Open problems in Neutrino physics

A. Yu. Smirnov

Max-Planck Institute fuer Kernphysik, Heidelberg, Germany

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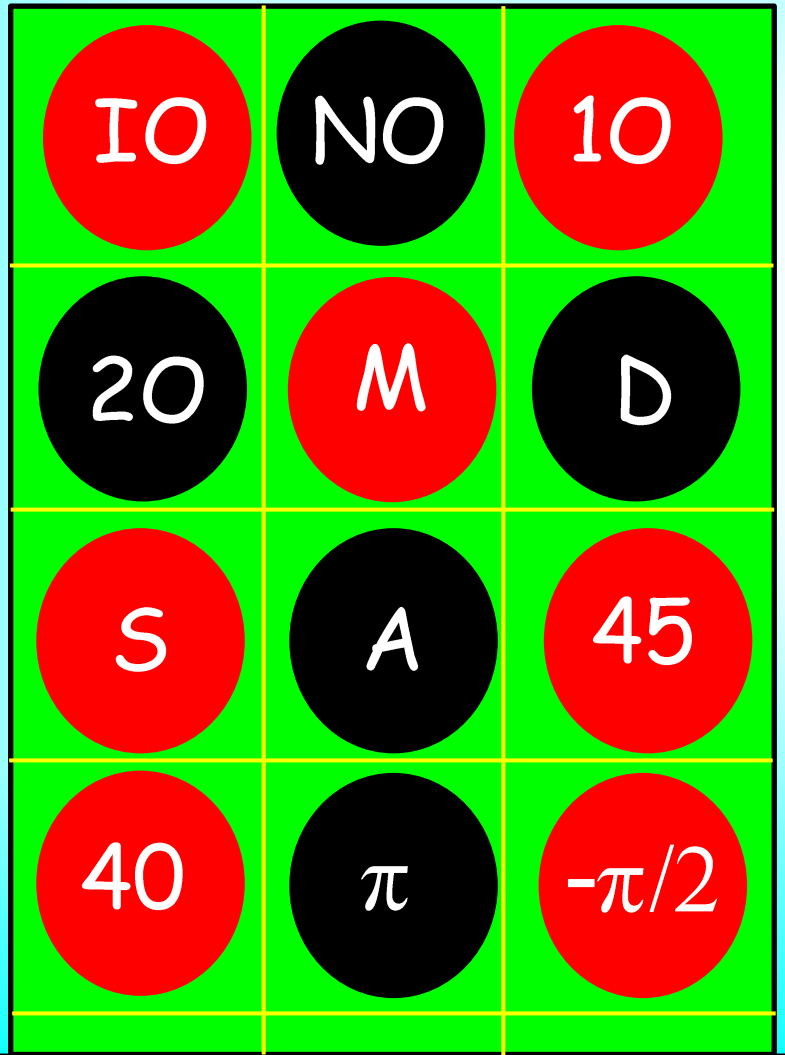
Neutrino Roulette

Casino room



Outline

Problems and goals

Summary: where we are

1. Establishing Nature of neutrino mass
2. Reconstruction of mass and flavor spectrum
3. Searches for new physics beyond 3 nu paradigm
4. Elaboration of remaining phenomenology
5. Uncovering physics behind neutrino mass and mixing
6. Finding neutrino connections

Summary: Where we are?

3ν - paradigm

All well established/confirmed results fit well a framework

- three neutrinos
  - with interactions described by the standard model
    - with masses and mixing

- negligible feedback of neutrino mass generation on the standard model

Old physics - new physics

Generation of neutrino implies new interactions, new physics

Neutrino masses

OLD PHYSICS:

ν_R RH components exist

usual Yukawa interactions:

$h\ \bar{L}\ H\ \nu_R + h.c.$

$h = 10^{-11}$

Consistent, stable,
no feedback

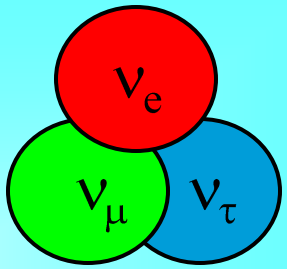
"Proof of principle"

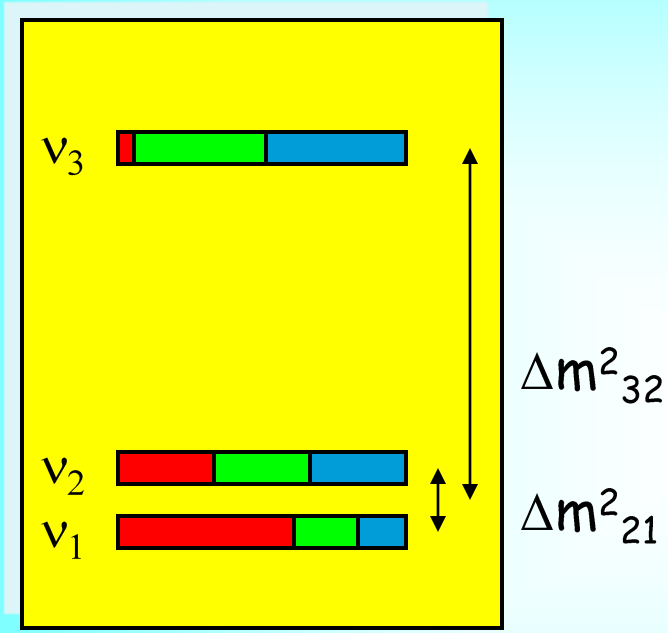
NEW PHYSICS

See-saw,
radiative, etc

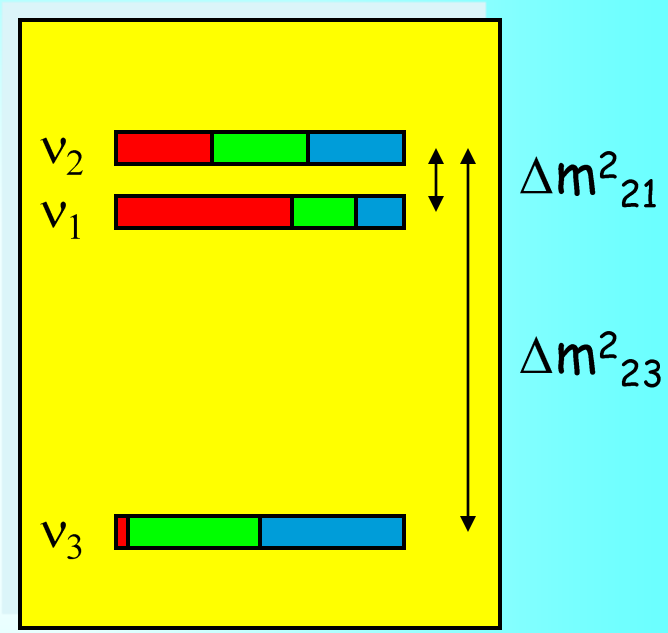
Feedback may be
substantial,
verifiable

Mass and flavor spectrum





FLAVOR
Normal mass ordering



FLAVOR
Inverted mass ordering

Still missing:

- mass ordering
- CP-violation
- absolute mass scale
- 2-3 mixing octant
- nature

That's all?

The biggest question and the biggest problem

Still we need to

Exclude the eV-mass sterile neutrino, measure the remaining parameters of spectrum (mass ordering, CP phase, absolute masses, establish nature of neutrinos ...) this may take 20 – 30 years

This may not be enough even with all other data from LHC, etc. to establish origins of neutrino mass (identify mechanism of mass generation, uncover related physics). Similar situation is in the quark sector now.

We will continue to test 3nu paradigm and perform blind unmotivated searches for new physics.

Elaborate remaining phenomenology (physics at the next level precision), especially in neutrino astrophysics (SN neutrinos, cosmic neutrinos of high energy, relic neutrinos)

Applied neutrino physics will be developed

Neutrinos as the tool, probe of different objects from quarks and hadrons nuclei to stars, Galaxies, large scale structures of the Universe

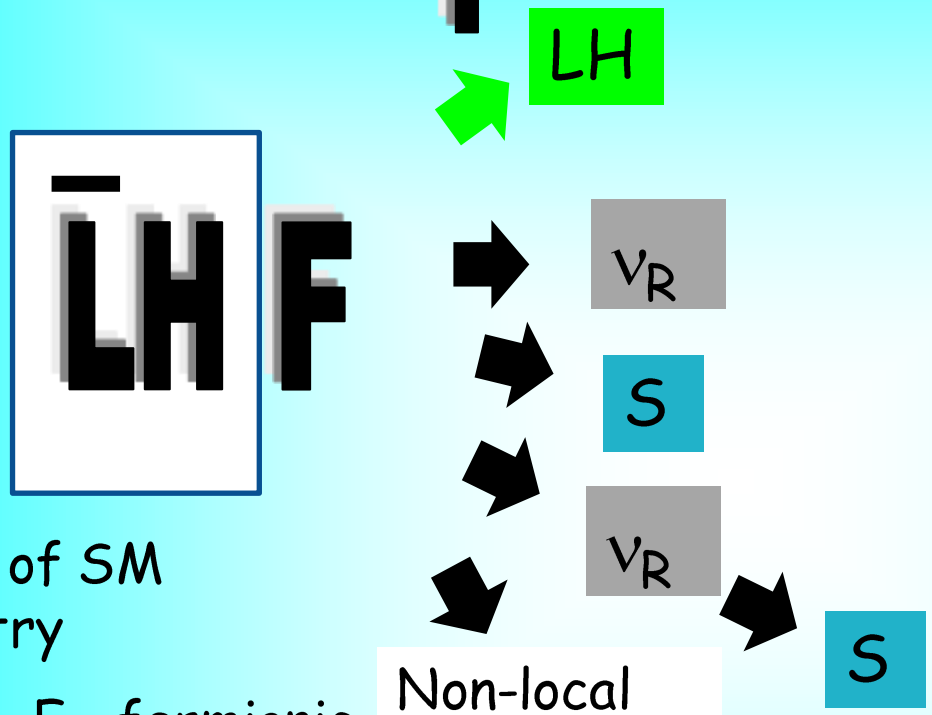
Neutrino technologies, control of reactors, neutrino geophysics, neutrino oscillation tomography

Still the hope is that neutrinos

will uncover New physics beyond the standard model, and shed some light on other problems of particle physics

Neutrino portal

Neutrino are special



via the portal:

Neutrino mass - seesaw
Large lepton mixing
Non Standard Interactions

SM is well protected

Singlet of SM symmetry group

F - fermionic operator

Non-local interactions

Interactions which violated fundamental symmetries

Singlet of symmetry group of hidden sector

$$\frac{1}{\Lambda^{n(F)\,-\,3/2}}\,L\,H\,F$$

Connection to the Higgs portal: $H^{+}H$

Nature of neutrino mass

Two aspects

Similar to cosmological constant

Smallness: is the neutrino mass of the same origins as masses of other particles?

Notice, oscillations test immediately dispersion relations and not masses

Suppression wrt. the EW scale

Finite value

see-saws type-I does both simultaneously

incomplete suppression

Mechanisms unrelated to suppression

No RH component
Dirac mass can not be formed

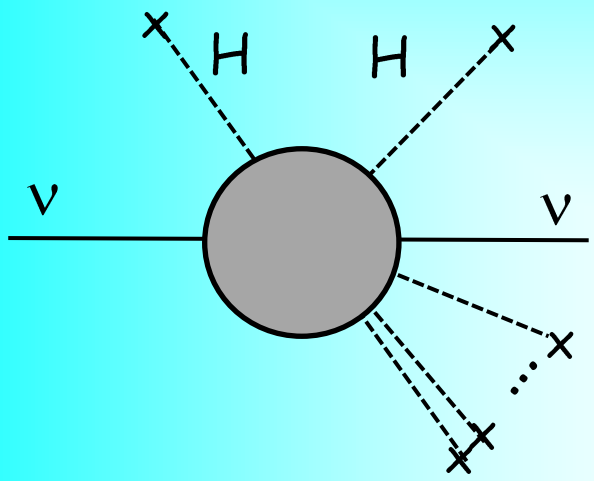
symmetry

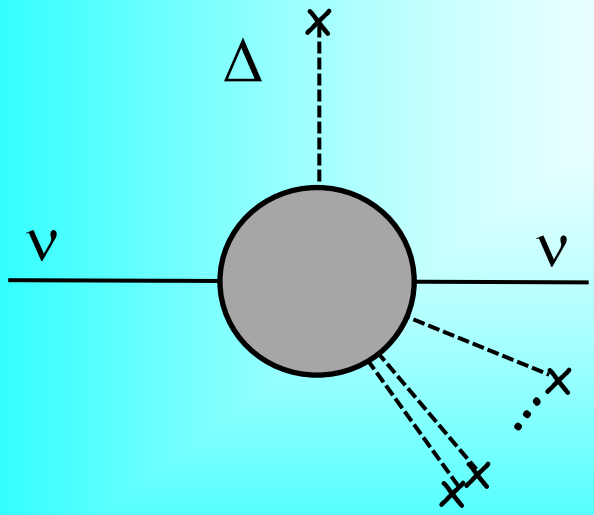
See-saw or multi-singlet mechanisms - suppression only finite contribution negligible

Seesaw type II

Radiative mechanisms

Origins of (finite) mass





Similarly for Dirac neutrinos

Hard mass related to the EW scale

small effective coupling

small induced VEV formed by large VEV's (seesaw II)

Soft mass

VEV created at small scales

melting at T ~ VEV

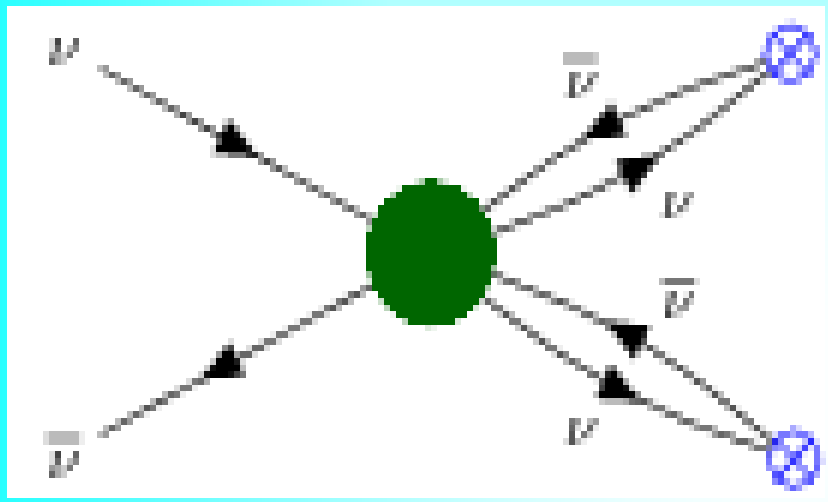
MAVAN

Environment dependent masses relic neutrinos

Gravitationally induced mass

Melting couplings

Soft couplings and small VEV's



Small neutrino masses
from gravitational θ-term

G. Dvali and L. Funcke,
Phys.Rev. D93 (2016) no.11, 113002
arXiv:1602.03191 [hep-ph]

Neutrino mass generation
through the condensate
(crossed blue circles) via
Non-perturbative interaction
(green circle).

Certain generic features independent on specific
scenario can be considered on phenomenological level

Tests of Nature of neutrinos

Extraction of masses, mass squared differences from processes at different conditions

Searches for dependence of mass on external variables

Vacuum – media with different densities, fields

Solar neutrinos-KamLAND

Energies (in medium, or if Lorentz is violated)

Epochs (red shifts)

MAVAN

Momentum transfer

On shell – off shell

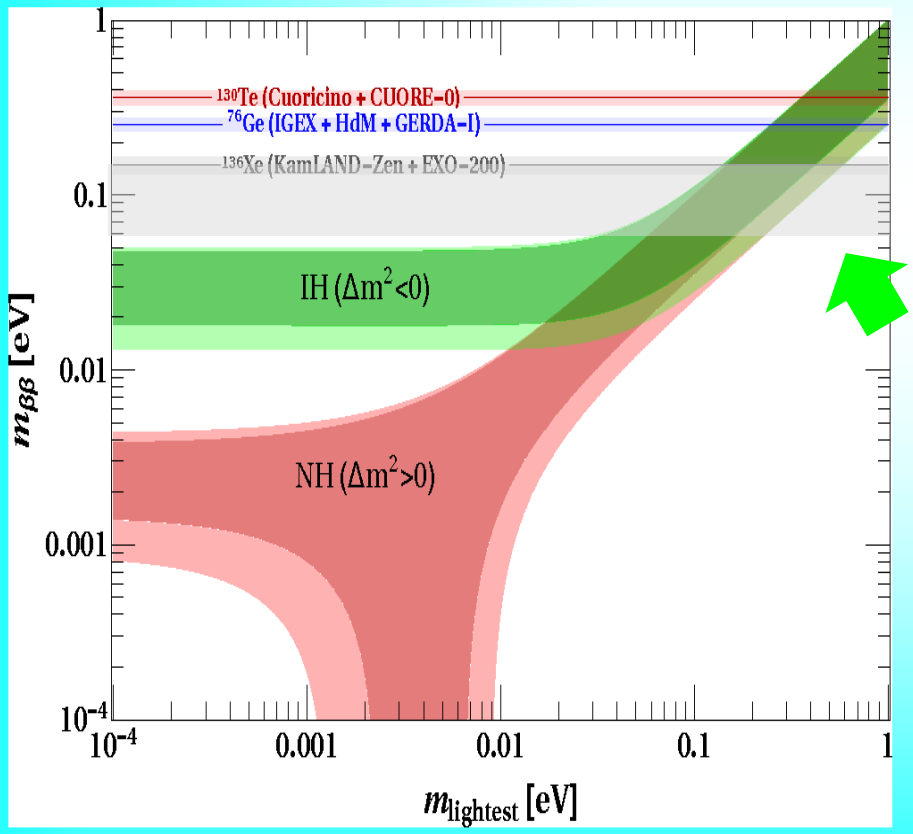
Neutrinoless Double beta decay – unique?

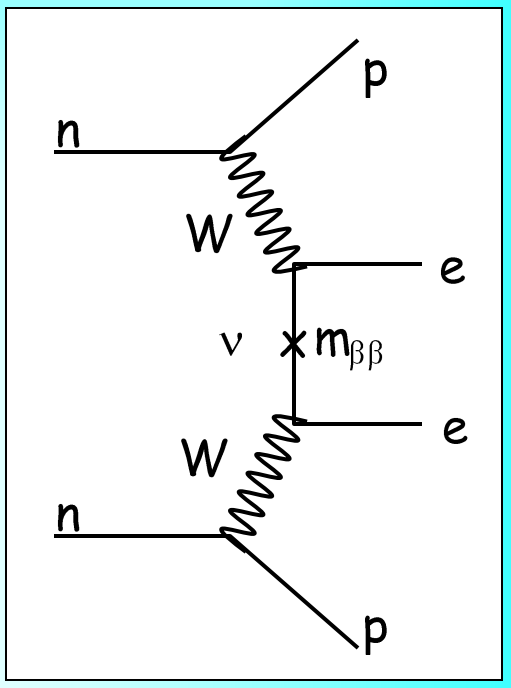
Double beta decay

NH: $m_{\beta\beta}$ = (2 - 4) meV

10 tons for NH

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





KamLAND-Zen

$m_{\beta\beta}$ < (60 - 161) meV, 90% CL
Depending on NME

A.Gando, et al, 1605.02889 [hep-ex]

Approaching IH band

Reconstruction of mass and flavor spectrum

Neutrino mass ordering

First glimpses

sensitivity: from atmospheric data, NOvA, also Cosmology

Phenomenology: well elaborated (atm., accelerator, SN, $\beta\beta_{0\nu}$-decay, ...)

Theory: some qualitative statements (IH – degeneracy), often – model and parameter dependent

Experiment: ORCA, PINGU, JUNO...

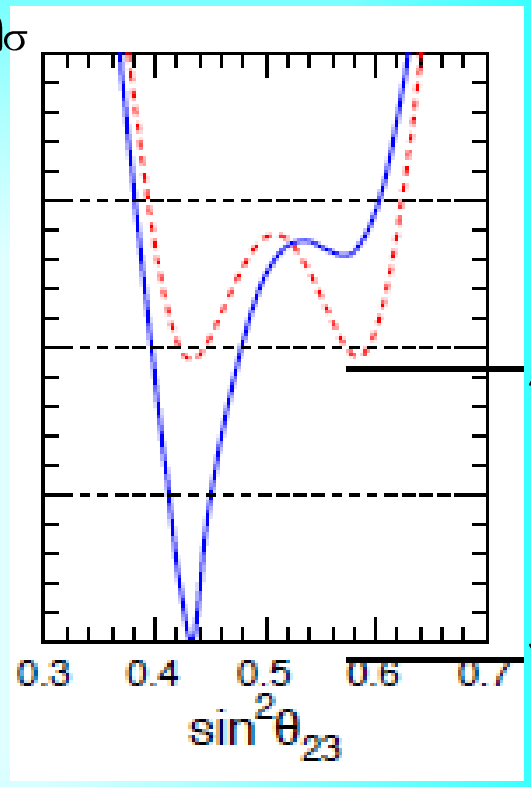
SN neutrino shells in Galaxy approach us!

CHiPS PACIFIC

PROBLEM

One or another hierarchy exists – Fundamental discovery , no loss experiment, in contrast to..... Stronger support of ORCA

Global fit



F. Capozzi et al, NOW 2016

but $\Delta\chi^2 = 1$ in NuFIT 2016 without atm. nu

CP- violation phase

First glimpses

- LBL + solar + reactors + atm.
- CPV: 2.4 σ
- hint for maximal CPV

$\delta \sim -\pi/2$

Stat. Fluctuation, systematics?
See how things will develop with new NOvA T2K data

J-PARC upgrade, key result in 2026
CPV discovery? Further strategy

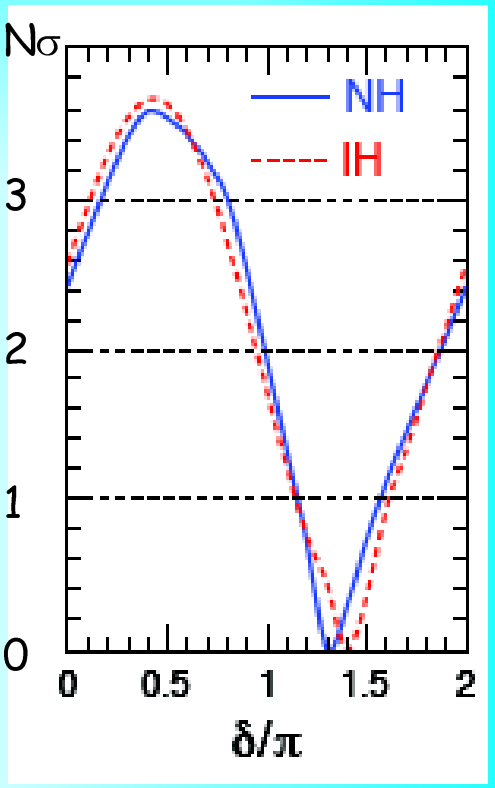
HK, DUNE precision measurements?
Low energy atm. neutrinos

PACIFIC

Theory

probe of the underlying physics, enters various test equalities

Special value of δ - symmetry?



two minima
F. Capozzi et al, NOW 2016

2-3 mixing, octant

Maximal or not?
T2K vs. NOvA / MINOS, 2.5 σ tension
non-standard matter effect?
But IceCube ...
J. Liao, D Marfatia, K .Whisnant, 1609.01786
S. Fukasawa, M. Ghosh, O.Yasuda 160904204

Fragile Atm. Neutrinos, SK, Ice Cube

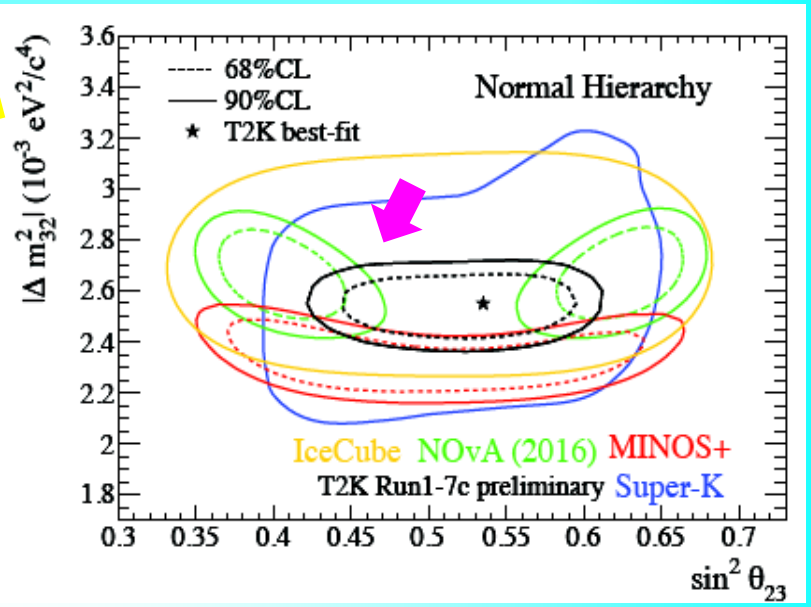
Affect sensitivity to mass hierarchy:
higher in 2nd octant

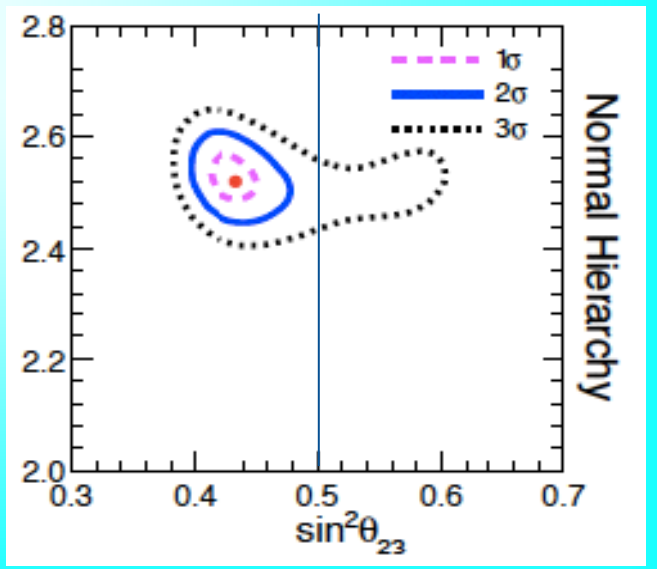
Crucial for existence of symmetry
behind the mixing pattern

the 2-3 deviation and 1-3 mixing related
→ from violation of the 2-3 symmetry

F. Capozzi et al, NOW 2016

Deviation from maximal





Absolute mass scale

COSMOLOGY: restrictions on degenerate spectrum and even IH

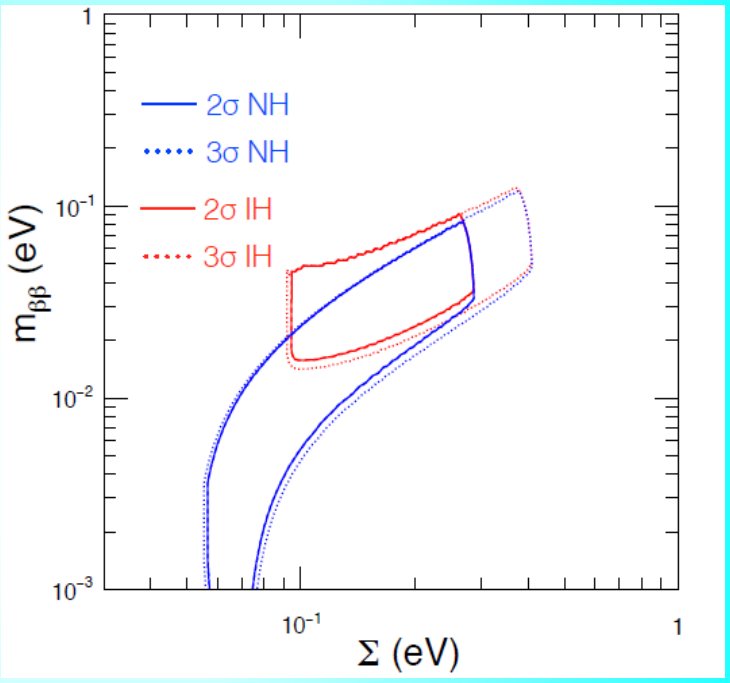
KATRIN 2018

Reconciling Cosmology bound and KATRIN sensitivity

Late formation of the neutrino mass

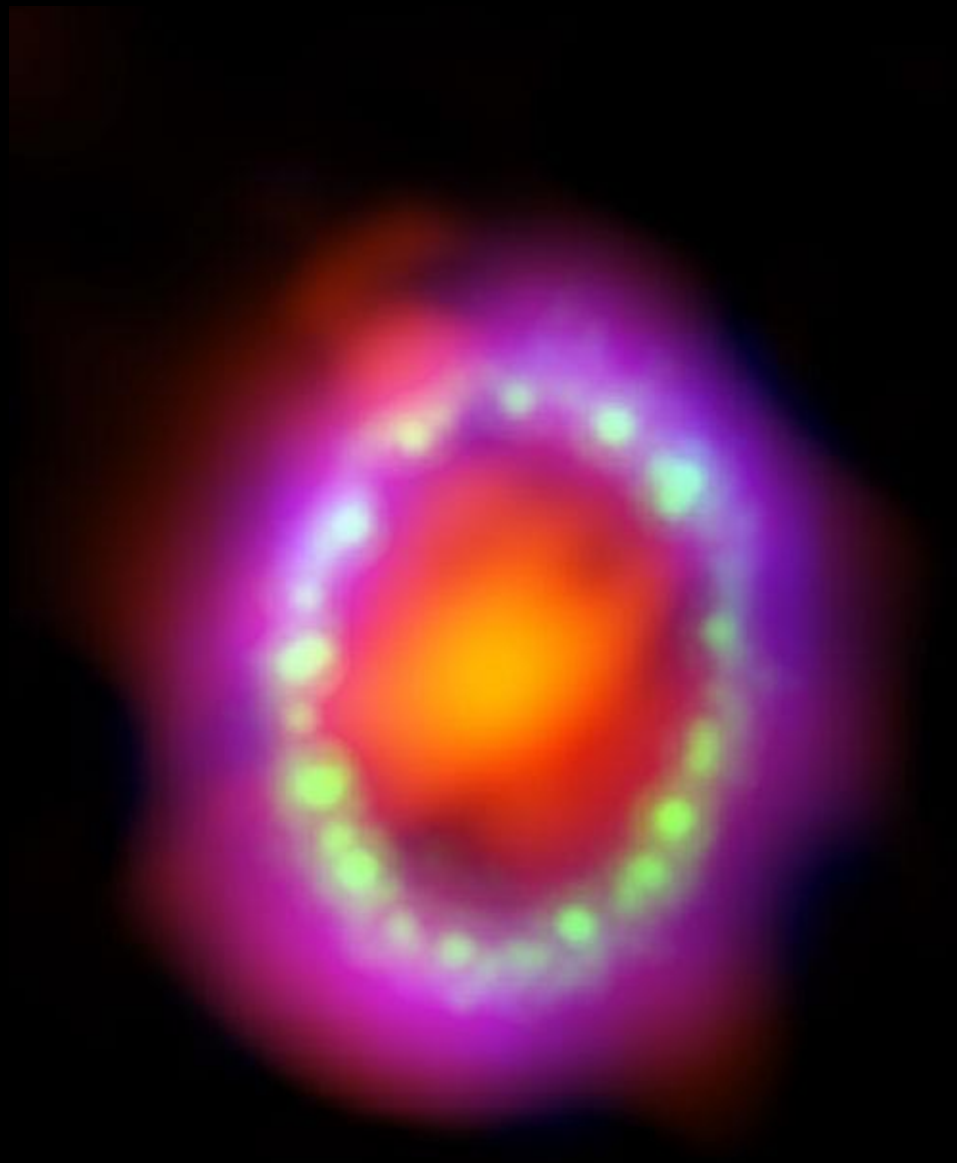
G. Dvali

Neutrinoless double beta decay Does not exist



F. Capozzi, et al weak

Remaining Phenomenology



Accomplish...

New neutrino sources

Natural neutrino sources and fluxes

- Astrophysics: origins, sources
- Propagation, properties of space-time, Universe content
- particle physics, new interactions

HE Cosmic neutrinos

Galactic contribution?
Anisotropy?
Energy spectrum

Relic neutrinos

- properties
- Local density (depends on mass hierarchy)
- PTOLOMY

Solar atmospheric neutrinos

New computations
physics
observation

Neutrinos from Dark Matter

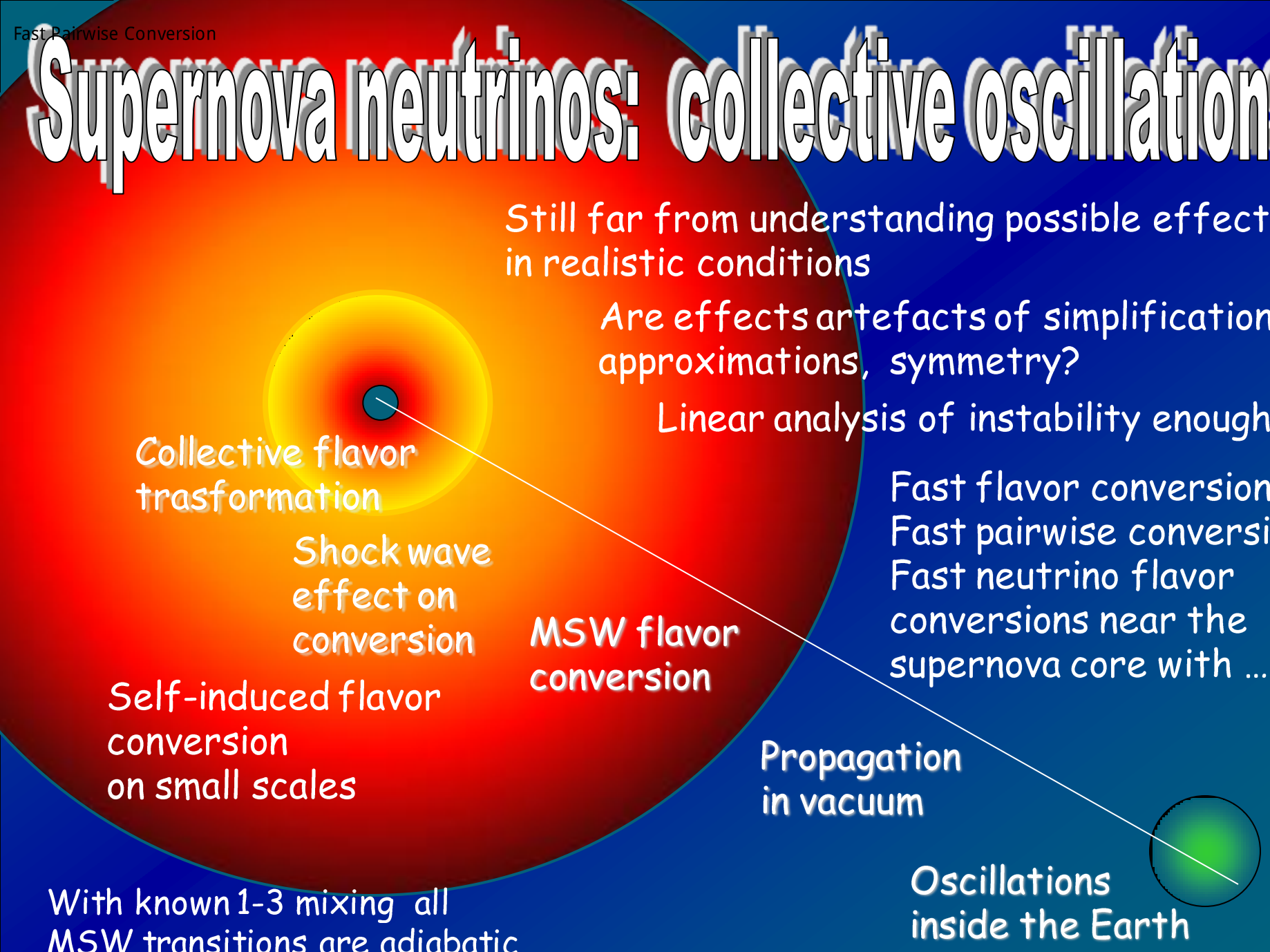
Decay, annihilation

Supernova neutrinos: collective oscillations

Still far from understanding possible effects in realistic conditions

Are effects artefacts of simplification, approximations, symmetry?

Linear analysis of instability enough?



Solar neutrinos

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

another reactor anomaly or new physics?

Fluxes: precise measurements of the pp-neutrino flux
also other fluxes % - sub % accuracy

CNO neutrinos — BOREXINO?

chemical abundance – helioseismology - SSM

D-N asymmetry, Earth matter effect
(zenith angle – energy dependence)

Neutrino oscillation
tomography, attenuation

Beyond 3v – paradigm

Indications and Anomalies

Experimental:

LSND

MiniBooNE

Gallium

REACTORS

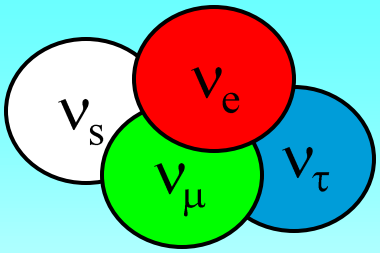
Solar-KamLAND

Δm^2

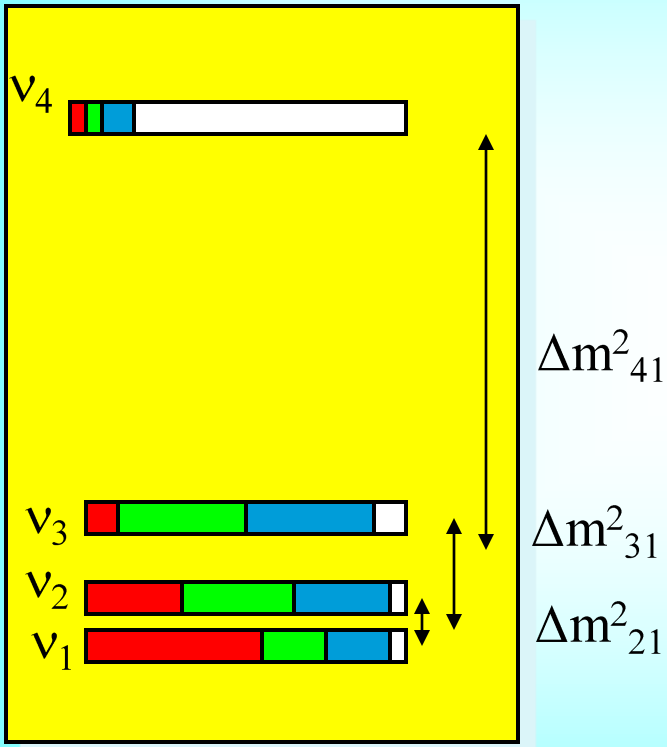
Theoretical motivations: Understanding Mass and mixing, Unification etc

Connection to other anomalies, Problems (common solutions)

(3 + 1) scheme



Interpretation



After the dust settle down

Strong perturbation of 3ν pattern:

$$\delta m_{\alpha\beta} \sim m_4 U_{\alpha 4} U_{\beta 4} \sim \sqrt{\Delta m_{32}^2}$$

Effect of possible sterile neutrinos can be neglected if

$$\delta m_{\alpha\beta} \ll \tfrac{1}{2}\sqrt{\Delta m_{21}^2} \sim 3\ 10^{-3}\ \text{eV}$$

$$|U_{\alpha 4}|^2 < 10^{-3}\,(1\ \text{eV}/m_4)$$

Related:

Non-unitarity

Non-universality

- additional radiation in the Universe
- bound from LSS

Race for Nothing?

Sterile revolution 2012. After discovery of 1-3 mixing

- Rich phenomenology
- Relatively cheap, and fast realization
- Little chance to discover compensated by strong impact of positive result

Redundant negative results

Daya-Bay

IceCube, DC

MINOS, MINOS+

SOX

PROSPECT

NEOS

ICARUS

MicroBooNE

SoLid

DANSS

SBND

Stereo

JSNS (J-PARC E-56)

Neutrino-4

Non-standard interactions

Motivation, indications

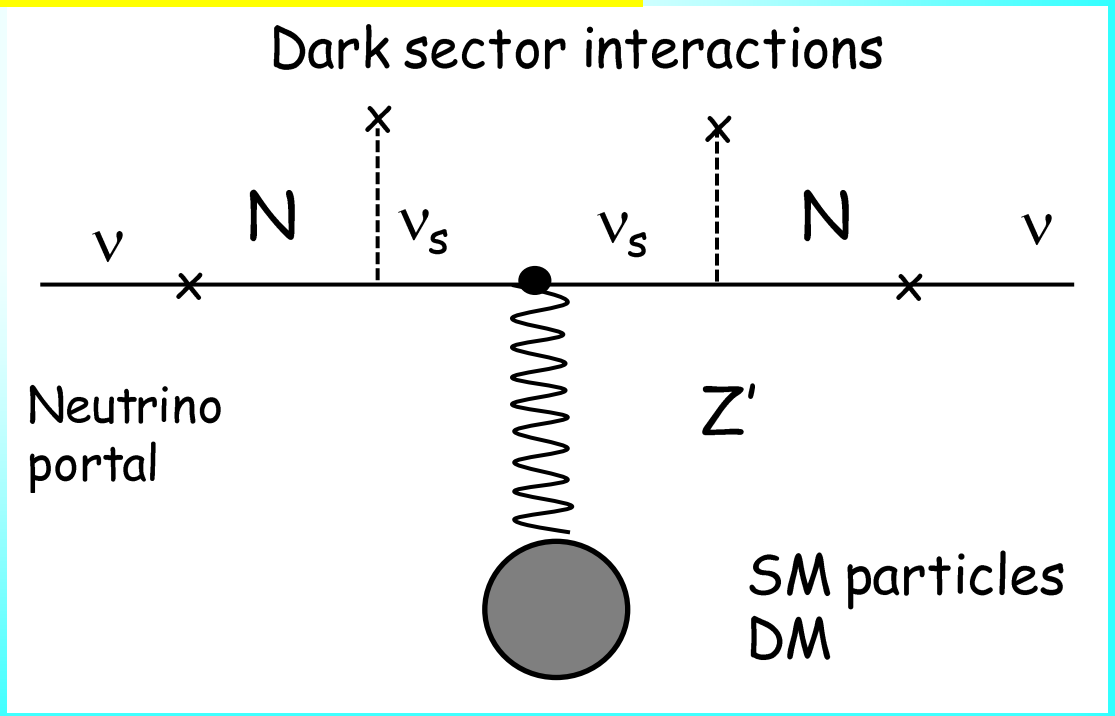
Solar neutrinos - KamLAND

J-PARC – NOvA/MINOS

Effects ~ $\Delta m^2_{21}/V$

New light sector

NSI via neutrino portal



Affects potential of sterile neutrinos

F. Capozzi,et al 1702.08464 [hep-ph]

Behind neutrino mass and mixing

High or low scale

- No hierarchy problem (even without SUSY)
- testable at LHC, new particles at 0.1 – few TeV scale
- LNV decays

Low scale seesaw

νMSM

Low scale

L-R

$\not{R}_p$-SUSY

Neutralino as RH neutrino

Inverse seesaw

Radiative

One loop

Two loops

Three loops

Four loops

High dimensional operators

Radiative seesaw

Small VEV

Higgs Triplet

New Higgs doublets

Connection to Dark Matter

Mixing and symmetry

Real or accidental?

Tri-bimaximal mixing

P. F. Harrison, D. H. Perkins, W. G. Scott
L. Wolfenstein

$$U_{tbm} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

0.15

0.62

0.78

$U_{tbm} = U_{23}(\pi/4)\, U_{12}$

$\sin^2\theta_{12} = 1/3$ 0.30 - 0.31

Accidental, numerology, useful for bookkeeping

Accidental symmetry (still useful)

There is no relation of mixing with masses (mass ratios)

Not accidental

Lowest order approximation which corresponds to weakly broken (flavor) symmetry of the Lagrangian

with some other physics and structures associated

flavons other new particles

Tests:

Sum rules... But in most of situations – just accidental, rather than follow from symmetries

Neutrinos and Unification

Do small neutrino masses indicate existence of high scale?

Leptons and quarks: similarity - unification

The simplest connection:

See-saw type-I

RH – neutrinos

$$M_R \sim \frac{V_{EW}^2}{m_\nu} = 10^8 - 10^{14}\ GeV$$

Seesaw type II – more complex connection

Corrections to Higgs mass if no SUSY?

$M_{3R} \sim M_{GUT} = 10^{16}$ GeV still possible

$$M_R \sim \frac{M_{GUT}^2}{M_{PL}}$$

Double seesaw connection to the Planck scale

Unification and difference of quark and lepton mixing patterns?

especially if common flavor symmetry is introduced

The difference is due to mechanism of neutrino mass generation but in the simplest seesaw (strong mass hierarchy, small mixing)

Quark and lepton mixing

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

From the Dirac matrices of charged leptons and neutrinos

Related to mechanism that explains smallness of neutrino mass

New neutrino structure

Two types of new physics ?

CKM type new physics

Neutrino new physics

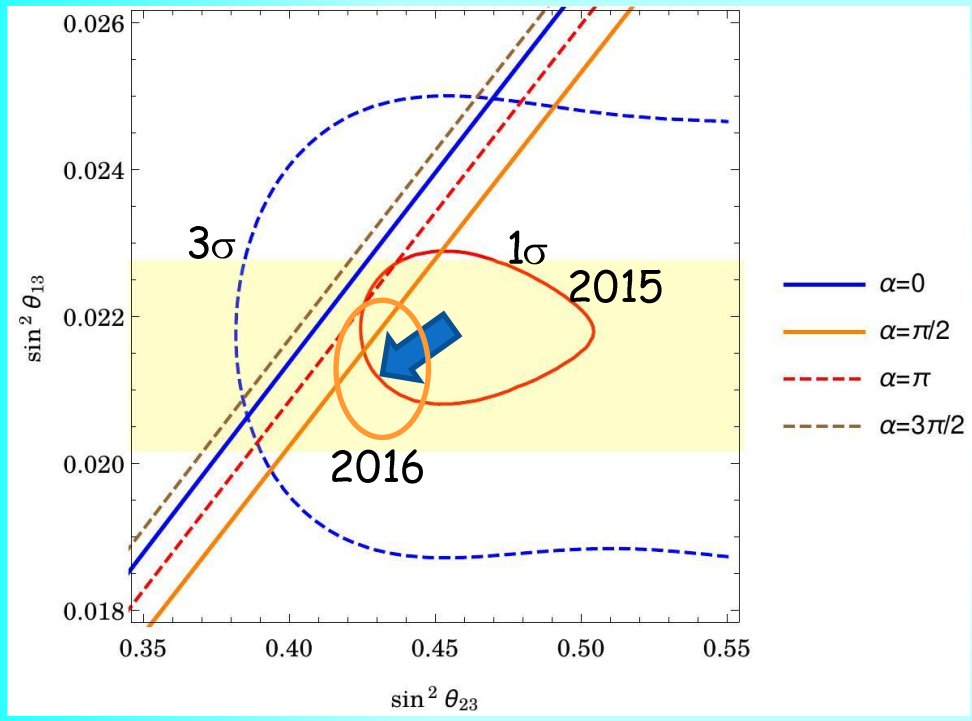
Can be naturally realized in the seesaw type I which after all is the most appealing mechanism of explanation of smallness of neutrino mass

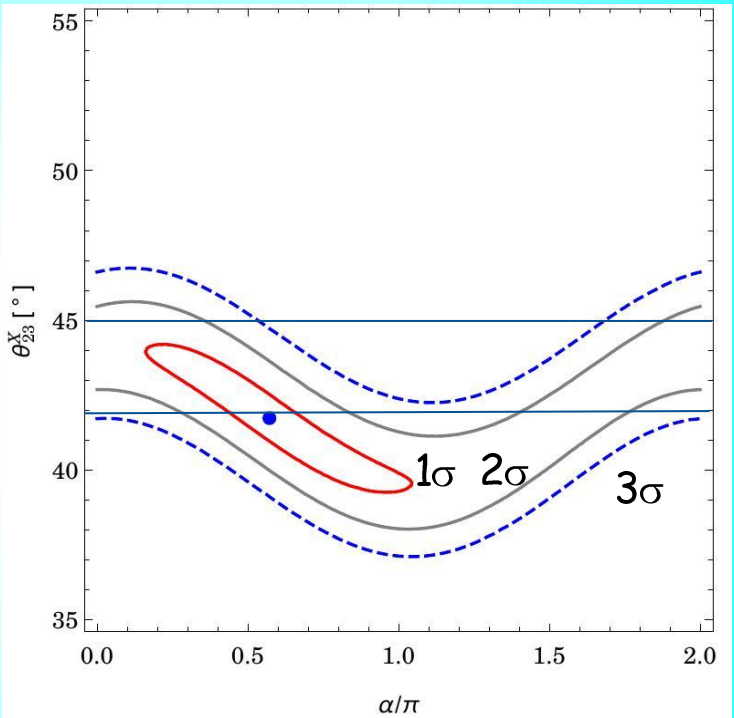
General relation

Normal mass ordering

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

$$\lambda = \sin\theta_C$$





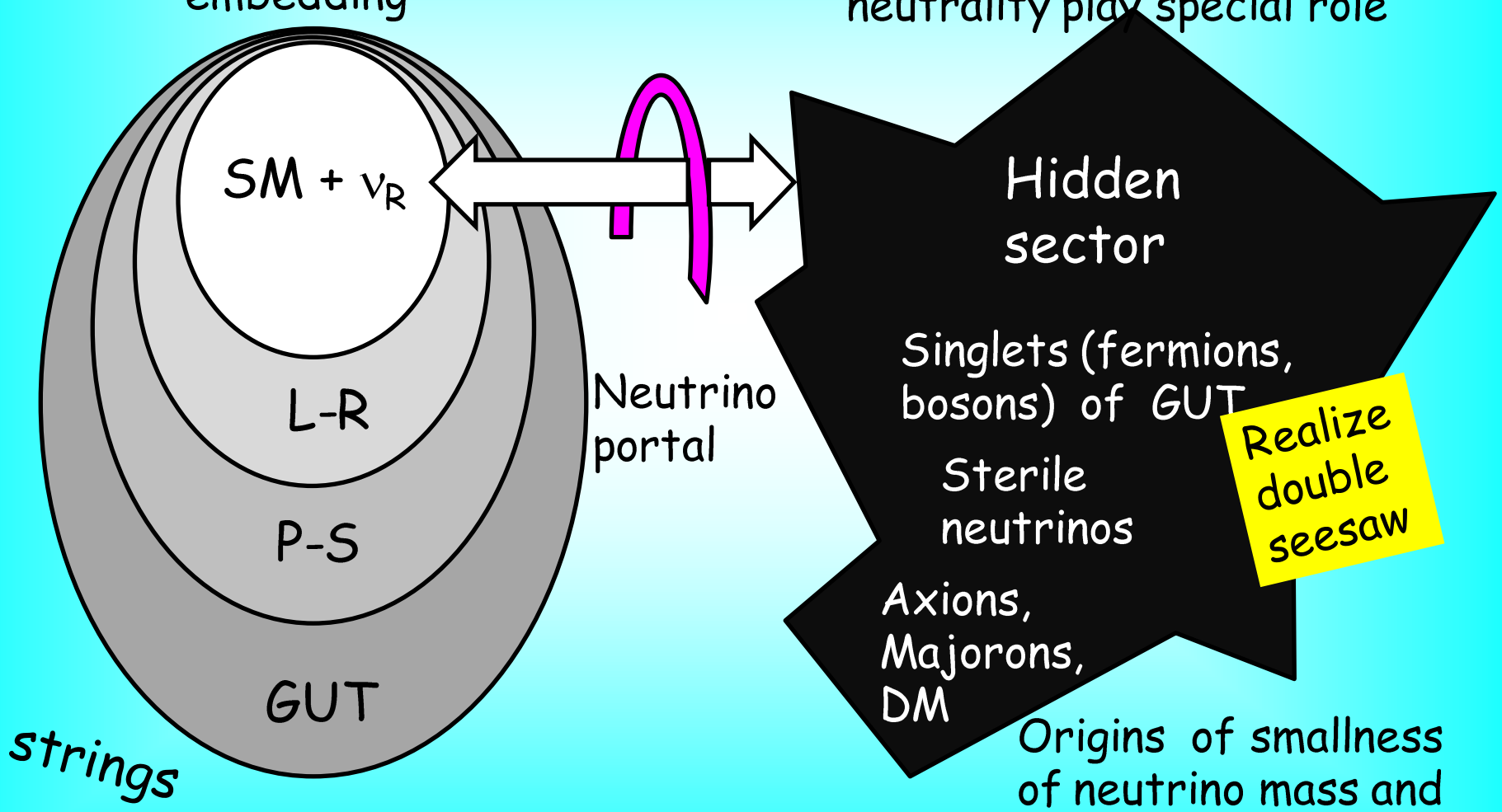
Dependence of 1-3 mixing on 2-3 mixing for different values of the phase α. Allowed regions from the global fit NuFIT 2015

Allowed values of parameters of U_X

Best fit value: $\theta^X_{23} = 42^0$

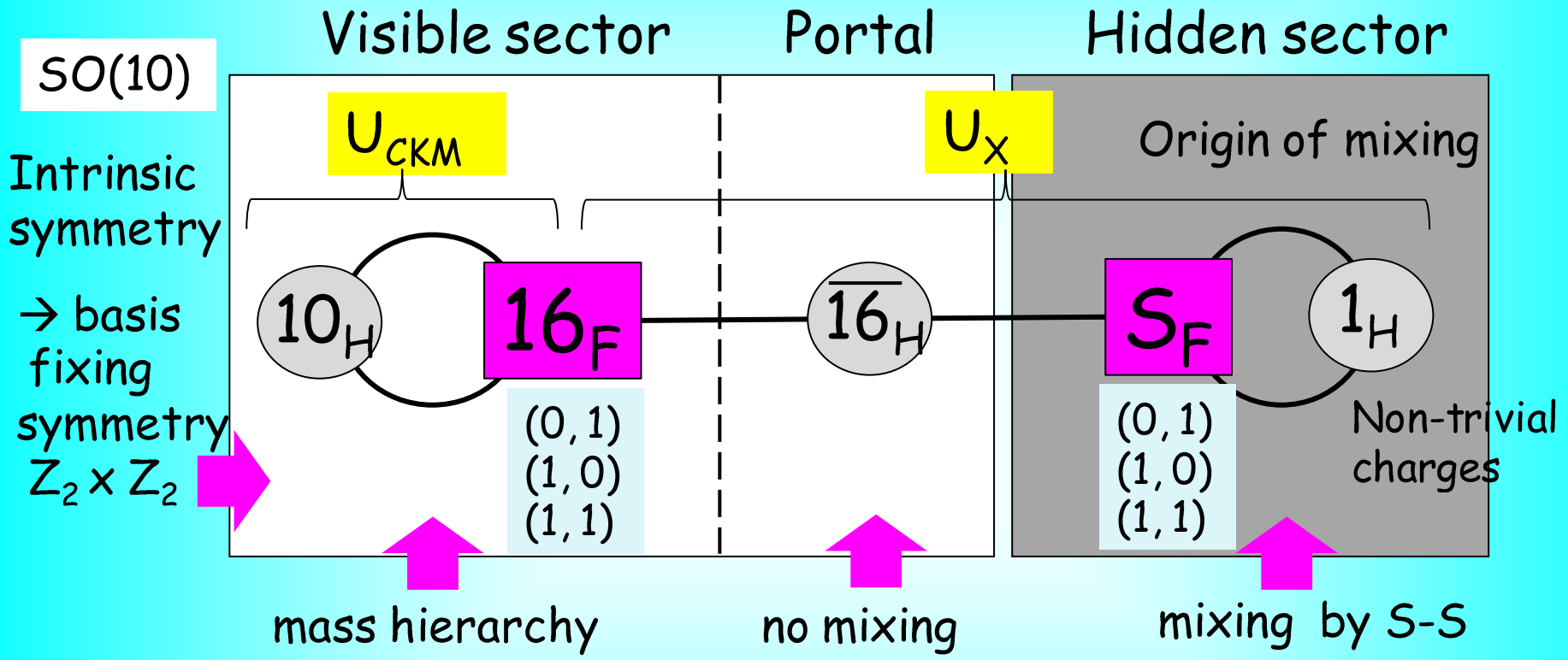
RGE effect from maximal mixing value at high scale

Mass and mixing from Hidden world



Realization scheme

Patrick Ludl, A.S
arXiv:1507.03494 [hep-ph]



CKM mixing - additional structures

$m_D \sim M_D = \text{diag}$

$M_X = d^T M_S d$

Double seesaw

due to non-trivial $Z_2 \times Z_2$ charges of 1_H

M_S ~ non-diagonal, can be further structured by Non-abelian G_{hidden}

Neutrino Connections

Connections

Any discovery in these fields
can have impact on neutrinos
→ Solutions in parallel sessions

LHC observables

Higgs physics

Dark matter

Lepton Flavor Violation

Axions

Dark energy

$(g-2)_\mu$

Anomalies In B-decays

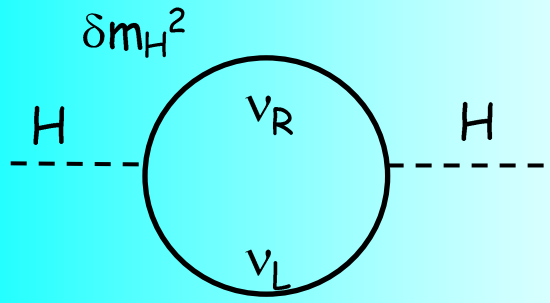
Lepton universality

Model dependent,
not unique

ν- mass and Higgs physics

bottom -up

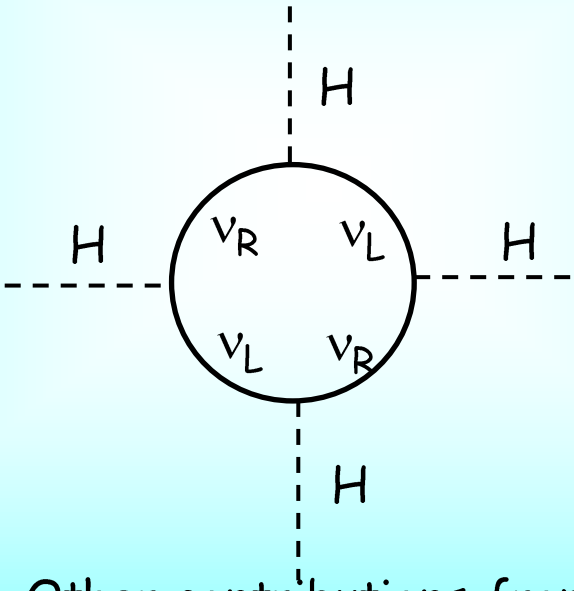
Correction to Higgs mass



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 ...

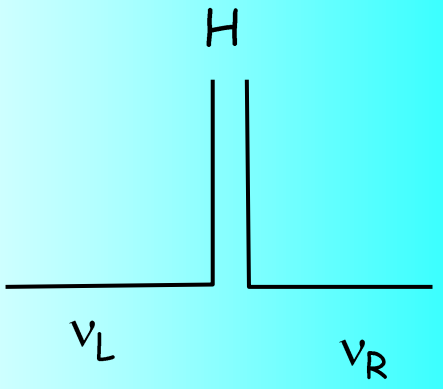
Correction to λ - 4 point coupling – vacuum stability



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

Neutrino option?

Brivio, M. Trott, 1703.10924 [hep-ph]

Whole Higgs potential is generated by the neutrino corrections

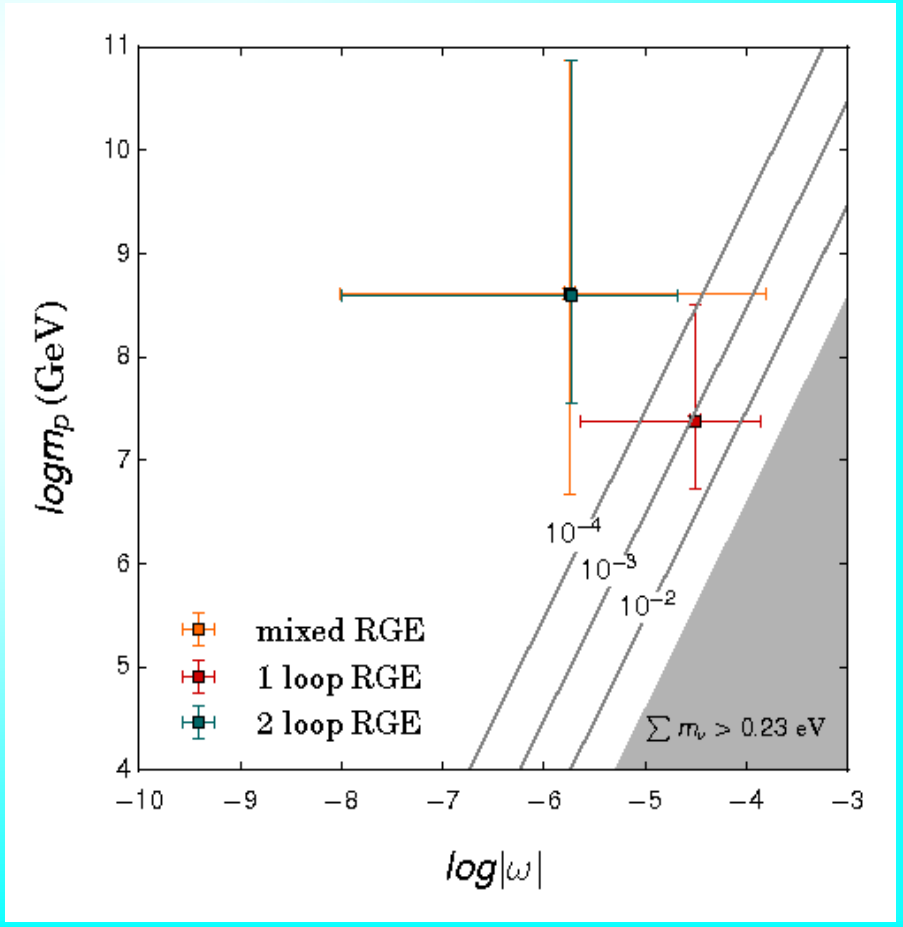
Both Higgs mass term and quartic coupling (absent at tree level) are generated by neutrino loops

RH neutrino masses is the origin of the EW scale

$M_R = 10^7 - 10^9$ GeV

$h = 10^{-6} - 10^{-4.5}$

Dirac Yukawa coupling



Neutrinos - Dark matter

Is the (hot) component of the DM

Mechanism of generation of small neutrino masses is related to DM

RH neutrinos as DM particles

Neutrino portal connects DM and neutrinos

DM particles participate (appear in loops) in generation of neutrino mass

The same symmetry is responsible for smallness of neutrino mass and stability of the DM

In conclusion

We measure neutrino parameters and neutrino interactions to establish the underlying physics and to use neutrinos with well known properties as tools for exploration of other objects

Neutrinos are unique in many senses and the hope is that their studies will uncover for us something fundamental which will shed light on existing problems in particle physics, astrophysics and Cosmology

At the same time, minimal scenario with Normal Ordering, no sterile and no NSI looks plausible

Back-up

Trends and implications

No new physics is found

No new physics at LHC in particular new physics which could be associated to low scale mechanisms of neutrino mass generation

- right Handed neutrinos, new heavy leptons
- right handed gauge bosons of the L-R symmetric models
- double charged scalars (of seesaw type II), etc
- new fermions and scalars which can participate in the radiative mechanism of neutrino mass generation

→ Bounds on masses / couplings of these new particles

No Lepton number violation, MEG, ….

Nothing yet at well motivated TeV-scale.
The next motivated scales are intermediate and then GUT

Neutrinos and Dark Universe

Active area of research

Connection: Neutrinos - Dark matter

will be further explored

Also possible connections to Dark radiation, Dark energy

Neutrinos as probe of Dark Universe:
High energy cosmic neutrinos,
Relic supernova neutrinos

Very light sector which may include

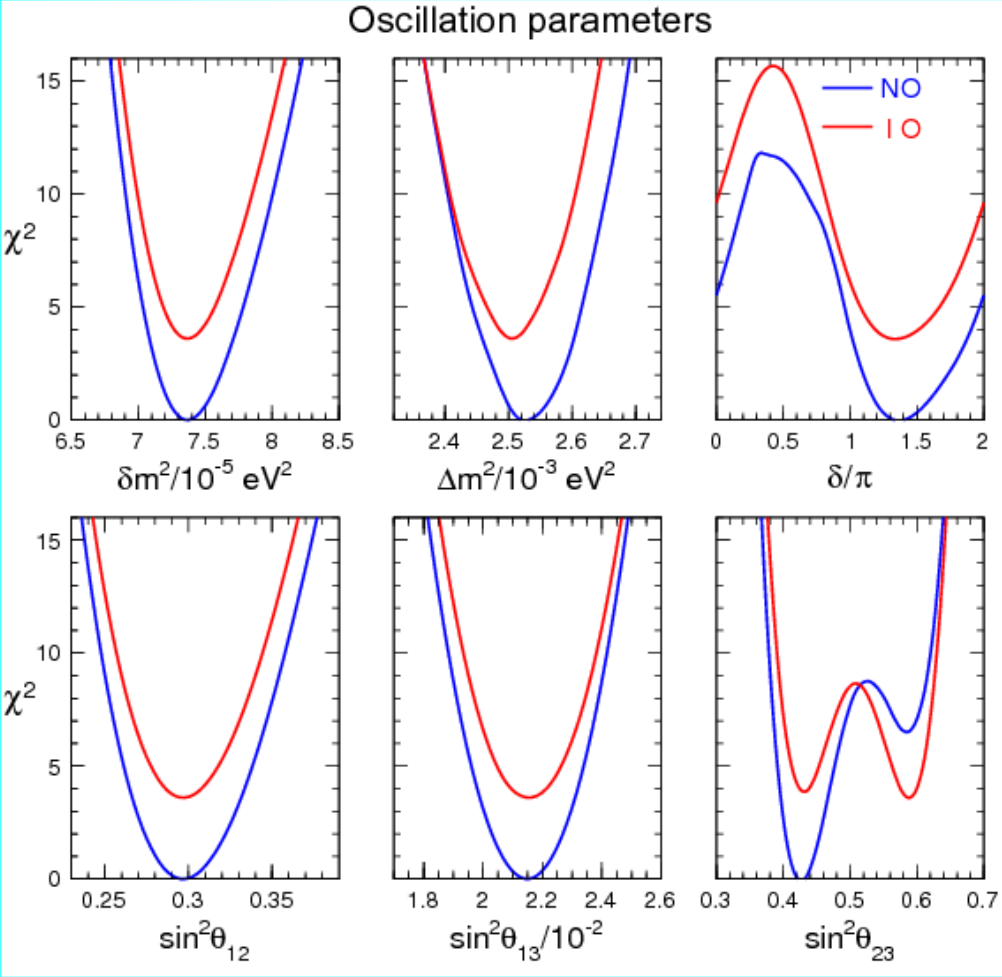
- new scalar bosons, majoron, axions,
- new fermions (sterile neutrinos, partially sterile),
- new gauge bosons (e.g. Dark photons)
- gravitinos

Neutrinos and Hidden/Dark Sector

Interaction via neutrino portal

New experimental techniques for low energy physics

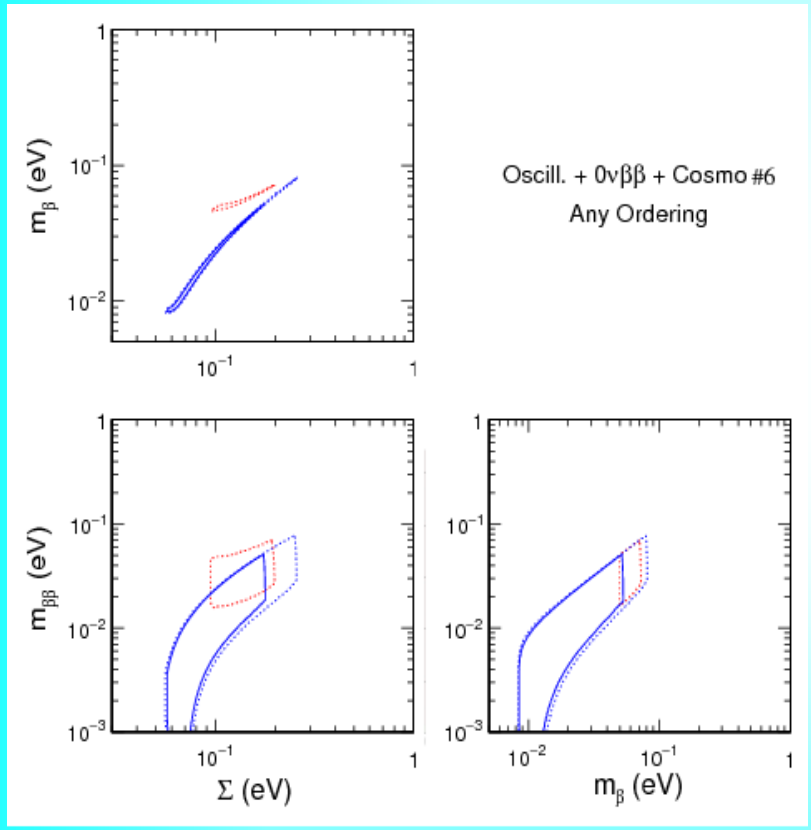
Mass ordering

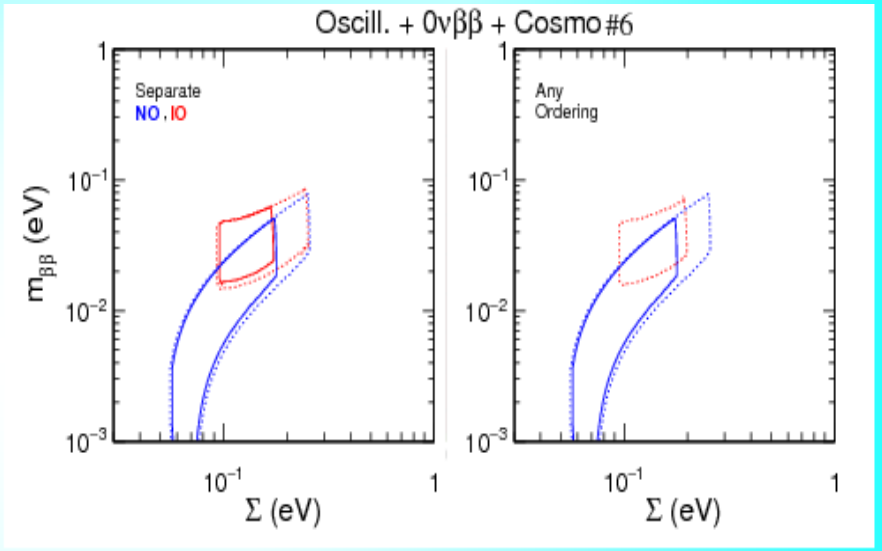


$\Delta\chi^2_{IO-NO} = 3.6$

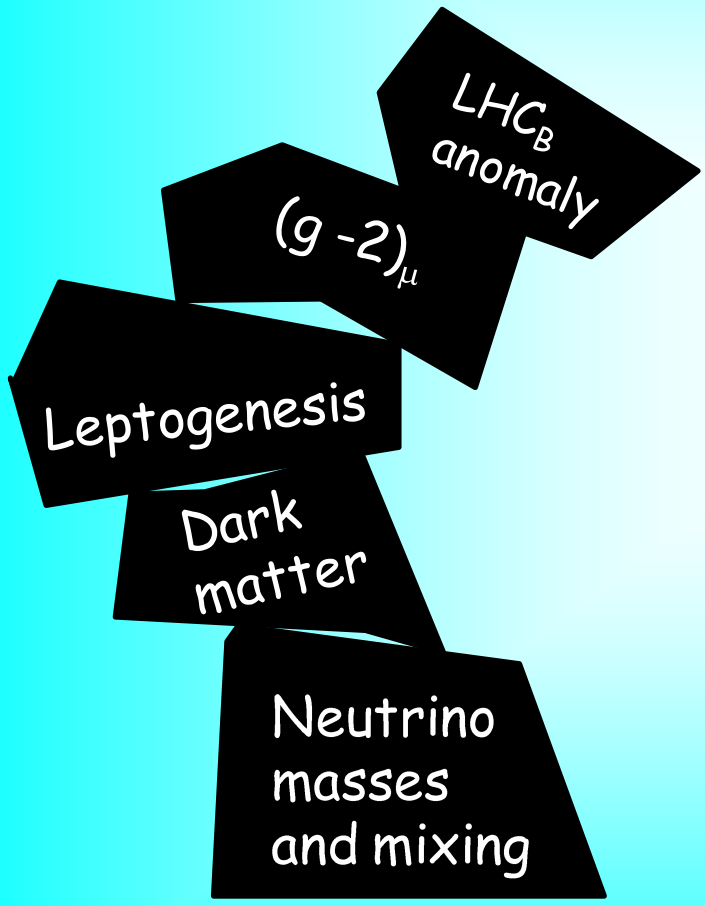
Mass ordering

F. Capozzi, et al. Phys.Rev. D95 (2017) no.9, 096014
arXiv:1703.04471 [hep-ph]





Model building



Most of the possible signals are model dependent and scale dependent

If at very high scales -- hopeless? indirect evidences?

predictions which testify for FS ?

Generic consequences?

Minimal model of flavor?

criteria

Models and BSM

Beyond Sensible and Motivated

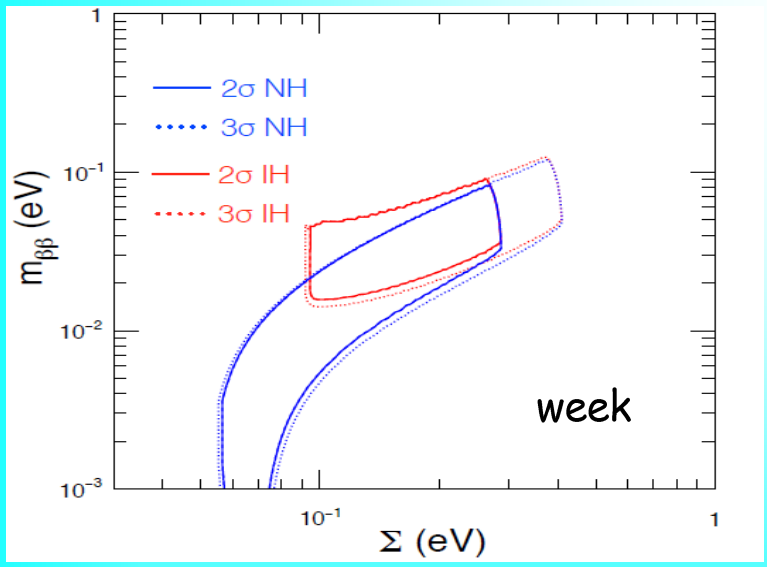
Absolute mass scale

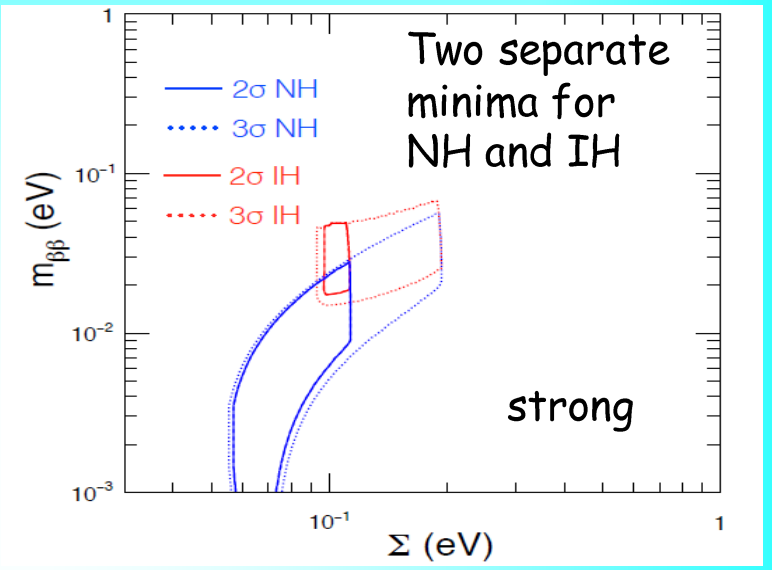
F. Capozzi et al, NOW 2016

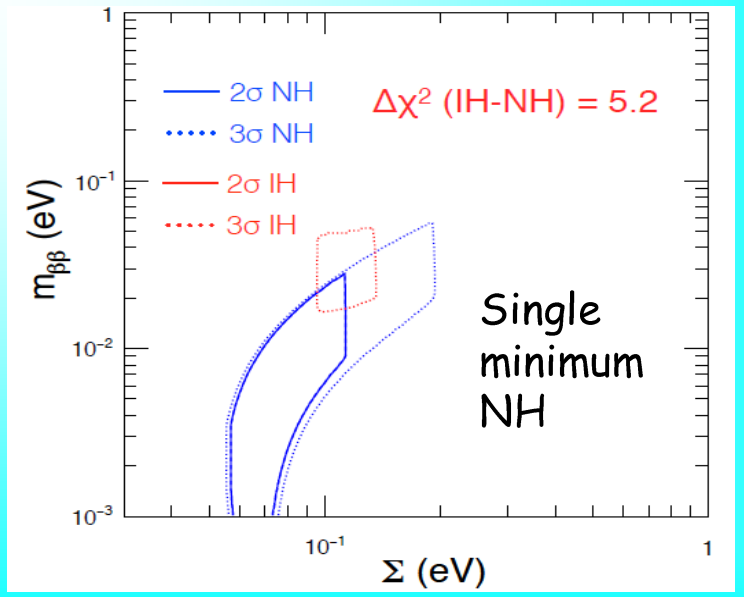
Bounds from oscillations and cosmology

Cosmology start to restrict IH

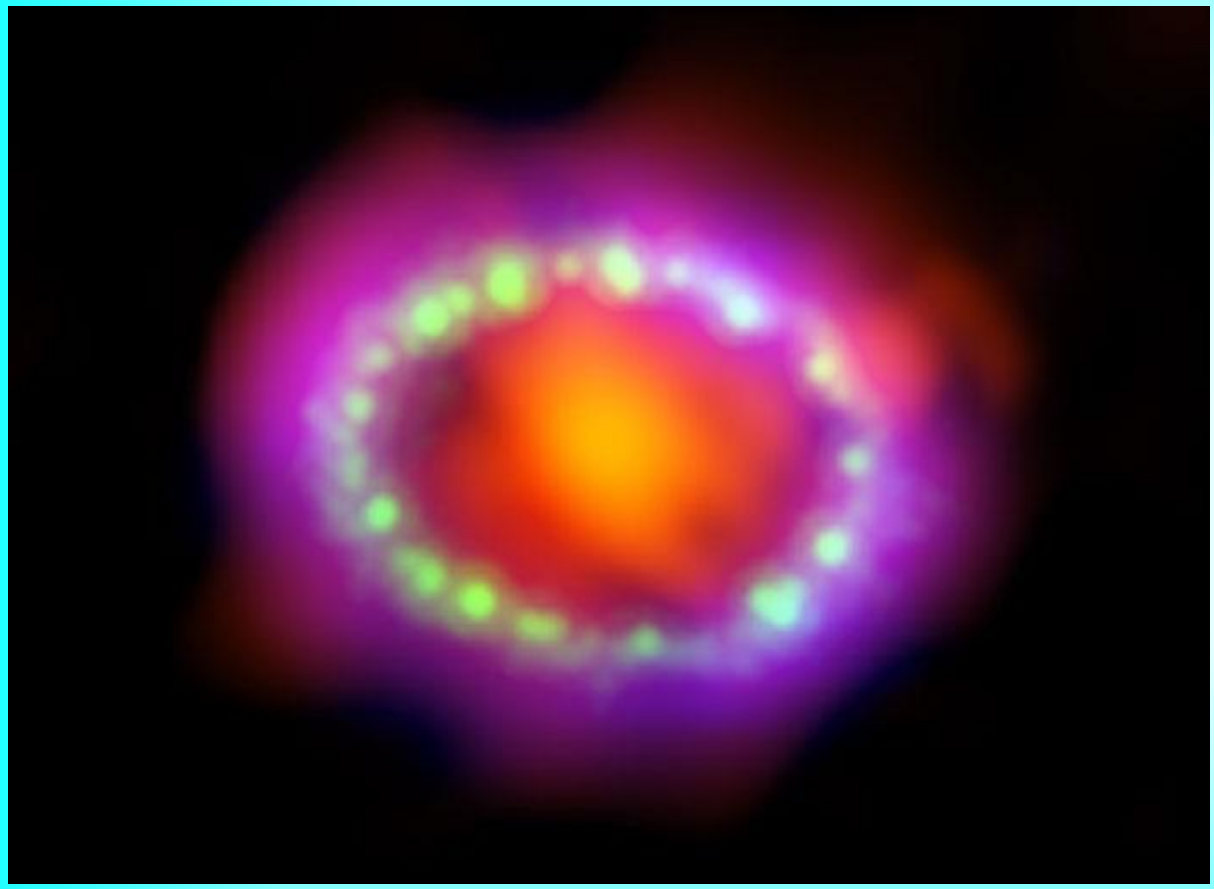
$$m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta}$$







SN 1987A



Composite image of the SN 1987A inner ring shows the fuzzy glow of X-rays seen by ALMA in orange. The green ring is visible light detected by the Hubble Space Telescope and the violet ring is the X-ray signal seen by Chandra. (Courtesy: NASA / ESA / A Angelich (NRAO / AUI / NSF) / R Kirshner (Harvard-Smithsonian CfA / Gordon and Betty Moore Foundation) / ALMA (ESO / NAOJ / NRAO) /

SN neutrinos

Fast flavor conversions of supernova neutrinos: Classifying instabilities via dispersion relations Francesco Capozzi , et al arXiv:1706.03360 [hep-ph] |

Flavor-dependent neutrino angular distribution in core-collapse supernovae Irene Tamborra, et al Astrophys.J. 839 (2017) 132, arXiv:1702.00060 [astro-ph.HE]

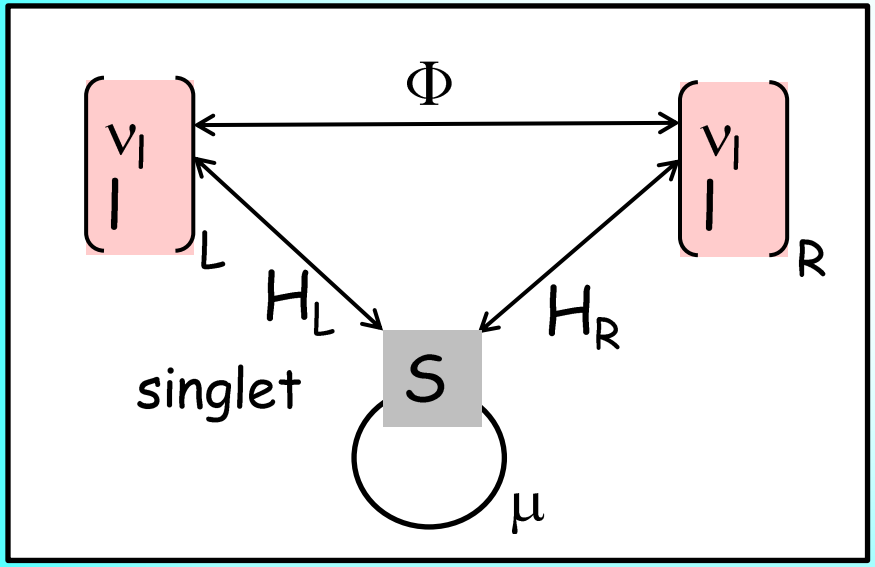
Prospects for Neutrino Spin Coherence in Supernovae. James Y. Tian, et al .,Phys.Rev. D95 (2017) no.6, 063004 arXiv:1610.08586 [astro-ph.HE]

Fast Pairwise Conversion of Supernova Neutrinos: A Dispersion-Relation Approach, Ignacio Izaguirre, et al., Phys.Rev.Lett. 118 (2017) no.2, 021101, arXiv:1610.01612 [hep-ph] |

Fast neutrino flavor conversions near the supernova core with realistic flavor-dependent angular distributions Basudeb Dasgupta , et al., JCAP 1702 (2017) no.02, 019, arXiv:1609.00528 [hep-ph]

Left-right models

Natural realization of seesaw
If low scale – small Dirac Yukawa couplings
Usual coupling – linear or inverse seesaw



$m_D = h \langle \Phi \rangle$

$M_L = h_L V_L$

$M_R = h_R V_R$

$m_\nu^{LS} = m_D^T M_R^{-1T} M_L + M_L^T M_R^{-1} m_D$

$m_\nu^{IS} = m_D^T M_R^{-1T} \mu M_R^{-1} m_D$

but then $V_L \ll V_R$ is required

Embedding in SO_{10}

B. Dev