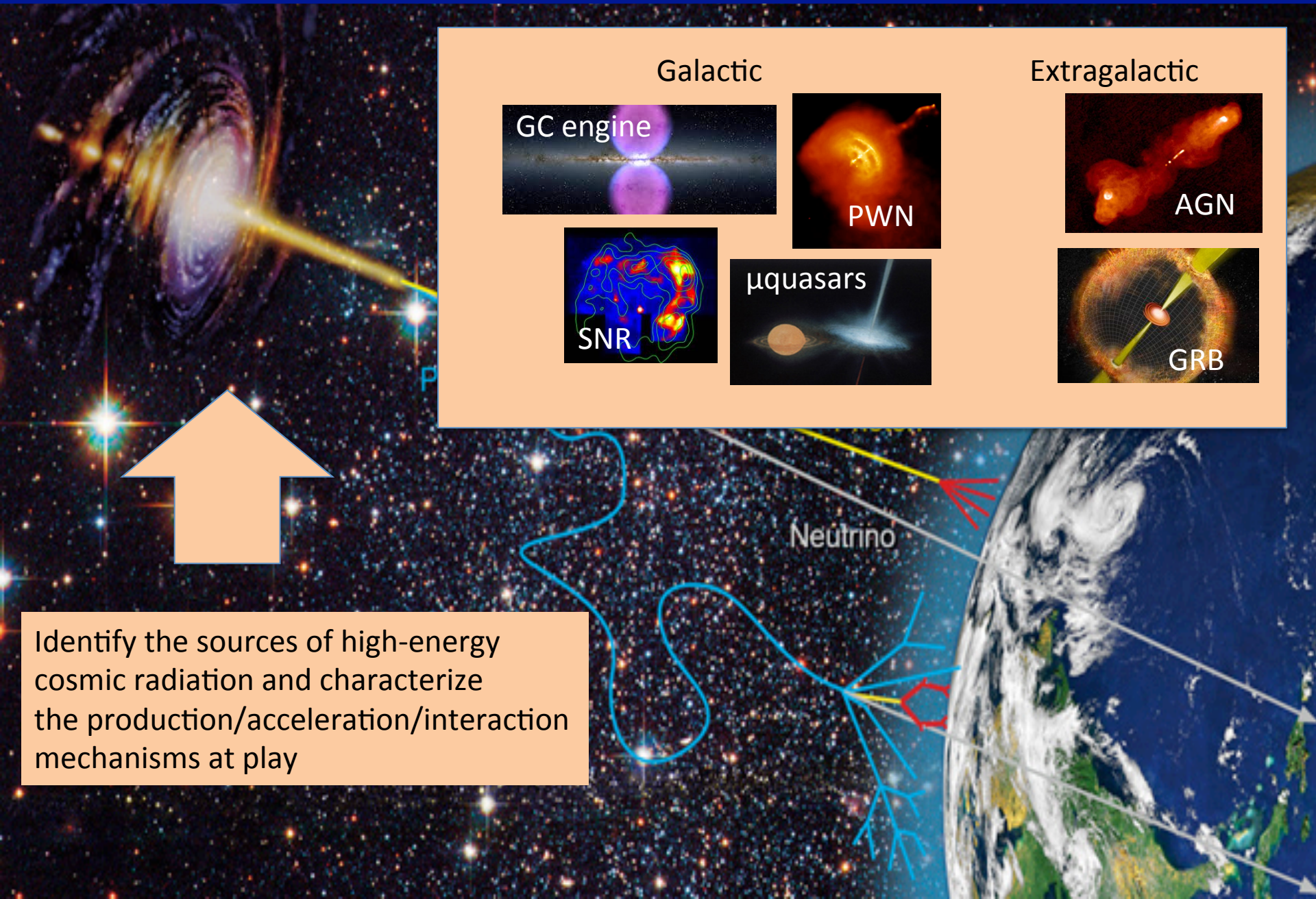
(high-energy) Multi-messenger astronomy with neutrinos, cosmic rays and gravitational waves

- an experimental review -

Véronique Van Elewyck
(APC & Université Paris Diderot)

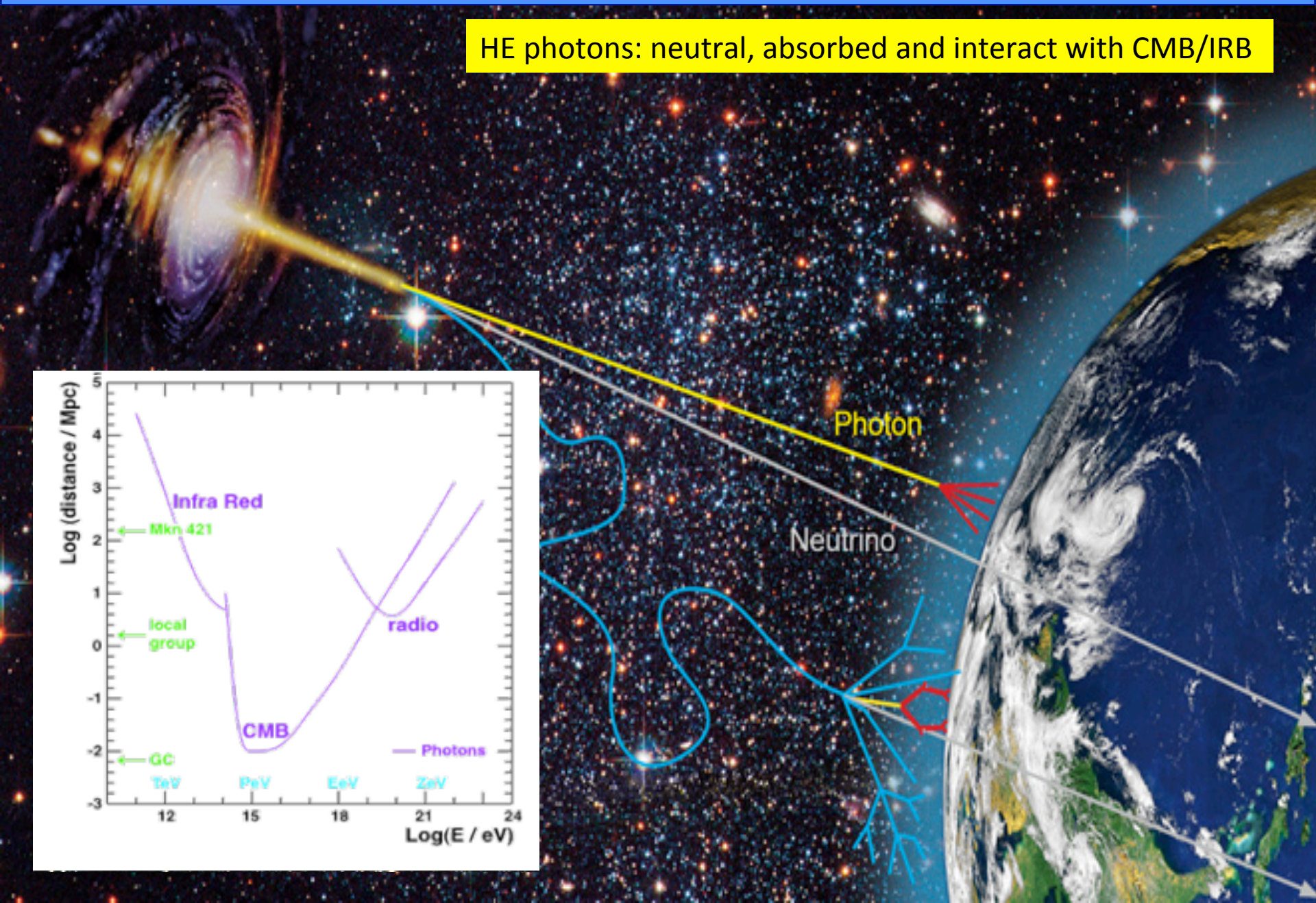
Multi-messenger astronomy: why and how



Identify the sources of high-energy cosmic radiation and characterize the production/acceleration/interaction mechanisms at play

Multi-messenger astronomy: why and how

HE photons: neutral, absorbed and interact with CMB/IRB



Multi-messenger astronomy: why and how

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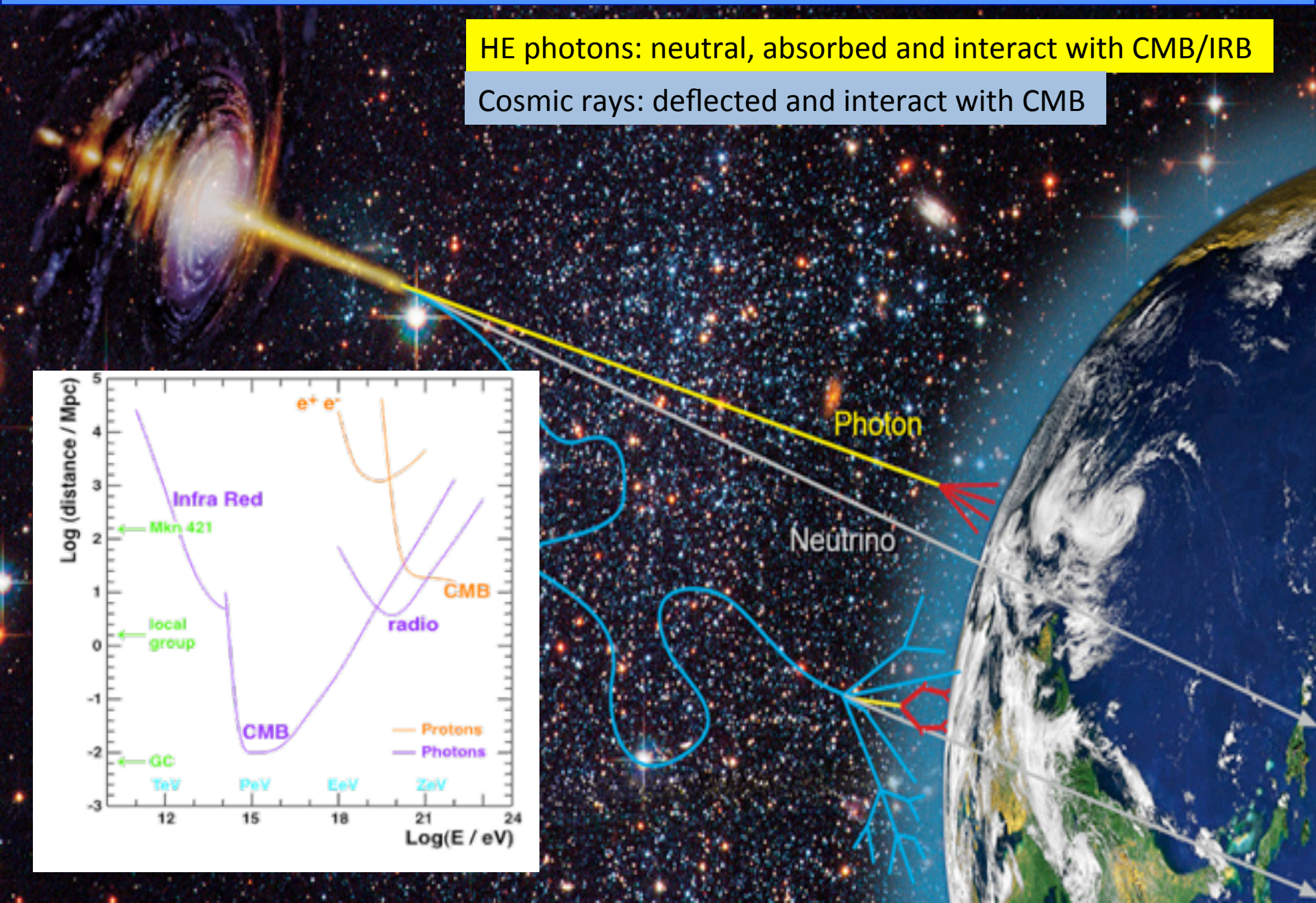
Cosmic rays: deflected and interact with CMB

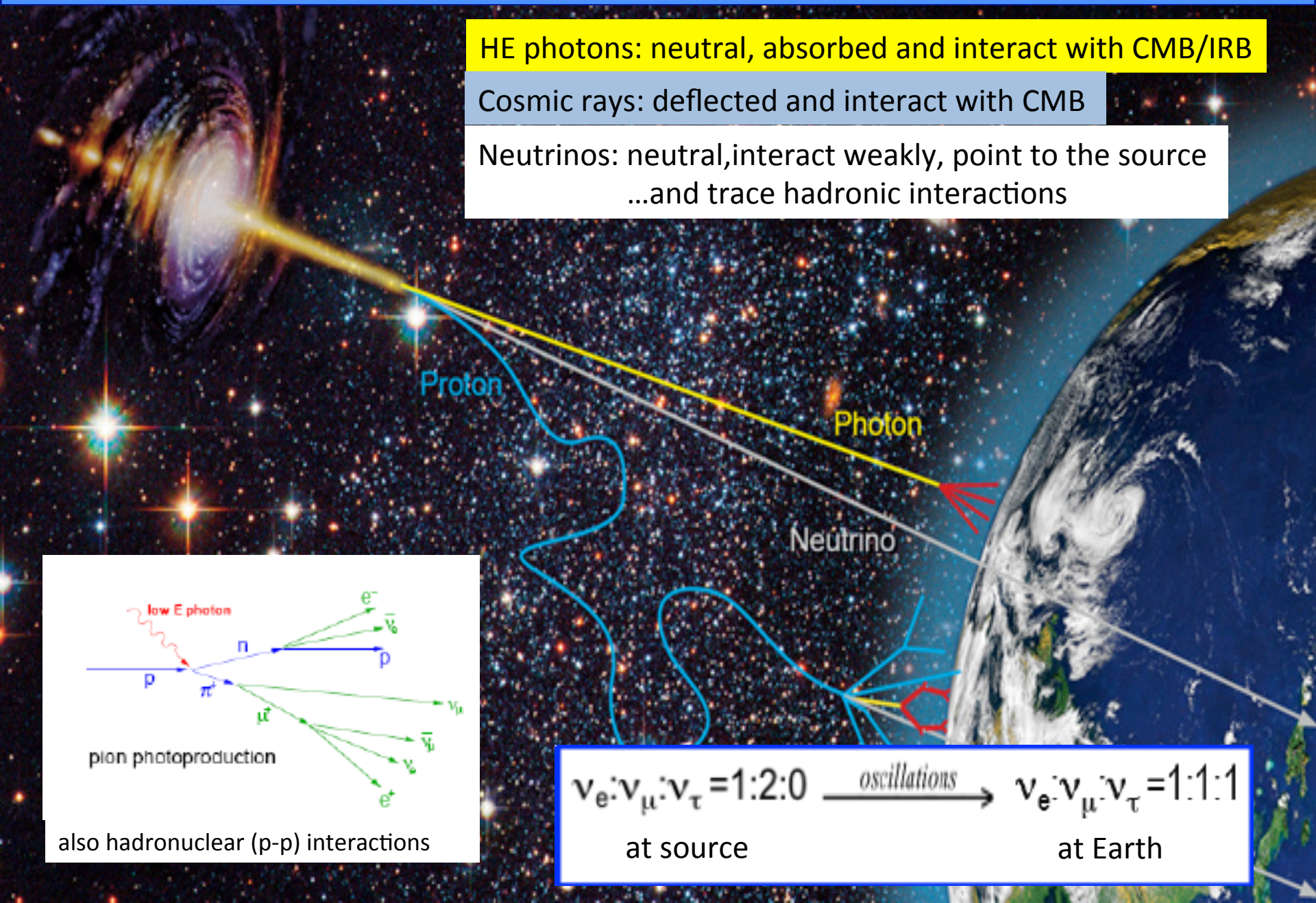


Multi-messenger astronomy: why and how

HE photons: neutral, absorbed and interact with CMB/IRB

Cosmic rays: deflected and interact with CMB

Neutrinos: neutral,interact weakly, point to the source
…and trace hadronic interactions



also hadronuclear (p-p) interactions

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

at source at Earth

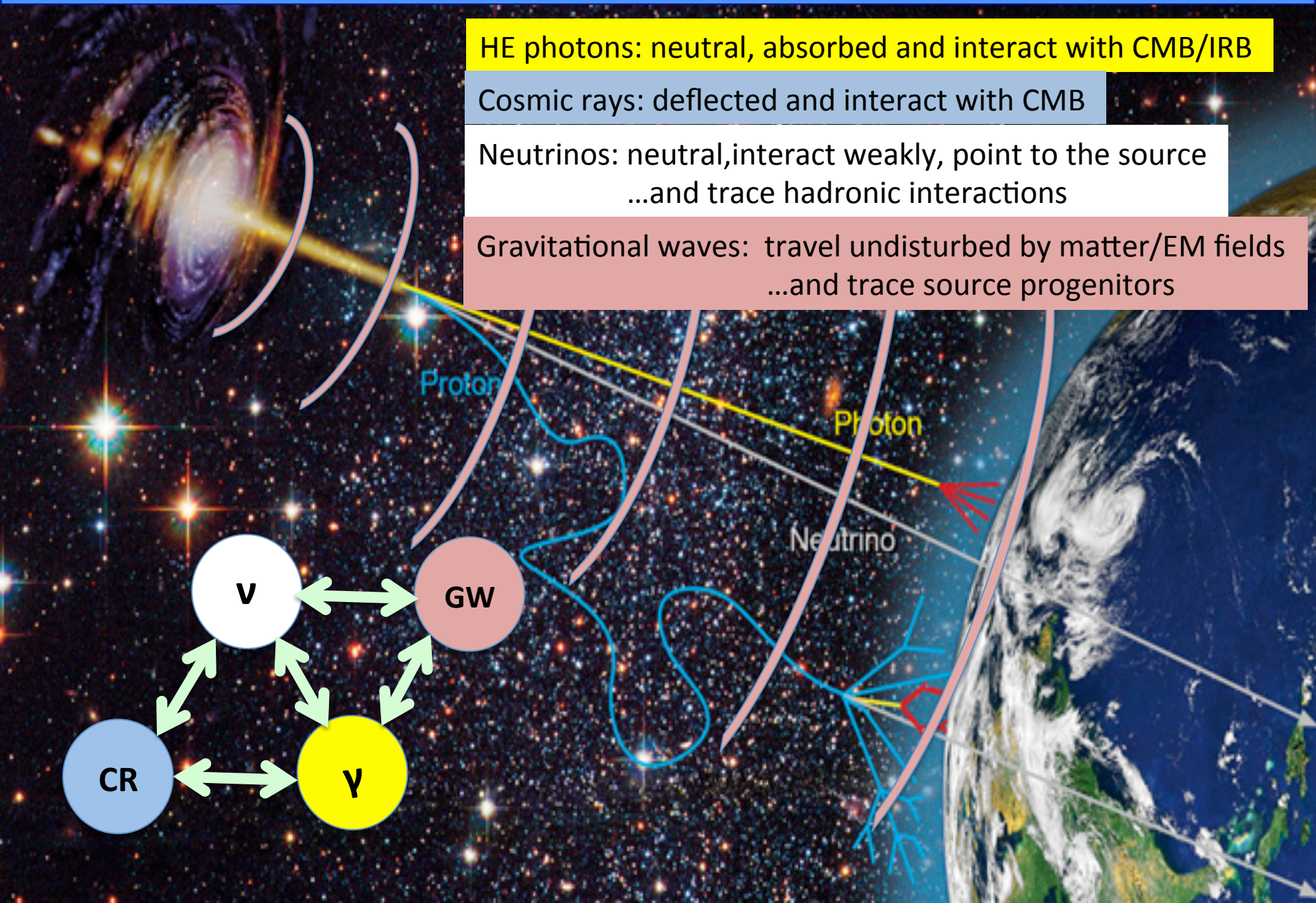
Multi-messenger astronomy: why and how

HE photons: neutral, absorbed and interact with CMB/IRB

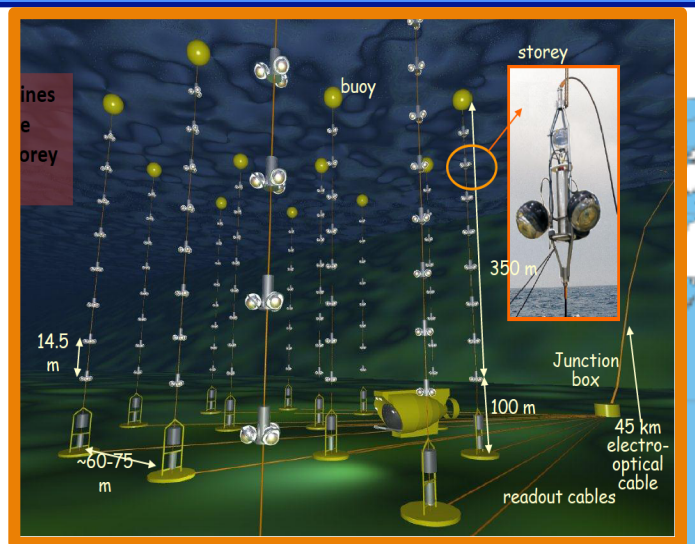
Cosmic rays: deflected and interact with CMB

Neutrinos: neutral,interact weakly, point to the source
…and trace hadronic interactions

Gravitational waves: travel undisturbed by matter/EM fields
…and trace source progenitors

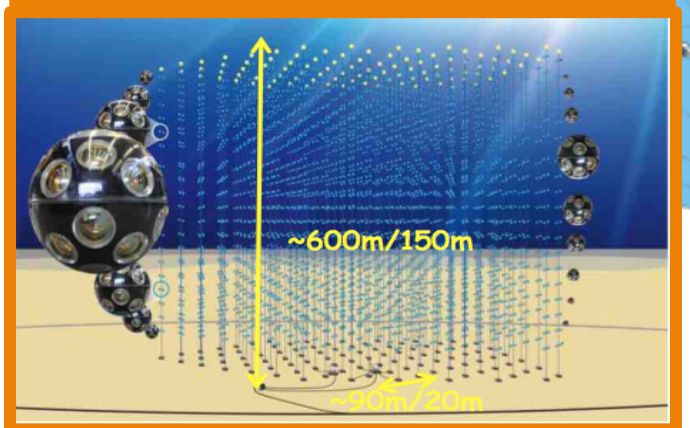


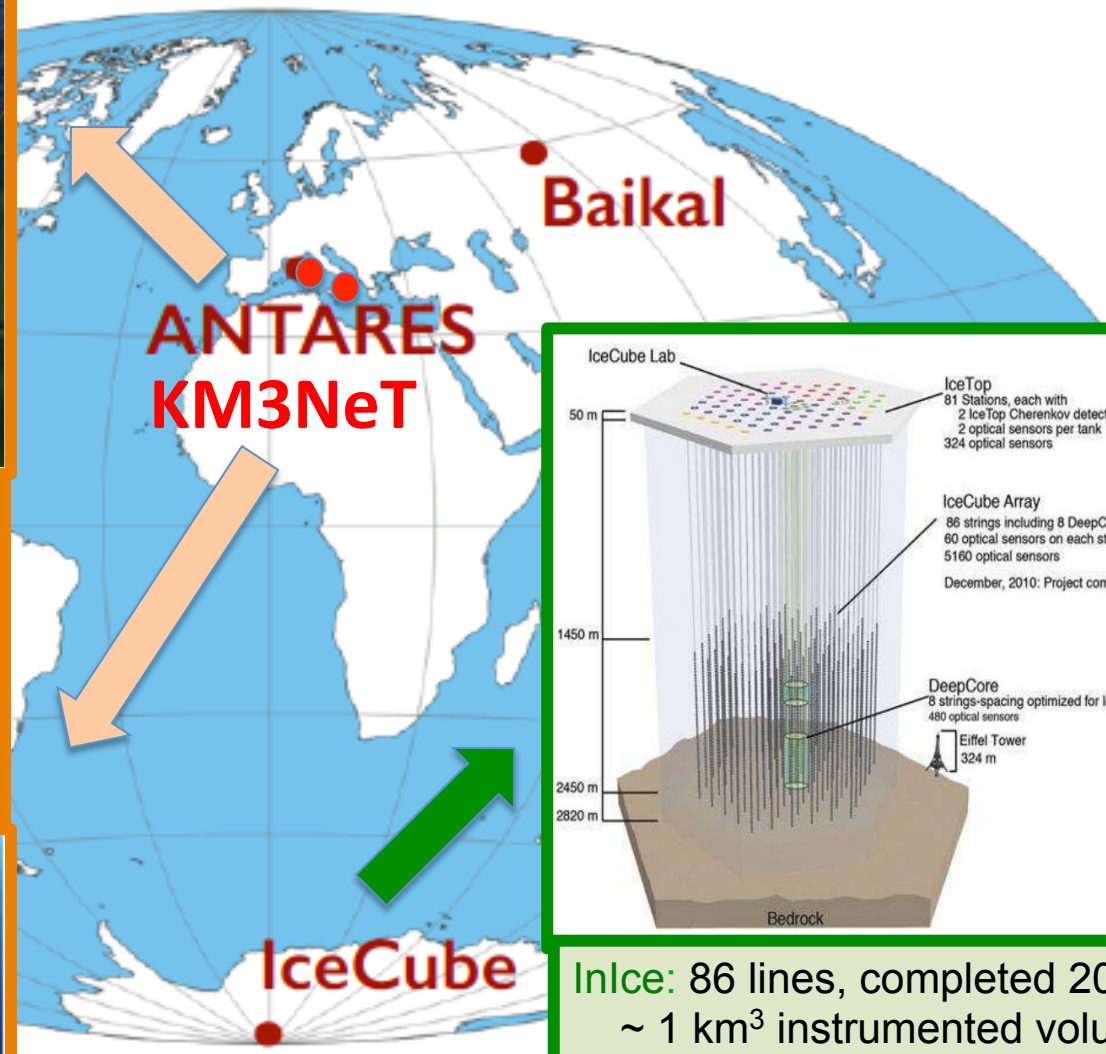
Neutrino telescopes today

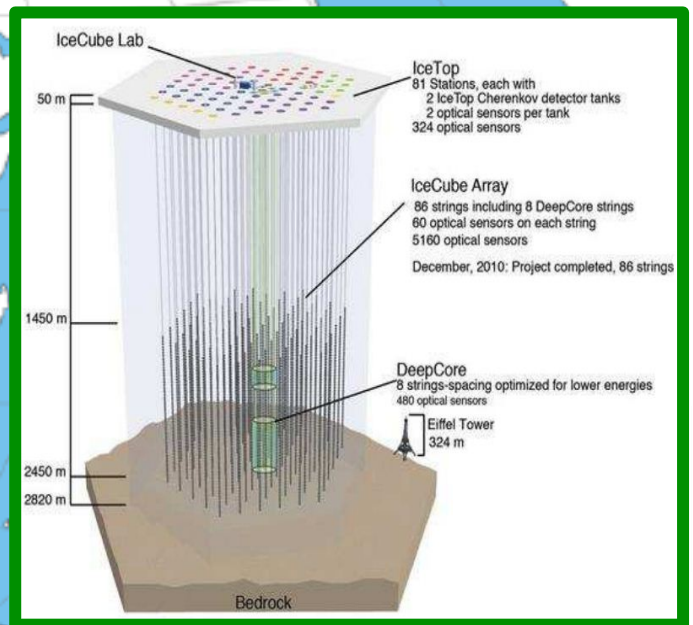


12 lines, completed 2008
~ 0,02 km^3 instrumented volume

Prototype for a km3-sized detector in the Mediterranean:
KM3NeT (ARCA & ORCA)
under construction







InIce: 86 lines, completed 2010
~ 1 km^3 instrumented volume

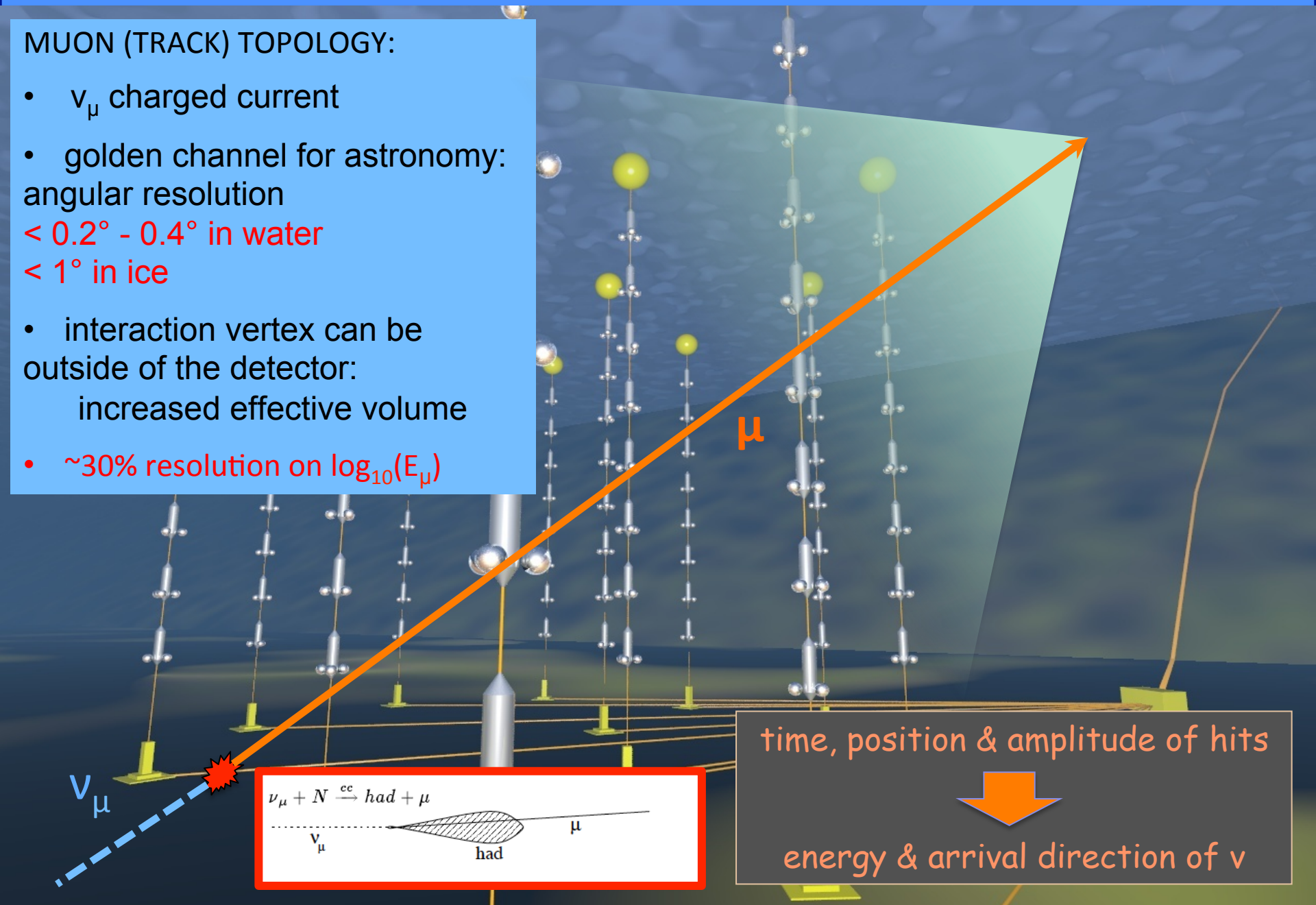
DeepCore: 8 lines, dense infill

IceTop: air shower array

Detection principle

MUON (TRACK) TOPOLOGY:

- ν_μ charged current
- golden channel for astronomy: angular resolution
  < 0.2° - 0.4° in water
  < 1° in ice
- interaction vertex can be outside of the detector:
  increased effective volume
- ~30% resolution on $\log_{10}(E_\mu)$



time, position & amplitude of hits

energy & arrival direction of ν

Detection principle

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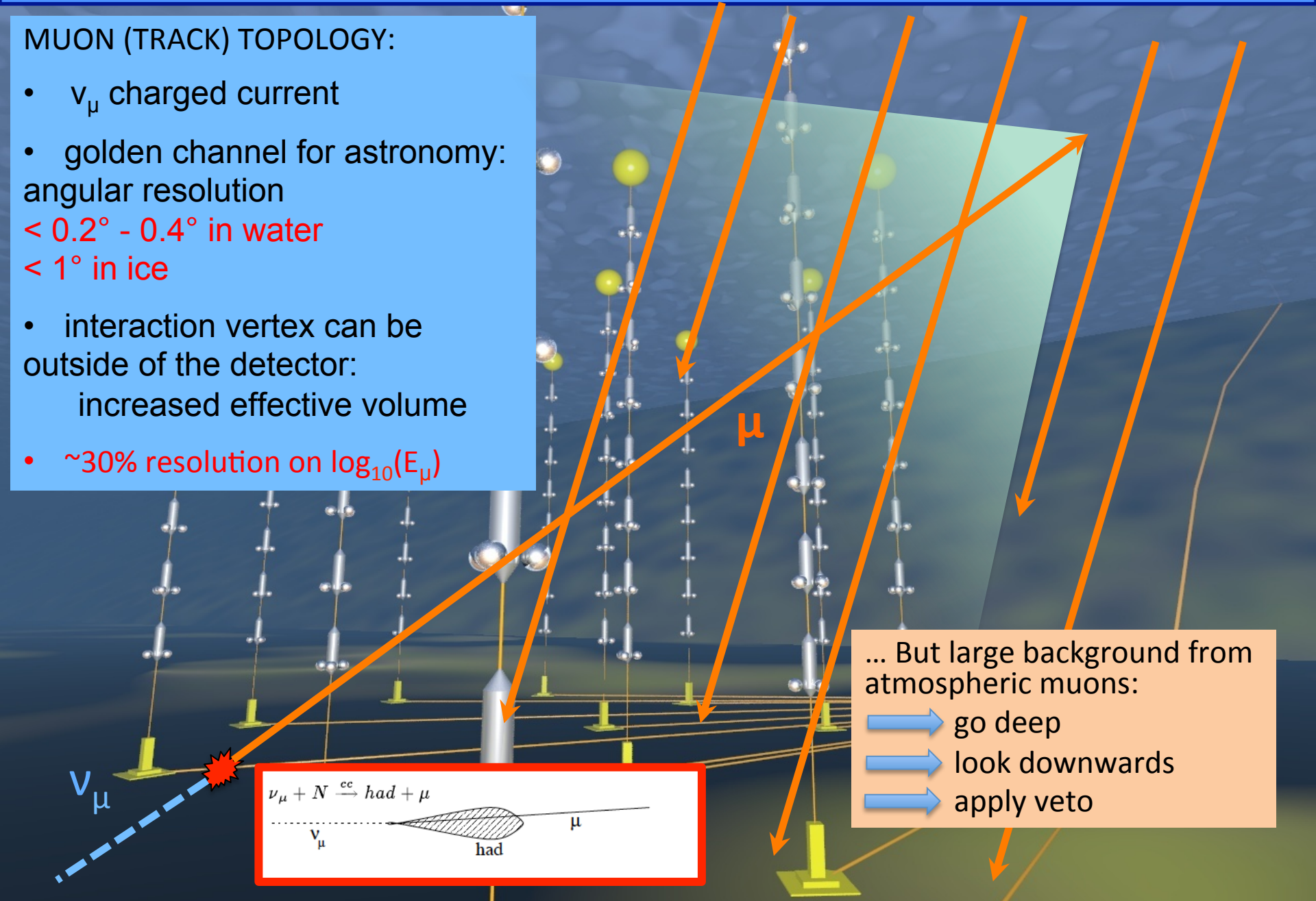


… But large background from atmospheric muons:

- go deep
- look downwards
- apply veto

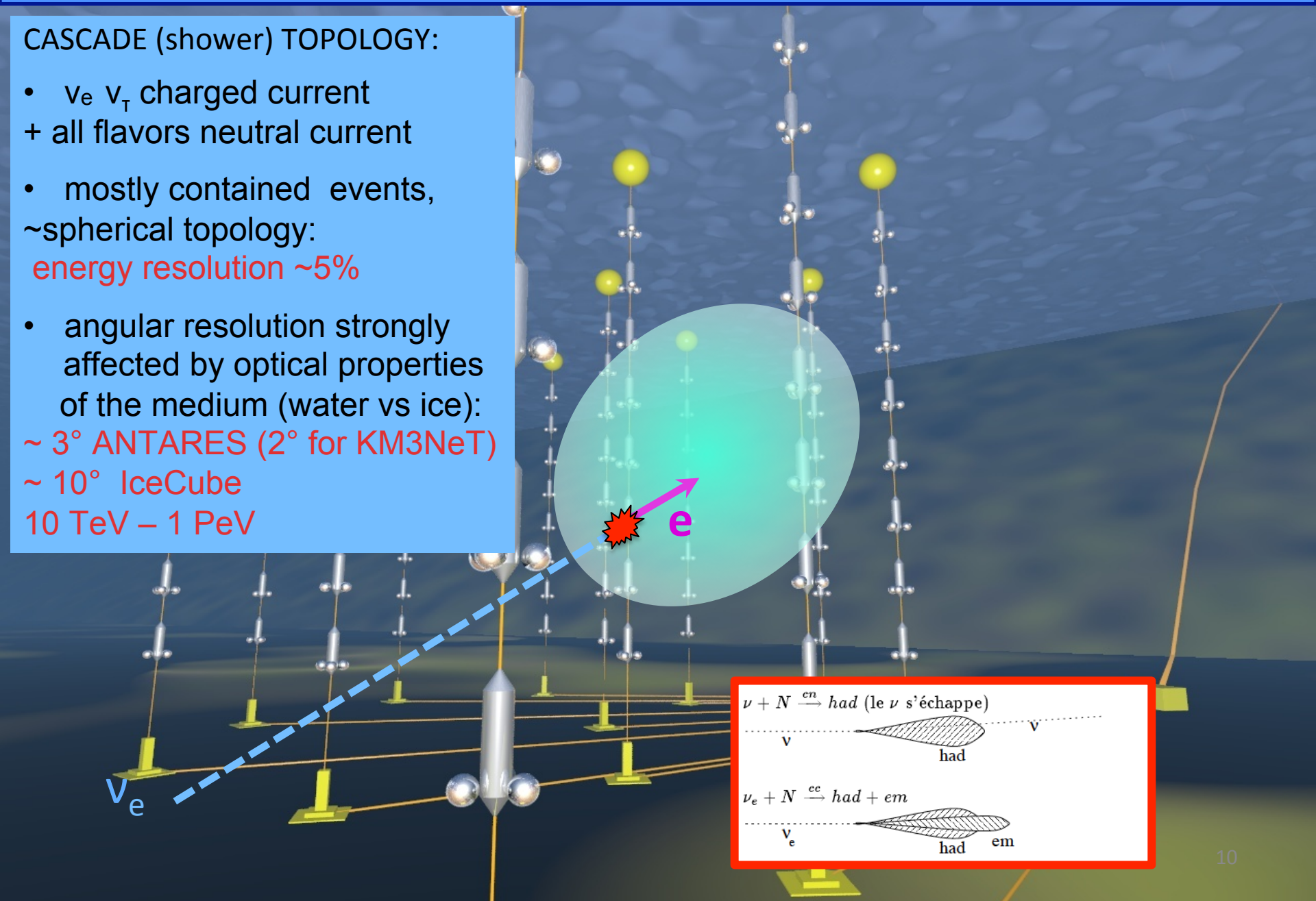
Detection principle

CASCADE (shower) TOPOLOGY:

- ν_e ν_τ charged current
+ all flavors neutral current

- mostly contained events,
~spherical topology:
energy resolution ~5%

- angular resolution strongly affected by optical properties of the medium (water vs ice):
~ 3° ANTARES (2° for KM3NeT)
~ 10° IceCube
10 TeV – 1 PeV

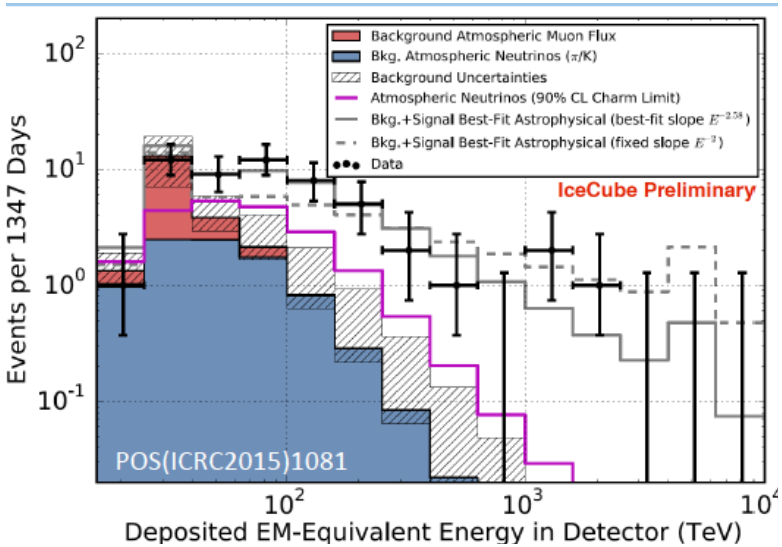


Status of neutrino astronomy

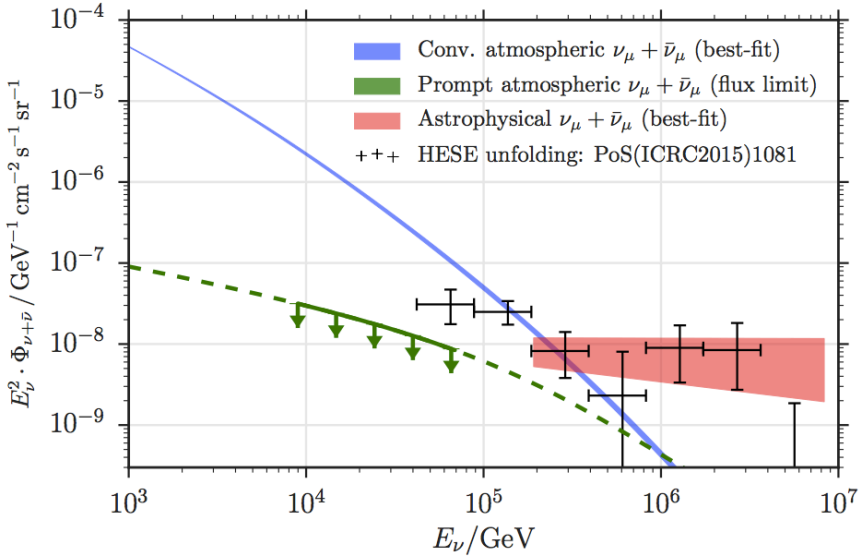
See A. Capone: ANTARES/KM3NeT – Astroparticle Physics Session Wed 12:00
See D. Grant: IceCube results – Plenary session Fri

The IceCube signal is robust… and challenging !

Discovery channel:
HESE, now 4-year sample
all-sky, all-flavour (tracks+cascades)



signal also observed in other channels:
e.g. upgoing ν_μ (tracks) from
Northern sky only



best fit (E > 30 TeV):
~ $E^{-2.6}$

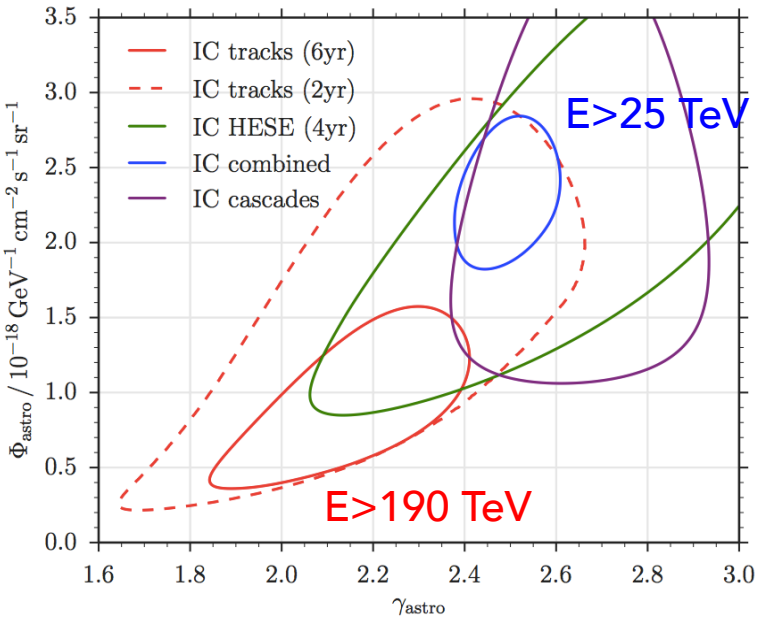
?

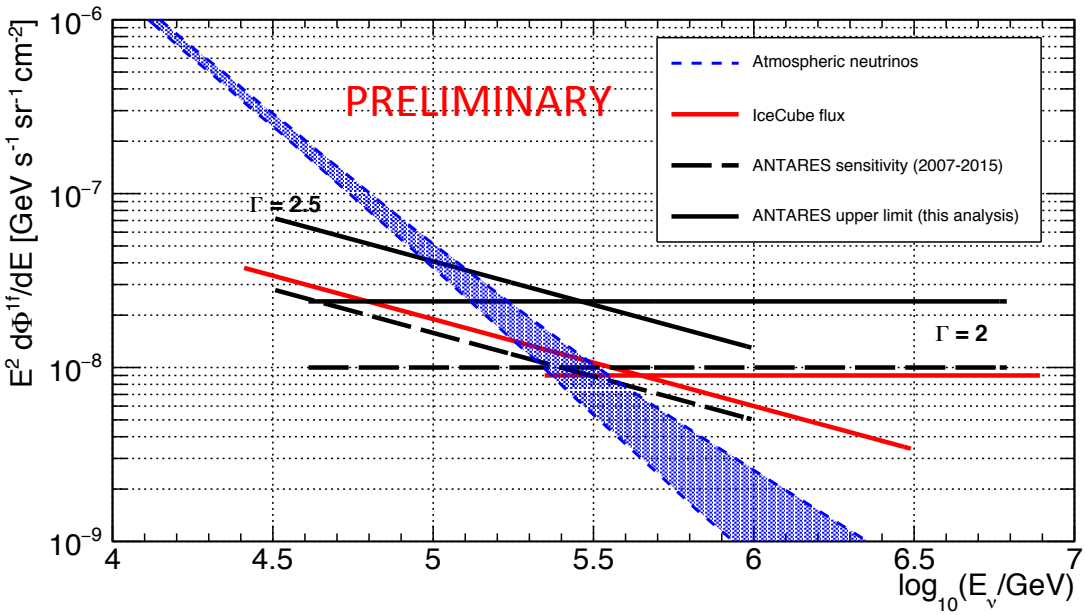
best fit (190 TeV – 8 PeV):
~ $E^{-2.1}$

Status of neutrino astronomy

Spectral index inferred from samples with
- different energy thresholds…
- different sky coverages…
- different flavour content…

➡ Indication of spectral break ?
➡ Indication of Galactic + extragalactic components ?



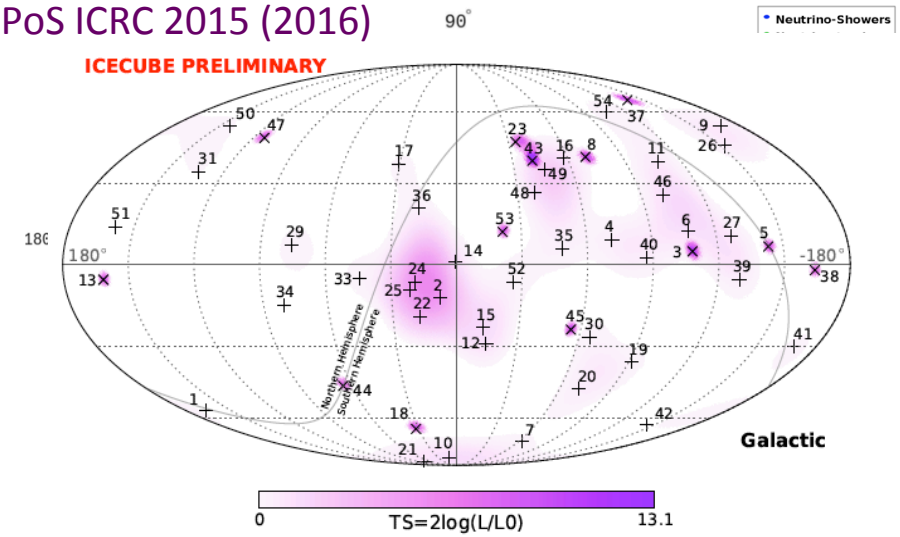


…Latest ANTARES results compatible with IceCube signal, but no significant excess yet:

2007-2015 combined (tracks +cascades)

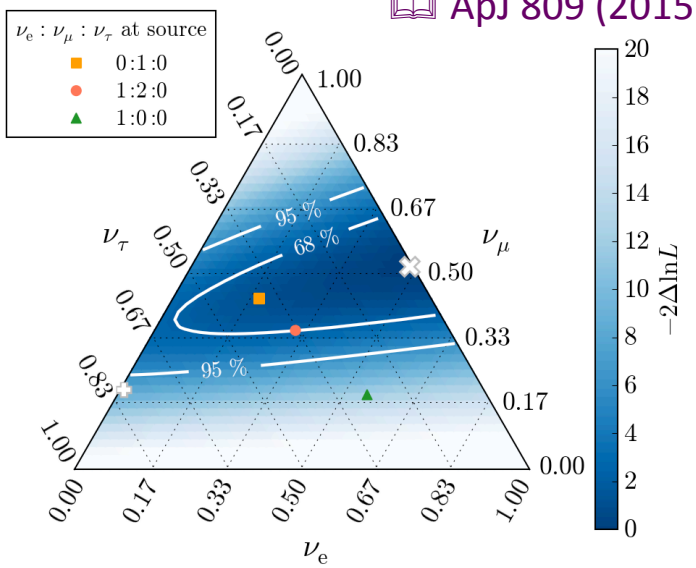
Status of neutrino astronomy

PoS ICRC 2015 (2016)



Signal consistent with an isotropic diffuse flux (> 100 sources)
No source identified
No electromagnetic counterpart observed

ApJ 809 (2015)



Event flavour distribution consistent with standard oscillations; excludes neutron decay scenario at 3.6 σ

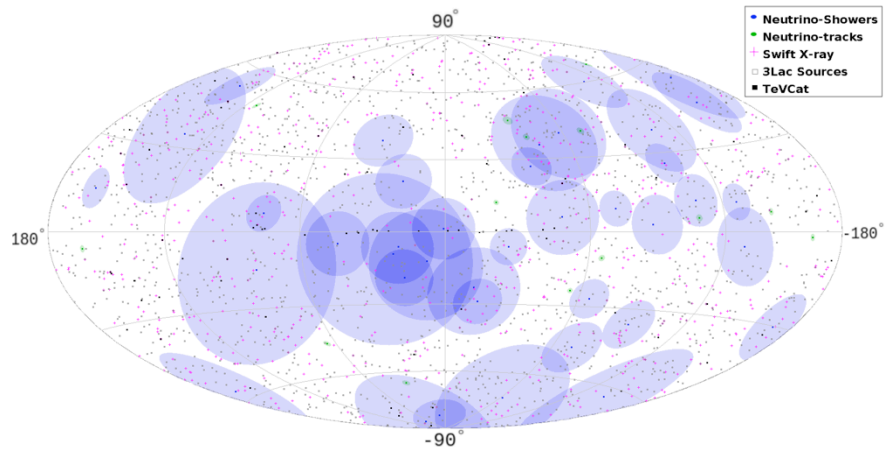
? WHERE AND WHICH ARE THE SOURCES ?

main observables: spectrum – composition – anisotropies

(same as for UHE cosmic rays !)

need good angular/energy accuracy
all-flavour astronomy
multi-messenger programs (TIME and SPACE coincidences)

Status of neutrino astronomy



Moharana et al., PoS ICRC 2015 (2016)

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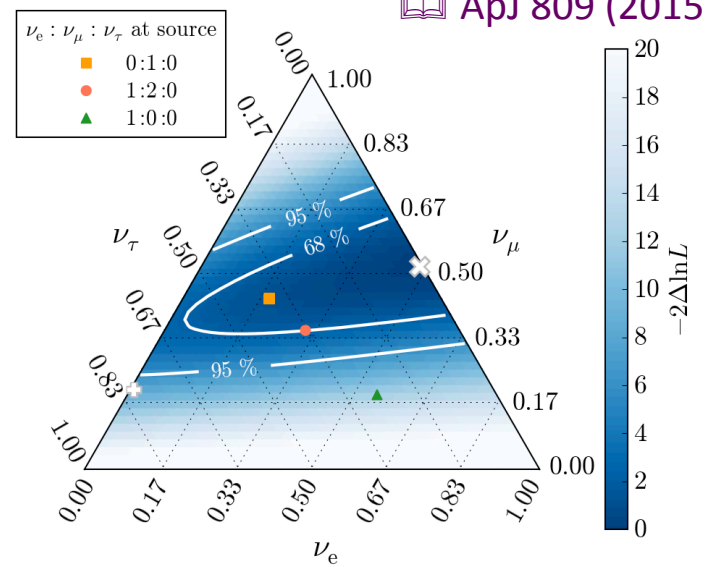

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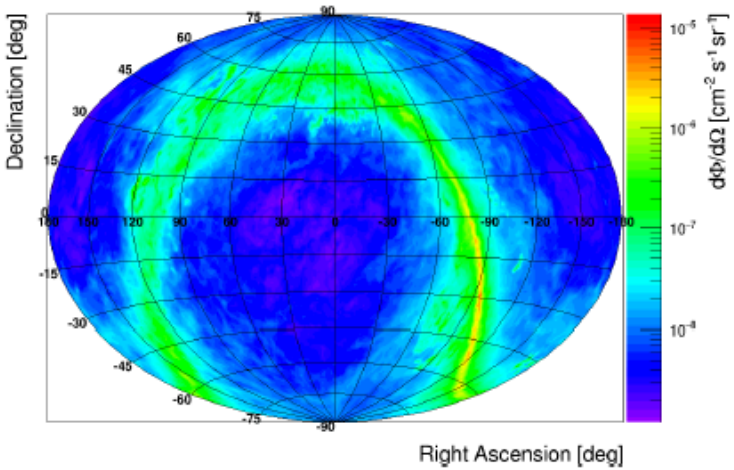
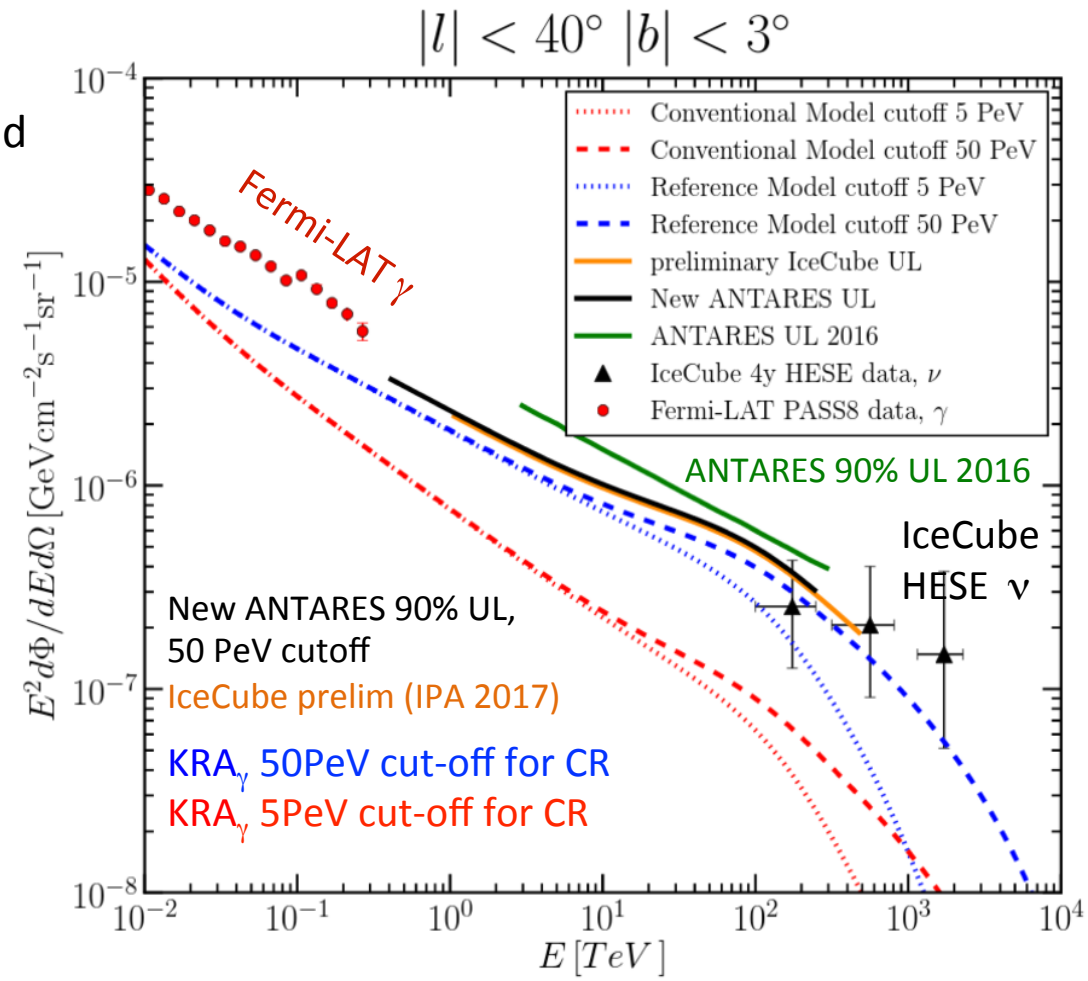
Searches for neutrinos from the Galactic Plane

Most recent analysis testing KRAγ model of CR diffusion in the Galaxy:

arXiv 1705.00497

radial dependance of the slope of the diffusion coefficient & the advective wind



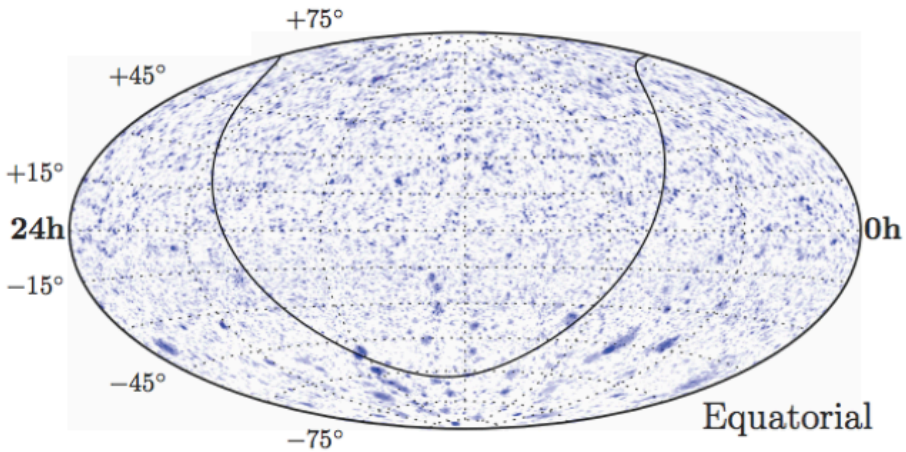


- ❖ Up to 19% of IceCube HESE sample can originate from Galactic CR diffusion
- ❖ Galactic CR interaction with gas cannot explain the spectral anomaly

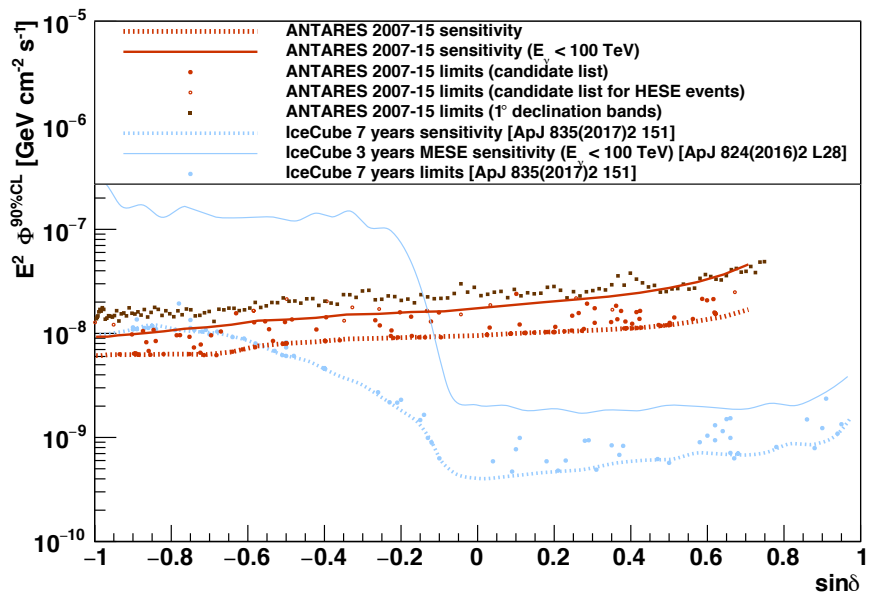
… combined study ANTARES+IceCube underway → increase in sensitivity expected

Searches for neutrino point sources

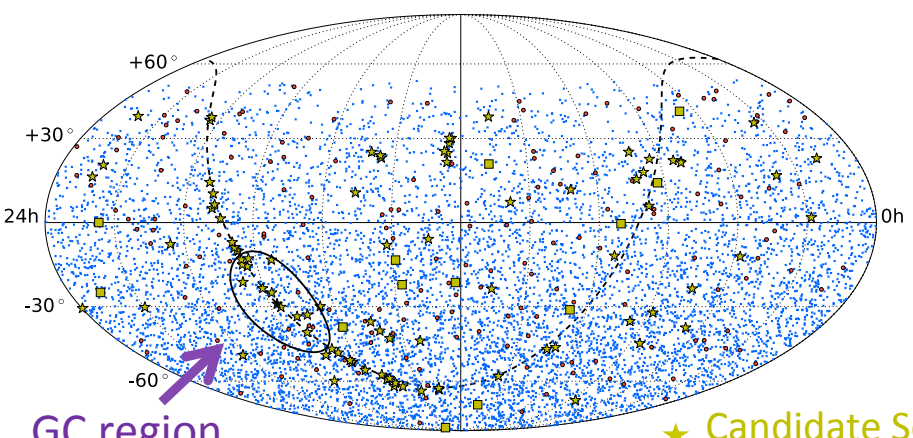
IceCube: 2008-2015, > 700 000 events
through-going + starting tracks
📖 ApJ 835 (2017)



All-sky + candidate sources:
No significant excess found so far in the data



ANTARES: 2007-2015
7629 tracks + 180 showers



GC region

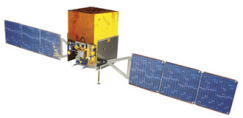
★ Candidate Sources
■ IC HESE tracks

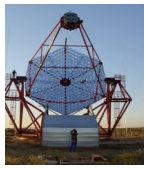
Complementarity ANTARES - IceCube at E < 100 TeV

Combined analysis 2007-2012
→ Further improvement in sensitivity
A new combined study underway…

📖 arXiv 1706.01857

Multi-messenger programs





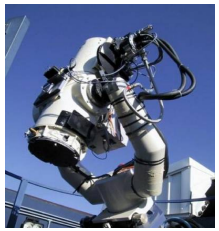
Gamma rays
GeV-TeV

Searches for neutrinos in coincidence with GRBs, blazars, microquasars, X-ray binaires,… Correlations with astrophysical catalogues…

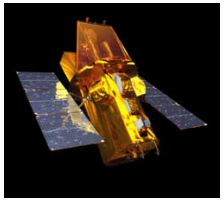
Ultra-high energy
Cosmic Rays

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…)

Gravitational
waves

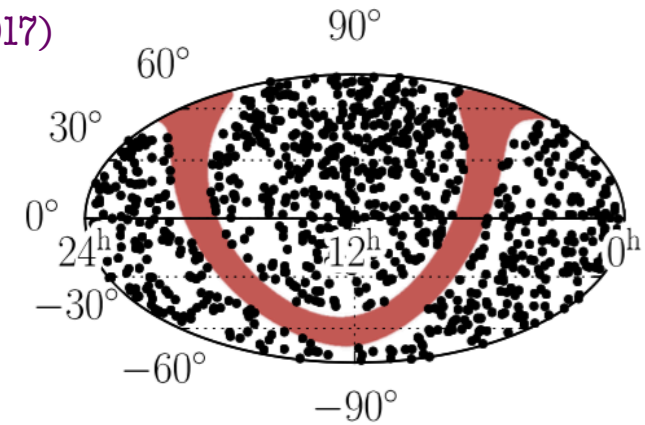
GWHEN: recherches conjointes de neutrinos HE et d'ondes gravitationnelles:
ANTARES+IceCube +LIGO+Virgo

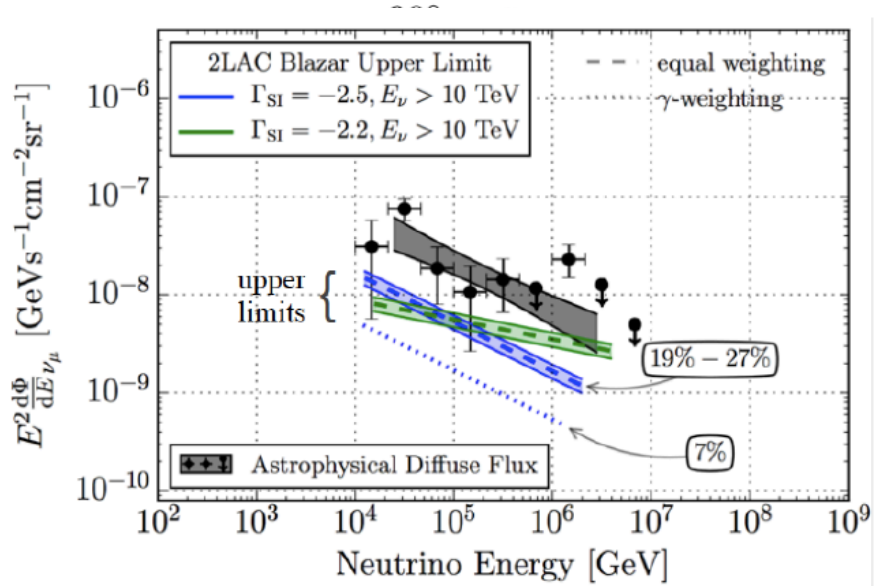
- Increase in sensitivity (independant datasets)
- Better understanding of astrophysical processes at play in the sources
- Huge effort in the development of real-time alert programs

Neutrino – EM connection: examples

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

📖 ApJ 835 (2017)





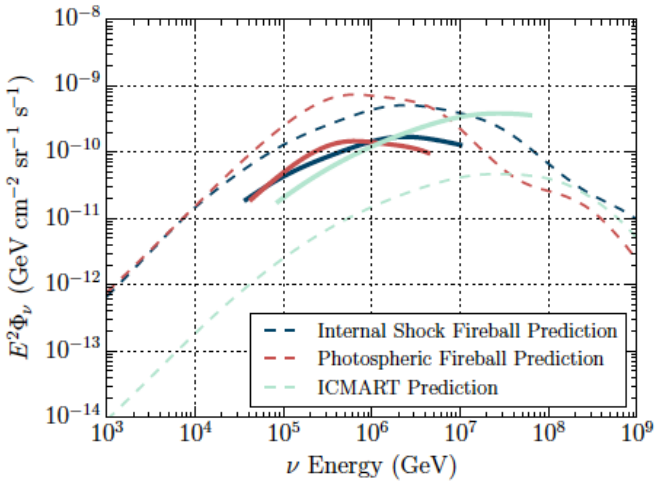
Blazars contribute less than 30% to Observed diffuse neutrino flux

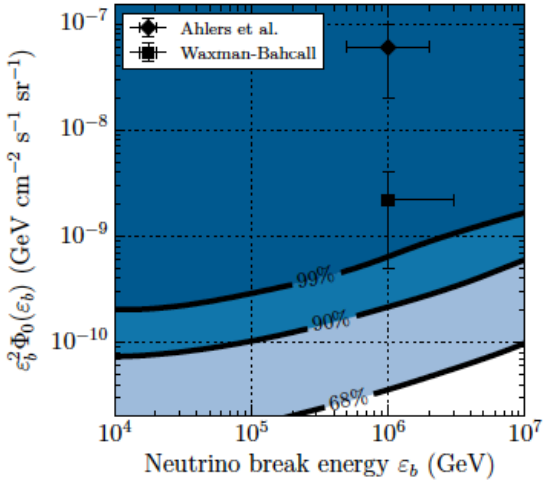
❖ **IceCube searches for prompt neutrinos in coincidence with Gamma-ray bursts**

All-sky, tracks & cascades
1172 GRBs correlated

GRBs contribute <1% to observed diffuse neutrino flux

Disfavours GRBs as main source of UHECR ?





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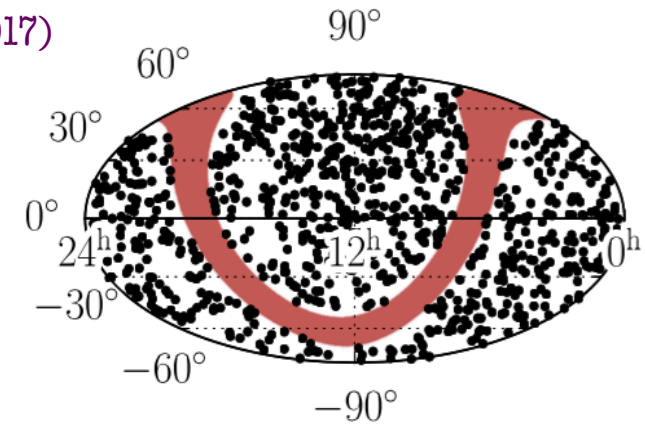
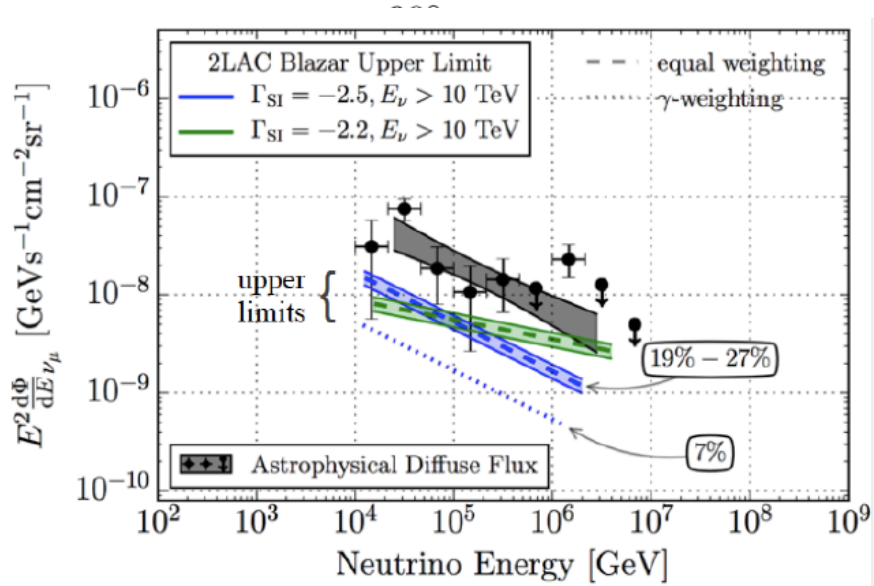


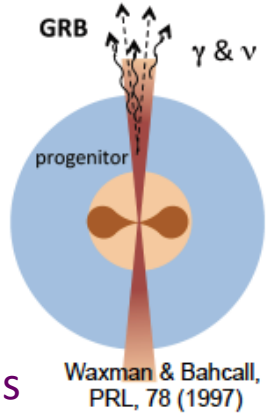


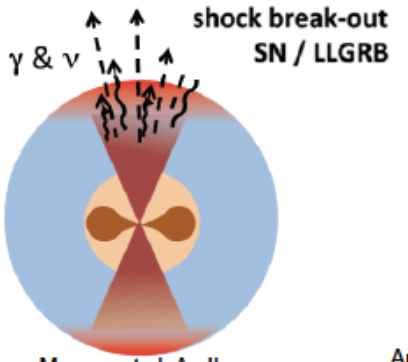
Blazars contribute less than 30% to Observed diffuse neutrino flux

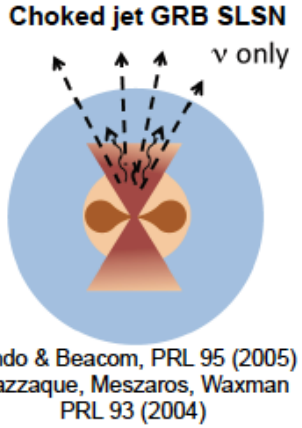
❖ **IceCube searches for prompt neutrinos in coincidence with Gamma-ray bursts**

…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



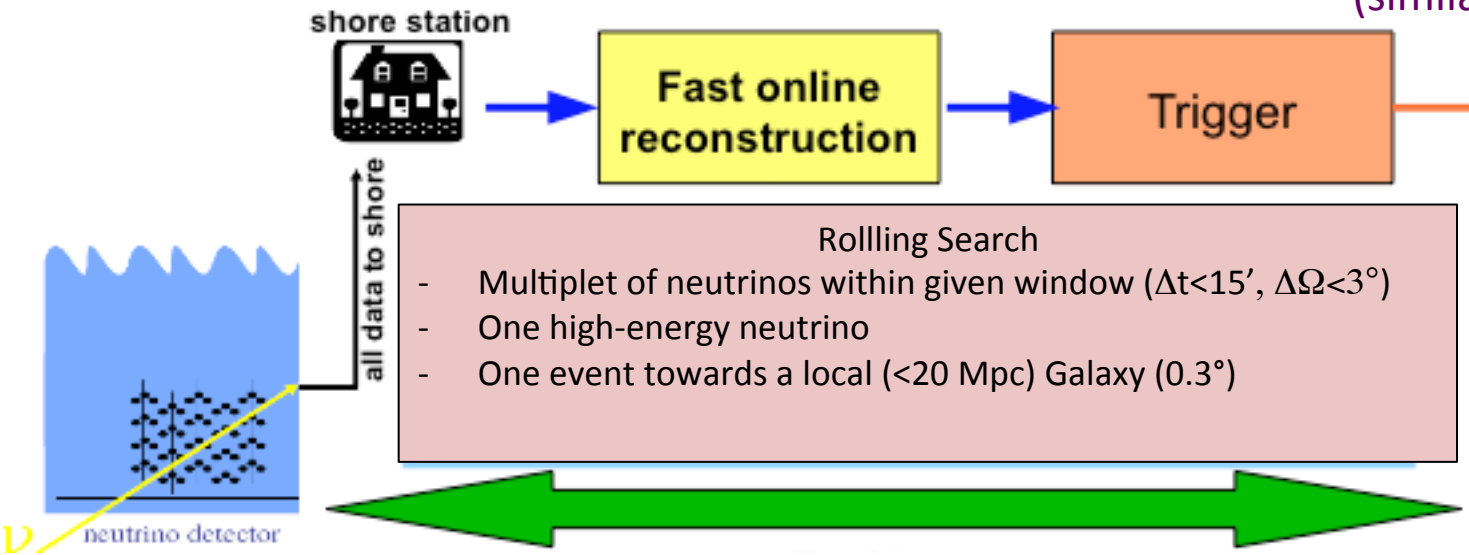




Credits A. Franckowiak

EM follow-up of neutrino events: ANTARES

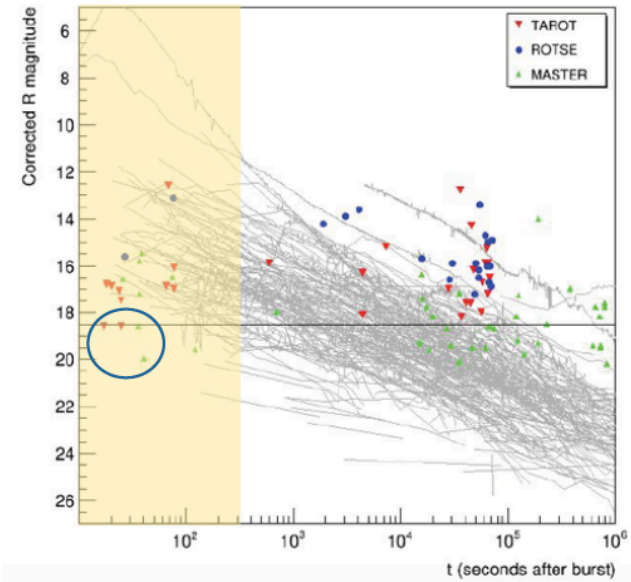
(similar program in IceCube)

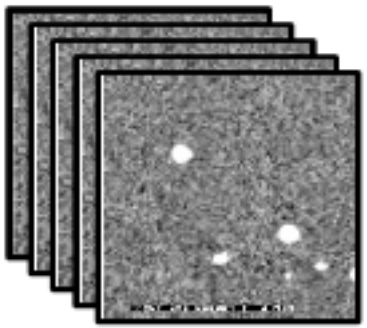


optical telescopes (TAROT/ROTSE/ ZADKO/MASTER)
Radio (MWA)
Xray (Swift)
Gamma-ray (Fermi, HESS, HAWC)

Minimal latency: alert sending (3-5s) + repositioning (<20s)

- Large sky coverage, high duty cycle
- 209 alerts since 2009; 13 follow-up with delay <1 min
- constraints on origin of individual neutrinos
- GRB origin unlikely

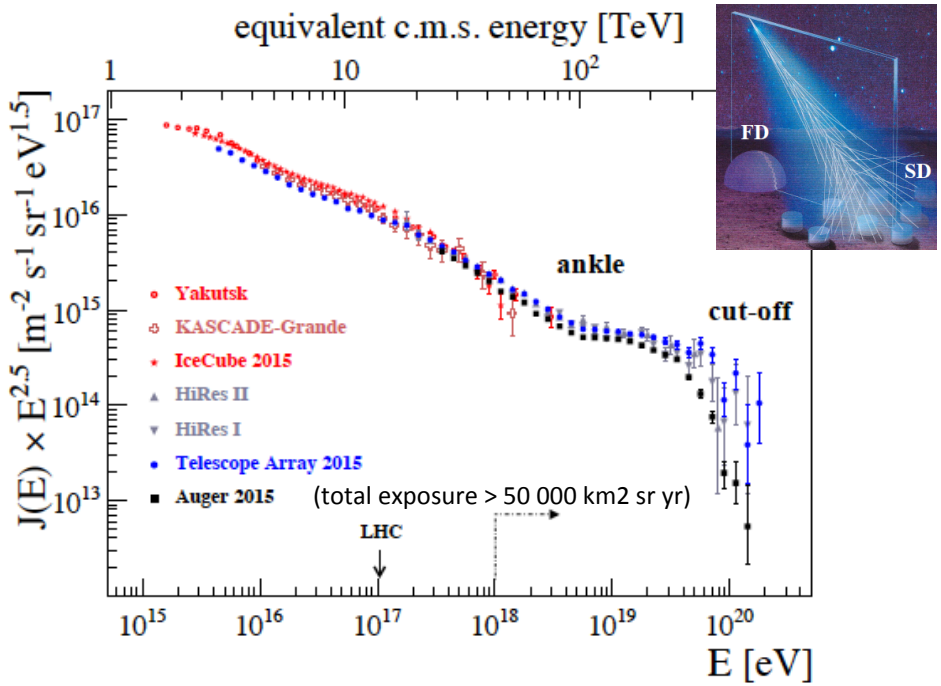




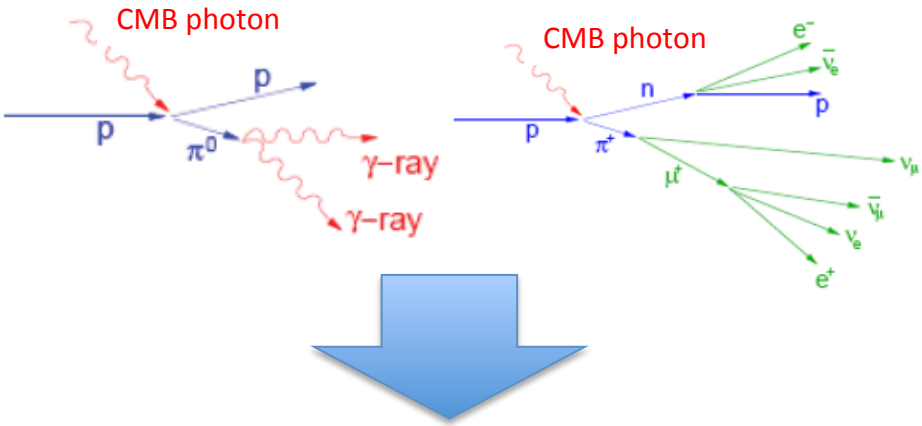
T_0, T_0 +1, 3, 9 and 27 days

📖 APP 35 (2012) 530
📖 JCAP 02:062 (2016)

Neutrinos and UHE cosmic rays



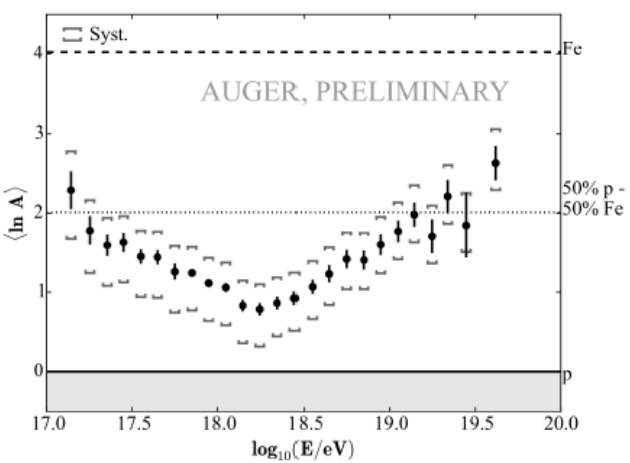
Auger observes the GZK cutoff in UHECR spectrum:



Guaranteed source of UHE neutrinos (and photons)

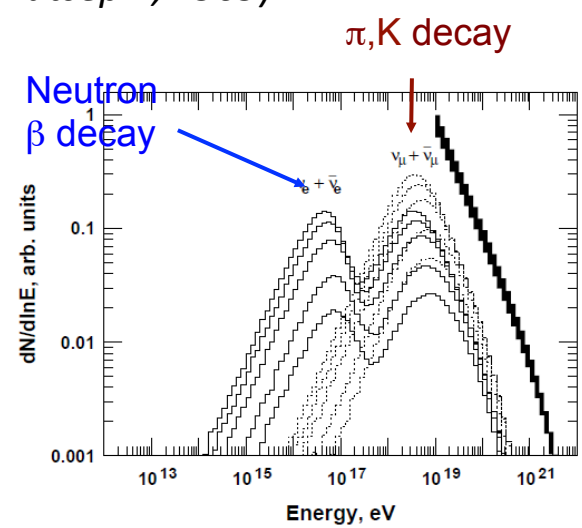
(Berezinky & Zatsepin, 1969)

EPOS LHC



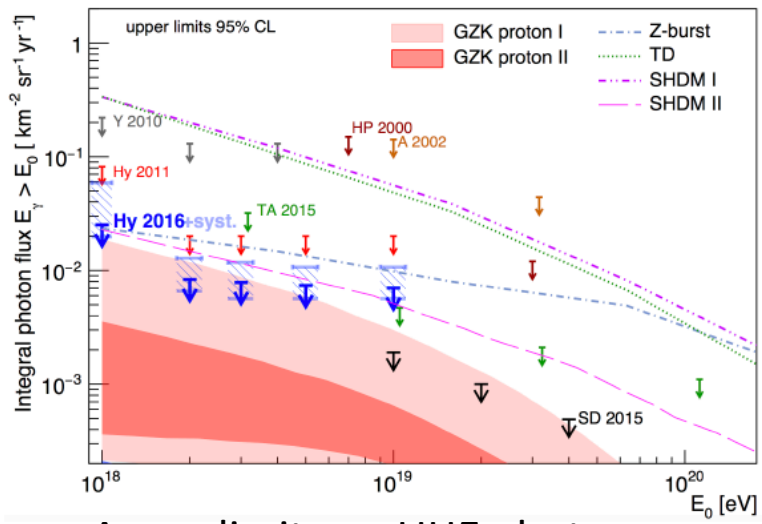
…but yield is highly dependant on UHECR composition (& source evolution):

post-LHC models favour mixed composition



Neutrinos and UHE cosmic rays (and photons)

📖 JCAP 04:009 (2017)

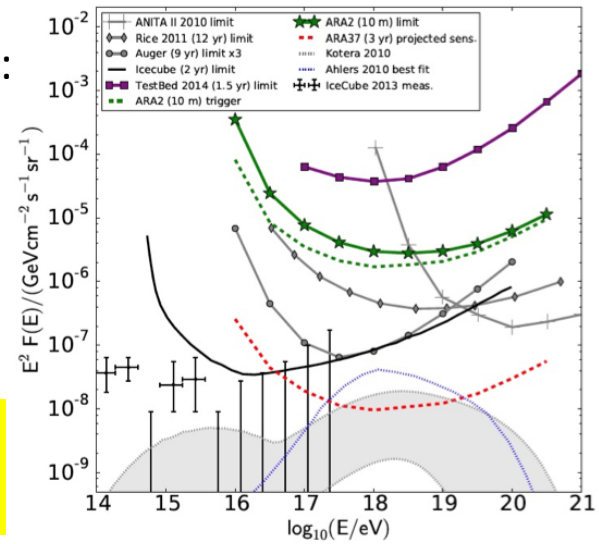


Auger limits on UHE photons: exclude most top-down scenarios

Limits on UHE neutrinos: Realistic cosmogenic fluxes still out of reach

Radio experiments promising !

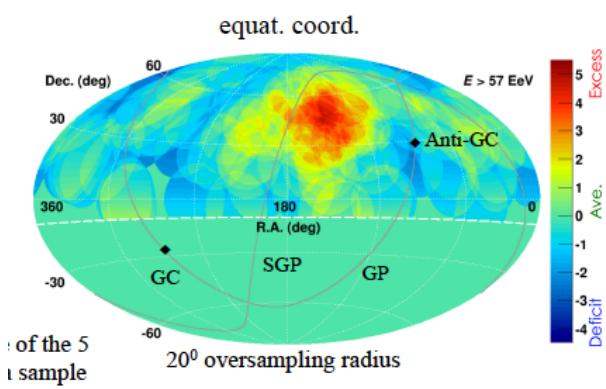
→ See talk by S. Klein APP session Wed. 11:30



Cross-correlation study IceCube/ Auger/TA data: no signal

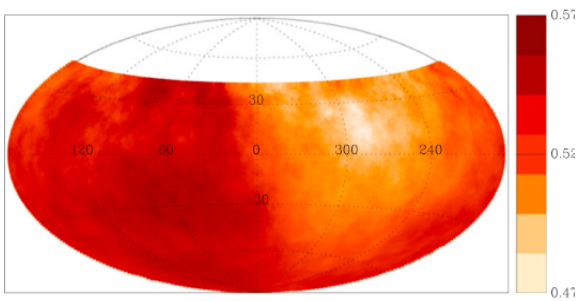
Similar analysis ongoing w/ANTARES

❖ Evidence of anisotropies in UHECR:



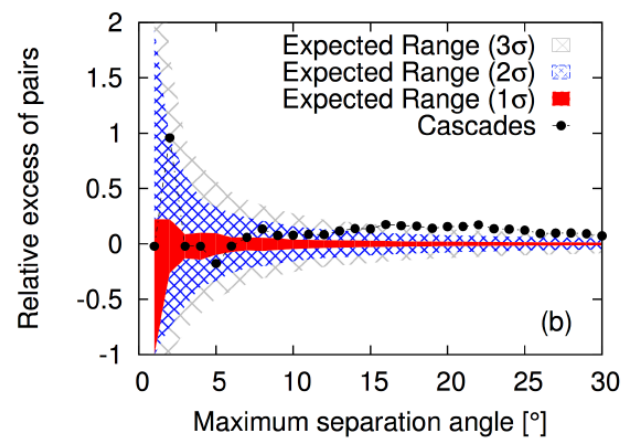
TA hot spot (E>5 x 10^{19} eV)

📖 PoS ICRC 2015 326 (2016)



Auger dipole (E> 8 x 10^{18} eV) extragalactic origin ?

📖 ApJ 802 (2015) 102

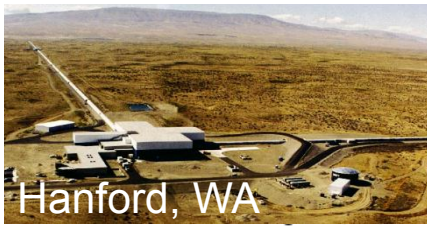


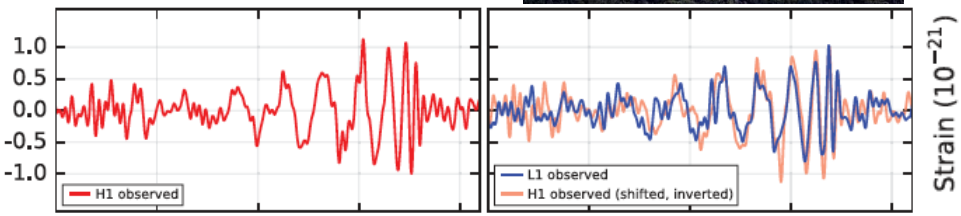
📖 JCAP 01:037 (2016)

Neutrinos and gravitational waves

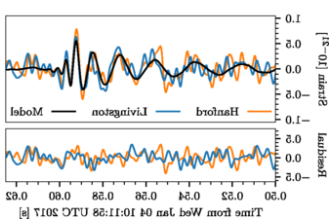
First detections of gravitational wave events:

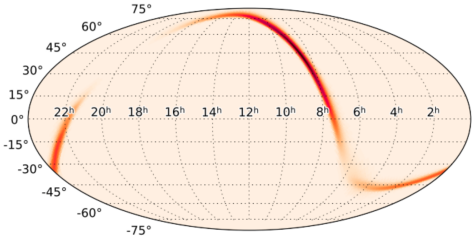
- GW150914



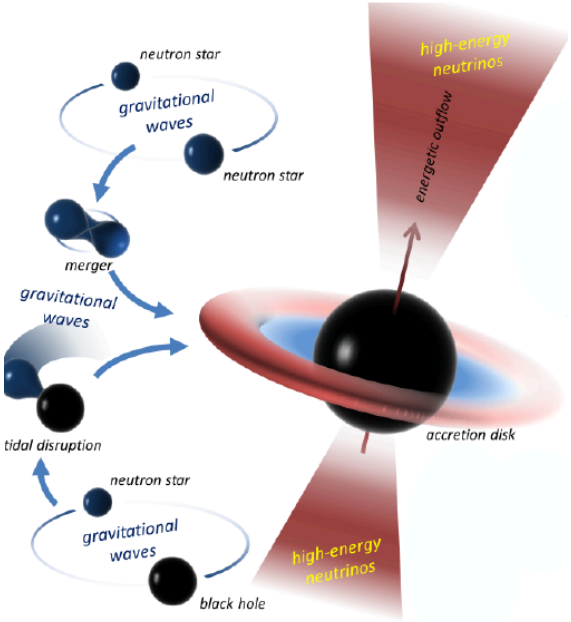


- LVT151012 (candidate, 1.7 σ significance)
- GW151226
- GW170104 90% error box: 1609 deg^2



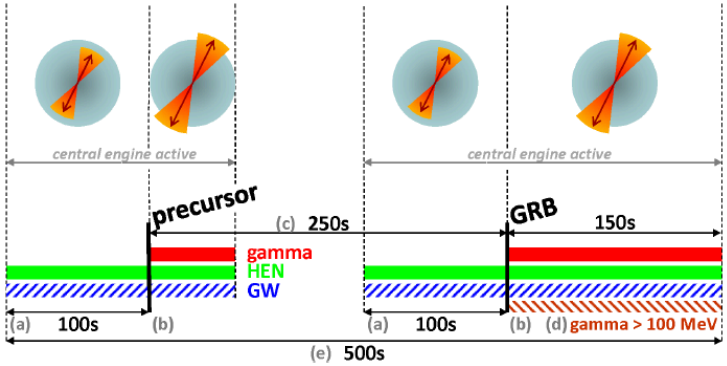


all interpreted as BH-BH mergers of a few 10s of solar masses (→ progenitors of short GRBs ?)



Neutrino emission expected along HE photons if hadronic content in the jet

Conservative time window for neutrino searches: ±500s around GW trigger

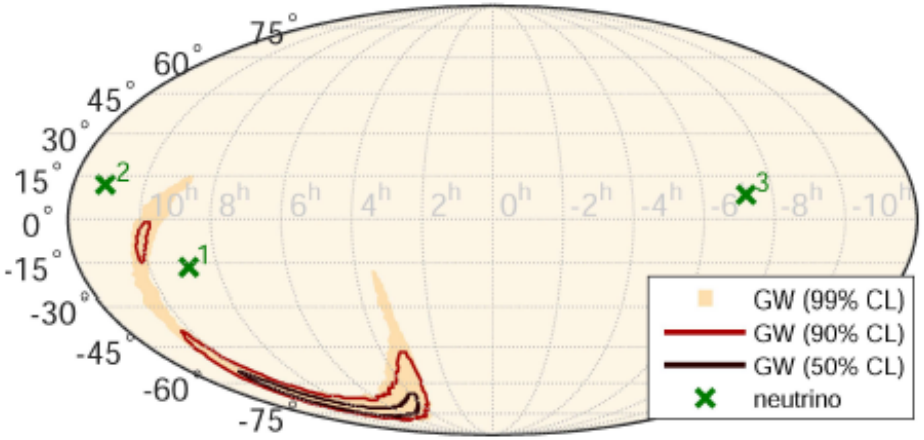


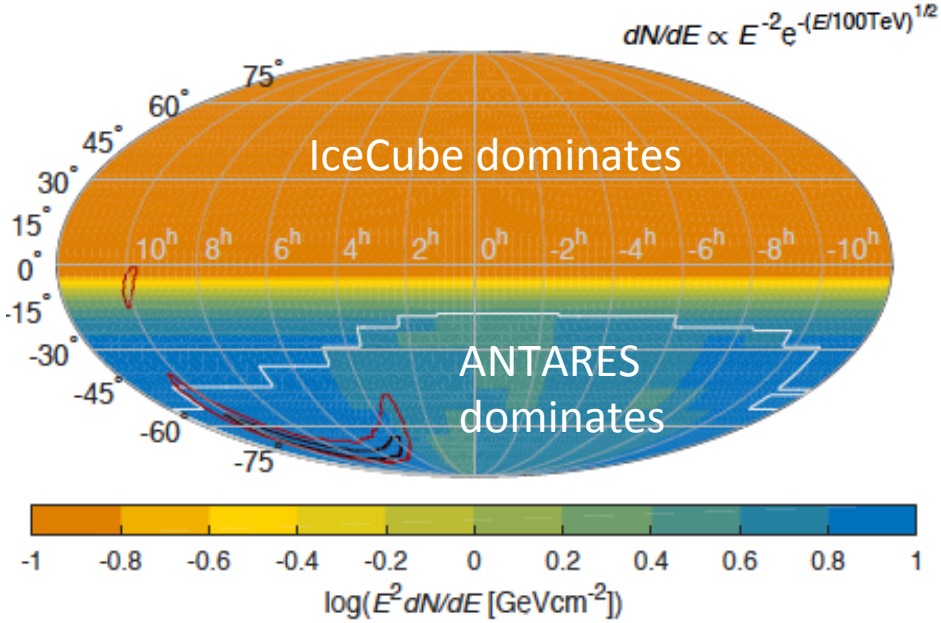
APP 35 (2011)

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

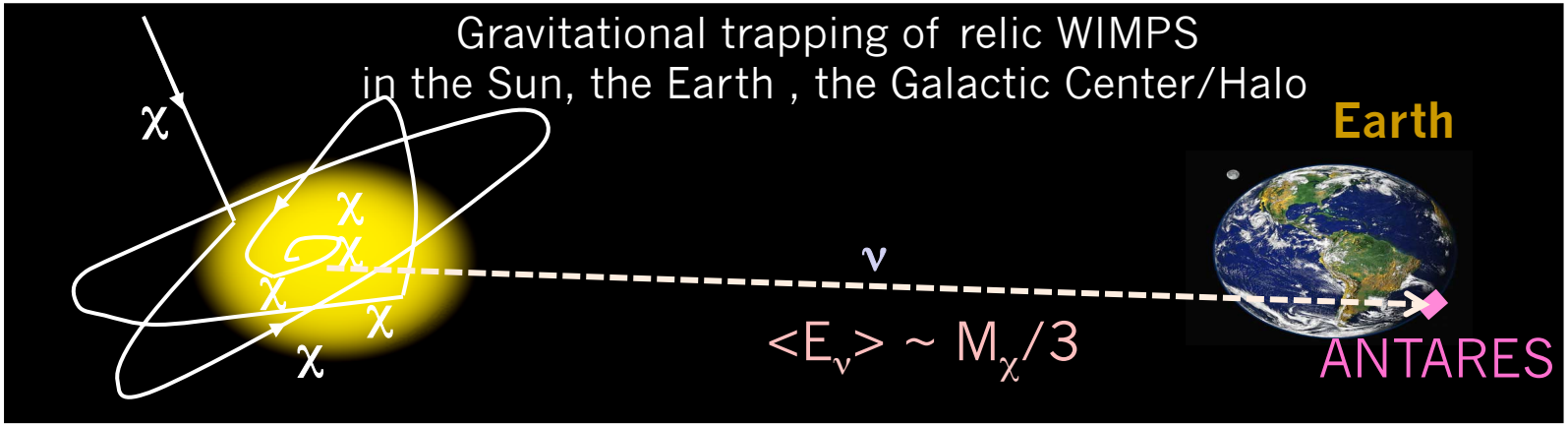
Upper limit on the integrated fluence:
[100 GeV – 100 PeV] or
[100 GeV – 100 TeV]:

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

➡ IceCube & ANTARES provide complementary constraints below ~100 TeV
➡ rapid observation of a neutrino counterpart could help reduce error box for further EM follow-up: error for GW150914 : 590 deg^2 ⟷ ANTARES resolution: : <0.5 deg^2

…neutrino telescopes now part of the online alert network of LIGO/Virgo (15/30 min latency)

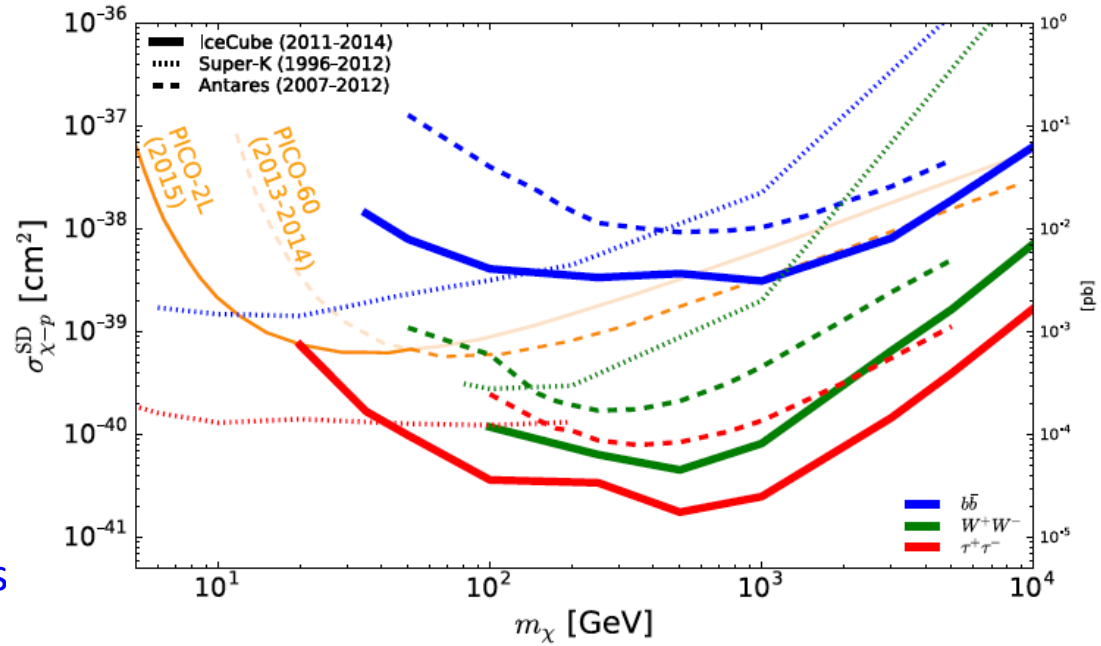
Indirect searches for dark matter



$$X_{\mathrm{WIMP}}\bar{X}_{\mathrm{WIMP}} \rightarrow \nu\bar{\nu},\ \mathrm{b\bar{b}},\ \mathrm{W^-W^+},\ \tau^-\tau^+,\ \mu^-\mu^+$$

Neutrinos from DM annihilation in the Sun:
assume capture and annihilation in equilibrium

- Neutrino telescopes +SK provide most stringent limits on spin-dependant WIMP-nucleon cross-section for a large range of masses
- excludes a fraction of pMSSM models

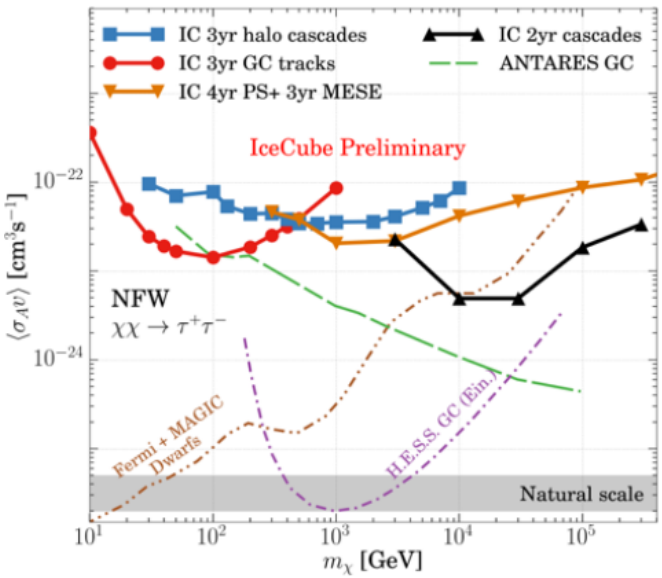


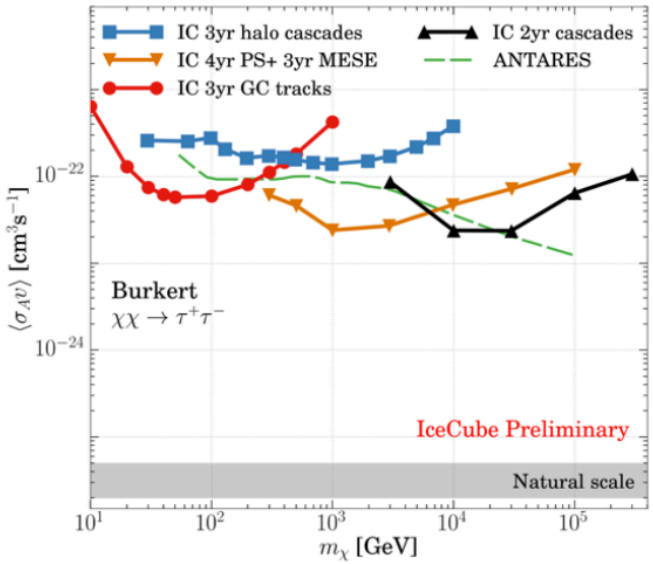
- See talks by A. Capone (ANTARES), M. Medici (IceCube), K. Frankiewicz (SuperK)– Astroparticle Physics Session Wed

IceCube, EPJ 77 (2017) 146
ANTARES, PLB759 (2016) 69

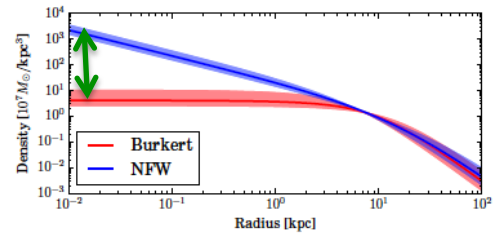
Indirect searches for dark matter

❖ **Neutrinos from DM annihilation in the Galactic center/Galactic halo:**



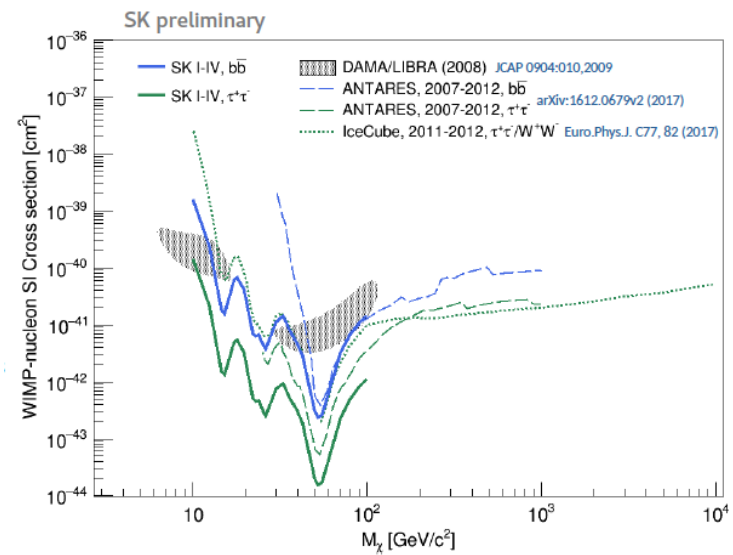


Signal sensitive to assumed halo profile, DM density at GC

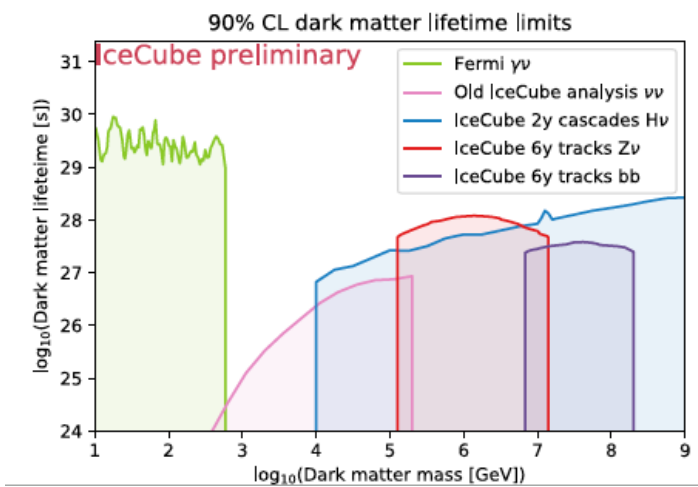


📖 IceCube, arXiv1705.08103
📖 ANTARES, PLB759 (2016) 69

❖ **Neutrinos from WIMP capture in Earth**



❖ **Neutrinos from WIMP decay in Galactic Halo** (Xν channel)



The future: KM3NeT & IceCube Gen2

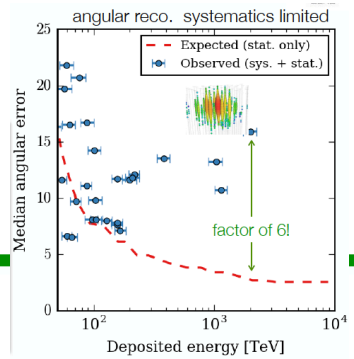
Exciting times for multimessenger astronomy: first cosmic neutrinos 2013
first gravitational waves 2016

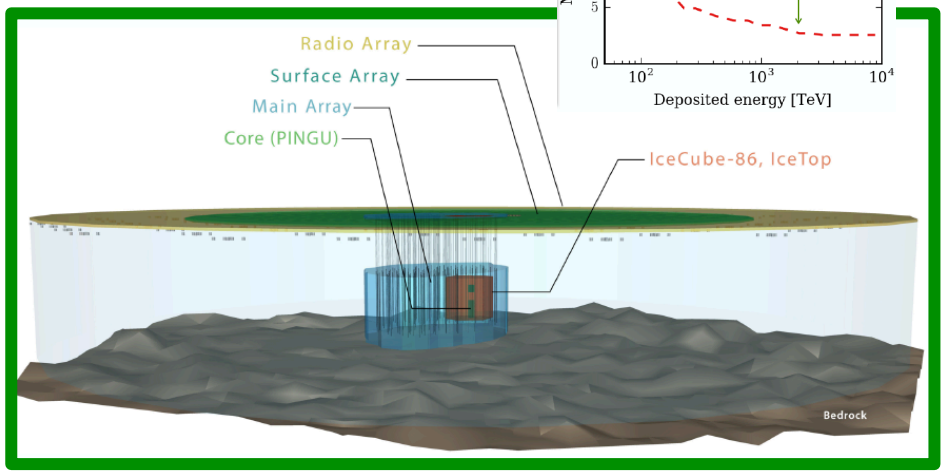
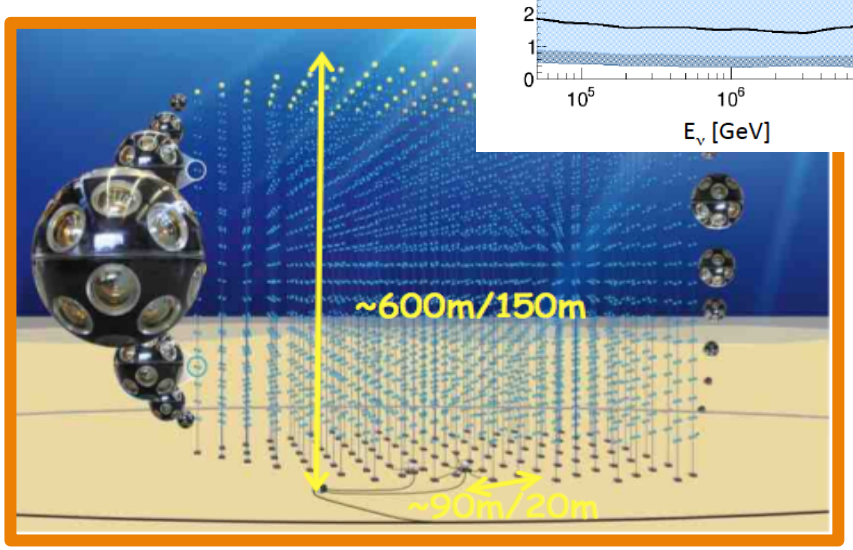
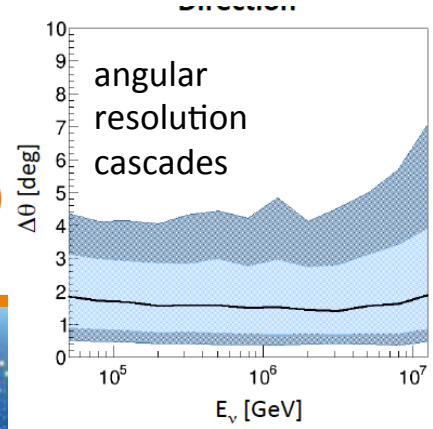
No neutrino sources detected/resolved yet

- possible identification of Galactic vs extragalactic components ?
- multi-messenger programs will be crucial to increase sensitivity
- need high-statistics (few km^3-scale), all-flavour neutrino astronomy

the next-generation neutrino telescopes is desirable !

IceCube Gen2
Phase-1: 7-line prototype
(dense array + calibration)





KM3NeT (ARCA+ORCA)
under construction