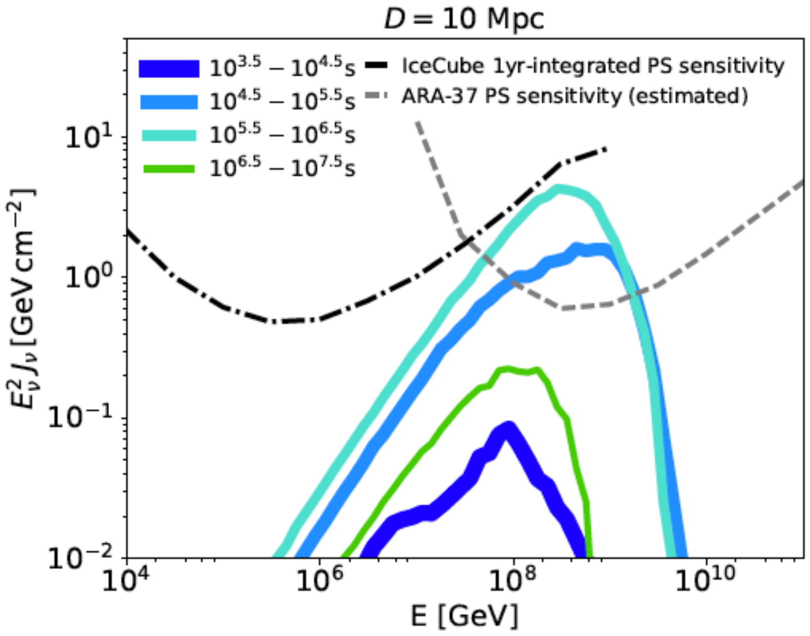
Neutron star – neutron star, or black-hole – neutron star merger

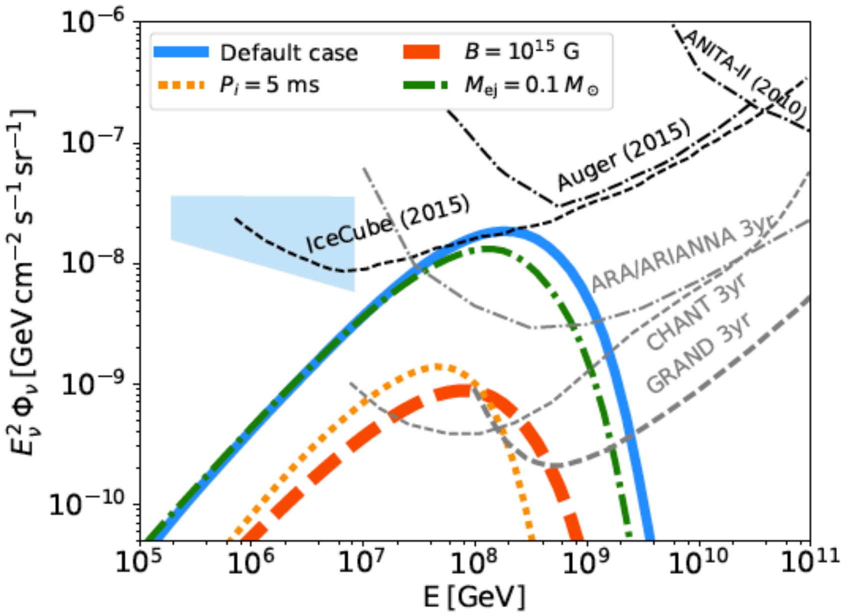
Likely to be the engines of short gamma ray bursts (like SGRB170817A)

HIGH-ENERGY NEUTRINOS FROM MILLISECOND MAGNETARS FORMED FROM THE MERGER OF BINARY NEUTRON STARS

KE FANG [1,2] & BRIAN D. METZGER[3]

arXiv:1707.04263

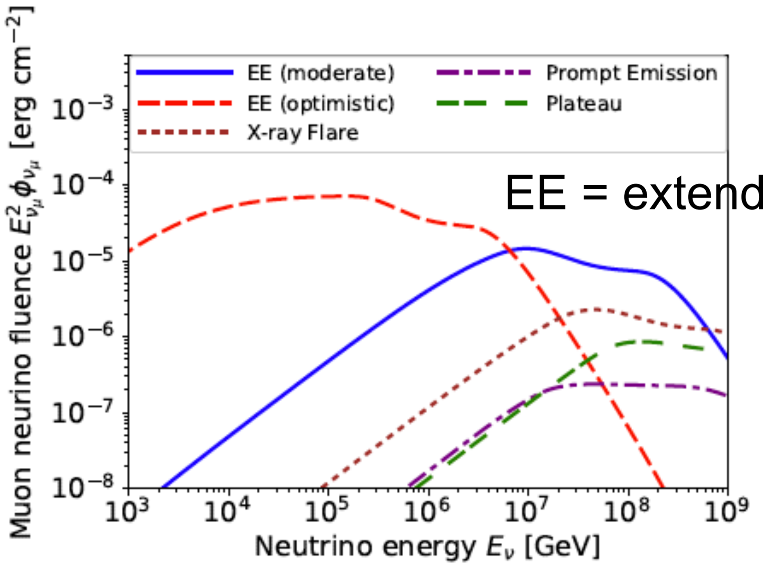




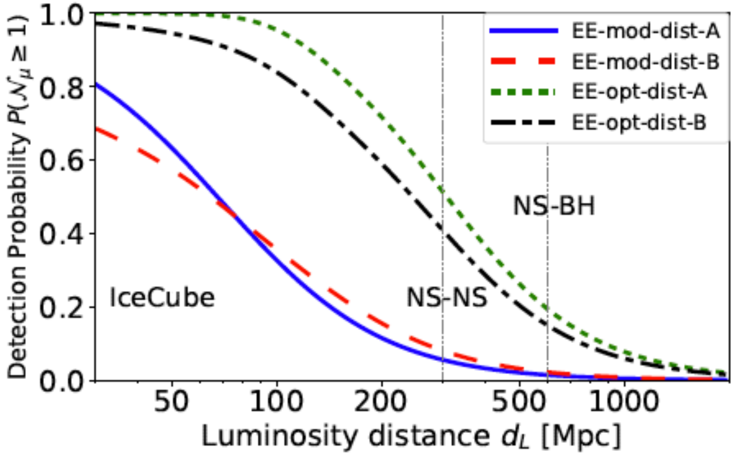
HIGH-ENERGY NEUTRINO EMISSION FROM SHORT GAMMA-RAY BURSTS: PROSPECTS FOR COINCIDENT DETECTION WITH GRAVITATIONAL WAVES

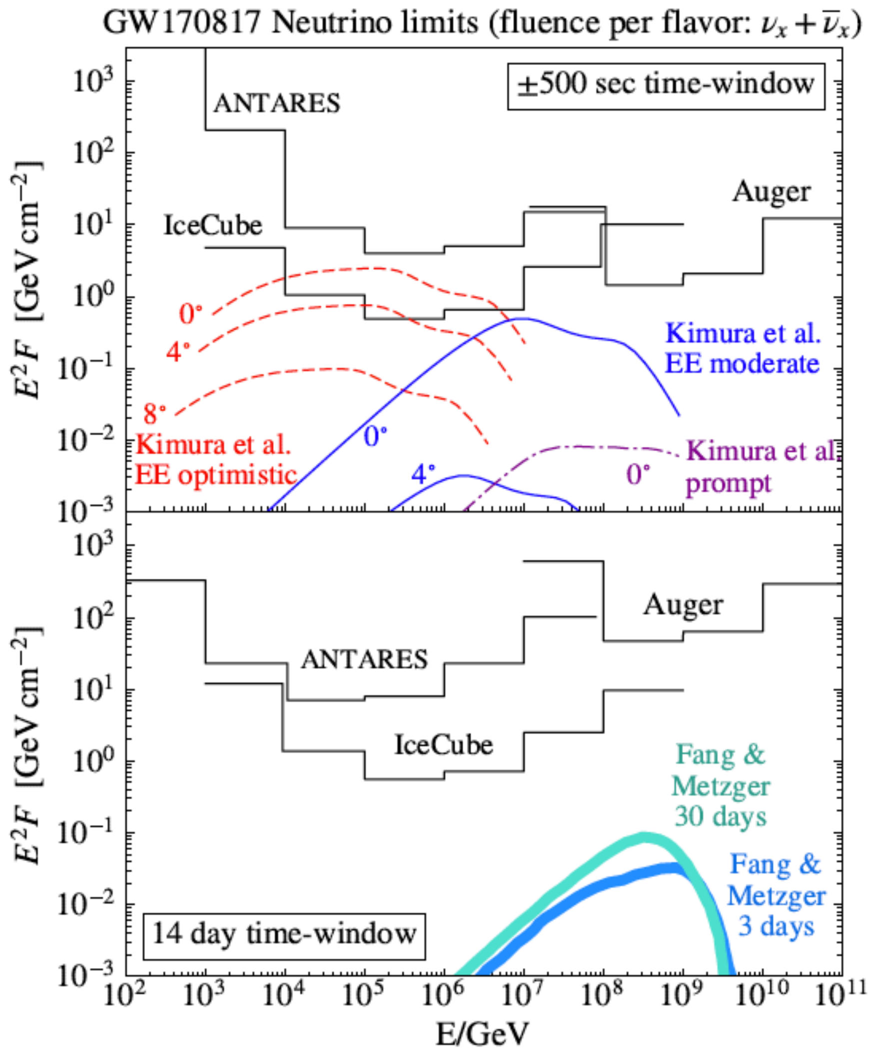
Shigeo S. Kimura[1,2,3], Kohta Murase[1,2,3,4], Peter Mészáros[1,2,3], Kenta Kiuchi[4]

Astrophys.J. 848 (2017) L4



EE = extended emission





Conclusions

We have a cosmic neutrino signal. Its magnitude is as high as can be expected,
close to Waxman-Bahcall bound. Universe seems to be making neutrinos efficiently.

Advantages of neutrinos: no attenuation, no deflection, large field of view,
high duty cycle, real-time alert, 0.1 degree angular resolution

Disadvantages: low cross sections, challenging detectors, backgrounds

IceCube sources are still unknown. Only multi-messenger approach will identify them.
Experiments + theory (modeling)!

Multi-messenger is more than bi-messenger