Heidelberg Physics Graduate Days, 6-9 April 2010

Neutrino Astronomy

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Lecture Plan

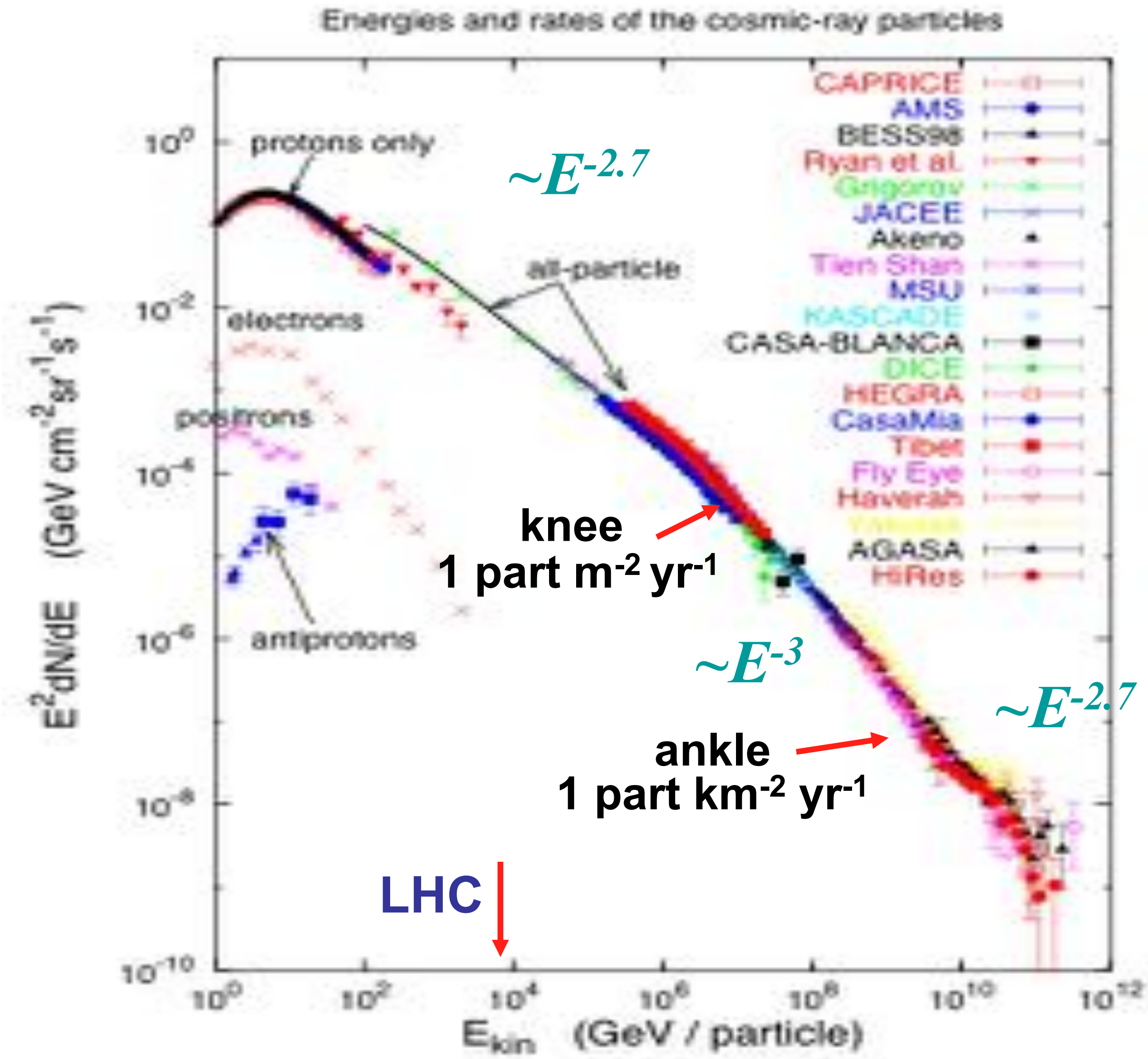
- Introduction: What is it all about?
- Neutrinos: The actors
- Selected topics in high-energy astrophysics
- Experimental observations
- Future plans and ideas

Organisational issues:

- 4 lectures 14:00-17:00, coffee break at 15:00
- Some intermediate exercises: do a few calculations …
- Please ask questions at <u>any</u> time!

Introduction

The Mysterious Cosmic Rays



- Particles impinging on Earth from outer space carry energies up to
  10^{21} eV
  (the kinetic energy of a tennis ball at ~200km/h.)
- The acceleration mechanisms are unknown.
- Cosmic rays carry a significant fraction of the energy of the universe – cosmologically relevant!
- Neutrinos play a key role in studying the origin of cosmic rays.

Neutrino Production Mechanism

- Neutrinos are produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \rightarrow \pi^{\pm}(K^{\pm} \ldots) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

Cosmic rays

$$\downarrow$$

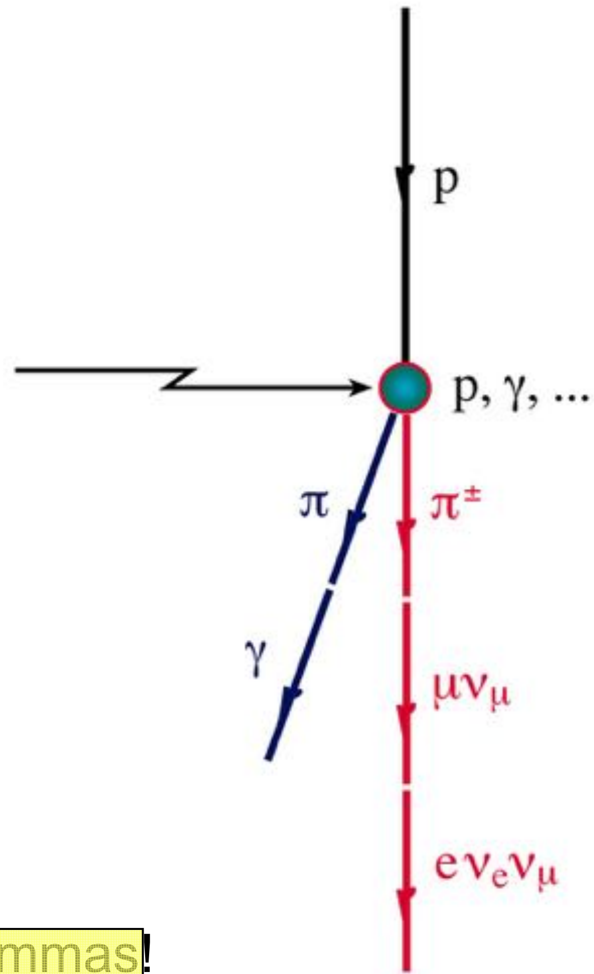
$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$

- Simultaneously, gamma production takes place:

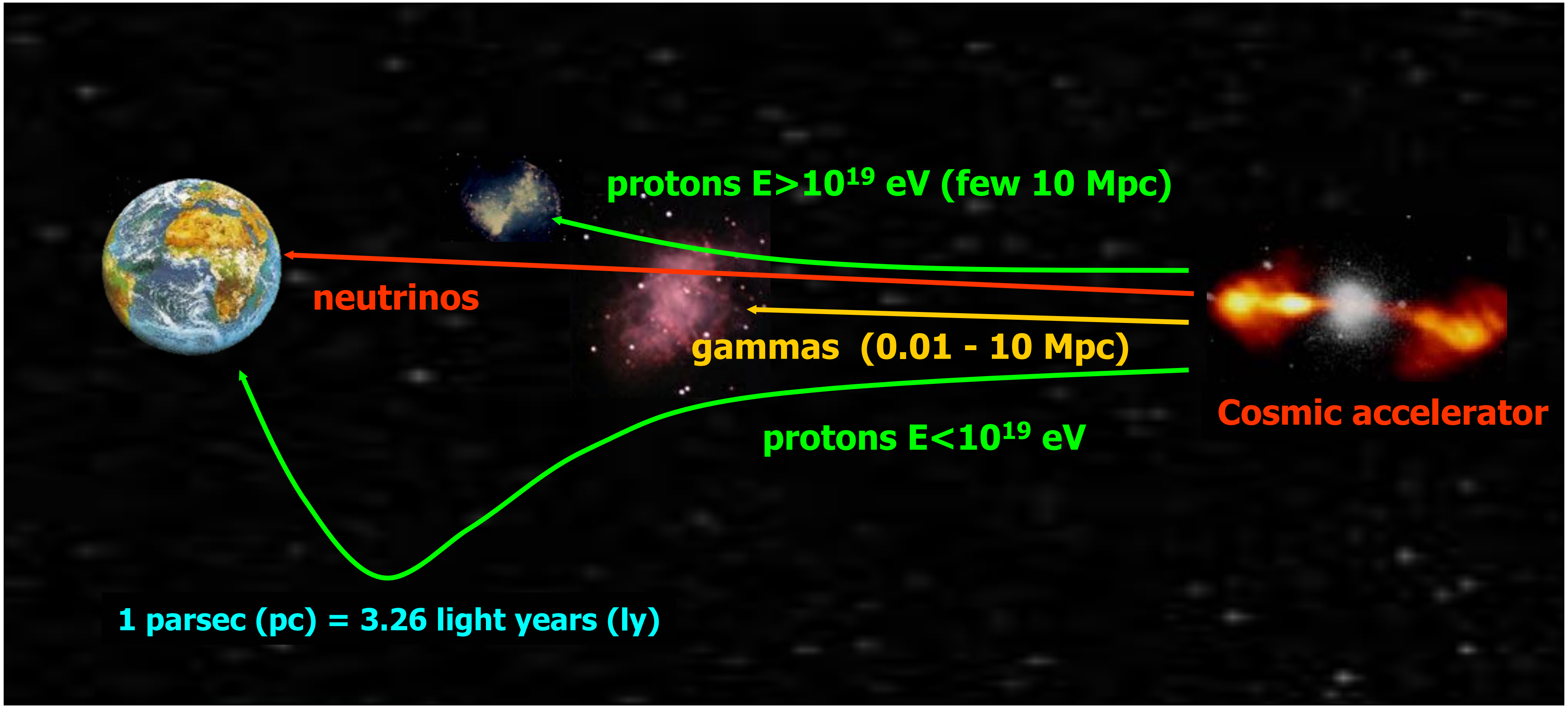
$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\,\gamma + Y$$

Cosmic rays

- Cosmic ray acceleration yields neutrinos and gammas!
- … but gammas also from purely leptonic processes

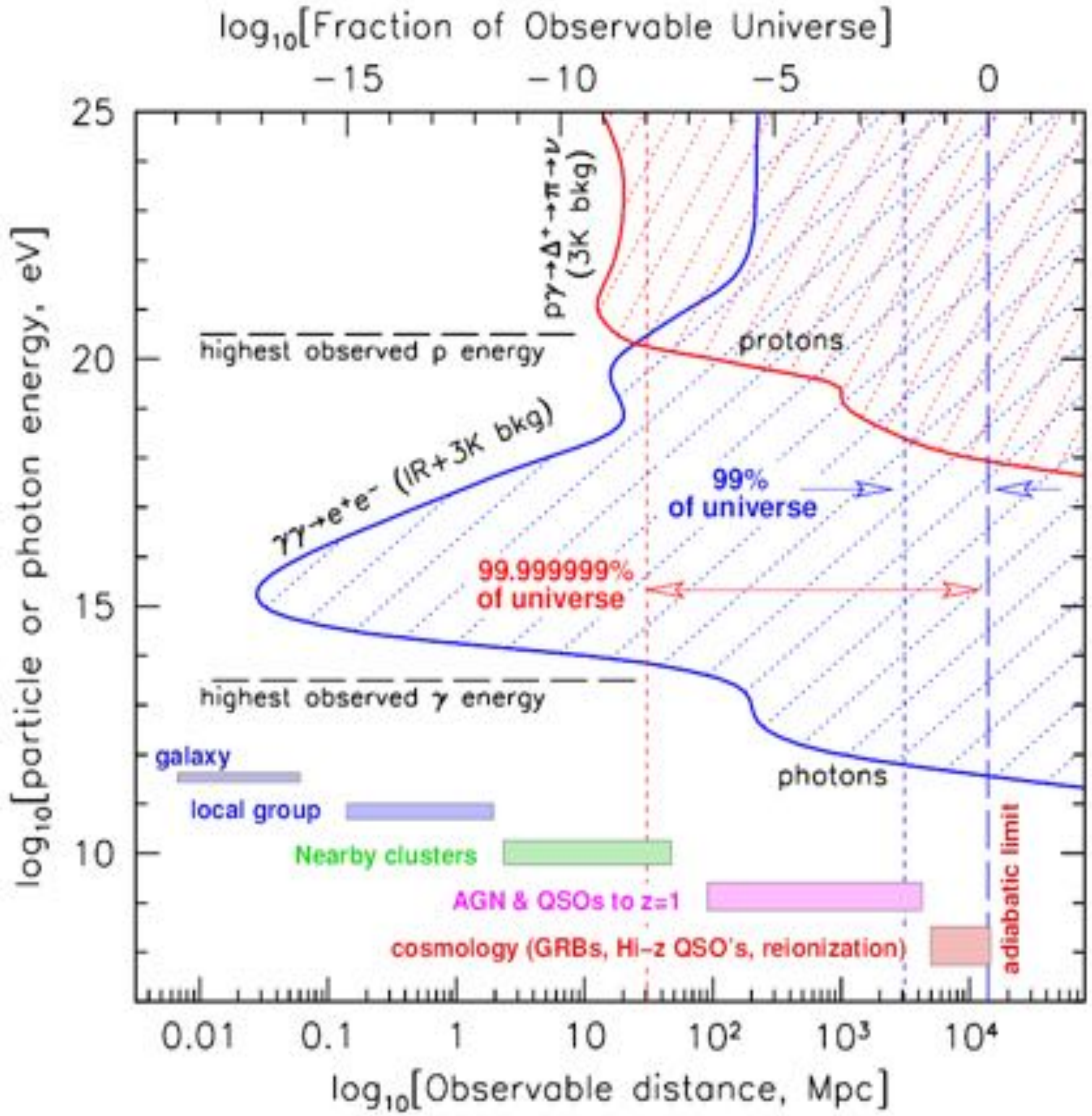


Particle Propagation in the Universe



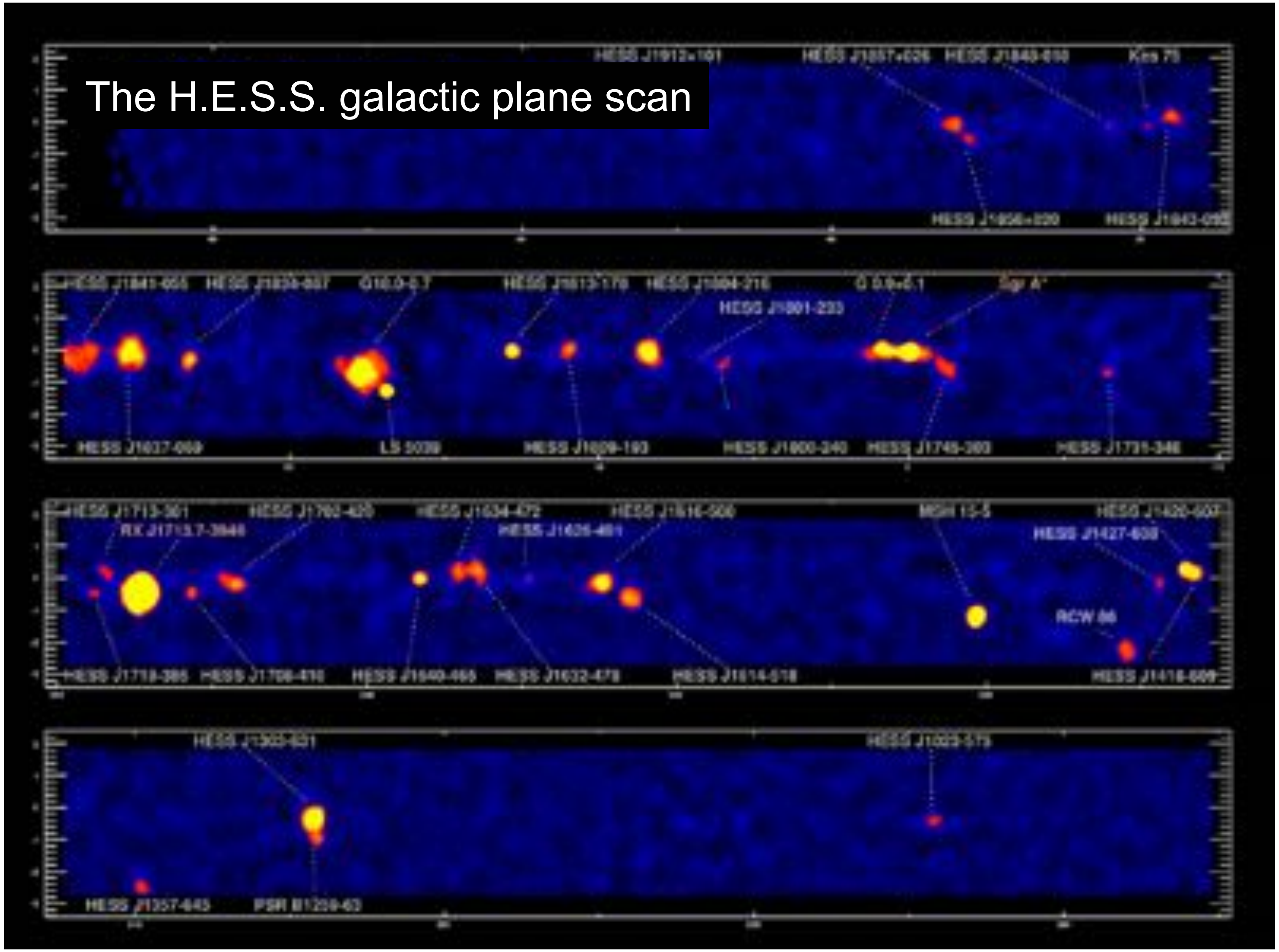
Photons: absorbed on dust and radiation;
Protons/nuclei: deviated by magnetic fields, reactions with radiation (CMB)

Transparency of the Universe



- Only neutrinos can "see" beyond the local Universe at energies above 100 TeV
- Only neutrinos can escape from dense environments
- Only neutrinos can unambiguously prove hadronic acceleration

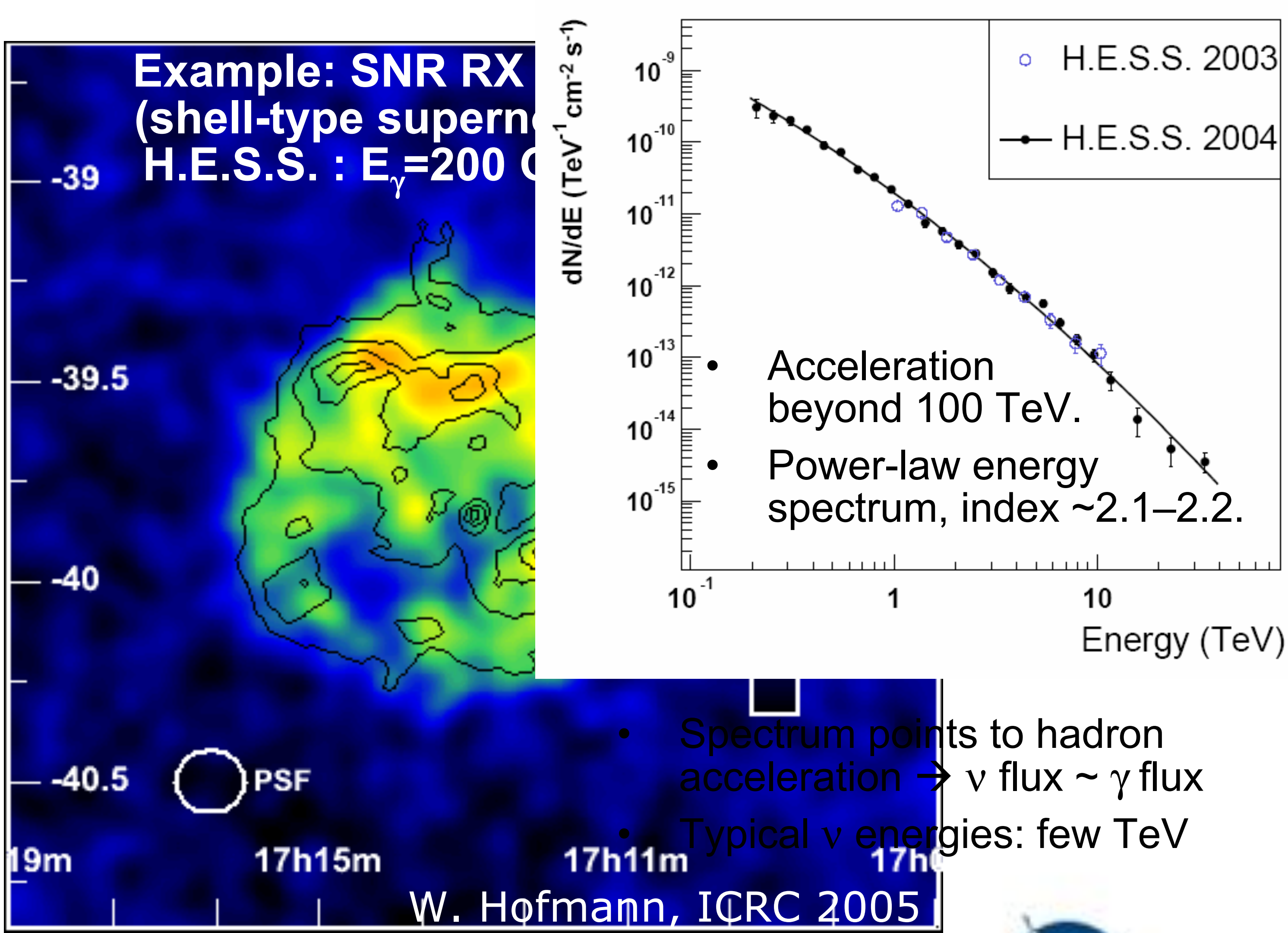
High-Energy γ Sources in the Galactic Disk



Status 2007:

- 18 Pulsar wind nebulae
- 7 Shell-type supernova remnants
- 4 Binaries
- 2 Diffuse
- 21 Unknown (no identified counterpart)

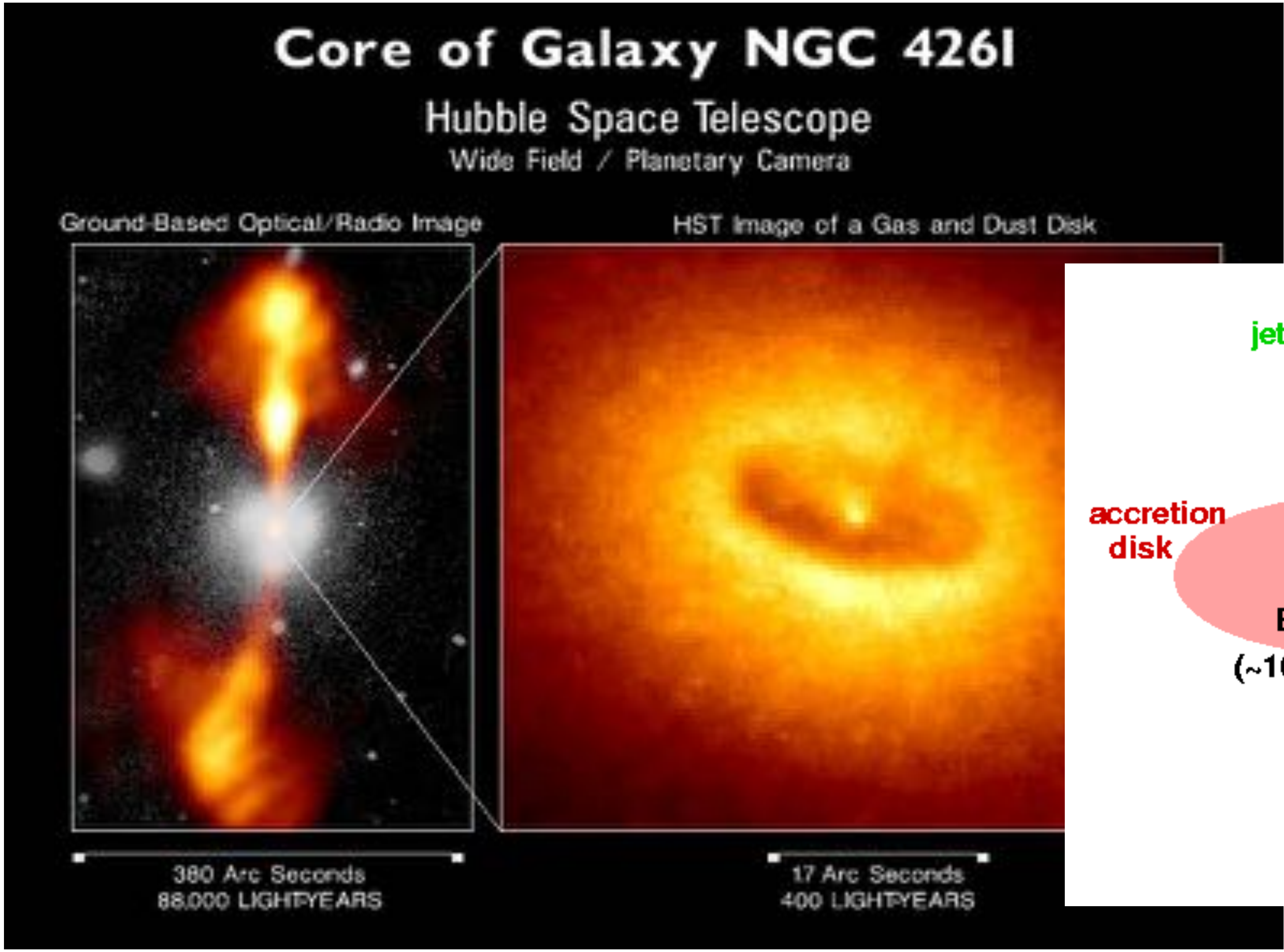
Example: ν's from Supernova Remnants



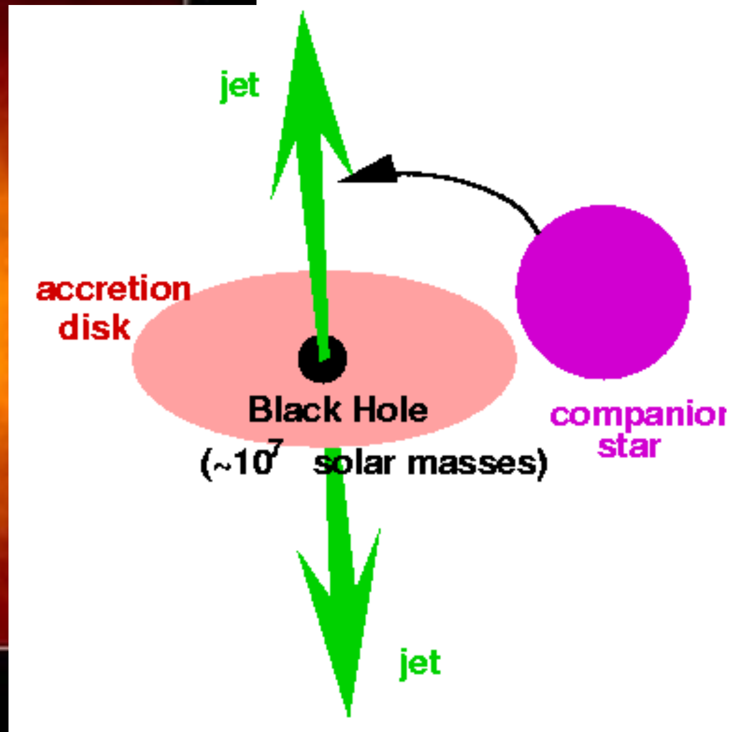
- Acceleration beyond 100 TeV.
- Power-law energy spectrum, index ~2.1–2.2.
- Spectrum points to hadron acceleration → ν flux ~ γ flux
- Typical ν energies: few TeV

W. Hofmann, ICRC 2005

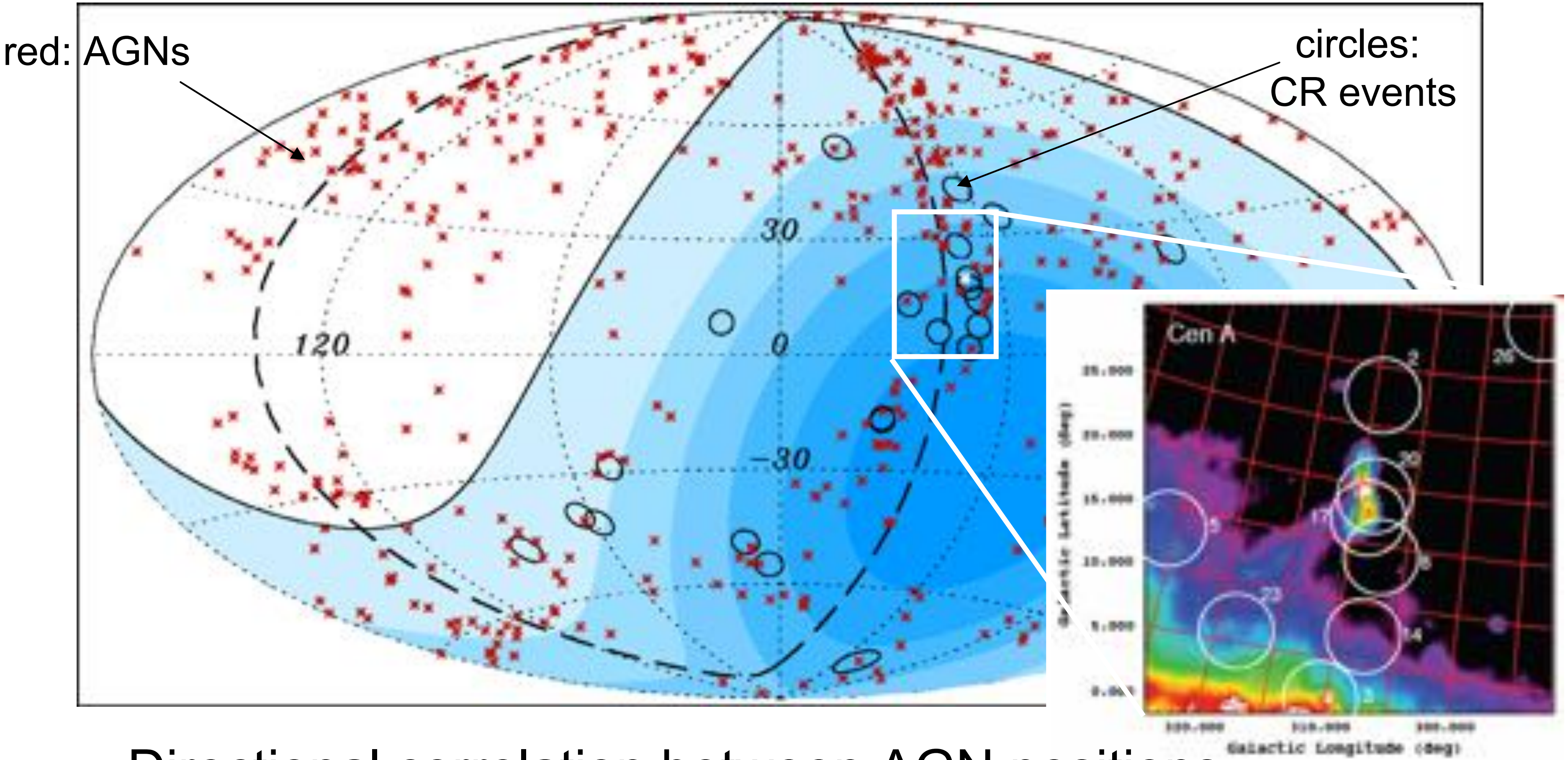
Candidate Accelerators: Active Galactic Nuclei (AGNs)



AGNs are amongst the most energetic phenomena in the universe.



Pierre Auger: First Hints at UHE Cosmic Ray Sources



- Directional correlation between AGN positions and cosmic rays ($E>10^{19.7}$eV, 27 events).
- Interpretation requires care and patience.

Science Cases for Neutrino Telescopes

- Astroparticle physics with neutrinos
  - “Point sources”: Galactic and extragalactic sources of high-energy neutrinos
  - The diffuse neutrino flux
  - Neutrinos from Dark Matter annihilation
- Search for exotics
  - Magnetic monopoles
  - Nuclearites, strangelets, …
- Neutrino cross sections at high(est) energies
- Earth and marine sciences
  - Long-term, continuous measurements in deep-sea
  - Marine biology, oceanography, geology/geophysics, …

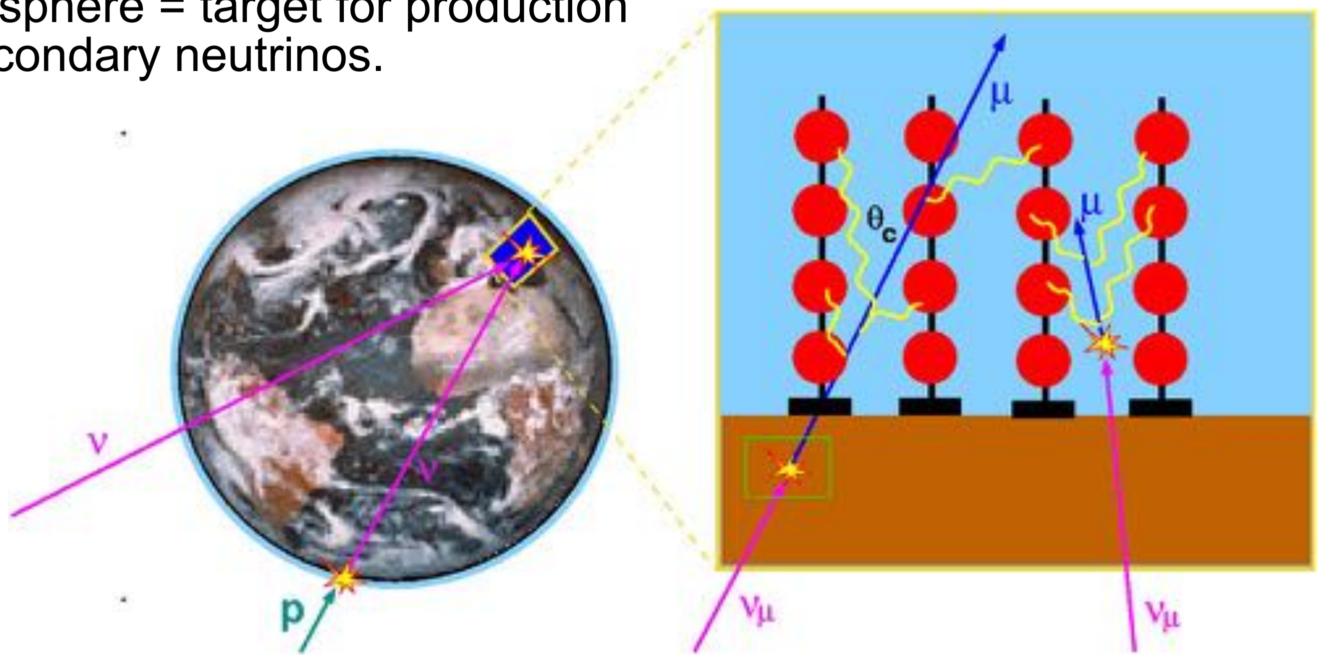
The Principle of Neutrino Telescopes

Role of the Earth:

- Screening against all particles except neutrinos.
- Atmosphere = target for production of secondary neutrinos.

Cherenkov light:

- In water: $\theta_C \approx 43°$
- Spectral range used: ~ 350-500nm.

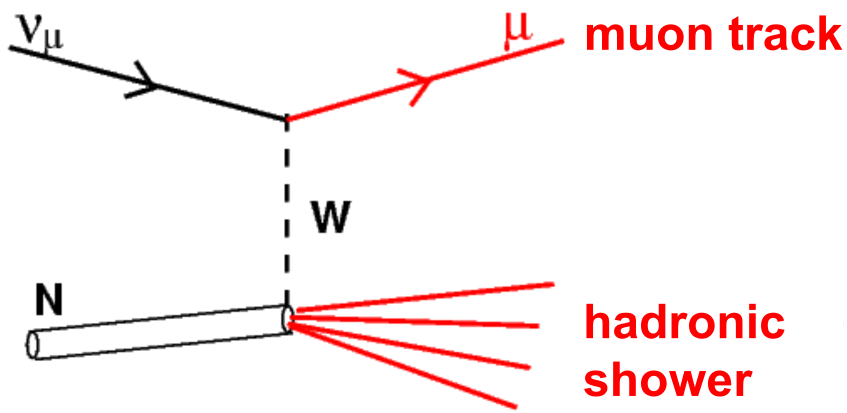


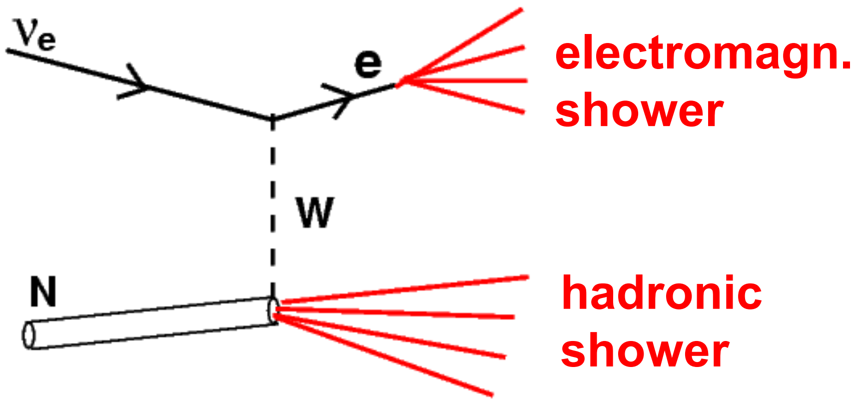
Angular resolution in water:

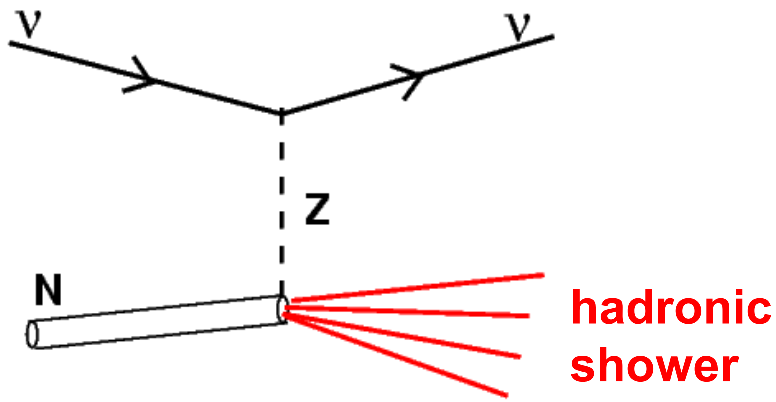
- Better than ~0.3° for neutrino energy above ~10 TeV, 0.1° at 100 TeV
- Dominated by angle(ν,μ) below ~10 TeV (~0.6° at 1 TeV)

Neutrino Interaction Signatures

- Neutrinos mainly from π-μ-e decays, roughly $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$;
- Arrival at Earth after oscillations: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$;
- Key signature: muon tracks from ν_μ charged current reactions (few 100m to several km long);
- Electromagnetic/hadronic showers: “point sources” of Cherenkov light.

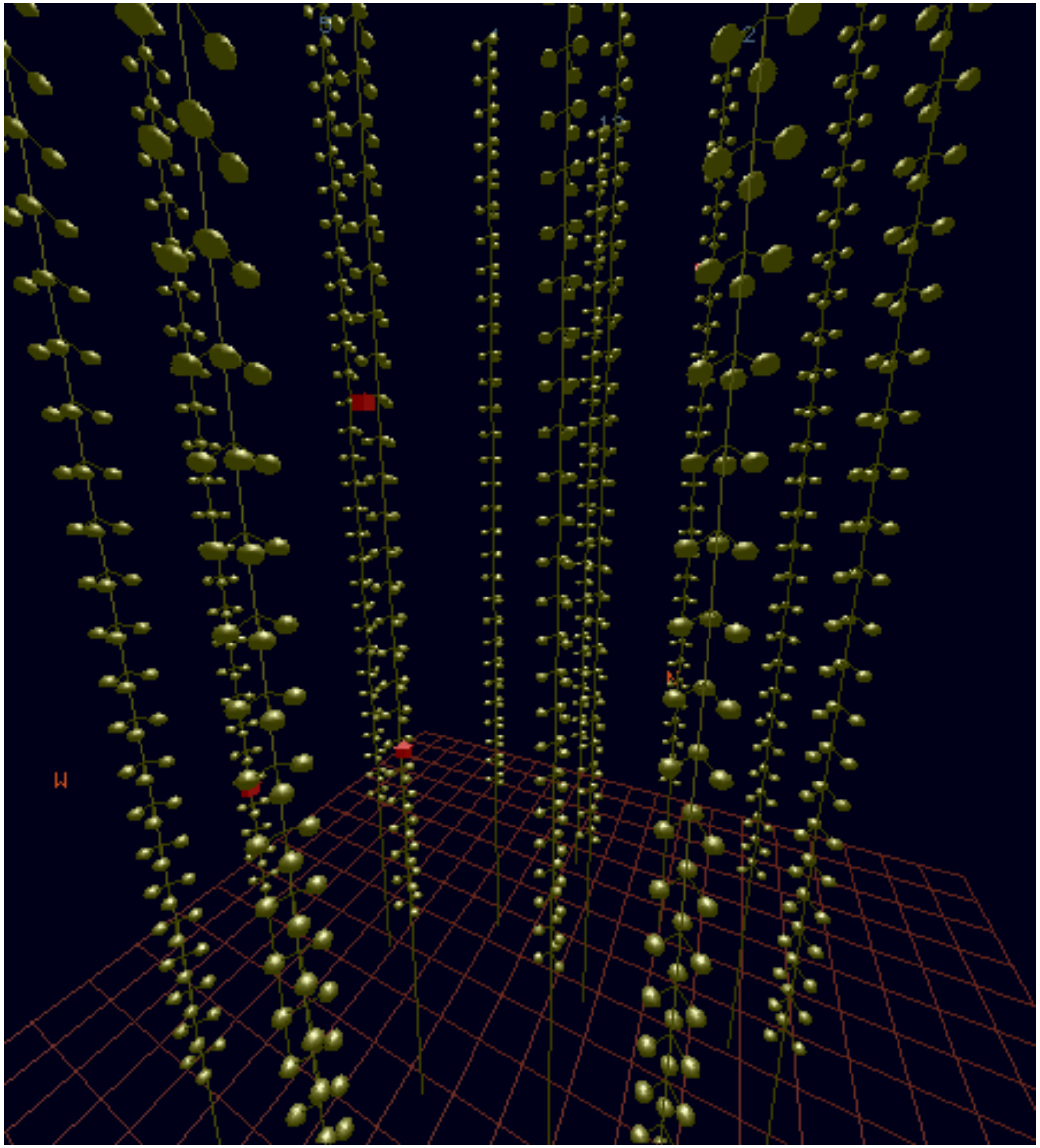






Muon Reconstruction

- The Cherenkov light is registered by the photomultipliers with nanosecond precision.
- From time and position of the hits the direction of the muon can be reconstructed to some 0.1°.
- Minimum requirement: 5 hits … in reality rather 10 hits.
- Position calibration to ~10cm required (acoustic methods).



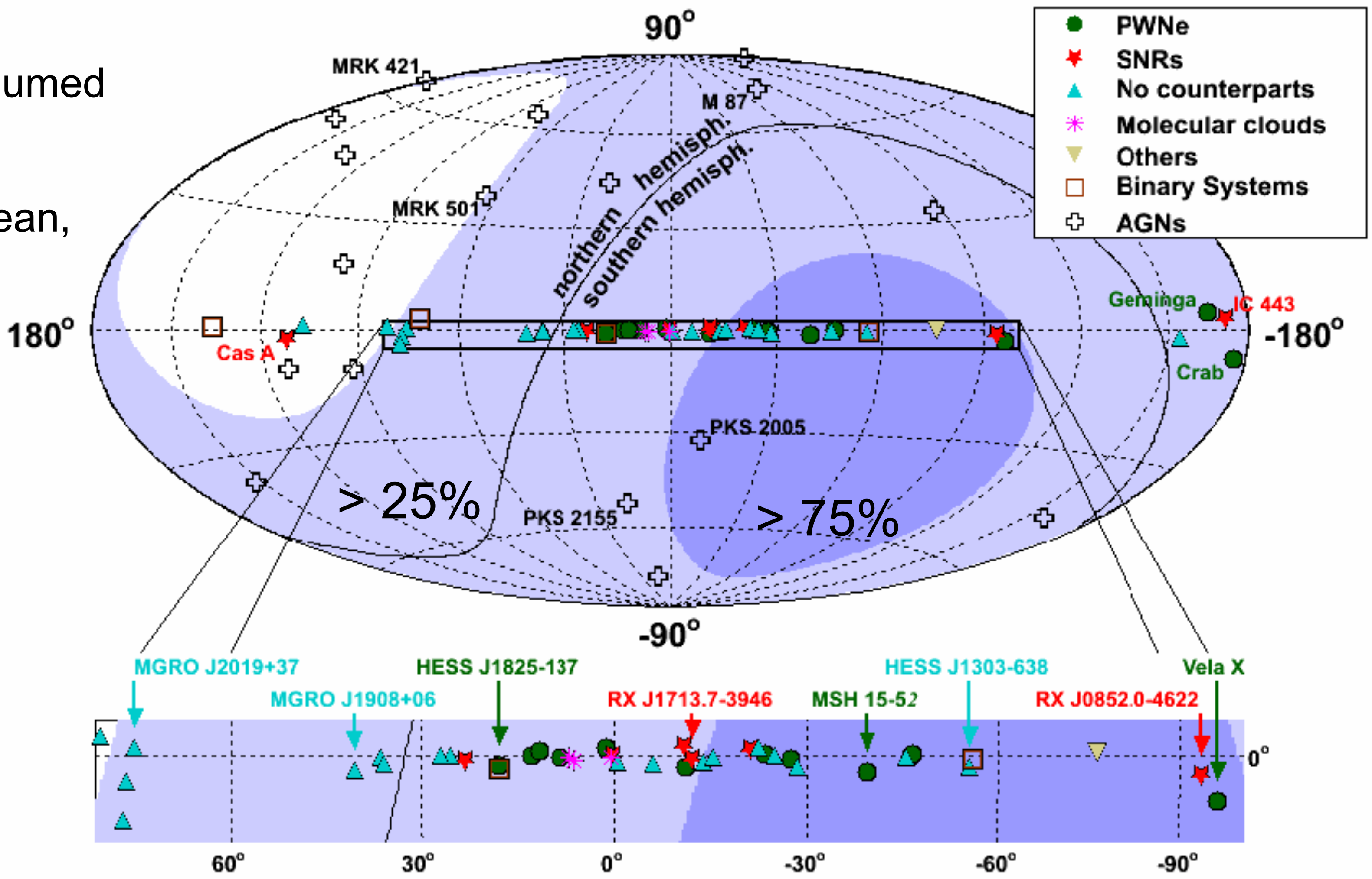
1.2 TeV muon traversing the detector.

The Neutrino Telescope World Map

South Pole and Mediterranean Fields of View

2π downward sensitivity assumed

In Mediterranean, visibility of given source can be limited to less than 24h per day

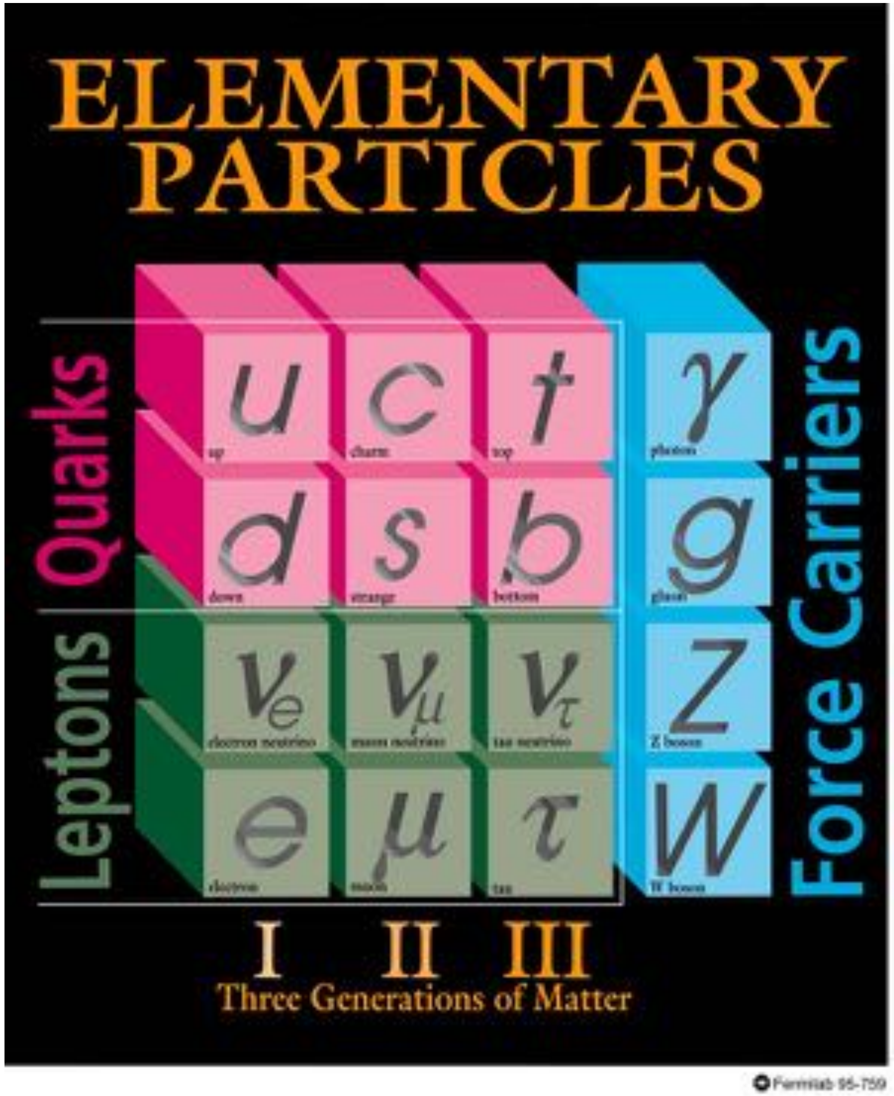


The Neutrino and its Interactions

A few historical facts

- 1930: Postulated by Pauli
  (energy/momentum, angular momentum in β decay)
- 1953: Discovery (Cowan & Reines)
- 1956: Helicity(ν)=-1 (parity violating)
- 1962: Neutrino flavours ($\nu_e \neq \nu_\mu$)
- 1967: Theory of electroweak interactions
  (Glashow, Salam, Weinberg)
- 1990: 3 light neutrino flavours (LEP, Z resonance)
- 1998: neutrino oscillations → neutrino mass
  discovery by Super-Kamiokande (atmospheric ν)
  longstanding hints from solar neutrinos

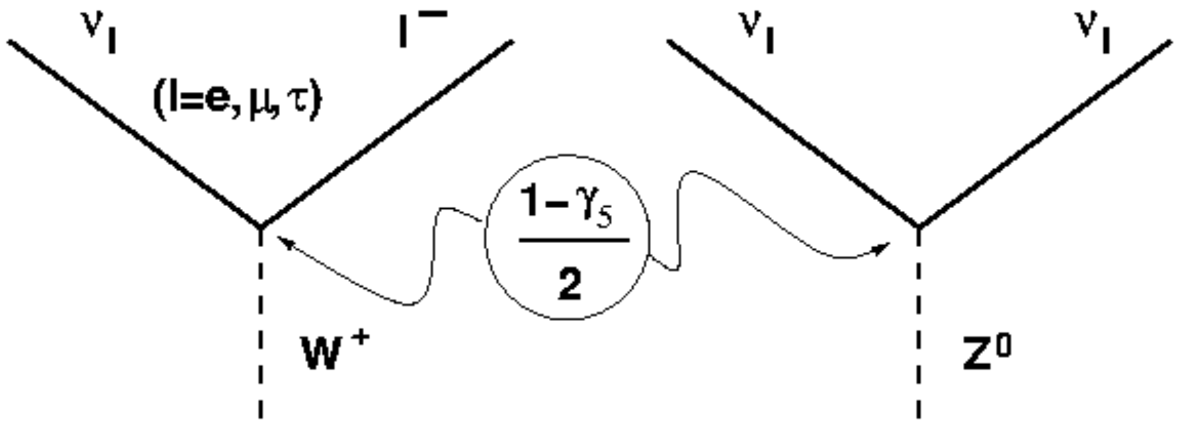
The Standard Model of particle physics



- Quarks (Spin ½):
  - subject to electroweak and strong interaction ("nuclear forces")
  - constituents of hadrons
    baryons: |qqq>
    mesons: $|q\bar{q}\rangle$
- Leptons (Spin ½):
  - only electroweak interaction
  - 3 different neutrinos
- Force carriers (Spin 1):
  - quanta of interaction fields

Neutrino properties (in the Standard Model)

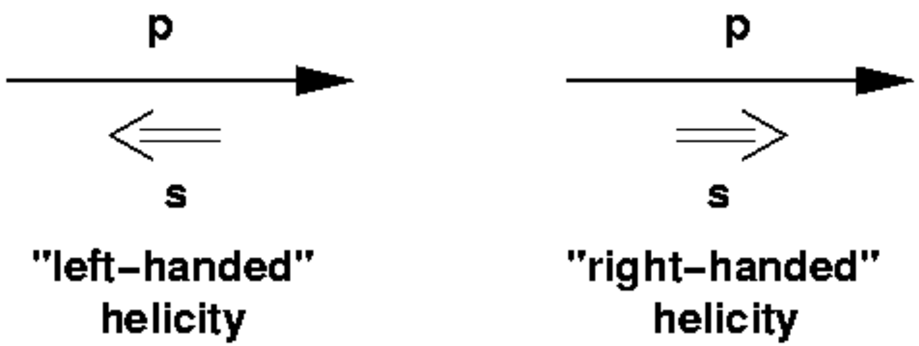
- Spin = ½
- Stable
- Charge = 0, magnetic moment = 0
- Mass: Was long thought to be = 0 (it is > 0 but tiny)
- Only weak interactions (conserve e, μ, τ numbers):



charged current neutral current

Helicity, chirality and mass (1)

- $(1-\gamma_5)/2$ = projection operator (chirality)
  produces "left-handed" chirality state (ν_L)
- Weak interaction exclusively couples to
  left-handed neutrinos (ν_L) and right-handed anti-neutrinos ($\bar{\nu}_R$)
- Why these names?
  Particles with mass = 0 have chirality = helicity



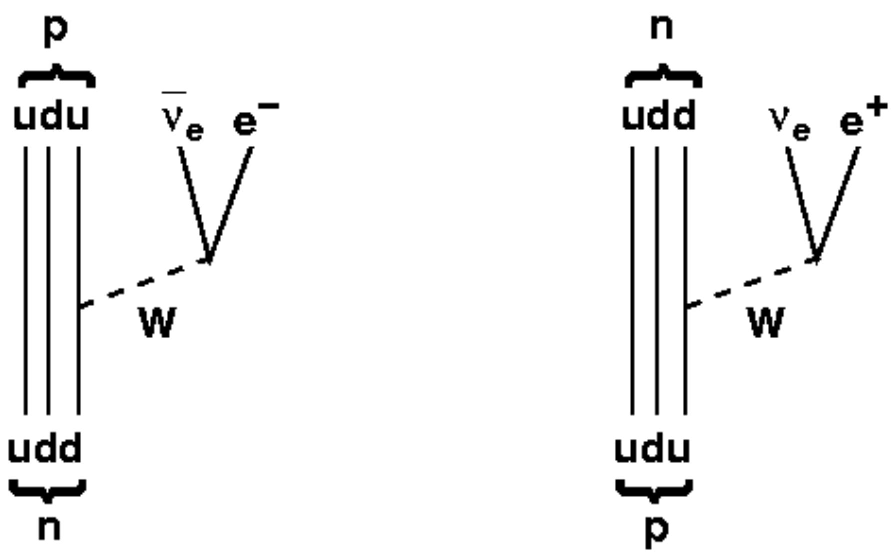
- Particles with mass > 0 have probability $1-\beta$ for "wrong helicity"

Helicity, chirality and mass (2)

- For all practical purposes (in this lecture!):
  neutrinos have spin anti-parallel to momentum
  anti-neutrinos have spin parallel to momentum
- In the Standard Model, there is no ν_R state!
- What about other fermions?
  - When coupling to W bosons: Well-defined chirality!
    However: They are heavier → (1-β) is smaller
  - Coupling to Z bosons: unequal mix of chiralities
  - Coupling to photon or gluon: “chirality-blind”

Neutrino production: β decay

- Known and studied for more than 100 years
- Principal processes: $n \rightarrow p + e^- + \bar{\nu}_e$ or $p \rightarrow n + e^+ + \nu_e$ (n may, p must be bound in nucleus)
- Feynman graphs:

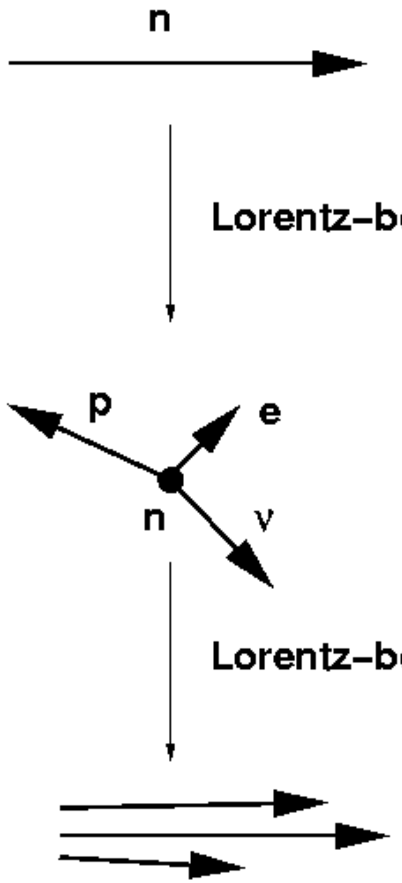


Questions to you

- Which type(s) of neutrinos come from the Sun?
  And from nuclear power plants?
- How many solar neutrinos are in your body at any given moment?
  Input: Sun produces 1 neutrino / 13.5 MeV fusion energy
  assume that 100% of this energy are radiated
  solar constant = 1.36 kW/m^2
  distance Earth-Sun: 1.5 x 10^8 km

Example kinematics: Neutron decay

Assume decay in flight of neutron (Lorentz factor $\gamma >> 1$):



$(E,p) = (\gamma M_n, \gamma\beta M_n)$

Lorentz–boost to n rest frame

max. momentum/energy of neutrino:
$M_n - M_p - m_e = 0.78$ MeV

Lorentz–boost to observer frame

typical energy of proton:
$\gamma \times M_p \sim$ neutron energy

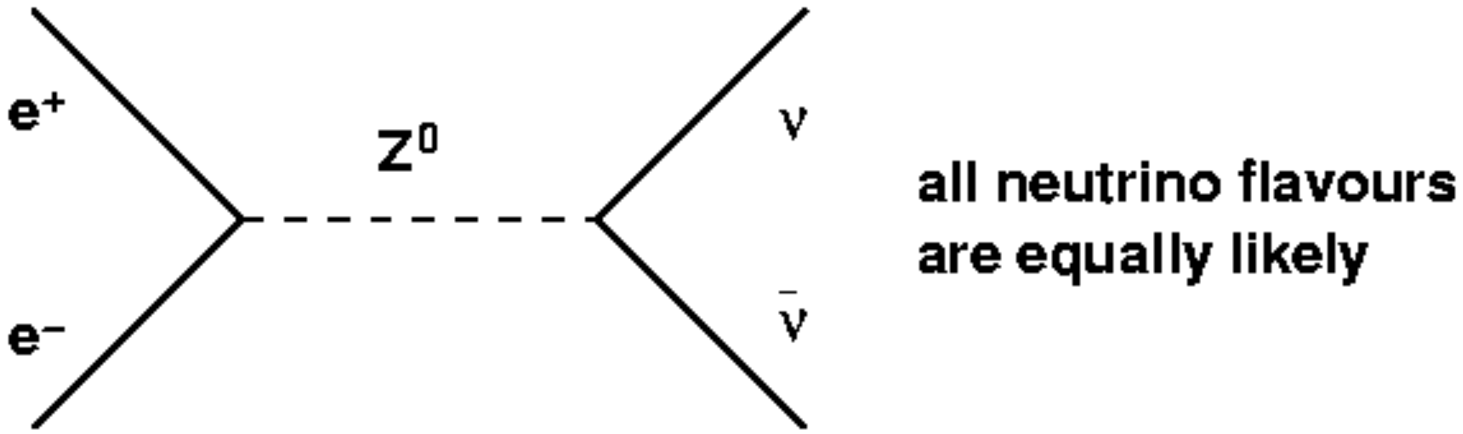
max. momentum/energy of neutrino:
$\gamma(1+\beta) \times 0.78$ MeV $\sim$ neutron energy / 1000

Neutrino production: π and K decays

- The lightest charged mesons can only decay through weak interaction:
  $\pi^+ = |u\bar{d}> \rightarrow \mu^+ + \nu_\mu$ and $\pi^- = |d\bar{u}> \rightarrow \mu^- + \bar{\nu}_\mu$ (~100%)
  $K^+ = |u\bar{s}> \rightarrow \mu^+ + \nu_\mu$ and $K^- = |s\bar{u}> \rightarrow \mu^- + \bar{\nu}_\mu$ (63%)
- Kinematics: $E_\nu(\text{from } \pi) < 0.25 \times E_\pi$
  $E_\nu(\text{from K}) < 0.78 \times E_K$
- π and K are copiously produced in any high-energy hadronic interaction. Automatically, there are also $\pi^0 \rightarrow \gamma + \gamma$ decays.
- The muons co-produced with the neutrinos may decay and produce further neutrinos:
  $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$ and $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

Neutrinos from leptonic processes

- Neutrinos may be pair-produced in dense, high-energy electronic plasmas:



- Requires at least T ~ 1 MeV ~ 10^{10} K
- Important during Supernova explosions, but negligible for dilute environments

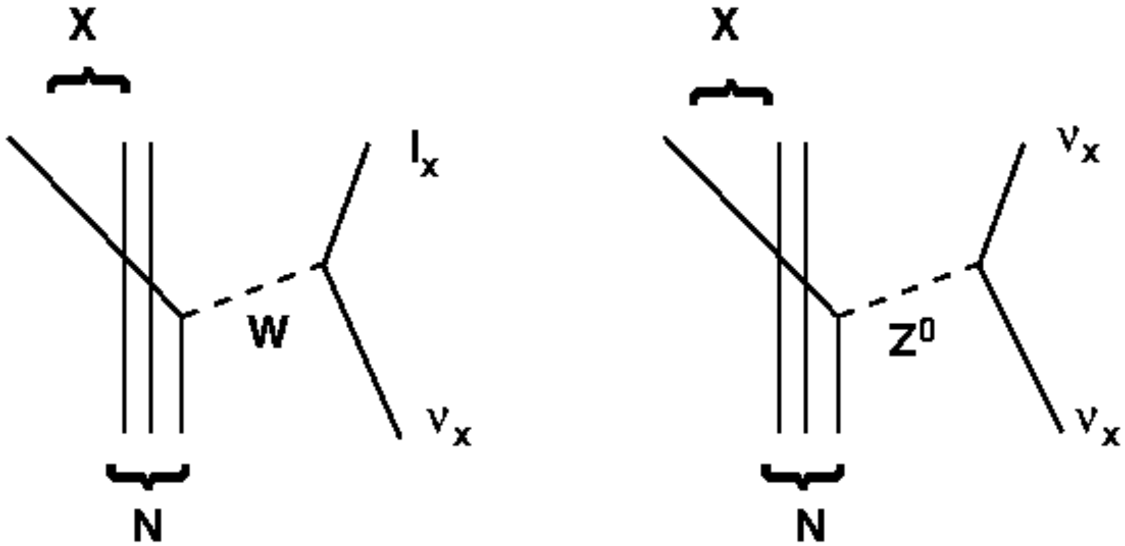
Neutrino interactions with nucleons / nuclei

reaction	energy threshold	type
$\nu_x + N,A \rightarrow \nu_x + N,A$	0	NC elastic scattering
$\nu_x + A \rightarrow l_x + A$	few MeV + m_l	CC coherent scattering
$\bar{\nu}_e + p \rightarrow e^+ + n$	few MeV	CC quasi-elastic scattering (also for nuclei)
$\nu_x + N \rightarrow l_x + N^* / \nu_x + N^*$	few 100 MeV + m_l	resonance production
$\nu_x + N,A \rightarrow l_x + X$	few GeV	CC deep-inelastic scattering
$\nu_x + N,A \rightarrow \nu_x + X$		NC deep-inelastic scattering

- Legend: N = nucleon (p, n)
  A = nucleus
  x = flavour tag (e, μ, τ)
  X = many-particle hadronic system

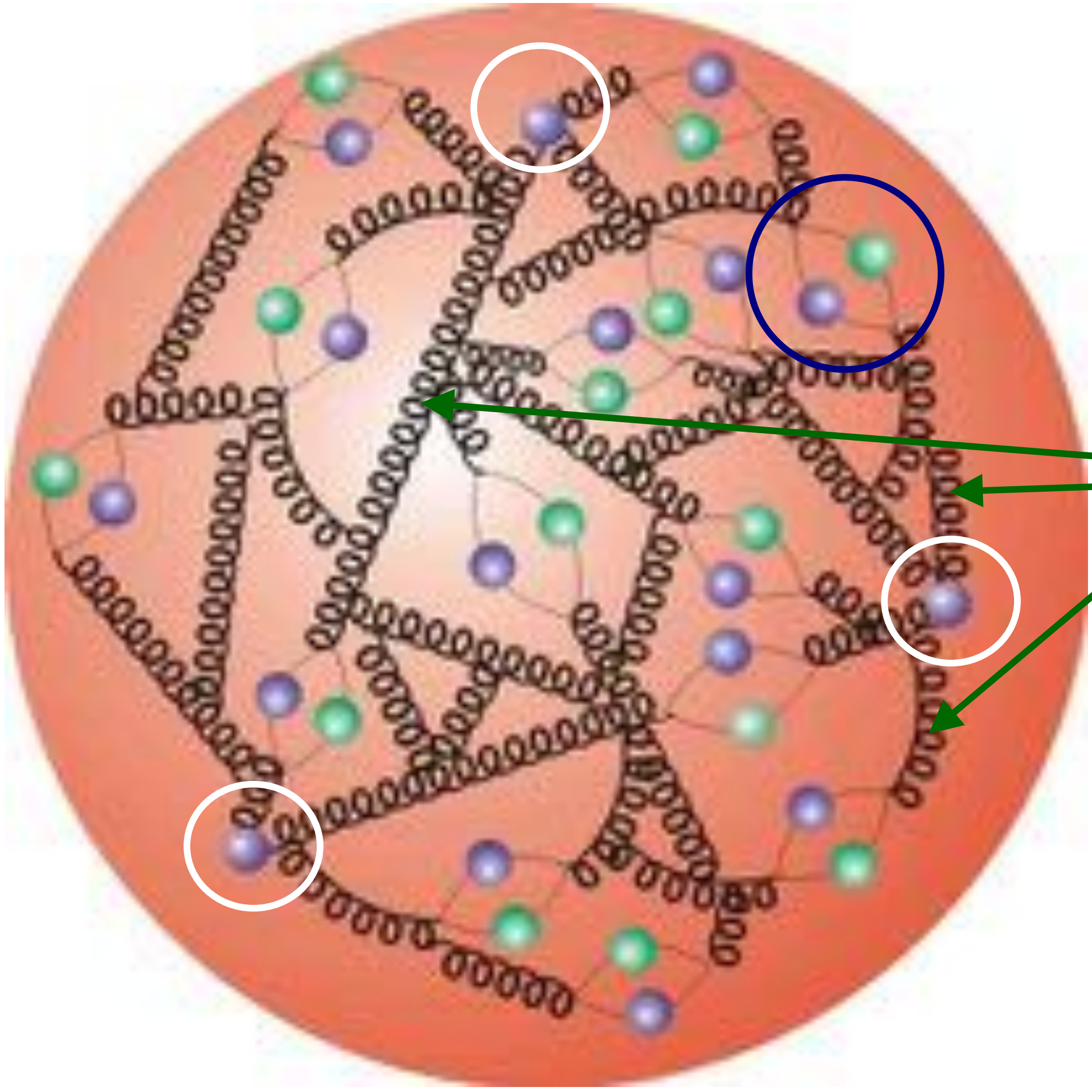
Neutrino deep-inelastic scattering

- Dominant process for neutrino energies above ~100 GeV
- Feynman graphs:



- Fragments of nucleon form new hadrons (hadronisation)
- Reactions investigated in detail in particle physics experiments … only for centre-of-mass energies up to ~300 GeV (HERA)

Quarks, anti-quarks and gluons in the proton



3 valence quarks

Many virtual quark anti-quark pairs (sea quarks)

Many gluons (carriers of the strong force)

… all (anti)quarks,
but not the gluons,
can interact with neutrinos

Particles, anti-particles, conserved numbers

- Each fermion has an anti-particle:

particles	anti-particles
e^-, μ^-, τ^-, ν_e, ν_μ, ν_τ, q (d,u,s,c,b,t)	e^+, μ^+, τ^+, $\bar{\nu}_{\bar{e}}, \bar{\nu}_\mu, \bar{\nu}_\tau$, $\bar{q}$ ($\bar{d}, \bar{u}, \bar{s}, \bar{c}, \bar{b}, \bar{t}$)

- There are conservation laws:

conserved number	name	remarks
$3(N(q)-N(\bar{q}))$	baryon number	in SM but not in Universe
$N(l^-)+N(\nu)-N(l^+)-N(\bar{\nu})$	lepton number	
same for e, μ, τ	e, μ, τ number	not in ν oscillations

Neutrino deep-inelastic cross section (1)

- Variables:
  x = fraction of nucleon momentum carried by quark (0<x<1)
  y = fraction of neutrino momentum transferred to X (0<y<1)
  $Q^2 = xys = -(\text{4-momentum of } W/Z)^2$
- CC cross section for $\nu_l + p \rightarrow l^- + X$ (lowest order, $s < 10^4$ GeV^2):

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2}{\pi} s \left[xd(x) + (1-y)^2 x\bar{u}(x) \right]$$

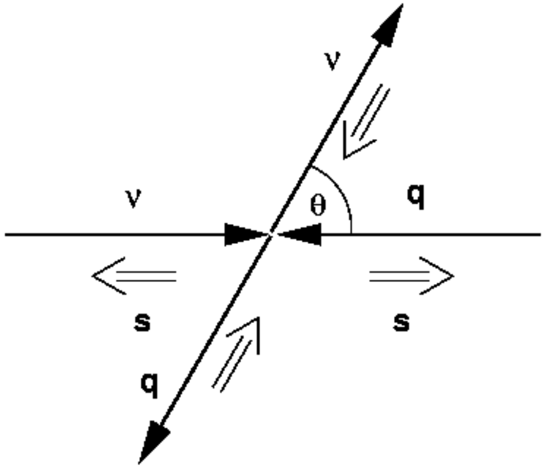
G_F = Fermi constant
= 1.17×10^{-5} GeV^{-2}

$xd(x)$ = momentum distribution of d-type quarks
$x\bar{u}(x)$ = momentum distribution of u-type anti-quarks

Incoherent sum of elastic νq and $\nu\bar{q}$ cross sections!

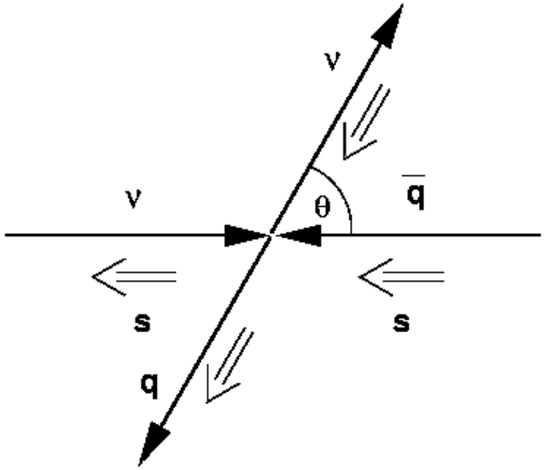
Neutrino deep-inelastic cross section (2)

The origin of the y dependence: Left-handed fermions …



νq or $\bar{\nu}\bar{q}$

Overall spin = 0,
any scattering angle possible

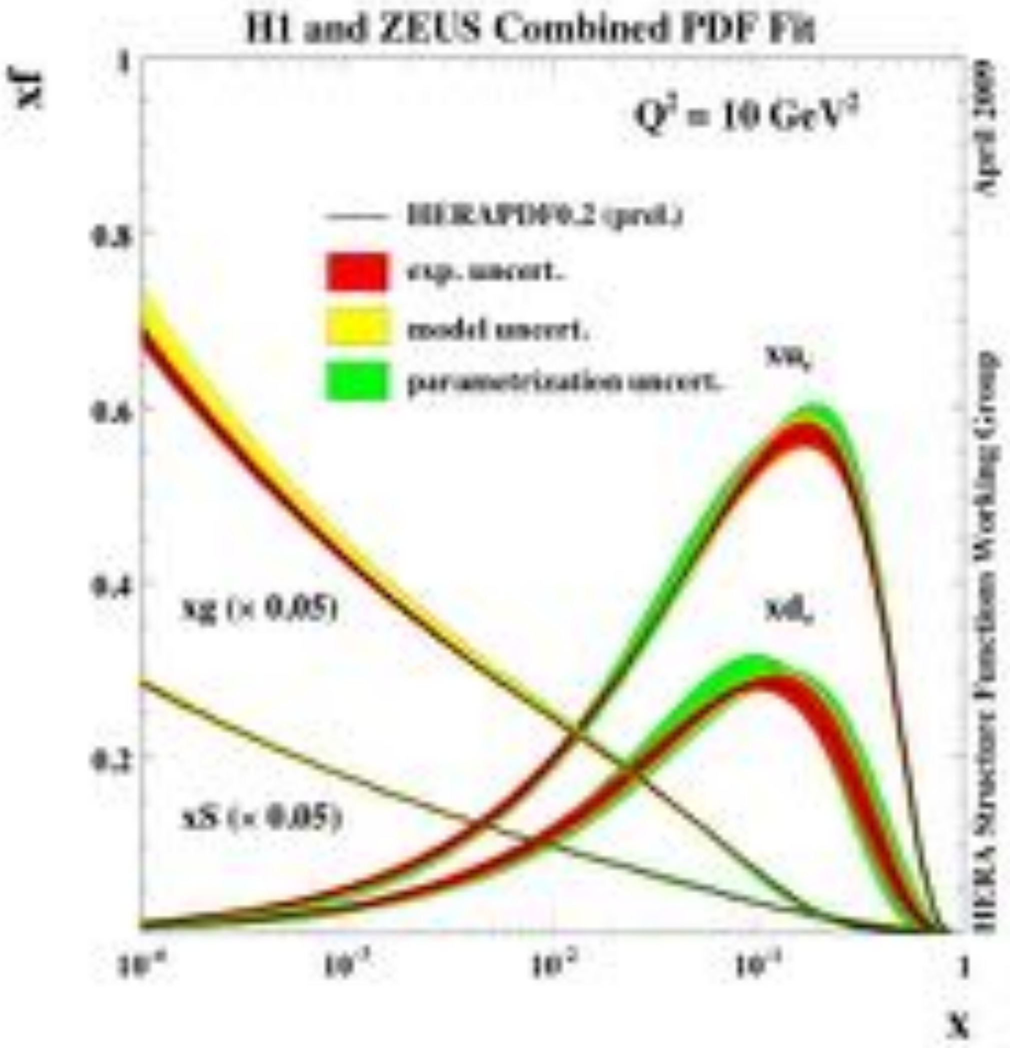


$\nu\bar{q}$ or $\bar{\nu}q$

Overall spin = 1,
large scattering angles suppressed

Neutrino deep-inelastic cross section (3)

The quark and anti-quark distributions



- For fixed x, the distributions also depend on Q^2=xys (QCD effect)
- Experimental measurements "only" down to x~10^{-4}
- Extrapolation to x=0 theoretically difficult, important for νN cross section at highest energies

Neutrino deep-inelastic cross section (4)

- Deep-inelastic scattering on neutrons:

  $u^n(x)=d^p(x)$; $d^n(x)=u^p(x)$; $\overline{u}^n(x)=\overline{d}^p(x)$; $\overline{d}^n(x)=\overline{u}^p(x)$;
  other sea quark and anti-quark distributions are identical

- Deep-inelastic scattering on nuclei:
  - To first approximation: Sum of inelastic scattering on nucleons
  - Usually described by "isoscalar parton distributions":

    $u^I(x)= d^I(x)=[u^p(x)+d^p(x)]/2$ and

    $\overline{u}^I(x)= \overline{d}^I(x)=[\overline{u}^p(x)+\overline{d}^p(x)]/2$

Questions to you

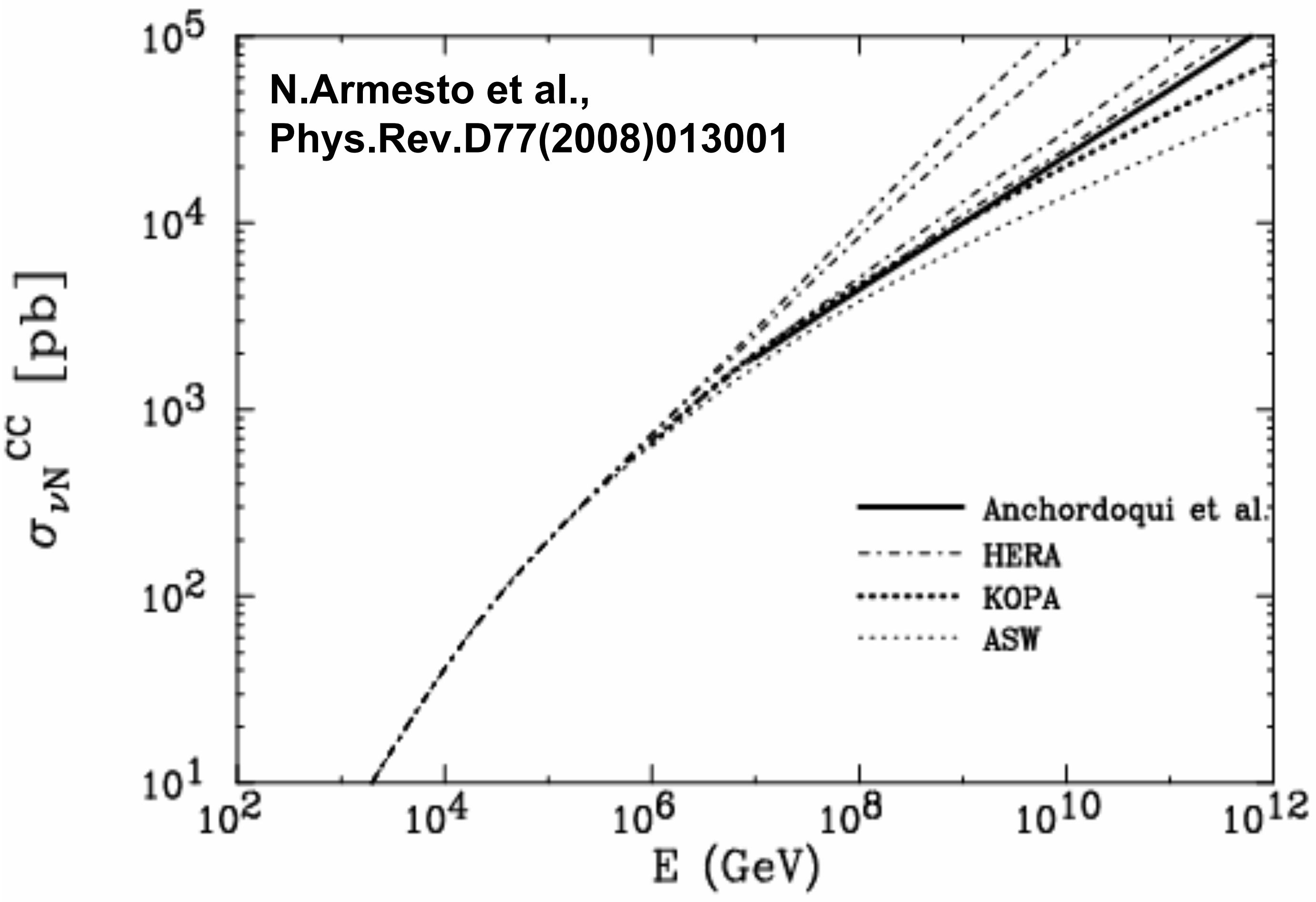
$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2}{\pi} s \left[x d(x) + (1-y)^2 x \bar{u}(x) \right]$$

G_F = Fermi constant
= 1.17×10^{-5} GeV^{-2}

$xd(x)$ = momentum distribution of d-type quarks
$x\bar{u}(x)$ = momentum distribution of u-type anti-quarks

- Show that the total cross section can be written as $\sigma = \sigma_0 E_\nu$
- Estimate the value of σ_0 for νp scattering
  Input: - ~50% of the proton momentum is carried by gluons, the rest by (anti-)quarks
  - 1 GeV^{-2} = 0.389×10^{-31} m^2
- Argue what is the formula for $\bar{\nu}p$ scattering

Neutrino deep-inelastic cross section (5)

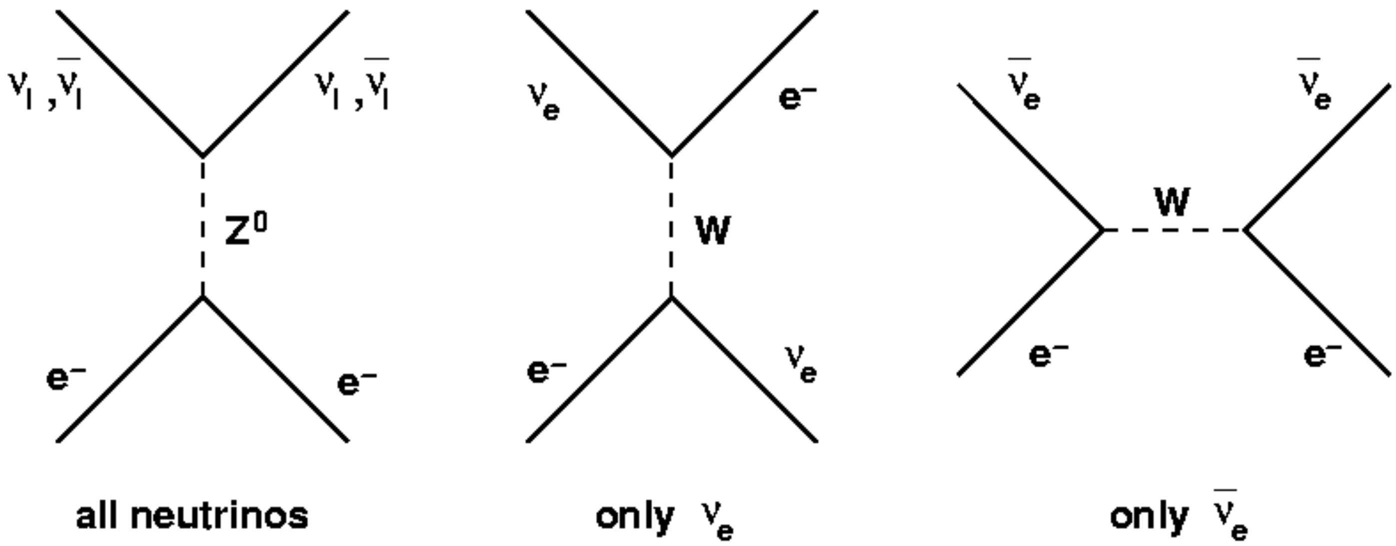


- For E<40TeV, σ~E
- For larger E, roughly $\sigma \sim E^{0.4}$
- Extrapolations uncertain
- Mostly relevant for neutrino astronomy: 10^2-10^7 GeV

Note: 1 pb = 10^{-40} m^2

Neutrino-electron elastic scattering

- Two interactions contribute:



- Different cross sections:

$$\sigma_{\mathrm{el}}[\nu_e e^-, \overline{\nu}_e e^-, \nu_{\mu,\tau} e^-, \overline{\nu}_{\mu,\tau} e^-] = [0.95, 0.40, 0.16, 0.13] \cdot \frac{E_\nu}{\mathrm{MeV}} \times 10^{-44}\,\mathrm{cm}^2$$

important for ν oscillations in matter!

Absorption length for neutrinos

- The average path length for a particle A travelling through a medium of particles B with number density ρ_B is

$$L = 1 / (\rho_B \sigma)$$

  where σ is the AB cross section.

- Order of magnitude for neutrinos:

  $\sigma = 10^{-40}\ m^2$, $\rho = 10^{23}/cm^3$ →
  $L = 10^{11}$ m ~ distance Earth – Sun

- Blessing and curse of neutrino astronomy:
  neutrinos pass through almost everything …
  also through the detector

Questions to you

- What are the mean free path lengths

  - of a 1 TeV ν in iron
  - of a 1 TeV ν in a neutron star

  Input: density of iron = 7.9×10^3 kg/m^3
  density of a neutron star = 3×10^{17} kg/m^3
  cross section ~ 6.7×10^{-43}m^2 x (E/GeV)
  1 GeV = 1.7×10^{-27} kg

- At what neutrino energy does the Earth become opaque to neutrinos?

  Input: $M_E = 6 \times 10^{24}$ kg (assume homogeneous)
  R_E = 6400 km

Neutrino oscillations: How they work

- Basic idea (Pontecorvo, 1957):
  If neutrinos have a (small) mass, their flavour and mass eigenstates can be different:

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U \cdot \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

- U is a unitary 3x3-matrix. If it is non-diagonal, a given flavour state consists of different mass states that develop different in time. This is the origin of neutrino oscillations.

Neutrino oscillations: Their origin

- Basic idea (Pontecorvo, 1957):
  If neutrinos have (small) different masses, their flavour and mass eigenstates can be different:

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- U is a unitary 3x3-matrix. If it is non-diagonal, a given flavour state consists of different mass states that develop differently in time. This is the origin of neutrino oscillations.

A challenge for you:

- Consider the 2-flavour case

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

and show that the probability for a ν_μ to appear at time t when a ν_e was produced at t = 0 is

$$P_{\nu_e \to \nu_\mu}(t) = \sin^2(2\theta) \cdot \sin^2\left(\frac{(m_1^2 - m_2^2)L}{4E_\nu}\right)$$

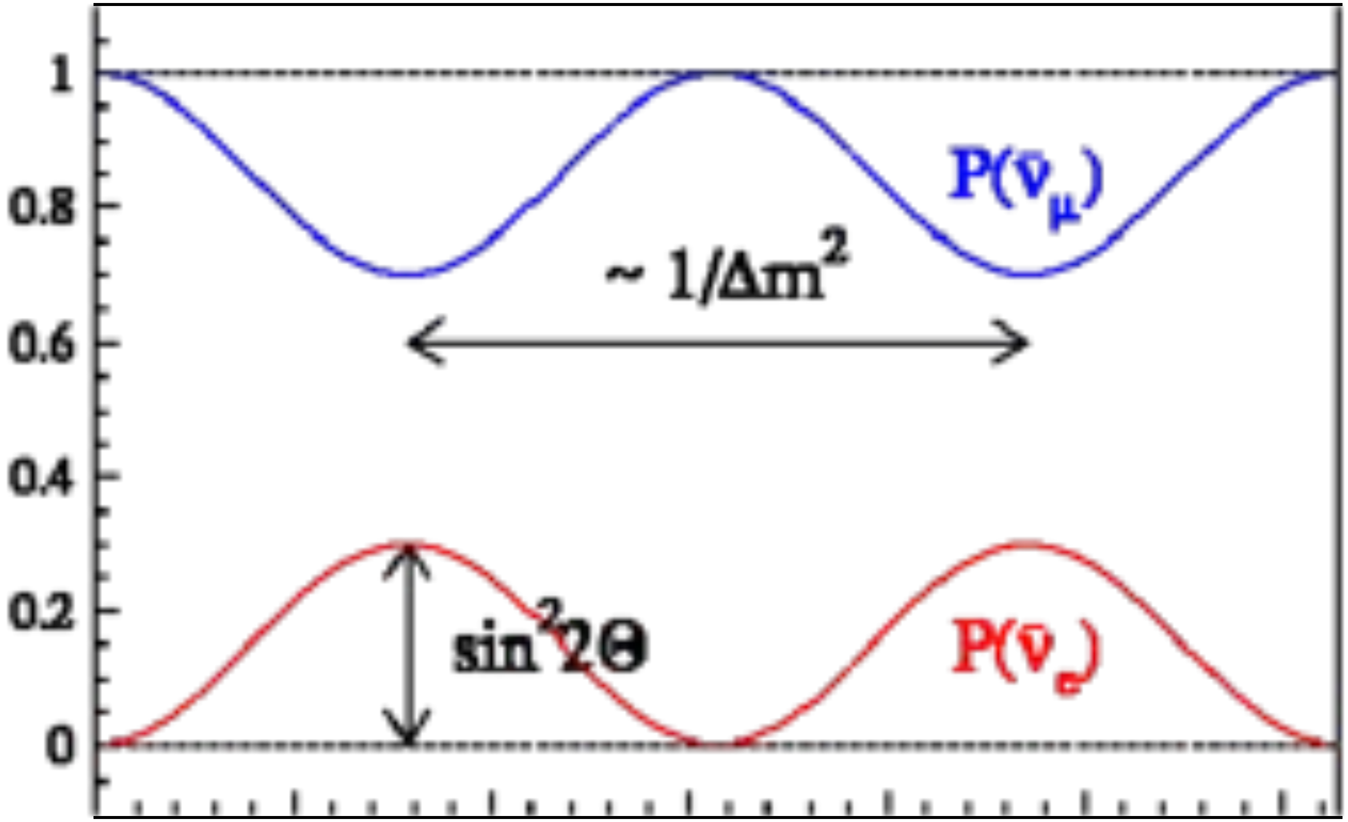
with L = tc.

- Show that the oscillation length is

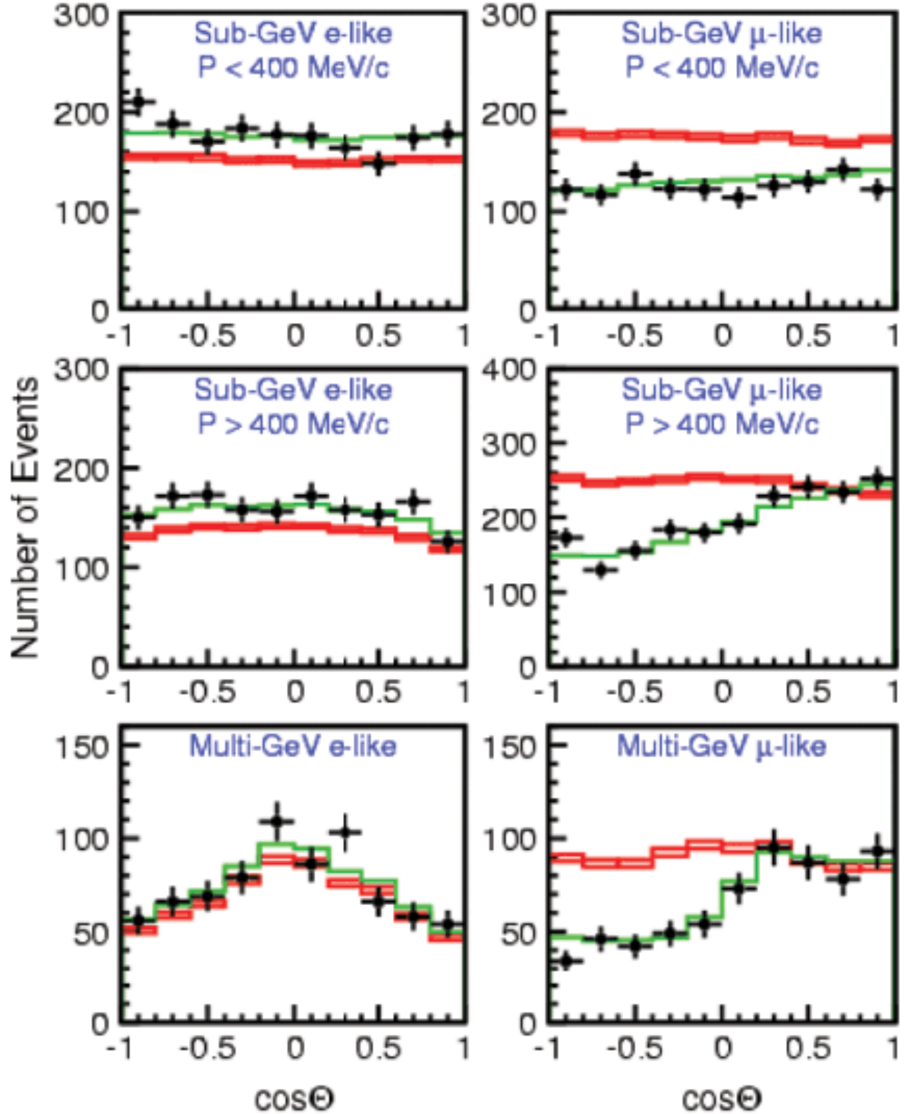
$$L_{\text{osc}} = \frac{4\pi E_\nu}{\Delta m^2} = 2.48 \frac{E_\nu(\text{GeV})}{\Delta m^2(\text{eV}^2)}\,\text{km}$$

Neutrino oscillations: The 2-flavour case

Here an illustration: Assume you produce a ν_μ at t = 0



Neutrino oscillations: Atmospheric neutrinos

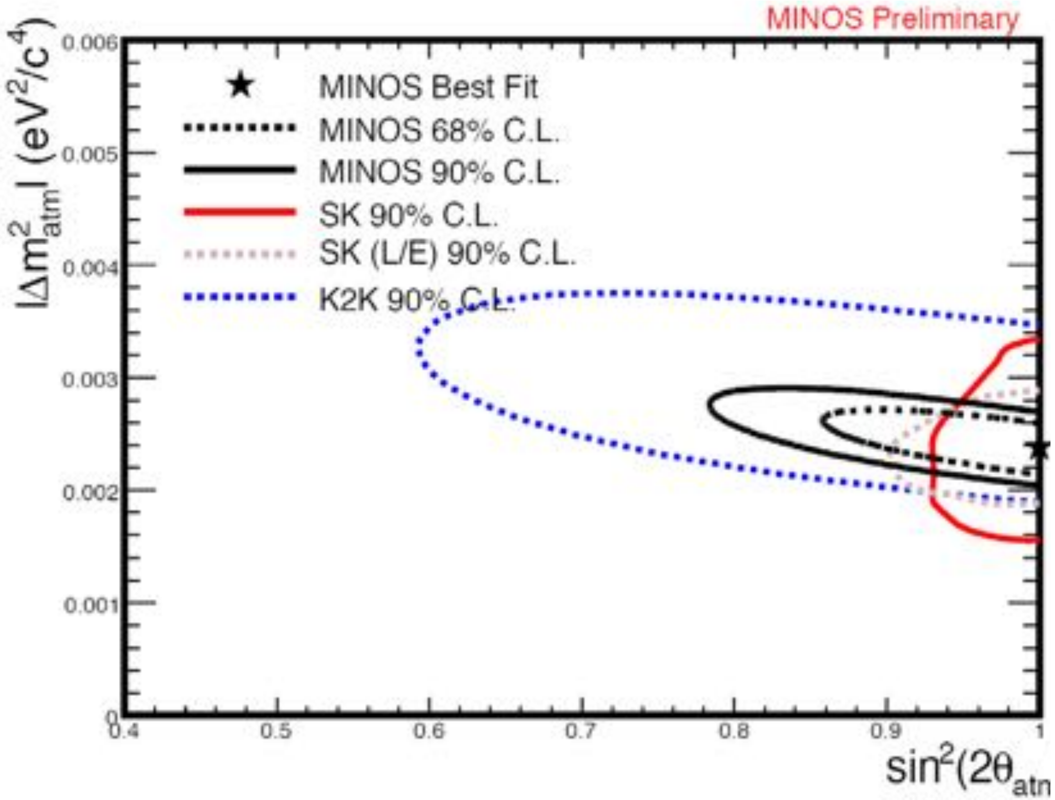


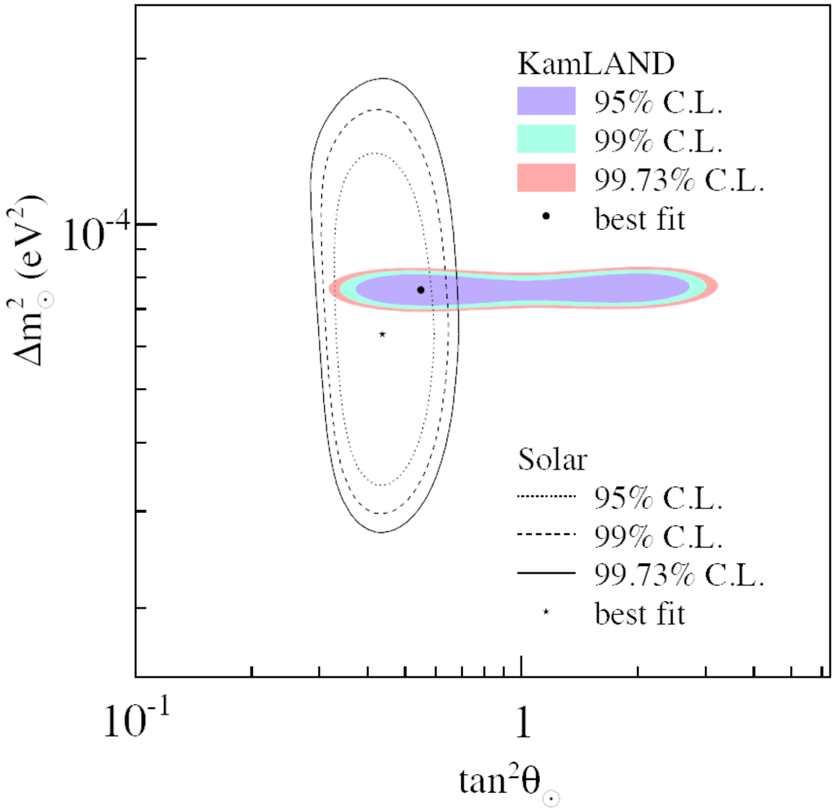
Missing ν_μ from below,
oscillation $\nu_\mu \leftrightarrow \nu_\tau$

Neutrino oscillations: Solar neutrinos

- History: A deficit of solar neutrinos has been observed in various experiments since the 1960's (Homestake)
- Long-standing doubts on viability of measurements and solar model
- Final breakthrough: Observation of "missing neutrinos" in NC mode: $\nu + d \rightarrow \nu + p + n$ (SNO experiment)
  - Neutrino oscillations fully confirmed for solar neutrinos and also for reactor neutrinos (KAMLAND experiment)
  - Matter-induced oscillations in Sun contribute (different cross sections for forward scattering → MSW effect)
- Consistent picture of 3-flavour oscillations is emerging

Neutrino oscillations: Parameters





Parameter values:

$$\theta_{atm} = 45^\circ \pm 7^\circ \qquad \theta_{sol} = 33.9^\circ{}^{+2.4^\circ}_{-2.2^\circ}$$

$$\Delta m^2_{atm} = 2.4^{+0.6}_{-0.5} \times 10^{-3}\,\mathrm{eV}^2 \qquad \Delta m^2_{sol} = 8.0^{+0.6}_{-0.4} \times 10^{-5}\,\mathrm{eV}^2$$

Neutrino oscillations: The 3-flavour picture

- Parameterisation of mixing matrix:

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atm.}} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

with

$$s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij}, \quad \delta = \text{CP-violating phase}$$

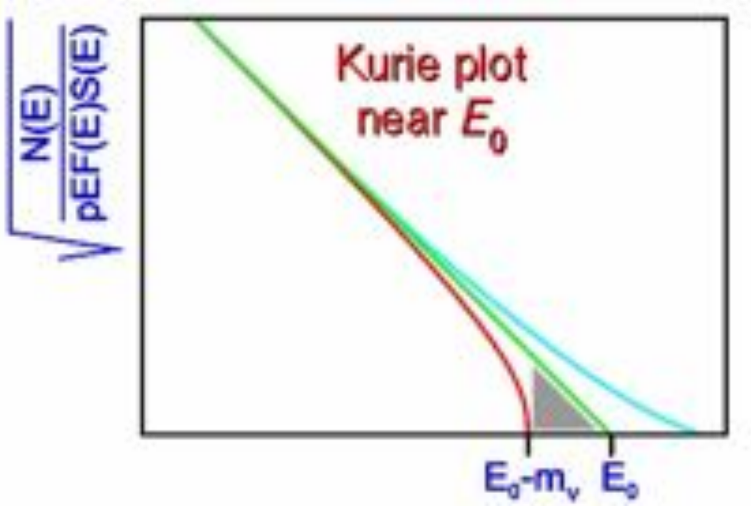
- For the 13-mixing, only upper limits exist.
  In neutrino astronomy, θ_{13}=0 can be assumed.

Neutrino oscillations: Impact on neutrino astronomy

- Neutrino oscillations change flavour ratio on way to Earth.
- Path length >> oscillation length →
  oscillation terms are averaged ($\sin^2(L/L_{osc}) \rightarrow \frac{1}{2}$)
- In most cases, high-energy (anti-)neutrinos are produced from π or K decays
  → flavour ratio $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0
- In this case, at Earth we have
  → flavour ratio $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1
- For neutrino telescopes, ν_μ-CC is the "favourite" channel
  → we would prefer not to have oscillations ☺

What we know about the neutrino mass

- It must be at least of the order $(\Delta m^2)^{1/2} \sim 0.005$ eV
- Direct measurement: Electron spectrum in tritium β decays



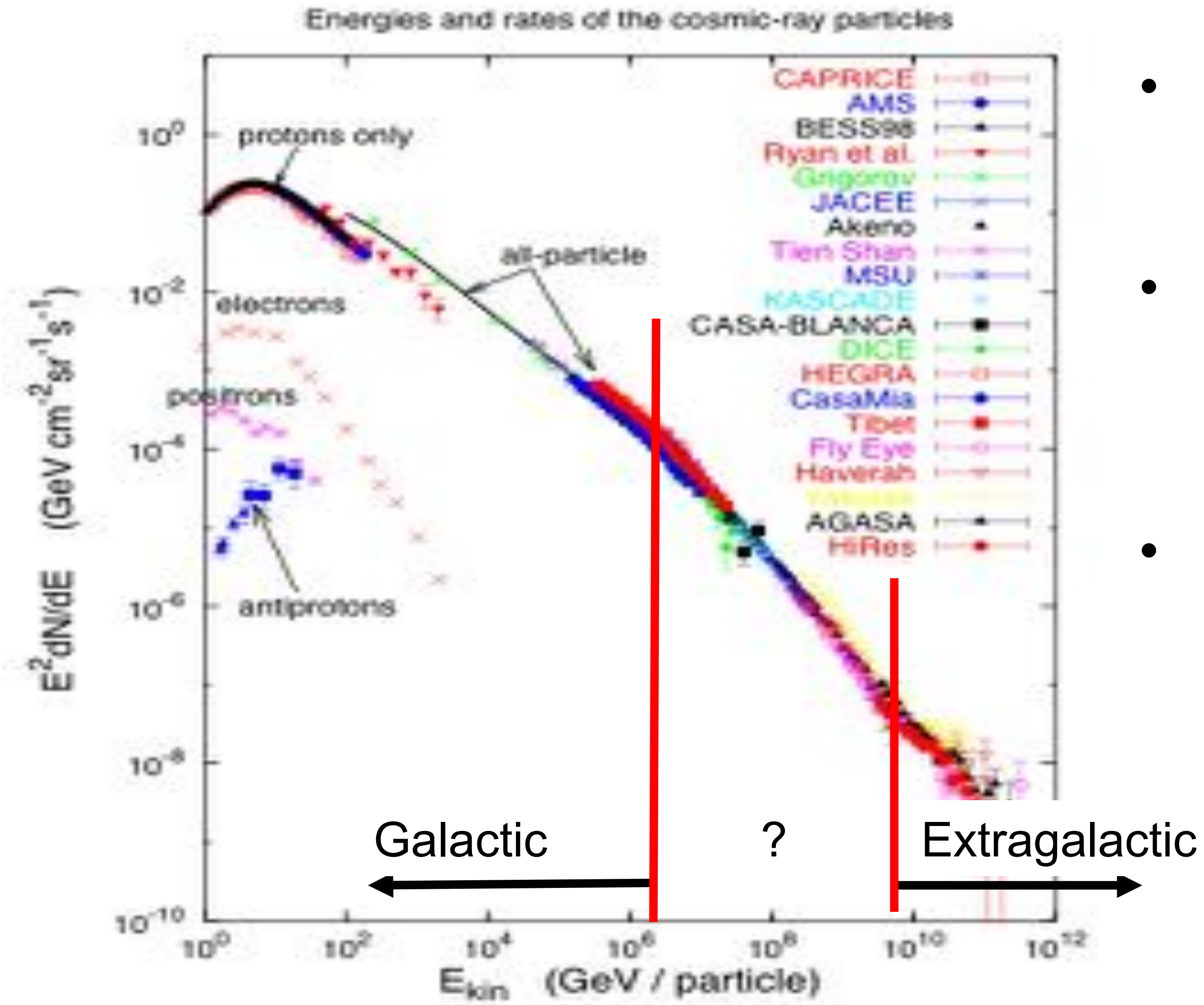
- Current upper limit (90% C.L.): $m_\nu < 2.2$ eV
  In a few years: sensitivity 0.2 eV (KATRIN experiment)
- Model-dependent constraints from cosmology

A side remark: Dirac vs. Majorana neutrinos

- In the Standard Model, all fermions are described by Dirac spinors; fermions and anti-fermions are different.
- Neutral fermions (= neutrinos) could in principle be their own anti-particles (→ described by Majorana spinors).
  This would allow for lepton-number violating processes such as neutrino-less double-beta decay ($0\nu\beta\beta$).
- Large theoretical interest:
  - Neutrino masses require either a Dirac (ν_R) or a Majorana ν
  - Combining both mass terms might "naturally" explain why neutrino masses are so small
- No obvious relation to neutrino astronomy ☹

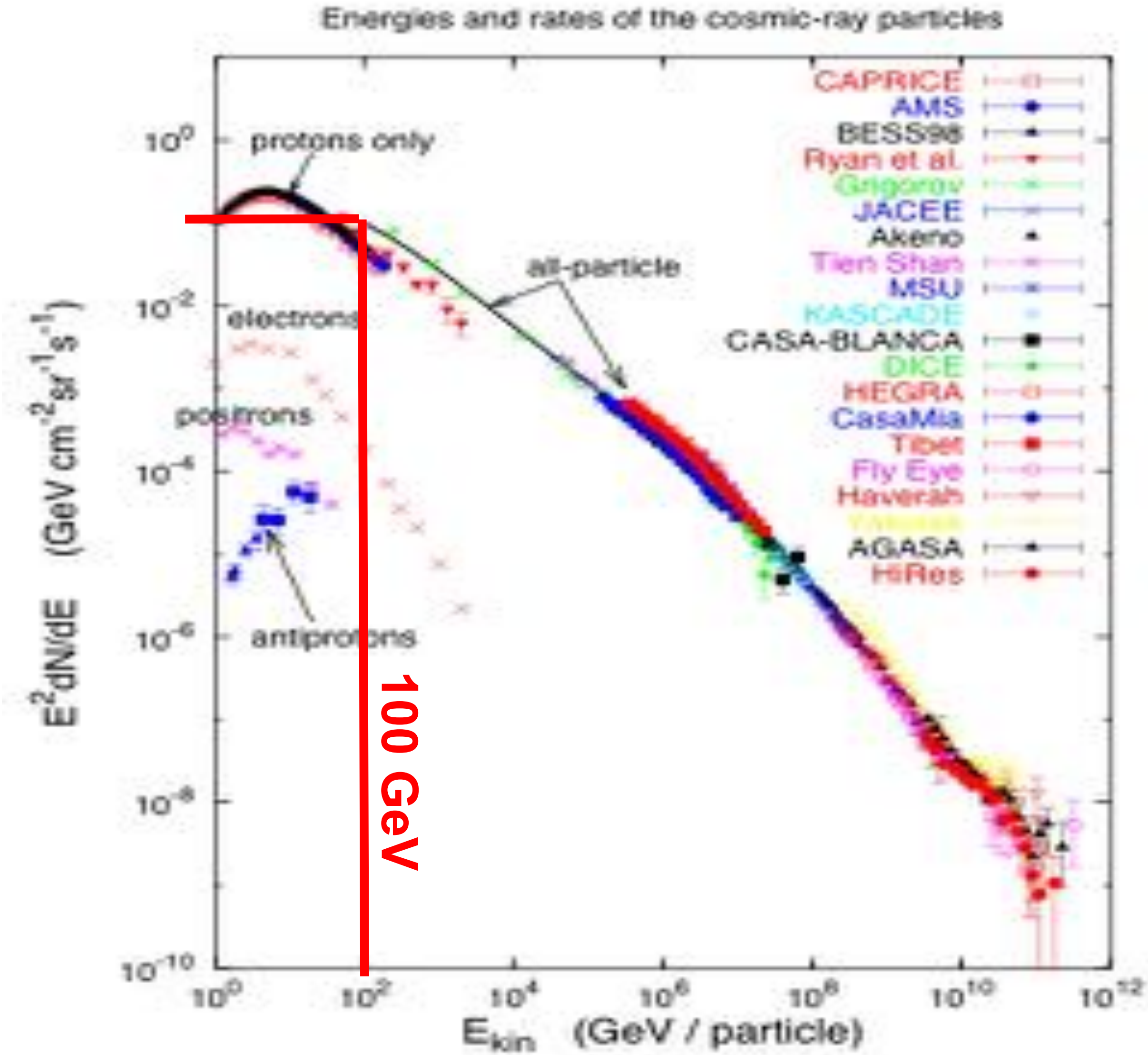
Neutrinos in High-Energy Astrophysics

The cosmic ray connection



- Can we identify candidate accelerators?
- Can we understand the power-law spectrum?
- Can we predict neutrino fluxes?

Questions to you



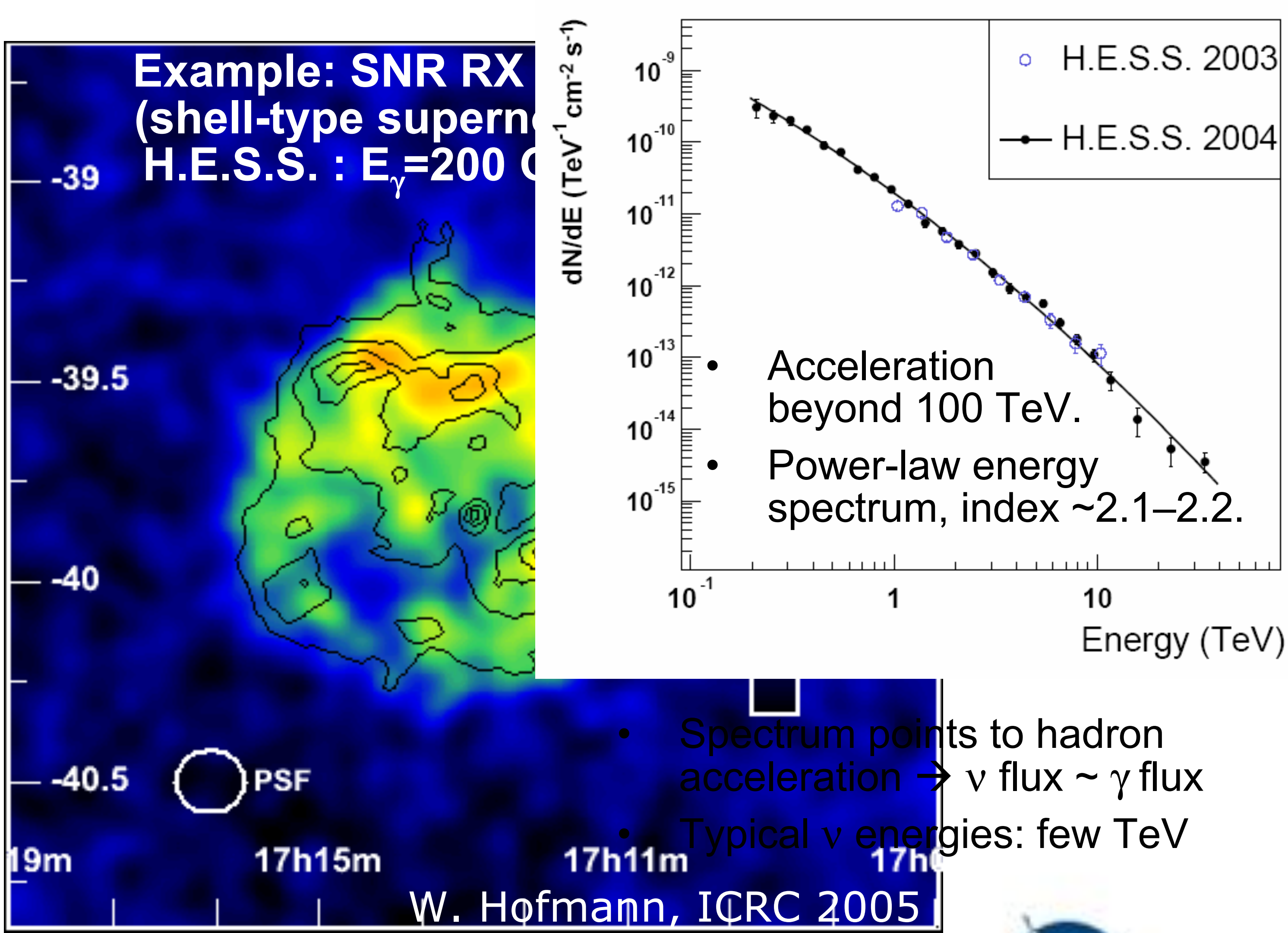
- Calculate energy density in Galactic cosmic rays for E>100GeV (use $dN/dE \sim E^{-2.7}$)
- Discuss whether your result is compatible with the total energy density $1 eV/cm^3$ of cosmic rays
- Calculate power needed to keep the energy density constant if escape time is 10^7 years

Natural and only known candidate: Supernovae

- In a Supernova, $\sim 10^{51}$ erg = 10^{44} J = 6×10^{62} eV are typically released as kinetic energy of ejected material
- There are 3 Supernovae / 100 years in our Galaxy
- This corresponds to a power density of 10^{-25} erg/cm^3/s
- The cosmic rays require 10^{-26} erg/cm^3/s

- We need a mechanism that transforms the Supernova energy to cosmic ray acceleration with ~10% efficiency!

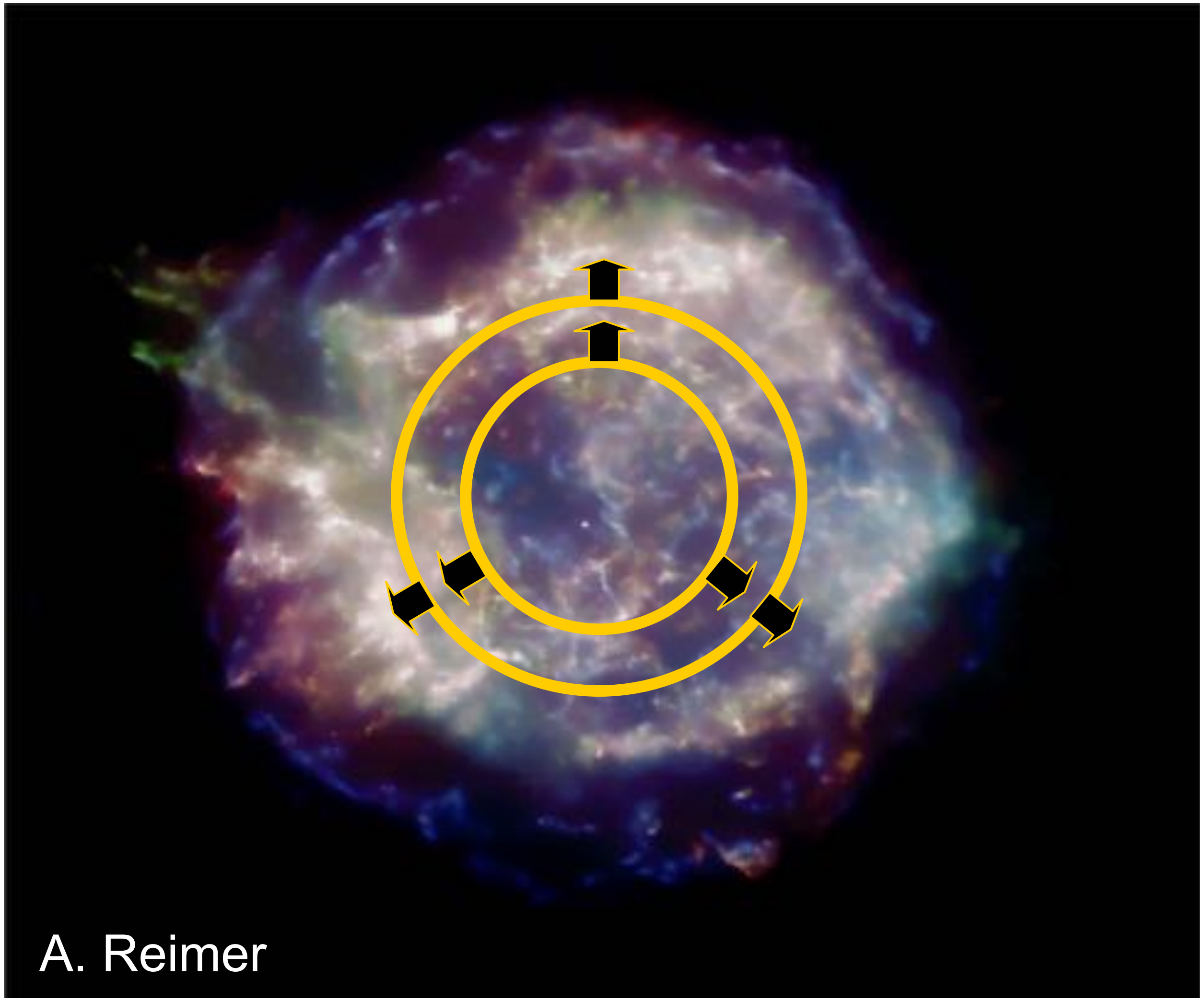
Evidence for particle acceleration in Supernovae



- Acceleration beyond 100 TeV.
- Power-law energy spectrum, index ~2.1–2.2.
- Spectrum points to hadron acceleration → ν flux ~ γ flux
- Typical ν energies: few TeV

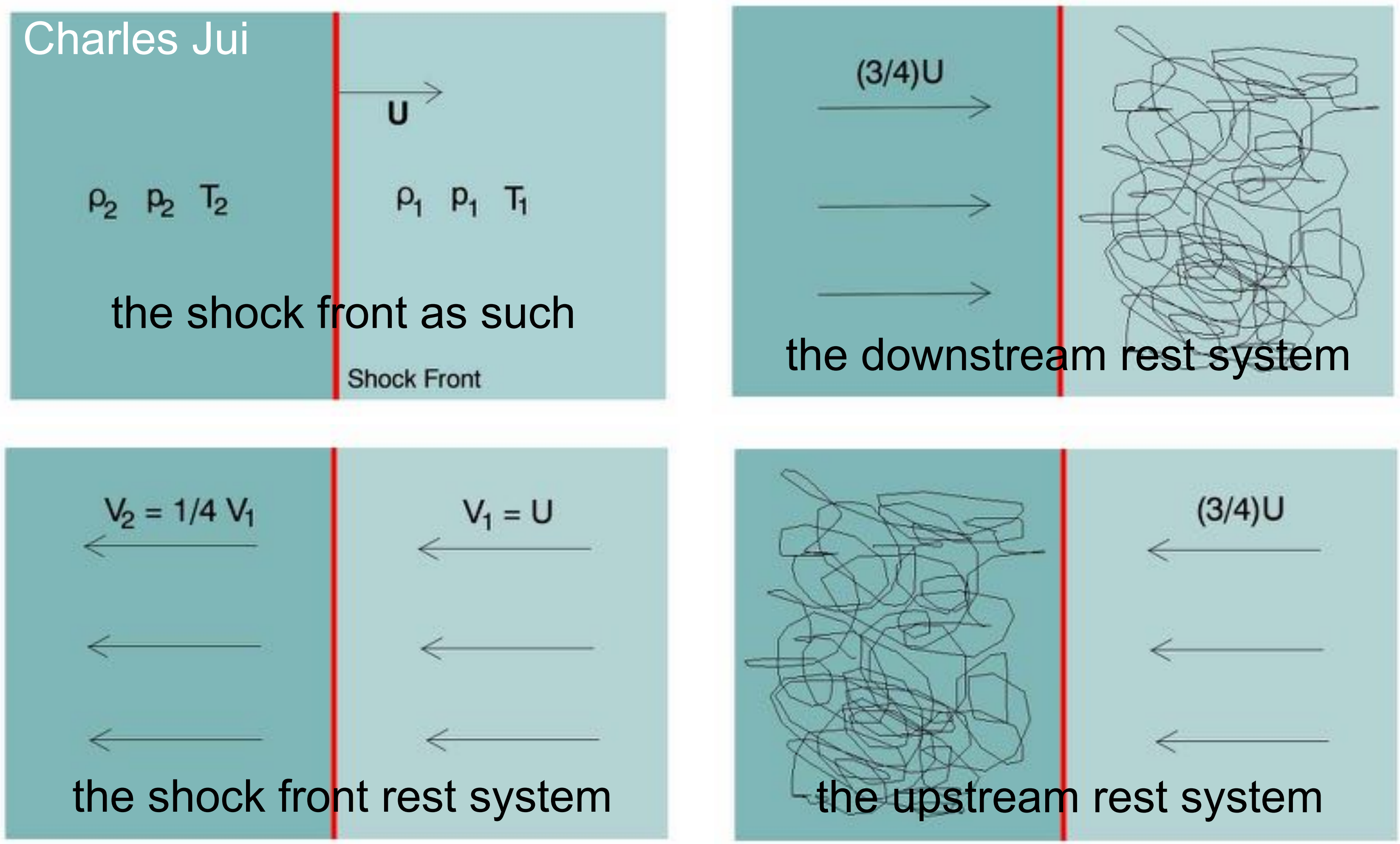
How does the acceleration work?

Common picture: Acceleration in shock fronts (Fermi mechanism)



- Supernova explosion emits very fast matter streams ($O(10^{6...7}$m/s))
- Shock fronts are formed when these hit the interstellar matter

Dynamics of a shock front



Each time a particle crosses the front, it enters "an approaching medium"

Acceleration in a shock front

- Assume relativistic particle, p~E, at one side of shock.
- If particle crosses shock, its energy in the rest frame on the other side is (vertical crossing assumed)

$$(E,p) \to (E',p') = (\gamma_u(E+\beta_u p), \gamma_u(p+\beta_u E)) \Rightarrow$$

$$\frac{E'-E}{E} = \gamma_u\left(1+\beta_u \frac{p}{E}\right) - 1 = \beta_u + \mathcal{O}(\beta_u^2)$$

- Multiple crossings yield increasing energy; require "turn-around" of particle in magnetic fields
- Escape probability per cycle ~u/c
- Not clear: "Injection problem", i.e. how does first acceleration beyond thermal energies work

Questions to you:

- Assume a constant escape probability p_{esc} and a relative energy gain ε per acceleration cycle
  - Calculate energy E_n and number N_n of particles still in the process after n cycles if you start with E_0 and N_0.
  - Show that the resulting energy spectrum is a power law. Determine its index as a function of p_{esc} and ε.

- Estimate the impact of the fact that the crossings are under random angles with respect to the shock front (remember: we assumed vertical crossing)

- Discuss why Fermi acceleration produces a $\sim E^{-2}$ spectrum but we observe $E^{-2.7}$

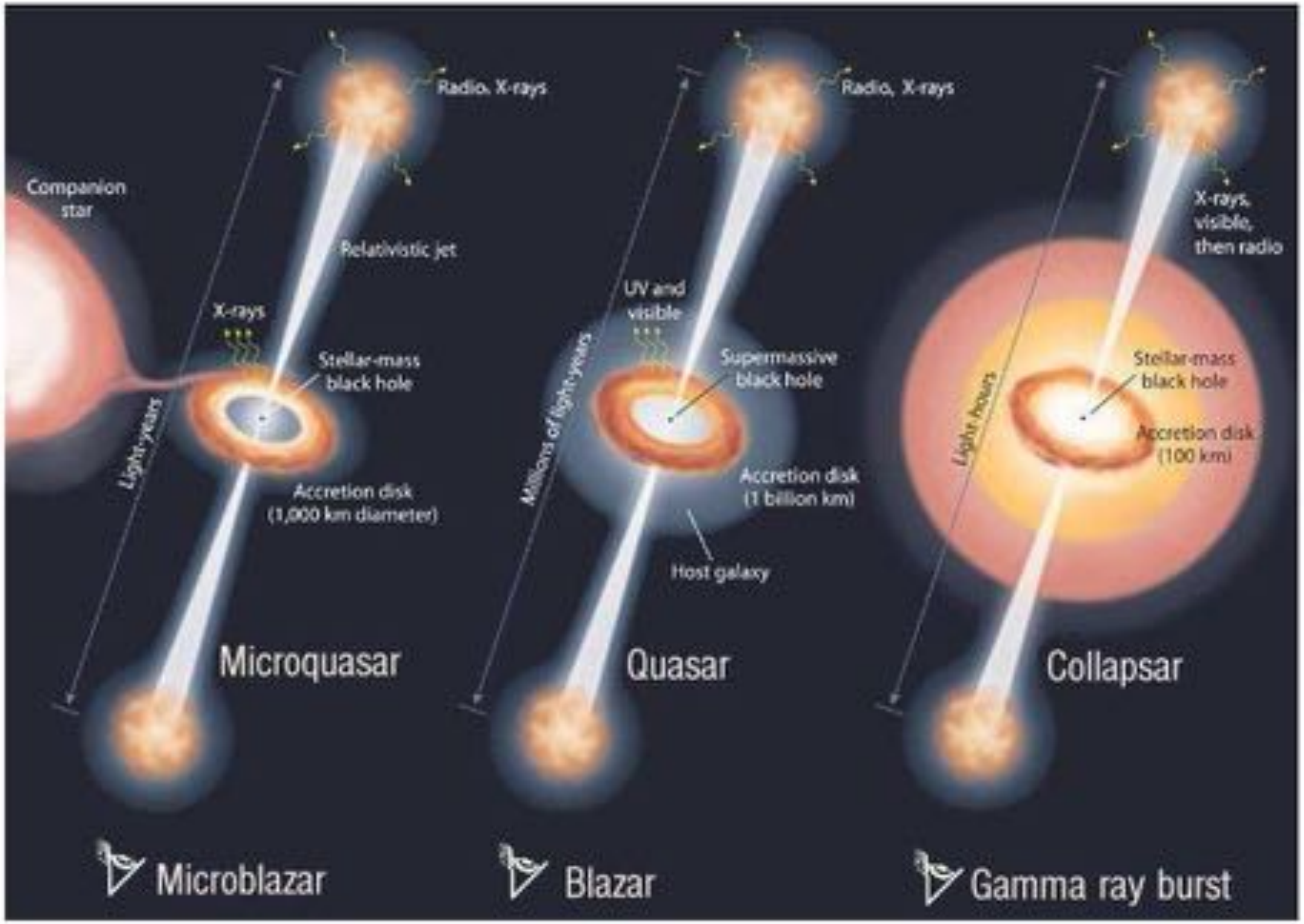
Do we have evidence for shock-front acceleration?

… yes, from X-ray observations

Shock fronts are omnipresent …

- Supernova shock waves
- Pulsar wind shocks
  particles accelerated in the field of pulsars (rotating neutron stars)
- Micro-quasar jet termination shock
  see below
- Galactic wind termination shock
- Shocks in solar wind
- AGN jet termination shocks
  see below
- GRB's
  see below
- …

Accretion systems: Micro-quasars, AGNs, GRBs



Question: What energies can be achieved?

- Larmor radius of circular particle path in magnetic field:

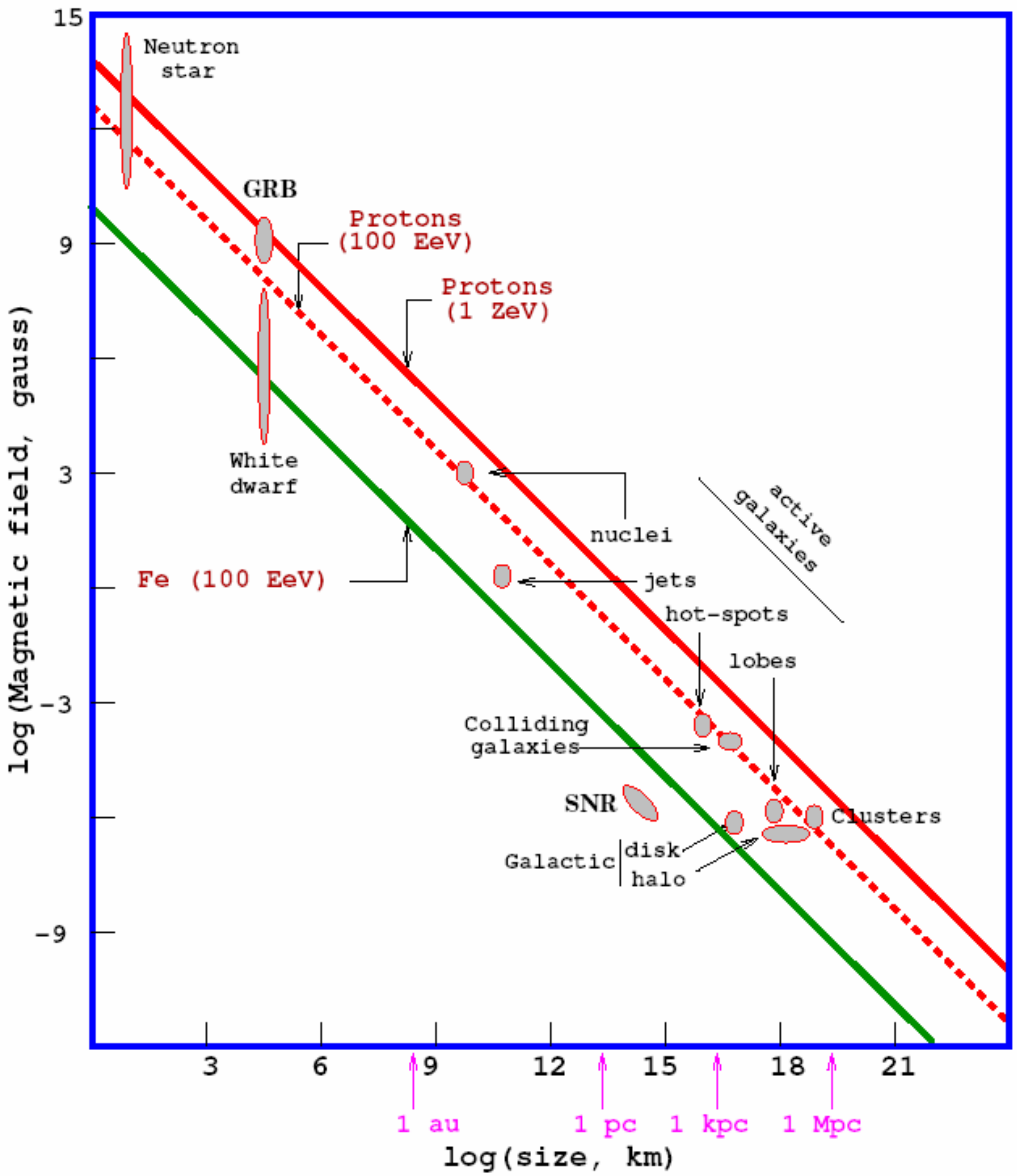
$$R = \frac{E}{qB} < \text{size } L \text{ of acceleration region} \Rightarrow$$

$$E_{\text{max}} \approx 3 \times 10^{10}\, Z\, (B/10\,\text{G})\, (R/10^{11}\,\text{km})\ \text{GeV}$$

- Further requirements:
  - acceleration must continue over long time (>1000 years)
  - Losses due to interactions or radiation must be small (→ limits matter density and B)
  - particles must be injected

The Hillas plot

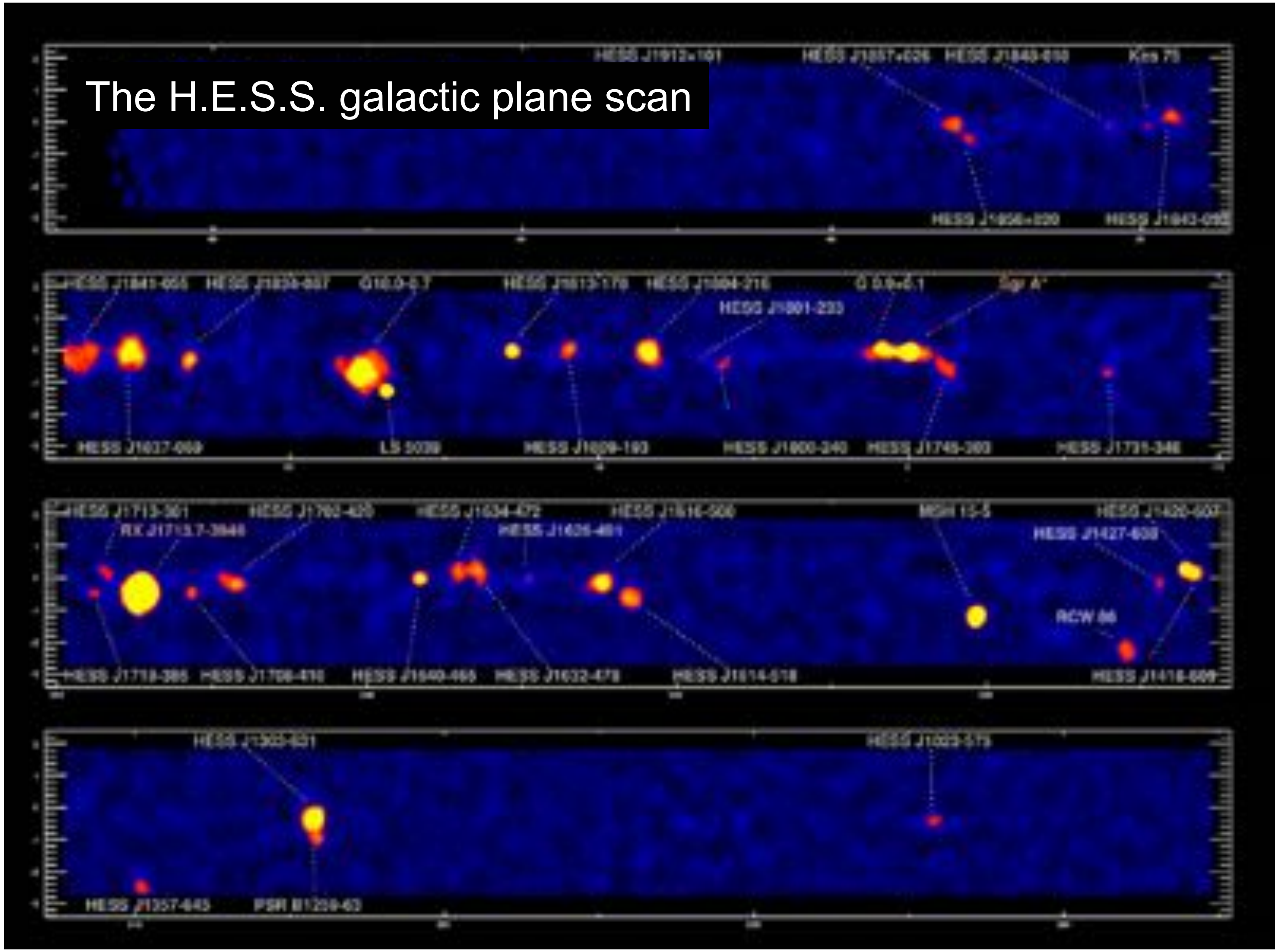
- Which astrophysical object might accelerate particles to what energies?
- Any energies beyond ~10^{21} eV would be difficult to explain.



Alternative ways to produce high-energy particles?

- Electromagnetic fields
  → pulsars, accretion processes with jet outflows
- Interactions of Cosmic rays with background fields
  → molecular clouds, radiation fields (CMB)
- Gravitational processes?
  No obvious way to accelerate single particles to highest energies (small coupling)
- Top-down scenarios
  - Idea: Super-heavy (10^{24}eV?), long-lived particles have been produced at Big Bang and are (part of) the Dark Matter.
  - Their decays could produce ultra-high energy secondaries.
  - Disfavoured by theory and observation (missing UHE gammas)
- Annihilation of Dark Matter particles (WIMPs)
  - Energy of secondaries limited to $M_{WIMP}/2$
  - Neutrino and gamma production directly or via W, Z, π decays

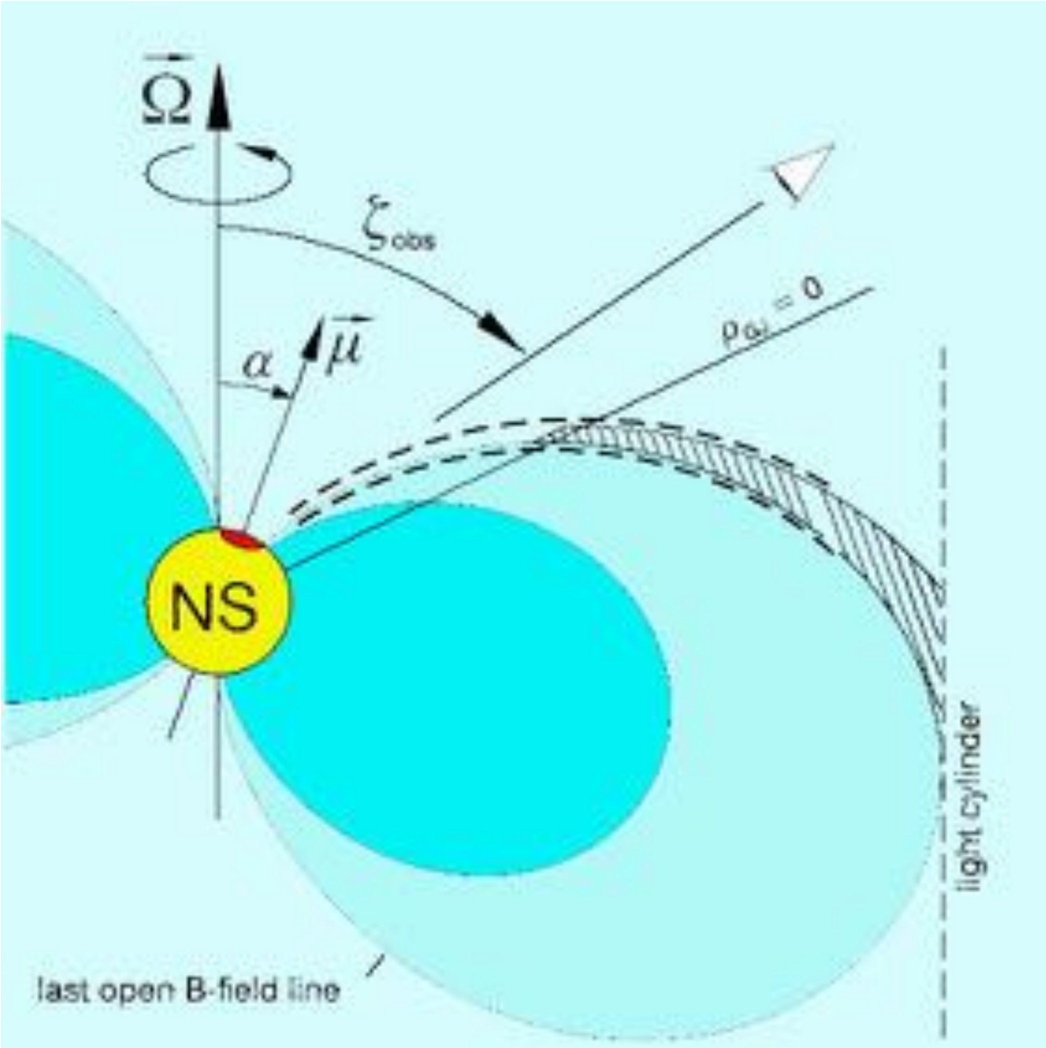
Galactic Disk: Let’s see what is there



Status 2007:

- 18 Pulsar wind nebulae
- 7 Shell-type supernova remnants
- 4 Binaries
- 2 Diffuse
- 21 Unknown (no identified counterpart)

Pulsars: What they are and how they work

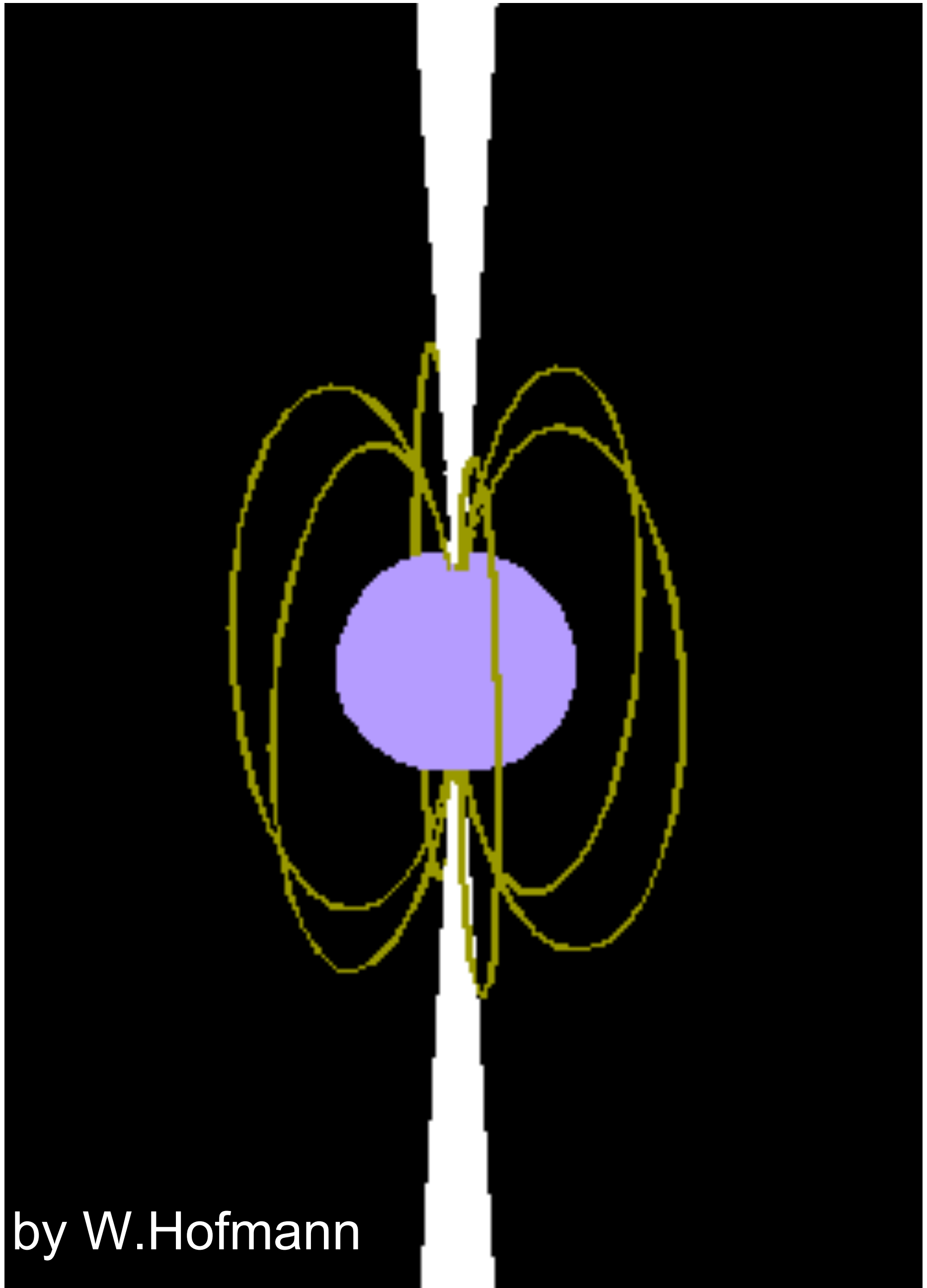


from J. Dyks et al.

- Neutron star with magnetic moment not parallel to rotation axis
- Particles are preferentially accelerated along B field lines
- Assumed to be only/mostly electron plasma (no neutrinos) … but no proof as yet!
- Particle stream hits surrounding matter → shock fronts

Pulsars: How we see them

- Beamed emission of electromagnetic radiation
- Illuminates spectator like a light-house
- Highest-accuracy periodicity known in nature



Questions to you

- During a Supernova explosion, a neutron star is formed (Radius R_{NS}=10km) carrying the full magnetic flux of its progenitor.

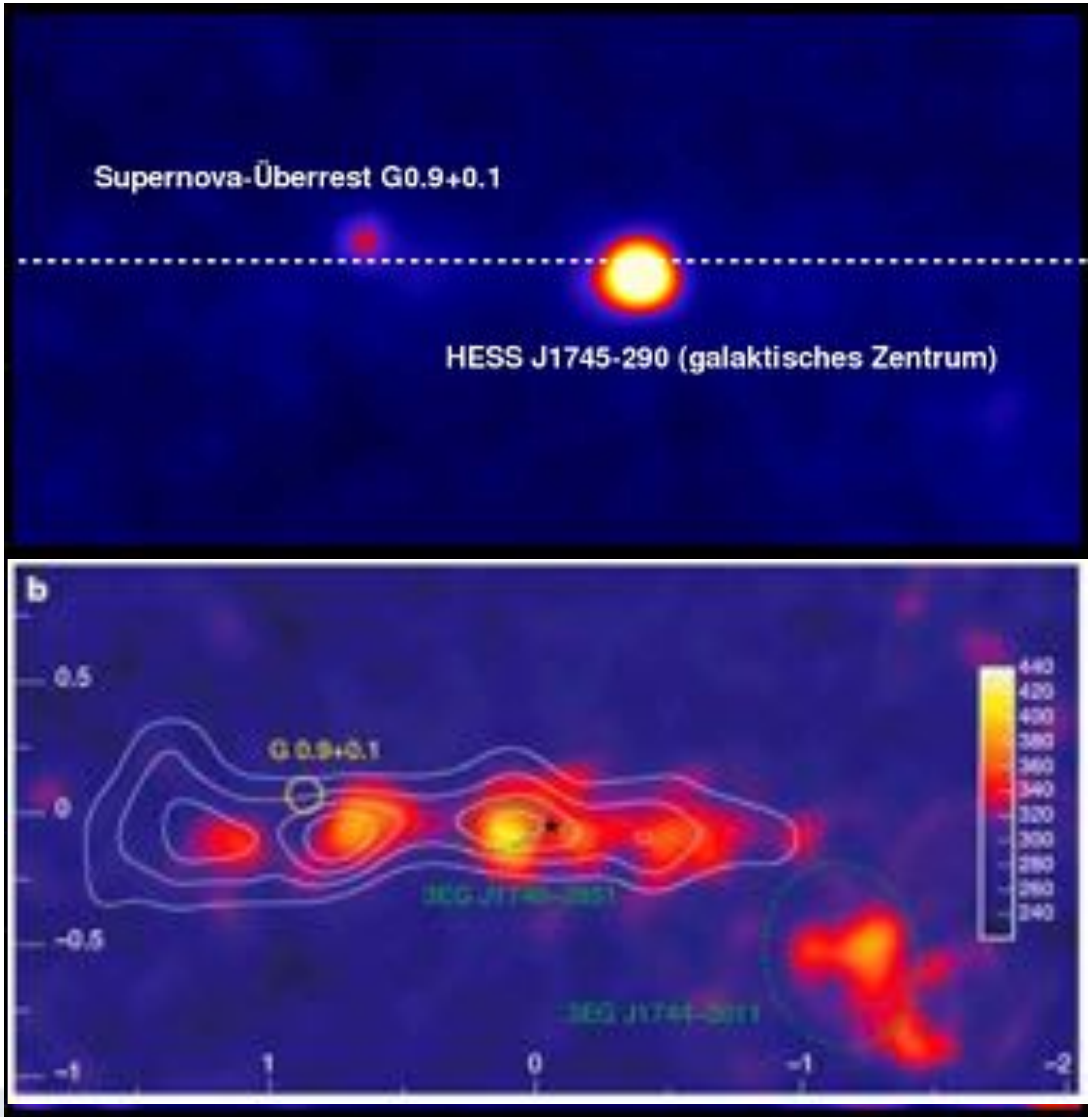
  Calculate its rotation frequency and its magnetic field assuming a solar-type progenitor

  Input: Solar radius = 7 x 10^5 km
  Solar mass = 2 x 10^{30} kg
  Solar rotational period = 25 days
  Solar magnetic field ~ 100 G

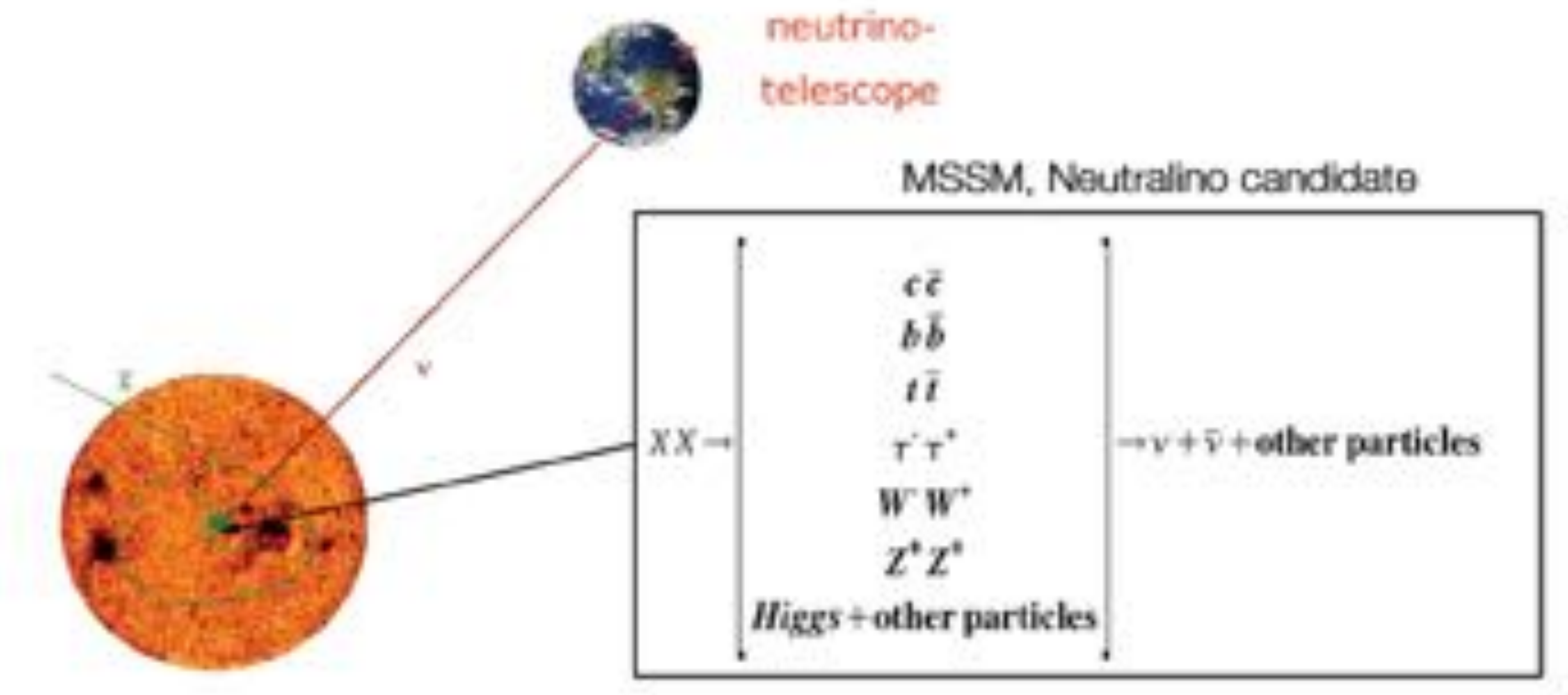
- Estimate the electric field strength resulting from the "B rotation"

Diffuse emissions of TeV gamma rays

- Top: HESS observation of Galactic Centre; Bottom: What remains after subtracting the “obvious sources”
- Interpretation: Interaction of cosmic rays from one of the point sources with molecular clouds
- Similar observation (Cygnus region) from MILAGRO experiment
- γ spectra point to “hard” cosmic ray spectrum



Dark Matter annihilation

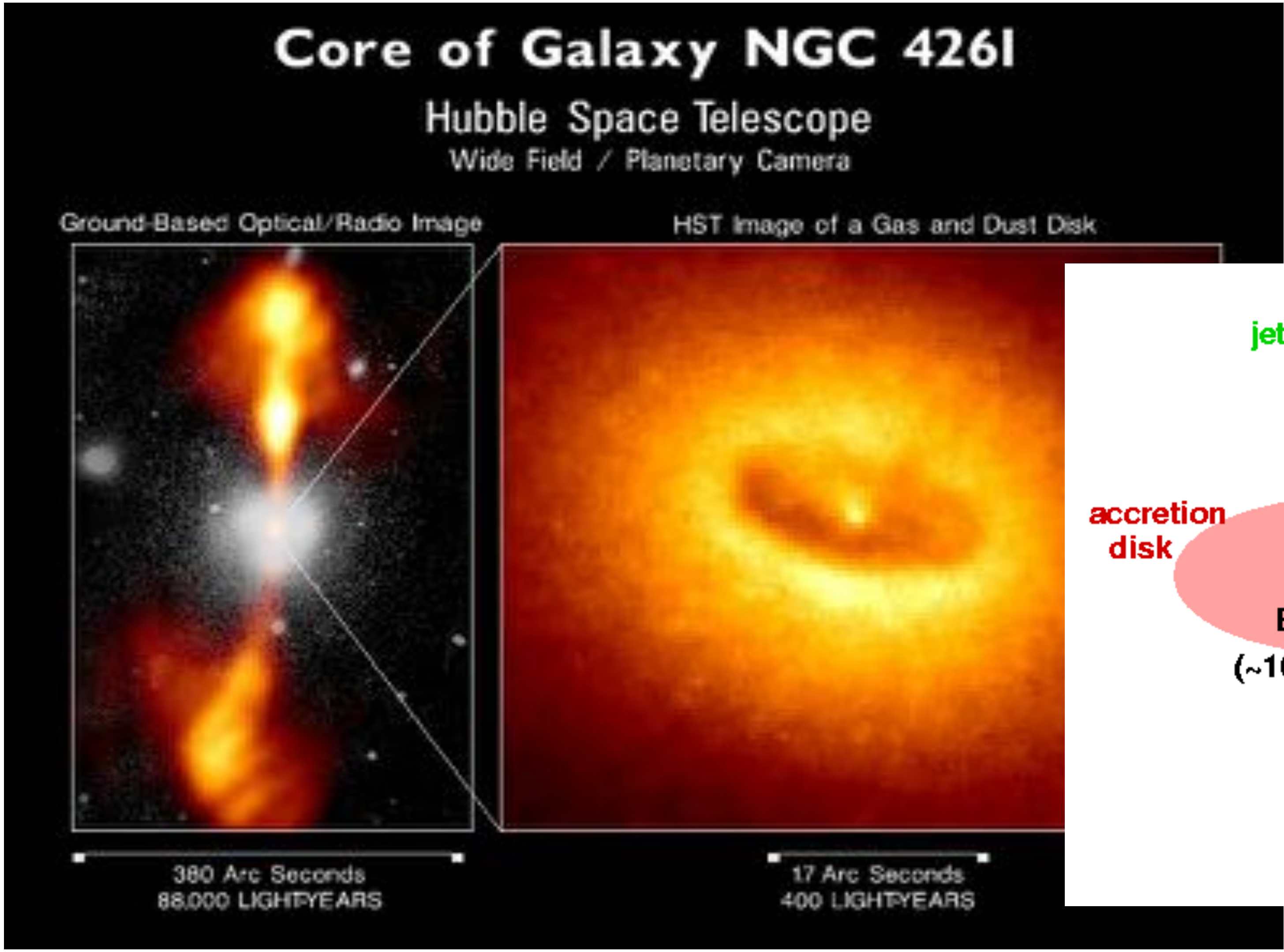


The neutrino spectrum depends strongly on reaction/decay mode

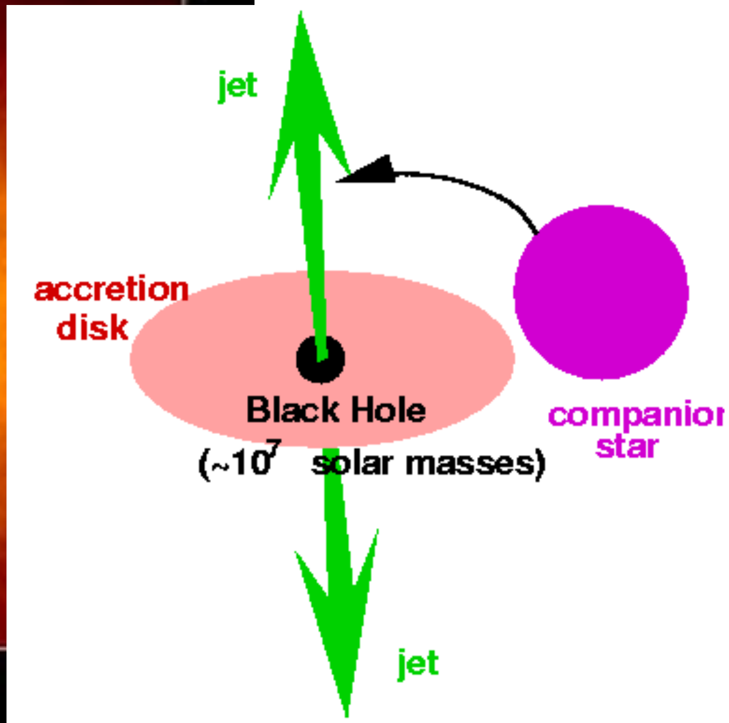
Summary: Potential Galactic neutrino sources

- The candidate accelerators of cosmic rays
  - Supernova remnants
  - Pulsar wind nebulae
  - Micro-quasars
  - …
- Interaction of cosmic rays with interstellar matter
  - Possibly strong ν signal if CR spectrum harder in Galactic Centre than on Earth
- WIMP annihilation
- Unknown sources – what are the H.E.S.S. "TeV gamma only" objects?

Extragalactic Candidates: Active Galactic Nuclei (AGNs) …



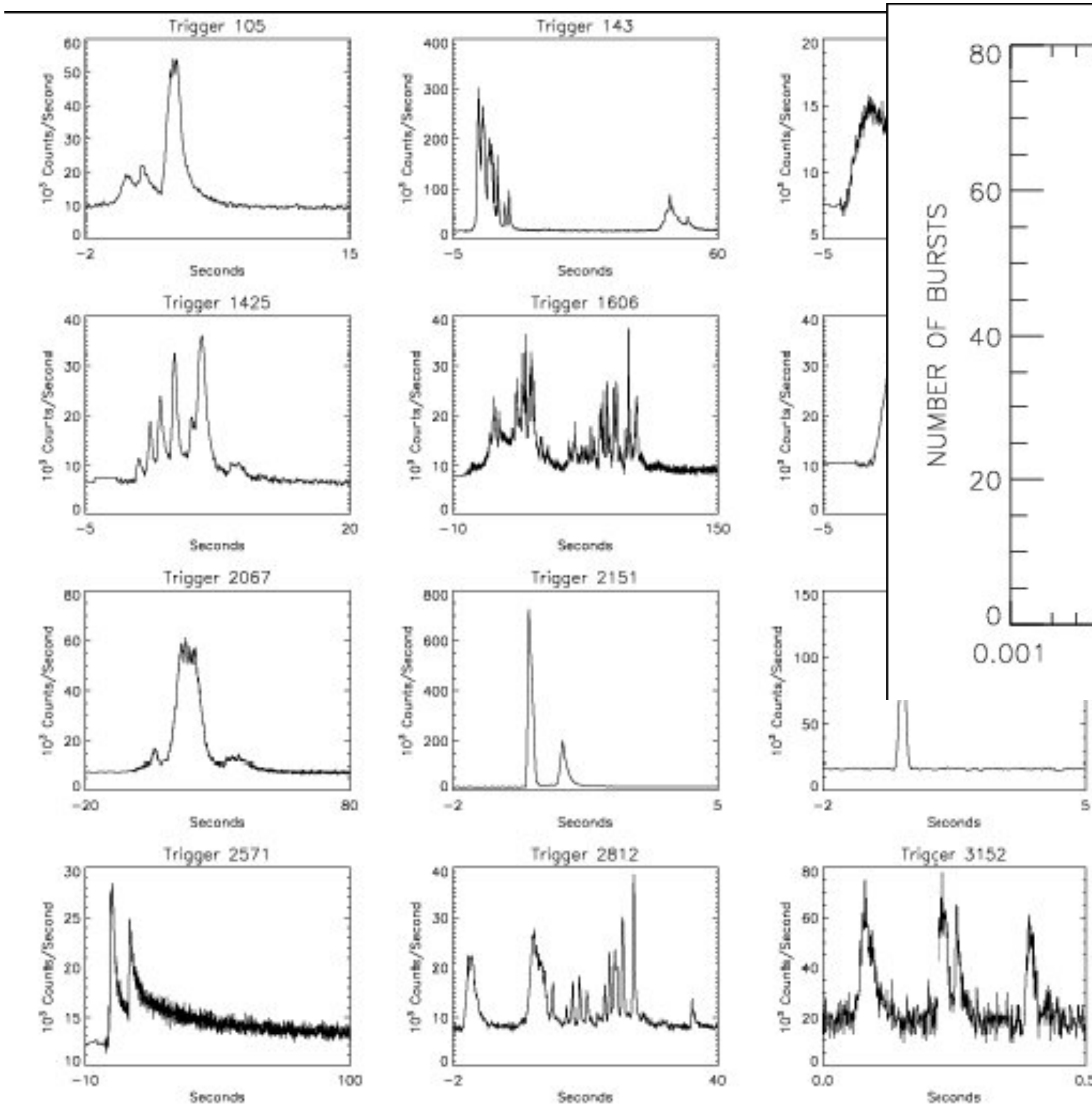
AGNs are amongst the most energetic phenomena in the universe.

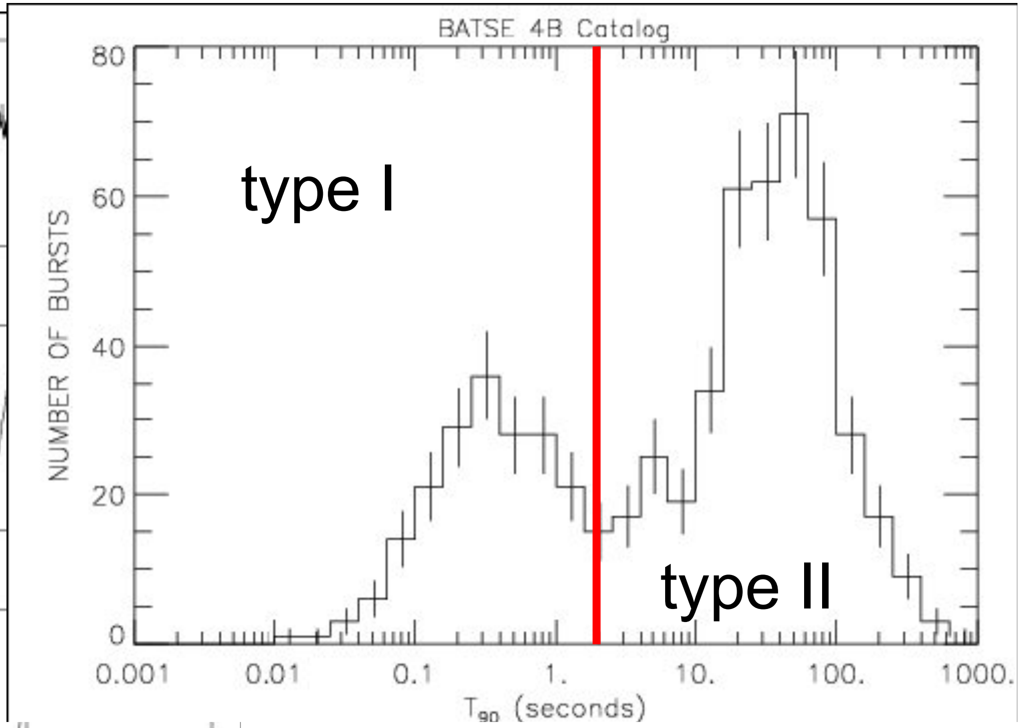


… and Gamma Ray Bursts (GRBs)

- Extremely energetic flashes of gamma emission
- Uniformly distributed on sky → extragalactic (huge distances, up to $z = 8.6 > 5$Gpc observed)
- Discovered by military satellite launched to survey Russian atomic bomb test activities
- Favourite models today:
  - Core-collapse Supernovae of particularly massive progenitor stars (Collapsars)
  - Mergers of two compact objects (neutron stars, black holes)

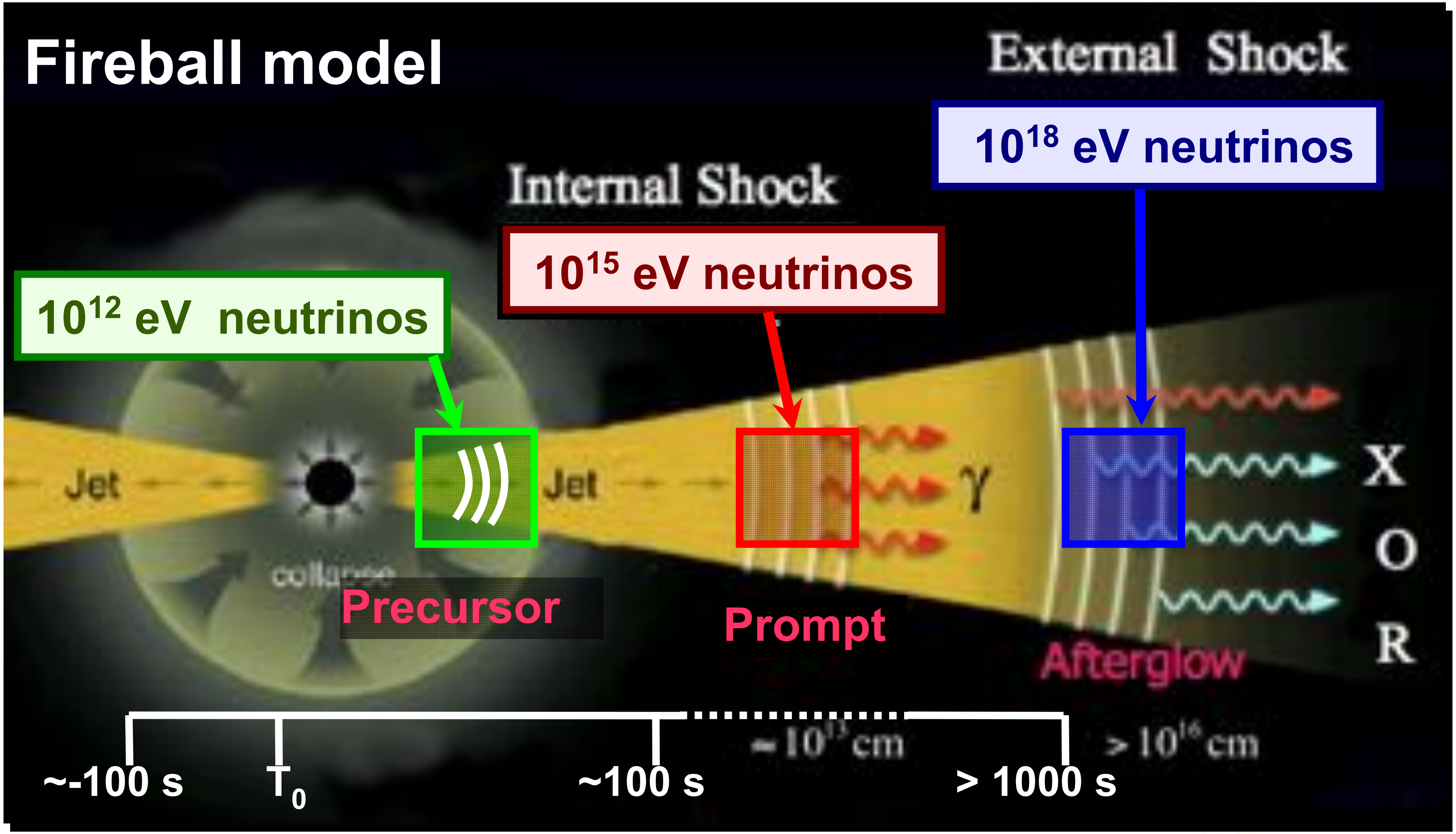
GRB light curves and duration





- Long GRBs: Energy ouput 10^{51}-10^{54} erg

A popular GRB model (for type II GRBs)

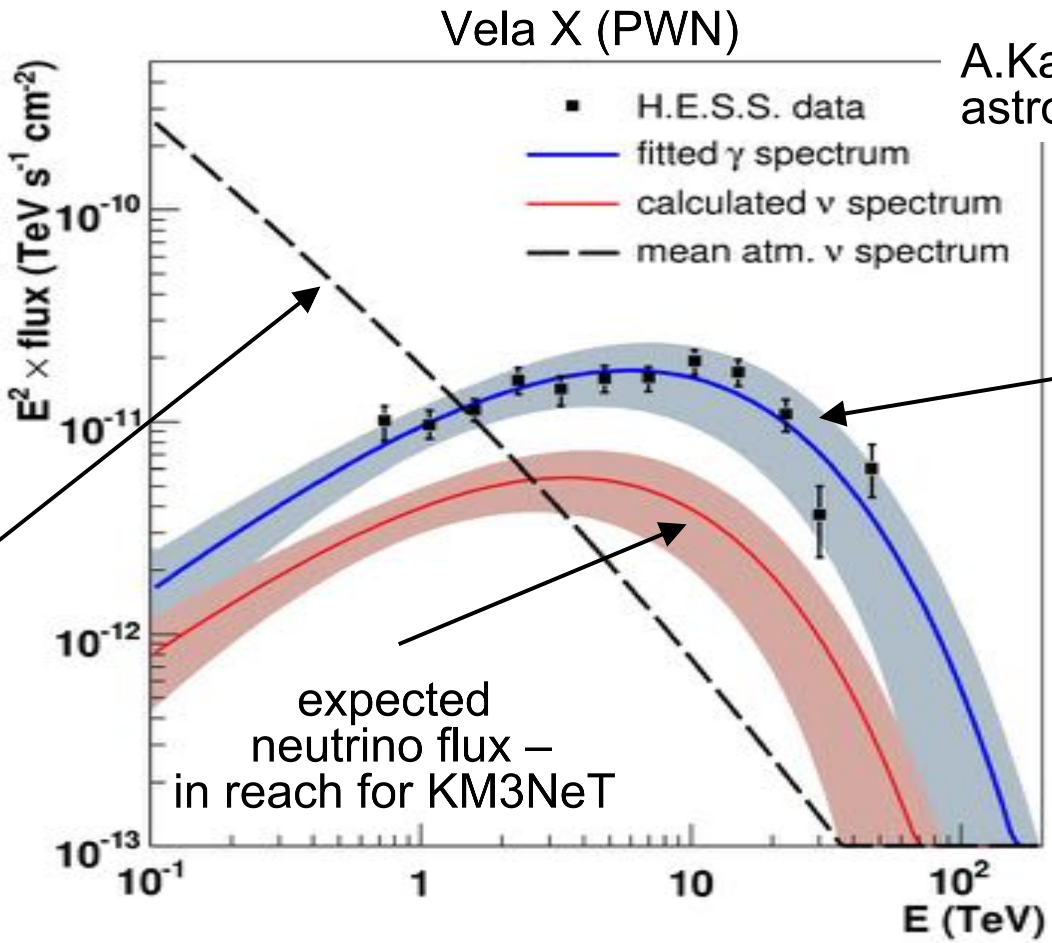


Potential Extragalactic Sources

- AGNs
  - Models are rather diverse and uncertain
  - The recent Auger results may provide an upper limit / a normalisation point at ultra-high energies
  - Note : Above some 100 TeV the neutrino telescope field of view is restricted downwards (ν absorption), but starts to be significant upwards.
- Gamma ray bursts
  - Unique signature: Coincidence with gamma observation in time and direction
  - Source stacking possible
- Both could satisfy the overall energetics

ν Flux Predictions from γ Measurements: PWN …

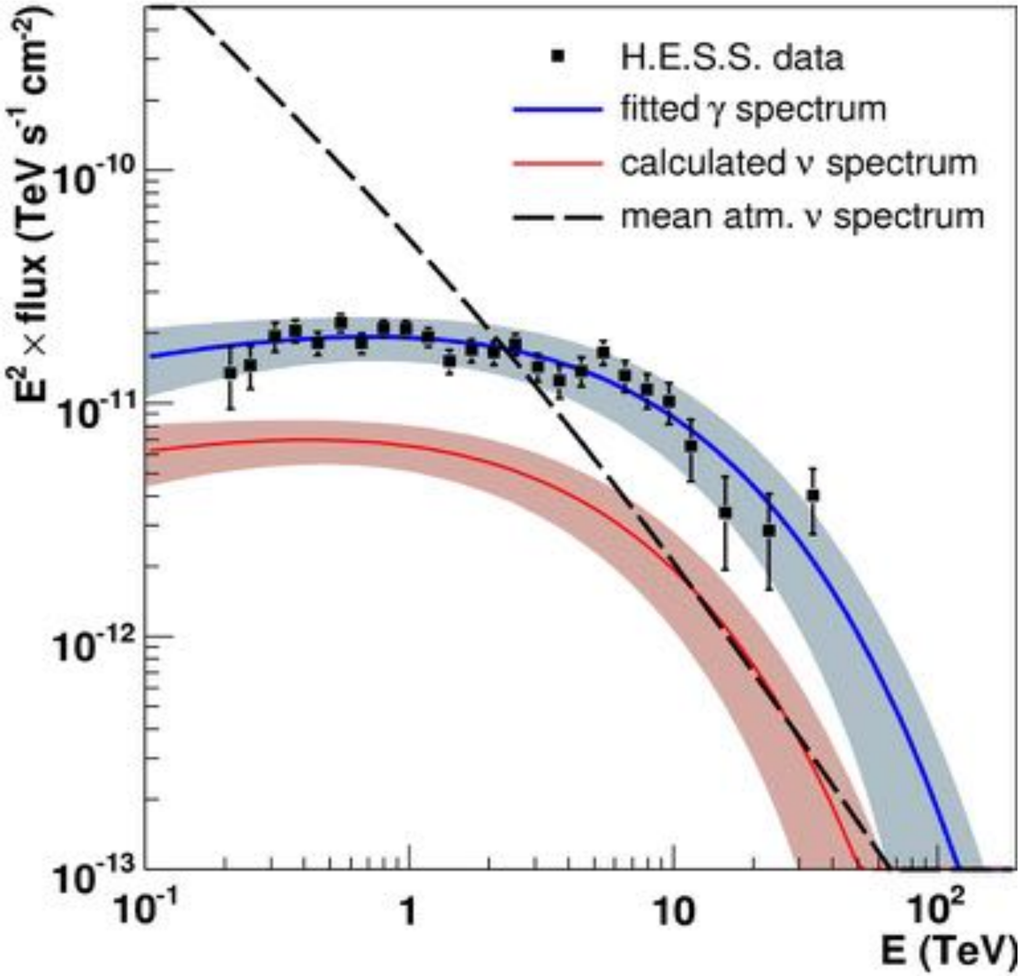
Note: hadronic nature of Vela X is not clear!



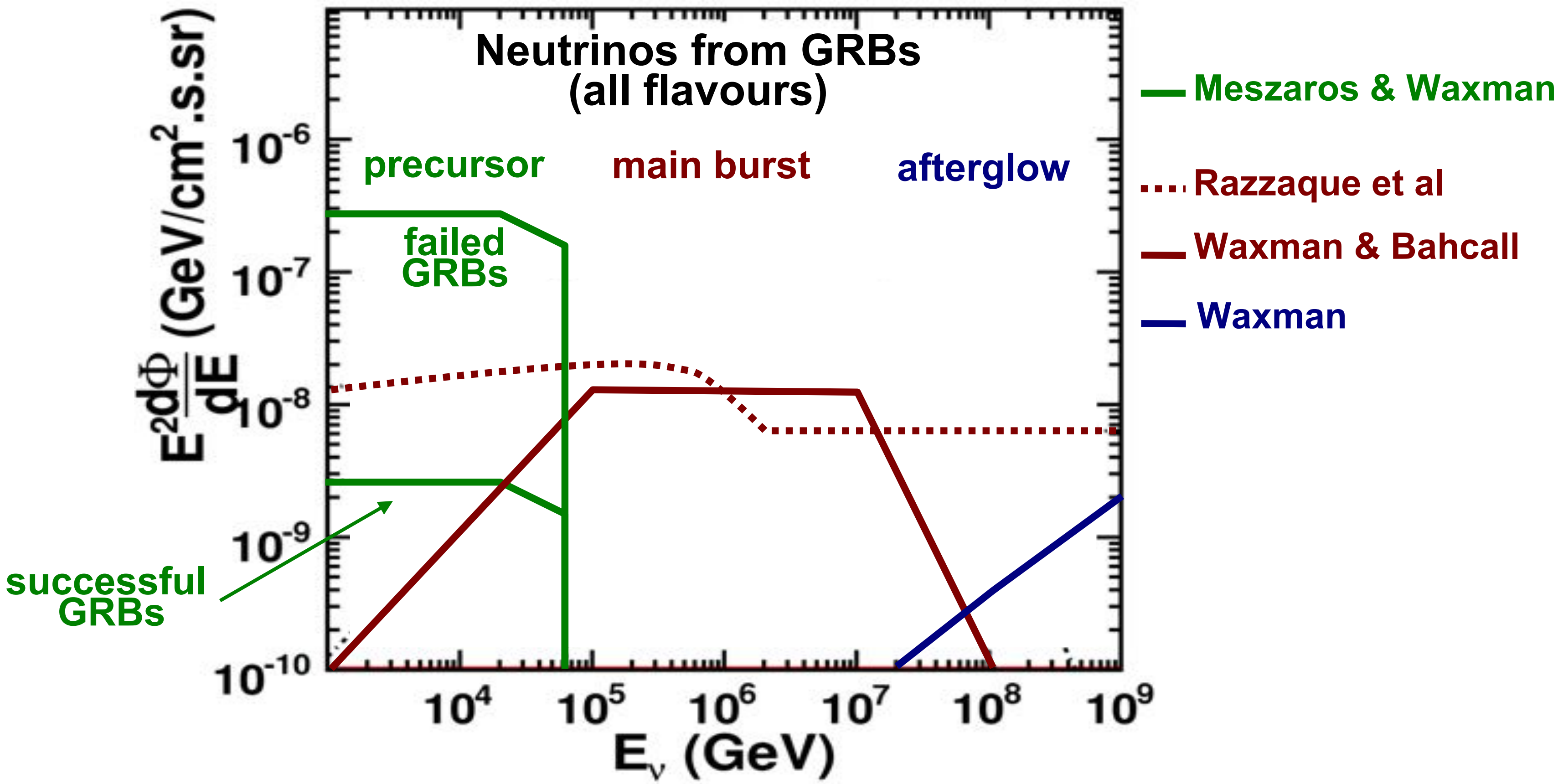
1 σ error bands include systematic errors (20% norm., 10% index & cut-off)

… SNR RXJ1713.7-3946

- Good candidate
  for hadronic acceleration.
- Expected signal
  well related to measured γ flux, but depends on energy cut-off.
- Few events/year
  over similar back-ground ($1 km^3$).
- KM3NeT sensitivity
  in the right ballpark!



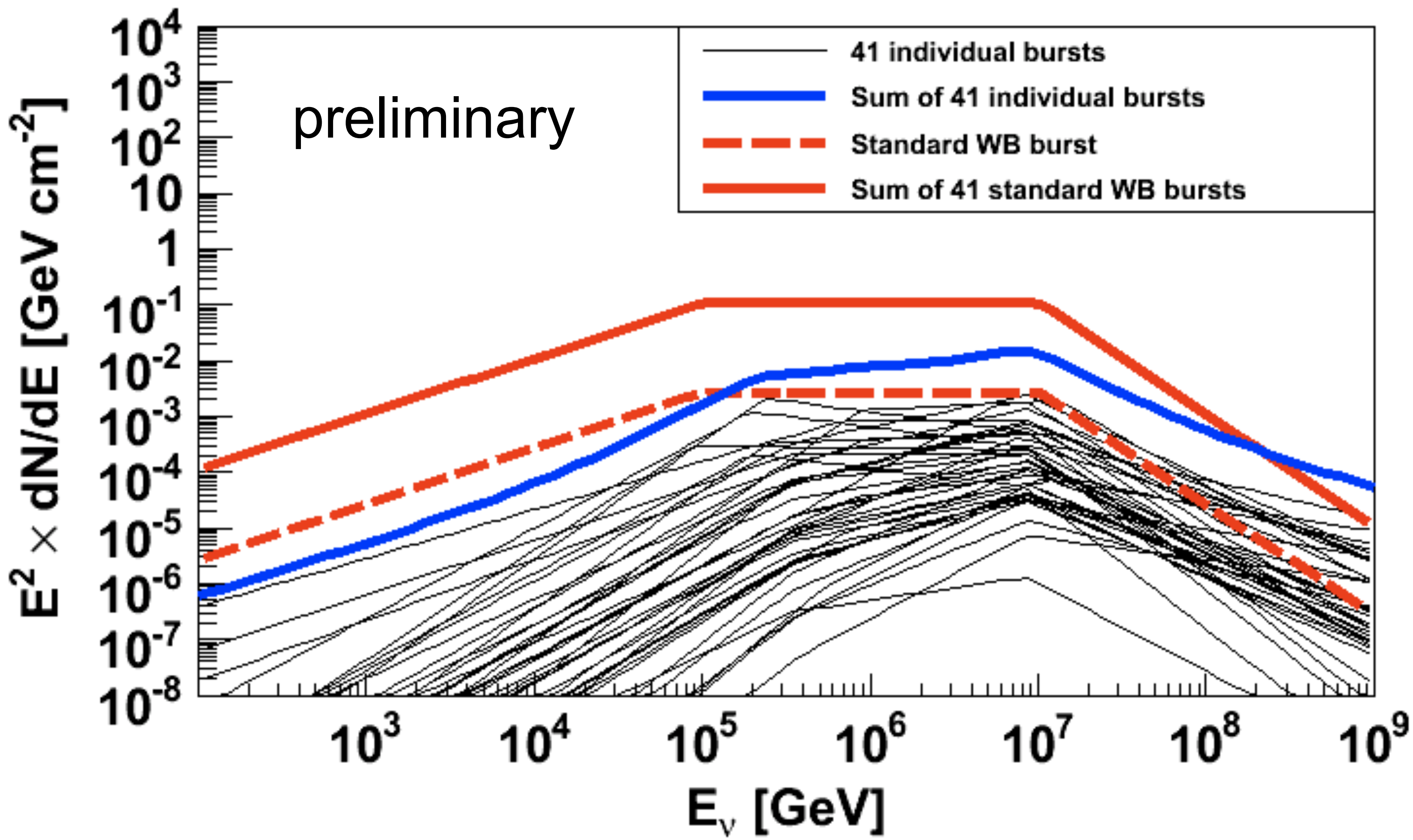
… and Gamma Ray Bursts (1)



- Only average fluxes → large burst-to-burst fluctuations
- Again: Hadronic nature not proven

Gamma Ray Bursts (2)

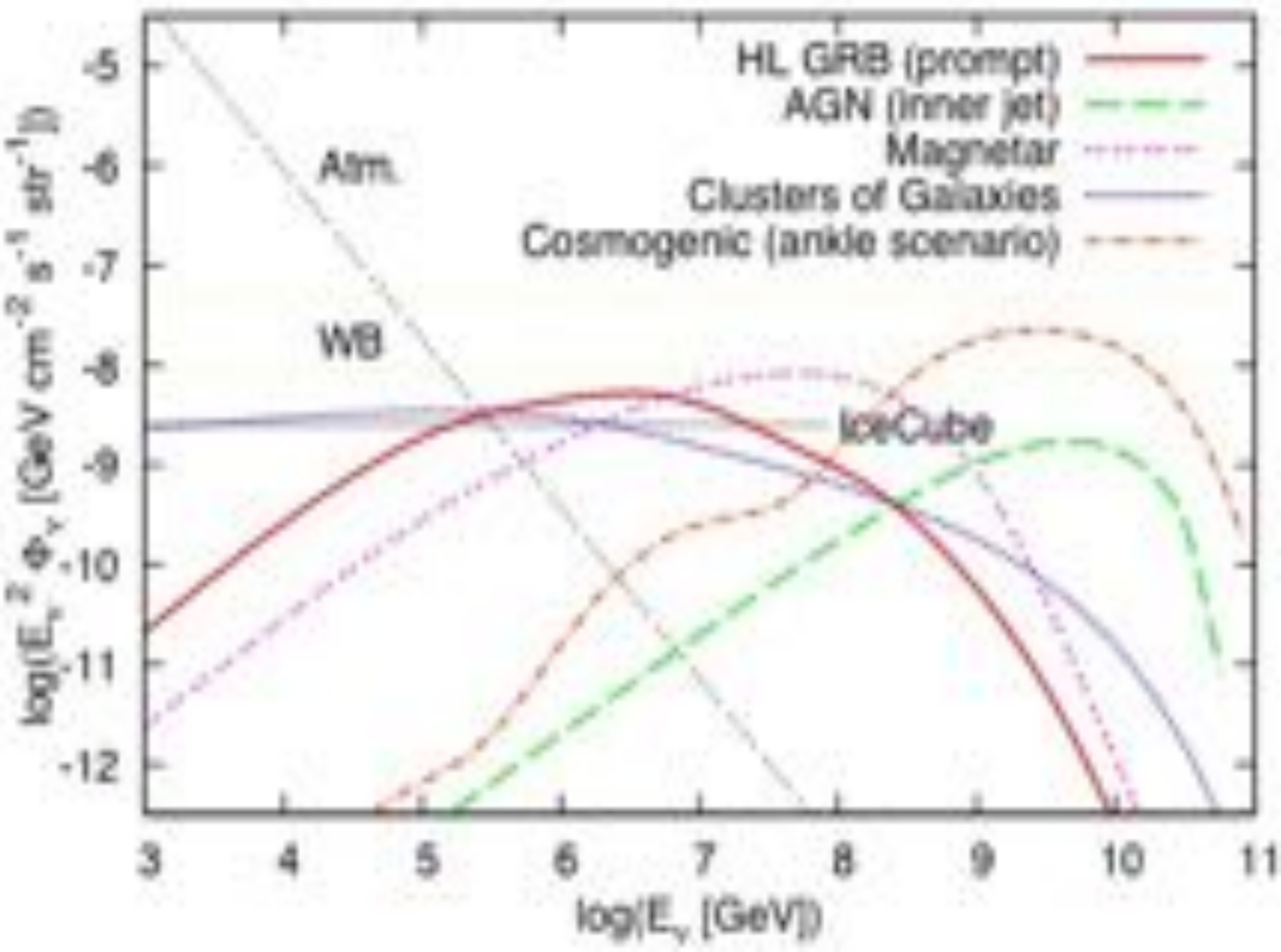
Individual predictions for 41 GRBs in period June 2007 - April 2008



Diffuse fluxes

- Composed of neutrinos from
  - unidentified point sources
  - cosmogenic origin ($p\gamma_{CMB} \rightarrow p\pi, n\pi$ GZK effect)

- WB = upper flux limit derived by Waxman and Bahcall from cosmic ray flux (does not apply to opaque sources)



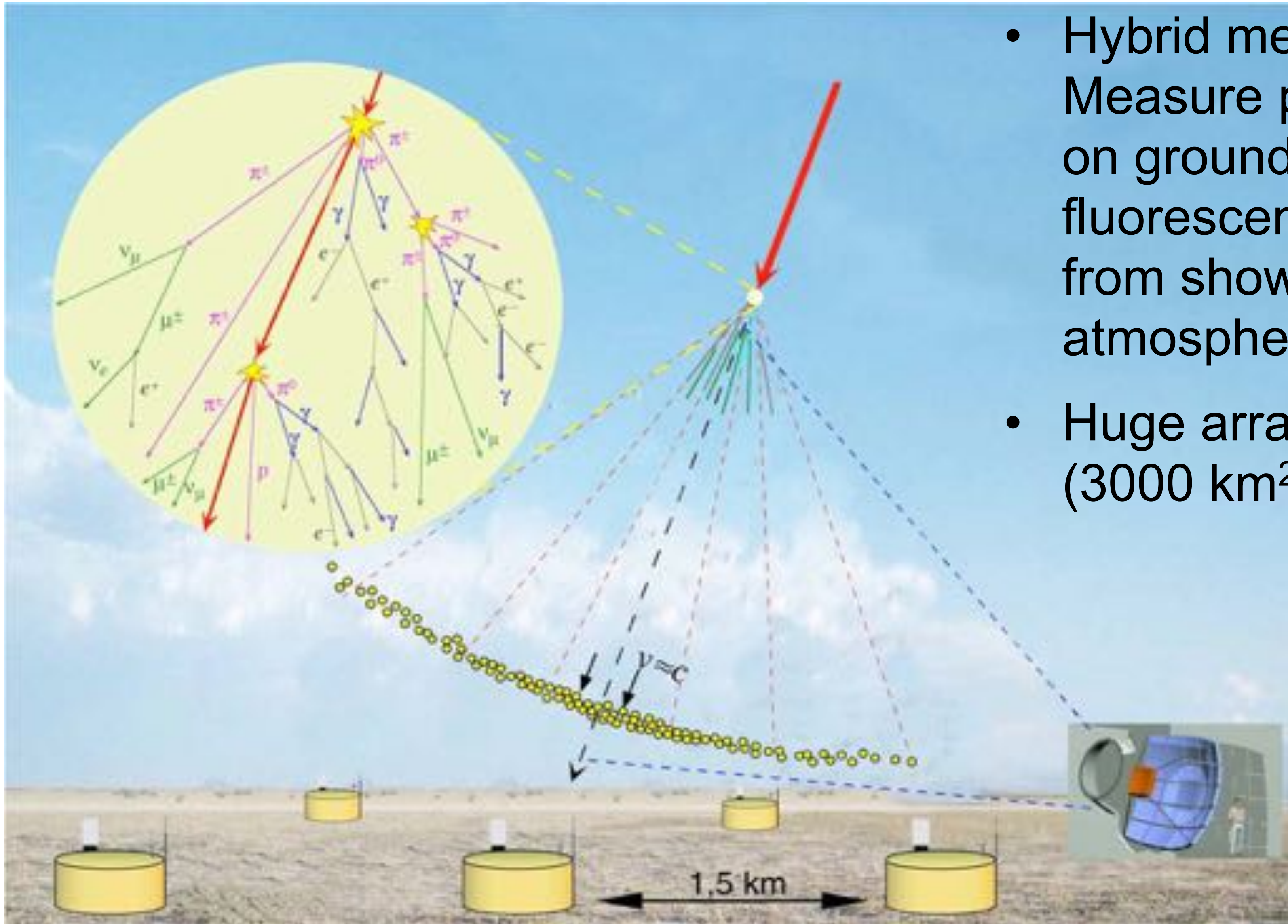
… but you never know !

Telescope	User	Date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi ...	1965	Sun, moon	Neutron stars, accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ-rays	Military	1960?	Thermonuclear explosions	Gamma-ray bursts

Taken from Francis Halzen

Experimental Observations

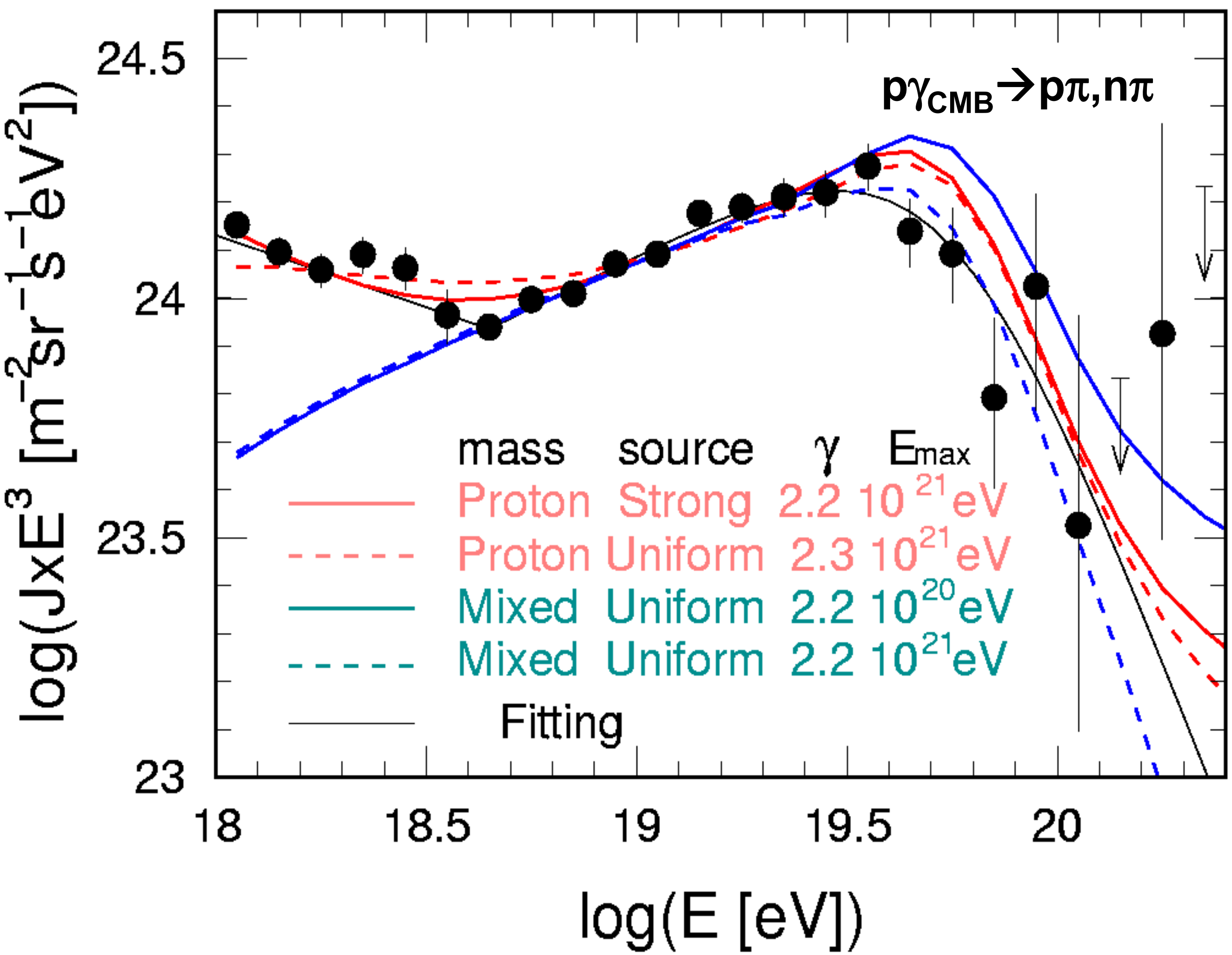
Pierre Auger: Cosmic rays at highest energies



- Hybrid method: Measure particles on ground and fluorescence light from shower in atmosphere
- Huge array (3000 km^2)

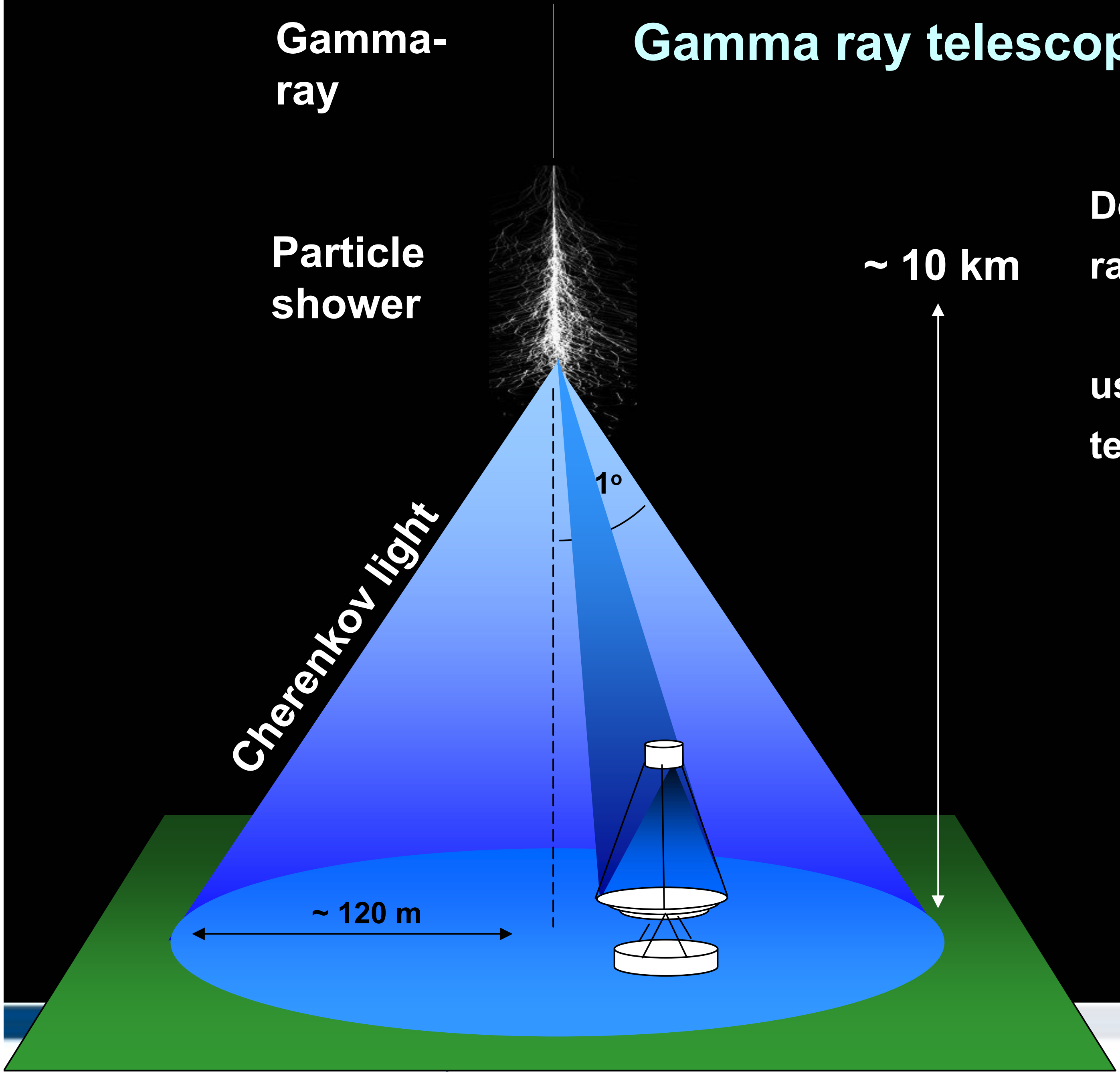
Pierre Auger Observatory: Tanks and telescopes

Energy spectrum of ultra-high energy cosmic rays



- Clear cut-off at $\sim 10^{19.5}$ eV
- Compatible with GZK effect (Greisen, Zatsepin, Kuzmin)
- Chemical composition of cosmic ray at these energies not yet understood.

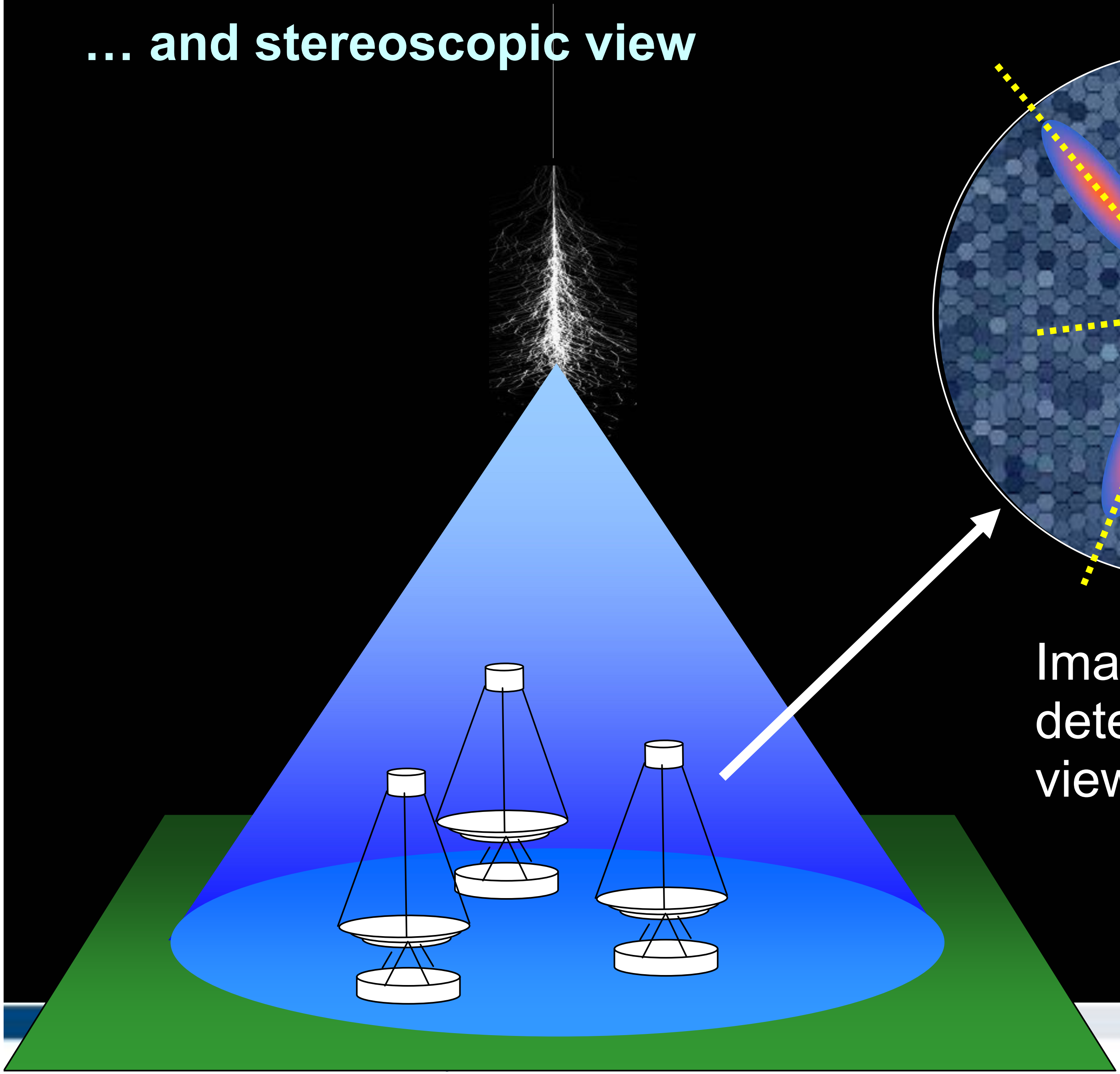
Gamma ray telescopes: Principle …



Detection of TeV gamma rays

using Cherenkov telescopes

… and stereoscopic view



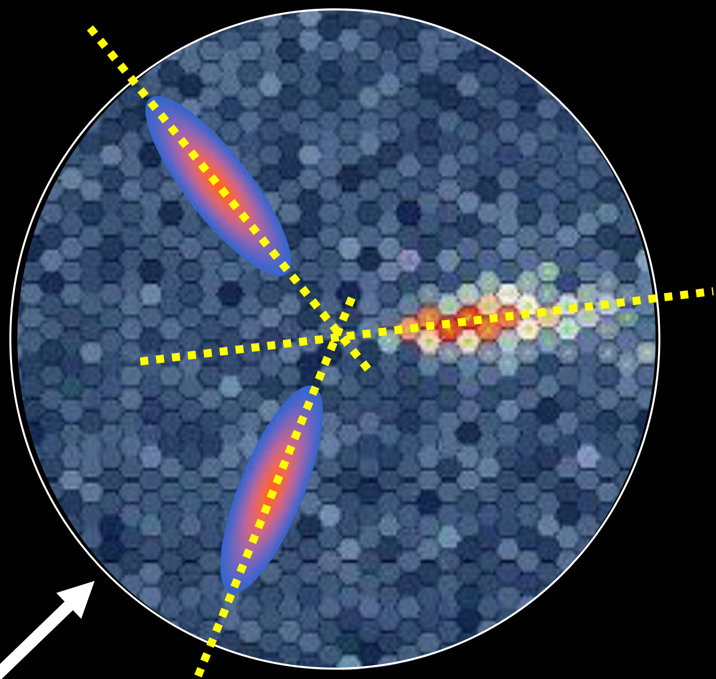


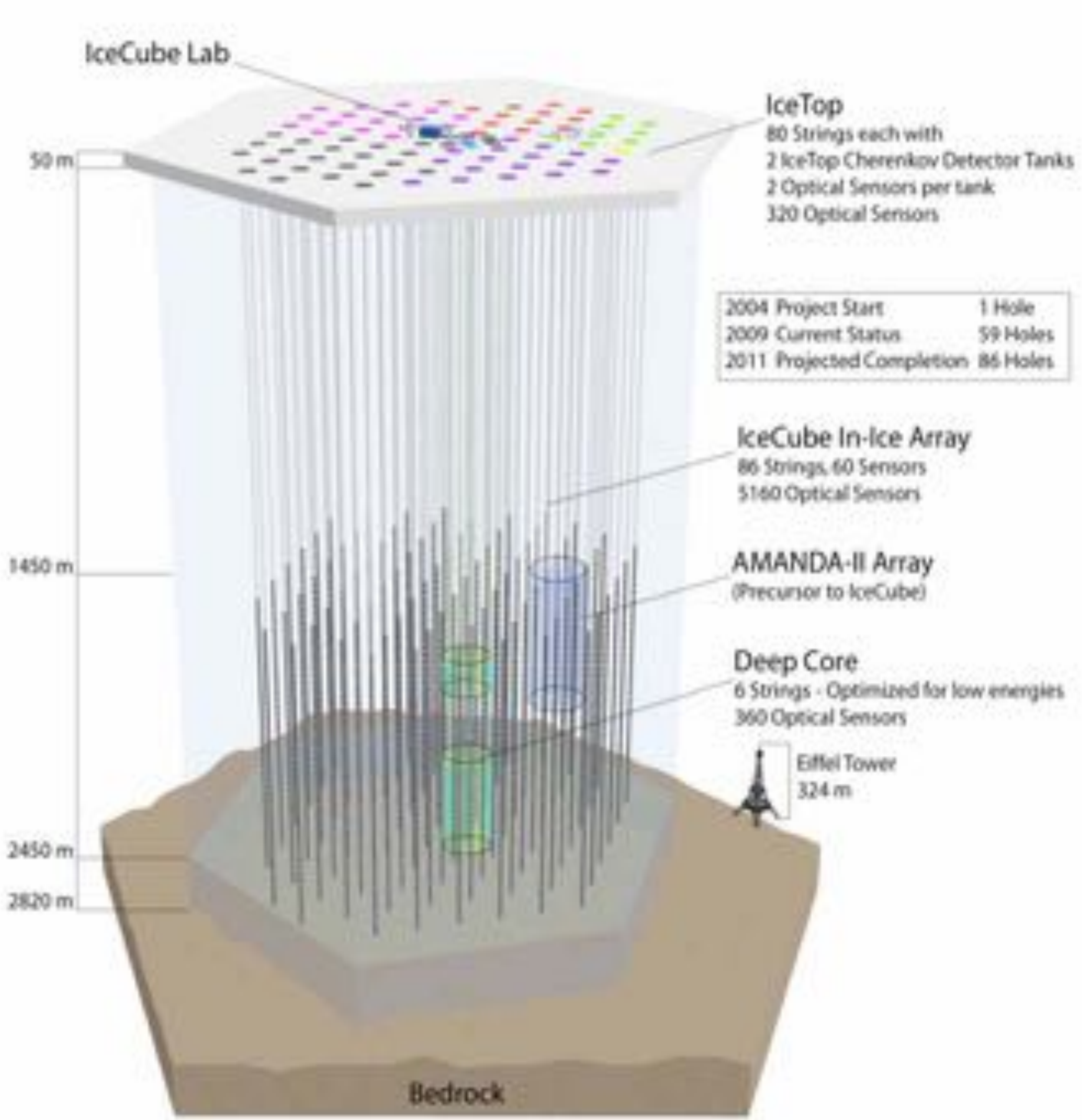
Image of source determined by three views

The H.E.S.S. telescope in Namibia

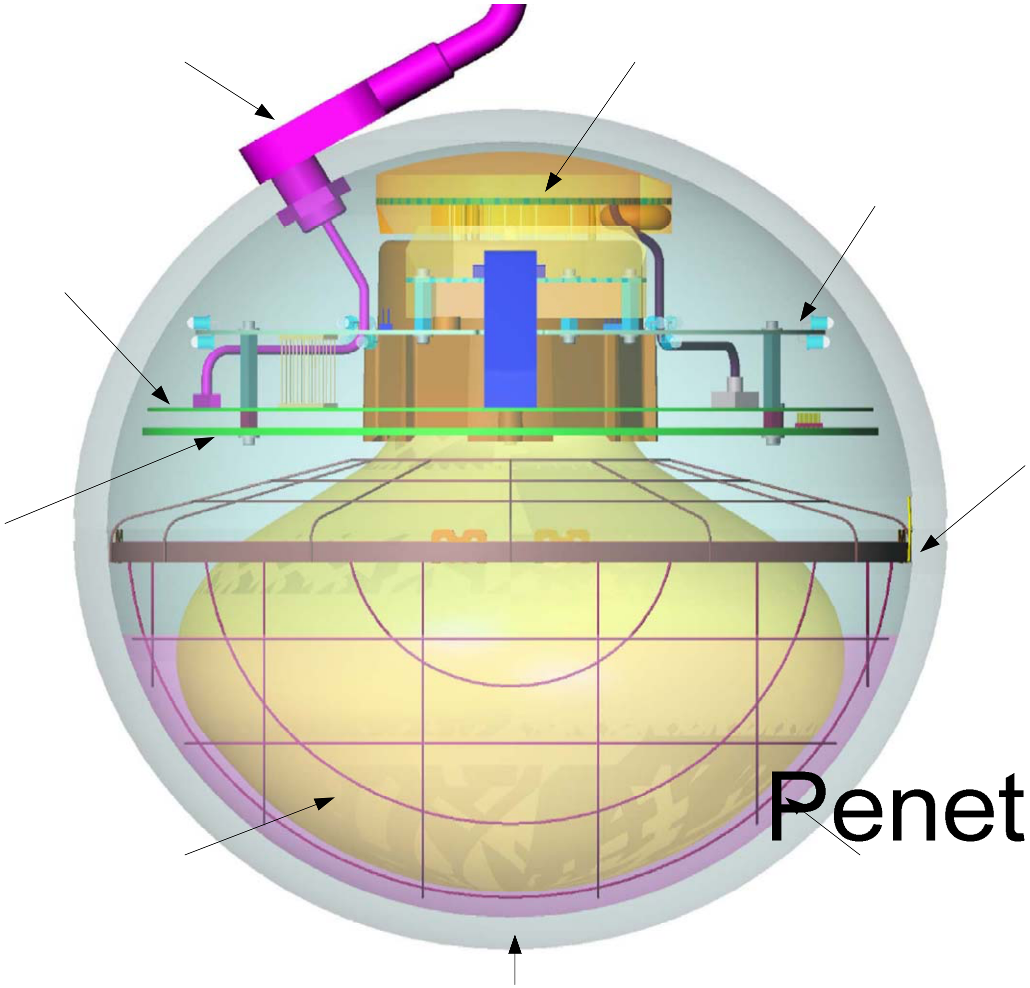
- 4 single telescopes, each ~100 m^2 mirror area
- A further large telescope is under construction

IceCube

- 4800 Digital Optical modules on 80 strings
- New: 6 additional strings (Deep Core)
- 160 ice-tank surface array (IceTop)
- Instrumenting 1 km^3 of Antarctic ice
- After Antarctic summer 2009/10: 79 strings deployed.

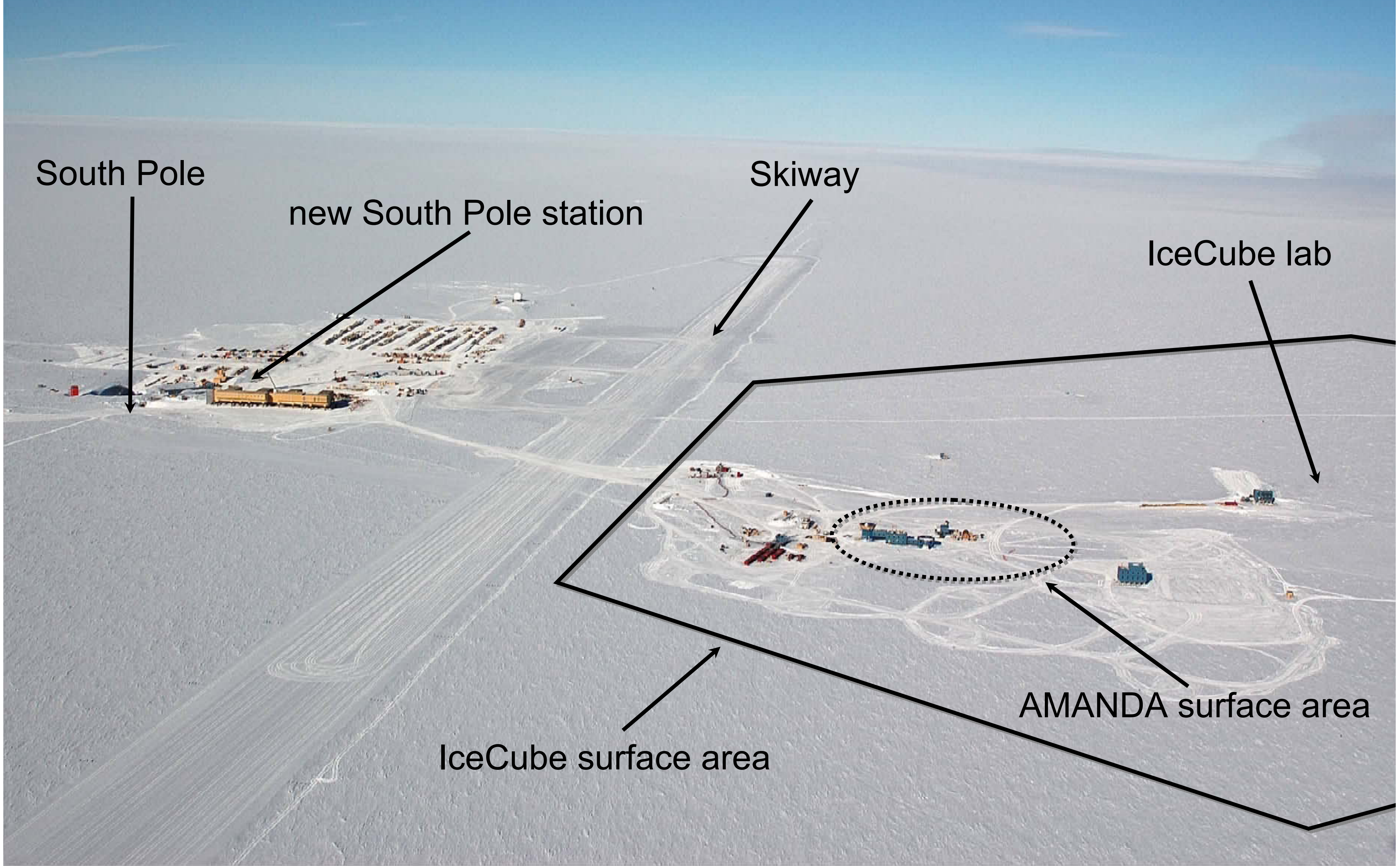


The IceCube Digital Optical Module (DOM)

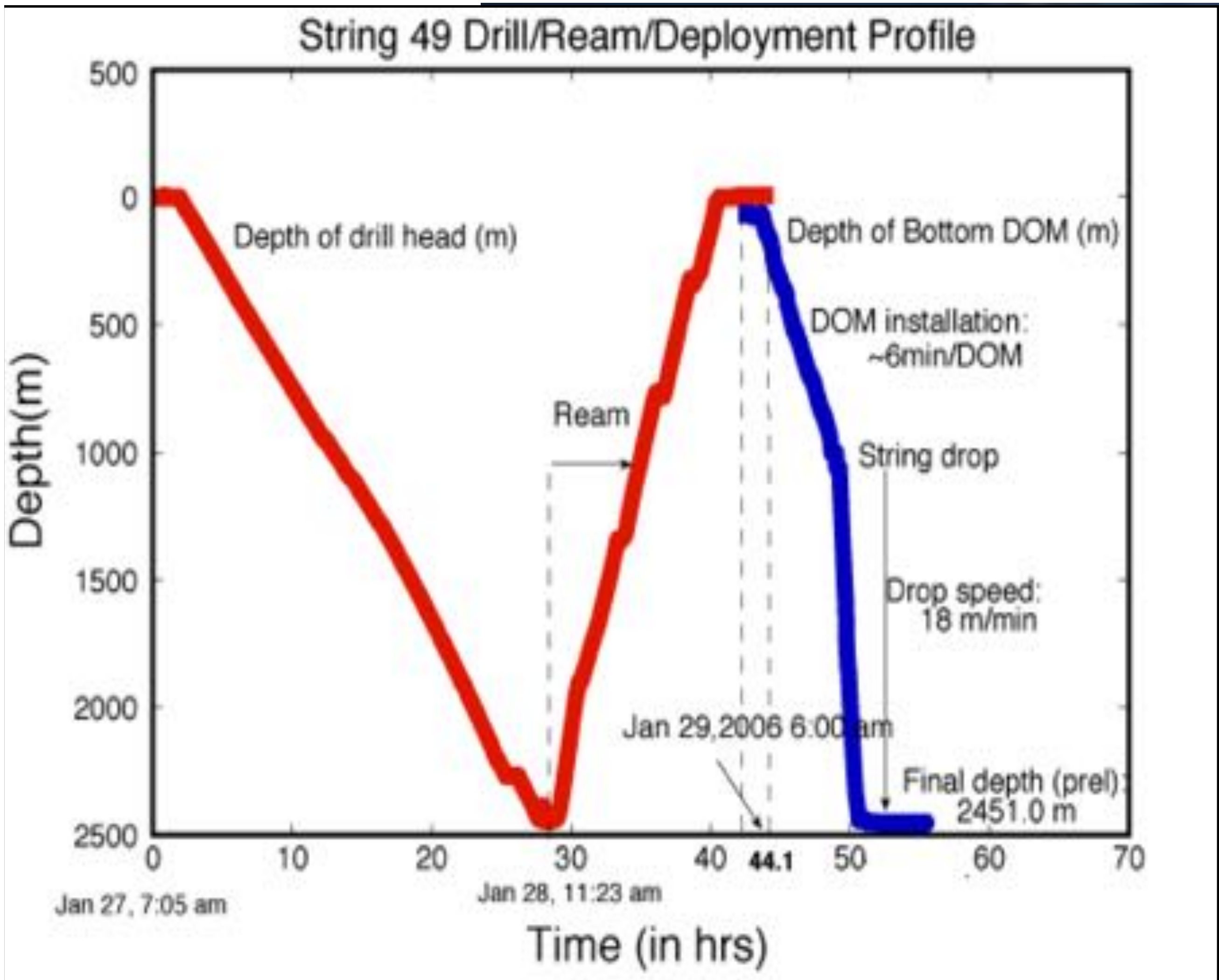


- On board HV, digitisation, and rate measurements (1.6ms bins)
- Low power: 3.75 W
- Low noise: ~ 260 Hz
- Fast timing: resolution between DOMs: $\Delta t < 5$ ns
- Large dynamic range:
  - 10^3 pe / 10 ns
  - 10^4 pe / 1 µs.

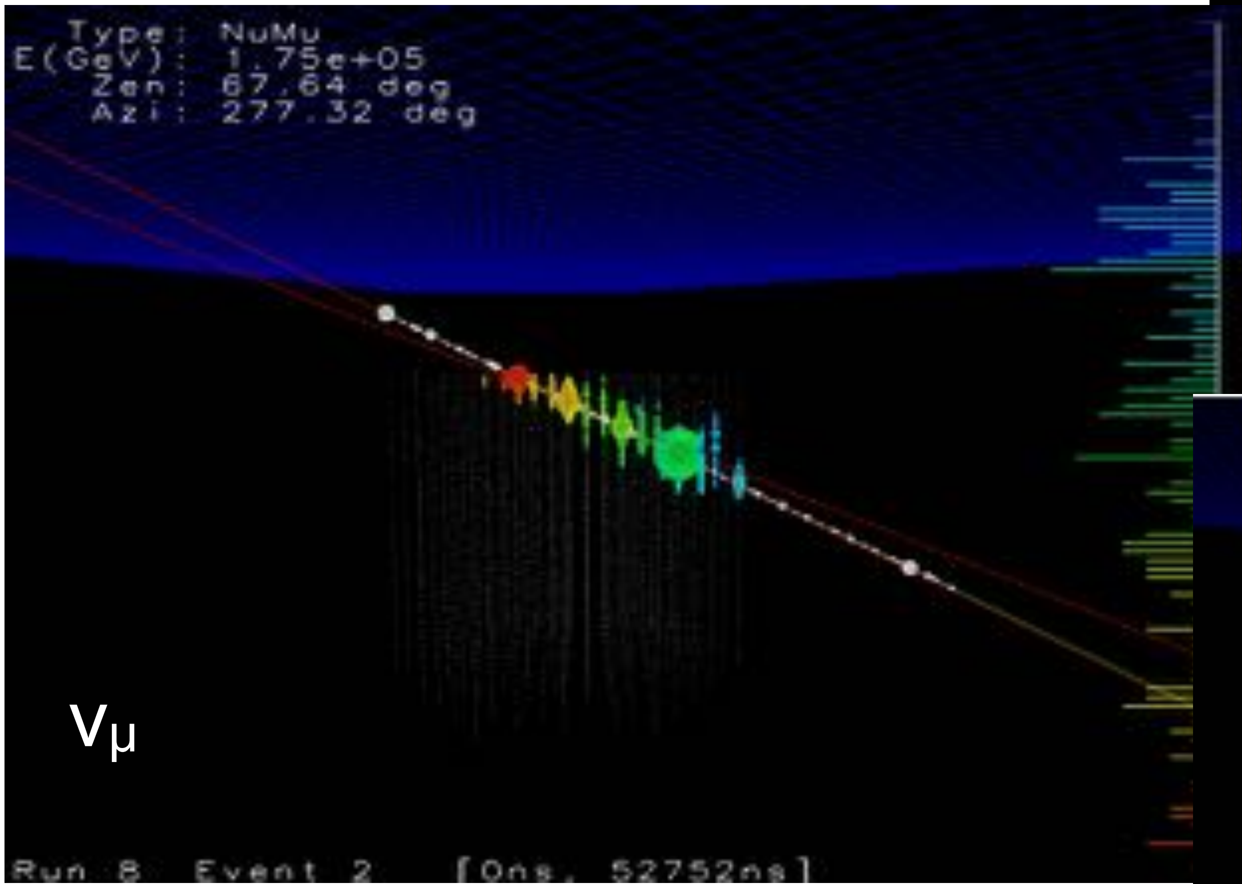
IceCube and AMANDA at the South Pole

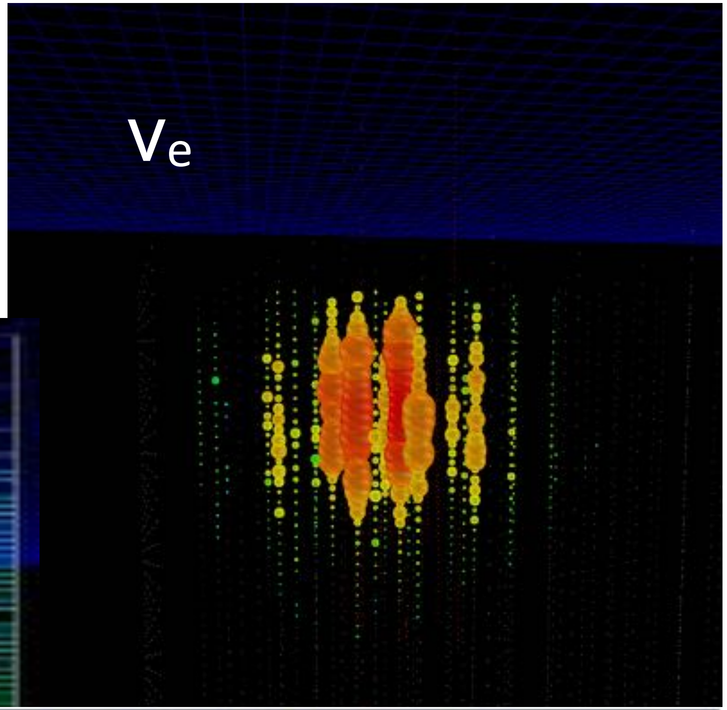


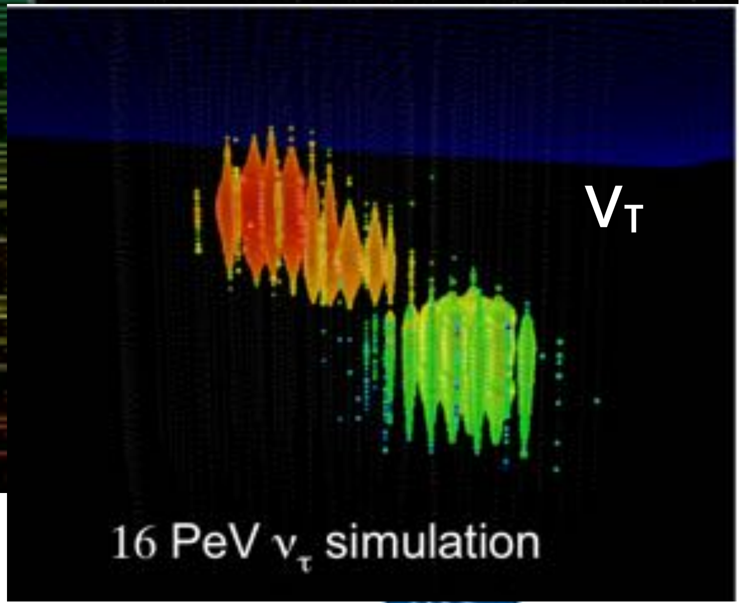
Drilling and deployment



Neutrino flavour signatures in IceCube (from simulations)

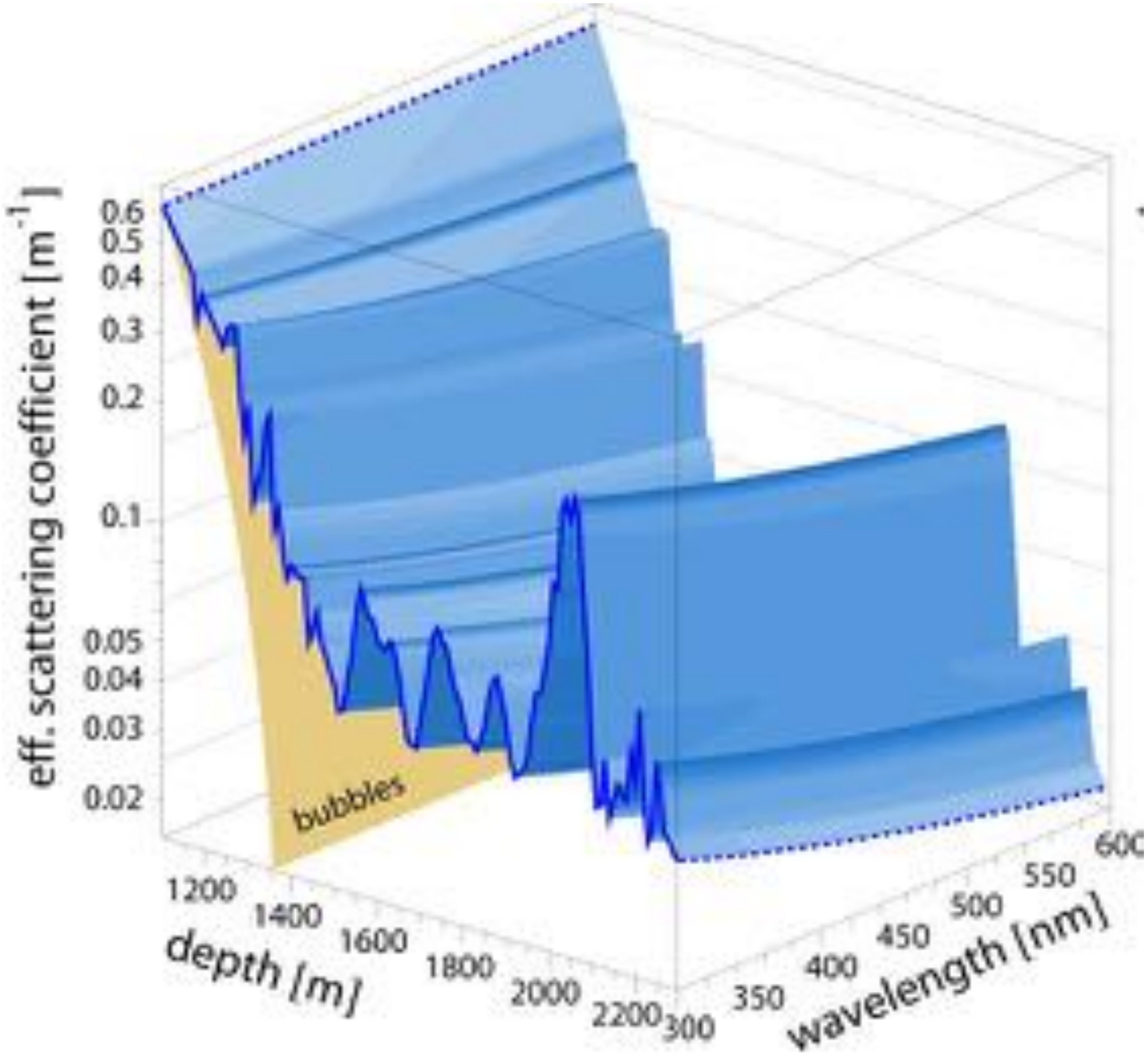






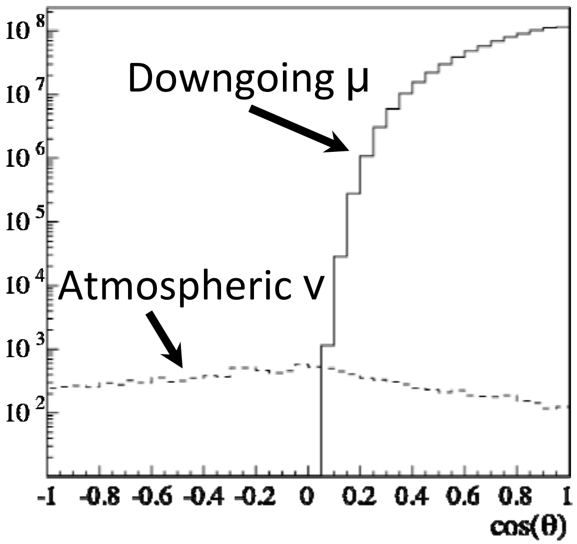
Ice properties

- Ice is scattering-dominated medium
  - λ_{abs} ~ 100 m
  - λ_{scat} ~ 20 m
- Analysis of data is sensitive to modeling of ice properties
- Ice properties measured with specialised device

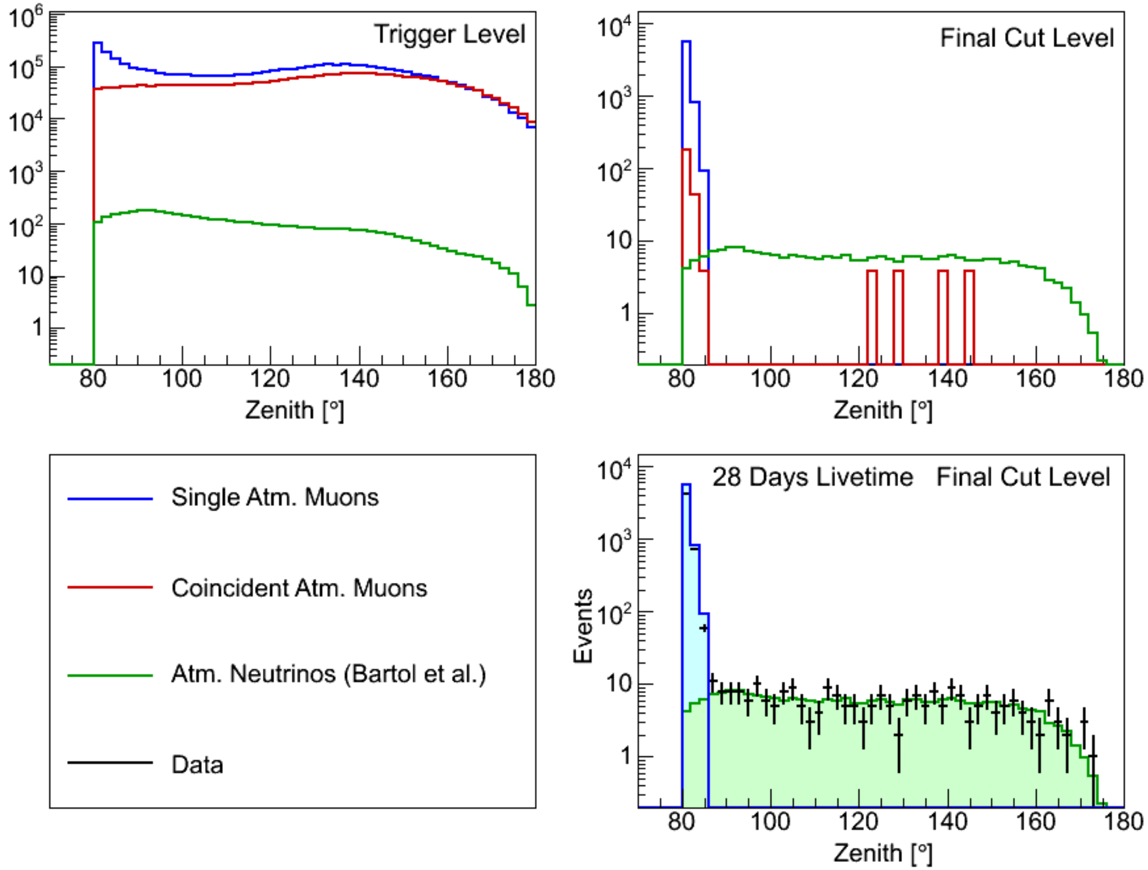


Signal and backgrounds

True Zenith Angle



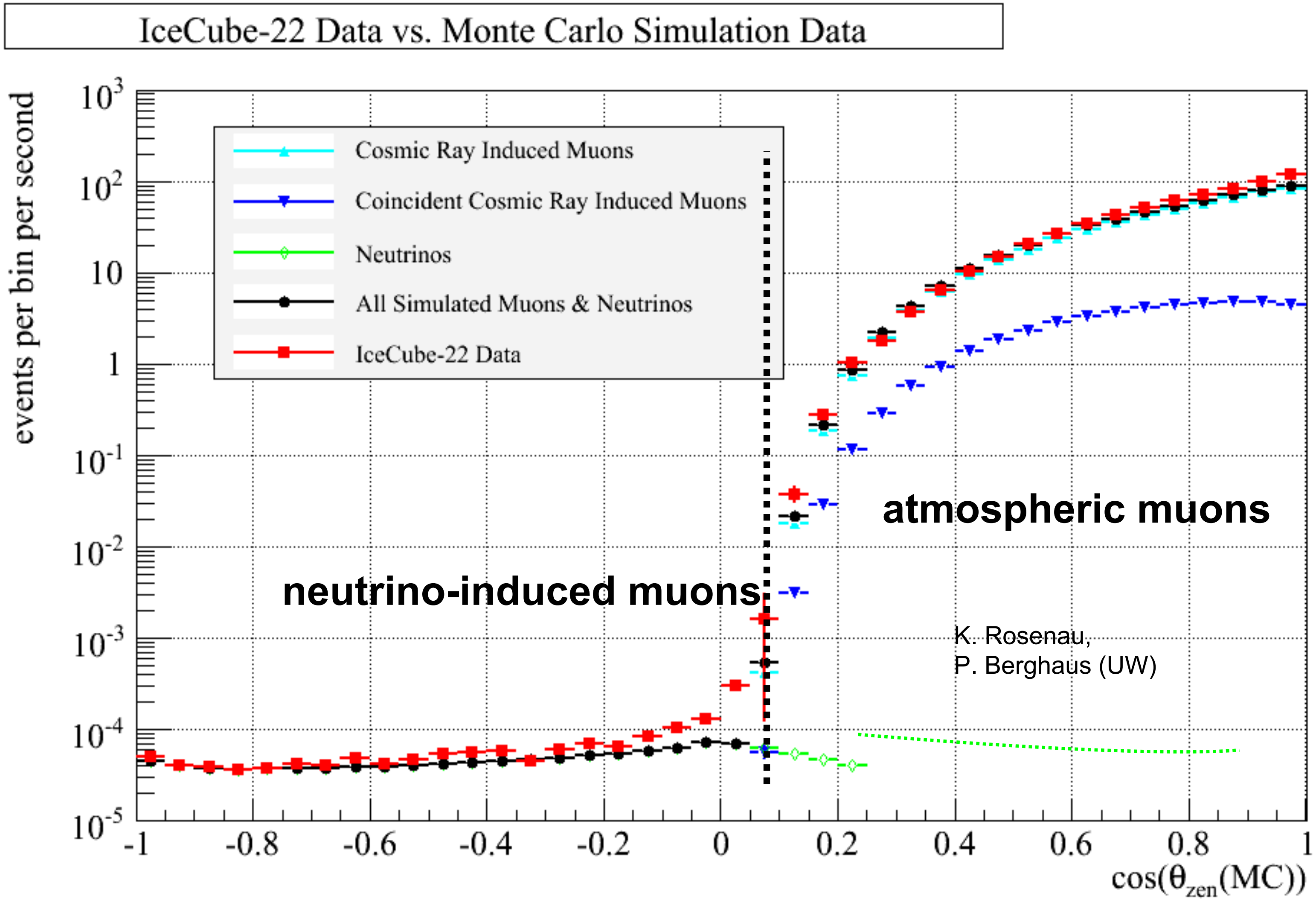
Reconstructed Zenith Angle



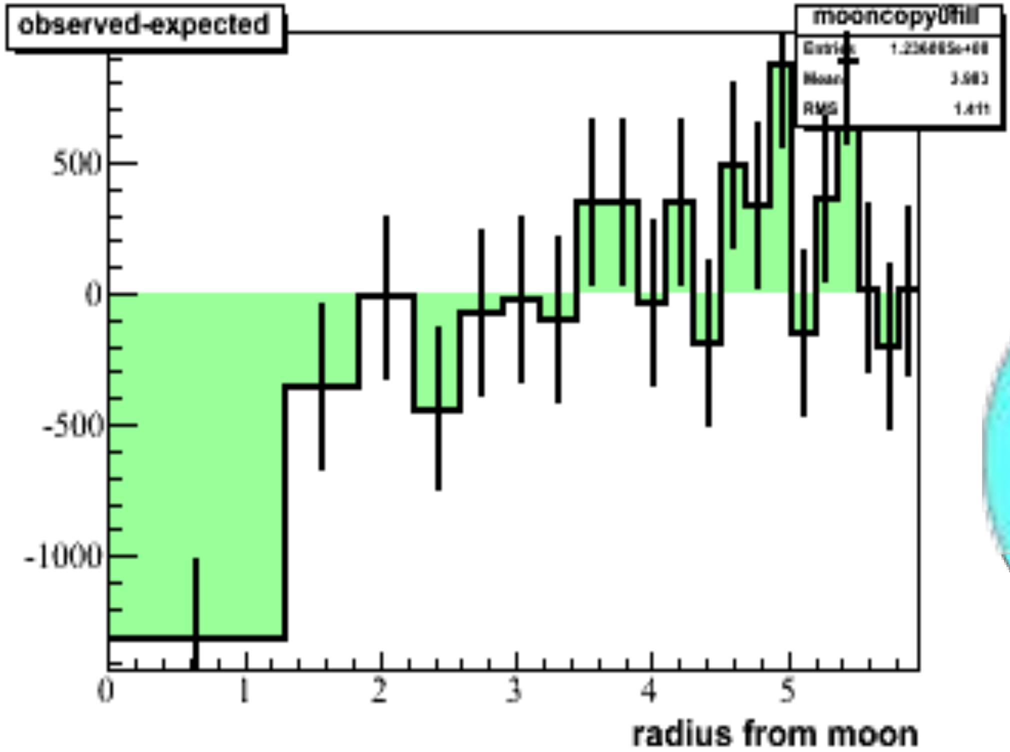
Cosmic ν backgrounds:

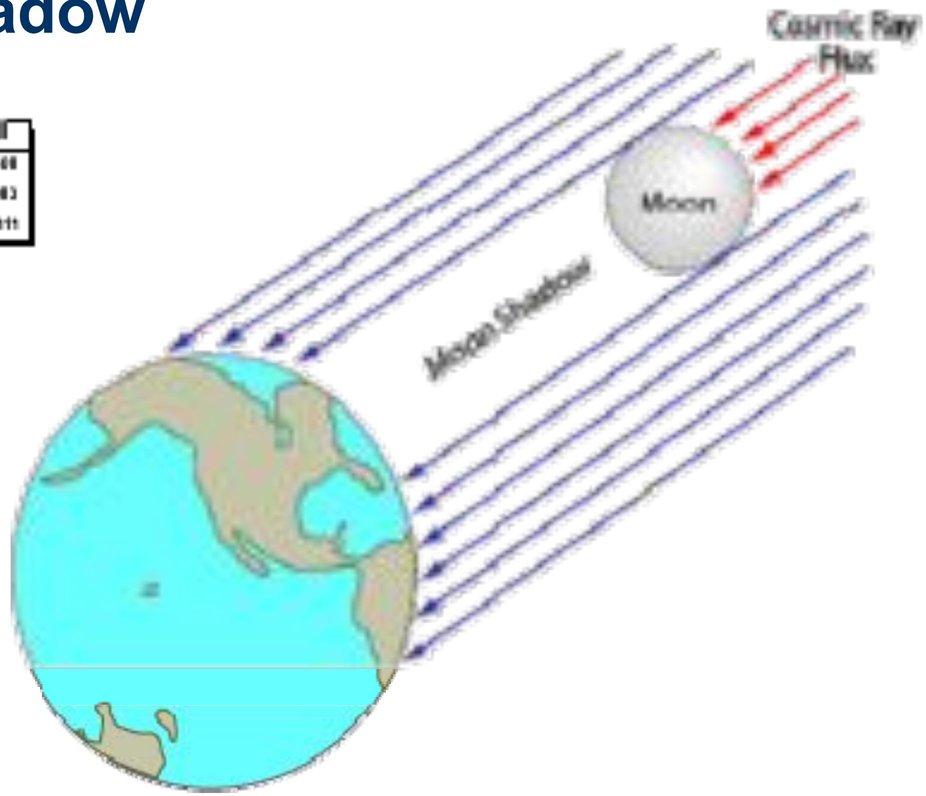
- Downgoing μ
- Coincident μ
- Atmospheric ν

IceCube muons (300 days with IC22)



Calibration with the moon shadow



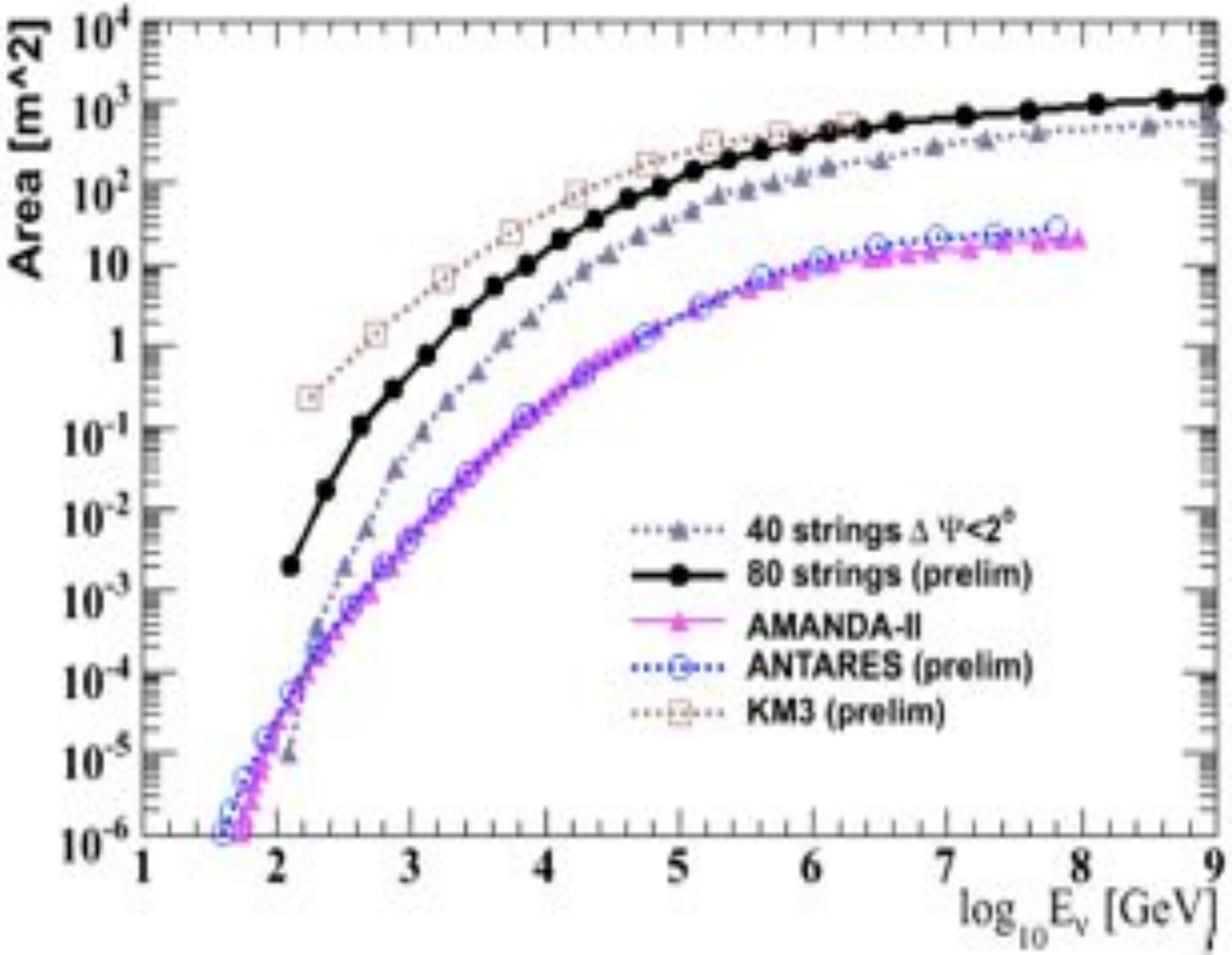


- Moon shadow observed in first 3 months of IC40 data
- Validates pointing capabilities of IceCube
- Will be used to investigate detector angular resolution

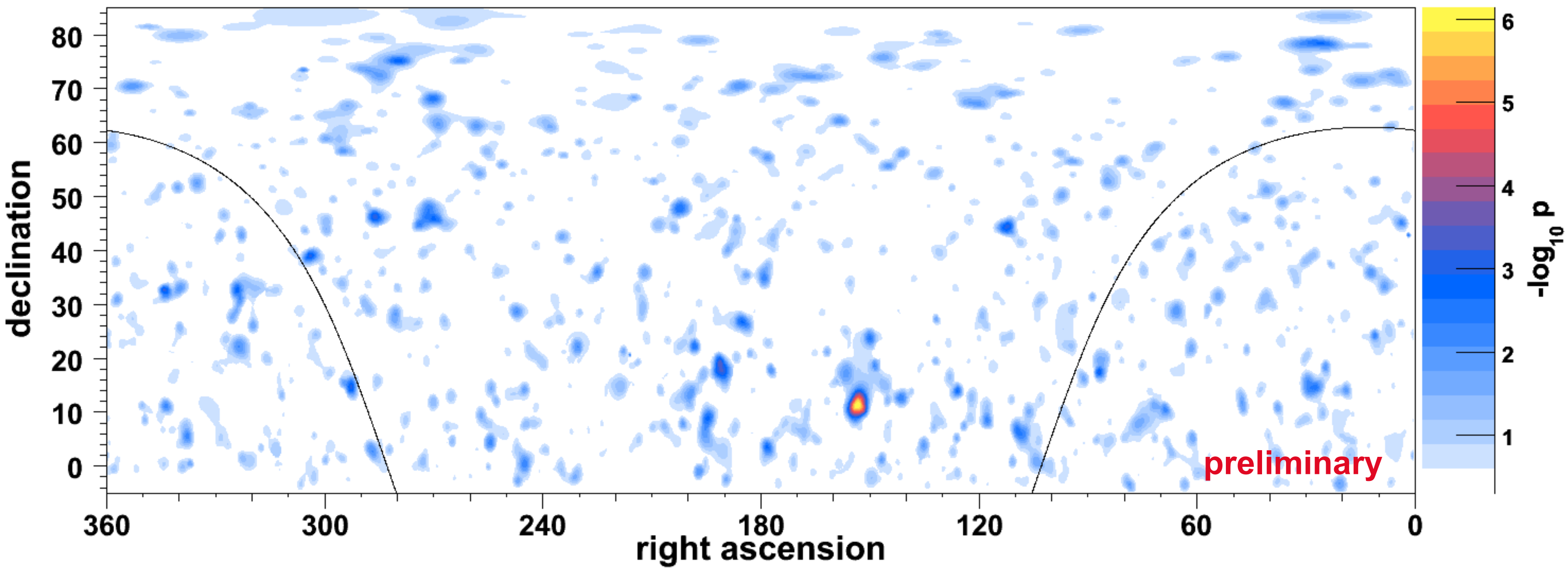
Preliminary

The effective area

- Effective area = size of a virtual detector that would detect all arriving muons
- 1-100m^2 in the most relevant energy regime

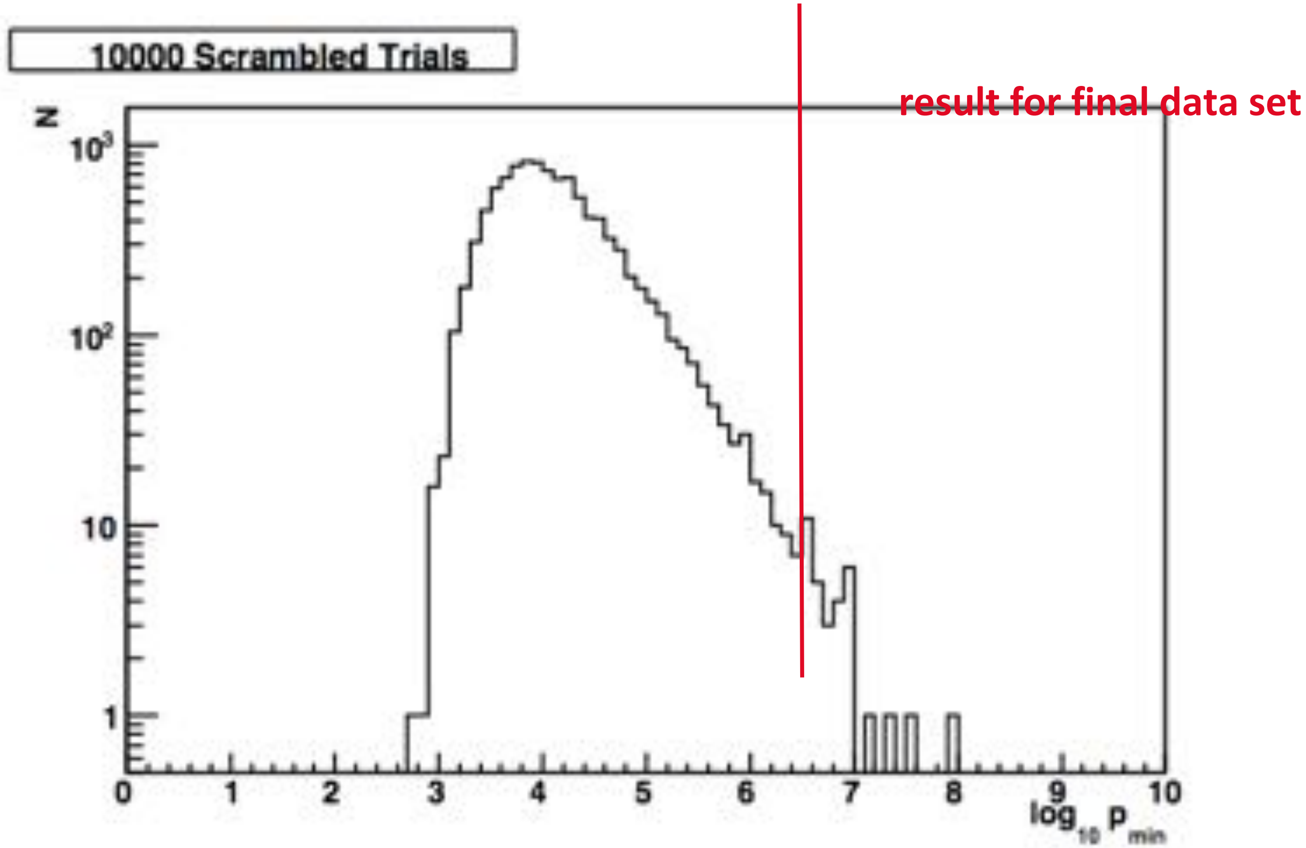


Point source search (IceCube 22)



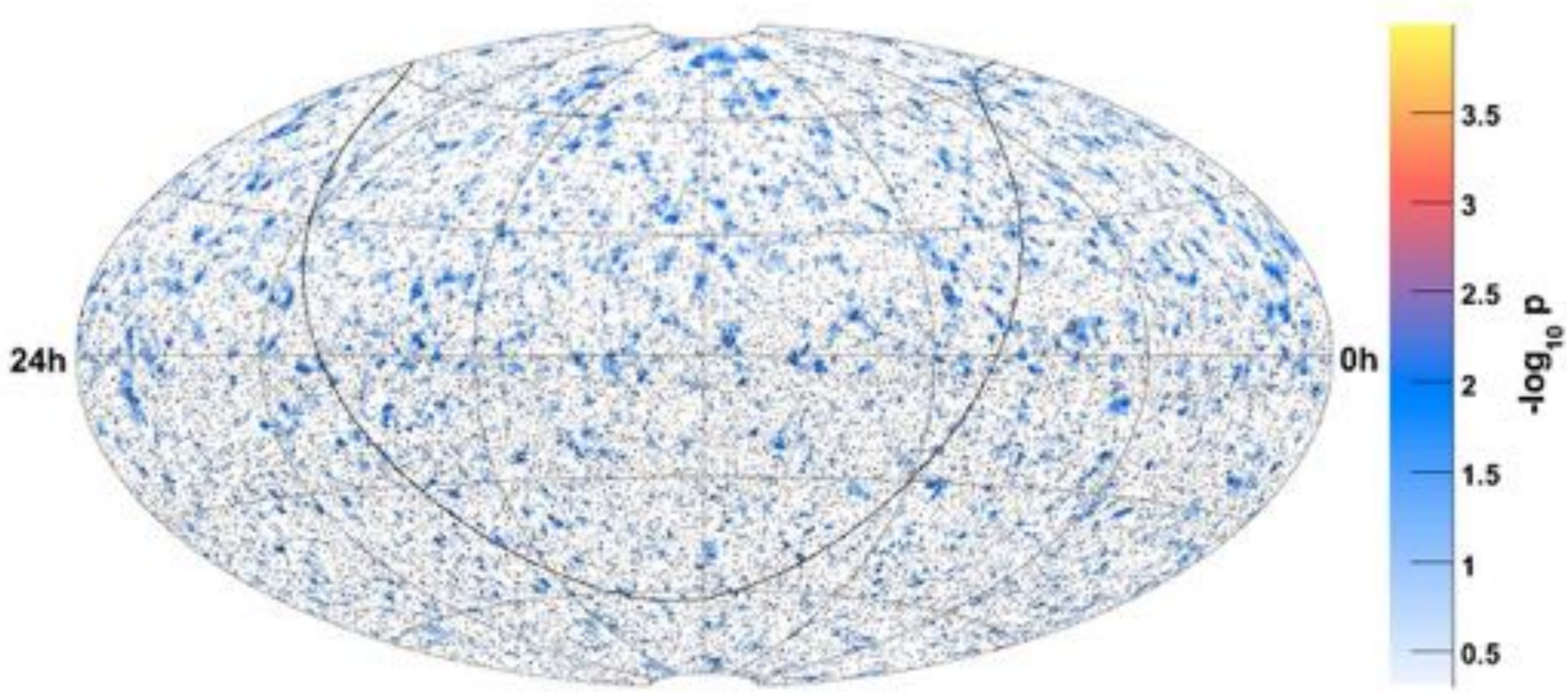
- **Hottest spot found at r.a. 153º , dec. 11º**
  pre-trial p-value: 7×10^{-7} (4.8 sigma)
- **Accounting for all trials, p-value for analysis is 1.34% (2.2 sigma).**
- **At this significance level, consistent with fluctuation of background.**

Assessing the real significance



Out of 10,000 trials of scrambled data sets, 67 (0.67%) have an event accumulation more significant than in the data

A preliminary result from IceCube 40:

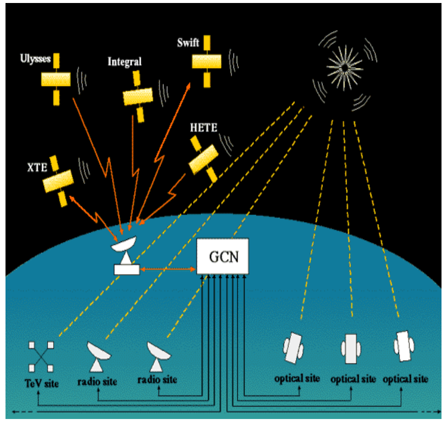


- Include southern sky for E_ν above ~1PeV
- No evidence for point sources yet

GRB Detection in the IceCube Era

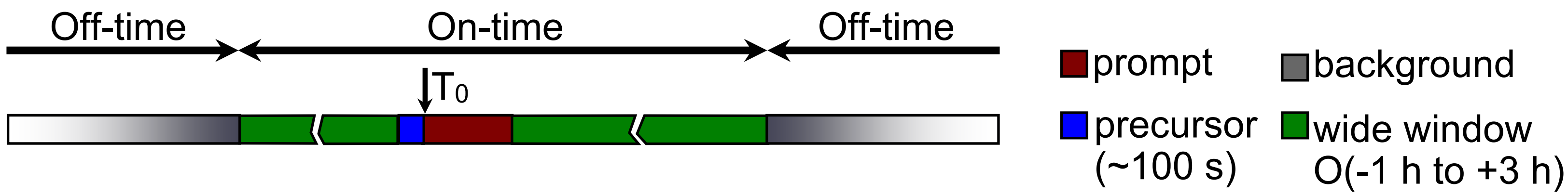
- GCN: Network of satellite and ground-based observatories
  - Satellites send GRB alerts to ground stations for follow-up observations
  - Swift workhorse until recently (~100 GRBs per year)
    Burst Alert Monitor: FoV=1.4 sr; *E* range 15–150 keV
- Fermi (GLAST) satellite:
  - Launch in June 2008; science since August '08
  - GBM (Burst Alert Monitor):
    FoV = 9.5 sr; *E* range: 8 keV–25 MeV
  - LAT (Large Area Telescope):
    FoV = 2.4 sr; *E* range: 20 MeV–300 GeV !
  - Expected to observe ~200 GRBs per year

GCN network



GRB analysis: Search method

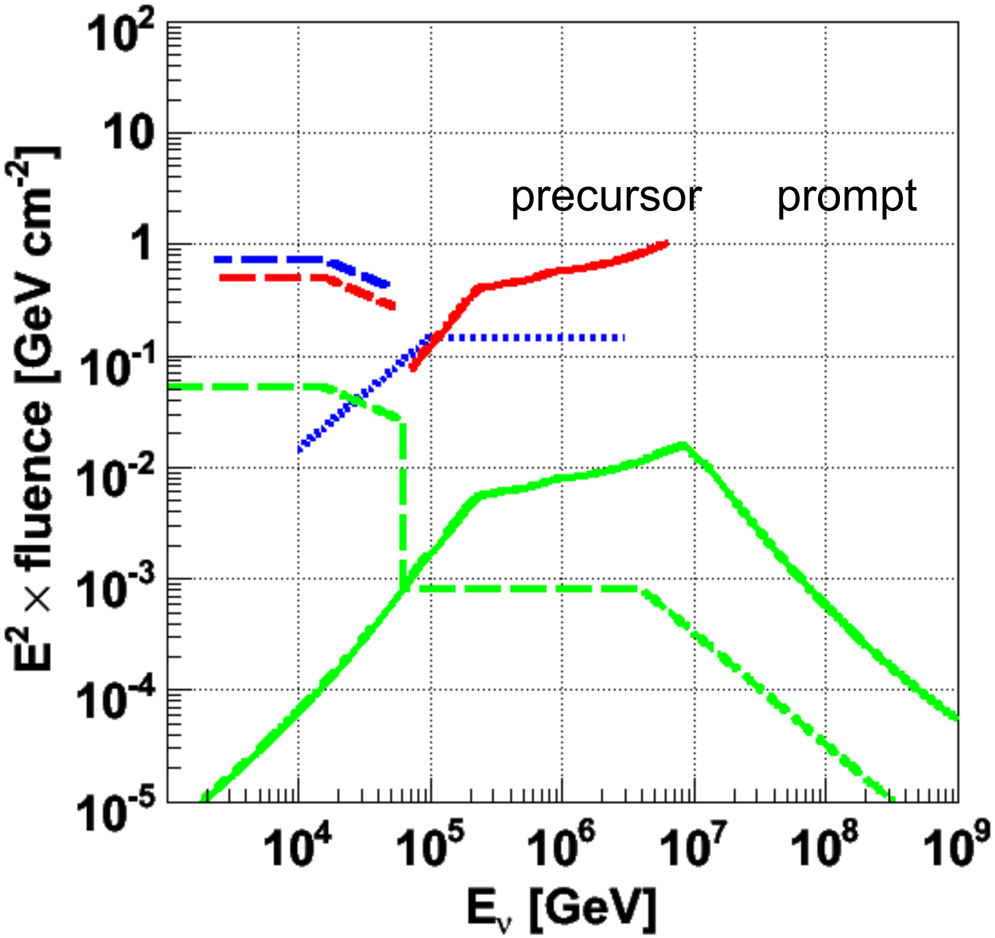
- Satellite-triggered searches
  (profit from known time + direction)



- Low number of events per burst expected → burst stacking

- Off-time data used as background

IceCube 22: upper limits on neutrino fluxes from GRBs



IceCube 22 strings

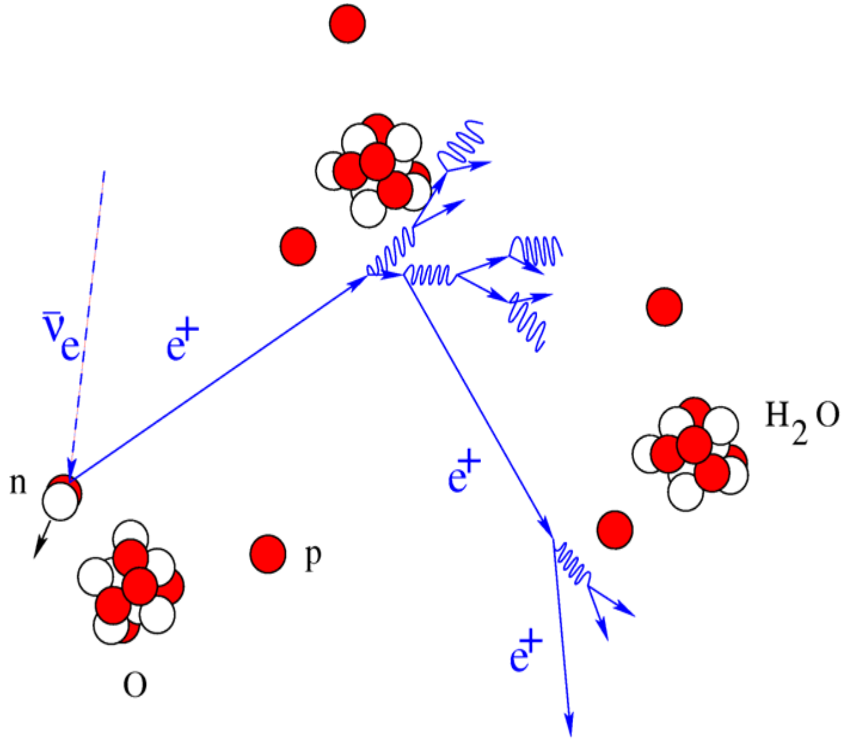
Final AMANDA limits
(Waxman & Bahcall, PRL 78, 2292)

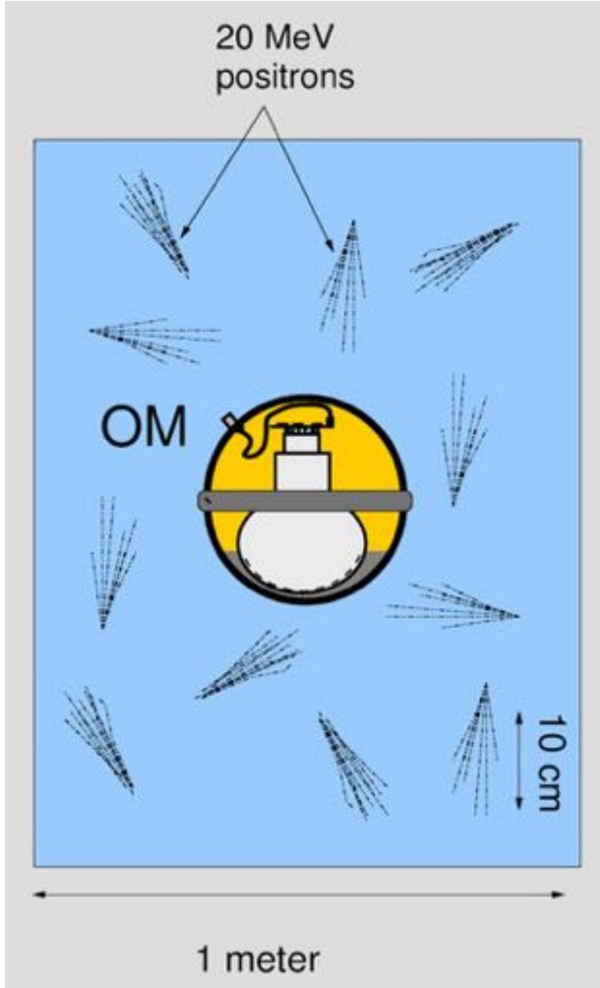
Models:

- prompt:
  sum of individual spectra
- precursor:
  Razzaque, Meszaros & Waxman
  Phys.Rev.D 68:628

AMANDA/IceCube as MeV ν detector

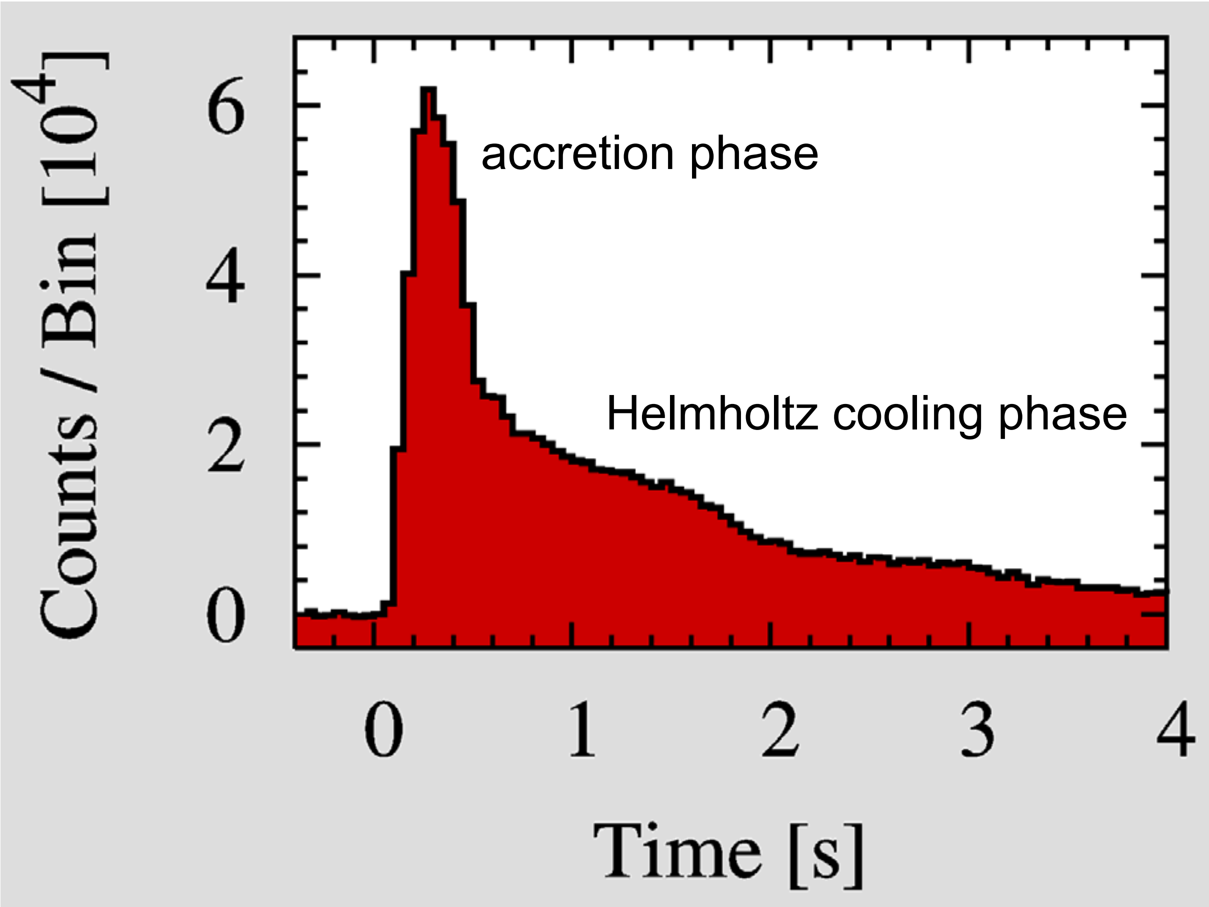
…first proposed by Halzen, Jacobsen & Zas, astro-ph/9512080





- ice uniformly illuminated
- detect correlated rate increase on top of PMT noise

AMANDA/IceCube as MeV ν detector (2)



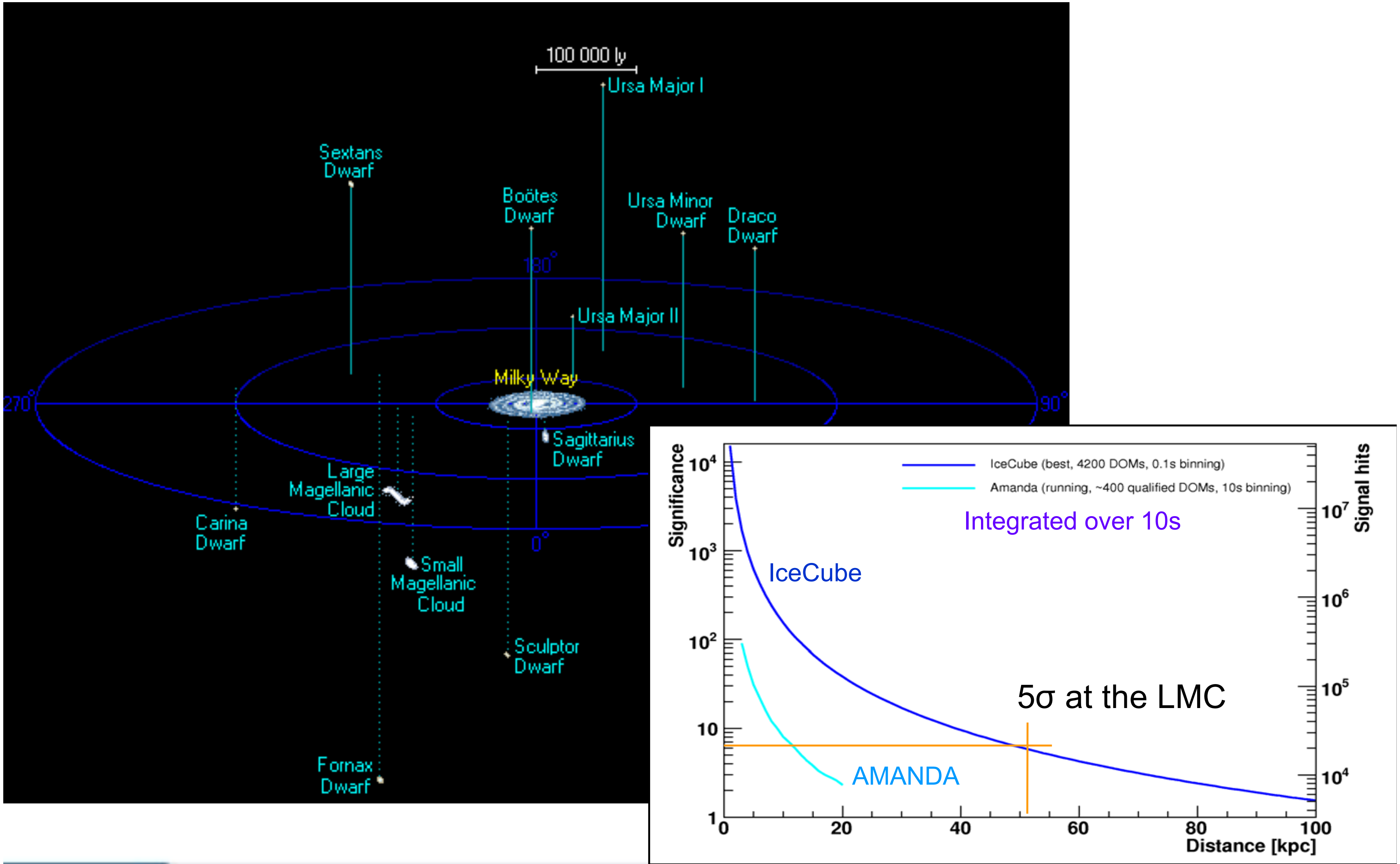
Disadvantages:
- no pointing
- intrinsic noise

Advantage:
- high statistics (0.25% stat. error)

Good for fine time structures (noise low)!

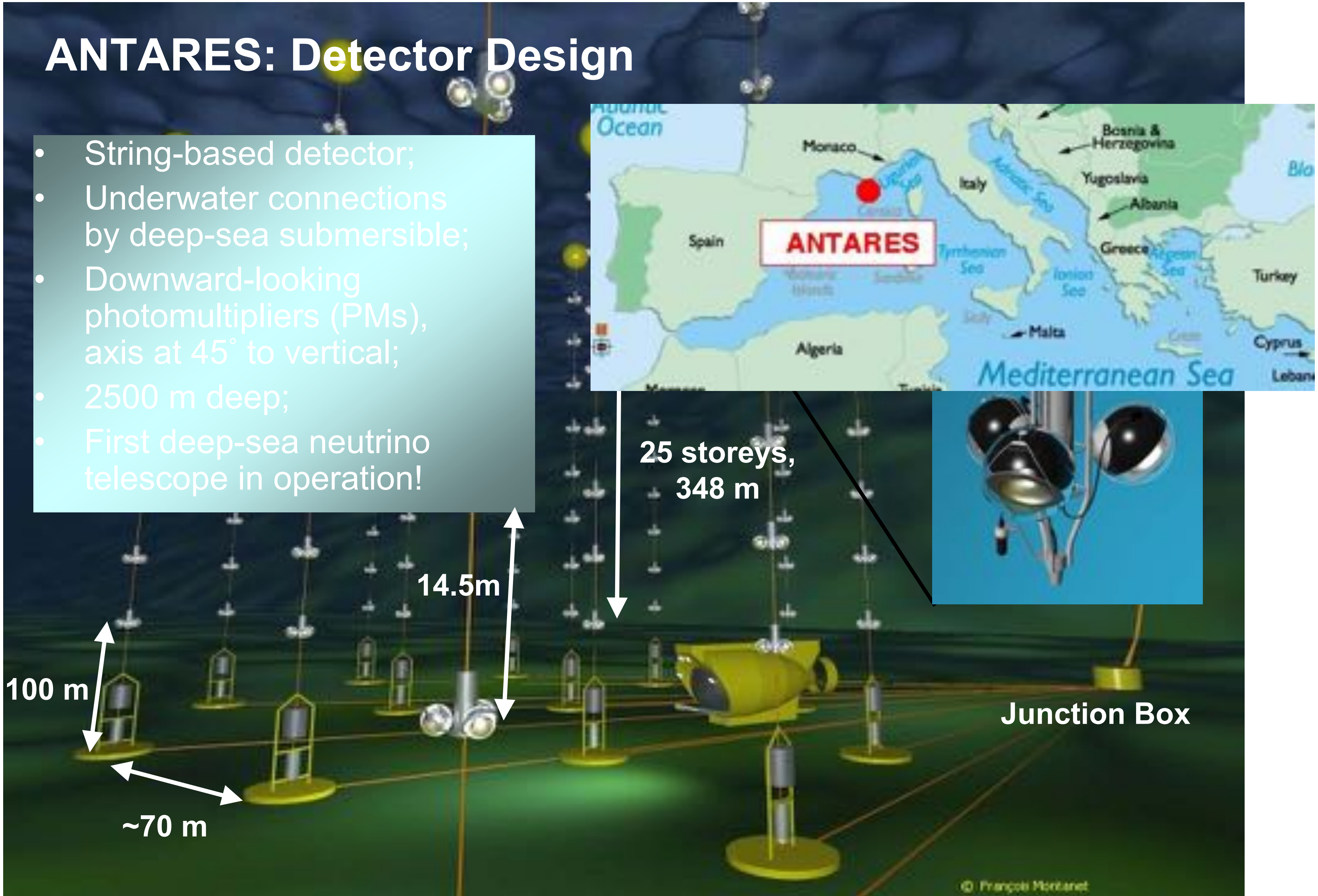
Simulation based on a numerical Livermore model, normalised to SN1987A at 10 kpc
Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216
See also: Dighe, Keil & Raffelt, hep-ph/0303210

AMANDA/IceCube range of sensitivity to Supernovae



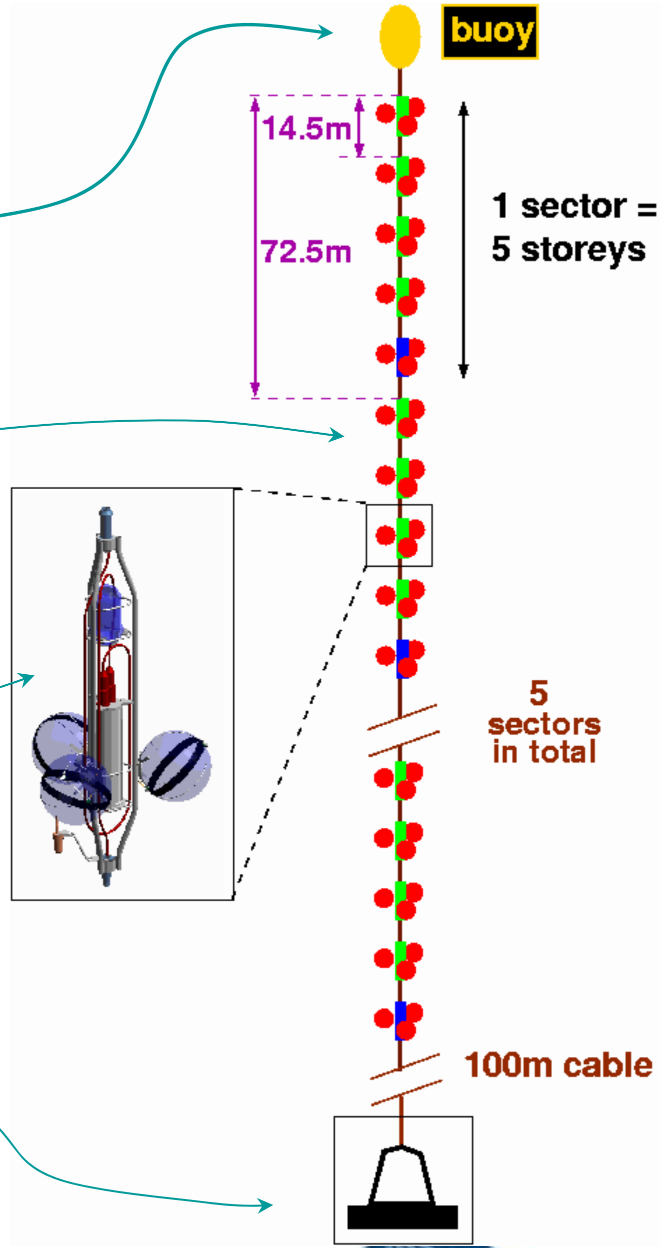
ANTARES: Detector Design

- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking photomultipliers (PMs), axis at 45° to vertical;
- 2500 m deep;
- First deep-sea neutrino telescope in operation!

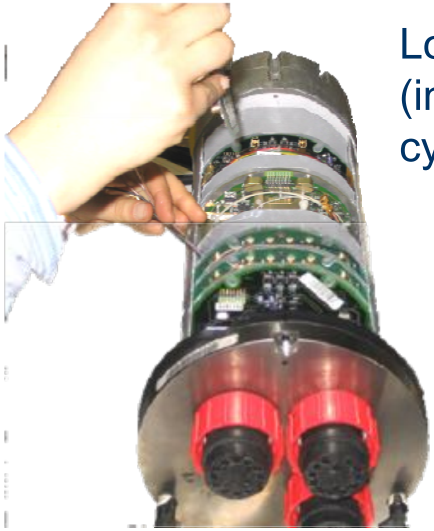


ANTARES: Detector Strings

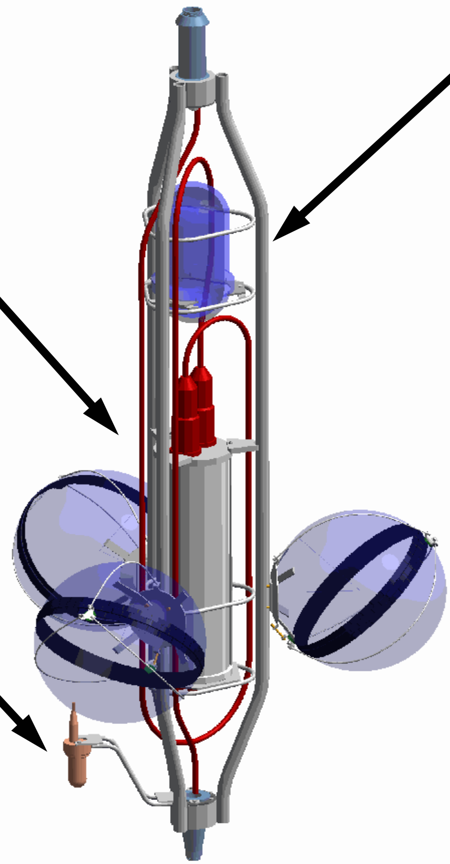
- Buoy:
  - buoyancy ~6400 N;
  - keeps string vertical to better than 20m displacement at top.
- Electro-optical-mechanical cable:
  - metal wires for power supply etc.;
  - optical fibers for data;
  - mechanical backbone of string.
- Storeys:
  - 3 optical modules per storey;
  - titanium cylinder for electronics;
  - calibration devices (light, acoustics).
- Anchor:
  - deadweight to keep string at bottom;
  - release mechanism operated by acoustic signal from surface.

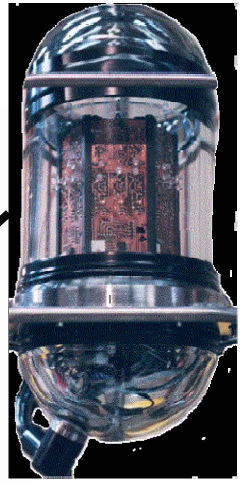


ANTARES: Components of a storey



Local Control Module
(inside a titanium
cylinder)





Optical Beacon
(blue LEDs) for timing
calibration
(4 per line)

Hydrophone RX
(5 Rx + 1 RxTx per line)

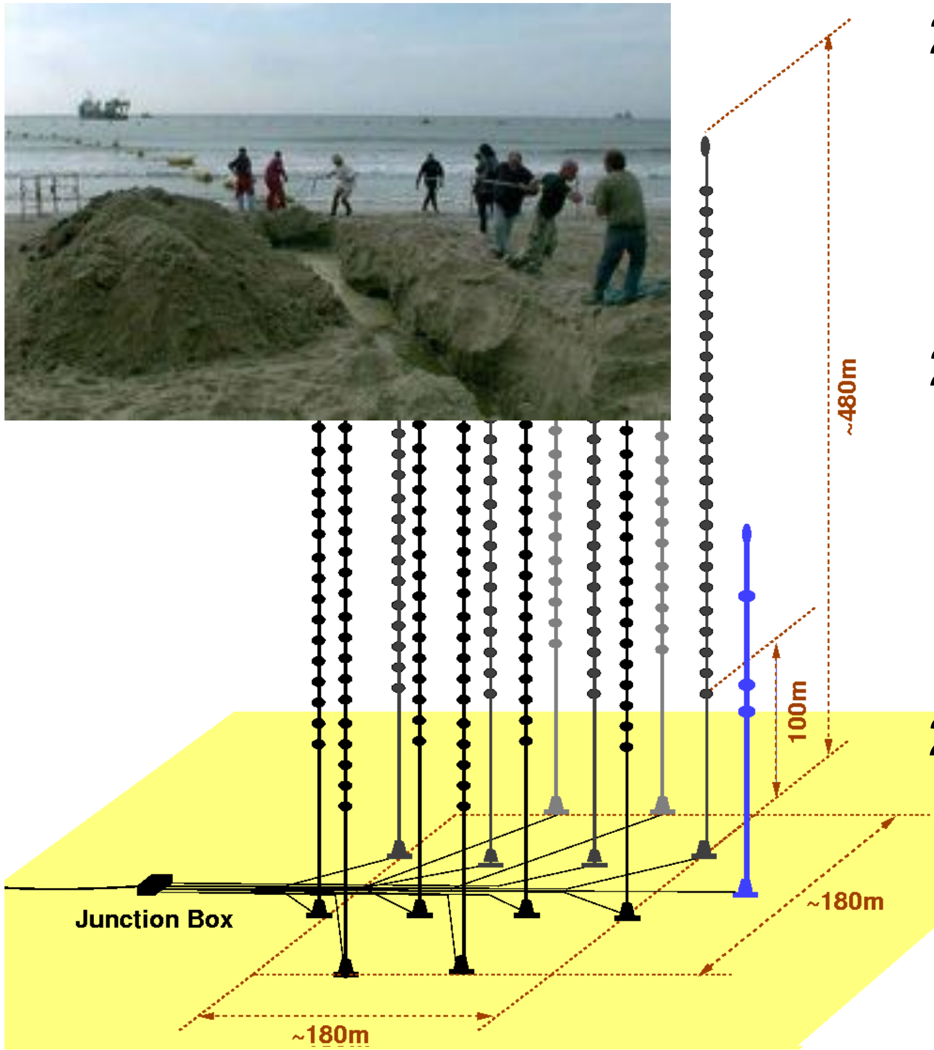
Optical Module:
17” glass sphere
10” PMT Ham. R7081-20
(14 stages)

ANTARES: Optical modules

- Photomultipliers:
  - transfer time spread ~2.7ns (FWHM);
  - quantum efficiency >20% for 330 nm < λ < 460nm;
- Glass spheres:
  - qualified for 600 bar;

43 cm

ANTARES construction milestones



2001 – 2003:

- Main Electro-optical cable in 2001
- Junction Box in 2002
- Prototype Sector Line (PSL) &
  Mini Instrumentation Line (MIL) in 2003

2005 – Now:

- Mini Instrumentation Line with OMs (MILOM) running since 12 April 2005
- Lines 1-5 running (connected between March 2006 and Jan. 2007)
- Lines 6+7 deployed March/April 2007

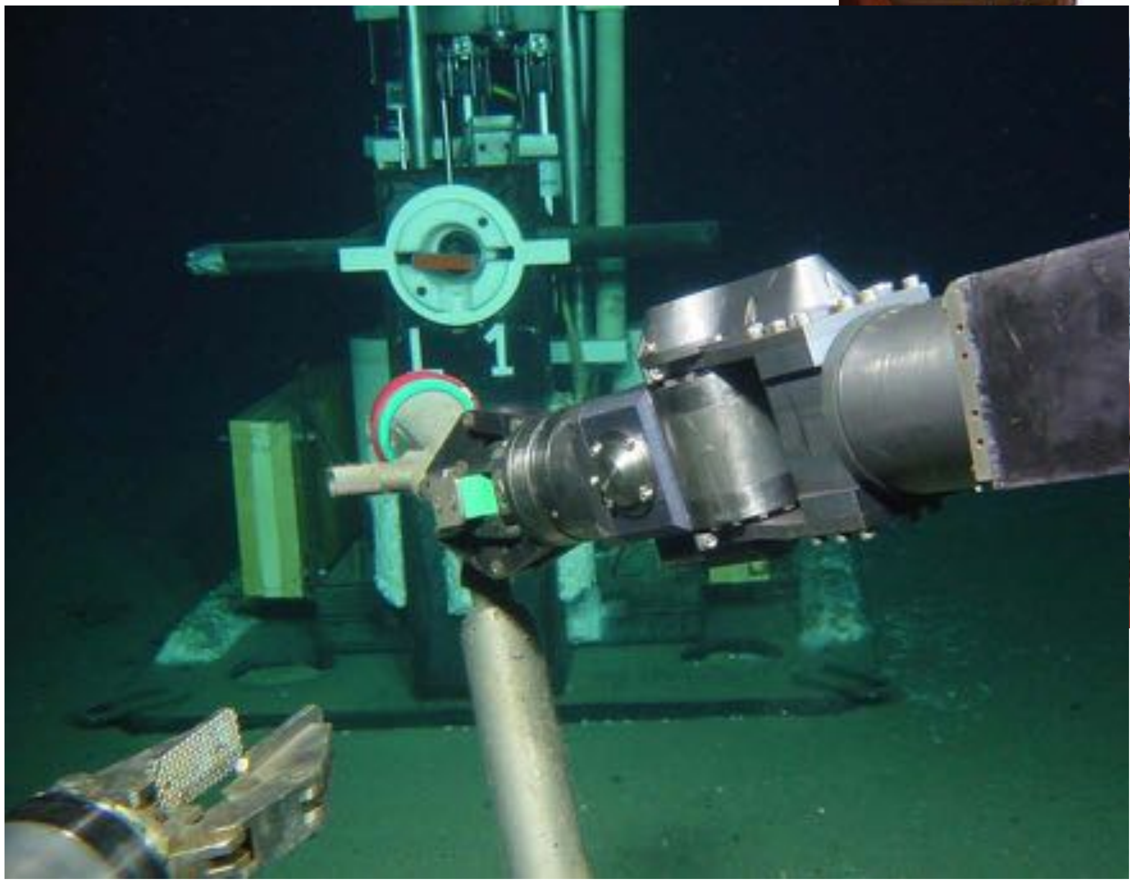
2007+:

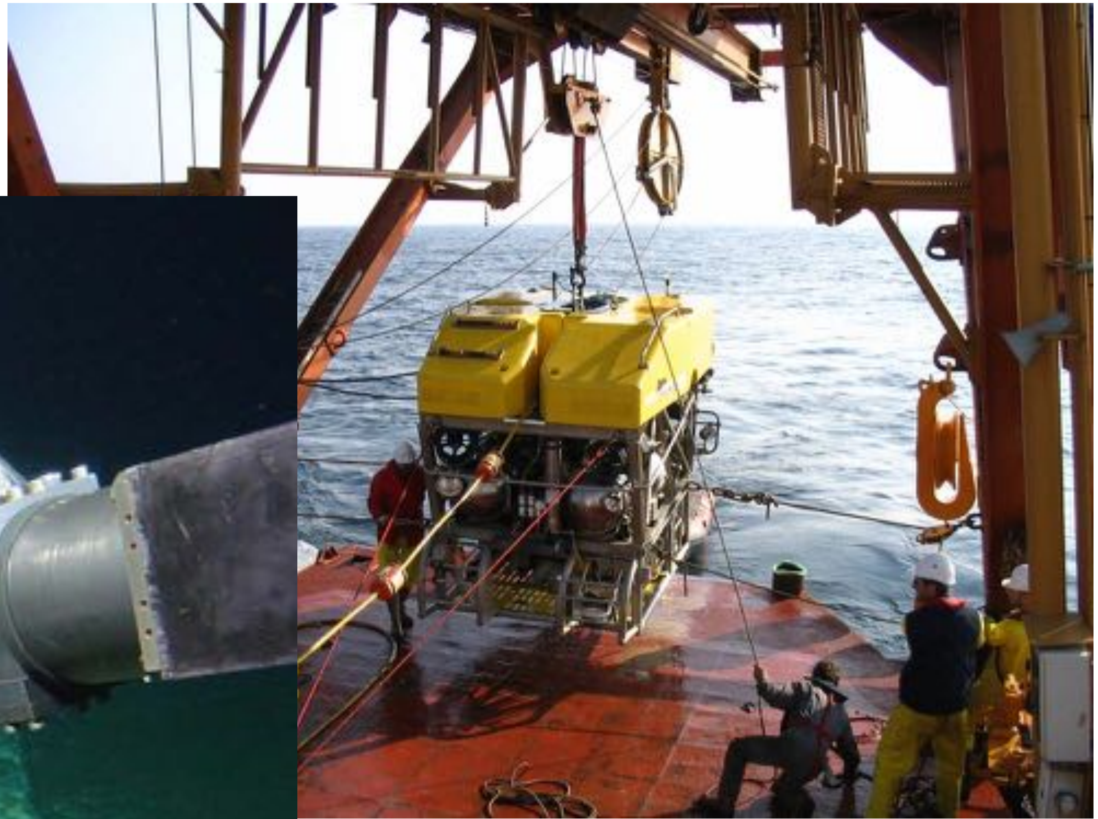
- Deployment / connection of remaining 5(7) lines
- Replacement of MILOM by full instrumentation line (IL)
- **Physics with full detector !**

ANTARES: First detector line installed …

14. Feb. 2006

… and connected by ROV Victor!

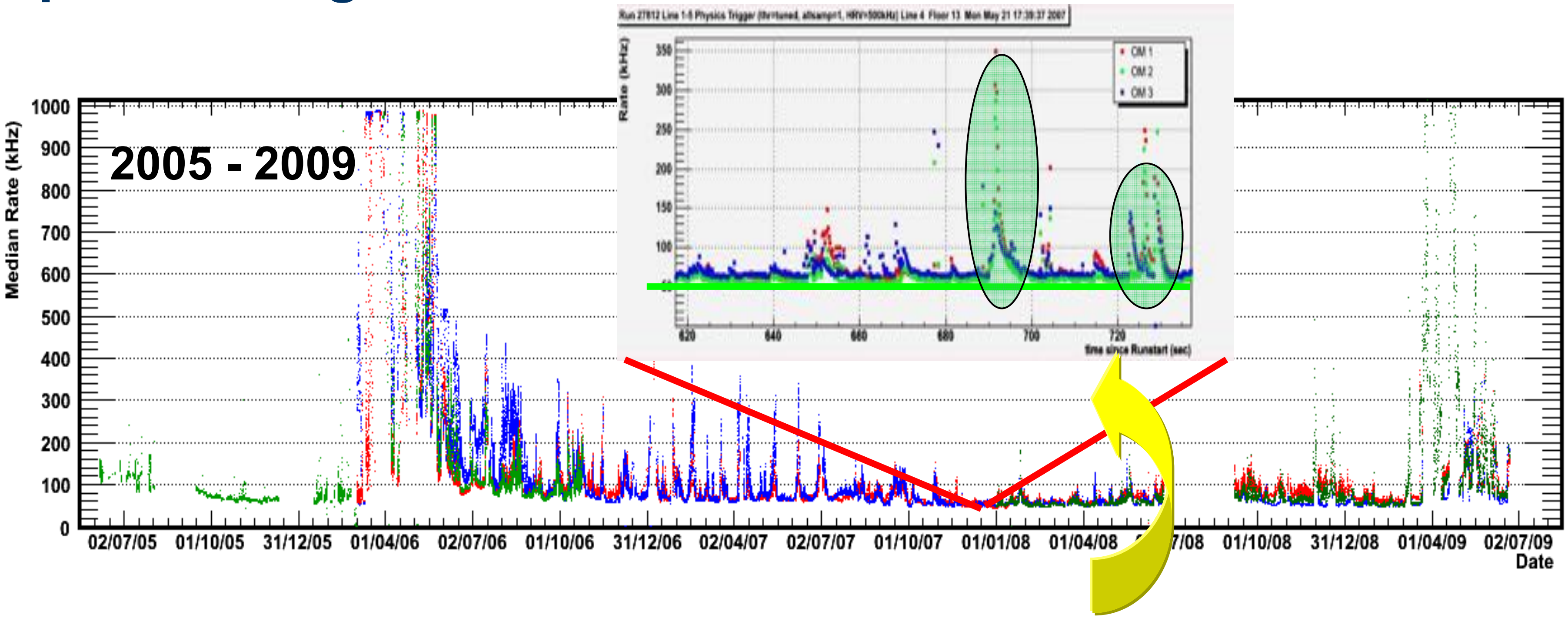




2. March 2006

(ROV = Remotely operated submersible)

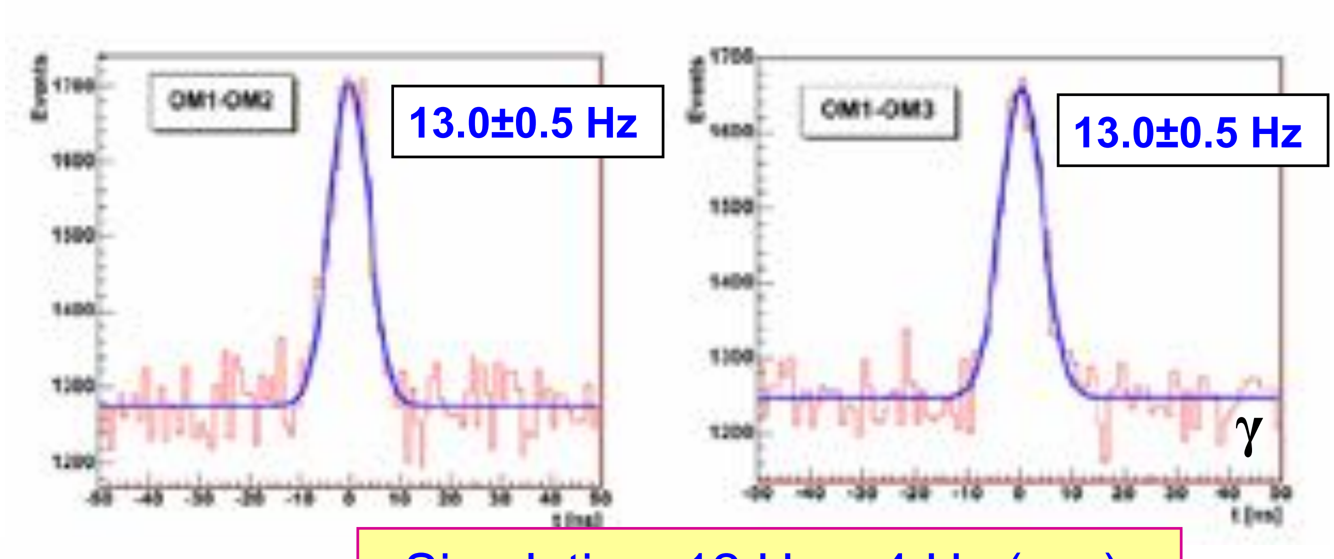
Optical background



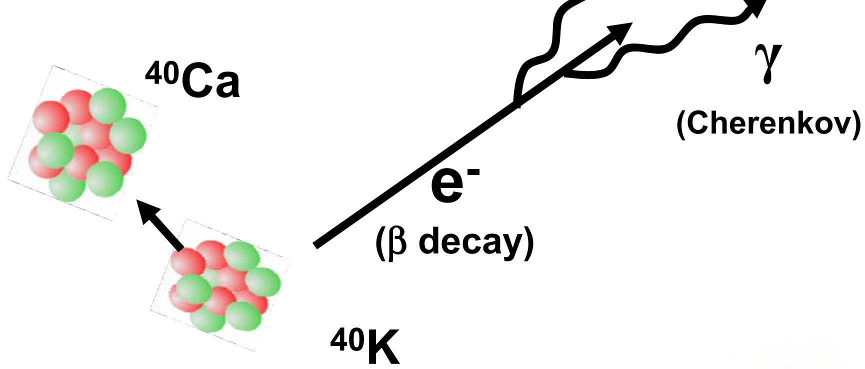
^{40}K decays and microorganisms
(rate ~70 kHz)

+ bursts from macro-organisms
(strongly affected by sea currents)

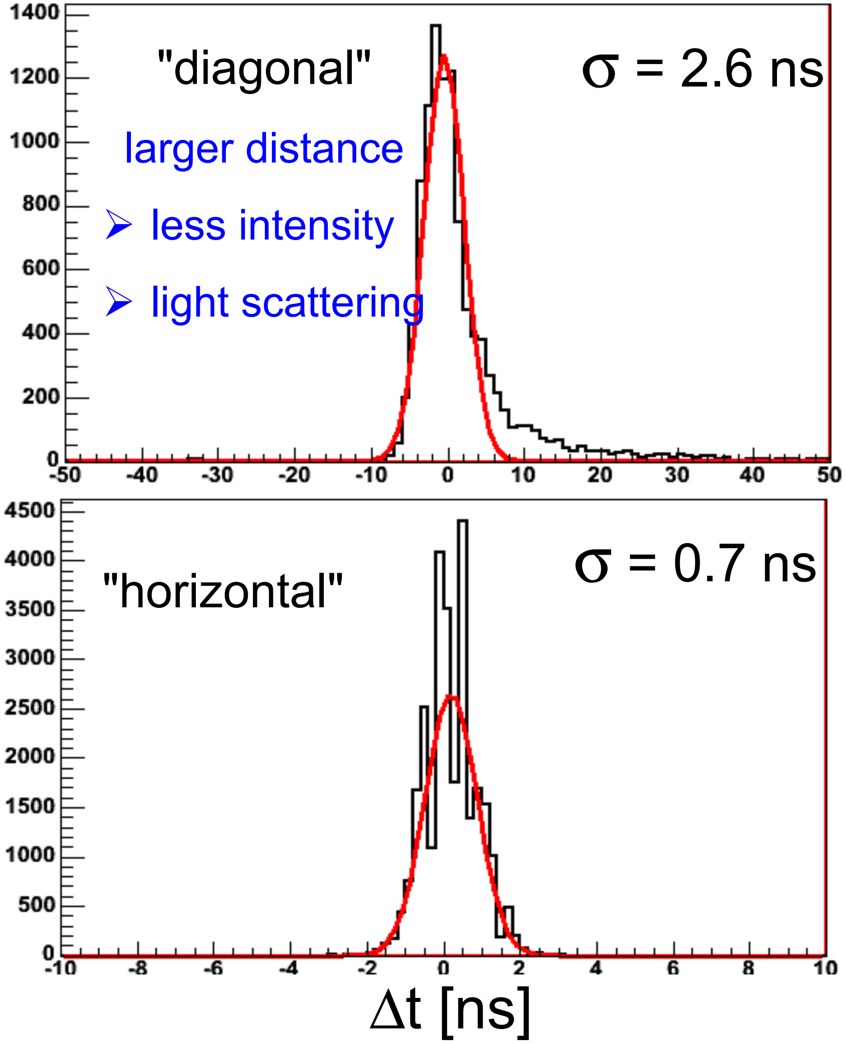
ANTARES: Coincidence rates from ^{40}K decays

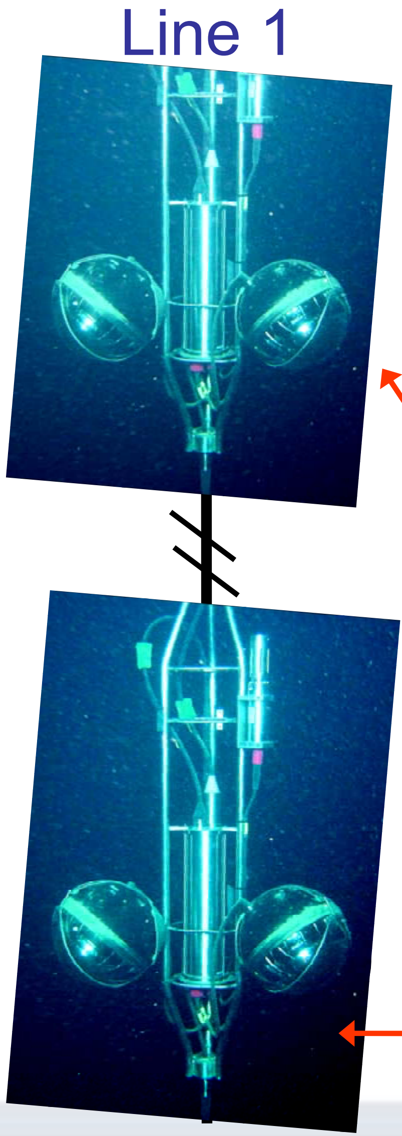


Simulation: 12 Hz ± 4 Hz (sys)



ANTARES: Time calibration with LED beacons

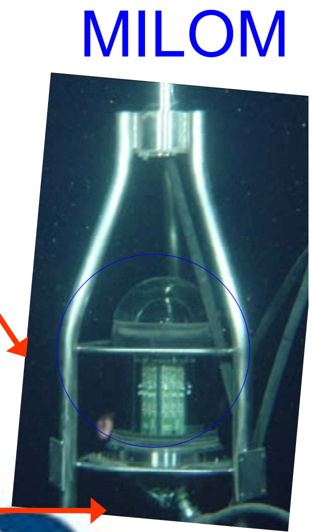




all timing measurements in good agreement with expectations

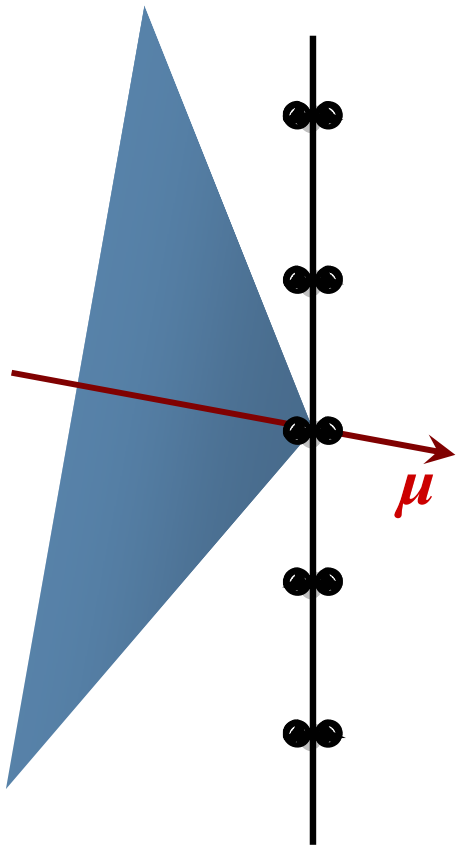
~150 m

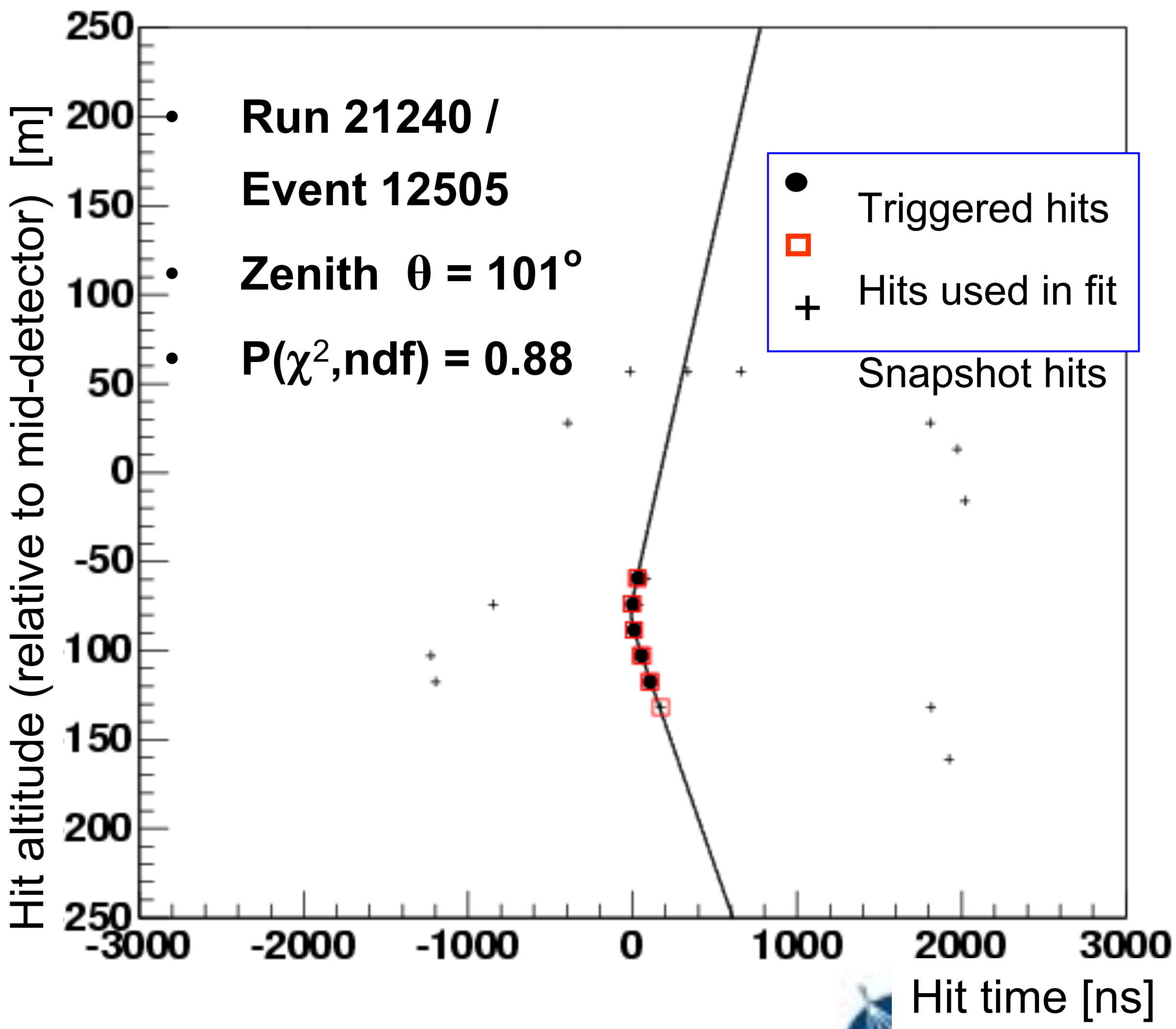
~70 m



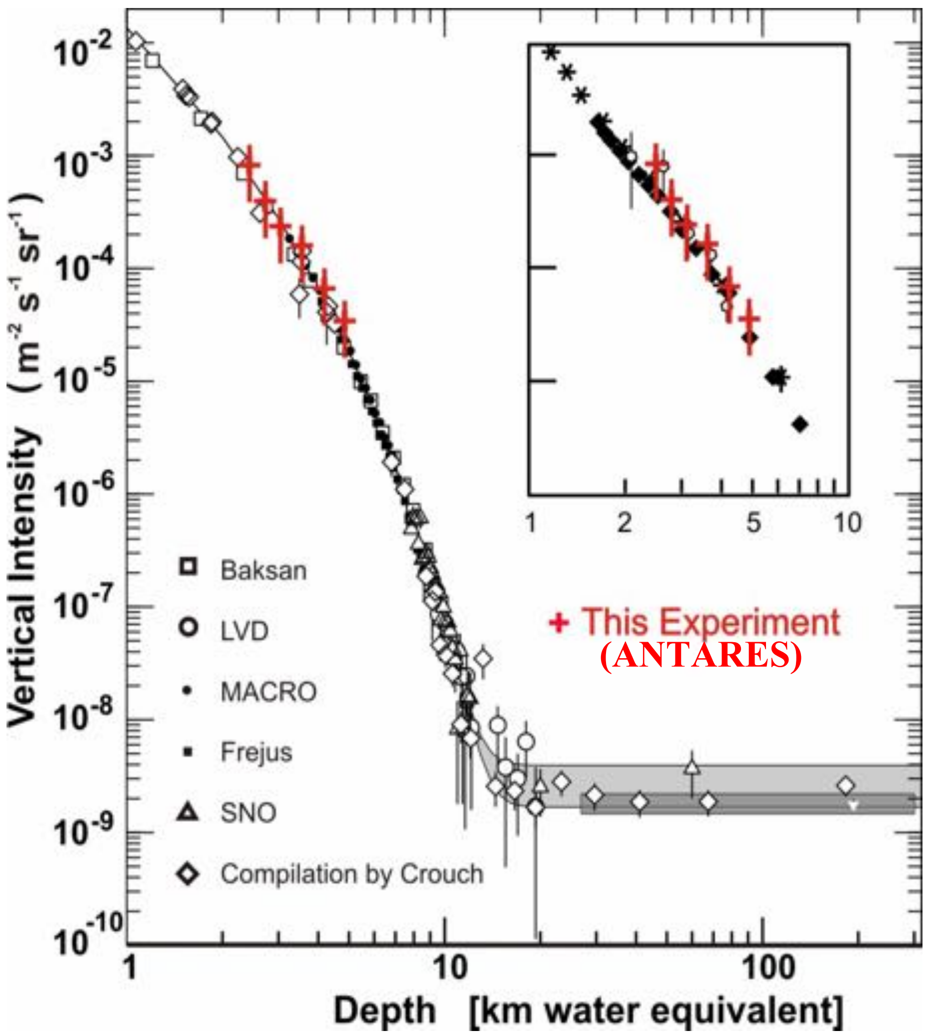
ANTARES: First atmospheric muons 2006

χ^2 minimisation to find zenith angle of track

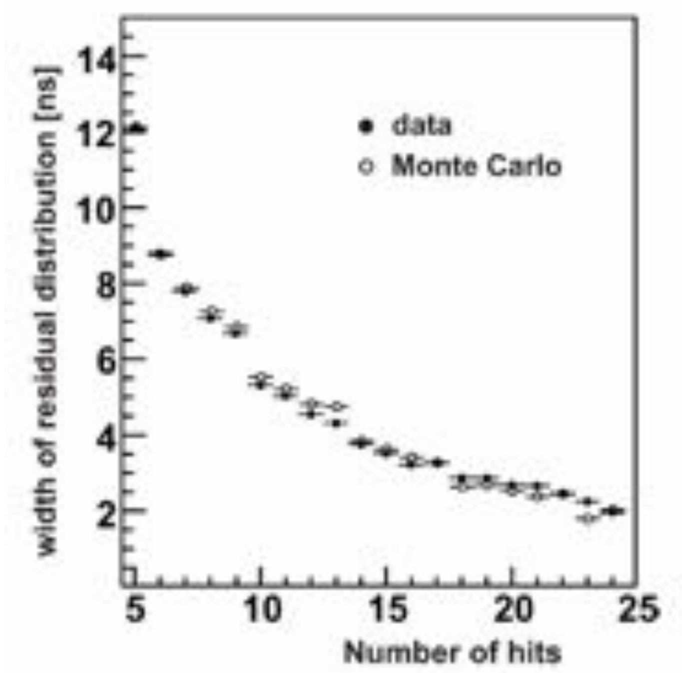




ANTARES: Muon measurement with first line

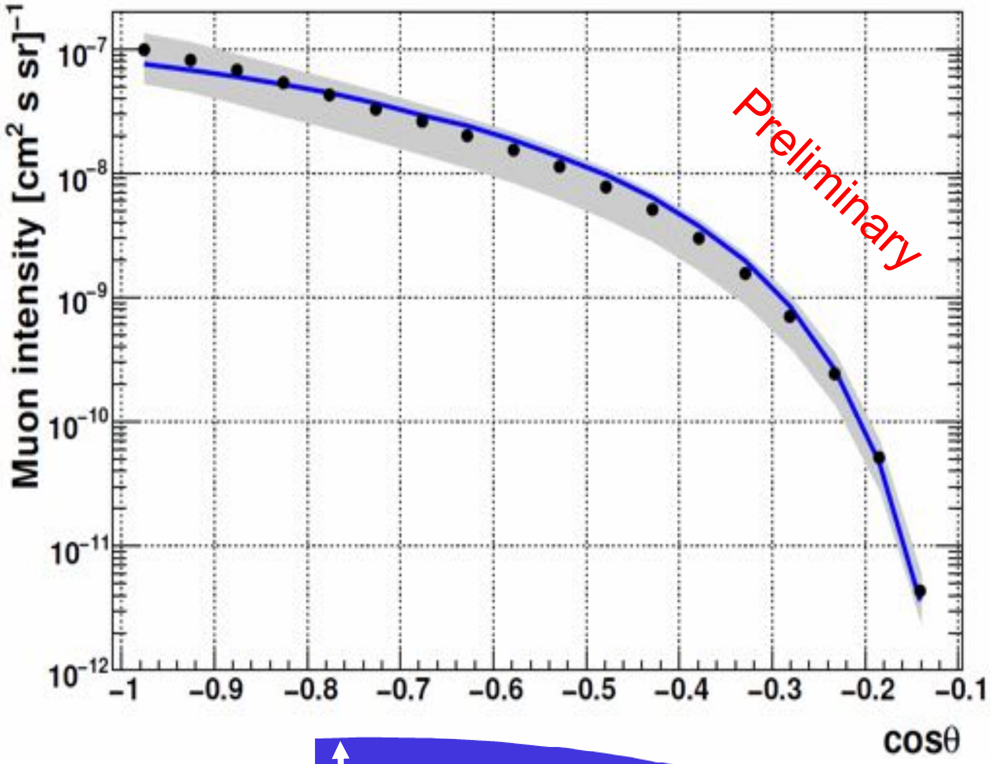


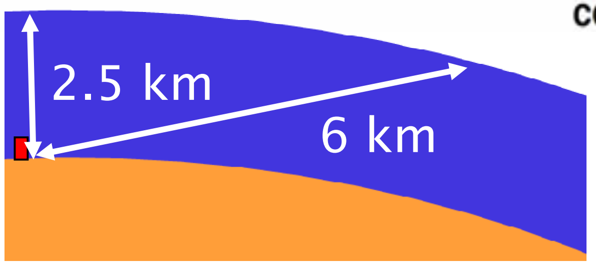
Width of time residual distribution vs. number of hits in track fit

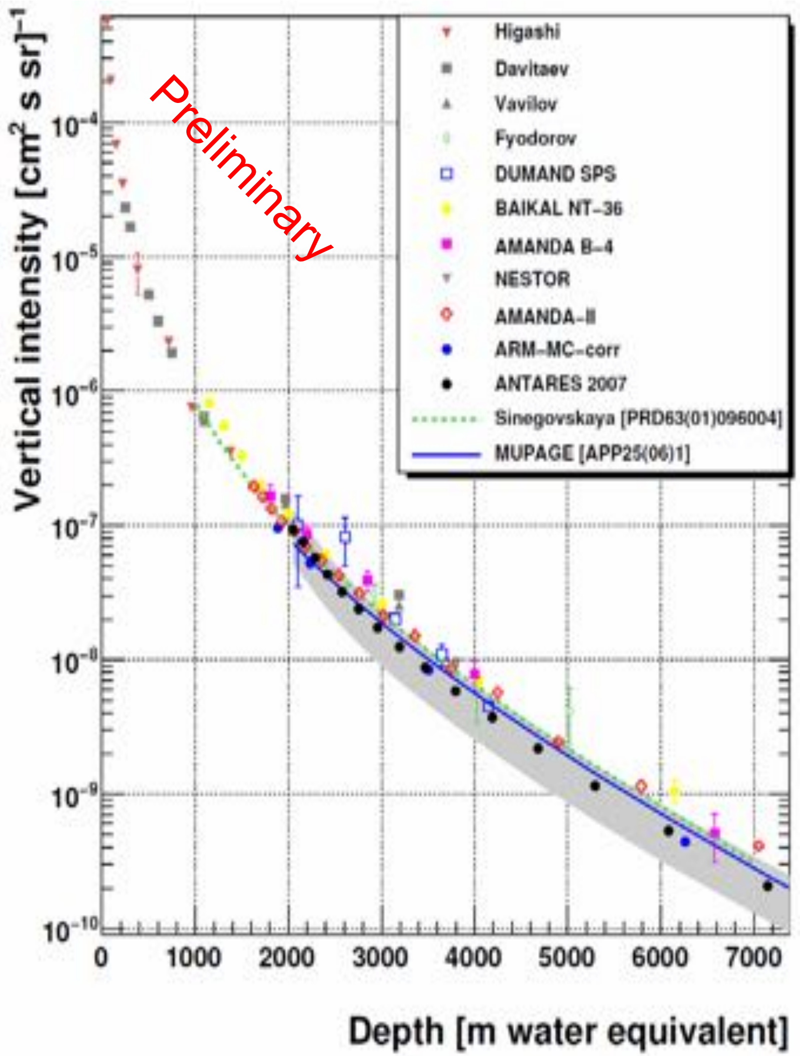


Performance of the First ANTARES Detector Line
(*Astroparticle Physics, 31(4), May 2009, 277-283*)

ANTARES: Muon depth-intensity relation with 5 lines

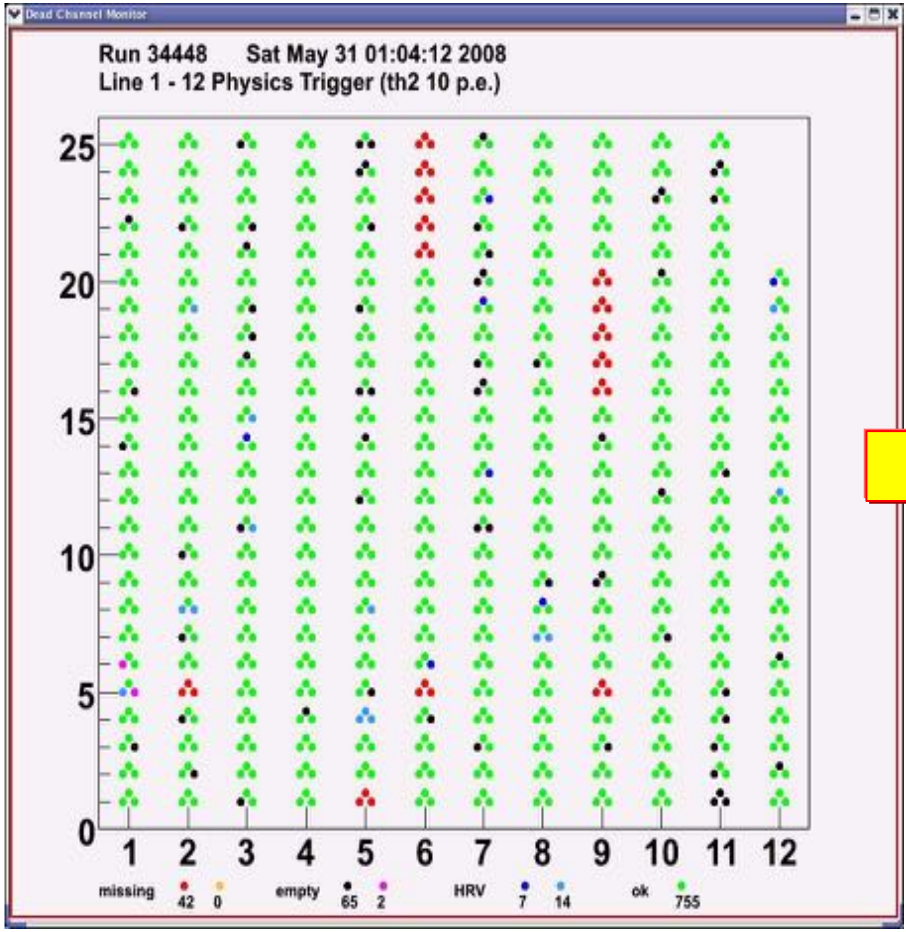


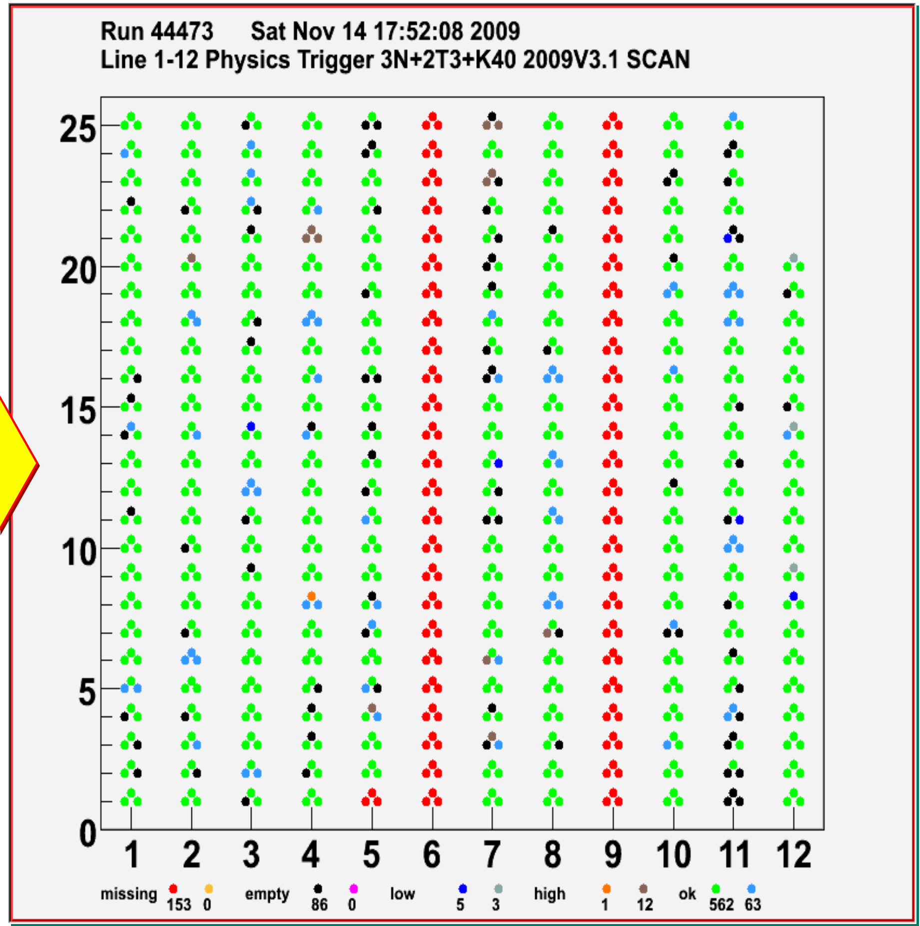




Good agreement with the Line1 and the coincidence rate results

Detector status





Construction complete: May 2008

- ~90% of optical modules operational
- Regular maintenance of in-situ infrastructure foreseen

Today

- Line 6 recovered in 2009,
  Line 9 will be recovered in 2010
- Line 12 repaired and reconnected in 2009

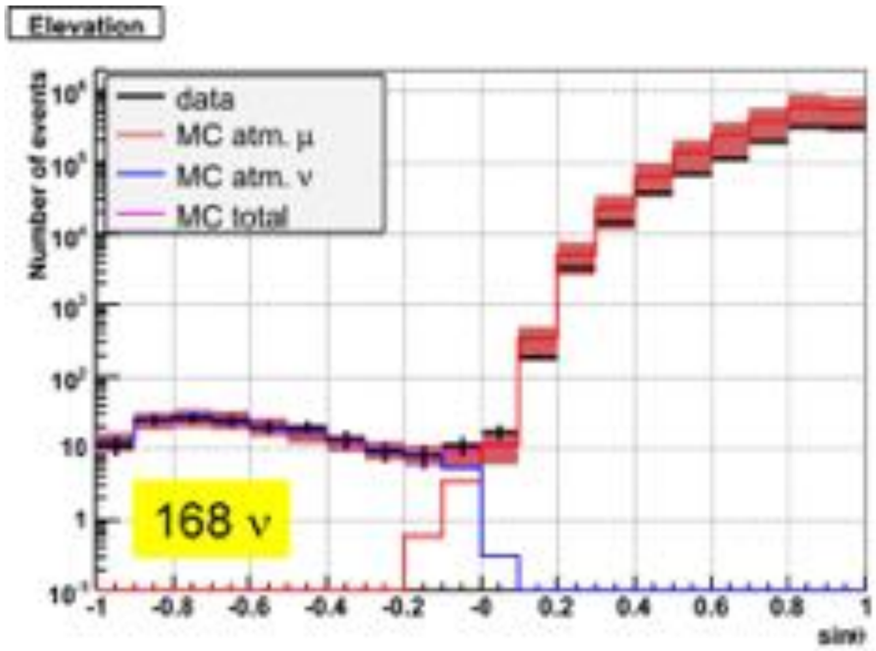
ANTARES: Neutrino events

2007 (5-line apparatus): 243 events

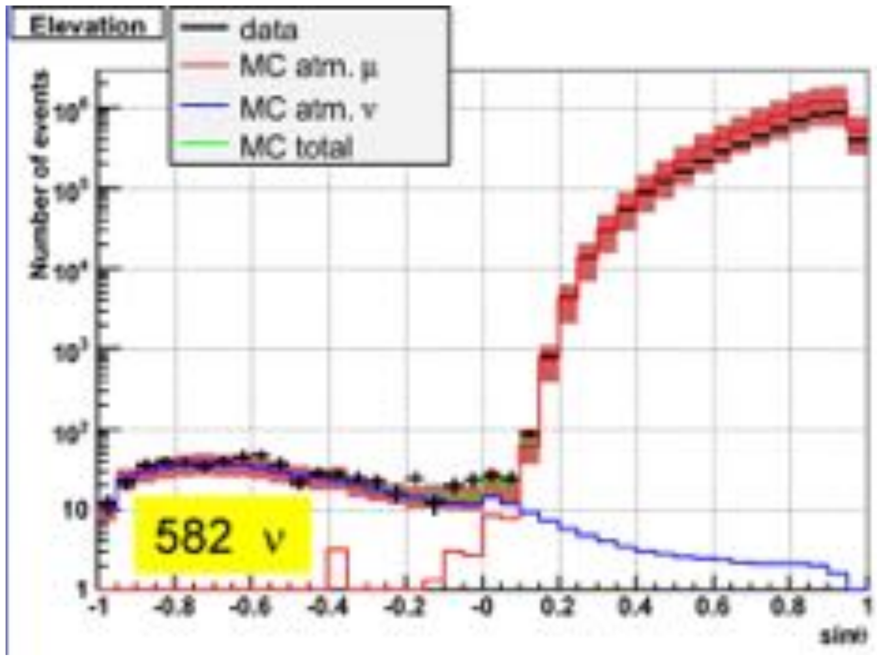
2008 (9/10/12-line apparatus): 749 events

2009 analysis in progress

→ up to Dec 2009 more than 1500 neutrino event collected



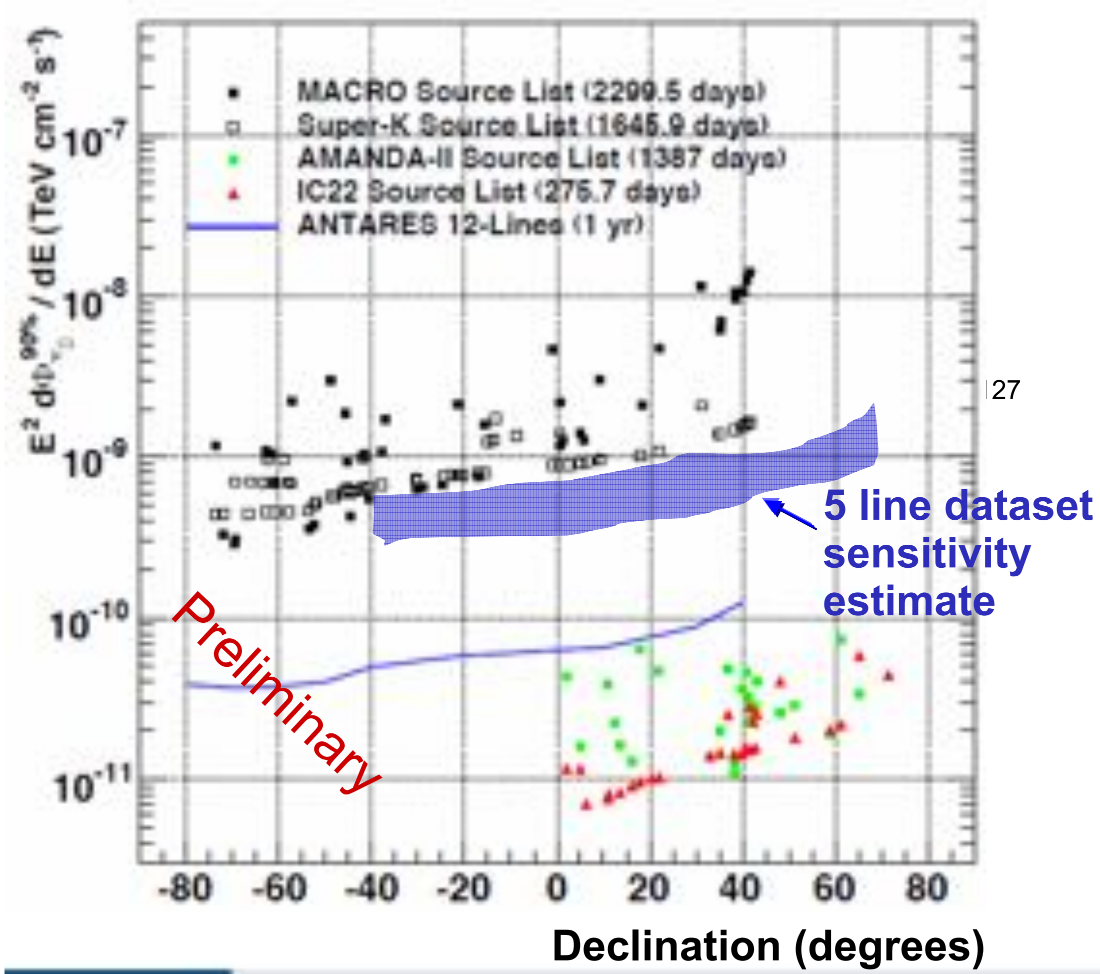
2007 'multi-line fit' events



2008 'multi-line fit' events

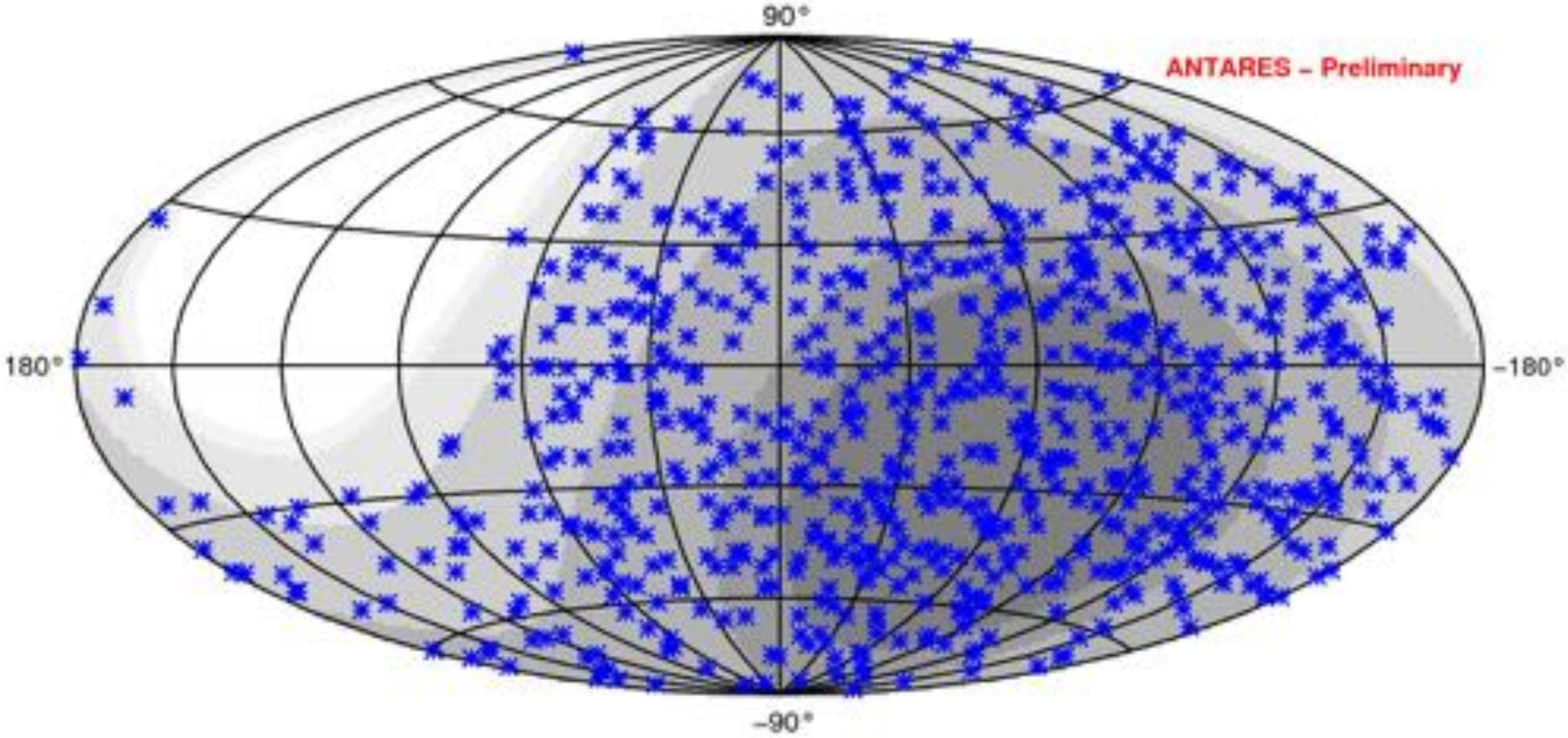
Sensitivity to point-like neutrino sources (5 Lines)

Based on a preliminary list of potential neutrino sources



- Effective live-time of 140 days (with reduced apparatus)
- Competitive with multi-year data taking of previous experiments

ANTARES neutrino sky map



Data of 2007 and 2008, 750 selected “multi-line” neutrinos, positions scrambled

Multi-messenger strategies with ANTARES

Principle:

→ Looser cuts increase detection efficiency

→ Detection by 2 experiments increases significance

ANTARES

Ligo/Virgo

Gravitational waves

→ Alerts

TAROT

Optical follow-up

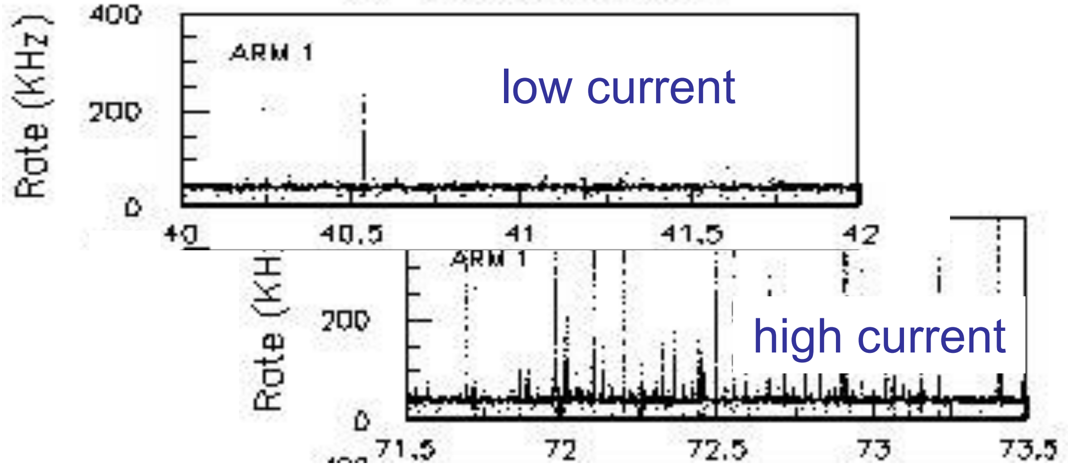
GCN

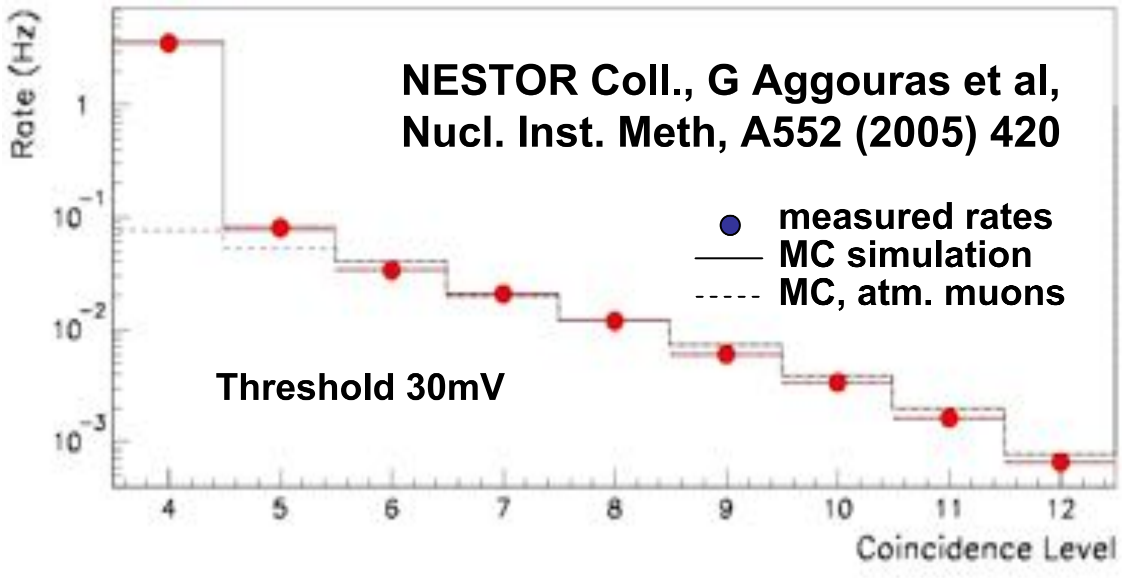
GRB γ satellites

NESTOR

- Tower based detector (titanium structures).
- Dry connections (recover − connect − redeploy).
- Up- and downward looking PMs (15’’).
- 4000-5200 m deep.
- Test floor (reduced size) deployed & operated in 2003.
- Deployment of 4 floors planned in 2009

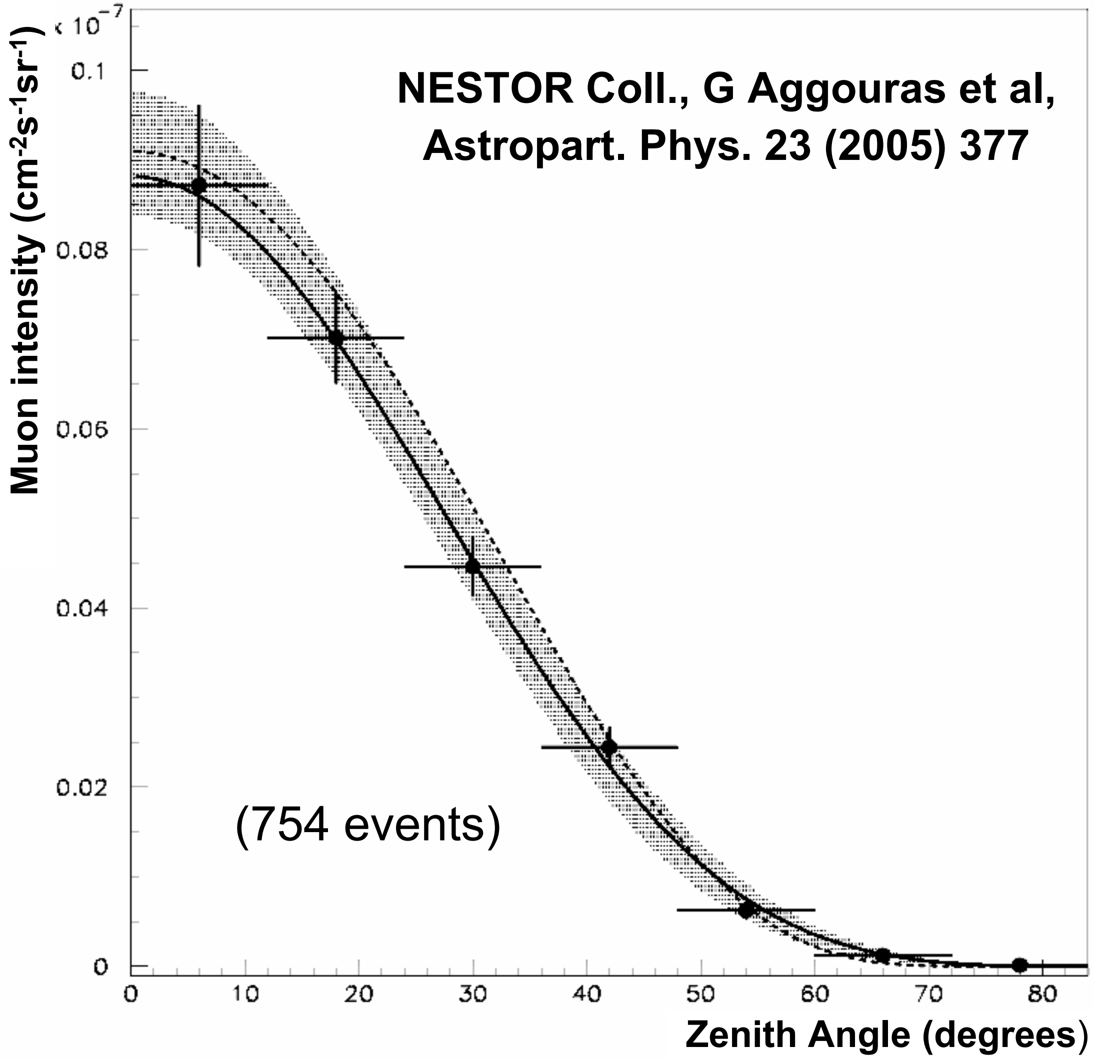
NESTOR: Data from the deep sea





- Background baseline rate of 45-50 kHz per PM
- Bioluminescence bursts correlated with water current, on average 1.1% of the time.
- Trigger rates agree with simulation including background light.
- For 5-fold and higher coincidences, the trigger rate is dominated by atmospheric muons.

NESTOR: Measurement of the muon flux



Atmospheric muon flux determination and parameterisation by

$$\frac{dN}{d\Omega \cdot dt \cdot ds} = I_0 \cdot \cos^{\alpha}\theta$$

α = 4.7 ± 0.5(stat.) ± 0.2(syst.)
I_0 = 9.0 ± 0.7(stat.) ± 0.4(syst.) x 10^{-9} cm^{-2} s^{-1} sr^{-1}

Results agree nicely with previous measurements and with simulations.

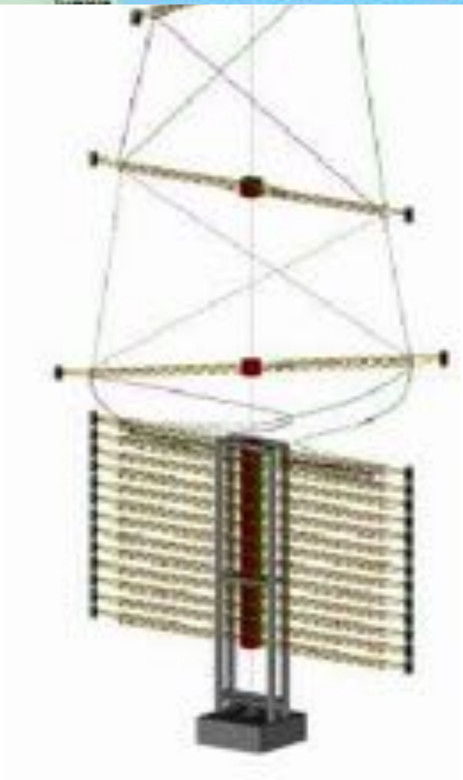
NESTOR: the Delta-Berenike platform

n

NeT

The NEMO project

- Extensive site exploration (Capo Passero near Catania, depth 3500 m);
- R&D towards km³: architecture, mechanical structures, readout, electronics, cables ...;
- Simulation.



Example: Flexible tower

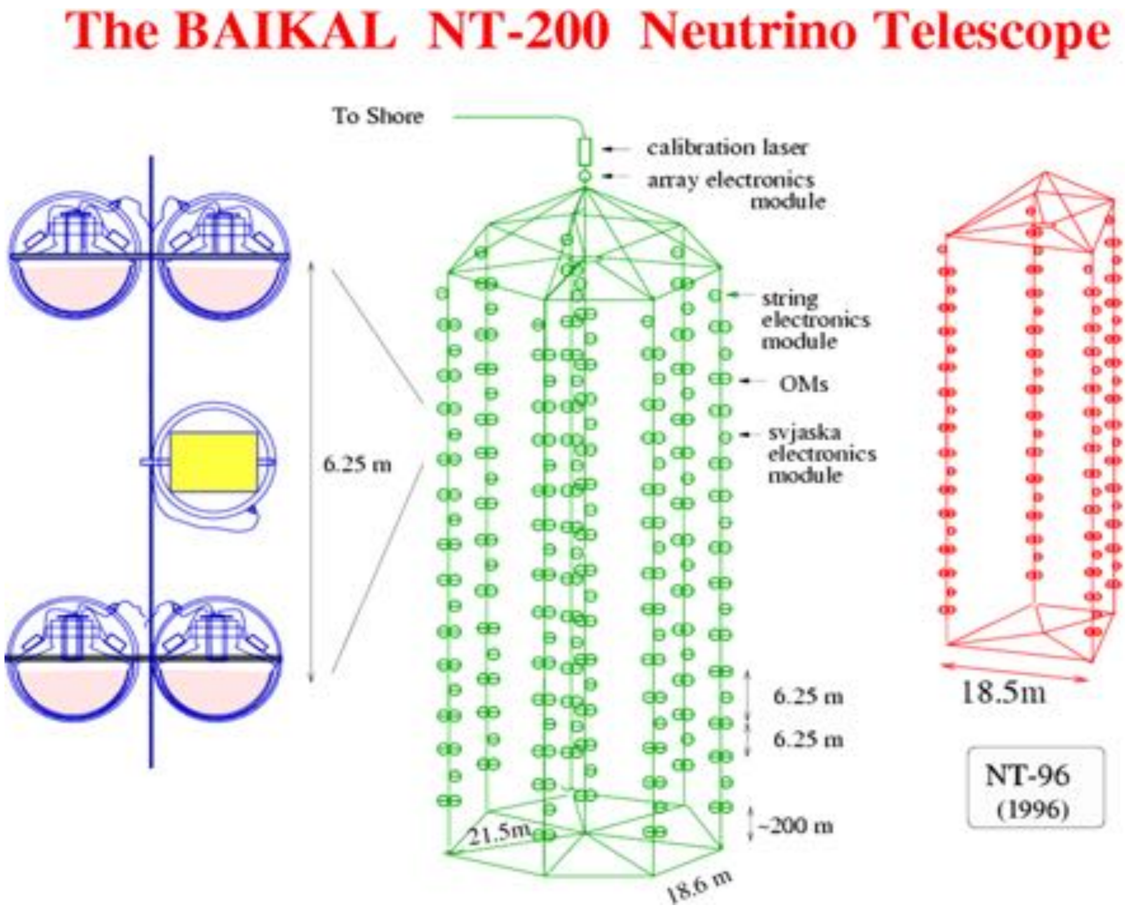
- 16 arms per tower, 20 m arm length, arms 40 m apart;
- 64 PMs per tower;
- Underwater connections;
- Up- and downward-looking PMs.

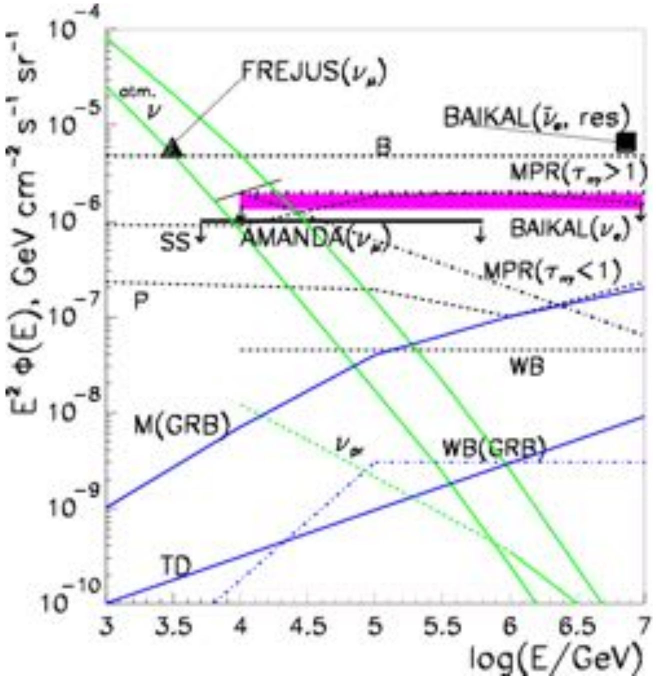
NEMO Phase I

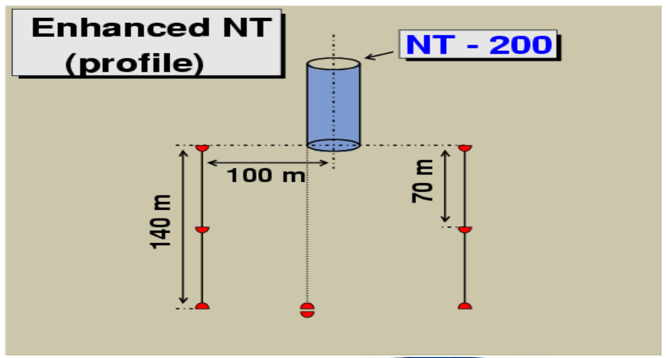

15:10:55
TST 208
25 Jan/05
ROV HDG :
DEPTH : 2079.2
ALTITUDE: -0.5
DOB :
KP :
LAT :
LONG:
0.00
0.000
00 00.0000N
000 00.00000

Lake Baikal: A fresh-water ν telescope

- Pioneers in under-water technology for ν telescopes.
- Many excellent physics results.
- Further upgrades planned, but km³ hardy reachable.



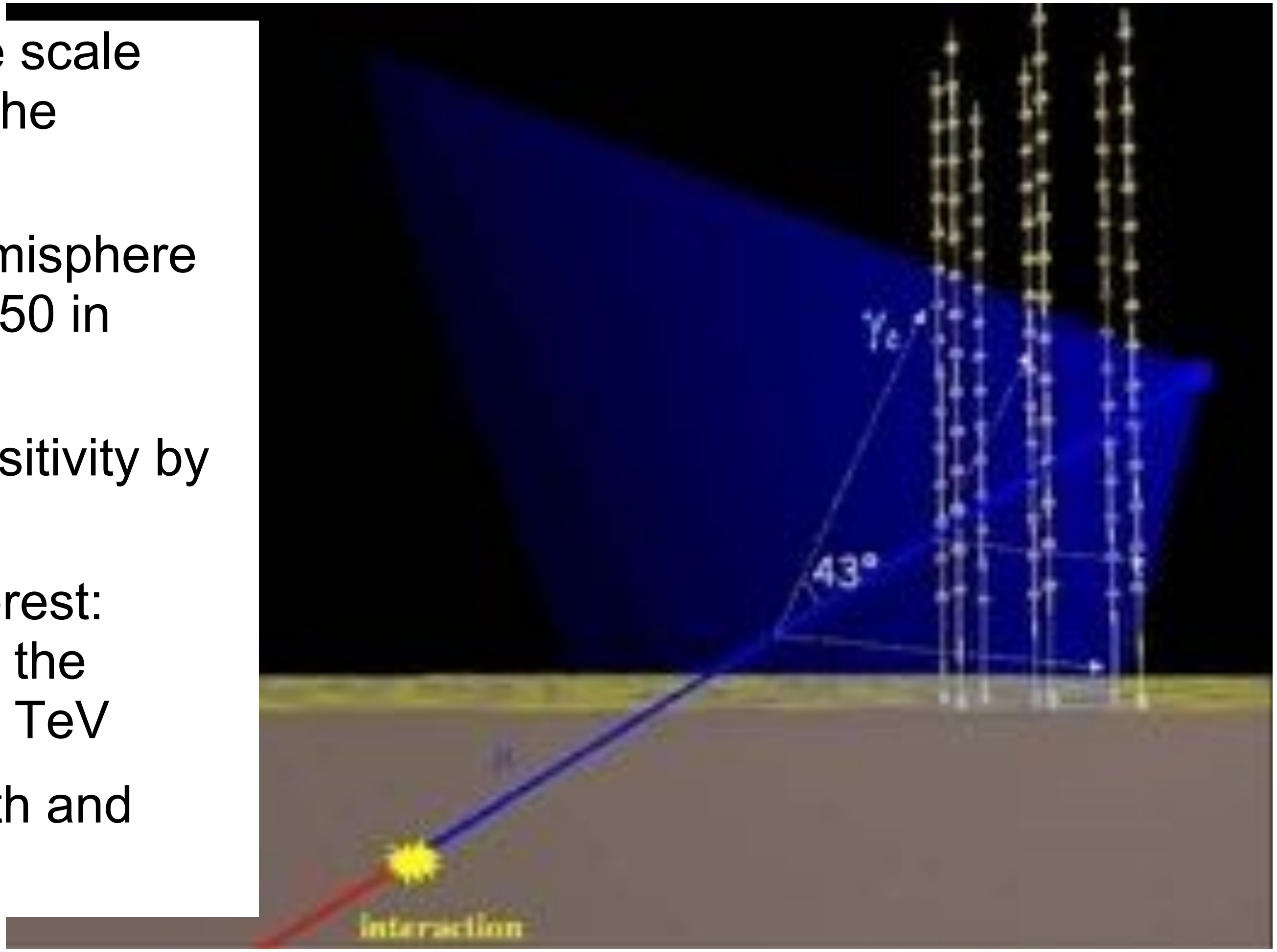




Future Plans and Ideas

KM3NeT: What is it?

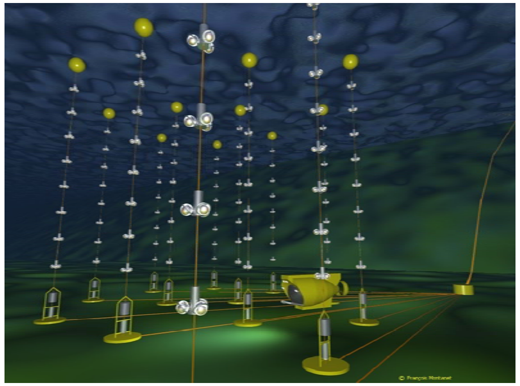
- Future cubic-kilometre scale neutrino telescope in the Mediterranean Sea
- Exceeds Northern-hemisphere telescopes by factor ~50 in sensitivity
- Exceeds IceCube sensitivity by substantial factor
- Focus of scientific interest: Neutrino astronomy in the energy range 1 to 100 TeV
- Provides node for earth and marine sciences



The objectives

- Central physics goals:
  - Investigate neutrino “point sources” in energy regime 1-100 TeV
  - Complement IceCube field of view
  - Exceed IceCube sensitivity
- Implementation requirements:
  - Construction time ≤4 years
  - Operation over at least 10 years without “major maintenance”

How to design a km^3 deep-sea ν telescope



scale up

dilute

new design

Existing telescopes " times 100" ?

- Too expensive
- Too complicated: production, deployment takes forever, maintenance impossible
- Not scalable (readout bandwidth, power, ...)

Large volume with same number of PMs?

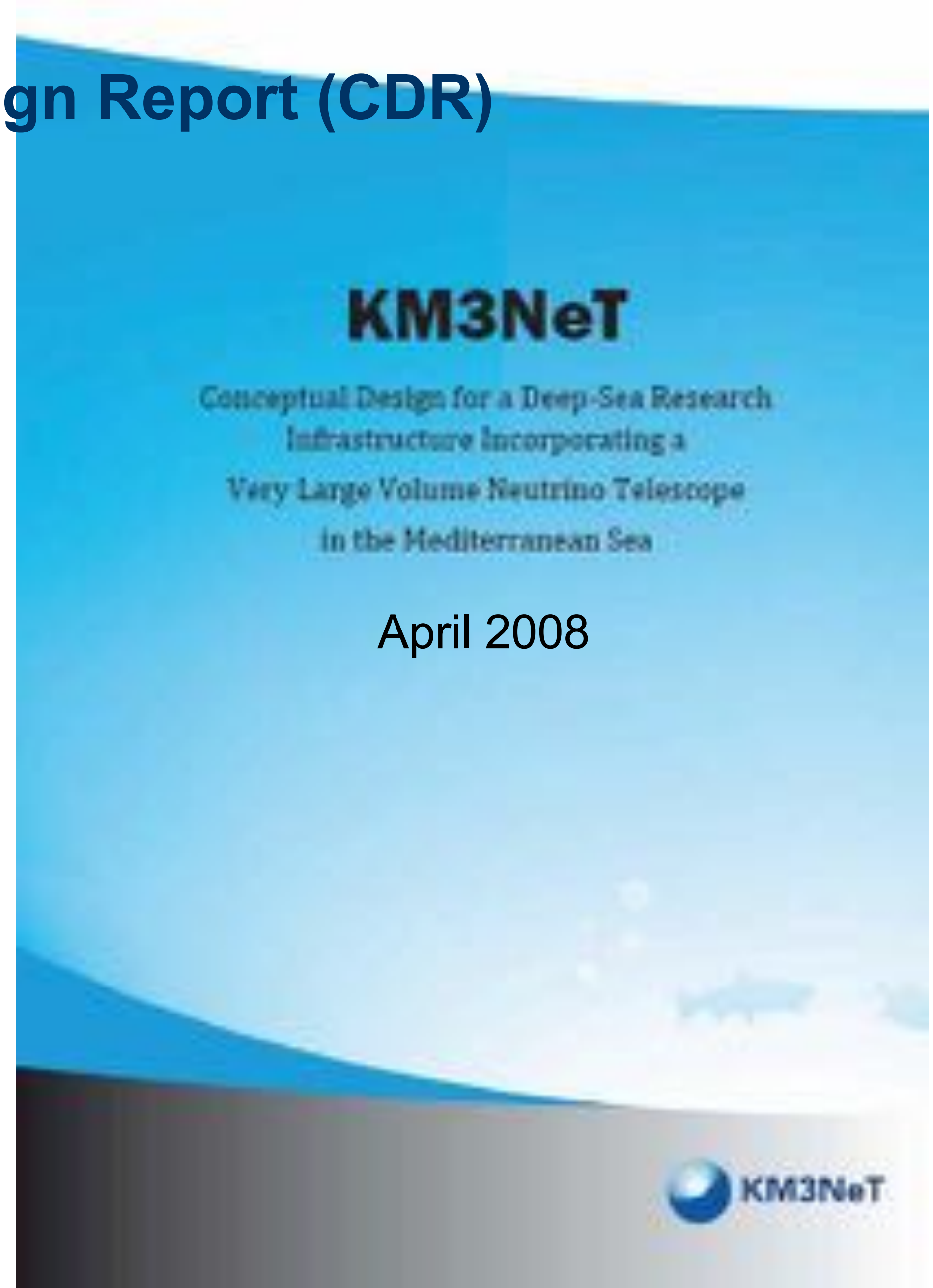
- PM distance: given by absorption length in water (~60 m) and PM properties
- Efficiency loss for larger spacing

R&D needed:

- Cost-effective solutions to reduce price/volume by factor 2-5
- Stability goal: maintenance-free detector
- Fast installation time for construction & deployment less than detector life time
- Improved components

The KM3NeT Conceptual Design Report (CDR)

- Mid-term result of 3-year EU-funded “Design Study” project
- Inventory of technical solutions and options
- Definition of design goals and specifications
- Review of physics case



The challenges 1: Technical design

- **Technical design**
  Objective: Support 3D-array of photodetectors and connect them to shore (data, power, slow control)
  - Optical Modules
  - Front-end electronics
  - Readout, data acquisition, data transport
  - Mechanical structures, backbone cable
  - Sea-bed network: cables, junction boxes
  - Calibration devices
  - Deployment procedures
  - Shore infrastructure
  - Assembly, transport, logistics
  - Risk analysis and quality control

Design rationale:

Cost-effective
Reliable
Producible
Easy to deploy

The challenges 2: Site & simulation

- **Site characteristics**
  Objective: Measure site characteristics (optical background, currents, sedimentation, …)

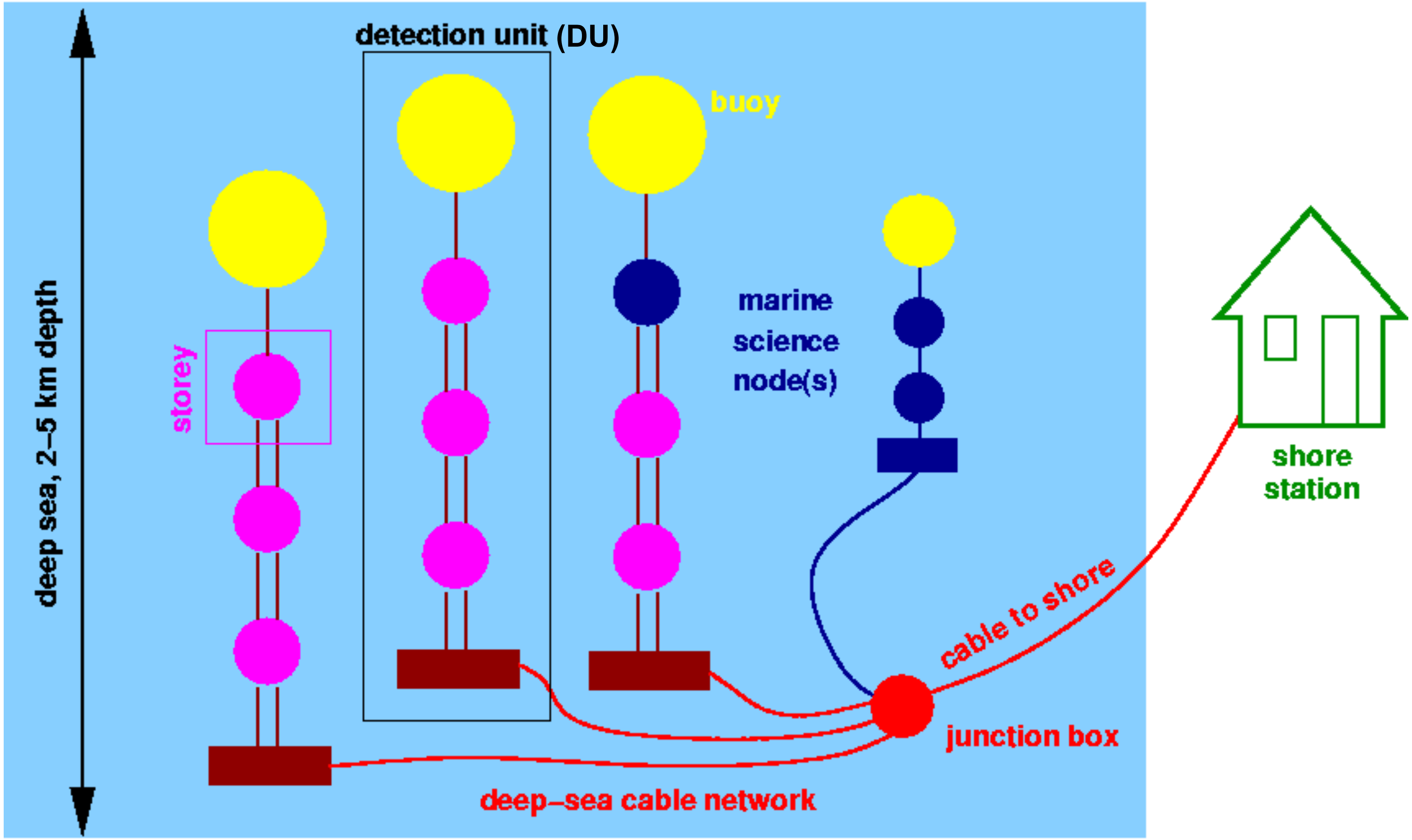
- **Simulation**
  Objective: Determine detector sensitivity, optimise detector parameters;
  Input: OM positions/orientations and functionality, readout strategy, environmental parameters
  - Simulation (using existing software)
  - Reconstruction (building on existing approaches)
  - Focus on point sources
  - Cooperation with IceCube (software framework)

The challenges 3: Towards a RI

- **Earth and marine science node**
  Objective: Design interface to instrumentation for marine biology, geology/geophysics, oceanography, environmental studies, alerts, …

- **Implementation**
  Objective: Take final decisions, secure resources, set up proper management/governance, construct and operate KM3NeT;
  - Prototyping and field tests
  - Cost estimates
  - Site decision
  - Time lines

The KM3NeT Research Infrastructure (RI)



Technical design: decisions and options

- Detection Unit:
  - Optical Modules (2+1 options)
  - Front-end electronics
  - Data transport
  - Mechanical structures (3 options)
  - General deployment strategy
  - Calibration (detailed solutions under study)
- Sea-bed network
- Marine science node

Green:

Preferred/unique solution, subject to validation

Black:

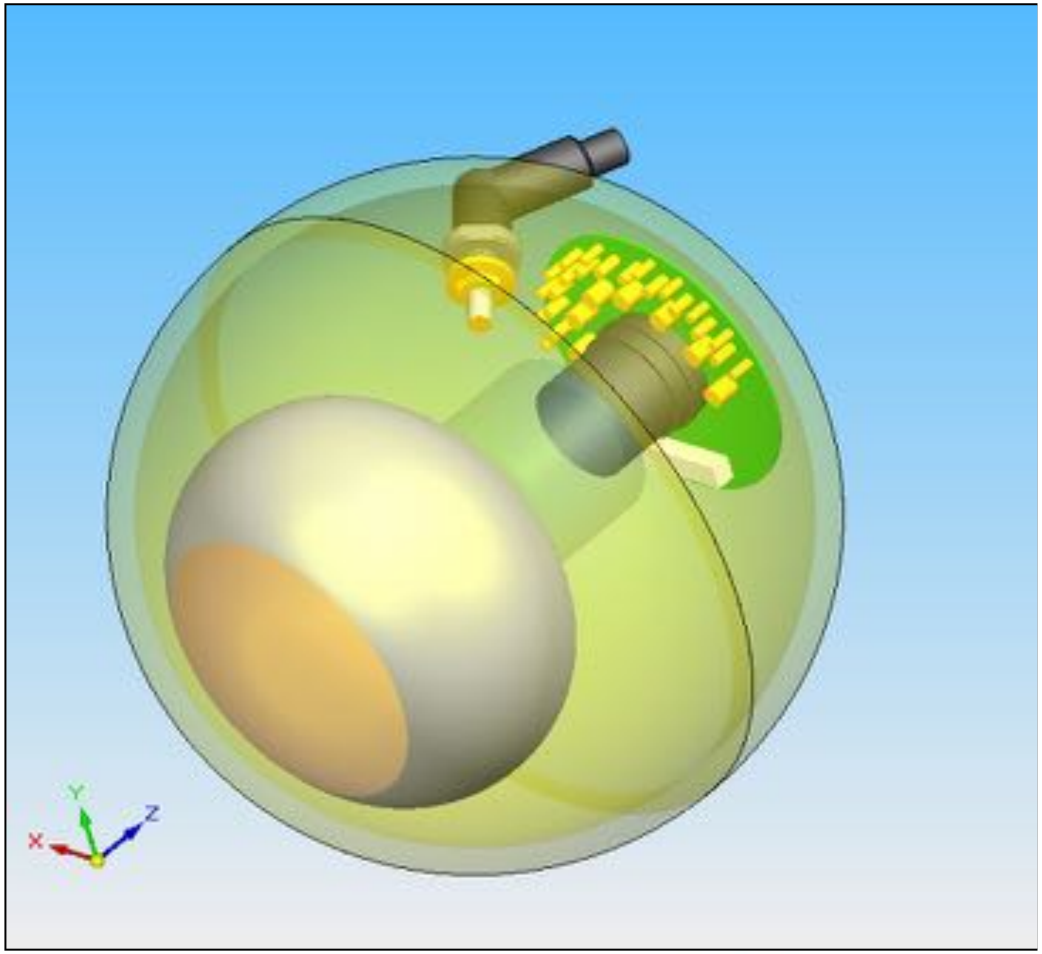
Several options

Some decisions require prototyping and field tests – too early to call!

OM "classical": One PMT, no electronics

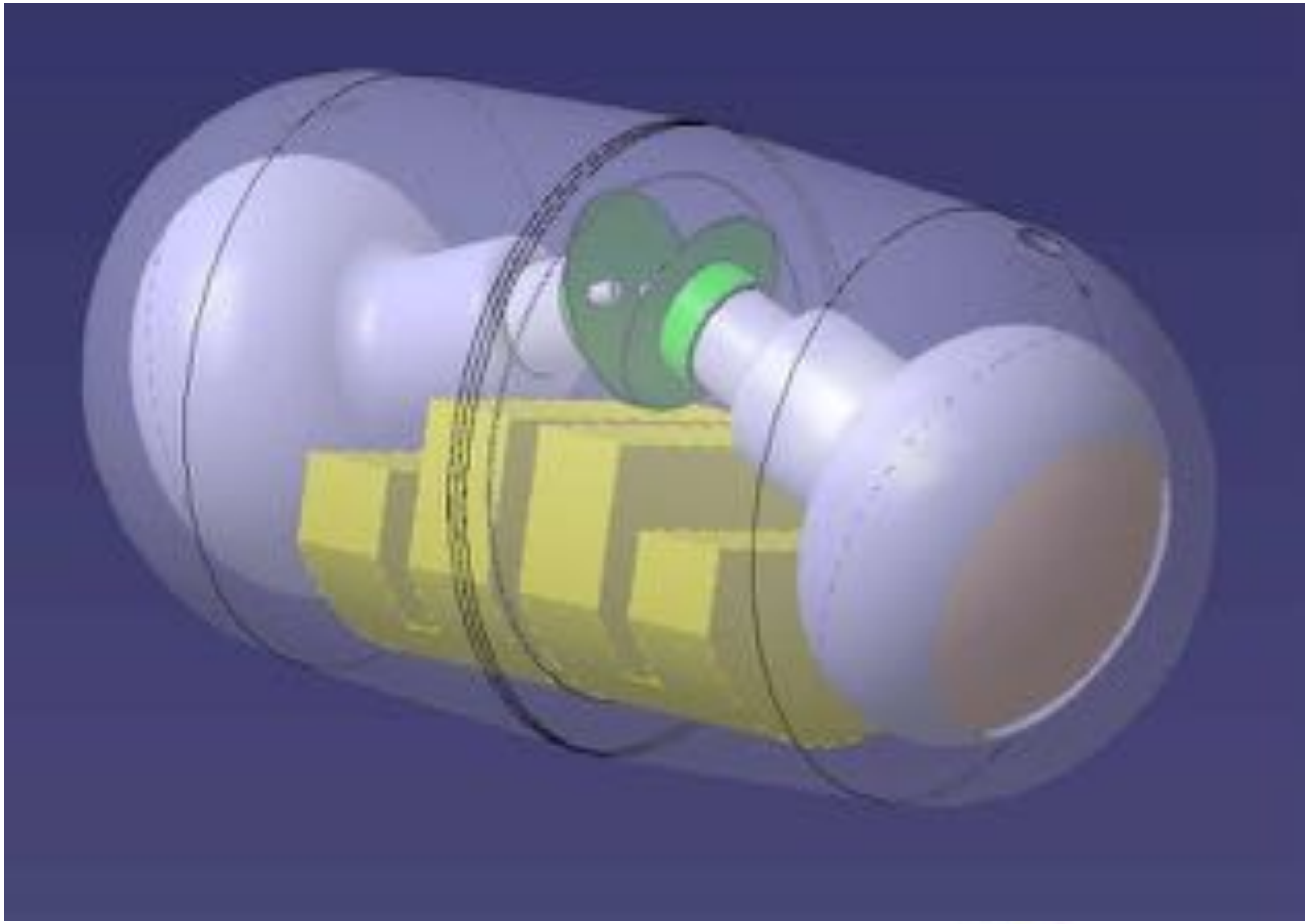
<u>Evolution from pilot projects</u>:

- 8-inch PMT, increased quantum efficiency (instead of 10 inch)
- 13-inch glass sphere (instead of 17 inch)
- no valve (requires "vacuum" assembly)
- no mu-metal shielding



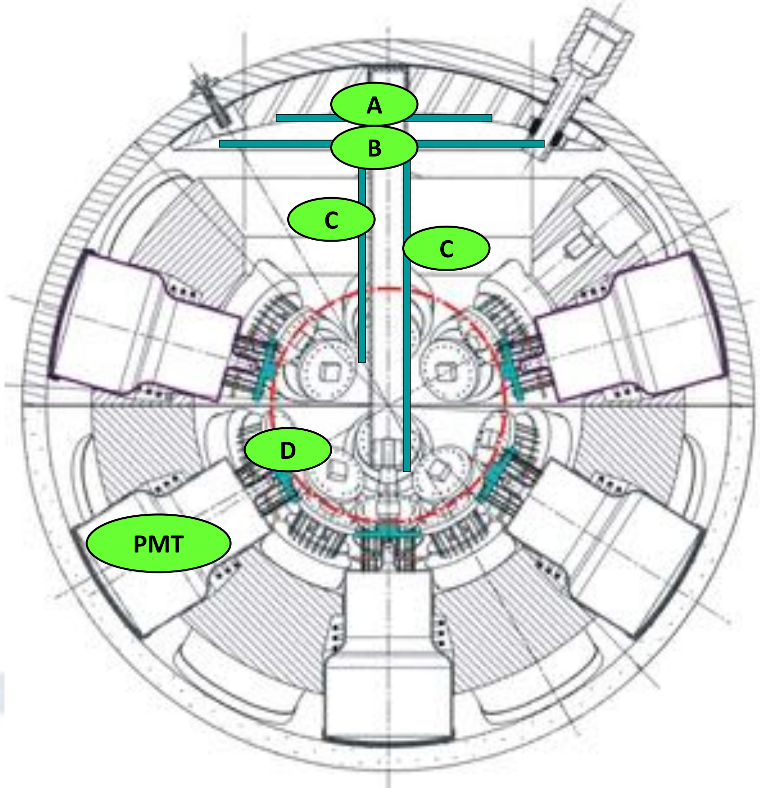
OM with two PMTs: The capsule

- Glass container made of two halves (cylinders with spherical ends)
- Mechanical stability under study
- Allows for integrating electronics



OM with many small PMTs

- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10" PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by compressible foam core
- 31 PMT bases (total ~140 mW) (**D**)
- Front-end electronics (**B,C**)
- Al cooling shield and stem (**A**)
- Single penetrator
- 2mm optical gel (ANTARES-type)

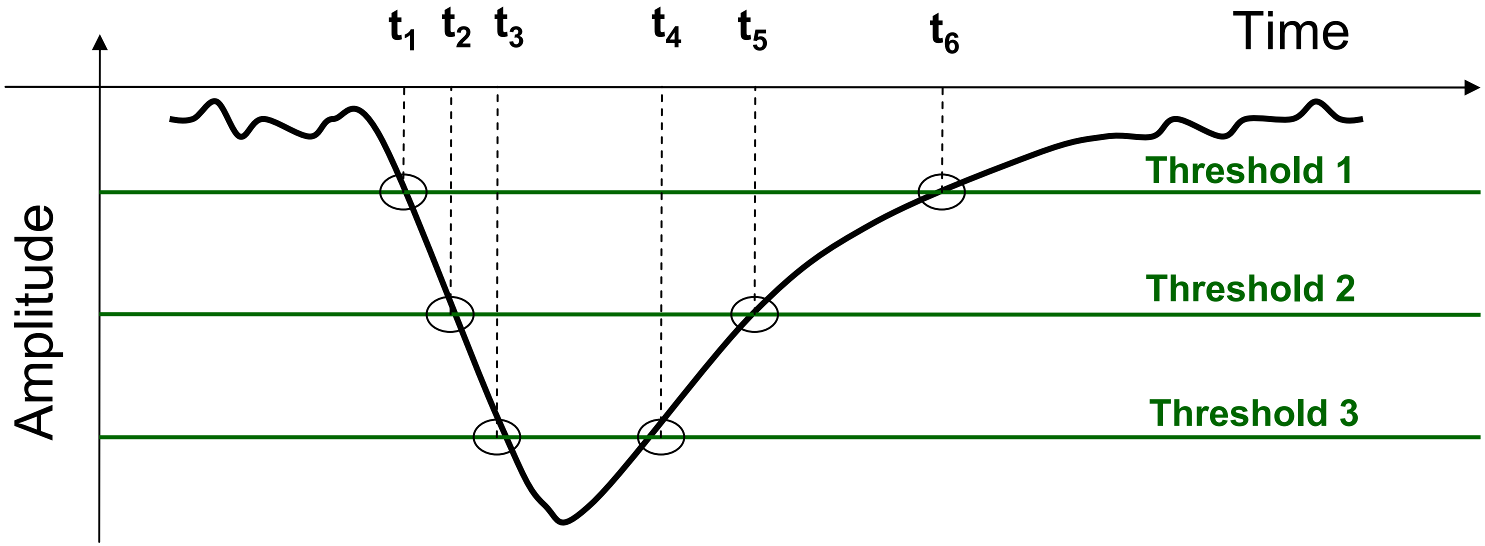


A Multi-PMT OM prototype

Acceptance improvement by using Winston cones under investigation

Front-end electronics: Time-over-threshold

From the analogue signal to time stamped digital data:



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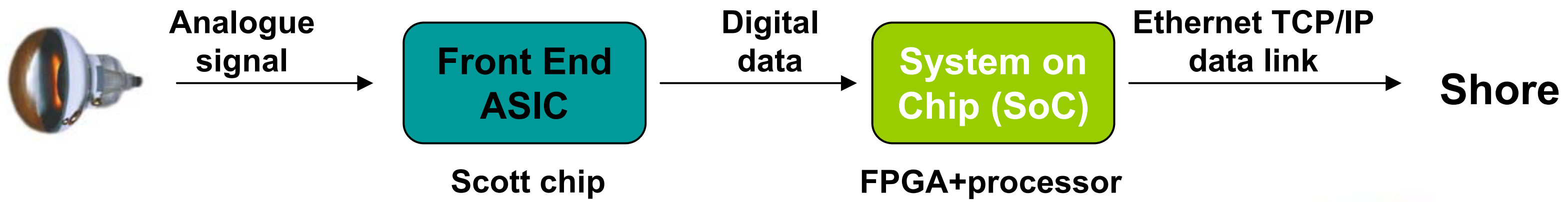
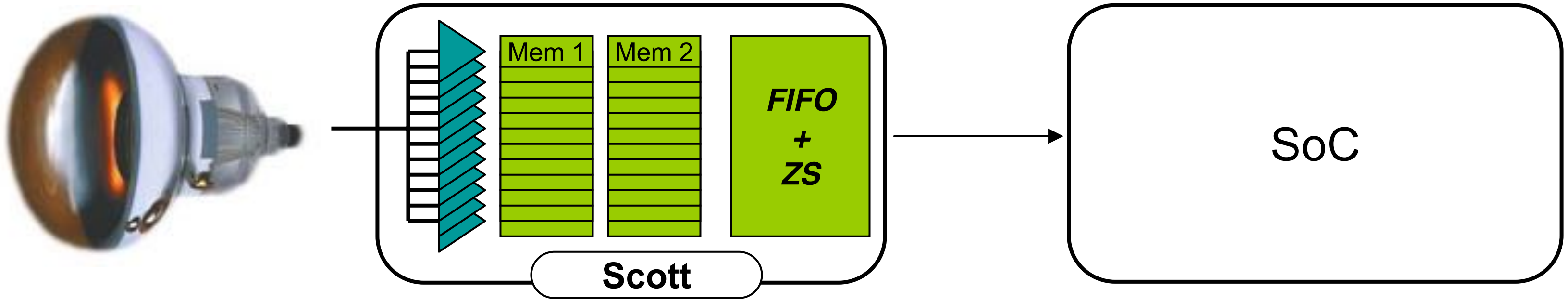
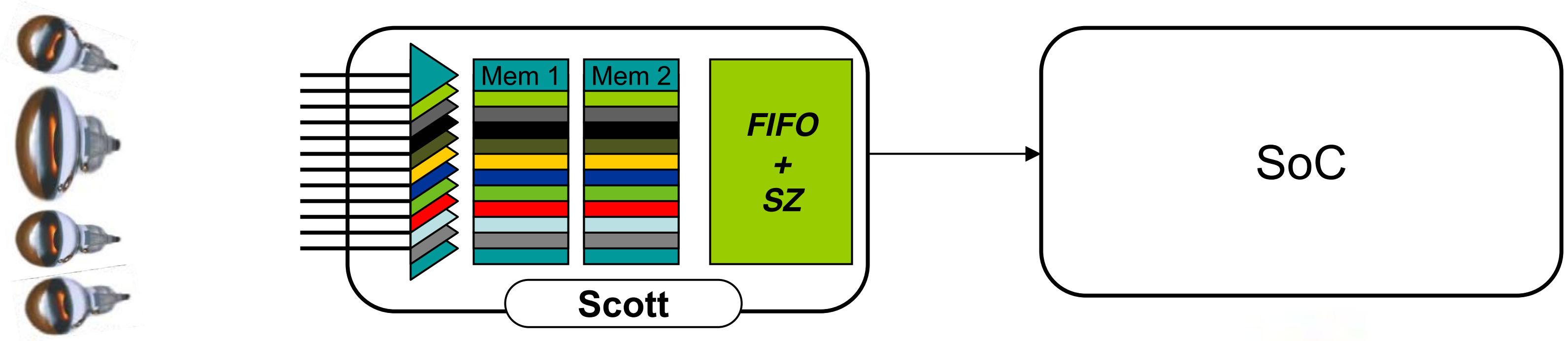


Same readout for single- and multi-PMT OMs

- N thresholds for 1 PMT



- N/k thresholds for k PMTs



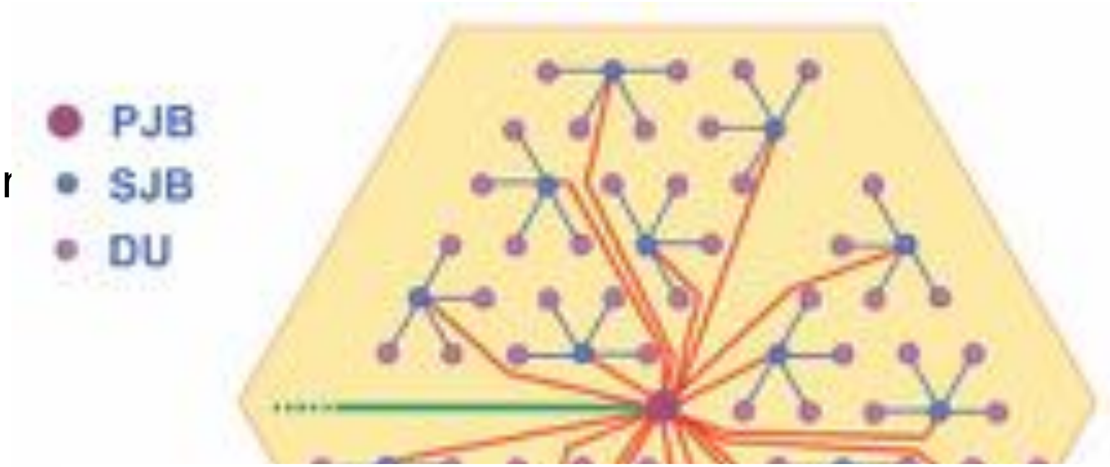
Data network

- All data to shore:
  Full information on each hit satisfying local condition (threshold) sent to shore
- Overall data rate ~ 100-300 Gbit/s
- Data transport:
  Optical point-to-point connection shore-OM
  Optical network using DWDM and multiplexing
  Served by lasers on shore
  Allows also for time calibration of transmission delays
- Deep-sea components:
  Fibres, modulators, mux/demux, optical amplifiers
  (all standard and passive)

The sea-floor infrastructure

- Requirements:
  - Distribute power
  - Support data network
  - Slow control communicatior
- Implementation:
  - Hierarchical topology
  - Primary & secondary junction boxes
  - Commercial cables and connectors
  - Installation requires ROVs

Example configuration:



- Layout and topology:
  - Depends on DU design, deployment procedure and "detector footprint"
  - Important for risk minimisation and maintainability
  - Ring topologies also considered

DUs: bars, strings, triangles

- Flexible towers with horizontal bars
  - Simulation indicates that “local 3D arrangement” of OMs increases sensitivity significantly
  - Single- or multi-PMT OMs
- Slender strings with multi-PMT OMs
  - Reduced cost per DU, similar sensitivity per Euro
- Strings with triangular arrangements of PMTs
  - Evolution of ANTARES concept
  - Single- or multi-PMT OMs
  - “Conservative” fall-back solution

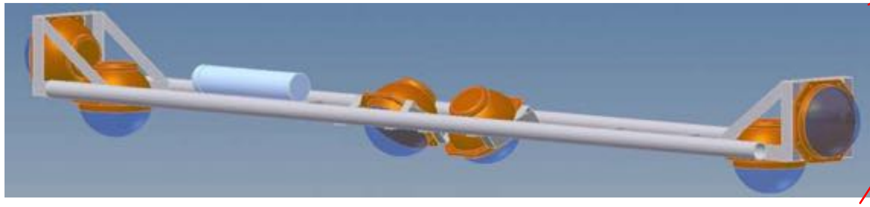
Reminder:

Progress in verifying deep-sea technology can be slow and painful

Careful prototype tests are required before taking final decisions

This is a task beyond the Design Study!

The flexible tower with horizontal bars

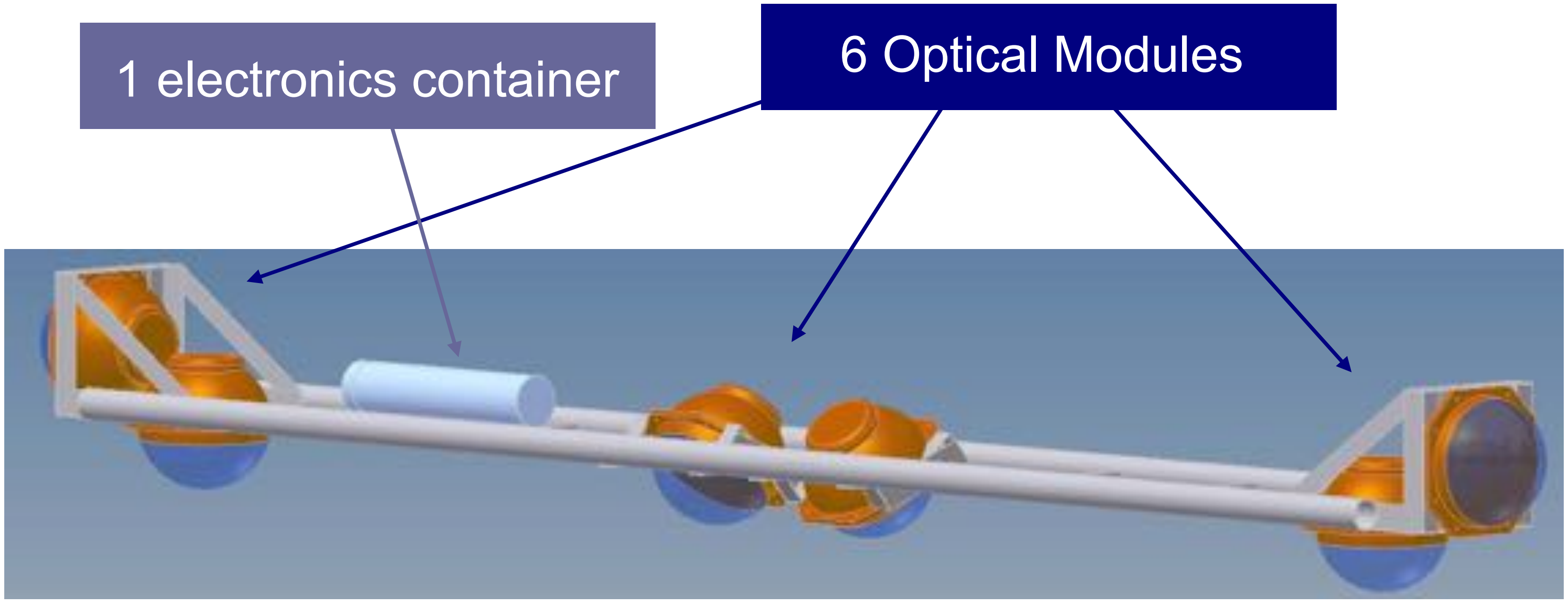


<u>Semi-rigid system of horizontal elements (storeys) interlinked by tensioning ropes:</u>

- 20 storeys
- Each storey supports 6 OMs in groups of 2
- Storeys interlinked by tensioning ropes, subsequent storeys orthogonal to each other
- Power and data cables separated from ropes; single backbone cable with breakouts to storeys
- Storey length = 6m
- Distance between storeys = 40 m
- Distance between DU base and first storey = 100m

The bar storey

- Light structure in marine Aluminium
- Total mass 115 kg, weight in water 300N
- Overall length x width = 6 m x 46 cm

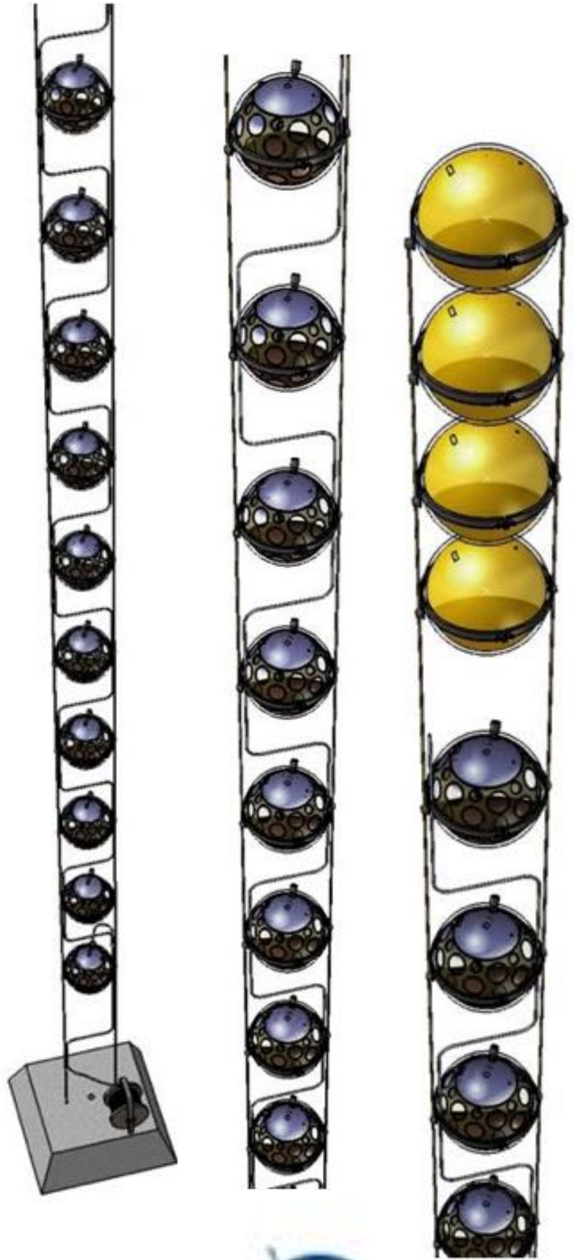


The slender string

- Mooring line:
  - Buoy (empty glass spheres, net buoyancy 2250N)
  - Anchor: concrete slab of 1m^3
  - 2 Dyneema ropes (4 mm diameter)
  - 20 storeys (one OM each), 30 m distance, 100m anchor-first storey
- Electro-optical backbone:
  - Flexible hose ~ 6mm diameter
  - Oil-filled

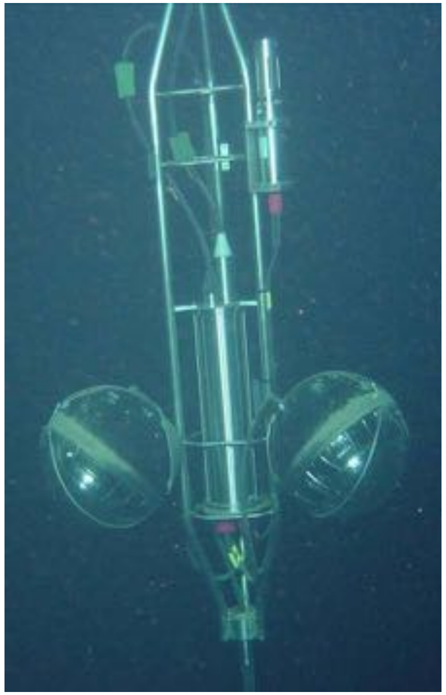
New concept, needs to be tested. Also for flexible tower if successful

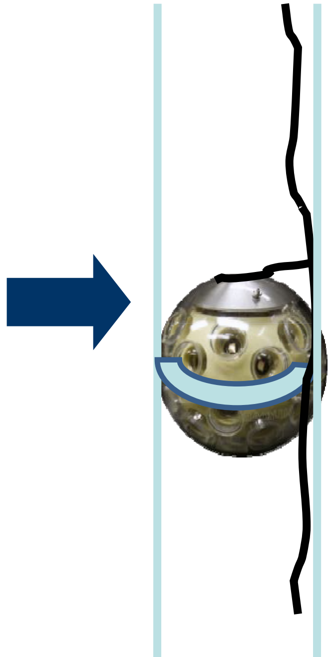
  - One single pressure transition
  - Star network between master module and optical modules



One storey = one multi-PMT OM

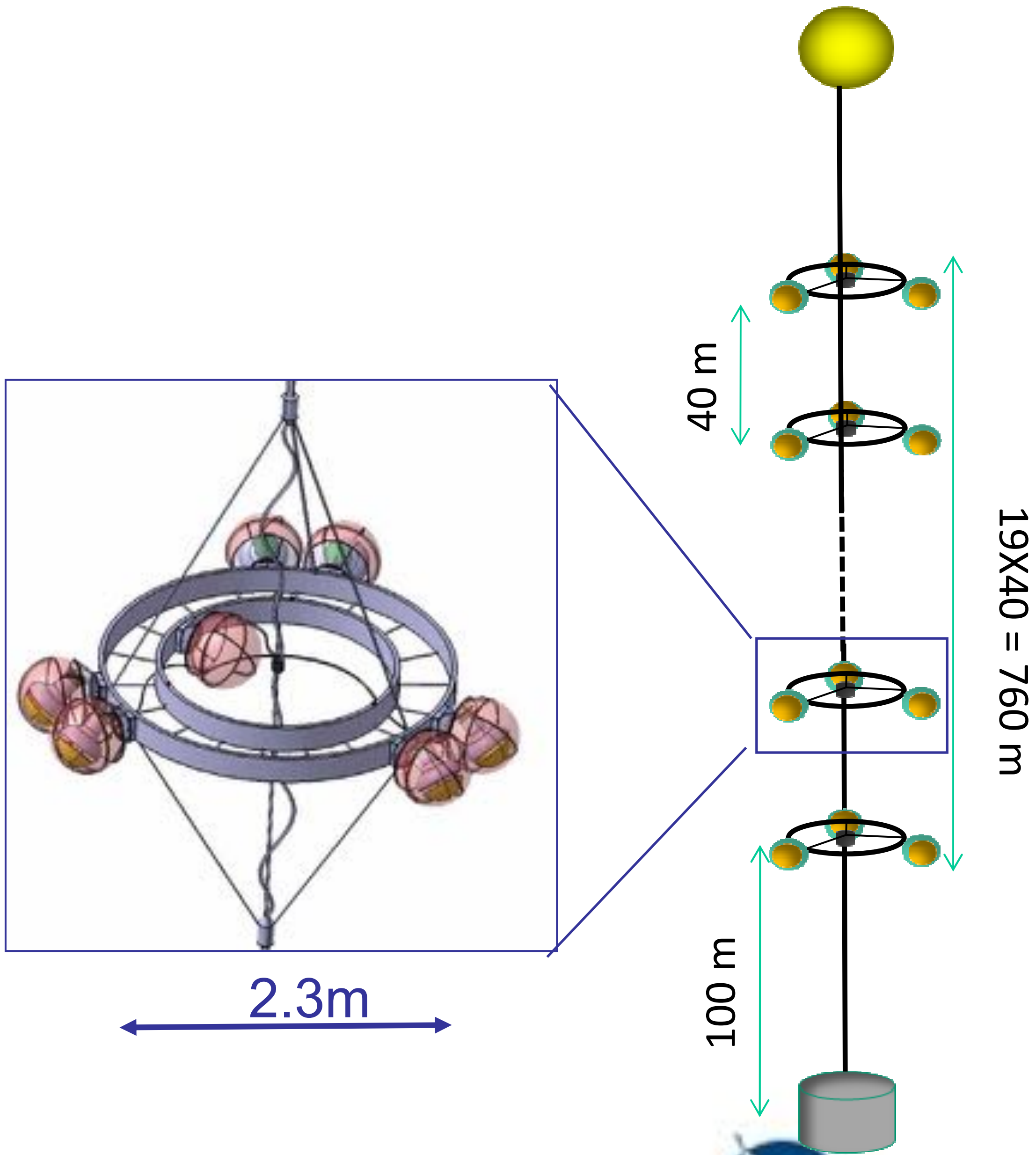
- Physics performance:
  - Photocathode area per storey similar to ANTARES
  - Excellent two-photon separation (random background rejection)
  - Looking upwards (atmospheric muon background rejection)
- Cost / reliability:
  - Simple mechanical structure
  - No separate electronics container
  - No separate instrumentation container





Triangle structure

- Evolution from ANTARES concept
- 20 storeys/DU, spacing 40m
- Backbone: electro-optical-mechanical cable
- Reduced number of electro-optical penetrations
- Use ANTARES return of experience



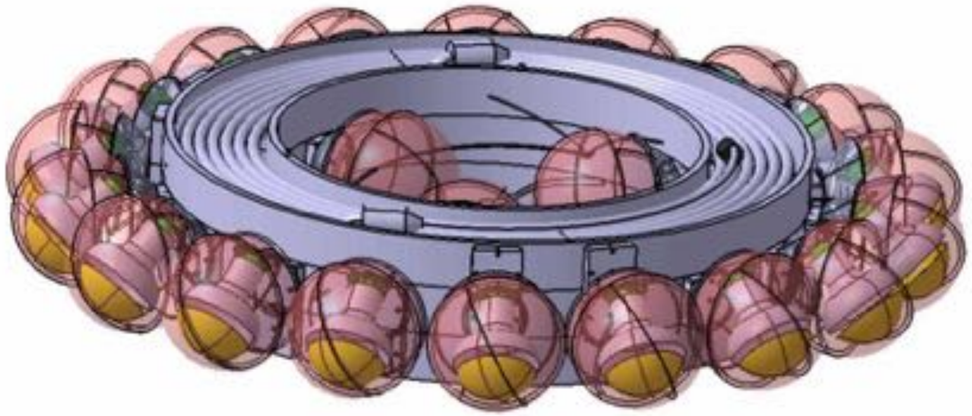
Deployment strategy

- All three mechanical solutions:
  Compact package – deployment – self-unfurling
  - Eases logistics
    (in particular in case of several assembly lines)
  - Speeds up and eases deployment;
    several DUs can be deployed in one operation
  - Self-unfurling concepts need to be thoroughly tested and verified
- Connection to seabed network by ROV
- Backup solution:
  "Traditional" deployment from sea surface

A flexible tower packed for deployment

Compactifying strings

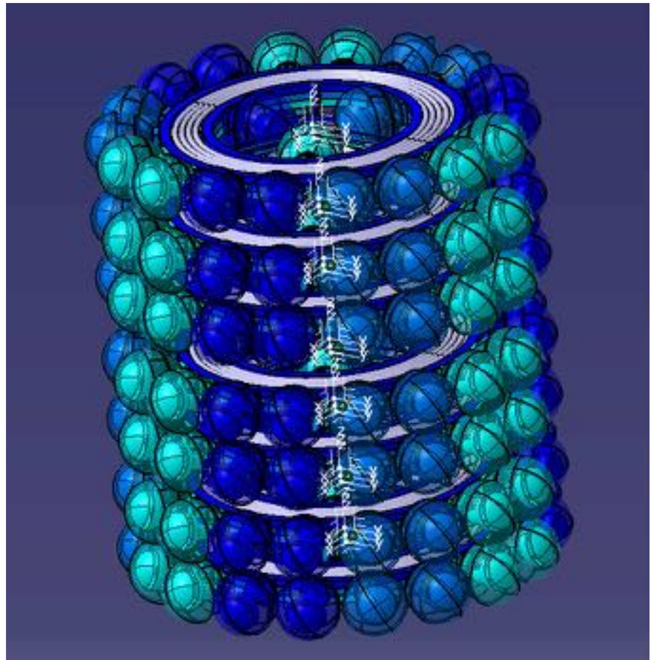
Slender string rolled up for self-unfurling (test in Dec. 2009):



3 triangles

↓

DU

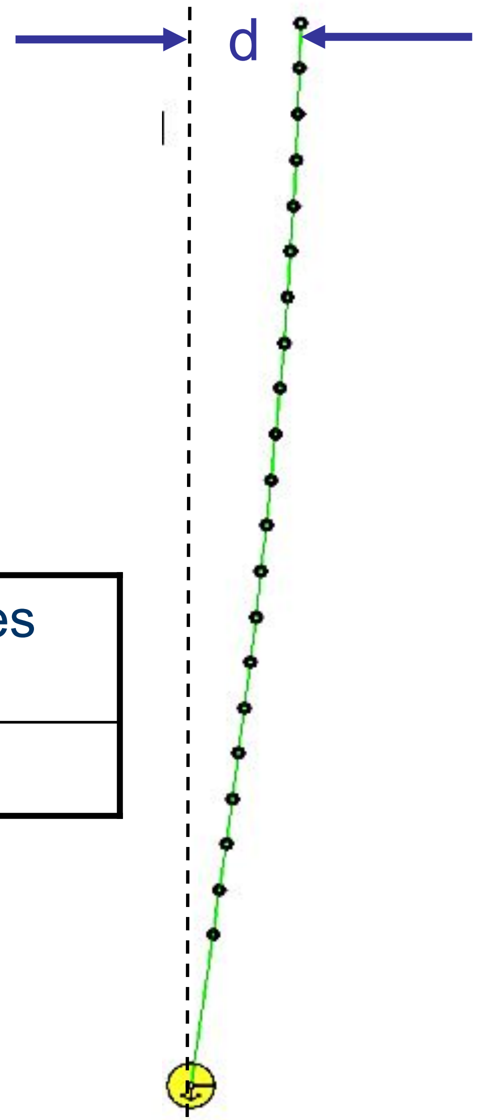


Hydrodynamic stability

- DUs move under drag of sea current
  - Currents of up to 30cm/s observed
  - Mostly homogeneous over detector volume
  - Deviation from vertical at top:

Current [cm/s]	flexible tower d [m]	slender string d [m]	triangles d [m]
30	84.0	83.0	87.0

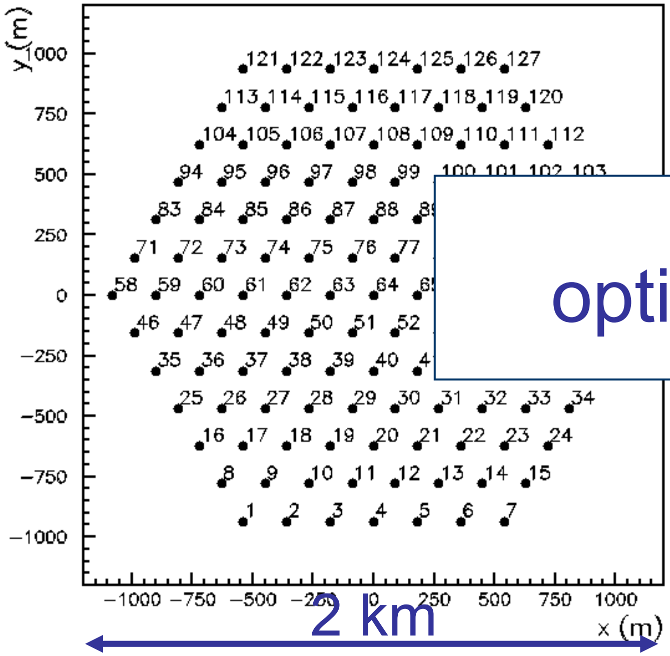
- Torsional stability also checked



Detector building blocks

- Different DU designs
  - require different DU distance
  - differ in photocathode area/DU
  - are different in cost

} different „building block footprints“

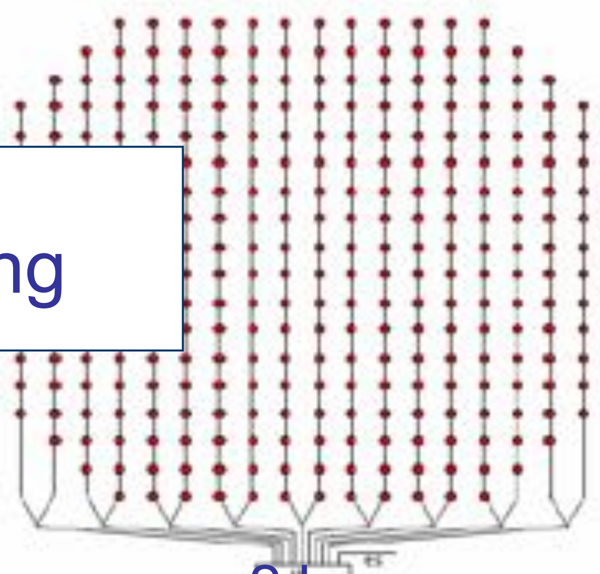


2 km

<u>Bars, triangle:</u>
127 DUs,
distance 180/150 m

Footprint
optimisation is ongoing

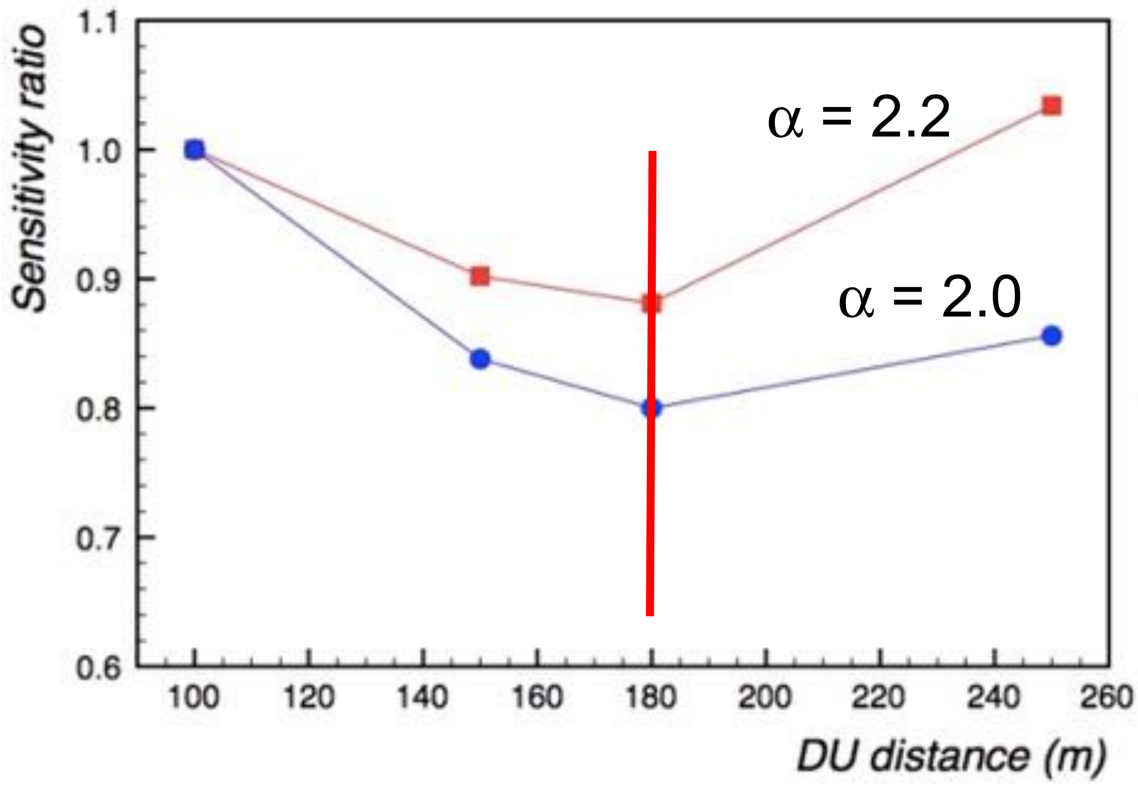
<u>Slender string:</u>
310 DUs,
distance 130 m



2 km

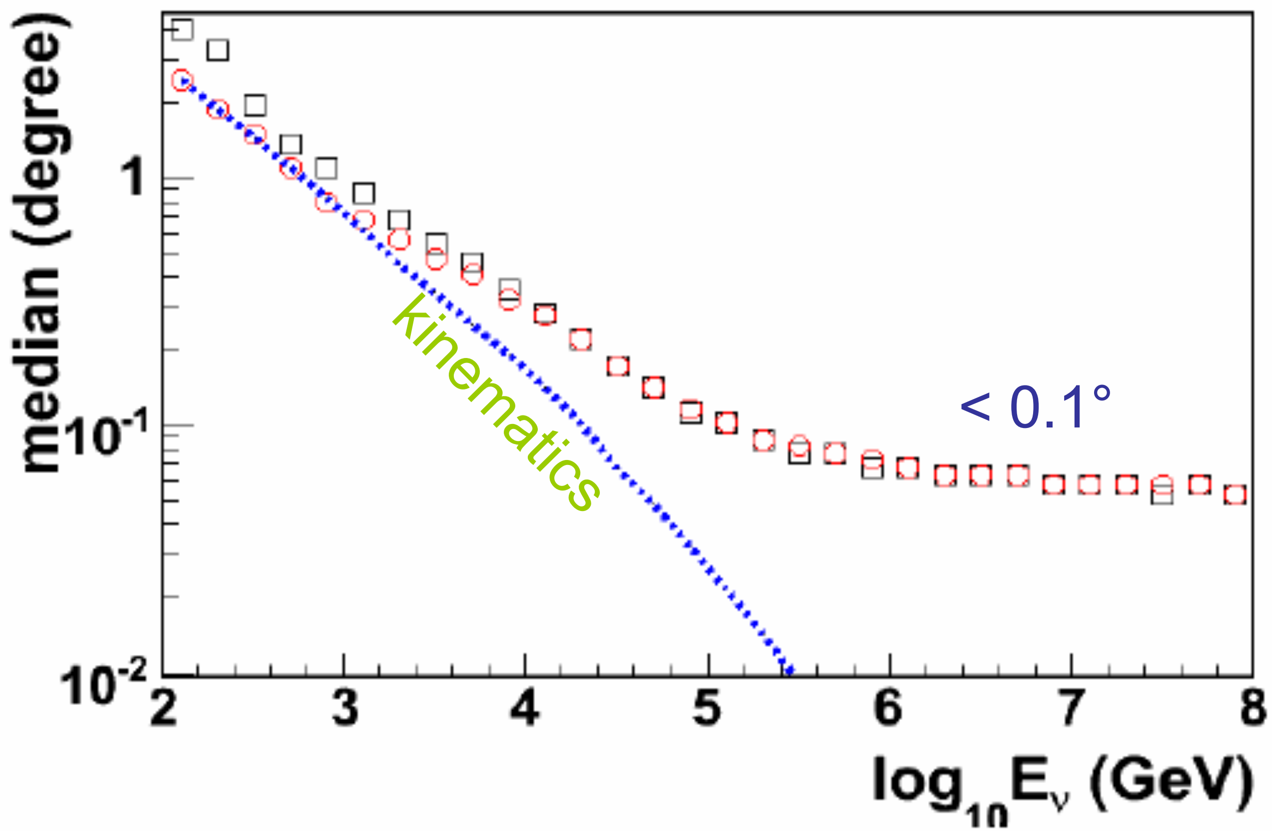
Optimisation studies

Example: Sensitivity dependence of point-source search on DU distance for flexible towers (for 2 different neutrino fluxes ~$E^{-\alpha}$, no cut-off)

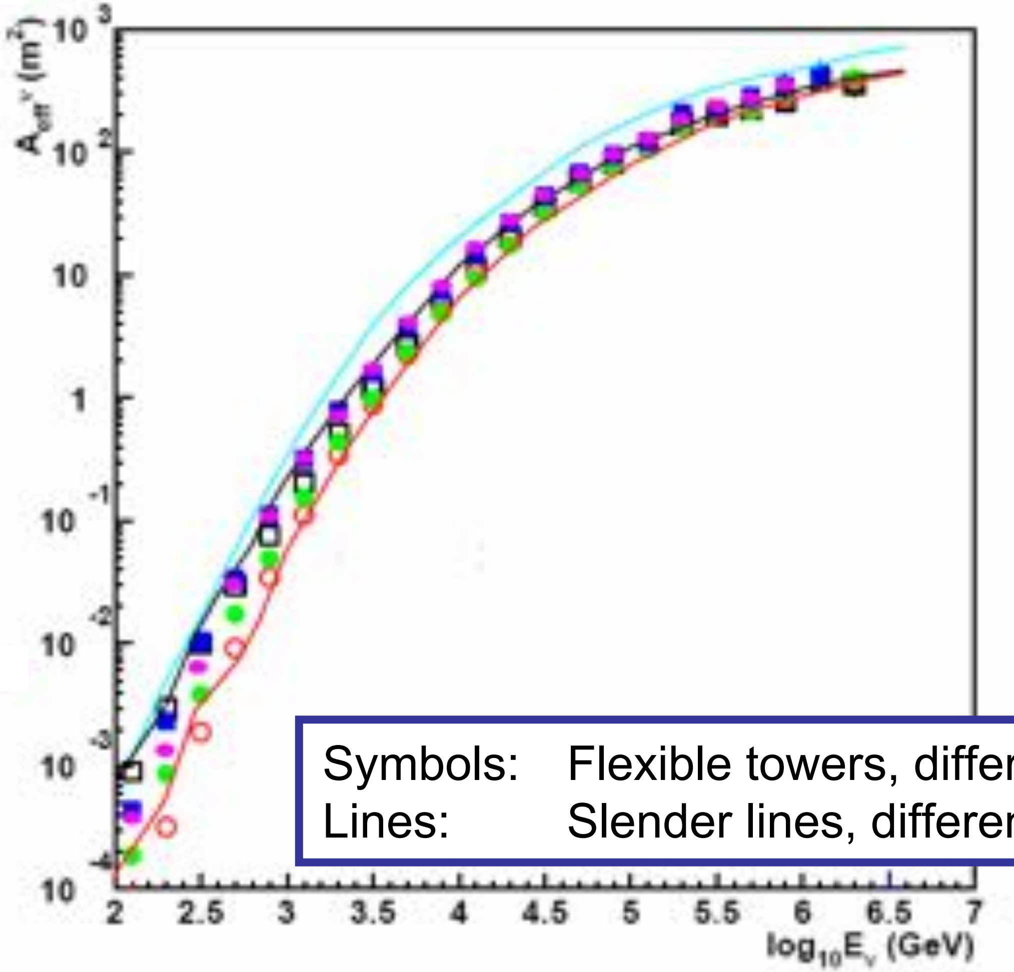


Angular resolution

- Investigate distribution of angle between incoming neutrino and reconstructed muon
- Dominated by kinematics up to ~1TeV



Effective areas (per building block)



Symbols:	Flexible towers, different quality cuts
Lines:	Slender lines, different quality cuts

- Results very similar for hard quality cuts
- Flexible towers with bars and slender strings "in same ballpark"
- Driven by overall photocathode area

Cost estimates

- Result of cost estimates (per building block):

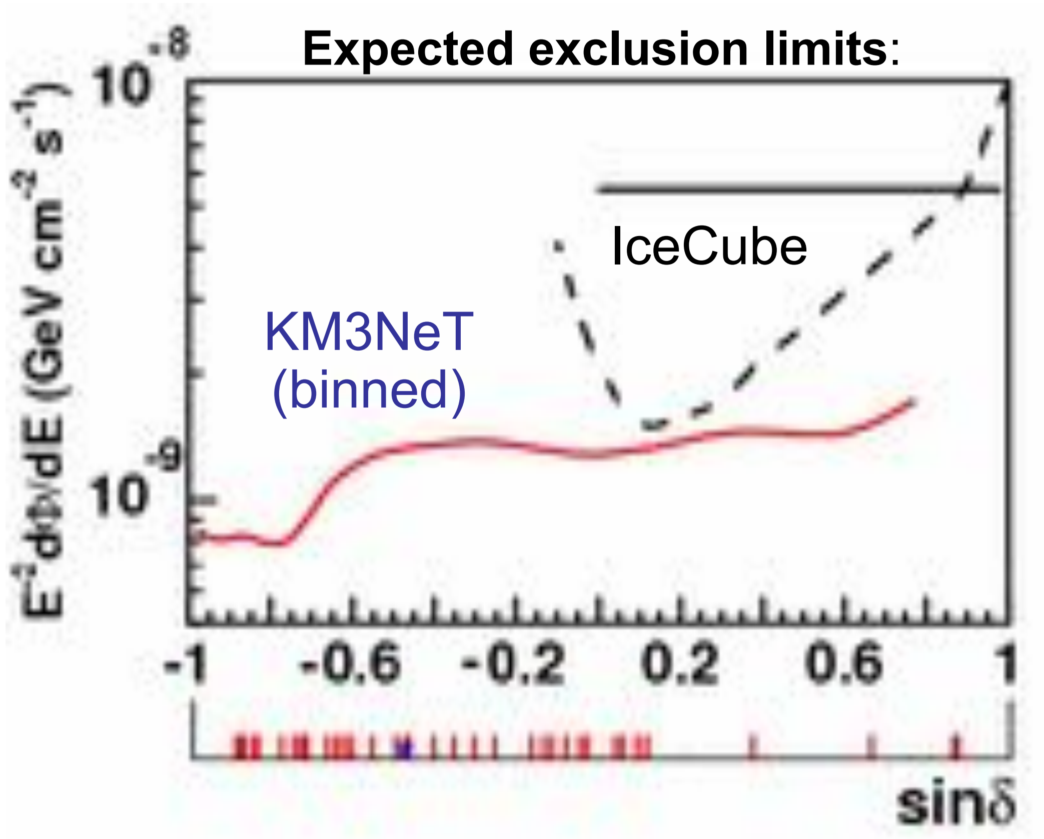
Concept	DU Cost (M€)	No. of DUs	Total DU Cost (M€)	Seafloor Infrastr. (M€)	Deploy-ment (M€)	TOTAL COST (M€)
Flexible towers	0.54	127	68	8	11	87
Slender strings	0.25	310	76	13	14	103
Triangles	0.66	127	83	8	7	99

- Assembly man power (OMs, DU…) is roughly estimated to be 10% of the DU cost

KM3NeT: Full configuration

- 2 “building blocks” needed to achieve objectives
- Increases sensitivity by a factor 2
- Overall investment ~220 M€
- Staged implementation possible
- Science potential from very early stage of construction on
- Operational costs 4-6 M€ per year (2-3% of capital investment), including electricity, maintenance, computing, data centre and management

Point source sensitivity (1 year)



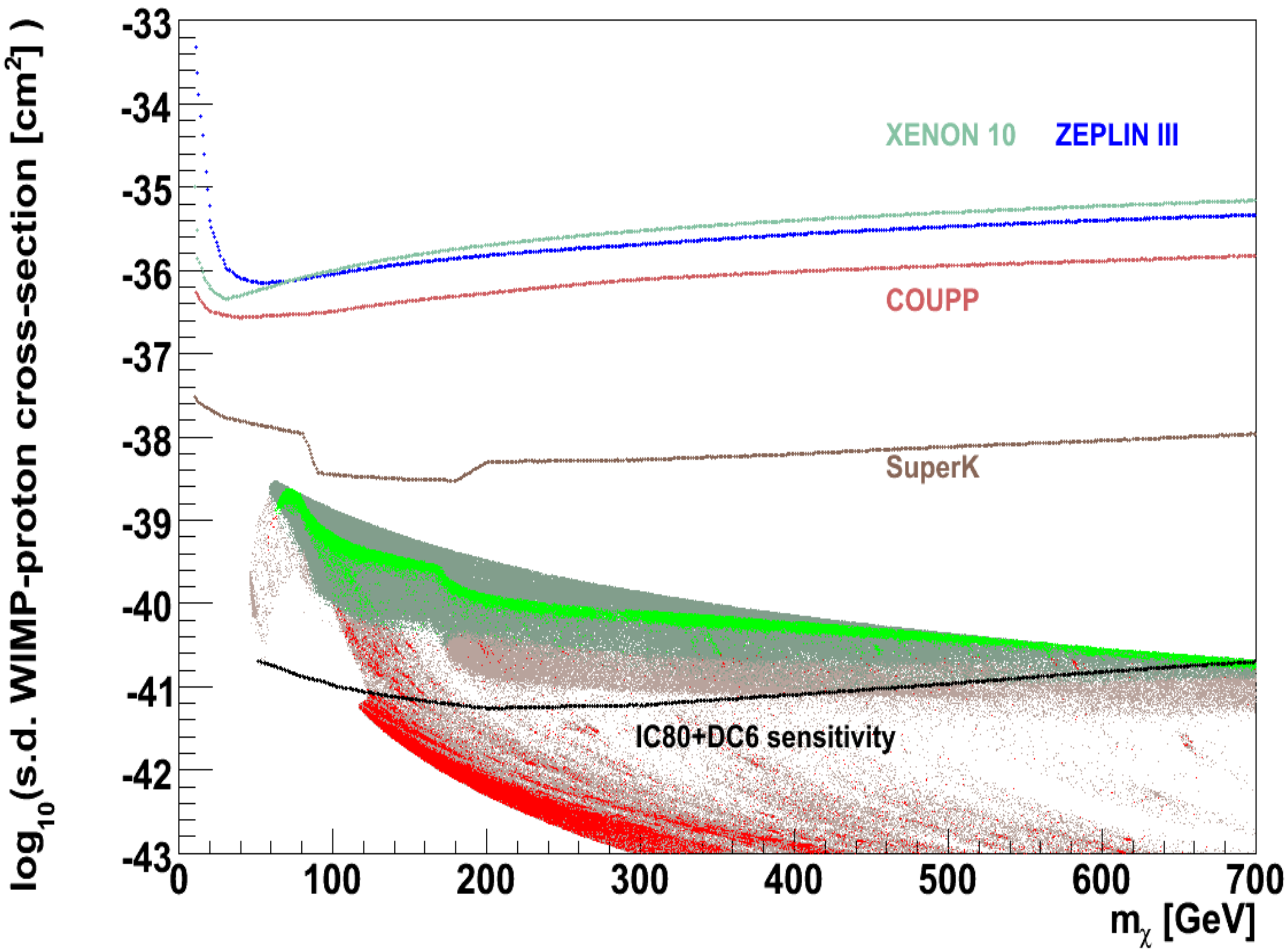
- - - R. Abbasi et al. Astro-ph (2009) scaled – unbinned method

—— Aharens et al. Astr. Phys. (2004) – binned method

□ Observed Galactic TeV-γ sources (SNR, unidentified, microquasars)
F. Aharonian et al. Rep. Prog. Phys. (2008)
Abdo et al., MILAGRO, Astrophys. J. 658 L33-L36 (2007)

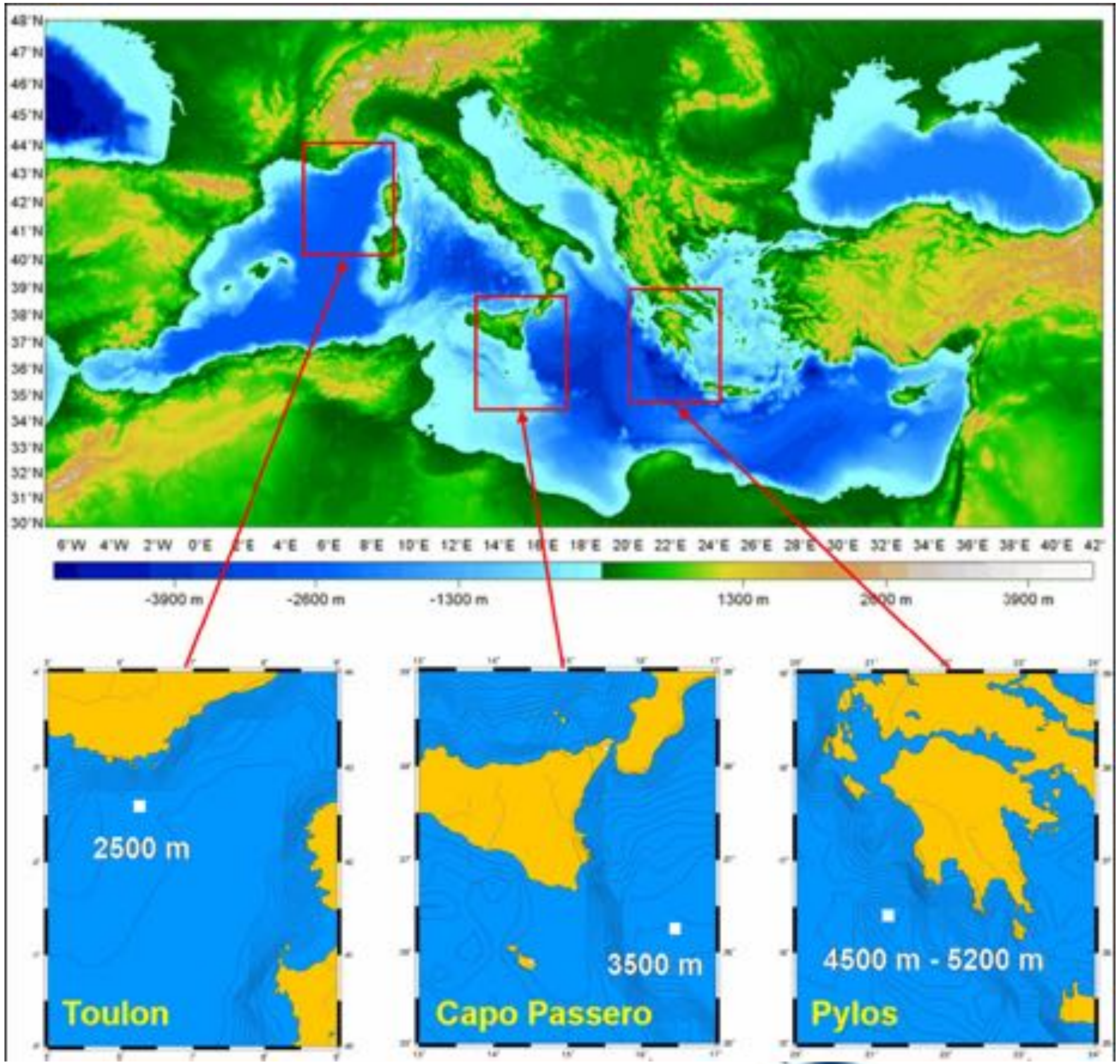
Sensitivity to neutralino annihilation in the Sun

- Exclusion limits in the mass/cross section plane
- Points: Scan of mSugra parameter phase space
- Green/red points: Compatible with CMB measurem. by WMAP; Green: in KM3NeT range Red: outside
- IceCube sensitivity strongly profits from Deep Core

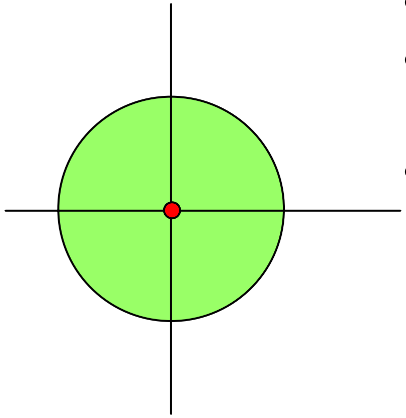


Candidate sites

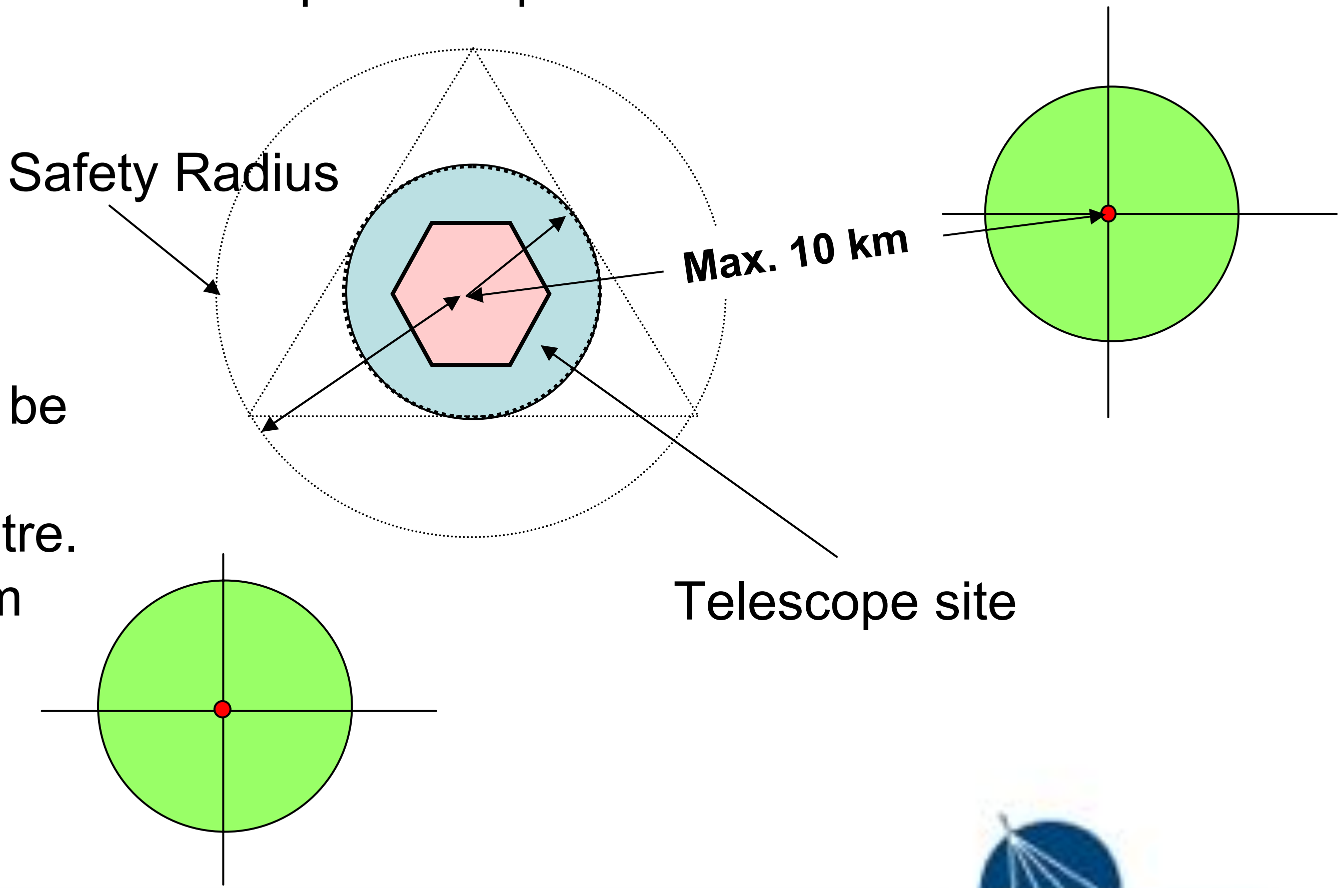
- Locations of the three pilot projects:
  - ANTARES: Toulon
  - NEMO: Capo Passero
  - NESTOR: Pylos
- Long-term site characterisation measurements performed
- Site decision requires scientific, technological and political input



The marine science node: Layout



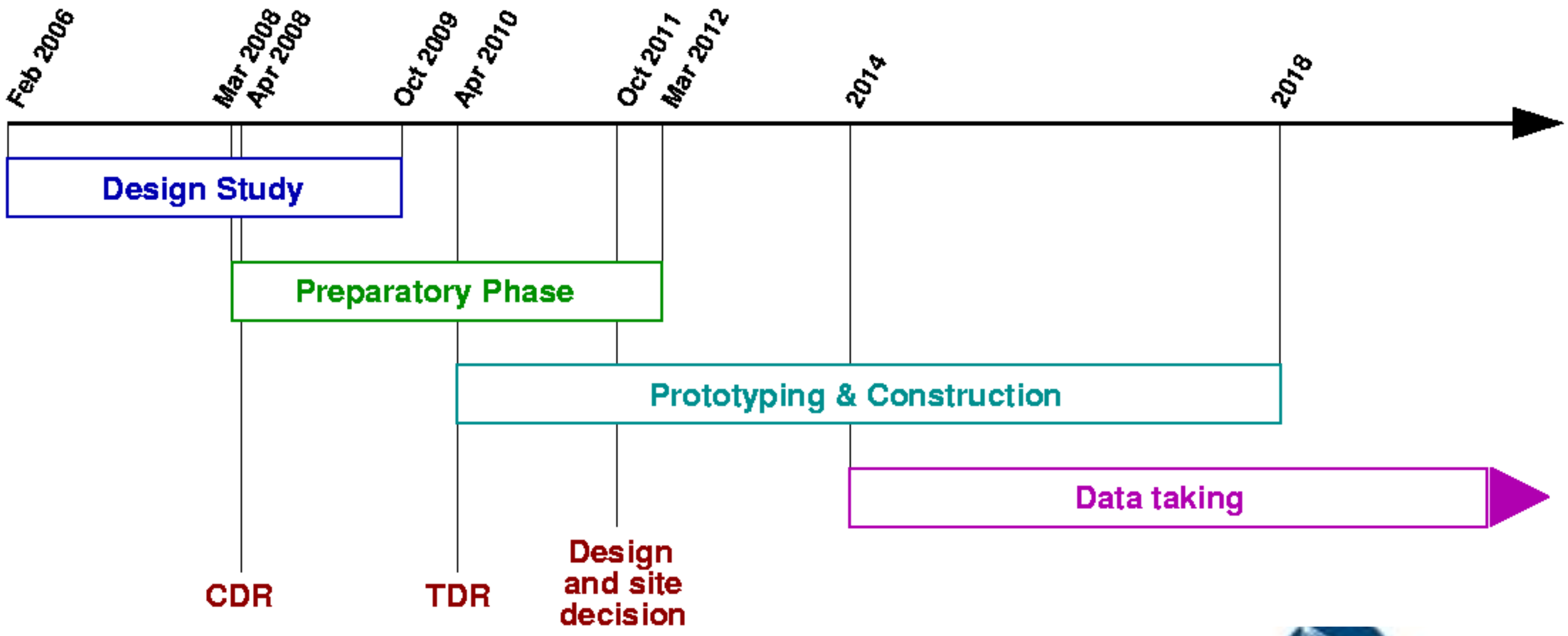
- Branches off primary junction box
- Implemented through specialised secondary junction boxes
- Main cable provides power and data connection



Each junction box can be located independently within 10km of the centre. Each requires a 500 m radius (minimum) “flat” area around it.

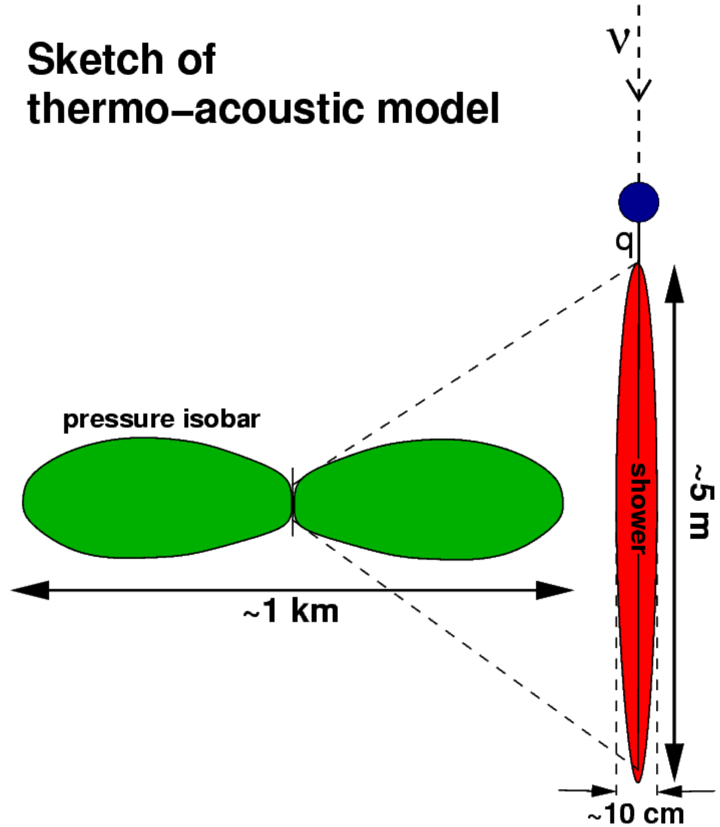
Next steps and timeline

- Next steps: Prototyping and design decisions
  - final decisions require site selection
  - expected to be achieved in ~18 months
- Timeline:

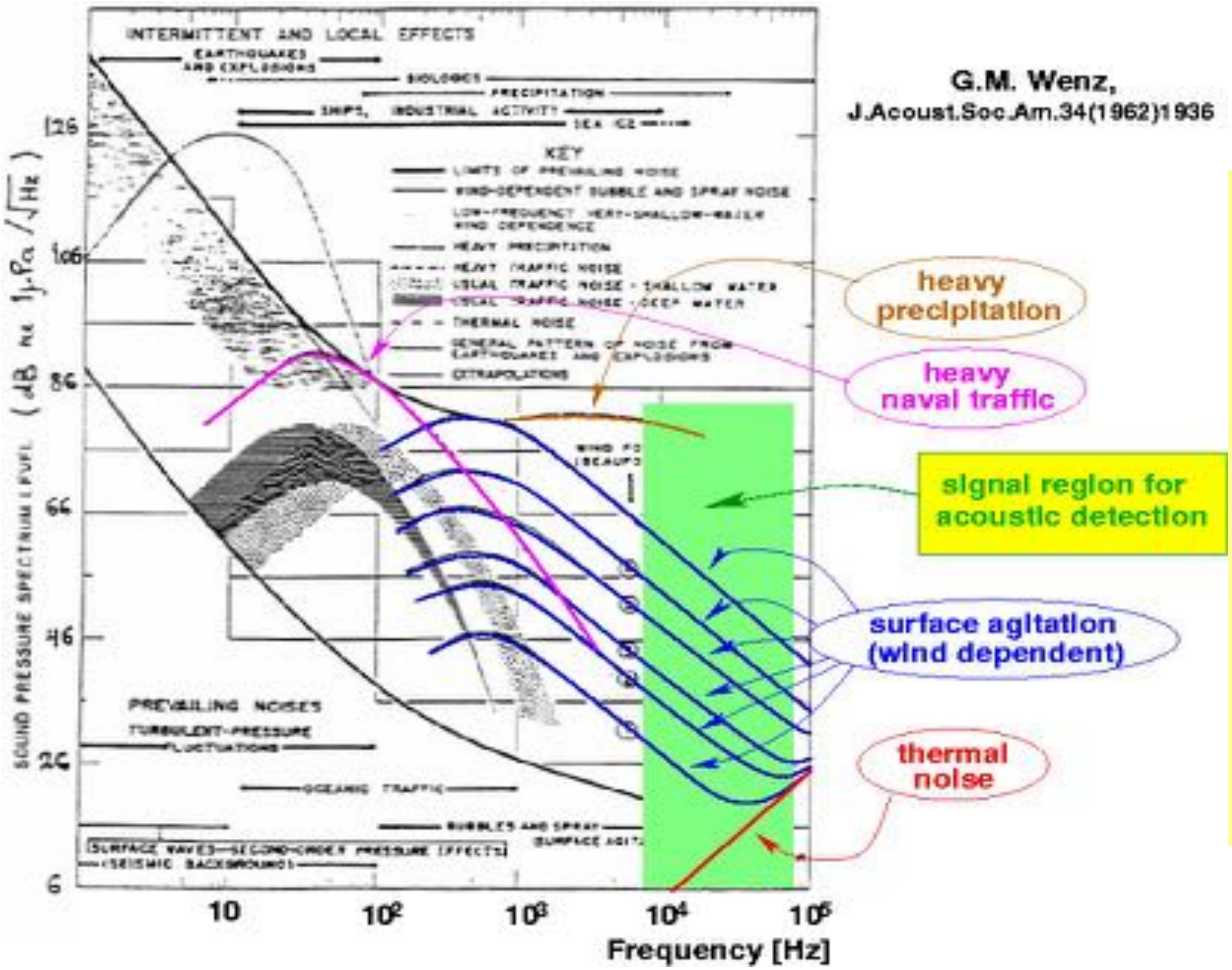


Acoustic detection of neutrinos

- Principle: local heating of medium in region of high-energy shower causes pressure wave (thermo-acoustic model);
- Bipolar signal of O(10µs) duration; amplitude ~10 µPa · E/PeV at 400m distance (in water);
- Might allow for very large instrumented volumes (attenuation length O(1 km));
- Currently rapidly growing interest in USA and Europe, studies for water, ice, salt;
- Option for ν detection at energies above $\sim 10^{17}$ eV?



Background conditions in the deep sea



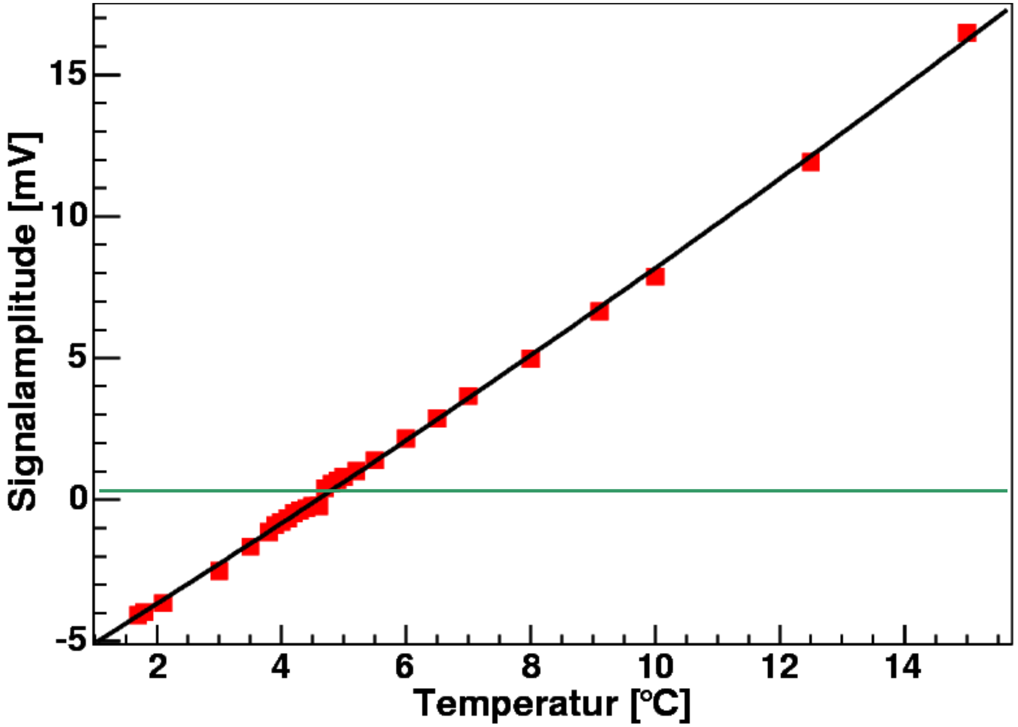
<u>Rough and optimistic estimate:</u>

signal ≈ noise at O(0.1-1 mPa)

(shower with 10-100 PeV @ 400m)

Acoustic detection R&D activities

- Sensor development, study/simulation of signal generation, test measurements,...
- Example: beam test measurements in Uppsala (cooperation Zeuthen/Erlangen): confirmation of expected T dependence.

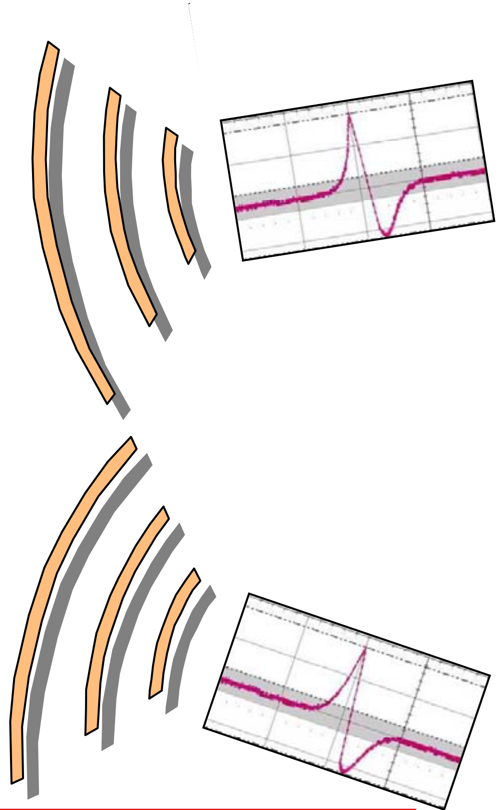


Arrangement of sensors

~1m : - local coincidences for suppression of uncorrelated background

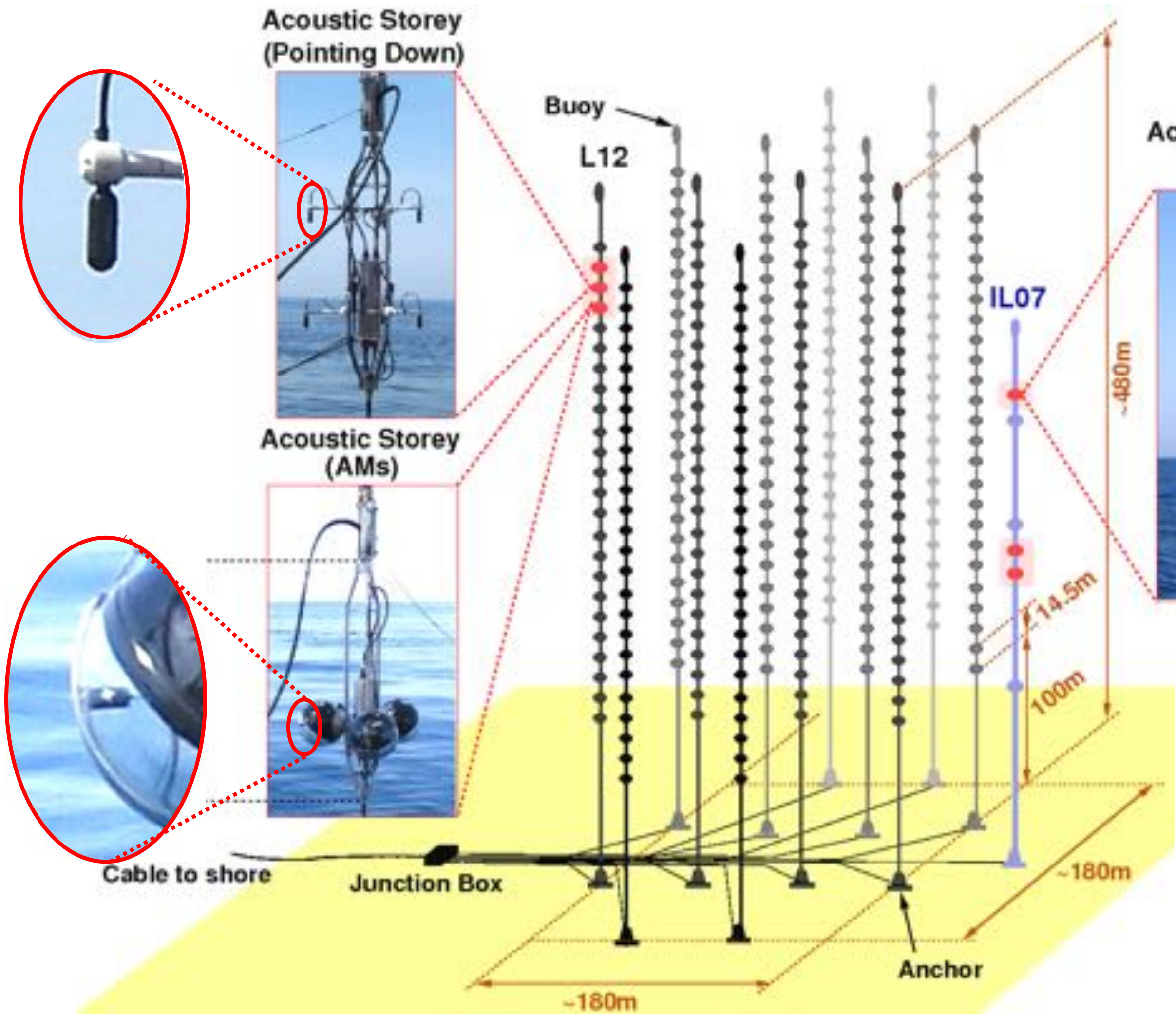
hydrophones

15m to 100m: directional reconstruction



Aim: measurement of "bipolar event density" in a large volume (km^3) for a long time (yr) with a dedicated array of acoustic sensors

The AMADEUS System of the ANTARES detector

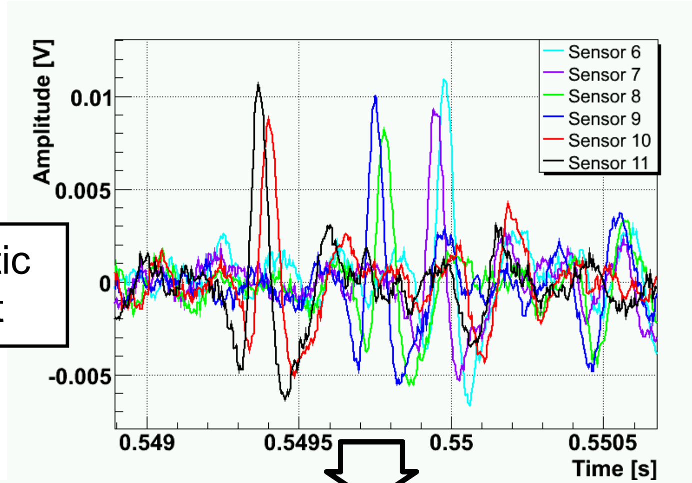


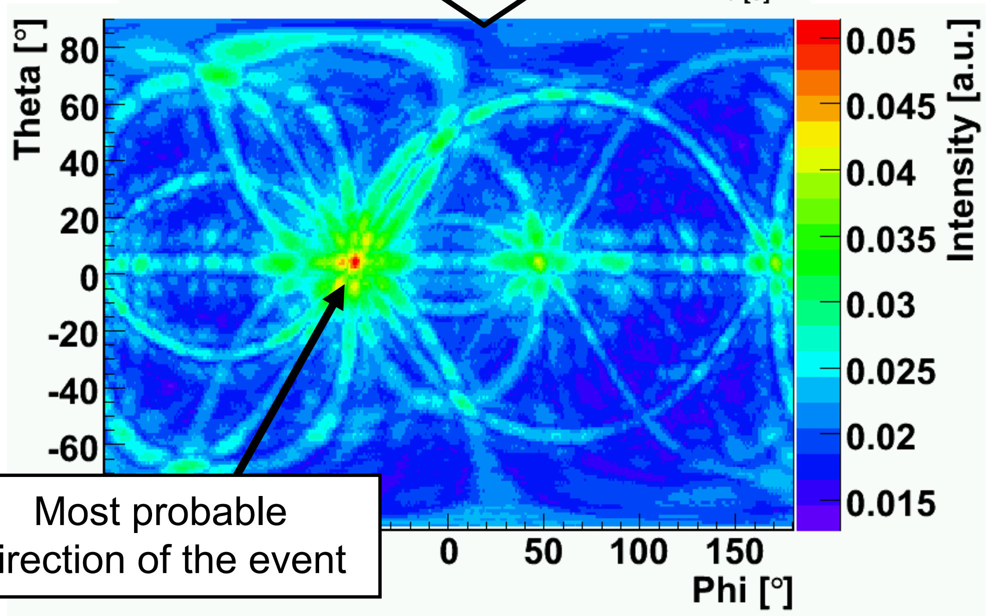
- taking data since 5-Dec-2007
- completely installed since 30-May-2008
- acoustic data from L12:
  until 24-Dec 2008
  restart 14-Nov 2009

Localisation of transient signals

Reconstruction of source distance with triangulation from several storeys

Acoustic event

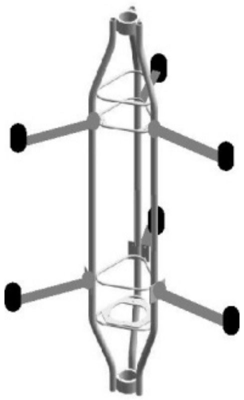




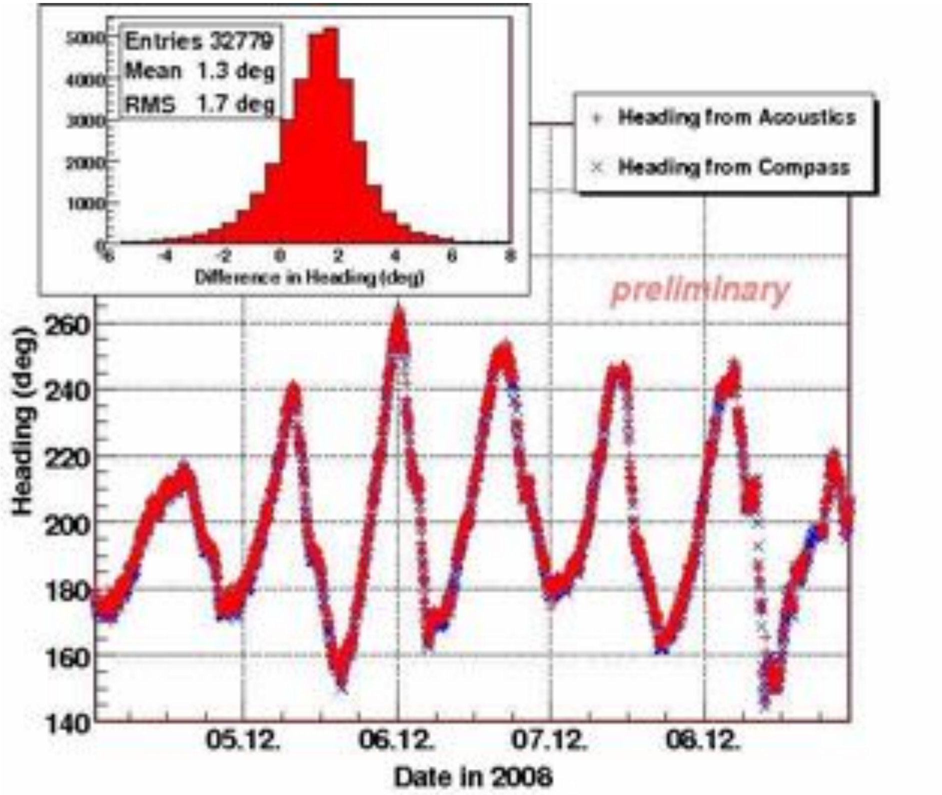
Most probable direction of the event

Positioning of Acoustic Storeys

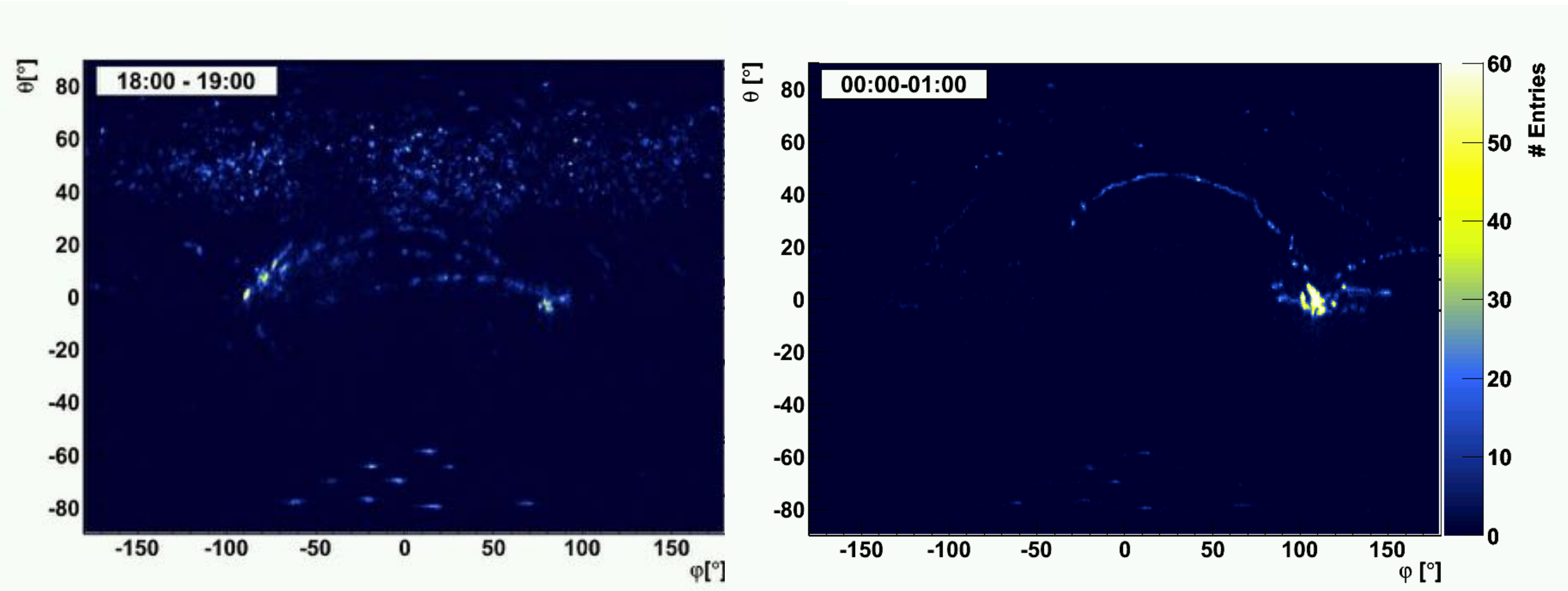
- use emissions from the ANTARES acoustic positioning system
- triangulate each hydrophone on a storey
- position/orientation by fitting storey geometry



Comparison to compass readings:



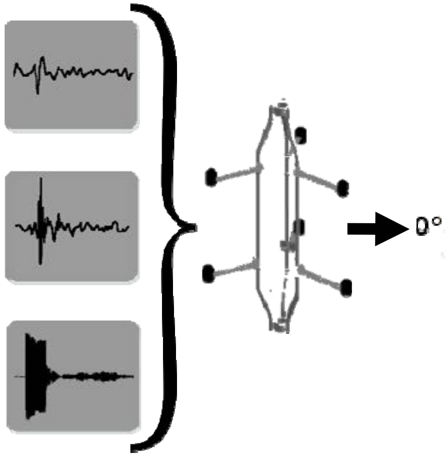
Shipping noise: Examples

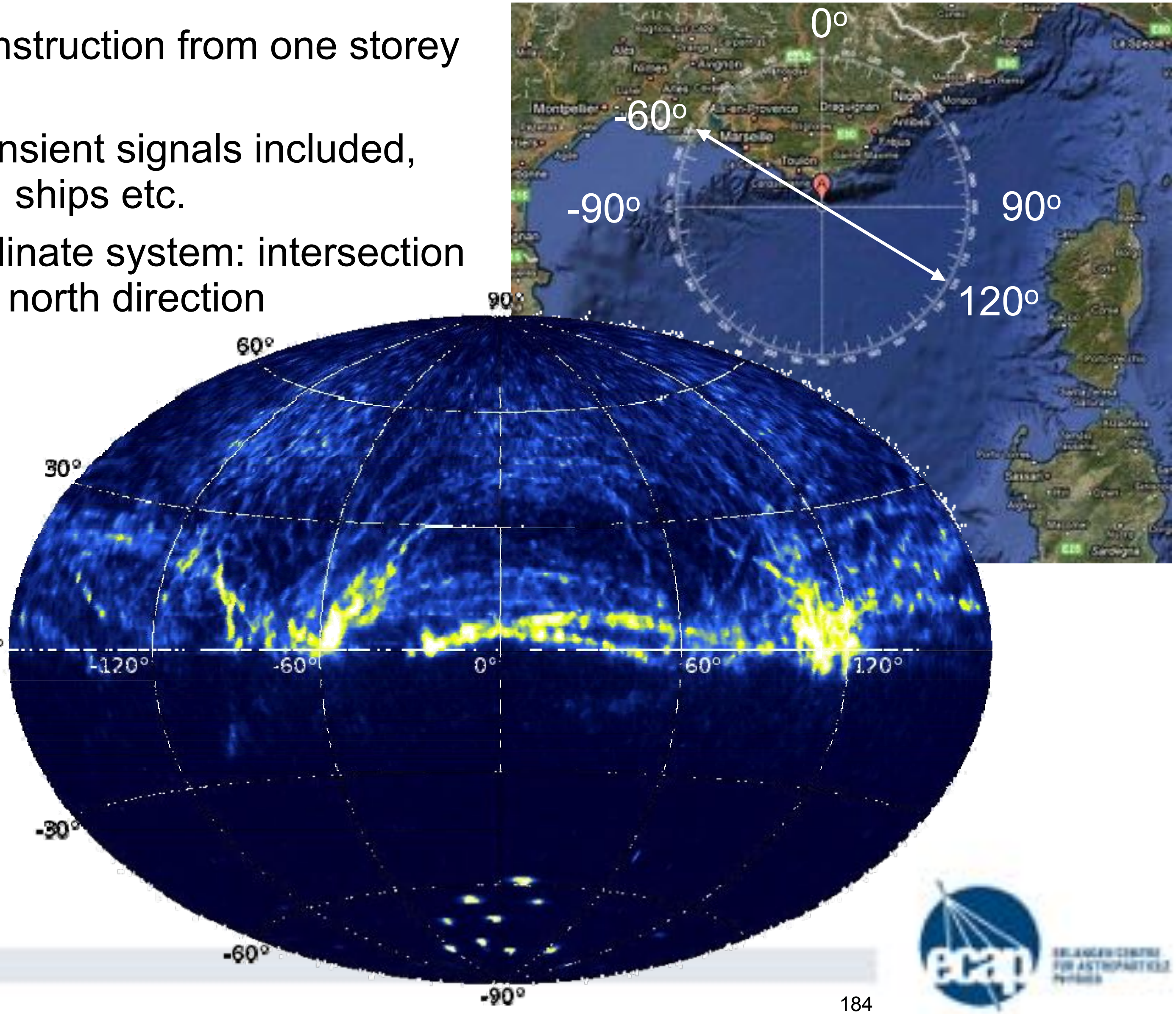


Note: θ=0 is sea surface at horizon, ϕ=0 is North

Source direction distribution

- Direction reconstruction from one storey on Line 12
- All types of transient signals included, sea mammals, ships etc.
- Origin of coordinate system: intersection of horizon and north direction

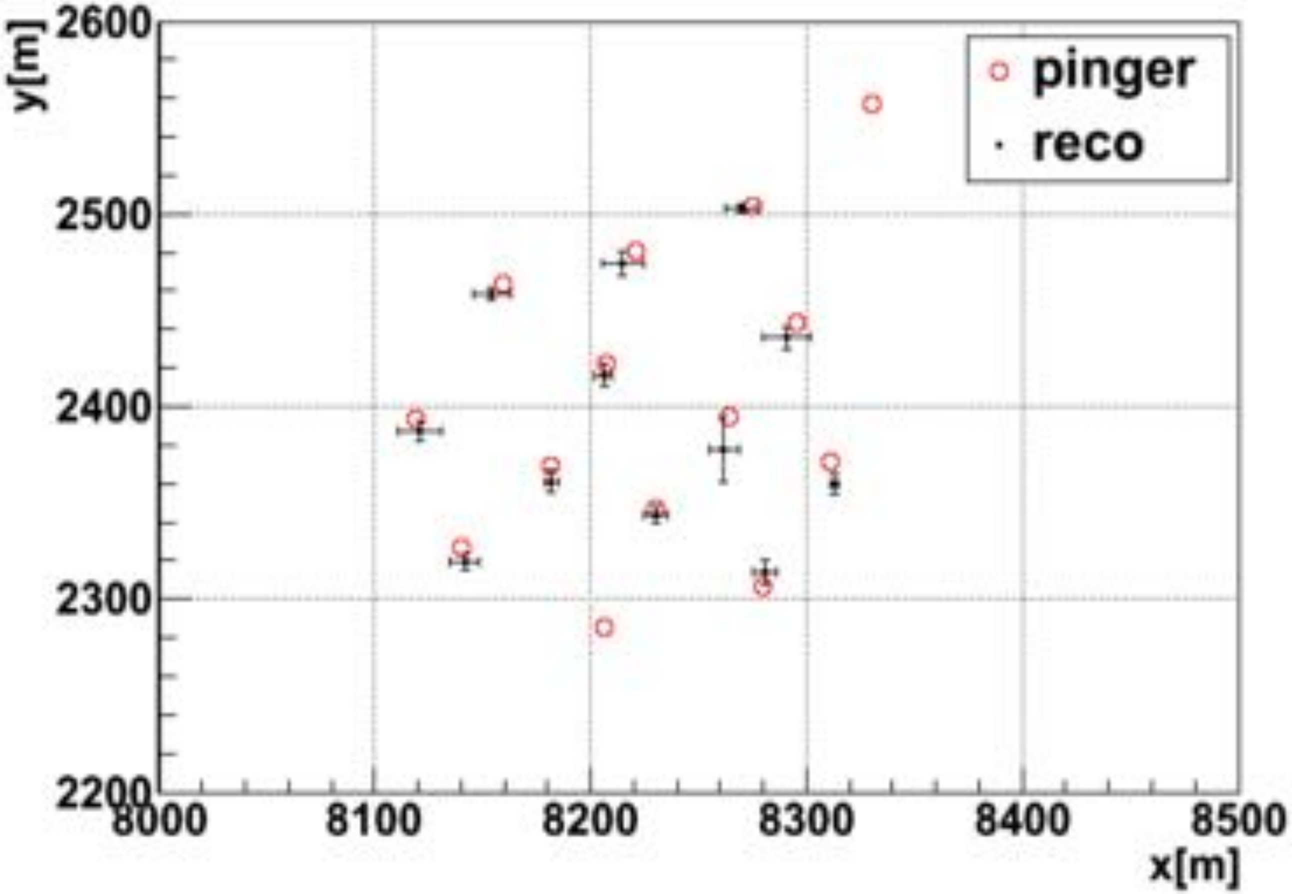




Reconstruction of acoustic emitters at line anchors

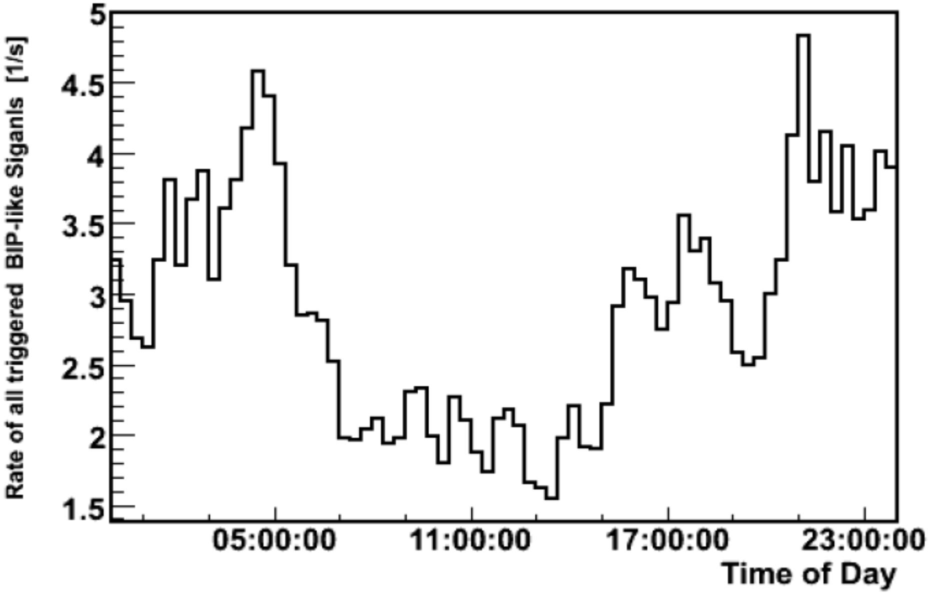
uncertainty of direction reconstruction ~ 1º

→ uncertainty in position ~ 2m @ 100m distance

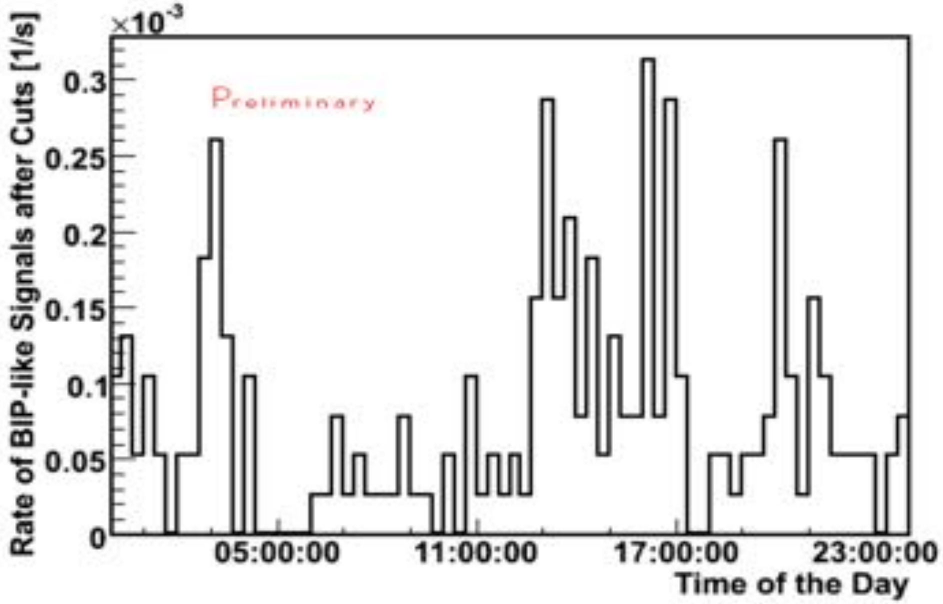


Event classification

all triggered events



neutrino-like events



suppression: 10^4

cuts on signal duration, number of peaks and correlation features