Gravitational Waves & High Energy Neutrinos joint analyses

Thierry Pradier

pradier@in2p3.fr

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

UNIVERSITY OF STRASBOURG

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GWHEN

- ANTARES : B. Baret, **B. Bouhou**, C. Donzaud, A. Kouchner, *Th. P.* (responsible for ANTARES), V. Van Elewyck
- LSC/VIRGO : *I. Bartos* (Columbia U.), **E. Chassande-Mottin (responsible for VIRGO)** (APC), *I. Di Palma* (AEI), **S. Márka (responsible for LIGO)**, Z. Márka (Columbia U.), M.-A. Papa (AEI), P. Sutton (Cardiff U.) [With contributions from : A. Dietz (LAPP), S. Kandhasamy, V. Mandic, E. Thrane (Minnesota U.), R. Williams (Caltech)]
- ICECUBE : **C. Finley** (OKC, Sweden), J. Becker & A. Herzog (Bochum, Germany)

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Some papers

- Results of the 1st GWHEN search (arxiv)
- GWHEN Thesis by B. Bouhou (APC, Paris) (DCC link)
- Method paper (arxiv)
- Coincidence TIme Window (arxiv)
- ANTARES and Multi-Messenger Astronomy (arxiv)
- Feasibility study (ANTARES) (arxiv)
- Search method (IceCube) (arxiv)

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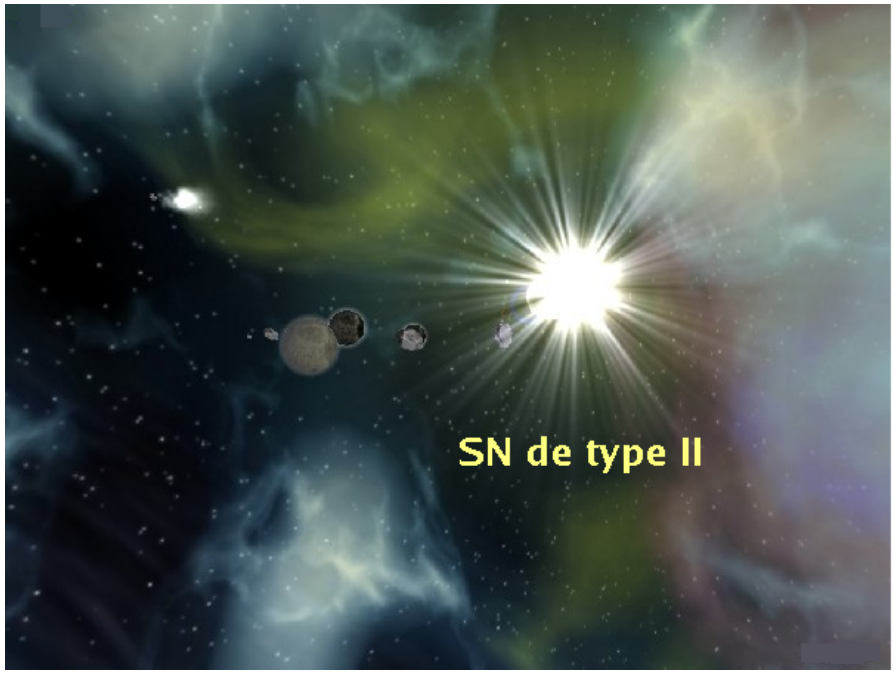
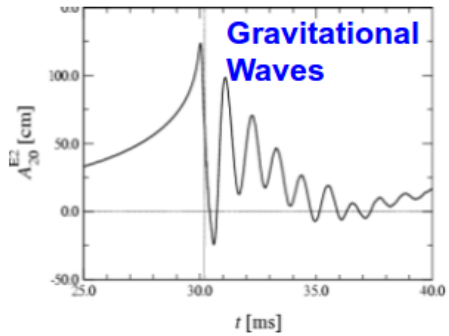
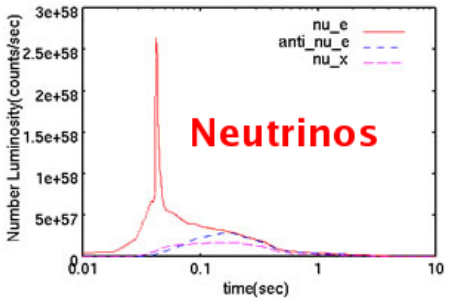
An example of GW-ν Coincidences : Type II SN







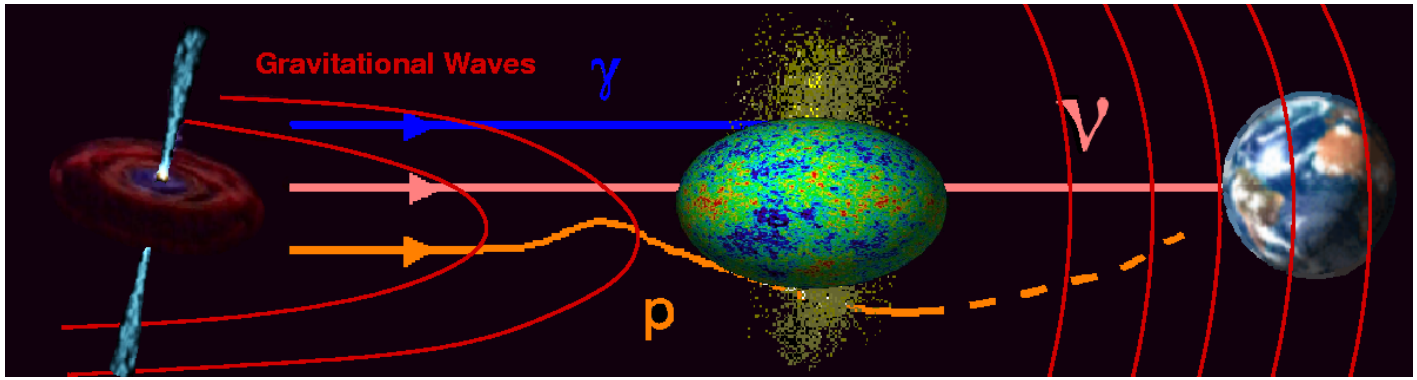
Type II SN

- $m_\nu \neq 0 : \delta t_{\text{propagation}} \simeq 5.15ms \left(\frac{L}{10kpc}\right) \left(\frac{m_\nu c^2}{1eV}\right)^2 \left(\frac{10MeV}{E_\nu}\right)^2$
- $E_\nu^{SN} \sim MeV$, $\delta t_{\text{GW}-\nu_e^{\text{flash}}} \lesssim 0.5\ ms$

  $\Rightarrow$ Limits on ν absolute mass scale from $\Delta t_{GW-\nu}$

▸ *N. Arnaud et al.*, Phys.Rev. D65 (2002) 033010

GWHEN in 2 words...



Gravitational Waves + High Energy Neutrinos

1 - Sources invisible in photon ? : *Dark Bursts*

2 - Coincident Detection *validate* both detections

3 - Unique Information on internal processes : accretion-ejection...

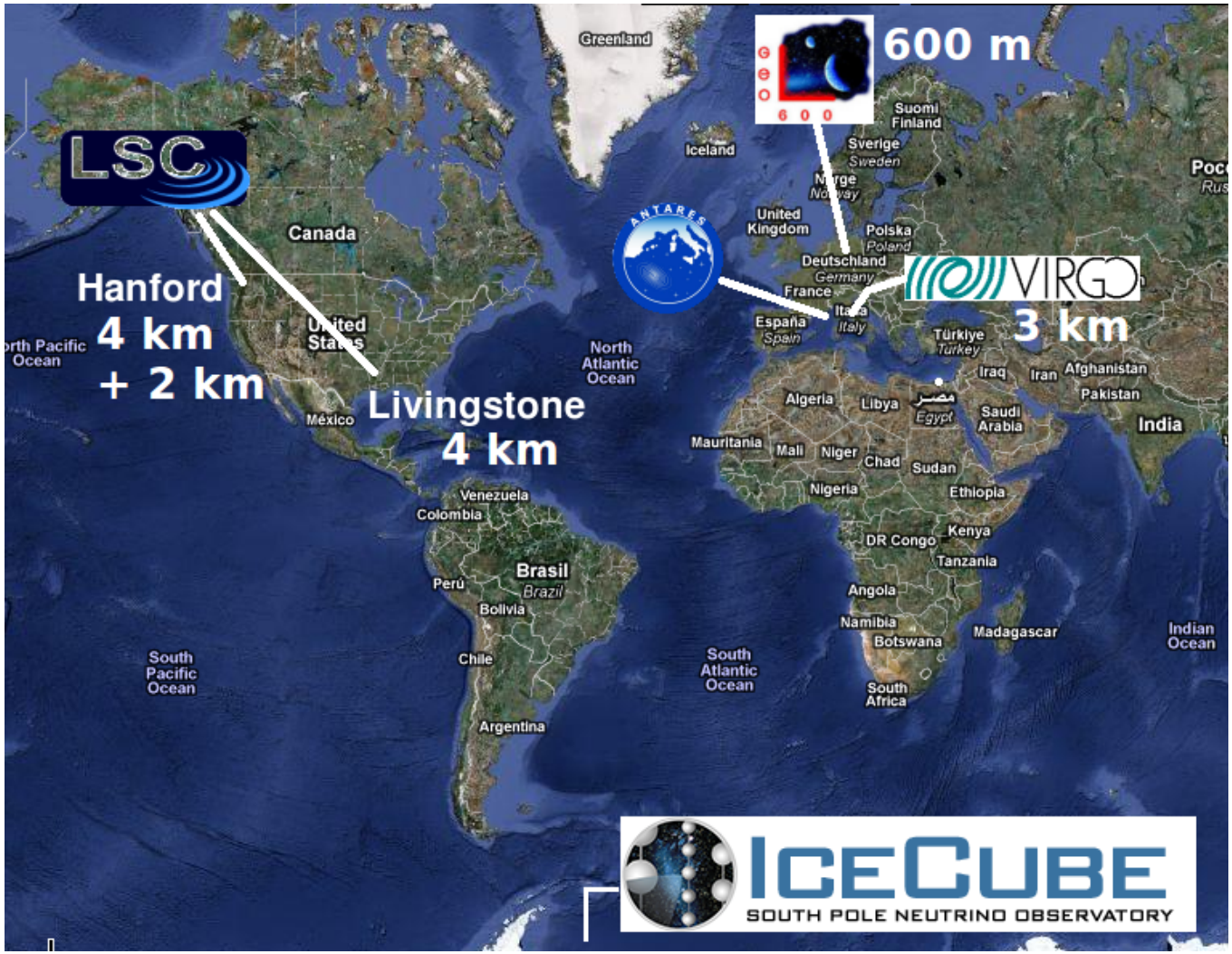
4 - Fundamental Physics ? :

- Quantum Gravity : $c^2 p^2 = E^2 \left[1 + \xi \left(\frac{E}{E_{QG}}\right) + \mathcal{O}\left(\frac{E^2}{E_{QG}^2}\right) + \ldots\right]$

$$\Rightarrow |\Delta t_{QG}| \simeq 0.15 ms \left(\frac{d}{10\ kpc}\right) \left(\frac{E_\nu^{HE}}{1\ TeV}\right) \left(\frac{10^{19}\ GeV}{E_{QG}}\right) \text{ pour } z \ll 1$$

- *S. Choubey & S. F. King*, Phys. Rev. D67 (2003) 073005
- *Th. P.*, NIM A 602-1 (2009) 268-274

GW Detectors : VIRGO+LIGO

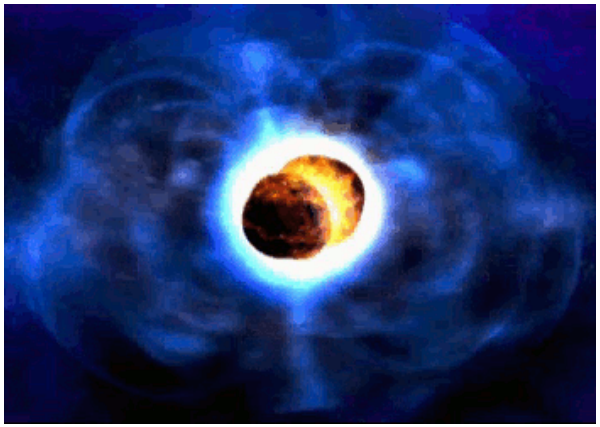


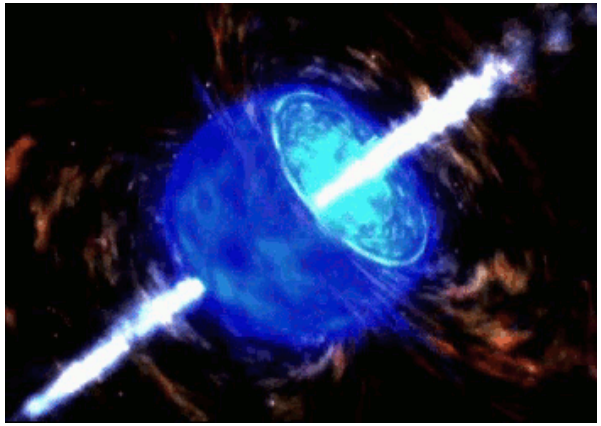
GW interferometers and HEN Telescopes

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
ANTARES	5L	0L	12L						KM3NeT	
Ice Cube	s	22s	40s	59s	79s	Ice Cube 86 strings				
LIGO	S5		S6						Advanced LIGO	
VIRGO	VSR1		VSR2	VSR3	+ GEO	GEO Only			Advanced VIRGO	

Completed - Publication soon | Analysis on-going | AstroWatch | Preparation of future analyses

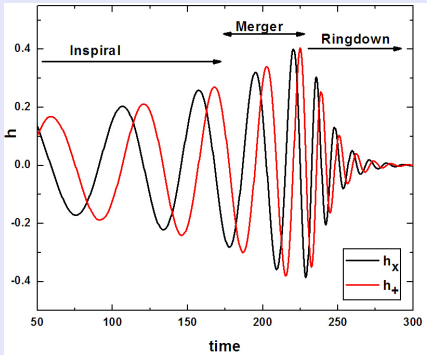
Gamma-Ray Bursters (GRBs)





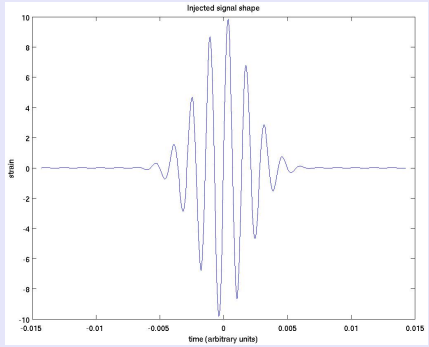
Short GRBs

Binary Mergers : BH or NS



Long GRBs

Collapsars - massive star collapse

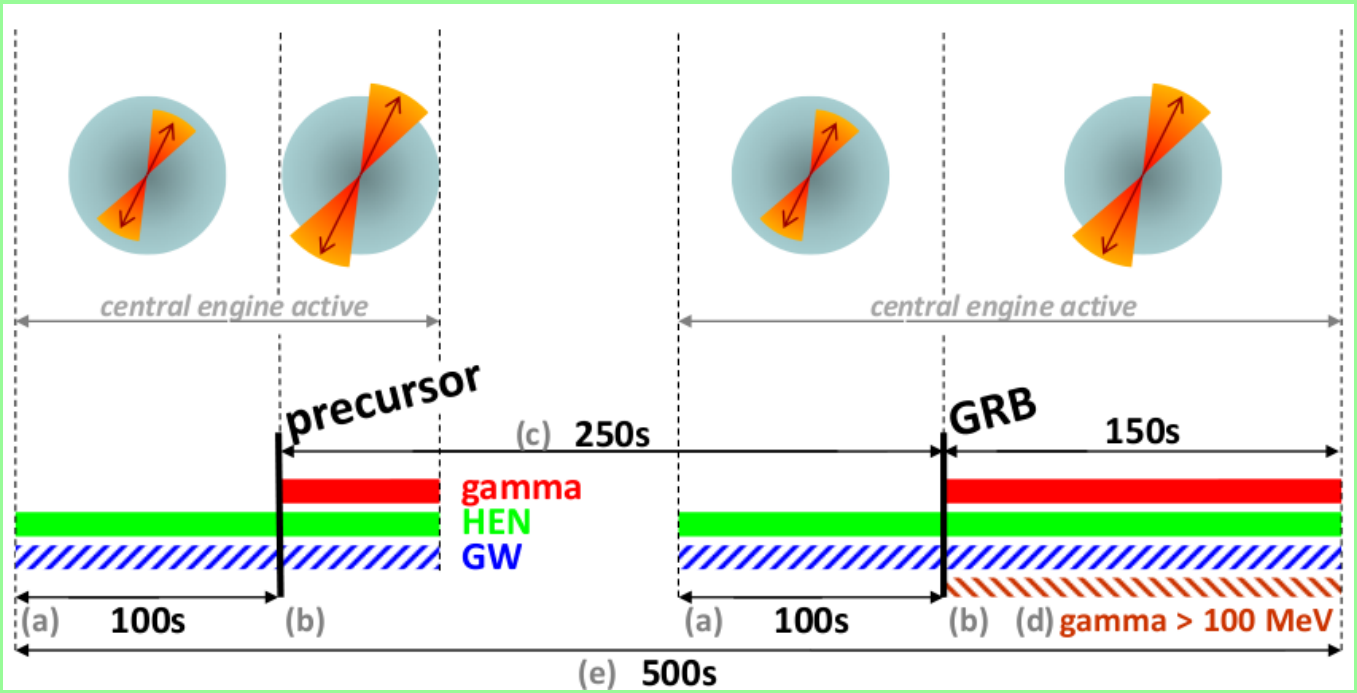


No Neutrinos ? ▸ ICECUBE results (2012)

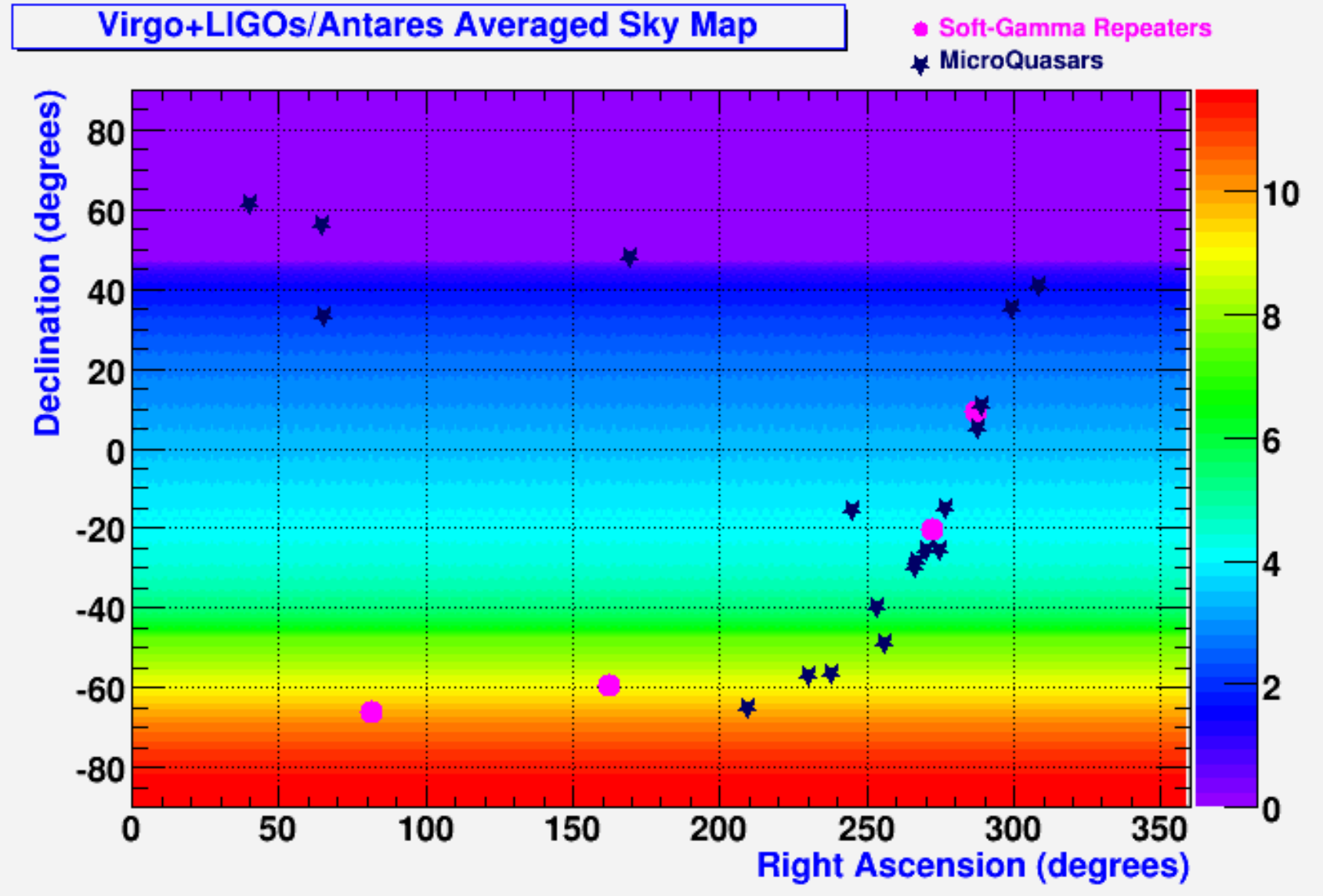
Time Window from long GRB observations

- *Bounding the Time Delay between High-energy Neutrinos and Gravitational-wave Transients from Gamma-ray Bursts*
- B. Baret *et al.*, Astroparticle Physics **35** (2011) 1-7

  $\Rightarrow$ $\Delta T = \pm 500$**s** arXiv:1101.4669

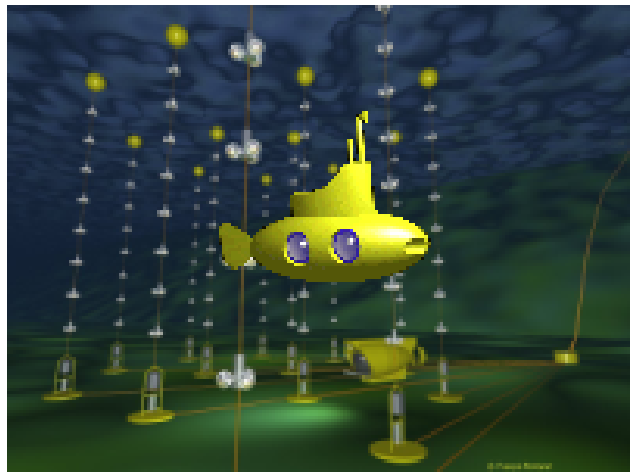


Visbility of some Galactic sources

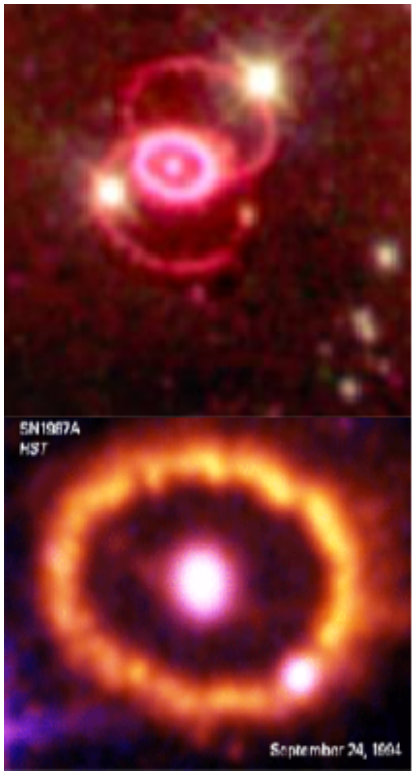


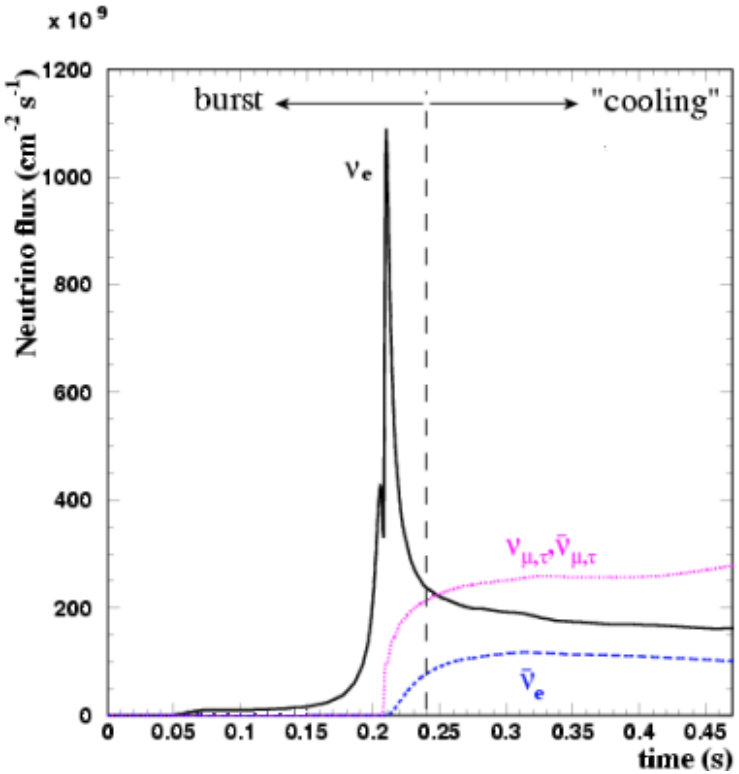
GW-HEN Joint Searches :

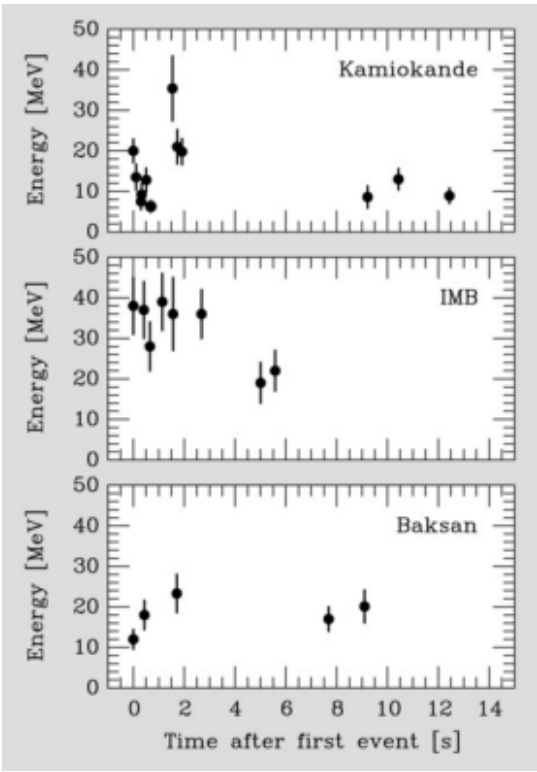
High Energy Neutrino Astronomy



An introduction to Neutrino Astronomy

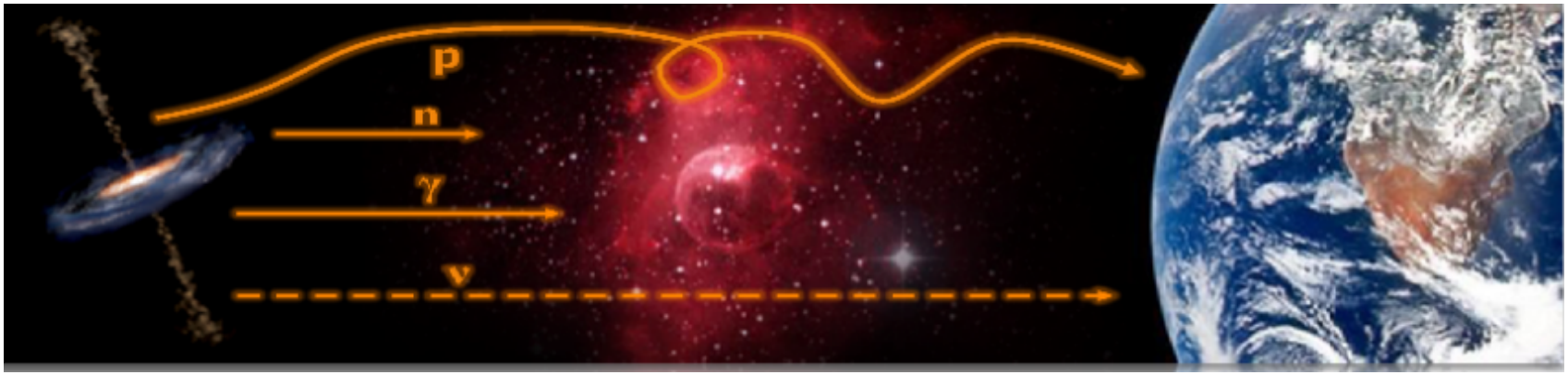






SN1987A : Birth of Neutrino Astronomy !

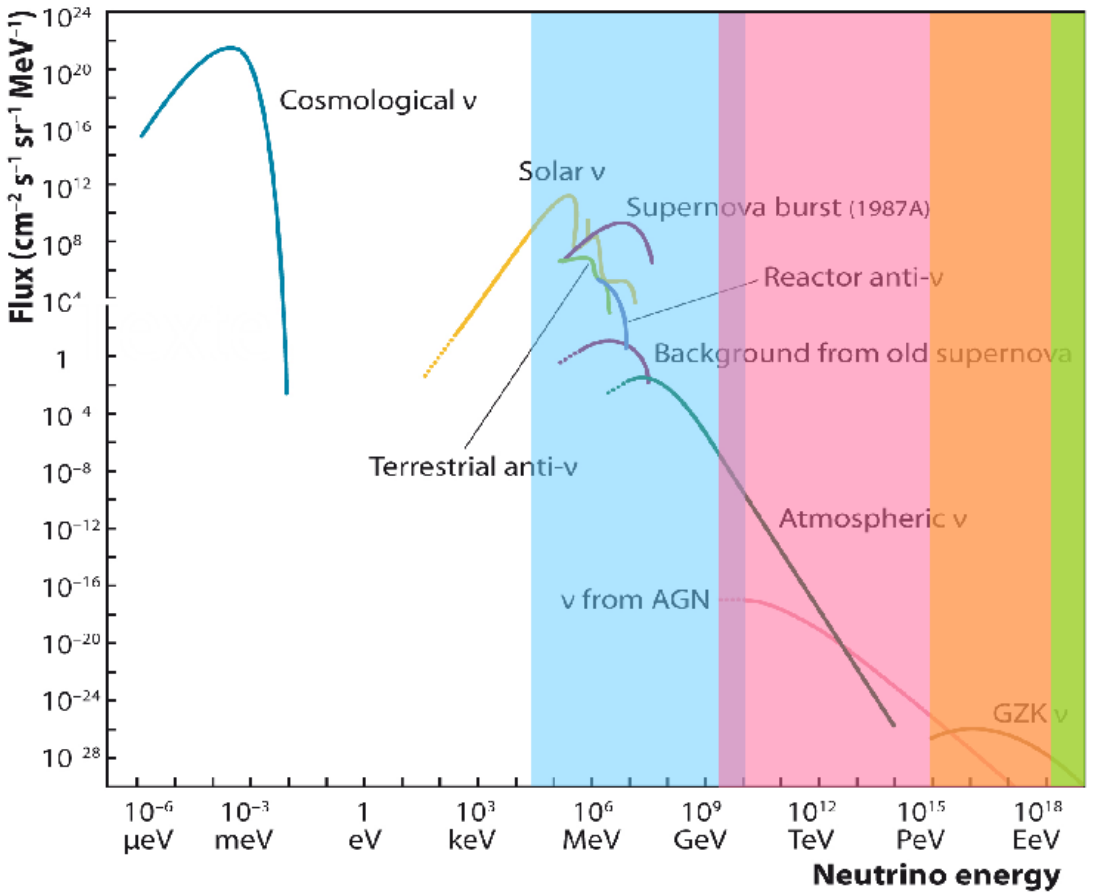
Neutrinos as Cosmic Messengers...



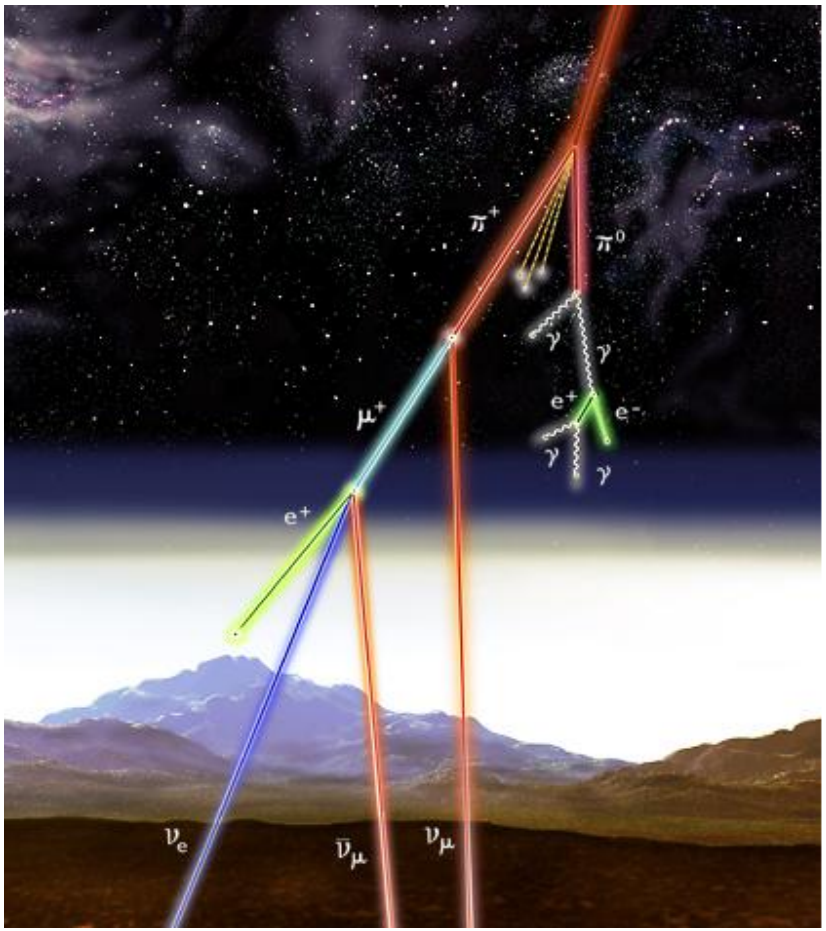
- Protons : **deflected by magnetic fields** ($E_p < 10^{19}\,GeV$) ; UHE interact with CMB photons ($\mathcal{L} \sim 30 Mpc$)
- Neutrons : decay ($\mathcal{L} \sim 10 kpc$ at $E \sim EeV$)
- Photons : **interact with ExtraGalactic Background Light** ($\mathcal{L} \sim 100 Mpc$) and CMB ($\mathcal{L} \sim 10 kpc$)
- Neutrinos : **neutral, weakly interacting**...

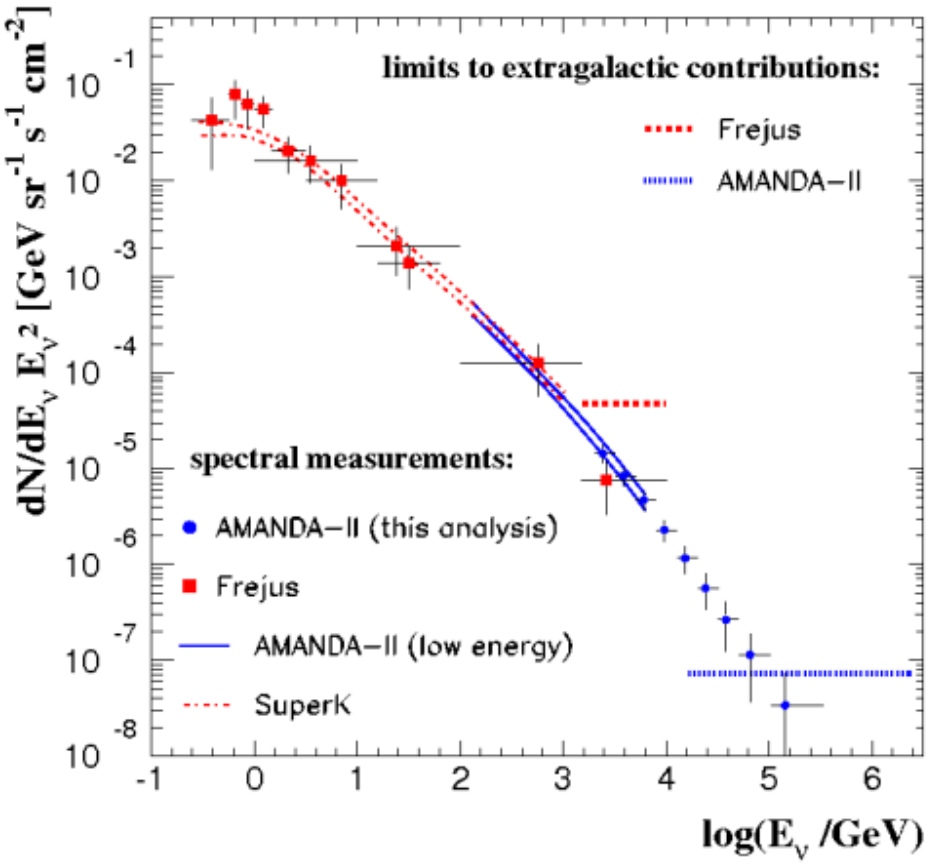
Sources of neutrinos...

- Under rock
- Under water/ice
- Acoustics/Radio
- Giant Air Shower



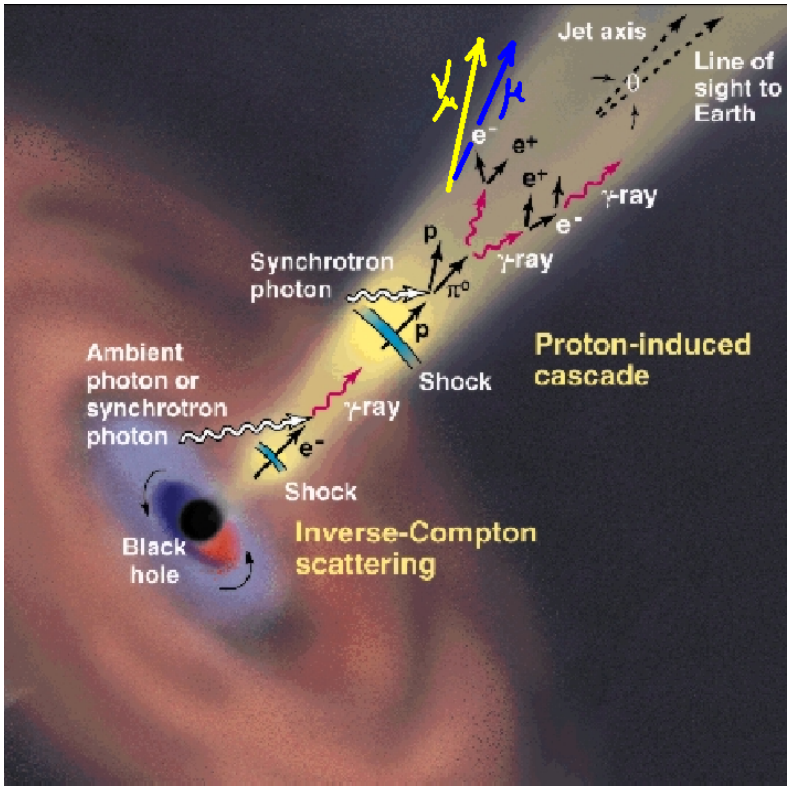
Atmospheric neutrinos



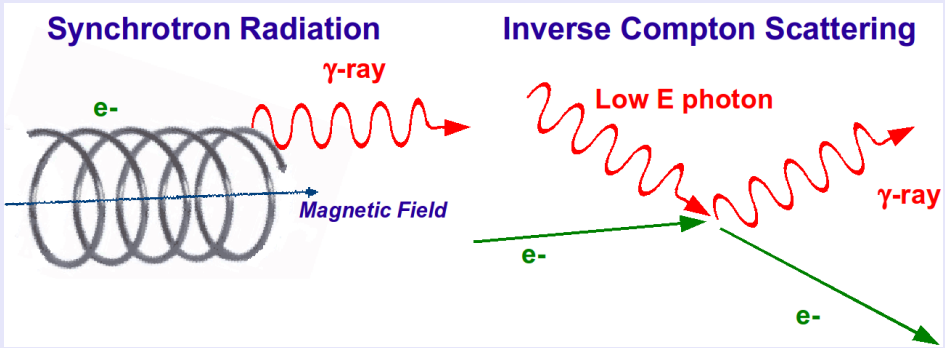


Background for detection of astrophysical neutrinos !

The Cosmic-Ray Connection



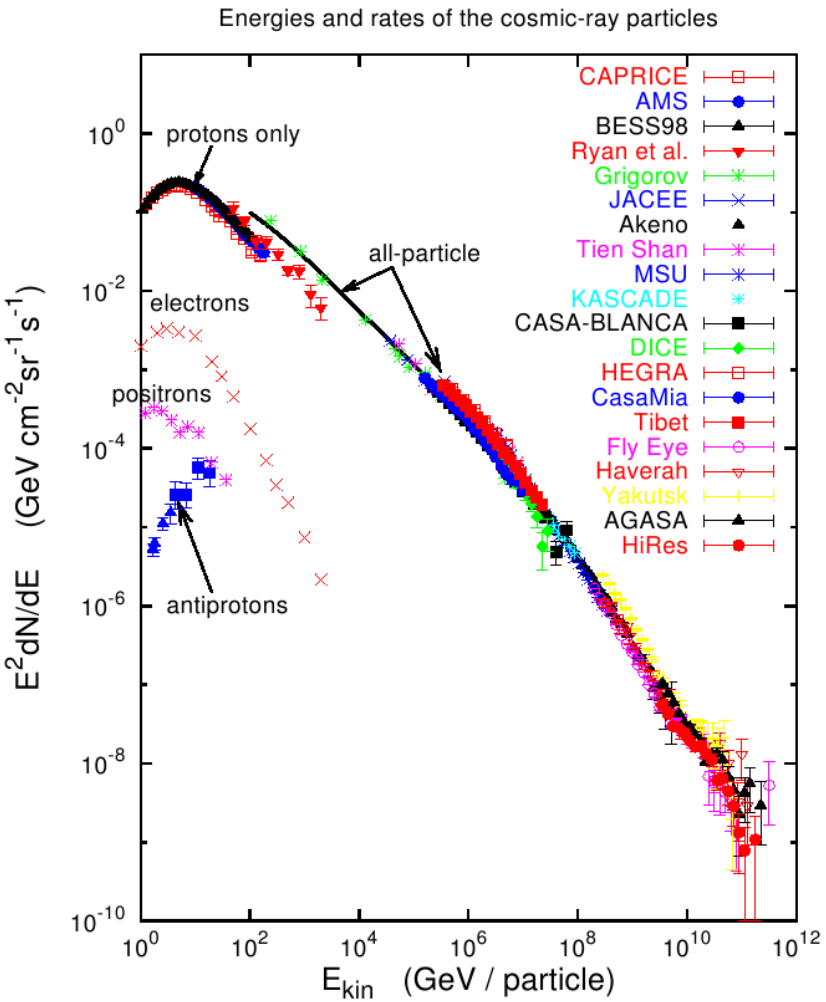
Leptonic Production of HE γ :



Hadronic Production of HE γ/CRs :

$$p/A + p/\gamma \longrightarrow \begin{array}{cc} \pi^0 & \pi^{\pm} \\ \downarrow & \downarrow \\ \gamma\gamma & \mu\ \nu_\mu \\ & \downarrow \\ & \nu_\mu \nu_e e \end{array}$$

The Cosmic-Ray Connection



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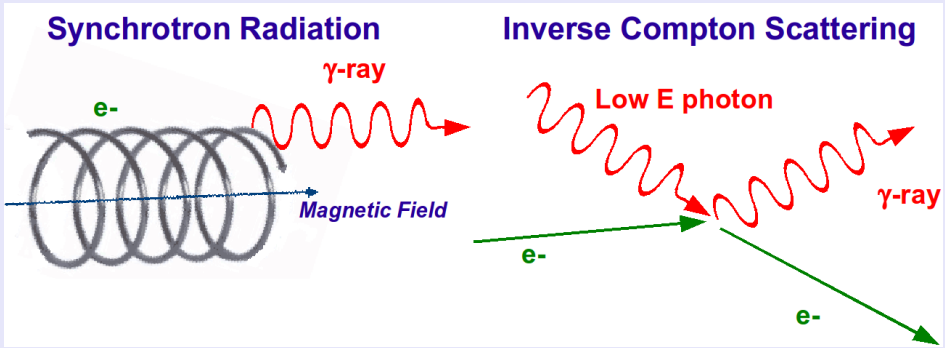

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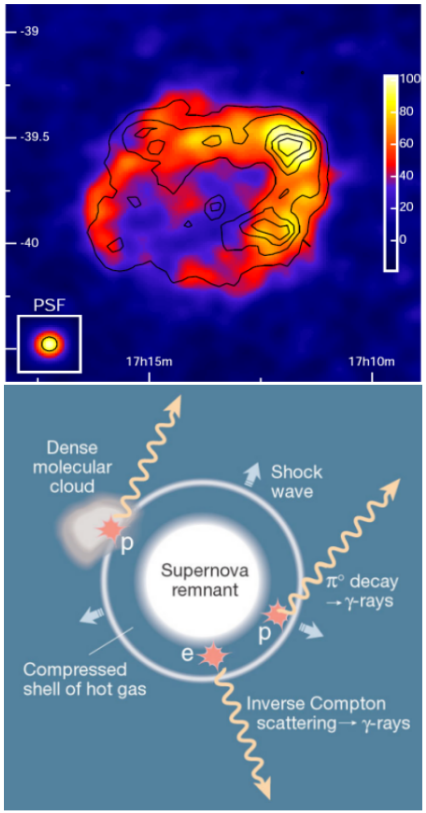
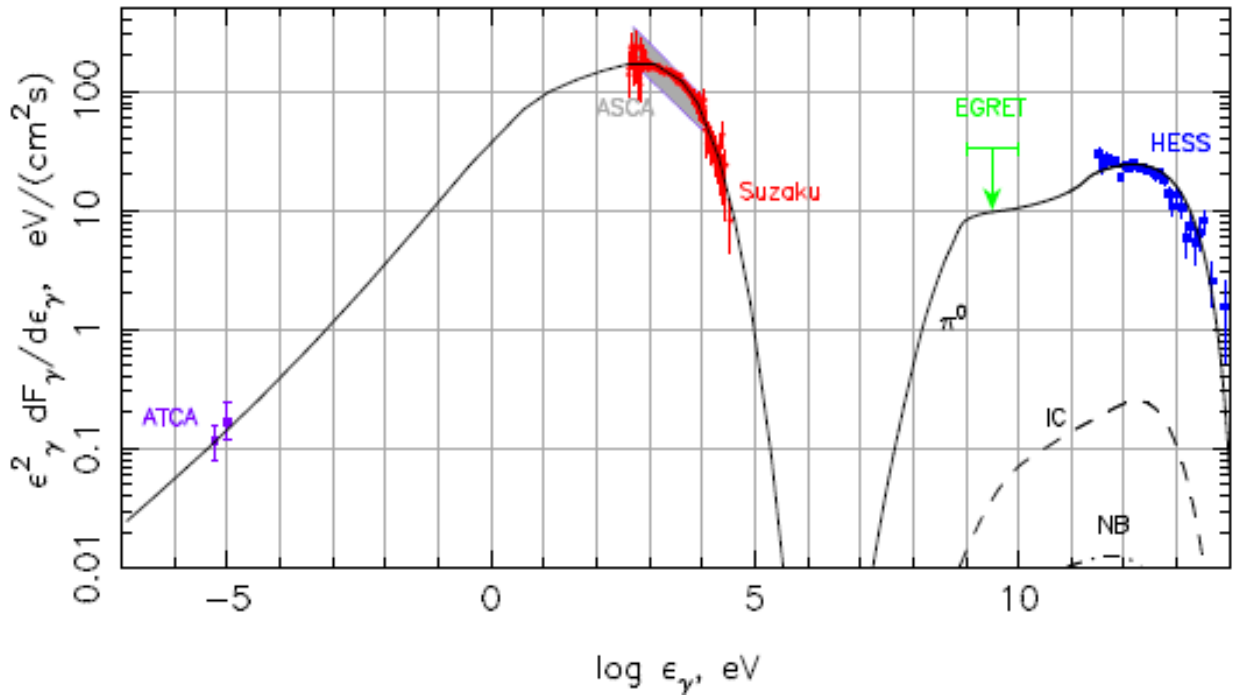
Neutrinos are the **smoking gun** of hadronic processes

A Hadronic origin for γ emission ?





The case of RXJ 1713-3946

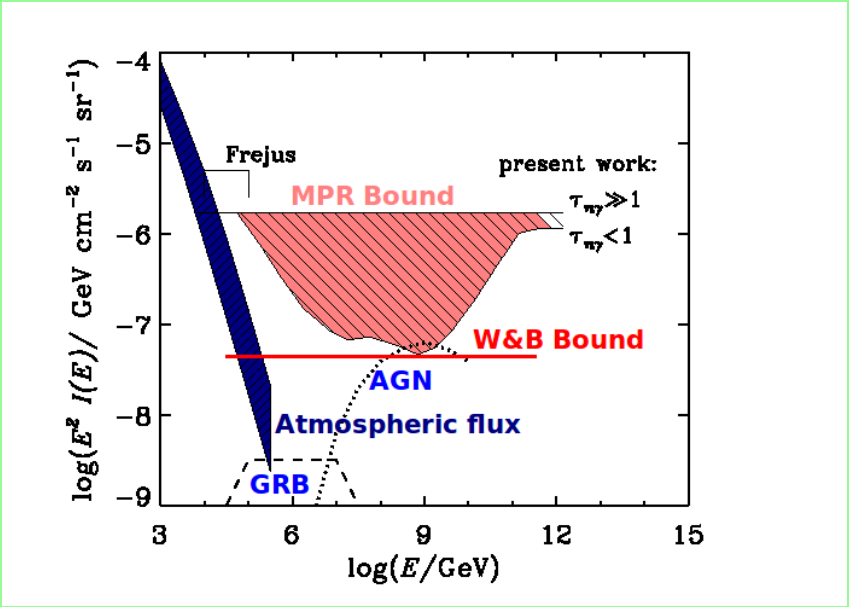
- Purely leptonic models not satisfactory
- Proton acceleration + beam dump on nearby molecular clouds ?

▸ Berezhko & Völk, arXiv:08100988v2

Upper Bounds for HEN from UHE Cosmic-Ray sources

Bounds for extra-galactic sources

- Waxman-Bahcall upper bound ▸ WB Paper
  - $E^2 \frac{dN}{dE} \approx 10^{44} erg/Mpc^3/yr$ from observed CR fluxes
  - Assume optically thin sources and evolution with z
- Mannheim, Protheroe, Rachen (MPR) Bound ▸ MPR Paper
  - Different injection spectra, optically thin/hidden sources

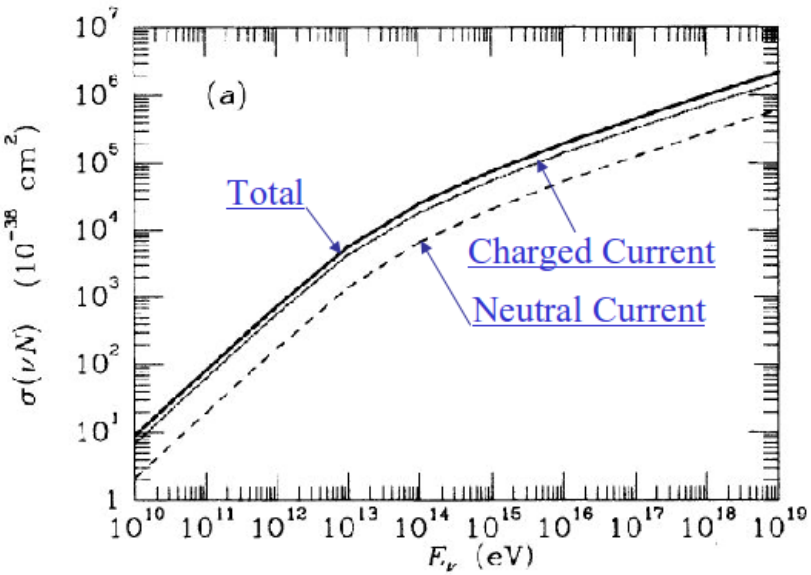


Upper Bounds for HEN from UHE Cosmic-Ray sources

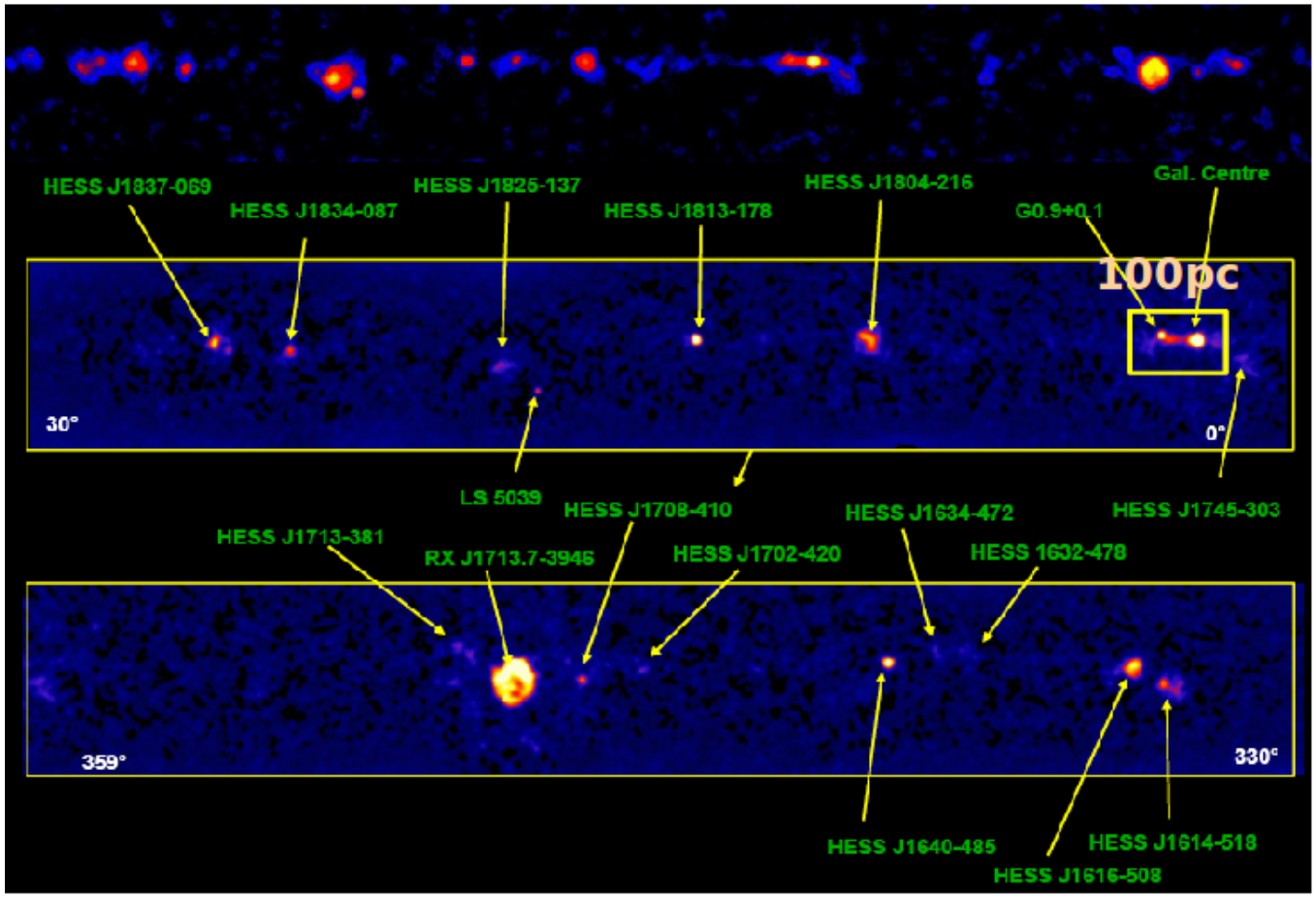
Bounds for extra-galactic sources

- $E_\nu^2 \Phi_\nu \lesssim 10^{-8} GeV.cm^{-2}.s^{-1}.sr^{-1}$
- $\Phi_\gamma^{\mathrm{Crab}}(E > 1\,TeV) \approx 10^{-11} cm^{-2}.s^{-1}$...
- With a ν cross-section $\in 10^{-35} - 10^{-33} cm^2$ for $TeV - PeV$...

  $\Rightarrow$ **Needs large detection volumes !**



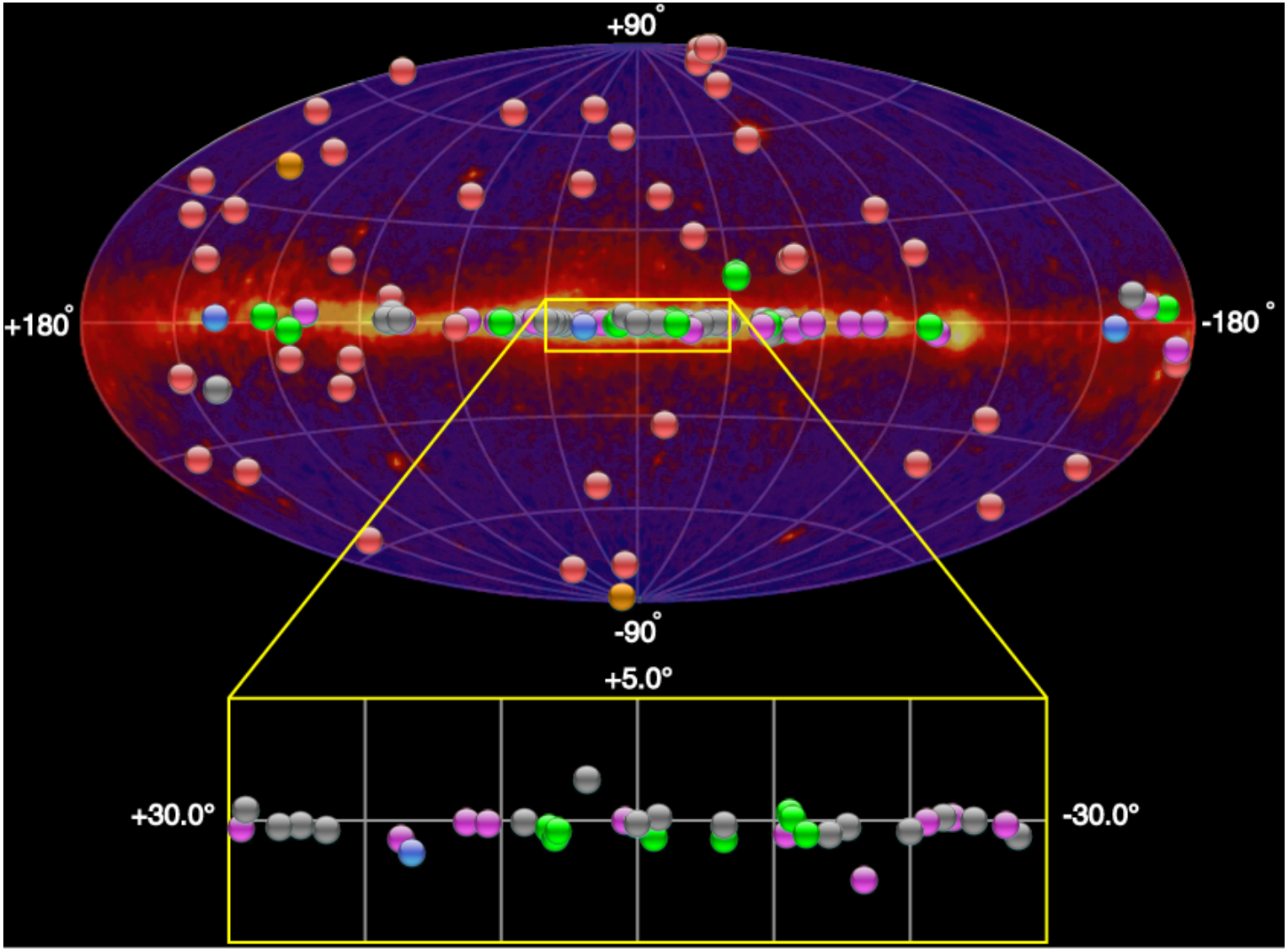
In the Galaxy...



The Galactic Plane - visible with Antares !

- Lots of New Sources discovered by HESS

The TeV Gamma-Ray Sky [QUICK]



The TeV Gamma-Ray Sky [QUICK]

How to compute a ν Flux from γ-Ray Observations

- Assume a **primary spectrum at the source**
- Describe the **interaction mechanism**
- **Renormalize expected flux to the observed HE γ flux**

Hadronic Production of HE γ/CRs :

$$
\begin{array}{lcccc}
p/A + p/\gamma & \longrightarrow & \pi^0 & \pi^{\pm} \\
 & & \downarrow & \downarrow \\
 & & \gamma\gamma & \mu\ \nu_\mu \\
 & & & \downarrow \\
 & & & \nu_\mu \nu_e e
\end{array}
$$

The TeV Gamma-Ray Sky [QUICK]

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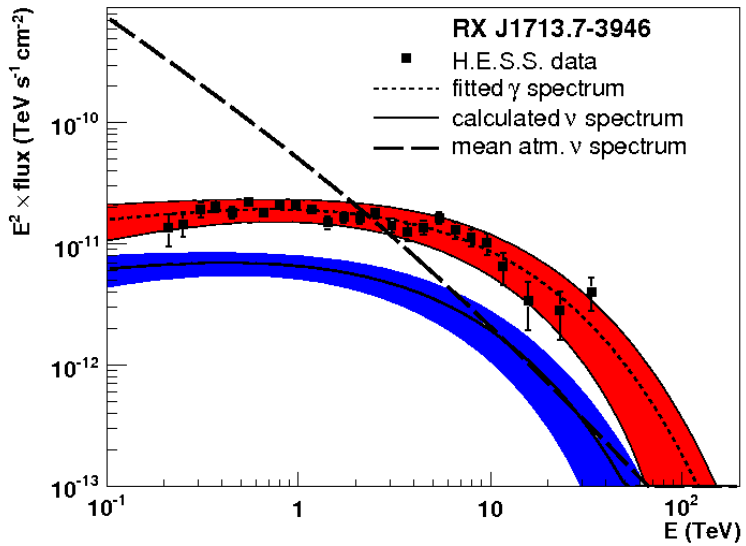
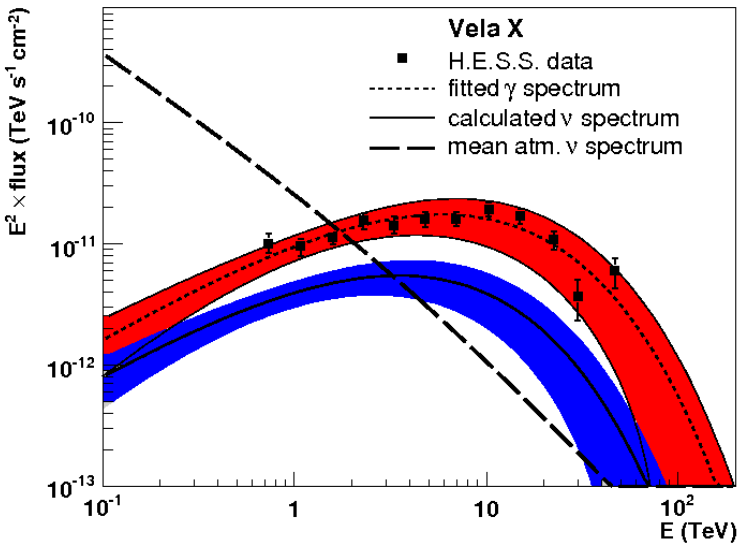
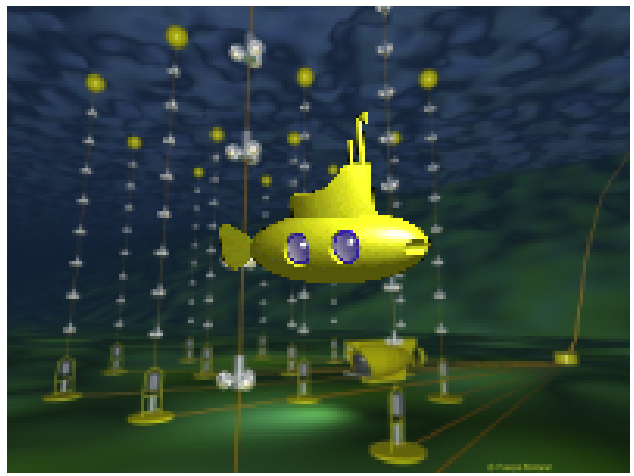




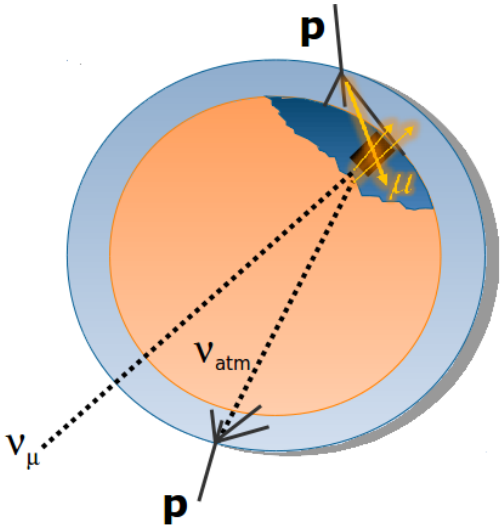
▶ A. Kappes et al. (2007)

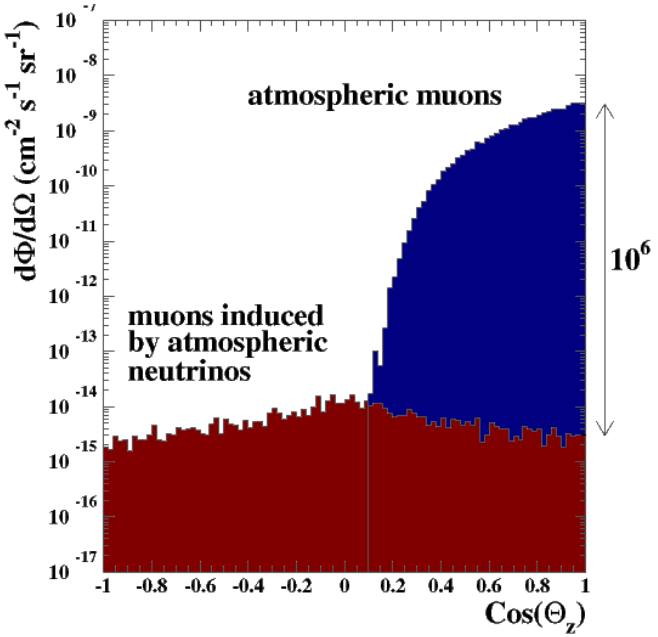
GW-HEN Joint Searches :

HEN Telescopes : principles, instruments



Detection of Cosmic Neutrinos

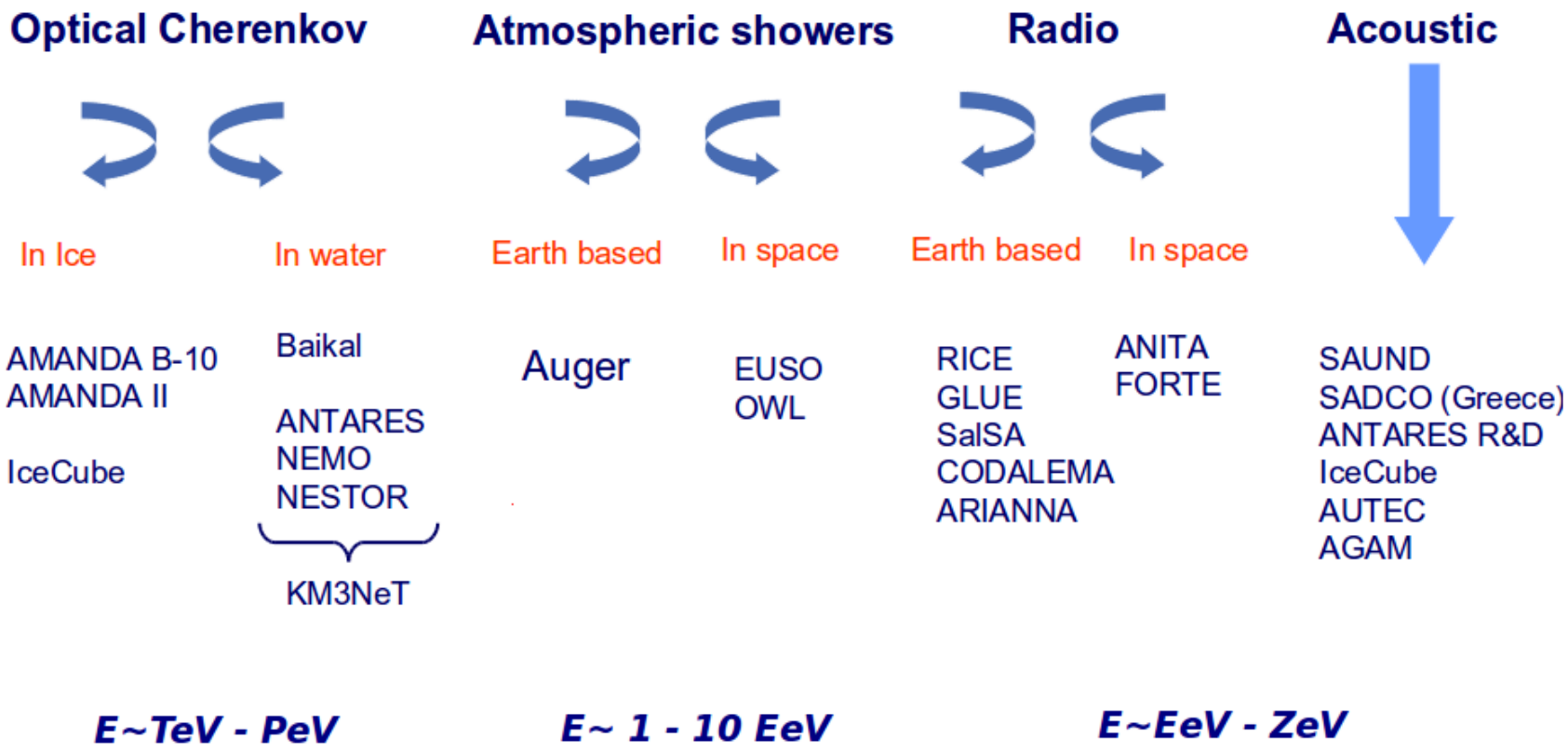




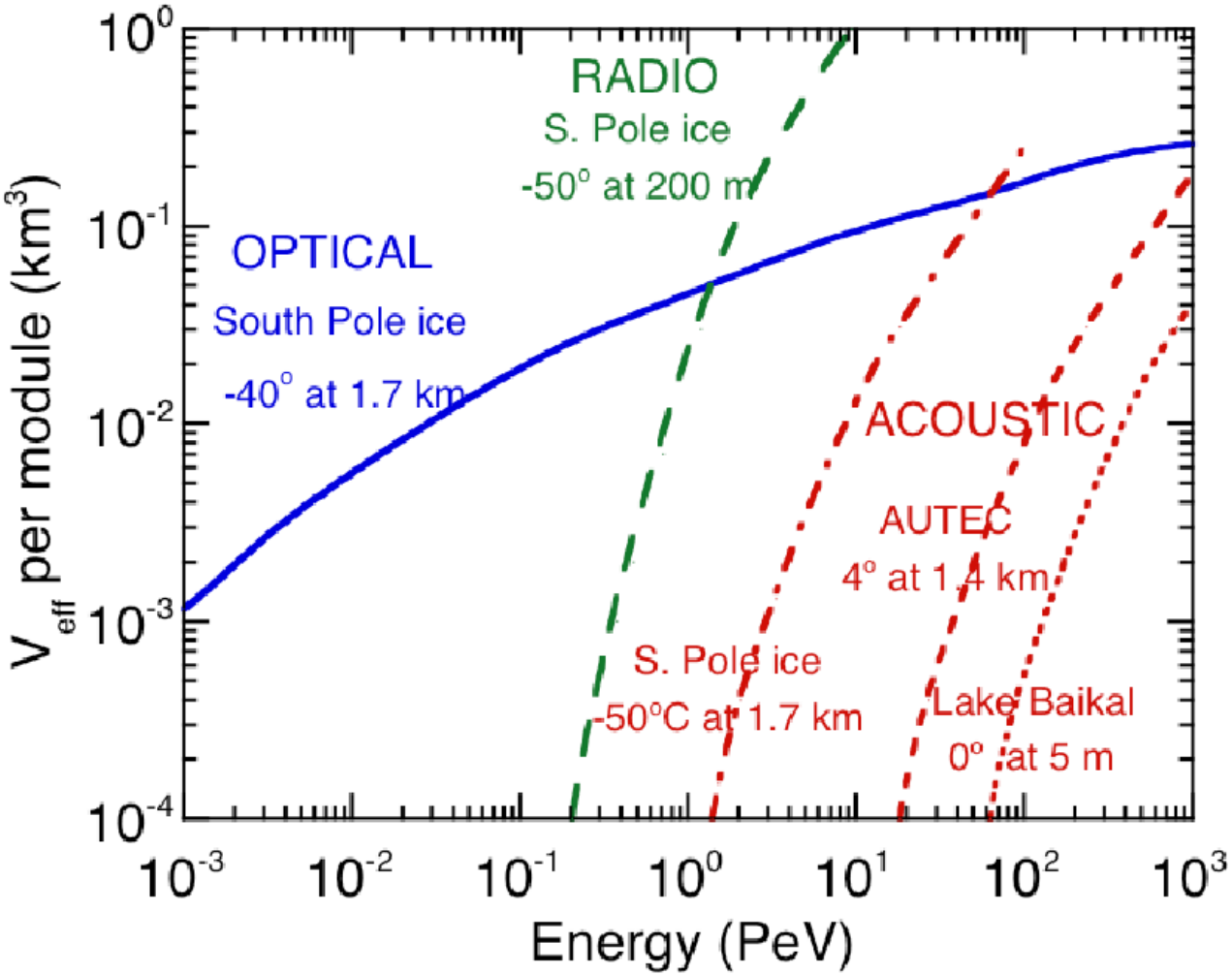
Idea of Markov (1960)

- *"We propose getting up an apparatus in an underground lake or deep in the ocean in order to separate charged particle direction by Cherenkov radiations"*
- Interaction $\nu_\mu + N \rightarrow \mu + X$ with $R_\mu \sim 1 - 10km$ in 1 TeV-1 PeV
- **Effective volume of detection increases with energy**
- **Colinearity of μ with ν increases with energy $\Rightarrow$ astronomy**

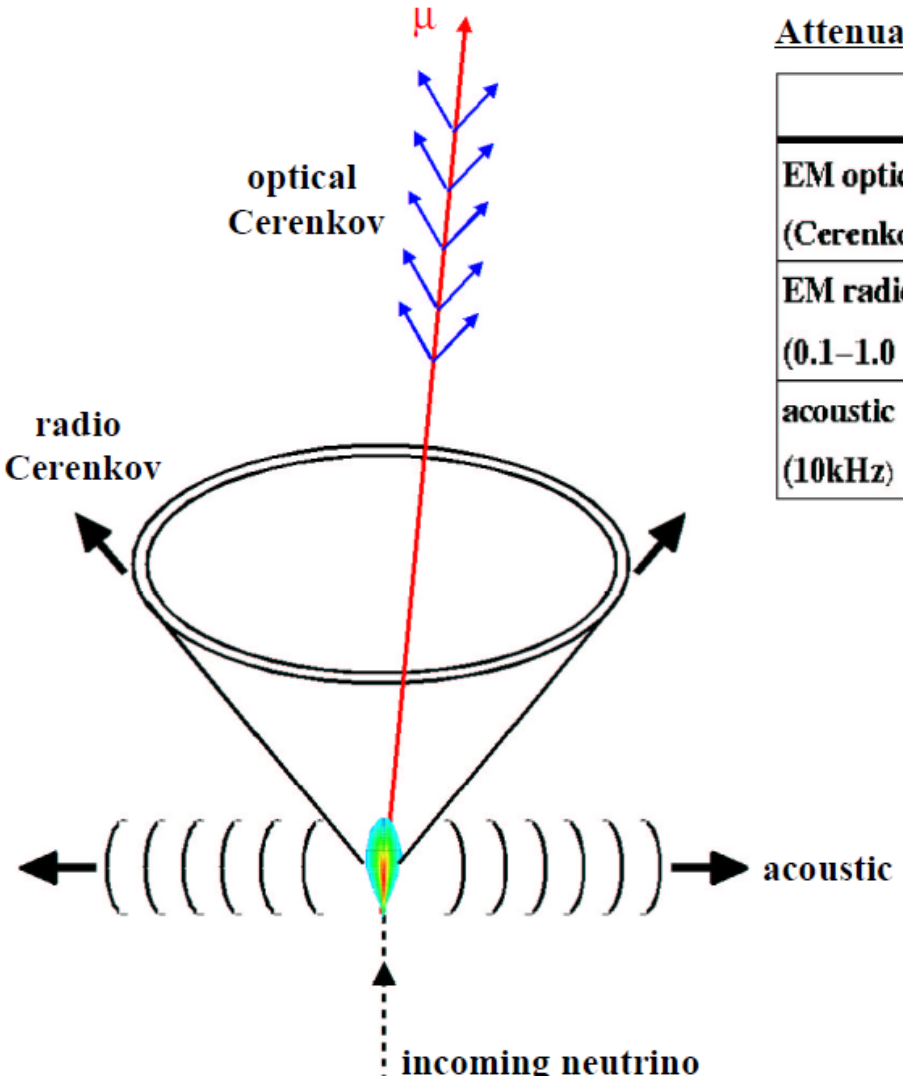
Detection of Cosmic Neutrinos



Detection of Cosmic Neutrinos [QUICK]

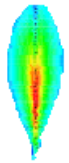


Acoustics and Radio [QUICK]

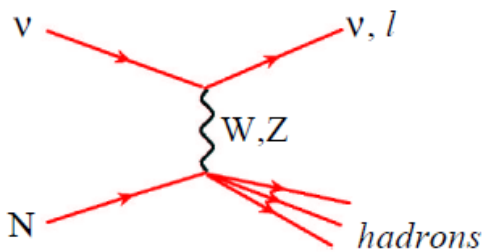


Attenuation Lengths :

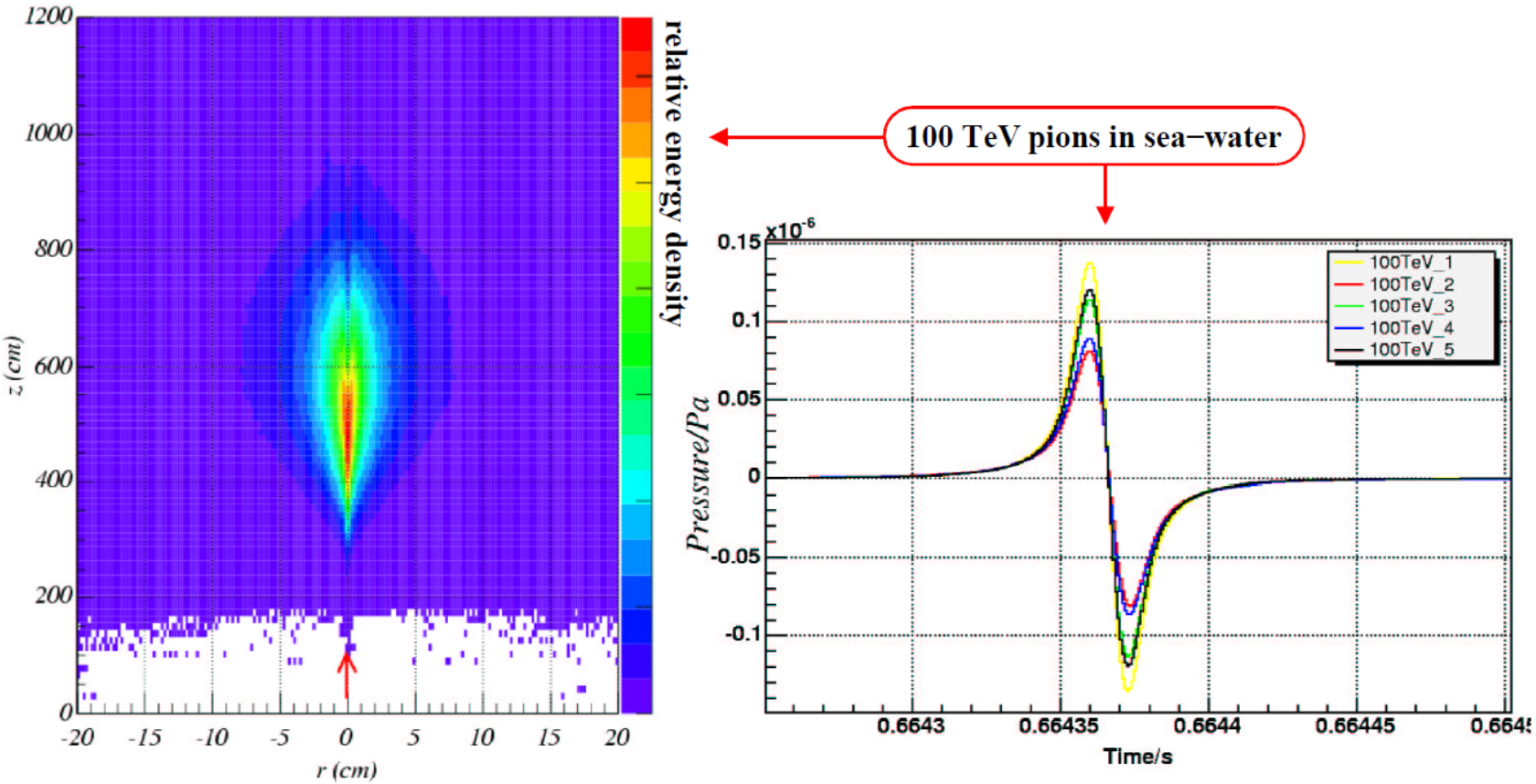
	water	ice	salt
EM optical (Cerenkov)	~ 50 m	~ 100 m	~ 0
EM radio (0.1–1.0 GHz)	~ 0	~few km	~1 km (?)
acoustic (10kHz)	~10 km	? (large)	? (large)



= hadronic shower (or EM shower for ν_e CC interactions)



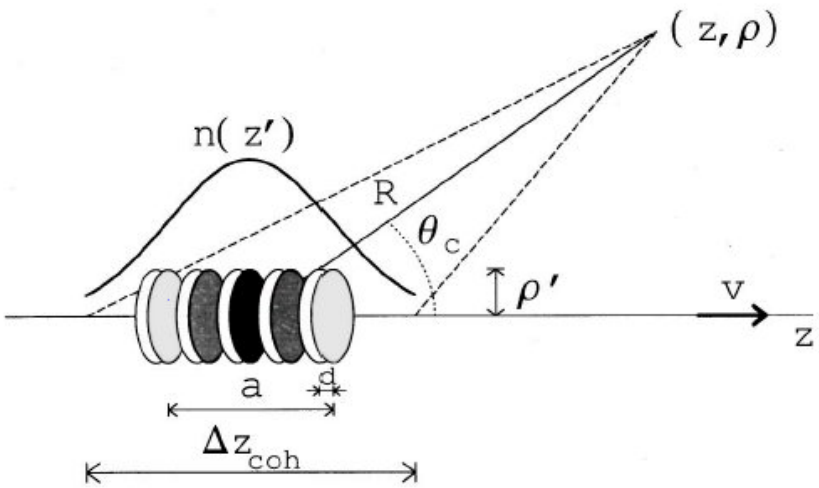
Acoustics and Radio [QUICK]

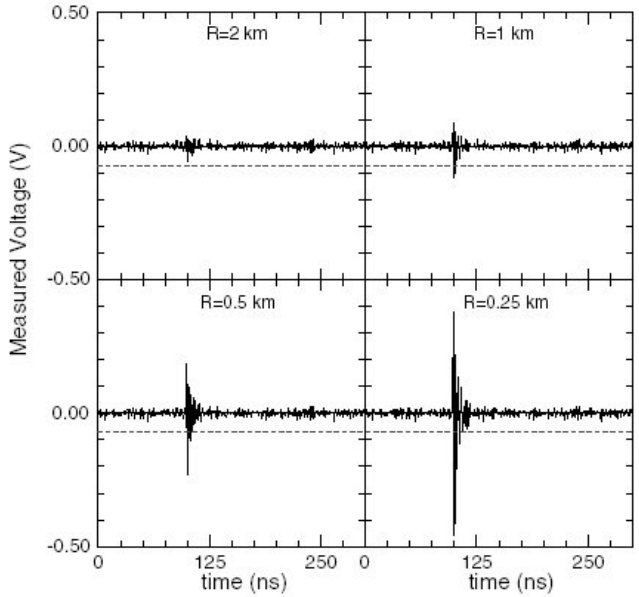


An Acoustic pulse

- R&D in Antares (Germany, Marseilles)

Acoustics and Radio [QUICK]





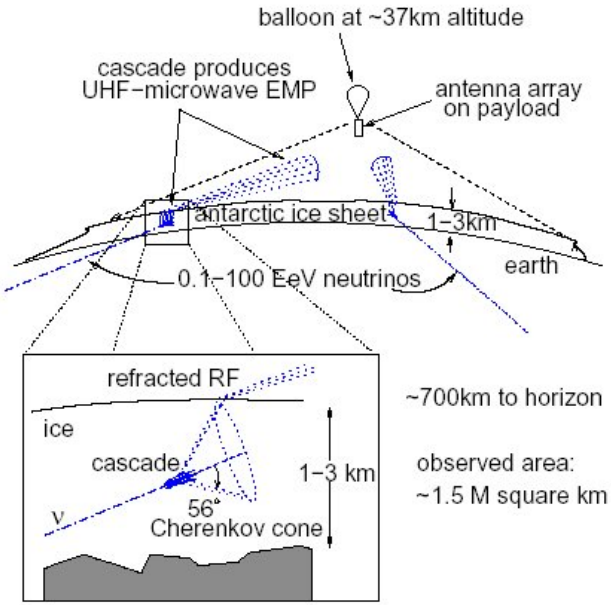
Askaryan Effect - used in Codalema, LOPES...

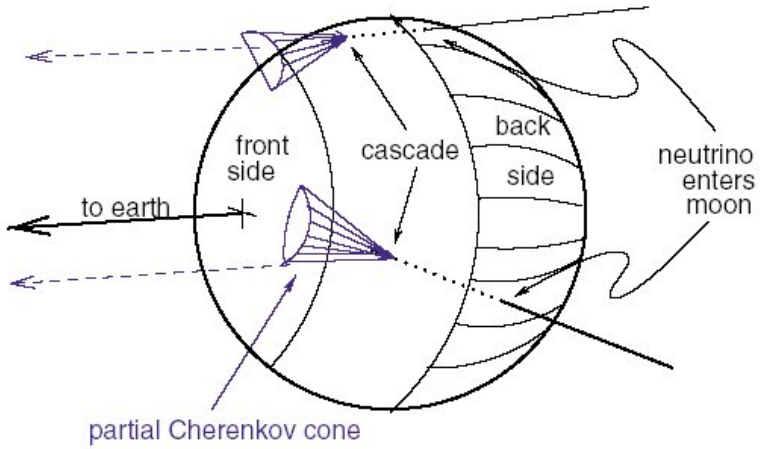
- Coherence length Δz along Oz axis of shower : fields arrive simultaneously at distance R if $\frac{dR}{dt} = v\cos\theta = \frac{c}{n}$
- But $\frac{dR}{dt}$ varies : $\frac{dR^2}{dt^2} = v^2\frac{\sin^2\theta}{R^2}$
- Coherence implies $\Delta R = \frac{1}{2}\frac{v^2\sin^2\theta}{R^2}\Delta t^2 < \lambda$
- $\Delta z_{\mathrm{coh}} = v\Delta t_{\mathrm{coh}} \approx \frac{\sqrt{\lambda R}}{\sin\theta}$

$\Rightarrow$ Optical domain : $\Delta z \ll a$, emitting zone around maximum

$\Rightarrow$ Radio domain : $\Delta z \gg a$

Acoustics and Radio [QUICK]





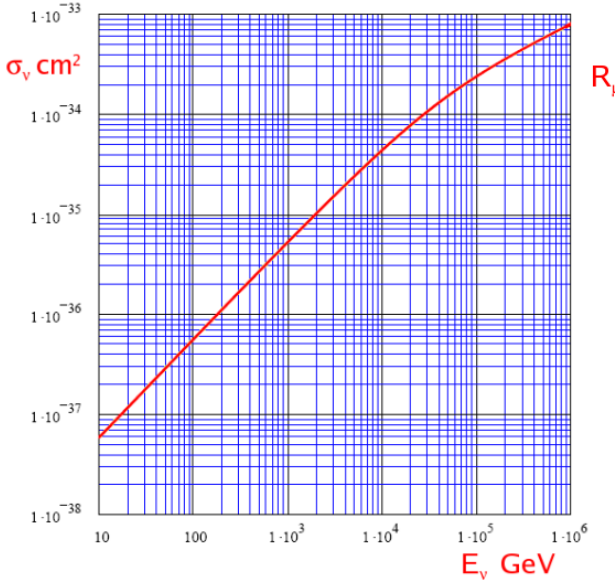
Askaryan Effect - used in Codalema, LOPES...

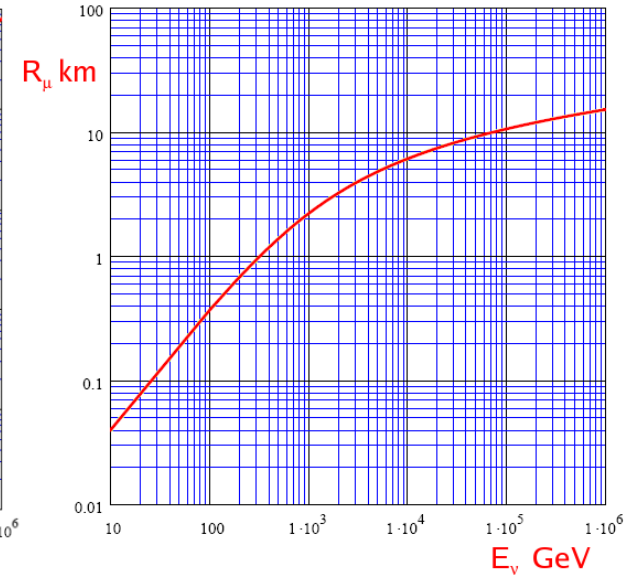
ANITA - GLUE

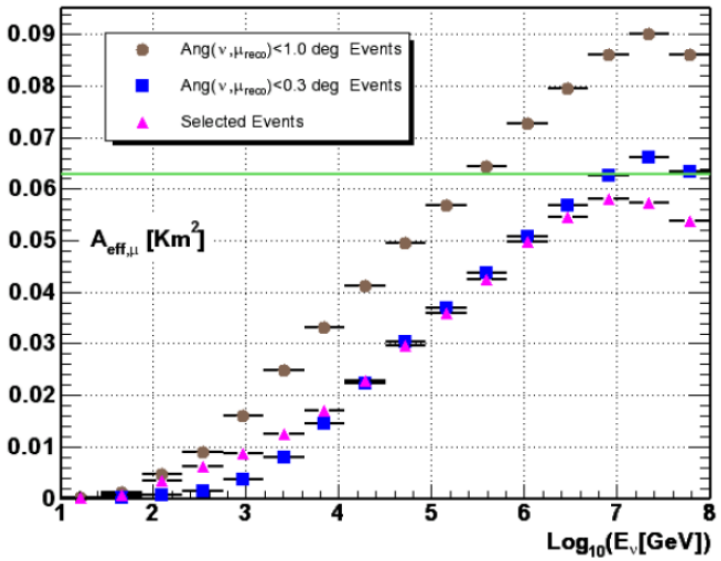
Event Rate & Detector Size

Event Rate N_ν & Luminosity needed

$$N_\nu \propto \Phi_\nu \times P_{\text{absorption}}(\theta, E) \times \underbrace{\sigma_\nu}_{\text{cross-section}} \times \underbrace{R_\mu}_{\mu \text{ range}} \times \underbrace{A_\mu}_{\text{Effective Area for } \mu}$$







Event Rate & Detector Size

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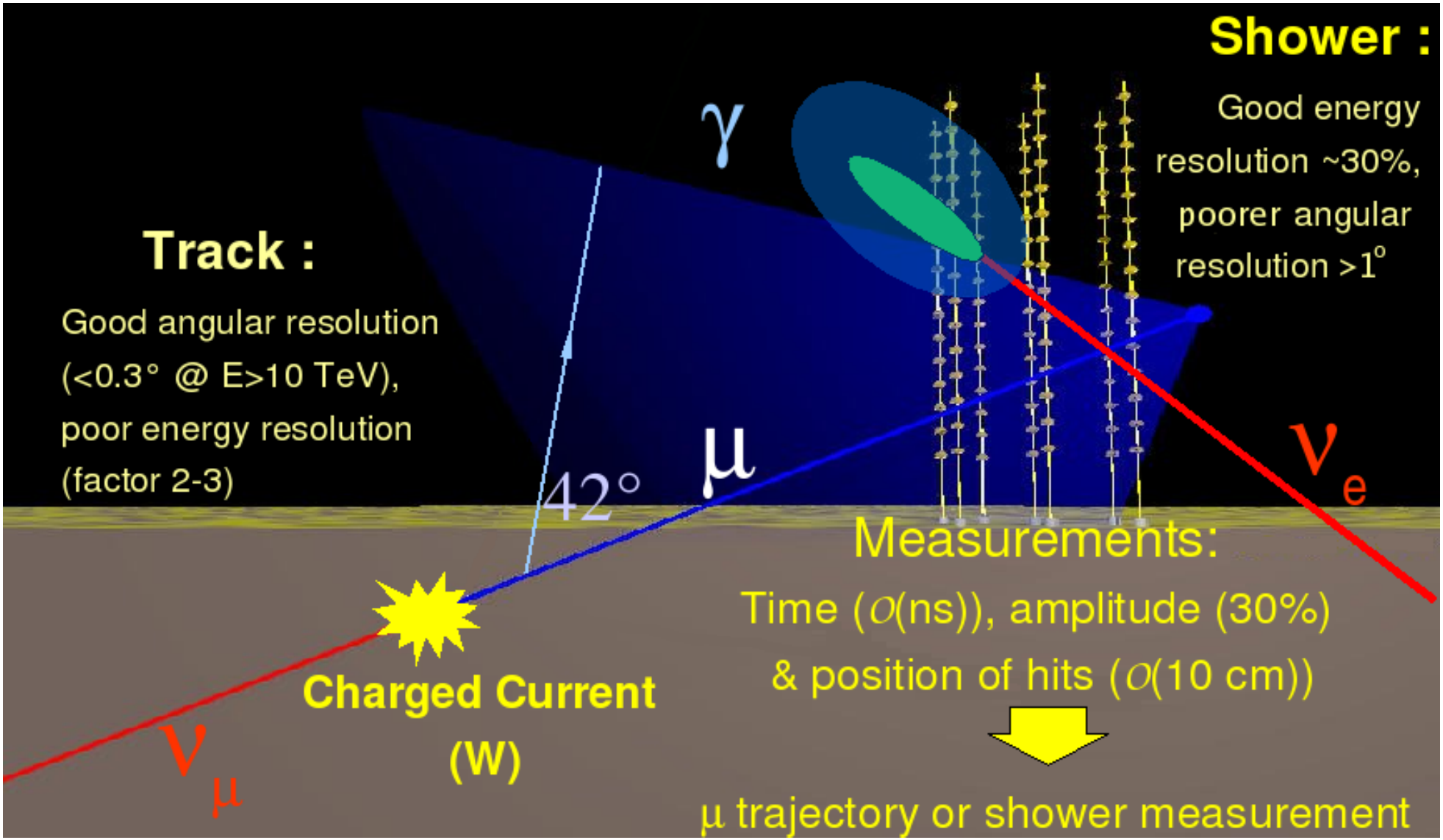
$$L_\nu = 4\pi d^2 \Phi_\nu \approx 10^{46} N_\nu \left(\frac{d}{4\,Gpc}\right)^2 \left(\frac{E_\nu}{100\,TeV}\right)^{1-\alpha} \left(\frac{A_\mu T}{km^2 yr}\right)^{-1} \text{ erg/s}$$

- $\alpha \sim 1$ for $E_\nu < 100\,TeV$, $\alpha \sim 0.5$ above 100 TeV
- Blazars $\sim Gpc$, $L \sim 10^{47}$ erg/s $\Rightarrow A_\mu \sim 1\ km^2$
- Galactic Sources $L_\nu \simeq 10^{35}$ erg/s for $A_\mu \sim 0.1\ km^2$

Optical detection of cosmic neutrinos



Number of detected muons... [QUICK]

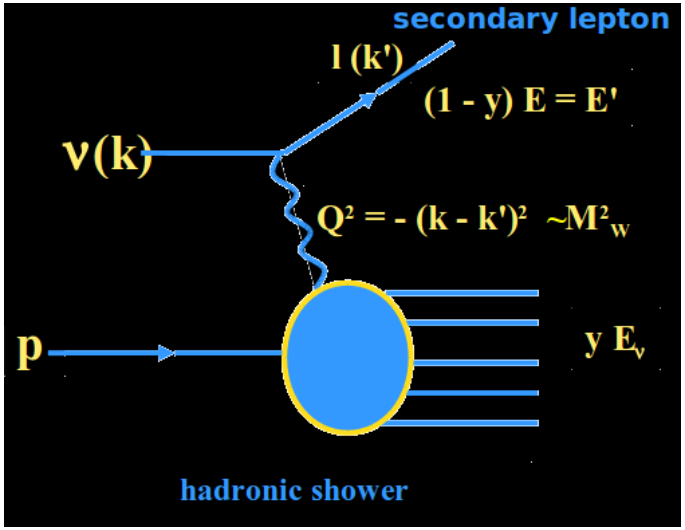
For area A and observation time T

- $N_\mu(\theta) = A.T. \int_{E_{\min}}^{E_\nu} \Phi_\nu(E_\nu, \theta) dE_\nu P_{\nu\to\mu} P_\oplus$
- $\Phi_\nu(E_\nu, \theta)$ neutrino spectrum
- $P_{\nu\to\mu}$ Probability to produce a detectable muon with $E_\mu > E_{\min}$
- $P_\oplus$ Earth transparency to HE neutrinos

Producing a detectable muon

- $P_{\nu\to\mu} \propto \int \frac{d\sigma}{dE_l} R_l(E_l, E_{\min}) dE_l$
- R_l **range of muon of energy** E_l **before it reaches** $E_{\min}$
- $\frac{d\sigma}{dE_l}$ differential interaction cross-section...

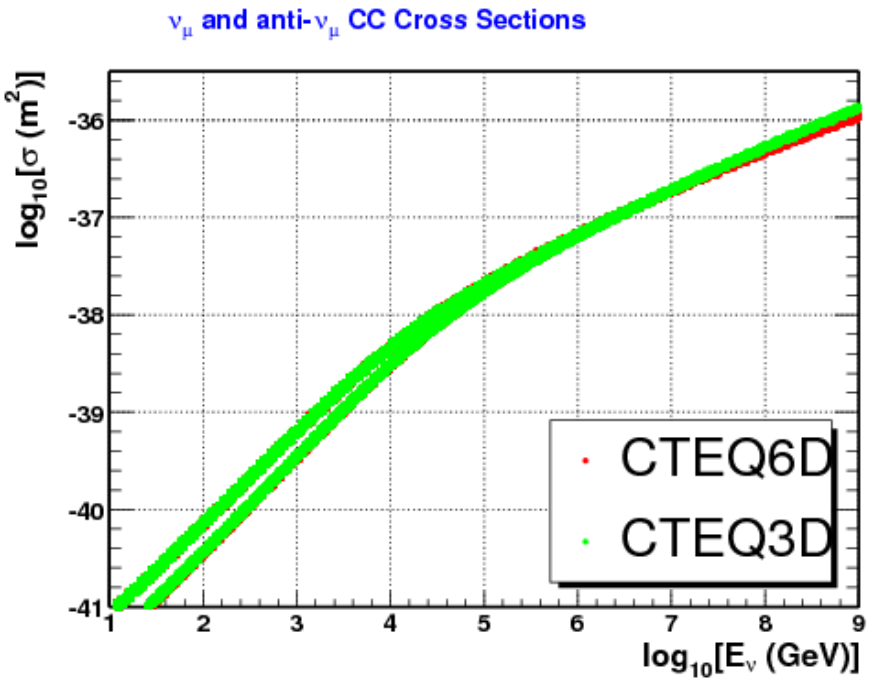
Interaction in Rock/Water/Ice [QUICK]



Deep-Inelastic Scattering

- $\frac{d\sigma}{dE_l} = \frac{2G_F^2 m_N E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\left[xq(x,Q^2)+x\bar{q}(x,Q^2)(1-y)^2\right]$
- m_N, M_W, nucleon and boson mass
- Q transfer momentum, $\nu = E_\nu - E_l$ hadronic energy in lab-frame
- $x = \frac{Q^2}{2m_N\nu}$ momentum fraction carried by parton
- $y = \frac{\nu}{E_\nu}$

Interaction in Rock/Water/Ice [QUICK]



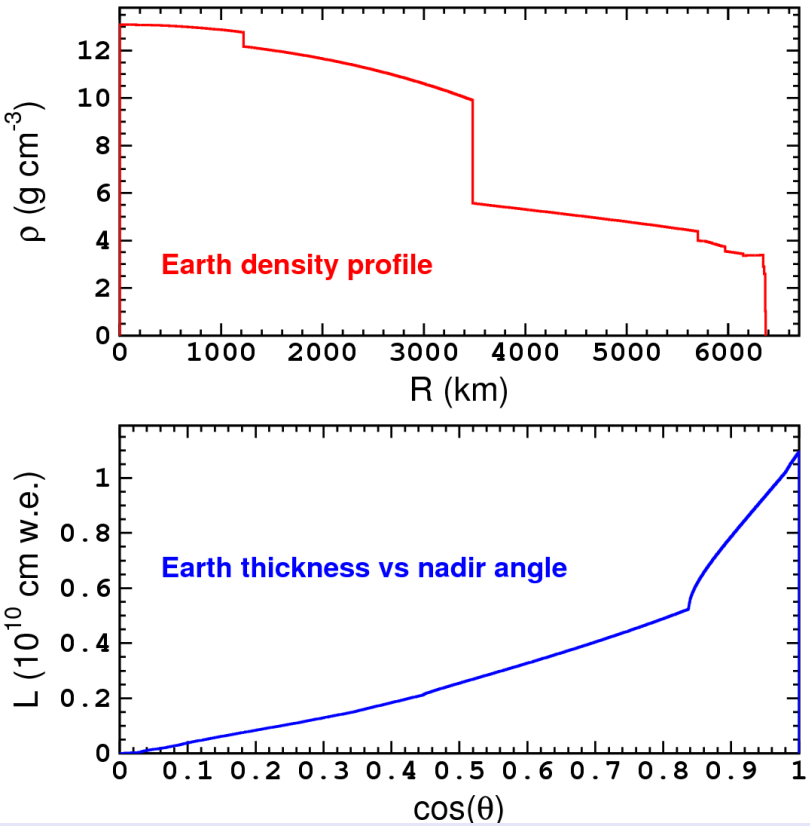
Deep-Inelastic Scattering

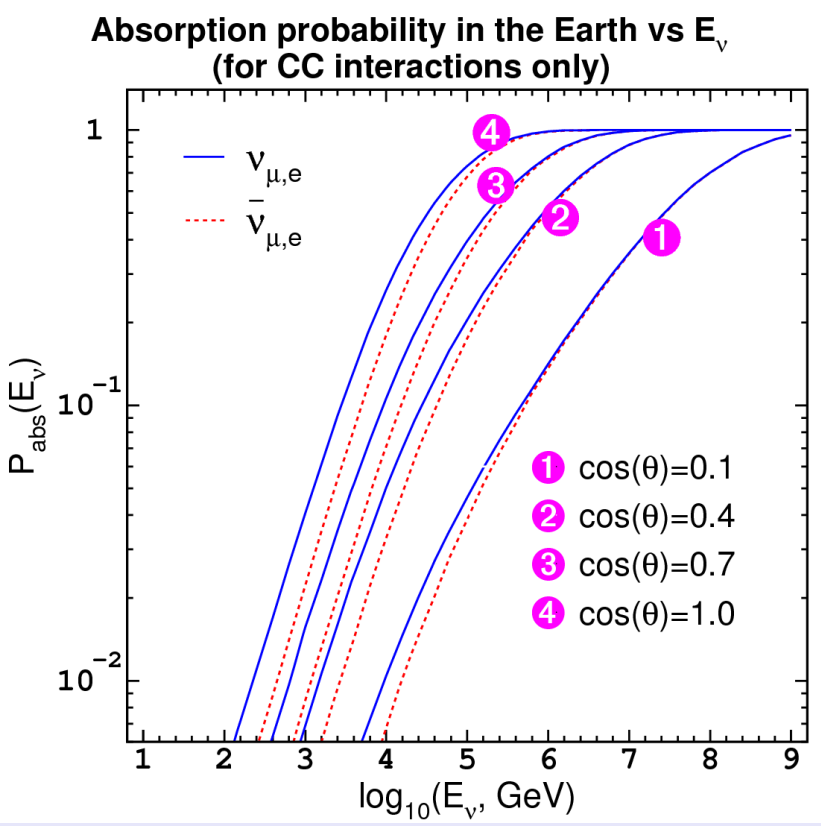
- $\sigma_{\nu N} \propto E_\nu$ below 5 TeV
- $\sigma_{\nu N} \propto E_\nu^{0.4}$ above 5 TeV
- **Pointing :** $\sqrt{< \theta^2_{\mu\nu} >} \approx \sqrt{\frac{m_N}{E_\nu}} \Rightarrow < \theta > \approx \frac{1.5^\circ}{\sqrt{E_\nu\,(TeV)}}$
- Colinear at high energy !

Interaction in Rock/Water/Ice [QUICK]

Transmission through Earth

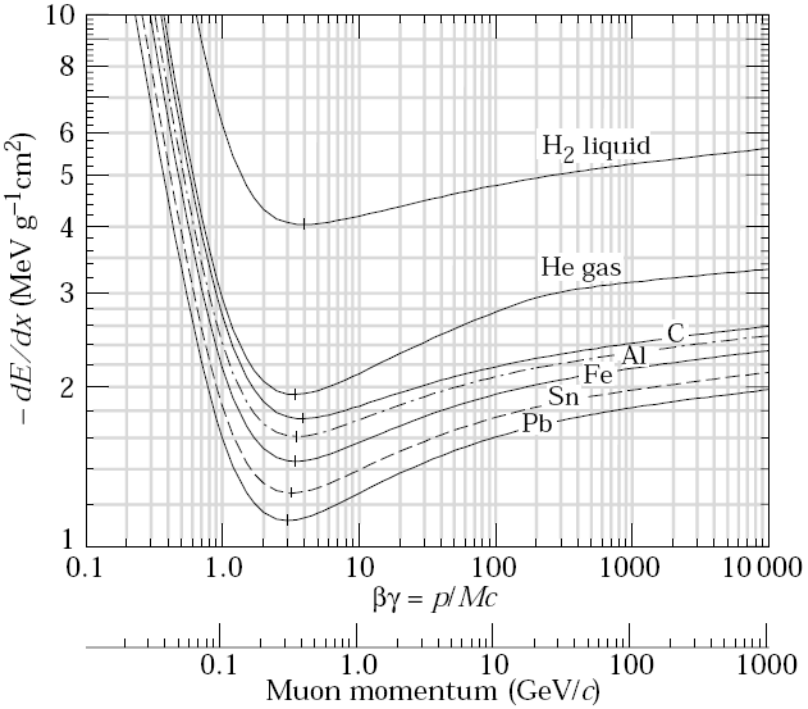
- $P_{\oplus} = e^{-l/\lambda}$, where $\lambda^{-1} = \rho \mathcal{N}_A \sigma_\nu(E_\nu)$





Muon Propagation - Energy Losses [QUICK]

- Ionization and atomic excitation : interactions with electrons in the media (continuous) - minimum at $2 MeV/g/cm^2$
- Radiative - discrete and stochastic
  - Bremmsstrahlung : accelerated particle through field of atomic nuclei $\propto 1/m^2$
  - Pair production : $\mu + N \rightarrow e^+ e^-$
  - Photonuclear : inelastic interaction of muon with nuclei, produces hadronic shower



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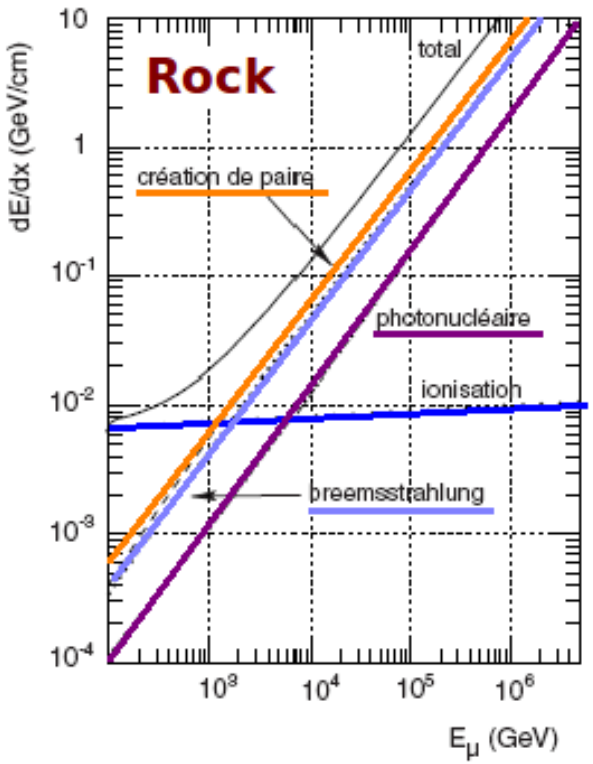
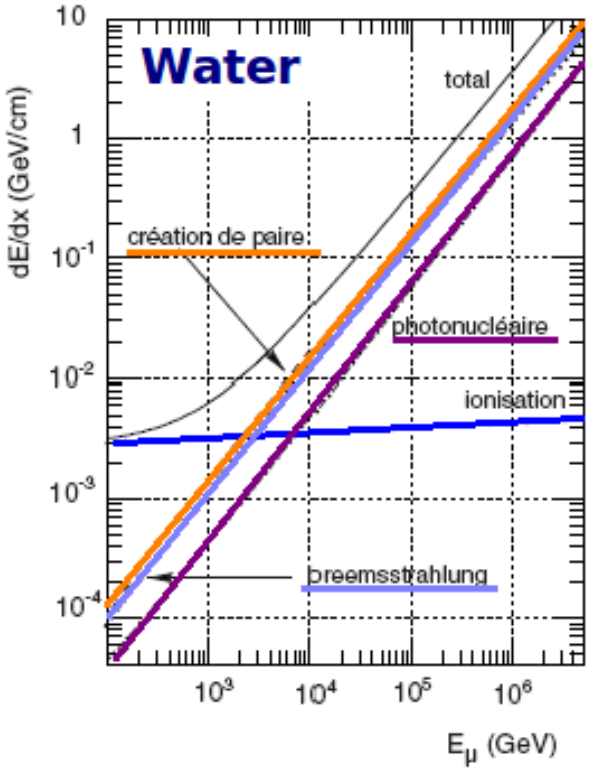
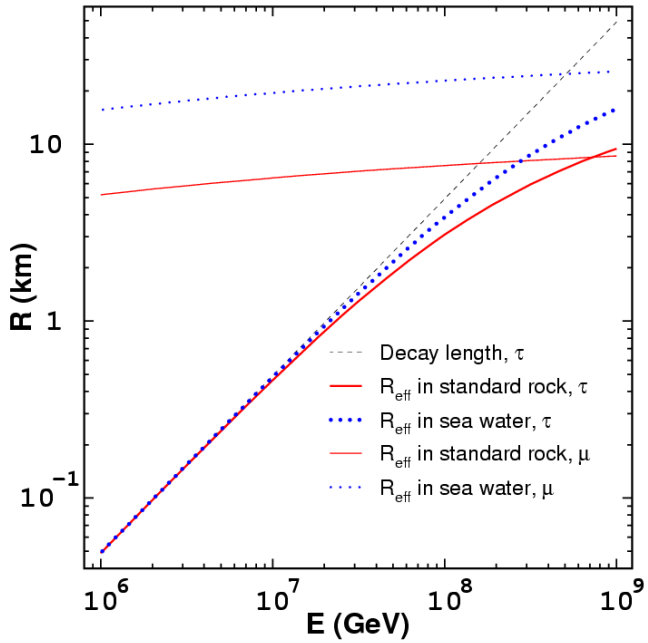




Energy Losses and muon range

- $-\frac{dE}{dx} = a(E) + b(E)E$

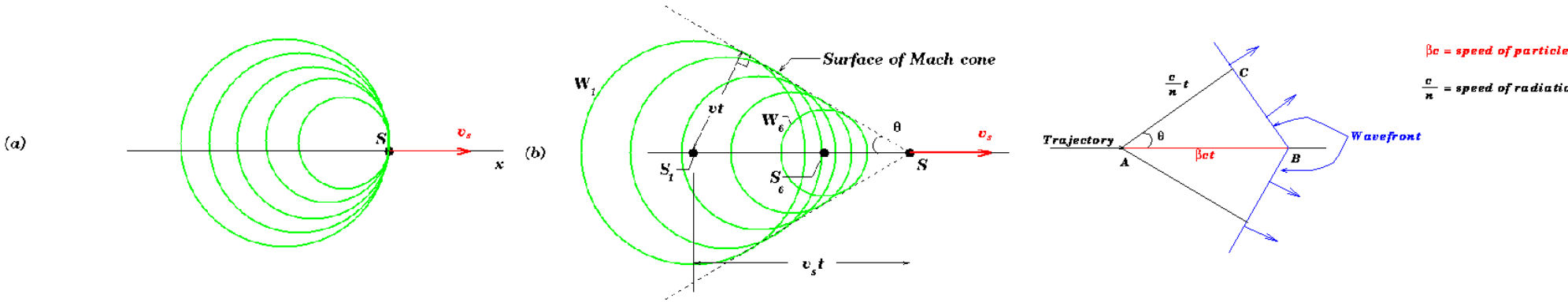
Muon Propagation - Energy Losses [QUICK]



Energy Losses and muon range

- Muon Range $R_\mu = \int_0^E \frac{dx}{dE} dE \approx \int_0^E \frac{dE}{a+bE} = \frac{1}{b} \log\left(1 + \frac{E}{E_c}\right)$ with $E_c = a/b$ critical energy
- For upgoing muons, the interaction volume is much larger than instrumented volume !

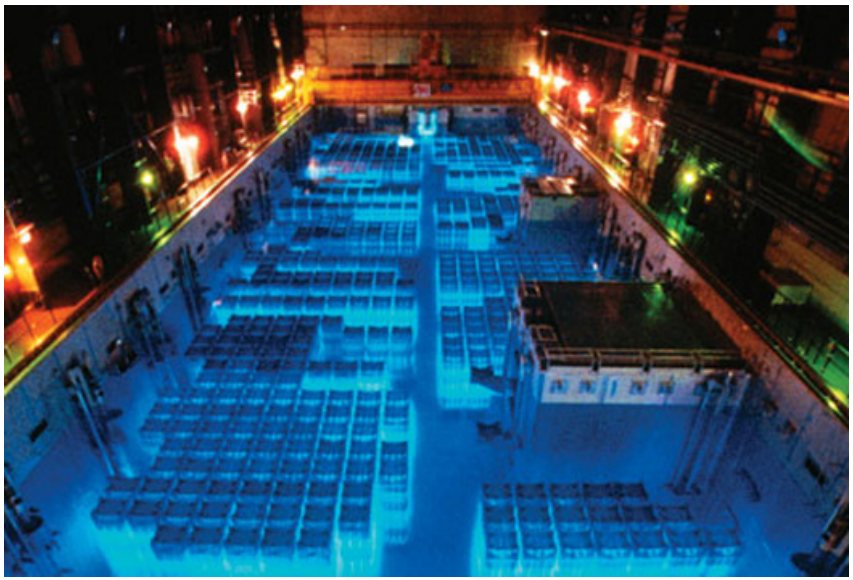
Muon Detection - Cherenkov Effect [QUICK]



Charged Particle with velocity $>$ phase velocity of light

- $v > \frac{c}{n}$ or $\beta > \frac{1}{n}$ refraction index
- Coherent emission along a cone of $\theta_C \sim$ constant
- $\theta_C \sim 1°$ in air, $\theta_C \sim 43°$ in water, $\theta_C \sim 41°$ in ice

Muon Detection - Cherenkov Effect [QUICK]



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Muon Detection - Cherenkov Effect [QUICK]

Number of Photons

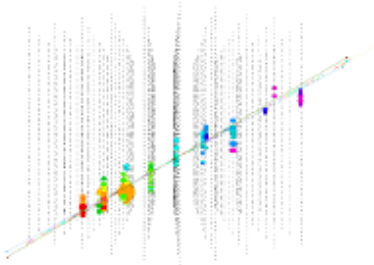
$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right) \approx \frac{2\pi\alpha}{\lambda^2}\sin\theta_C^2$$

- Between 300-600 nm, $\frac{dN}{dx} \approx 350$ photons/cm
- $\frac{d^2N}{dEdx} \approx 370\sin^2\theta_C(E)eV^{-1}cm^{-1} \approx 10^{-4} \times 2MeV/cm$
- **But directional effect !**

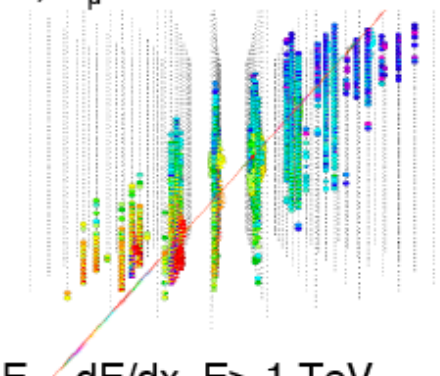
Event Topologies

Muon neutrino

a) E_μ=10 TeV ~ 90 hits



b) E_μ=6 PeV ~1000 hits

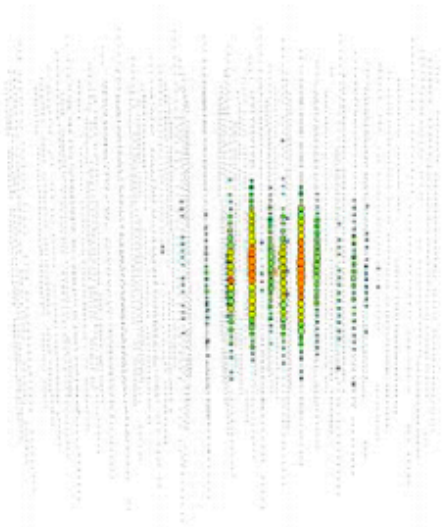


E ~ dE/dx, E> 1 TeV

Energy Res. : log(E)~0.3
Angular Res.: 0.8 -2 deg

Electron neutrino

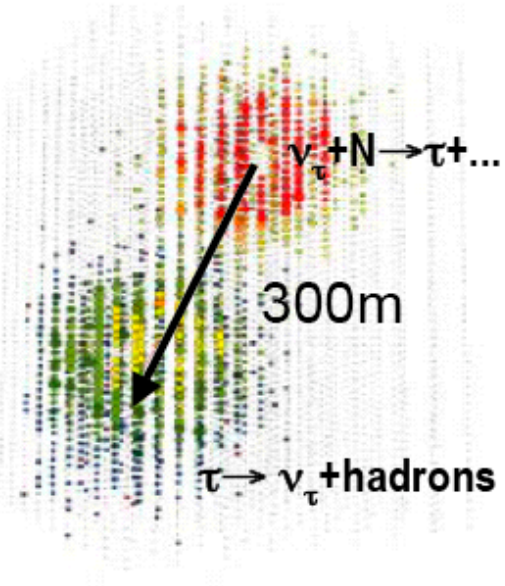
E = 375 TeV



Energy Res. log(E)~0.1-0.2
Poor Angular Resolution

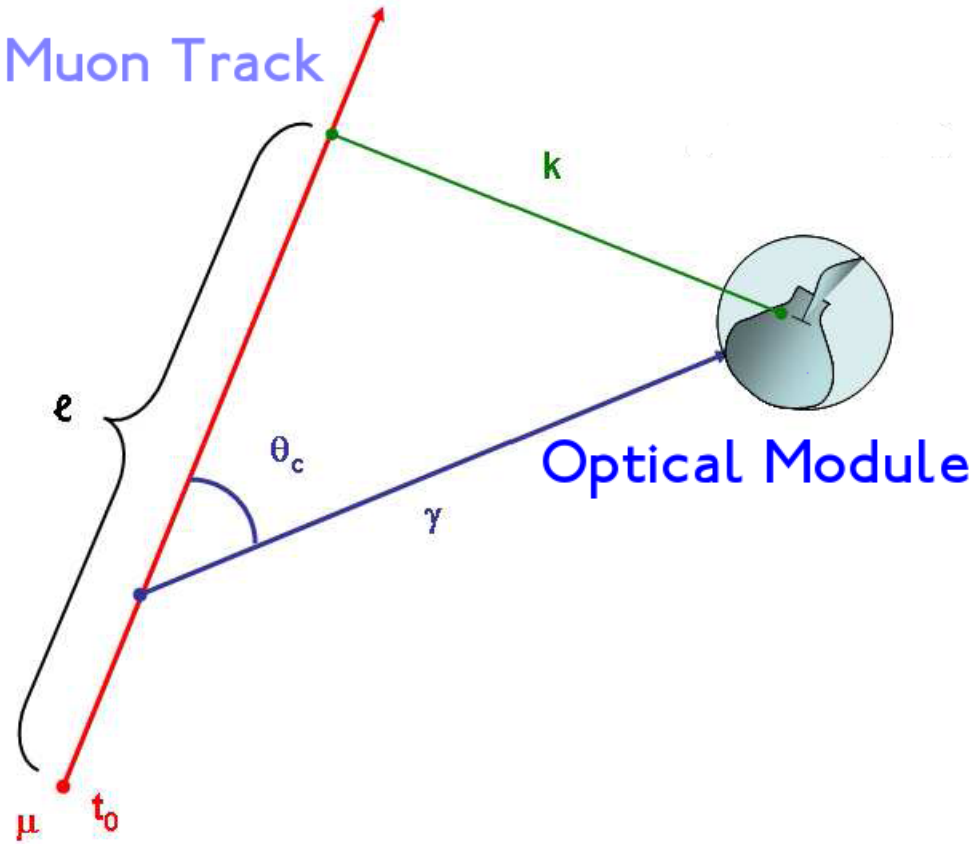
Tau neutrino

E = 10 PeV



Double-bang signature
above ~ 1 PeV
Very low background
Pointing capability
Best energy measurement

Reconstruction of the track...

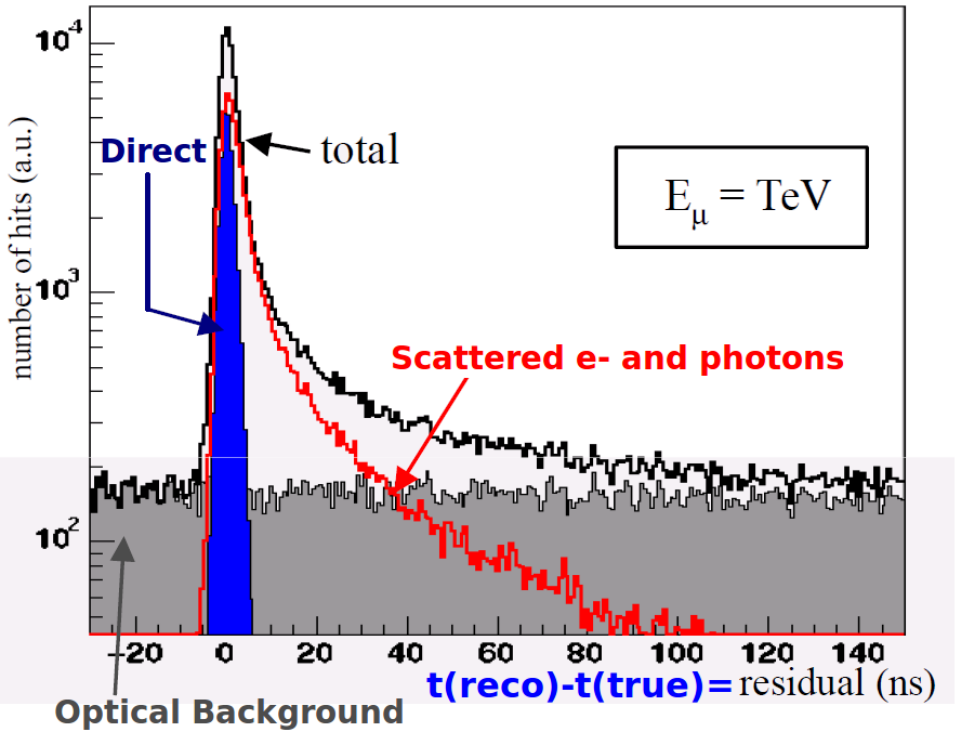


A χ^2 minimisation

$$t_{\text{theory}} = t_0 + \frac{1}{c}\left(l - \frac{k}{\tan\theta_C}\right) + \frac{1}{v_g}\left(\frac{k}{\sin\theta_C}\right)$$

- 5 parameters : $t_0, \theta, \phi, x_0, y_0$

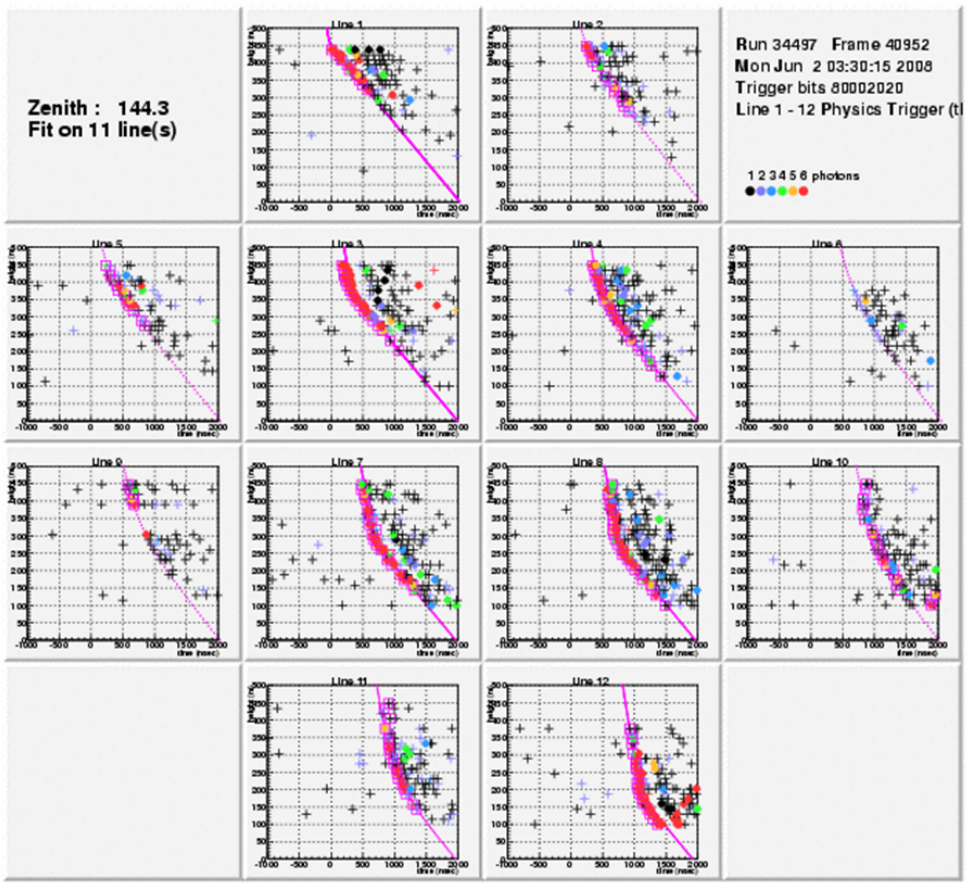
Reconstruction of the track...



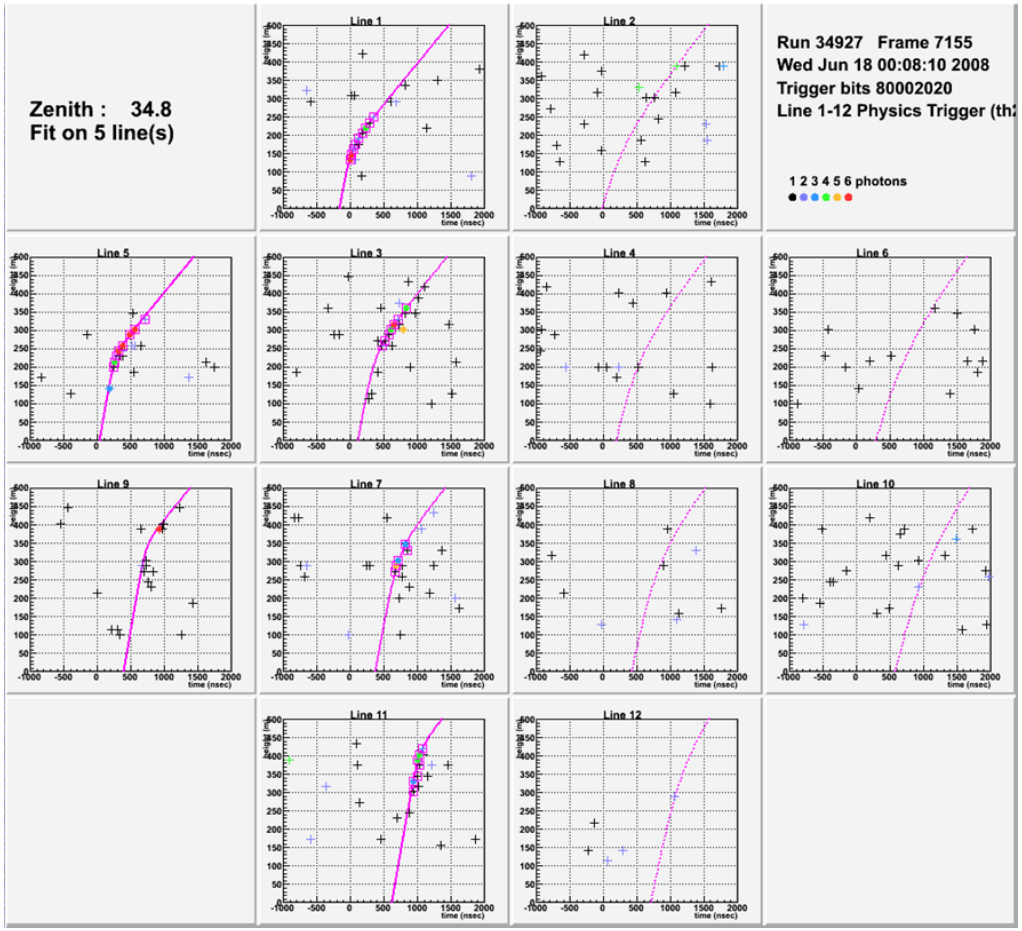
Importance of scattering

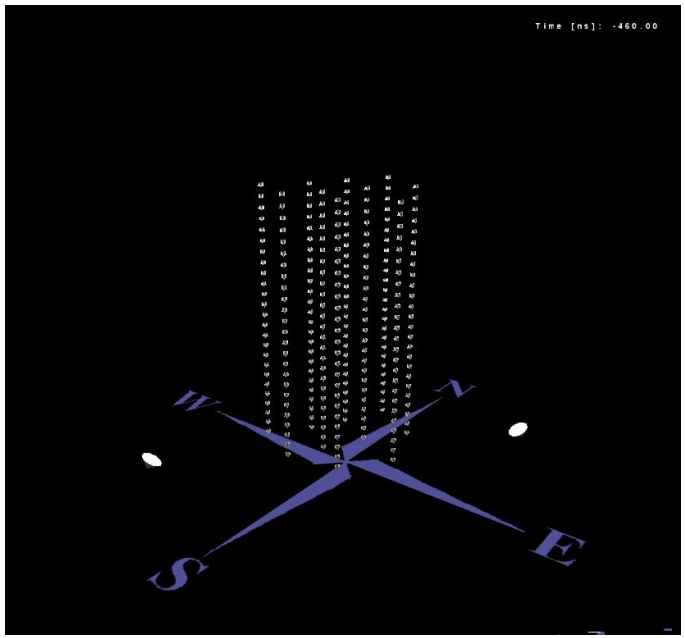
- **Few of photons are direct !**
- Impact on angular resolution

Atmospheric μ (downward) event



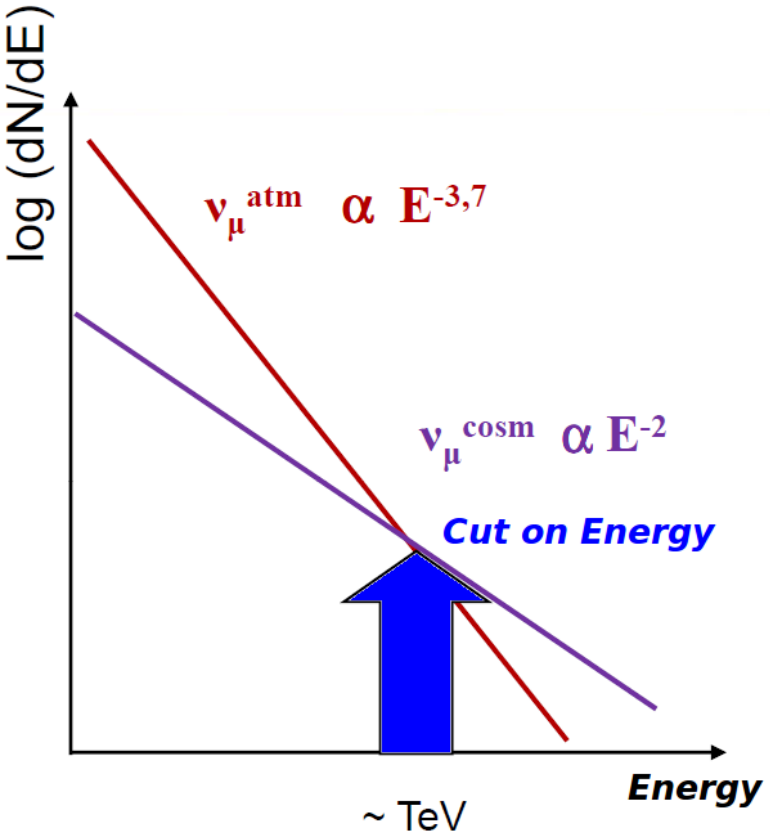
Atmospheric ν (upward) event

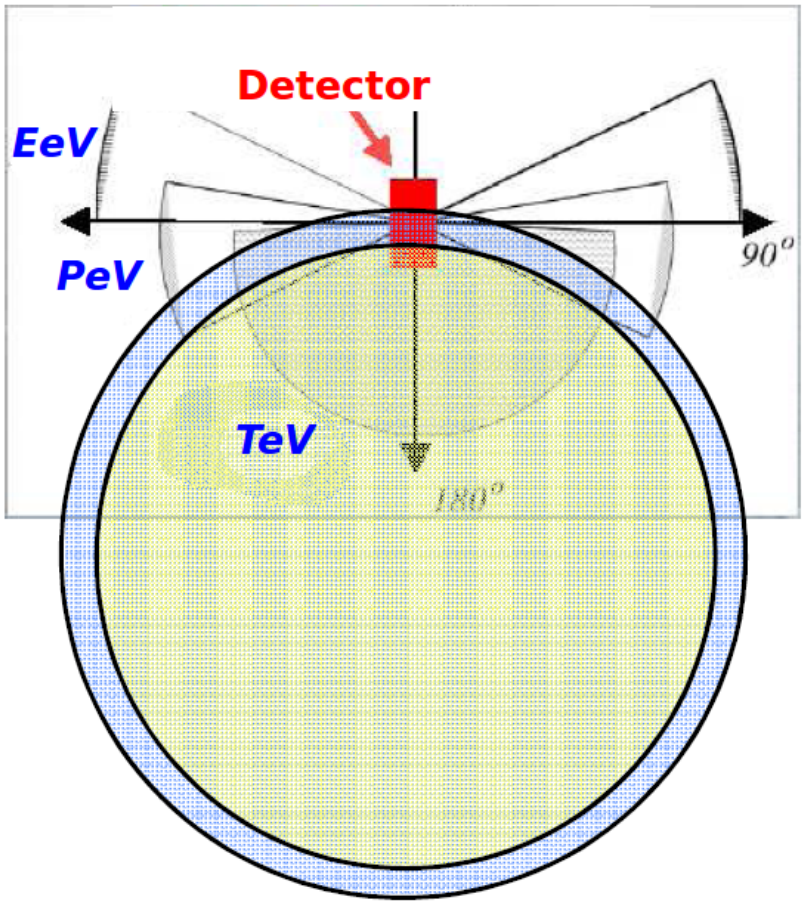




Atmospheric or Cosmic ?

Methods to distinguish between Atmospheric and Cosmic Neutrinos...

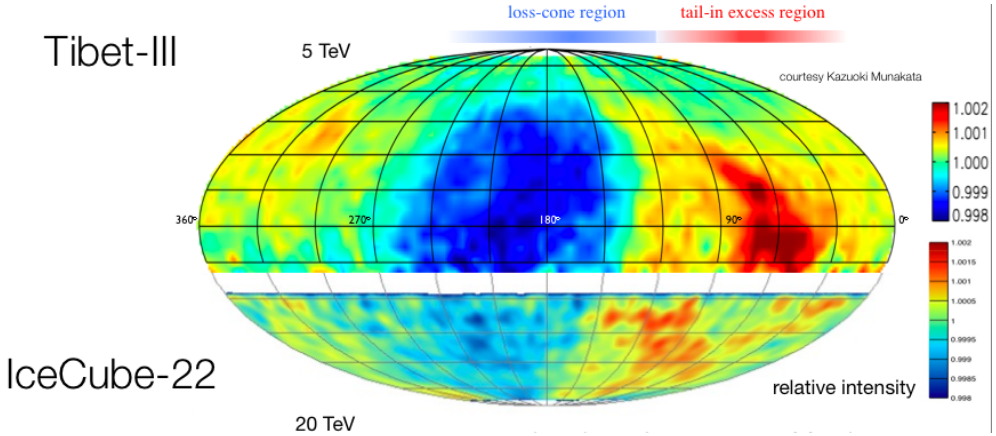


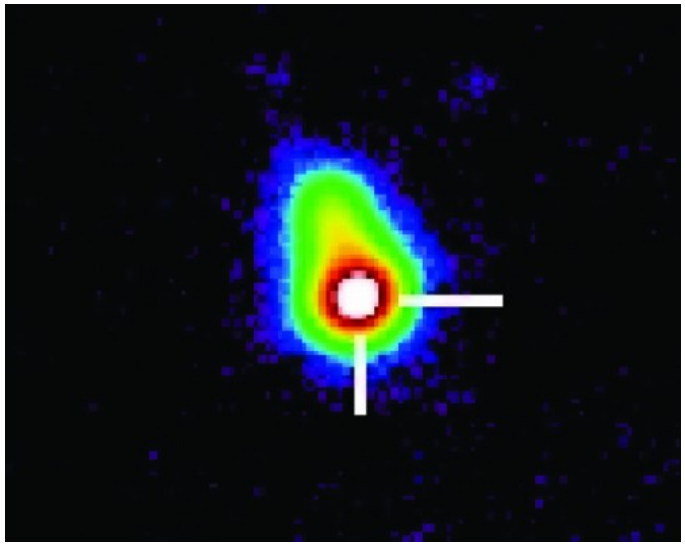


Look for an excess at high energies...⇒ **need good energy resolution**

Atmospheric or Cosmic ?

Methods to distinguish between Atmospheric and Cosmic Neutrinos...





Look for anisotropies/excess around chosen sources $\Rightarrow$ **need good angular resolution**

Confirmation with other messengers : GRBs, optical follow-up, gravitational waves...

Different radiators... [QUICK]

Photons are absorbed and scattered

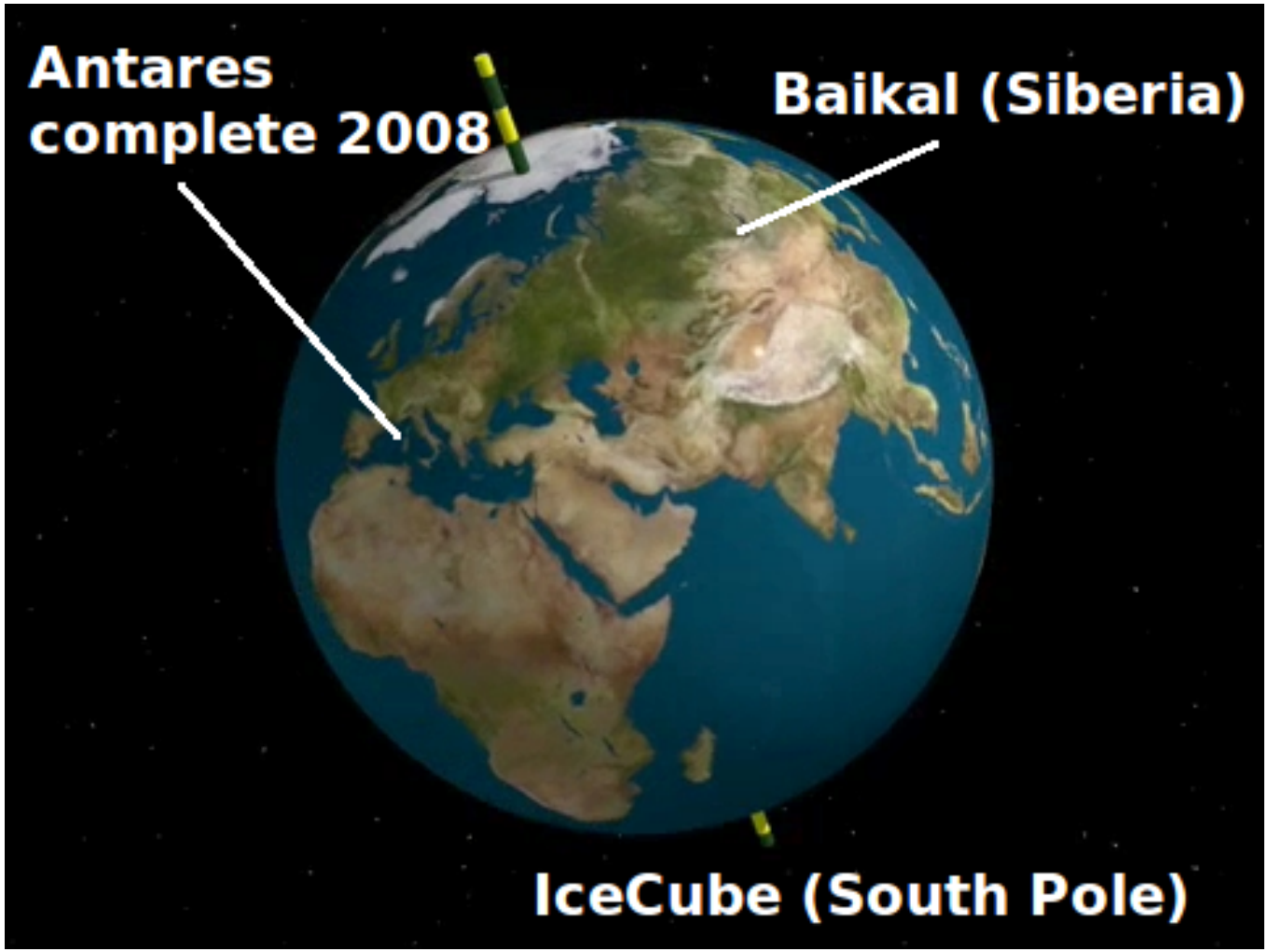
$$I(r) \propto \frac{1}{R} e^{-R/\lambda_{\mathrm{att}}}$$

- Note the $1/R$ because light on a cone, not on a sphere ! (`not so easy to demonstrate!`)
- Here Attenuation length : $\frac{1}{\lambda_{\mathrm{att}}} = \frac{1}{\lambda_{\mathrm{abs}}} + \frac{1}{\lambda_{\mathrm{scatt}}}$

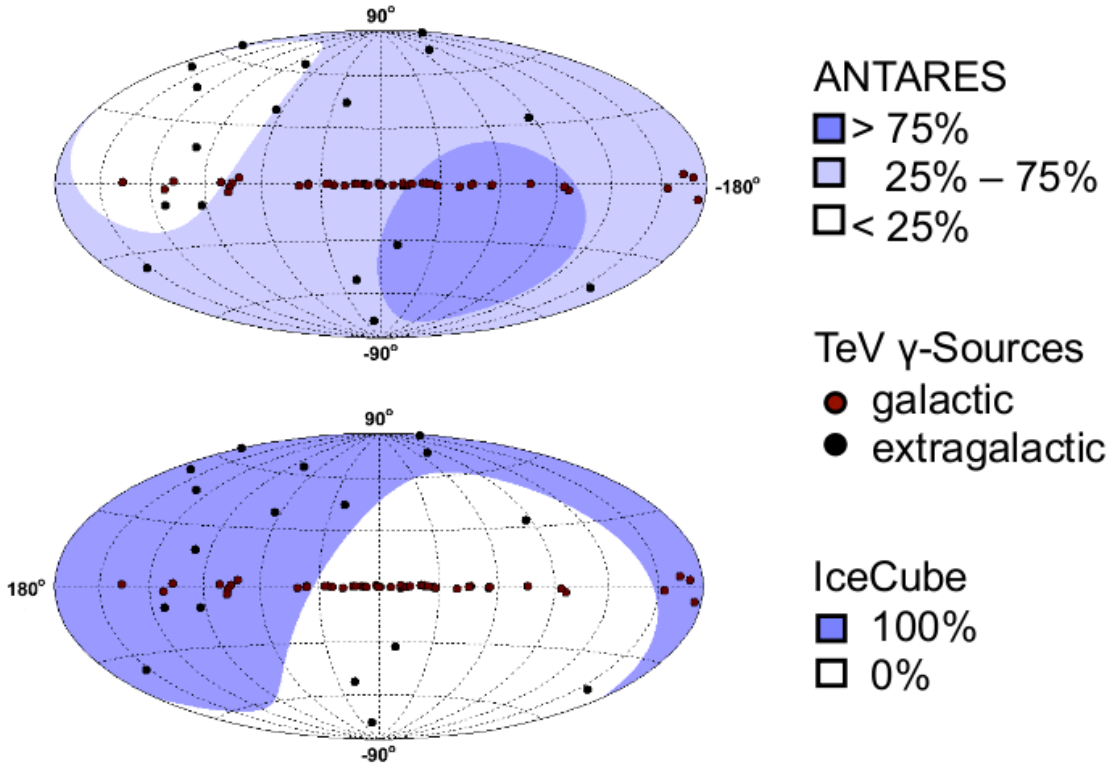
Medium	Attenuation	Absorption	Scattering	$\Delta\theta$ 10 TeV
Sea water	40-50m	50-60m	>200m	0.2°
Lake Baikal	20m	15-30m	>100m	1.5°
Polar Ice		100m	25m	3°

- Ice : no current, no bioluminescence, no β decay from salt
- Water : less scattering, better angular resolution

Neutrino Telescopes in the World...



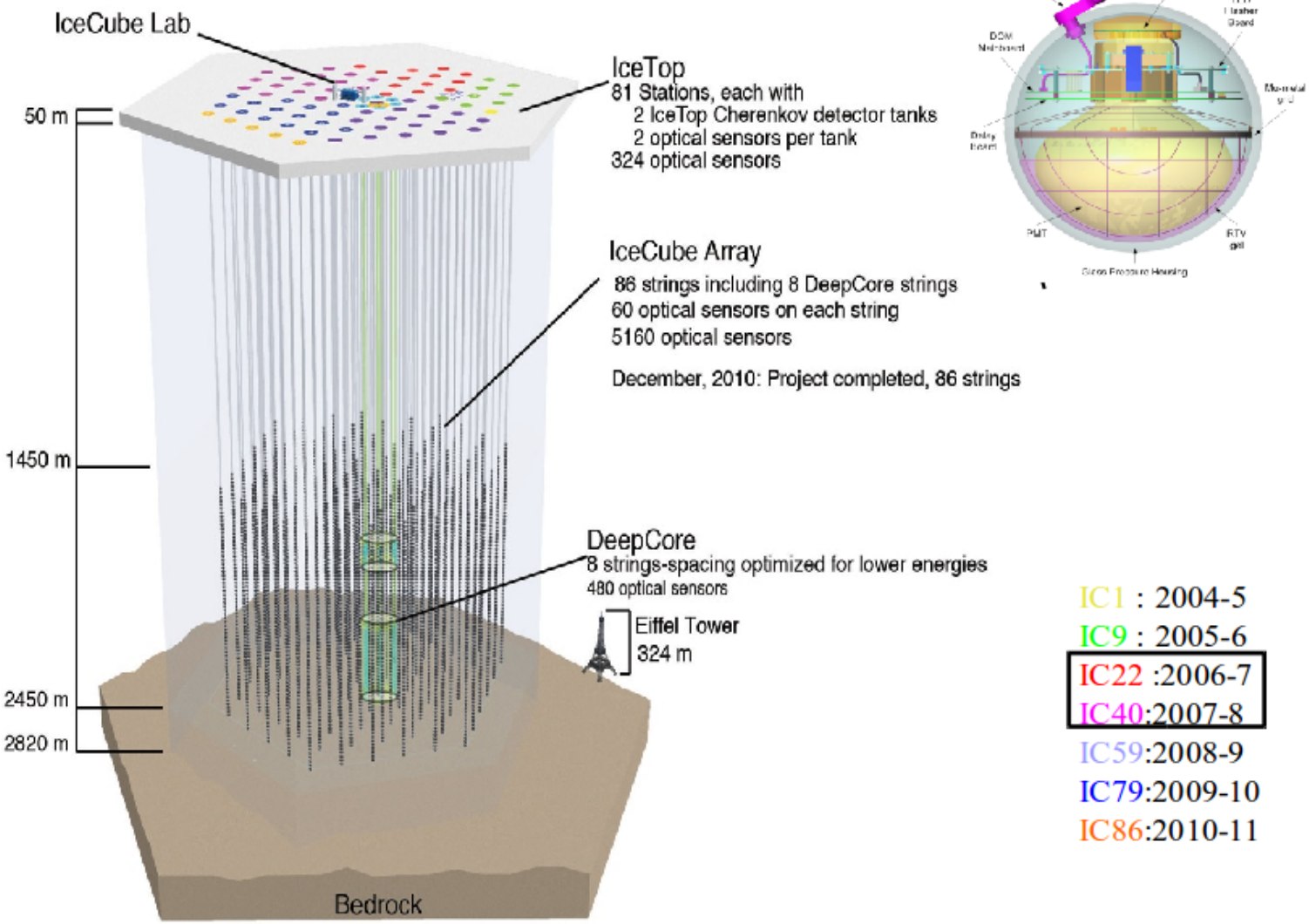
Neutrino Telescopes in the World...



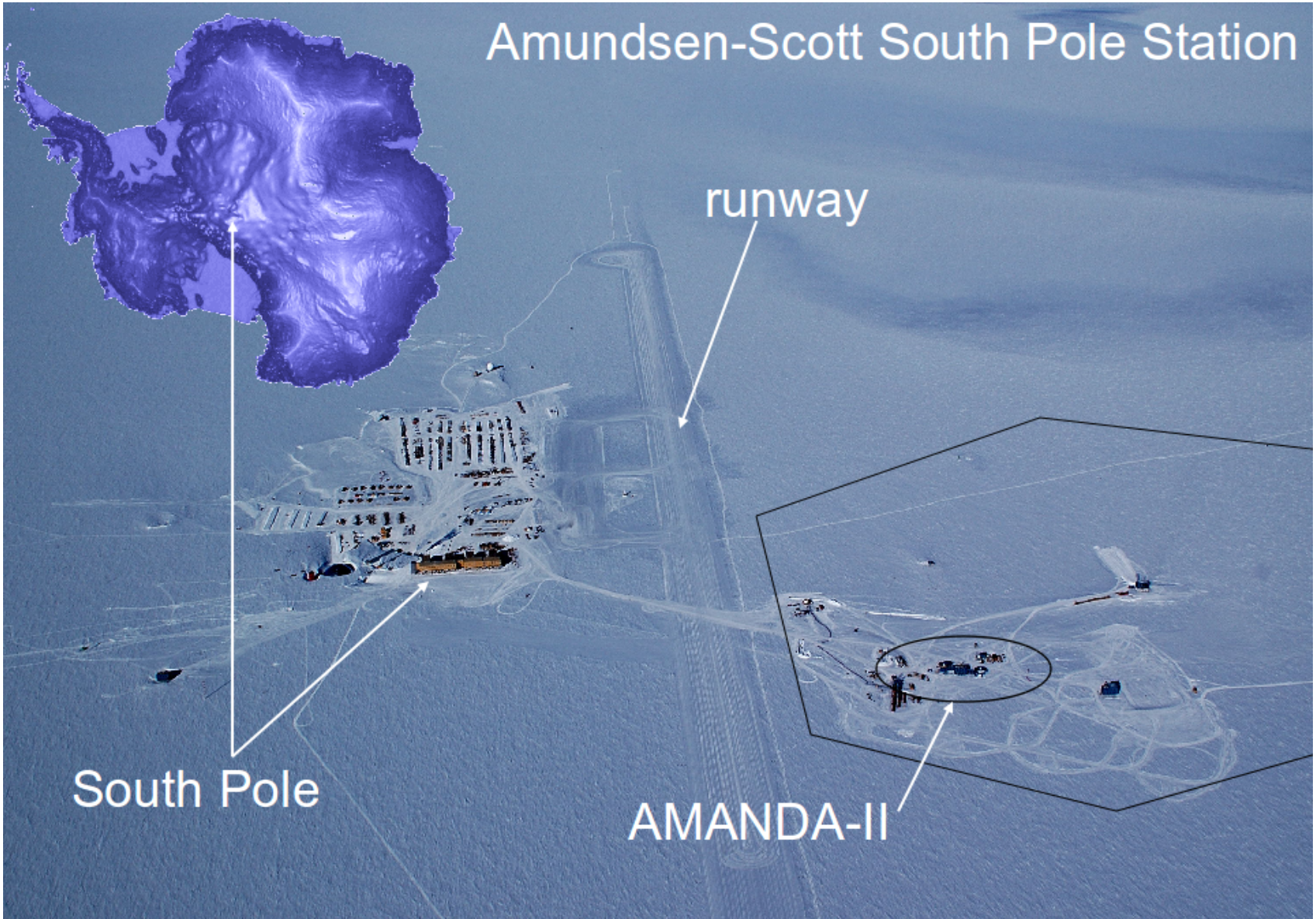
Different Telescopes are complementary

- 0.5π sr instantaneous overlap
- 1.5π sr integrated overlap

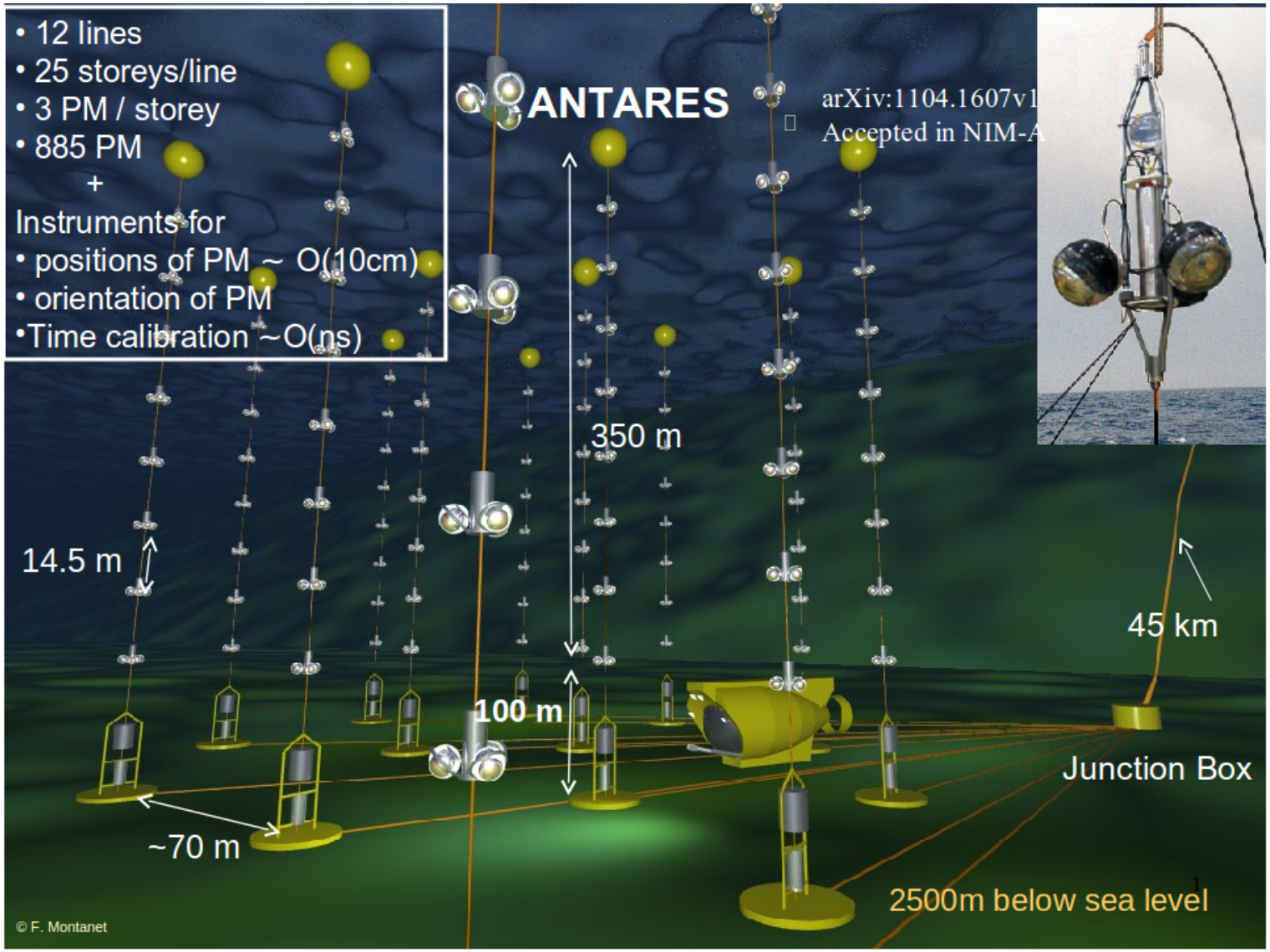
IceCube


IceCube Lab
50 m
1450 m
2450 m
2820 m
Bedrock
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
IC1 : 2004-5
IC9 : 2005-6
IC22 :2006-7
IC40:2007-8
IC59:2008-9
IC79:2009-10
IC86:2010-11

IceCube


Amundsen-Scott South Pole Station
runway
South Pole
AMANDA-II

Antares


• 12 lines
• 25 storeys/line
• 3 PM / storey
• 885 PM
+
Instruments for
• positions of PM ~ O(10cm)
• orientation of PM
•Time calibration ~O(ns)
ANTARES
arXiv:1104.1607v1
Accepted in NIM-A
350 m
14.5 m
100 m
~70 m
45 km
Junction Box
2500m below sea level
© F. Montanet

Antares

Antares

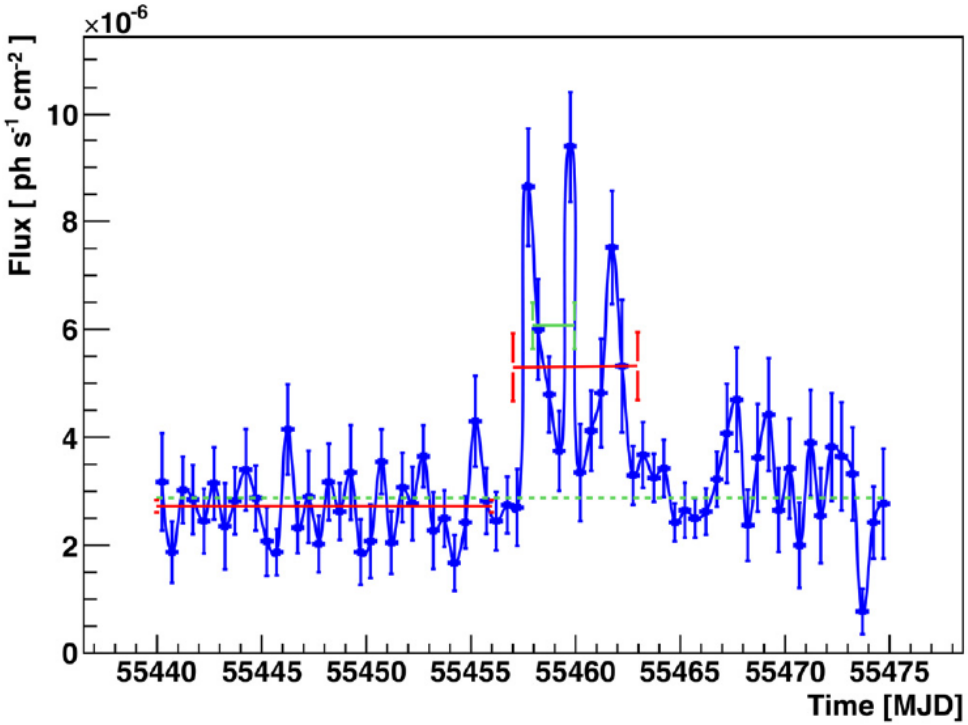
Antares

The ANTARES Collaboration

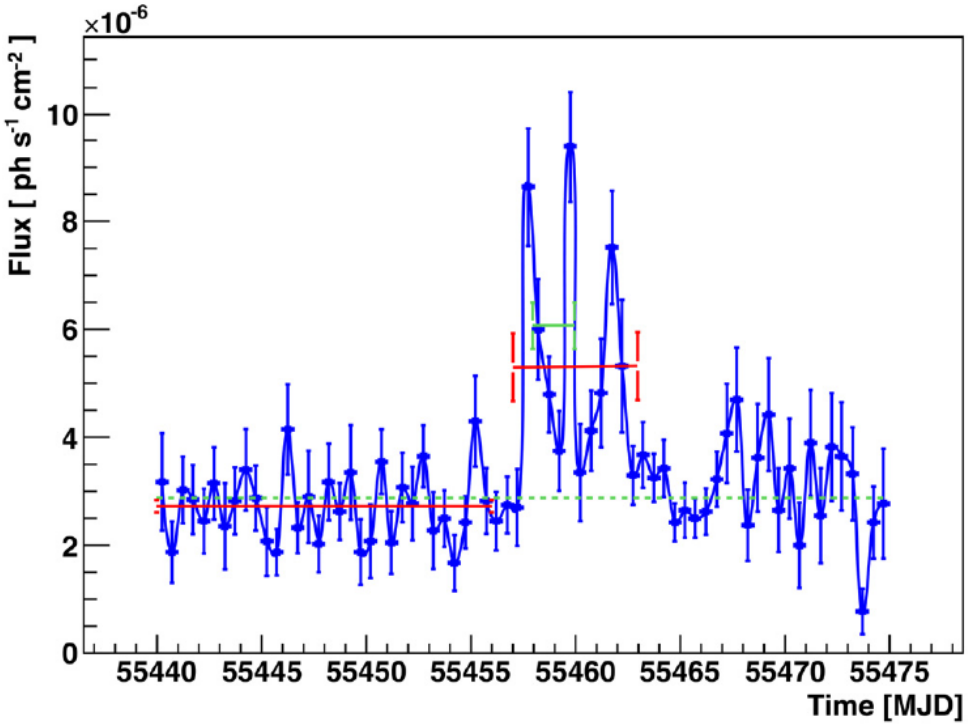
▶ ANTARES Site

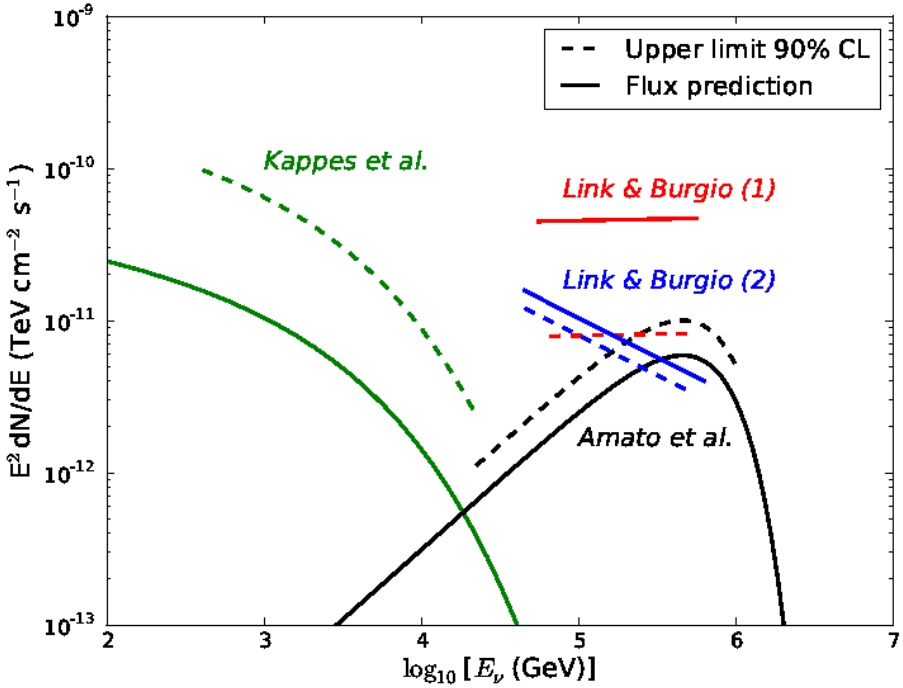
▶ ANTARES Publications

Time dependent searches : Flare of the Crab Nebula

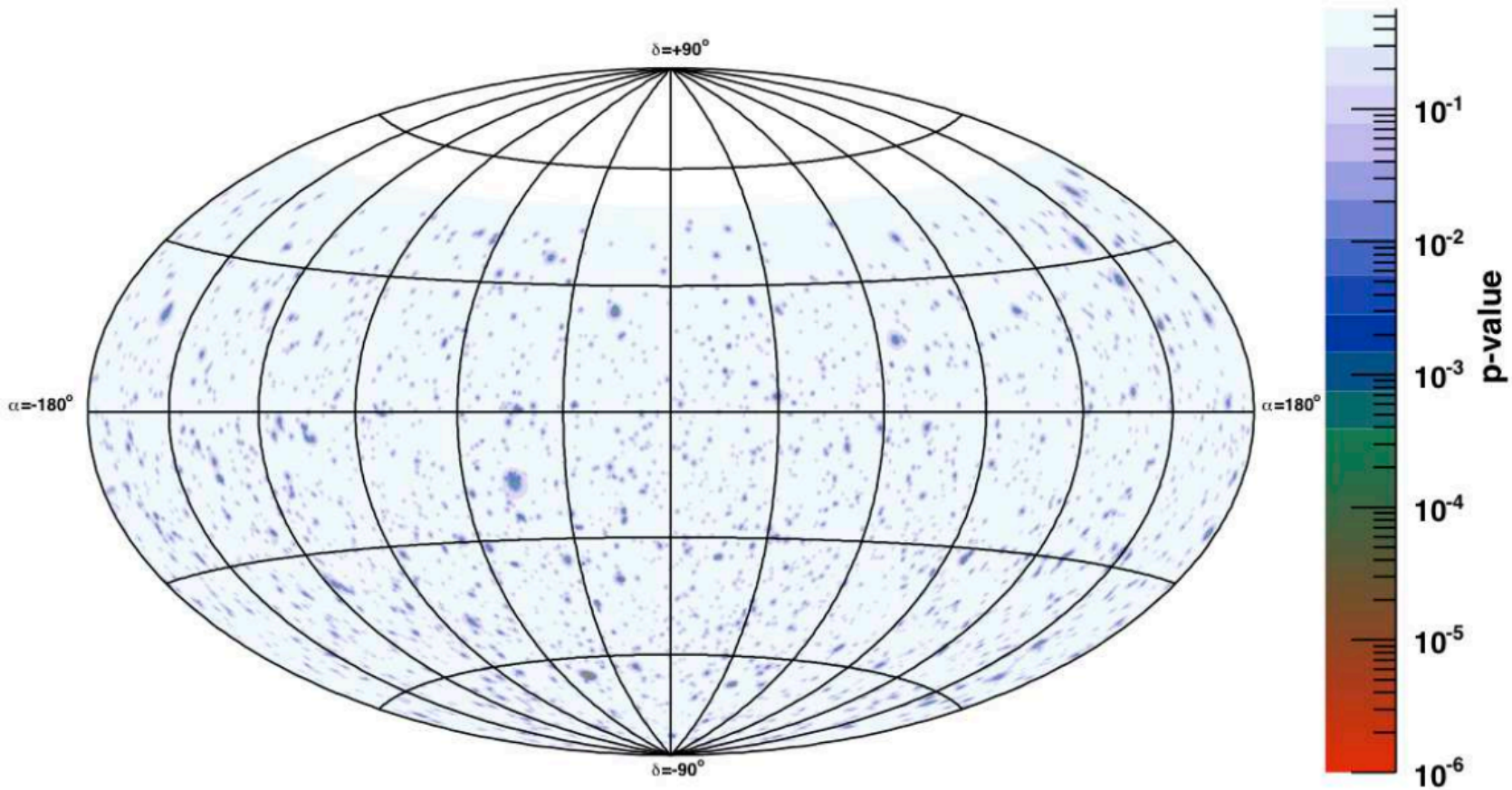


Time dependent searches : Flare of the Crab Nebula





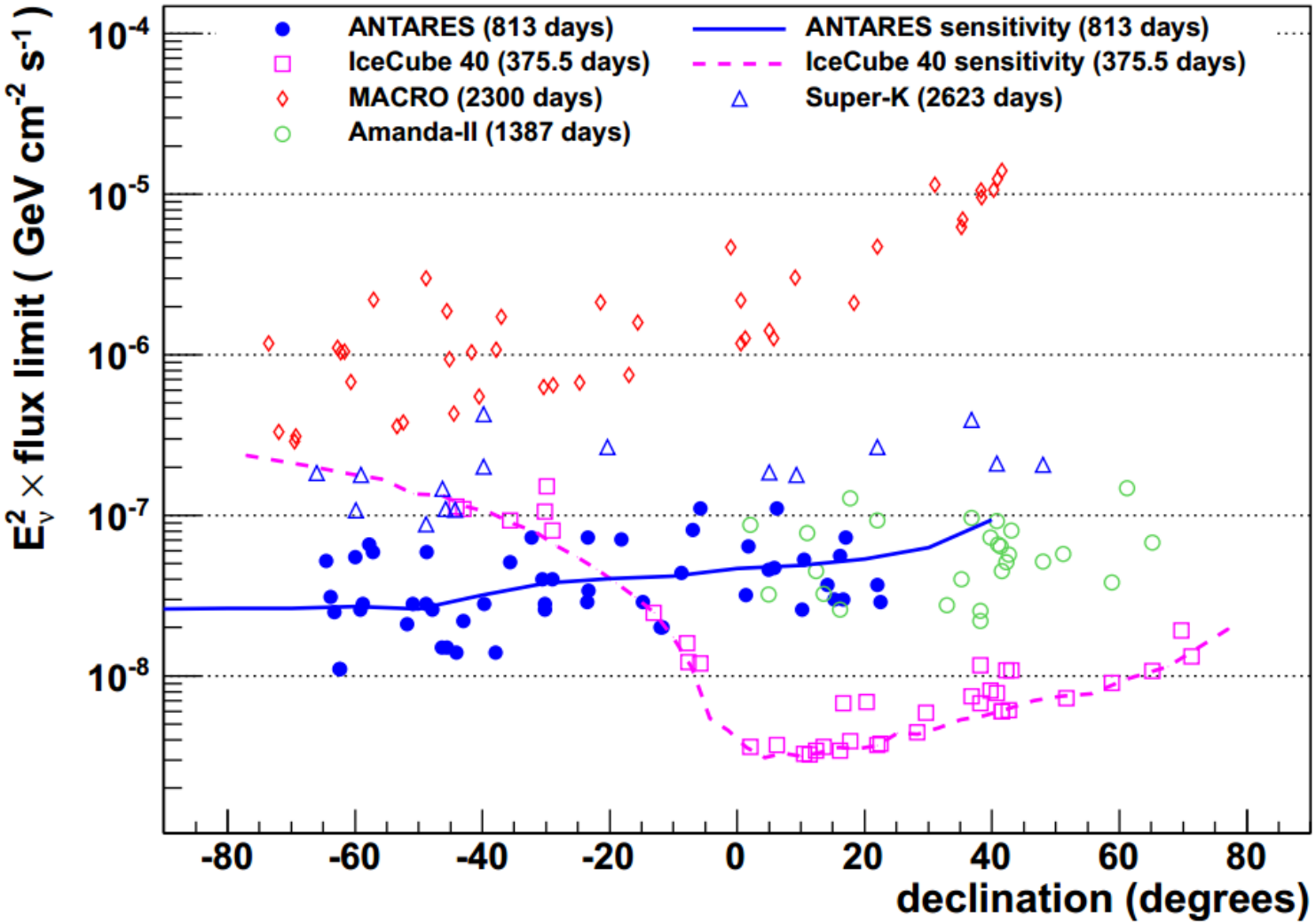
Time independent Point Source Searches



- ANTARES **Skymap of HEN events**

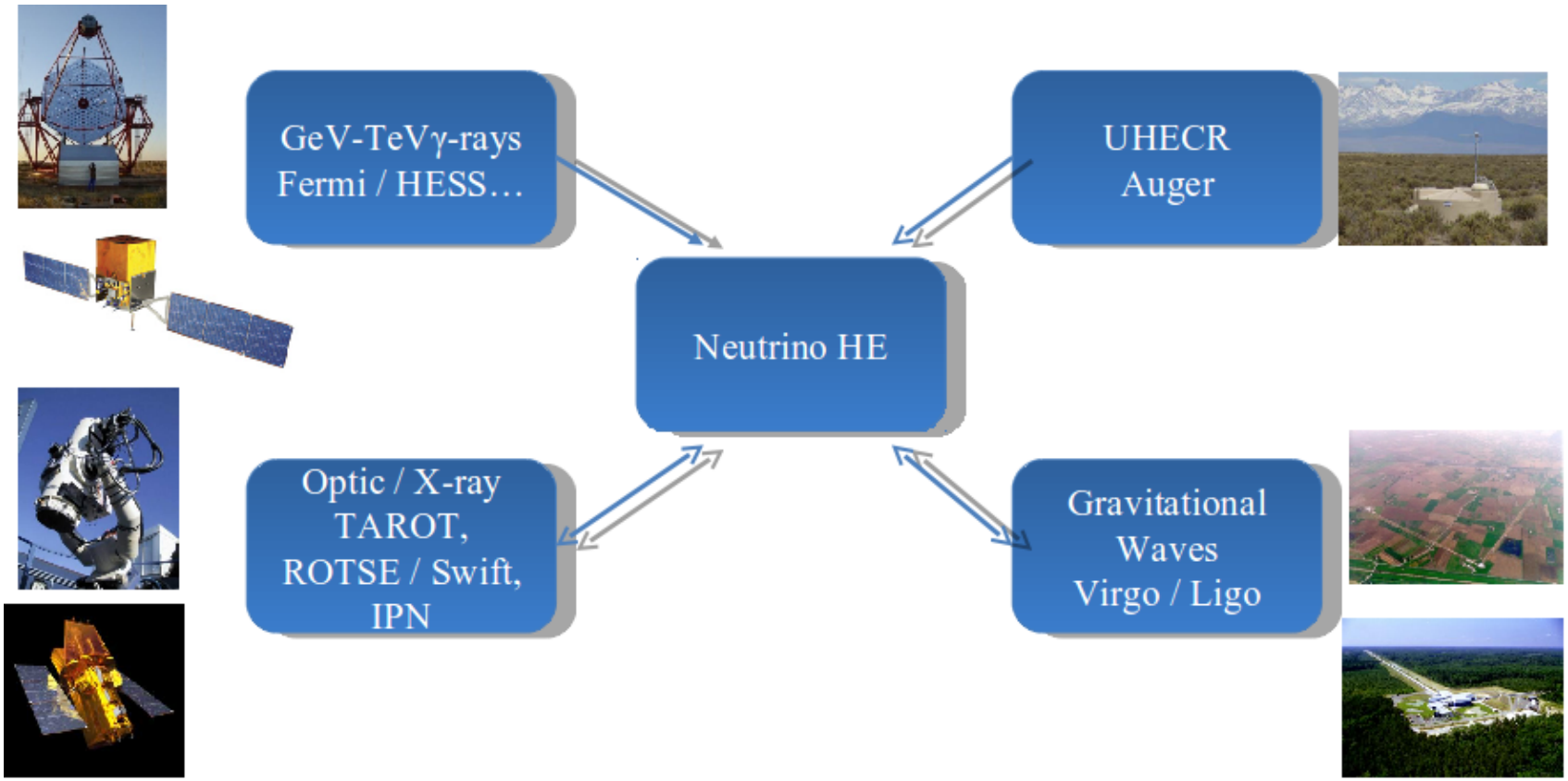
▸ Antares Point Sources Paper

Time independent Point Source Searches



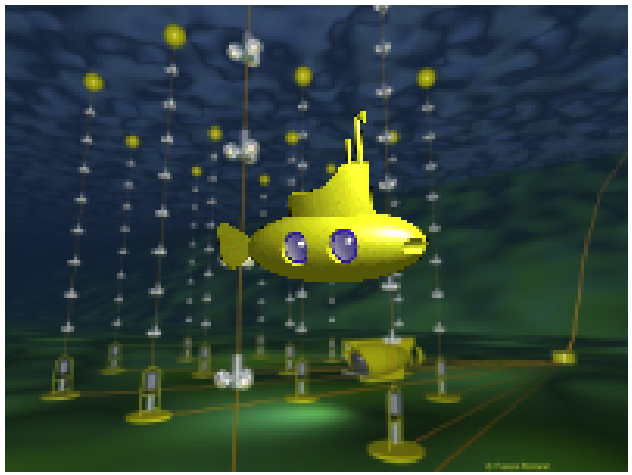
▸ Antares Point Sources Paper

Correlations with other messengers...

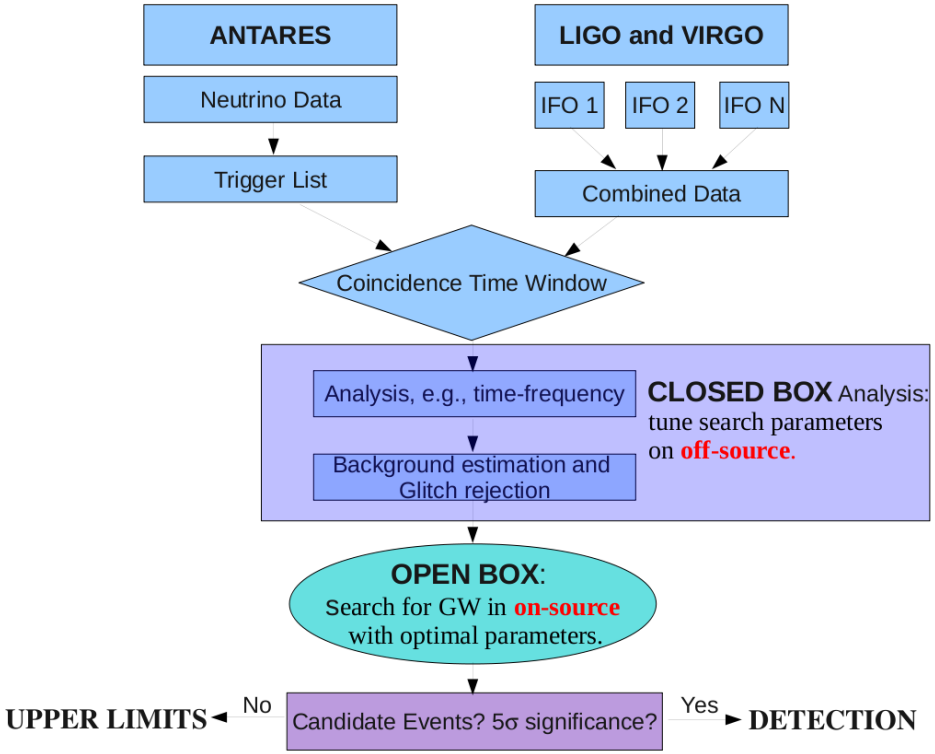


GW-HEN Joint Searches :

The GWHEN Analyses



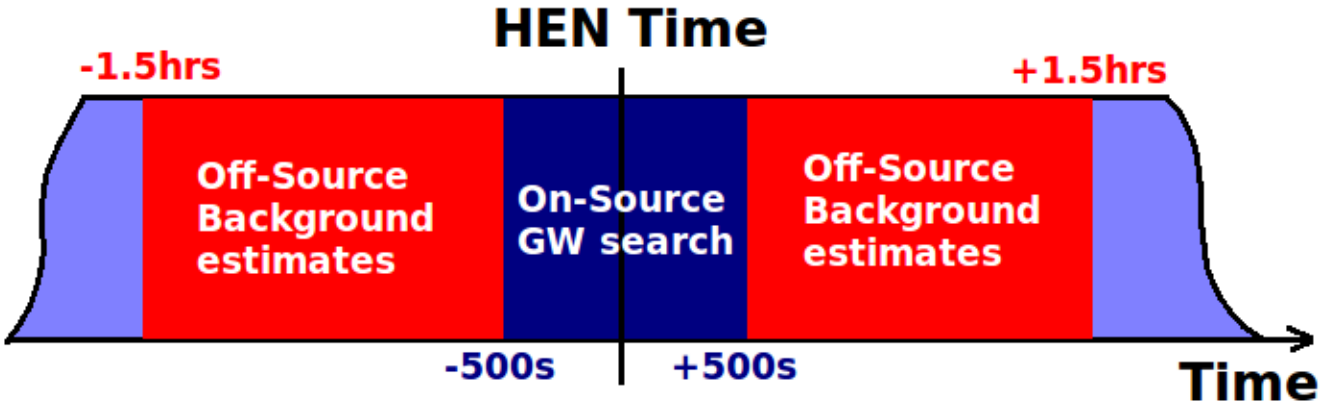
1st GWHEN search : Analysis Strategy



Analysis of 2007 data

- Sub-optimal detectors : no optimization
- **Time provided by HEN candidate**
- **Position by HEN direction ± Error Box**

1st GWHEN search : Analysis Strategy



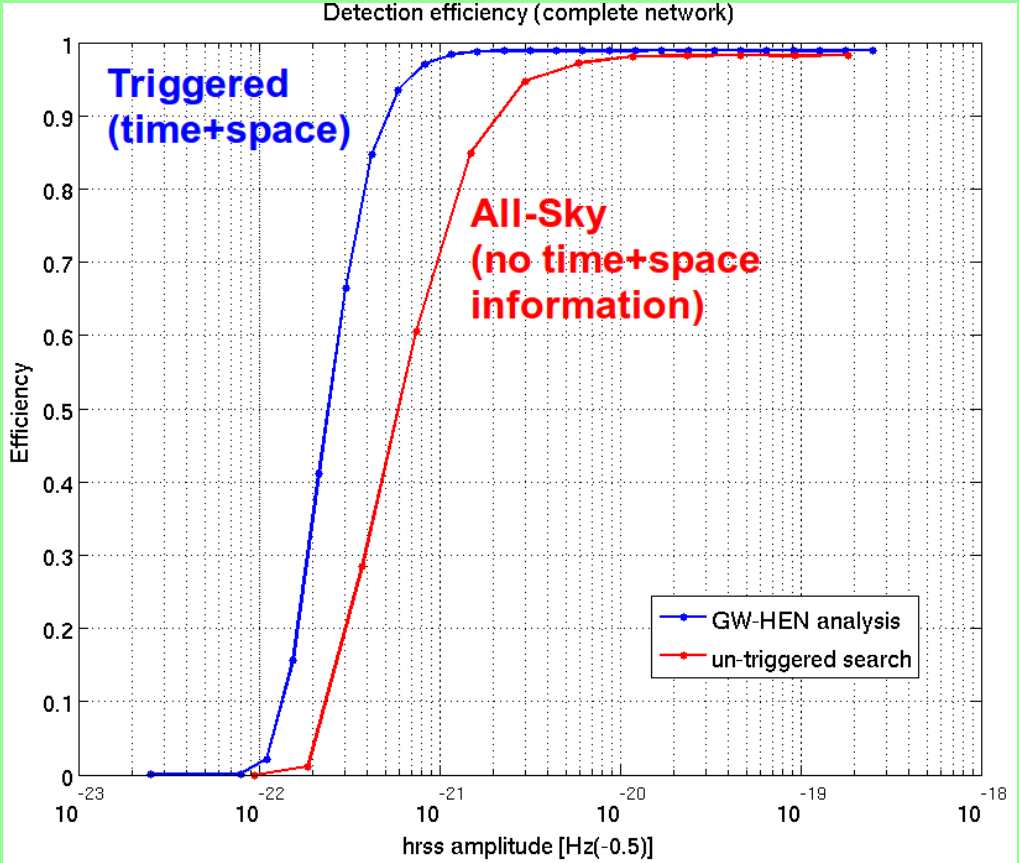
X-Pipeline GW Search

- **On-source** : Search for GW events $\pm 500s$ around each HEN event, within HEN box **(see later)**
- **Off-source** : all other data within $\pm 1.5hr$ of the HEN, divided into blocks of the same length as the on-source period - same IFO state [a]
  - Background estimates ($\sim$ 2000 before follow-up)
  - Significance of **on-source** compared to **off-source**
  - *Closed box analysis* : tuning of search parameters off-source

a. IFO = interferometer

Advantages of a triggered search

A Triggered search (time+space) is more efficient !



- **Smallest detectable signals**
- **Factor 2.5 (4) improvement** at the 50% (90%) level

GWHEN with 2007 data [5 line detector]

ANTARES-5 Lines + VSR1-S5 - End Sept. 2007

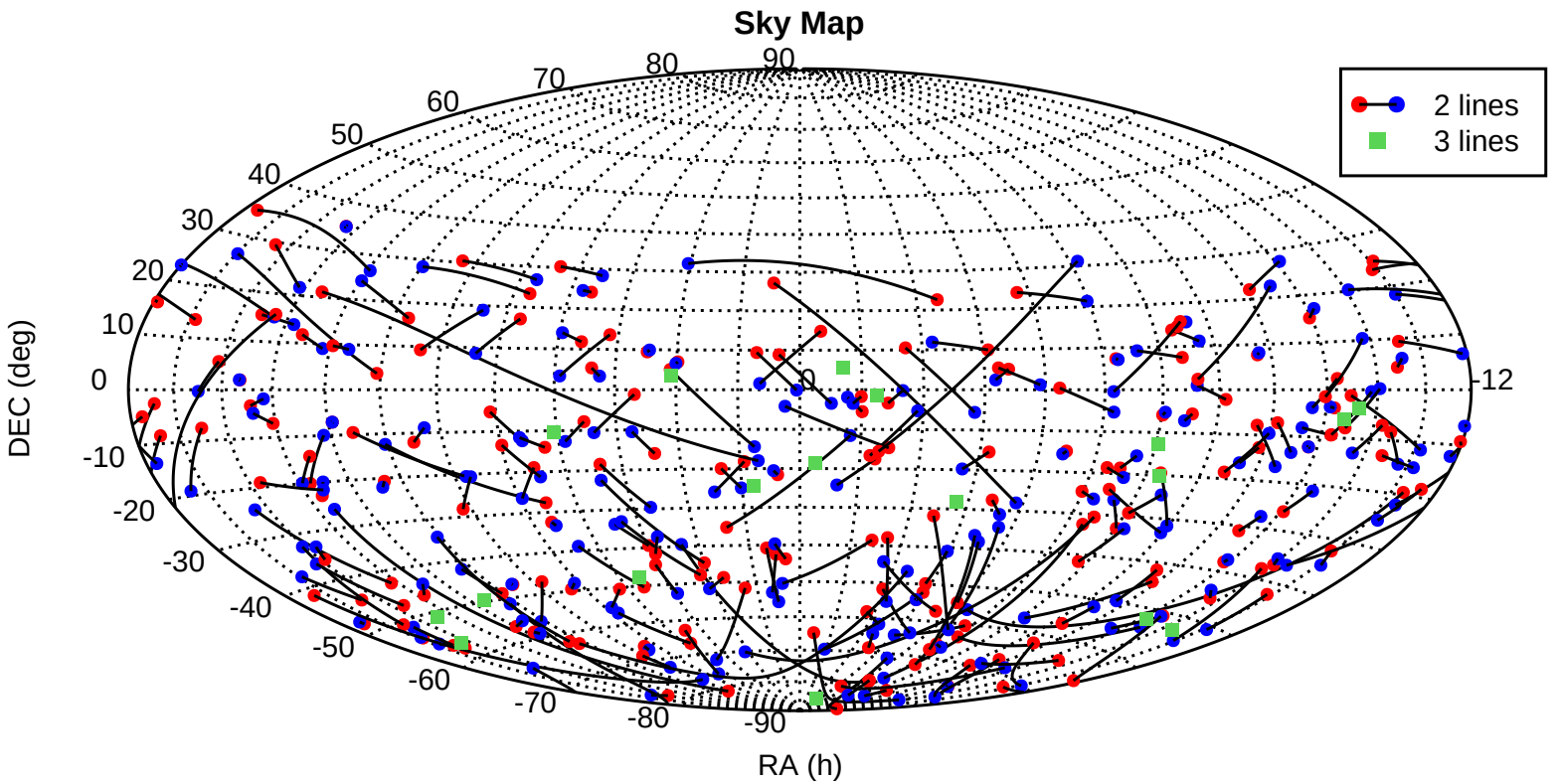
- 104 days of concomittant data taking
  - $\Rightarrow$ Point Sources Analysis selection cuts

HEN List for 2007

- 144 events reconstructed with 2 Lines
- 14 events with 3 Lines or more
  - $\Rightarrow$ 73% of the original HEN list have analyzable GW counterpart (more than 1 IFO)

GWHEN with 2007 data [5 line detector]

Sky Map of HEN Events



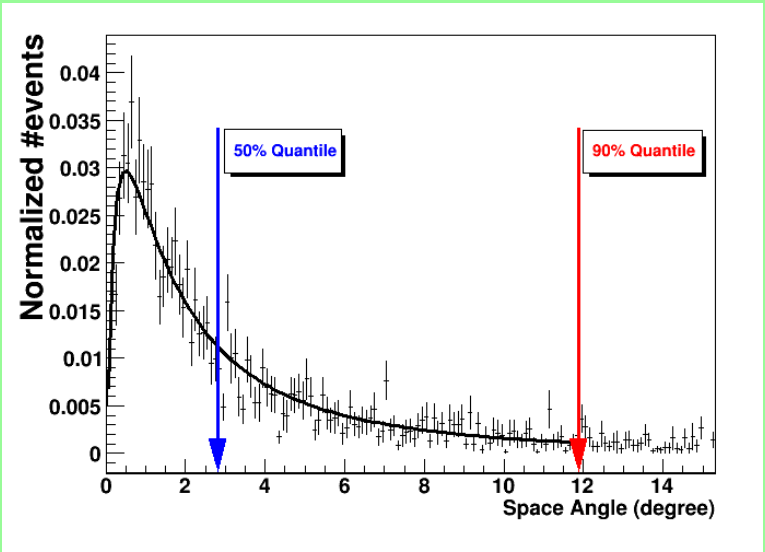
GWHEN with 2007 data [5 line detector]

HEN error box

- Angular accuracy depends on direction/declination and energy/number of hits
- Parametrization (log-normal) of $\theta^{3D}_{\text{true - reco.}}$ for each (dec, n_{hits})

$$f(x) = \frac{1}{\sqrt{2\pi}} \frac{e^{-\frac{\ln^2 \frac{x-\theta}{m}}{2\sigma^2}}}{(x-\theta)\sigma}$$

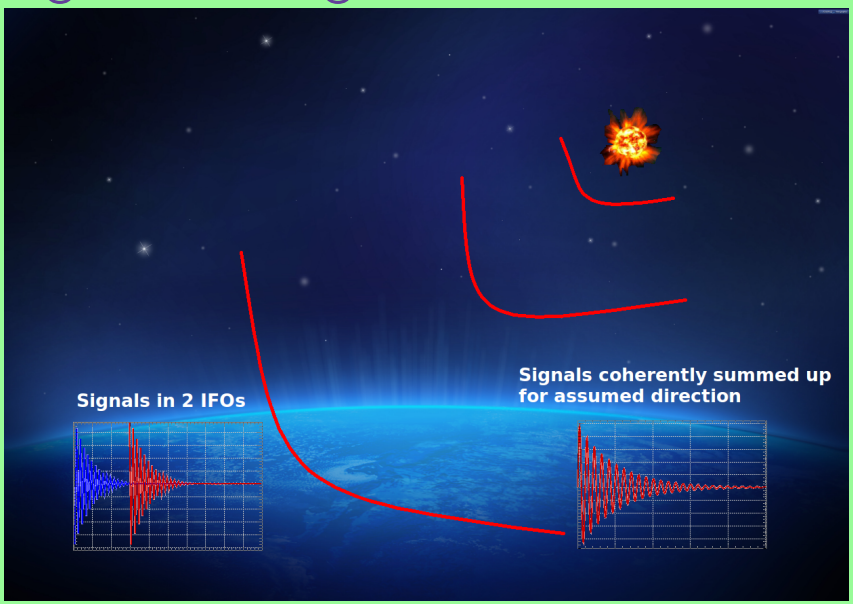
- Error Box for GW Search = 90% quantile of histogram



GWHEN with 2007 data [5 line detector]

HEN error box used in GW search

- Error box divided in a grid of ~ 100 pixels
- Assume known direction of signals $\Rightarrow$ known delays between IFOs
- Hanford +Livingstone +Virgo data streams *coherently* combined

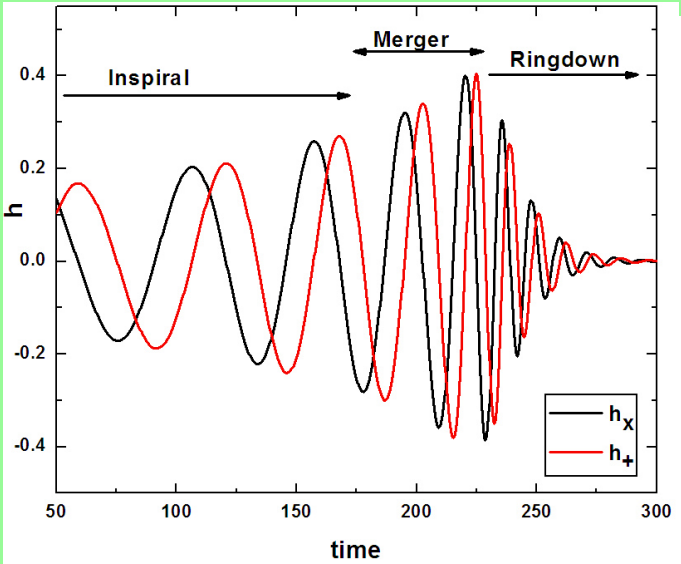


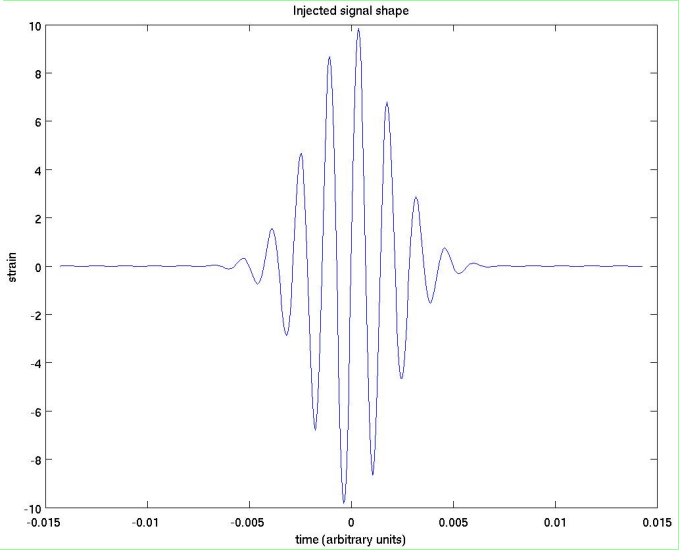
- **High Cut-off Frequency = 500Hz** for all events
  - $\Rightarrow$ Additional search up to 2kHz for higher energy 3 Line events
  - $\Rightarrow$ Also, lesser muon contamination

GW Exclusion distances and Binomial Tests

Final result : GW Exclusion Distances

- Injected Waveform to obtain amplitude upper limits ⇒ exclusion distances
- Binary Mergers : NS+NS, NS+BH ⇒ $D_{90\%} \sim 10$ Mpc
- Collapse : Sine-Gaussian
  - ⇒ LF : $D_{90\%} \sim 10$ Mpc
  - ⇒ HF : $D_{90\%} \sim 1$ Mpc





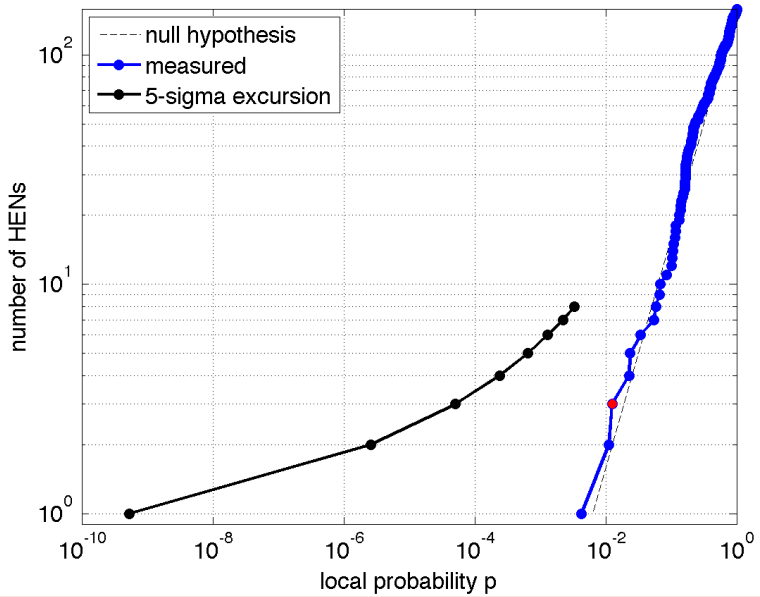
GW Exclusion distances and Binomial Tests

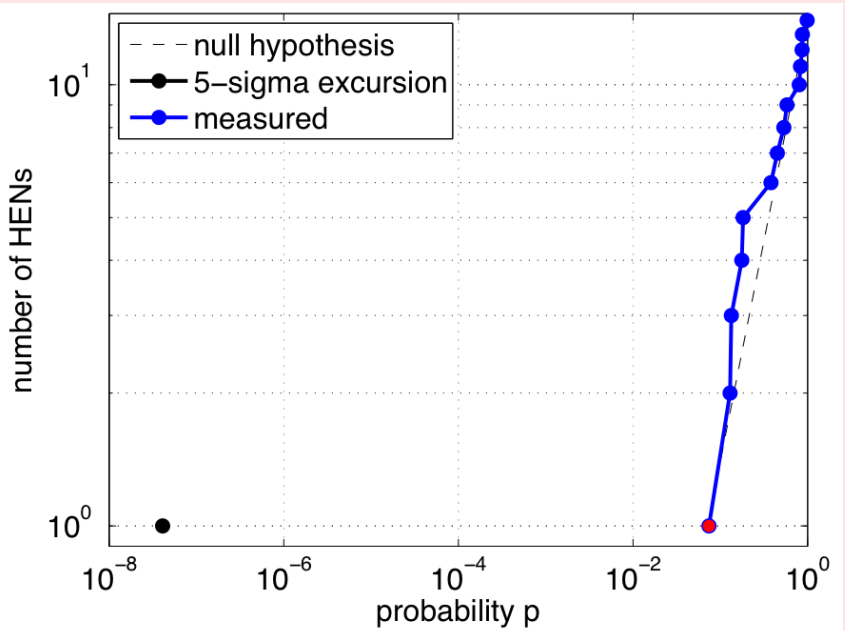
Final result : Binomial Test

- Binomial test : $P_{N,p} = \frac{N!}{(N-n)!n!} p^n (1-p)^{N-n}$
- Probability for getting n or more events at least as significant as p_n
- p_n probabilities ordered in increasing values (p_1 is the loudest event)
- Test association of 5% of the highest GW p-values with HEN
  - 8 over 158 HEN (2L+3L) in Low Frequency Search
  - 1 over 14 HEN (3L) in High Frequency Search

GW Exclusion distances and Binomial Tests

Results for Binomial Tests - LF and HF





- Test association of 5% of the highest GW p-values with HEN
- No significant association : post-trial significance of largest deviations $\sim 66\%$

Derivation of the Horizons

No coincident detection $\Rightarrow$ $N_{\mathrm{GWHEN}} \leq 2.3$ (90% C.L.)

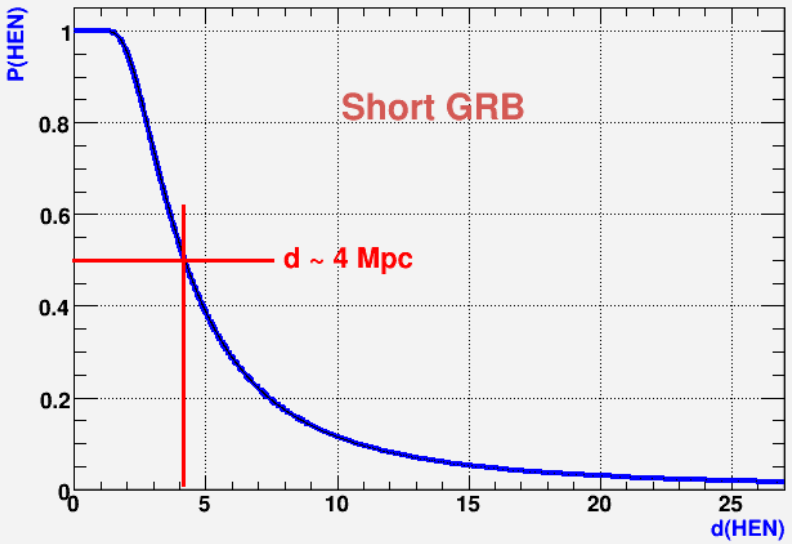
- $N_{\mathrm{GWHEN}} = \rho_{\mathrm{GWHEN}} V_{\mathrm{GWHEN}} T_{\mathrm{obs}}$, with $T_{\mathrm{obs}} \sim 104$ days
  - $\Rightarrow$ $\rho_{\mathbf{GWHEN}} \leq \frac{2.3}{V_{\mathbf{GWHEN}} T_{\mathbf{obs}}}$
- ρ_{GWHEN} : density of objects with collapse/coalescence (GW) followed by jet (HEN) within $\pm 500s$ in local universe
  - $\Rightarrow$ Test of **non-constrained** *gravitational* origin of *jet* formation
- V_{GWHEN} effective volume of the search, which depends on Horizon
- GWHEN Horizon $d_{\mathrm{horizon}} = min\left(d_{\mathrm{max}}^{\mathrm{HEN}}, d_{\mathrm{max}}^{\mathrm{GW}}\right)$
  - $\Rightarrow$ $d_{\mathrm{max}}^{\mathrm{HEN}}$ typical distance for e.g. short GRB (SGRB)/long GRB (LGRB)
  - $\Rightarrow$ $d_{\mathrm{max}}^{\mathrm{GW}}$ typical distance for e.g. NS-NS or NS-BH coalescence

- $d_{\mathrm{max}}^{\mathrm{GW}} \approx 14$ Mpc for SGRB (mergers), 22 Mpc for LGRB (collapse)
- HEN Horizon distances :
  - $\Rightarrow$ $d_{\mathrm{max}}^{\mathrm{HEN}} \approx 4$ Mpc for SGRB, $d_{\mathrm{max}}^{\mathrm{HEN}} \approx 12$ Mpc for LGRB
- $P_{\mathrm{GWHEN}}(r) = P_{\mathrm{GW}}(r) \times P_{\mathrm{HEN}}(r)$ detection efficiency

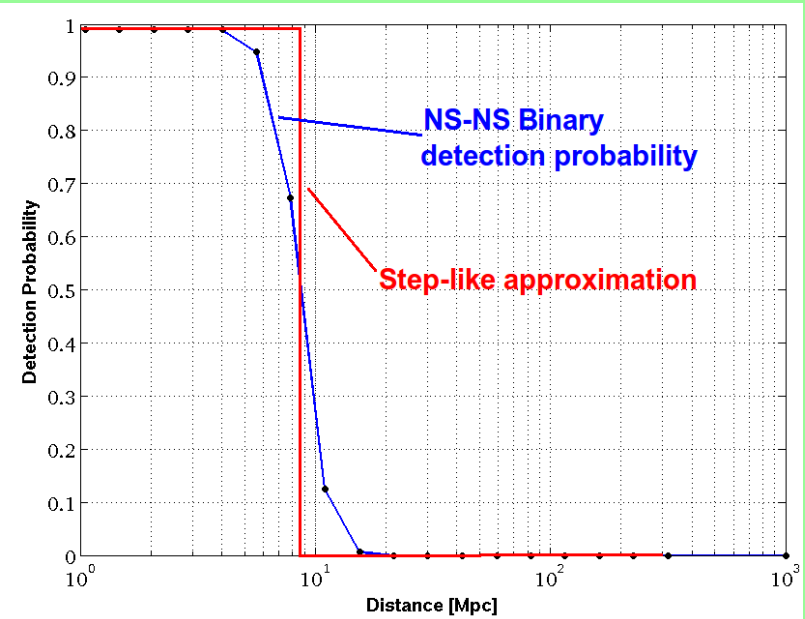
Effective volume of the search

V_{GWHEN}

- $V_{\mathrm{GWHEN}} = 2\pi \int_0^{\infty} P_{\mathrm{GWHEN}}(r) r^2 dr \times \int_{-\pi/2}^{\pi/2} v(\delta) \cos\delta d\delta$
- $V_{\mathrm{GWHEN}}^{\mathrm{SGRB}} \approx 1.34 \times 10^2$ Mpc^3, $V_{\mathrm{GWHEN}}^{\mathrm{LGRB}} \approx 8.42 \times 10^3$ Mpc^3



HEN Detection Prob.



GW Detection Prob.

Density limits for SGRB and LGRB

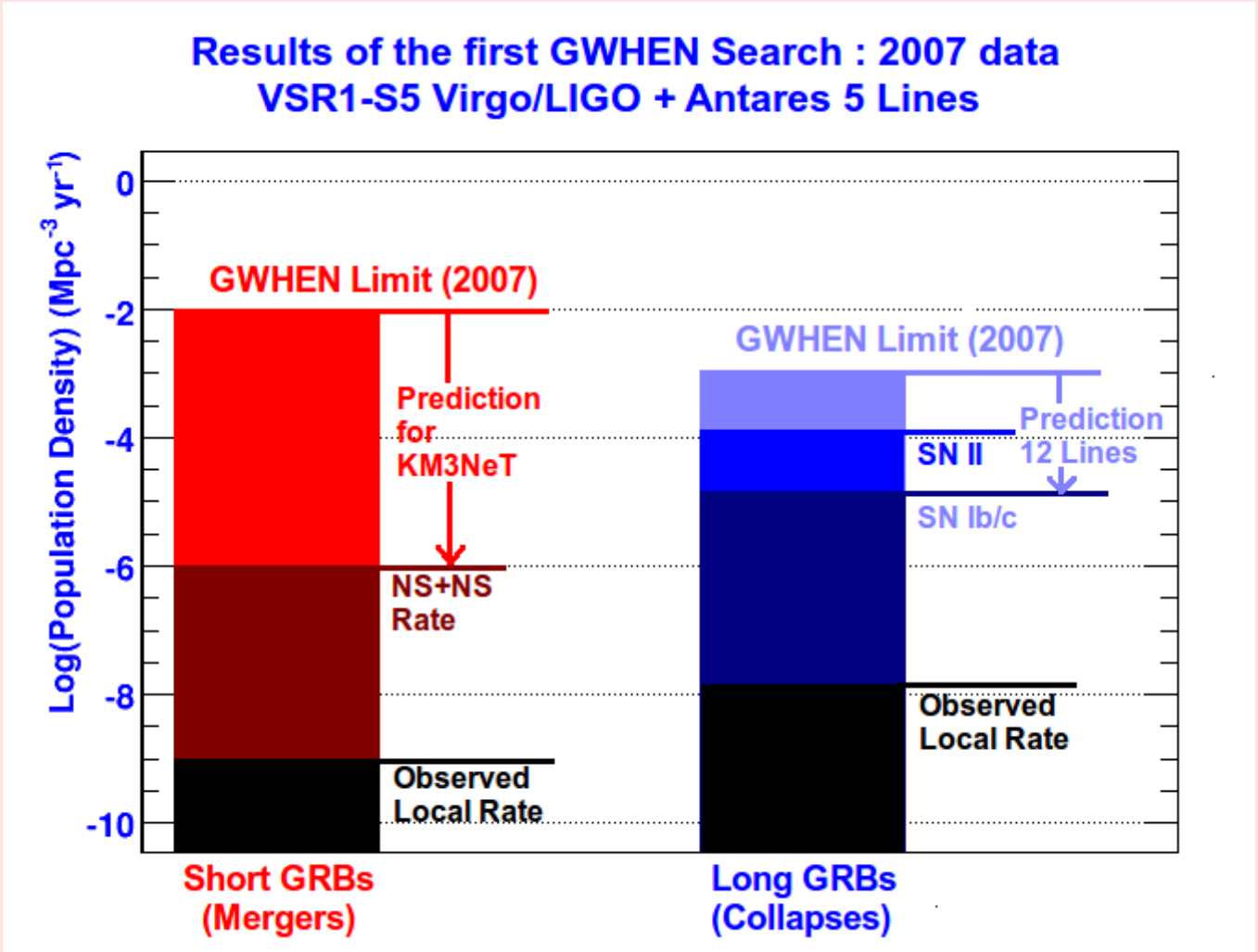
ρ_{GWHEN} for SGRB and LGRB

- $\rho^{\mathbf{SGRB}}_{\mathbf{GWHEN}} = 1.1 \times 10^{-2} / \mathbf{Mpc}^3 / \mathbf{yr}$
  $\Rightarrow$ to be compared with **typical merger rates**...
- $\rho^{\mathbf{LGRB}}_{\mathbf{GWHEN}} = 1.0 \times 10^{-3} / \mathbf{Mpc}^3 / \mathbf{yr}$
  $\Rightarrow$ to be compared with **typical star collapse rates**...

$\Rightarrow$ **First limits on density of Mergers/Collapses (GW) followed by jet pointing towards Earth (HEN)**

Limits vs estimated rates

Summary



1st GWHEN Paper

A First Search for coincident Gravitational Waves and High Energy Neutrinos using LIGO, VIRGO and ANTARES data from 2007

The ANTARES Collaboration, the LIGO Scientific Collaboration and the VIRGO Collaboration

ArXiV :1205.3018

- Public page with tables of HEN candidate events, figures, outreach

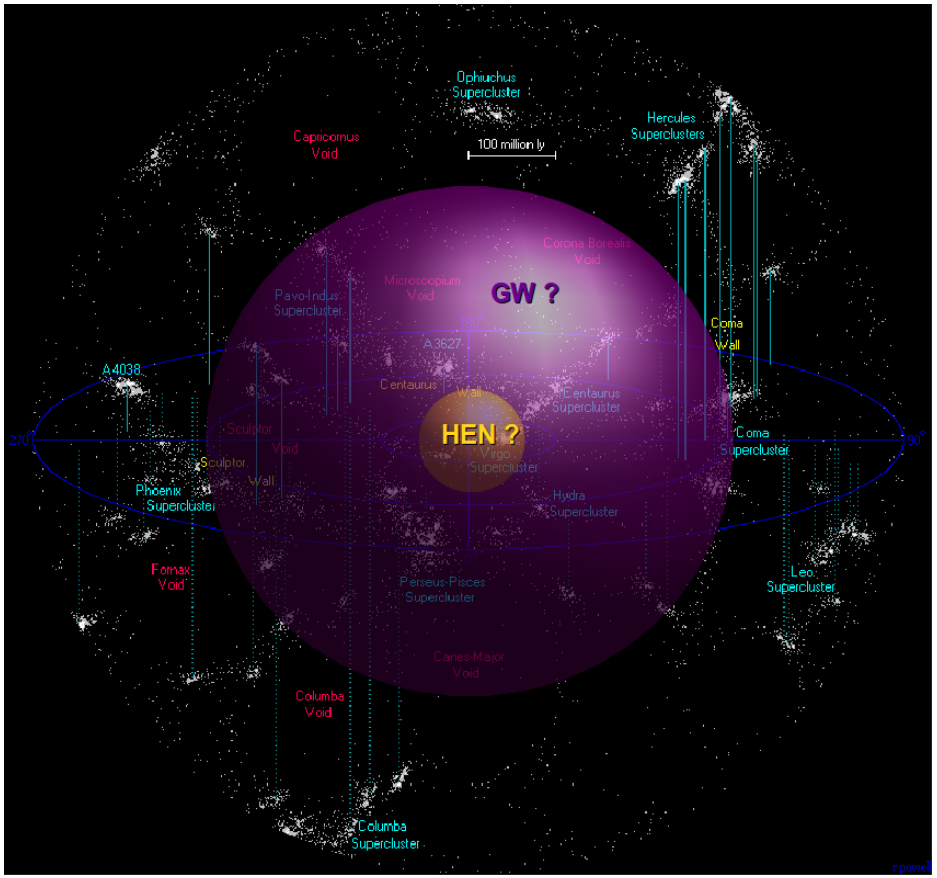
⇒ https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=p1200006

ANTARES 12 lines + VIRGO/LIGO [Ongoing]

12 Line+VSR2/S6 - Jul. 2009, Oct. 2010

- 84/45 days with 2/3 interferometers
- New **GW Software (suitable for joint simulations)**
- New **HEN reconstruction strategy (smaller error boxes)**

ANTARES 12 lines + VIRGO/LIGO [Ongoing]



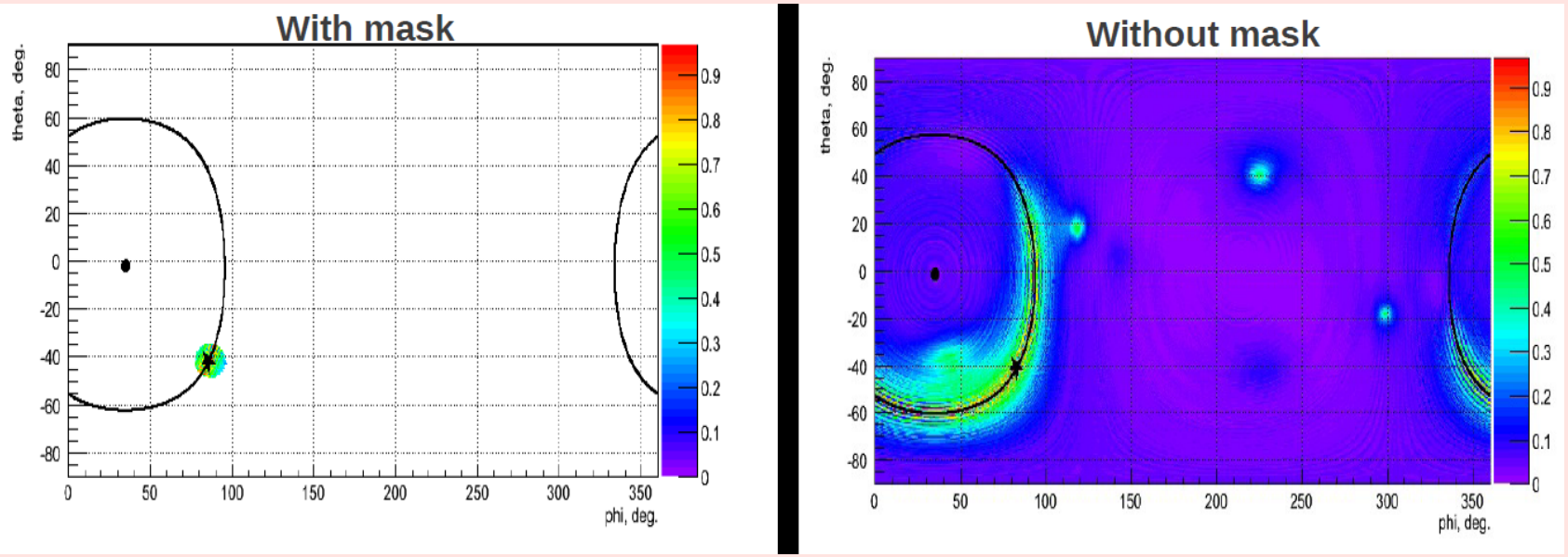
Efficiency limited by *weakest experiment*

⇒ *Equalization/optimization* of Horizons necessary...

⇒ Depends on considered Model : GW frequency, HEN spectral index...

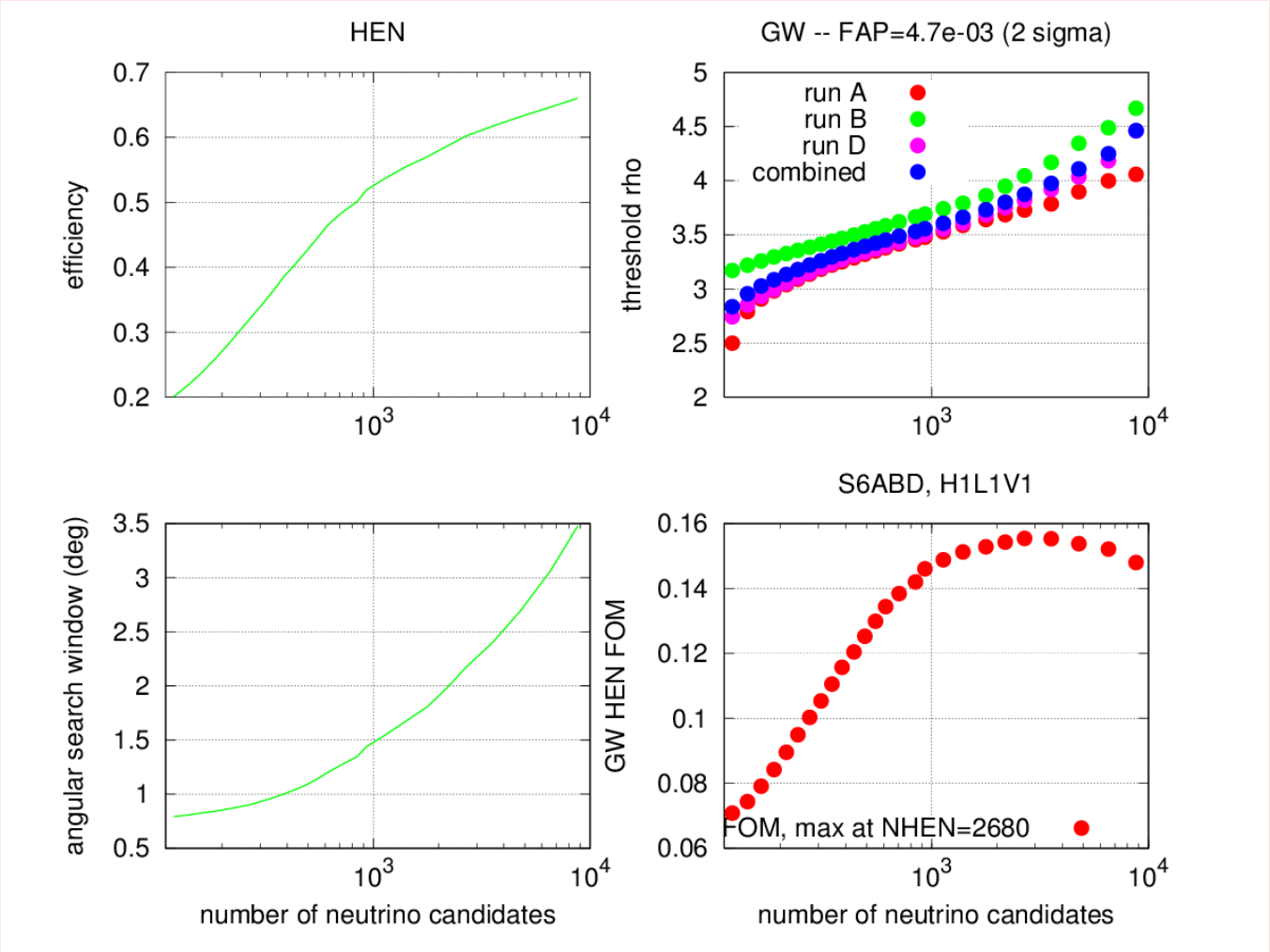
ANTARES 12 lines + VIRGO/LIGO [Ongoing]

A new optimized analysis



ANTARES 12 lines + VIRGO/LIGO [Ongoing]

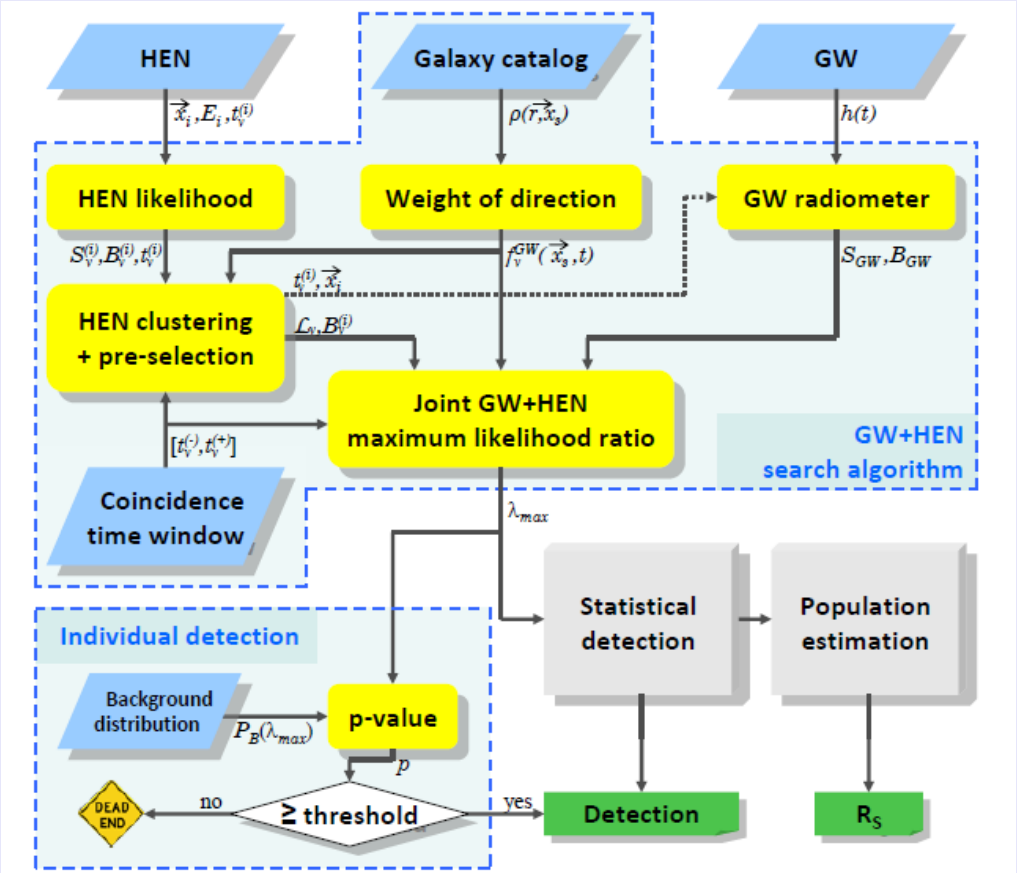
A new optimized analysis



ICECUBE-VIRGO/LIGO [Ongoing]

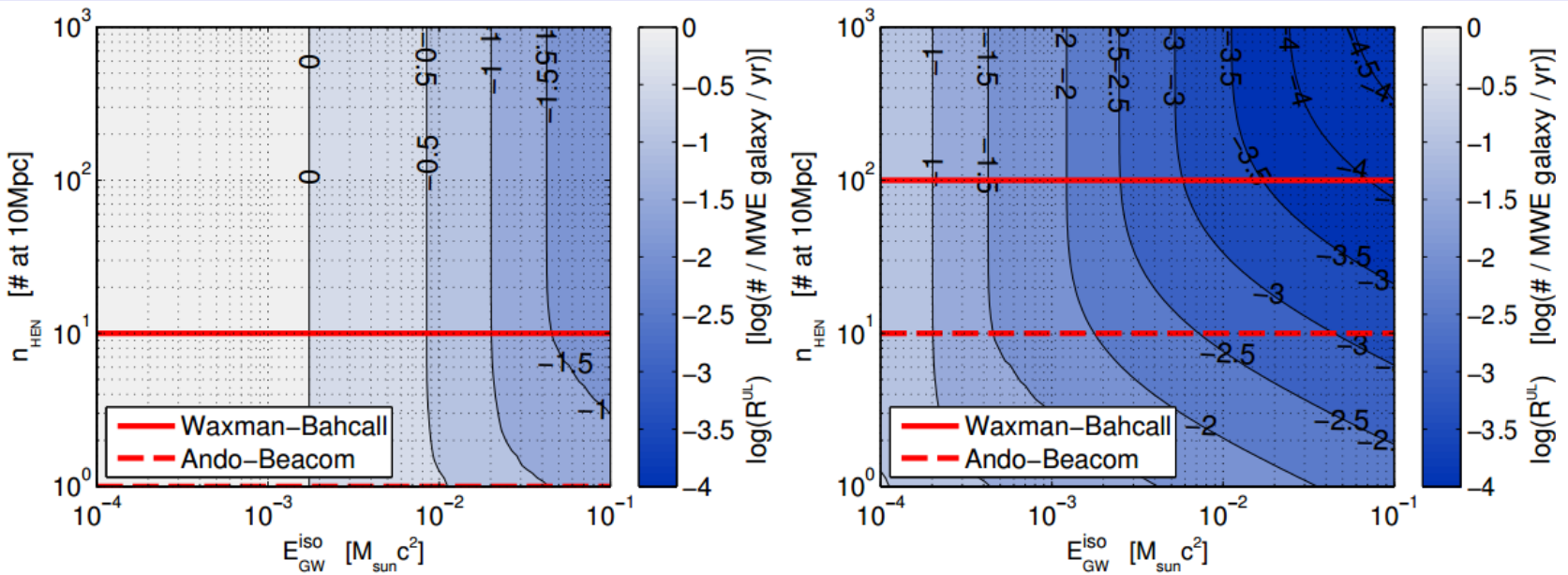
IC22 + VSR1/S5 in 2007

- $\sim$ 100 days of concomittant data, 1200 HEN candidates
- Re-weighting of events wrt Galaxy Catalogue



IceCube-Virgo/LIGO [Ongoing]

IC22 + VSR1/S5 in 2007



IC22 - Virgo/LIGO IC86 - Advanced IFOs

▸ B. Baret et. al, Physical Review D 85 (2012) 103004

Future analyses

Other possible analyses ?

- Joint VIRGO-**GEO** run in 2011 - AstroWatch (GEO) after that
- ...and prepare for **Advanced Interferometers**