Beyond the Standard Model
Summary of the course

Successful application of the particle physics and gravity to the Universe as a whole

✓ Laws of gravitation over the whole Universe $\Rightarrow$ expansion of the Universe. Hubble law

✓ Laws of thermodynamics. $\Rightarrow$ Hot Big Bang theory.

✓ Atomic physics. Thomson scattering $\Rightarrow$ properties of cosmic microwave background radiation

✓ Nuclear physics. Nuclear cross-section. Binding energy $\Rightarrow$ Primordial synthesis of elements. Helium abundance

✓ Particle physics. Weak interactions (Fermi theory) $\Rightarrow$ decoupling of neutrinos (primordial element abundance)

✓ Particle physics of the curved space time $\Rightarrow$ inflationary theory. Generation of primordial perturbations
Did we succeed?
CMB anisotropy map

CMB temperature is anisotropic over the sky with $\delta T / T_{\text{CMB}} \sim 10^{-5}$

WMAP-5 results with subtracted galactic contribution (courtesy of WMAP Science team)
CMB anisotropies (cont.)

- The temperature anisotropy $\delta T(\hat{n})$ is expanded in spherical harmonics $Y_{lm}(\hat{n})$:

$$\delta T(\hat{n}) = \sum_{l,m} a_{lm} Y_{lm}(\hat{n})$$

- $a_{lm}$'s are Gaussian random variables (before sky cut)

- CMB anisotropy (TT) power-spectrum: 2-point correlation function

$$\langle \delta T(\hat{n}) \delta T(\hat{n}') \rangle = \sum_{l=0}^{\infty} \frac{2l + 1}{4\pi} C_l P_l(\hat{n} \cdot \hat{n}')$$

$P_l(\hat{n} \cdot \hat{n}')$ – Legendre polynomials

- Multipoles $C_l$'s

$$C_l = \frac{1}{2l + 1} \sum_{m=-l}^{l} |a_{lm}|^2$$

probe correlations of angular scale $\theta \sim \pi/l$
The WMAP 5-year TT power spectrum along with recent results from the ACBAR (Reichardt et al. 2008, purple), Boomerang (Jones et al. 2006, green), and CBI (Readhead et al. 2004, red) experiments. The red curve is the best-fit $\Lambda$CDM model to the WMAP data.
Is this a success?

Starting from \( \ell \sim 100 \) or so we do not even see error bars on the data points.

Yet the model successfully predicts all the wiggles.
Is this a success?
• We understand only about 5% of the total composition of the Universe
Beyond the Standard Model problems

- Why is our universe devoid of **anti-matter**? What violated symmetry between particles and anti-particles in the early Universe?

- Why neutrinos **oscillate** – disappear and then re-appear in a different form? What makes them massive?

- What is **Dark Matter** that accounts for some 86% of the total matter density in the Universe and have driven the formation of structure in the early Universe?

- What drives **inflation**?

- Why cosmological constant is **almost** zero?

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Oleg Ruchayskiy  Relativity & cosmology-II  10
New dark matter particle?

• To create a dark matter particle is easy:
  – assume heavy neutral particle, no interacting with the Standard Model.
  – Assume its coupling to something in the very early Universe
  – Produce something that serves as cold dark matter but does not have any observable signatures!

• **Not a physical model** – makes no predictions

• A model for baryon asymmetry of the Universe:
  – Assume a lepto-quark (particle $X$ that decays $X \rightarrow \bar{q} + \bar{\ell}$ and $X \rightarrow q + q'$
  – Assume that $X$ freezes out non-relativistic (a la WIMP) and then decays
  – Assume CP-violation in the processes $X \rightarrow qq$ and $X \rightarrow \bar{q}\bar{q}$

• Good baryogenesis scenario (all numbers may be made to work), but again not testable
What we want?

A model that would allow to solve not one but several problems with few assumptions ("Okkam’s razor").

Testable predictions
• Accelerator searches had confirmed Standard Model again and again. Different experiments had verified each others findings

• All predicted particles have been found
No new physics (Exotics)

- Proton decay: \( \tau_p \rightarrow \pi^0 + e^+ \) > \( 8.2 \times 10^{33} \) years
  baryon number violation

- New weakly interacting massive particles

- Axion searches

- Millicharges

- Paraphotons

- Neutron electric dipole moment
  CP violation in strong interactions

- Neutrinoless double beta decay
  Lepton number violation

- No \( \mu \rightarrow e + \gamma \) or \( \mu^+ \rightarrow e^+e^-e^+ \)
Cosmic rays

- Historically cosmic rays were the first accelerators (positron, muons, ...)

- Today we detect photons, electrons/positrons, protons/antiprotons, nuclei (iron), neutrinos up to very high energies

- Everything is consistent with our knowledge of astrophysics and particle physics
Neutrino physics

Natural: The Sun; The Earth’s atmosphere; Supernovae within our galaxy; The Earth’s crust; Cosmic accelerators
Man made: Nuclear power plants; Neutrino superbeams and factories
Neutrino oscillation experiments

- **40 years ago:** neutrinos were thought strictly massless and flavour lepton number was conserved (no $\mu \rightarrow e + \gamma$, no $\tau \rightarrow eee$, etc.)

- **Today:** neutrino oscillations confirmed by many independent experiments (both appearance and disappearance data)
Consider the simplest case: two flavours, two mass eigen-states. Matrix $U$ is parametrized by one mixing angle $\theta$

\[
|\nu_e\rangle = \cos \theta |1\rangle + \sin \theta |2\rangle \\
|\nu_\mu\rangle = \cos \theta |2\rangle - \sin \theta |1\rangle
\]

Let take the initial state to be $\nu_e$ (created via some weak process) at time $t = 0$:

\[
|\psi_0\rangle = |\nu_e\rangle = \cos \theta |1\rangle + \sin \theta |2\rangle
\]

Then at time $t > 0$

\[
|\psi_t\rangle = e^{-iE_1t} \cos \theta |1\rangle + \sin \theta |2\rangle e^{-iE_2t}
\]

We detect the particle later via another weak process

(e.g. $\nu_? + n \rightarrow p + \mu^-/e^-$)
Neutrino oscillations

- The probability of conversion $\nu_e \rightarrow \nu_\mu$ is given by

$$P(\nu_e \rightarrow \nu_\mu) = |\langle \nu_\mu | \psi_t \rangle|^2 = \sin^2(2\theta) \sin^2 \left(\frac{(E_2 - E_1)t}{2}\right)$$

- The probability to detect $\nu_e$ is given by

$$P(\nu_e \rightarrow \nu_e) = |\langle \nu_e | \psi_t \rangle|^2 = \cos^2(2\theta) \sin^2 \left(\frac{(E_2 - E_1)t}{2}\right)$$
Fermion number conservation?

- Apparent violation of flavour lepton number for neutrinos can be explained by the presence of the non-zero neutrino mass

\[
\mathcal{L} = \begin{pmatrix} \overline{\nu}_e \\ \overline{\nu}_\mu \\ \overline{\nu}_\tau \end{pmatrix} \left[ i \partial - V_{\text{Fermi}} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} + \begin{pmatrix} \overline{\nu}_e \\ \overline{\nu}_\mu \\ \overline{\nu}_\tau \end{pmatrix} \begin{pmatrix} m_{11} & m_{12} & \cdots \\ m_{21} & m_{22} & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}
\]

- In this case only one fermion current (total lepton fermion number) is conserved:

\[
J^\mu = \sum_{i=e, \mu, \tau} \overline{\nu}_i \gamma^\mu \nu_i
\]  

while any independent \( J_i^\mu = \overline{\nu}_i \gamma^\mu \nu_i \) is not conserved.
The prediction is: neutrinos oscillate, i.e. probability to observe a given flavour changes with the distances travelled:

$$P_{\alpha \rightarrow \beta} = \sin^2(2\theta) \sin^2 \left( 1.267 \frac{\Delta m^2 L}{E} \frac{\text{GeV}}{\text{eV}^2 \text{km}} \right)$$

Mass difference: $\Delta m^2$, Neutrino energy: $E$ (keV-MeV in stars, GeV in air showers, etc. Distance traveled: $L$
Neutrino oscillations

- Eq. (2) predicts that probability oscillates as a function of the ratio $E/L$. This is indeed observed:

in this plot the distance between reactor and detector is fixed and the energy of neutrinos is different, therefore $E/L$ is different
Reactor neutrino anomalies?

The Reactor Antineutrino Anomaly

- Observed/predicted averaged event ratio: $R = 0.927 \pm 0.023$ (3.0 $\sigma$)

Diagram:
- Ratio of Observed to Predicted Reactor-$\nu$'s
- Reactor Antineutrino Anomaly (2011-)
- $\rightarrow v$-oscillation
- Terra Incognita to be explored
- $> 20$ projects....
- Solar Neutrino Anomaly (1968-2001)
- $\rightarrow v$-oscillation
- $\rightarrow v$-oscillation

Th. Lasserre – TPC-Paris 2012
Data from different experiments are consistent and allow to provide a **global fit** to the neutrino oscillations parameters.
All anomalies together cannot be true!

All data would be consistent if red contours were to the left of both green and blue contours.
Beyond the Standard Model physics
Example
Neutrino oscillations

WEAK SYMMETRY

Number of leptons is conserved in each generation

i.e. we know with high precision that muons $\mu$ cannot convert into electrons $e$.

By virtue of the electroweak symmetry neutrinos do not change their types (i.e. $\nu_e \leftrightarrow \nu_\mu$)

To break symmetry between electron and neutrino we need Higgs boson

FORBIDDEN
Higgs condensate

- Higgs boson (spin-0 particle) couples left to right chiralities of fermion
- In the absence of mass term left and right components are independent
- Gauge transformations should rotate left and right by the same phase (otherwise mass term won’t be gauge invariant)

\[
\bar{\psi}(i\gamma^\mu \partial_\mu - \mathbb{M})\psi = \begin{pmatrix} \psi_R^* \\ \psi_L^* \end{pmatrix} \begin{pmatrix} \gamma^0 & i(\partial_t + \vec{\sigma} \cdot \vec{\nabla}) \\ i(\partial_t - \vec{\sigma} \cdot \vec{\nabla}) & \gamma^0 \end{pmatrix} \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} = 0
\]
Oscillations $\Rightarrow$ new particles!

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{2}{3}$ up</td>
<td>$\frac{2}{3}$ charm</td>
</tr>
<tr>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>$\frac{-1}{3}$ down</td>
<td>$\frac{-1}{3}$ strange</td>
</tr>
<tr>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>$&lt;0.0001$ eV</td>
<td>$\sim 0.01$ eV</td>
</tr>
<tr>
<td>left</td>
<td>left</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>muon neutrino</td>
</tr>
<tr>
<td>0.511 MeV</td>
<td>105.7 MeV</td>
</tr>
<tr>
<td>Left</td>
<td>Right</td>
</tr>
</tbody>
</table>

Left chirality

Right chirality
Oscillations ⇒ new particles!

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</tr>
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<td>$-\frac{1}{3}$</td>
</tr>
<tr>
<td>Left</td>
<td>Left</td>
</tr>
<tr>
<td>up</td>
<td>charm</td>
</tr>
<tr>
<td>$2.4 \text{ MeV}$</td>
<td>$1.27 \text{ GeV}$</td>
</tr>
<tr>
<td>$4.8 \text{ MeV}$</td>
<td>$104 \text{ MeV}$</td>
</tr>
</tbody>
</table>

$\nu_e$, $\nu_\mu$, $\nu_\tau$, $N_1$, $N_2$, $N_3$

Left chirality

Right chirality

Right components of neutrinos?!
Neutrino Minimal Standard Model

- New particles \((N_1, N_2, N_3)\) carry no charges with respect to known interactions

  that is why they are often called **sterile neutrinos**

- They have different mass from left neutrinos

  that is why they are sometimes called **heavy neutral leptons**

- They are **heavier** than ordinary neutrinos but interact **much weaker**
Sterile neutrinos behave as superweakly interacting massive neutrinos with a smaller Fermi constant $\vartheta \times G_F$.

- This mixing strength or mixing angle is

$$\vartheta_{e,\mu,\tau}^2 = \frac{|M_{\text{Dirac}}|^2}{M_{\text{Majorana}}^2} = \frac{M_{\text{active}}}{M_{\text{sterile}}} \approx 5 \times 10^{-11} \left(\frac{\text{1 GeV}}{M_{\text{sterile}}}\right)$$
So what?

WANTED
Massive neutral particle
Interacting weaker than neutrino
Baryogenesis with sterile neutrinos

Sterile neutrinos may provide all conditions necessary for successful baryogenesis:

- Their “weaker-than-weak” interaction ($\phi G_F$) means that they go out of equilibrium much earlier than even neutrinos.

- Their mass matrix may contain additional CP-violating phases (a la CP violating phases of CKM matrix).

- Their Majorana masses violate lepton number.

This class of scenarios is called LEPTOGENESIS.
Sterile neutrino dark matter

- **Sterile neutrino** is a new neutral particle, interacting **weaker-than-neutrino**

- Never was in thermal equilibrium in the early Universe \( \Rightarrow \)

\[ \Rightarrow \text{Its abundance } \textbf{slowly builds up} \text{ but never reaches the equilibrium value} \]

\[ \Rightarrow \text{avoids Tremaine-Gunn-like bound} \]

\[
\begin{align*}
q & \rightarrow W^\pm \\
\nu & \rightarrow Z^0 \nonumber\end{align*}
\]

- Once every \( \sim 10^8 \text{ div } 10^{10} \) scatterings a sterile neutrino is created instead of the active one
• Very hard/impossible to search at LHC

• Very hard/impossible to search in laboratory experiments

• Can be **decaying** with the lifetime exceeding the age of the Universe

• Can we detect such a rare decay?

• **Yes!** if you multiply the probability of decay by a large number – amount of DM particles in a galaxy (typical amount $\sim 10^{70} - 10^{100}$ particles)

\[
\begin{align*}
N_S &\rightarrow \nu \\
\nu &\rightarrow e^\pm \\
\nu &\rightarrow W^\mp \\
W^\mp &\rightarrow W^\mp \\
W^\mp &\rightarrow \gamma
\end{align*}
\]
**One** assumption about physics behind neutrino oscillations (existence of new particles $N_1$, $N_2$, $N_3$) may also explain the existence of dark matter and matter-antimatter asymmetry of the Universe.
Particles of the $\nu$MSM

Masses of sterile neutrinos as those of other leptons
Yukawas as those of electron or smaller

Neutrino Minimal Standard Model == $\nu$MSM

$\nu$MSM predicts that this picture holds up to the “Planck scale energies” (when Compton wavelength $\sim$ Schwarzschild radius of particle)
How to test this model?
Can be **decaying** with the lifetime exceeding the age of the Universe

Can we detect such a rare decay?

**Yes!** if you multiply the probability of decay by a large number – amount of DM particles in a galaxy (typical amount $\sim 10^{70} - 10^{100}$ particles)

Two-body decay into two massless particles ($\text{DM} \rightarrow \gamma + \gamma$ or $\text{DM} \rightarrow \gamma + \nu$) ⇒ narrow decay line

\[
E_{\gamma} = \frac{1}{2} m_{\text{DM}} c^2
\]

The width of the decay line is determined by **Doppler broadening**
Detection of An Unidentified Emission Line
We detect a weak unidentified emission line at $E = (3.55-3.57) \pm 0.03$ keV in a stacked XMM spectrum of 73 galaxy clusters spanning a redshift range 0.01-0.35. MOS and PN observations independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is significantly detected in all three independent MOS spectra and the PN "all others" spectrum. It is also detected in the Chandra spectra of Perseus with the flux consistent with XMM (though it is not seen in Virgo)…
We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset...
### Data

#### Our data

<table>
<thead>
<tr>
<th>Object</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M31 galaxy</td>
<td>XMM-Newton, center &amp; outskirts</td>
</tr>
<tr>
<td>Perseus cluster</td>
<td>XMM-Newton, outskirts only</td>
</tr>
<tr>
<td>Blank sky</td>
<td>XMM-Newton</td>
</tr>
</tbody>
</table>

#### Bulbul et al. 2014

<table>
<thead>
<tr>
<th>Object</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>73 clusters</td>
<td>XMM-Newton, central regions of clusters only</td>
</tr>
<tr>
<td>Perseus cluster</td>
<td>Chandra, center only</td>
</tr>
<tr>
<td>Virgo cluster</td>
<td>Chandra, center only</td>
</tr>
</tbody>
</table>

**Position:** 3.5 keV. Statistical error for line position $\sim 30$ eV. Systematics ($\sim 50$ eV – between cameras, determination of known instrumental lines)

**Lifetime:** $\sim 10^{28}$ sec (uncertainty $\mathcal{O}(10)$)
Bulbul et al. took only 2 central XMM observation – 14′ around the cluster’s center.

We took 16 observations excluding 2 central XMM observations to avoid modeling complicated central emission.
Andromeda galaxy (zoom 3–4 keV)

Normalized count rate [cts/sec/keV]

M31 ON-center

No line at 3.5 keV

Data - model [cts/sec/keV]

Energy [keV]

No line at 3.5 keV

Line at 3.5 keV

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• All spectra blue-shifted in the reference frame of clusters

• Instrumental background processed similarly and subtracted
A dedicated experiment


Proposal to Search for Heavy Neutral Leptons at the SPS

Expression of Interest. Endorsed by the CERN SPS council

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A dedicated experiment
Energy & Intensity frontier

known physics

Energy frontier:
LHC

Weak coupling frontier:
Generic beam dump facility at CERN

unknown physics

Interaction strength

Energy
Other examples?

- Grand Unification theory (combine all gauge interactions into one big gauge group):