Astronomy with Neutrinos : The invisible particles from the sky

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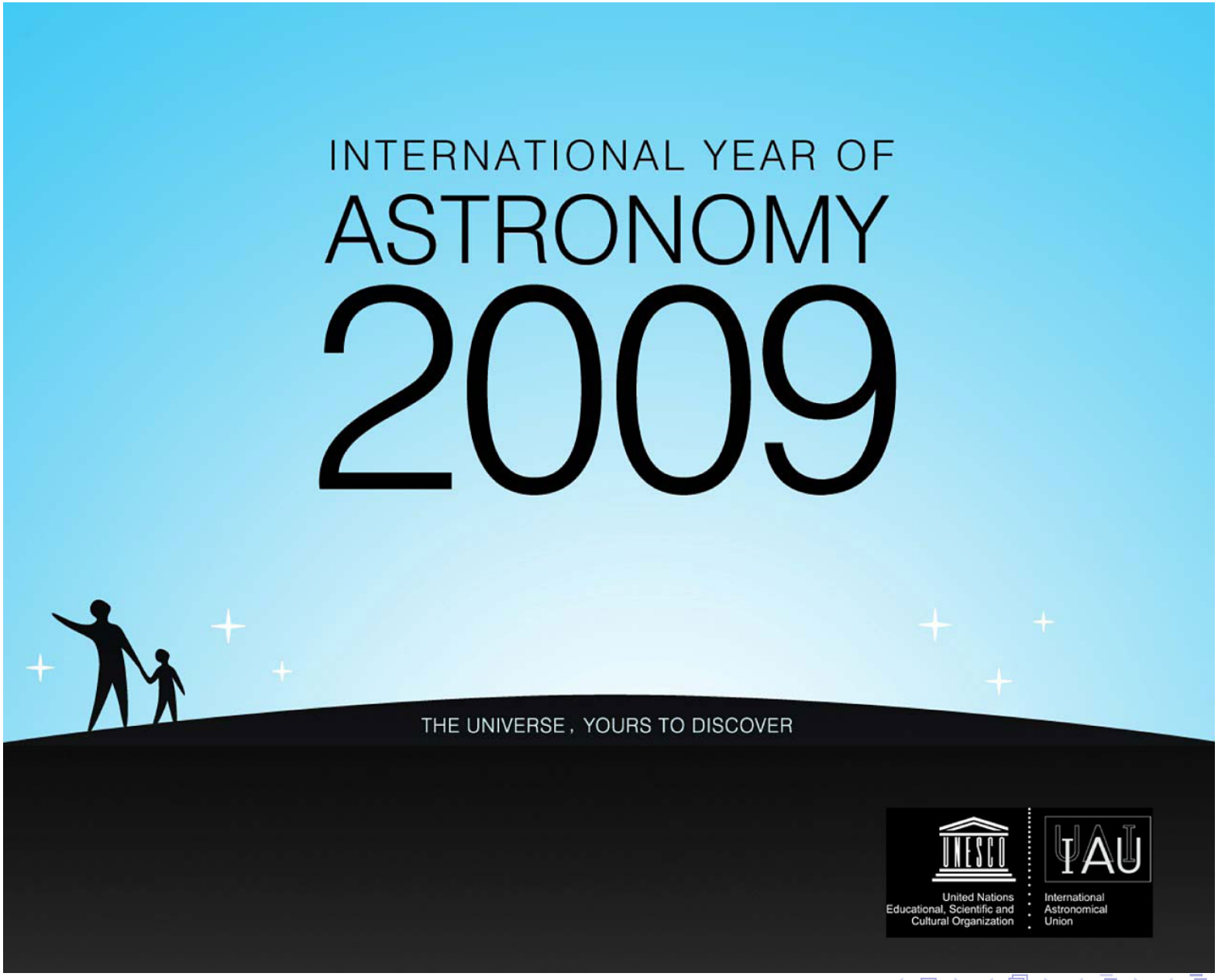
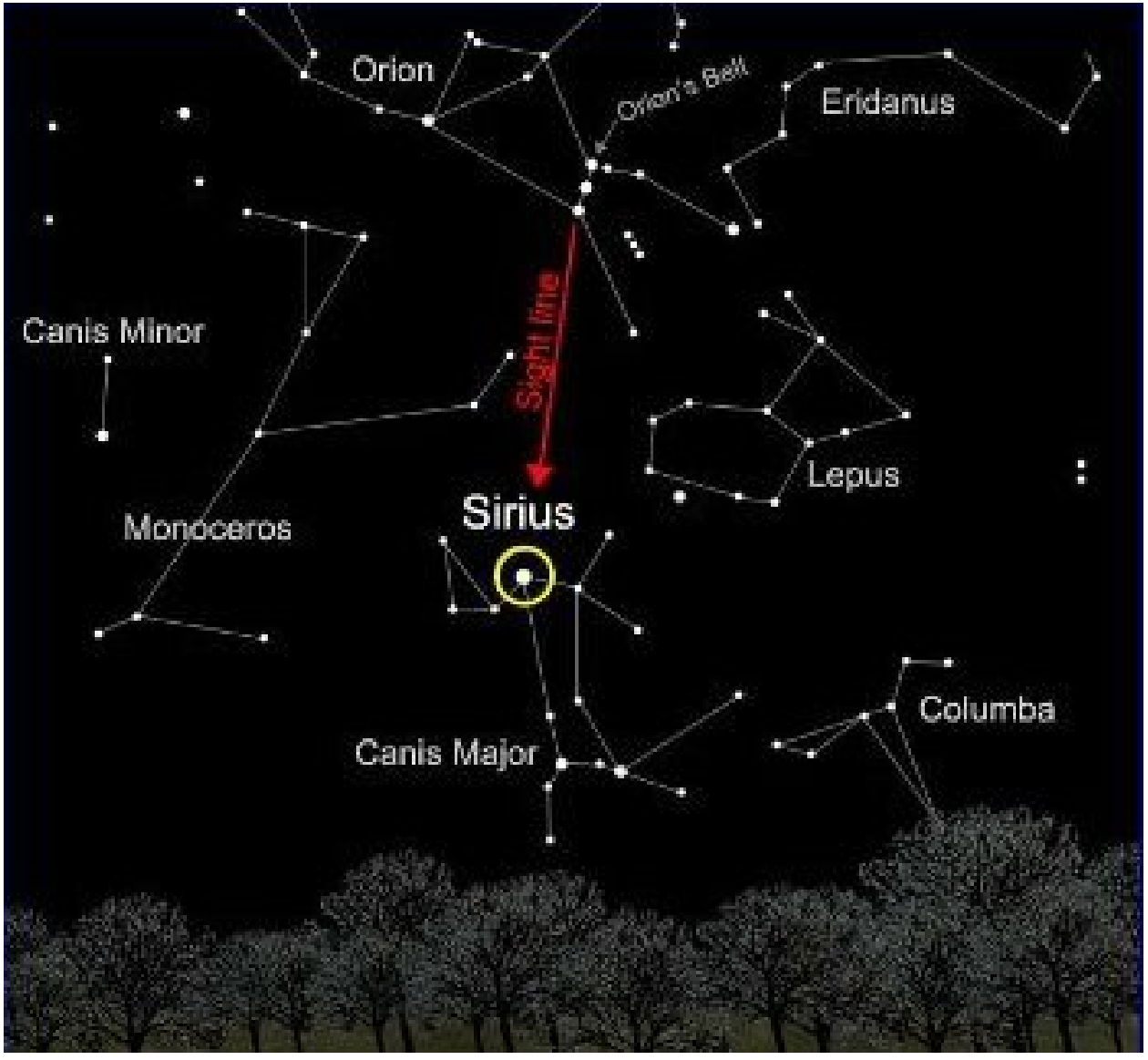
JNCASR, Bangalore, July 18, 2009

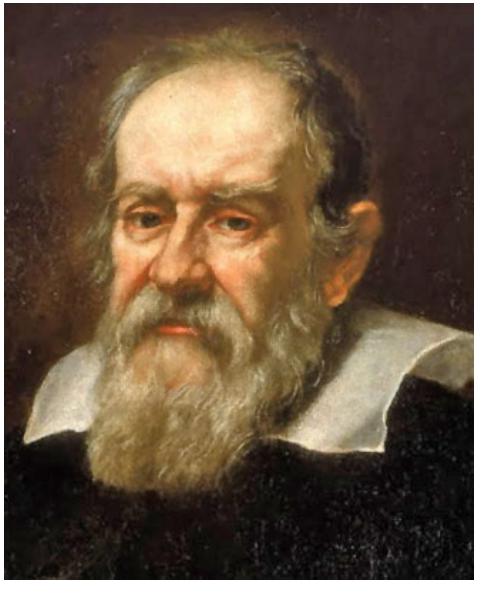
2009: International Year of Astronomy

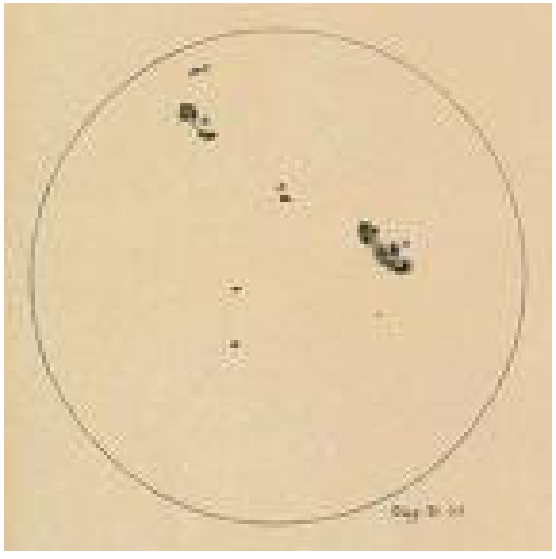


Ancient astronomy

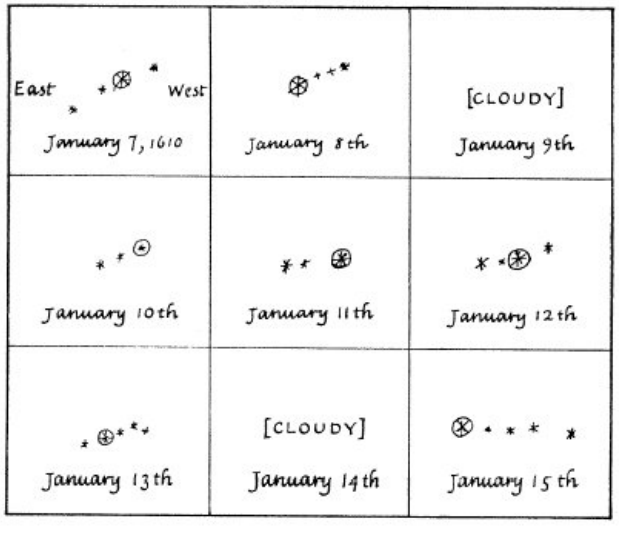


400 years ago: Birth of *Astronomy with Telescopes*

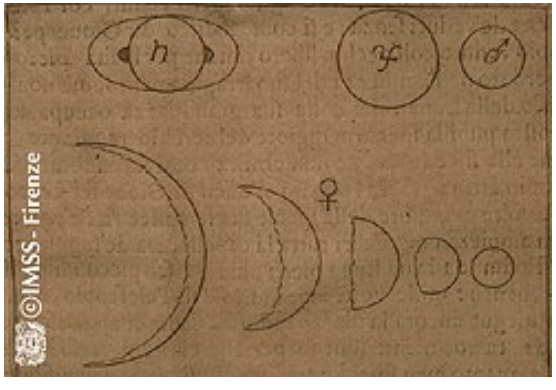




Sunspots

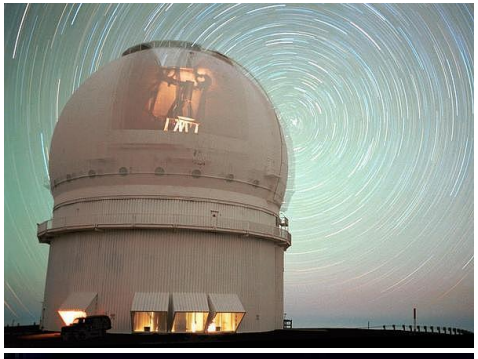


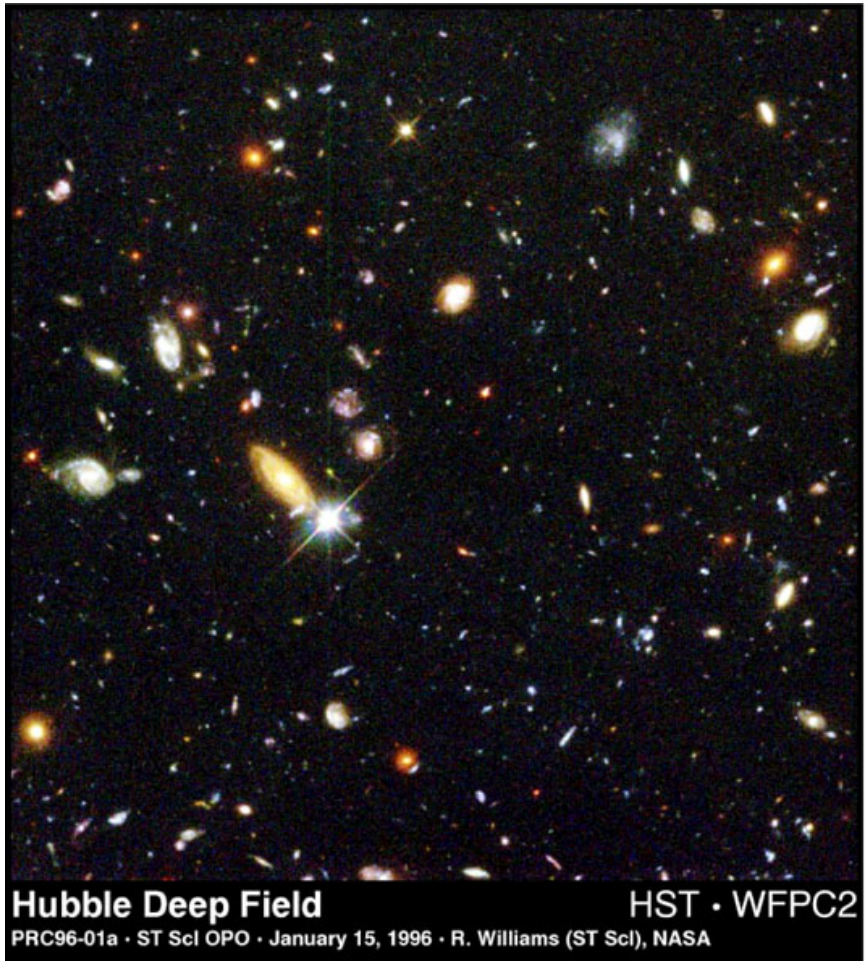
Moons of Jupiter



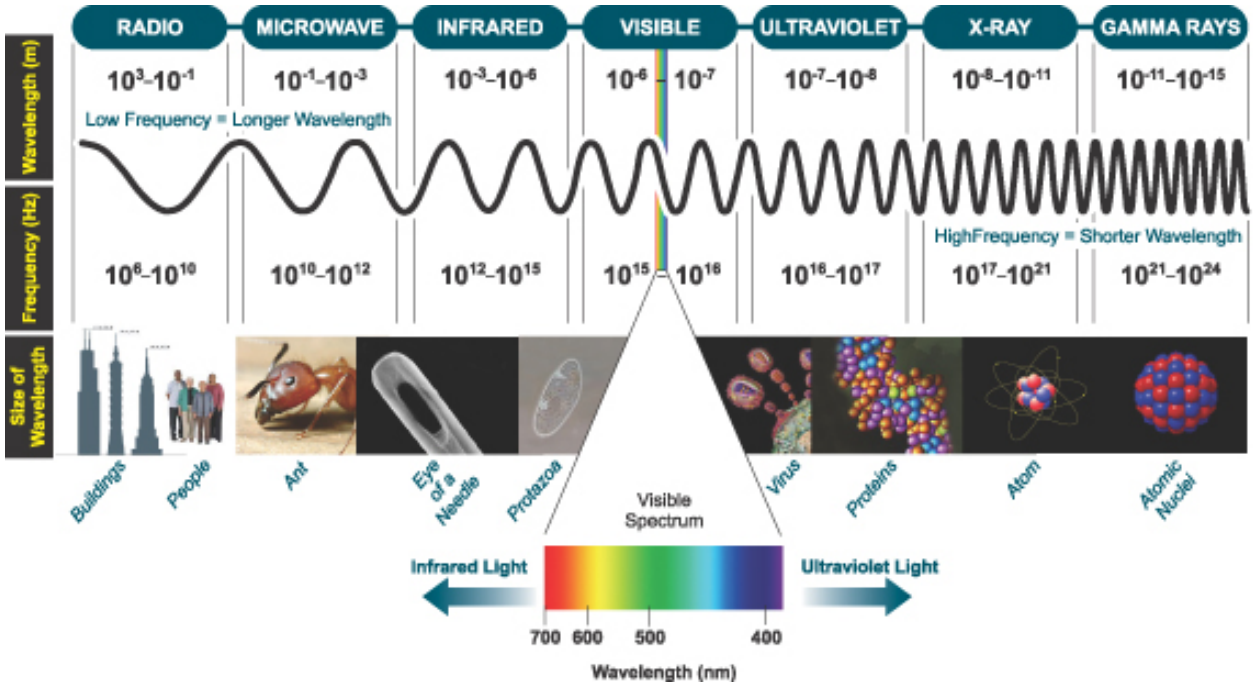
Phases of Venus

Last 400 years: bigger and better telescopes

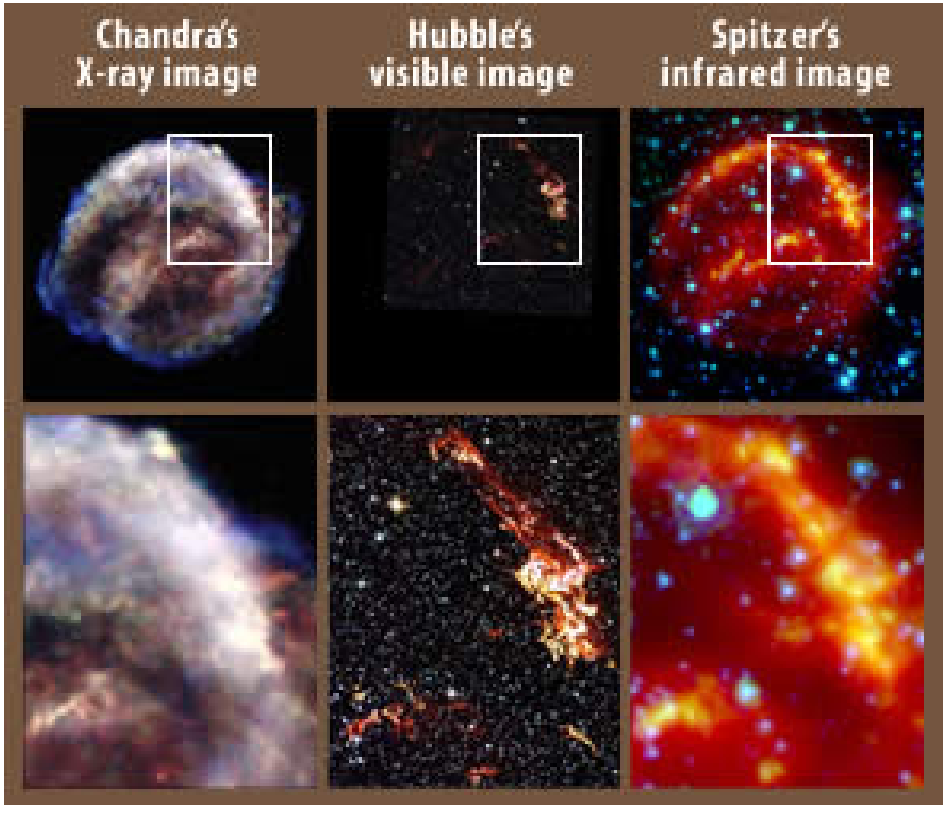




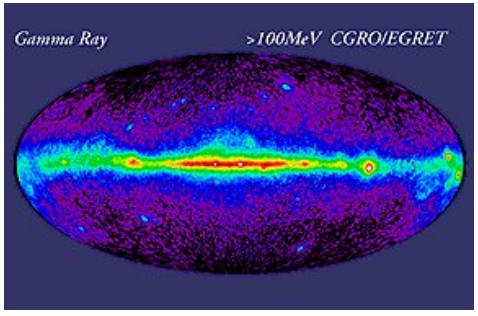
Astronomy with light



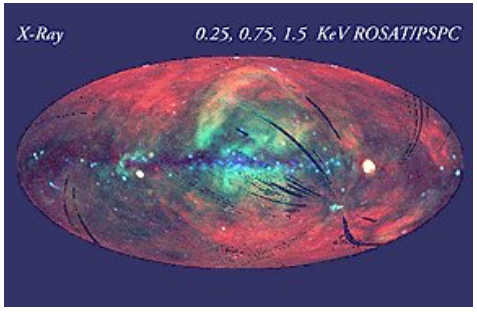
Kepler's supernova at different wavelengths



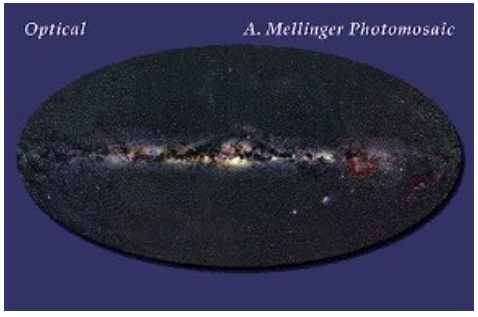
Universe at different wavelengths



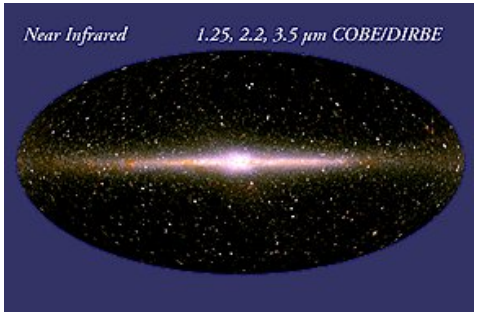
Gamma ray



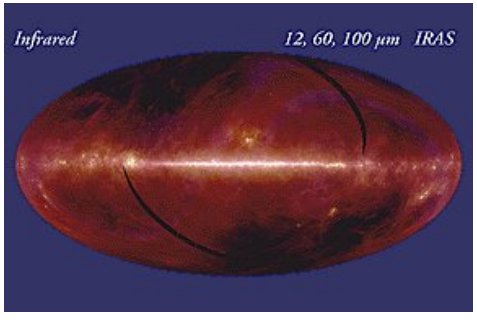
X-ray



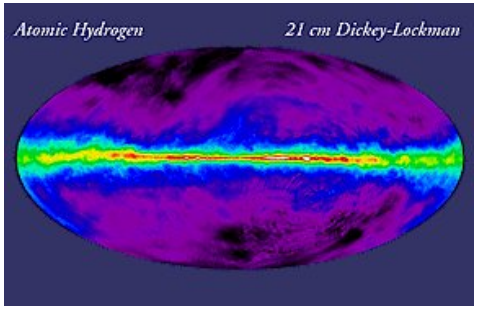
Visible



Near infrared



Infrared



Radio waves

Observations at different wavelengths reveal different aspects of astrophysics

Astronomy: how to look at the sky ?

Identify “messengers”

- “Messengers”: particle/waves that carry information
- Need to know nature of these messengers:
  - Short-lived / long-lived ?
  - Obstructed by matter / pass through matter ?
  - Travel straight / change directions ?

Build detectors to detect messengers

- Optical telescopes for visible light
- Antennas for radio waves

Place detectors at appropriate locations

- Top of mountains, away from artificial light
- Outside the earth’s atmosphere: on satellites / in space

Is light the only messenger ?

A trustworthy messenger: NEUTRINO (ν)

- Travels with (almost) the speed of light
- Travels in a straight line
- Brings information from deep within the stars (Not possible with light)

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Neutrinos

1. What are neutrinos
2. Brief history and open problems
3. What can we observe in neutrinos
4. How do we observe with neutrinos

Neutrinos

Where do neutrinos come from ?

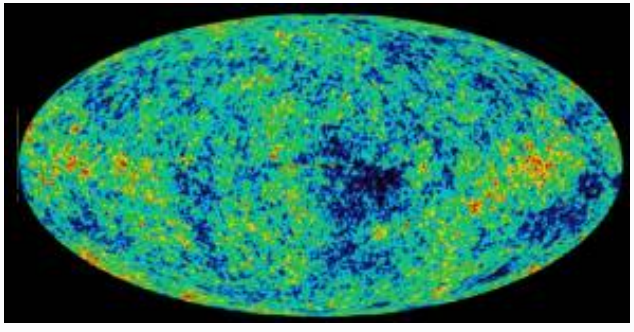
Particles that accompany radioactive β decay

Byproducts of almost all nuclear reactions

From the sun: 60 billion per cm^2 per second:

During the day AND night

The second most abundant particles in the universe:
300 per cm^3 even in empty space



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- Cosmic neutrino background: 300 neutrinos / cm^3

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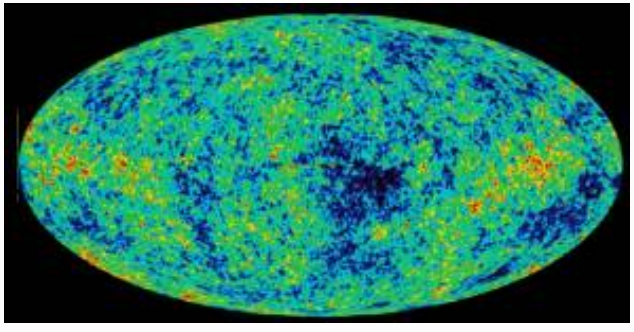

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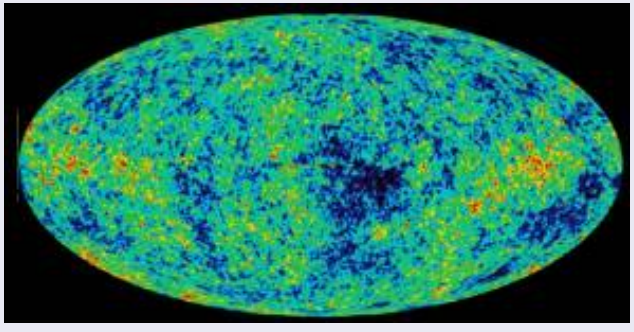

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Why don't we observe them everywhere around us ?

The most weakly interacting particles

- Do not interact with light $\Rightarrow$ Invisible
- Stopping radiation with lead shielding:
  - Stopping α, β, γ radiation: 50 cm
  - Stopping neutrinos from the Sun: hundreds of light years !
- Advantage: Can observe deep inside stars

How do we observe them ?

- Build HUGE detectors: e.g. $100m \times 20m \times 20m$
- Wait for a looooong time: e.g. one neutrino per day

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Unique features of neutrinos

The lightest massive particles

A million times lighter than the electron

Break left-right symmetry maximally

Reactions as seen in a mirror do not occur

May be their own antiparticles

Neutrino = Antineutrino ?

May have created the matter-antimatter asymmetry

Responsible for our existence !

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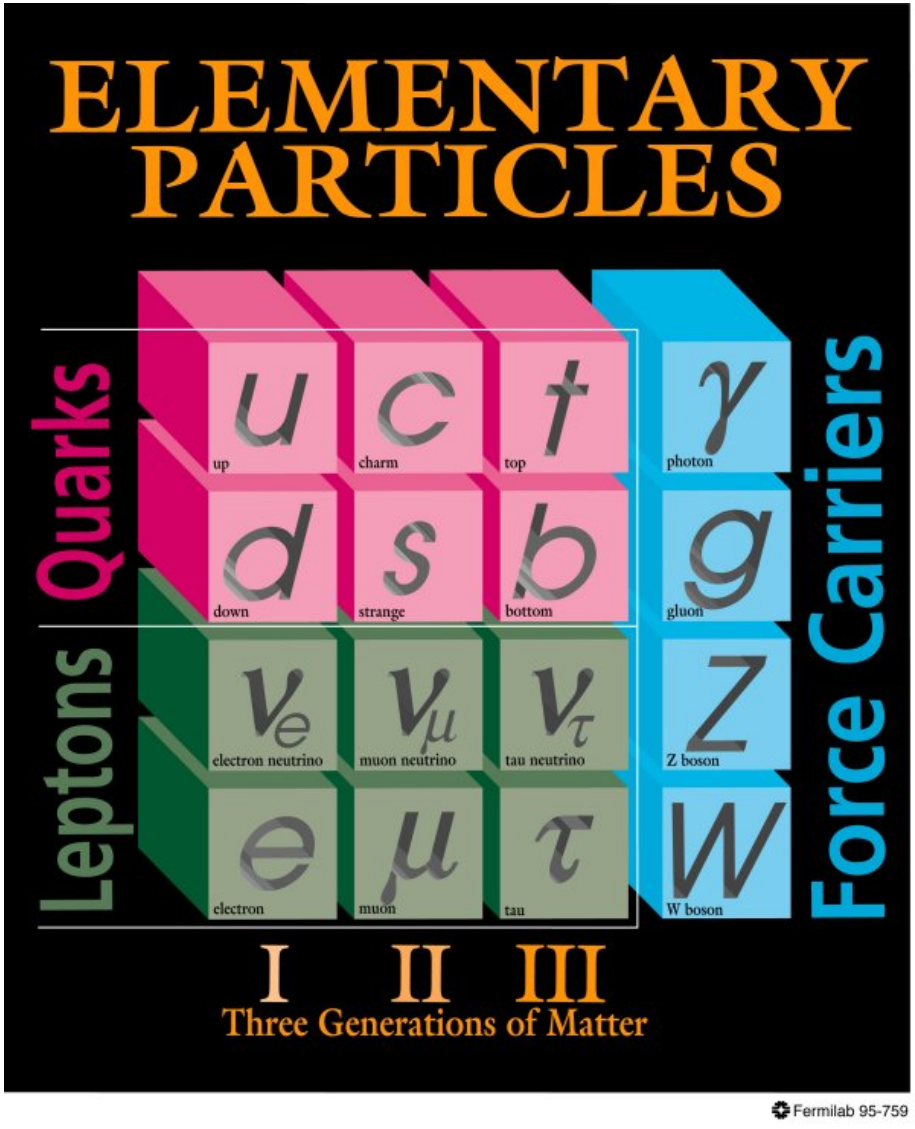
The Standard Model of Particle Physics

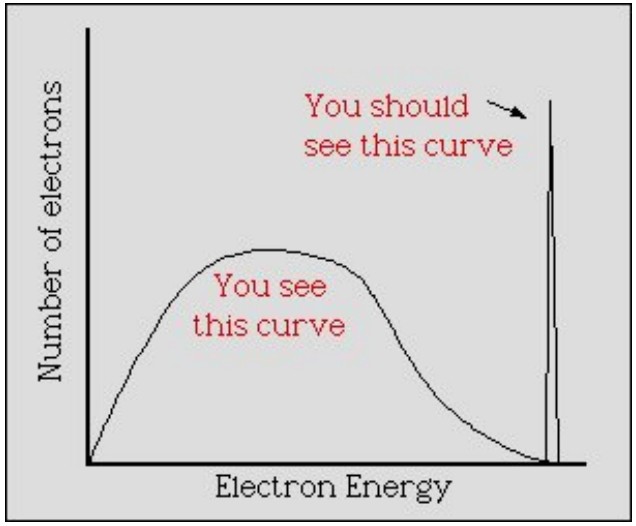


- 3 neutrinos:
  ν_e, ν_μ, ν_τ
- chargeless
- spin 1/2
- almost massless

Neutrinos

Neutrinos postulated but unobserved: 1932 – 1956

- Beta decay: ${}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N + e^{-}$



- In any two-body decay, energy of final products is fixed.
- $\Rightarrow$ Electron should have a fixed energy
- Energy-momentum conservation in grave danger !!

A reluctant solution (Pauli): postulate a new particle

Discoveries of neutrinos

Electron neutrino ν_e: 1956

Reines-Cowan: Nobel prize 1995

- Reactor neutrinos: $\bar{\nu}_e + p \rightarrow n + e^+$

Muon neutrino ν_μ: 1962

Steinberger-Schwartz-Lederman: Nobel prize 1988

- Neutrinos from pion decay: $\pi^- \rightarrow \mu^- + \nu_{(\mu)}$
- $\nu_{(\mu)} + N \rightarrow N' + \mu^-$
- Always a muon, never an electron/positron

Tau neutrino ν_τ: 2000

DONUT experiment at Fermilab: $\nu_\tau + N \rightarrow \tau + N'$

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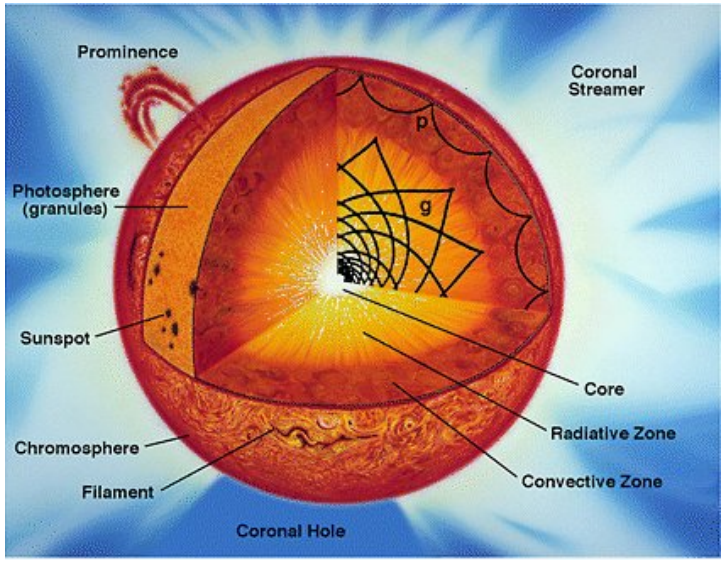
Solar neutrino puzzle (1960s – 2002)



Missing electron neutrinos

- Nuclear fusion: mainly $4\,{}^1_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + 2e^+ + 2\nu_e$
- Neutrinos come millions of years before the light
- Only about half the expected number of ν_e observed !

Solution to the solar neutrino puzzle ($>$ 40 years)

- Neutrinos have nonzero mass and they mix with each other
- ν_e convert to ν_μ/ν_τ and hence are “lost”

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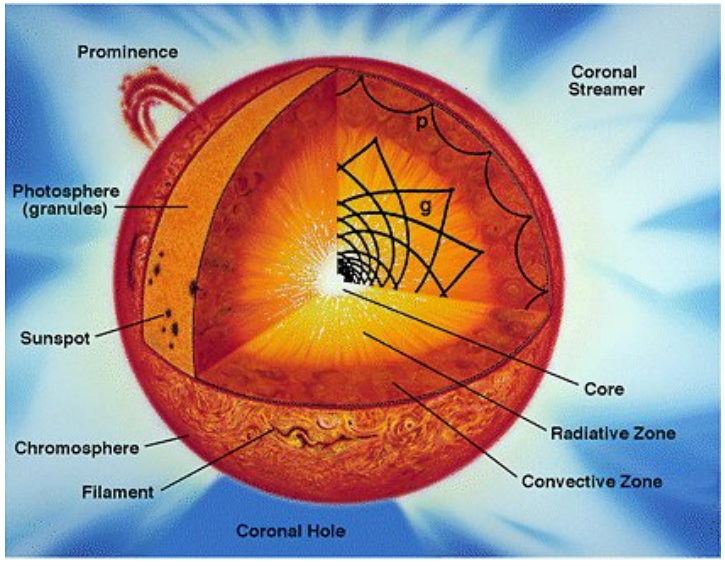

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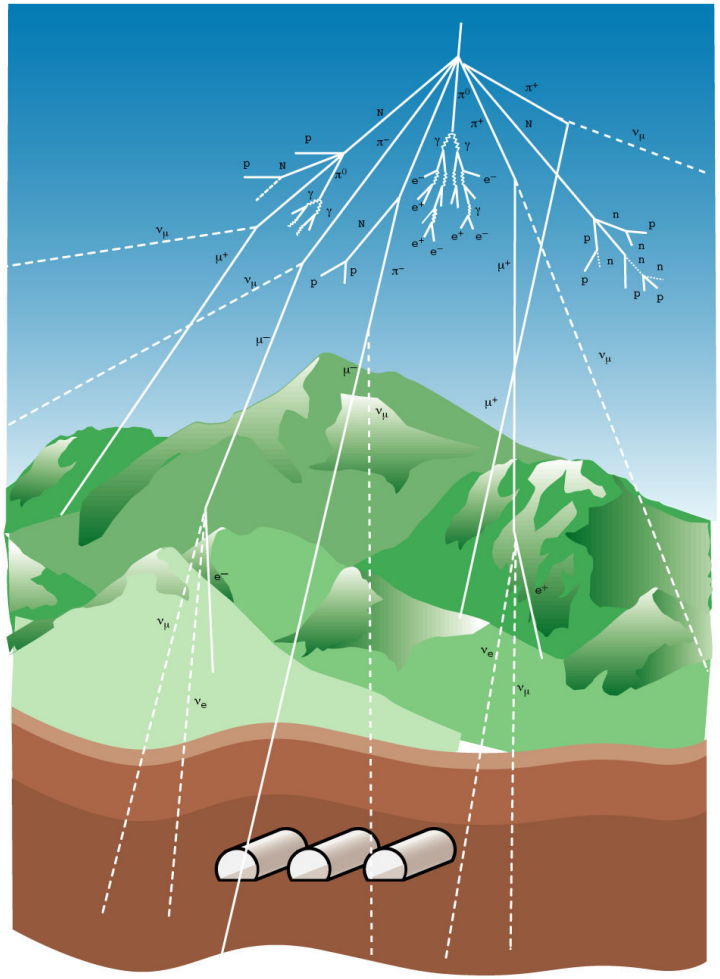
Atmospheric neutrino puzzle (1980s – 1998)



Missing muon neutrinos

- Cosmic rays produce ν_e and ν_μ in the atmosphere
- All ν_e are detected as per expectations
- Up to half the ν_μ are lost when they travel through the Earth

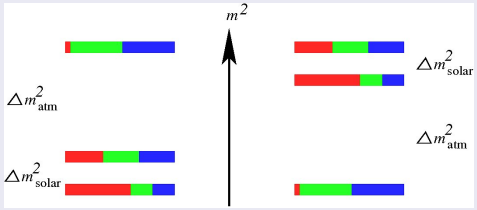
Solution to the atmospheric neutrino puzzle ($>$ 20 years)

- Neutrinos have nonzero mass and they mix with each other
- $\nu_\mu \longrightarrow \nu_\tau$ and hence are "lost" (Neutrino oscillations)

Current status and open questions

ν_e, ν_μ, ν_τ mix among each other

- Current experiments only give $|m^2_{\nu_2} - m^2_{\nu_3}|$
- $m_2 > m_3$ or $m_3 > m_2$? (Mass ordering problem)



- What are the absolute neutrino masses m_1, m_2, m_3 ?

More open questions

- Are there more than 3 neutrinos ?
- Are neutrinos their own antiparticles ? ...
- Did neutrinos create more protons than antiprotons ?

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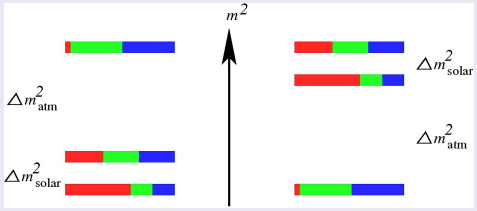

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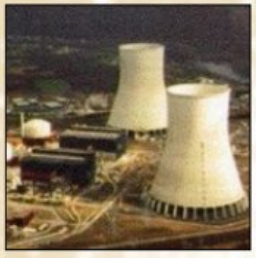
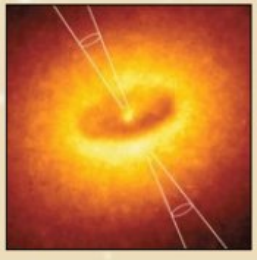
Neutrinos

Neutrino sources

Where do Neutrinos Appear in Nature?

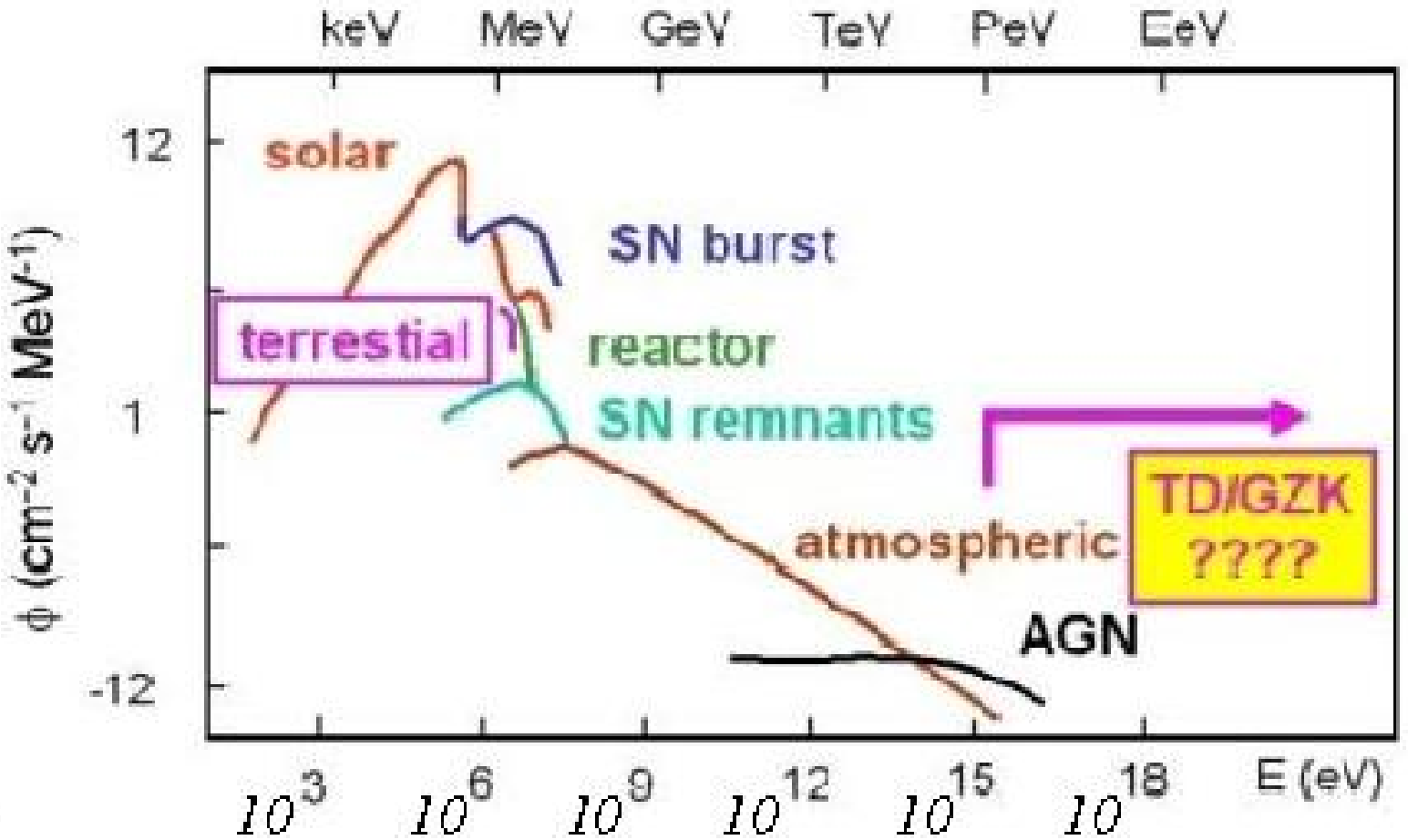
- ✓ Earth Crust (Natural Radioactivity)
- ✓ Nuclear Reactors
- ✓ Particle Accelerators
- ✓ Earth Atmosphere (Cosmic Rays)



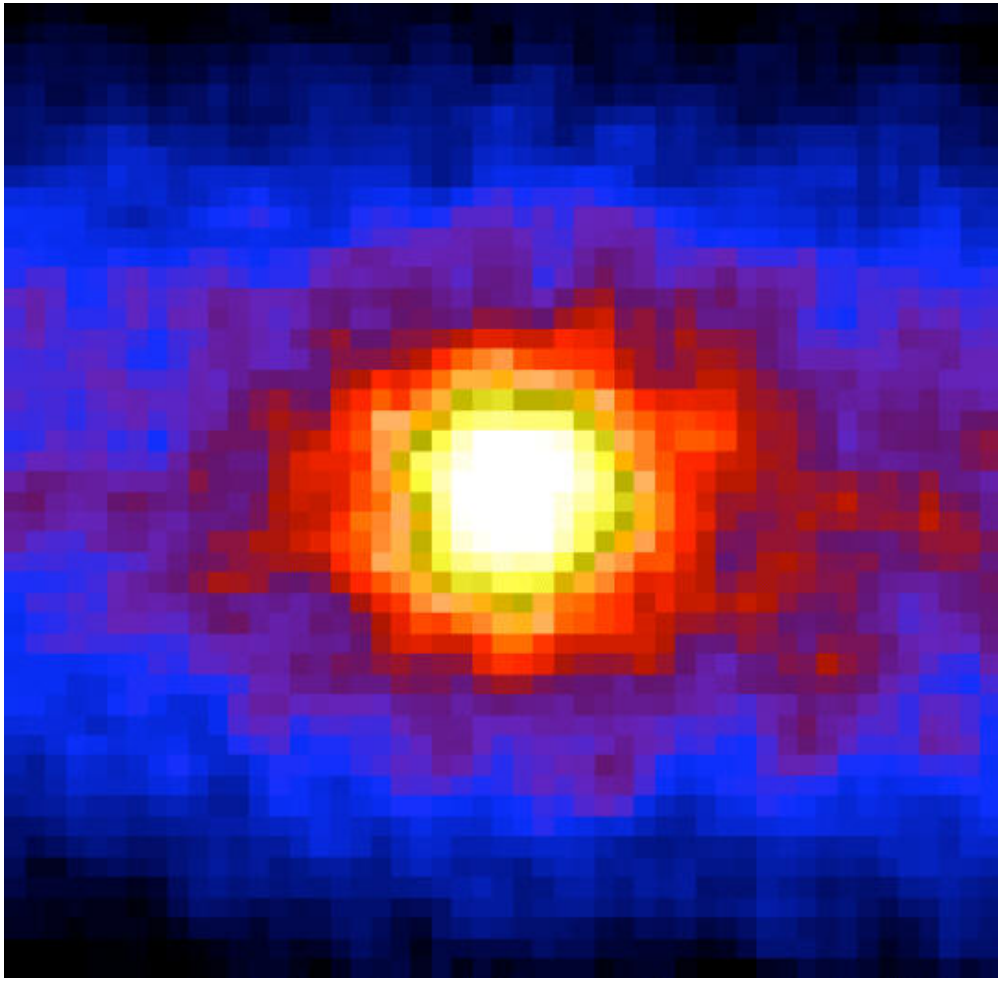


- Sun ✓
- Supernovae (Stellar Collapse) SN 1987A ✓
- Cosmic Big Bang (Today 330 ν/cm^3) Indirect Evidence
- Astrophysical Accelerators Soon ?

Astrophysical neutrinos and their energies



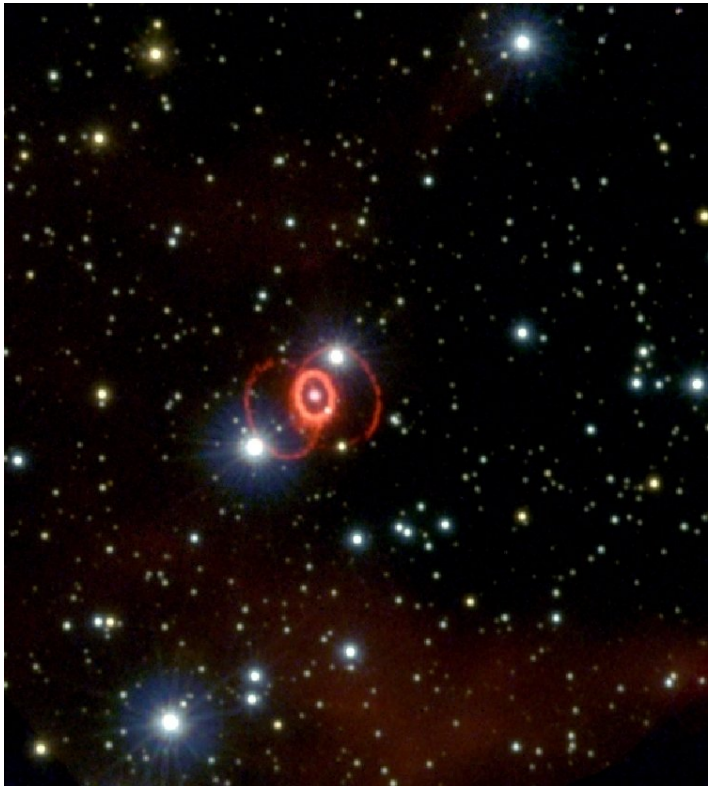
The Sun in neutrinos



Central spot: $\sim 10^\circ$

Supernova explosions

Crab nebula



SN1987A

Early warning of supernova explosions

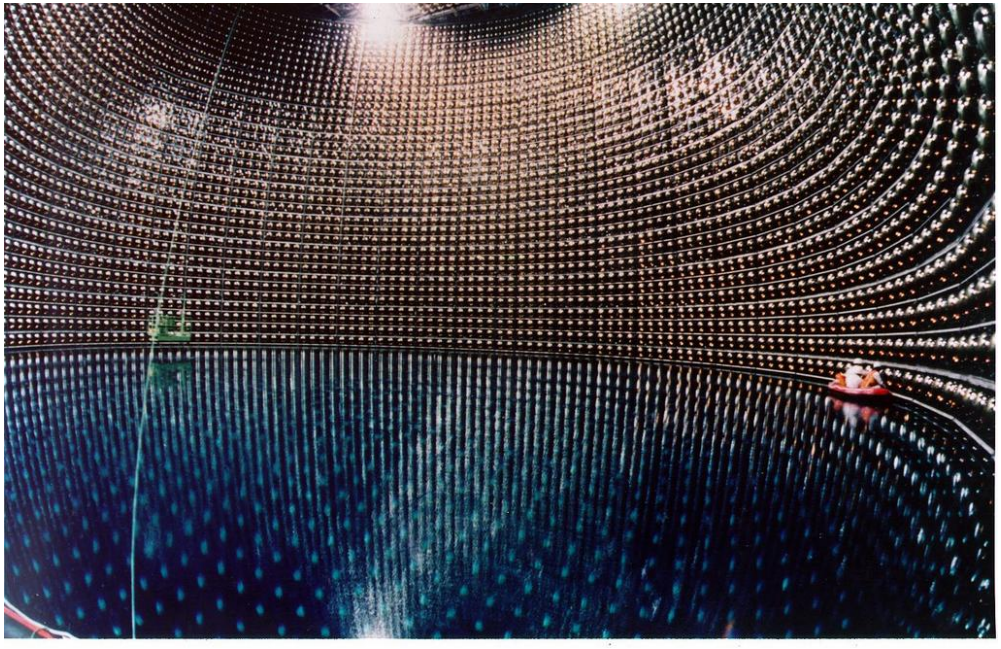
Neutrinos arrive $\sim$ 10 hours before light !

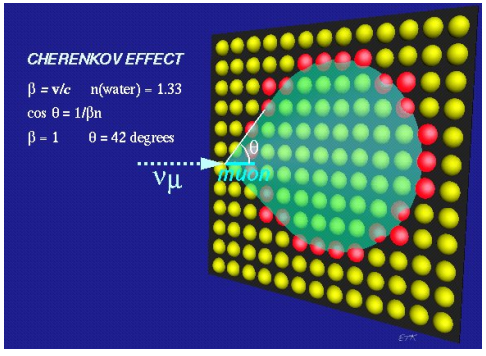
Gamma ray bursts

- Extremely energetic events
- Exact nature still unknown
- Neutrinos may provide a clue
- Neutrinos not observed yet

Neutrinos

Current largest detector: SuperKamiokande



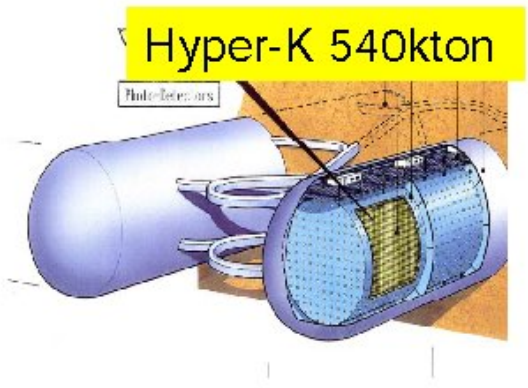


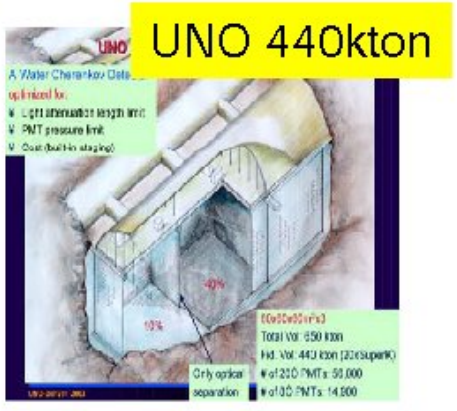
Cherenkov radiation

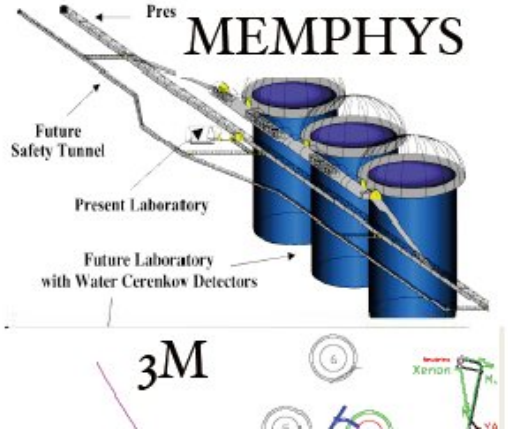
50 kilotons of water: the most successful so far

- Observed solar neutrinos
- Observed atmospheric neutrinos
- Observed the supernova SN87A

Bigger and better: Megaton detectors

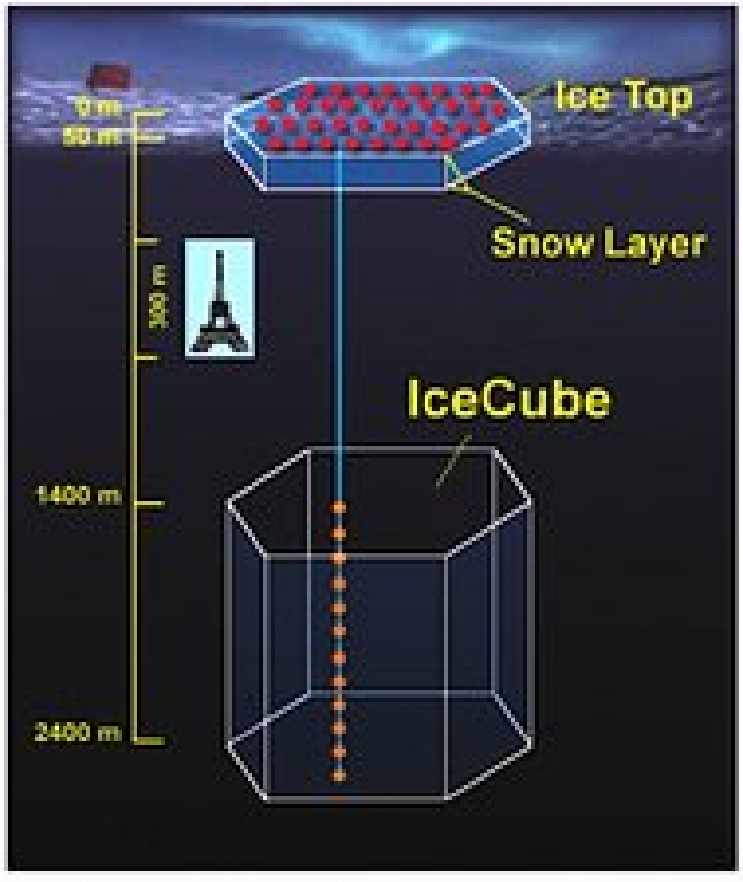


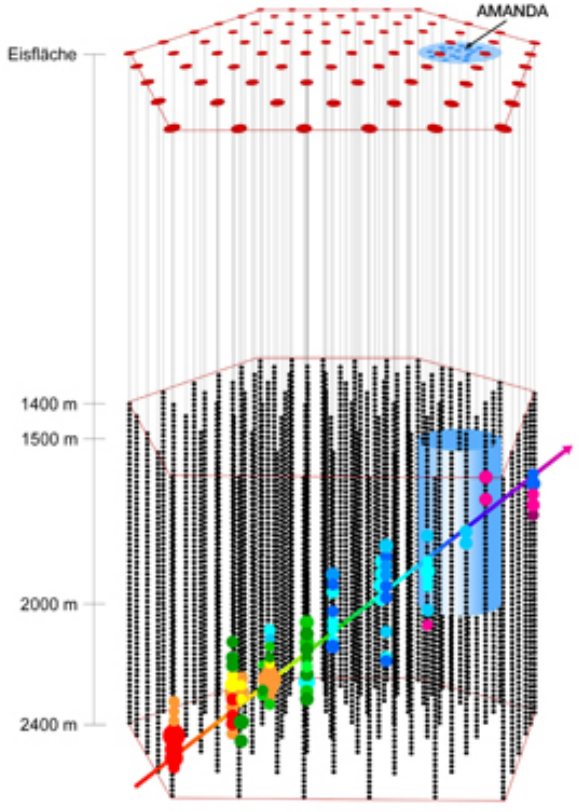




- R&D continues...
- Have to locate deep underground to remove cosmic ray background

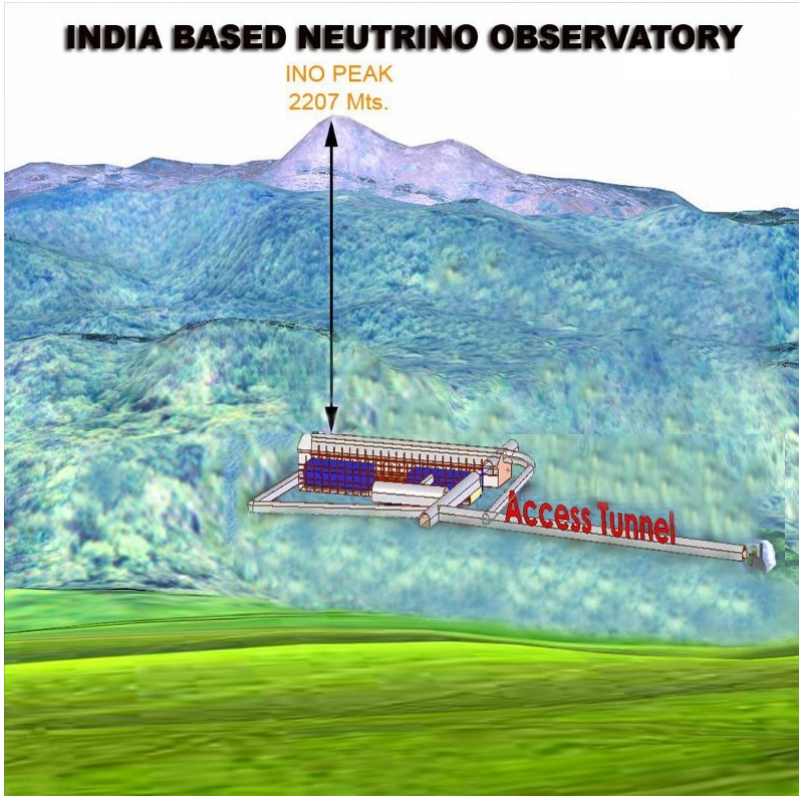
Below the antarctic ice: Gigaton IceCube





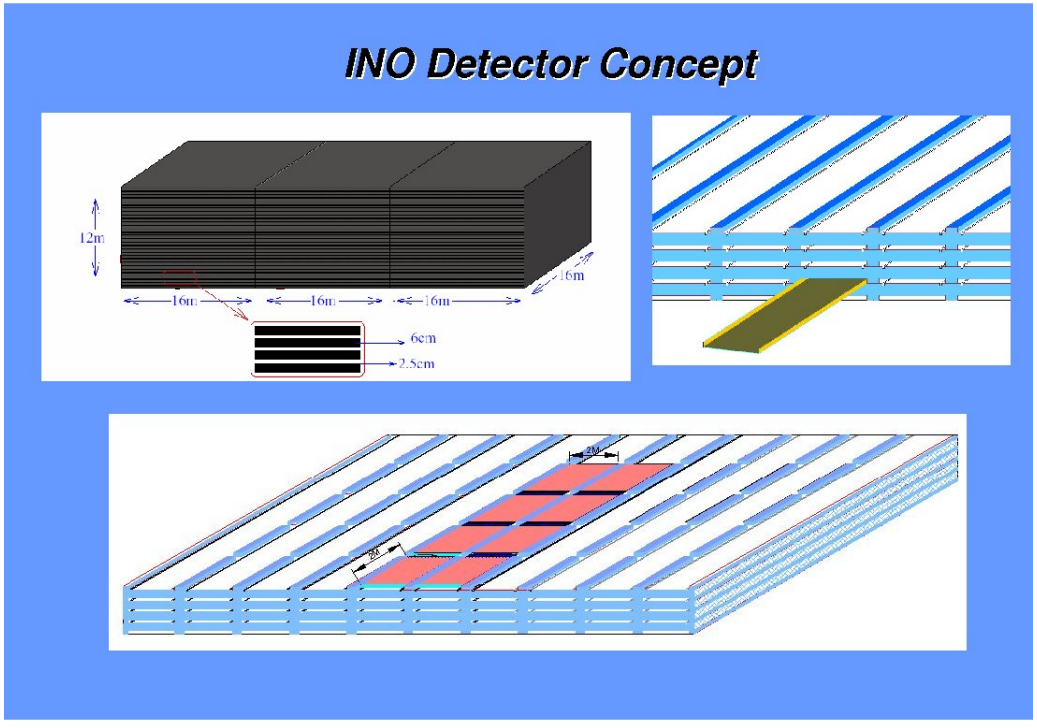
Only look at “upward-going” neutrinos
to remove cosmic ray background

Coming soon inside a mountain near you: INO



- PUSHEP, in Masinagudi, near Ooty
- 1 km rock coverage from all sides

The ICAL detector inside INO



- 50 kiloton of magnetized iron
- Resistive Plate Chambers (RPCs): R&D in progress
- $\gtrsim$ 25 years: a lifelong project

What is the “cutting-edge” research in neutrinos

- Solar experiments:
  measuring the energy of the sun in neutrinos
- Reactor / short baseline experiments:
  Measuring the masses and mixing angles accurately
- “Neutrino factories”:
  Long baseline experiments that span the Earth
- Neutrino telescopes: Looking for extremely energetic neutrinos from the cosmic rays
- India-based Neutrino Observatory (INO):
  Atmospheric and long baseline experiments

Lots of opportunities and excitement for curious minds

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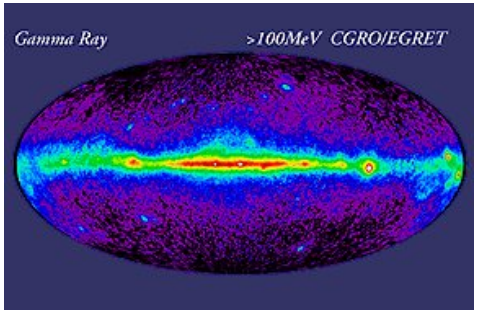
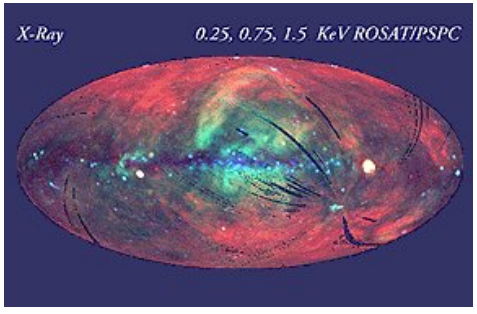
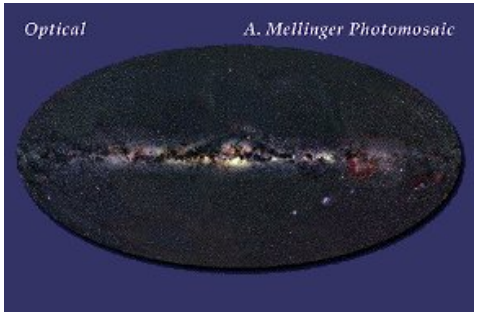
Universe at different wavelengths



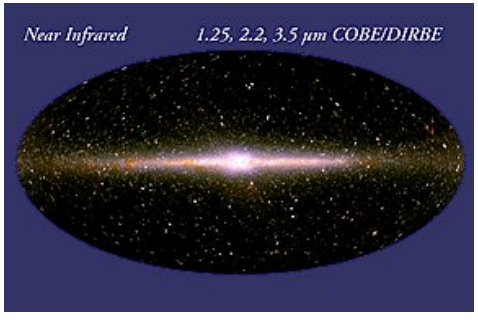
Gamma ray



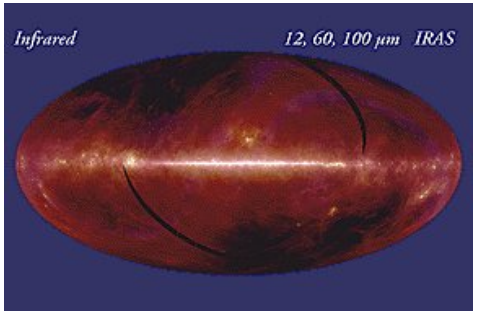
X-ray



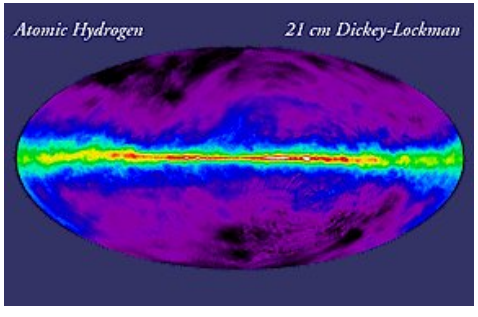
Visible



Near infrared

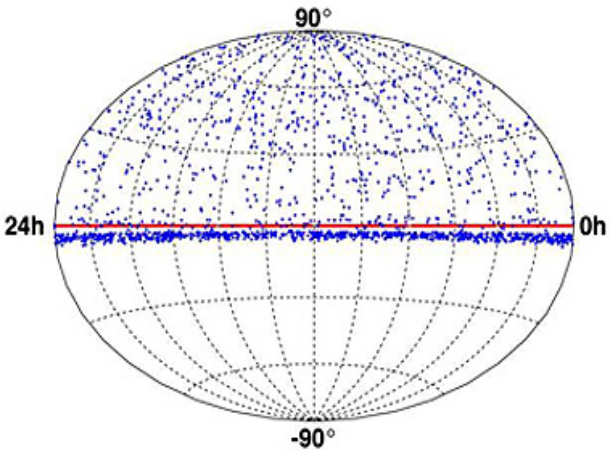


Infrared

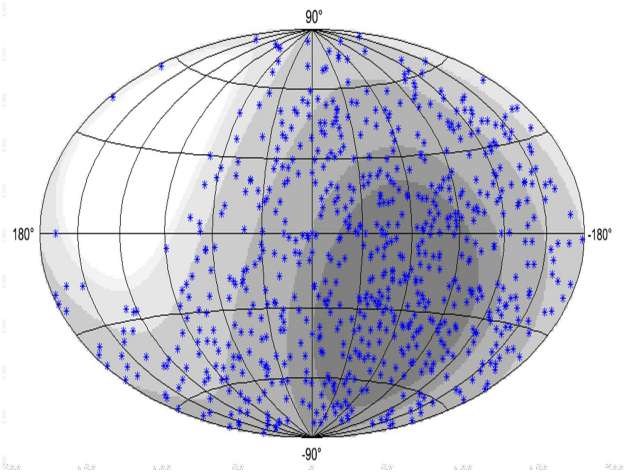


Radio waves

Current sky map in neutrinos



From the South Pole

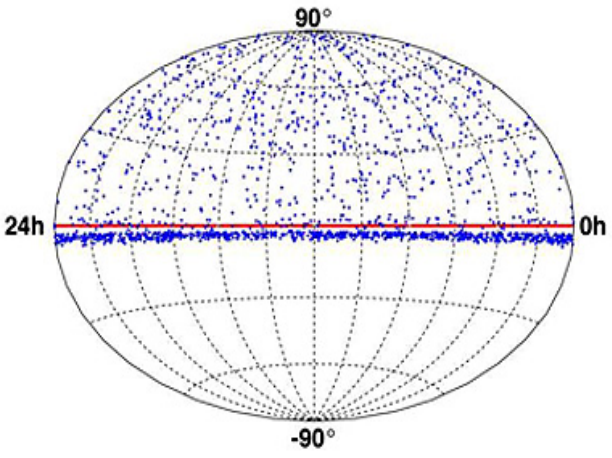


From the Mediterranean Sea

- Neutrinos: still an unexplored territory
- A lot of hidden secrets waiting to be revealed
- In search of ideas / technologies / inventions

All are welcome to join the exciting journey

Current sky map in neutrinos



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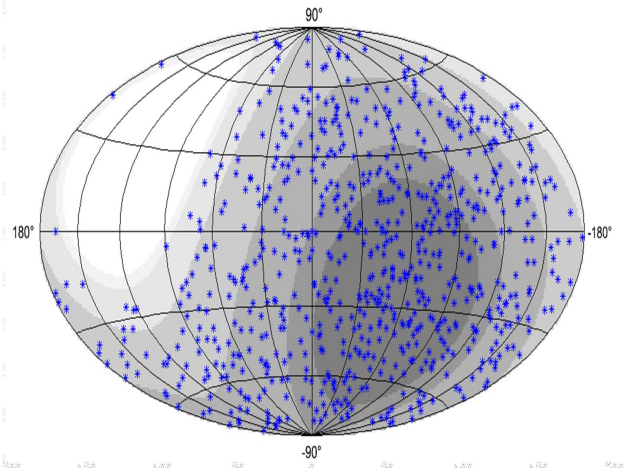

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