QUEST FOR NEW PHYSICS DRIVEN BY EXPERIMENT AND SIMPLICITY

Oleg Ruchayskiy

Xth Rencontres du Vietnam

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As a particle physicists we want to build “The Theory” such that

- All observed phenomena are explained
- All predicted particles are discovered
- The resulting theory is mathematical self-consistent

Are we there yet?
All predicted particles are found!

Century long quest came to its end – all predicted particles have been found!

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Mass of the Higgs boson $\sim 126$ GeV means that the Standard Model is a consistent weakly-coupled theory up to very high scales (probably to the Planck scale)

Bezrukov et al. “Higgs boson mass and new physics” [1205.2893]

Also Degrassi et al. [1205.6497], Buttazzo et al. [1307.3536]
"It is expected that the difference between the MC mass definition and the formal pole mass of the top quark is up to the order of 1 GeV" [1403.4427]
Is this the end?

✓ All predicted particles of the Standard Model have been found 😊
✓ The theory behind these particles and their interactions stays mathematically consistent to very high energies 😊

Did we just had the last Nobel Prize in particle physics?
Particle physics: neutrino oscillations

Cosmology and astrophysics: particle physics (coupled to Einstein gravity) applied to the Universe as a whole faces the challenges of

– dynamics of gravitating objects at scales from galactic to cosmological (dark matter?)
– absence of primordial asymmetry of the Universe

Possibly

– initial conditions for the Universe (inflation?)
– accelerated expansion of the Universe (dark energy?)
Expectations for new physics?

- Unsolved problems $\Rightarrow$ **new particles should exist**
- We did not detect them $\Rightarrow$ they are **heavy**
- How heavy can they be? – Not too much!
- Indeed, Higgs mechanism gives mass to all the particles

$\text{heavy particle} \iff \text{Strong interaction with Higgs boson} \Rightarrow \text{Large quantum corrections to the Higgs boson mass}$

this is known as “gauge hierarchy problem”

- $\Rightarrow$ New physics should be about electroweak scale?
Searches for new physics at LHC

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**CMS Exotica Physics Group Summary – ICHEP, 2014**

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### Leptoquarks
- stopped gluino (cloud)
- HSCP gluino (cloud)
- HSCP stop (cloud)
- q=2/3e HSCP
- q=3e HSCP

### Long-Lived Particles
- neutralino, ctau=25cm, ECAL time

### RS Gravitons
- RS1(γγ), k=0.1
- RS1(ee,uu), k=0.1
- RS1(jj), k=0.1
- RS1(WW→4j), k=0.1

### Dark Matter
- SSM Z'(ττ)
- SSM Z'(jj)
- SSM Z'(bb)
- SSM W'(ej)+Z'(µµ)
- SSM W'(WZ→ljll)
- SSM W'(WZ→lj4j)

### Heavy Gauge Bosons
- ADD (γγ), nED=4, MS
- ADD (ee,µµ), nED=4, MS
- ADD (j+MET), nED=4, MD
- ADD (γ+MET), nED=4, MD
- QBH, nED=4, MD=4 TeV
- NR BH, nED=4, MD=4 TeV

### Excited Fermions
- e* (M=Λ)
- μ* (M=Λ)
- q* (qg)
- q* (qγ)
- b*

### Multijet Resonances
- dijets, Λ+ LL/RR
- dijets, Λ- LL/RR
- dimuons, Λ+ LLIM
- dimuons, Λ- LLIM
- di-electrons, Λ+ LLIM
- di-electrons, Λ- LLIM
- single e, Λ HnCM
- single μ, Λ HnCM
- inclusive jets, Λ+
- inclusive jets, Λ-

### Large Extra Dimensions
- String Scale (jj)
- Large Extra Dimensions

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**CMS Preliminary**

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**Oleg Ruchayskiy**

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**QUEST FOR NEW PHYSICS DRIVEN BY MINIMALITY...**
Heavy or light?

- Unsolved problems ⇒ new particles should exist ✓

- We did not detect them ⇒ they are heavy light but very weakly interacting

- Higgs mechanism gives mass to all the particles
  
  \[
  \text{No heavy particle} \implies \text{No corrections to the Higgs boson mass}
  \]

Is it possible to resolve the BSM problems with light very weakly interacting particles?

▶ Complete (testable?) theory, valid up to Planck scale?
Two directions

Known physics

Unknown physics

New physics at electroweak scale explored at LHC (energy frontier)

Focus of this proposal:
Feebly coupled particles to be searched at SHIP experiment at CERN (intensity frontier)

Mass of particles

Interaction strength

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QUEST FOR NEW PHYSICS DRIVEN BY MINIMALITY...
Neutrino oscillation between three generations
Neutrino oscillations mean that there exist new particles!
Oscillations ⇒ new particles!

Right components of neutrinos?!
Scale of sterile neutrino masses?

See-saw formula

\[ |F| \quad \text{Neutrino Yukawa interaction} \]

\[ M_{\text{active}} \sim \frac{v^2 |F|^2}{M_N} \]

\( M_N \quad \text{Neutrino Majorana mass} \)

Mass of sterile neutrinos is not determined by neutrino oscillations!
Sterile neutrinos behave as superweakly interacting massive neutrinos with a smaller Fermi constant \( \vartheta \times G_F \)

- This mixing strength or mixing angle is

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

- Another name \( \Rightarrow \) heavy neutral leptons (or HNL)
If sterile neutrinos exist – how to find them?
Bounds on sterile neutrinos

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Bounds on sterile neutrinos
Ya. Zel’dovich: The Universe is the poor man’s accelerator: experiment doesn’t need to be funded, and all we have to do is to collect the experimental data and interpret them properly.

Why?

⇒ Primordial plasma could have reached the densities and temperatures unachievable in the lab for the longest possible times.

⇒ Especially relevant if we are after some effects due to very-weakly-interacting particles/rare processes.
Lifetime of HNLs

- Mode that always exists $N \rightarrow \nu \bar{\nu} \nu$

- Estimate lifetime from **neutrino oscillations**

\[
\text{Lifetime}_{N} = \left( \frac{\vartheta^2 G_F M_N^5}{86\pi^3} \right)^{-1} \approx 0.3 \text{ sec} \left( \frac{1 \text{ GeV}}{M_N} \right)^4
\]

For illustration only! The width of the line can be even larger
Sterile neutrino and BAU

Red stripes: ranges of masses where generation of BAU is possible (approximate)

Sterile neutrinos with their Majorana masses + CP phases in the Yukawa matrix satisfy all three Sakharov conditions and generate baryon asymmetry of the Universe (via leptogenesis)
• Very long-lived particles ⇒ dark matter?

• Take $M_N \sim 1$ keV. Lifetime $\tau_N \sim 10^{24}$ sec — is this long enough?

• Fraction of decayed DM particles: $\frac{\text{Age of the Universe}}{\tau_N} \sim 10^{-6}$
Lifetime of $\tau_N$

- **But!** in a galaxy like Andromeda or Milky Way (total mass $M_{\text{gal}} \sim 10^{12} M_\odot$) there would be $10^{75}$ DM particles with the mass 1 keV

- **Subdominant** ($\text{Br} \sim \frac{1}{123}$) decay channel: $N \rightarrow \nu + \gamma$

\[ \Gamma_{N \rightarrow \nu \gamma} = \frac{9\alpha G_F^2 \vartheta^2 M_N^5}{256\pi^4} \]
\[ E_\gamma = \frac{1}{2} M_N \]

- Therefore, decay of a small fraction of $10^{75}$ particles releases $\sim 10^{40}$ erg/sec in 0.5 keV photons

- The entire X-ray luminosity of Andromeda galaxy in the range 0.1 – 2.4 keV is $L_X \sim \text{few} \times 10^{39}$ erg/sec (90% of which is coming from point sources)
Dark matter and neutrino oscillations

- Two neutrino mass splitting ⇒ need (at least) two sterile neutrino

- Are they Dark matter? ⇒ No way! Very short lifetime

- Third sterile neutrino? ⇒ Yes! Great DM (its exact properties depend on two other sterile neutrinos)

Sterile neutrino is a viable dark matter candidate in a model with at least two other sterile neutrinos
Neutrino Minimal Standard Model ($\nu$MSM)

Talk by D. Gorbunov on Friday

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

Detection of An Unidentified Emission Line

**Prediction?** Dark matter should be decaying, emitting monochromatic photon

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul, Maxim Markevitch, Adam Foster, Randall K. Smith, Michael Loewenstein, and Scott W. Randall

1 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
2 NASA Goddard Space Flight Center, Greenbelt, MD, USA.


[1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, and J. Franse

1 Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
2 Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

[1402.4119]
**Unidentified spectral line at** $E \sim 3.5$ keV

<table>
<thead>
<tr>
<th>Source</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boyarsky et al. 2014</td>
<td>M31 galaxy XMM-Newton, center &amp; outskirts</td>
</tr>
<tr>
<td></td>
<td>Perseus cluster XMM-Newton, outskirts only</td>
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<tr>
<td></td>
<td>Blank sky XMM-Newton</td>
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</tbody>
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<td>Bulbul et al. 2014</td>
<td>73 clusters XMM-Newton, central regions of clusters only. Up to $z = 0.35$, including Coma, Perseus</td>
</tr>
<tr>
<td></td>
<td>Perseus cluster Chandra, center only</td>
</tr>
<tr>
<td></td>
<td>Virgo cluster Chandra, center only</td>
</tr>
</tbody>
</table>

**Position:** $3.52 \pm 0.02$ keV.

**Lifetime:** $\sim 10^{28}$ sec (uncertainty $\mathcal{O}(10)$)

**Significance:** Between $4\sigma$ and $5\sigma$ (global, taking into account trial factors)
Surface brightness profile (Perseus)

Perseus cluster surface brightness profile

NFW DM line, $r_s = 360$ kpc
NFW DM line, $r_s = 872$ kpc
$\beta$-model, $\beta = 0.71$, $r_c = 287$ kpc

This is not a fit!
Sterile neutrino DM with such parameters is not completely cold and would leave its imprints in the formations of structures.
Resonant enhancement

Conversion of $\nu$ to $N$ is enhanced whenever “levels” cross and virtual neutrino goes “on-shell” (analog of MSW effect but for active-sterile mixing)

Shi & Fuller
[astro-ph/9810076]

Laine & Shaposhnikov
[0804.4543]
Dark matter and neutrino oscillations

- Two neutrino mass splitting \(\Rightarrow\) need (at least) two sterile neutrino

- Are they Dark matter? \(\Rightarrow\) No way! Very short lifetime

\[
\text{Lifetime}_{N} = \left(\frac{\vartheta^2 G_F^2 M_N^5}{86\pi^3}\right)^{-1} \\
\approx 0.3 \text{ sec } \left(\frac{1 \text{ GeV}}{M_N}\right)^4
\]

- Third sterile neutrino? \(\Rightarrow\) Can be dark matter

**Lepton asymmetry** needed for its production can be created by two other sterile neutrinos
A dedicated experiment


Proposal to Search for Heavy Neutral Leptons at the SPS

Expression of Interest. Endorsed by the CERN SPS council

Talk by N. Serra on Friday
Conclusions

- Observable beyond-the-Standard-Model puzzles mean that **new particles exist**

- These particles can be either **heavy** or **super-weakly interacting**

- Neutrino oscillations suggest that sterile neutrinos (heavy neutral leptons) do exist

- Such particles can explain baryon asymmetry of the Universe, provide dark matter candidate and explain neutrino oscillations

- The simplest model that incorporates all that (the $\nu$MSM) looks like Standard Model from the point of view of todays’ experiments

- SHIP and other **intensity frontier** experiments

- **Cosmic frontier** to compliment the direct searches
Thank you for your attention
Surface brightness profile (M31)

M31 surface brightness profile

On-center
Off-center 2σ upper bound
NFW DM line, c = 11.7
NFW DM line, c = 19

This is not a fit!
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.
• All spectra blue-shifted in the reference frame of clusters

• Instrumental background processed similarly and subtracted
Higher masses (PRELIMINARY!)

From M. Shaposhnikov’s talk at TLEP-7 workshop