Physics of Massive Neutrinos

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(IHEP, Beijing)

- **A:** Neutrino history and lepton family
- **B:** Neutrino masses and flavor mixing
- **C:** Description of neutrino oscillations
- **D:** Implication of neutrino oscillations
- **E:** θ_{13} hint and sterile neutrino puzzle
- **F:** On TeV neutrino physics at the LHC
- **G:** Extreme corners in the neutrino sky
- **H:** Cosmic baryon number asymmetry

ν

ν

ν

@Lectures at CP3, UCL, Louvain-la-Neuve, Belgium, Jan 2012

Lecture E

- ★ **Why theta(13) is very important?**
- ★ **Reactor + accelerator experiments**
- ★ **Light sterile neutrino puzzle**

Significance of θ_{13}

Why is the measurement of θ_{13} extremely important?

★ **θ_{13} is a fundamental parameter of lepton flavor physics**

★ **θ_{13} controls the fine effects of leptonic CP violation**

★ **θ_{13} is a very sensitive model / theory discriminator**

★ **θ_{13} can set a bound of accuracy for new physics search**

The future neutrino experiments rely, more or less, on θ_{13}. If it were too small, there would be no way to see CPV.

Possible impact of θ_{13} on astrophysics and cosmology:
Cosmic ν's, Matter-Antimatter asymmetry, Supernovae.....

So we must try to get it!

So What if $\theta_{13} = 0$?

In principle, $\theta_{13} = 0$ is almost impossible!

In principle, $\theta_{13} = 0$ is more interesting!

$$\theta_{13} < 12^\circ$$

CHOOZ upper limit

Note that $\theta_{13} = 0$ would hold, if there were mass degeneracy of charged leptons or neutrinos (with Majorana phases Ψ_i):

☆ $m_1 = m_3$ **with** $\Psi_1 = \Psi_3$ **or** $m_2 = m_3$ **with** $\Psi_2 = \Psi_3$

☆ $m_e = m_\mu$ **or** $m_e = m_\tau$

But all these conceptually interesting limits are unrealistic

Is there any good (theoretical) reason for $\theta_{13} = 0$? Noooo!

Consequence of $\theta_{13} = 0$

- ★ **Dirac CP-violating phase (δ) would not be well defined**
- ★ **Leptonic unitarity triangles would then collapse to lines**
- ★ **There would be no matter effects on m_3 and θ_{23} for the constant matter profile**

Together with $\theta_{23} = \pi/4$, $\theta_{13} = 0$ can have an interesting impact on Ultrahigh-energy cosmic neutrino fluxes (from distant astro-physical sources) to be detected at neutrino telescopes.

$$\phi_e : \phi_\mu : \phi_\tau = 1:2:0 \xrightarrow{\text{oscillations}} \phi_e : \phi_\mu : \phi_\tau = 1:1:1$$

The situation will change if $\theta_{13} \neq 0$ (see Lecture G)

Comments

★ **Theorists love very special numbers, such as 0, ½, 1, π.**

★ **Experimentalists should have no bias --- what they can have are error bars; i.e., how close a quantity is to 0, 1, ...**

Therefore, θ_{13} must be measured no matter how small it is

Various predictions for θ_{13} from phenomenological models

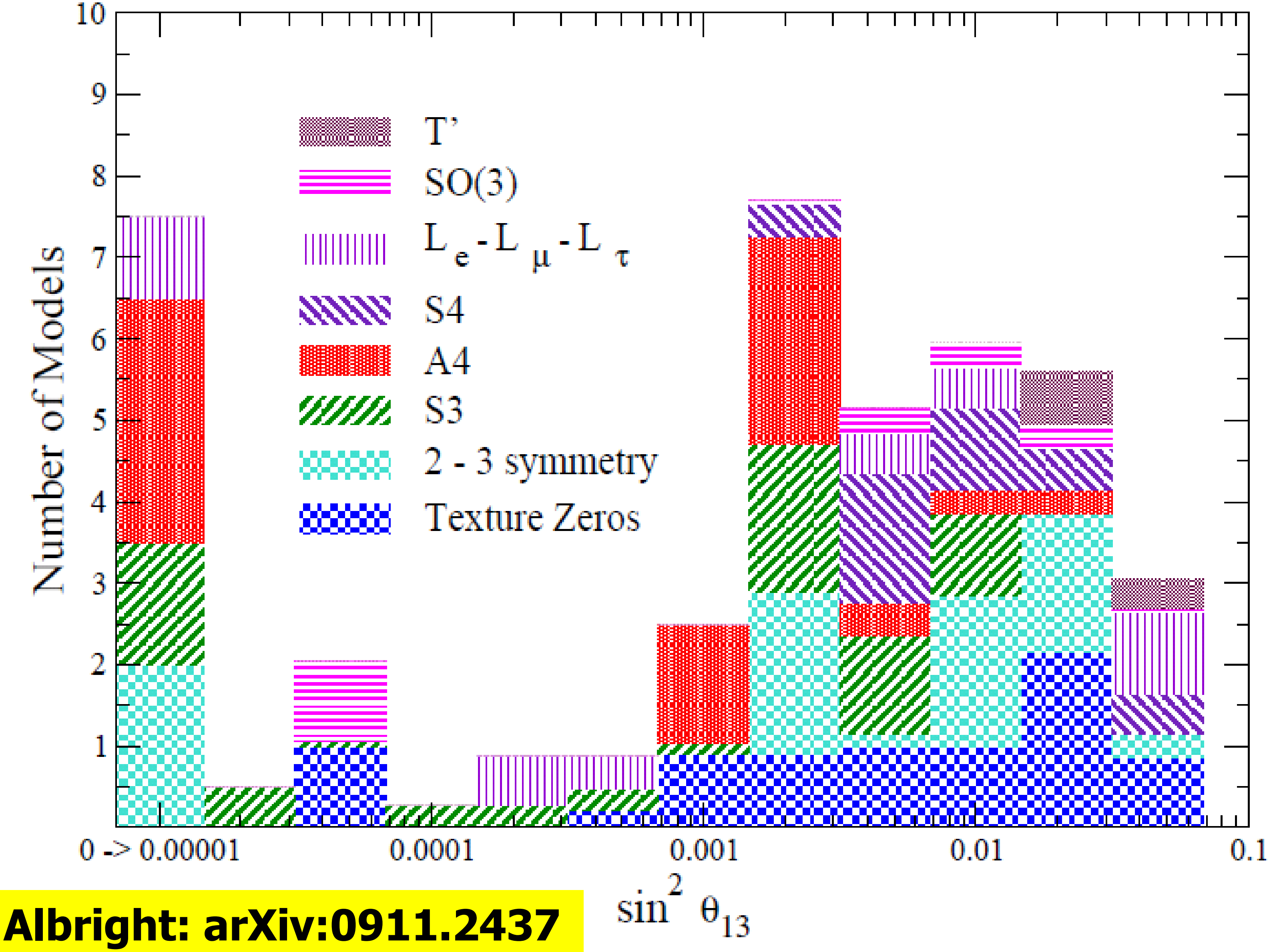
★ **θ_{13} is given in terms of mass ratios of leptons or quarks**

★ **θ_{13} is given by other known ν—oscillation parameters**

★ **Something from "nothing": a quantum correction to θ_{13}**

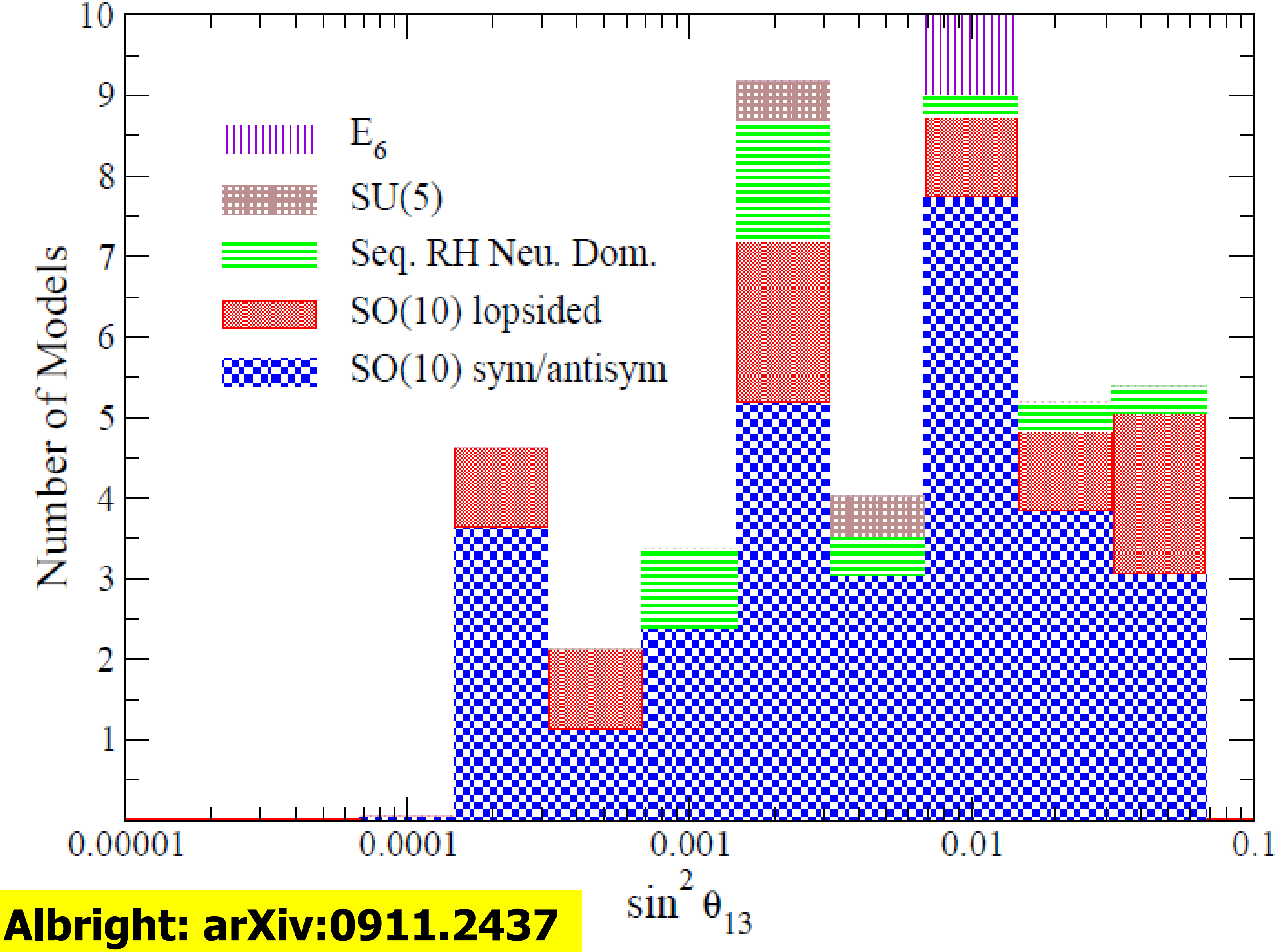
What have theorists thus far done to understand θ_{13}?

Statistics (non-GUT)



C.H. Albright: arXiv:0911.2437

Statistics (GUT)



C.H. Albright: arXiv:0911.2437

Accelerator Experiments

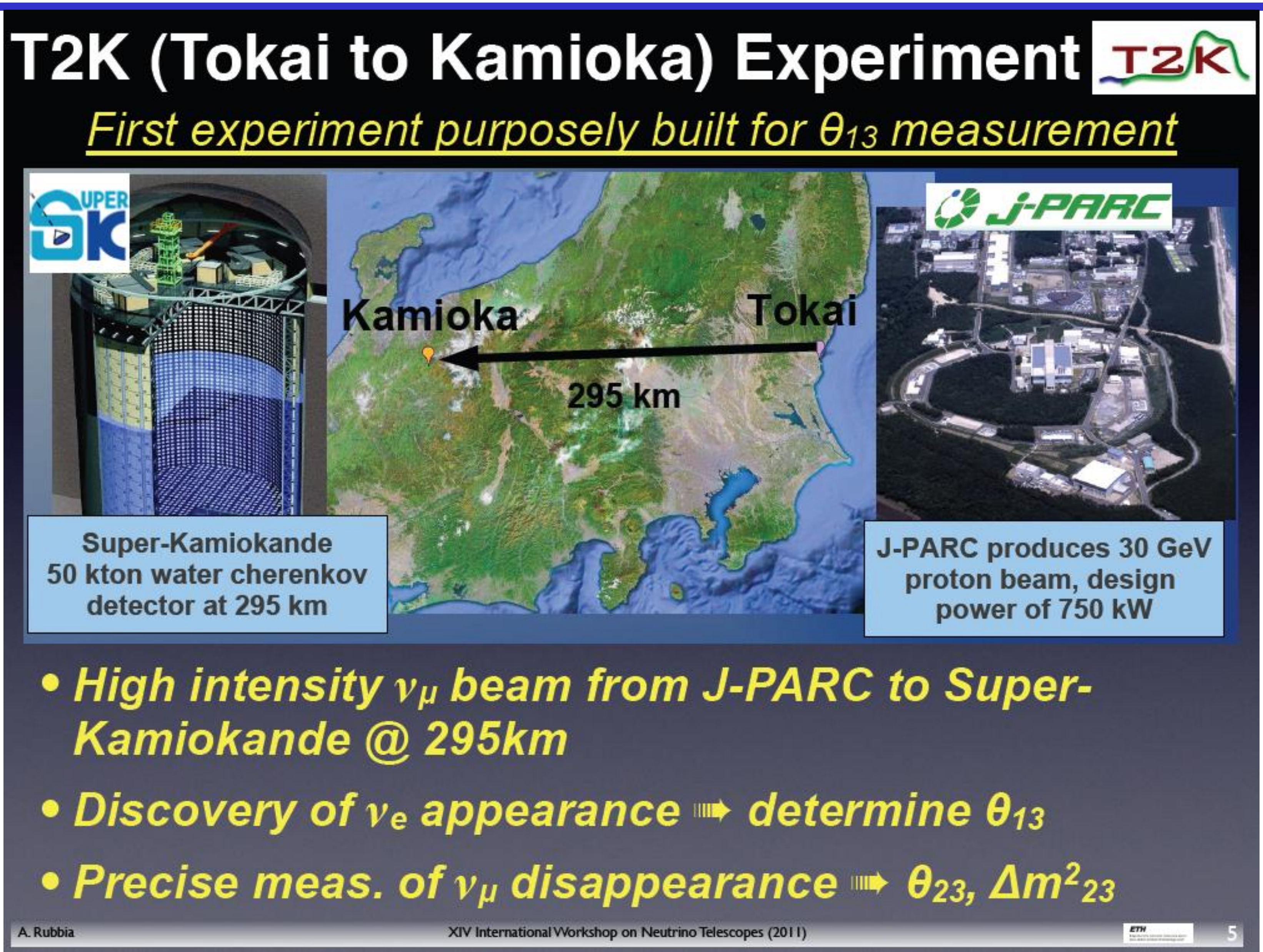
Appearance Experiments and Matter effects: for neutrino energies in the GeV range / baselines longer than 100 km, terrestrial matter effects are not negligible.

$$\boxed{\begin{aligned} P_{\mu e} \approx {} & \sin^2 2\theta_{13}\, s_{23}^2 \frac{\sin^2(A-1)\Delta}{(A-1)^2} + \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta) \\ & \times \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} + \alpha^2 \sin^2 2\theta_{12}\, c_{23}^2 \frac{\sin^2 A\Delta}{A^2}. \end{aligned}}$$

$$\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}, \qquad A \equiv \frac{2EV}{\Delta m_{31}^2}, \qquad \alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}. \qquad \boxed{V = \sqrt{2} G_F N_e}$$

Parameter correlation: it depends on all the six oscillation parameters. Terrestrial matter effects can help determine the neutrino mass hierarchy.

T2K Layout



T2K (Tokai to Kamioka) Experiment

First experiment purposely built for θ_{13} measurement

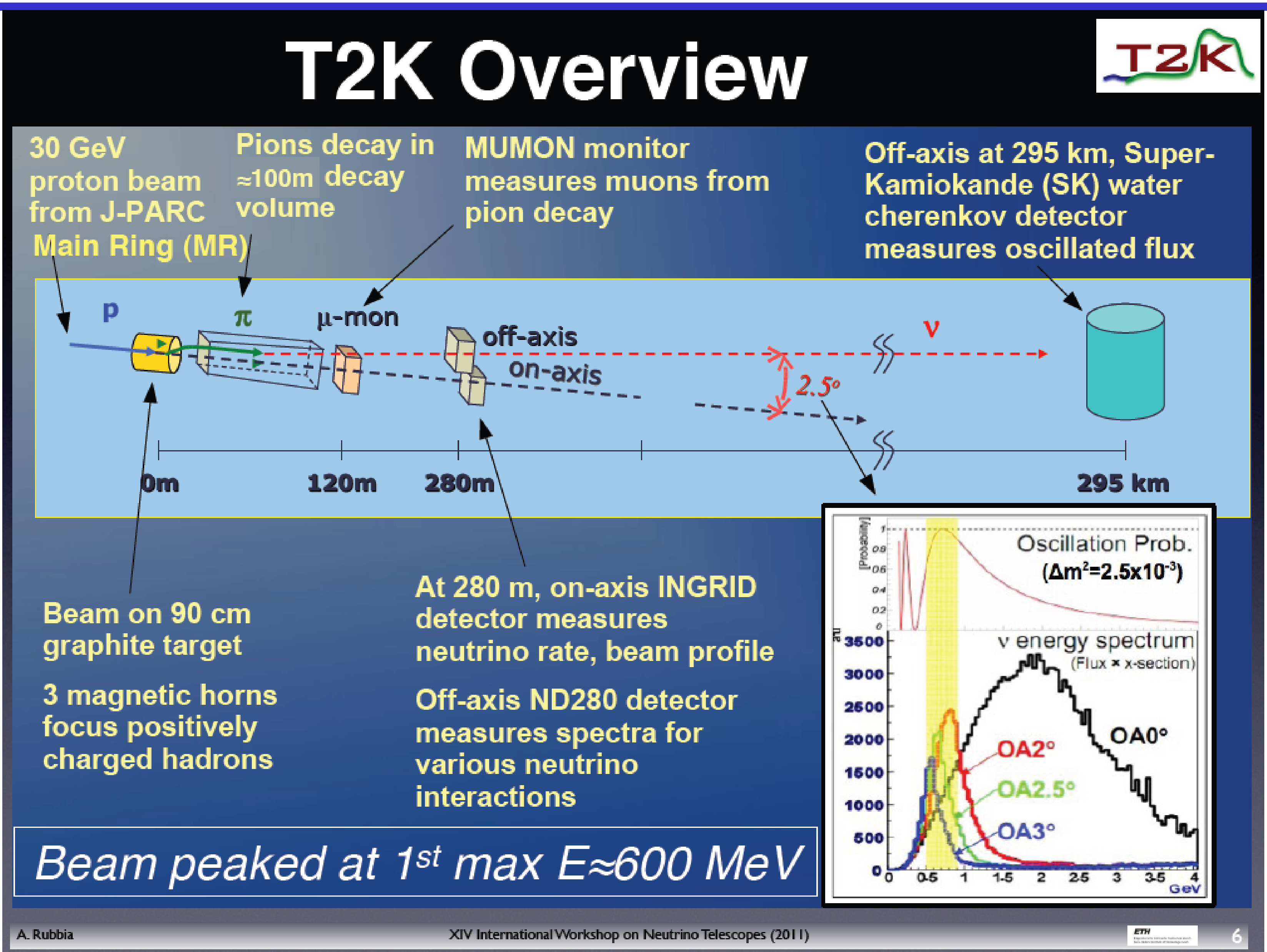
Super-Kamiokande 50 kton water cherenkov detector at 295 km

J-PARC produces 30 GeV proton beam, design power of 750 kW

- ***High intensity ν_μ beam from J-PARC to Super-Kamiokande @ 295km***
- ***Discovery of ν_e appearance ➡ determine θ_{13}***
- ***Precise meas. of ν_μ disappearance ➡ θ_{23}, Δm^2_{23}***

A. Rubbia XIV International Workshop on Neutrino Telescopes (2011) 5

T2K Parameters



T2K Overview

30 GeV proton beam from J-PARC Main Ring (MR)

Pions decay in ≈100m decay volume

MUMON monitor measures muons from pion decay

Off-axis at 295 km, Super-Kamiokande (SK) water cherenkov detector measures oscillated flux

Beam on 90 cm graphite target

3 magnetic horns focus positively charged hadrons

At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

Off-axis ND280 detector measures spectra for various neutrino interactions

Beam peaked at 1st max E≈600 MeV

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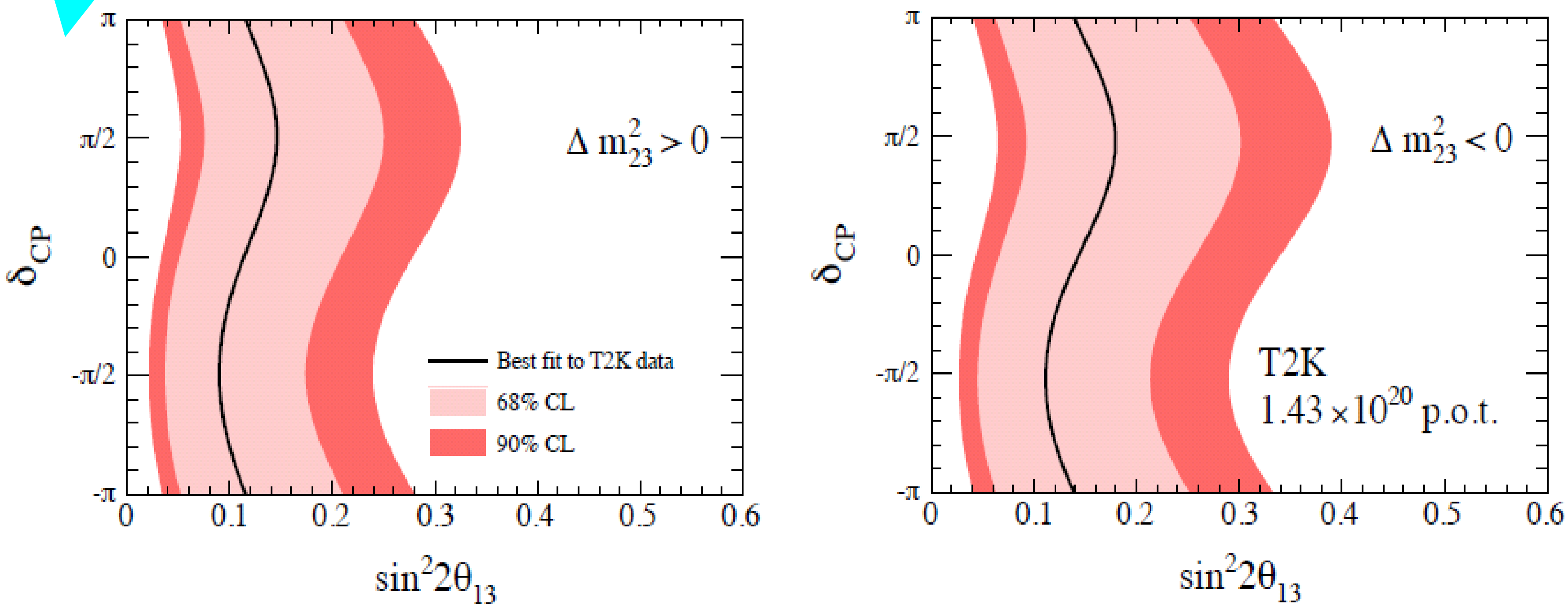
NEW 06/2011

Allowed region of $\sin^2 2\theta_{13}$ as a function of δ_{CP}

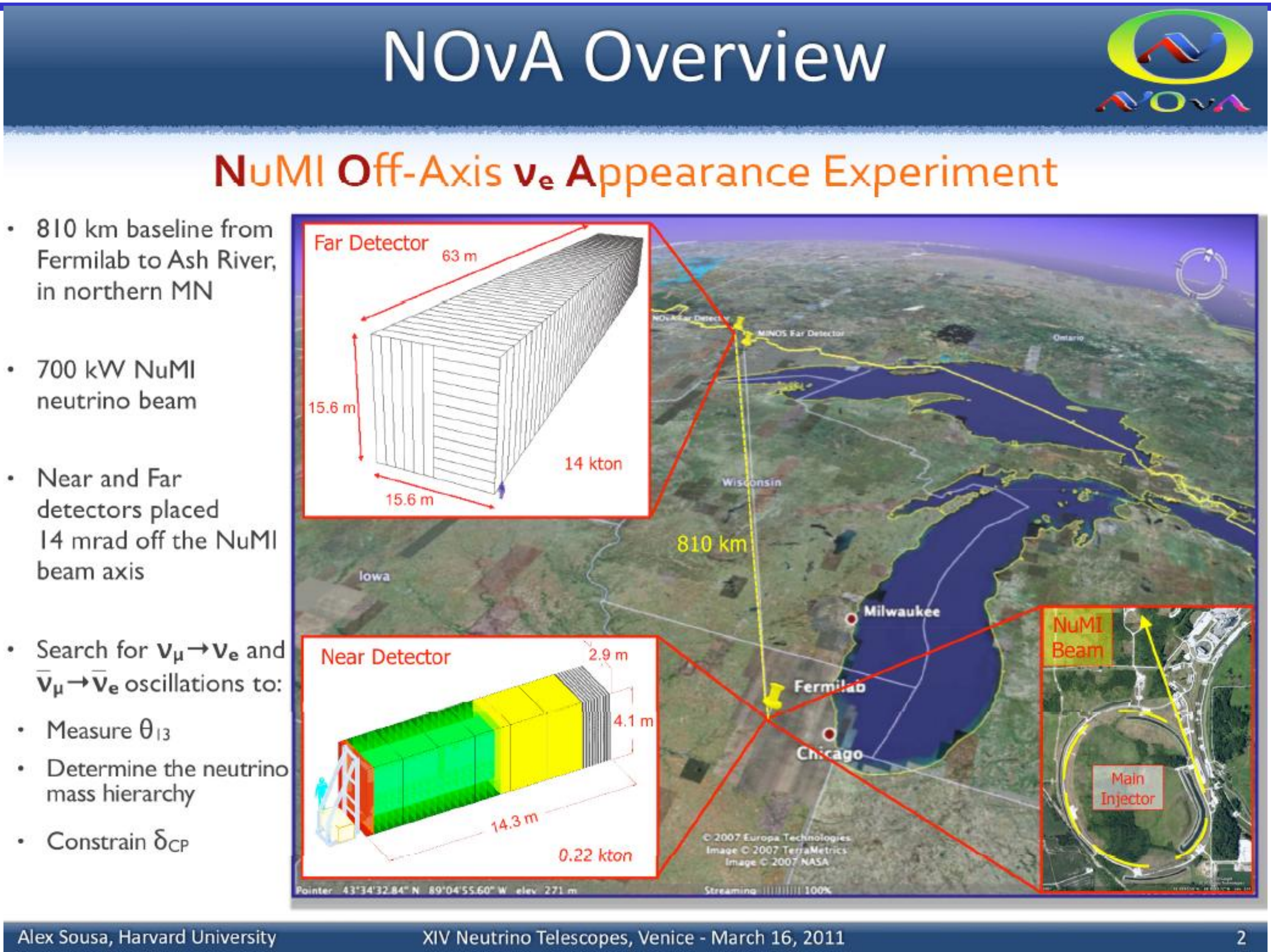
(assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1)



90% C.L. interval & Best fit point (assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1, δ_{CP}=0)

$0.03 < \sin^2 2\theta_{13} < 0.28$	**$0.04 < \sin^2 2\theta_{13} < 0.34$**
$\sin^2 2\theta_{13} = 0.11$	**$\sin^2 2\theta_{13} = 0.14$**

NOνA Experiment

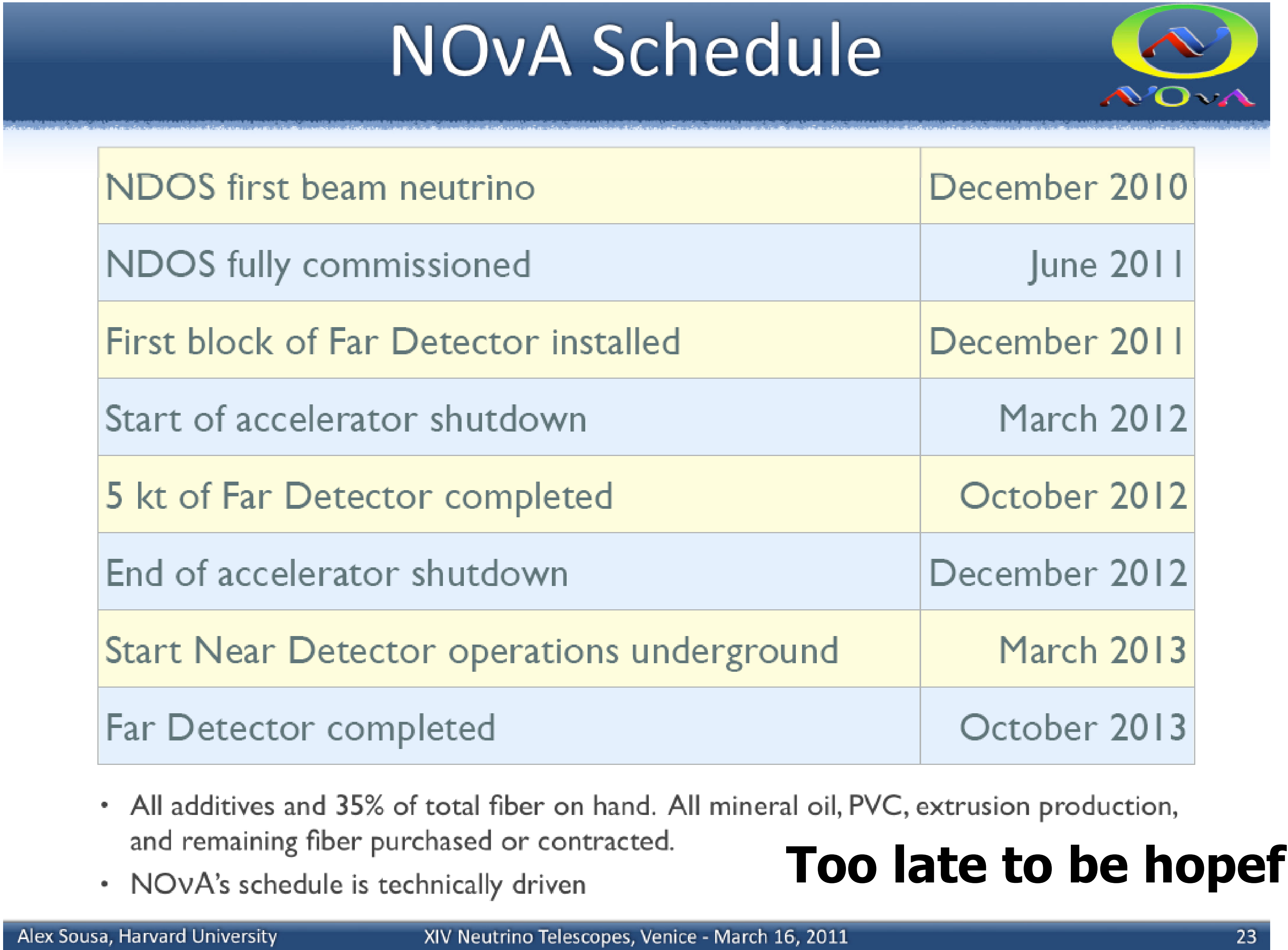


NOvA Overview

NuMI Off-Axis ν_e Appearance Experiment

- 810 km baseline from Fermilab to Ash River, in northern MN
- 700 kW NuMI neutrino beam
- Near and Far detectors placed 14 mrad off the NuMI beam axis
- Search for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations to:
  - Measure θ_{13}
  - Determine the neutrino mass hierarchy
  - Constrain δ_{CP}

NOνA Roadmap



NOvA Schedule

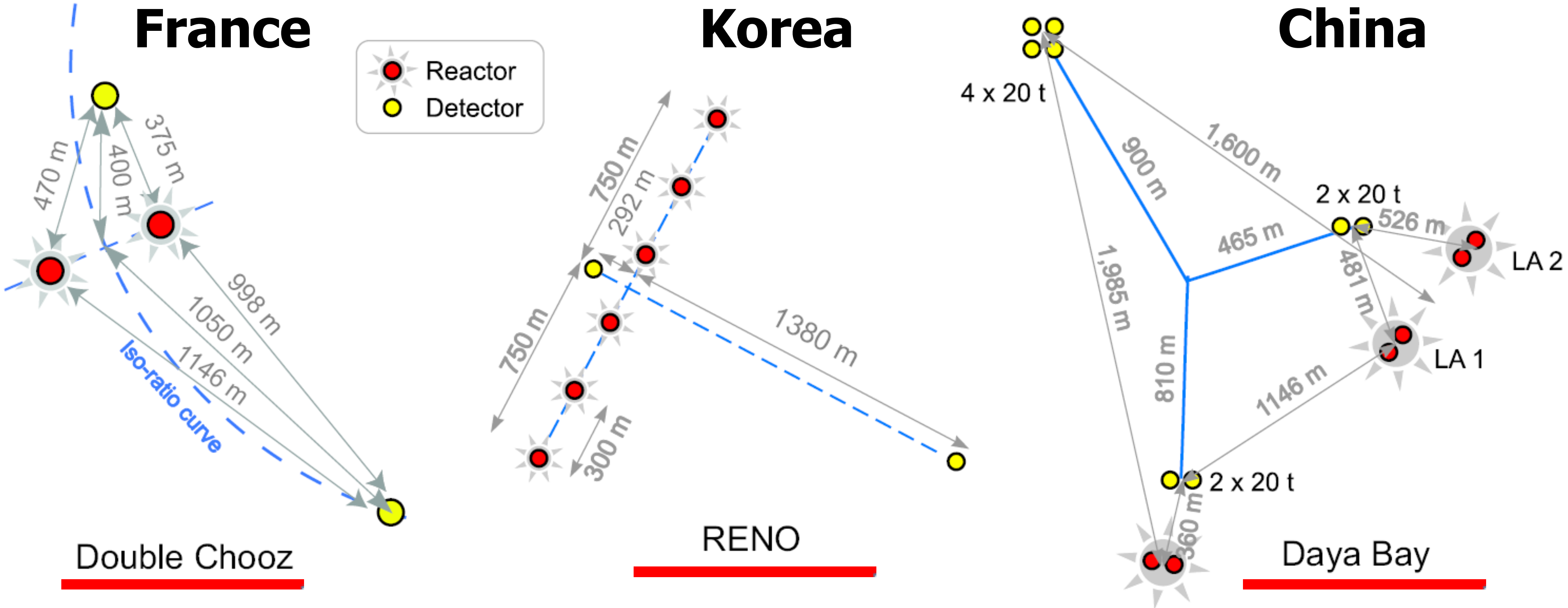
NDOS first beam neutrino	December 2010
NDOS fully commissioned	June 2011
First block of Far Detector installed	December 2011
Start of accelerator shutdown	March 2012
5 kt of Far Detector completed	October 2012
End of accelerator shutdown	December 2012
Start Near Detector operations underground	March 2013
Far Detector completed	October 2013

- All additives and 35% of total fiber on hand. All mineral oil, PVC, extrusion production, and remaining fiber purchased or contracted.
- NOvA's schedule is technically driven

Alex Sousa, Harvard University XIV Neutrino Telescopes, Venice - March 16, 2011 23

Too late to be hopeful?

Reactor Experiments



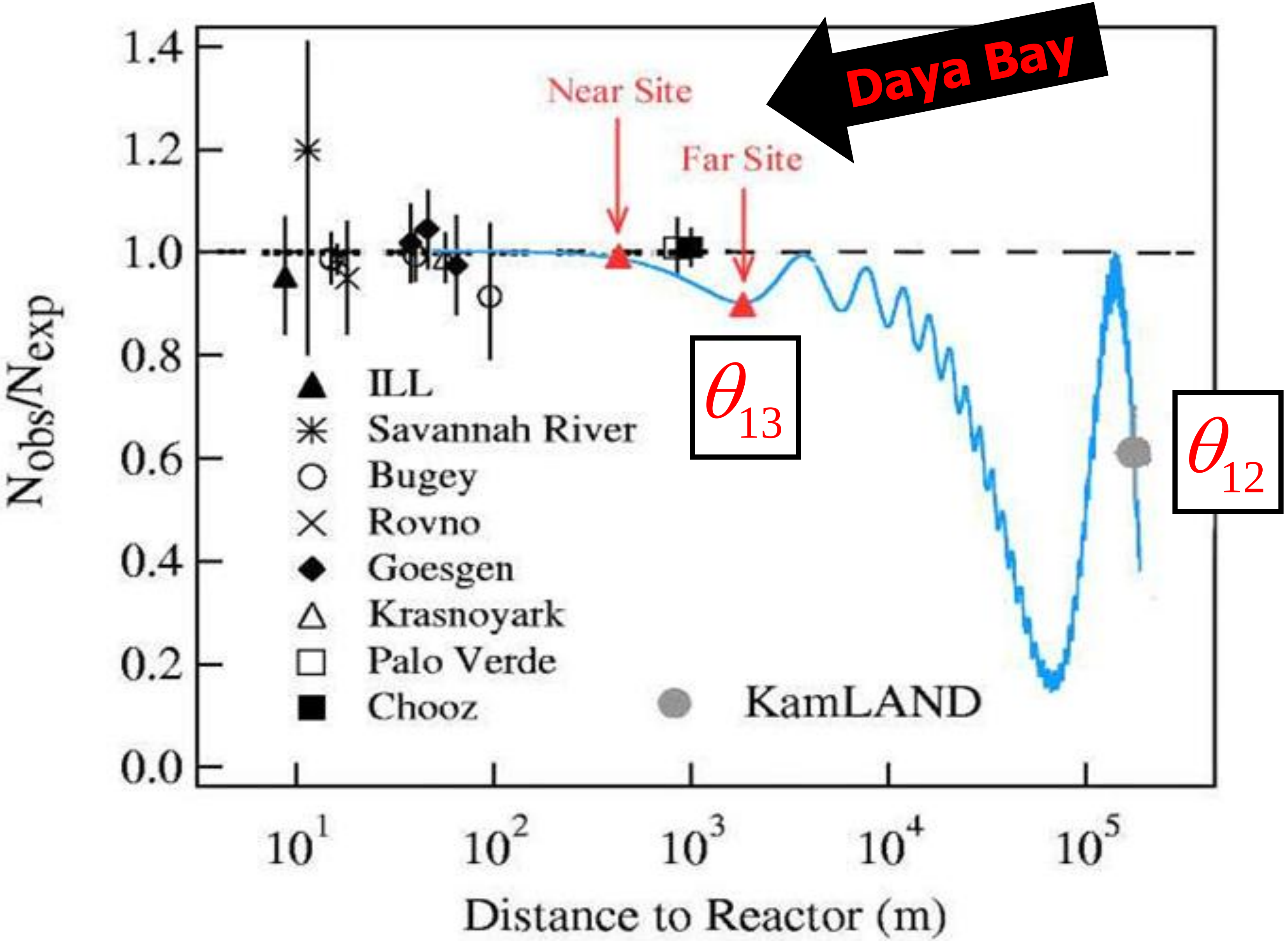
Thermal power **Baseline** **Detector mass**

Mezzetto, Schwetz (2010)

Setup	P_{Th} (GW)	L (m)	m_{Det} (t)	Events/year	Backgrounds/day
Daya Bay [20]	17.4	1700	80	10×10^4	0.4
Double CHOOZ [21]	8.6	1050	8.3	1.5×10^4	3.6
RENO [22]	16.4	1400	15.4	3×10^4	2.6

Signal

$$P(\overline{\nu_e} \rightarrow \overline{\nu_e}) \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\frac{\Delta m^2_{atm} L}{E}\right) \quad \text{(Reactor)}$$



Neutrino Detection

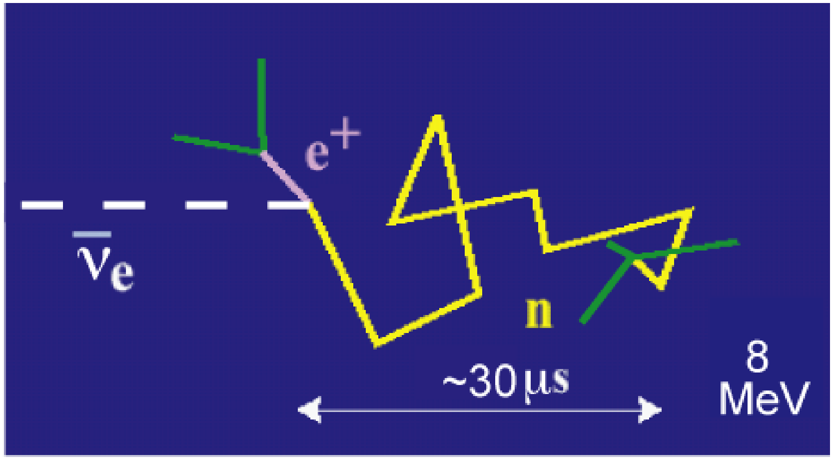
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

Inverse-β reaction in liquid scintillator

τ ≈ 180 or 28 μs (0.1% Gd)

$n + p \rightarrow d + \gamma$ (2.2 MeV)

$n + Gd \rightarrow Gd^* + \gamma$ (8 MeV)



Neutrino Event: coincidence in time, space and energy

Backgrounds:

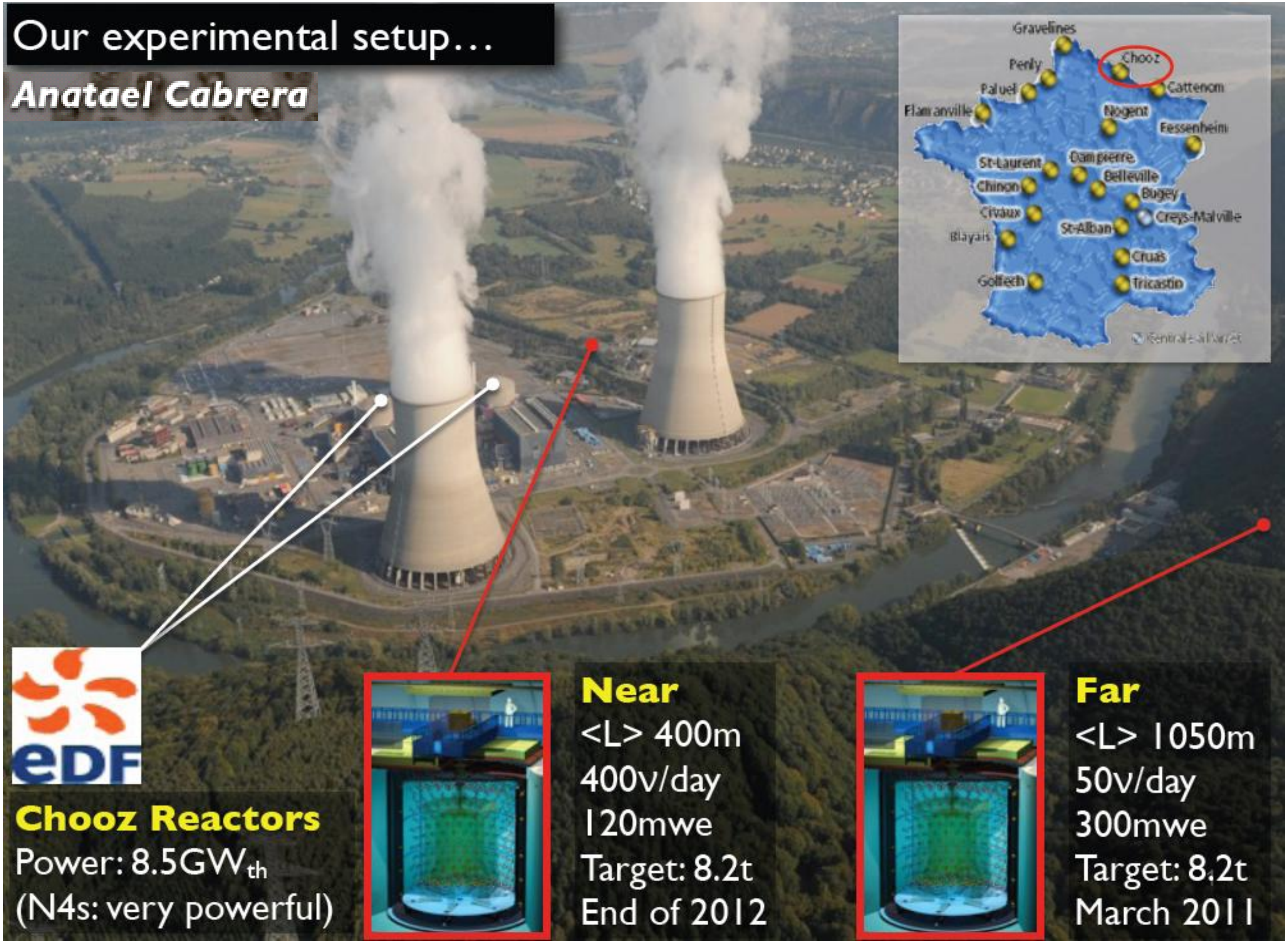
uncorrelated signals from cosmic rays and natural radioactivity;

correlated signals from neutrons generated by cosmic muons.

Neutrino energy:

$$E_{\overline{\nu}} \cong T_{e^+} + \underbrace{T_n}_{\text{10-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\text{1.8 MeV: Threshold}}$$

Double Chooz



Our experimental setup…

Anatael Cabrera

Chooz Reactors

Power: $8.5GW_{th}$

(N4s: very powerful)

Near

<L> 400m

400ν/day

120mwe

Target: 8.2t

End of 2012

Far

<L> 1050m

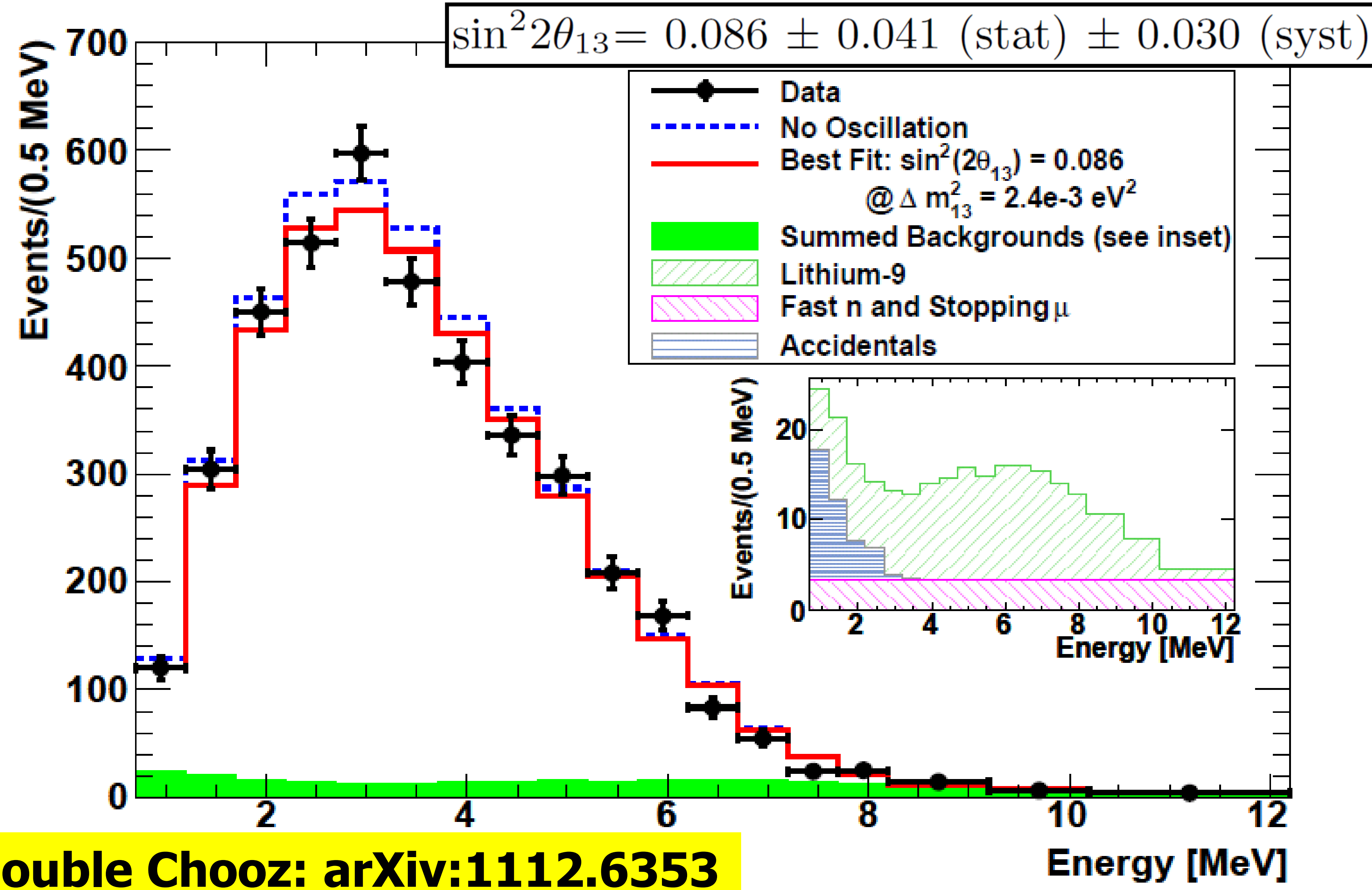
50ν/day

300mwe

Target: 8.2t

March 2011

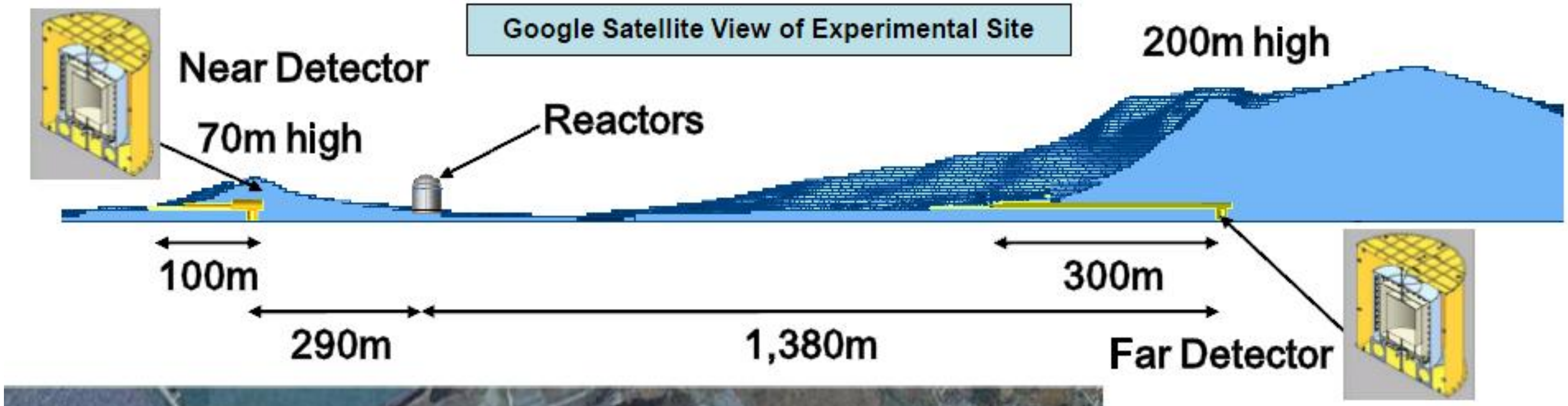
Fast Result



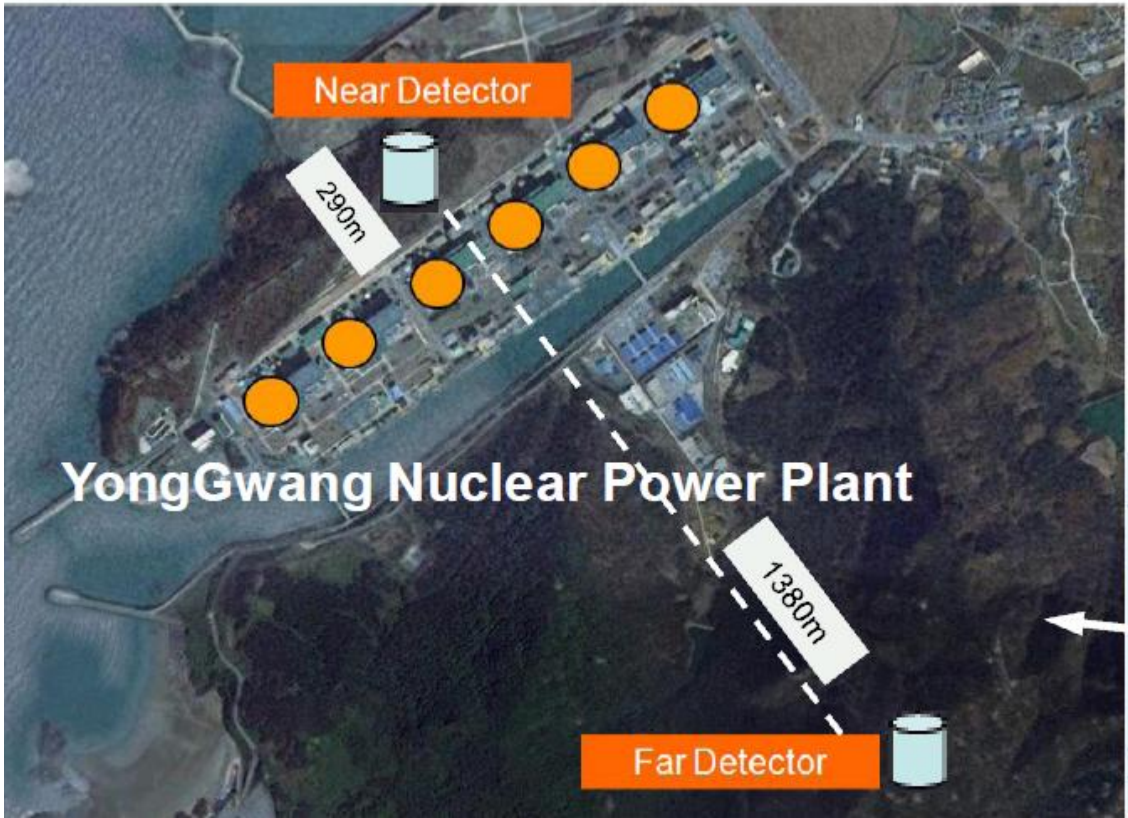
$\sin^2 2\theta_{13} = 0.086 \pm 0.041\ (\mathrm{stat}) \pm 0.030\ (\mathrm{syst})$

Double Chooz: arXiv:1112.6353

RENO Experiment



Google Satellite View of Experimental Site

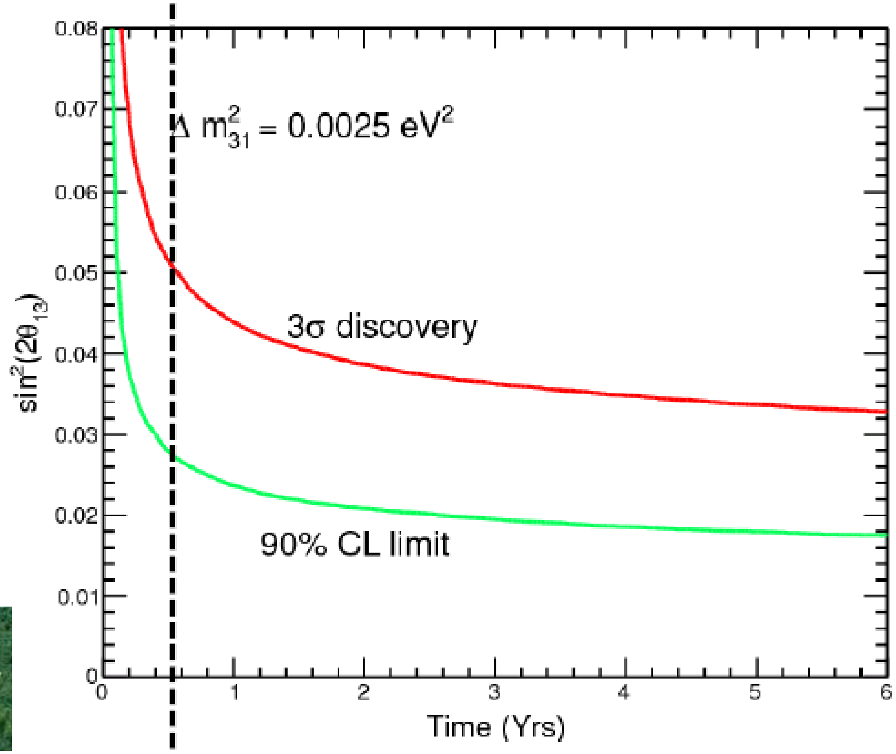


RENO ν θ_{13}

KNRC Korea Neutrino Research Center

Expectation

- First results on $\sin^2(2\theta_{13})$ ~0.05 are expected to be available within a half year
  - Goal: ~0.07 (end of this yr)
  ~0.05 (March, 2012)

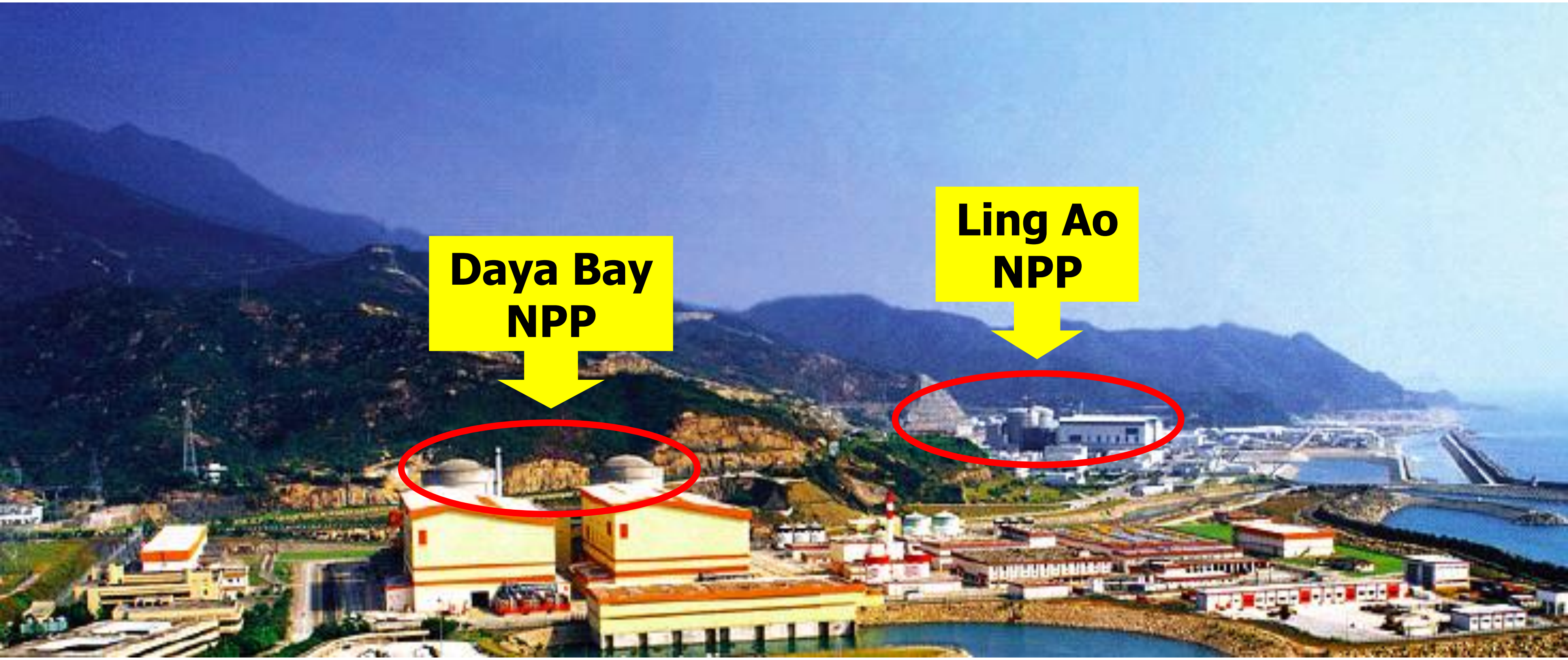


Data taking
August 2011

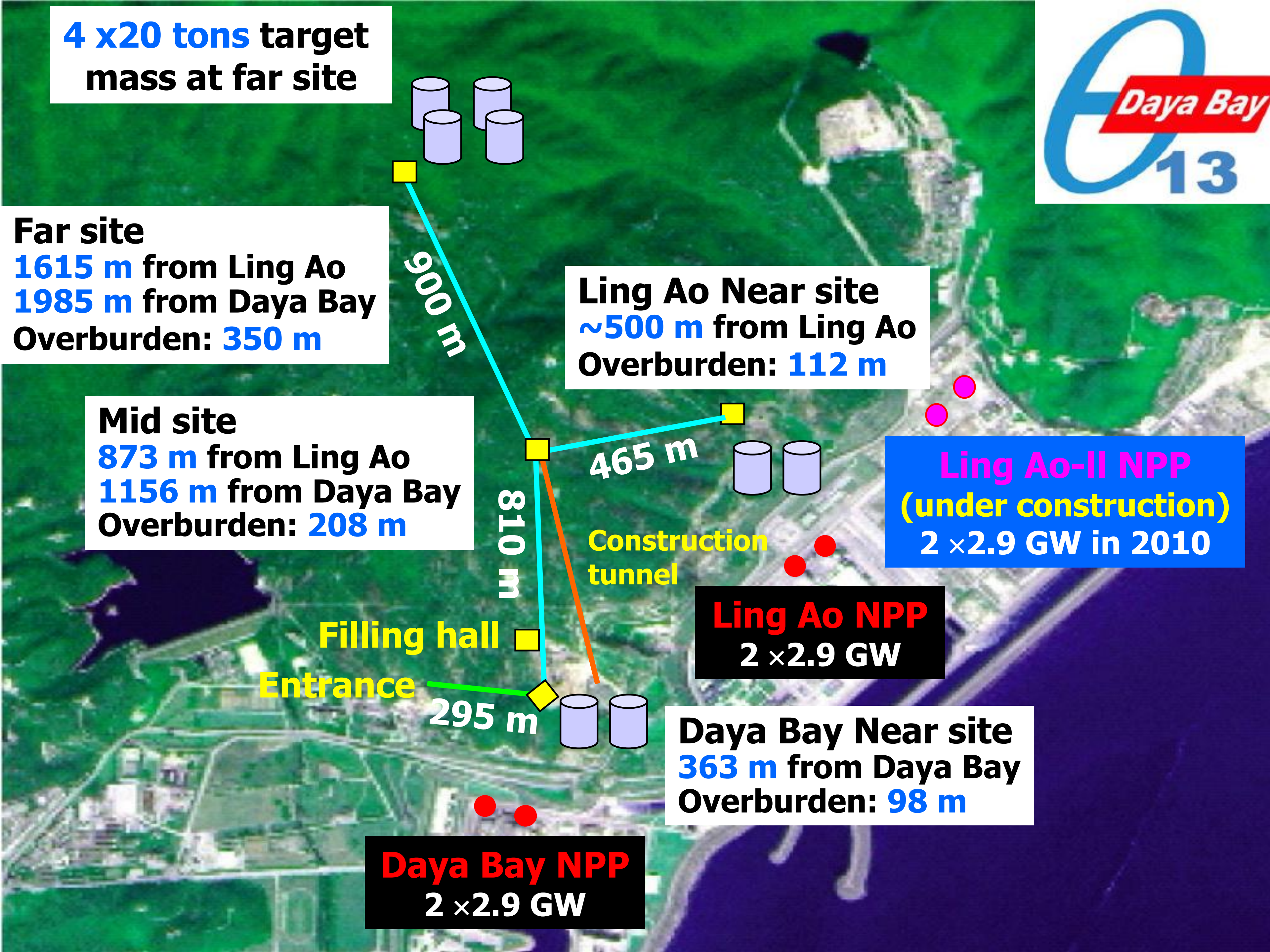
Data analysis

- RENO group hope to tell the value of $\sin^2(2\theta_{13})$ at the anticipated time
  - Goal: Neutrino 2012 @ Kyoto (June, 2012)

Daya Bay Experiment



- ★ Totally six reactor cores in 2011 (17.4 GW_{th}).
- ★ Mountains near by, easy to construct an underground laboratory to suppress cosmogenic backgrounds.
- ★ Supported strongly by the NPP and local government.



4 x20 tons target mass at far site

Far site
1615 m from Ling Ao
1985 m from Daya Bay
Overburden: 350 m

Mid site
873 m from Ling Ao
1156 m from Daya Bay
Overburden: 208 m

Ling Ao Near site
~500 m from Ling Ao
Overburden: 112 m

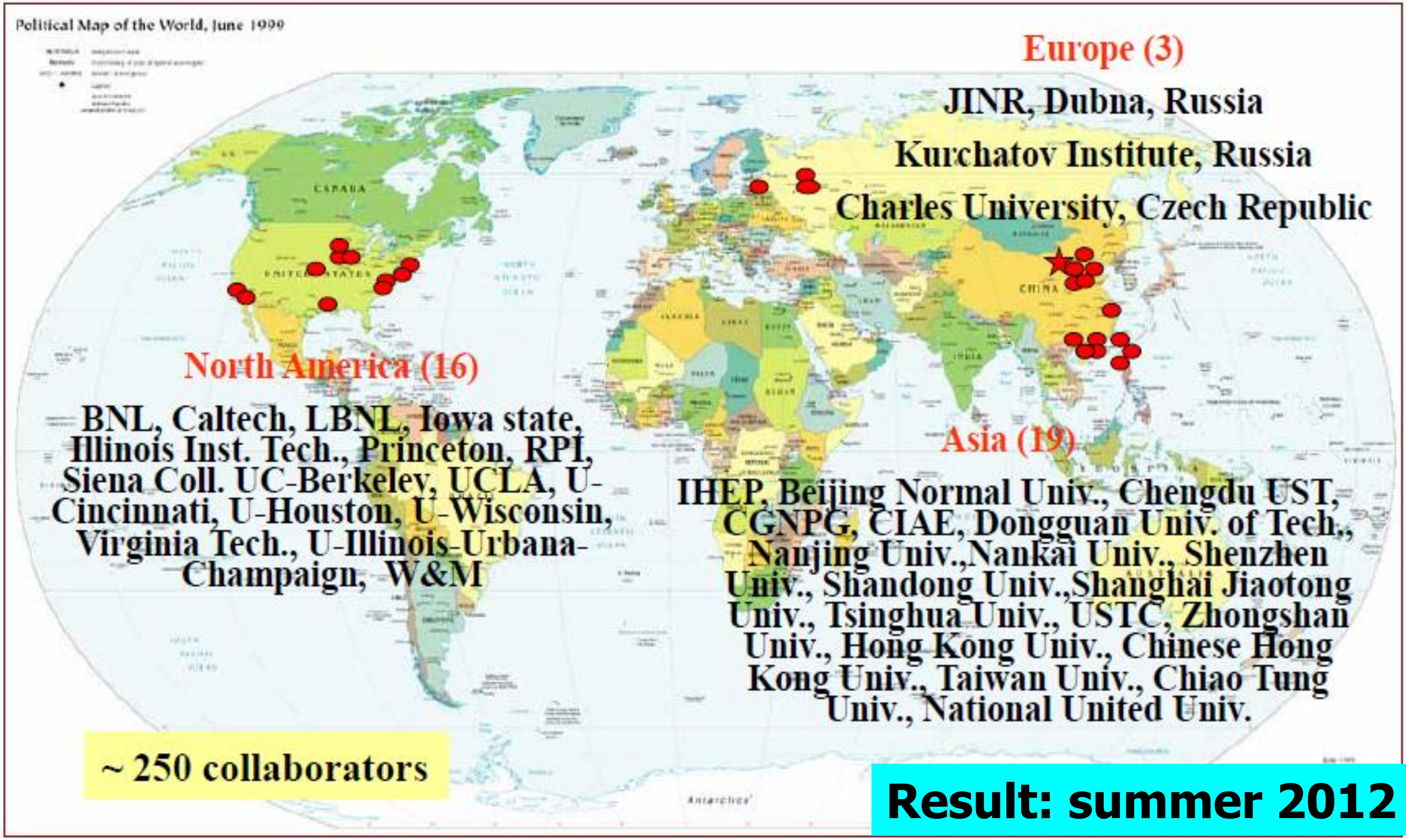
Daya Bay Near site
363 m from Daya Bay
Overburden: 98 m

Ling Ao-II NPP
(under construction)
2 ×2.9 GW in 2010

Ling Ao NPP
2 ×2.9 GW

Daya Bay NPP
2 ×2.9 GW

The Collaboration



Europe (3)

JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

North America (16)

BNL, Caltech, LBNL, Iowa state, Illinois Inst. Tech., Princeton, RPI, Siena Coll. UC-Berkeley, UCLA, U-Cincinnati, U-Houston, U-Wisconsin, Virginia Tech., U-Illinois-Urbana-Champaign, W&M

Asia (19)

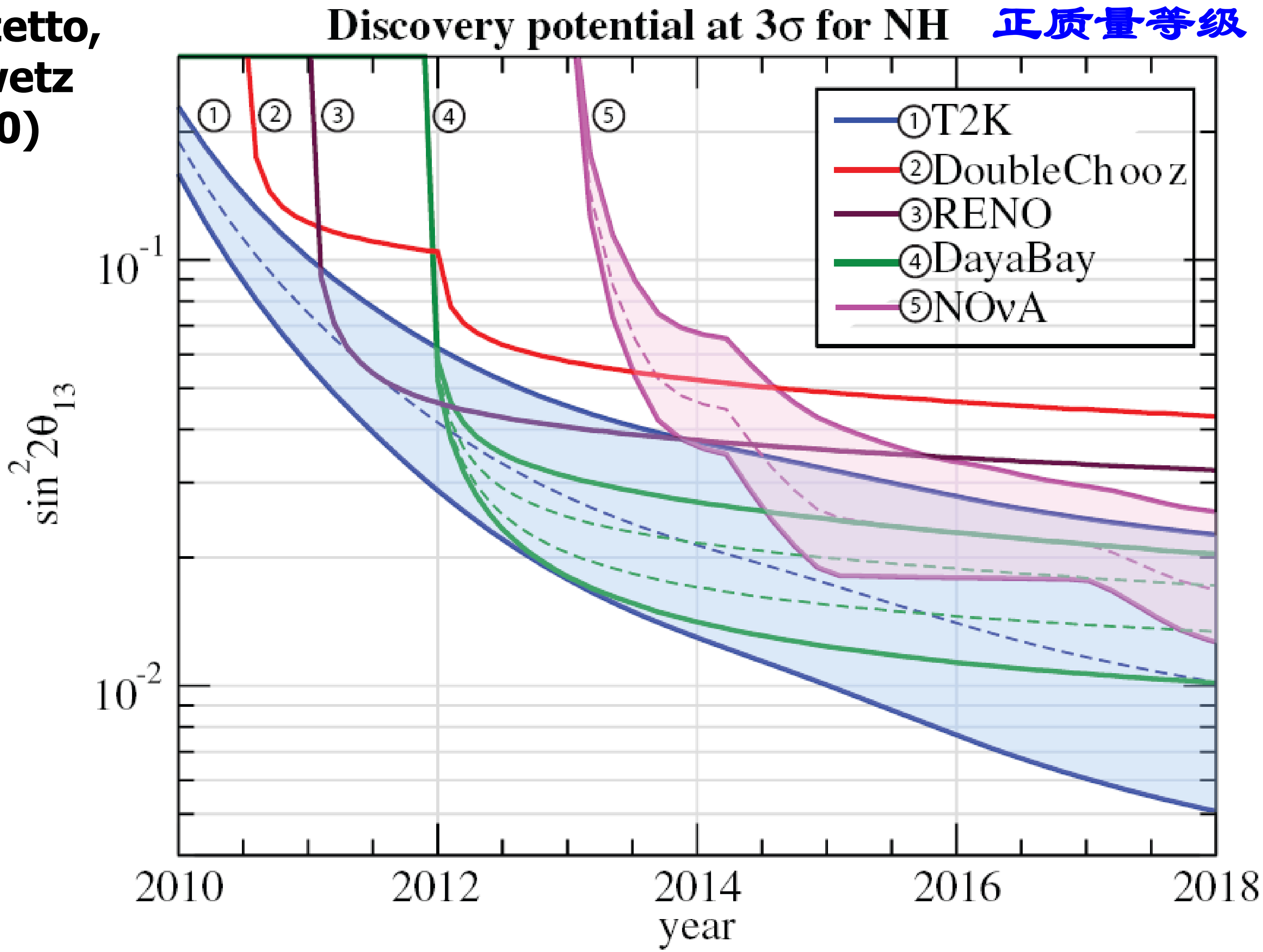
IHEP, Beijing Normal Univ., Chengdu UST, CGNPG, CIAE, Dongguan Univ. of Tech., Nanjing Univ.,Nankai Univ., Shenzhen Univ., Shandong Univ.,Shanghai Jiaotong Univ., Tsinghua Univ., USTC, Zhongshan Univ., Hong Kong Univ., Chinese Hong Kong Univ., Taiwan Univ., Chiao Tung Univ., National United Univ.

~ 250 collaborators

Result: summer 2012

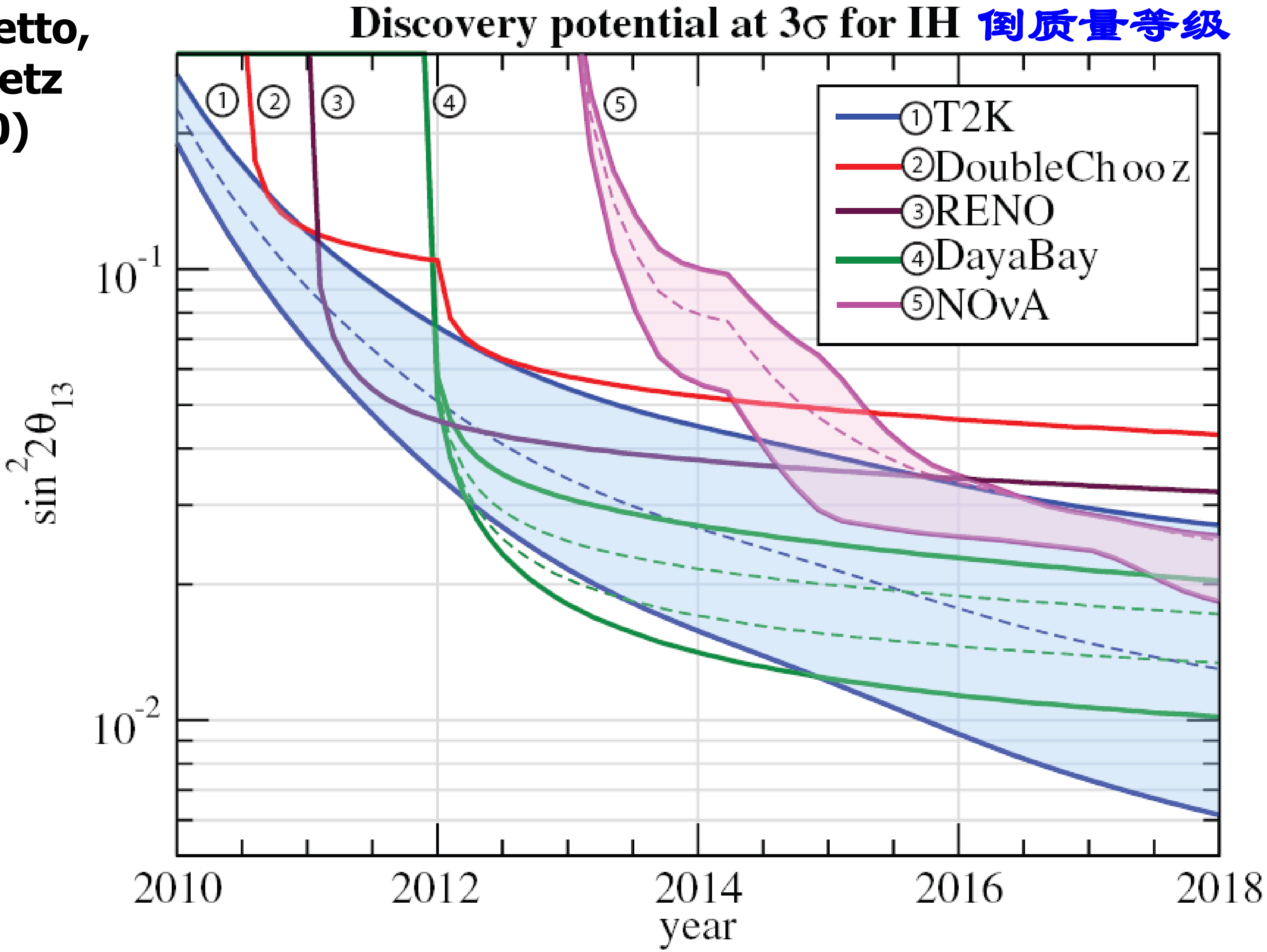
Comparison (1)

Mezzetto, Schwetz (2010)



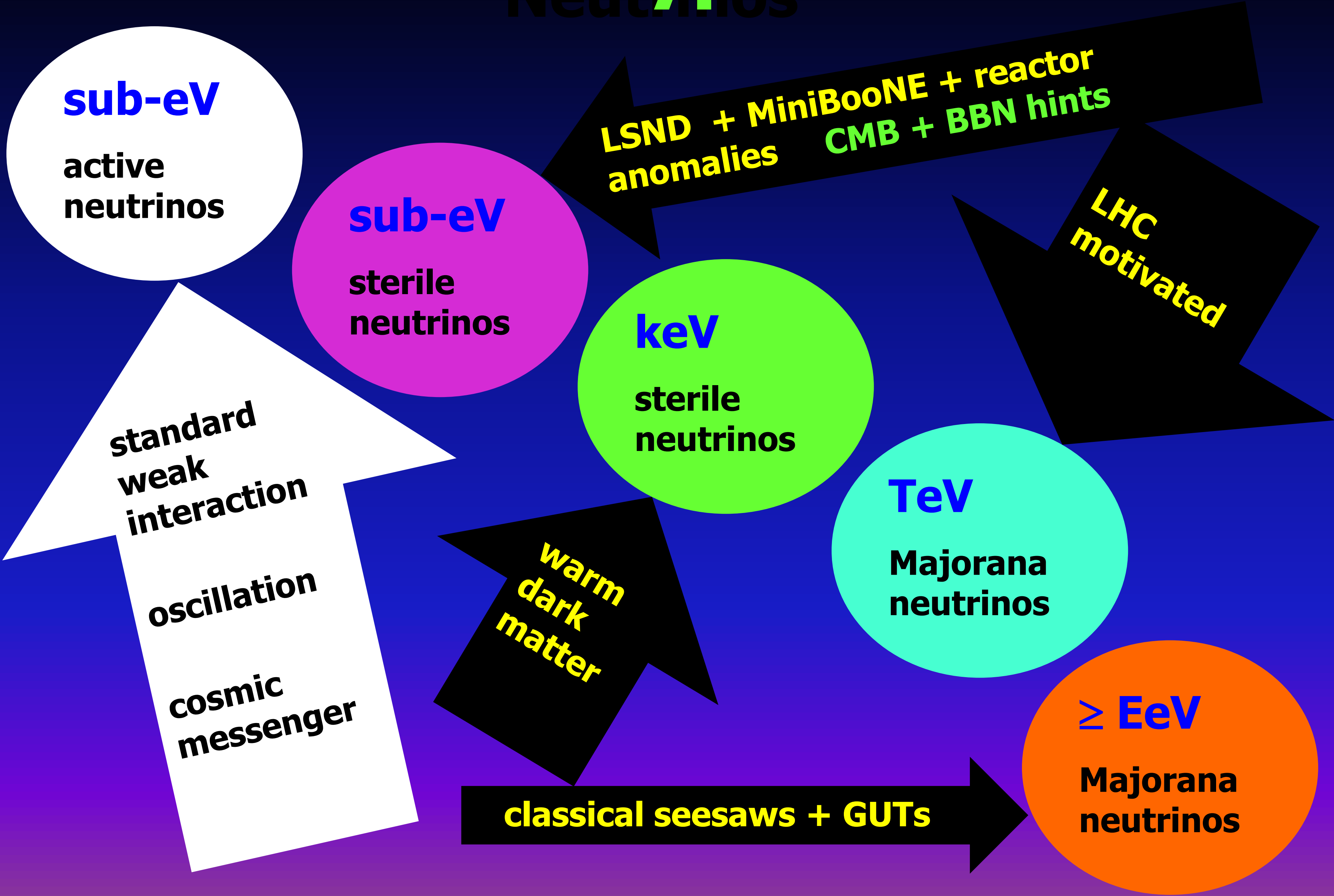
Comparison (2)

Mezzetto, Schwetz (2010)



Real + Hypothetical ν's

Neutrinos



sub-eV

active
neutrinos

sub-eV

sterile
neutrinos

keV

sterile
neutrinos

TeV

Majorana
neutrinos

≥ EeV

Majorana
neutrinos

standard
weak
interaction

oscillation

cosmic
messenger

LSND + MiniBooNE + reactor
anomalies

CMB + BBN hints

LHC
motivated

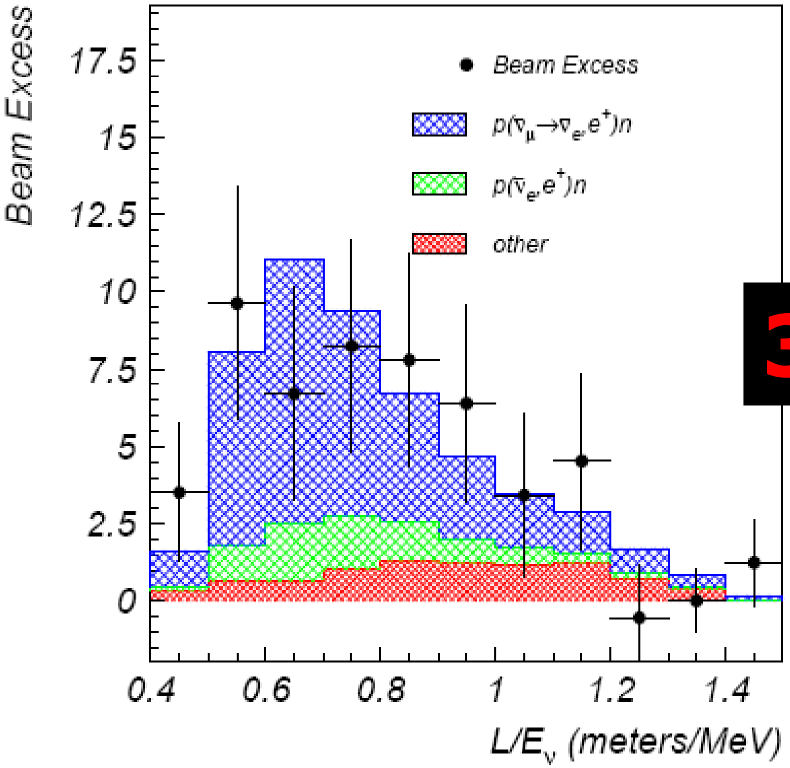
warm
dark
matter

classical seesaws + GUTs

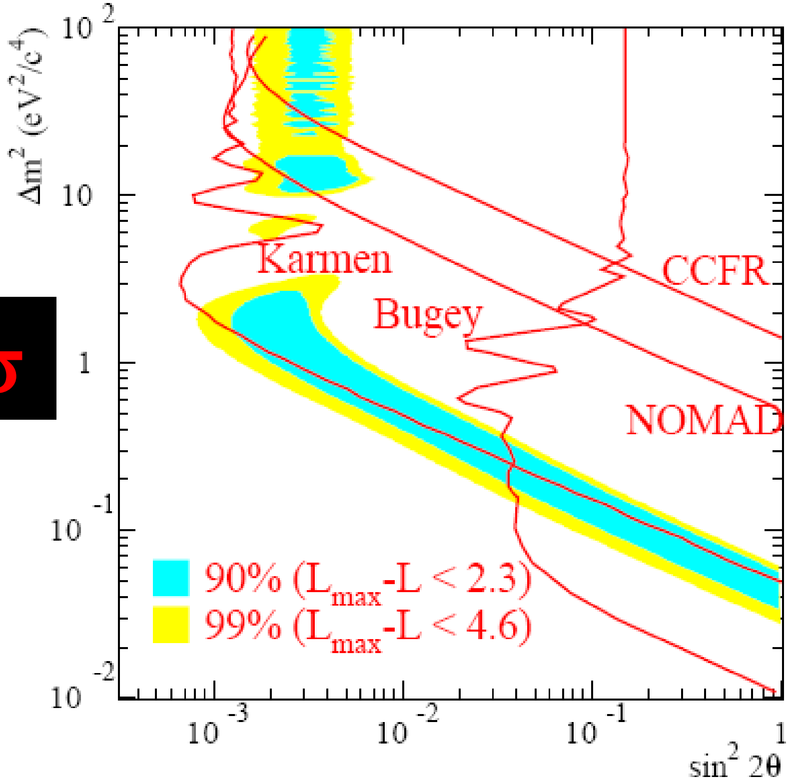
LSND Anomaly?

[LSND, PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\text{m}$ $\quad 20\,\text{MeV} \leq E \leq 200\,\text{MeV}$



3.8 σ



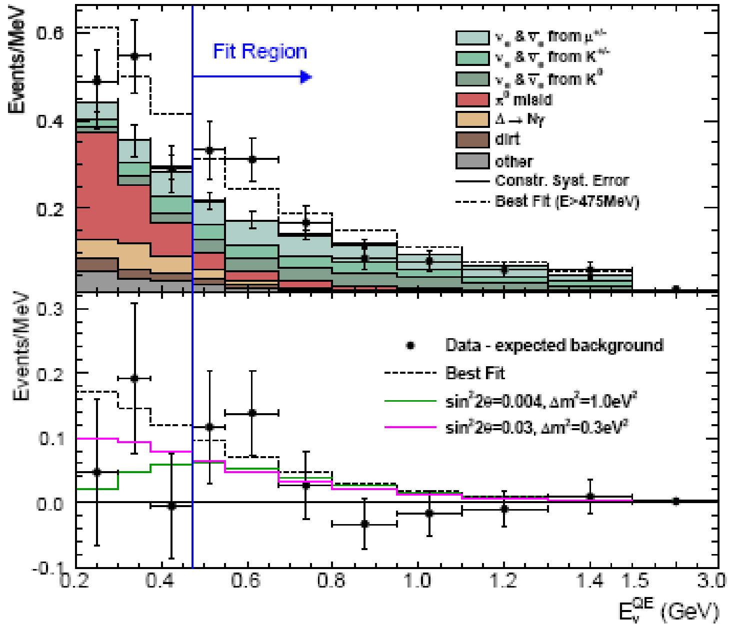
$$\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}})$$

MiniBooNE Anomaly?

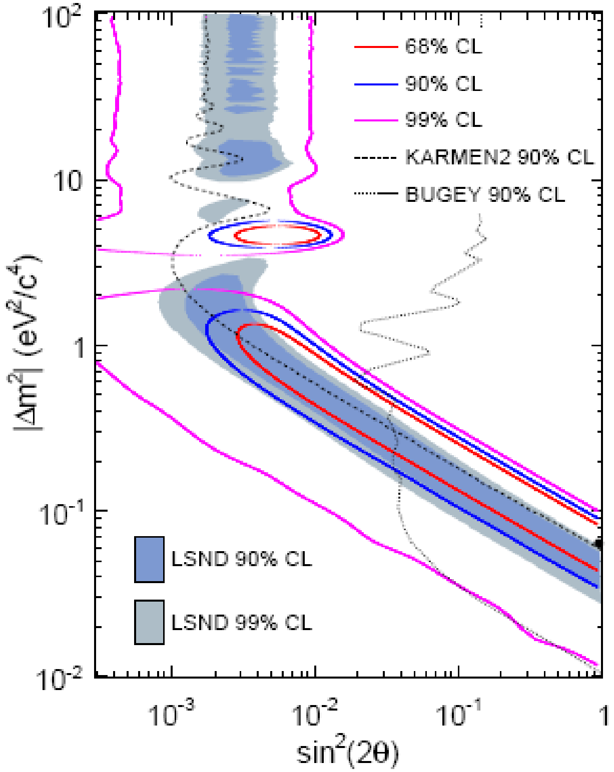
[PRL 103 (2009) 111801; PRL 105 (2010) 181801]

1.9 σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 541\,\text{m}$ $475\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$



[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]



Agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal!

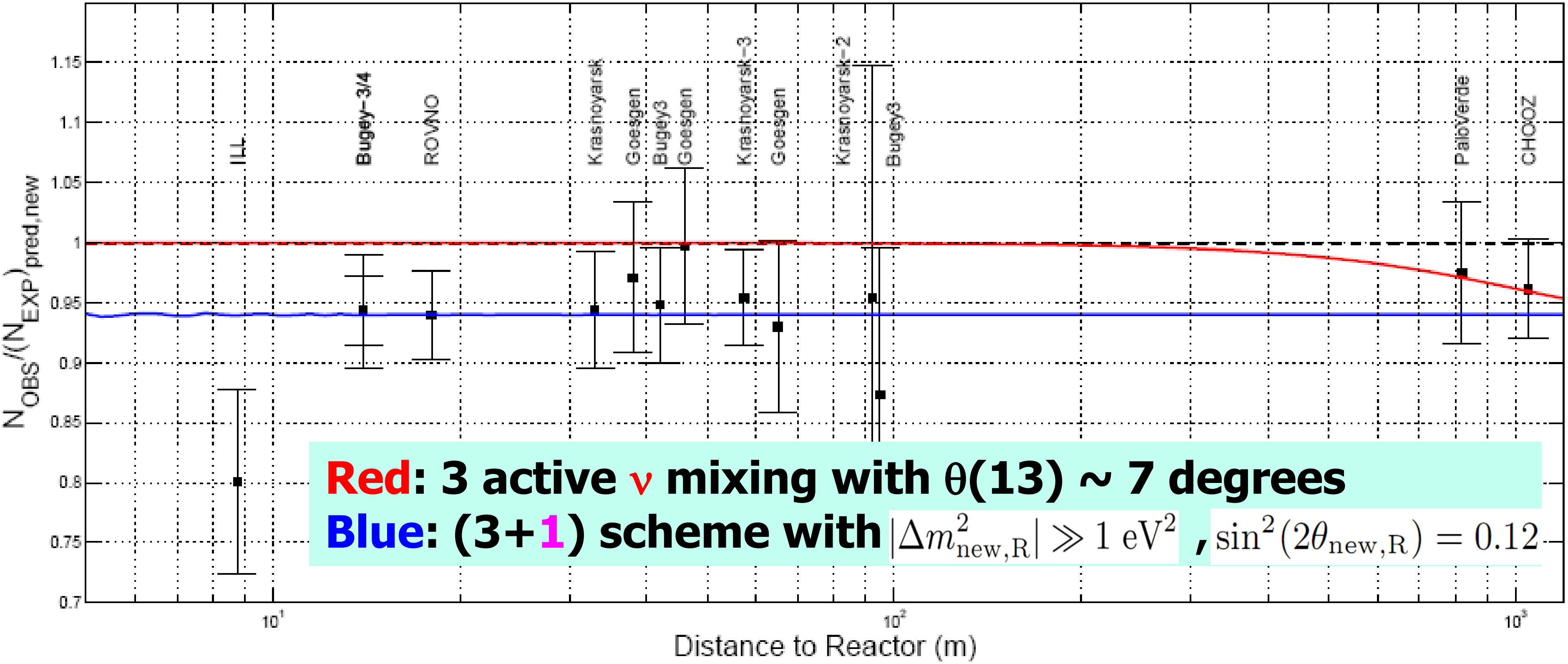
Similar L/E but different L and E $\Longrightarrow$ Oscillations!

Reactor anti-ν Anomaly?

A new calculation of the reactor antineutrino flux.

T. Mueller et al, PRC 83, 054615 (2011); G. Mention et al, PRD 83, 073006 (2011).

The detected flux normalization is increased by about 3%.



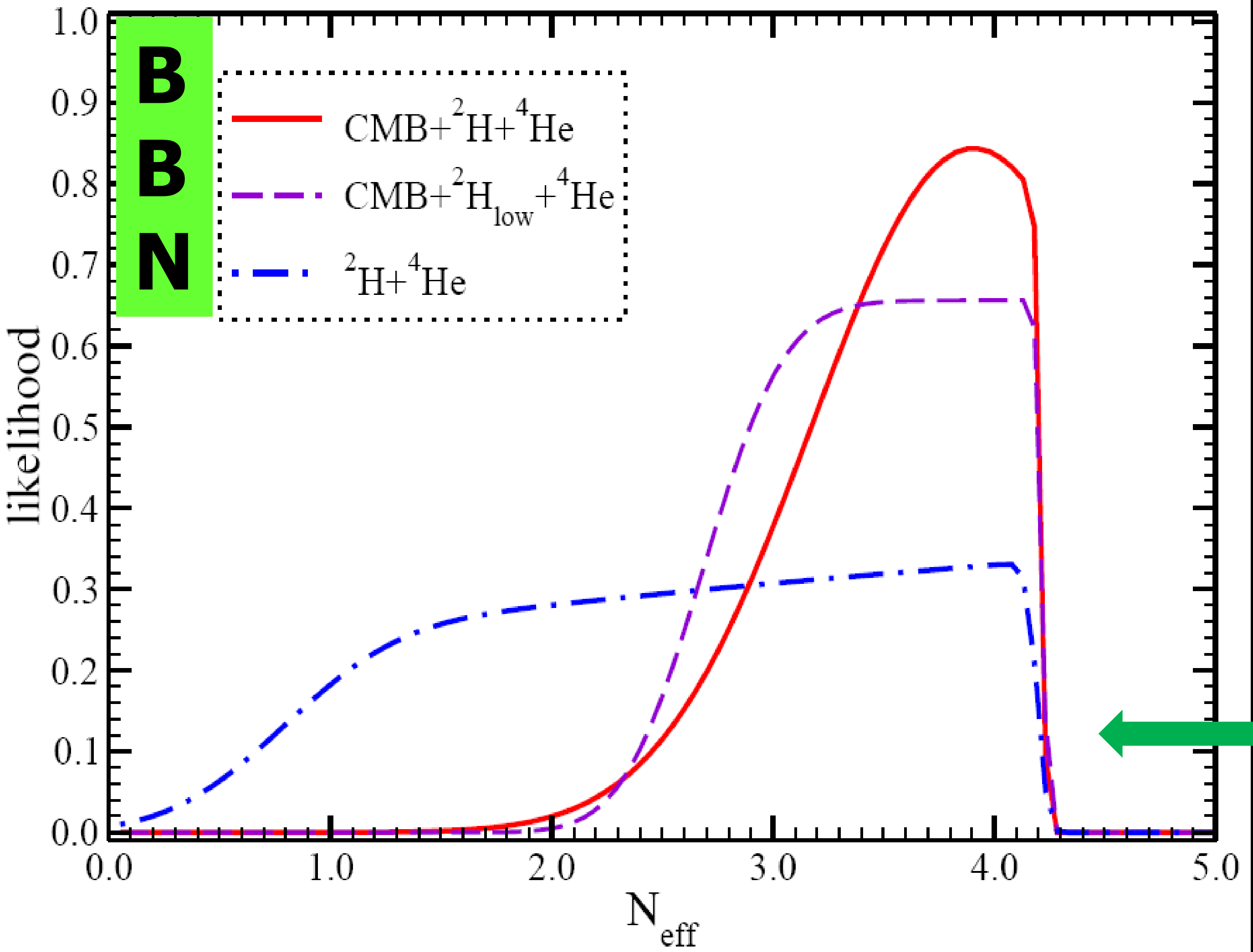
Red: 3 active ν mixing with $\theta(13)$ ~ 7 degrees

Blue: (3+1) scheme with $|\Delta m^2_{\mathrm{new,R}}| \gg 1\ \mathrm{eV}^2$ **,** $\sin^2(2\theta_{\mathrm{new,R}}) = 0.12$

Deviation from unity at 98.4% C.L.: the reactor antineutrino anomaly.

Sub-eV Sterile ν's?

BBN: current data only allow **one** sub-eV **sterile** neutrino;
CMB: current data can allow **two** sub-eV **sterile** neutrinos.



G. Mangano,
P. Serpico,
arXiv:1103.1261

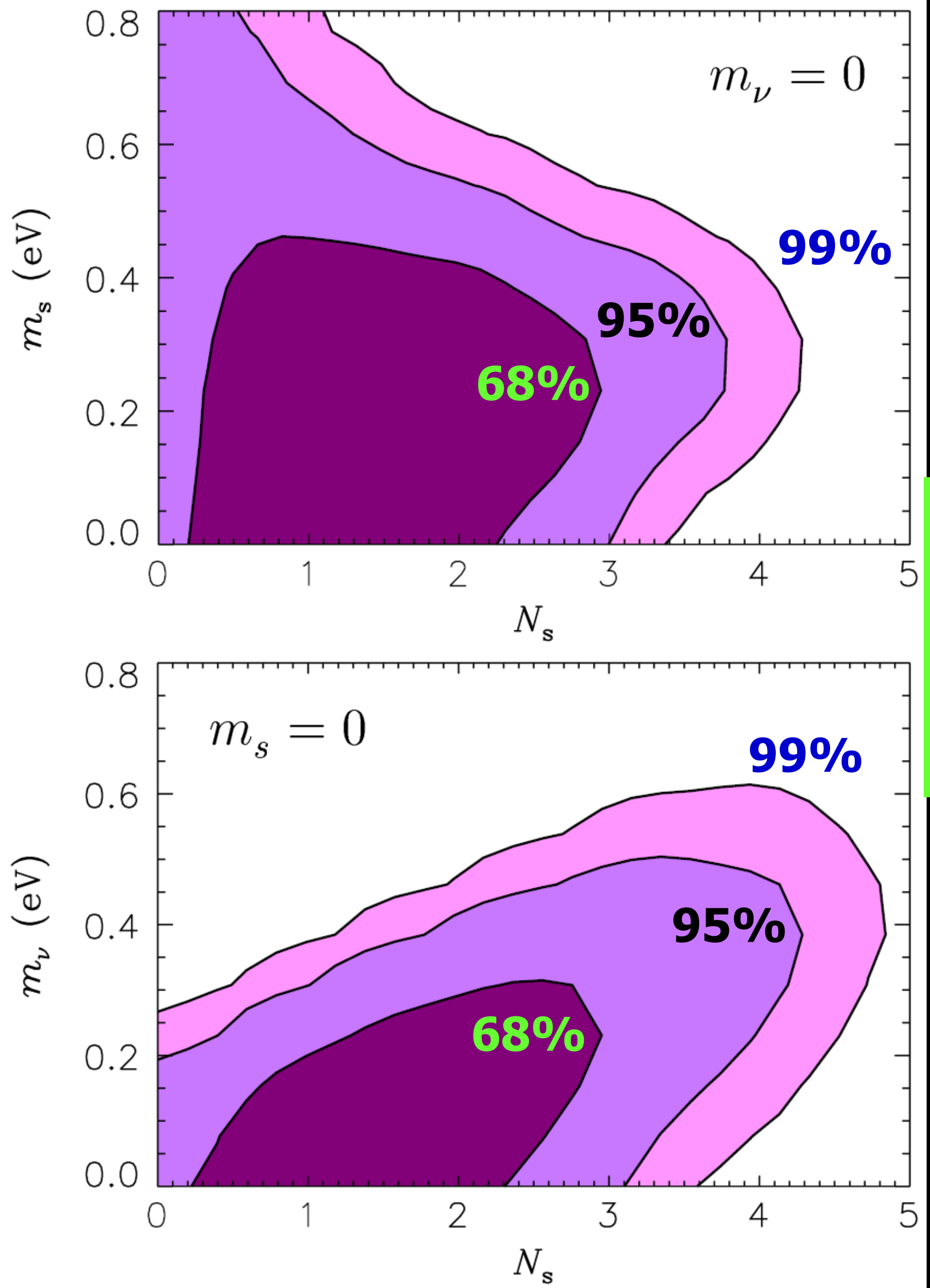
$N_{\rm eff} < 4.2$

(95% C.L.)

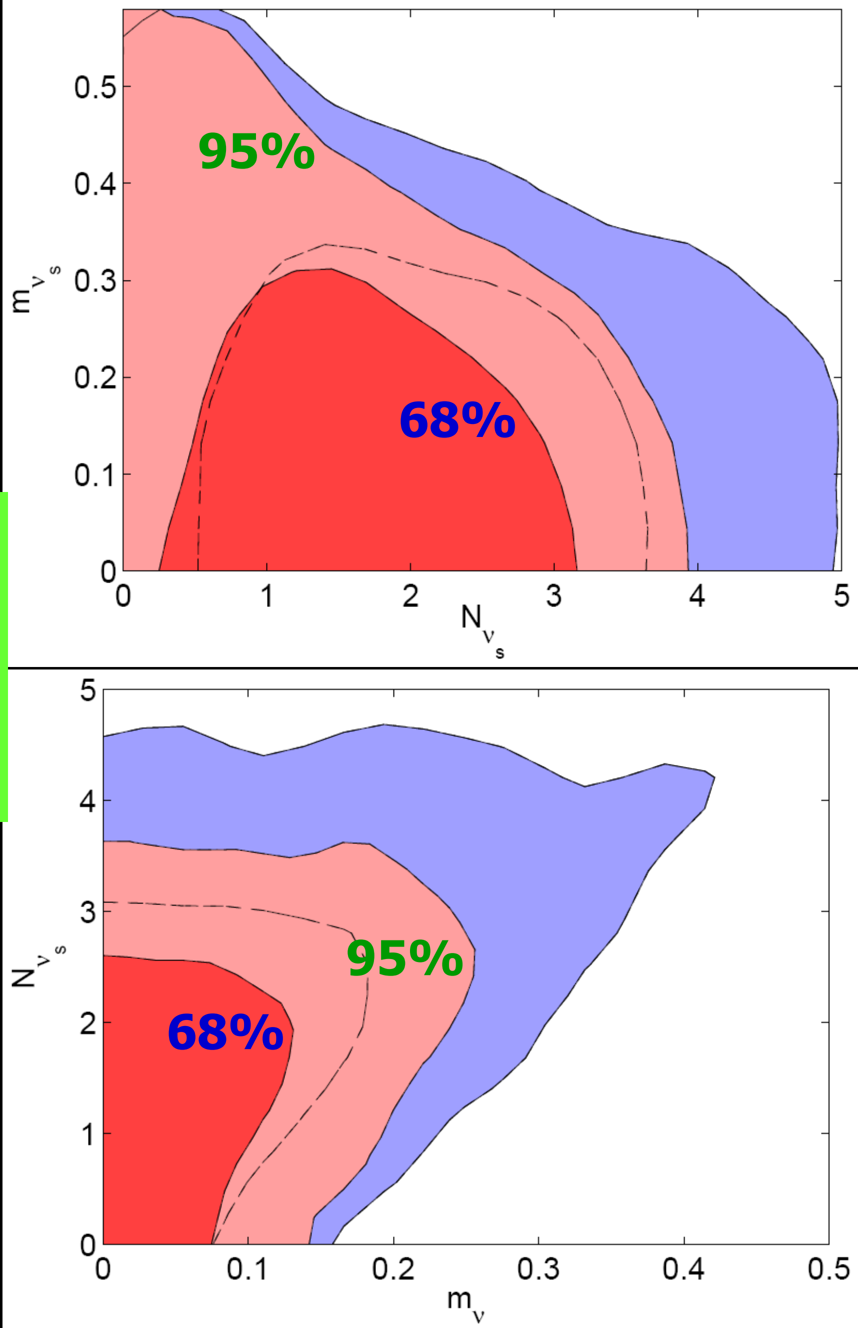
The sharp cut-off is due to a He-4 abundance upper bound (<0.2631)

$N_{\rm eff}^{\rm SM} = 3.046$

Hamann et al, arXiv:1006.5276; 1108.4136 **Giusarma et al**, arXiv:1102.4774



C M B



(3+3) Flavor Mixing

active flavor

sterile flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_x \\ \nu_y \\ \nu_z \end{pmatrix} = \mathcal{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \nu_6 \end{pmatrix}$$

mass state

A Full Parametrization

$$\mathcal{U} = \begin{pmatrix} 1 & 0 \\ 0 & U_0 \end{pmatrix} \begin{pmatrix} A & R \\ S & B \end{pmatrix} \begin{pmatrix} V_0 & 0 \\ 0 & 1 \end{pmatrix}$$

sterile part **interplay** **active part**

$$\begin{pmatrix} V_0 & 0 \\ 0 & 1 \end{pmatrix} = O_{23} O_{13} O_{12} \; ,$$

$$\begin{pmatrix} 1 & 0 \\ 0 & U_0 \end{pmatrix} = O_{56} O_{46} O_{45} \; ,$$

$$\begin{pmatrix} A & R \\ S & B \end{pmatrix} = O_{36} O_{26} O_{16} O_{35} O_{25} O_{15} O_{34} O_{24} O_{14}$$

Full parametrization:

15 rotation angles

15 phase phases

Xing, arXiv:1110.0083

$$O_{12} = \begin{pmatrix} c_{12} & \hat{s}_{12}^* & 0 & 0 & 0 & 0 \\ -\hat{s}_{12} & c_{12} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad O_{34} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & c_{34} & \hat{s}_{34}^* & 0 & 0 \\ 0 & 0 & -\hat{s}_{34} & c_{34} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad O_{16} = \begin{pmatrix} c_{16} & 0 & 0 & 0 & 0 & \hat{s}_{16}^* \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ -\hat{s}_{16} & 0 & 0 & 0 & 0 & c_{16} \end{pmatrix}$$

$$O_{13} = \begin{pmatrix} c_{13} & 0 & \hat{s}_{13}^* & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ -\hat{s}_{13} & 0 & c_{13} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad O_{15} = \begin{pmatrix} c_{15} & 0 & 0 & 0 & \hat{s}_{15}^* & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -\hat{s}_{15} & 0 & 0 & 0 & c_{15} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad O_{26} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & c_{26} & 0 & 0 & 0 & \hat{s}_{26}^* \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -\hat{s}_{26} & 0 & 0 & 0 & c_{26} \end{pmatrix}$$

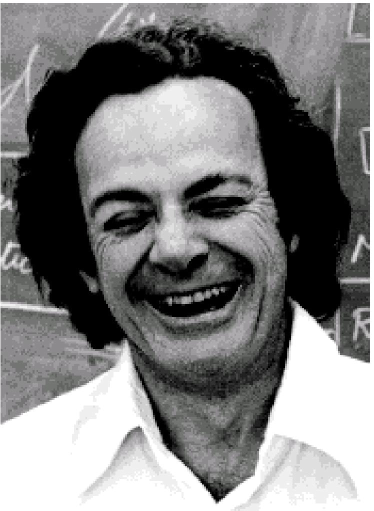
$$O_{23} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & c_{23} & \hat{s}_{23}^* & 0 & 0 & 0 \\ 0 & -\hat{s}_{23} & c_{23} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad O_{25} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & c_{25} & 0 & 0 & \hat{s}_{25}^* & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -\hat{s}_{25} & 0 & 0 & c_{25} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad O_{36} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & c_{36} & 0 & 0 & \hat{s}_{36}^* \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -\hat{s}_{36} & 0 & 0 & c_{36} \end{pmatrix}$$

$$O_{14} = \begin{pmatrix} c_{14} & 0 & 0 & \hat{s}_{14}^* & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ -\hat{s}_{14} & 0 & 0 & c_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad O_{35} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & c_{35} & 0 & \hat{s}_{35}^* & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -\hat{s}_{35} & 0 & c_{35} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad O_{46} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{46} & 0 & \hat{s}_{46}^* \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -\hat{s}_{46} & 0 & c_{46} \end{pmatrix}$$

$$O_{24} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & c_{24} & 0 & \hat{s}_{24}^* & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -\hat{s}_{24} & 0 & c_{24} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad O_{45} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{45} & \hat{s}_{45}^* & 0 \\ 0 & 0 & 0 & -\hat{s}_{45} & c_{45} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad O_{56} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{56} & \hat{s}_{56}^* \\ 0 & 0 & 0 & 0 & -\hat{s}_{56} & c_{56} \end{pmatrix}$$

Why a Particular Basis?

Theories of the known, which are described by different physical ideas, may be equivalent in all their predictions and are hence scientifically indistinguishable. However, they are not psychologically identical when trying to move from that base into the unknown. For different views suggest different kinds of modifications which might be made. I, therefore, think that a good theoretical physicist today might find it useful to have a wide range of physical viewpoints and mathematical expressions of the same theory available to him.



(**R.P. Feynman**, "The Development of the Space Time View of Quantum Electrodynamics", **Nobel lecture**, reprinted in Physics Today, August 1966)

A useful language: Diagrams, Parametrizations, ……

Questions

1) Do you feel happy / painful / sorry to introduce sterile neutrinos into the SM (remember Weinberg's theorem)?

2) How many species of sterile neutrinos should be taken into account for your this or that purpose? 1? 2? 3? ….?

3) If all the current experimental and observational hints disappear, will the sterile neutrino physics still survive?

4) Do you like to throw many stones to only kill few birds or just the opposite? And is this a very stupid question?

Weinberg's *3rd law of progress in theoretical physics* (83):

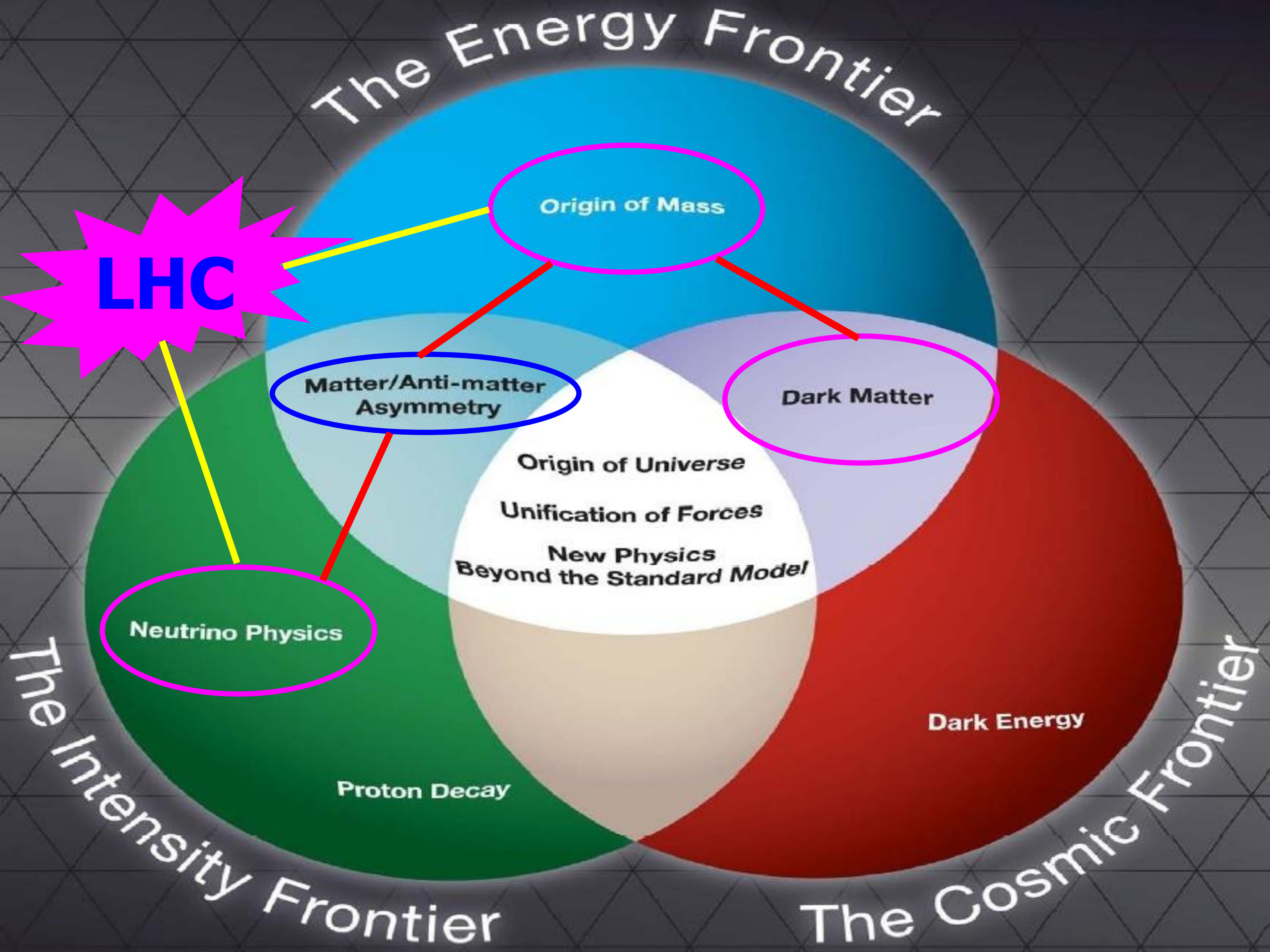
You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you will be sorry ……………………………………… What could be better?

Lecture F

★ Ways to Generate Neutrino Mass

★ TeV Seesaws: Natural/Testable?

★ Collider Signals of TeV Seesaws?



The Energy Frontier

LHC

Origin of Mass

Matter/Anti-matter Asymmetry

Dark Matter

Origin of Universe

Unification of Forces

New Physics Beyond the Standard Model

Neutrino Physics

Proton Decay

Dark Energy

The Intensity Frontier

The Cosmic Frontier

Within the SM

All ν's are massless in the SM, a result of the model's simple structure:

---- SU(2)_L×U(1)_Y gauge symmetry and Lorentz invariance;

Fundamentals of the model, mandatory for consistency of a QFT.

---- Economical particle content:

No right-handed neutrinos --- a Dirac mass term is not allowed.

Only one Higgs doublet --- a Majorana mass term is not allowed.

---- Mandatory renormalizability:

No dimension ≥ 5 operators: a Majorana mass term is forbidden.

To generate ν-masses, one or more of the constraints must be relaxed.

--- The gauge symmetry and Lorentz invariance cannot be abandoned;

--- The particle content can be modified;

--- The renormalizability can be abandoned.

How many ways?

Beyond the SM (1)

Way 1: to relax the requirement of **renormalizability** (S. Weinberg 79)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{\mathcal{L}_{\rm d=5}}{\Lambda} + \frac{\mathcal{L}_{\rm d=6}}{\Lambda^2} + \cdots$$

In the SM, the lowest-dimension operator that violates lepton/baryon number is

$$\frac{1}{M} HHLL$$

neutrino mass

Seesaw: $m_{1,2,3} \sim \langle H \rangle^2 / M$

$$m_{1,2,3} < 1\,\mathrm{eV} \Rightarrow M > 10^{13}\ \mathrm{GeV}$$

$$\frac{1}{M^2} QQQL$$

proton decay

Example : $p \to \pi^0 + e^+$

$$\tau_p > 10^{33}\ \text{years} \Rightarrow M > 10^{15}\ \mathrm{GeV}$$

Neutrino masses/proton decays: windows onto physics at high scales

Beyond the SM (2)

Way 2: to add **3 right-handed** neutrinos & demand a (**B** - **L**) symmetry

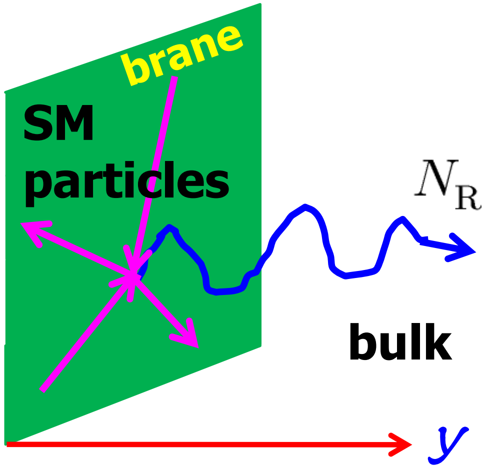
A pure Dirac mass term

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + {\rm h.c.}$$

$$\begin{aligned} M_l &= \frac{v}{\sqrt{2}} Y_l \\ M_\nu &= \frac{v}{\sqrt{2}} Y_\nu \end{aligned}$$

The hierarchy problem: $y_i / y_e = m_i / m_e \lesssim 0.5 \text{ eV} / 0.5 \text{ MeV} \sim 10^{-6}$

A very speculative way out: the smallness of **Dirac** masses is ascribed to the assumption that ***N*_R** have access to an extra spatial dimension (Dienes, Dudas, Gherghetta 98; Arkani-Hamed, Dimopoulos, Dvali, March-Russell 98) :



The wavefunction of ***N*_R** spreads out over the extra dimension ***y***, giving rise to a suppressed Yukawa interaction at ***y* = 0**.

$$\left[\overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R}\right]_{y=0} \sim \boxed{\frac{1}{\sqrt{L}}} \left[\overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R}\right]_{y=L}$$

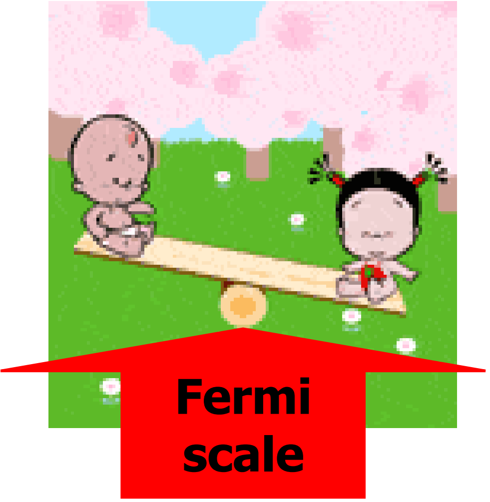
(e.g., King 08)

$\Lambda_{\bf String} / \Lambda_{\bf Planck} \sim 10^{-12}$

Beyond the SM (3)

Seesaw: add **new heavy degrees of freedom** and allow (**B**-**L**) violation:

Seesaw—A Footnote Idea:
H. Fritzsch, **M. Gell-Mann**,
P. Minkowski, PLB 59 (1975) 256



T-1: SM + 3 right-handed neutrinos (Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2}\overline{N^c_{\rm R}} M_{\rm R} N_{\rm R} + {\rm h.c.}$$

T-2: SM + 1 Higgs triplet (Konetschny, Kummer 77; Magg, Wetterich 80; Schechter, Valle 80; Cheng, Li 80; Lazarides et al 80; Mohapatra, Senjanovic 80)

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \frac{1}{2}\overline{l_{\rm L}} Y_\Delta \Delta i\sigma_2 l^c_{\rm L} - \lambda_\Delta M_\Delta H^T i\sigma_2 \Delta H + {\rm h.c.}$$

variations

T-3: SM + 3 triplet fermions (Foot, Lew, He, Joshi 89)

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} \sqrt{2} Y_\Sigma \Sigma^c \tilde{H} + \frac{1}{2}{\rm Tr}\left(\overline{\Sigma} M_\Sigma \Sigma^c\right) + {\rm h.c.}$$

combinations

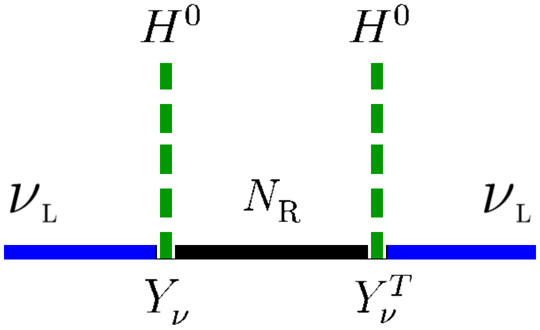
Seesaws

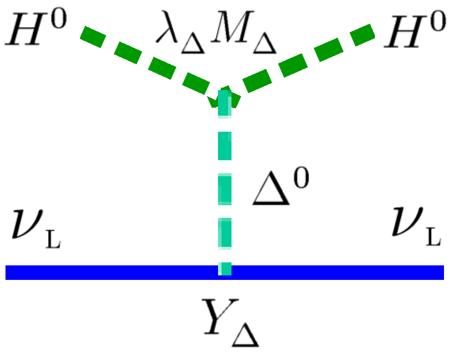
Weinberg operator: the unique **dimension-five** operator of ν-masses after integrating out the heavy degrees of freedom.

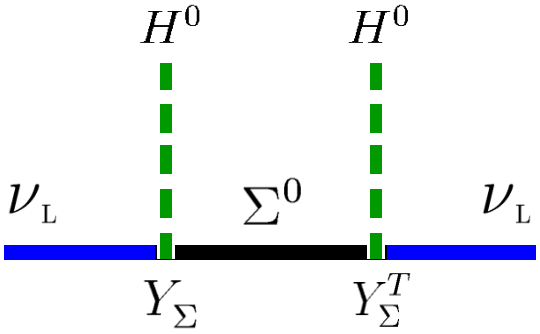
$$\frac{\mathcal{L}_{\rm d=5}}{\Lambda} = \begin{cases} \frac{1}{2}\left(Y_\nu M_{\rm R}^{-1} Y_\nu^T\right)_{\alpha\beta} \overline{l_{\alpha\rm L}}\,\tilde{H}\tilde{H}^T l^c_{\beta\rm L} + \text{h.c.} \\ -\frac{\lambda_\Delta}{M_\Delta}\left(Y_\Delta\right)_{\alpha\beta} \overline{l_{\alpha\rm L}}\,\tilde{H}\tilde{H}^T l^c_{\beta\rm L} + \text{h.c.} \\ \frac{1}{2}\left(Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T\right)_{\alpha\beta} \overline{l_{\alpha\rm L}}\,\tilde{H}\tilde{H}^T l^c_{\beta\rm L} + \text{h.c.} \end{cases}$$

$$M_\nu = \begin{cases} -\frac{1}{2} Y_\nu \frac{v^2}{M_{\rm R}} Y_\nu^T & \text{(Type 1)} \\ \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta} & \text{(Type 2)} \\ -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T & \text{(Type 3)} \end{cases}$$

After SSB, a Majorana mass term is $-\mathcal{L}_{\rm mass} = \frac{1}{2}\overline{\nu_{\rm L}} M_\nu \nu_{\rm L}^c + \text{h.c.}$ $\langle\tilde{H}\rangle = v/\sqrt{2}$

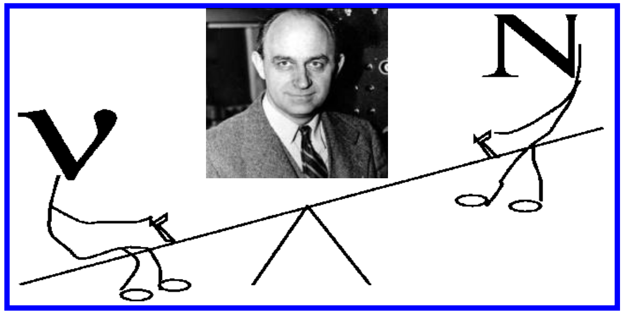


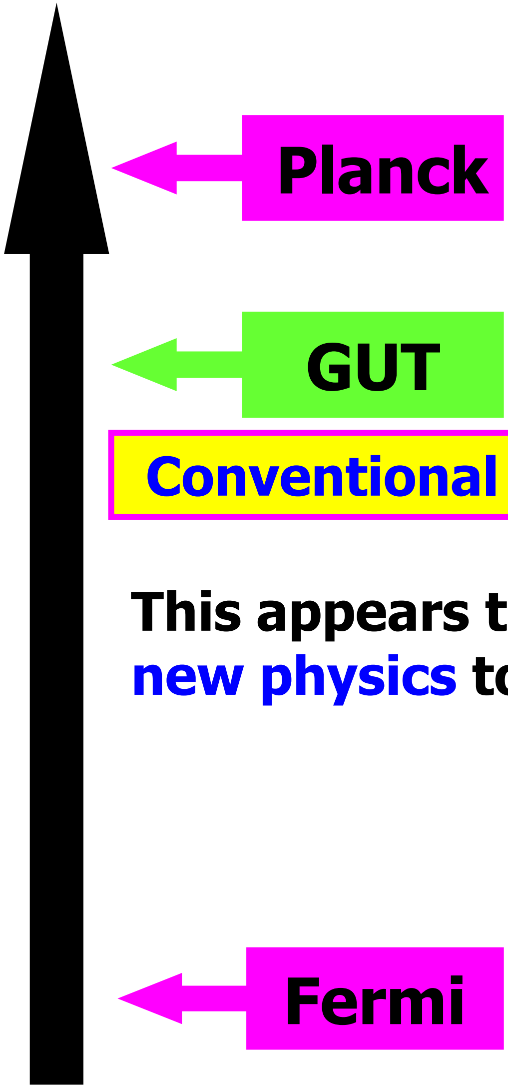




Seesaw Scale?

What is the energy scale at which the seesaw mechanism works?





Planck

GUT to unify strong, weak & electromagnetic forces

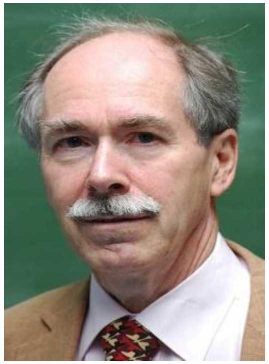
Conventional Seesaws: heavy degrees of freedom near GUT

This appears to be rather reasonable, since one often expects new physics to appear around a fundamental scale

Fermi

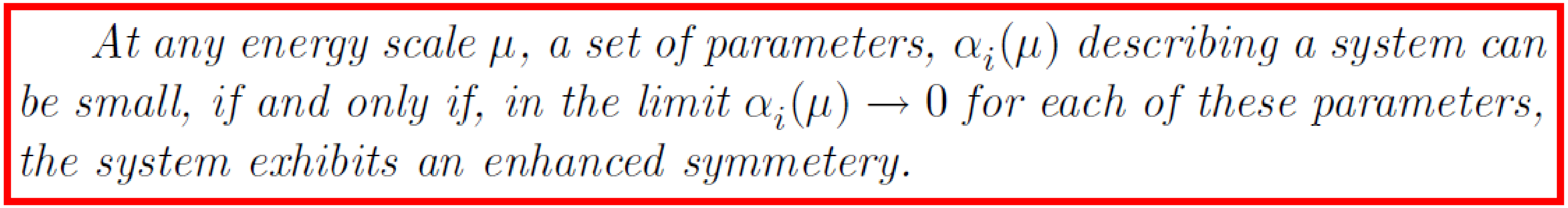
- **Naturalness √**
- **Testability ✗**
- **Uniqueness ✗**
- **Hierarchy ✗**

Lower Scale?



There is no direct evidence for a large or extremely large seesaw scale. So eV-, keV-, MeV- or GeV-scale seesaws are all possible, at least in principle; they are technically natural according to 't Hooft's naturalness criterion.

't Hooft's naturalness criterion (80):



> *At any energy scale μ, a set of parameters, $\alpha_i(\mu)$ describing a system can be small, if and only if, in the limit $\alpha_i(\mu) \to 0$ for each of these parameters, the system exhibits an enhanced symmetery.*

Potential problems of low-scale seesaws:

---- No obvious connection to a theoretically well-justified fundamental scale (for example, Fermi scale, TeV scale, GUT or Planck scale).

---- The neutrino Yukawa couplings are simply tiny, no actual explanation of why the masses of three known neutrinos are so small.

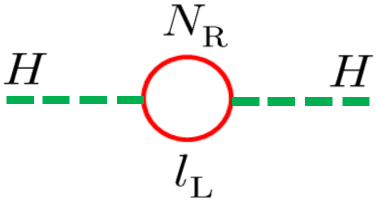
---- A very low seesaw scale doesn't allow canonical thermal leptogenesis to work, though there might be a very *contrived* way out.

Hierarchy Problem

Seesaw-induced fine-tuning problem: the Higgs mass is very sensitive to quantum corrections from the heavy degrees of freedom in seesaw (Vissani 98; Casas et al 04; Abada et al 07)

Type 1:

$$\delta m_H^2 = -\frac{y_i^2}{8\pi^2}\left(\Lambda^2 + M_i^2 \ln\frac{M_i^2}{\Lambda^2}\right)$$

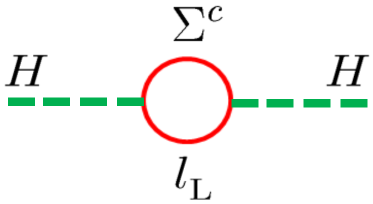


Type 2:

$$\delta m_H^2 = \frac{3}{16\pi^2}\left[\lambda_3\left(\Lambda^2 + M_\Delta^2 \ln\frac{M_\Delta^2}{\Lambda^2}\right) + 4\lambda_\Delta^2 M_\Delta^2 \ln\frac{M_\Delta^2}{\Lambda^2}\right]$$

Type 3:

$$\delta m_H^2 = -\frac{3y_i^2}{8\pi^2}\left(\Lambda^2 + M_i^2 \ln\frac{M_i^2}{\Lambda^2}\right)$$



here y_i & M_i are eigenvalues of Y_ν (or Y_Σ) & M_R (or M_Σ), respectively.

An illustration of fine-tuning

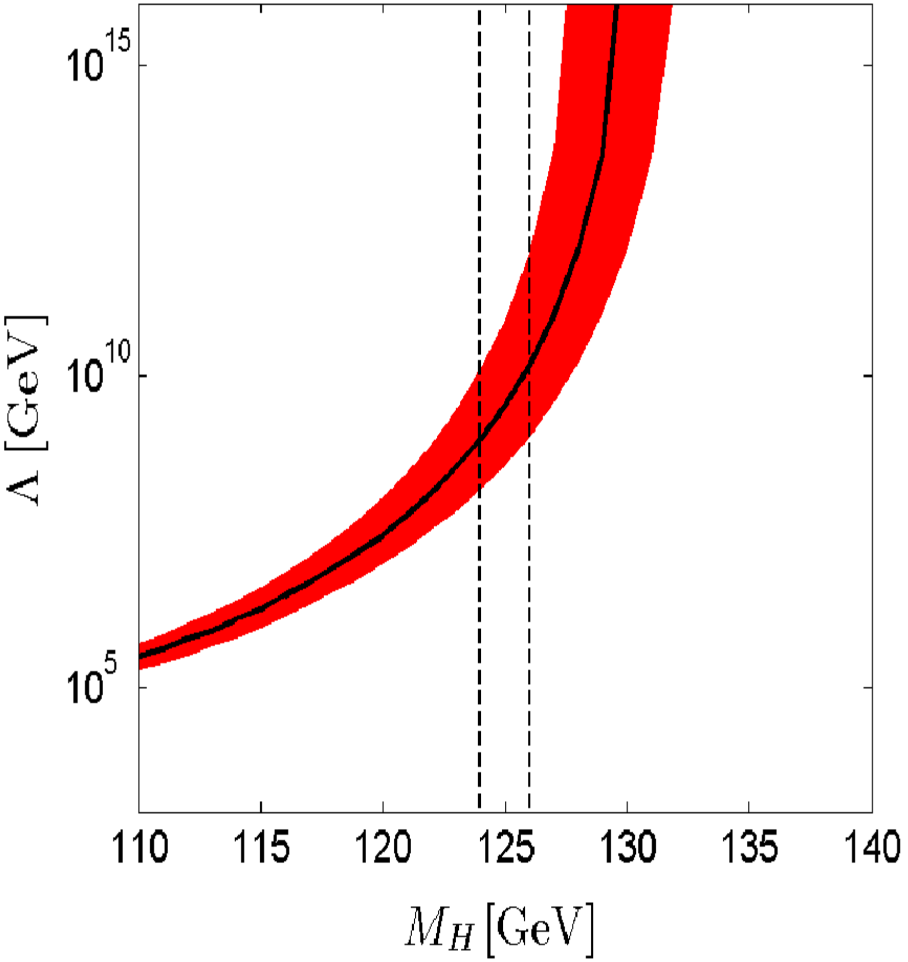
$$M_i \sim \left[\frac{(2\pi v)^2|\delta m_H^2|}{m_i}\right]^{1/3} \sim \underline{10^7\text{GeV}}\left[\frac{0.2\ \text{eV}}{m_i}\right]^{1/3}\left[\frac{|\delta m_H^2|}{0.1\ \text{TeV}^2}\right]^{1/3}$$

Possible way out: (1) **Supersymmetric** seesaw? (2) **TeV-scale** seesaw?

SM Vacuum

J. Elias-Miro et al., arXiv:1112.3022

Xing, Zhang, Zhou, arXiv:1112.3112



Gauge hierarchy and desert puzzles

Planck scale — $\Lambda \sim 10^{19}$ GeV

Oasis of new physics

something new ? — $\Lambda \sim 10^{10}$ GeV ?

Gauge desert

Fermi scale — $\Lambda \sim 10^{2}$ GeV

Oasis of SM physics

QCD scale — $\Lambda \sim 10^{2}$ MeV

TeV Neutrino Physics?

Why

to discover the SM Higgs boson

to verify Yukawa interactions

to pin down heavy seesaw particles

to test seesaw mechanism(s)

Not

to measure low-energy effects

Try

Type-1 Seesaw

Type-1 Seesaw: add 3 *right-handed* Majorana neutrinos into the SM.

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2}\overline{N^{\rm c}_{\rm R}} M_{\rm R} N_{\rm R} + {\rm h.c.}$$

or

$$-\mathcal{L}_{\rm mass} = \overline{e_{\rm L}} M_l E_{\rm R} + \frac{1}{2}\overline{(\nu_{\rm L} \quad N^{\rm c}_{\rm R})} \begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R}\end{pmatrix}\begin{pmatrix}\nu^{\rm c}_{\rm L}\\ N_{\rm R}\end{pmatrix} + {\rm h.c.}$$

Diagonalization (flavor basis ⇒ mass basis):

$$\begin{pmatrix} V & R \\ S & U \end{pmatrix}^\dagger \begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R}\end{pmatrix} \begin{pmatrix} V & R \\ S & U \end{pmatrix}^* = \begin{pmatrix} \widehat{M}_\nu & \mathbf{0} \\ \mathbf{0} & \widehat{M}_N \end{pmatrix}$$

$$V^\dagger V + \underline{S^\dagger S} = V V^\dagger + \underline{R R^\dagger} = 1$$

Hence *V* is not unitary

Seesaw: $$M_\nu \equiv V \widehat{M}_\nu V^T \approx -M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$$

$$R \sim S \sim M_{\rm D} / M_{\rm R}$$

Strength of Unitarity Violation

$$V \approx \left(1 - \frac{1}{2} R R^\dagger\right) V_{\rm unitary}$$

Natural or Unnatural?

Natural case: **no large cancellation in the leading seesaw term.**

$$\underbrace{M_\nu}_{0.01\ \text{eV}} \approx \underbrace{M_D}_{100\ \text{GeV}} \underbrace{M_R^{-1}}_{10^{15}\ \text{GeV}} \underbrace{M_D^T}_{100\ \text{GeV}}$$

$$R \sim S \sim M_D / M_R \sim 10^{-13}$$

$$\text{Unitarity Violation} \sim 10^{-26}$$

Unnatural case: **large cancellation in the leading seesaw term.**

$$\underbrace{M_\nu}_{0.01\ \text{eV}} \approx \underbrace{M_D}_{100\ \text{GeV}} \underbrace{M_R^{-1}}_{1\ \text{TeV}} \underbrace{M_D^T}_{100\ \text{GeV}}$$

$$R \sim S \sim M_D / M_R \sim 10^{-1}$$

$$\text{Unitarity Violation} \sim 10^{-2}$$

TeV-scale (right-handed) Majorana neutrinos: small masses of 3 light Majorana neutrinos come from sub-leading perturbations.

Structural Cancellation

Given diagonal *M_R* with 3 mass igenvalues *M_1*, *M_2* and *M_3*, the leading (i.e., type-I seesaw) term of the active neutrino mass matrix vanishes, if and only if *M_D* has rank 1,

$$\boldsymbol{M}_{\mathrm{D}} = m \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{pmatrix}$$

and if

$$\frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} = 0$$

$$\boldsymbol{M_\nu \approx M_{\mathrm{D}} M_{\mathrm{R}}^{-1} M_{\mathrm{D}}^{T} = 0}$$

(Buchmueller, Greub 91; Ingelman, Rathsman 93; Heusch, Minkowski 94; ……; Kersten, Smirnov 07).

Tiny ν-masses can be generated from tiny corrections to this complete "structural cancellation", by deforming *M_D* or *M_R* .

Simple example:

$$M'_{\mathrm{D}} = M_{\mathrm{D}} + \epsilon X_{\mathrm{D}}$$

$$\begin{aligned} M'_\nu &= M'_{\mathrm{D}} M_{\mathrm{R}}^{-1} M'^{\,T}_{\mathrm{D}} \\ &\approx \epsilon \left(M_{\mathrm{D}} M_{\mathrm{R}}^{-1} X_{\mathrm{D}}^{T} + X_{\mathrm{D}} M_{\mathrm{R}}^{-1} M_{\mathrm{D}}^{T} \right) + \mathcal{O}(\epsilon^2) \end{aligned}$$

Fast Lessons

Lesson 1: two necessary conditions to test a seesaw model with heavy right-handed Majorana neutrinos at the LHC:

---Masses of heavy Majorana neutrinos must be of *O* (1) TeV or below

---Light-heavy neutrino mixing (i.e. *M*_D/*M*_R) must be large enough

Lesson 2: A collider signature of the heavy Majorana ν's is essentially decoupled from masses and mixing parameters of light ν's.

Lesson 3: non-unitarity of the light ν flavor mixing matrix might lead to observable effects in ν oscillations and rare processes.

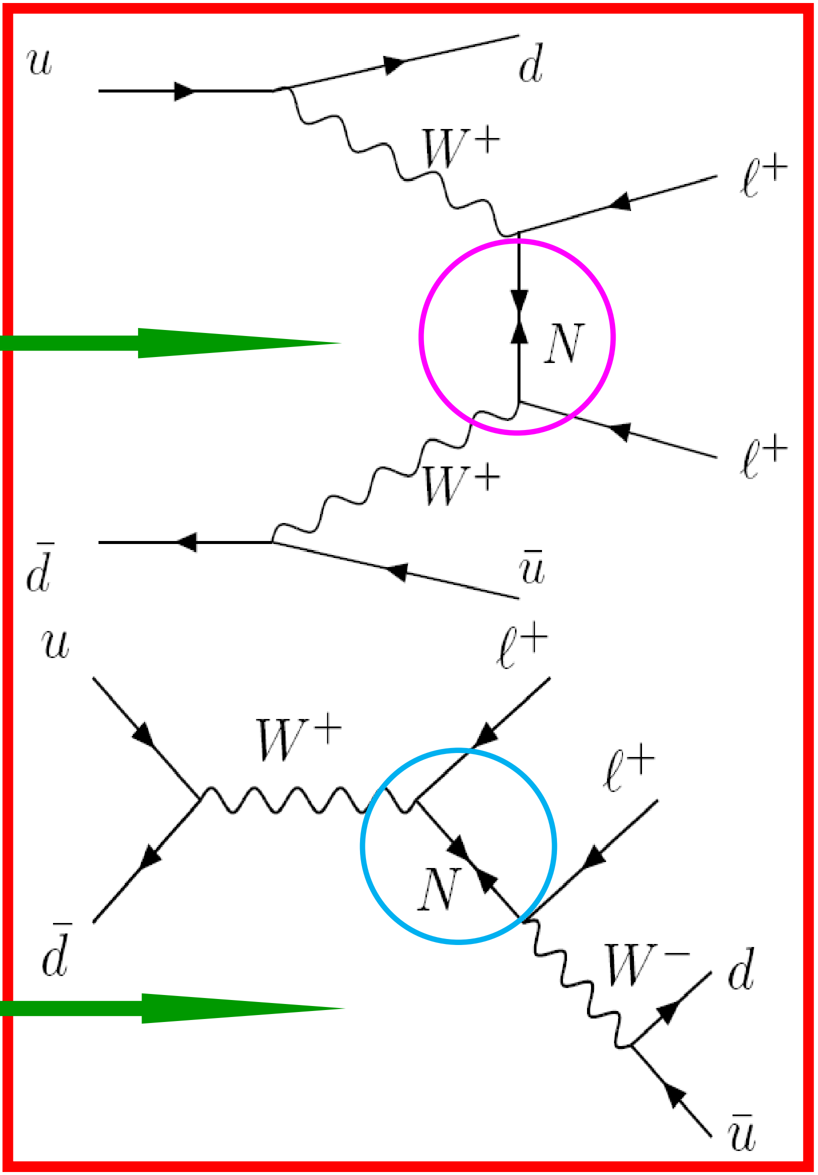
Lesson 4: nontrivial limits on heavy Majorana ν's could be derived at the LHC, if the SM backgrounds are small for a specific final state.

$\Delta L = 2$ like-sign dilepton events

$$pp \to W^\pm W^\pm \to \mu^\pm\mu^\pm jj \text{ and } pp \to W^\pm \to \mu^\pm N \to \mu^\pm\mu^\pm jj$$

Collider Signature

Lepton number violation: like-sign dilepton events at hadron colliders, such as Tevatron (~2 TeV) and LHC (~14 TeV).



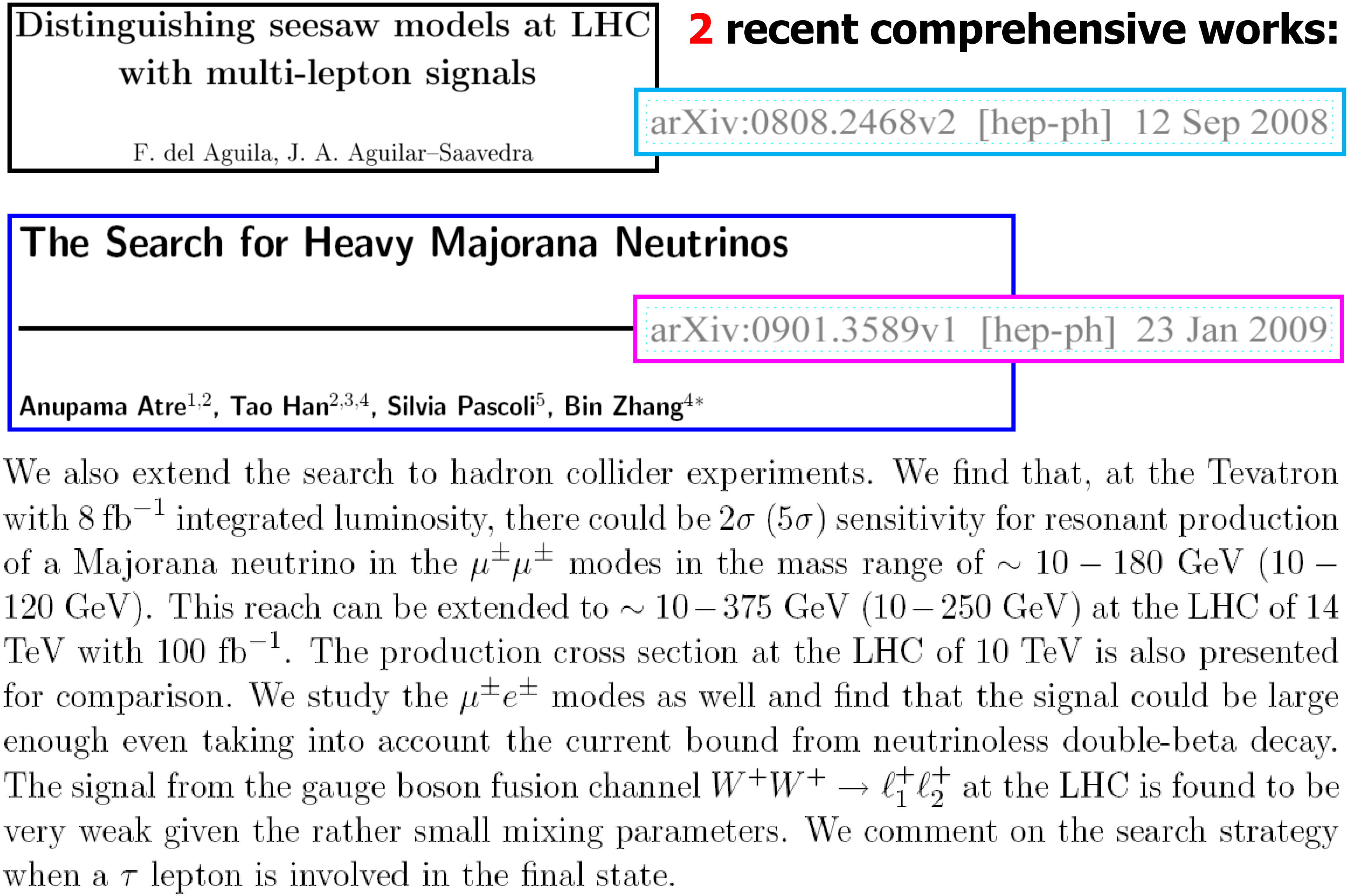
collider analogue to 0νββ decay

dominant channel

N can be produced on resonance

Testability at the LHC

2 recent comprehensive works:



Distinguishing seesaw models at LHC with multi-lepton signals

F. del Aguila, J. A. Aguilar–Saavedra

arXiv:0808.2468v2 [hep-ph] 12 Sep 2008

The Search for Heavy Majorana Neutrinos

arXiv:0901.3589v1 [hep-ph] 23 Jan 2009

Anupama Atre[1,2], Tao Han[2,3,4], Silvia Pascoli[5], Bin Zhang[4*]

We also extend the search to hadron collider experiments. We find that, at the Tevatron with 8 fb^{-1} integrated luminosity, there could be 2σ (5σ) sensitivity for resonant production of a Majorana neutrino in the $\mu^\pm\mu^\pm$ modes in the mass range of $\sim 10 - 180$ GeV $(10 - 120$ GeV). This reach can be extended to $\sim 10 - 375$ GeV $(10 - 250$ GeV) at the LHC of 14 TeV with 100 fb^{-1}. The production cross section at the LHC of 10 TeV is also presented for comparison. We study the $\mu^\pm e^\pm$ modes as well and find that the signal could be large enough even taking into account the current bound from neutrinoless double-beta decay. The signal from the gauge boson fusion channel $W^+W^+ \to \ell_1^+\ell_2^+$ at the LHC is found to be very weak given the rather small mixing parameters. We comment on the search strategy when a τ lepton is involved in the final state.

Non-unitarity

Type-1 seesaw: a typical signature would be the unitarity violation of the 3×3 neutrino mixing matrix *V* in the charged-current interactions

Current experimental constraints at the 90% C.L. (Antusch *et al* 07):

$$|VV^\dagger| \approx \begin{pmatrix} 0.994 \pm 0.005 & < 7.0 \cdot 10^{-5} & < 1.6 \cdot 10^{-2} \\ < 7.0 \cdot 10^{-5} & 0.995 \pm 0.005 & < 1.0 \cdot 10^{-2} \\ < 1.6 \cdot 10^{-2} & < 1.0 \cdot 10^{-2} & 0.995 \pm 0.005 \end{pmatrix}$$

$\mu \to e + \gamma$ etc, *W* / *Z* decays, *universality*, ν-oscillation.

$$|V^\dagger V| \approx \begin{pmatrix} 1.00 \pm 0.032 & < 0.032 & < 0.032 \\ < 0.032 & 1.00 \pm 0.032 & < 0.032 \\ < 0.032 & < 0.032 & 1.00 \pm 0.032 \end{pmatrix}$$

accuracy of a few percent!

Extra CP-violating phases exist in a non-unitary ν mixing matrix may lead to observable *CP-violating effects* in short- or medium-baseline ν oscillations (Fernandez-Martinez *et al* 07; Xing 08).

Typical example: non-unitary CP violation in the ν_μ → ν_τ oscillation, an effect probably at the percent level.

Type-2 Seesaw

Type-2 (Triplet) Seesaw: add one SU(2)_L Higgs triplet into the SM.

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \frac{1}{2}\overline{l_{\rm L}} Y_\Delta \Delta i\sigma_2 l^c_{\rm L} + {\rm h.c.}$$

$$\Delta \equiv \begin{pmatrix} H^- & -\sqrt{2}\ H^0 \\ \sqrt{2}\ H^{--} & -H^- \end{pmatrix}$$

or

$$-\mathcal{L}_{\rm mass} = \overline{e_{\rm L}} M_l E_{\rm R} + \frac{1}{2}\overline{\nu_{\rm L}} M_{\rm L} \nu^c_{\rm L} + {\rm h.c.}$$

$$M_{\rm L} \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

Potential:

$$V(H,\Delta) = -\mu^2 H^\dagger H + \lambda\left(H^\dagger H\right)^2 + \frac{1}{2}M_\Delta^2 {\rm Tr}\left(\Delta^\dagger \Delta\right) - \left[\lambda_\Delta M_\Delta H^T i\sigma_2 \Delta H + {\rm h.c.}\right]$$

***L* and *B–L* violation**

Naturalness? (t' Hooft 79, …, Giudice 08)

(1) *M_Δ* is O(1) TeV or close to the scale of gauge symmetry breaking.
(2) *λ_Δ* must be tiny, and *λ_Δ* =0 enhances the symmetry of the model.

$$M_{\rm L} \approx \lambda_\Delta Y_\Delta \frac{{\rm v}^2}{M_\Delta}$$

0.01 eV

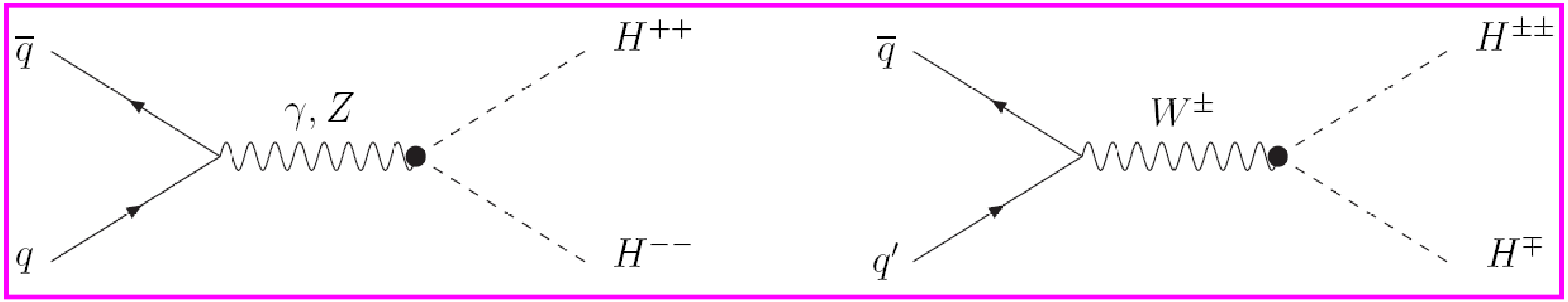
1 TeV

$$\lambda_\Delta Y_\Delta \sim 10^{-12} \Rightarrow \begin{cases} Y_\Delta \sim 1, \lambda_\Delta \sim 10^{-12} \\ \lambda_\Delta \sim Y_\Delta \sim 10^{-6} \\ \ldots\ldots \end{cases}$$

Collider Signature

From a viewpoint of direct tests, the triplet seesaw has an advantage:

The SU(2)_L Higgs triplet contains a doubly-charged scalar which can be produced at colliders: it is dependent on its mass but independent of the (small) Yukawa coupling.



Typical LNV signatures: $\boxed{H^{\pm\pm} \to l^{\pm}_{\alpha} l^{\pm}_{\beta}}$ $\boxed{H^{+} \to l^{+}_{\alpha} \bar{\nu}_{\beta}}$ $\boxed{H^{-} \to l^{-}_{\alpha} \nu}$

$$\mathcal{B}(H^{\pm\pm} \to l^{\pm}_{\alpha} l^{\pm}_{\beta}) = \frac{(2-\delta_{\alpha\beta})|(M_{\rm L})_{\alpha\beta}|^2}{\sum\limits_{\rho,\sigma} |(M_{\rm L})_{\rho\sigma}|^2} \,, \qquad \mathcal{B}(H^{+} \to l^{+}_{\alpha} \overline{\nu}) = \frac{\sum\limits_{\beta} |(M_{\rm L})_{\alpha\beta}|^2}{\sum\limits_{\rho,\sigma} |(M_{\rm L})_{\rho\sigma}|^2}$$

Testability at the LHC

Lesson one: **the above branching ratios purely depend on 3 neutrino masses, 3 flavor mixing angles and the CP-violating phases.**

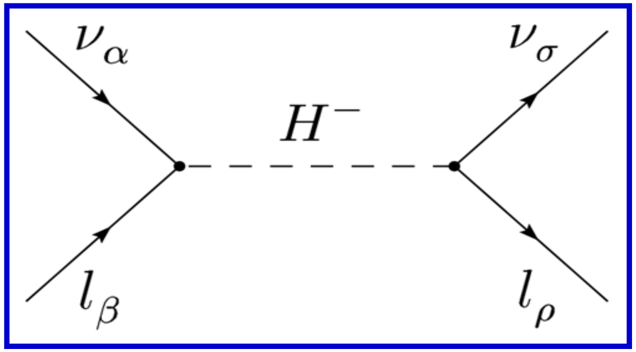
Lesson two: **the Majorana phases may affect LNV** $H^{\pm\pm} \longrightarrow l_\alpha^\pm l_\beta^\pm$ **decay modes, but they do not enter** $H^+ \longrightarrow l_\alpha^+ \bar{\nu}_\beta$ **and** $H^- \longrightarrow l_\alpha^- \nu$ **processes.**

$$\left|(M_{\rm L})_{\alpha\beta}\right|^2 = \left|\sum_{i=1}^{3}\left(m_i V_{\alpha i} V_{\beta i}\right)\right|^2 , \qquad \sum_{\beta}\left|(M_{\rm L})_{\alpha\beta}\right|^2 = \sum_{i=1}^{3}\left(m_i^2 \left|V_{\alpha i}\right|^2\right)$$

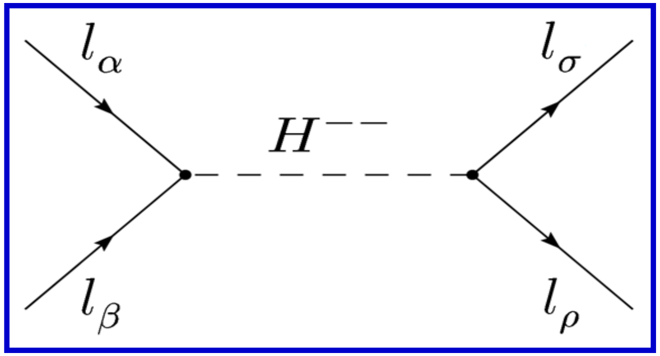
Dimension-6 operator:
(2 low-energy effects)

$$\frac{\mathcal{L}_{\rm d=6}}{\Lambda^2} = -\frac{(Y_\Delta)_{\alpha\beta}\,(Y_\Delta)^\dagger_{\rho\sigma}}{4M_\Delta^2}\left(\overline{l_{\alpha \rm L}}\gamma^\mu l_{\sigma \rm L}\right)\left(\overline{l_{\beta \rm L}}\gamma_\mu l_{\rho \rm L}\right)$$

1) NSIs of 3 neutrinos



2) LFV of 4 charged leptons



Type-3 Seesaw

Type-3 Seesaw: add 3 SU(2)_L triplet fermions (Y = 0) into the SM.

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} \sqrt{2} Y_\Sigma \Sigma^c \tilde{H} + \frac{1}{2} {\rm Tr}\left(\overline{\Sigma} M_\Sigma \Sigma^c\right) + {\rm h.c.}$$

$$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$$

or

$$-\mathcal{L}_{\rm mass} = \overline{(e_{\rm L} \quad \Psi_{\rm L})} \begin{pmatrix} M_l & \sqrt{2} M_{\rm D} \\ \mathbf{0} & M_\Sigma \end{pmatrix} \begin{pmatrix} E_{\rm R} \\ \Psi_{\rm R} \end{pmatrix} + \frac{1}{2} \overline{(\nu_{\rm L} \quad \Sigma^0)} \begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^T & M_\Sigma \end{pmatrix} \begin{pmatrix} \nu_{\rm L}^c \\ \Sigma^{0\,c} \end{pmatrix} + {\rm h.c.}$$

$$M_l = Y_l v/\sqrt{2}\,, \quad M_{\rm D} = Y_\Sigma v/\sqrt{2}\,, \quad \Psi = \Sigma^- + \Sigma^{+c}$$

Diagonalization of the neutrino mass matrix:

$$\begin{pmatrix} V & R \\ S & U \end{pmatrix}^\dagger \begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^T & M_\Sigma \end{pmatrix} \begin{pmatrix} V & R \\ S & U \end{pmatrix}^* = \begin{pmatrix} \widehat{M}_\nu & \mathbf{0} \\ \mathbf{0} & \widehat{M}_\Sigma \end{pmatrix}$$

Seesaw formula:

$$M_\nu \equiv V \widehat{M}_\nu V^T \approx -M_{\rm D} M_\Sigma^{-1} M_{\rm D}^T$$

Comparison between type-1 and type-3 seesaws (Abada et al 07):

a) The 3×3 flavor mixing matrix *V* is non-unitary in both cases (CC);

b) The modified couplings between *Z* & neutrinos are different (NC);

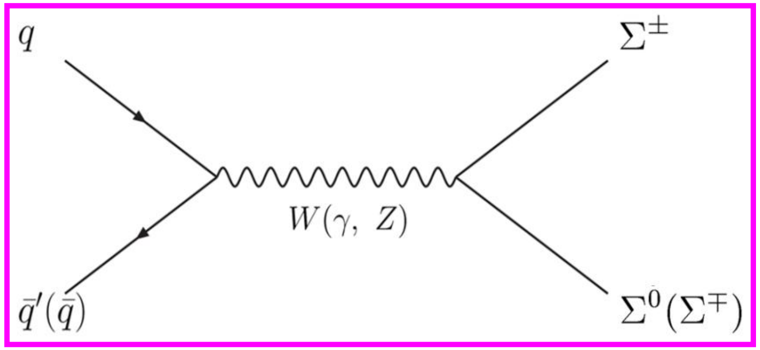
c) Non-unitary flavor mixing is also present in the coupling between *Z* and charged leptons in the type-3 seesaw (NC).

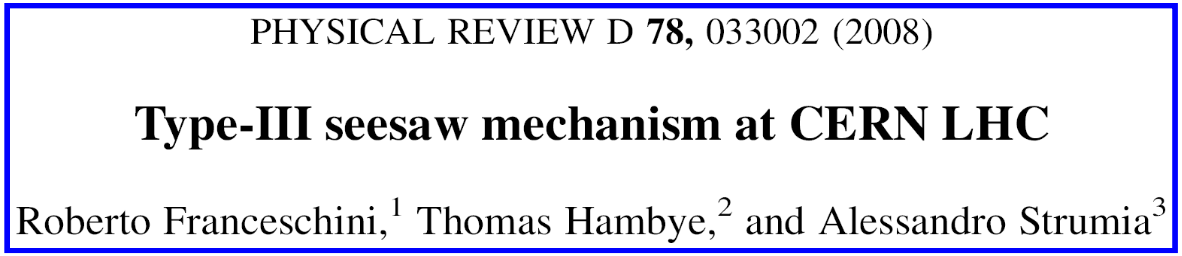
Testability at the LHC

LNV signatures at the LHC:

$$pp \to \Sigma^+\Sigma^0 \to l_\alpha^+ l_\beta^+ + Z^0 W^-(\to 4j)$$

$$pp \to \Sigma^-\Sigma^0 \to l_\alpha^- l_\beta^- + Z^0 W^+(\to 4j)$$

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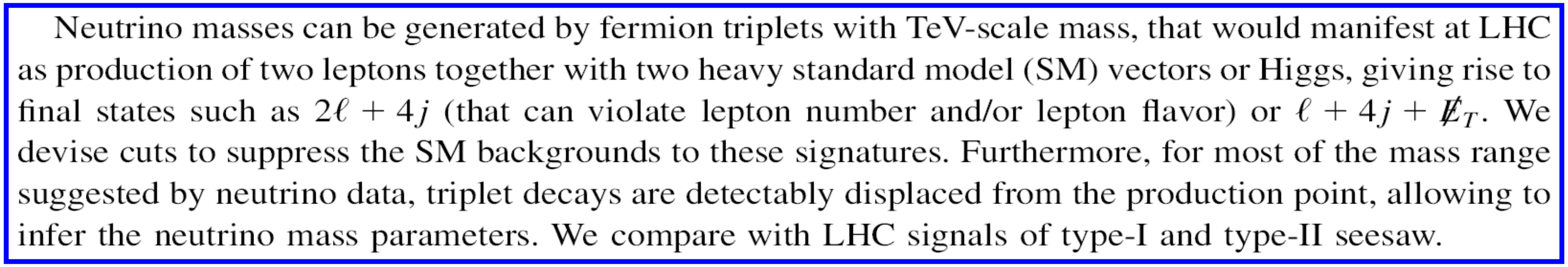
Type-III seesaw mechanism at CERN LHC

Roberto Franceschini,[1] Thomas Hambye,[2] and Alessandro Strumia[3]


Neutrino masses can be generated by fermion triplets with TeV-scale mass, that would manifest at LHC as production of two leptons together with two heavy standard model (SM) vectors or Higgs, giving rise to final states such as $2\ell + 4j$ (that can violate lepton number and/or lepton flavor) or $\ell + 4j + \not{E}_T$. We devise cuts to suppress the SM backgrounds to these signatures. Furthermore, for most of the mass range suggested by neutrino data, triplet decays are detectably displaced from the production point, allowing to infer the neutrino mass parameters. We compare with LHC signals of type-I and type-II seesaw.


Distinguishing seesaw models at LHC
with multi-lepton signals

F. del Aguila, J. A. Aguilar–Saavedra

2 latest comprehensive works.

arXiv:0808.2468v2 [hep-ph] 12 Sep 2008

Low-energy Tests

Type-3 seesaw: a typical signature would be the non-unitary effects of the 3×3 lepton flavor mixing matrix ***N*** in both CC and NC interactions.

Current experimental constraints at the 90% C.L. (Abada *et al* 07):

$$|NN^\dagger| \approx \begin{pmatrix} 1.001 \pm 0.002 & < 1.1 \cdot 10^{-6} & < 1.2 \cdot 10^{-3} \\ < 1.1 \cdot 10^{-6} & 1.002 \pm 0.002 & < 1.2 \cdot 10^{-3} \\ < 1.2 \cdot 10^{-3} & < 1.2 \cdot 10^{-3} & 1.002 \pm 0.002 \end{pmatrix}$$

accuracy at 0.1%.

These bounds are stronger than those obtained in the type-1 seesaw, as the flavor-changing processes with charged leptons are allowed at the tree level in the type-3 seesaw.

Two types of LFV processes:

Radiative decays of charged leptons: $\mu \to e + \gamma$, $\tau \to e + \gamma$, $\tau \to \mu + \gamma$.

Tree-level rare decays of charged leptons: $\mu \to 3\,e$, $\tau \to 3\,e$, $\tau \to 3\,\mu$, $\tau \to e + 2\,\mu$, $\tau \to 2\,e + \mu$ (Abada et al 07, 08; He, Oh 09)

TeV leptogenesis or muon g-2 problems? (Strumia 08, Blanchet, Chacko, Mohapatra 08, Fischler, Flauger 08; Chao 08, Biggio 08; ……)

Seesaw Trivialization

Linear trivialization: use three types of seesaws to make a family tree.

Type 1 + Type 2

Type 1 + Type 3

Type 2 + Type 3

Type 1 + Type 2 + Type 3

Weinberg's ***3rd law of progress in theoretical physics*** (83):

You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you will be sorry .... **What could be better?**

Linearly trivialized seesaws usually work at super-high energies.

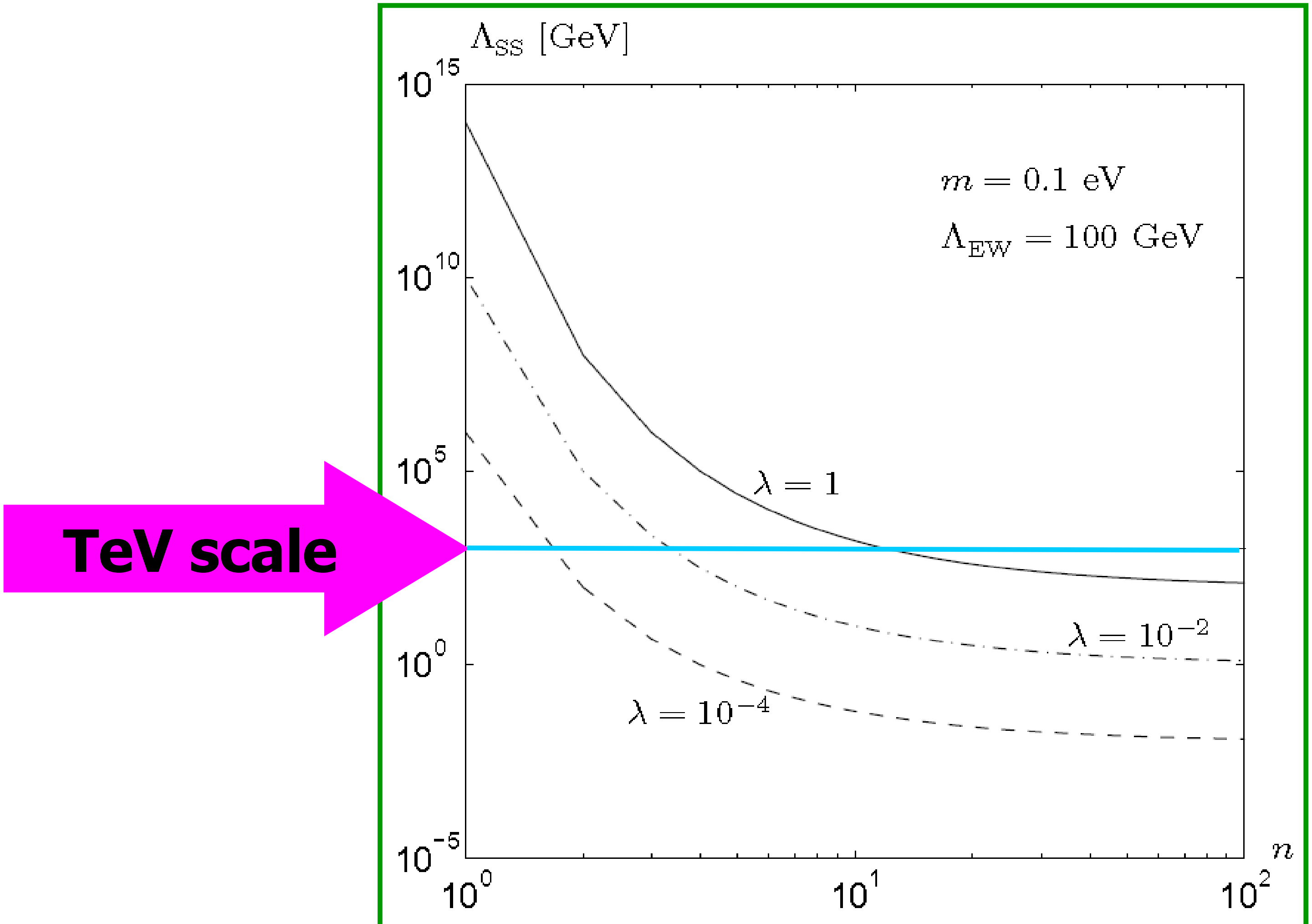
Multiple trivialization: well motivated to lower the seesaw scale.

Illustration

Neutrino mass:

$m \sim (\lambda\Lambda_{\mathrm{EW}})^{n+1}/\Lambda_{\mathrm{SS}}^{n}$

$$\Lambda_{\mathrm{SS}} \sim \lambda^{\frac{n+1}{n}} \left[\frac{\Lambda_{\mathrm{EW}}}{100\ \mathrm{GeV}}\right]^{\frac{n+1}{n}} \left[\frac{0.1\ \mathrm{eV}}{m}\right]^{\frac{1}{n}} 10^{\frac{2(n+6)}{n}}\ \mathrm{GeV}$$



TeV scale

Example: Inverse Seesaw

The Inverse Seesaw: SM + 3 heavy right-handed neutrinos + 3 gauge singlet neutrinos + one Higgs singlet (Wyler, Wolfenstein 83; Mohapatra, Valle 86; Ma 87).

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \overline{N^{\rm c}_{\rm R}} Y_S \Phi S_{\rm R} + \frac{1}{2}\overline{S^{\rm c}_{\rm R}} \mu S_{\rm R} + {\rm h.c.}$$

LNV: tiny

ν-mass matrix:

$$\overline{\left(\nu_{\rm L} \quad N^{\rm c}_{\rm R} \quad S^{\rm c}_{\rm R}\right)} \begin{pmatrix} \mathbf{0} & M_{\rm D} & \mathbf{0} \\ M_{\rm D}^T & \mathbf{0} & M_S \\ \mathbf{0} & M_S^T & \mu \end{pmatrix} \begin{pmatrix} \nu^{\rm c}_{\rm L} \\ N_{\rm R} \\ S_{\rm R} \end{pmatrix}$$

$$\begin{aligned} M_{\rm D} &= Y_\nu \langle H \rangle \\ M_S &= Y_S \langle \Phi \rangle \end{aligned}$$

Effective light ν-mass matrix

$$M_\nu \approx M_{\rm D} \frac{1}{M_S^T} \mu \frac{1}{M_S} M_{\rm D}^T \quad \Longleftrightarrow \quad -\mathcal{L}_{\rm mass} = \frac{1}{2} \overline{\nu_{\rm L}} M_\nu \nu^c_{\rm L} + {\rm h.c.}$$

Merit: more natural tiny ν-masses and appreciable collider signatures; Fault: some new degrees of freedom. **Is Weinberg’s 3rd law applicable?**

Multiple seesaw mechanisms: to *naturally* lower seesaw scales to TeV (Babu et al 09; Xing, Zhou 09; Bonnet et al 09, etc).

Appendix

Misguiding principles for a theorist to go beyond the SM

(Schellekens 08: “The Emperor’s Last Clothes?”)

- Agreement with observation
- Consistency
- Uniqueness
- Naturalness
- Simplicity
- Elegance
- Beauty
- ……

?