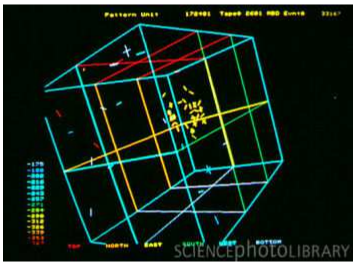
The University Of Sheffield.



Neutrinos and the Universe

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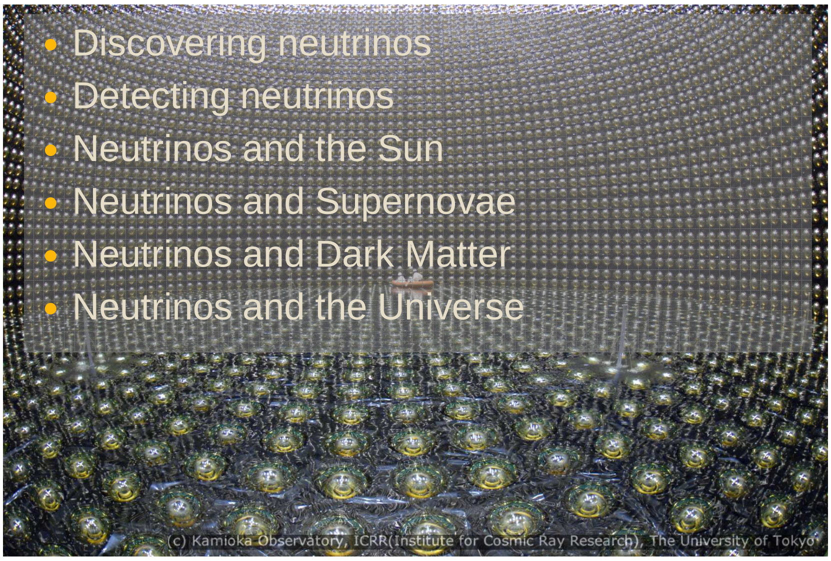
University of Sheffield

Neutrinos and the Universe



- Discovering neutrinos
- Detecting neutrinos
- Neutrinos and the Sun
- Neutrinos and Supernovae
- Neutrinos and Dark Matter
- Neutrinos and the Universe

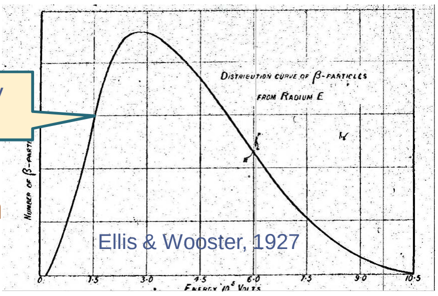
(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Discovering neutrinos

- Neutrinos have
  - no charge
  - very little mass
  - very weak interactions with everything else
- Why would anyone suspect their existence?
  - radioactive β decay
    $X \rightarrow X' + e^- + \bar{\nu}_e$

should have
$E = \Delta mc^2$

obviously
doesn't!



Ellis & Wooster, 1927

  - Wolfgang Pauli suggested emission of an additional particle (1930)

Discovering neutrinos

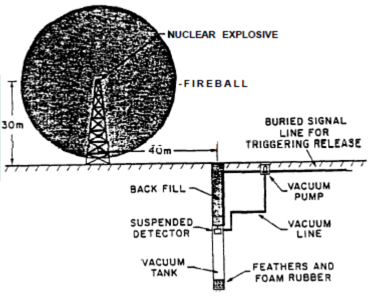
- Fermi's theory of weak force (1933) assumed the existence of the neutrino, but nobody had detected one directly
  - Pauli worried that he might have postulated a particle which was literally impossible to detect
- Neutrinos interact so weakly that they are very hard to see
  - you need a very intense source to make up for the extremely small chance of any given neutrino interacting

Discovering neutrinos

- Enter Fred Reines and Clyde Cowan (1950s)
  - Plan A: use a bomb!
    - lots of neutrinos from fission fragments
    - detect via $\bar{\nu}_e + p \rightarrow e^+ + n$

detect γ rays produced when it annihilates with e^-

late γ rays emitted when it is captured by a nucleus



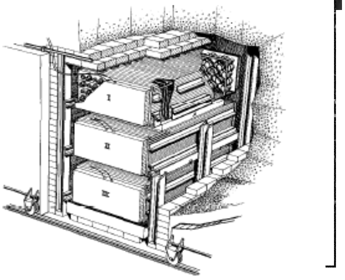
- problem—need your detector to survive the blast...

Discovering neutrinos

- Enter Fred Reines and Clyde Cowan (1950s)
  - Plan B: use a nuclear reactor
    - lots of neutrinos from fission fragments
    - detect via $\bar{\nu}_e + p \rightarrow e^+ + n$

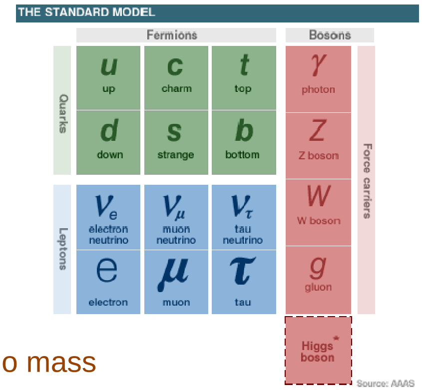
detect γ rays produced when it annihilates with e^-

late γ rays emitted when it is captured by a nucleus



- detector survives... can repeat experiment

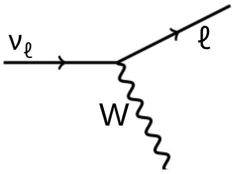
Neutrinos and their friends



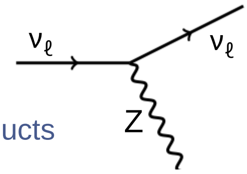
- Standard Model of particle physics has three different neutrinos
  - each associated with a charged lepton
- All have similar properties
  - no charge and almost no mass
  - interact only via weak force and gravity
  - apparently completely stable
- Recognise difference when they interact
  - each will produce only its own charged lepton

Detecting neutrinos

- Neutrinos interact in two ways:
  - charged current
    - neutrino converts to charged lepton (electron, muon, [tau])
    - you detect the lepton



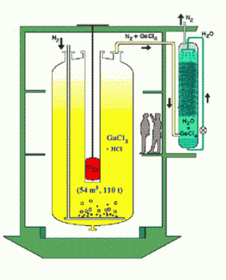
  - neutral current
    - neutrino just transfers energy and momentum to struck object
    - you detect the recoil, or the products when it breaks up



- Either way you need a cheap method of detecting charged particles—usually leptons

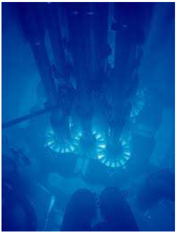
Detecting neutrinos

- Radiochemical methods
  - neutrino absorbed by nucleus converting neutron to proton
    - new nucleus is unstable and decays
    - detect decay
  - no directional or timing information
    - but good performance at low energies
    - used for solar neutrinos
      - ^{37}Cl, ^{71}Ga

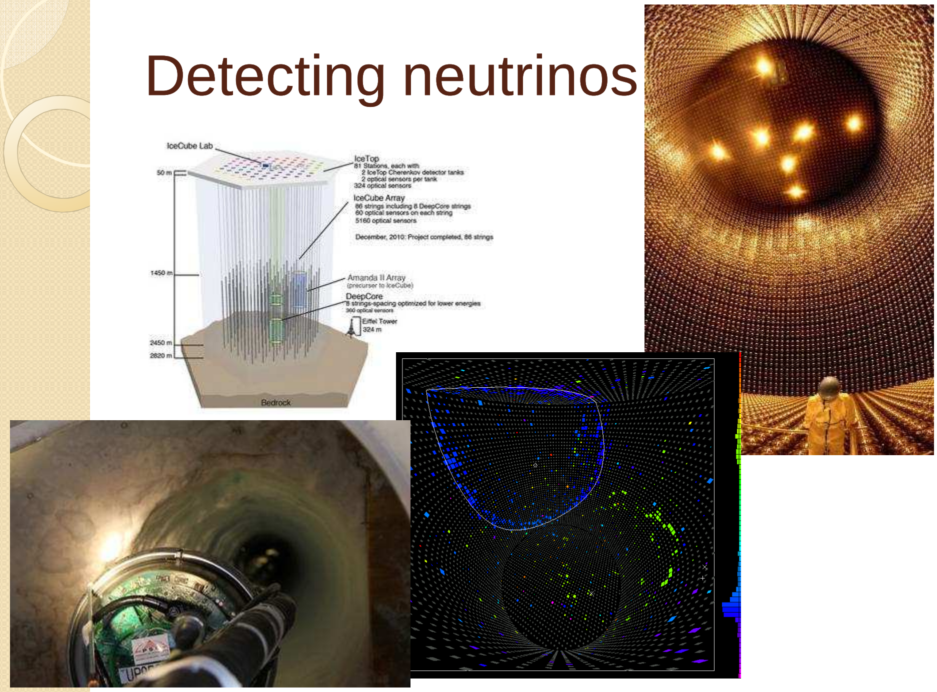


Detecting neutrinos

- Cherenkov radiation
  - nothing travels faster than the speed of light **in a vacuum**
    - but in transparent medium light is slowed down by factor *n*
    - charged particles aren't
    - result: particle "outruns" its own electric field, creating shock front similar to sonic boom
    - seen as cone of blue light
  - good directional and timing information, some energy measurement

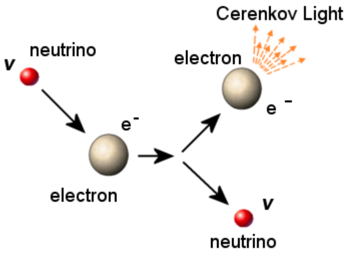


Detecting neutrinos

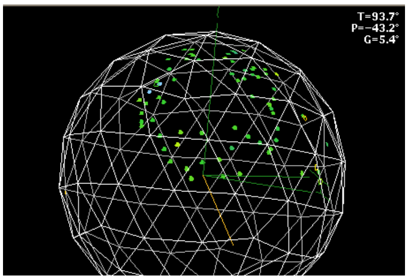


Neutrinos and the Sun

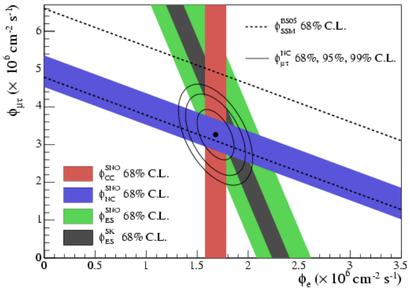
- The Sun fuses hydrogen to helium
  - 4 ^{1}He → ^{4}He + 2e^{+} **+ 2ν_e**
    - 65 **billion** neutrinos per square centimetre per second at the Earth
    - unfortunately rather low energy, so difficult to detect even by neutrino standards
  - radiochemical experiments detected too few neutrinos
    - so did water Cherenkovs
  - **Solar Neutrino Problem**



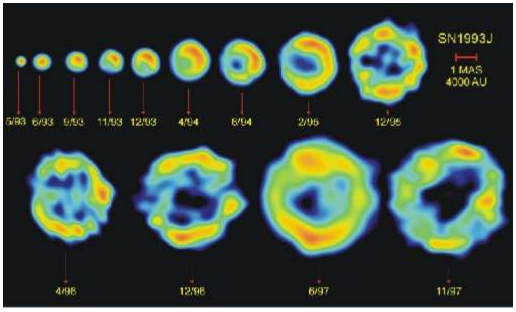
Neutrinos and the Sun



- Solar problem or neutrino problem?
  - need to count **all** neutrinos—not just those associated with electrons
- SNO experiment
  - heavy water
    - $\nu_e + d \rightarrow p + p + e^-$
    - $\nu + d \rightarrow p + n + \nu$
    - $\nu + e^- \rightarrow \nu + e^-$
  - total number fine—neutrinos change their flavour

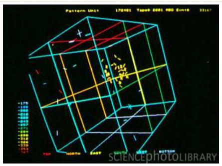


Neutrinos and supernovae

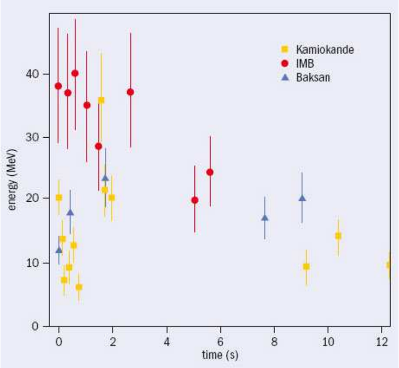


- Massive stars explode as supernovae when they form an iron core which collapses under gravity
  - neutron star formed: $p + e^- \rightarrow n + \nu_e$
  - also thermal neutrino production, e.g. $e^+e^- \rightarrow \nu\bar{\nu}$
  - 99% of the energy comes out as neutrinos
    - and neutrinos drive the shock that produces the explosion

Supernova 1987A



- In Large Magellanic Cloud, 160000 light years away
- First naked-eye SN for nearly 400 years
- 20-25 neutrinos detected

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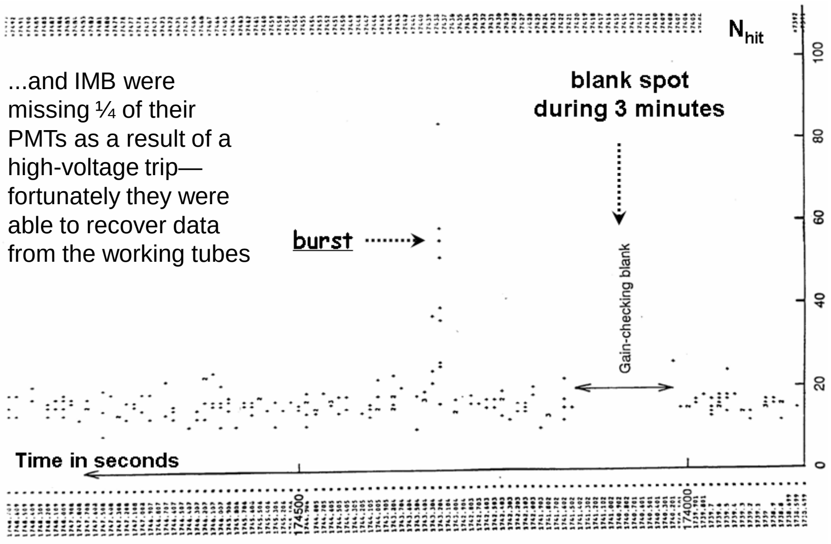
Kamiokande nearly missed the SN because of routine calibration, which took the detector offline for 3 minutes just before the burst...

...needless to say they changed their calibration strategy immediately aferwards so that only individual channels went offline!

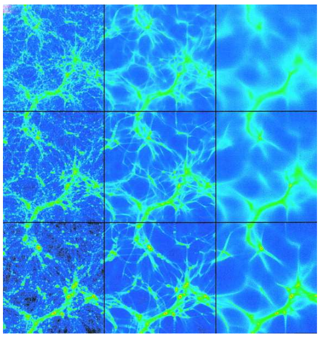
...and IMB were missing ¼ of their PMTs as a result of a high-voltage trip—fortunately they were able to recover data from the working tubes



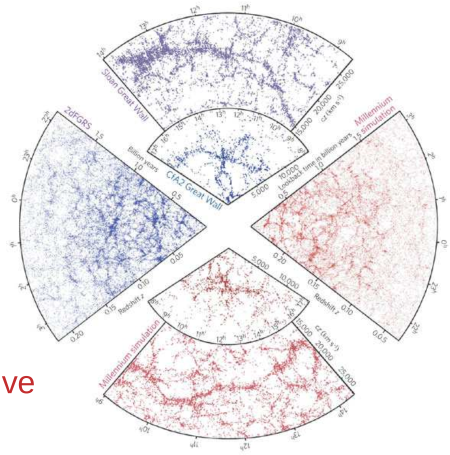
Neutrinos and Dark Matter

- If neutrinos change type
  - which they do, as shown by solar neutrino results
- then they must have (different) masses
  - essentially to provide an alternative labelling system
- Neutrinos are **very** common in the cosmos
  - ~400/cc
- so could massive neutrinos solve the dark matter problem?
  - note that "massive" neutrinos have very *small* masses—travel close to speed of light in early universe (**hot dark matter**)

"Hot" and "cold" dark matter



Faster-moving ("hot") dark matter smears out small-scale structure



Simulations with cold dark matter reproduce observed structures well

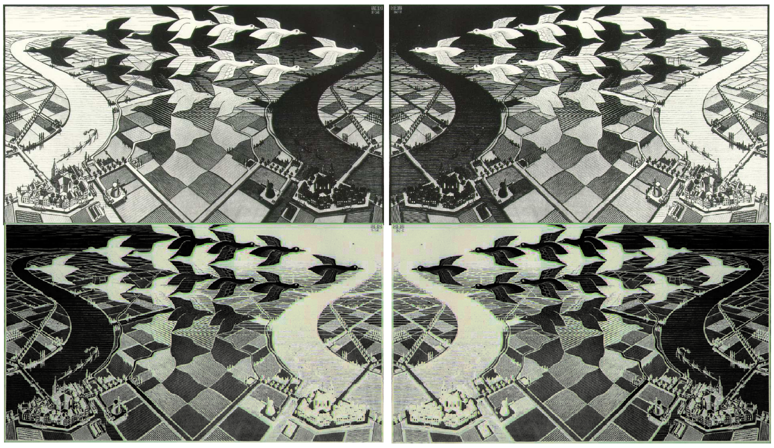
Dark matter is **not** massive neutrinos

Neutrinos and the Universe

- Matter in the Universe *is* matter
  - not 50/50 matter/antimatter
  - why not?
    - masses of matter and antimatter particles are the same
    - interactions almost the same
    - should be produced in equal quantities in early universe
- Sakharov conditions for matter-antimatter asymmetry
  - baryon number violation
    - to get B>0 from initial B=0
  - lack of thermodynamic equilibrium
    - to ensure forward reaction > back reaction
  - CP violation

What is CP violation?

- C = exchange particles and antiparticles
- P = reflect in mirror (*x*,*y*,*z*) → (-*x*,-*y*,-*z*)
- CP = do both

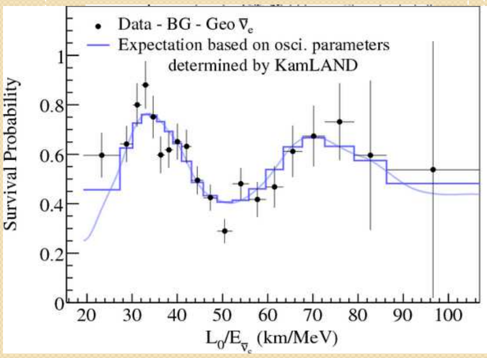


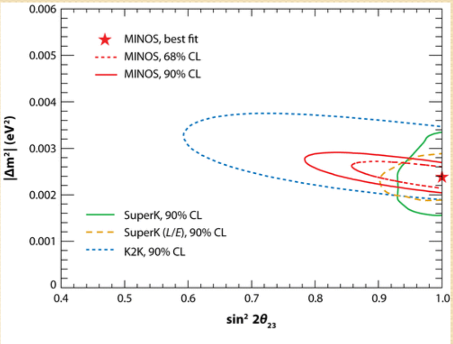
Neutrinos and CP violation

- Standard Model nearly but not quite conserves CP
  - CP violation observed in decays of some mesons (qq̄ states)—K^0, B^0
    - however this is not enough to explain observed level of asymmetry
  - neutrino sector is the other place where CP violation expected
    - consequence of flavour changes
    - need all three types of neutrinos to be involved

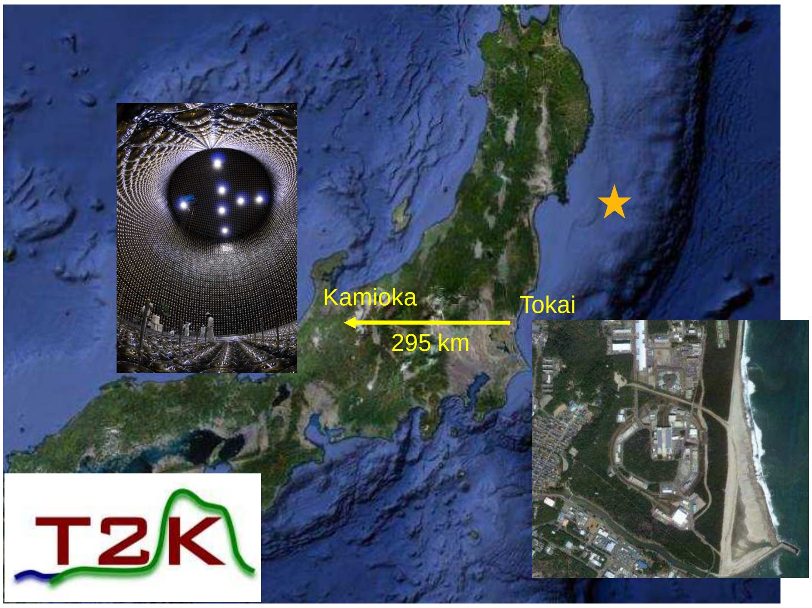
Neutrino Oscillations

Solar neutrinos	Atmospheric neutrinos
ν_e into either ν_μ or ν_τ established by SNO	ν_μ into ν_τ established by Super-Kamiokande

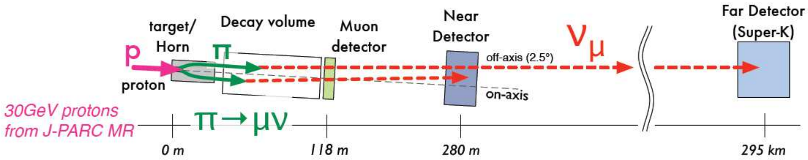




The third neutrino oscillation

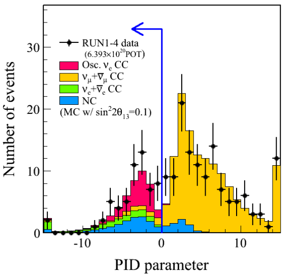


T2K measurement



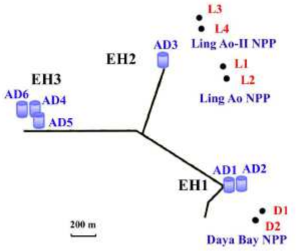
- Make ν_μ beam—search for ν_e appearance
- Find 28 events
  - expect 4 or 5 background
  - for normal hierarchy

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

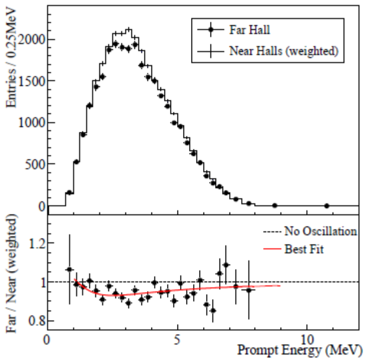


Reactor experiments

- Observe disappearance of low-energy $\bar{\nu}_e$ (energy too low to see expected $\bar{\nu}_\mu$)
- Good signals from Daya Bay (China), RENO (Korea), Double Chooz (France)



$\sin^2 2\theta_{13} = 0.093 \pm 0.009$



Conclusion

Neutrinos are fascinating but difficult to study

Present and future neutrino experiments can tell us much about the Universe we live in

Watch this space!