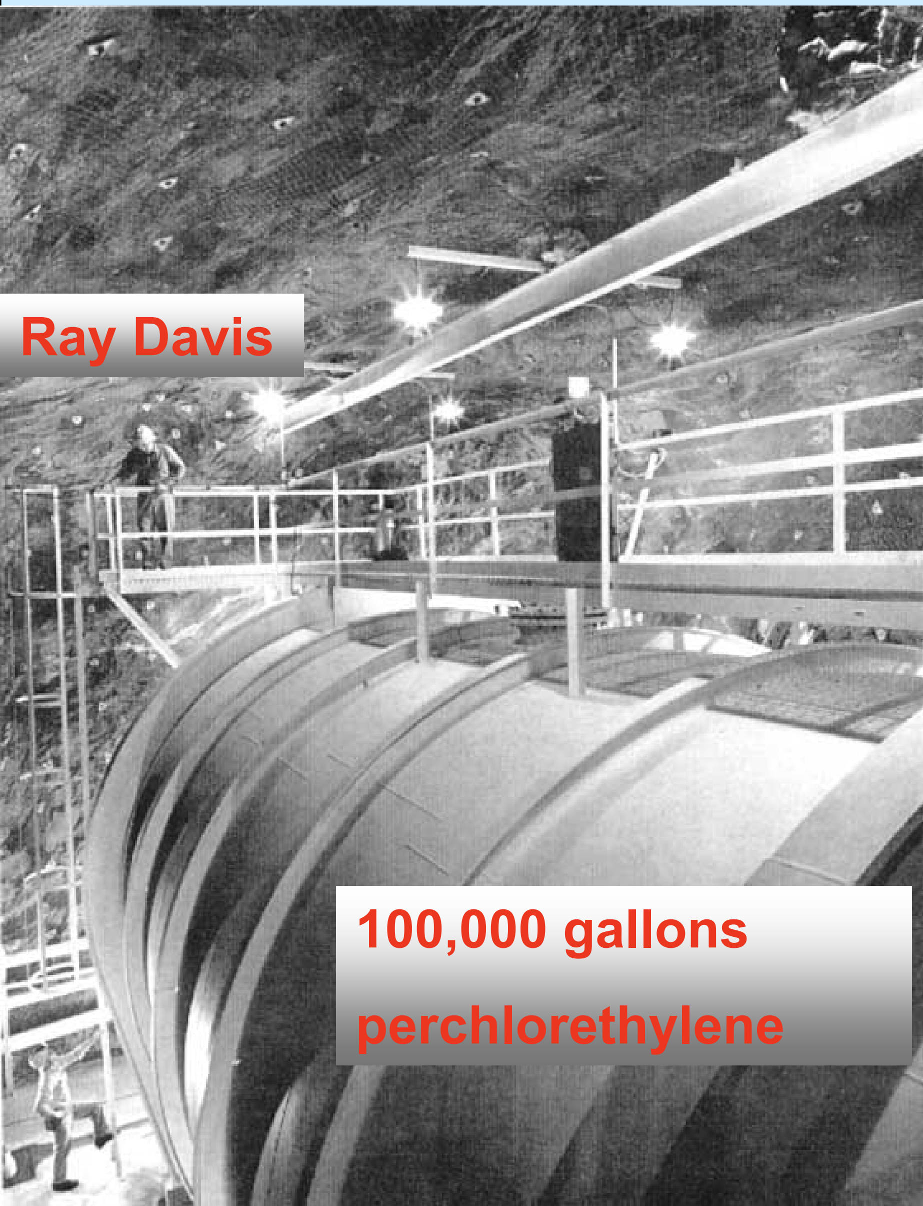
UHE Neutrino Astronomy…
An Invitation to Nature's Laboratories

David Saltzberg (UCLA), SLAC SUMMER INSTITUTE LECTURE, AUGUST 2008

What are the ways we get <u>all</u> our information about the universe beyond the Solar System?

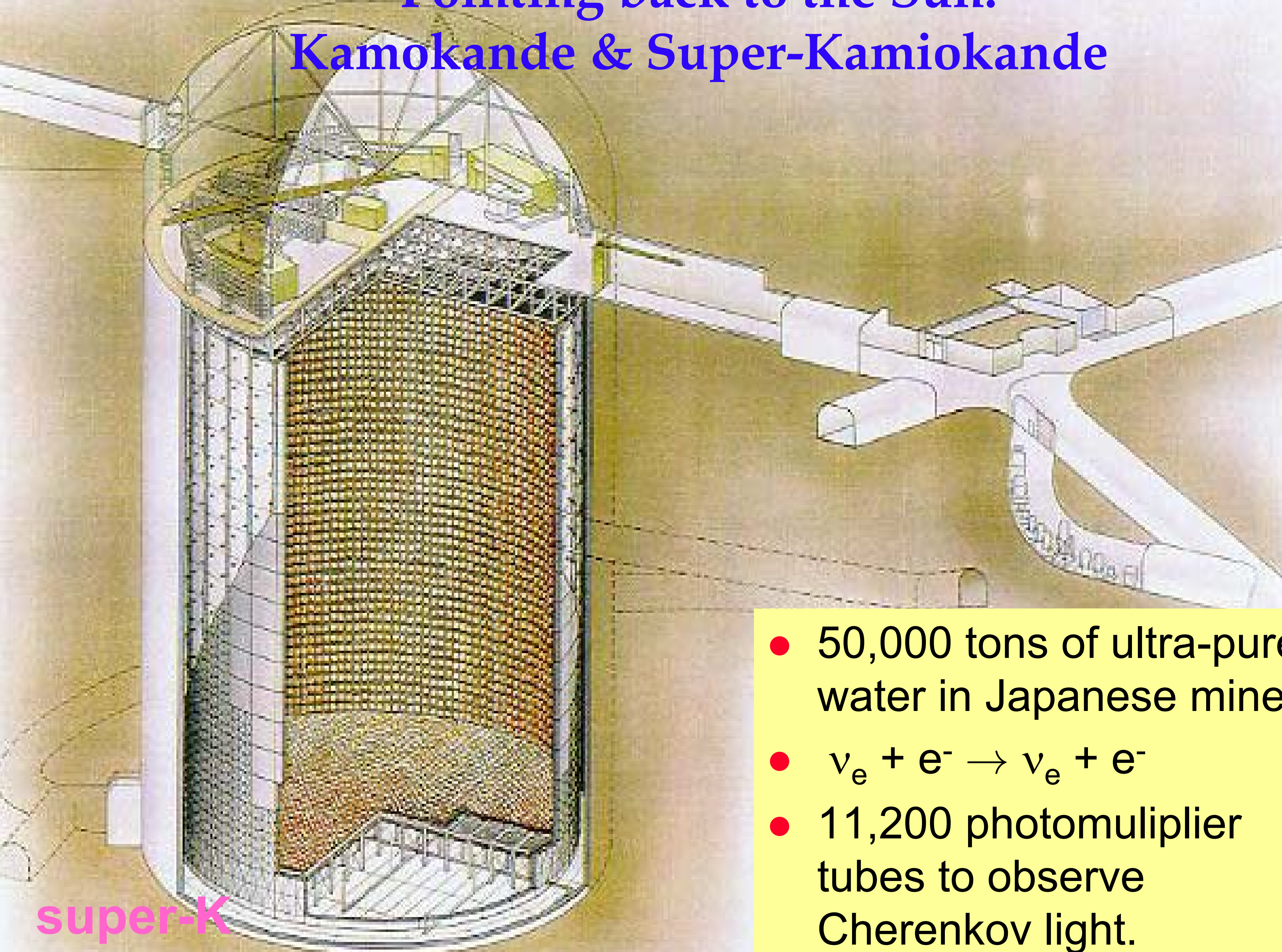
1967
The First Detection of Astrophysical Neutrinos: The SUN



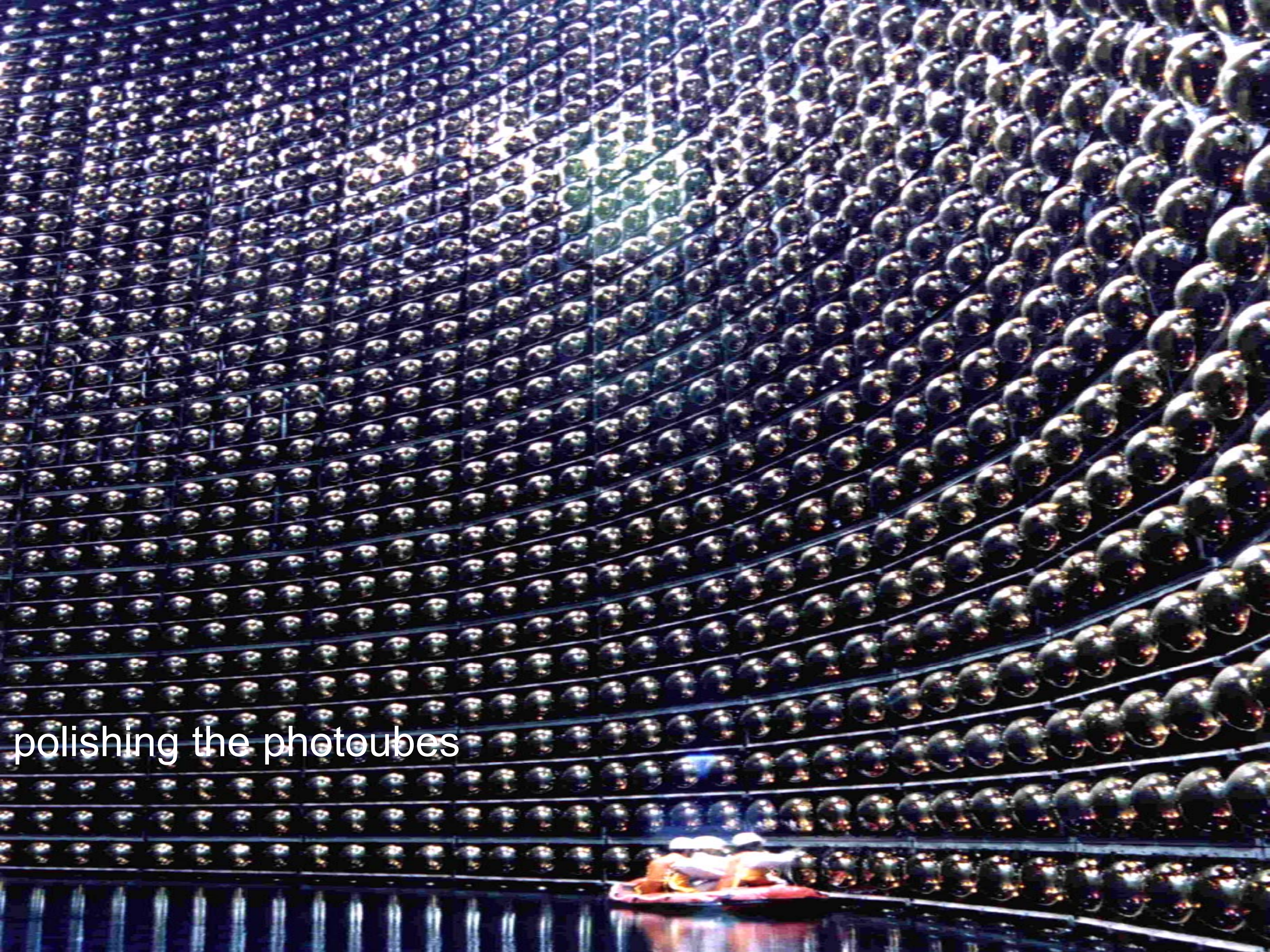
only ν_e

- Why the sun shines:
  - $4H^+ \rightarrow He^{+2} + 2\, e^+ + 2\nu_e$
- Homestake Mine
  - $^{37}Cl + \nu_e \longrightarrow {}^{37}Ar + e^-$: Count every ^{37}Ar by radioactive decay
  - Energy threshhold: 0.814 MeV
- saw only 1/3 of the expected flux of neutrinos
  - ?? $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$??
  - requires neutrinos to have mass
  - $[H_{weak}, H_{total}] \neq 0$

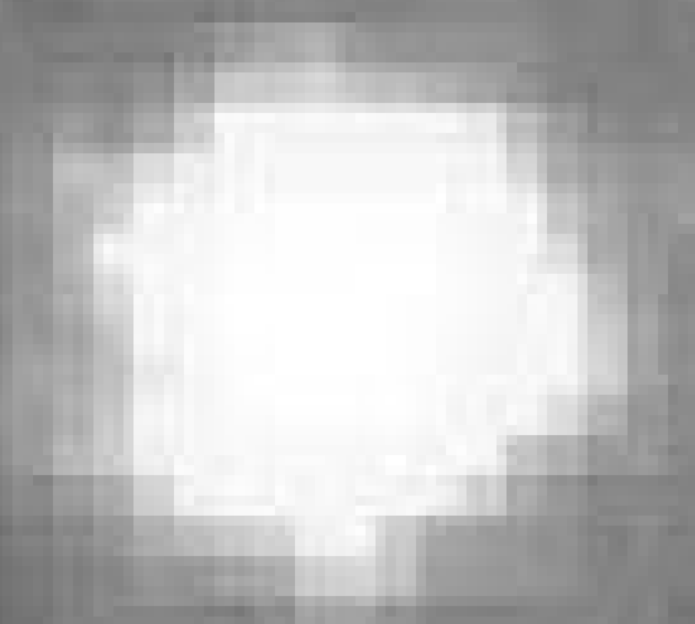
Pointing back to the Sun: Kamokande & Super-Kamiokande



- 50,000 tons of ultra-pure water in Japanese mine
- $\nu_e + e^- \rightarrow \nu_e + e^-$
- 11,200 photomuliplier tubes to observe Cherenkov light.

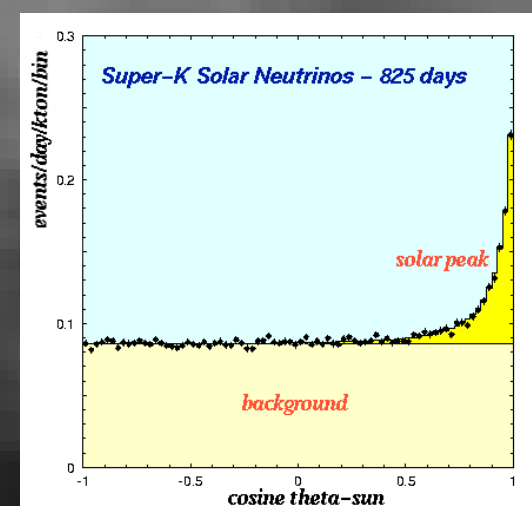

polishing the photoubes

Core of Sun is “seen”

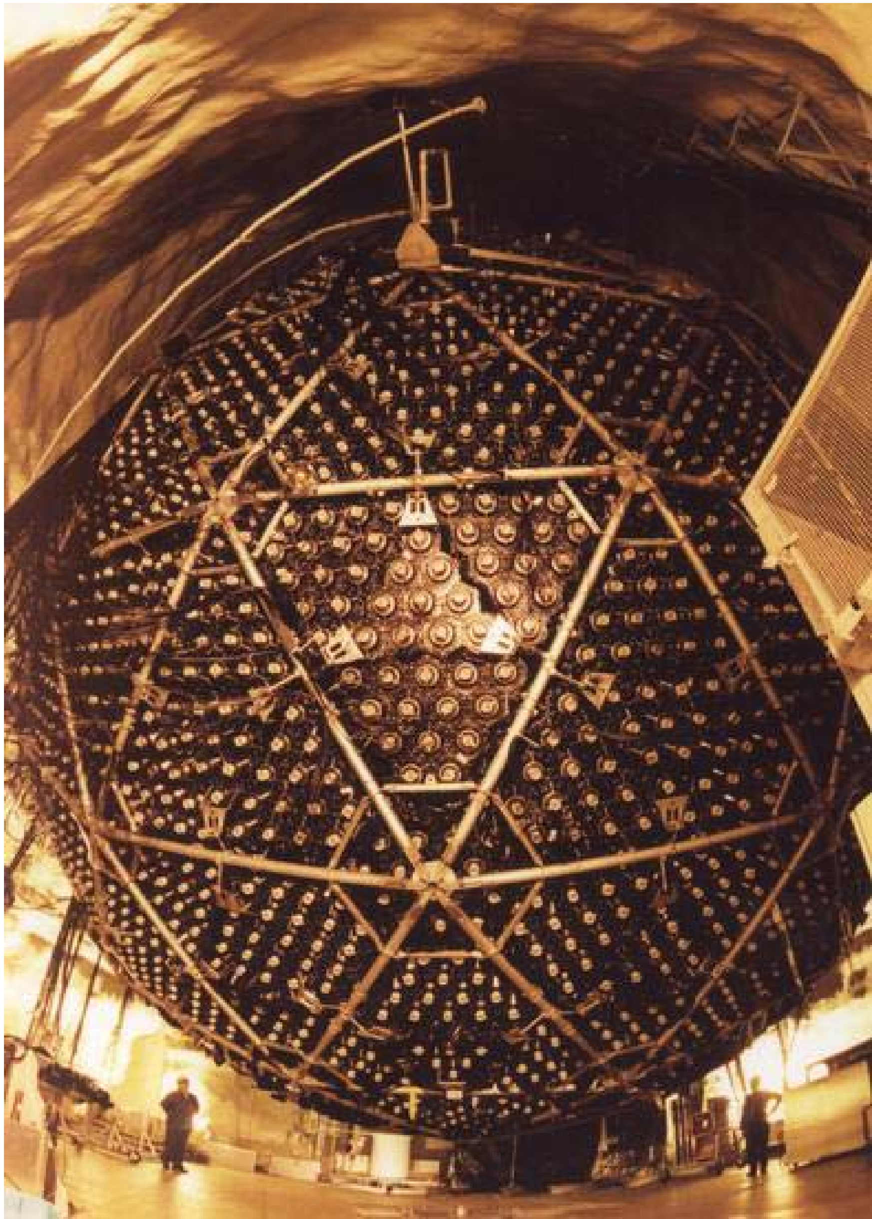


↗ Neutrinos see deeper

•But only ~half the event rate that was expected



But what about the deficit of neutrinos?

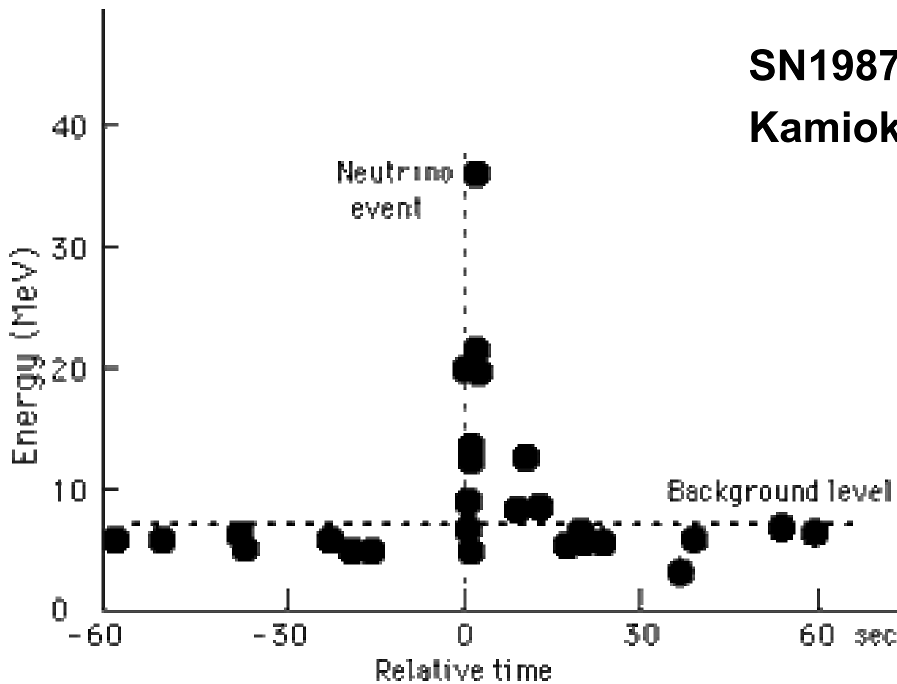


- Sudbury Neutrino Observatory built with 1000 tons of "heavy water" $H_2O \rightarrow D_2O$
- Can see all neutrino flavors at once:
  - $\nu_X + d \rightarrow n + p + \nu_X$
- 2001: Clearly showed "missing" neutrinos were there, they had just changed from ν_e to ν_μ after produced.
- The very first observation of neutrino astronomy changed our understanding of nature

Astrophysical Neutrino Sources
The story so far

SN1987A

Kamiokande



(also seen by IMB)

lack of dispersion→ν mass limits

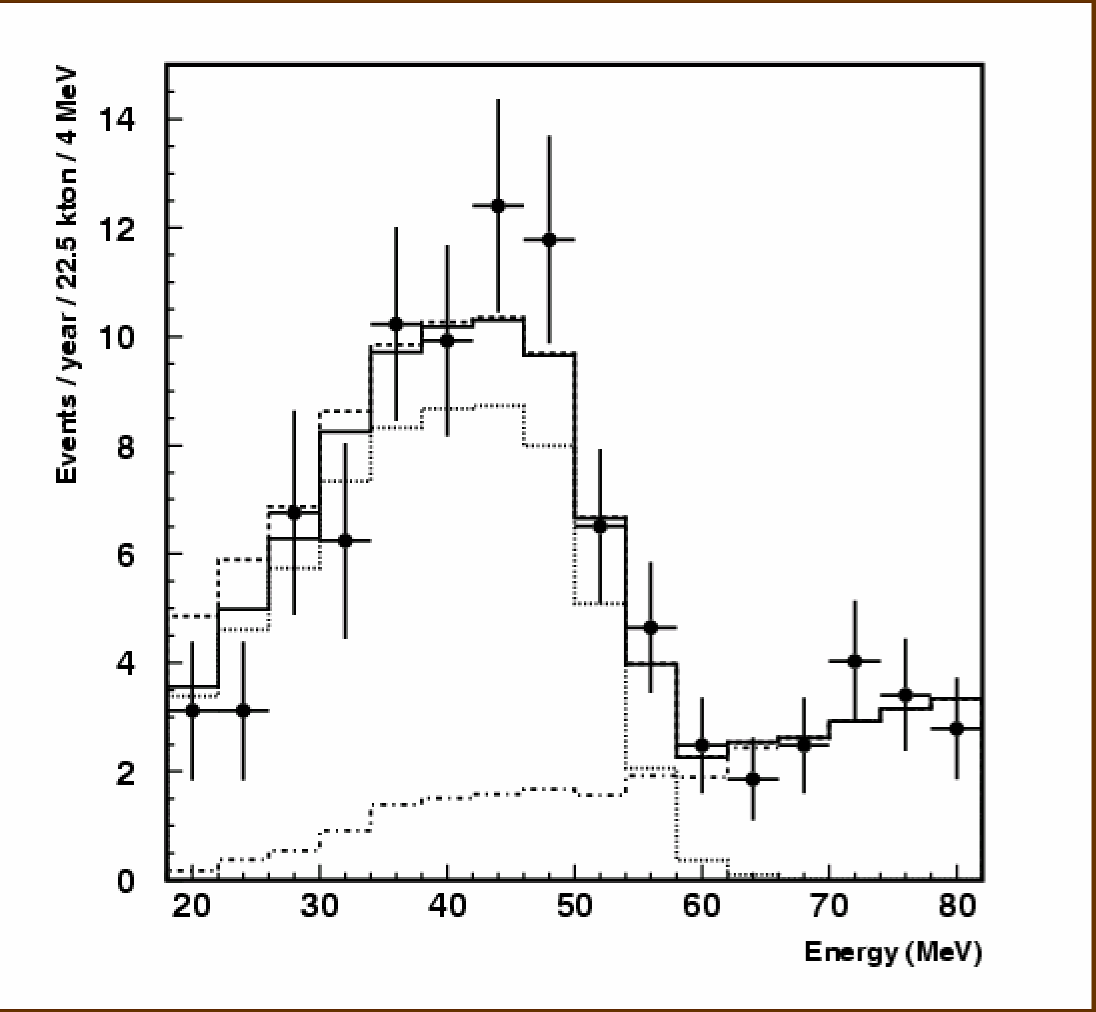
rate → limit on ν_e decay

Astrophysical Neutrino Sources
The story so far

Every source has:

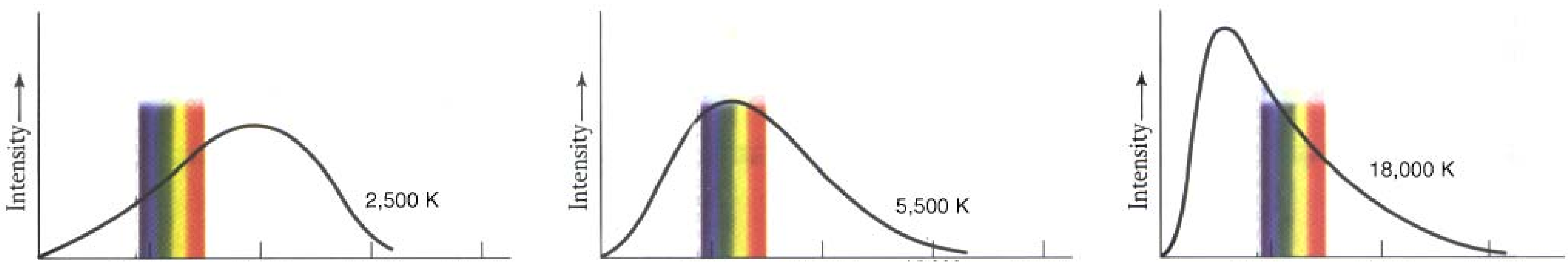
1. **Has had major impact on particle physics**
2. **Looks deepest into the source**
3. **Won a Nobel Prize**

Searching for a 3rd (Guaranteed) Source: Diffuse SNae neutrinos



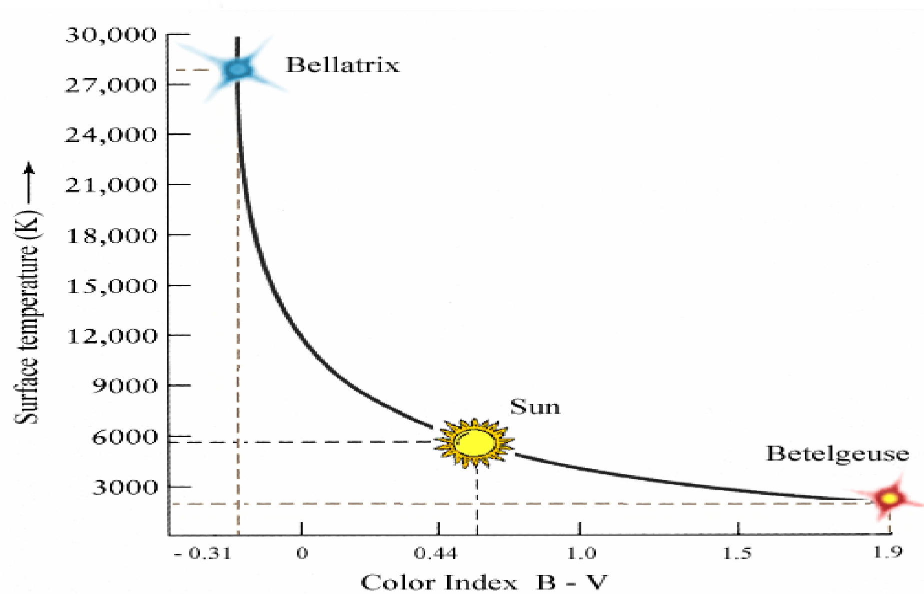
- Super-K looks for a diffuse flux of relic neutrinos from SuperNovae
- Data (points) consistent with background (solid)

- <u>**Before 1920’s**</u>**.   No expectation of Radio Emission from astrophysical sources**
  - **Far away from the “blackbody” peak**



I. This star appears red

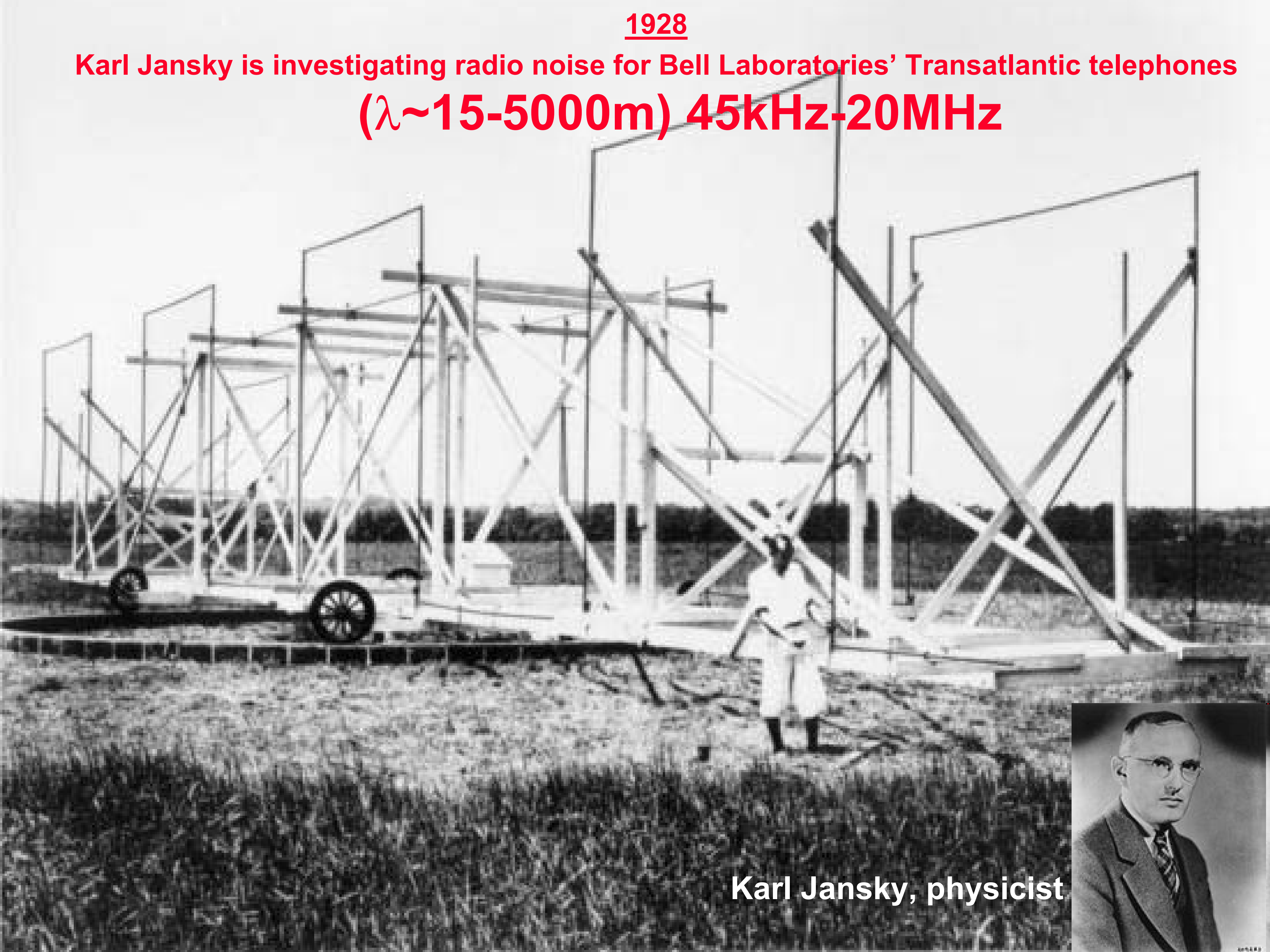
This star appears blue



1928

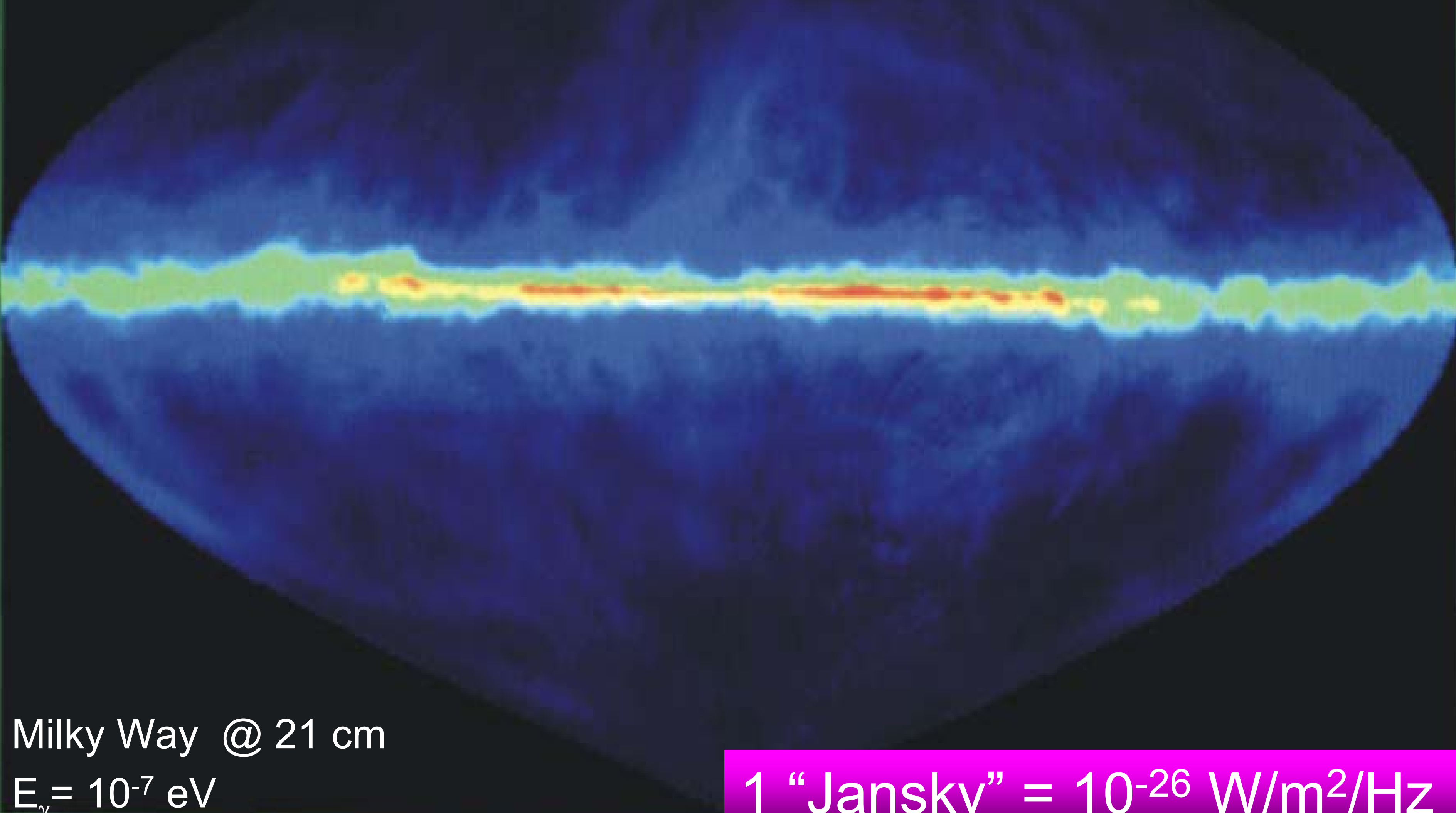
Karl Jansky is investigating radio noise for Bell Laboratories' Transatlantic telephones

(λ~15-5000m) 45kHz-20MHz



Karl Jansky, physicist

1928: Jansky sees an asymmetry in emission→ Evidence the galactic center is a particle accelerator

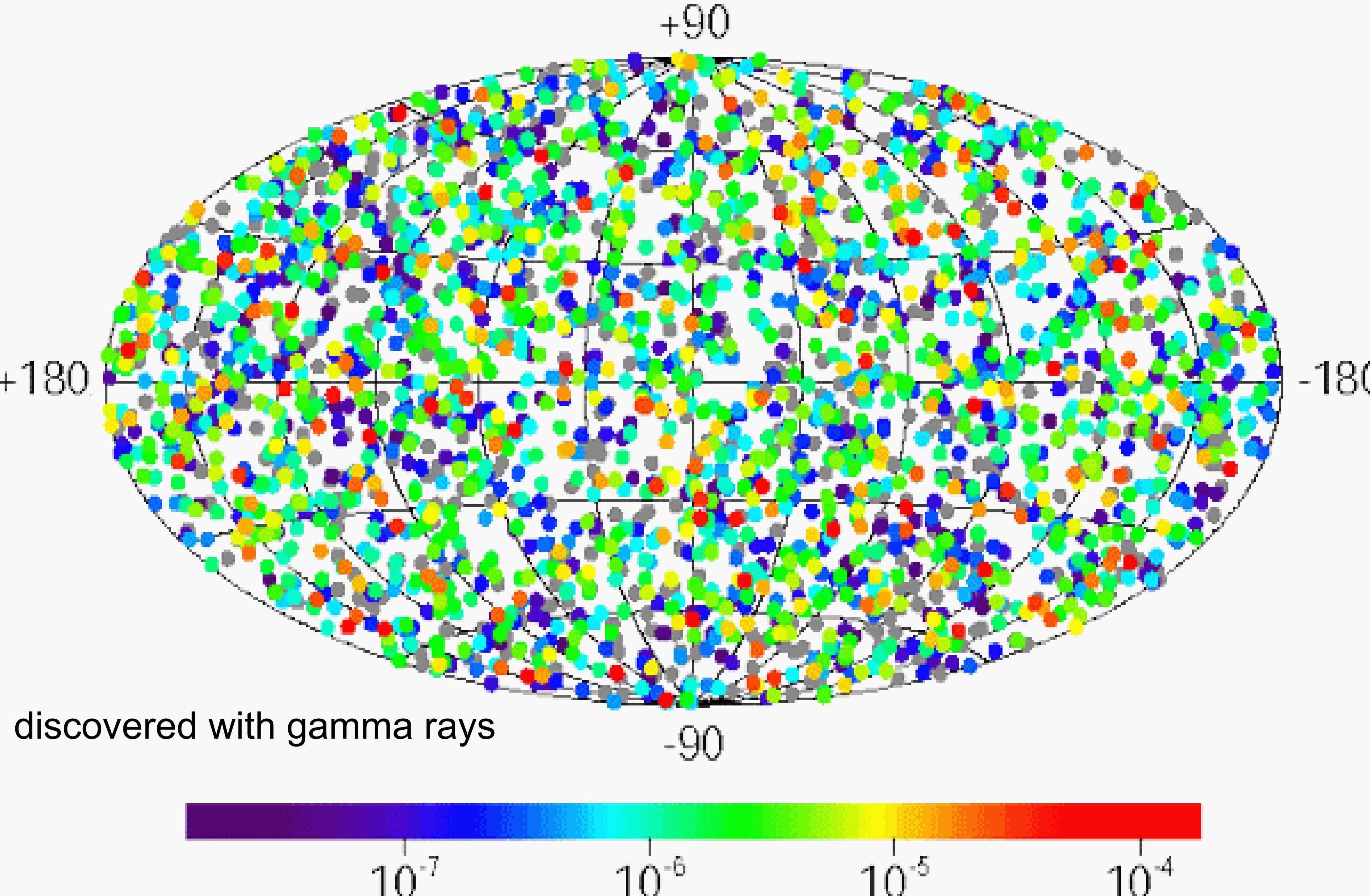


Milky Way @ 21 cm

$E_\gamma = 10^{-7}$ eV

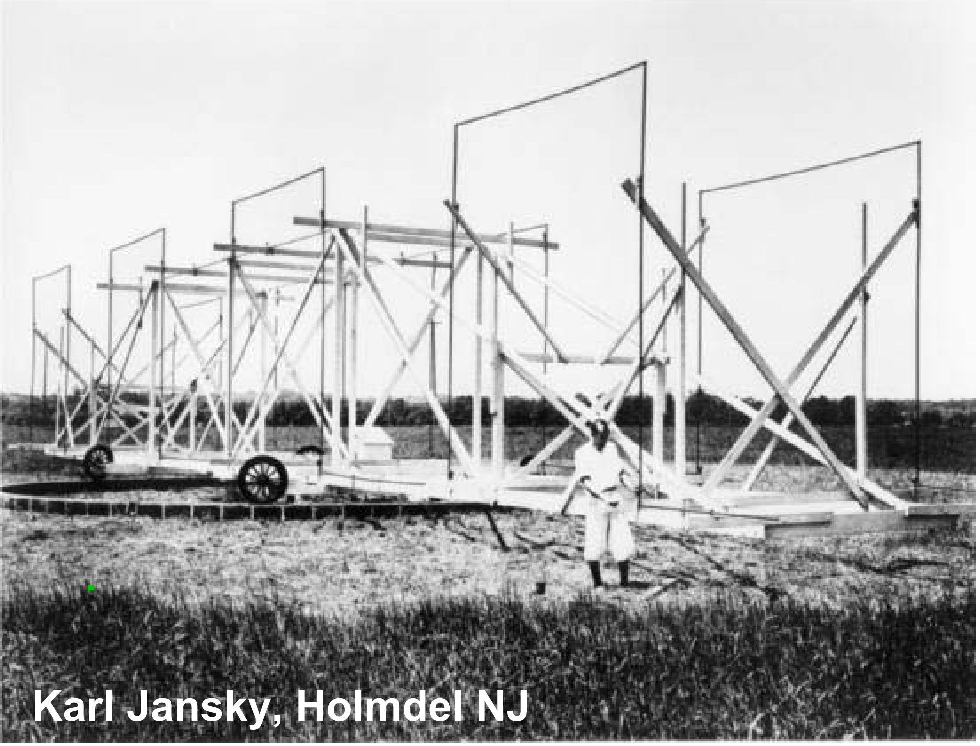
1 "Jansky" = 10^{-26} W/m^2/Hz

2704 BATSE Gamma-Ray Bursts



The range of photon astronomy

Radio Astronomy
<10^{-6} eV photons

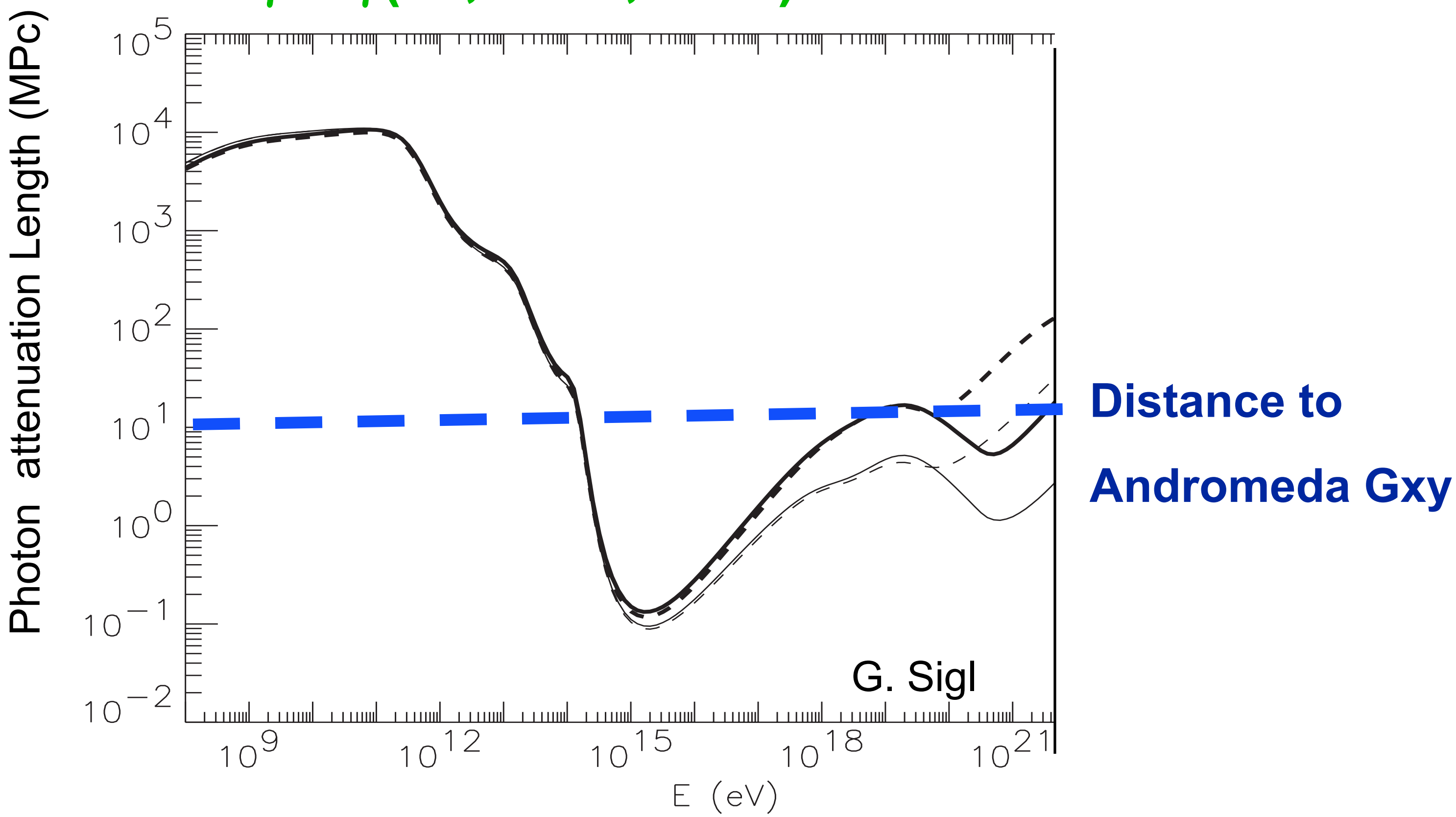


Atmospheric Cherenkov
>10^{12} eV photons

…and everything in between

The end of extra-galactic photon astronomy

$\gamma + \gamma(\text{IR,CMB,URB}) \rightarrow e^+ e^-$



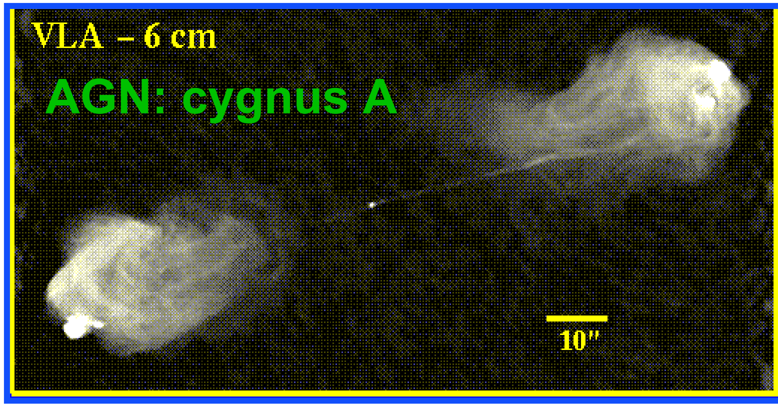
But no cutoffs for neutrinos!

"Bottom-Up" Sources?

- **Cosmic Accelerators:**

  $R_{gyro} \sim Ze\ B\ /\ p$

  $E < 10^{18}$ eV Z (R/kpc) (B/μG)



- **Supernovae ?**

  (B~10^{-3} G so up to ~ 10^{16-18} eV)

- **Pulsars?**

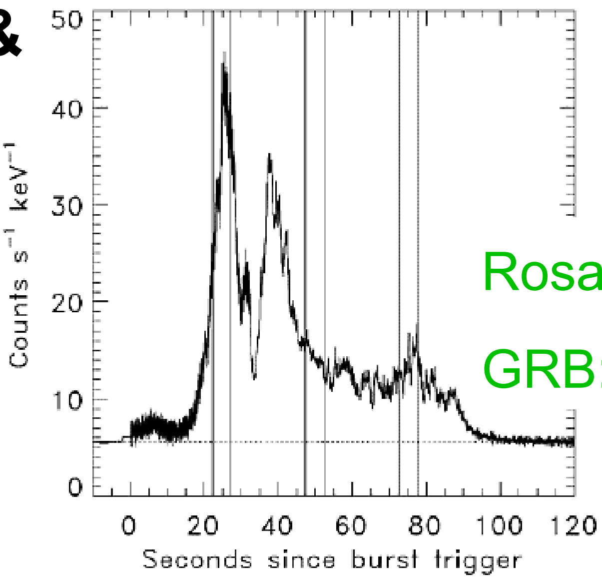
  (10^{12} G but dense environment & sources must be extragalactic)

- **Active Galactic Nuclei?**

  (but energy loss?)

- **Gamma-Ray Bursts?**

  (but $E_{tot}^{UHECR} = E_{obs}^{MeV}$ γ's)



Rosat MeV γ's

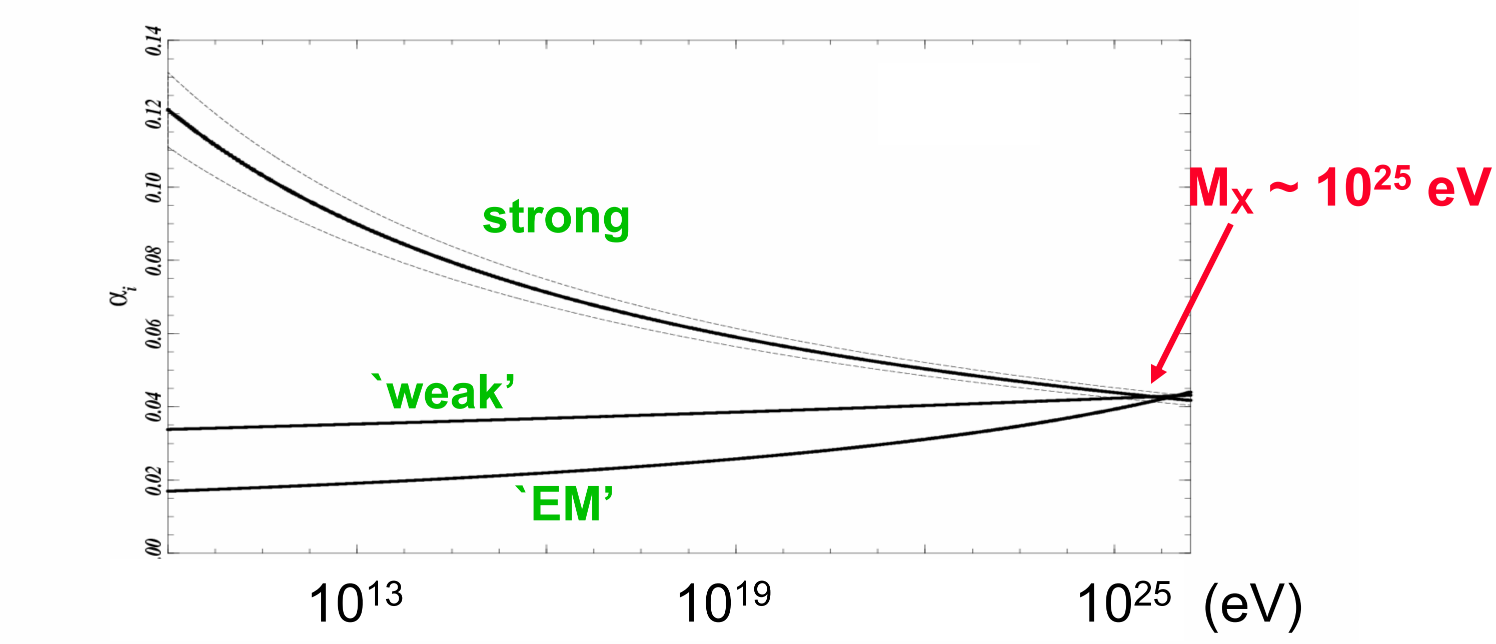
GRB: 990123

How many neutrinos to expect per photon from astrophysical sources?

- **Pion production and decay:**
  - **Isospin invariance:** **$N_\nu / N_\gamma \sim 3$**
    - $\pi^+ : \pi^0 : \pi^- = 1:1:1$
    - $\pi^0 \rightarrow \gamma\,\gamma$
    - $\pi^+ \rightarrow \mu^+ \nu_\mu$
      $\rightarrow e^+ \nu_e + \nu_\mu$
- **Beam Dump:** **$N_\nu / N_\gamma \sim \infty$**
- **Electron synchrotron $N_\nu/N_\gamma = 0$!**

"Top-Down" Sources?

- Exotic Physics: UHECR would result from decays of super-heavy particles.
- Example: Grand Unified Supersymmetric Theories:



Is its lifetime comparable to age of universe or is it ~10^{-40} sec?

Loophole—produce them continuously by "topological defects" remaining from Big Bang

A "guaranteed" source

- **GZK with protons:** $p + \gamma_{6K\ CMB} \rightarrow \Delta^* \rightarrow n + \pi^{\pm}$

$$\hookrightarrow \mu\nu$$
$$\hookrightarrow e\nu\nu$$

~10^{19} eV

(NOT a typo)

neutrinos

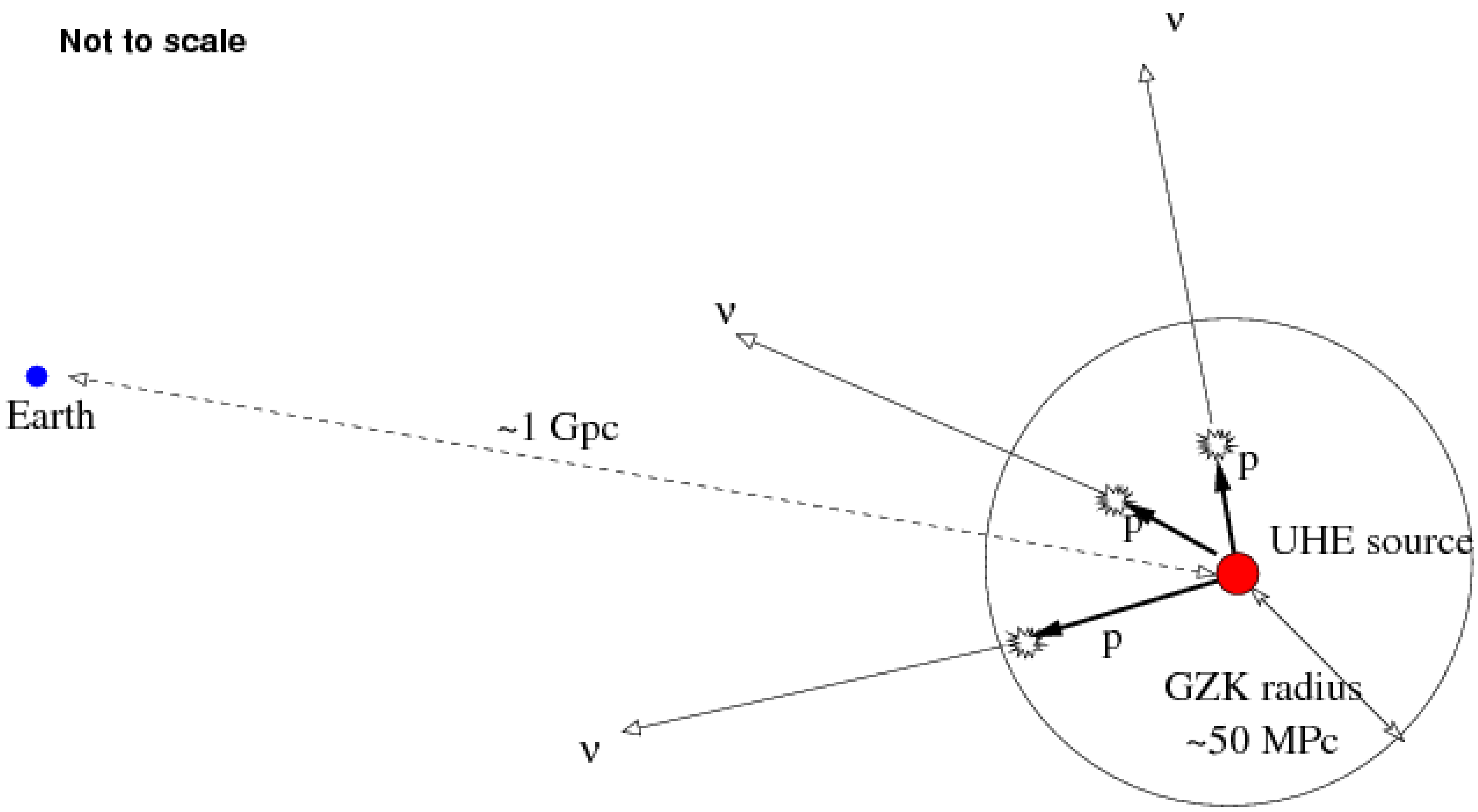
- **GZK with nuclei:**

$$Fe + \gamma_{6K\ CMB} \rightarrow 26p + \sim 30n$$

$$\Downarrow$$

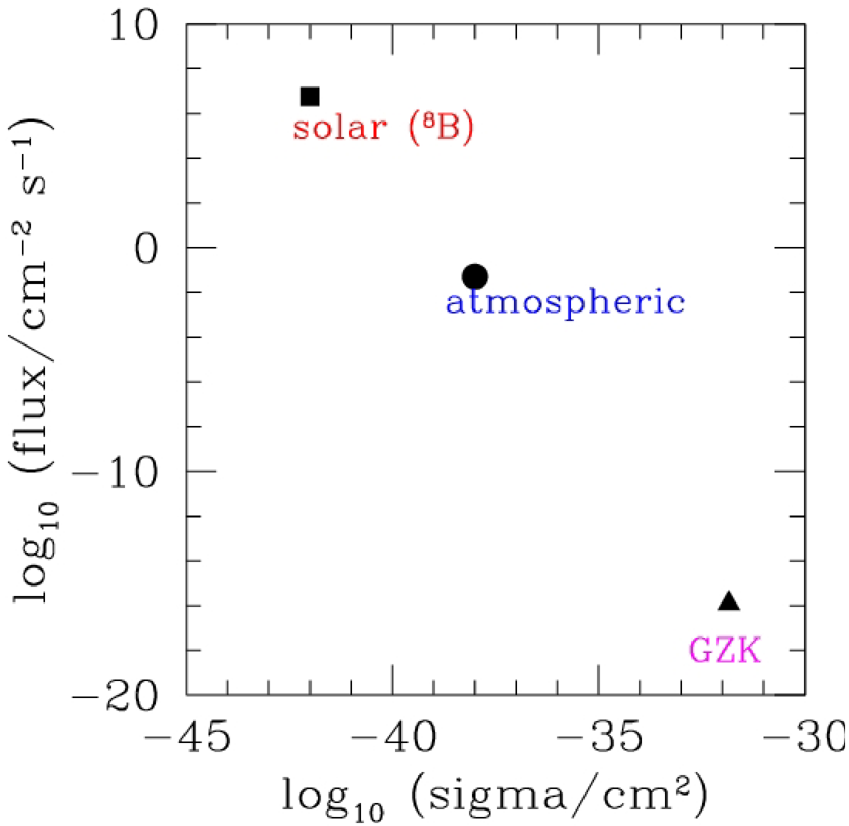
$$30 \times (n \rightarrow p\ e^-\ \overline{\nu})$$

Even GZK Neutrinos Point Back



$\delta\theta$ ~ 10Mpc/1000Mpc ~ 30 arcminutes

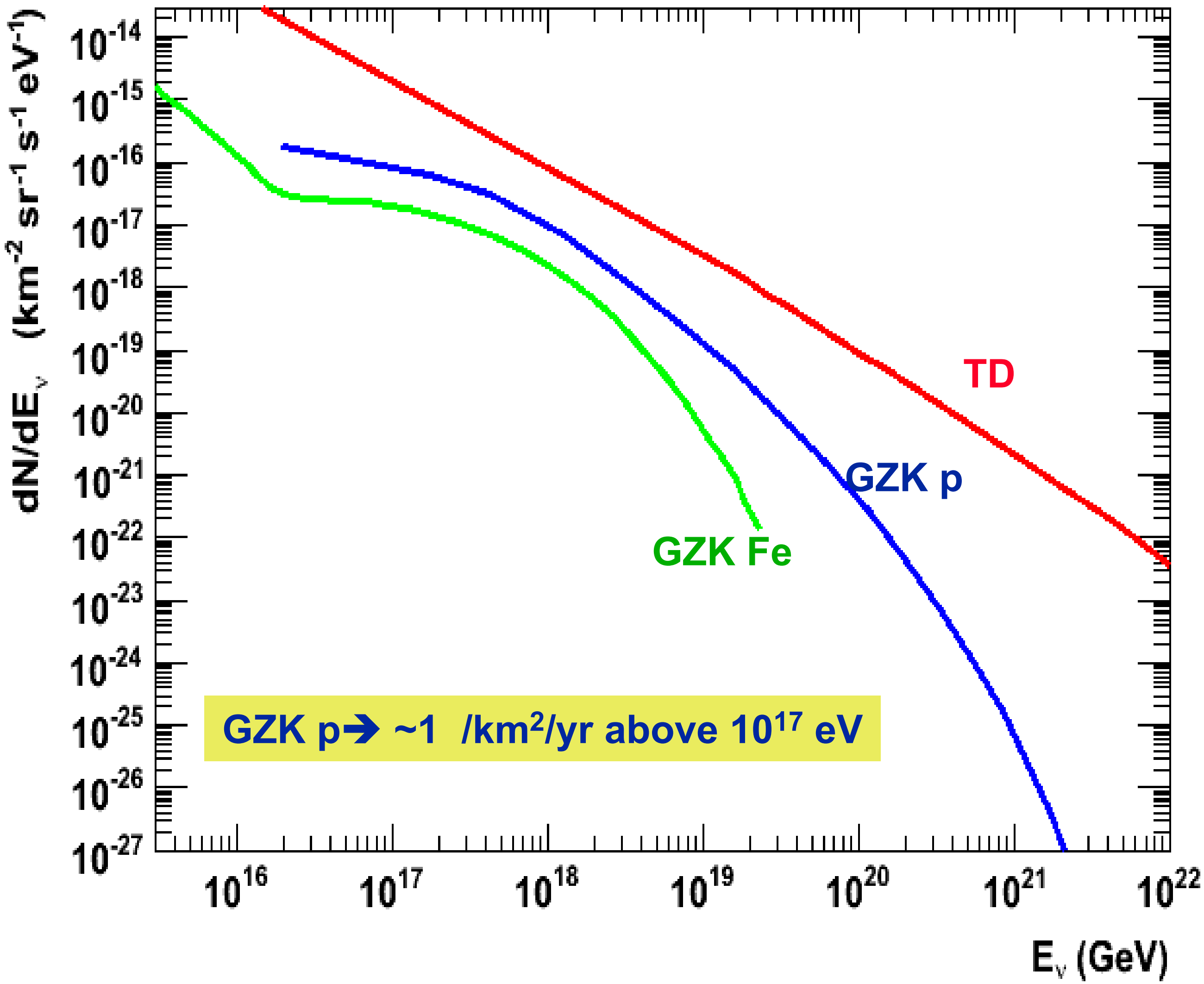
Energy/Flux range of neutrinos



- **$L_{interaction}^{\nu}$ ~ only 500 km of rock at 10^{19} eV**
- **Earth attenuation is significant above 10^{15} eV**

The UHE ν Beam

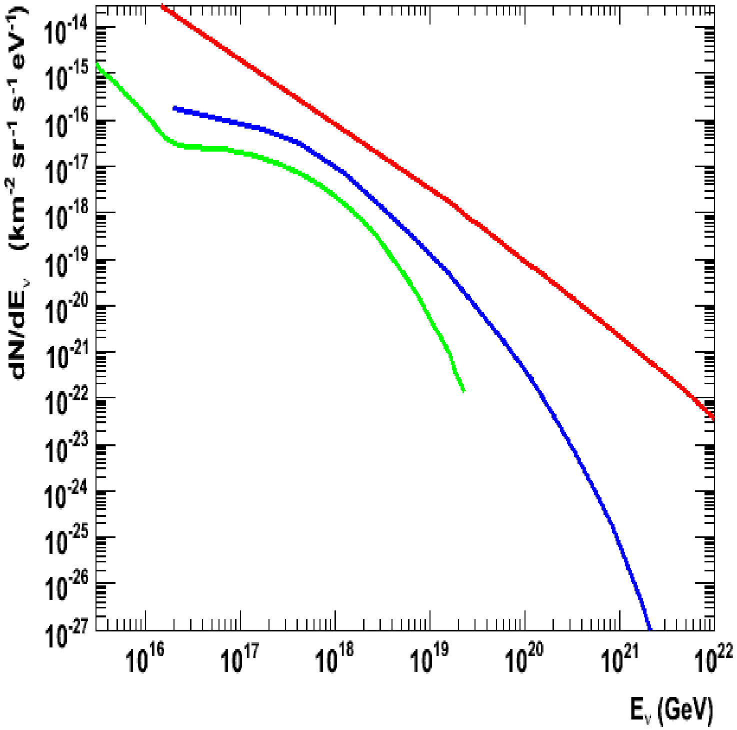
$$\text{brightness } (I_E) = \frac{d^4N}{dA\,d\Omega\,dt\,dE}$$



- GZK p : Engel, Seckel, Stanev, PRD 64,093010
- GZK Fe: Ave, Busca, Olinto, Watson,Yamamoto, Astropart. Phys., 23, 19
- TD: Yoshida, Dai Jui, Sommers, Ap. J. 479, 547

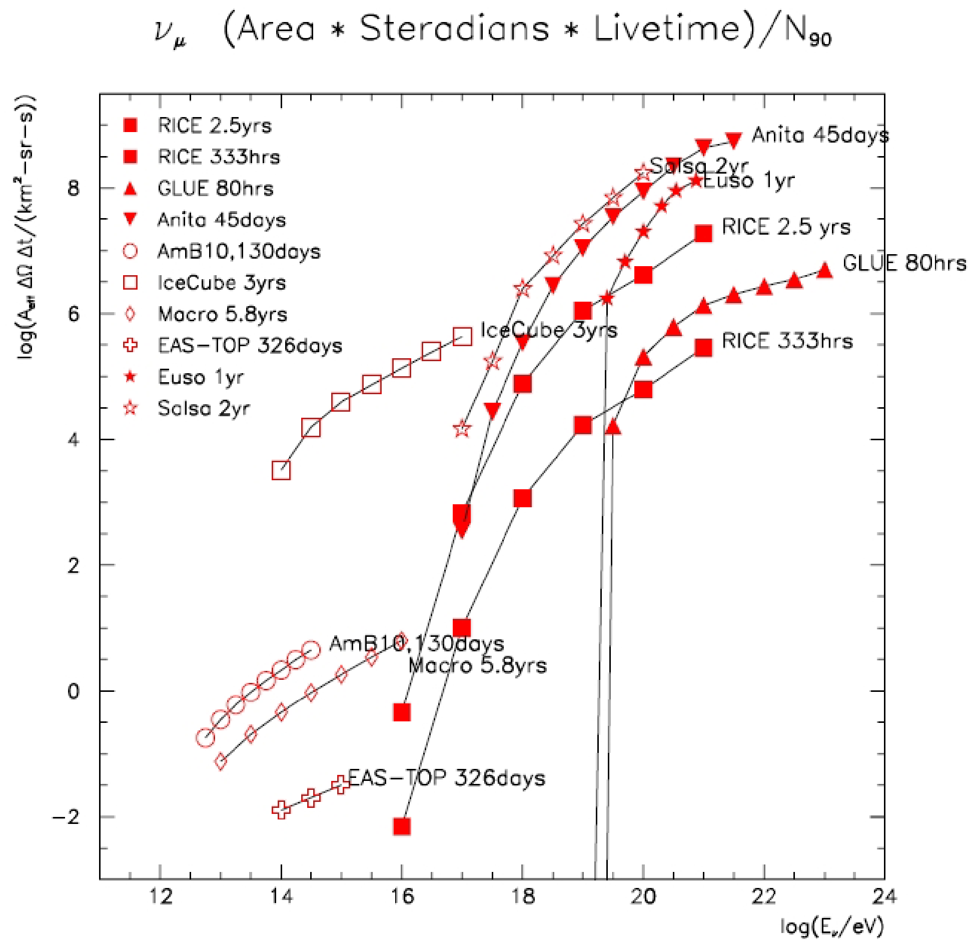
A perpetual problem in Particle Astrophysics

- **Theorists predict I_E**
  (# /area /sr /time /energy)
  - ↗ **also called dN/dE, "brightness"**
- **Expermintalists can only measure**
  - ↗ **$N = \int_{E1}^{E2} I_E(E)\, dE\, dA\, d\Omega\, dt$**
- **➔ Oddball situation. No model-independent limits without binning. "Limits get worse" as binning resolution improves**
- **Homework: Possible solutions?….**



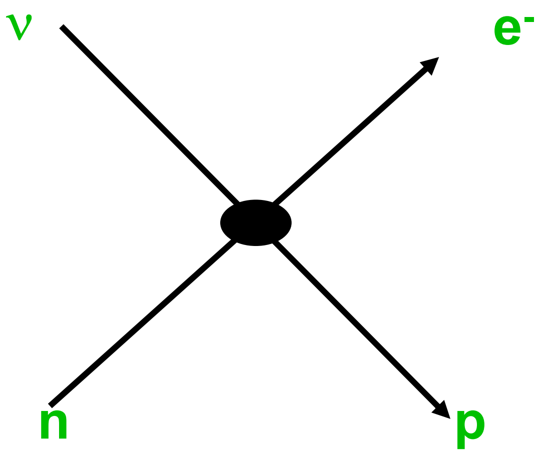
One reasonable(?) approach to comparing experiments

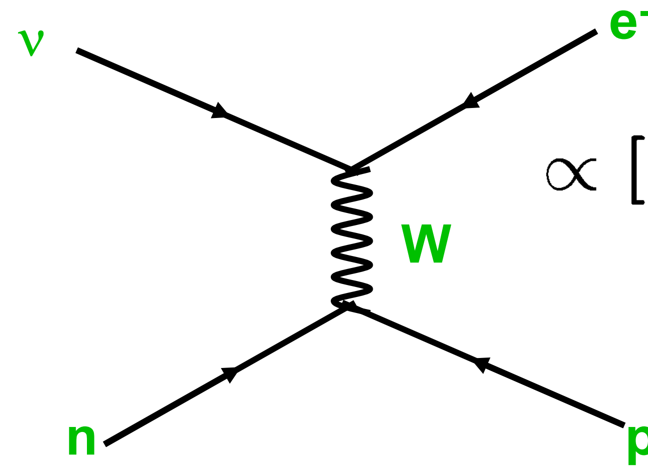
- Give [A Δ Ω] vs. Energy for all
- Some attempt to correct for differing backgrounds?



illustrative purposes (a bit out of date)

Neutrino interaction





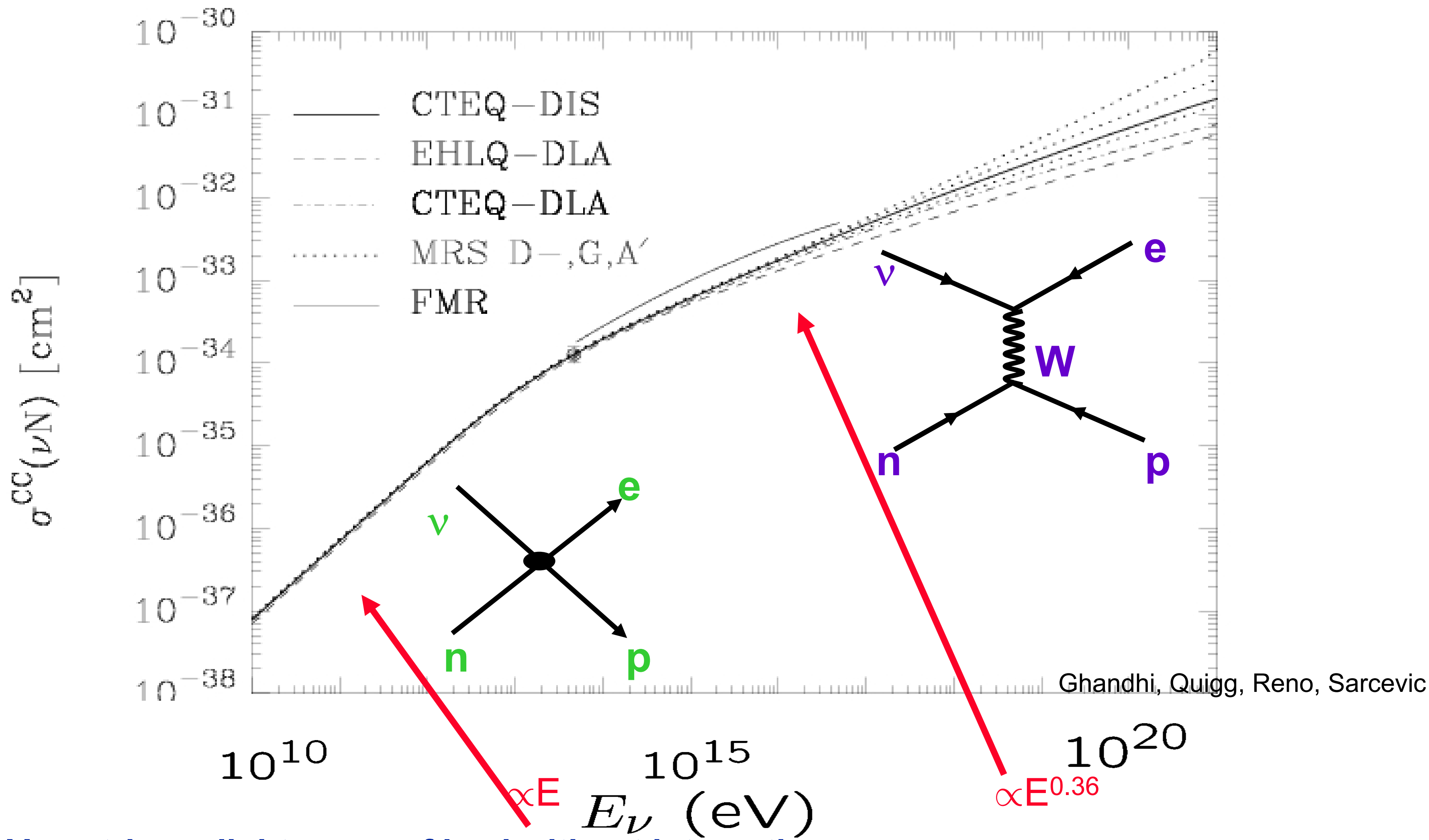
$$\propto \left[\frac{1}{1+(q^2/M_W^2)}\right]^2$$

- Say strength is G_F, a constant; beta decay $\Rightarrow$ $G_F \sim 1.16 \times 10^{-5}$ GeV^{-2}

$$\sigma \sim G_F^2\ E_\nu$$

but only $\propto E^{0.36}$ for $E_\nu > 10^{15}$eV

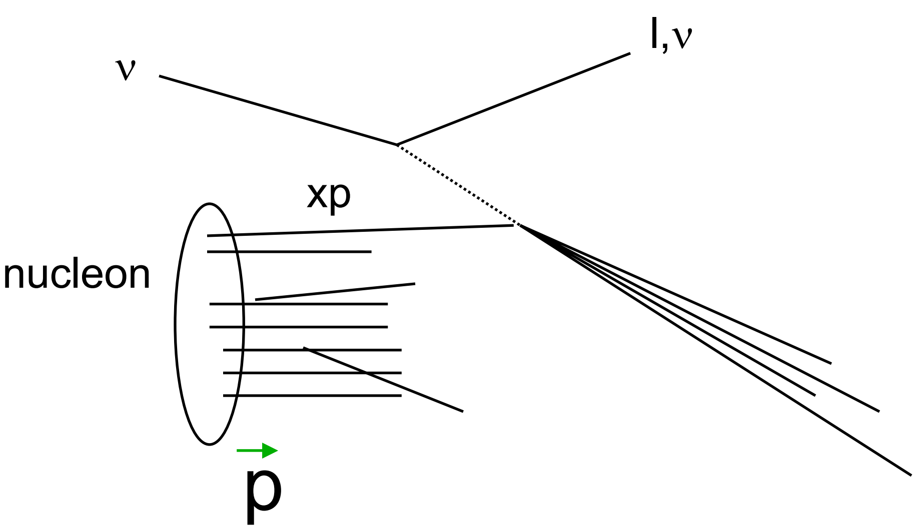
Neutrino interactions in the Standard Model

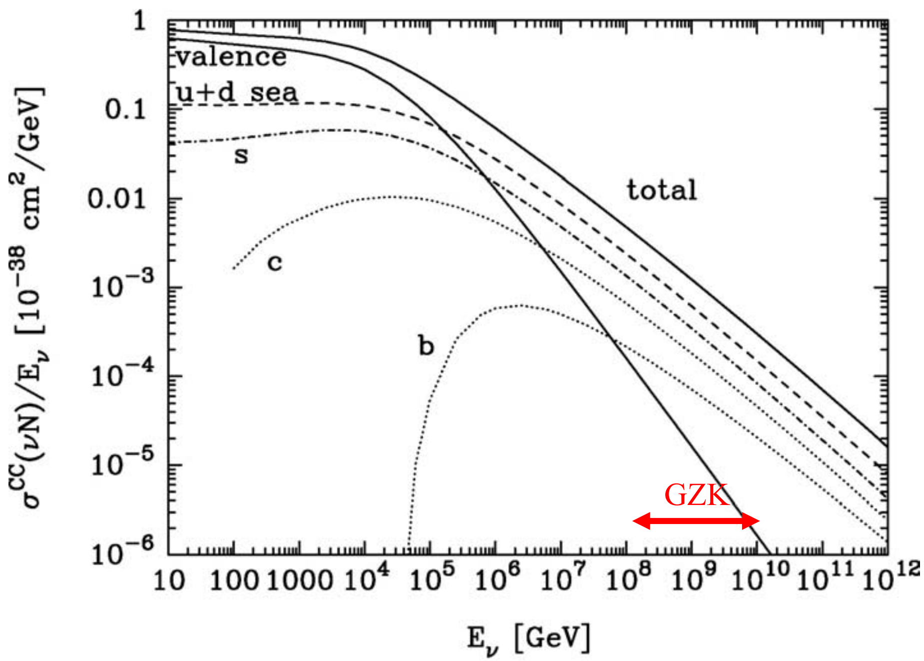


- MeV neutrino: light-years of lead without interacting
- 10^{21} eV neutrino: tens of kilometers of rock without interacting

Even SM is Probing an extreme regime

- Extreme regime: More likely to scatter off of bottom sea than down valence.





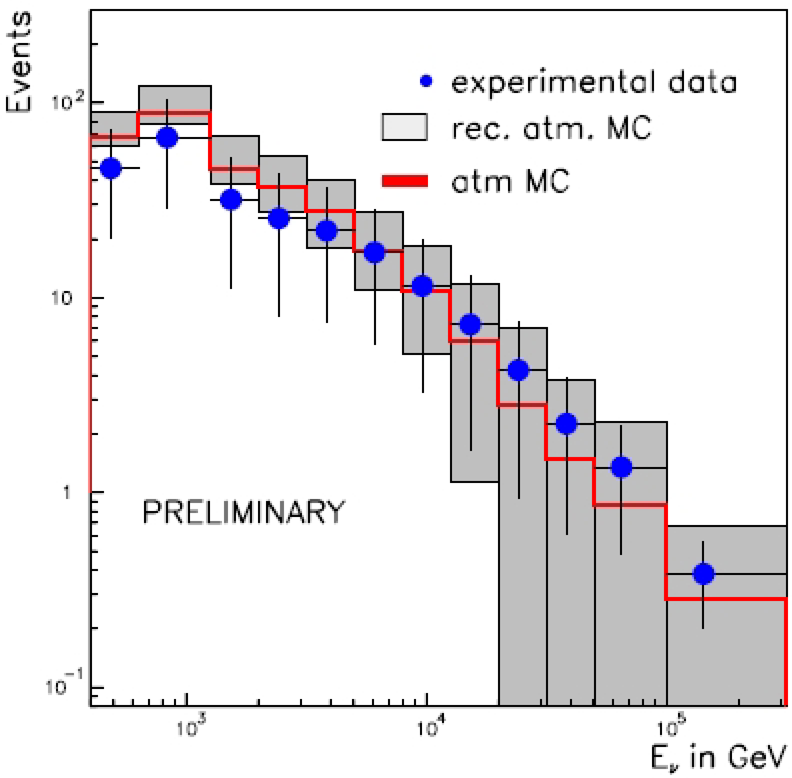
- **This is not HERA**
  - **HERA tests proton structure to x~10^{-4} (& only 10^{-2} at "high" Q^2)**
  - **UHE ν probe proton structure to x~10^{-8} at high Q^2**

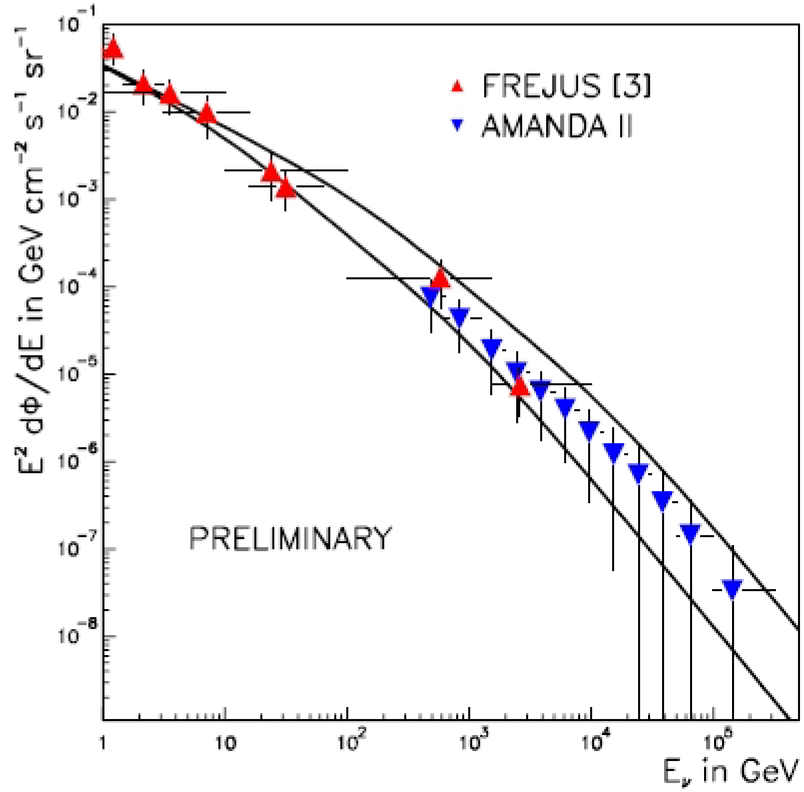
Numerology
(Homework: check inputs)

- **What detection volume is needed?**
  - **Crab Flux of > 10 TeV gamma rays ~ 10^{-12} / cm^2 / s**
    ~ 100,000 /km^2/yr
  - **Neutrino cross section ~ 10^{-34} cm^2 at 10 TeV**
  - **Interaction length is ~50,000 km in water , so ~0.00002 chance of interacting in 1 km**
  - **Assuming N_nu / N_gamma ~3**
  - **Detector can see up to half the sky -- Rates ~6 nu/ km^3 / year ?**

- **A detector of order 1 km^3 * str is required**
  - **Look for natural media**

More Problems: atmospheric backgrounds





- **Sources above a background are convincing**
- **Question: How to prove an isotropic excess?**

Cherenkov Radiation

Excess charge moving faster than *c/n* in matter emit Cherenkov Radiation

$$\boxed{\frac{dP_{CR}}{d\nu} \propto \nu d\nu}$$

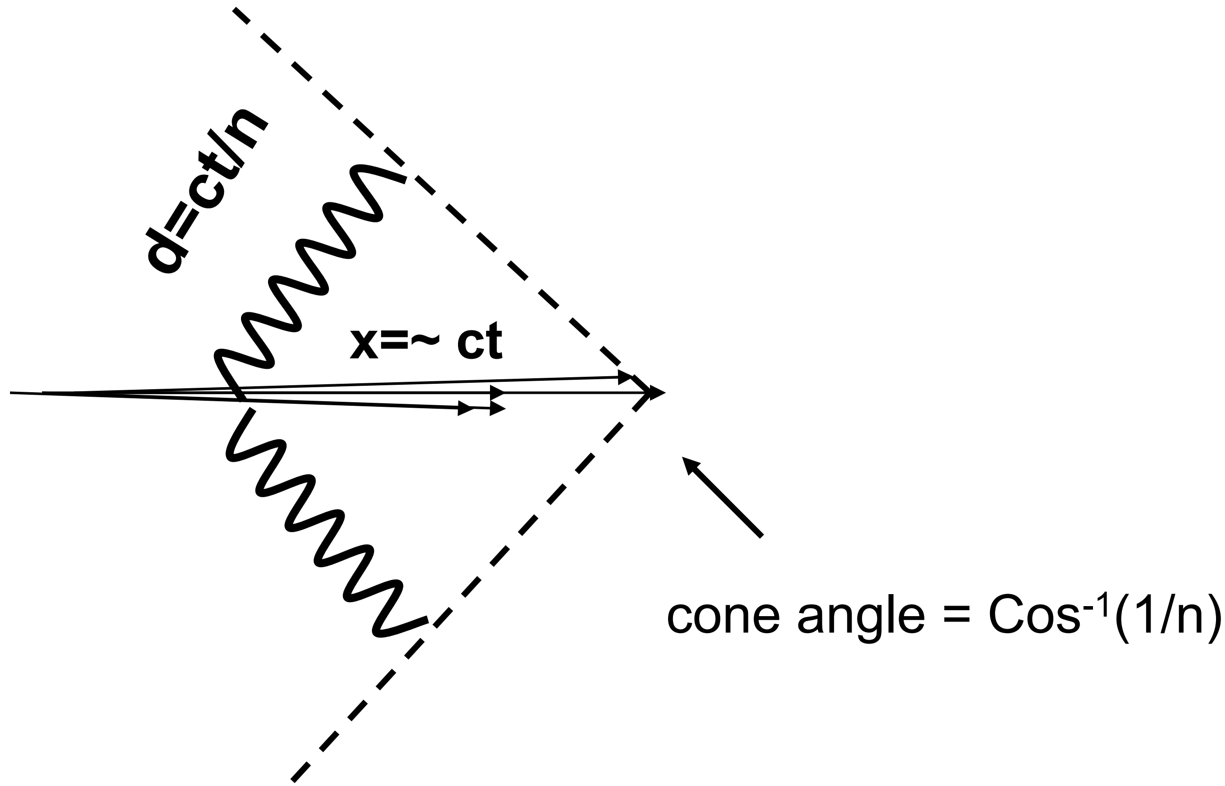
Each charge emits field $|E| \propto e^{ik\cdot r}$ and Power $\propto |E_{tot}|^2$

In dense material $R_{Moliere} \sim 10cm$.

$\lambda << R_{Moliere}$ (optical case), <u>random phases</u> $\Rightarrow$ $P \propto N$

Cherenkov Radiation

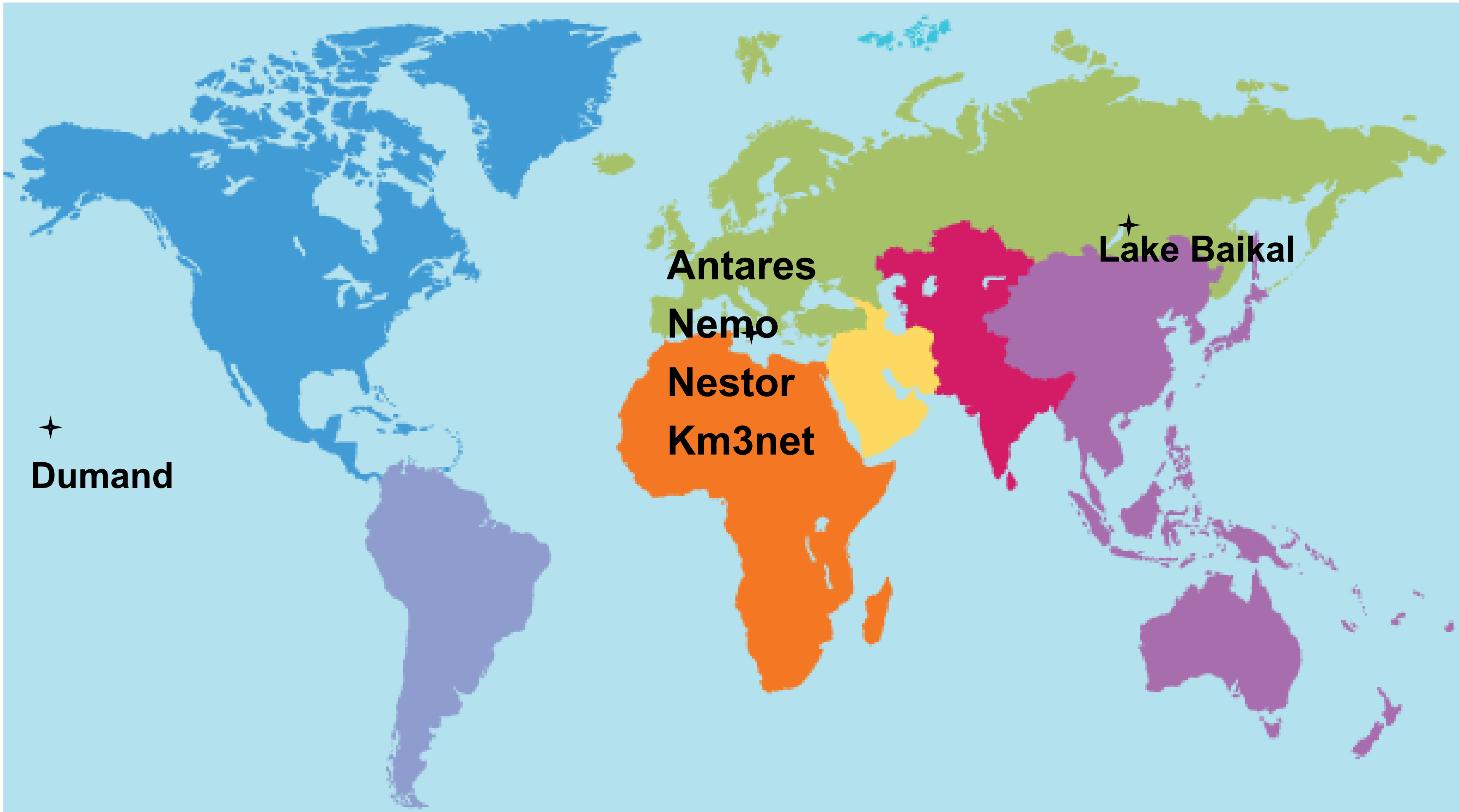
$$\boxed{\frac{dP_{CR}}{d\nu} \propto \nu d\nu}$$



Ice Target at SLAC

Now a Movie…

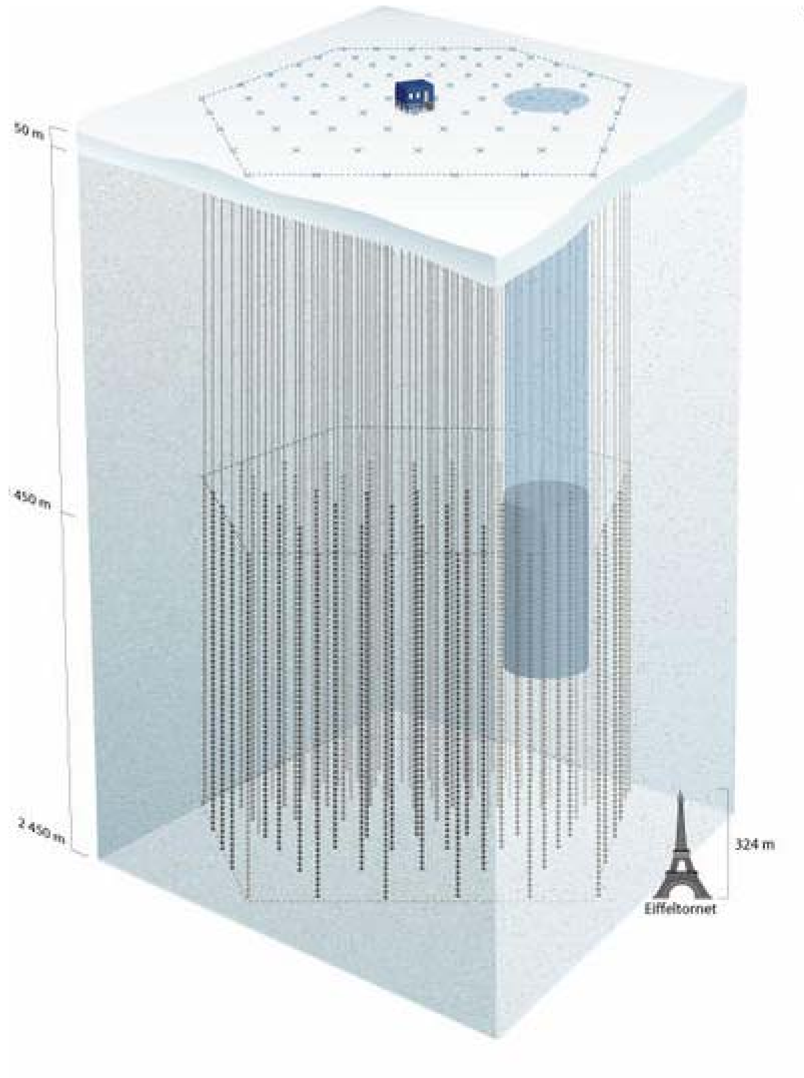
Natural Water Optical Detectors
past & present



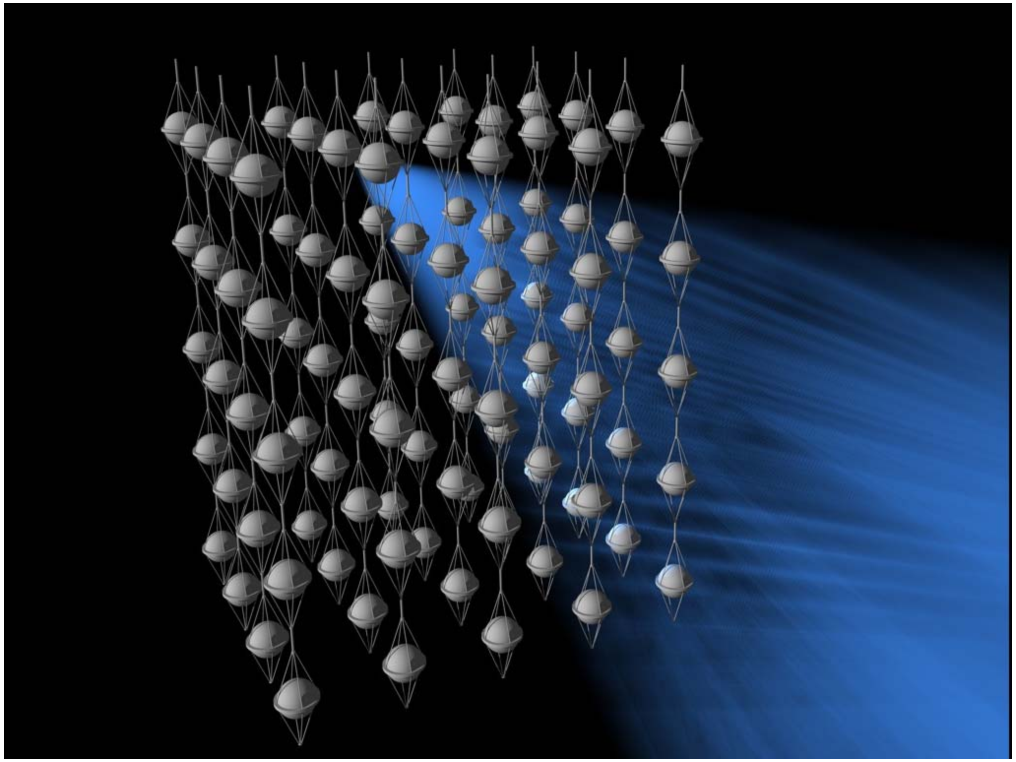
Amanda

Ice Cube

Amanda→IceCube

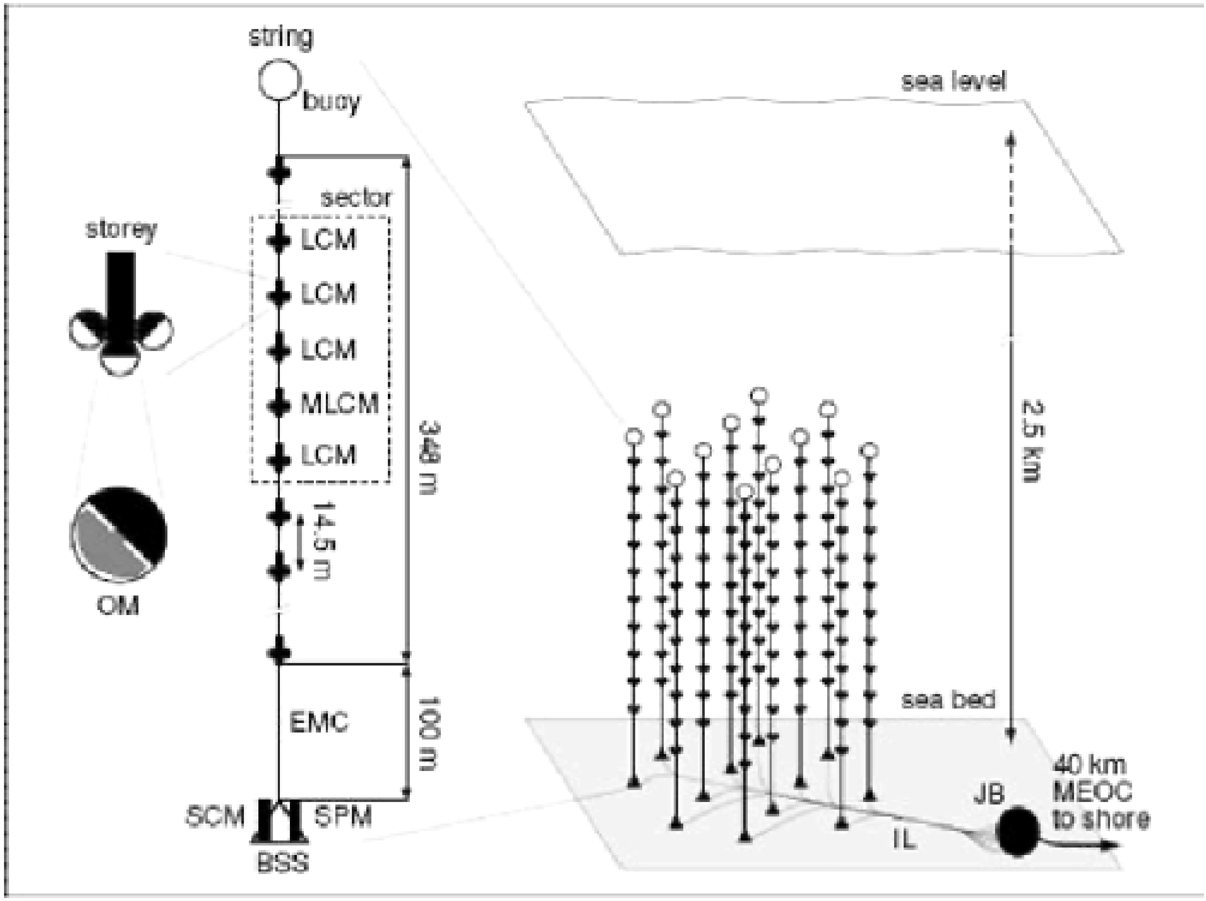


IceCube



- Status 40 of 80 strings deployed
- Completion in 2011-12 season

Antares



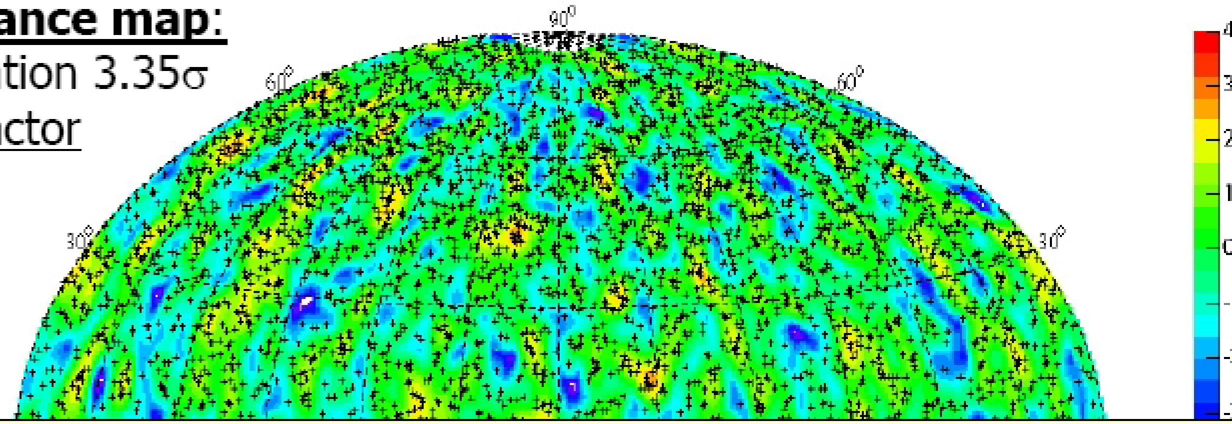
Five strings and transmission to shore already deployed

Lake Baikal

Amanda 4 year Sky Map

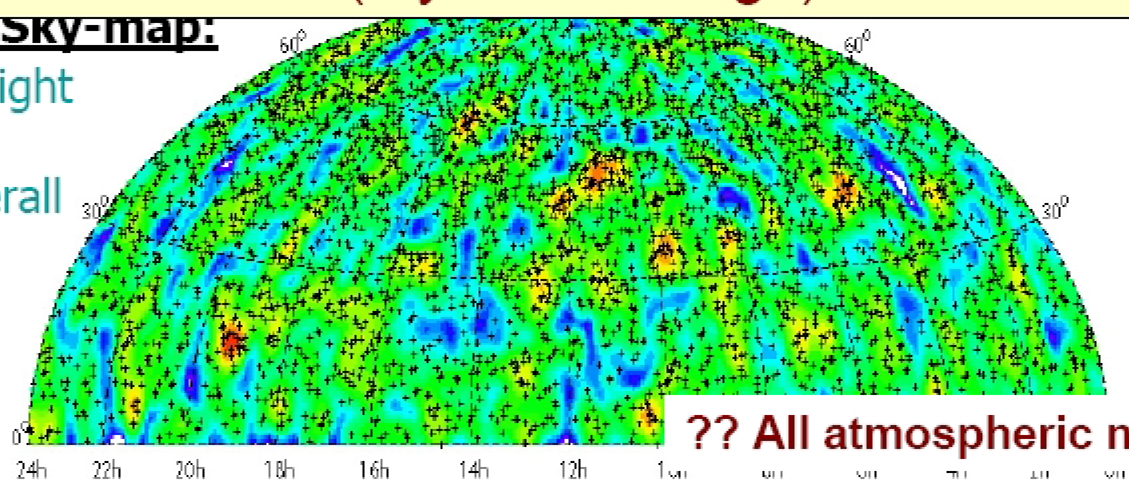
Unbinned statistical analysis: use track resolution (pdf) for each event

The **Significance map:**
Highest deviation 3.35σ
before trial factor
correction



No statistically significant excess from steady point sources
(4 years average)

Scrambled Sky-map:
Randomize right
ascension to
evaluate overall
probabilities



?? All atmospheric neutrinos ??

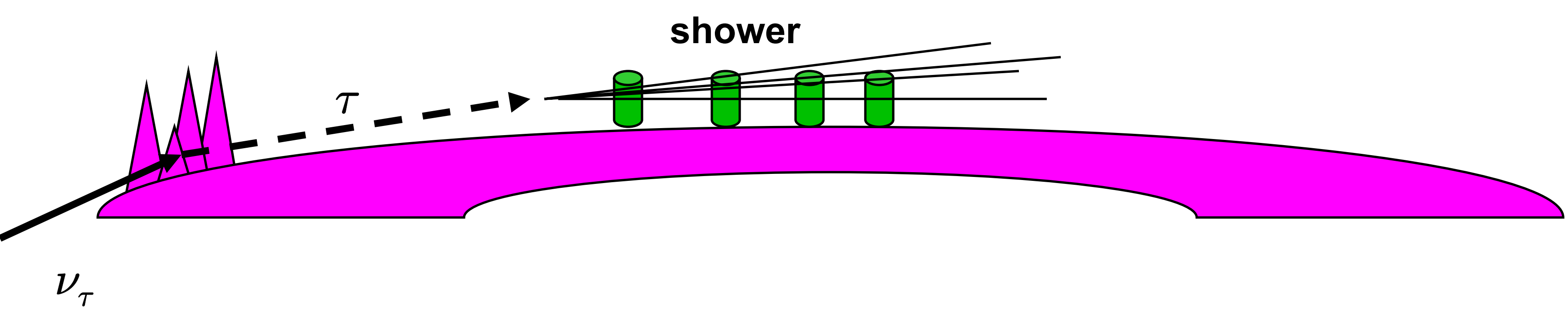
[From Elisa Rescondi, Aspen 05]

Comparison of liquid vs. solid water

- Bioluminescence: water has high singles rate
- Scattering ice: ~20m, water >100m
- Absorption ice~ 100m, water ~ 40m
- Deployment issues

Auger ν Search

- **Other natural media = Earth + Air**

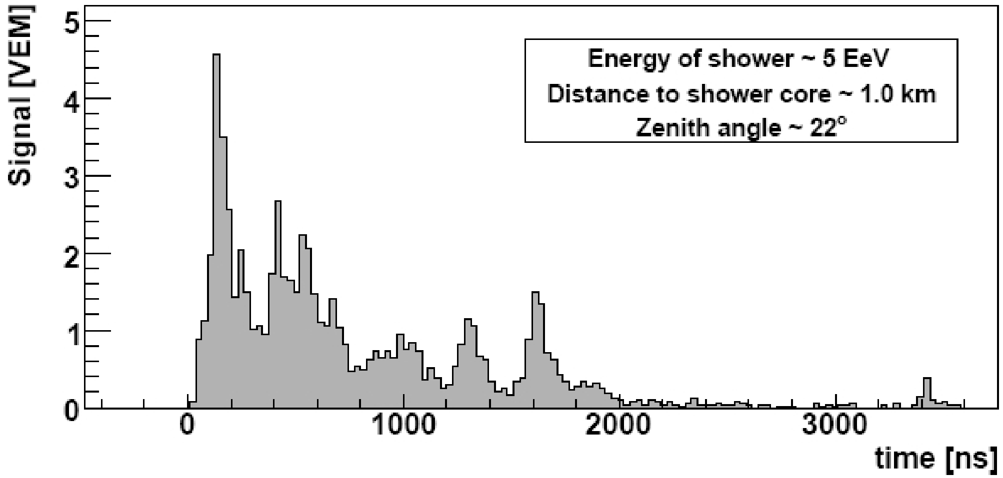


- **now SD based**
- **could also use FD**

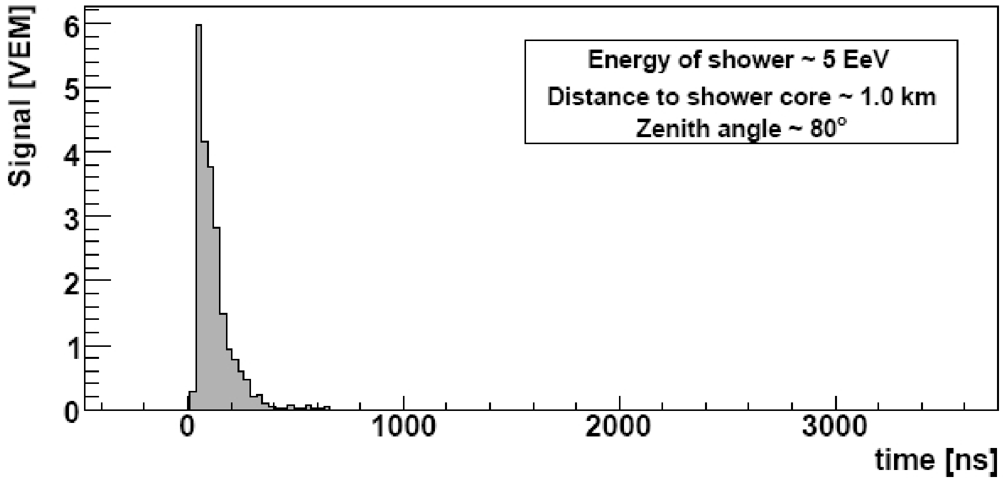
Even if $\nu_e : \nu_\mu : \nu_\tau$ is 1:2:0 at source ….

→ 1: 1: 1 after oscillations

Auger



Young and electromagnetic



Old and muonic

- Look for young showers, coming from horizon

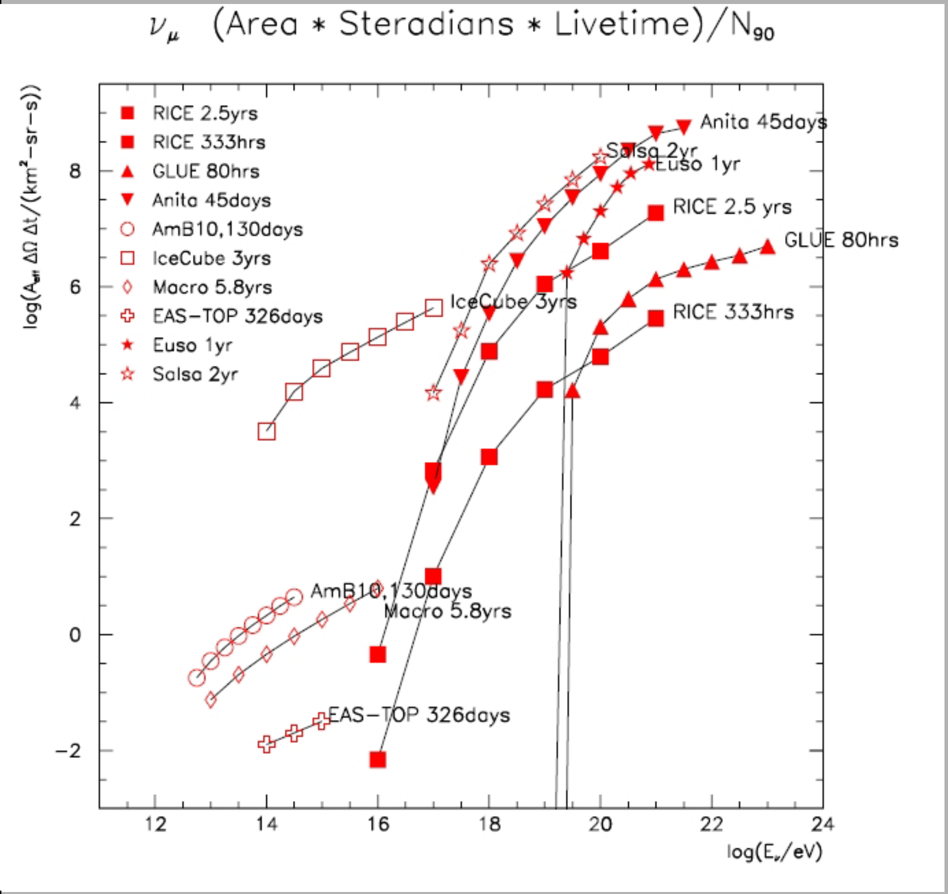
What can you do with your ν telescope?

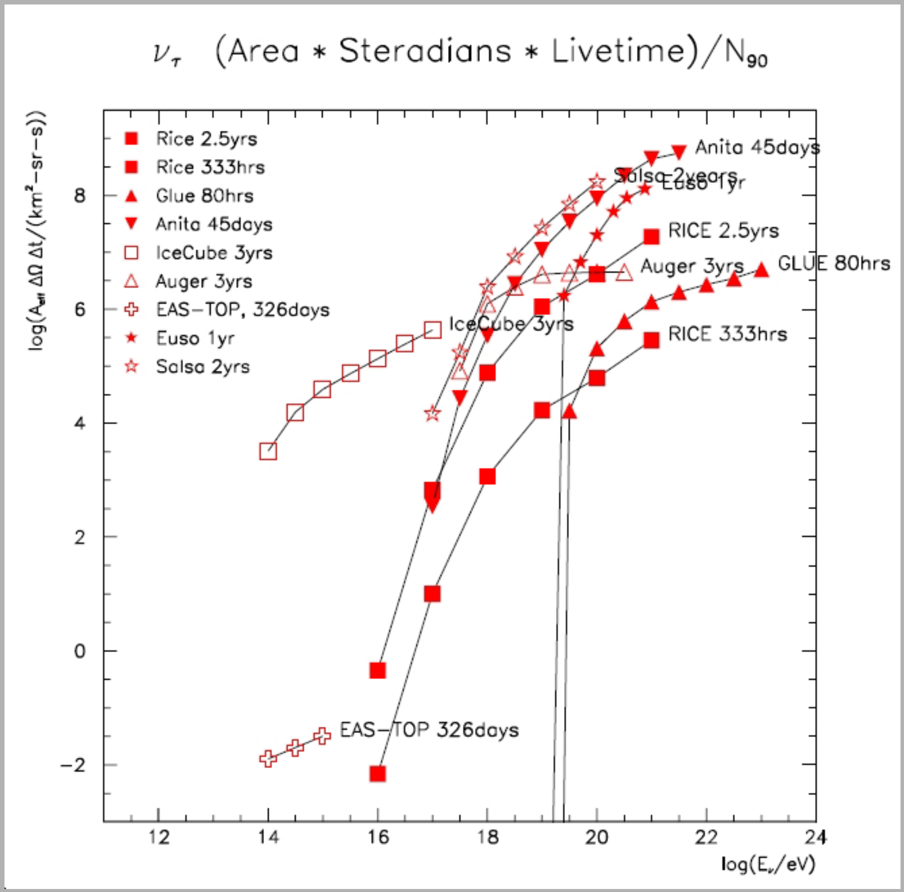
- Excellent guide → Look at list of Amanda papers:
  - **Search for extraterrestrial point sources of high energy neutrinos with AMANDA-II**
  - **Search for a Diffuse Flux of Cosmic Neutrinos**
  - **Limits on the muon flux from neutralino annihilations at the center of the Earth with AMANDA**
  - **Limits to the muon flux from neutralino annihilations in the Sun with the amanda detector.**
  - **Observation of high energy atmospheric neutrinos with AMANDA.**
  - **The search for muon neutrinos from gamma-ray bursts with AMANDA B-10 and AMANDA-II**
  - **Search for magnetic monopoles etc.**

Next Lecture

- **How can we go beyond $1km^3$?**
- **Why would a particle physicist be interested in this anyway?**

Comparison of Detector Discovery Potential: $[A\Delta\Omega]_{eff} \times \Delta t_{live} / N_{90}$

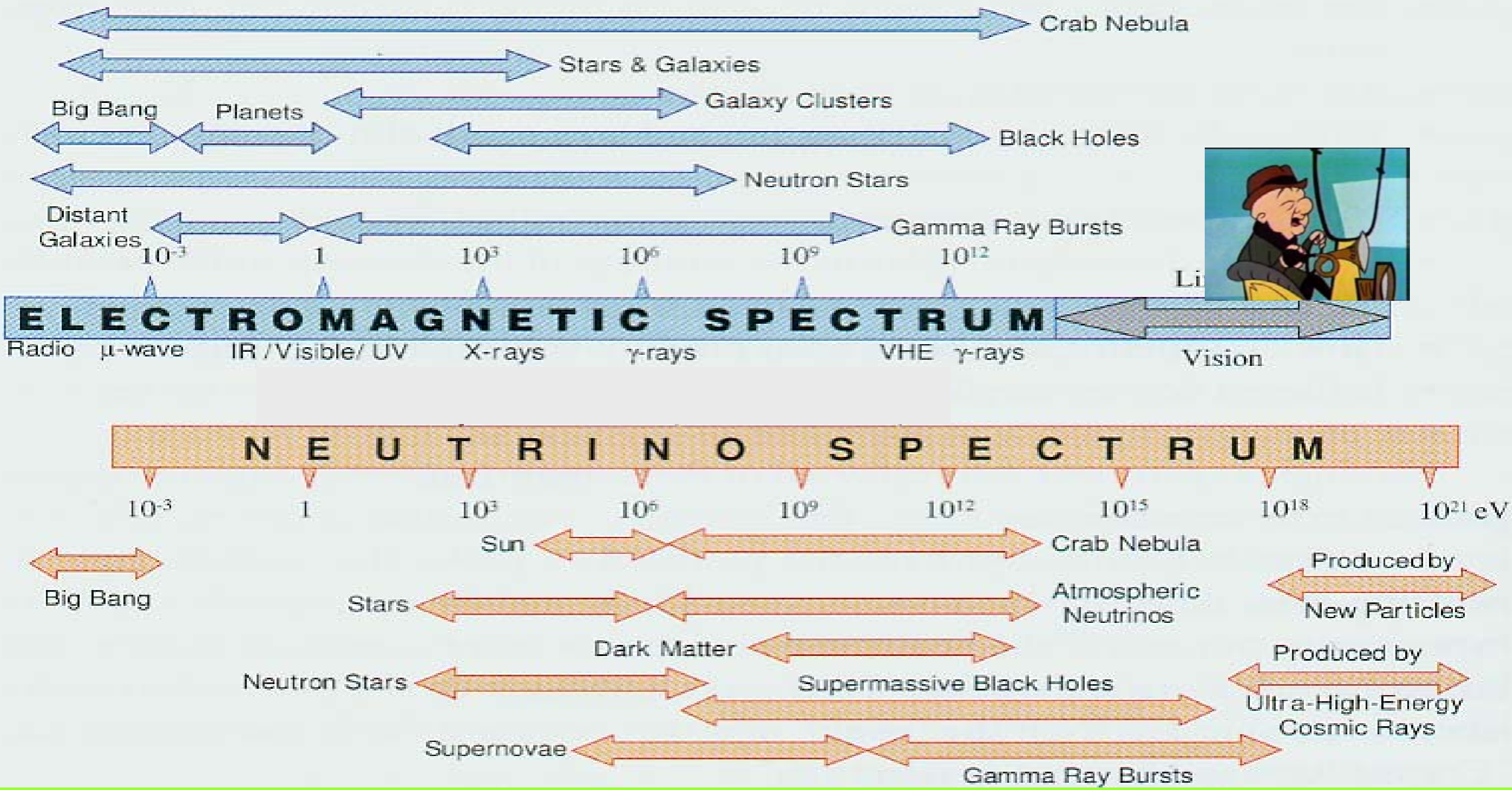




ν_μ ν_τ

illustrative purposes (a bit out of date)

Conclusion-I (for an astronomer):



accessible with optical techniques in natural media

from
Nat. Research council