Landscape of Neutrino Physics

A. Yu. Smirnov

Max-Planck Institute for Nuclear Physics, Heidelberg, Germany

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Landscape:

visible features of area of land

Five elements:
- Physical element of land form
- Water bodies
- Leaving elements (vegetation)
- Human elements (architecture)
- Transitory elements (lighting, weather...)

What is what in neutrino physics?

Spires: 354 documents with word “landscape”

String L.
Potential energy L.
Nuclear structure L.
Inflationary L.

G. Charpak: L. of experimental areas
L. Susskind: Anthropic L.
G. ’t Hooft: Subatomic L.
J. Ellis: Physics L. After Higgs discovery
...

BIG PICTURE
More than big picture?

For this I will treat the landscape as composition / variety of diverse elements with certain harmony and probably deep connection.

A kind of overall view which allows to see/understand/infer something that can not be seen reviewing specific topics.

trends
relative importance and significance
Hot and dominant structures
Relations and interplay of different elements
New anomalies, problems
Missing elements
Content:

1. Introduction to the ψ - landscaping
2. Highlights, advances and anomalies
3. On landscape of theory
Introduction to landscaping
Importance
Impact
(# of papers, Citations)

- set-up (F, prop, det.)
- 3ν paradigm
- beyond 3ν paradigm

Phenomenology
Experiment

Theory
different coordinates

Neutrino sources
Sources

Atmosphere
Cosmic rays
Accelerators
\beta\beta - decays
\mu, \pi - decays
\beta - decays
Rad. sources
Supernova
Sun
Reactors
Earth (Geo-)
Big Bang
Energy
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<th>BB</th>
<th>Sun</th>
<th>Geo.</th>
<th>React.</th>
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Since TAUP 2013: 50 papers, 5 reviews

Experiments

★ BOREXINO: pp-flux in agreement with LMA
★ SuperK: 3σ D-N asymmetry due to Earth matter effect

Fluxes:

CNO neutrinos - still to measure.
Higher accuracy of the pp-flux measurements is important
Still open issue: surface chemical abundance - helioseismology - SSM

Beyond 3ν paradigm

Bounds on:
- νs
- NSI
- Neutrino decay  (after low energy BOREXINO data)
Open issues

Absence of upturn of the spectrum

Large D-N asymmetry

1.6 times difference of values of $\Delta m^2_{21}$ extracted from solar and KamLAND data

1.6 times larger value of matter potential extracted from global fit

Can be related at about 3$\sigma$ - level

Solar data alone - very good description at small $\Delta m^2_{21}$

Reactor anomaly should affect KamLAND result

KamLAND

New physics

New sub-leading effects

Non-standard neutrino interaction

Very light sterile neutrinos

another reactor anomaly?

in solar neutrinos?
Extra sterile neutrino with $\Delta m^2_{01} = 1.2 \times 10^{-5}$ eV$^2$, and $\sin^2 2\alpha = 0.005$

Non-standard interactions with
$\varepsilon^u_D = -0.22$, $\varepsilon^u_N = -0.30$
$\varepsilon^d_D = -0.12$, $\varepsilon^d_N = -0.16$

NSI due exchange by light (MeV scale mass) mediators with small couplings allow to avoid existing bounds.
Experiments

SuperKamiokande: update, attempts of nu-barnu separation, CP phase, MO, at about 1σ level

Ice Cube: measurements of $\nu_\mu$ $\nu_\tau$ fluxes at high (up to PeV) energies

DeepCore: observation of oscillations, observation of cascades

ANTARES: oscillations

Fluxes computations

Update, various improvements
Fluxes and flavor ratios for $E = 0.1$ TeV - 10 PeV

New contribution to conventional flux
Charm production, new using LHC and RHIC data

Crucial for future

M. Honda et al, 1502.03916
T. S. Sinegovskaya et al, 1407.3591
T. Gaisser, 1409.4924
A. Bhattacharya et al, 1502.01076
Atmospheric $\nu_\mu$ disappearance, 3 years of data

*IceCube Collaboration (M.G. Aartsen et al.).*  
*arXiv:1410.7227 [hep-ex]*

comparable in precision with present accelerator experiments

Even better in future

Deviation from maximal: symmetry or no symmetry, Quadrant

K. Clark
Megaton-scale Ice Cherenkov Array

- 100 GeV
- 0.01 GeV
- 10 - 15 GeV
- 3 GeV
- 0.5 - 1 GeV
- Few Mtons in sub-GeV range

3 times denser array than PINGU

S. Razzaque, A.Y.S. 1406.1407 hep-ph
Megaton-scale Ice Cherenkov Array
Determination of mass ordering \[\rightarrow\] PINGU

Crucial developments of detection techniques

\[\sigma\]

Mass Hierarchy Sensitivity

\[\theta_{NH}=42^\circ, \theta_{IH}=48^\circ\]

PINGU

ICAL

KM3Net/ICAL PRELIMINARY

\[\Delta \chi^2_{ICAL}\]

NORMAL HIERARCHY

Fixed Parameters

- Without systematic errors
- With systematic errors

Marginalized

- Without systematic errors
- With systematic errors

\[\sin^2 \theta_W (true)=0.5, \sin^2 \theta_W (true)=0.1\]

PRELIMINARY
S-distributions for different values of $\delta$

$$S_{ij} = \frac{N_{ij}^{\delta} - N_{ij}^{\delta=0}}{\sqrt{N_{ij}^{\delta=0}}}$$

Super PINGU, 1 year

Flavor misidentification reduces distinguishability by factor $1.5 - 2$

$S_{\delta} \sim 3$, for $\delta = 3/2\pi$

4 years of exposure

$S^{\text{tot}} = \left[\sum_{ij} S_{ij}^2\right]^{1/2}$

ORCA: effect of $\delta_{\text{CP}}$ ~0.5 $\sigma$
Beyond 3ν paradigm

ν_S  SuperK bound on ν_S - ν_μ and ν_S - ν_τ  1410.2008

eV mass scale  IceCube result on ν_S - ν_μ - mixing: expected  J. Salvado

NSI  Constrains on NSI in propagation  S. Fukasawa 1405.4664

S. Fukasawa, O. Yasuda 1503.08056

R Gandhi et al, 1409.5755

VFS  Tests of Lorentz invariance (bound on SME parameters)  SuperK: 1410.4267

Lorentz and CPT with ICAL  R. Gandhi et al, 1402.6265

Constrains on violation of equivalence principle with IC  A. Esmaili et al, 1404.3608
Supernova neutrinos

- Rich and complicated physics and astrophysics
- Unresolved questions concerning neutrino production and propagation (collective effects)
- New effects uncovered

Fluxes

Neutrino driven SN explosion

- New computational capacities
- New (refined) codes
- 3D computations
- Neutrino transport

Successful explosion

more reliable and detailed fluxes

SASI (Standing Accretion Shock Instability)
modulation of neutrino fluxes (40 - 50 Hz)

LESA (Lepton-number Emission Self-sustained Asymmetry)
directional lepton asymmetry

I. Tambora, et al., 1406.0006
Collective flavor transformations

The multi-azimuthal angle (MAA) instabilities. Suppression by matter effect 1402.1767

Spontaneous breaking of symmetries of bulb model in 2D and 3D flavor conversion (directional dependence)

Self-induced flavor conversion on small scales A Mirizzi 1506.06805

Effect of fluctuations in time on instabilities S. Chakraborty et al, 1507.07569

Sensitivity to time evolution of $\nu$-spectra S. Abbar, H Duan, 1509.01538 B Dasgupta A Mirizzi

Shock wave effects

Turbulence effect

Stimulated transformations

Distorted phase effect

Updated evolution of the density profile used Jing Xu et al, 1412.7240

K. Patton, et al 1407.7835

S. Abbar, H Duan, 1509.01538 B Dasgupta A Mirizzi

Neutrino spin coherence $\nu - \bar{\nu}$ transformations in nu gases
Mass ordering

collective effects:
specific time varying collective effects at the accretion phase

Time profiles of events in SK (mostly sensitive to anti $\nu$) and in LAr TPC (mostly sensitive to $\nu$)

Absolute scale

$\nu_S$ Impact of on early time flux (neutronization)

Oscillations in core
Periodicity in $\nu$ luminosity

Wu, Qian et al 1412.8587

with JUNO, LiAr DUNE

SN Nucleosynthesis

Diffuse neutrino fluxes

Neutrinos from pre SN star

A. Esmaili and P. Serpico
Normal hierarchy

Inverted hierarchy

Level crossings

No Earth matter effect provided that initial fluxes of $\nu_\mu'$ and $\nu_\tau'$ are identical.

Collective effects and shock waves may change this.
Experiments

$\sin^2 \theta_{13}$ systematically decreased with time in all experiments and now $3\sigma$ below the benchmark value $\frac{1}{2} \sin^2 \theta_C$.

Higher flux - deficit of signal
Bump at 4 - 6 MeV

can be accounted by uncertainties due to contribution of forbidden transitions?

A.C Hayes et al, 1506.00583

Daya Bay - in agreement with previous measurements, thus confirming anomaly

$F_{\text{obs}} / F_{H-M} = 0.946 +/- 0.022$

$F_{\text{obs}} / F_{\text{ILL-F}} = 0.991 +/- 0.023$
very SBL experiments

For search for eV-scale steriles

PROSPECT
Neutrino 4
SM-3
...

Medium BL experiments

JUNO, RENO-50:
Mass ordering (hierarchy) precision measurements of $\Delta m^2_{21}, \theta_{12}$

clarify Solar - KamLAND tension

Studies of requirements effects of systematics

Beyond 3$\nu$ paradigm:

NSI ,
$\nu_s$
$\nu$ decay
Constrains on $\nu_S$ - parameters from Daya Bay (for relatively small mass)

- $\nu_S$ - in large Extra D framework
- NSI at production, detection

Effect of NSI at production and detection on determination of oscillation parameters

NSI in anti $\nu - e$ scattering

I. Girardi et al, 1405.6540

1408.6301
Cosmic neutrinos

- PeV neutrinos: 57 documents, includes also low (MeV) energies
- Astrophysical neutrinos: 56 documents

**Experiments**
- Dominated by IC
- 37 + ... events, track with $E > 2.6$ PeV

**Bounds from ANTARES**
- affects various interpretations
- DM decay?

**Analysis of IC events**
- impressive progress
- Neutrino self-veto

**Energy spectrum**
- cut off at few PeV?

**Flavor composition, ratios**
- gap in (0.3 - 1) PeV range?
- spectral index (power sp.?)
**Origins**

**Propagation**
- Averaged vacuum oscillations
- Matter conversion in source (at low energies)
- Interactions in the interstellar/Galactic medium
  - e.g. with DM if non-standard physics involved

**Correlations**
- Directionality, isotropy, correlations with other objects/events, γ sources

**Sources**
- Extragalactic
- With significant contribution from G.

**Coincidence:**
- $F_{IC} \sim F_{WB}$

**E. Waxman**
- Universal mechanism of acceleration of CR with $E^{-2}$
- “Calorimeter” neutrino sources

**In BZ range?**
- Stars forming galaxies with large magnetic field
NOvA observed: 33 events, expected: 201 events after 7.6% of expected exposure

$\nu_\mu$ - disappearance

$\nu_e$ - appearance

Likelihood Identification selection observed: 6 events

expected (NH, $\theta_{23} = \pi/4$):

- $5.62 \pm 0.72$ events ($\delta_{CP} = 3\pi/2$)
- $2.24 \pm 0.29$ events ($\delta_{CP} = \pi/2$)
- bgd. $0.94 \pm 0.09$ events

Library event matching selection observed: 11 events

The phase $\delta_{CP} = 3\pi/2$ is preferred in agreement with T2K result

Global fit with NOvA: $\delta_{CP} = 0$ is disfavored at $2\sigma$; $\delta_{CP} = \pi/2$ - at $3\sigma$

At the end of NOvA / T2K operation CP violation can be established at $> (3 - 4)\sigma$
Relic standard neutrinos

Cosmology

$\Sigma m < 0.136 \text{ eV (95 \% CL)}$

Planck 2015 + BAO+ HST

E. Di Valentino, et al
1507.08665 [astro-ph.CO]

$\Sigma m < 0.23 \text{ eV (95 \% CL)}$

Planck 2015 + TT + low P

WDM neutrinos

3.5 kev X ray line

A Boyarsky et al, 1402.4119

$\theta_{as}^2 \sim 2 \times 10^{-11}$

$m_S \sim 7 \text{ keV}$

Contribution to active neutrino masses

$\delta m \sim \theta_{as}^2 m_S \sim (1 - 2) \times 10^{-7} \text{ eV}$

Too small $\nu_S$ is not RH neutrino

Drago dwarf Galaxy: observations analysis
Double beta decay

\[ m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\phi} \]

Constraints from cosmological surveys and from oscillations. The 1\(\sigma\) region for the IH case is not present at this confidence level. The grey band is the 95\% C.L. excluded region coming from Cosmology.

S. Dell’Oro, et al, 1505.02722 [hep-ph]
Establish relations between neutrinos and other phenomena

Establish relations between neutrino parameters

Identify physics behind neutrino mass

Unification

Neutrino mixing: 115 doc
Lepton mixing: 70
Neutrino mass: 309

LHC physics
LMV
DM
DE
BAU

Masses, mixing, phases

theory of flavor

make predictions for $\delta_{CP}$, $\Delta \theta_{23}$, mass hierarchy

GUT
Setup

embedding

$SM + \nu_R$

L-R

P-S

GUT

QFT

strings

parallel structures

Hidden sector

Streile neutrinos

Neutrino portal
Scales of new physics

GUT - Planck mass

$\frac{V_{EW}^2}{m_\nu}$

PeV

Electroweak - LHC

$m_\nu$

Scales of neutrino masses themselves

Relation to dark energy, MAVAN?

28 orders of magnitude

High scale seesaw
Quark - lepton
symmetry / analogy
GUT

Low scale seesaw,
radiative mechanisms, RPV,
high dimensional operators

Neutrino mass itself is the
genuine scale of new physics

Spurious scale?
Mixing

d from symmetry to anarchy and randomness

Complicated constructions, especially if quarks are included

with intermediate possibilities

Not much to add
- String landscape
- Multiverse?
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<tr>
<th>Coordinates</th>
<th>To fill in: exercise for theoreticians</th>
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<td>Explicit Model building</td>
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<td>Mechanisms of $m_\nu$</td>
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<td>$SM + \nu_{mass}$</td>
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Correction to Higgs mass

Correction to $\lambda$ - 4 point coupling - vacuum stability

Higgs as composite state of neutrinos

Upper bound on mass $M_R < 10^7$ GeV
→ leptogenesis ?
→ cancellation (a kind of SUSY)

$F. Vissani$ ...
$J. Elias-Miro$ et al,
$R. Volkas$, et al,
$M. Fabbrichesi$ ...

$\delta m_H^2$

New strong int.
Generate 4 fermionic coupling

Recent:
$J. Krog, C. T. Hill$
$1506.02843$
$C. Bonilla et al, 1506.04031$
PMNS & CKM

\[ U_{\text{PMNS}} = U_{\text{CKM}} + U_X \]

where \[ U_{\text{CKM}} \sim V_{\text{CKM}} \]

has similar hierarchical structure determined by powers of \[ \lambda = \sin \theta_C \]

From the Dirac matrices of charged leptons and neutrinos

Prediction for the 1-3 mixing

\[ \sin^2 \theta_{13} = \sin^2 \theta_{23} \sin^2 \theta_C (1 + O(\lambda^2)) \]

\[ \sin^2 \theta_{13} \sim \frac{1}{2} \sin^2 \theta_C \]

in a good agreement with measurements

Quark mixing

my prejudice

C. Giunti, M. Tanimoto
H. Minakata, A Y S
Z - Z. Xing
J Harada
S Antusch, S. F. King
Y Farzan, A Y S
M Picariello, ...

\[ U_X \] has some special form determined by symmetry related to mechanism that explains smallness of neutrino mass

\[ U_X \sim U_{23}(\pi/4) U_{12} \]
Some additional physics is involved in the lepton sector which explains smallness of neutrino mass and difference of the quark and lepton mixing patterns.

Quarks and leptons know about each other, Q L unification, GUT or/and Common flavor symmetries.

Two types of new physics

Indicates SO(10): no CKM mixing in the first approximation.

Various predictions of CP phase.
Set-up

Visible sector

Hidden sector

$G_{Yukawa}$

$G_{basis}$

$G_{hidden}$

$G_{portal}$

$G_{basis}$

$SM \rightarrow SO(10)$

Fermions $\{1_{S}^{i}\}$

Bosons $\{1_{H}^{j}\}$

Patrick Ludl  A.S
Conclusions
Mature field with long history: In the first approximation (leading effects) phenomenology is elaborated and explored.

Next phase: sub-leading effects at % and sub-% level
New effects, new opportunities, new challenges

Supernova neutrinos: the place where we do not understand even lowest order effects.
From 1D to 2D and 3D.
Are we ready to analyse signal if arrives tomorrow?

Large atmospheric neutrino detectors with low energy thresholds
with very strong physics/discovery potential
(MO, $\delta_{CP}$, NSI, $\nu_S$) relatively cheap

Dedicated program of for higher accuracy predictions of the atmospheric neutrino fluxes
Cosmic / astrophysical neutrinos (origins, new physics, )

Sterile neutrinos
Mass ordering
CP-violation

Sooner than expected?

MO affects fluxes signals from many sources
Sterile neutrinos as well as NSI affect everything

Neutrinos ↔ Higgs physics
Dark matter
Axions

Reactor
Gallium anomaly
LSND/MiniBooNE
Solar - KamLAND tension
Look at the tables...

Still many directions
Scale(s) of new physics?
Symmetry or no symmetry?

- big picture a kind of snapshot

In contrast, neutrino physics is subject of fast developments

Breakthrough in one particular area may drastically change the \( \nu \) landscape
Variety of results, experiments, models, estimations, approaches, experiments, schemes, bounds, projects, searches, methods, computations, topics, frameworks.

From titles of papers and talks.

What can be seen/understood/infer that can not be seen reviewing specific topics.

Making sense.

Comparison of different topics directions.

Anomalies problems.

New quality.

Certain harmony.

Dominant elements.

Hot trends relative importance.