# Neutrino detectors

## and the physics they teach us

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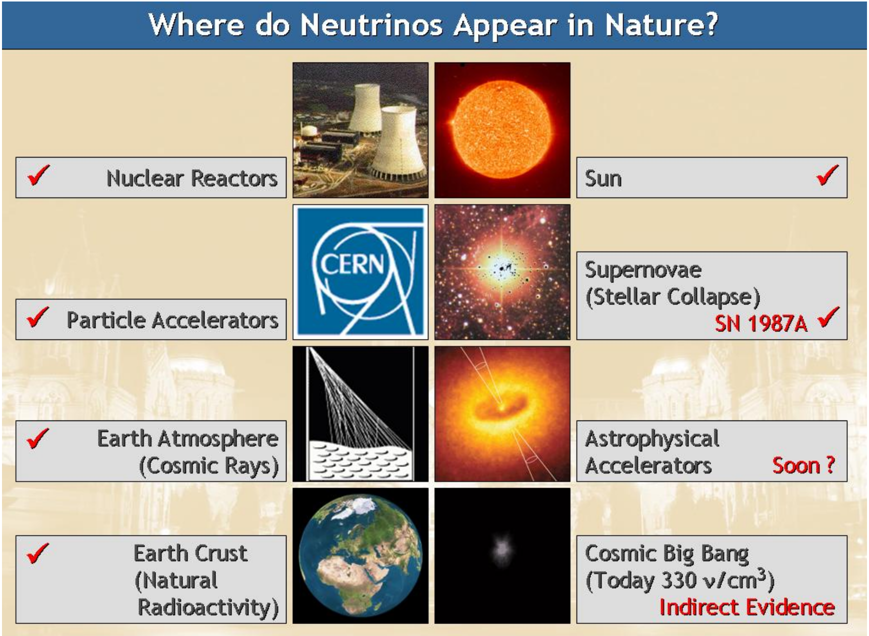
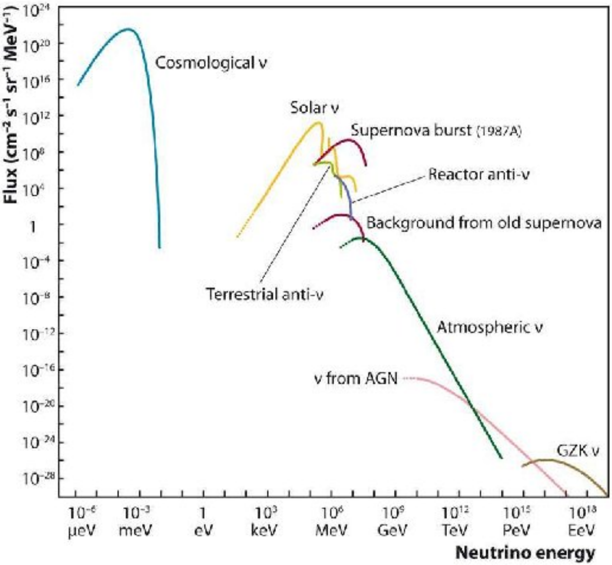
Mumbai, India

SYMPHY 2014, IITB, April 13th, 2014

# Omnipresent neutrinos



# Energy spectra of neutrino sources



# Detection: motivations and problems

## Motivations for neutrino detection

- Understanding nuclear reactions inside the Sun
- Monitoring nuclear reactors and radioactivity of the Earth
- Observing astrophysical phenomena
- Standard Models of particle physics and cosmology

## Problem with neutrino detection

- They interact extremely weakly !
- SuperKamiokande detector: 50,000,000 lit water
  - Number of neutrinos passing every day: $\sim 10^{25}$
  - Number of neutrinos detected every day: $\sim 10$
- Need LARGE detectors running for a loooong time

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# Neutrino detectors

1. Discoverers
2. Sun-seekers
3. Earth-watchers
4. Sky-gazers
5. New ideas...

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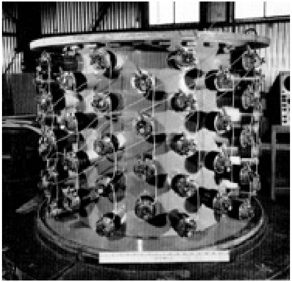
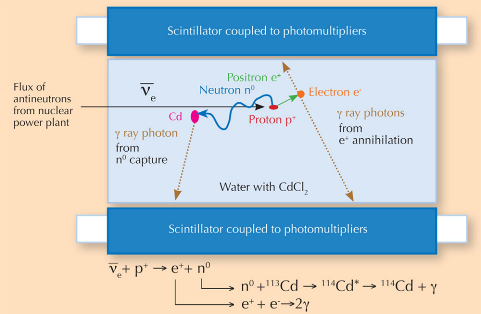
# The long-awaited discovery of electron (anti)neutrino

## Reines and Cowan 1956: Scintillator





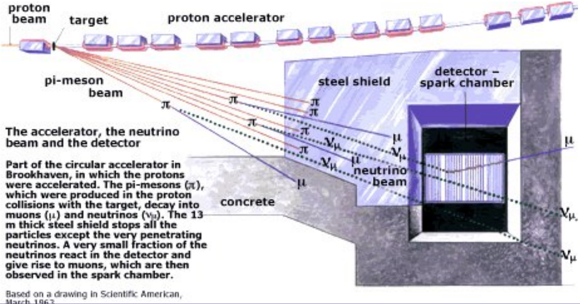

### The million-dollar particle

- Reactor neutrinos: $\bar{\nu}_e + p \to n + e^+$
- $e^+ + e^- \to \gamma + \gamma$ (0.5 MeV each)
- $n +^{108} \mathrm{Cd} \to^{109} \mathrm{Cd}^* \to^{109} \mathrm{Cd} + \gamma$ (delayed)

Nobel prize 1995

# The serendipitous discovery of the muon neutrino

Steinberger-Schwartz-Lederman 1966: Spark chamber



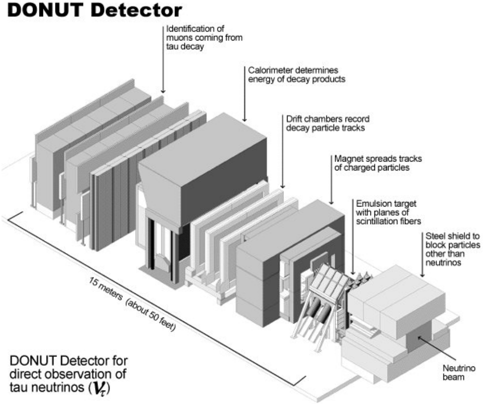

## Muon neutrino: an unexpected discovery

- Neutrinos from pion decay: $\pi^- \to \mu^- + \bar{\nu}$
- Expected: $\bar{\nu} + N \to N' + e^+$ ??
- Observed: always a muon, never an electron/positron
- This must be a new particle, not $\bar{\nu}_e$, but $\bar{\nu}_\mu$

Nobel prize 1988

# The expected discovery of the tau neutrino

DONUT@Fermilab, 2000: emulsion+calorimeter




## Combination of many detectors needed

- $\nu_\tau \to \tau$, whose decays need to be observed
- Emulsion + Drift chamber + Calorimeter + Muon chamber

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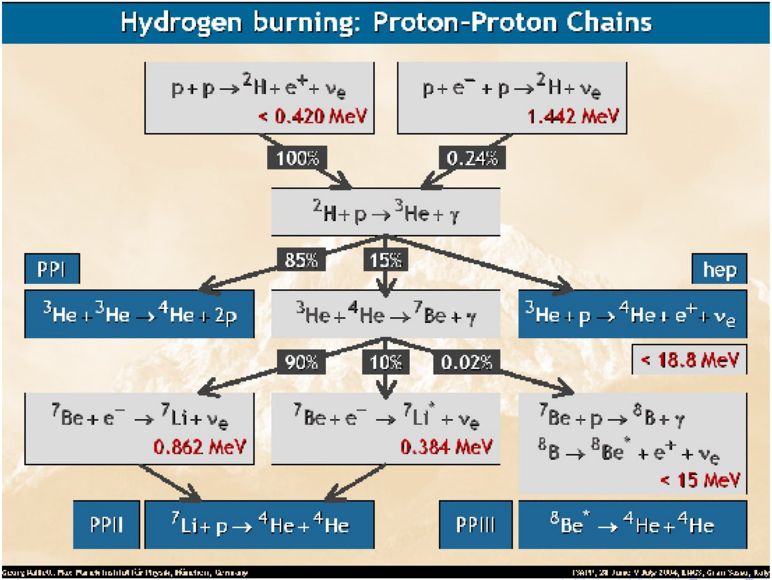
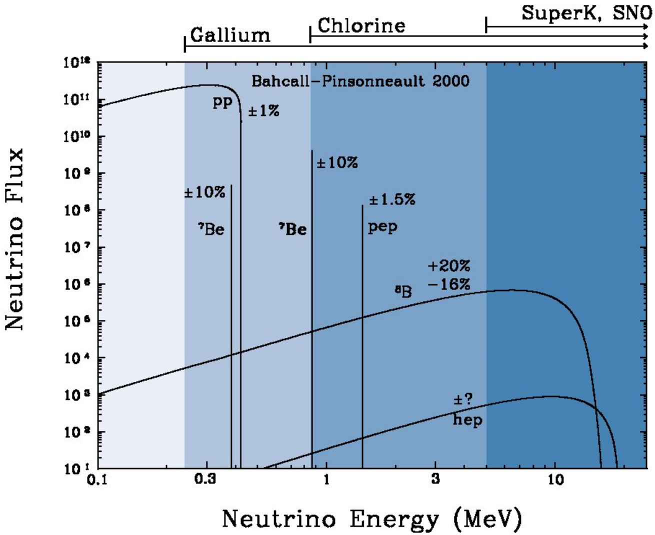
# Neutrinos from the Sun

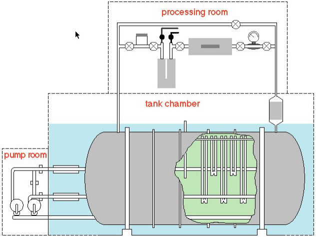


# Spectrum of solar neutrinos



# Neutrinos from the Sun: Homestake experiment

Chlorine radiochemical

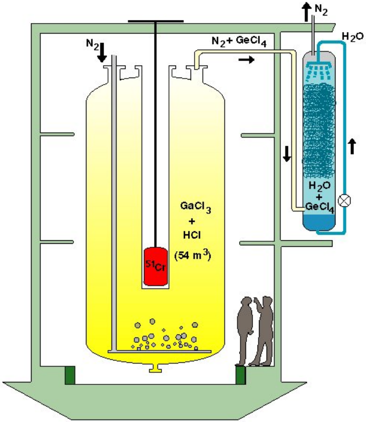



- $\nu_e + \mathrm{Cl} \rightarrow \mathrm{Ar} + e^-$
- Individual Ar atoms counted every few weeks
- No energy measurement
- First detection of solar $\nu_e$

Davis: Nobel prize 2002

# Even lower energy threshold: Gallex experiment

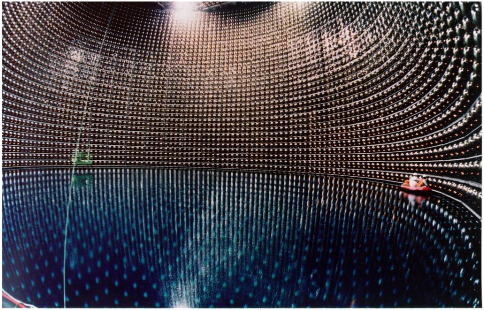
Gallium radiochemical

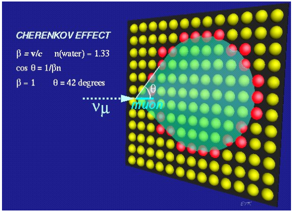



- $\nu_e + \mathrm{Ga} \to \mathrm{Ge} + e^-$
- No energy measurement
- Threshold 0.233 MeV

# Solar spectrum measurement: SuperKamiokande

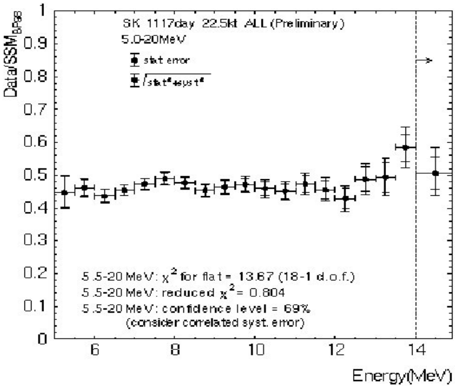
Water Cherenkov

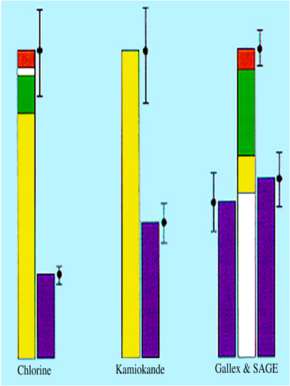





- $\nu_e + e^- \rightarrow \nu_e + e^-$(fast)
- $v_{e^-} > c_{\mathrm{water}} \Rightarrow$ Cherenkov light

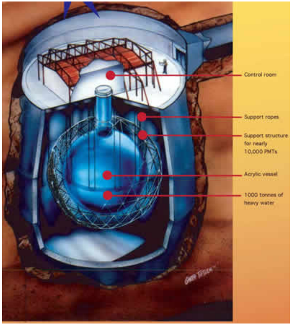
# The solar neutrino problem

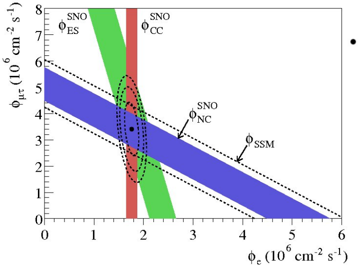



- SuperKamiokande spectrum gives almost energy-independent suppression
- Different experiments give different suppression

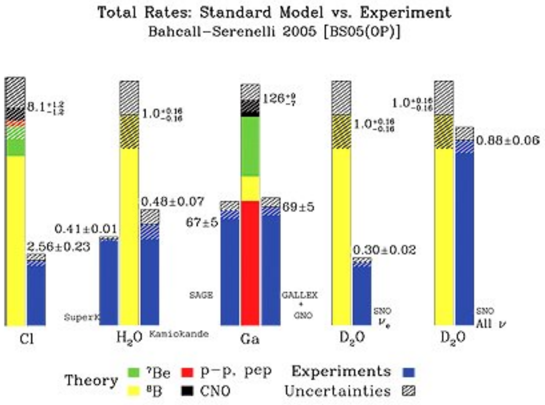
# Heavy water Cherenkov experiment: SNO



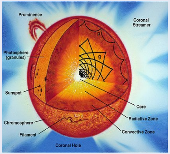

- Heavy water Cherenkov
- $\nu_e \; D \to p \; p \; e^-$
  sensitive to $\Phi_e$
- $\nu_{e,\mu,\tau} \; e^- \to \nu_{e,\mu,\tau} \; e^-$
  Sensitive to $\Phi_e + \Phi_{\mu\tau}/6$
- $\nu_{e,\mu,\tau} \; D \to n \; p \; \nu_{e,\mu,\tau}$
  sensitive to $\Phi_e + \Phi_{\mu\tau}$
- Neutral current: no effect of oscillations

# Solar neutrino problem settled



# The mystery of missing Solar neutrinos (1-10 MeV)

## The source and the puzzle (1960s–2002)




- Neutrinos essential for the sun to shine: many modes of producing $\nu_e$
- Neutrino flux measured at the Earth only 30%–50% of the calculated value

## Solution through "neutrino oscillations in matter"

- Neutrinos have different masses, $\nu_e$ mixes with others
- The matter inside the Sun affects $\Delta m^2$ and $\theta$ (MSW effect)
- A level crossing (resonance) takes place inside the Sun, which determines how many $\nu_e$ survive.
- Can measure $\Delta m^2_\odot$ and $\theta_\odot$

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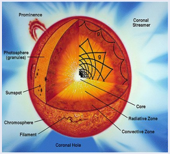


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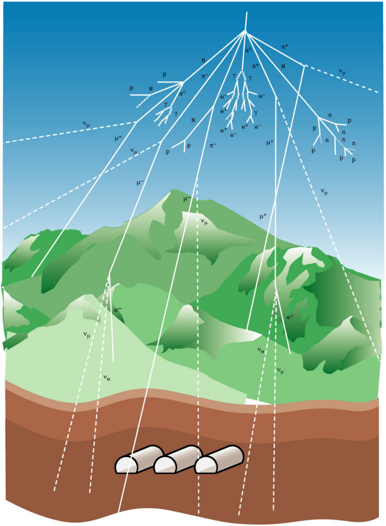
# Neutrino detectors

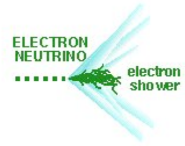
# Neutrinos from cosmic rays



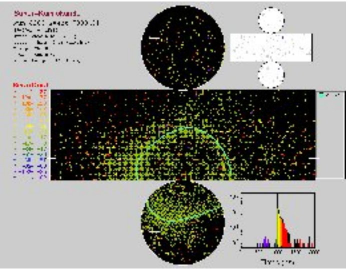
- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- "$\nu_\mu$" flux $= 2\times$ "$\nu_e$" flux
- "Down" flux = "Up" flux

# How to detect $\nu_e$ and $\nu_\mu$ through Cherenkov cones

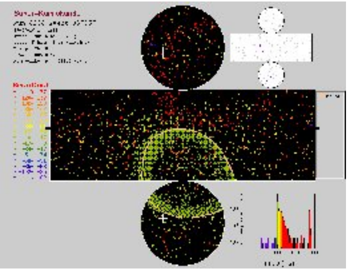
Water Cherenkov







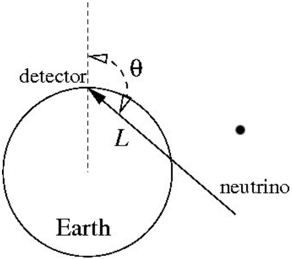
Diffused ring



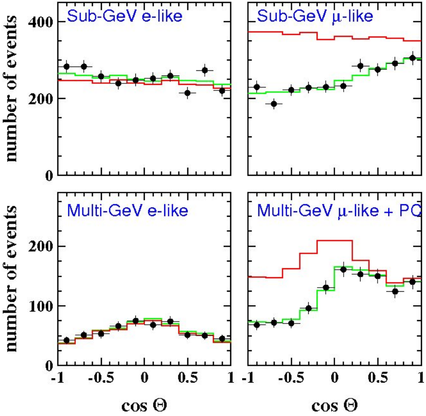
Sharp ring

# Atmospheric neutrino puzzle

Zenith angle:

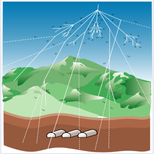



Zenith angle dependence:



# The anomaly in atmospheric neutrinos (1–50 GeV)

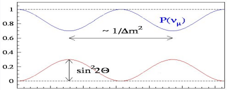
## The source and the puzzle (1980s–1998)



- Cosmic rays $\oplus$ atmosphere $\Rightarrow$ pions and muons $\Rightarrow$ decay to neutrinos ($\nu_\mu$ and $\nu_e$)
- Expect almost isotropic flux of neutrinos
- Almost half the $\nu_\mu$ are lost while passing through the Earth, no $\nu_e$ are lost.

## Solution through "vacuum oscillations"

- Neutrinos have different masses, $\nu_\mu$ and $\nu_\tau$ mix
- Quantum Mechanics predicts neutrino oscillations:




$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

- Can measure $\Delta m^2_{\mathrm{atm}}$ and $\theta_{\mathrm{atm}}$

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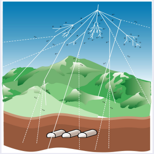

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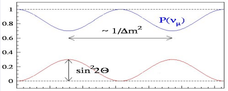


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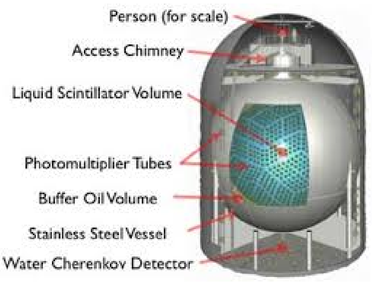
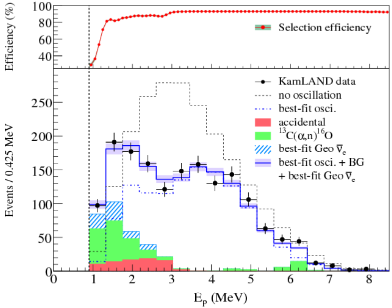
# Geoneutrinos

Liquid scintillator



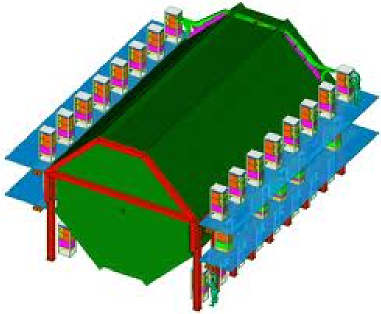




## Geoneutrinos: $\bar{\nu}_e$

- Produced due to natural radioactivity in the Earth's crust
- Recently confirmed, after separating reactor neutrinos
- Useful for understanding Earth's radioactivity

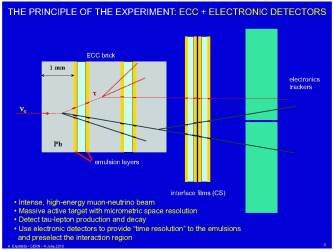
# Beam-catcher (long baseline) detectors

Iron+sciltillator



MINOS

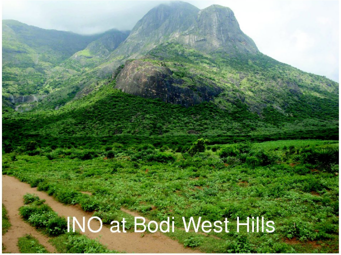
emulsion+iron



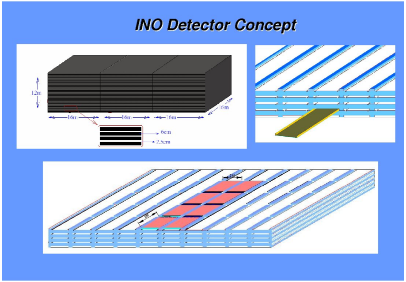

OPERA

# The future of atmospheric neutrino detectors

## Iron calorimeter (ICAL)




IITK 3-5 May 2010 – p. 4

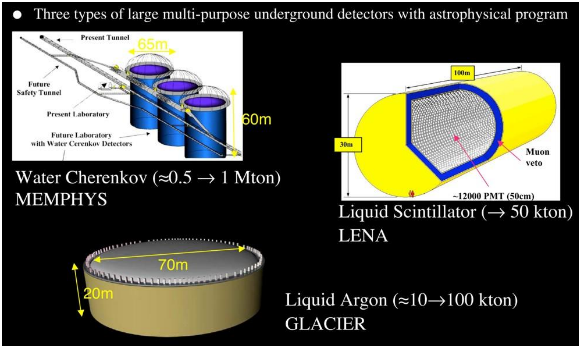



### India-based Neutrino Observatory

- Under a mountain, inside a tunnel (Bodi Hills, TN)
- 1 km rock coverage from all sides
- 50 kiloton of magnetized iron (50 000 000 kg)
- Can distinguish $\nu_\mu$ from $\bar{\nu}_\mu$: muon tracking
- Can measure hadron energy in neutrino events

# Future multipurpose mega-scale detectors

Water Cherenkov, scintillator, liquid Argon




## Each detector with its own advantages

- Water Cherenkov: cheap, can make large volume
- Scintillator: better energy measurement
- Argon: more sensitive to $\nu_e$ even in MeV range

# Neutrino detectors

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# Neutrinos as astrophysical messengers

## Messenger properties

- No bending in magnetic fields $\Rightarrow$ point back to the source
- Minimal obstruction / scattering $\Rightarrow$ can arrive directly from regions from where light cannot come.
- This messenger may have unknown interesting properties !

## Sources

- Stars, Earth's atmosphere and crust
- Astrophysical phenomena with large $\nu$ flux
- Diffused fluxes accumulated over the lifetime of universe

## Detectors

- Water / ice Cherenkov, scintillators, liquid Ar, Lead
- Big, bigger and still bigger size !
- Energy resolution, time resolution, and directionality

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# High energy ($E \gtrsim 100$ GeV) sources

## Secondaries of cosmic rays

- Primary protons interacting within the source or with CMB photons $\Rightarrow \pi^{\pm} \Rightarrow$ Decay to $\nu$

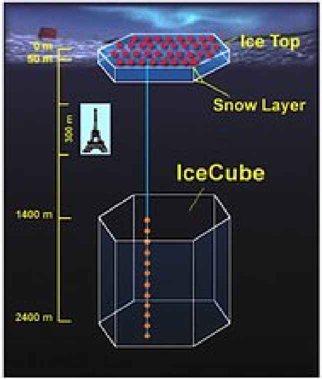
## AGNs and GRBs

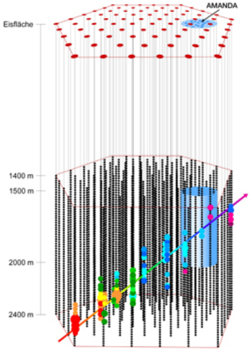
- Neutrinos produced by particle decays / nuclear reactions / pair production in extreme environments
- Can give measurable diffused flux in near future

# Below the antarctic ice: Gigaton IceCube

1 gigaton water = 1 000 000 000 000 litres

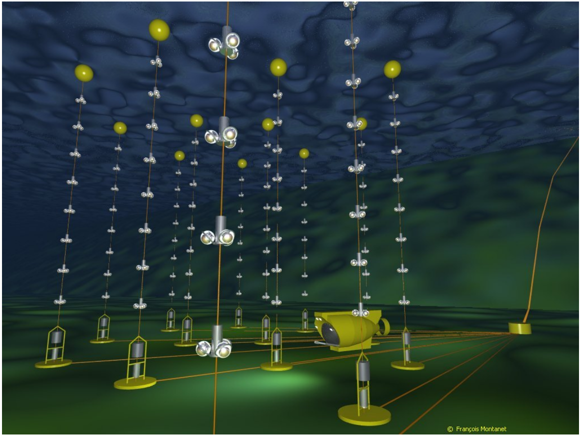
Ice Cherenkov



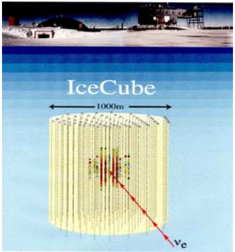
# below the mediterranian

Sea-water Cherenkov




ANTARES

# Detection of HE neutrinos: water/ice Cherenkov

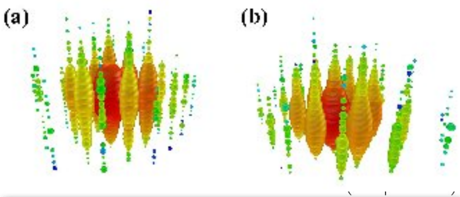


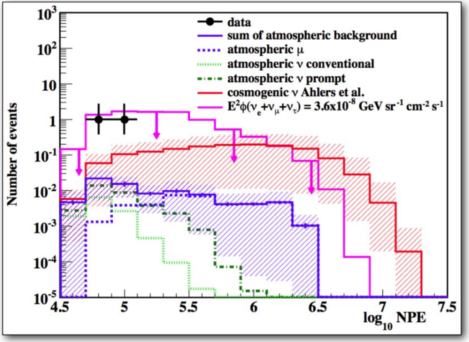

- Thresholds of $\sim$ 100 GeV, controlled by the distance between optical modules
- Track for $\nu_\mu$
- Cascade for $\nu_e$, hadrons, $\nu_\tau$
- Double-bang for $\nu_\tau$ ?

## Preferred energy ranges

- Down-going neutrinos: atmospheric muon background becomes insignificant only for $E \gtrsim 10^{16-17}$ eV
- Up-going neutrinos: $E \lesssim 10^{16}$ eV, since more energetic neutrinos get absorbed in the Earth

# The two PeV events at Icecube




Talk by Darren Grant

- Two events at $\sim$ 1 PeV energies found
- Cosmogenic ? X Glashow resonance? X atmospheric ?

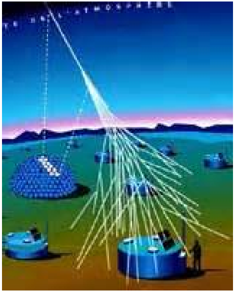
Roulet et al 2013 ++ many

- IceCube analyzing 28 events from 30 TeV to 1.1 PeV
- Constraints on Lorentz violation: $\delta(v^2-1) \lesssim \mathcal{O}(10^{-18})$

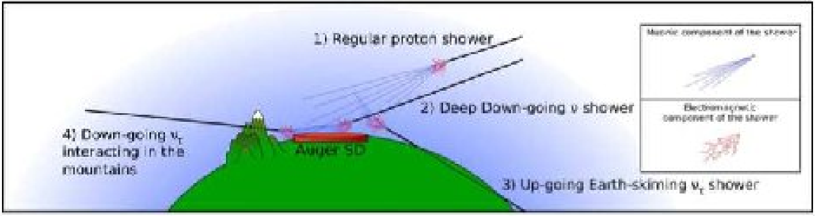
Borriello, Chakraborty, Mirizzi, 2013

# Detection of UHE neutrinos: cosmic ray showers

**Scintillator + fluorescent telescope**



- Neutrinos with $E \gtrsim 10^{17}$ eV can induce giant air showers (probability $\lesssim 10^{-4}$)
- Deep down-going muon showers
- Deep-going $\nu_\tau$ interacting in the mountains
- Up-going Earth-skimming $\nu_\tau$ shower

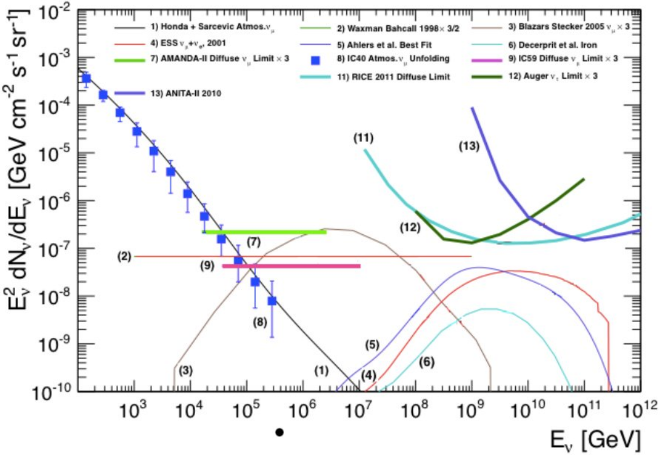


# Detection through radio waves: ANITA

Radio antenna


- Charged particle shower $\Rightarrow$ Radio Askaryan: charged clouds emit coherent radio waves through interactions with $\mathbf{B}_{\rm Earth}$ or Cherenkov
- Detectable for $E \gtrsim 10^{17}$ eV at balloon experiments like ANITA

# Limits on UHE neutrino fluxes




Talk by Darren Grant

Waxman-Bahcall, AMANDA, ANITA, RICE, Auger, IceCube
Also expect complementary info from: NEMO, NESTOR, ANTARES, KM3NET ...

# Flavor information from UHE neutrinos

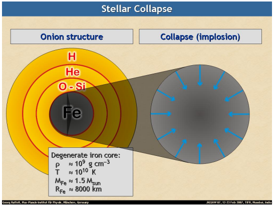
- Neutrino flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ from primary sources:
  Neutron source $1 : 0 : 0$,
  Pion source $1 : 2 : 0$,
  Dense sources that absorb muons $0 : 1 : 0$
- $L/E$ large $\Rightarrow$ oscillations change the flavor ratio.
  Pion source: approx $1 : 1 : 1$
  Muon-absorbing sources: $1 : 2 : 2$
- Decaying neutrinos can skew the flavor ratio even further:
  as extreme as $6 : 1 : 1$ or $0 : 1 : 1$
  Ratio measurement $\Rightarrow$ improved limits on neutrino lifetimes

Beacom et al, PRL 2003

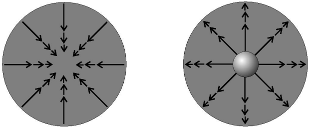
(The numbers obtained with bimaximal mixing)

# A core-collapse SN ⇒ $10^{58}$ neutrinos in 10 sec

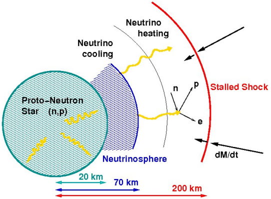
Gravity ⇒



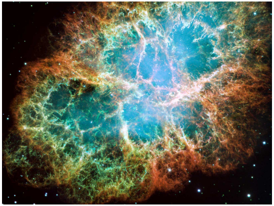

Strong nuclear force ⇒



Weak nuclear force (Neutrino push) ⇒



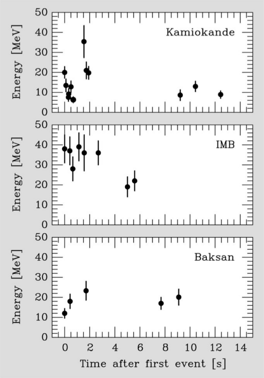

Electromagnetism (Hydrodynamics) ⇒



(Crab nebula, SN seen in 1054)

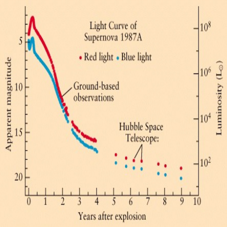
# Detection of neutrinos from SN1987A ($E \sim 10$ MeV)

Neutrinos:
Feb 23, 1987

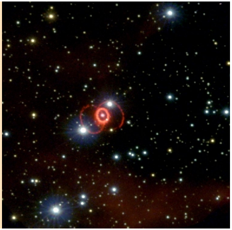



Water Cherenkov, scintillator

Light curve:
1987-1997



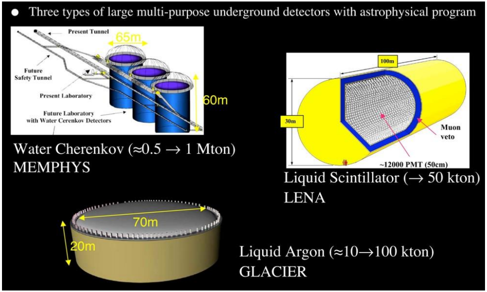

Hubble image:
now

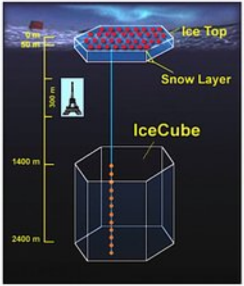


- Neutrinos reached a few hours before light
- Confirmed the SN cooling mechanism through neutrinos
- Constraints on SN parameters and limits on new physics models

Koshiba Nobel prize 2002

# Gearing up for future SN neutrino detections




- Water Cherenkov / liquid scintillator / liquid Ar detectors for tracking individual neutrinos (HK, LENA, ....)
- Large-volume ice Cherenkov for determining luminosity to a high accuracy (integrated Cherenkov glow)
- LBNE liquid Ar ? If it is underground...

# Major reactions at the large detectors (SN at 10 kpc)

## Water Cherenkov detector: size advantage (events at SK)

- $\bar{\nu}_e p \to n e^+$: ($\sim 7000 - 12000$)
- $\nu e^- \to \nu e^-$: $\approx 200 - 300$
- $\nu_e +^{16} O \to X + e^-$: $\approx$ 150–800

## Carbon-based scintillation detector: $\Delta E$ advantage

- $\bar{\nu}_e p \to n e^+$ ($\sim$ 300 per kt)
- $\nu + {}^{12}C \to \nu + X + \gamma$ (15.11 MeV)
- $\nu p \to \nu p$

## Liquid Argon detector: $\nu_e$ spectrum advantage

- $\nu_e + {}^{40}Ar \to {}^{40}K^* + e^-$ ($\sim$ 300 per kt)

## Lead detector:

- CC: $\nu_e +^{208}\mathrm{Pb} \to^{207}\mathrm{Bi} + n + e^-$,
  $\nu_e +^{208}\mathrm{Pb} \to^{206}\mathrm{Bi} + 2n + e^-$
- NC: $\nu_x +^{208}\mathrm{Pb} \to^{207}\mathrm{Pb} + n$, $\nu_x +^{208}\mathrm{Pb} \to^{206}\mathrm{Pb} + 2n$

# What supernova neutrinos can tell us

## On neutrino masses and mixing

- Identify neutrino mass ordering: normal or inverted

## On supernova astrophysics

- Locate a supernova hours before the light arrives
- Track the shock wave through neutrinos while it is still inside the mantle (Not possible with light)

# Neutrino detectors

1. Discoverers
2. Sun-seekers
3. Earth-watchers
4. Sky-gazers
5. New ideas...

# Some new detector ideas

## Mossbauer neutrinos

- Production: $^{3}\mathrm{H} \longrightarrow {}^{3}\,\mathrm{He}^{+} + \bar{\nu}_e + e^{-}$(bound)
- Detection: $^{3}\mathrm{H} \longleftarrow {}^{3}\,\mathrm{He}^{+} + \bar{\nu}_e + e^{-}$(bound)
- Resonance enhancement of $10^{12}$, line width $\sim 10^{-11}$ eV, if embedded in a crystal
- Neutrino oscillations visible on tabletop !

## Indium-based detectors

- $\nu_e + {}^{115}\,\mathrm{In} \rightarrow {}^{115}\,\mathrm{Sn} + e^{-}$
- $E_e = E_\nu - 0.115$ MeV $\Rightarrow$ low threshold
- Solar Be neutrinos would give monochromatic electrons

## Atomic tritium detectors for CMB (relic) neutrinos

- $\nu_e + N_1(A, Z) \rightarrow N_2(A, Z+1) + e^{-}$
- $E \sim 0.16$ meV $\Rightarrow$ almost zero threshold required
- Strong confirmation of Standard Model of cosmology

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# Concluding remarks

- Neutrino detectors have used ideas that combine nuclear physics, atomic physics, particle physics, chemistry, electrodynamics, material science ...
- There are still unexplored ideas that can help us probe the world of neutrinos even deeper
- Challenges for material science and technology development