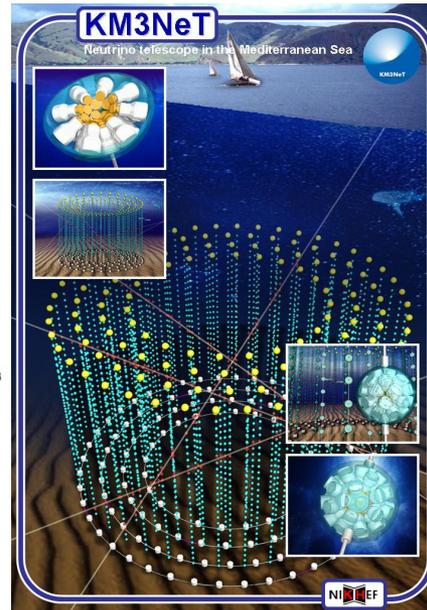
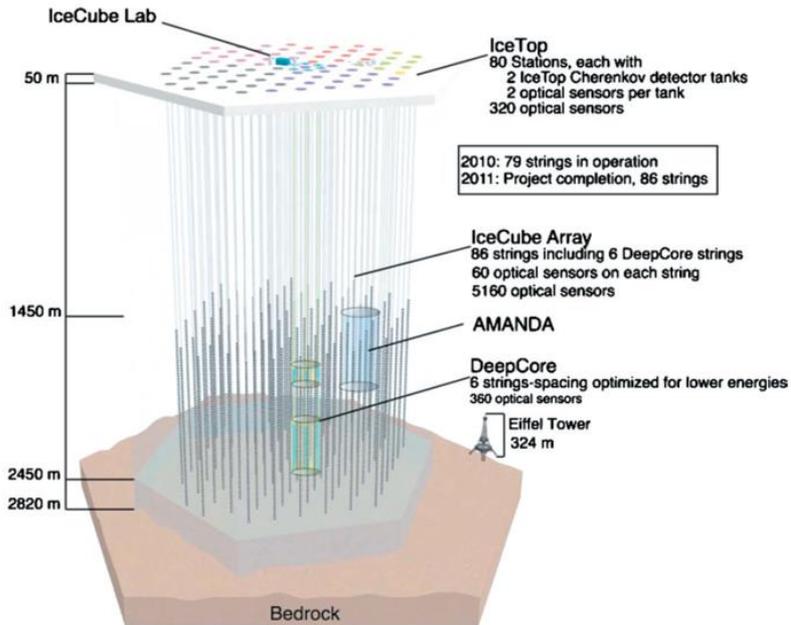


New detectors in neutrino (astro)physics

IMPRS Retreat, 2011, Hamburg

Jan Wagner



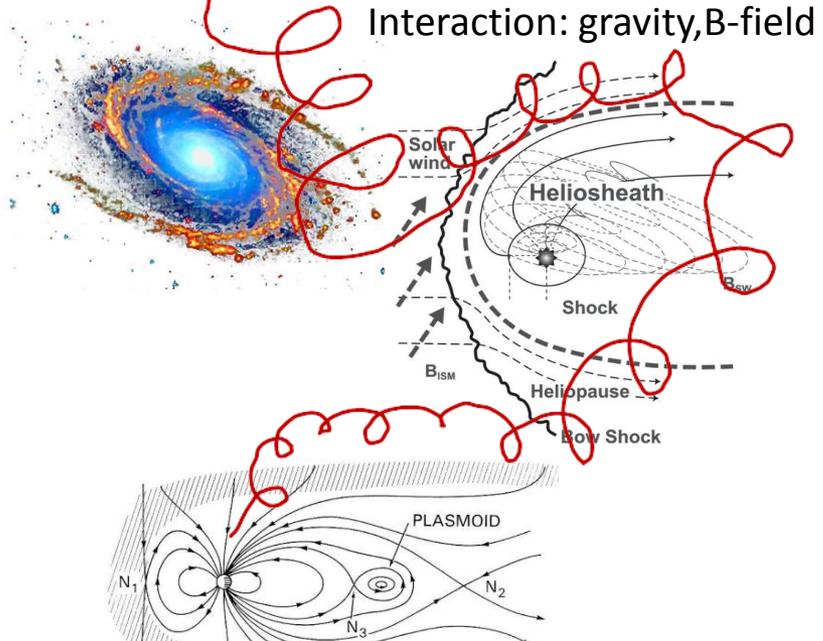
Overview

- Cosmic ray and neutrino behaviour, detection
- Cherenkov-type detector size vs energy
- New Cherenkov-type detector examples
- New neutrino oscillation experiments
- Direct neutrino mass measurement
- Cosmic neutrino background
- Summary

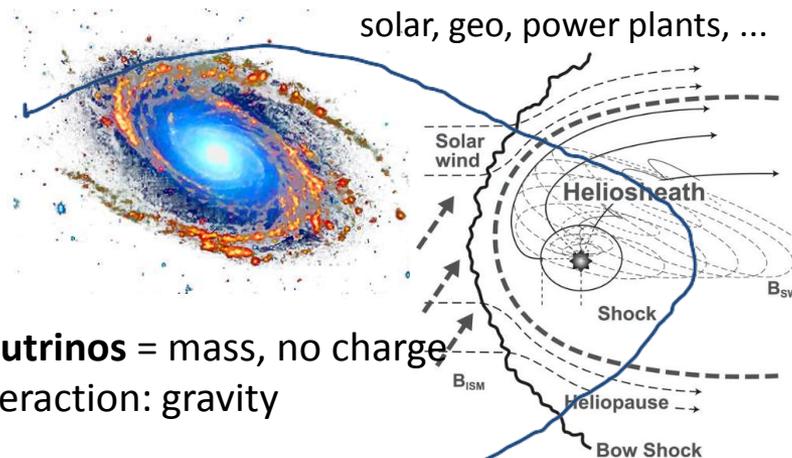
Cosmic rays and neutrinos

CR sources: AGN, SN, SMBH, Big Bang, ...

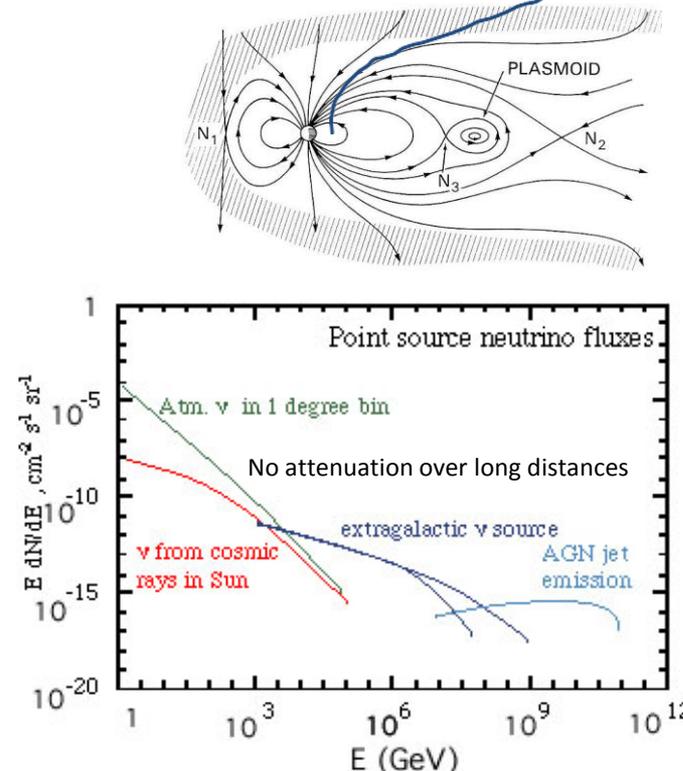
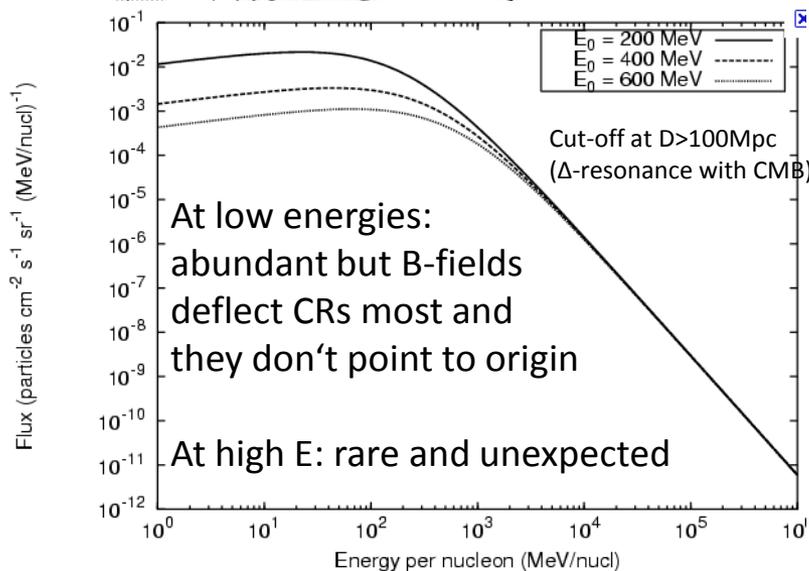
Cosmic rays = 89% protons
Interaction: gravity, B-field



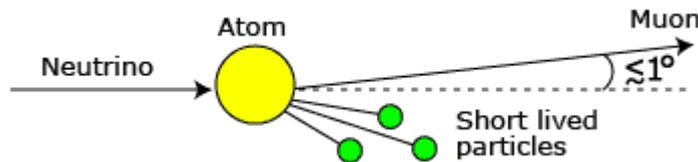
ν sources: AGN, SN, SFR, GC DM, solar, geo, power plants, ...



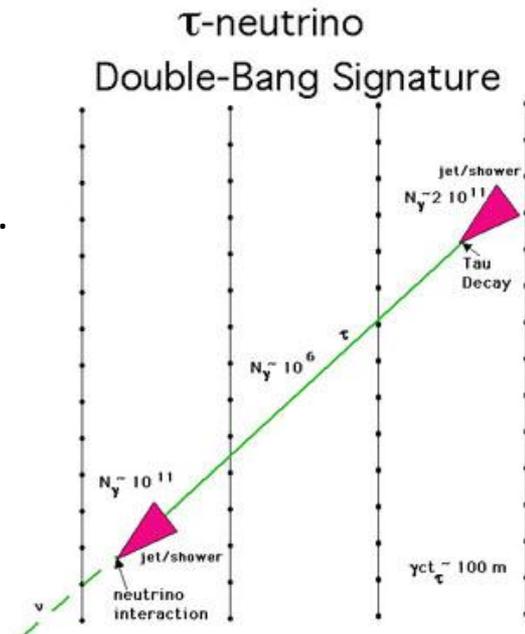
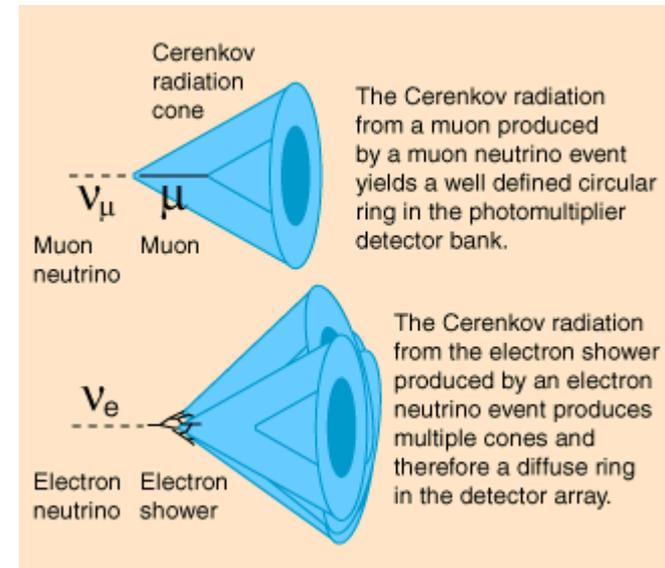
Neutrinos = mass, no charge
Interaction: gravity



Detecting neutrinos and CRs

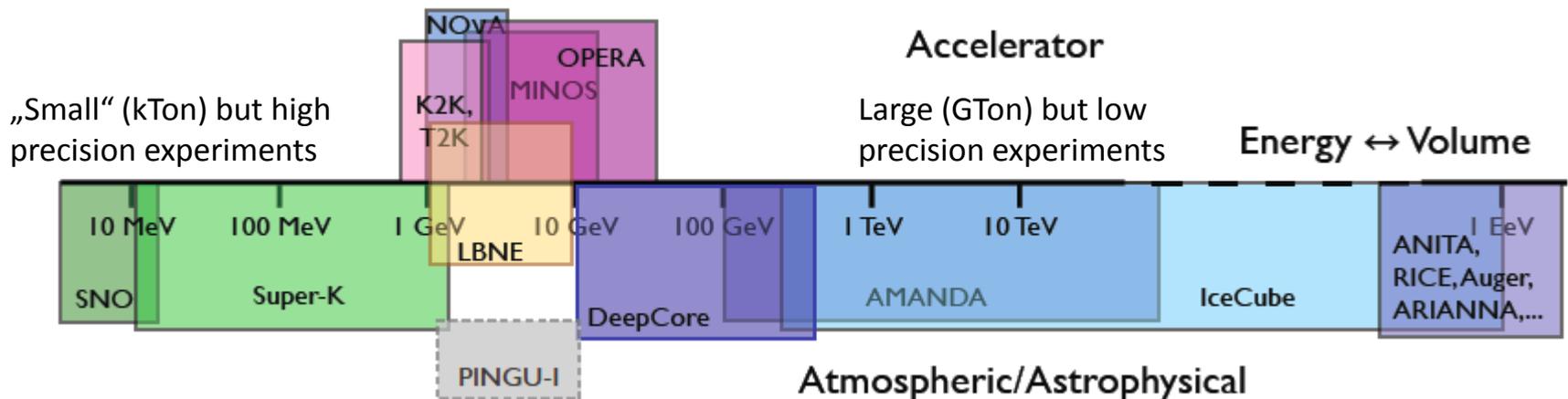


- Neutrino interaction types:
 - **Neutral current** and **Elastic scattering**: flavor unchanged, interaction partner accelerated, may produce Cherenkov glow, diffuse cones
 - **Charged current**: ν_e, ν_μ, ν_τ neutrino transforms into corresponding charged lepton (e, muon, tau) and decays and/or produces Cherenkov, with characteristic cones
- Indirect neutrino detection:
 - (long term: neutrino modulates **radioactive decay rate** e.g. in ^{54}Mn (2010 solar ν flux experiment, controversial))
 - **Calorimeters**, or **Scintillators** ($>1.8\text{MeV}$; $p \Rightarrow n + e^+$), or detection of **Cherenkov** light cone / radio pulse
- Trajectory of heavy muon matches ν_μ trajectory, can determine direction of neutrino source. Same for tau.
- Cosmic ray secondary particles contain muons. Can also be observed with Cherenkov detector.
- Neutrino flavor can be deduced from cone pattern
- Observing flavors mix allows neutrino oscillation experiments (Fermilab Long Baseline Neutrino Experiment 2015+) ; Physics beyond Standard Model



Cherenkov ring detector size

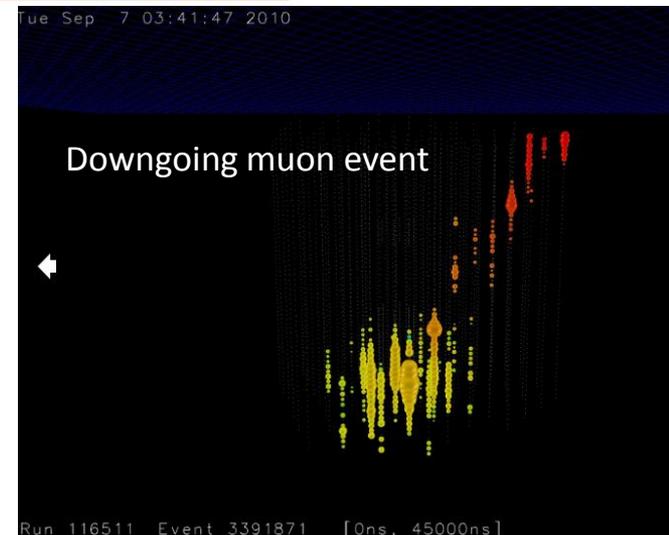
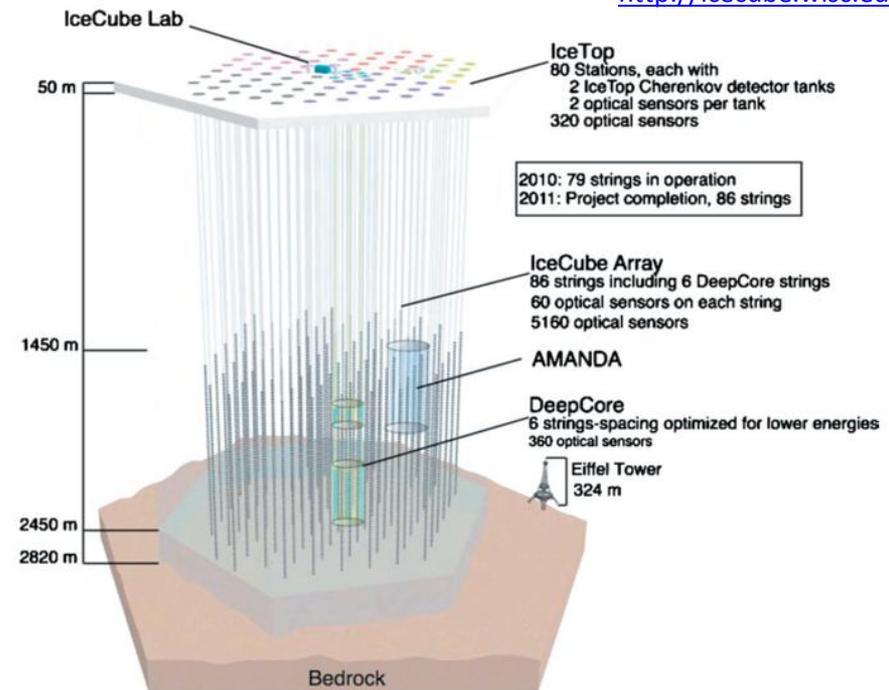
- Higher neutrino energy => larger cross-section and shorter interaction length
 - PeV energies: interaction length shorter than earth diameter
- Detector high energy limit: Volume
 - 100 PeV neutrino has $L=300\text{km}$, expected flux $10/\text{km}^2\text{yr}$
 - => $0.03\text{ events}/\text{km}^3\text{yr}$ => required volume $\gg 10\text{ km}^3$
- Detector low energy and angular resolution limit: sensor spacing
 - supernova neutrinos $\sim 10\text{MeV}$ => ~ 200 Cherenkov photons
 - detector mass absorbs (water) or scatters (ice) photons
 - to measure SN neutrino light curve, need e.g. 20cm sensor spacing in water
- New neutrino observatories: increase volume, add dense sensor subarrays



IceCube + DeepCore + PINGU-I/II

<http://icecube.wisc.edu>

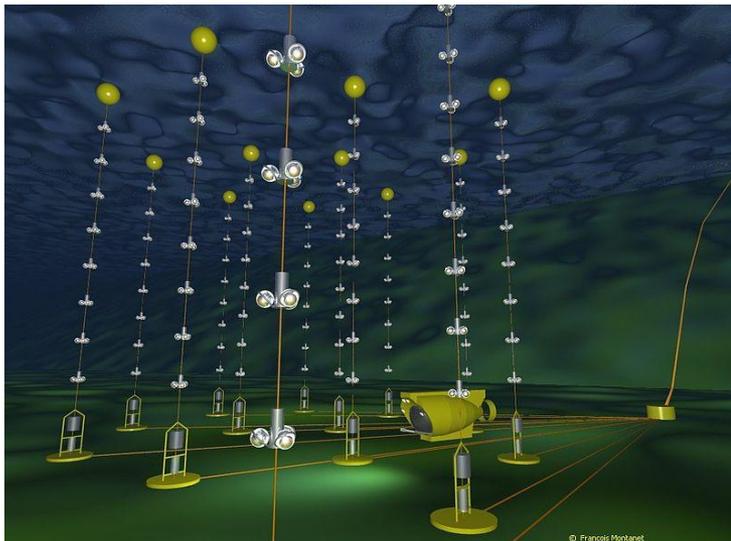
- South Pole, 2000m depth, 1 km³ of ice, 5160 optical sensors (PMTs)
- E= 200 GeV ... 1 EeV, has largest effective area (100m²) and best point src sensitivity
- IceTop 160 surface tanks for detecting cosmic ray shower (atm. neutrino vetoing, or separate CR experiments)
- DeepCore was added to lower to 10 GeV
- PINGU-I (in 2014/15) will lower to 1 GeV
- Main science:
 - Supernova Early Warning System
 - Map of southern galactic SNs
 - Measure neutrino fluxes from different source types (AGN, SN, pulsars, ...)
 - Track for correlation with GRB events
 - Neutrino oscillation θ_{13} parameter ($\ll 1$)
 - Dark Matter: probe mass of WIMPs or neutralinos
- Future science (PINGU-I, II): 1 GeV and sub-GeV reach
 - Proton decay limit to 10³⁶ years
 - SN neutrinos beyond 1 Mpc for ~1 SN per year
 - Further limit WIMP mass range



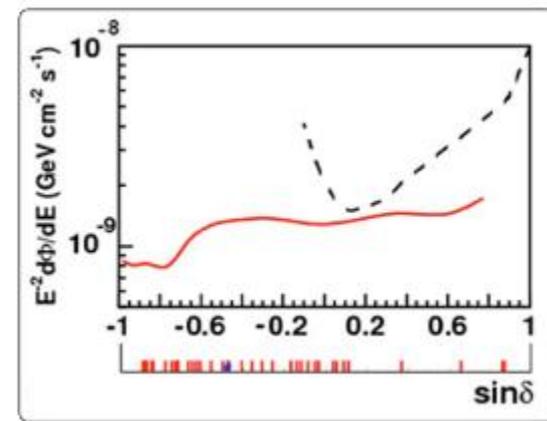
<http://www.astrophys-space-sci-trans.net/7/157/2011/astra-7-157-2011.pdf>

KM3NeT (EU)

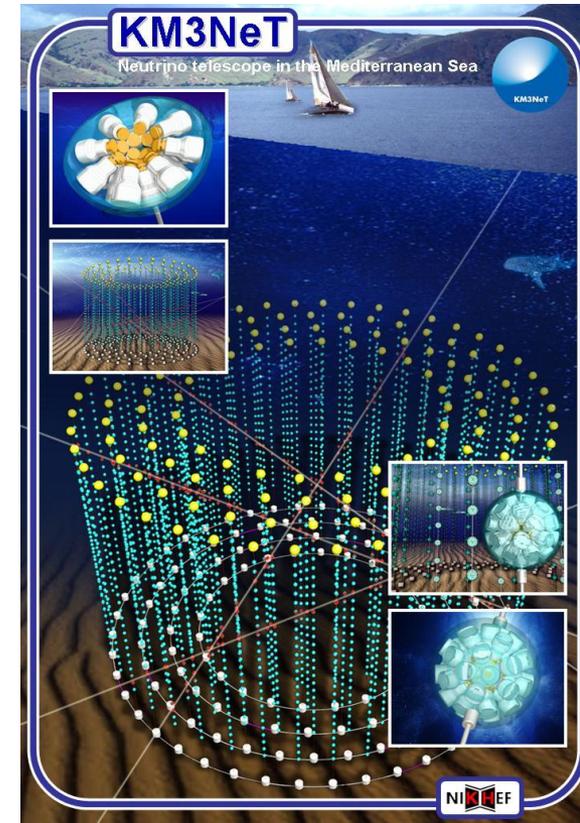
- IceCube so far no point sources detected yet. Too low sensitivity (?)
- KM3Net: *same science as IceCube* but in 3 km³
 - Mediterranean, Northern hemisphere, water, construction 2012-2014
 - Plans 10 GeV – 100 TeV, area 4.2 km²km
 - Better angular resolution (0.1 vs 3 deg)
 - Better point source sensitivity
- Re-uses ANTARES, NEMO pilot projects



<http://www.km3net.org/home.php>

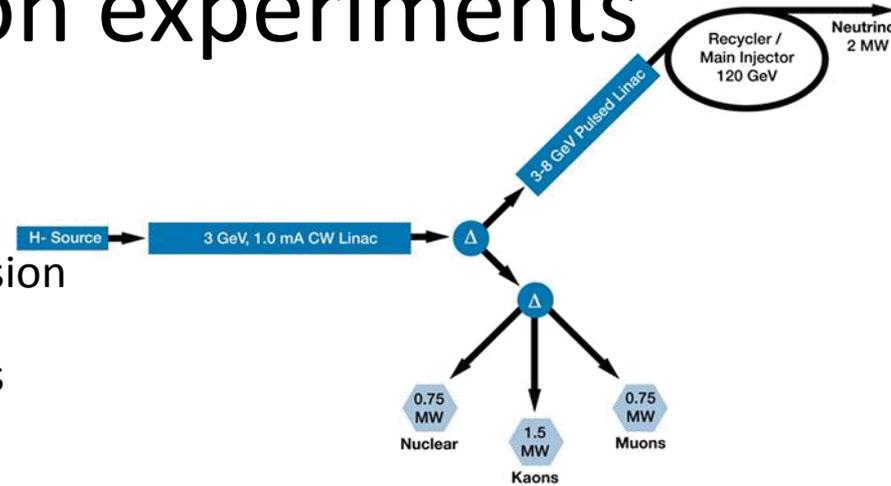


Point source sensitivities vs source declination: IceCube (dashed) and KM3NeT.



Neutrino oscillation experiments

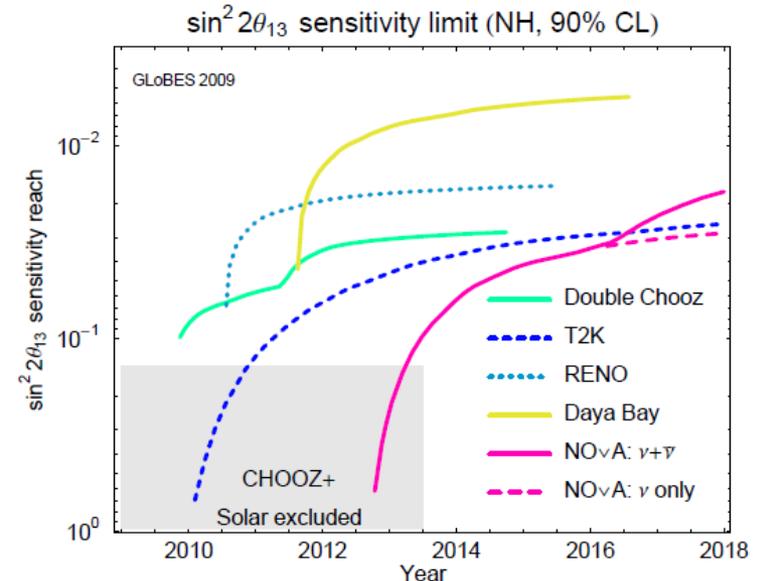
- Solar neutrino deficit => neutrinos must be superposition of 3...4 mass eigenstates
Physics outside of Standard Model
- Neutrinos change flavor over distance, conversion enhanced by electrons in matter
- Beam neutrinos observed at >100km baselines
 - 2006-2010: Los Alamos LSND, Fermilab MiniBooNE, Karlsruhe KARMEN
 - 2010: CERN OPERA found tau in ν_μ beam
 - 2011: T2K Tokai to Kamioka 295km found six ν_e in ν_μ beam
- 2012 or later: Fermilab Project X combined with Long Baseline Neutrino Experiment; Double Chooz; Fermilab NOvA and chinese Daya Bay
 - Higher precision measurement of ν_e/ν_μ oscillation parameter $\theta_{13} \ll 1$ – perhaps zero??



Fermilab Project X : 8 GeV LINAC, recycler for 60-120 GeV neutrino target, observatories Sudbury and Sanford Laboratory ~1000km baseline

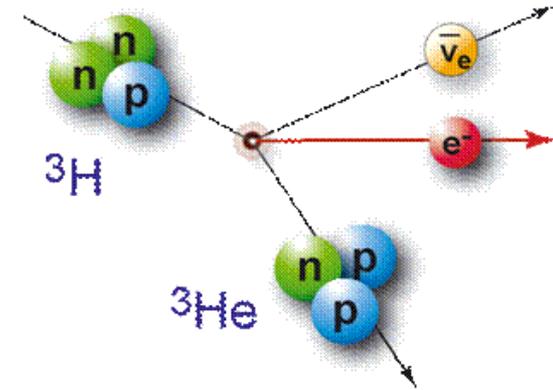
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} = \begin{bmatrix} 0.85 & 0.53 & 0 \\ -0.37 & 0.60 & 0.71 \\ 0.37 & -0.60 & 0.71 \end{bmatrix}$$



Karlsruhe Tritium Neutrino Experiment

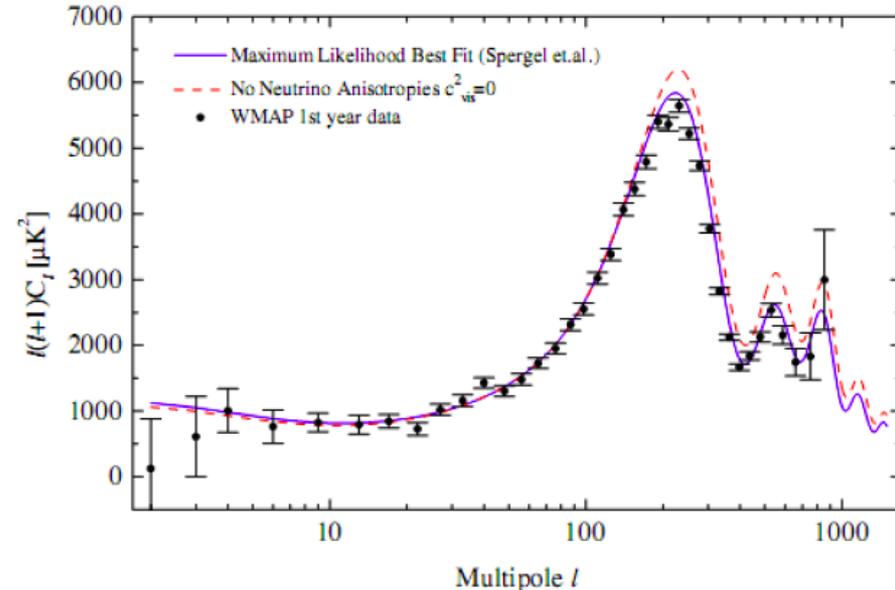
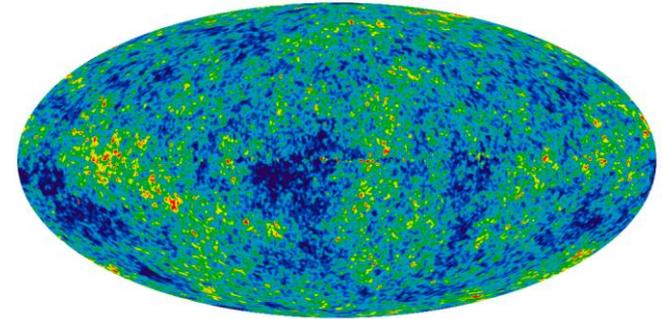
- Neutrino oscillation only indication of ν having mass – KATRIN is a direct mass measurement attempt
- Idea: ν_e mass in Tritium beta decay = $E_{\text{kin}}(\text{massless } \nu_e \text{ model}) - E_{\text{kin}}(\text{observed})$
- Magnetic collimator and filter to select electrons above adjustable threshold, remove „background“ electrons
- Calorimetric measurement of the selected higher-energy electrons
- Older experiments:
0.5 eV sensitivity, no ν_e mass found
- KATRIN: 0.2 eV sensitivity, 10^{15} decays/s
- KATRIN may rule out massive neutrinos as significant particles in Dark Matter halos



KATRIN spectrometer / magnetic collimator
During transport to Karlsruhe site 2011

Cosmic Neutrino Background

- Deeper look into Big Bang
 - Hadron epoch end @1s:
neutrinos decouple, relic neutrinos
 - ...
 - Recombination end @379000yr:
cosmic microwave background
- From WMAP CMB data, at 95.5% confidence, neutrino background is expected at 1.95 K (2.5 MeV)
- ~2.5MeV is below minimum energy thresholds of interactions used in current detectors -- impossible to observe CNB?
- Some papers: CNB might be detectable just barely with KATRIN-type experiments.
- Luck depends on neutrino mass...



CMB temperature angular power spectrum
Dashed red: model with no neutrino anisotropies
Dots: WMAP data. Solid blue: ML fit of WMAP data

Summary

- Several indirect methods for neutrino telescopes; Scintillation (Long Neutrino Baseline Expt (not described here)), Cherenkov (IceCube, KM3NeT) calorimeter/decay (KATRIN)
- Cherenkov cones are characteristic to flavor => can measure flavor ratios directly (e:muon:tau)
- New detectors: improve limits to neutrino oscillation parameters, neutrino mass, existence of cosmic neutrino point sources,
- Lots of astrophysical advances in next 10 years
- Major cosmological advances -- if CNB could soon be observed (with KATRIN?)

Thank you for your attention!