11. Geoneutrinos

Anti-neutrinos from the Earth – A new probe to study the interior of the Earth

- What is the amount of uranium (U), thorium (Th) and kalium ($^{40}$K) in the Earth?
- Test a fundamental geochemical paradigm: the Bulk Silicate Earth
- Determine the radiogenic contribution to terrestrial heat flow

- A georeactor at the core of the Earth?

- Measured results from KamLAND (2005) and Borexino (2010)
  - needs a liquid scintillation detector (SNO+, LENA)
11. Geoneutrinos
Heat production in the Earth

- The total heat flow emitted by the Earth is approximately 45 TW
  - equivalent to the heat production of 15000 power plants of 1000 MWel
- The heat flow has been measured at approximately 25000 locations at the surface of the Earth
  - the map shows large variations (factor of 20) between the locations
- The heat is generated, for example, by the natural radioactivity inside the Earth
  - Uranium (U), Thorium (Th), and Potassium (K)
- The same radioactive decays are believed to be the source of geoneutrinos
11. Geoneutrinos

The Earth heat flow
11. Geoneutrinos
Models for the Earth
11. Geoneutrinos
Models for the Earth

- The deepest drill hole approximately 12 km
  - at Kola Peninsula, Russia
  - initial aim 15 km, 12.261 km reached at 1989 ($T = 180\, ^\circ C$)
  - difficult to drill much deeper due to high temperature and pressure ($15\, \text{km}: T = 300\, ^\circ C$)
  - approximately one-third on the Baltic continental crust

- Information on the deeper parts obtained/derived from
  - the speed, reflection and refraction of seismic waves
  - the moment of inertia and precession motion of planets
  - physical, chemical and minerological data obtained from meteorites

- The most accepted model of the Earth composition is the Bulk Silicate Earth model (BSE)
  - direct and indirect information combined
  - estimated radiogenic heat production of U, Th, and K in the crust and mantle ($r < 3000\, \text{km}$) not explained correctly
11. Geoneutrinos

Anti-neutrinos from the Earth

- Uranium, thorium and potassium in the Earth release heat together with anti-neutrinos
  - $^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8 \cdot ^4\text{He} + 6e^- + 6\bar{\nu}$
  - $^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6 \cdot ^4\text{He} + 4e^- + 4\bar{\nu}$
  - $^{40}\text{K} \rightarrow ^{40}\text{Ca} + e^- + \bar{\nu}$ (K1, 88.8 %)
  - $^{40}\text{K} + e^- \rightarrow ^{40}\text{Ar} + \nu$ (K2, 11.2 %)

<table>
<thead>
<tr>
<th>Decay chain</th>
<th>$Q$ [MeV]</th>
<th>$t_{1/2}$ [10$^9$ yr]</th>
<th>$E_{\text{max}}$ [MeV]</th>
<th>$\epsilon_H$ [W/kg]</th>
<th>$\epsilon_{\bar{\nu}}$ [kg$^{-1}$ \cdot s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>51.7</td>
<td>4.47</td>
<td>3.26</td>
<td>0.95 \times 10^{-4}</td>
<td>7.41 \times 10^7</td>
</tr>
<tr>
<td>Th</td>
<td>42.8</td>
<td>14.0</td>
<td>2.25</td>
<td>0.27 \times 10^{-4}</td>
<td>1.63 \times 10^7</td>
</tr>
<tr>
<td>K1</td>
<td>1.32</td>
<td>1.28</td>
<td>1.31</td>
<td>0.36 \times 10^{-8}</td>
<td>2.69 \times 10^4</td>
</tr>
</tbody>
</table>
11. Geoneutrinos

Anti-neutrinos from the Earth – decay chains
11. Geoneutrinos

Anti-neutrinos from the Earth

- High-energy part of neutrinos from U and Th are above the 1.8-MeV threshold for inverse beta decay: $\bar{\nu} + p \rightarrow n + e^+$
  - can be detected, for example, by liquid scintillation detector

- Different components may be distinguished due to different energy spectra: $\bar{\nu}$ with highest energy comes from uranium

- Main source of background: neutrinos from nuclear reactors
  - energy spectra not complete overlapping:
    nuclear reactor neutrinos originate from fission fragments
    (geoneutrinos from the chains)
  - neutrino oscillations (depends on energy and distance)
11. Geoneutrinos

Anti-neutrinos from the Earth – the energy spectrum
11. Geoneutrinos

KamLAND – Kamioka Liquid scintillator Antineutrino Detector – 1 kton, depth 1 km
11. Geoneutrinos

KamLAND – measured geo-$\nu$ energy spectrum
11. Geoneutrinos

KamLAND – Results & Outlook

- The total number of observed $\bar{\nu}_e$ was 152 in the energy window relevant for geo-$\nu$'s
- Background events: $127 \pm 13$
  - reactor neutrinos: $80.4 \pm 7.2$
  - radioimpurities of $^{210}$Pb: $42 \pm 11$
    
    ($\alpha$-decay of $^{210}$Po: $\alpha + ^{13}$C $\rightarrow ^{16}$O + n)
    can be purified; result of Borexino $\Rightarrow$ factor $\sim 150$ lower

- Measuring time 749 days ($\sim 2$ years)
- Number of target protons $3.5 \times 10^{31}$
- Estimated that geo-$\nu$’s arrived in the distance of 200 km

- In Japan, large reactor neutrino background $\Rightarrow$
11. Geoneutrinos

Reactor-ν vs geo-ν events – worldwide
Data collected between December 2007 and December 2009, corresponding to 537 days of live time
  - 252 ton·yr fiducial exposure

Approximately 10 events were associated to geo-neutrinos, with the rate of approximately 4 per 100 kton per year

The observed $\bar{\nu}$-spectrum above 2.6 MeV was compatible with background from European nuclear reactors (mean base line 1000 km)
  - nuclear reactors do not exist in Italy

The hypothesis of an active geo-reactor at the center of the Earth having a power greater that 3 TW was excluded at 95% CL

Statistics not (yet) enough for accurate conclusions
  - Measurement time of 4 time more is planned (1000 ton·yr)
11. Geoneutrinos

Borexino – Geo-neutrino spectrum
11. Geoneutrinos

Table 3
Comparison the Borexino measurement of geo-$\bar{\nu}_e$ with predictions. See text for details.

<table>
<thead>
<tr>
<th>Source</th>
<th>Geo-$\bar{\nu}_e$ rate [events/(100 ton yr)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borexino</td>
<td>$3.9^{+1.6}_{-1.3}$</td>
</tr>
<tr>
<td>BSE [16]</td>
<td>$2.5^{+0.3}_{-0.5}$</td>
</tr>
<tr>
<td>BSE [31]</td>
<td>$2.5\pm0.2$</td>
</tr>
<tr>
<td>BSE [5]</td>
<td>3.6</td>
</tr>
<tr>
<td>Max. Radiogenic Earth</td>
<td>3.9</td>
</tr>
<tr>
<td>Min. Radiogenic Earth</td>
<td>1.6</td>
</tr>
</tbody>
</table>

- Hints that all terrestrial heat comes from radiogenic elements
11. Geoneutrinos

Reactor neutrino events per kiloton at Pyhäsalmi
11. Geoneutrinos

LENA – Geo-neutrino spectrum in Pyhäsalmi

- Geo-$\nu$ events in Pyhäsalmi $\sim 1300$ per year
  - nuclear reactor $\nu$ events $\sim 300$
  - $^{210}$Pb events $\sim 10$
- 2 TW hypothetical georeactor at the core of the Earth could be identified after one year measurement
- 5 years measurement
  - red curve for Th, blue curve for U
11. Geoneutrinos

Reactor neutrinos – $\Theta_{13}$

- $\Theta_{12} \sim 32.5$ deg
- $\Theta_{13} \sim 10$ deg
- $\Theta_{23} \sim 40$ deg

The third mixing angle $\Theta_{13}$ was measured by several experiments during a couple of last years
  - allows $\delta$(CP) to be determined with long baseline neutrino beams
11. Geoneutrinos

Reactor neutrinos – $\Theta_{13}$, Daya Bay, China

- **AD1 – AD6**, AntiNeutrino detectors (liquid scintillation detectors)
  - quite small, some tens of tons
- **D1, D2, L1–L4**, nuclear reactors
- Plans to upgrade to 20 kton
  - measuring the MH
12. Proton Decay

Motivation – Standard model of particle physics

- The present particle physics uses the concepts of the model called the Standard Model of particle physics
- It describes the universe in terms of matter (fermions) and forces (bosons)
  - uses 17 fundamental particles and their interactions
    - $\Rightarrow$ Higgs is predicted, and observed
  - describes $\sim$200 particles and their interactions
  - gravity not included
- SM works well, it explains nearly all experimental data collected so far, but not, for example
  - matter-antimatter asymmetry
  - non-baryonic dark matter
  - neutrino oscillation ($\nu$ masses)
12. Proton Decay

Motivation – Physics beyond the Standard model

- Standard model is not wrong, it can be extended
  - an extension to include neutrino masses is now needed
- More elaborated ideas, not yet experimentally verified, to extend the Standard Model are
  - supersymmetry (an idea to explain dark matter)
  - grand unified theories (an idea to unify electro-weak and strong interactions)
  - supergravity (an idea to unify gravity into fundamental particles)
  - superstrings and M-theory (an idea to unify 4 forces in full quantum theory)

- Some terminology
  - Hadrons – particles made of quarks and anti-quarks
    - Baryons – particles made of three quarks
    - Mesons – made of a quark and an anti-quark
  - Leptons - fundamental particles ($e, \mu, \tau, \nu$’s)
12. Proton Decay

General – 1

- General conservation laws – valid in all fields of physics – do not prevent proton of decaying
  - energy, electric charge and (linear and angular) momentum
- Free neutron is unstable: \( n \rightarrow p + e^- + \nu \) (\( \tau_n \approx 12 \text{ min} \))
  - neutron is heavier than proton
- Electron is stable
  - it is the lightest charged particle
- Most of the Grand Unified Theories (GUTs) predict that proton is unstable
  - both Super-Symmetric and non Super-Symmetric models
  - \( \tau_p \sim 10^{33-37} \text{ years (upper limit)} \)
- Proton decay has not been observed, the current limits of SK are (for non-SUSY channels)
  - \( \tau_p(p \rightarrow e^+ + \pi^0) > 8.2 \times 10^{33} \text{ years} \)
  - \( \tau_p(p \rightarrow \mu^+ + \pi^0) > 6.6 \times 10^{33} \text{ years} \)
12. Proton Decay

General – 2

- An idea that proton may be unstable, Sakharov 1967
  - an explanation of the matter-antimatter asymmetry in the universe requires CP violation and baryon number non-conservation (p-decay)

- The proton decay is a probe of fundamental interactions at extremely short distances (Planck scale) or high energies ("post-GZK")
  - an instrument for the investigation of the grand unification, of Planck-scale physics and of quantum gravity and string and M theories

⇒ It is essential to construct new experiments to search for proton decay or improve the current limits
⇒ LAGUNA

- Proton decay would perhaps be the most significant results of the future large-volume next-generation detectors (LAGUNA, Hyper-K, UNO, ...)
  - unique test of GUTs
  - important also if not observed ⇒ ruling out models not correct

- Postulated at the first time 1974
12. Proton Decay

The Grand Unified Theories (GUTs) aim to unify electromagnetic, weak and strong interactions at high energies (small distances)

- $E \sim 10^{15-16}$ GeV ($> 10^4 \times$ GZK), $R \sim 10^{-32}$ m
- Experimental verification not possible with current colliders ($E_{pp, LHC} \approx 10^9$ GeV) $\Rightarrow$ proton decay

Predicts that proton is unstable

- Two quarks in a proton transform into a lepton and an antiquark
- Baryon and lepton number violation

Simplest of the GUTs – minimal SU(5)

- The dominant decay mode is $p \rightarrow e^+ + \pi^0$ with $\tau_p \sim 10^{31}$ years, but this has already been ruled out by SK and others

Supersymmetric GUTs (SUSY GUTs)

- Baryon and lepton number violation (but conserve $B - L$)
- Make life time longer and increase possible decay channels
- For $p \rightarrow e^+ + \pi^0$, $\tau_p \sim 5 \times 10^{35\pm1}$ years (WC)
- For $p \rightarrow K^+ + \nu$, the dominant SUSY-GUT decay channel $\tau_p \sim (0.3 - 3) \times 10^{34}$ years (LSCI)
In standard model, proton decay is not allowed
- more a coincidence than a general principle
- a bound neutron is stable against all decay modes
- proton decay allowed in (many) standard model extensions

In GUTs – if baryon number conservation is violated, neutron can also decay
- the lifetime of a bound neutron would be comparable to the lifetime of a proton
- they would have different decay modes

Theoretical predictions have large deviations
- no clear picture yet
- large range of predicted $\tau_p$ and several possible decay channels
- some models already ruled out by experiments

The physics of proton decay could also be linked to the excess of matter over antimatter in the Universe
- baryon number violation
- evidence of asymmetry seen in the decay of $K^-$ and $K^+$
12. Proton Decay

GUT – Grand Unified Theories – Unification of forces

- Running Coupling Constant
  The strength of the interaction (varying as a function of the energy)

- In the beginning of the Universe one force only
  - separation due to cooling/expansion
### 12. Proton Decay

**GUT – Estimations for proton life times**

**Table 3.** Summary of several predictions for the proton partial lifetimes (years). References for the different models are: (1) [43], (2) [44, 45], (3) [46], (4) [47, 48, 49, 50], (5) [51, 52, 53, 54], (6) [55], (7) [56], (8) [57].

<table>
<thead>
<tr>
<th>Model</th>
<th>Decay modes</th>
<th>Prediction</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georgi-Glashow model</td>
<td>-</td>
<td>ruled out</td>
<td>(1)</td>
</tr>
<tr>
<td>Minimal realistic non-SUSY $SU(5)$</td>
<td>all channels</td>
<td>$\tau_p^{upper} = 1.4 \times 10^{36}$</td>
<td>(2)</td>
</tr>
<tr>
<td>Two Step Non-SUSY $SO(10)$</td>
<td>$p \to e^+\pi^0$</td>
<td>$\approx 10^{33-38}$</td>
<td>(3)</td>
</tr>
<tr>
<td>Minimal SUSY $SU(5)$</td>
<td>$p \to \bar{\nu}K^+$</td>
<td>$\approx 10^{32-34}$</td>
<td>(4)</td>
</tr>
<tr>
<td>SUSY $SO(10)$ with $10_H$, and $126_H$</td>
<td>$p \to \bar{\nu}K^+$</td>
<td>$\approx 10^{33-36}$</td>
<td>(5)</td>
</tr>
<tr>
<td>M-Theory($G_2$)</td>
<td>$p \to e^+\pi^0$</td>
<td>$\approx 10^{33-37}$</td>
<td>(6)</td>
</tr>
<tr>
<td>$SU(5)$ with $24_F$</td>
<td>$p \to \pi^0 e^+$</td>
<td>$\approx 10^{35-36}$</td>
<td>(7)</td>
</tr>
<tr>
<td>Renormalizable Adjoint $SU(5)$</td>
<td>$p \to \pi^0 e^+$</td>
<td>$\approx 10^{35-36}$</td>
<td>(8)</td>
</tr>
</tbody>
</table>
12. Proton Decay

Estimation of the life time – Application of biology

- An average human body
  - 80 kg, 60 % of H₂O
  - 1 cm³ of H₂O contains $10^{23}$ protons (of H₂O)
  - consists of approximately $\sim 10^{28}$ protons

- If $\tau_p \sim 10^{28}$ years would result in $\sim 1$ decay·year⁻¹
  - If $\tau_p \sim 10^{26}$ years would result in $\sim 100$ decays·year⁻¹

- From this simple estimation it can be concluded that the lower limit of the proton life time can not be much lower than $\sim 10^{27}$ years
  - proton decay is a high-energy phenomena ($\sim 1$ GeV)
    - it would destroy thousands of molecules
  - otherwise people would die on cancer in the age of teen-age or young adults
12. Proton Decay
Experiments – General

- Water Cerenkov detector – $\text{H}_2\text{O}$
  Liquid scintillation detector – $\text{C}_{16}\text{H}_{18}$ (PXE)
  - the free protons (two in $\text{H}$ of water and 18 in $\text{H}$ of PXE) and eight oxygen- and $6 \times 16$ carbon-protons are assumed to decay with equal probability

- For the case of a free proton in hydrogen, the momenta of the decay particles ($e^+, \pi^0$) or ($\mu^+, \pi^0$) or ($K^+, \bar{\nu}$), or ... are uniquely determined by two-particle kinematics

- For the bound protons (in oxygen and carbon), the decay-particle momenta are no longer determined by simple two-particle kinematics.
  (Small) corrections from
  - the Fermi motion of the protons (Fermi momentum, $\sim 250$ MeV/c for $p$ in $^{12}\text{C}$)
  - the nuclear binding energy ($m_p^* = m_p - E_b$)
  - the meson–nuclear interaction (in O and C)

should be considered
12. Proton Decay

Decay signals – Water Cerenkov

- Main channel: $p \rightarrow e^+ + \pi^0$
- $\tau(\pi^0) \approx 8.4 \times 10^{-17}$ s
- $B \sim 98.8\%$
Main channel: $p \rightarrow K^+ + \bar{\nu}$

- $\tau(K^+) \approx 1.2 \times 10^{-8}$ s
- $B(K^+ \rightarrow \mu^+ + \nu_\mu) \sim 63$ %
- $B(K^+ \rightarrow \pi^+ + \pi^0) \sim 21$ %

- $T(\bar{\nu}) \approx 339$ MeV
- $T(K^+) \approx 105$ MeV (Can be detected by LSCI)
12. Proton Decay

The IMB experiment (Irvine–Michigan–Brookhaven) – General

- The first experiment dedicated to the proton decay
  - IMB – University of California (Irvine), University of Michigan, Brookhaven National Laboratory
  - C. McGrew et al., PRD 59 (1999) 052004
    Search for nucleon decay using the IMB-3 detector

- The IMB-3 detector situated
  - at the Fairport salt mine, Ohio, operated by Morton International
  - at depth 1900 feet (∼600 m) (→ muon rate: \( R_\mu \approx 3 \text{ Hz} \))

- Tank
  - dimensions: 17 m × 17.5 m × 23 m (∼cubic)
  - filled with ultrapure \( \text{H}_2\text{O} \) of \( 2.5 \times 10^6 \) gallons (∼10 milj. litres)
  - 2048 8-inch PMTs

- Fiducial mass (IMB-3): 3.3 kton

- Water Cerenkov detector
12. Proton Decay

The IMB experiment (Irvine–Michigan–Brookhaven) – The tank
12. Proton Decay

The IMB experiment (Irvine–Michigan–Brookhaven) – Results

- Did not observe proton decay, but detected (IMB-1) neutrinos from SN1987A
- 851 days of exposure
  - 7.6 kton·year
    (≈4.6 × 10^{33} \text{nucleon} \cdot \text{yr})
  - 935 contained events observed
- Looked for 44 different modes of nucleon decay
  - 18 for neutron and 26 for proton decay
- Saw no evidence for nucleon decay
  - IMB-1 & IMB-3: \( p \rightarrow \pi^0 + e^+ \) (\( \rightarrow \gamma + \gamma + e^+ \)): \( \tau_p > 8.5 \times 10^{32} \text{ yr} \)
Super-Kamiokande is a 50 kton water Cerenkov detector
- at Kamioka Observatory, Japan
- depth 1 km
12. Proton Decay

Proton decay in SK – 2

- H. Nishino et al., PRL 102 (2009) 141801
Search for Proton Decay via $p \rightarrow e^+ + \pi^0$ and $p \rightarrow \mu^+ + \pi^0$ in a Large Water Cherenkov Detector

- SK-I and SK-II
  - SK-I: April 2006 – September 2001 (11146 20-inch PMTs)
  - SK-II: October 2002 – October 2005 (5182 20-inch PMTs)
  - SK-III was completed in June 2006 (when all the PMTs were reinstalled)

- Data from 91.7 kton·yr (SK-I) and 49.2 kton·yr (SK-II)
  - 1489 and 798 live days, respectively

- Results: no proton decays were observed
  - $p \rightarrow e^+ + \pi^0 \implies \tau_p > 8.2 \times 10^{33}$ yr (prev $\tau_p > 1.6 \times 10^{33}$ yr, SK)
  - $p \rightarrow \mu^+ + \pi^0 \implies \tau_p > 6.6 \times 10^{33}$ yr (prev $\tau_p > 4.7 \times 10^{32}$ yr, IMB)

- SK-III – already three years of data collected
  - predicted by theory: $\tau_p \sim 5 \times 10^{35\pm1}$ years
12. Proton Decay

LAGUNA

- Three detector options
  - GLACIER – 100 kton, liquid argon TPC
  - LENA – 50 kton, liquid scintillator
  - MEMPHYS – 600 kton, water Cerenkov

- Depths
  - GLACIER – more than 1000 mwe (∼300 m)
  - LENA – more than 4000 mwe (∼1.4 km)
  - MEMPHYS – more than 3000 mwe (∼1.0 km)

- In LAGUNA detectors at most few proton-decay signals per year
  - needs clear signal identification
  - main background source is atmospheric neutrinos ($v_\mu$), at shallow depths also cosmogenic background contributes

- Predicted $\tau_p \approx 10^{33-36}$ years by most of the GUTs
  - this range is possible to study by LAGUNA detectors
  - good sensitivity for different decay modes
12. Proton Decay

LAGUNA – GLACIER

- GLACIER – 100 kton liquid argon TPC, variable depths
- $p \rightarrow e^+ + \pi^0$, $\pi^0 \rightarrow 2\gamma$'s
  - assuming perfect particle and track identification, a background level of 1 event·Mton$^{-1}$·year$^{-1}$
  - if no signal seen in 10 years $\Rightarrow \tau_p > 4 \times 10^{34}$ years

- $p \rightarrow K^+ + \bar{\nu}$, $K^+ \rightarrow \mu^+ + \bar{\nu}_\mu$ (63 %)
  $\rightarrow \pi^+ + \pi^0$ (21 %)
  - less than 1 % of the $K$'s are mis-identified as protons (using $dE/dx$ vs $R$ and applying Neural Network algorithm)
  - good selection efficiency (atm-$\nu$ background less than one event·Mton$^{-1}$·year$^{-1}$)
  - if no signal seen in 10 years $\Rightarrow \tau_p > 6 \times 10^{34}$ years
12. Proton Decay
LAGUNA – LENA

▶ LENA – 50 kton liquid scintillator, depth 4000 mwe
▶ \( p \rightarrow e^+ + \pi^0, \quad \pi^0 \rightarrow 2\gamma's \)
  ▶ produces a 938 MeV signal
  ▶ \( e^+ \) and \( \pi^0 \) propagate approximately 4 metres (in opposite directions) before being stopped
  \( \Rightarrow \) background rejection from atm-\( \nu_\mu \)'s
  ▶ If no signal seen in 10 years \( \Rightarrow \tau_p > 10^{34} \) years

▶ \( p \rightarrow K^+ + \bar{\nu}, \quad K^+ \rightarrow \mu^+ + \bar{\nu}_\mu \) (63 %)
  \( \quad \rightarrow \pi^+ + \pi^0 \) (21 %)
  ▶ a monoenergetic signal of \( T_K \approx 105 \) MeV from \( K^+ \), and a delayed signal from its decay
  \( \Rightarrow \) coincidence signal \( \approx 257 \) MeV (\( K + \mu \)) or \( \approx 459 \) MeV (\( K + \pi \)'s)
  ▶ background rate \( \approx 0.064 \) year\(^{-1} \) by assuming coincidence signal and pulse shape analysis
  ▶ If no signal seen in 10 years \( \Rightarrow \tau_p > 4 \times 10^{34} \) years
12. Proton Decay
LAGUNA – MEMPHYS (or Hyper-K, one tank)

- MEMPHYS – 600 kton water Cerenkov, depth > 3000 mwe
- \( p \rightarrow e^+ + \pi^0, \quad \pi^0 \rightarrow 2\gamma's \)
  - estimated atm-\( \nu \) background \( \sim 2.25 \text{ event} \cdot \text{Mton}^{-1} \cdot \text{year}^{-1} \)
  - If no signal seen in 10 years \( \Rightarrow \tau_p > 10^{35} \text{ years} \)

- \( p \rightarrow K^+ + \bar{\nu}, \quad K^+ \rightarrow \mu^+ + \bar{\nu}_\mu \) (63 \%)
  \( \rightarrow \pi^+ + \pi^0 \) (21 \%)
  - a monoenergetic signal of \( T_K \approx 105 \text{ MeV} \) from \( K^+ \) can not be detected, but its decay products can be detected
    \( \Rightarrow \) not favoured channel for WC
  - If no signal seen in 10 years \( \Rightarrow \tau_p > 2 \times 10^{34} \text{ years} \)
12. Proton Decay
LAGUNA – Comparison & Conclusion

- GUTs $\implies \tau_p \sim 10^{33-37}$ years (upper limit)
  - Hyper-K and LAGUNA detectors have possibilities to detect proton decay if the current theories are correct
  - anyway, much better limits and ruling out of models obtained

<table>
<thead>
<tr>
<th></th>
<th>GLACIER</th>
<th>LENA</th>
<th>MEMPHYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+\pi^0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon(%)$/Bkgd (Mton year)</td>
<td>45/1</td>
<td>-</td>
<td>43/2.25</td>
</tr>
<tr>
<td>$\tau_p/B$ (90% C.L., 10 years)</td>
<td>$0.4 \times 10^{35}$</td>
<td>-</td>
<td>$1.0 \times 10^{35}$</td>
</tr>
<tr>
<td>$\bar{\nu}K^+$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon(%)$/Bkgd (Mton year)</td>
<td>97/1</td>
<td>65/1</td>
<td>8.8/3</td>
</tr>
<tr>
<td>$\tau_p/B$ (90% C.L., 10 years)</td>
<td>$0.6 \times 10^{35}$</td>
<td>$0.4 \times 10^{35}$</td>
<td>$0.2 \times 10^{35}$</td>
</tr>
</tbody>
</table>
13. Dark Matter

Evidence for dark matter – Coma galaxy cluster

- At the beginning of 1930’s F. Zwicky observed that galaxies in the Coma cluster were moving too fast in order to remain (by gravity) in the cluster
  - something else, that cannot be seen, must be holding the galaxies together in the cluster

- More evidence until 40 years later (Vera Rubin)
  - the gas and stars in the outer parts of galaxies were moving too fast with respect to the observed mass
    \[ \Rightarrow \text{rotation curve} \]
13. Dark Matter
Evidence for dark matter – Rotation curves

- Rotation velocity measurements of star and galaxies as a function of distance
- Spiral galaxy has most of the luminous material concentrated in a central hub and a thin disk
- If only luminous material exist, then
  - for stars inside the hub $M(< r) \propto r^3$ and therefore $v \propto r$
  - for stars outside the hub $M \sim$ constant and $v \propto r^{-1/2}$
  \[\implies\] Velocity should increase at small distances and decrease at large distances

- It is observed, on the contrary, that the rotation curves are quite flat at large distances (halo)
  \[\implies\] the bulk of the galactic mass – typically 80–90% – would be in the form of dark (i.e. non-luminous) matter in the halo
13. Dark Matter

Evidence for dark matter – Rotation curves of galaxy NGC6503

\[
\begin{align*}
V_c (\text{km s}^{-1}) & \quad \text{Radius (kpc)} \\
\end{align*}
\]
13. Dark Matter

Evidence for dark matter – Halo
13. Dark Matter

Evidence for dark matter – WMAP
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Evidence for dark matter – WMAP – results
13. Dark Matter

Evidence for dark matter – Planck

Angular scale

$D_{\ell}[\mu K^2]$ vs Multipole moment, $\ell$
13. Dark Matter

Evidence for dark matter – Planck

Before Planck

After Planck
13. Dark Matter

Evidence for dark matter – Conclusion

- There is astrophysical and cosmological evidence that large quantities of dark matter must be hidden somewhere in the universe
  - the dynamics of galaxies and galactic clusters can only be understood if the dominating part of the gravitation is caused by non-luminous matter

- What can the non-luminous matter be?
13. Dark Matter

Dark matter candidates – terminology

- Baryonic dark matter
- Non-baryonic dark matter

Baryonic dark matter
- ordinary matter consisting of protons and neutrons
- all that can or cannot be seen: interstellar dust, giant planets, 'old' stars (white, red and brown dwarfs), black holes, ...
- MACHOs – MAssive Compact Halo Objects
- It is known to exist but it explains only a small part of dark matter

Non-baryonic dark matter
- classified according to temperature in the early universe (decoupling)
  - cold dark matter
  - warm dark matter
  - hot dark matter
13. Dark Matter

Dark matter candidates – non-baryonic dark matter

- **Hot dark matter**
  - relativistic particles
  - example candidate: neutrinos
  -⇒ known to exist, but are hot
  -⇒ masses not heavy enough and number not large enough to explain dark matter

- **Warm dark matter**
  - semi-relativistic particles
  - example candidates: keV-mass sterile neutrinos and gravitons
  -⇒ not yet experimentally known to exist

- **Cold dark matter**
  - non-relativistic particles
  - example candidates: neutralinos, axions, WIMPZILLAs, solitons (B-balls and Q-balls), etc
  -⇒ the most popular hypothesis for dark matter: WIMPs (Weakly Interacting Massive Particles)
13. Dark Matter and Galaxy formation

- The question of galaxy formation is closely related with the problem of dark matter

- The models of galaxy formation depend very sensitively on whether the universe is dominated by hot or cold dark matter
  - models assume galaxies have originated from (quantum) fluctuations which have developed to larger gravitational structures
  - two different scenarios can be distinguished: hot and cold dark matter
13. Dark Matter
and Galaxy formation – hot dark matter

- Low-mass and relativistic neutrinos could easily escape from mass structures
- Fluctuations below a certain critical mass would have not grown to galaxies
  - for neutrinos of 20 eV a critical mass of $\sim 10^{16} \text{ M}_{\text{SUN}}$ is required for the structure formation to set in
- 'Top-down scenario'
  - first largest structures (superclusters), then clusters and galaxies latest
    - allows only small $z$ values ($z \leq 1$), but Hubble observations show that large galaxies exist for $z \geq 3$
    - This is one argument to exclude neutrinos as main dark matter component
13. Dark Matter
and Galaxy formation – cold dark matter

- Massive, weakly interacting and mostly non-relativistic particles will be gravitationally bound already to mass fluctuations of smaller sizes.
- If cold dark matter dominate, the models show that initially small mass structures collapse and can grow by further mass attractions to form galaxies.
- 'Bottom-up scenario' – the galaxies would then develop to galactic clusters and later superclusters.
  - cold dark matter then favours a scenario in which smaller structures would be formed first and then develop into larger structures.
  - confirmed by observations of, for example, COBE and WMAP satellites.
In supersymmetric theories each fermion (half-integer spin) is associated with a bosonic (integer spin) partner and each boson has a fermionic partner:
- squark, slepton, ...
- gluino, photino, zino, higgsino, neutralino, gravitino, ...
- doubles the number of elementary particles
- no SUSY particles have been found

From accelerator experiments \( \Rightarrow \) masses higher than 100 GeV \((100m_p)\)

Massive SUSY particle would decay to lighter SUSY particles, and eventually to the lightest superparticle:
- the lightest SUSY particle (LSP) would be stable

The LSP is the most favourite candidate for WIMPs:
- neutralino
13. Dark Matter

Dark matter experiments – WIMPs

- Direct or indirect experiments

- Direct experiments for dark matter
  - scattering of a WIMP inside the detector material is observed
  - results in a low-energy recoil nucleus
  - WIMP rate may be expected to exhibit time dependence

- Indirect experiments for dark matter
  - gravitational trapping of WIMPs close to a mass centre (the core of the Sun or the Earth)
  - detection of the annihilation (or decay) products of WIMPs (high-energy neutrinos)
  - large-volume liquid scintillation or water Cherenkov detector
13. Dark Matter

Indirect experiments – LENA

- 50 kton liquid scintillation detector
- Expected signal in LENA after 10 years in Pyhäsalmi
  - inverse beta decay
- For two values of dark matter particles
- Discrete peak(s)

- Dashed lines describe background events (contributions from reactor neutrinos, DSNB, and atmospheric neutrinos)
The WIMP velocities are expected to be of the order of galactic escape velocities, \( v_\chi \sim 10^{-3}c \) (non-relativistic).

With \( m_\chi \sim 100 \text{ GeV} \) the maximum energy of the recoil nucleus (of \( A \sim 50 \)) of the detector is \( E_{r,\text{max}} \sim 50 \text{ keV} \):

- uniform distribution between 0 and \( E_{r,\text{max}} \)
- very low-energy recoil \( \implies \) difficult to observe

Event rates in a detector varies depending whether the cross section is spin-dependent (incoherent) of coherent:

- \( R \sim 1 \text{ event} \cdot \text{kg}^{-1} \cdot \text{day}^{-1} \) for coherent
- \( R \sim 0.01 \text{ event} \cdot \text{kg}^{-1} \cdot \text{day}^{-1} \) for incoherent

For coherent scattering it is required that \( A \ll 50 \), where \( A \) is the detector nucleus mass number:

- usually \(^{76}\text{Ge}\) or \(^{131}\text{Xe} \implies \) large \( A \) and incoherent scattering
13. Dark Matter

Direct experiments – 2

- Tens of experiments have been carried out and at least several are currently operational
  - detector masses from few 100 grams to few kilograms
  - most used also for double $\beta$-decay experiments: MIBETA, EDELWEISS, H&M, IGEX, CUORICINO, ...

- Techniques
  - ionisation detectors (Ge), solid scintillation detectors (NaI/CsI), cryogenic detectors (Ge), noble gases as liquids (Xe)

- Low counting rates $\Rightarrow$ extra care for background subtraction
  - high-energy neutrons

- Future experiments aims to several hundreds of kilos of detector material
  - GERDA, MAJORANA, EDELWEISS (Ge), ZEPLIN, XMASS-DM, XENON100 (LXe)
13. Dark Matter

Direct experiments – CRESST

- Cryogenic Rare Event Search with Superconducting Thermometer
  - working temperature $\sim 15$ mK
- WIMP elastic scattering on nuclei at the absorber
  - scintillating $\text{CaWO}_4$ crystals ($33 \times 300$ g modules)
  - low-activity copper and lead shielding
- Measures $\Delta T$ and scintillation light
  - sensitive for very low-energy events
  - efficient background reduction
- Situates at Gran Sasso, Italy at $\sim 1.2$ km
- 730 kg·days data taking in 2011 (with 8 modules)
  - 67 events in the acceptance window for WIMPs
  - $4\sigma$ significance that does not originate from four major background source
- CDMS (Cryogenic Dark Matter Search), Soudan Mine, Minnesota
  - three events at $3\sigma$
13. Dark Matter

Direct experiments – CRESST at Gran Sasso
13. Dark Matter

CRESST – Results and comparison to other experiments (2012)