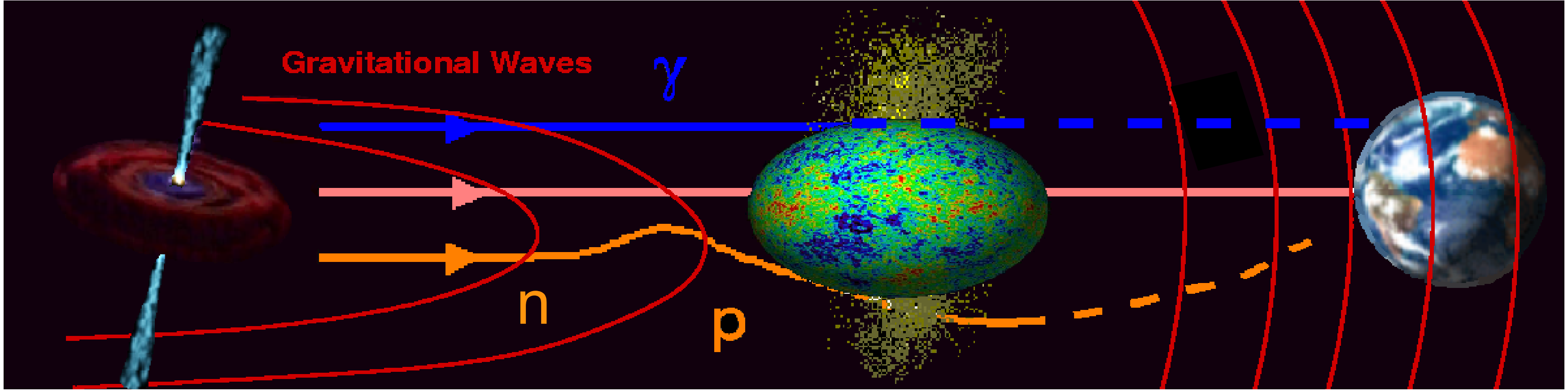
ANTARES
and the status of
High-energy Neutrino Astronomy

Véronique Van Elewyck
(APC & Université Paris Diderot)

- Neutrino telescopes: why, how and where
- Limits on astrophysical and GZK neutrino fluxes
- Atmospheric neutrinos
- Atmospheric muons and link with cosmic rays

Neutrino astronomy: why ?



- **Long-range,weakly-interacting messengers:**
  - no interactions with ambient matter (ISM, molecular clouds,...) nor radiation (CMB/IR/radio backgrounds),
  - no deflection by magnetic fields

→ neutrinos travel cosmological distances and point back to their source

- **Deep-source messengers**:
  - escape also from optically thick media
  - provide complementary information to γ/cosmic rays

→ discovery potential for hidden sources

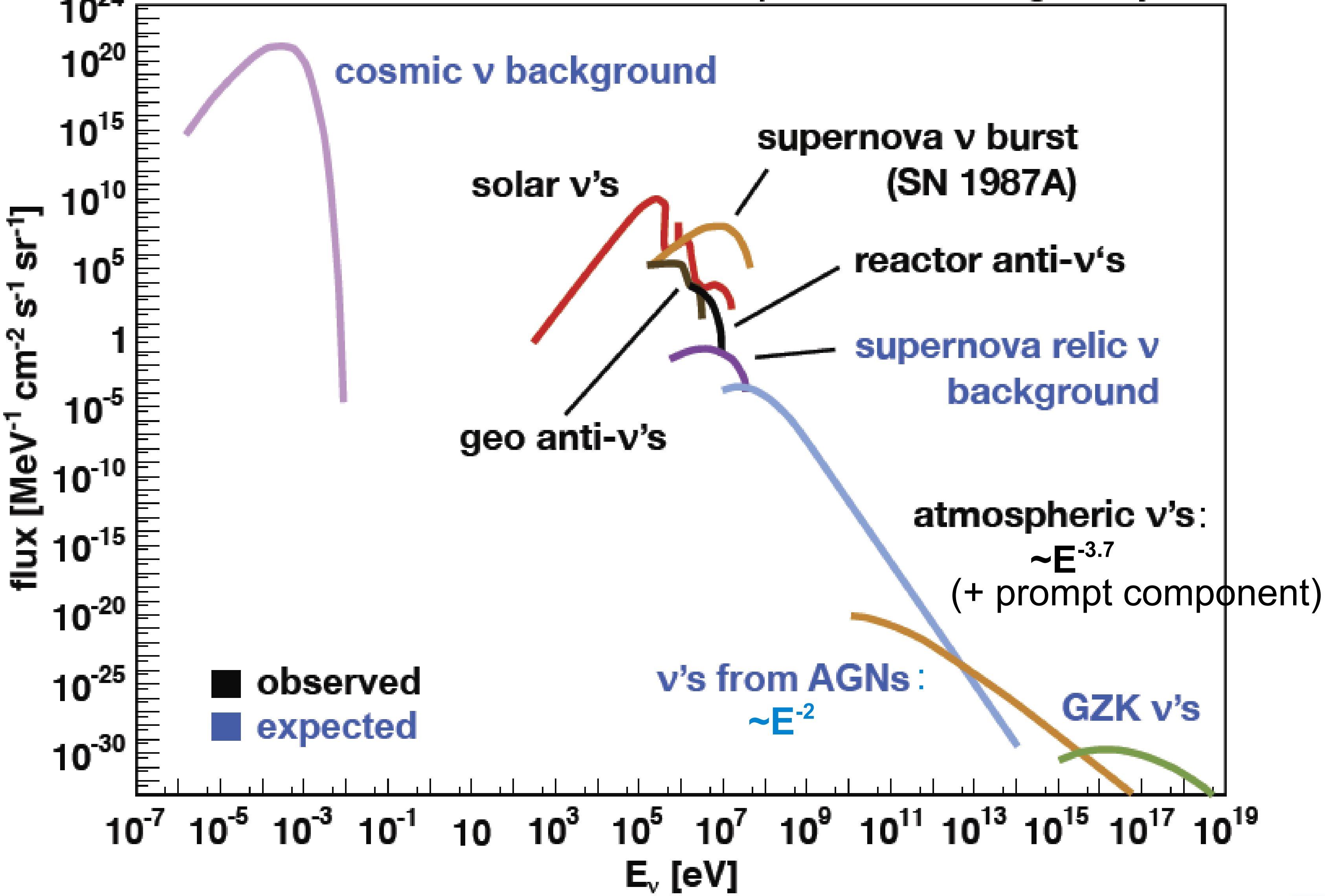
- **Smoking gun for hadronic acceleration in the sources:**

$$p + p(\gamma) \rightarrow \pi^{\pm} + X$$
$$\hookrightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_\mu + \nu_e$$

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

at source at Earth

Neutrino astronomy: why ?



reproduced from Xing, Nusky 2011

Neutrino astronomy: why ?

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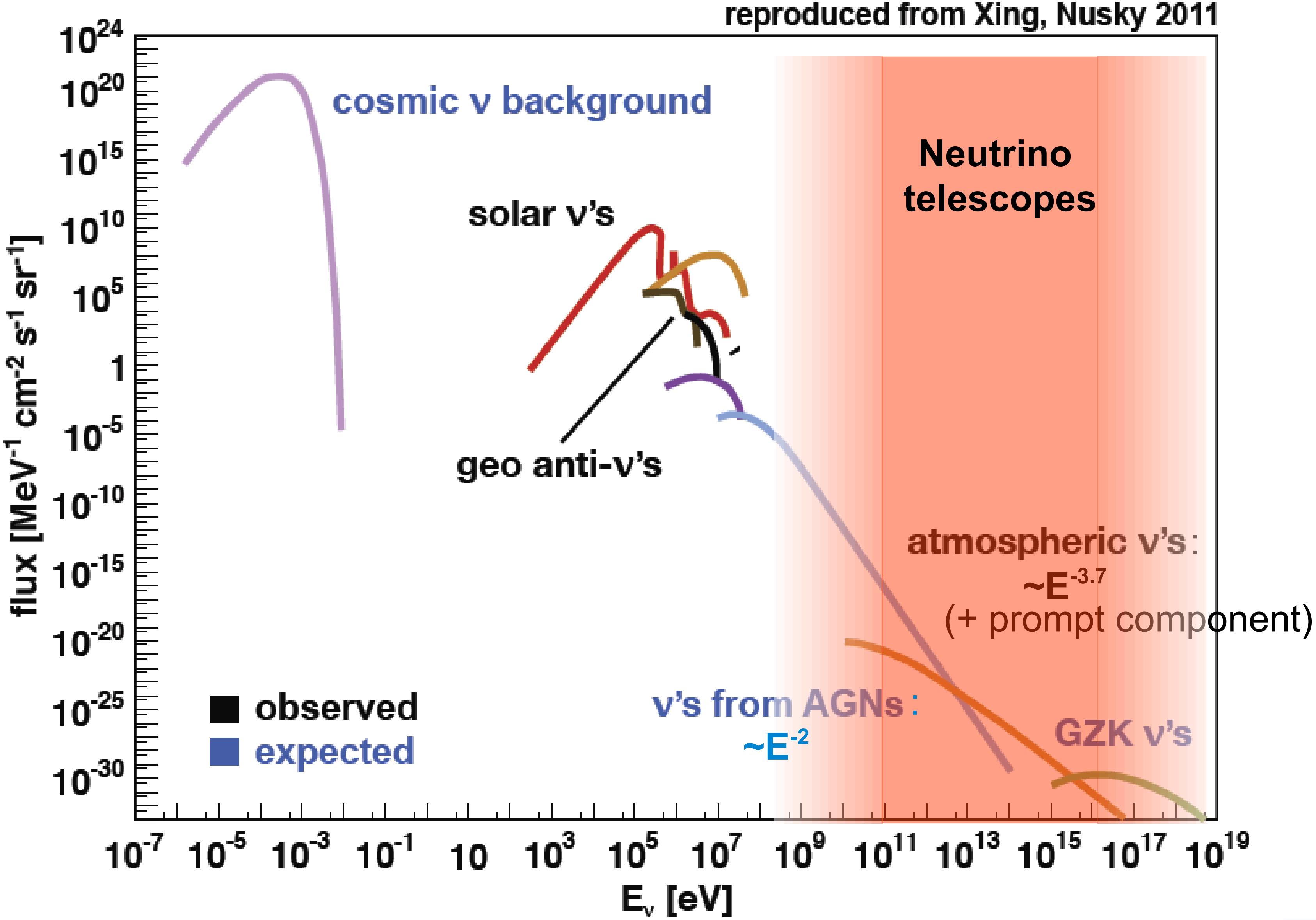
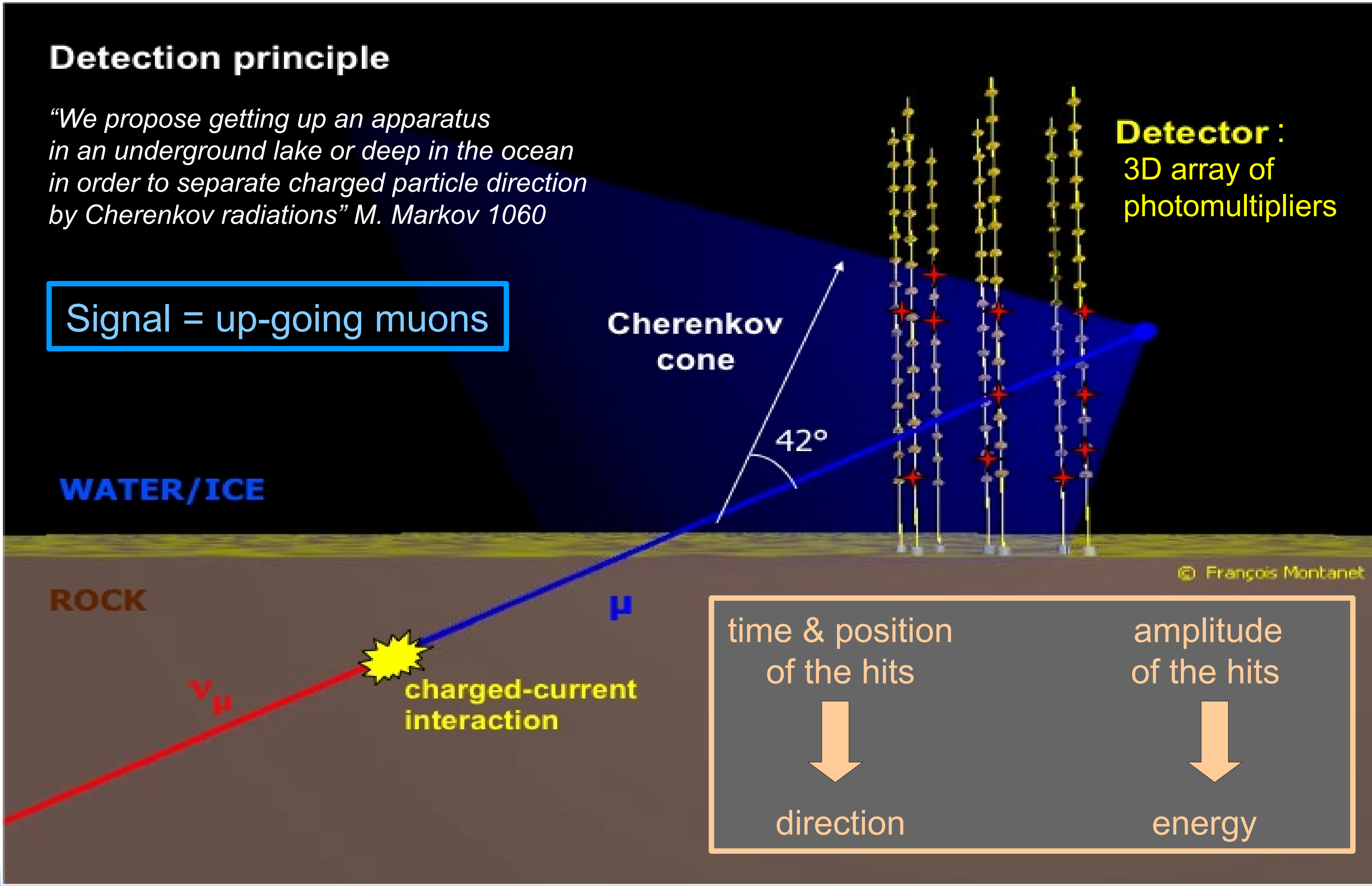


Neutrino astronomy: how ?



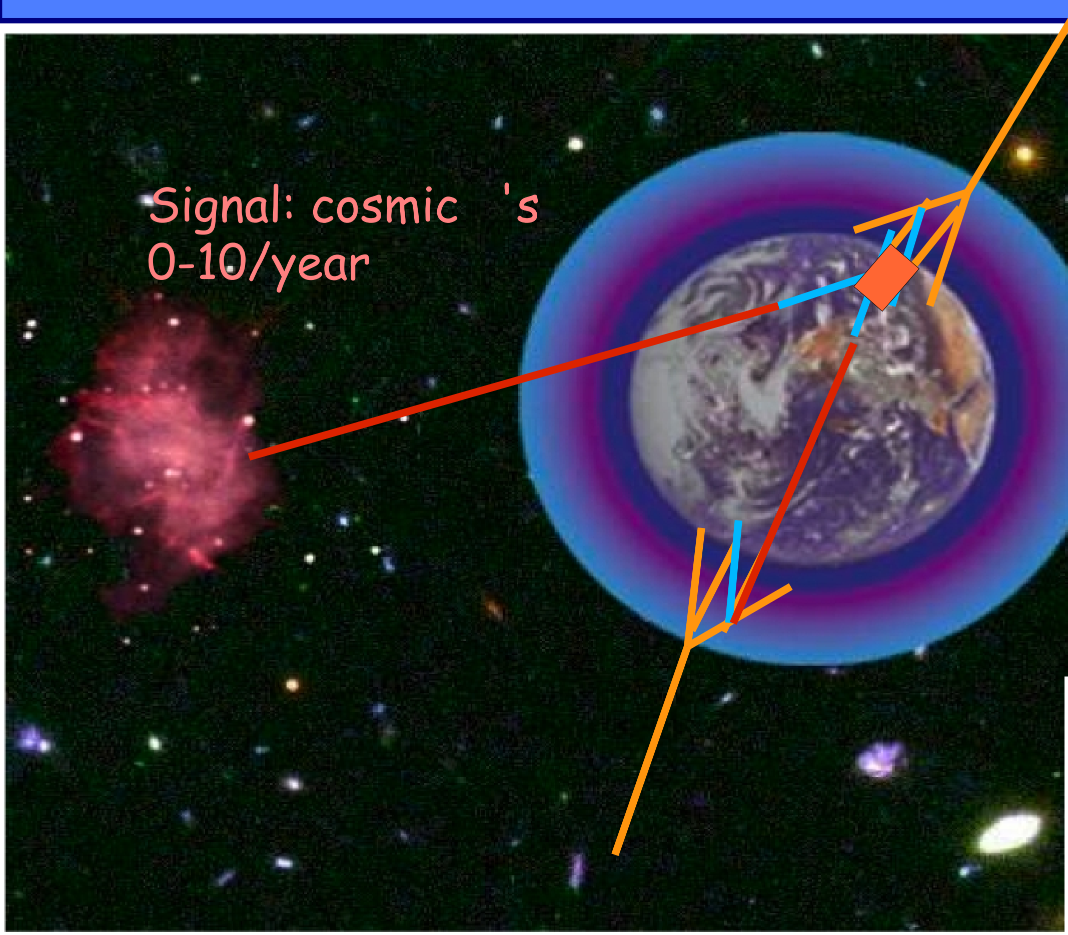
“We propose getting up an apparatus in an underground lake or deep in the ocean in order to separate charged particle direction by Cherenkov radiations” M. Markov 1060

Signal = up-going muons

Detector :
3D array of photomultipliers

time & position of the hits	amplitude of the hits
⇩	⇩
direction	energy

Neutrino astronomy: how ?



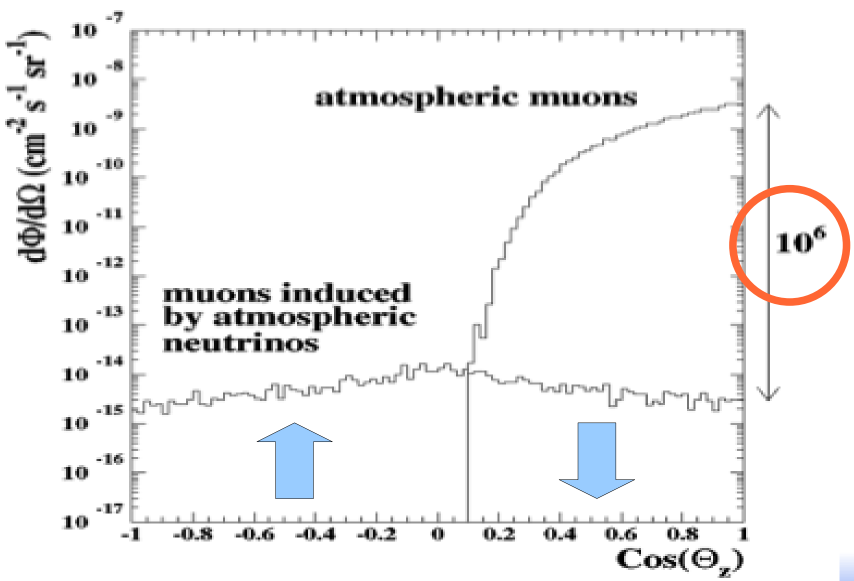
Physical backgrounds:

- Atmospheric muons:

~ 10^8/yr – 10^{10}/yr in detectors
mostly down-going BUT can be misreconstructed as up-going

- 's from atmospheric neutrinos:

~10^3/yr – 10^5/yr in detectors
irreducible background



→ detectors are buried deep

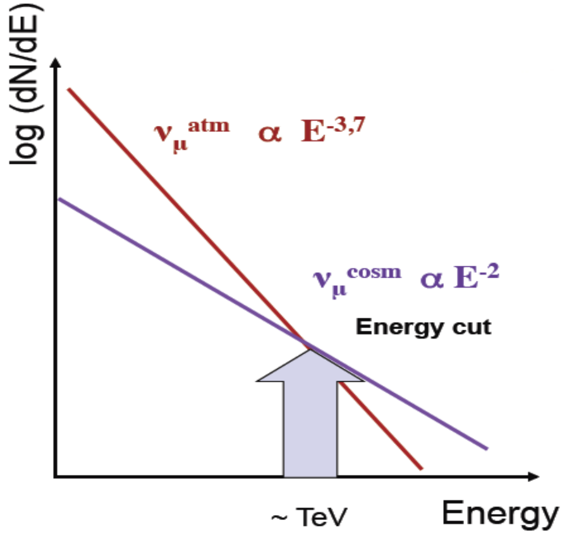
→ detectors look downwards

- cut on zenith angle > 90°
- cut on track quality

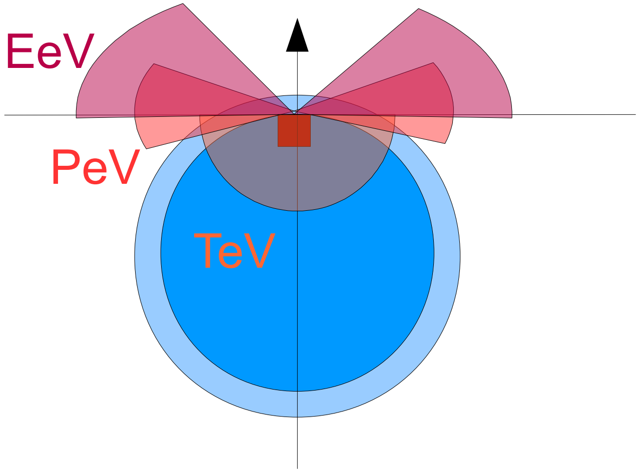
Neutrino astronomy: how ?

How to identify cosmic neutrinos ?

- Excess at high energies (→ diffuse flux analyses)



  - concerns mainly extra-galactic sources (AGNs, GRBs)
  - requires good charge calibration
  - the Earth becomes opaque to neutrinos above PeV:



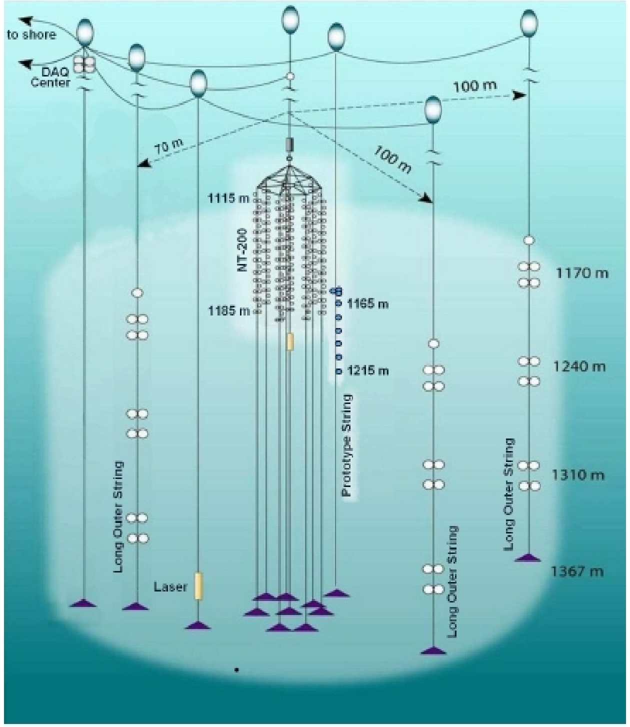
- Anisotropies (clustering) on the sky (→ point source searches)
  - requires good angular accuracy

- Coincidence with other astrophysical signals (→ multi-messenger studies)
  - requires space & time consistency with other probes:
    GRB alerts, optical follow-up, GW+HEN,...

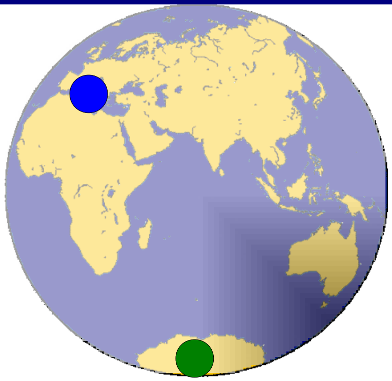
Neutrino astronomy: where ?

in the Lake Baikal:

NT200+ since 2005
since 2008: 2 prototype strings
for a km^3-scale detector



Neutrino astronomy: where ?



in the Mediterranean Sea:
ANTARES

12 lines, completed May 2008
~ 0,015 km^3 instrumented volume
~ 0.5° angular resolution

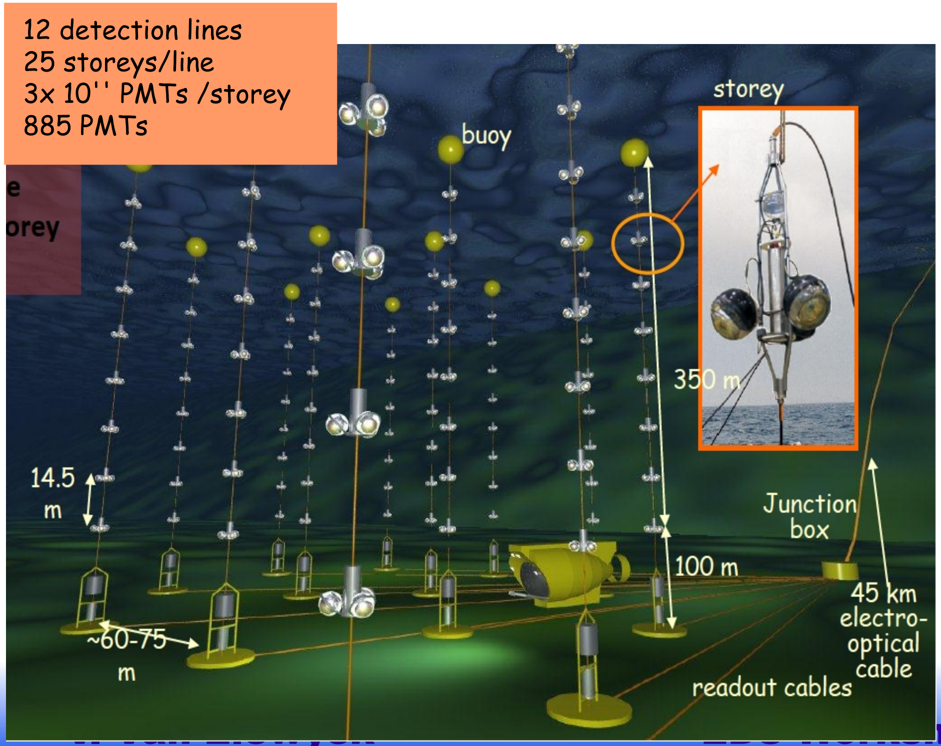
project for a km^3-scale detector: KM3NeT

at the South Pole:
IceCube

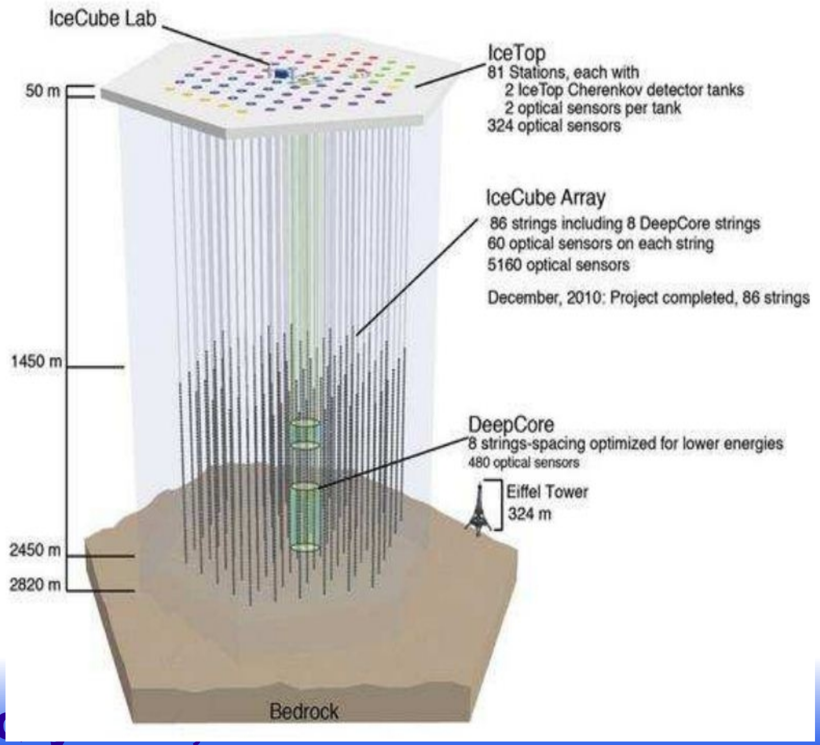
InIce: 86 lines, completed end 2010
~ 1 km^3 instrumented volume
~ 1° angular resolution

DeepCore: denser infill, 8 strings
optimised for lower energies

IceTop: air shower detectors



12 detection lines
25 storeys/line
3x 10'' PMTs /storey
885 PMTs



Neutrino astronomy: where ?

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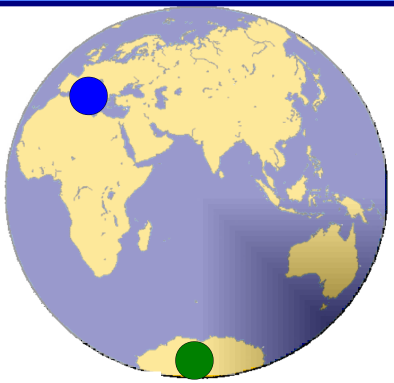
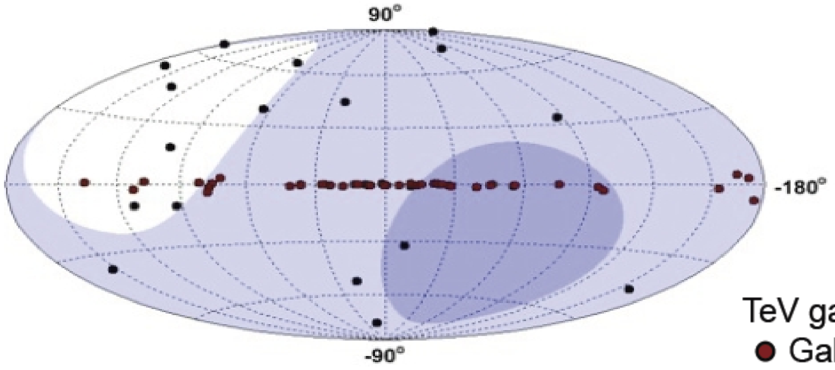
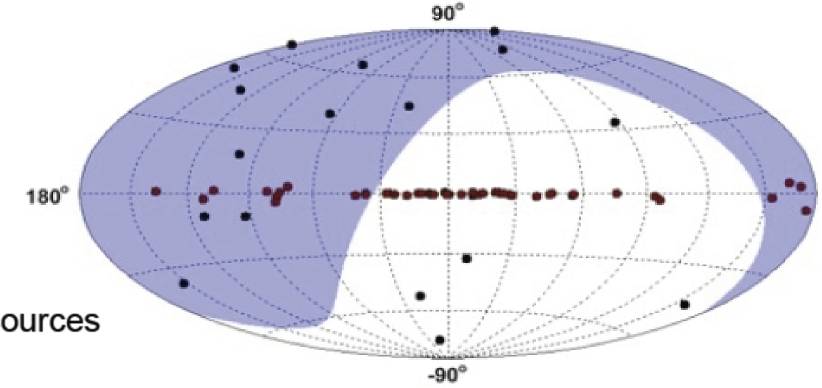


at the South Pole:
IceCube

Visibility Mediterranean (Antares)
- ■ > 75%
- ▨ 25% – 75%
- □ < 25%

Visibility South Pole (IceCube)
- ■ 100%
- □ 0%





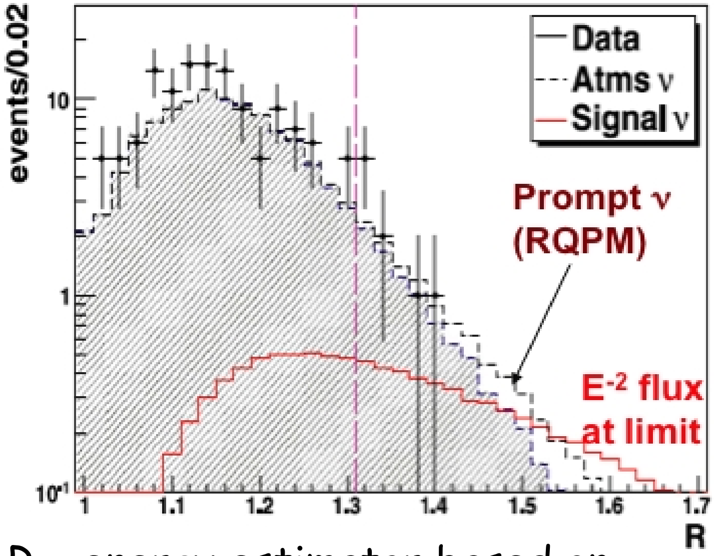
TeV gamma-ray sources
- ● Galactic
- ● extragalactic

good complementarity in the fields of view

Diffuse astrophysical neutrinos

Limits for diffuse fluxes

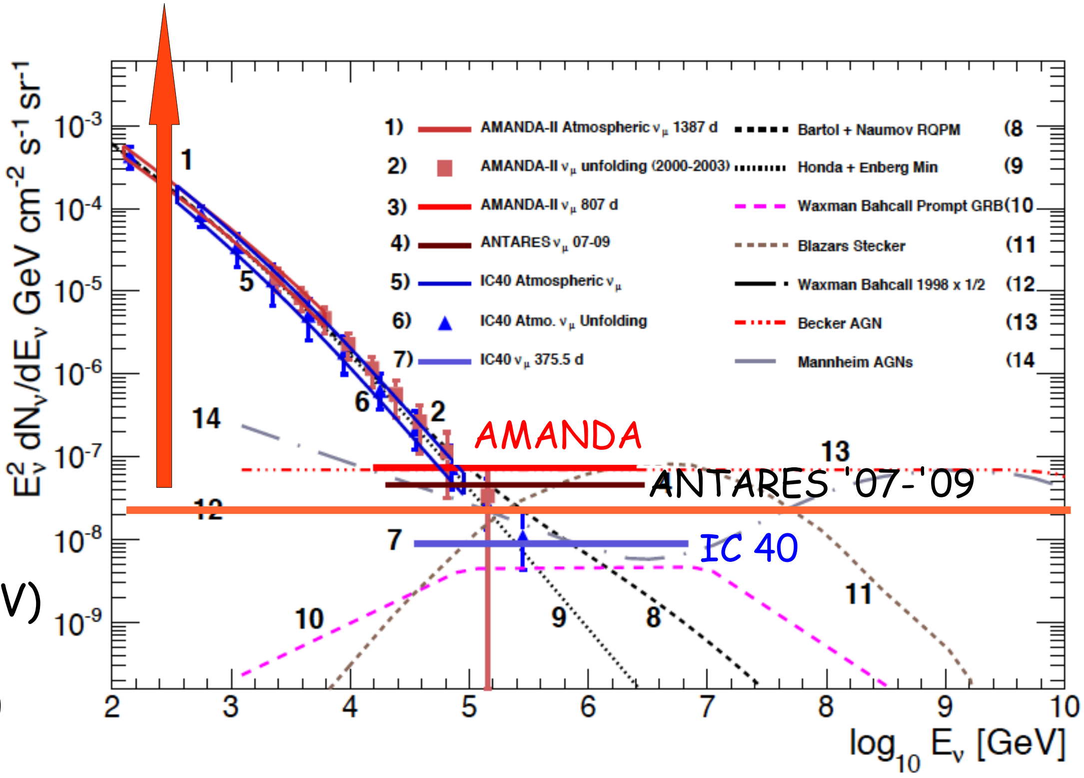
Example: ANTARES
data 2007-2009 (335 active days)



R = energy estimator based on
the mean multiplicity of hits per PMT
R > 1.31 ↔ 90% of signal (20 TeV,2 PeV)
9 events in sample
expected 8.7 atmospheric μ (+ 2 prompt)

- Extragalactic origin
(...otherwise not diffuse)
main candidate sources : AGNs, GRBs

- Waxman-Bahcall benchmark flux:
derived from oberved UHE cosmic ray flux



Diffuse astrophysical neutrinos

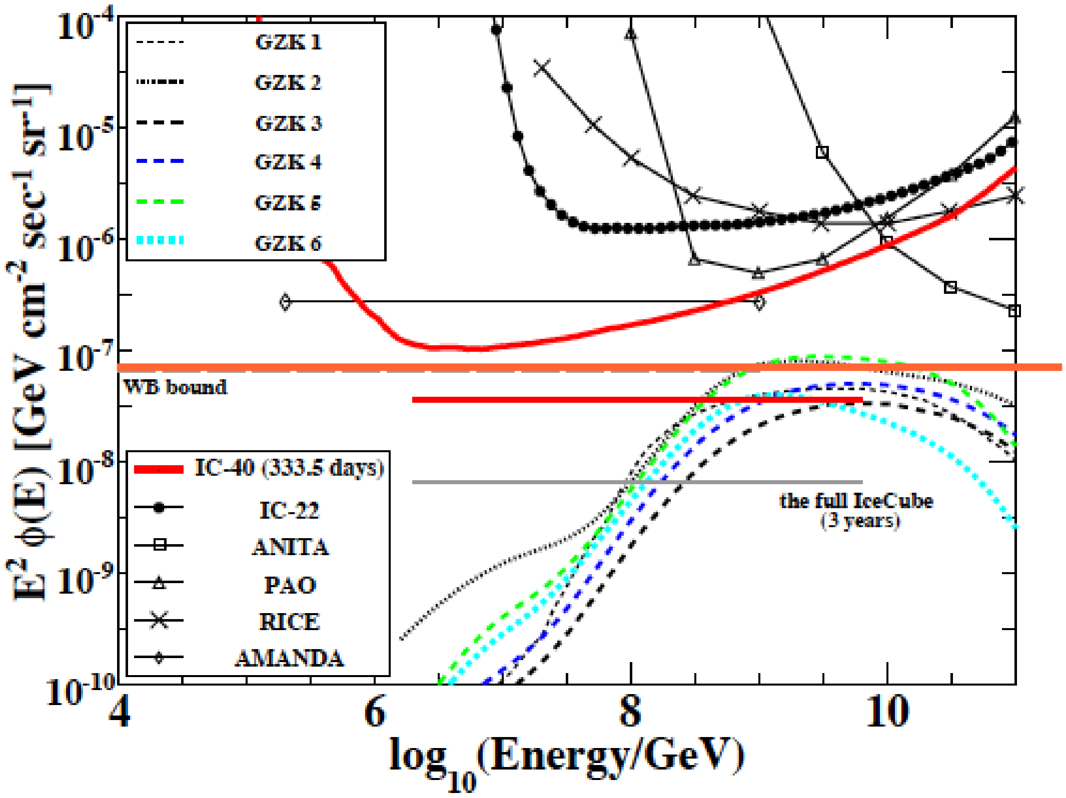
Limits for UHE fluxes (all flavours)

Targeted signal: cosmogenic neutrinos

GZK cut-off:

$$p/A + {}_{\text{CMB/IR}} \rightarrow \pi^{\pm} + X$$
$$\hookrightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_\mu + \nu_e$$

- focus on down-going tracks near the horizon
- large energy deposit in the detector
- main background:
  down-going atmospheric μ bundles



IC 40 sample (April '08 – May '09)

- cut on total charge recorded in PMTs (= $N_{\text{photoelectrons}}$)
- cuts on the inclination of the track

Diffuse astrophysical neutrinos

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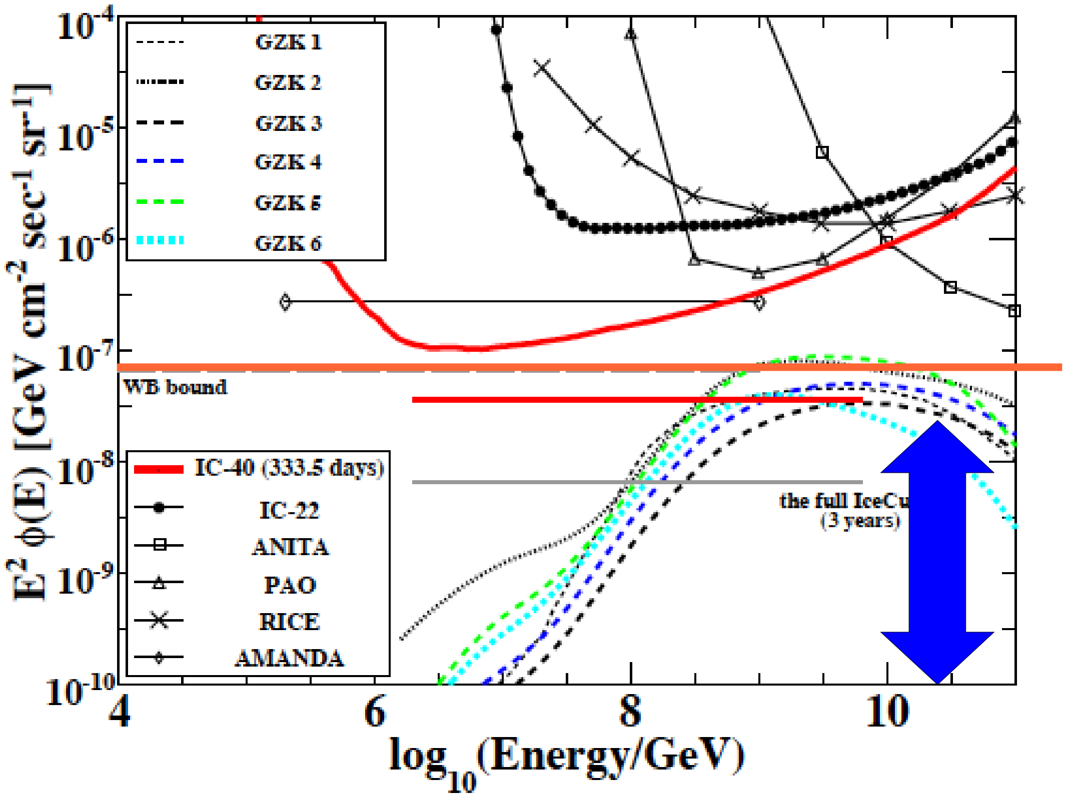
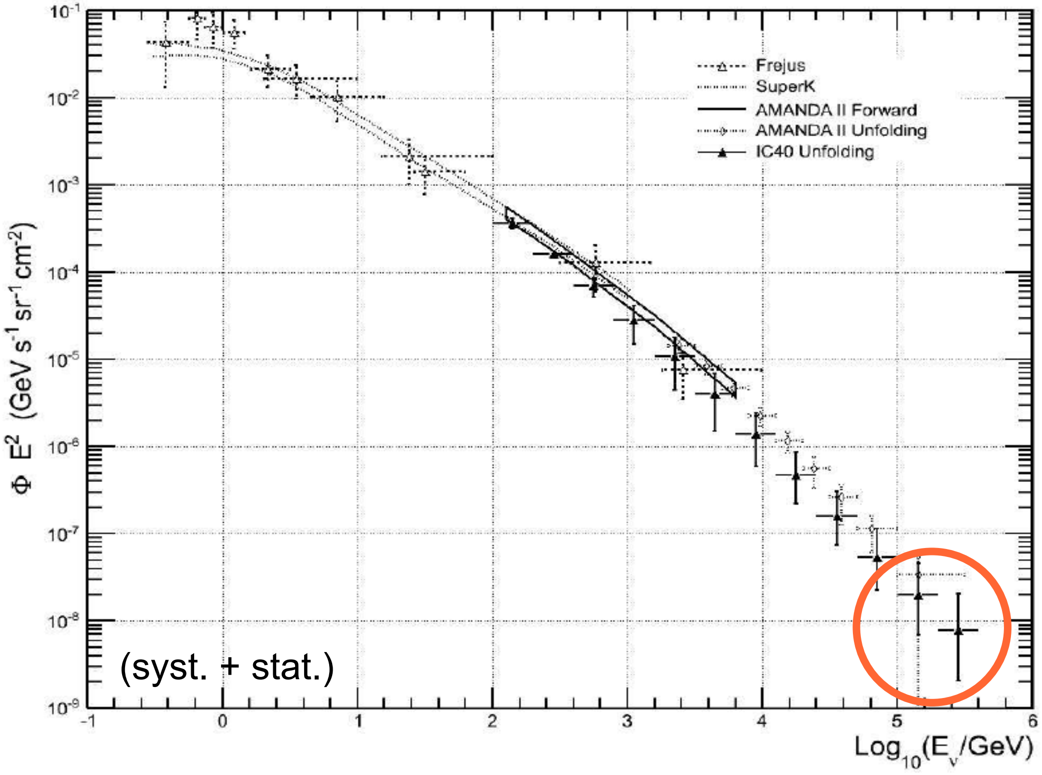


model predictions vary substantially !
(depend on UHECR composition and source distribution)

Atmospheric neutrinos

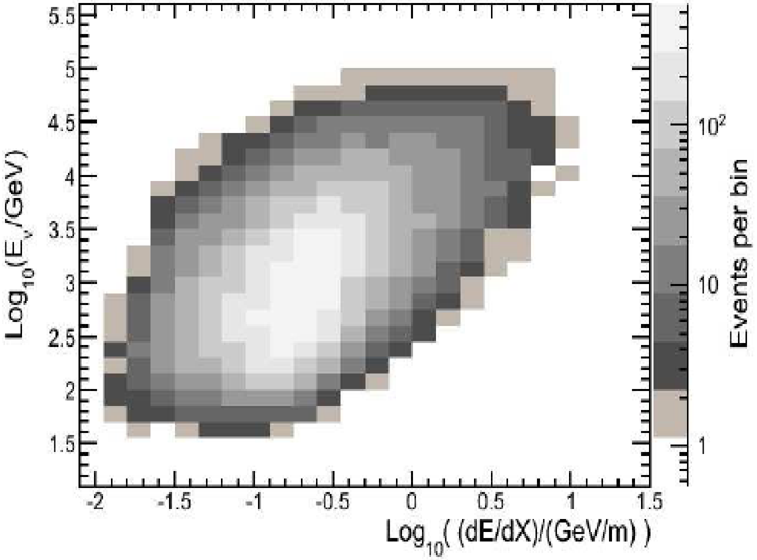
IC40: most precise and extended measurement to date

zenith-averaged flux 97° → 180°, + ‾



(syst. + stat.)

uses unfolding algorithm to extract ν energy from μ energy deposited in detector



extends up to 400 TeV

Atmospheric neutrinos

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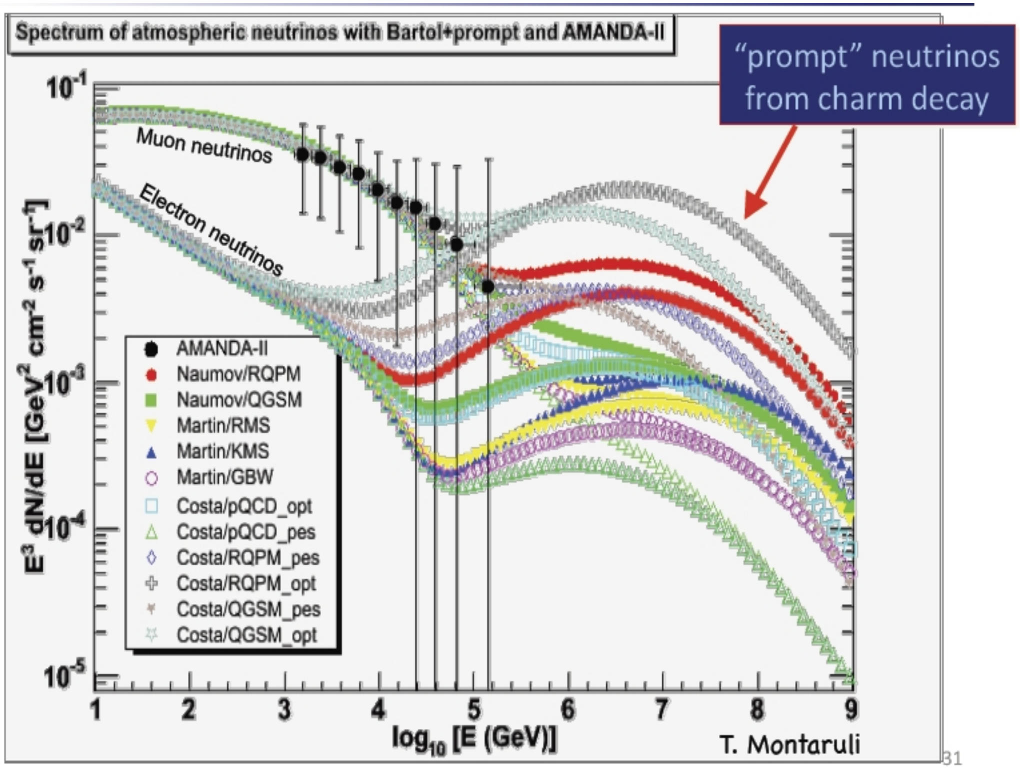
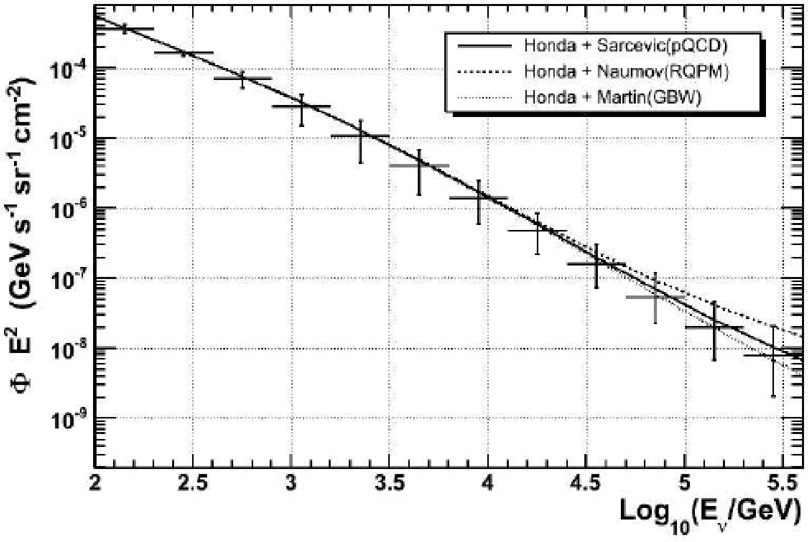


"prompt" neutrinos from charm decay

...but systematics still too high to disentangle the prompt component:



(main sources of uncertainties:
optical module acceptance,
ice properties & data/MC mismatch)

Atmospheric muons

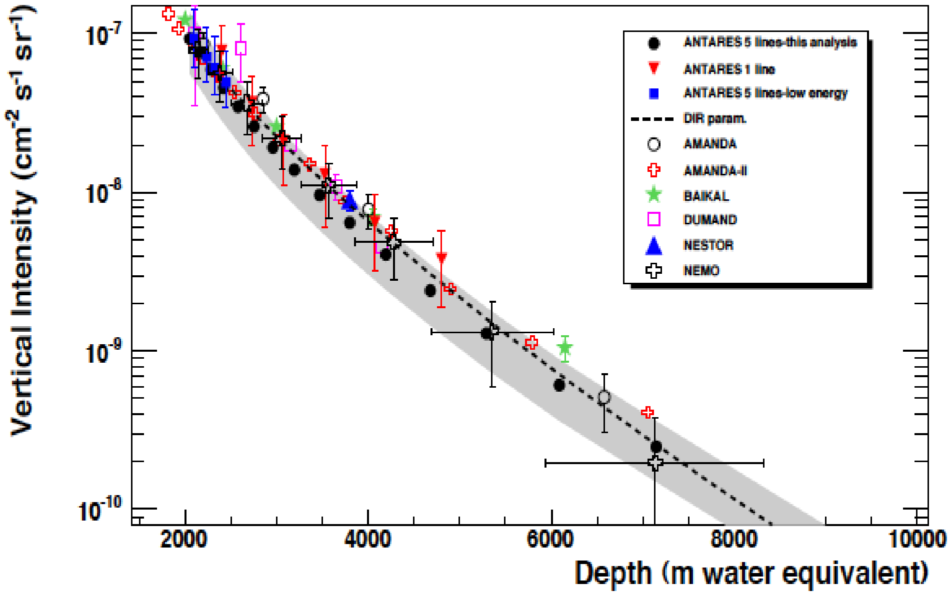
Depth-intensity relation (ANTARES)

number of tracks

mean multiplicity

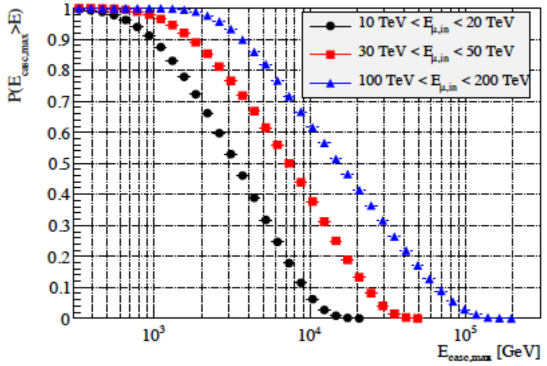
$$I(\theta, h_o) = \frac{N(\theta, h_o) \cdot \mu(\theta, h_o)}{A_{eff}(\theta) \cdot T \cdot \Delta\Omega(\theta)}$$

then convert to vertical intensity I(θ=0)

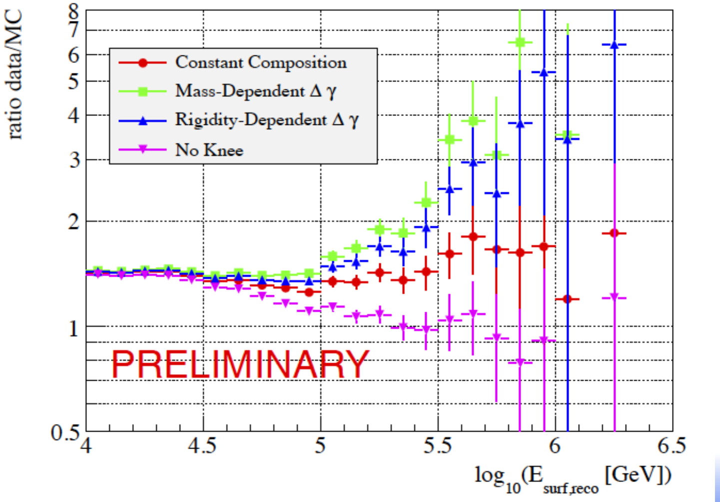


BUT complicated to obtain the energy spectrum:
muons from air showers arrive in large-multiplicity bundles...not resolved

Ongoing studies in IceCube:
identification of single HE muons through catastrophic energy losses



probe CR composition up to the knee



✍ Procs. ICRC 2011, arXiv:1111.2735

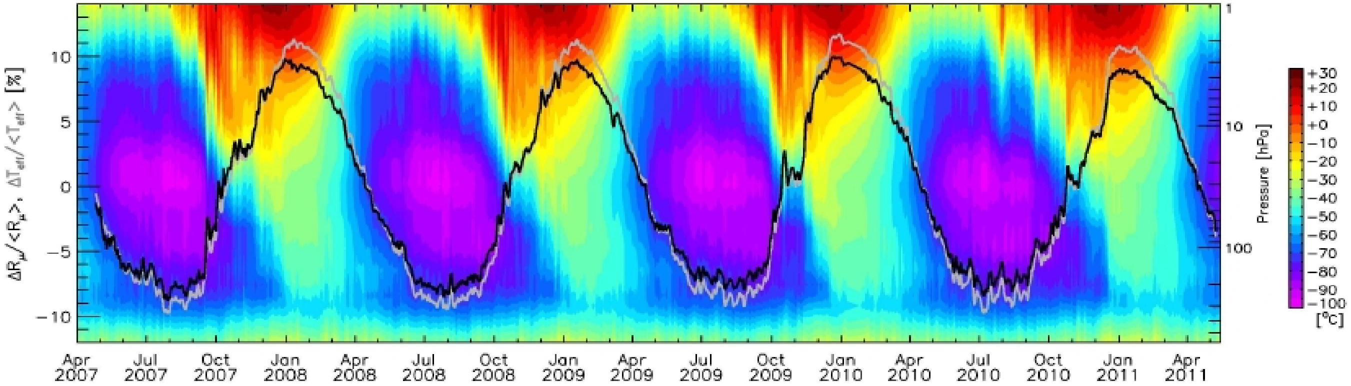
Atmospheric muons

Other CR-related studies

- Seasonal variation of the muon rate:

highly correlated with temperature, ±8% annual modulation

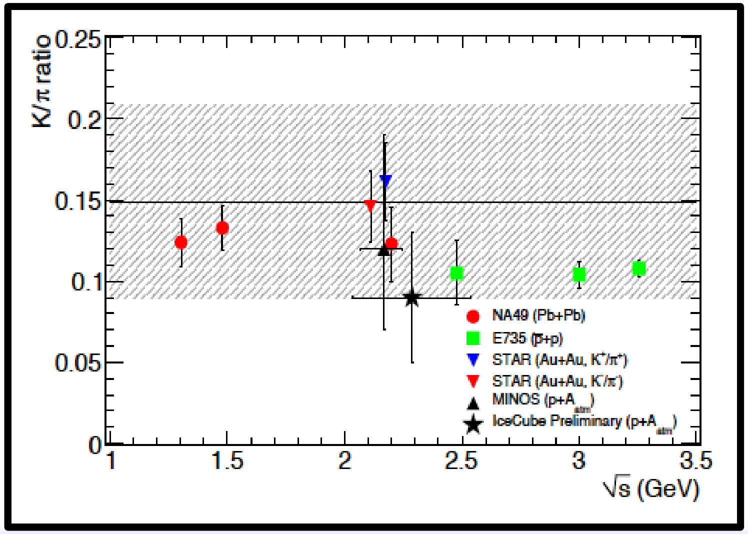
IceCube: 4 years of data, 1,5 Gevents
primary cosmic ray median energy ~20 TeV



muon rate
temperature

critical energy for decay/interaction of π, K depends on atmosphere density

→ probe of Kaon/Pion ratio



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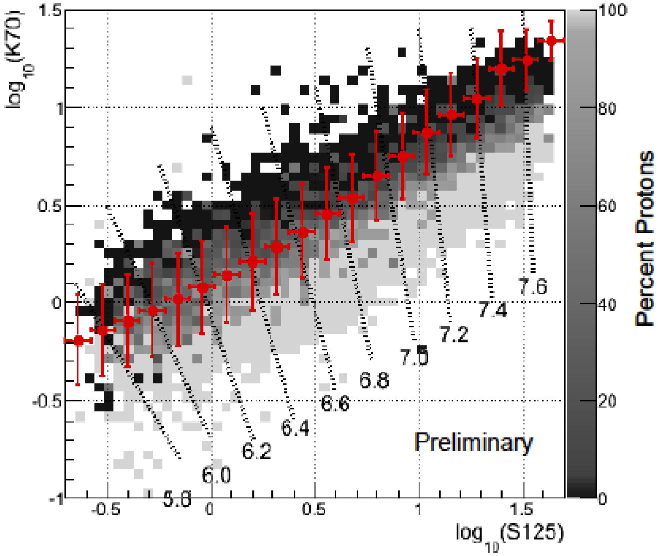
Atmospheric muons

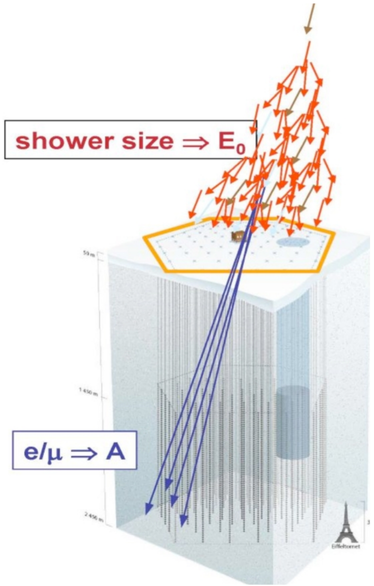
Combined IceCube-IceTop measurements

IceTop: lateral distribution of the shower
IceCube: muon bundle

- CR composition studies

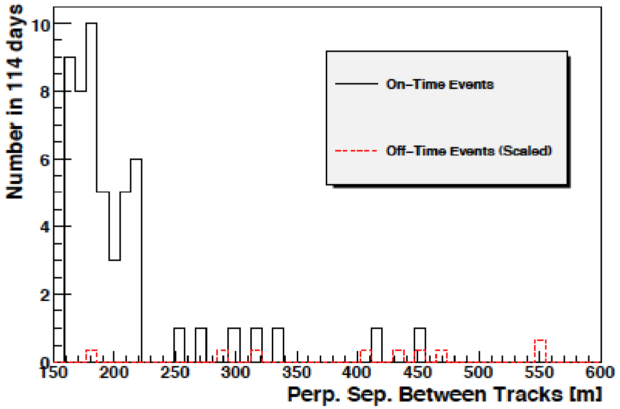
S(125): shower size parameter in IceTop
→ primary CR energy proxy
K(70): muon energy proxy





- Study of high p_T muons

separate track coincident with a low-p_T bundle (as reconstructed in IceTop)
Background: double-coincident CRs
Preliminary study with IC22 + IT26



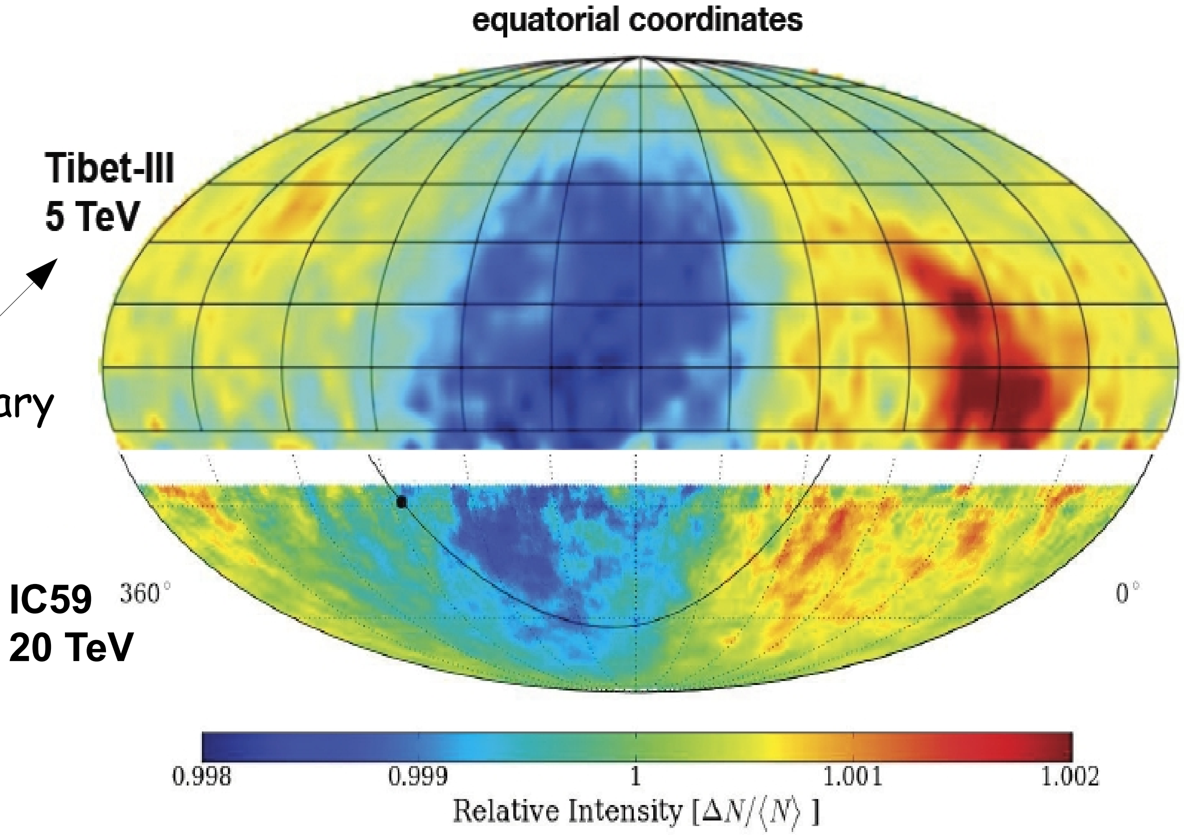
Atmospheric muons

Cosmic ray large-scale anisotropy

- remove non-physical effects (downtime of detector,...)
- estimate a reference map by scrambling real data in time (θ,φ kept unchanged)
- construct relative intensity map $\Delta N/N_{ref}$

matches anisotropy observed by Tibet experiment

median primary energy

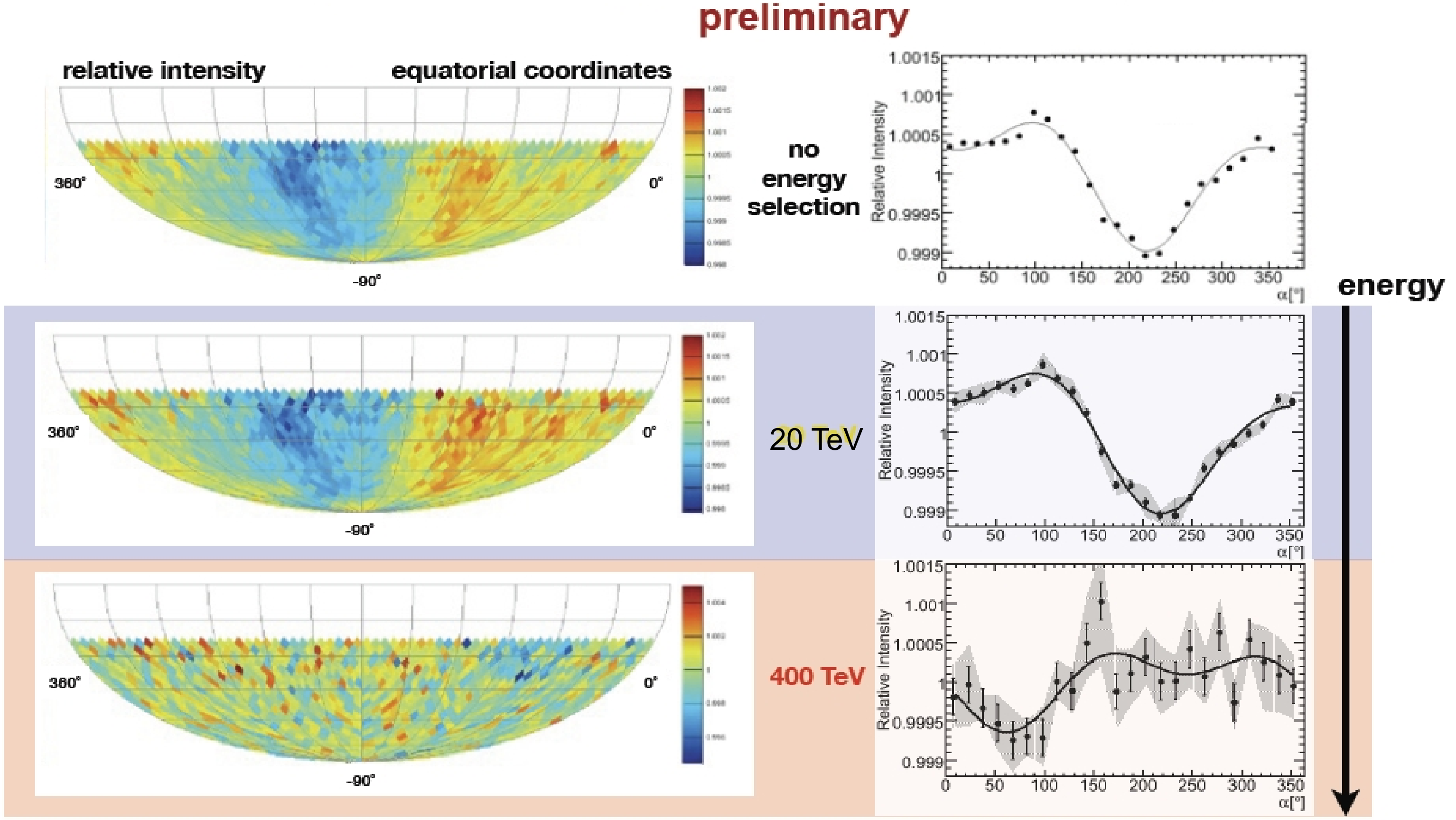


gyroradius < 1 pc
in μG galactic magnetic field
closest sources ~100 pc

...CRs should not point back !

Cosmic ray large-scale anisotropy

...different features at higher energies



Desiati, Nusky 2011

Not explained...

Conclusions and Perspectives

- ANTARES and IceCube completed & operating:

- demonstrated the feasibility of large-scale neutrino telescopes

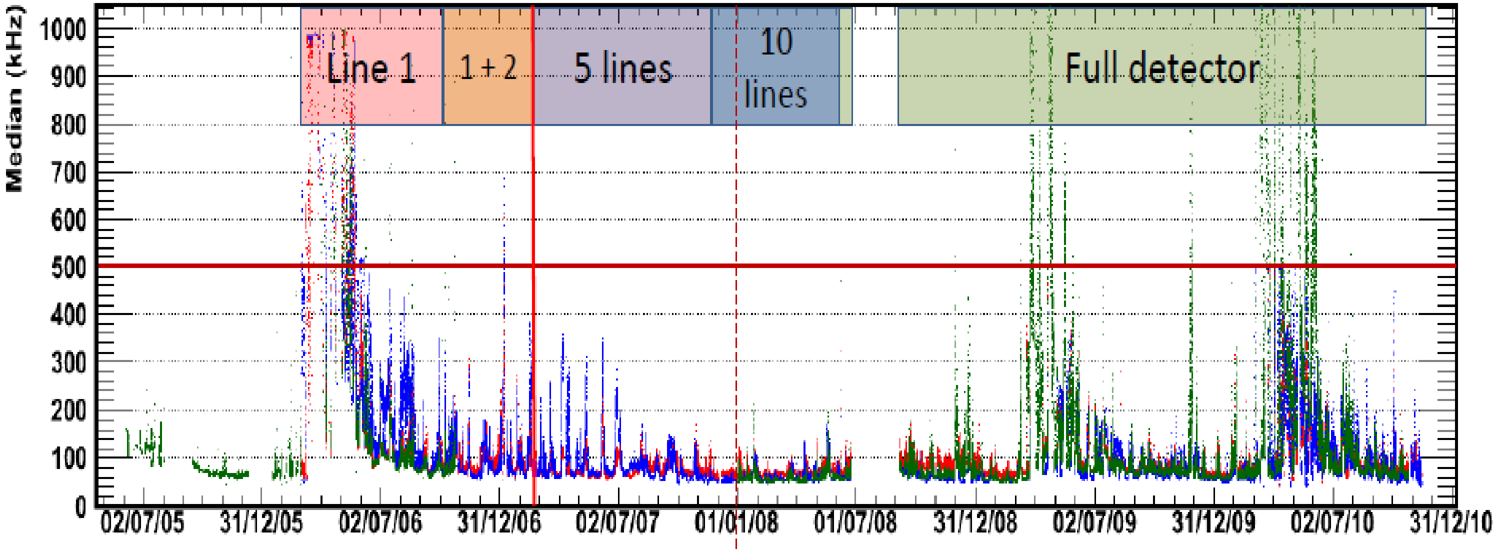
- full-sky coverage now achieved (but with different sensitivities)
  … a (few-)km3 instrument in the Northern Hemisphere is desirable: KM3NeT

- Analysis results so far:
  - Searches for cosmic & GZK neutrinos with negative results
  - Many astrophysics topics being investigated:
    point and extended sources
    multimessenger programs to enhance the sensitivity of the detector
    (optical & X-ray follow-up, coincidences with GRBs & AGN flares, ...)
  - A lot of particle physics to be done with neutrino telescopes !

  Interesting prospects for cosmic ray physics:
  - study of prompt component in atmospheric muon/neutrino spectra
  - CR composition studies up to the knee
  - muon distribution profile
    ...systematics to be fought !
  - intriguing 0,1% anisotropy signal at primary CR energy ~ 20 TeV
    compatible with Tibet observations – no astrophysical explanation ?

Backup slides

ANTARES operating conditions



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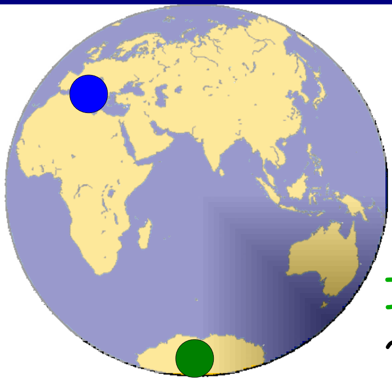

in the Mediterranean Sea:
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12 lines, completed May 2008
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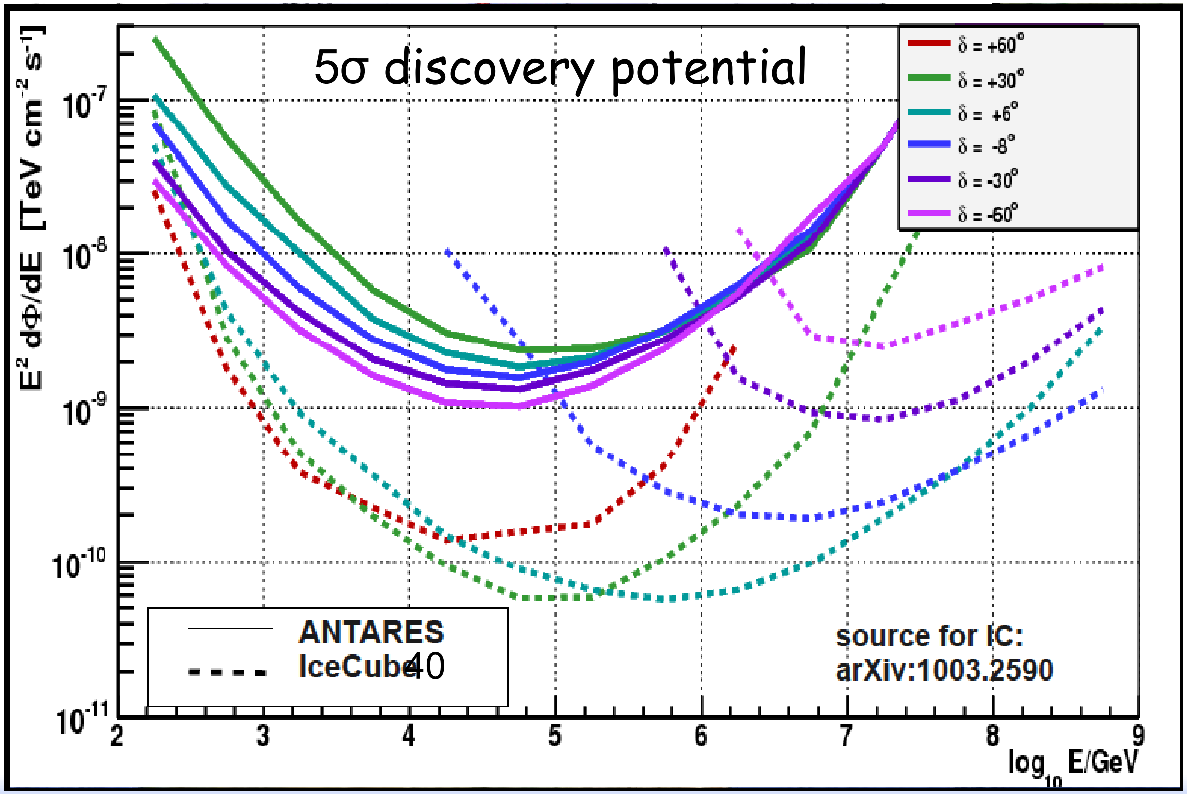
ANTARES especially
suited for
galactic sources
at $\delta<0$ and E ~TeV-PeV



source for IC:
arXiv:1003.2590

KM3NeT: a km3-scale detector in the Mediterranean

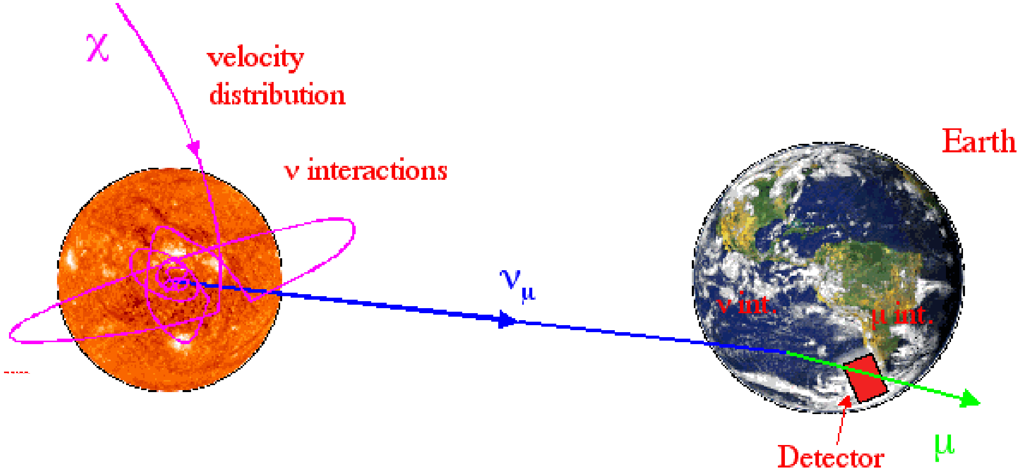
Dark matter searches

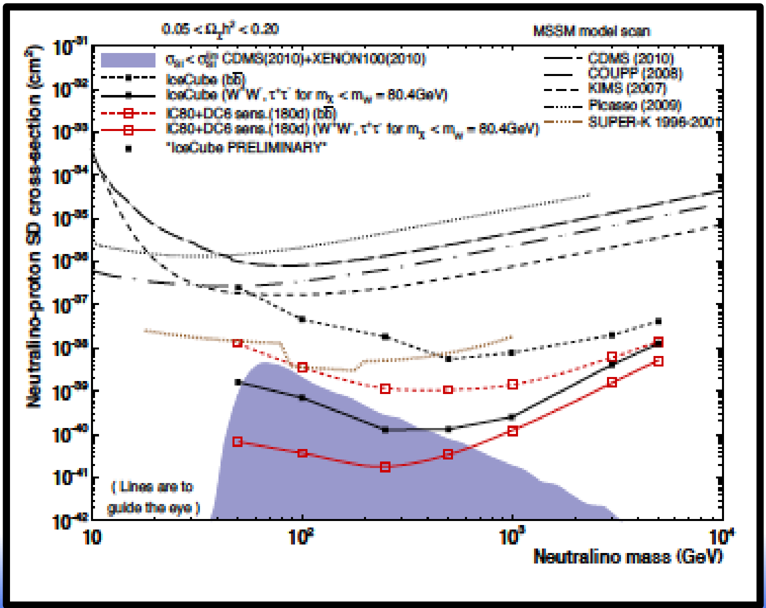
Indirect searches for DM:

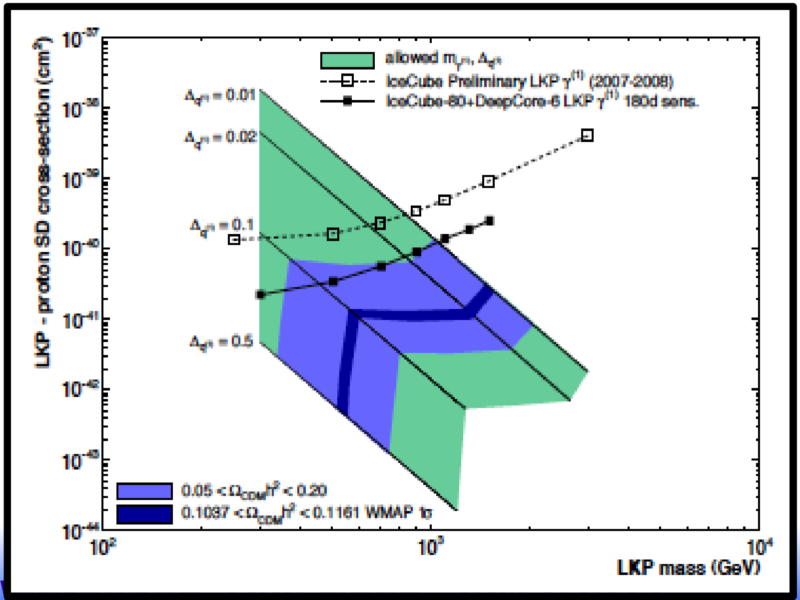
look for an excess of from the annihilation of WIMPs (m~ 10 GeV – few TeV) trapped in the Sun (or in our/a galaxy)

Most popular candidates:

- in MSSM:
    lightest neutralino
    « hard » (W^+W^-,$\tau^+\tau^-$) or « soft » ($b\bar{b}$)
    decay channels
- in universal extra-dimension models:
    lightest Kaluza-Klein particle (LKP)







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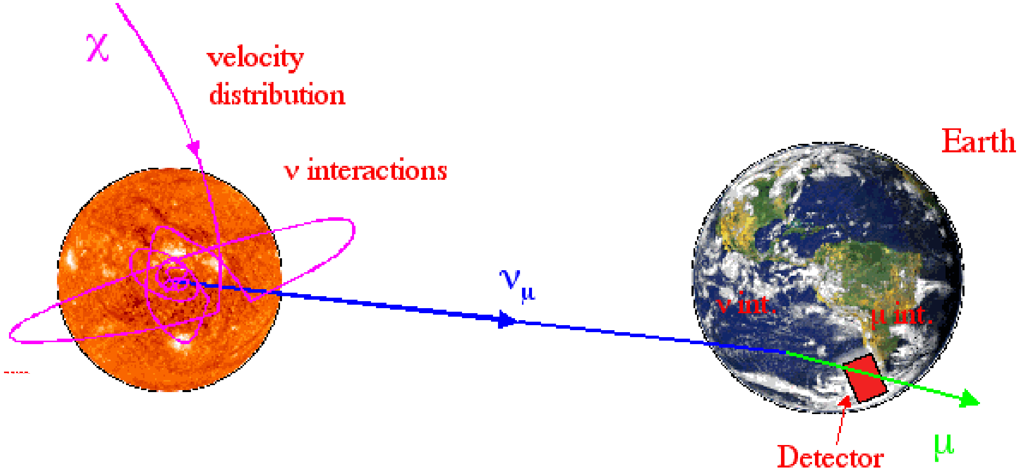

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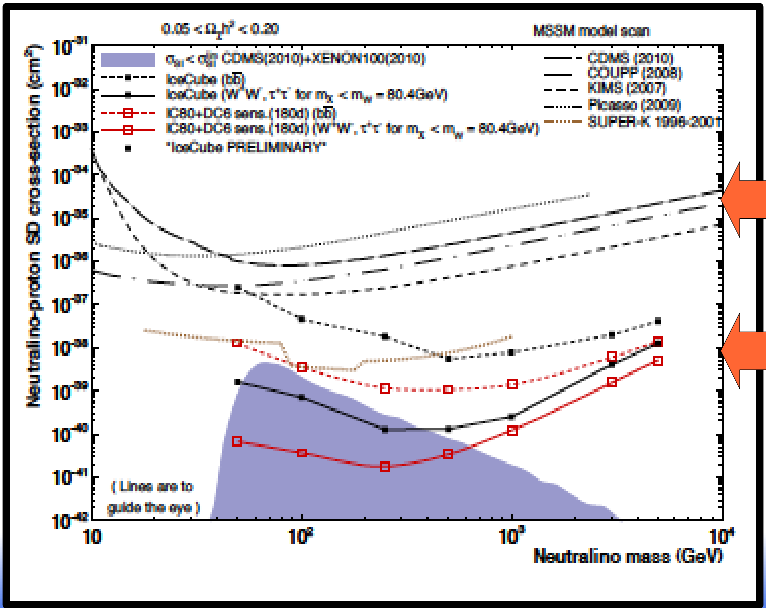
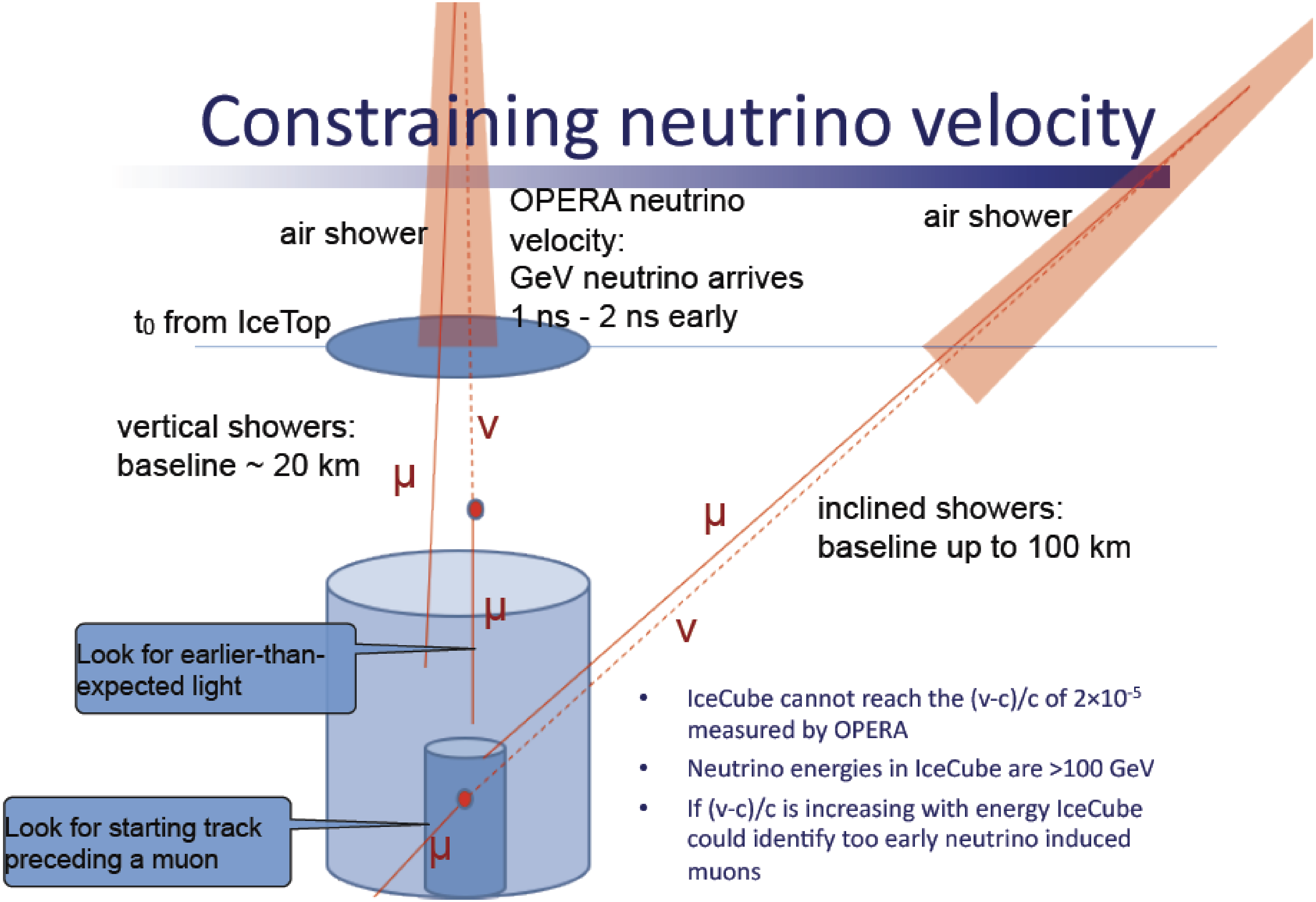


Indirect searches better than direct ones ! (especially in models with spin-dependent σ)

Importance of DeepCore infill:

- improves sensitivity to low-mass WIMPS
- allows to look downwards: increases observation time towards the Sun

Constraining neutrino velocity



OPERA neutrino velocity:
GeV neutrino arrives
1 ns - 2 ns early

vertical showers:
baseline ~ 20 km

inclined showers:
baseline up to 100 km

Look for earlier-than-expected light

Look for starting track preceding a muon

- IceCube cannot reach the (v-c)/c of 2×10^{-5} measured by OPERA
- Neutrino energies in IceCube are >100 GeV
- If (v-c)/c is increasing with energy IceCube could identify too early neutrino induced muons

ANTARES operating conditions

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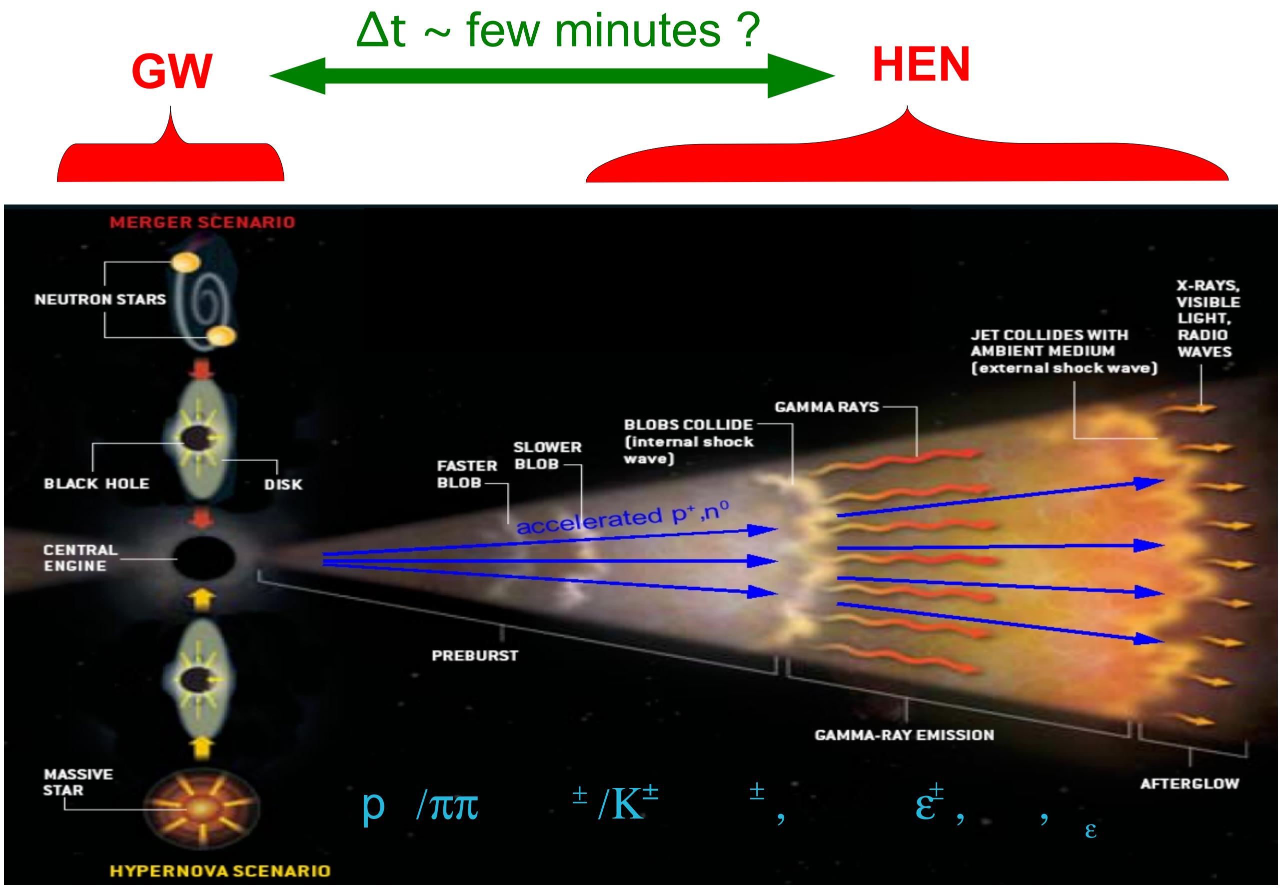
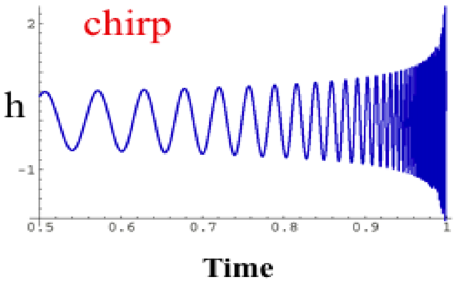
Usual suspects: long & short GRBs

The fireball model



Short-Hard GRBs:
coalescing binaries involving BH and/or neutron stars.
→ GW associated to coalescence process (inspiral)



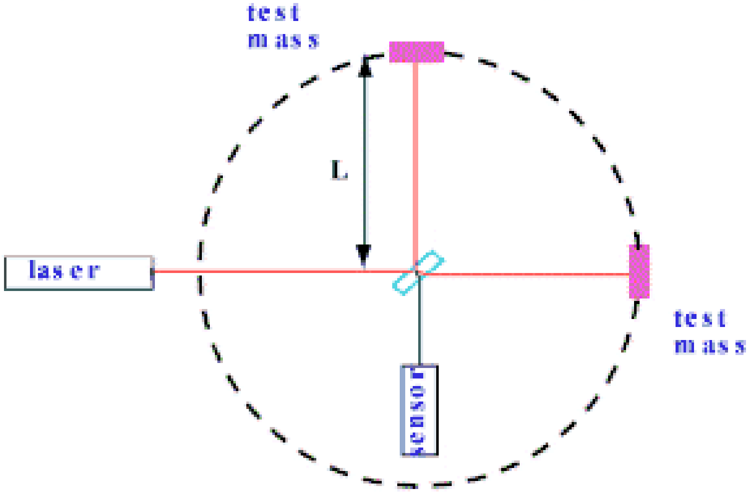
Long-Soft GRBs:
associated to core-collapse supernovae (collapsars)
→ GW burst during collapse (faint ?, unmodelled)

HEN emitted during GRB prompt (p) & afterglow (pp) phases from interaction of accelerated protons with ambient matter/radiation
(fainter signal expected for long GRBs as a result of the cosmological distribution)

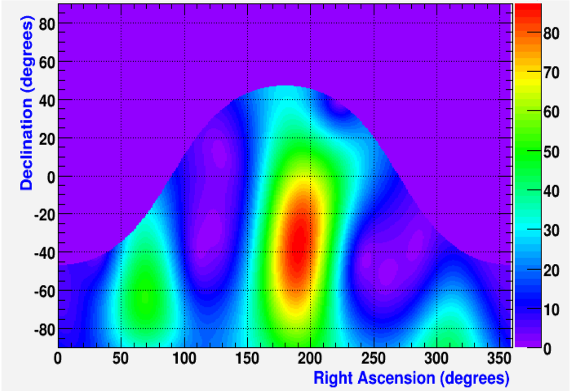
The detectors

- LIGO Hanford: 4 km (+ 2 km) arms
- LIGO Livingston: 4 km arms
- VIRGO (Pisa, Italy): 3 km arms

Michelson interferometers:
suspended mirrors act as free test masses



VIRGO + LIGO + ANTARES
instantaneous sky coverage ~ 30%



(equatorial coordinates)

current sensitivity to GW amplitude

$$h = \frac{\delta L}{L} \sim 10^{-21}$$

More (speculative) suspects among GRBs

Low-luminosity GRBs (llGRBs)

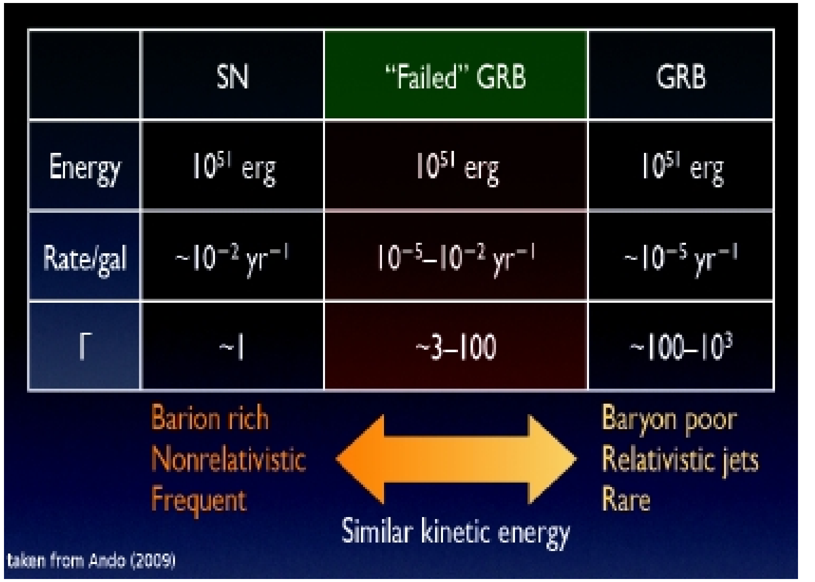
- γ-ray luminosity few orders of magnitude smaller

→ smaller Lorentz factor, smaller optical depth ?

- Observational evidence for llGRB/SN connection

→ produced by a particularly energetic population of core-collapse SNe ?

- larger event rate predicted in local universe
- BUT mechanism debated, presence of jets is uncertain *(Bromberg, Nakar & Piran, 2011)*



	SN	"Failed" GRB	GRB
Energy	10^{51} erg	10^{51} erg	10^{51} erg
Rate/gal	$\sim 10^{-2}$ yr^{-1}	10^{-5}–10^{-2} yr^{-1}	$\sim 10^{-5}$ yr^{-1}
Γ	~1	~3–100	~100–10^{3}

Barion rich
Nonrelativistic
Frequent

Baryon poor
Relativistic jets
Rare

Similar kinetic energy

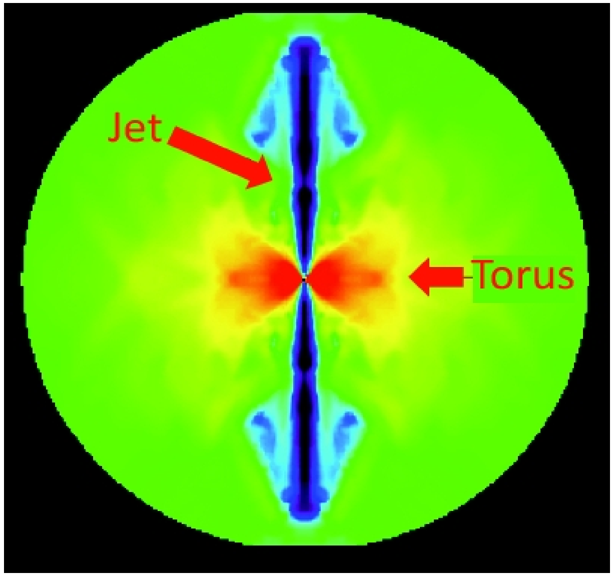
taken from Ando (2009)

Failed GRBs:

from mildly relativistic, baryon-rich and optically thick jets ? missing link between (long) GRBs and SNe ?
(Ando & Beacom, 2005)

Choked GRBs:

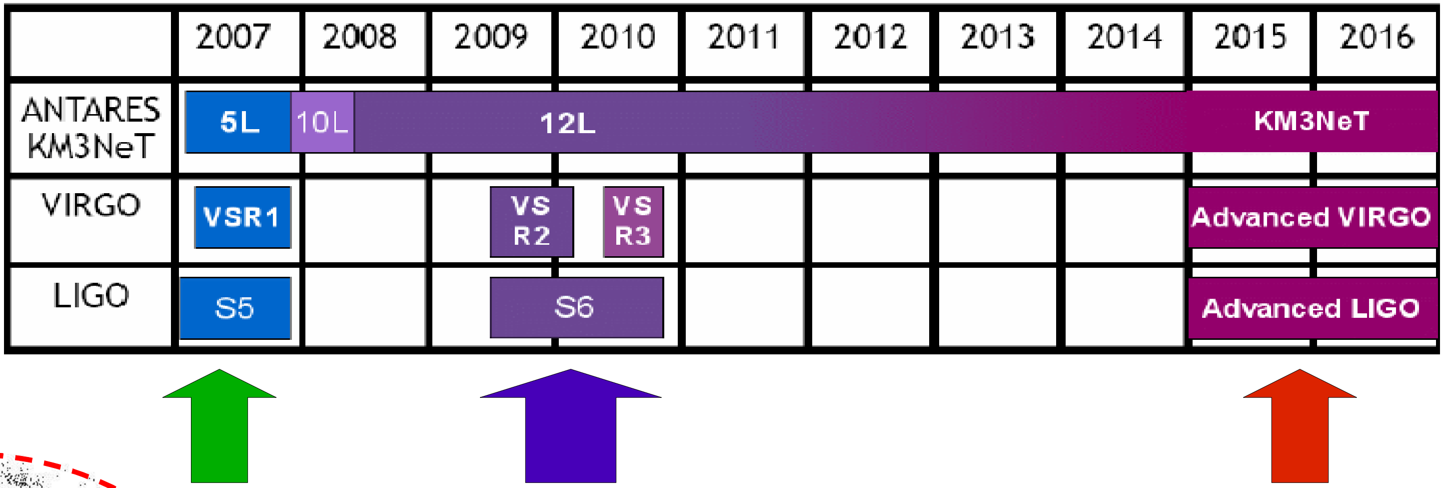
successfull jets unable to break through the stellar envelope ?
(Eichler & Levinson, 1999; Mészaros & Waxman, 2001)

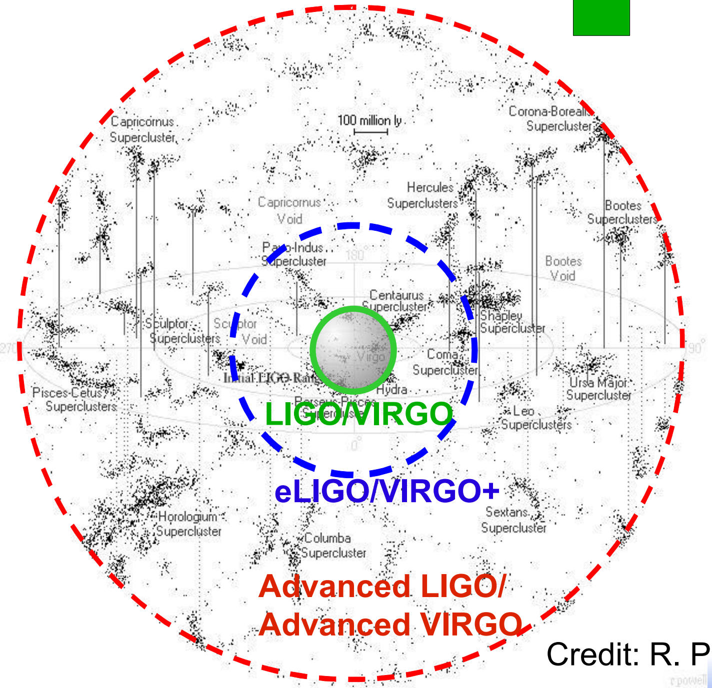


→ potentially strong HEN/GW emitters;
→ not observable in photons
→ models poorly constrained and still debated

The detectors

Periods of concomitant data taking:





Credit: R. Powell

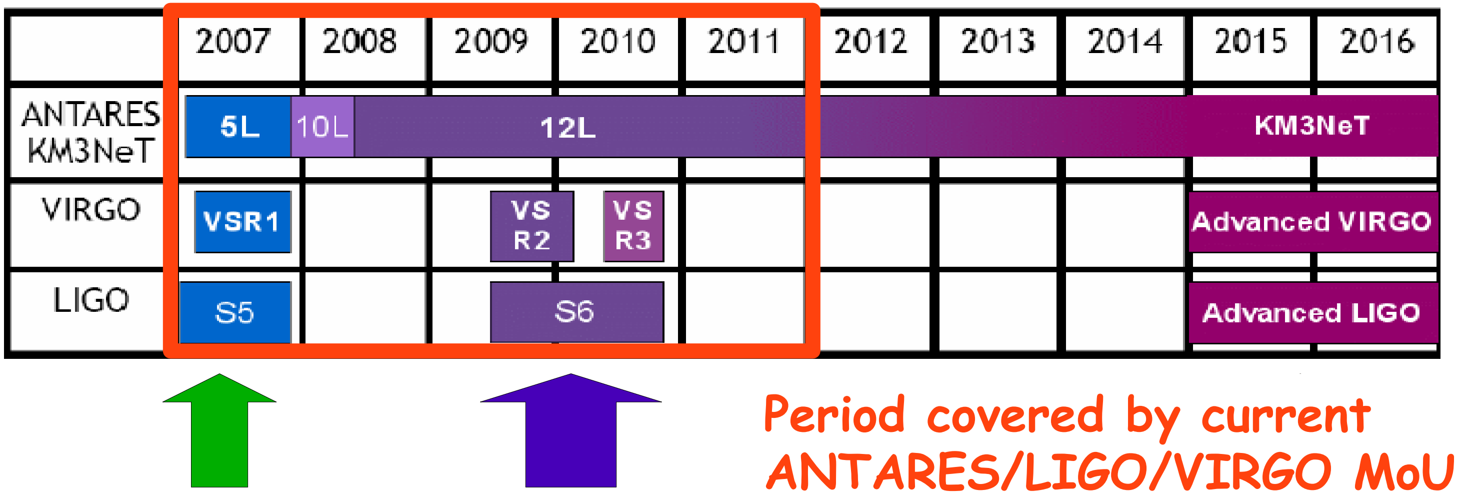
First-generation detectors VIRGO/LIGO 2007 detection horizon for standard binary sources: ~ 15 Mpc (~1 binary merger/ 100 years...)

Recent upgrades (VIRGO+/eLIGO) 2009-2010: sensitivity x 2 (expected) → probed volume x 8

Advanced detectors ~2015:
sensitivity x 10 → probed volume x 1000
(~ 1 Gpc^3 for BH mergers, ~ 40 mergers/yr)

The detectors

Periods of concomitant data taking:



Period covered by current ANTARES/LIGO/VIRGO MoU

- GW/HEN common challenge: faint & rare signals on top of abundant noise or background events.

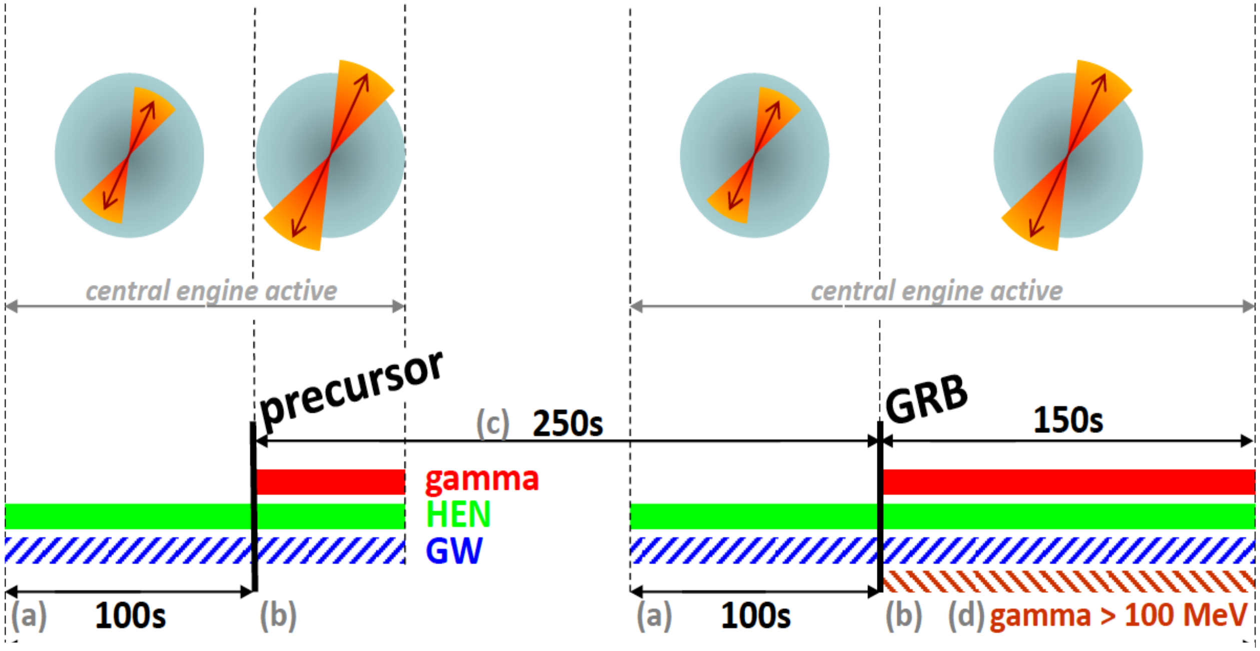
→ search methodology: combination of GW/HEN event lists + search for coincidences in predefined time windows

(independant detectors → low combined False Alarm Rate)

Bounding the GW-HEN time window

A case study: long GRBs

B. Baret et al., AstroPart. Phys. 35 (2011), 1-7



Observational benchmarks:

- γ-ray emission: t ~150 s based on the t_{90} distribution in BATSE bursts (Fermi HE -ray emission also within 150 s)
- 10-20% of GRBs have precursors: $t_{precursor}$ ~250 s from BATSE GRBs

☆ HEN emission from internal shocks in relativistic outflow (also BEFORE it emerges from the stellar envelope: Δt ~100 s)

☆ GW emission associated to the activity of central engine (BH ringdown + gravitational instabilities in accretion disk + ...)

} connected to γ-ray emission

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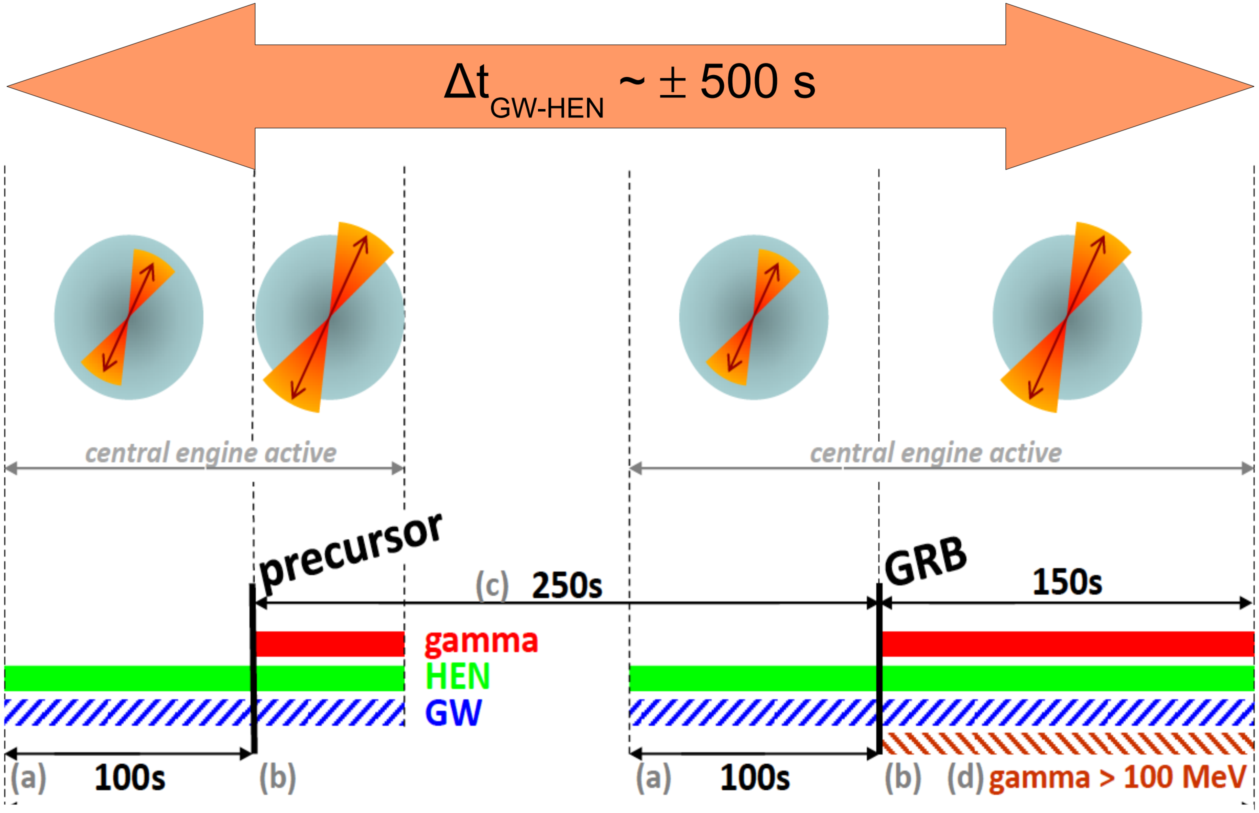

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connected to
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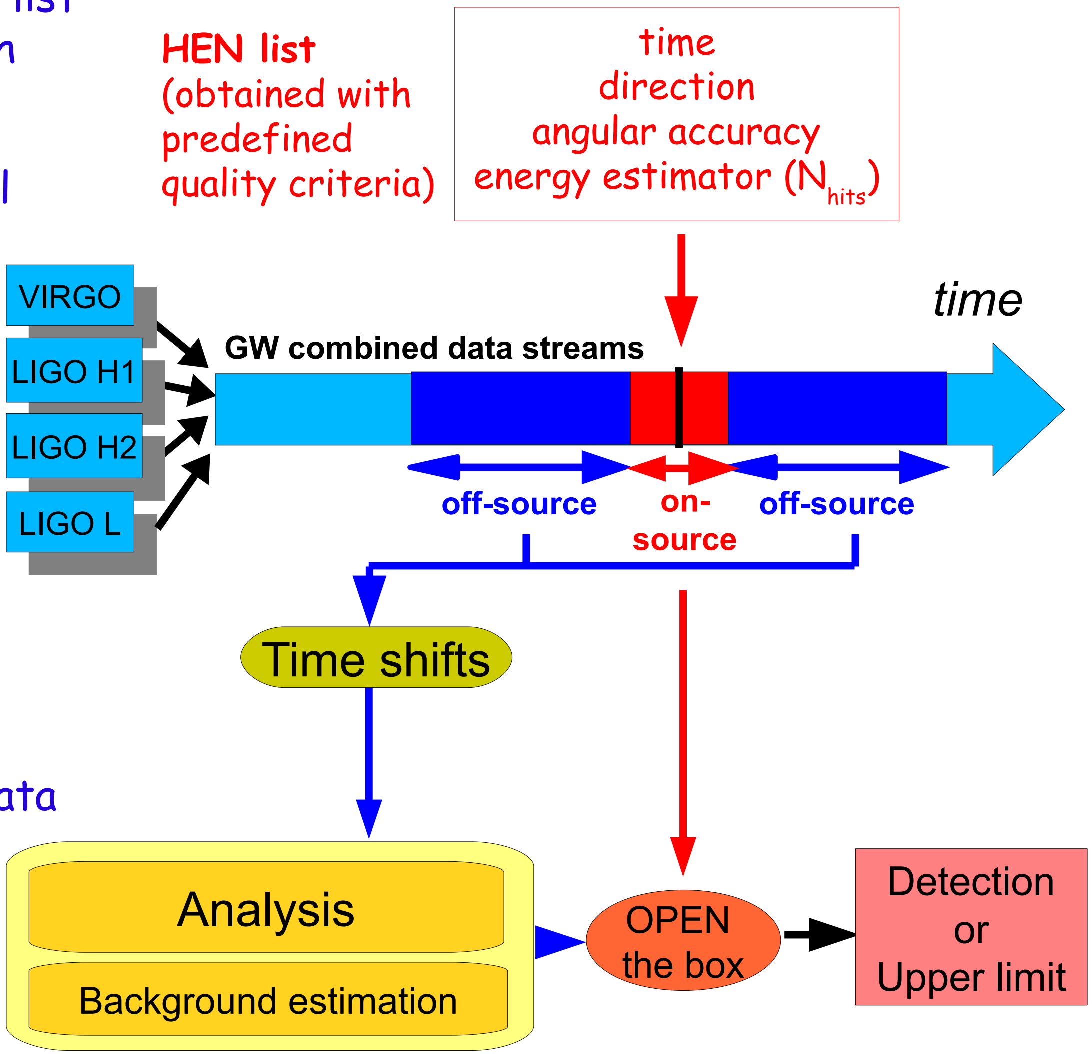
Joint analysis strategies

- ANTARES 5L /LIGO S5/VIRGO VSR1 (2007) data analysis

- « HEN-triggered » search: HEN event list as an external input for GW burst search
  - uses specific analysis chain looking for unmodelled GW bursts from external triggers (e.g. GRB alerts): X-pipeline
    P. Sutton et al., New J. Phys. 12 (2010)
    (a variant with inspiral templates also being developed: STAMP)
- on-source time window: ± 500 s around HEN arrival time
- GW spatial search box defined by (event-by-event) HEN angular accuracy
- Closed-box analysis: parameters tuned on off-source, time-shifted GW data
- high computational cost: O(100) neutrinos   O(month) processing with X-pipeline
  - *Analysis nearly completed*



HEN list
(obtained with predefined quality criteria)

time
direction
angular accuracy
energy estimator (N_{hits})

VIRGO
LIGO H1
LIGO H2
LIGO L

GW combined data streams

time

off-source
on-source
off-source

Time shifts

Analysis
Background estimation

OPEN the box

Detection or Upper limit