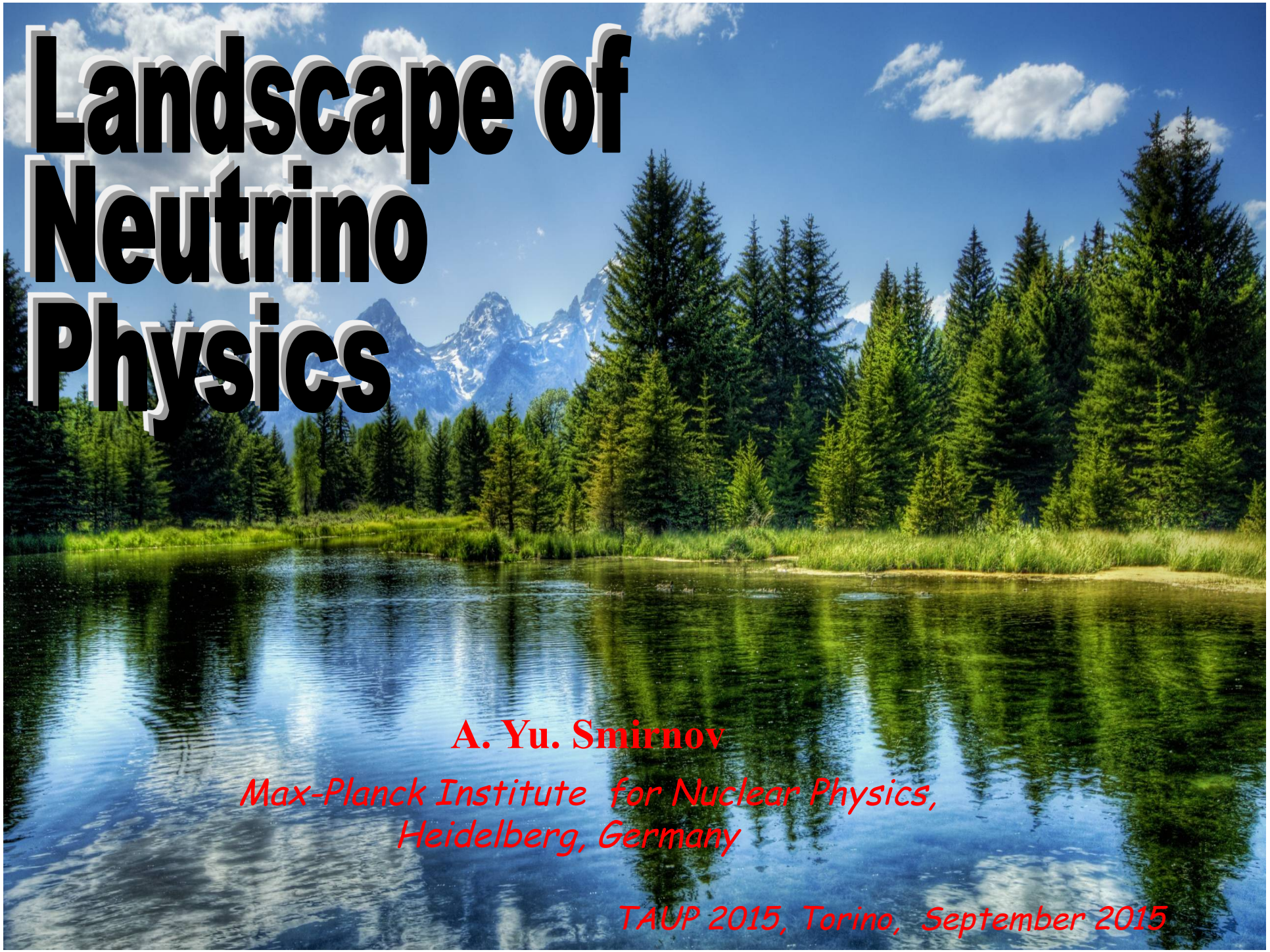


Landscape of Neutrino Physics

A. Yu. Smirnov

Max-Planck Institute for Nuclear Physics, Heidelberg, Germany

TAUP 2015, Torino, September 2015

Landscape:

according to Wikipedia:

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

Missing elements

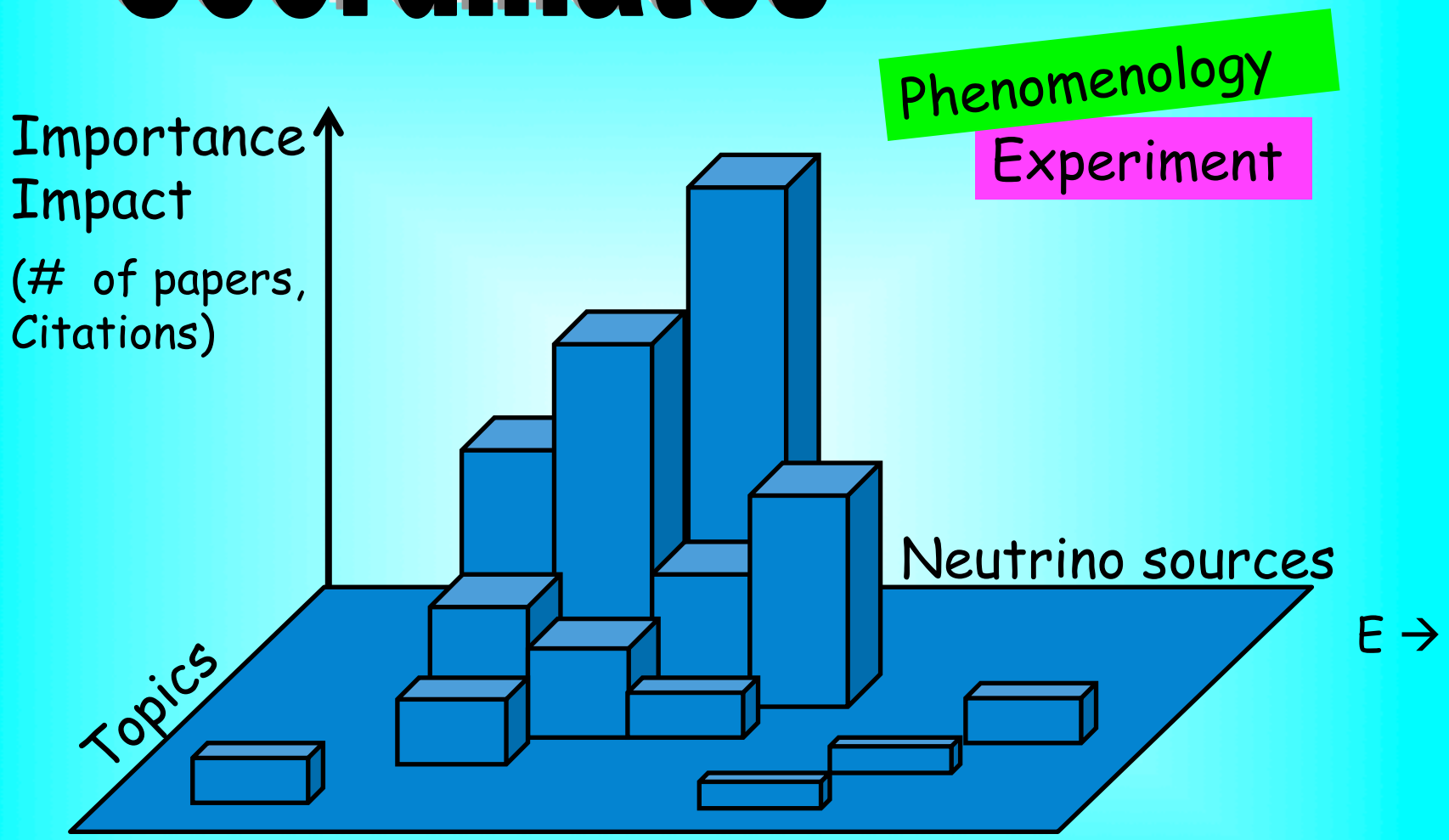
New anomalies, problems

Content:

1. Introduction to the ν - landscaping
2. Highlights, advances and anomalies
3. On landscape of theory

Introduction to v- landscaping

Coordinates



Phenomenology

Experiment

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

Theory

different coordinates

Sources

Energy

Atmosphere Cosmic rays

Accelerators

ββ - decays

μ, π - decays

Supernova

Rad. sources

β - decays

Sun Reactors

Earth (Geo-)

Big Bang

Topics

Set-ups

Fluxes

Propagation

Detection

and goals

3ν - paradigm

Interactions

Mass ordering

δ_{CP}

m_0

θ_{23}

$\not{L}$

α_i

precision measurements

applications

Beyond 3ν - paradigm

ν_s

NSI

μ_ν

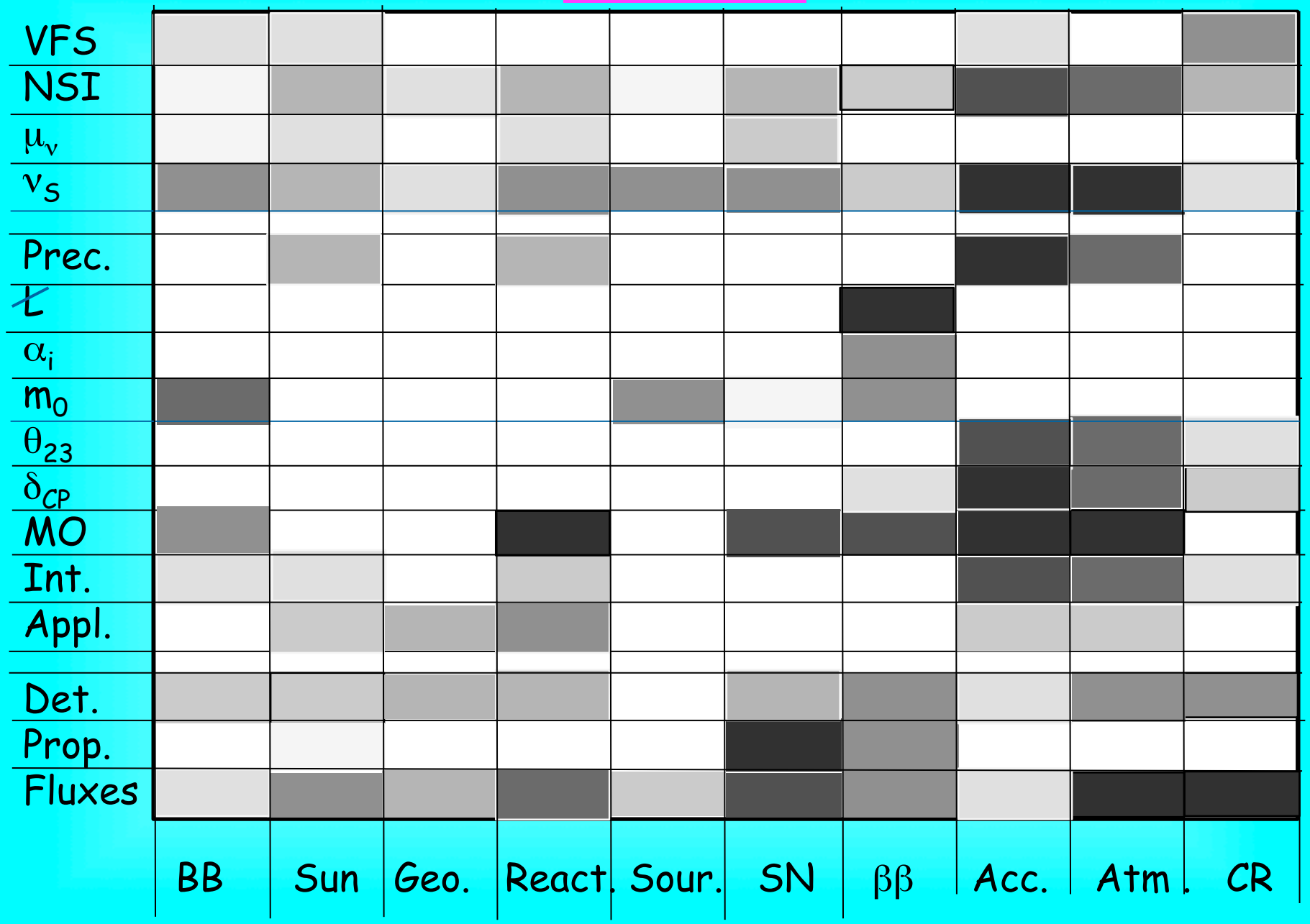
Violation of Fundamental symmetries

CPT

Lorentz

Equivalence principle

relevance


VFS
NSI
μ_ν
ν_s
Prec.
$\not{L}$
α_i
m_0
θ_{23}
δ_{CP}
MO
Int.
Appl.
Det.
Prop.
Fluxes
BB
Sun
Geo.
React.
Sour.
SN
$\beta\beta$
Acc.
Atm.
CR


Highlights
Advances
Anomalies
www.DesktopCollector.com

Solar neutrinos

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:

- ν_S
- NSI
- Neutrino decay (after low energy BOREXINO data)

Open issues

or persisting tension

Absence of upturn of the spectrum

at about 3σ - level

Large D-N asymmetry

1.6 times difference of values of Δm^2_{21} extracted from solar and KamLAND data

1.6 times larger value of matter potential extracted from global fit

Can be related

KamLAND

another reactor anomaly?

Solar data alone - very good description at small Δm^2_{21}

Reactor anomaly should affect KamLAND result

New physics

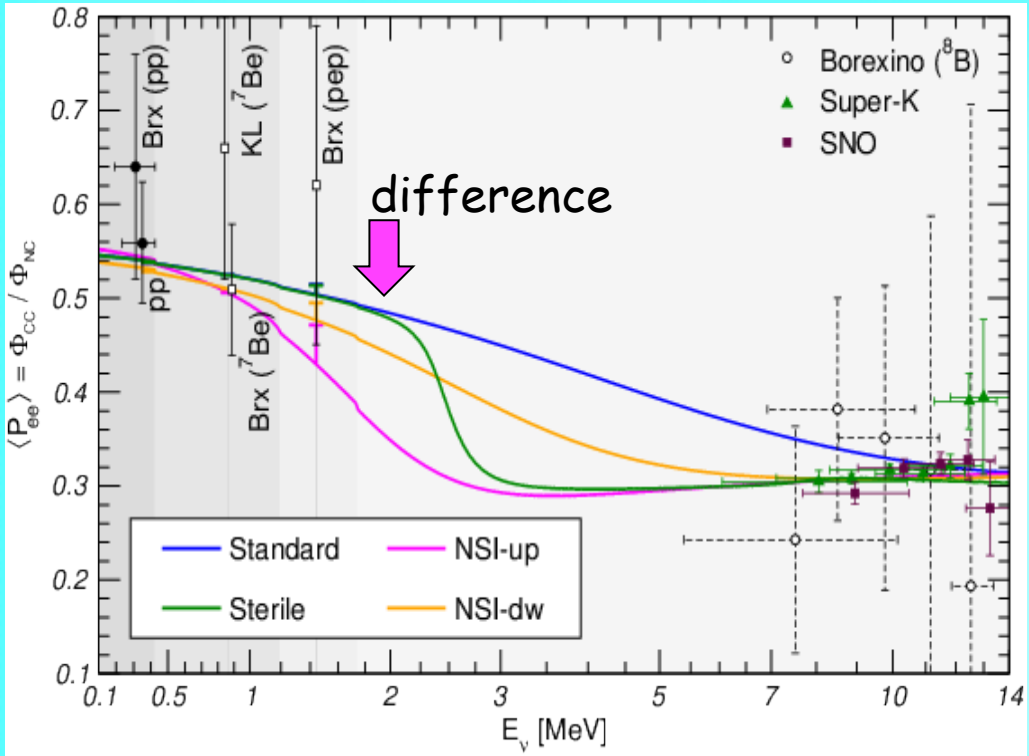
in solar neutrinos?

Non-standard neutrino interaction

Very light sterile neutrinos

New sub-leading effects

New physics effects



M. Maltoni, A.Y.S.

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

M. Pospelov
Y. Farzan

Atmospheric neutrinos

53 documents, 1 review since TAUP 2013

Experiments

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

Ice Cube: measurements of ν_μ ν_e fluxes at high (up to PeV) energies *1410.1749*

★ DeepCore: observation of oscillations, observation of cascades

ANTARES: oscillations

Fluxes computations

Update, various improvements *M. Honda et al, 1502.03916*

Fluxes and flavor ratios for E = 0.1 TeV – 10 PeV *T. S. Sinegovskaya et al, 1407.3591*

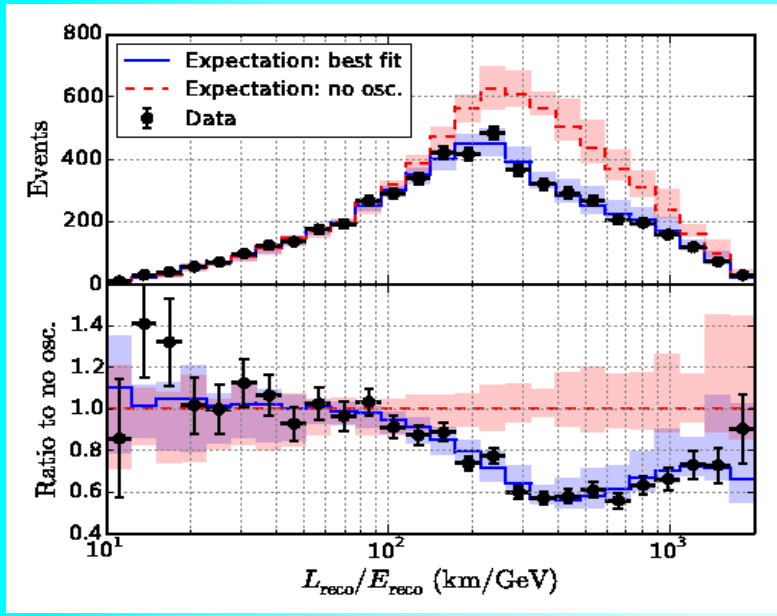
New contribution to conventional flux *T. Gaisser, 1409.4924*

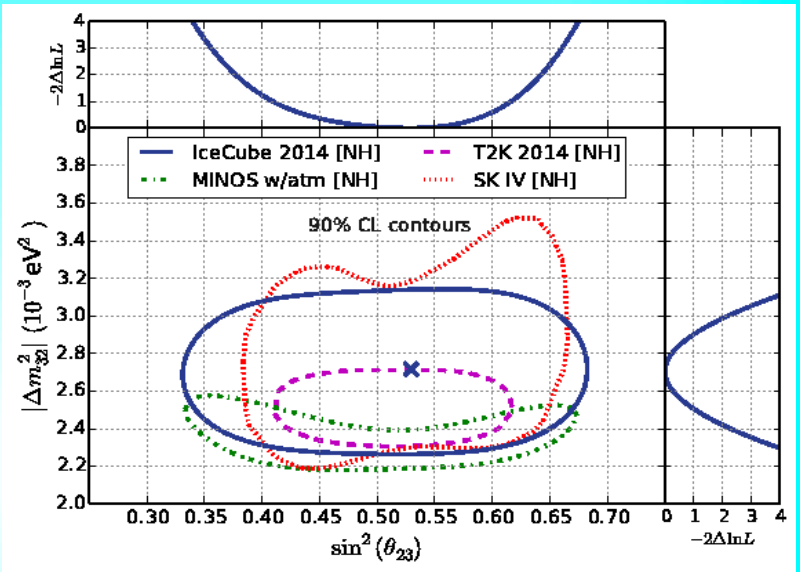
Charm production, new using LHC and RHIC data *A. Bhattacharya et al, 1502.01076*

Crucial for future

DeepCore, PINGU...

Deviation from maximal: symmetry or no symmetry, Quadrant





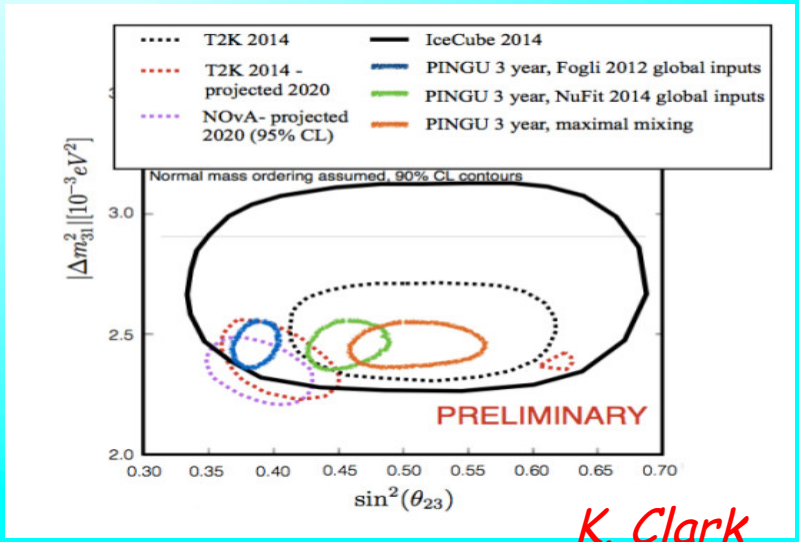
Atmospheric ν_μ disappearance, 3 years of data

IceCube Collaboration (M.G. Aartsen et al.).

arXiv:1410.7227 [hep-ex] /

comparable in precision with present accelerator experiments

Even better in future



K. Clark

Ice Cube

100 GeV

Deep Core

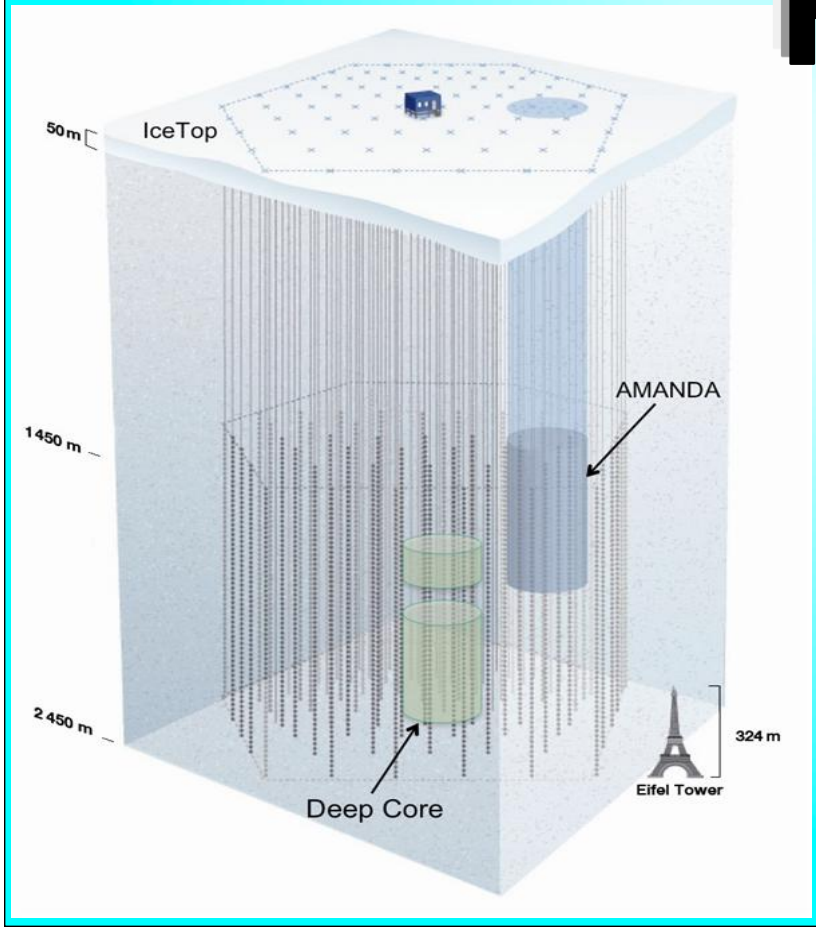
10 - 15 GeV

PINGU

3 GeV

ORCA

Mass hierarchy



Super-PINGU -ORCA

3 times denser array than PINGU

0.5 – 1 GeV

Few Mtons in sub-GeVrange

S. Razzaque, A.Y.S. 1406.1407 hep-ph

Megaton-scale Ice Cherenkov Array

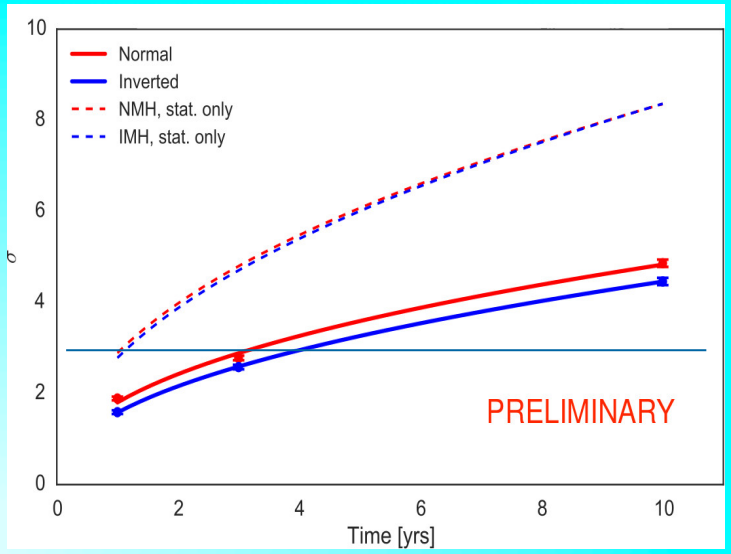
MICA

0.01 GeV

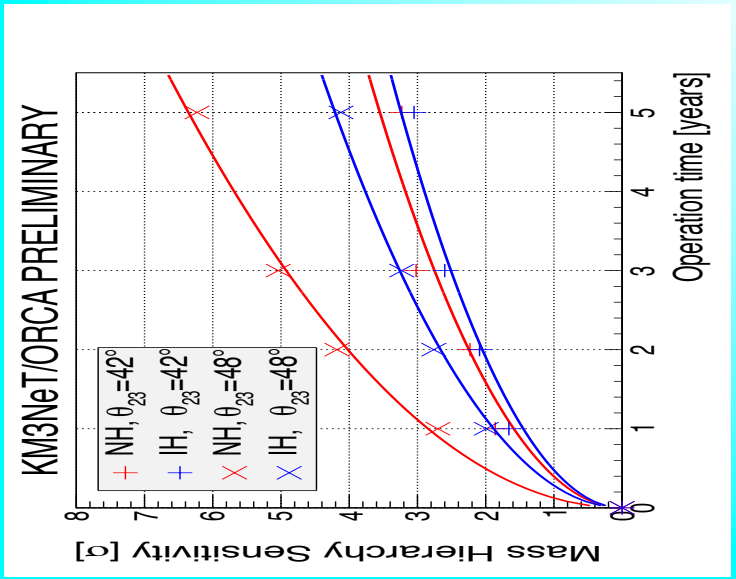
Determination of mass ordering

Crucial developments of detection techniques

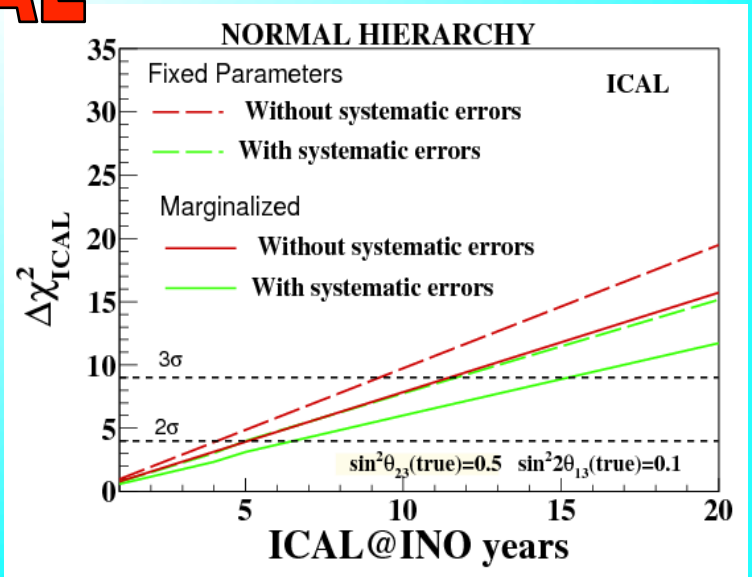
PINGU



ORCA



ICAL



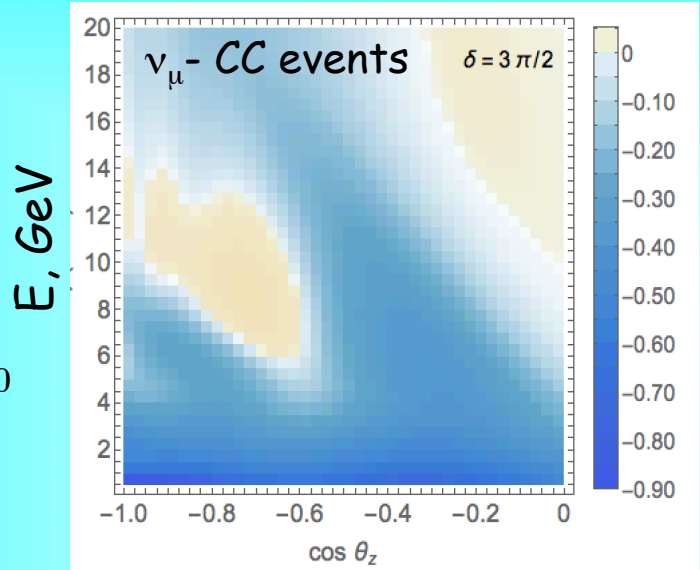
CP violating phase

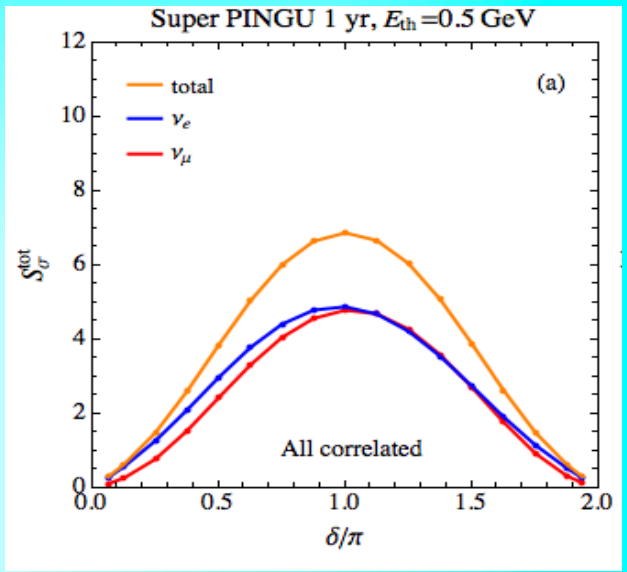
S. Razzaque, A.Y.S.
arXiv: 1406.1407 v2
hep-ph

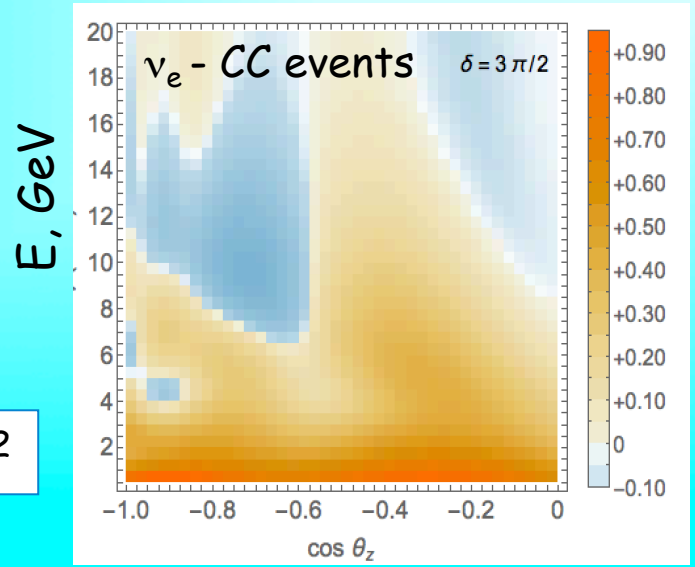
S-distributions for different values of δ

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

Super PINGU, 1 year







Total distinguishability

$$S^{tot} = [\Sigma_{ij} S_{ij}^2]^{1/2}$$

Flavor misidentification reduces distinguishability by factor 1.5 - 2

$S_\sigma \sim 3$, for $\delta = 3/2\pi$
4 years of exposure

ORCA: effect of δ_{CP} ~0.5 σ

Beyond 3ν paradigm

ν_S

eV mass scale

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

★ 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

103 documents, 1 review

From 1D to 2D and 3D

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

serious progress

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

Propagation

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)

A Mirizzi 1506.06805

Self-induced flavor conversion on small scales

S. Chakraborty et al, 1507.07569

Effect of fluctuations in time on instabilities

Sensitivity to time evolution of ν-spectra

S. Abbar, H Duan, 1509.01538

B Dasgupta A Mirizzi

Turbulence effect

Stimulated transformations

Distorted phase effect

Sensitivity to spectrum of turbulence

K. Patton, et al 1407.7835

Shock wave effects

Updated evolution of the density profile used

Jing Xu et al, 1412.7240

Neutrino spin coherence

$\nu - \bar{\nu}$ transformations in nu gases

Within and beyond 3ν paradigm

Mass ordering

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

Time profiles of events in SK (mostly sensitive to anti ν) and in LAr TPC (moostly sensitive to ν)

Absolute scale

Wu, Qian et al 1412.8587

with JUNO, LiAr DUNE

ν_S

Impact of on early time flux (neutronization)

Oscillations in core
Periodicity in ν luminosity

A. Esmaili and P. Serpico

SN Nucleosynthesis

Diffuse neutrino fluxes

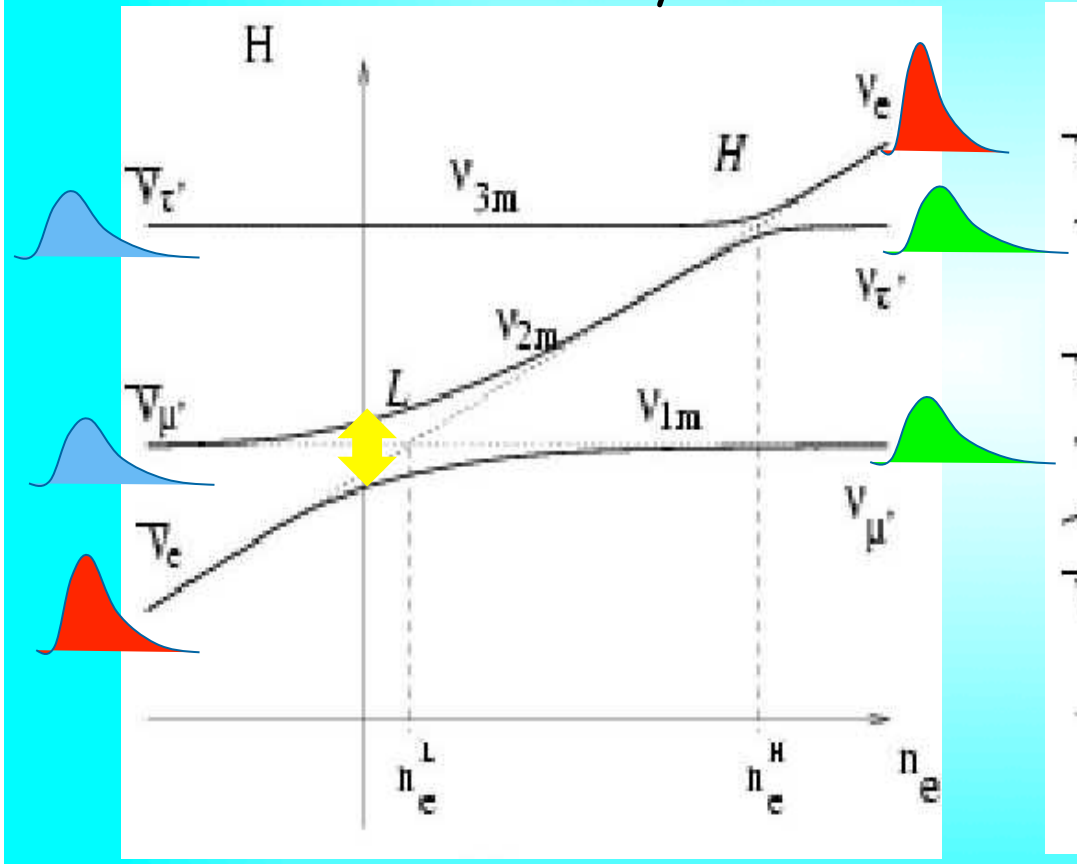
Neutrinos from pre SN star

Earth matter effect and hierarchy

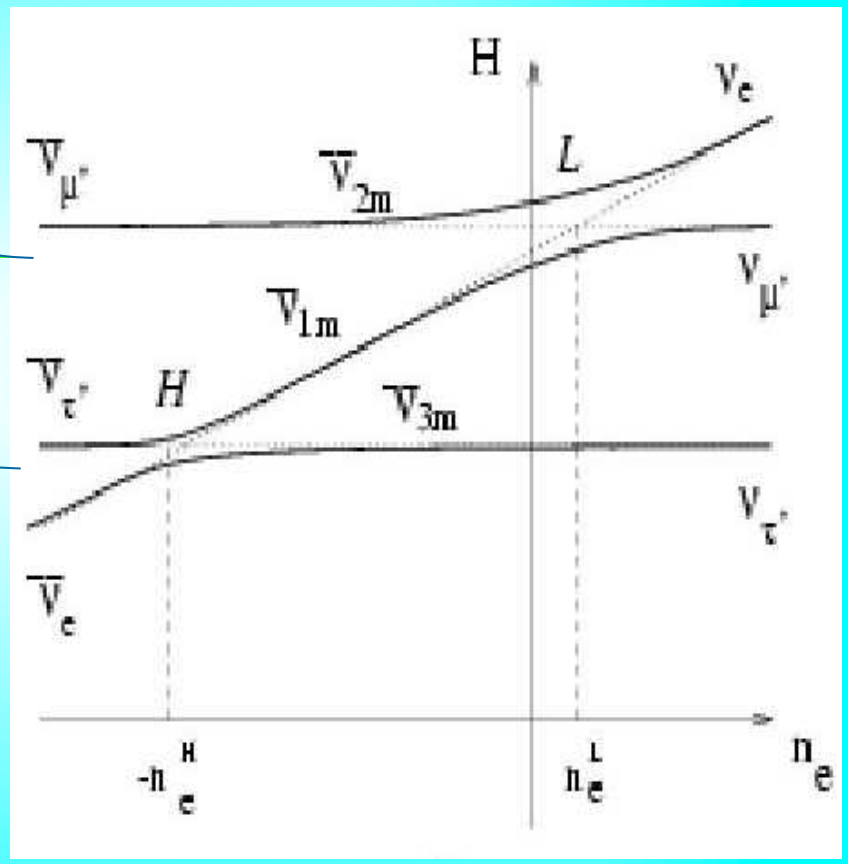
Adiabatic evolution

Level crossings

Normal hierarchy



Inverted hierarchy



No Earth matter effect provided that initial fluxes of ν_μ' and ν_τ' are identical

Collective effects and shock waves may change this.

Reactor neutrinos

63 documents,
many proceedings

Experiments

$\sin^2\theta_{13}$ systematically decreased with time in all experiments and now 3σ below the benchmark value

$\frac{1}{2}\sin^2\theta_C$

Flux

two anomalies

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

1508.04233

$F^{obs} / F^{H-M} = 0.946 +/- 0.022$

$F^{obs} / F^{ILL-F} = 0.991 +/- 0.023$

Toward future measurements

very SBL experiments

For searcher for eV-scale steriles

PROSPECT
Neutrino 4
SM-3
...

clarify Solar - KamLAND tension

Medium BL experiments

JUNO, RENO-50:
Mass ordering (hierarchy)
precision measurements of Δm^2_{21} , θ_{12}

Studies of requirements
effects of systematics

Beyond 3ν paradigm:

NSI ,
ν_S
ν decay

Beyond 3ν paradigm

Constrains on ν_S – parameters from Daya Bay (for relatively small mass)

I. Girardi et al, 1405.6540

- ν_S - in large Extra D framework
- NSI at production, detection

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

1408.6301

NSI in anti ν – e scattering

Cosmic neutrinos

95 documents

PeV neutrinos: 57 documents,
Astrophysical neutrinos: 56

Includes also low (MeV) energies

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

Flavor composition, ratios

- cut off at few PeV ?
- 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

Accelerator neutrinos

NOvA after 7.6% of expected exposure *B. Rebel*

ν_μ - disappearance observed : 33 events, expected: 201 events bgrd: 2

ν_e - appearance

Likelihood Identification selection observed: 6 events

expected (NH, $\theta_{23} = \pi/4$): 5.62 +/- 0.72 events ($\delta_{CP} = 3\pi/2$)
2.24 +/- 0.29 events ($\delta_{CP} = \pi/2$)
bgrd. 0.94 +/- 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 disafavored at 2σ; $\delta_{CP} = \pi/2$ - at 3σ

A. Marrone

At the end of NOvA / T2K operation CP violation can be established at > (3 – 4) σ

Big Bang neutrinos

Relic standard neutrinos

Cosmology

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

Planck 2015 + BAO+ HST

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

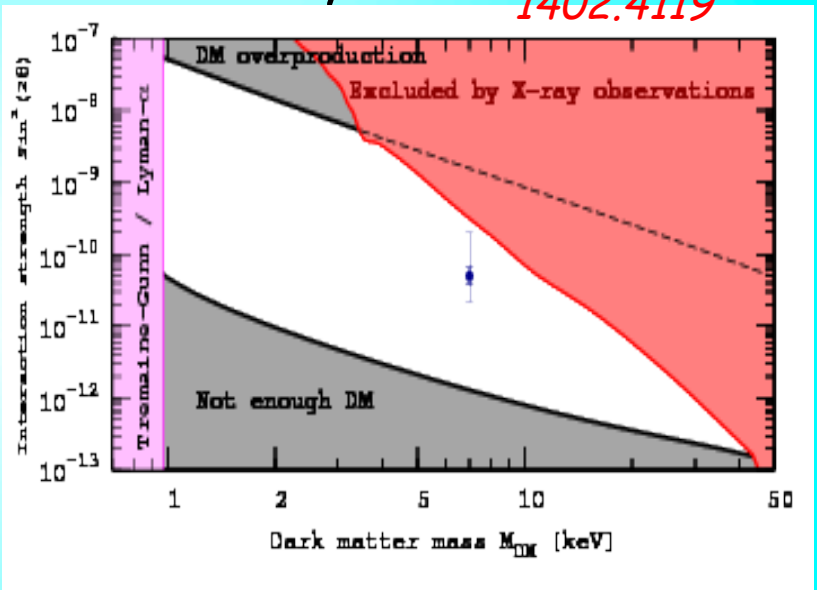
$\Sigma m < 0.23$ eV (95 % CL)

Planck 2015 + TT + low P

WDM neutrinos

3.5 kev X ray line

A Boyarsky et al, 1402.4119



$\theta_{aS}^2 \sim 2\ 10^{-11}$ $m_S \sim 7$ keV

Contribution to active neutrino masses

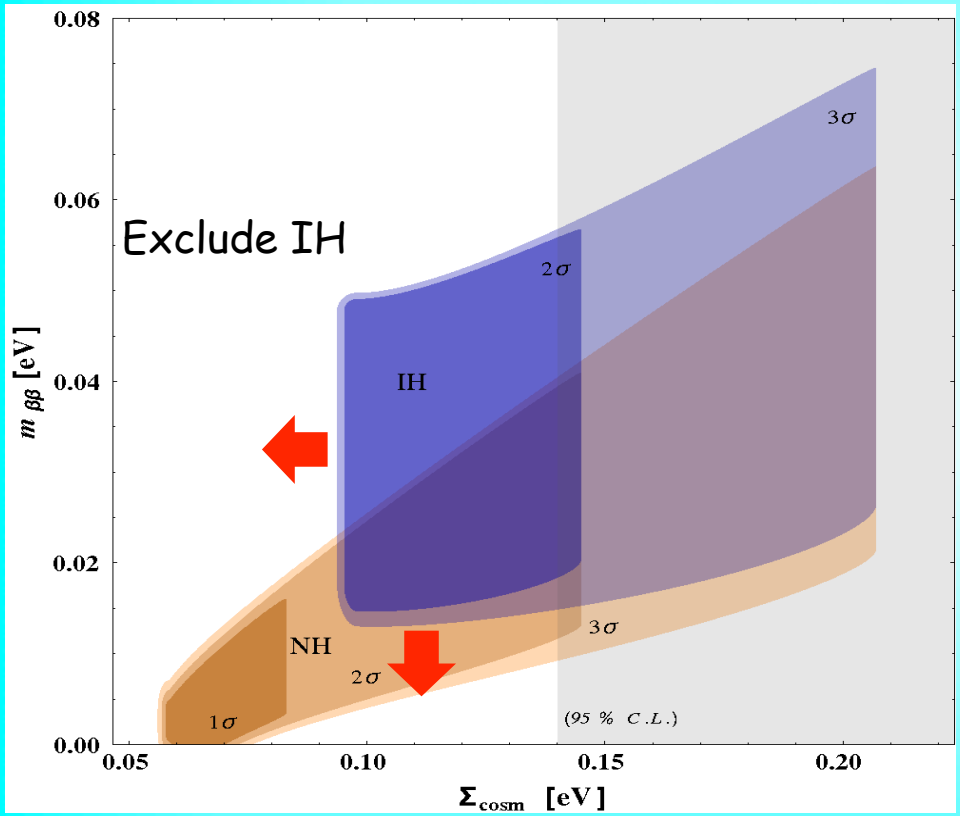
$\delta m \sim \theta_{aS}^2 m_S \sim (1 - 2)\ 10^{-7}$ eV

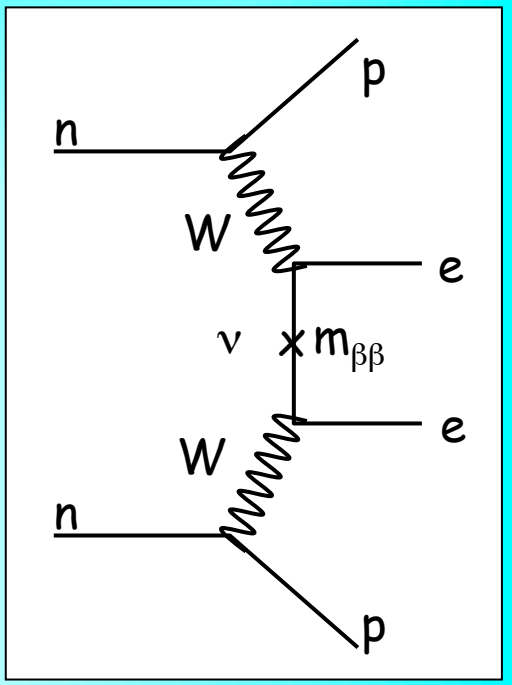
Drago dwarf Galaxy: observations analysis

Too small ν_S is not RH neutrino

Double beta decay

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





S. Dell'Oro, et al, 1505.02722 [hep-ph]

Constraints from cosmological surveys and from oscillations.
The 1 σ 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

Theory Landscape

Goals

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

Establish relations between neutrinos and other phenomena

LHC physics

DM
DE
BAU

LFV
LNV

Establish relations between neutrino parameters

Masses, mixing, phases

Identify physics behind neutrino mass

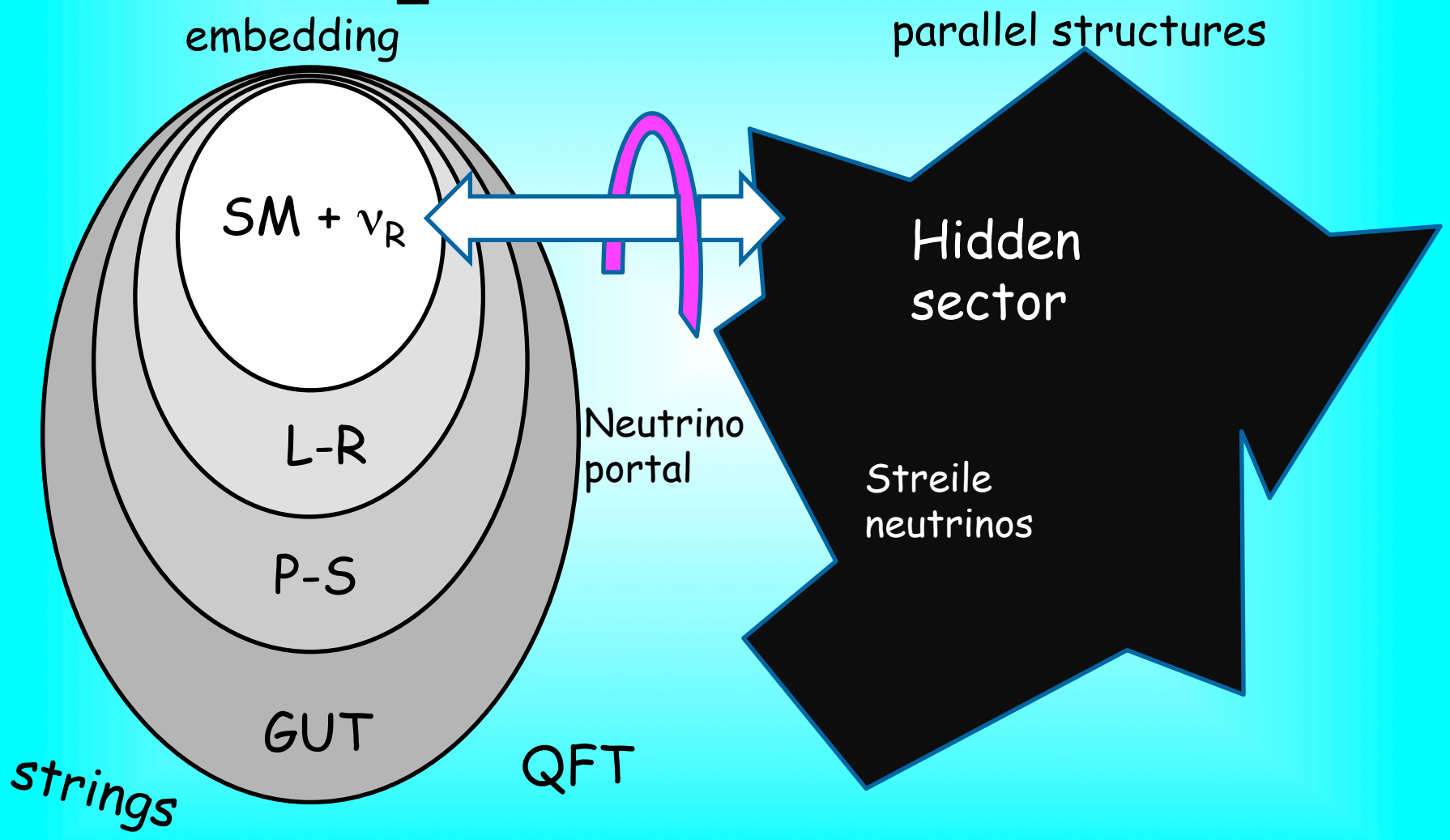
theory of flavor

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

Unification

GUT

Setup


embedding
parallel structures
SM + ν_R
L-R
P-S
GUT
strings
QFT
Neutrino portal
Hidden sector
Streile neutrinos

Scales of new physics

GUT - Planck mass

28 orders of magnitude

High scale seesaw
Quark- lepton symmetry /analogy GUT

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

PeV

Electroweak - LHC

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

eV- sub-eV

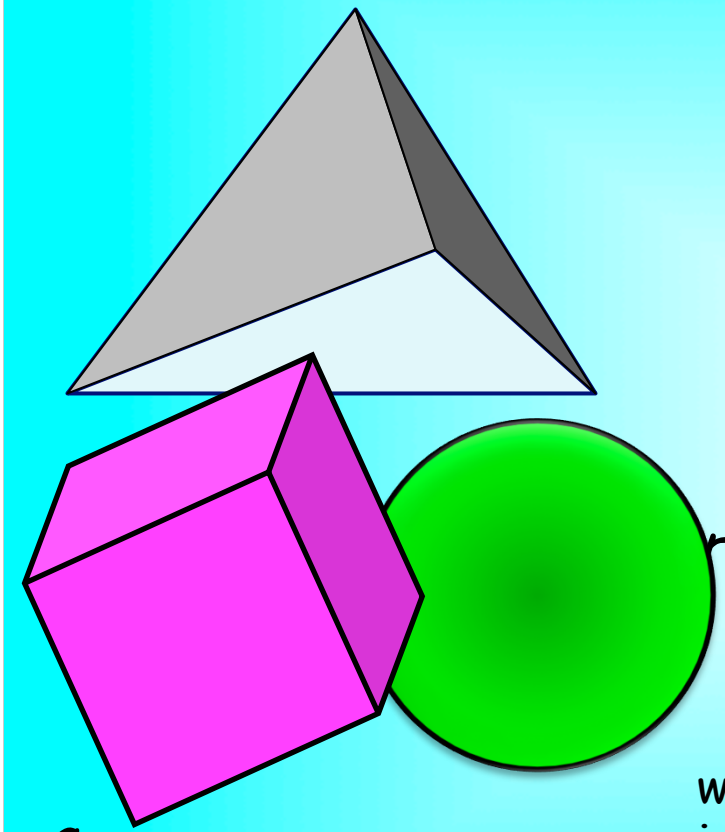
Scale of neutrino masses themselves
Relation to dark energy, MAVAN?

m_ν

Spurious scale?

Neutrino mass itself is the fundamental scale of new physics

Mixing



Complicated constructions, especially if quarks are included

from symmetry to anarchy and randomness

with intermediate possibilities

Not much to add
- String landscape
- Multiverse?

Coordinates

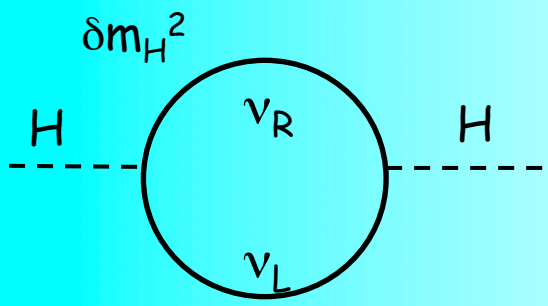
To fill in: exercise for theoreticians

	Abel	non-Ab	Abel	non-Abel		
	continuos		discrete			
	symmetries				partial anarchy	anarchy
Explicit Model building						
Mechanisms of m_ν						
effective operators						
Mass matrices						
SM + ν_{mass}						

ν- mass and Higgs physics

bottom -up

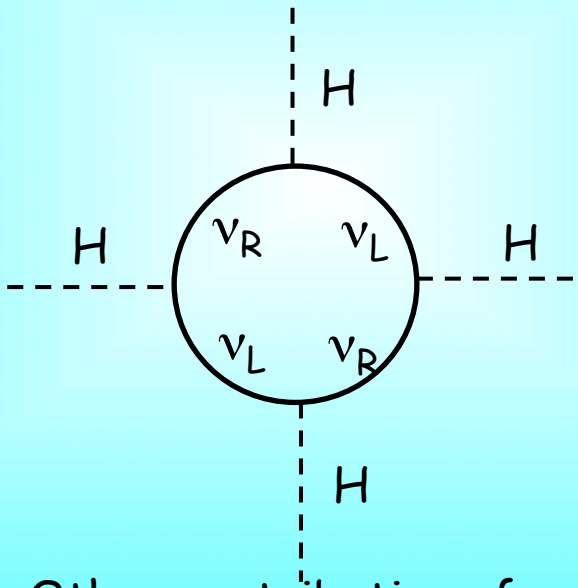
Correction to Higgs mass



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 ...

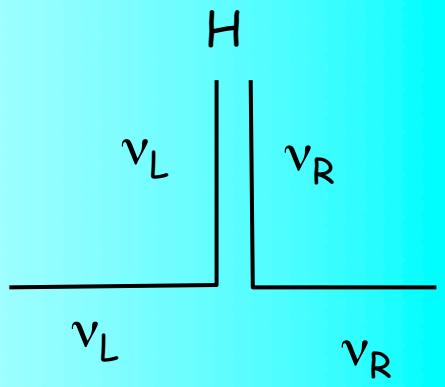
Correction to λ - 4 point coupling – vacuum stability



Other contributions from particles associated to neutrino mass generation, e.g. Higgs triplets

C. Bonila et al, 1506.04031

Higgs as composite state of neutrinos



New strong int.
Generate 4 fermionic coupling

Recent:
J. Krog, C. T. Hill 1506.02843

PMNS & CKM

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 , … .

$$U_{PMNS} = U_{CKM}^{+} U_X$$

where $U_{CKM} \sim V_{CKM}$

has similar hierarchical structure determined by powers of

$\lambda = \sin\theta_C$

From the Dirac matrices of charged leptons and neutrinos

U_X has some special form determined by symmetry

related to mechanism that explains smallness of neutrino mass

$$U_X \sim U_{23}(\pi/4)\, U_{12}$$

Prediction for the 1-3 mixing

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

$$\sin^2\theta_{13} \sim \tfrac{1}{2} \sin^2\theta_C$$

in a good agreement with measurements

What does this mean?

if not accidental

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

- Some additional physics is involved in the lepton sector which explains smallness of neutrino mass and difference of the quark and lepton mixing patterns

- Two types of new physics

CKM

Neutrino new physics

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

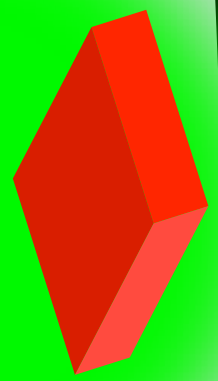
Various predictions of CP phase

Set-up

Patrick Ludl A.S

CKM

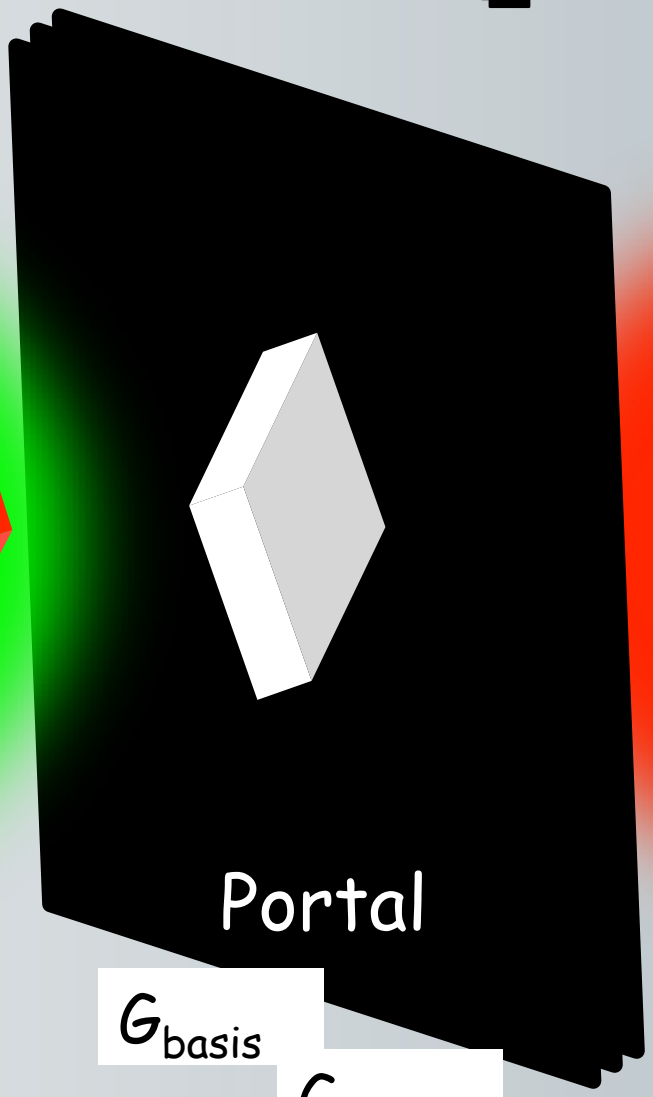
SM → SO(10)



G_{Yukawa}

Visible sector

G_{basis}



Portal

G_{basis}

G_{portal}

Neutrino

fermions $\{1_S^i\}$

bosons $\{1_H^j\}$

G_{hidden}

Hidden sector


Conclusions

Trends

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?

New developments

Large atmospheric neutrino detectors with low energy thresholds

with very strong physics/ discovery potential (MO, δ_{CP}, NSI, ν_S) relatively cheap

Dedicated program of for higher accuracy predictions of the atmospheric neutrino fluxes

What is hot

Cosmic / astrophysical neutrinos
(origins, new physics,)

Sterile neutrinos

hopefully can be resolved soon

Mass ordering
CP-violation

Sooner than expected?

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

Relations

Neutrinos

Higgs physics
Dark matter
Axions

Anomalies

Reactor
Gallium anomaly

LSND/MiniBooNE

Solar - KamLAND tension

What is missed?

Look at the tables...

Theory

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

Landscape

- big picture a kind of snapshot

In contrast, neutrino physics is subject of fast developments

Breakthrough in one particular area may drastically change the ν landscape

Backup

Landscape

From titles
of papers and talks

Variety of

measurements
results
models
estimations
schemes
approaches
searches
experiments
bounds
problems
methods
projects
topics
developments
computations
frameworks

Making sense

What can be seen/
understood/infer
from this overall view

that can not be seen
reviewing specific topics

New quality
Certain harmony

Comparison of different
topics directions

hot
trends

Dominant
elements

Anomalies
problems

relative
importance