Light Sterile Neutrinos

Marco Laveder

Dipartimento di Fisica e Astronomia "G. Galilei", Università di Padova

and

INFN, Sezione di Padova

Neutrino Unbound: http://www.nu.to.infn.it

Krakow, Poland

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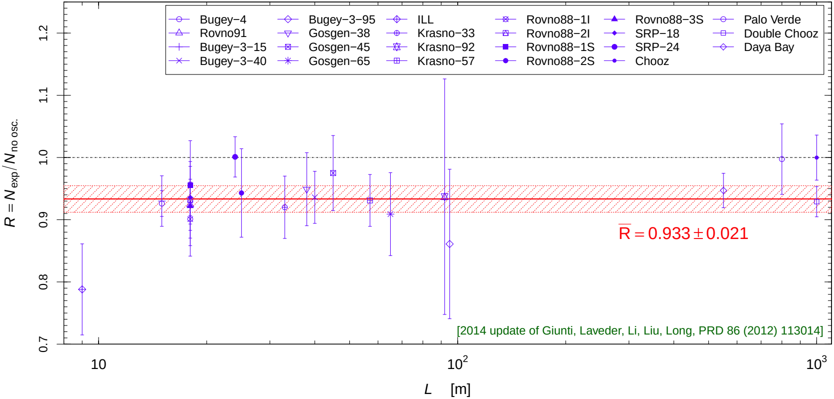
Indications of SBL Oscillations Beyond 3ν

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006; update in White Paper, arXiv:1204.5379]

New reactor $\bar{\nu}_e$ fluxes

[Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



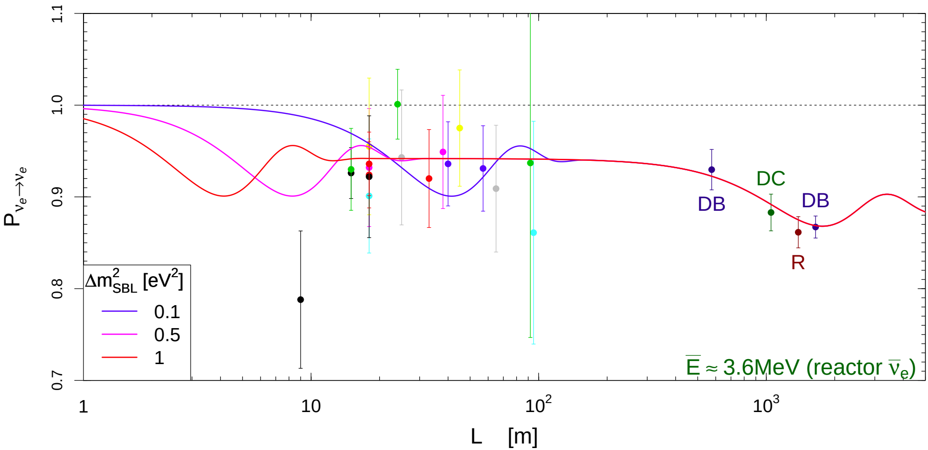
$\bar{\nu}_e \to \bar{\nu}_e$ $\quad L \sim 10 - 100\,\mathrm{m}$ $\quad E \sim 4\,\mathrm{MeV}$

Nominal $\approx 3.1\sigma$ deficit $\quad \Delta m^2 \gtrsim 0.5\,\mathrm{eV}^2$ $\quad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

[see also: Sinev, arXiv:1103.2452; Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Ivanov et al, PRC 88 (2013) 055501]

Problem: unknown $\bar{\nu}_e$ flux uncertainties?

[Hayes, Friar, Garvey, Jonkmans, PRL 112 (2014) 202501; Dwyer, Langford, PRL 114 (2015) 012502]



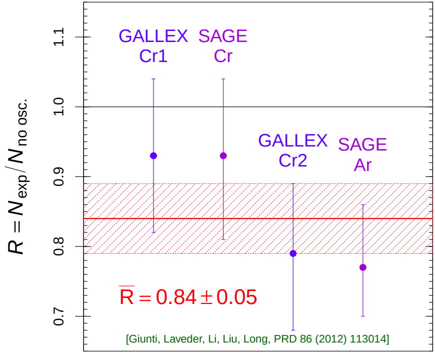
$P_{\nu_e \to \nu_e}$
1.1
1.0
0.9
0.8
0.7
Δm^2_{SBL} [eV^2]
0.1
0.5
1
DB
DC
DB
R
$\overline{E} \approx 3.6$MeV (reactor $\overline{\nu}_e$)
1
10
10^2
10^3
L [m]

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\qquad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$



$\bar{\nu}_e \to \bar{\nu}_e \qquad E \sim 0.7\,\text{MeV}$

$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$

$\langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

Nominal $\approx 2.9\sigma$ anomaly

$\Delta m^2 \gtrsim 1\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807]

[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344; MPLA 22 (2007) 2499; PRD 78 (2008) 073009; PRC 83 (2011) 065504]

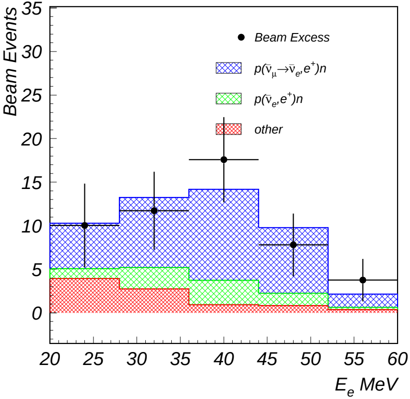
[Mention et al, PRD 83 (2011) 073006]

- ${}^{3}\text{He} + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + {}^{3}\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]
- $E_{\text{th}}(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-) = 233.5 \pm 1.2\,\text{keV}$ [Frekers et al., PLB 722 (2013) 233]

LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\qquad L \simeq 30\,\mathrm{m}$ $\qquad 20\,\mathrm{MeV} \le E \le 60\,\mathrm{MeV}$



- Well known source of $\bar{\nu}_\mu$:

$$\mu^+ \text{ at rest} \to e^+ + \nu_e + \bar{\nu}_\mu$$

- $\bar{\nu}_\mu \xrightarrow[L \simeq 30\,\mathrm{m}]{} \bar{\nu}_e$

- Well known detection process of $\bar{\nu}_e$:

$$\bar{\nu}_e + p \to n + e^+$$

- But signal not seen by KARMEN with same method at $L \simeq 18\,\mathrm{m}$

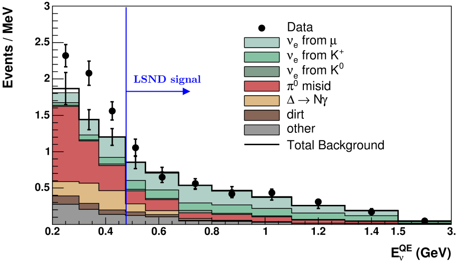
[PRD 65 (2002) 112001]

Nominal $\approx 3.8\sigma$ excess $\qquad \Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

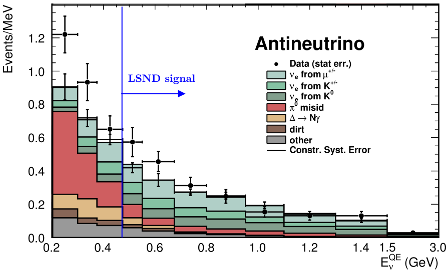
MiniBooNE

$L \simeq 541\,\mathrm{m}$ $200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]

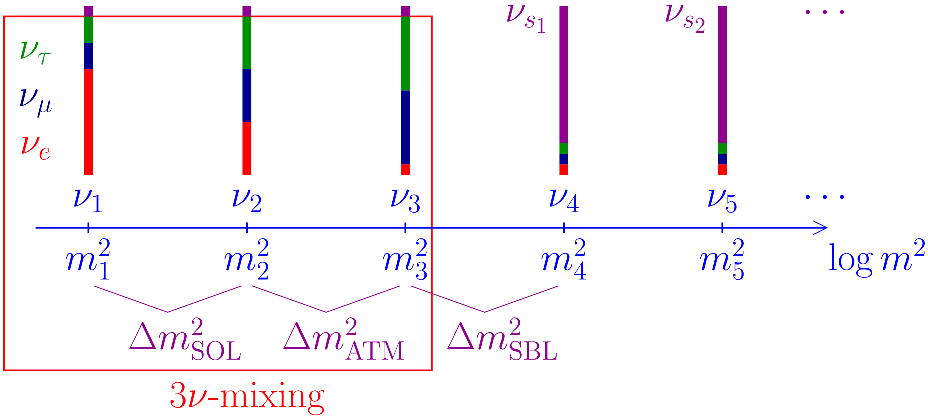


$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\mathrm{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Terminology: a eV-scale sterile neutrino

means: a eV-scale massive neutrino which is mainly sterile

Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions
- Active left-handed neutrinos can mix with non-SM singlet fermions often called right-handed neutrinos Neutrino Portal [A. Smirnov, arXiv:1502.04530]
- Light anti-ν_R are light sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions

[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

$$\begin{array}{ccccc} \Delta m^2_{21} \ll & |\Delta m^2_{31}| \ll & |\Delta m^2_{41}| \leq & \ldots & \\ \nu_1 & \nu_2 & \nu_3 & \nu_4 & \ldots \\ \nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \ldots \end{array}$$

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

Perturbation of 3ν Mixing: $|U_{e4}|^2 \ll 1\,,\ |U_{\mu 4}|^2 \ll 1\,,\ |U_{\tau 4}|^2 \ll 1\,,\ |U_{s4}|^2 \simeq 1$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \boxed{U_{\mu 4}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \boxed{U_{\tau 4}} \\ U_{s1} & U_{s2} & U_{s3} & \boxed{U_{s4}} \end{pmatrix}$$

↑ SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases
- But CP violation is not observable in current SBL experiments!
- Observable in LBL accelerator exp. sensitive to $\Delta m^2_{\rm ATM}$ [de Gouvea, Kelly, Kobach, PRD 91 (2015) 053005; Klop, Palazzo, PRD 91 (2015) 073017] and solar exp. sensitive to $\Delta m^2_{\rm SOL}$ [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]

3+1: Appearance vs Disappearance

- Amplitude of ν_e disappearance:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- Amplitude of ν_μ disappearance:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

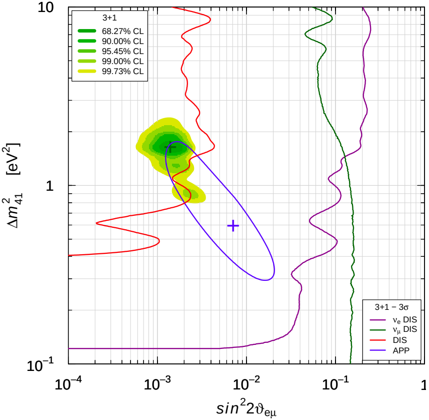
- Upper bounds on ν_e and ν_μ disappearance $\Rightarrow$ strong limit on $\nu_\mu \to \nu_e$

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

- Similar constraint in 3+2, 3+3, ..., 3+N_s! [Giunti, Zavanin, arXiv:1508.03172]

Global 3+1 Fit

Our Fit

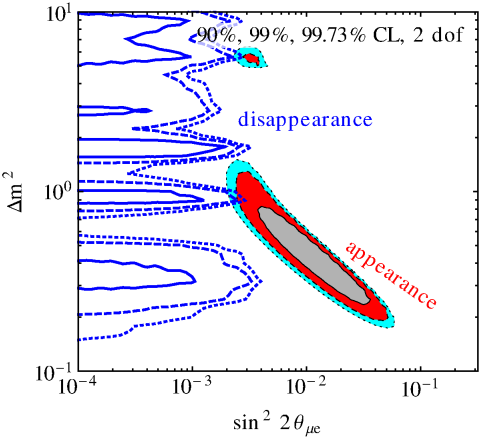


GoF = 5%

PGoF = 0.1%

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008]
[Gariazzo, Giunti, Laveder, Y.F. Li, Zavanin, arXiv:1507.08204]

Kopp, Machado, Maltoni, Schwetz

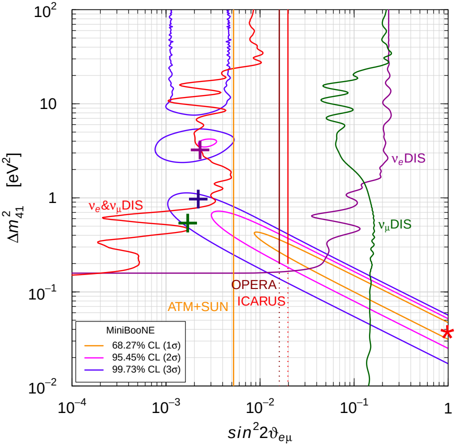


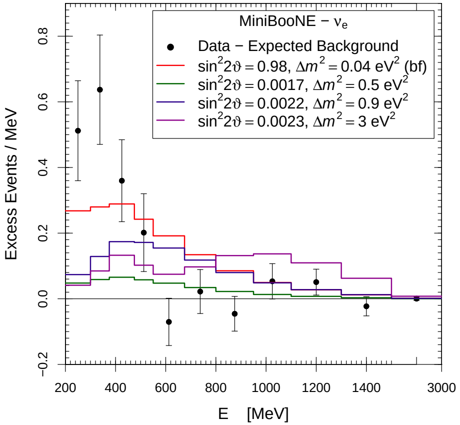
GoF = 19%

PGoF = 0.01%

[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

MiniBooNE Low-Energy Excess?

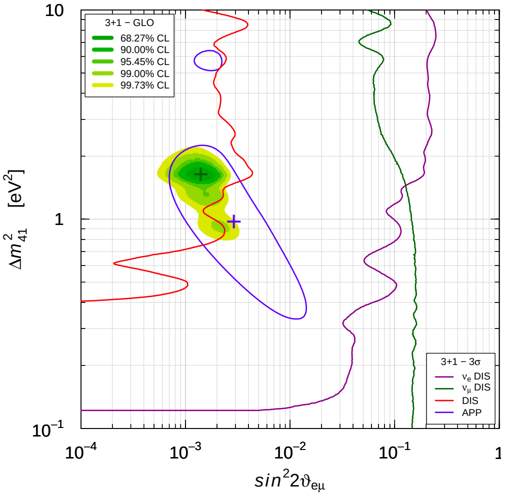




- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$
- Neutrino energy reconstruction problem? [Martini, Ericson, Chanfray, PRD 87 (2013) 013009]
- MB low-energy excess is the main cause of bad APP-DIS PGoF $= 0.04\%$
- Pragmatic Approach: discard the Low-Energy Excess because it is very likely not due to oscillations

Pragmatic 3+1 Fit

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008; Gariazzo, Giunti, Laveder, Y.F. Li, Zavanin, arXiv:1507.08204]



MiniBooNE $E > 475\,\mathrm{MeV}$

GoF $= 26\%$ PGoF $= 7\%$

- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA ($\not{\nu}_s$), ICARUS ($\not{\nu}_s$), KARMEN ($\not{\nu}_s$), NOMAD ($\not{\nu}_s$), BNL-E776 ($\not{\nu}_s$)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC ($\not{\nu}_s$), Solar ($\not{\nu}_s$)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW ($\not{\nu}_s$), MINOS ($\not{\nu}_s$), Atmospheric ($\not{\nu}_s$), MiniBooNE/SciBooNE ($\not{\nu}_s$)

No Osc. nominally disfavored at $\approx 6.3\sigma$

$\Delta\chi^2/\mathrm{NDF} = 47.7/3$

Effective SBL Oscillation Probabilities in 3+2 Schemes

$$\Delta_{kj} = \Delta m^2_{kj} L/4E$$

$$\eta = \arg[U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}]$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\Delta_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\Delta_{51}$$
$$+ 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin\Delta_{41} \sin\Delta_{51} \cos(\Delta_{54} \overset{(+)}{-} \eta)$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2\Delta_{41} + |U_{\alpha 5}|^2 \sin^2\Delta_{51})$$
$$- 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2\Delta_{54}$$

[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004; Maltoni, Schwetz, PRD 76 (2007) 093005; Karagiorgi et al, PRD 80 (2009) 073001; Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801; Giunti, Laveder, PRD 84 (2011) 073008; Donini et al, JHEP 07 (2012) 161; Archidiacono et al, PRD 86 (2012) 065028; Jacques, Krauss, Lunardini, PRD 87 (2013) 083515; Conrad et al, AHEP 2013 (2013) 163897; Archidiacono et al, PRD 87 (2013) 125034; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008; Girardi, Meroni, Petcov, JHEP 1311 (2013) 146; Gariazzo, Giunti, Laveder, Y.F. Li, Zavanin, arXiv:1507.08204]

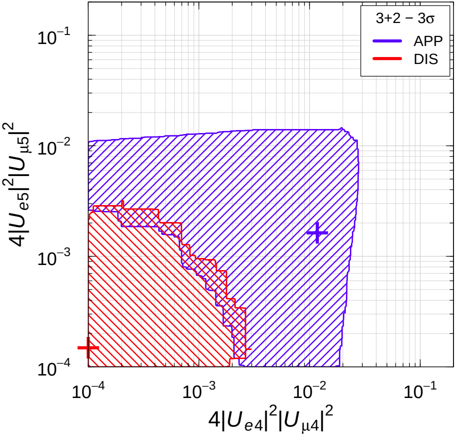
- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

  4 more parameters: $\underbrace{\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu 4}|^2}_{3+1}, \Delta m^2_{51}, |U_{e5}|^2, |U_{\mu 5}|^2, \eta$

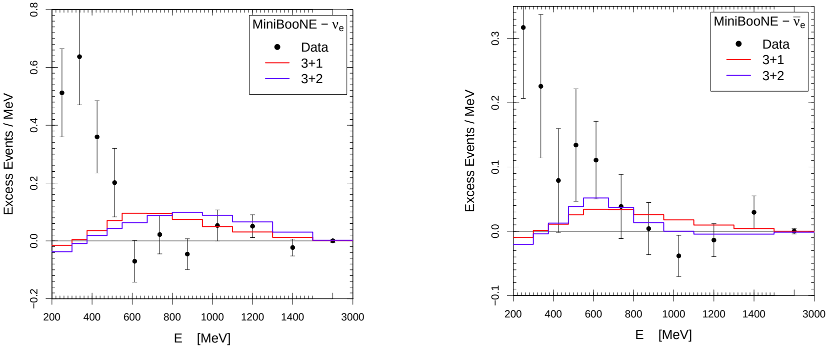
Global Fits	Our Fit		KMMS	
	3+1	3+2	3+1	3+2
GoF	5%	7%	19%	23%
PGoF	0.1%	0.04%	0.01%	0.003%

- Our Fit: Gariazzo, Giunti, Laveder, Y.F. Li, Zavanin, arXiv:1507.08204
- KMMS: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050

APP-DIS 3+2 Tension:



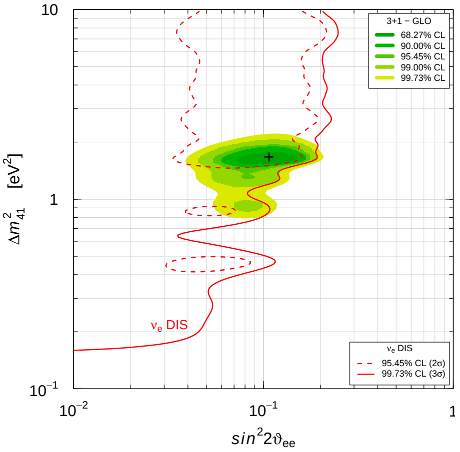
3+2 cannot fit MiniBooNE Low-Energy Excess

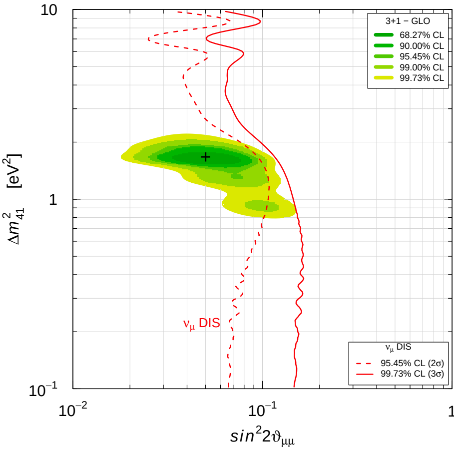


- Note difference between 3+2 ν_e and $\bar{\nu}_e$ histograms due to CP violation
- 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- 3+2 fit of low-energy excess as bad as 3+1
- Claims that 3+2 can fit low-energy excess do not take into account constraints from other data
- Conclusion: forget 3+2! (at least until new data require it)

ν_e and ν_μ Disappearance

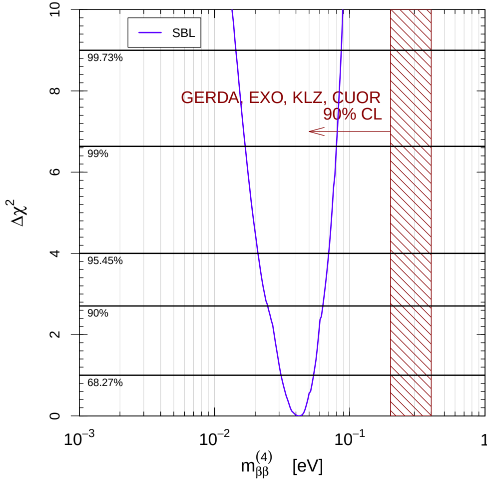
[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008; Gariazzo, Giunti, Laveder, Y.F. Li, Zavanin, arXiv:1507.08204]





Neutrinoless Double-β Decay

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3 + |U_{e4}|^2 e^{i\alpha_{41}} m_4$$



Pragmatic 3+1 Fit

[Giunti, Laveder, Li, Long, 2014]

$$m_{\beta\beta}^{(k)} = |U_{ek}|^2 m_k$$

$$m_1 \ll m_4$$

$$\Downarrow$$

$$m_{\beta\beta}^{(4)} \simeq |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

surprise:

possible cancellation with $m_{\beta\beta}^{(3\nu)}$

[Barry et al, JHEP 07 (2011) 091]

[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

[Giunti, Zavanin, JHEP 07 (2015) 171]

Future experiments @ reactors

Projects	Ref	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)
Nucifer (FRA)	[1]	70	0.75	7	13
Stereo (FRA)	[2]	50	1.75	[8.8-11.2]	18
Neutrino 4 (RUS)	[3]	100	2.2	[6-12]	few
Poseidon (RUS)	[4]	100	~ 3	[5-8]	~ 15
DANSS (RUS)	[5]	3000	0.9	[9.7-12.2]	50
Solid (GBR)	[6]	[45-80]	3	[6-8]	10
Hanbit (KOR)	[7]	2800	1	27	[10-23]
Hanaro (KOR)	[7]	30	0.5	6	few
Prospect (USA)	[8]	20-120	1 & 10	4 & 18	few
CARR (CHN)	[9]	60	-	7 & 15	few

Future experiments @ accelerators

Projects	Ref	P (MW)	M_{target} (tons)	E (MeV)	L (m)
SBN (USA)	[10]	> 0.09	[112 & 89 & 476]	~ 800	[110 & 470 & 600]
JPARC MLF (JPN)	[11] [12]	~ 1	50	~ 40	[17-23]
KPipe (JPN)	[13]	~ 1	684	~ 236	[32-152]
nuPRISM (JPN)	[14]	~ 1	[4000-8000]	[200-1000]	[1000-2000]
IsoDAR-KamLAND (JPN)	[15] [16]	0.6	1000	~ 6.5	[10-40]
IsoDAR-JUNO (CHN)	[16]	0.6	20000	~ 6.5	[20-100]
OscSNS (USA)	[17]	1.4	450	~ 40	[50-70]

Borexino source experiment

Expected Sensitivity (Phase A)

Neutrino 2014
Additional information: JHEP08 (2013) 038

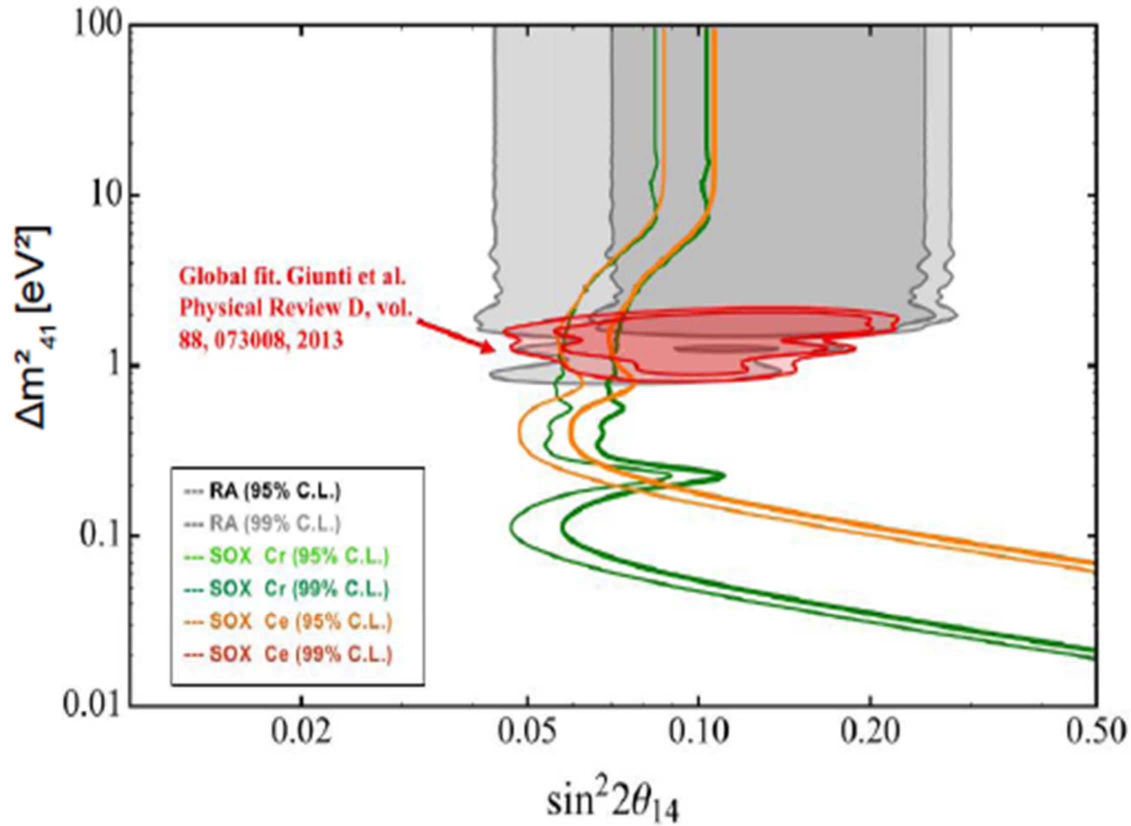
sources in pit

^{51}Cr

- Time: ~100 days
- Activity: 10 MCi
- r_{FV} < 3.3 m

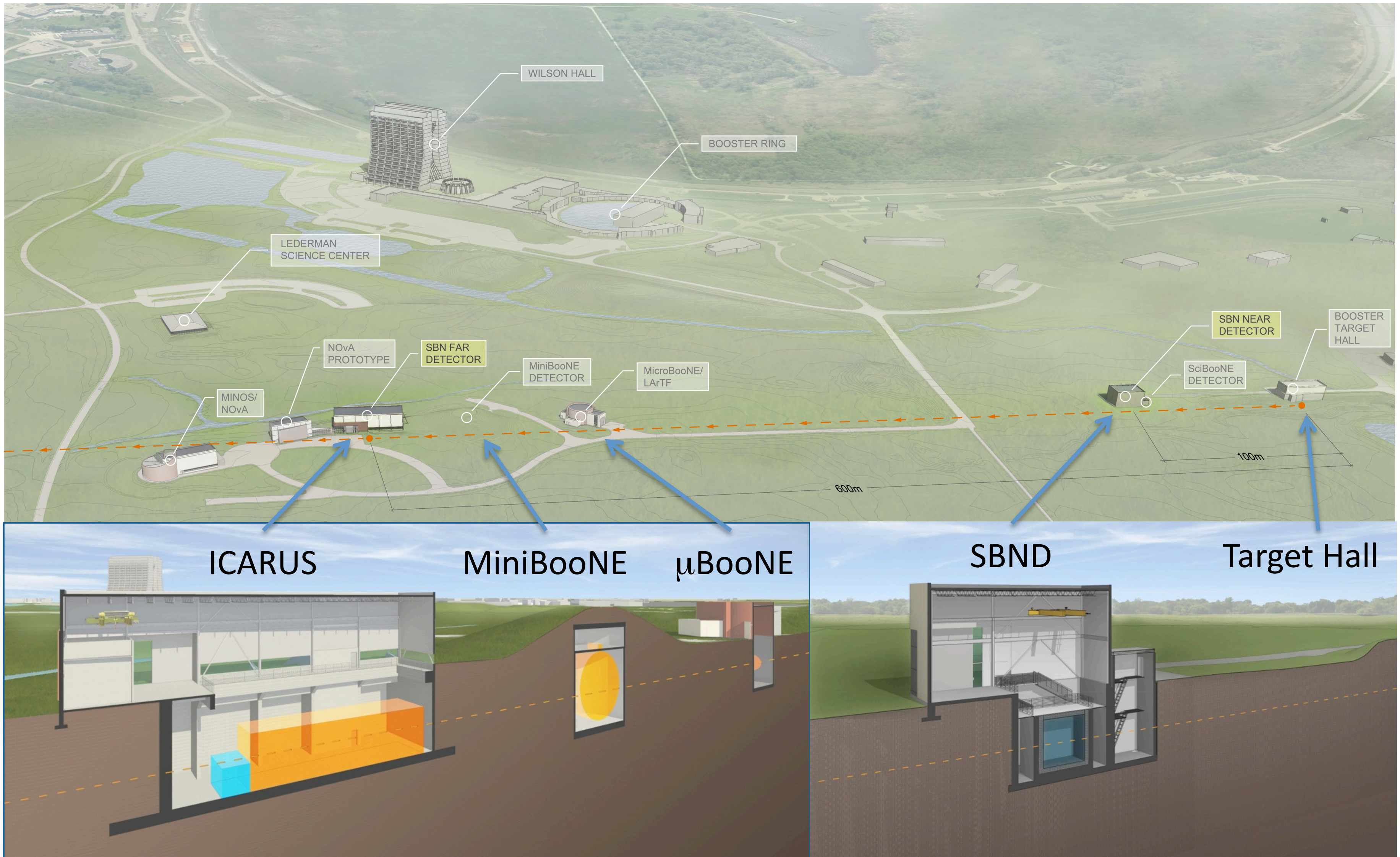
^{144}Ce-^{144}Pr

- Time: ~1.5 years
- Activity: 100 kCi
- r_{FV} < 4.25 m

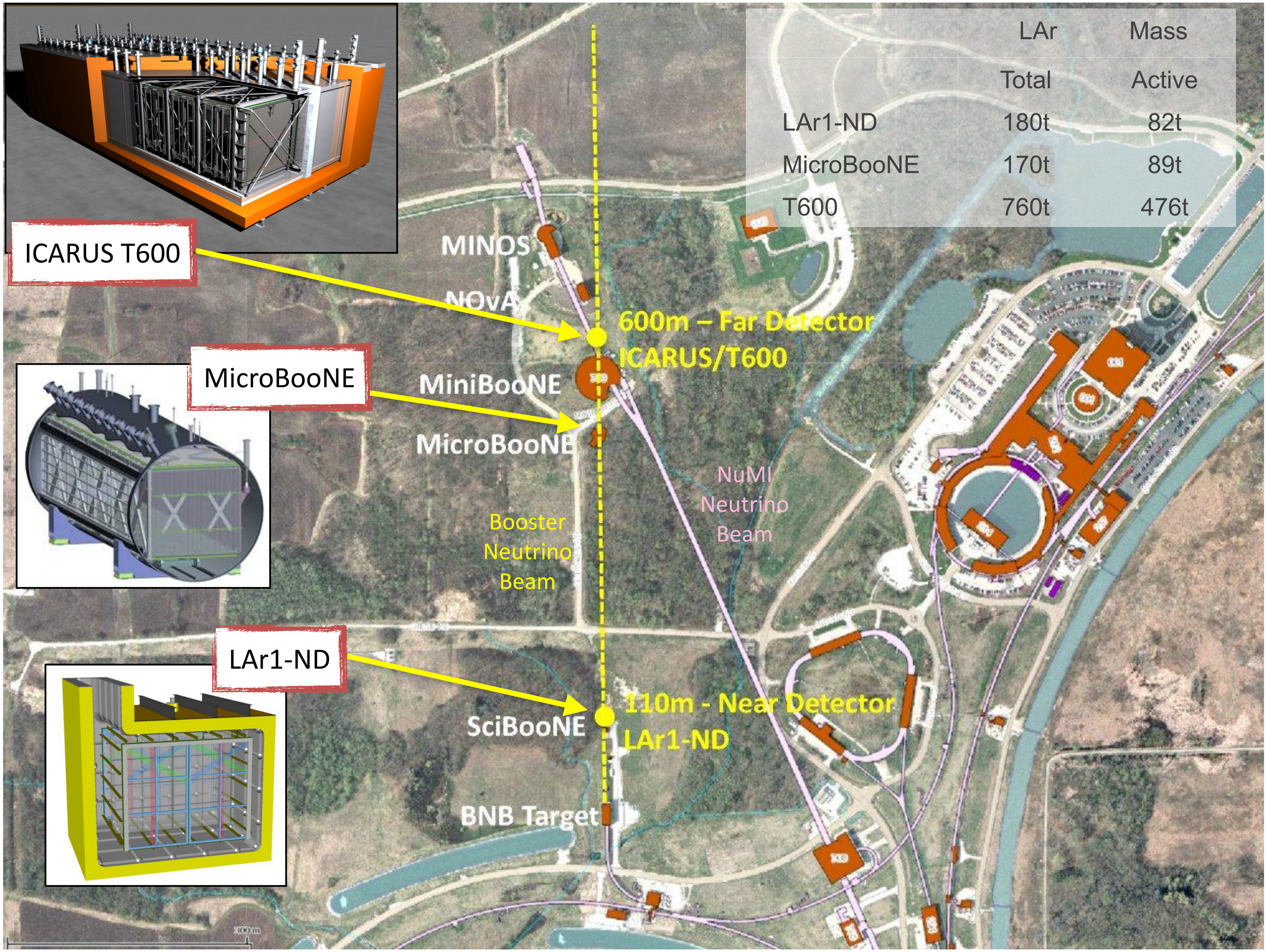


r_{FV}: Radius of fiducial volume

SBN: A Multi-LAr TPC Short-Baseline Program at FNAL

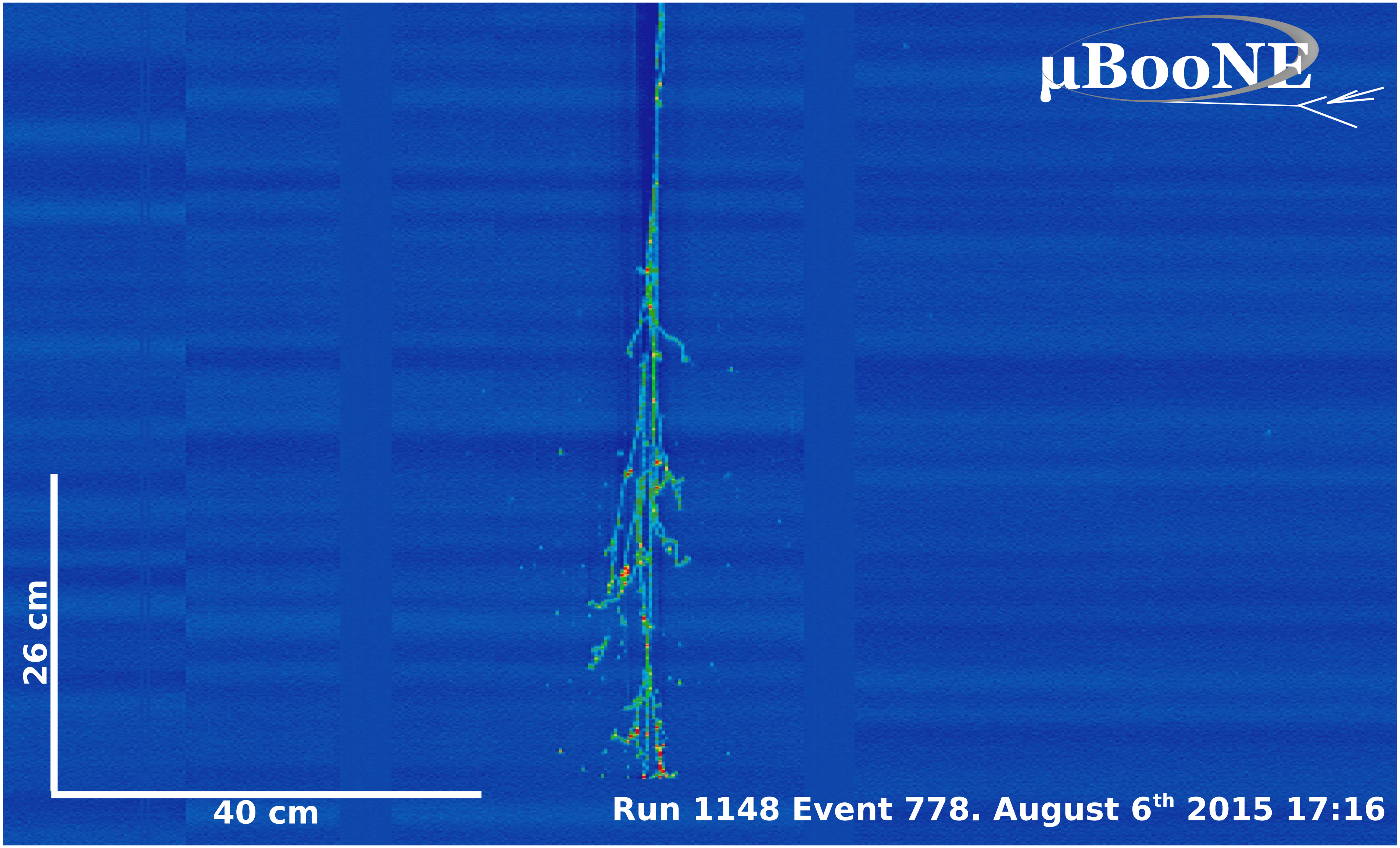


SBN: A Multi-LAr TPC Short-Baseline Program at FNAL

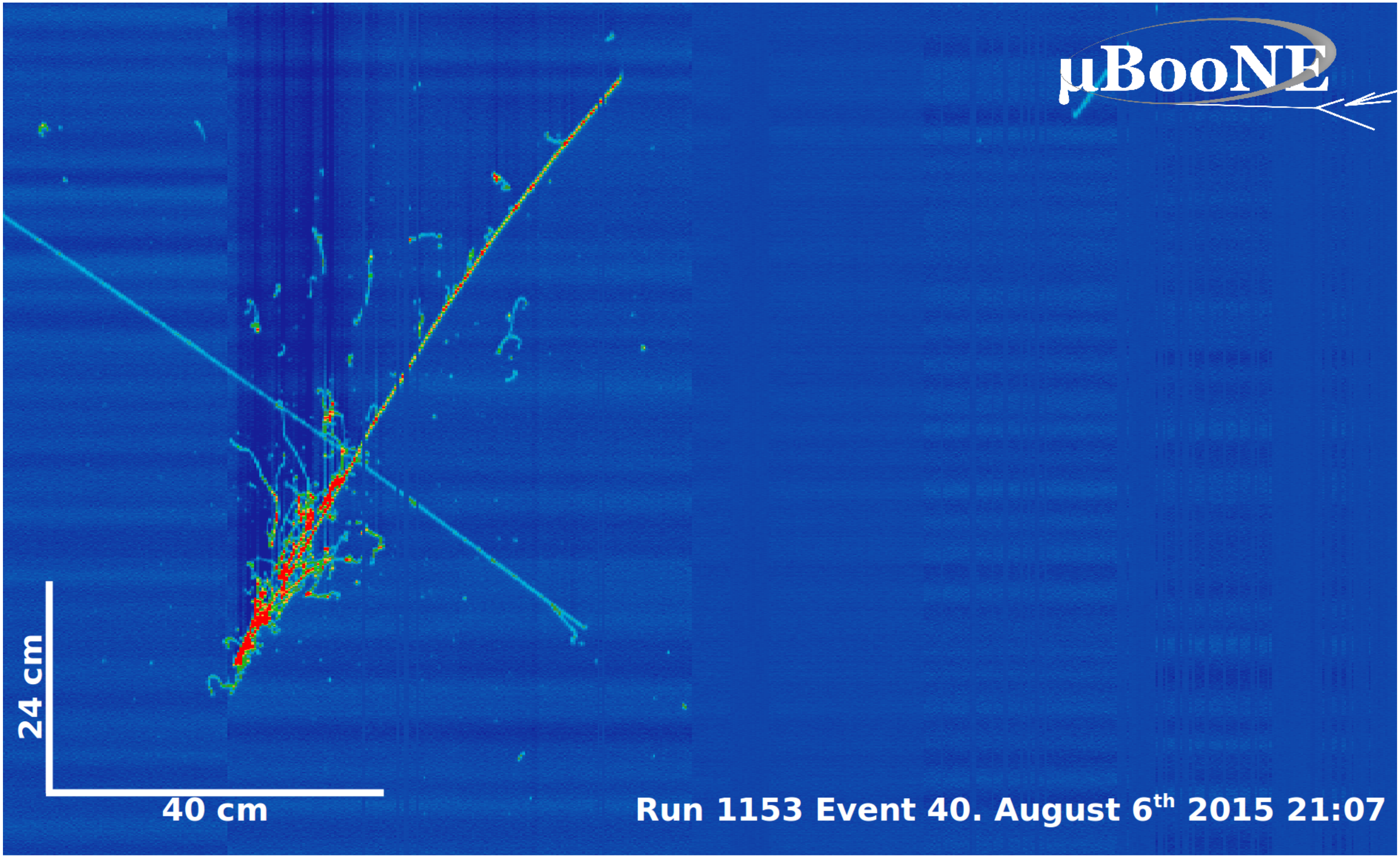


	LAr Total	Mass Active
LAr1-ND	180t	82t
MicroBooNE	170t	89t
T600	760t	476t

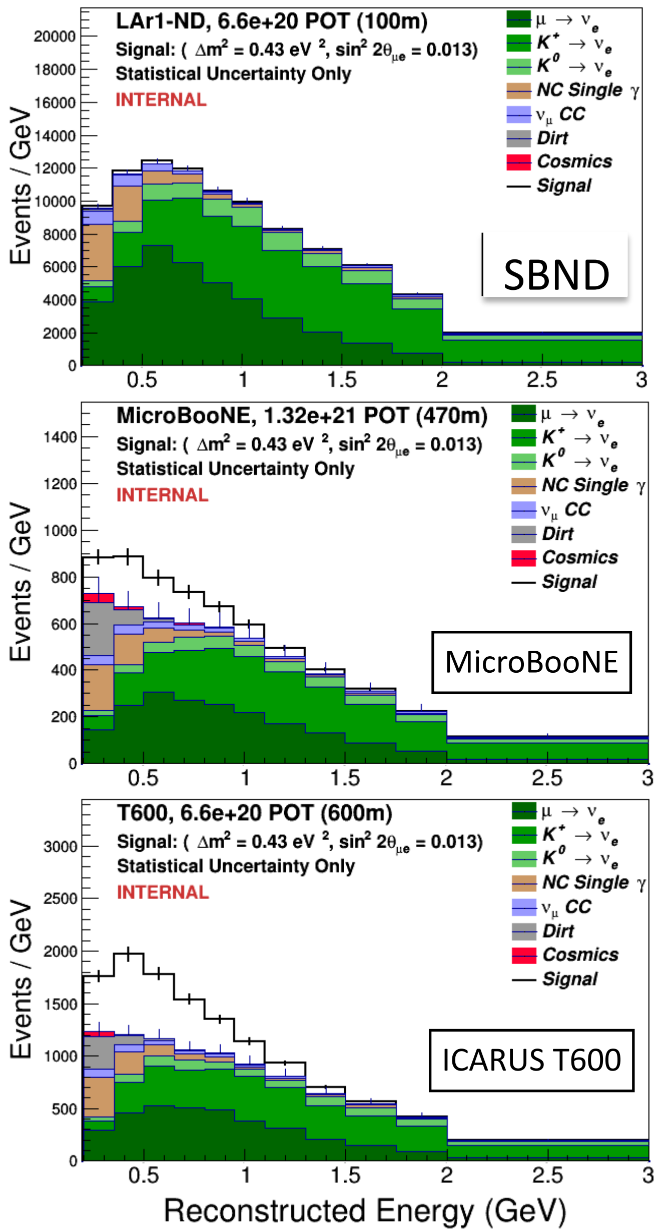
MicroBooNE Now Observing Cosmic Ray Events

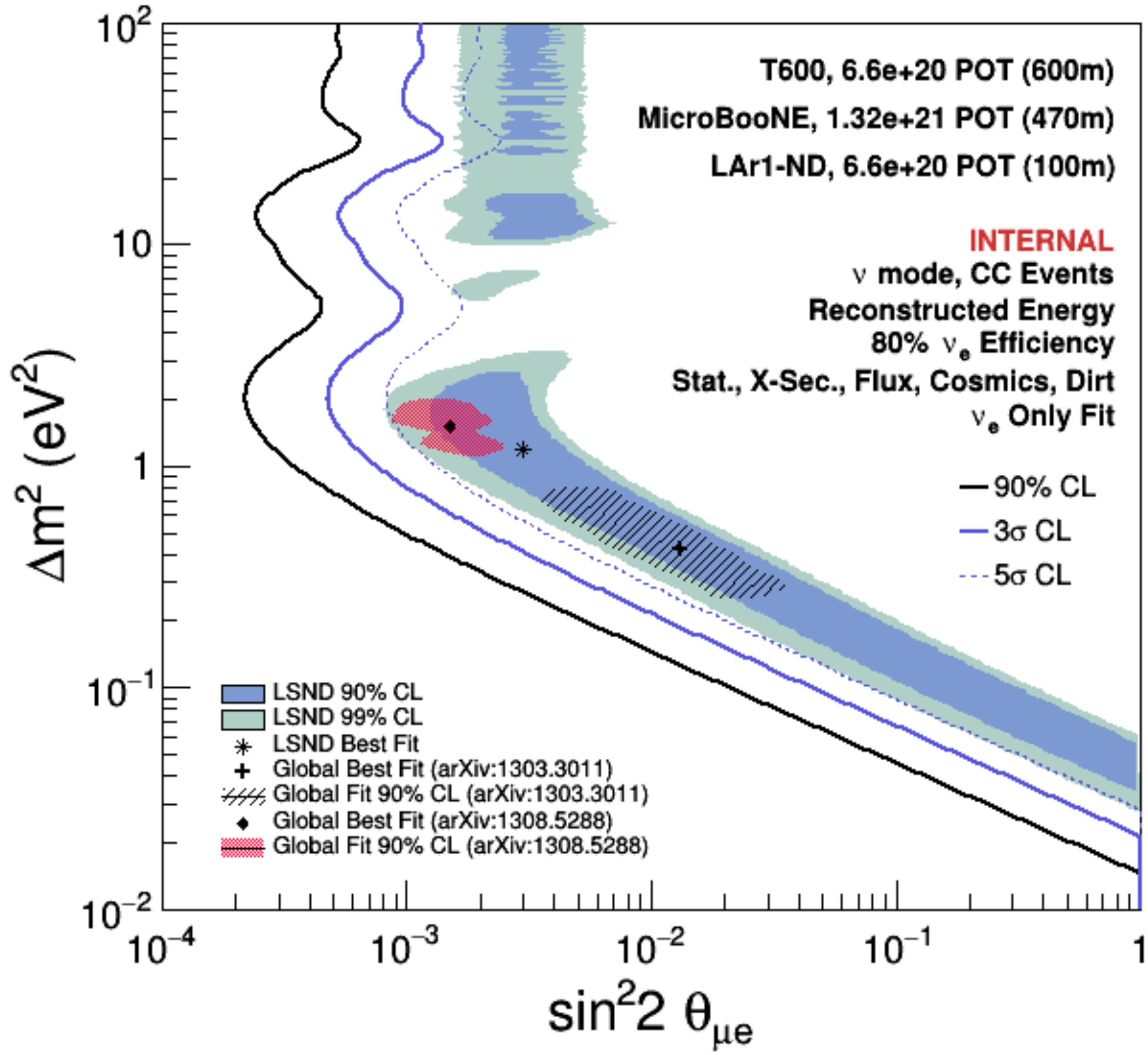


MicroBooNE Now Observing Cosmic Ray Events



ν_e Appearance Sensitivity





Conclusions

- Short-Baseline ν_e and $\bar{\nu}_e$ Disappearance:
  - Experimental data agree on Reactor $\bar{\nu}_e$ and Gallium ν_e anomalies.
  - Problem: unknown systematic uncertainties (Reactor $\bar{\nu}_e$ flux).
  - Many promising projects to test unambiguously short-baseline ν_e and $\bar{\nu}_e$ disappearance in a few years with reactors and radioactive sources.

  - Independent tests through effect of m_4 in β-decay and $\beta\beta_{0\nu}$-decay.
- Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:
  - Not seen by other SBL $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ experiments.
  - MiniBooNE experiment has been inconclusive.
  - Experiments with near detector are needed to check LSND signal!
  - Promising Fermilab program aimed at a conclusive solution of the mystery: a near detector (LAr1-ND), an intermediate detector (MicroBooNE) and a far detector (ICARUS-WA104), all Liquid Argon Time Projection Chambers.

Goodness of Fit

- Assumption or approximation: Gaussian uncertainties and linear model
- $\chi^2_{\rm min}$ has χ^2 distribution with Number of Degrees of Freedom

$$\text{NDF} = N_{\rm D} - N_{\rm P}$$

$N_{\rm D}$ = Number of Data $\qquad$ $N_{\rm P}$ = Number of Fitted Parameters

- $\langle \chi^2_{\rm min} \rangle = \text{NDF}$ $\qquad$ $\text{Var}(\chi^2_{\rm min}) = 2\text{NDF}$
- $\text{GoF} = \int_{\chi^2_{\rm min}}^{\infty} p_{\chi^2}(z, \text{NDF})\, dz$ $\qquad$ $p_{\chi^2}(z, n) = \dfrac{z^{n/2-1} e^{-z/2}}{2^{n/2}\Gamma(n/2)}$

Parameter Goodness of Fit

Maltoni, Schwetz, PRD 68 (2003) 033020, arXiv:hep-ph/0304176

- Measure compatibility of two (or more) sets of data points A and B under fitting model
- $\chi^2_{\rm PGoF} = (\chi^2_{\rm min})_{\rm A+B} - [(\chi^2_{\rm min})_{\rm A} + (\chi^2_{\rm min})_{\rm B}]$
- $\chi^2_{\rm PGoF}$ has χ^2 distribution with Number of Degrees of Freedom

$$\text{NDF}_{\rm PGoF} = N_{\rm P}^{\rm A} + N_{\rm P}^{\rm B} - N_{\rm P}^{\rm A+B}$$

- $\text{PGoF} = \int_{\chi^2_{\rm PGoF}}^{\infty} p_{\chi^2}(z, \text{NDF}_{\rm PGoF})\, dz$

Cosmology

- neutrinos in equilibrium in early Universe through weak interactions:

$$\nu\bar{\nu} \leftrightarrows e^+e^- \qquad \overset{(-)}{\nu} e \leftrightarrows \overset{(-)}{\nu} e \qquad \overset{(-)}{\nu} N \leftrightarrows \overset{(-)}{\nu} N$$

$$\nu_e n \leftrightarrows p e^- \qquad \bar{\nu}_e p \leftrightarrows n e^+ \qquad n \leftrightarrows p e^- \bar{\nu}_e$$

- weak interactions freeze out $\Longrightarrow$ active $(\nu_e, \nu_\mu, \nu_\tau)$ neutrino decoupling

$$\Gamma_{\text{weak}} = N\sigma v \sim G_F^2 T^5 \sim T^2/M_P \sim \sqrt{G_N T^4} \sim \sqrt{G_N \rho} \sim H$$

$$T_{\nu\text{-dec}} \sim 1\,\text{MeV} \qquad t_{\nu\text{-dec}} \sim 1\,\text{s}$$

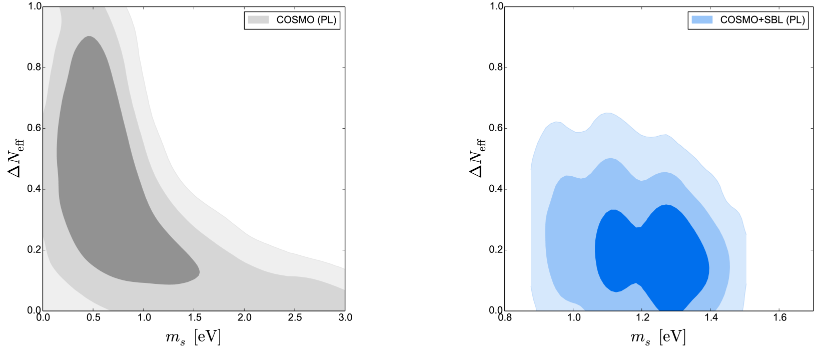
- sterile neutrinos can be produced by $\nu_{e,\mu,\tau} \to \nu_s$ oscillations before active neutrino decoupling $(t_{\nu\text{-dec}} \sim 1\,\text{s})$
- energy density of radiation before matter-radiation equality:

$$\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right]\rho_\gamma \qquad (t < t_{\text{eq}} \sim 6 \times 10^4\,\text{y})$$

$$N_{\text{eff}}^{\text{SM}} = 3.046 \qquad \Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$$

- sterile neutrino contribution: $\rho_s = (T_s/T_\nu)^4 \rho_\nu \quad \Rightarrow \quad \Delta N_{\text{eff}} = (T_s/T_\nu)^4$

- ν_s with $m_s = \simeq \sqrt{\Delta m^2_{41}} \sim 1\,\text{eV}$ become non-relativistic at $T_\nu \sim m_s/3$ ($t_{\nu_s\text{-nr}} \sim 2.0 \times 10^5\,\text{y}$, before recombination at $t_{\text{rec}} \sim 3.8 \times 10^5\,\text{y}$)



[Gariazzo, Giunti, Laveder, JCAP 1504 (2015) 023]

See also: { [Archidiacono, Fornengo, Gariazzo, Giunti, Hannestad, Laveder, JCAP 1406 (2014) 031]
[Bergstrom, Gonzalez-Garcia, Niro, Salvado, JHEP 1410 (2014) 104]

Without oscillation data: { [Giusarma, Di Valentino, Lattanzi, Melchiorri, Mena, PRD 90 (2014) 043507]
[Zhang, Li, Zhang, PLB 740 (2015) 359]
[Dvorkin, Wyman, Rudd, Hu, PRD 90 (2014) 083503]
[Zhang, Li, Zhang, EPJC 74 (2014) 2954]

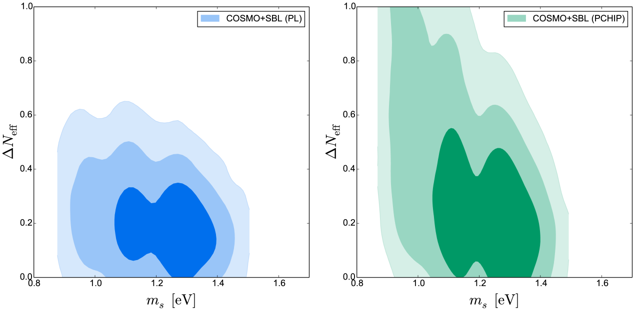
Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$

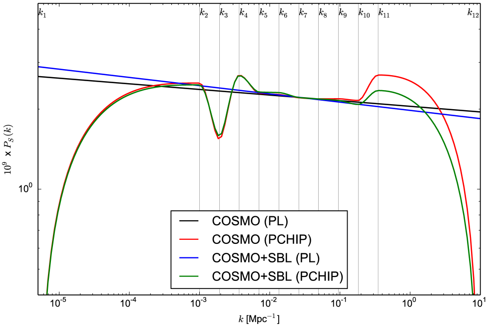
Sterile neutrinos are thermalized $(\Delta N_{\text{eff}} = 1)$ by active-sterile oscillations before neutrino decoupling [Dolgov, Villante, NPB 679 (2004) 261]

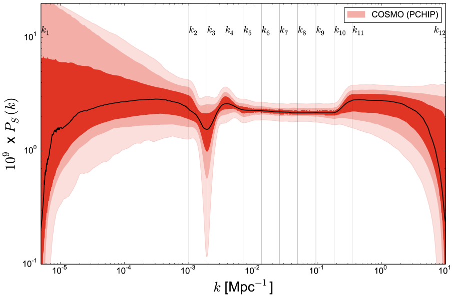
Proposed mechanisms to avoid the tension:

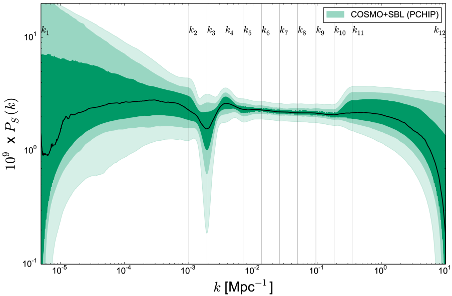
- Large lepton asymmetry [Hannestad, Tamborra, Tram, JCAP 1207 (2012) 025; Mirizzi, Saviano, Miele, Serpico, PRD 86 (2012) 053009; Saviano et al., PRD 87 (2013) 073006; Hannestad, Hansen, Tram, JCAP 1304 (2013) 032]
- Enhanced background potential due to interactions in the sterile sector [Hannestad, Hansen, Tram, PRL 112 (2014) 031802; Dasgupta, Kopp, PRL 112 (2014) 031803; Bringmann, Hasenkamp, Kersten, JCAP 1407 (2014) 042; Ko, Tang, PLB 739 (2014) 62; Archidiacono, Hannestad, Hansen, Tram, PRD 91 (2015) 065021; Mirizzi, Mangano, Pisanti, Saviano, PRD 90 (2014) 113009, PRD 91 (2015) 025019; Tang, arXiv:1501.00059]
- A larger cosmic expansion rate at the time of sterile neutrino production [Rehagen, Gelmini JCAP 1406 (2014) 044]
- MeV dark matter annihilation [Ho, Scherrer, PRD 87 (2013) 065016]
- Invisible decay [Gariazzo, Giunti, Laveder, arXiv:1404.6160]
- Free primordial power spectrum of scalar fluctuations (Inflationary Freedom) [Gariazzo, Giunti, Laveder, JCAP 1504 (2015) 023]

Inflationary Freedom



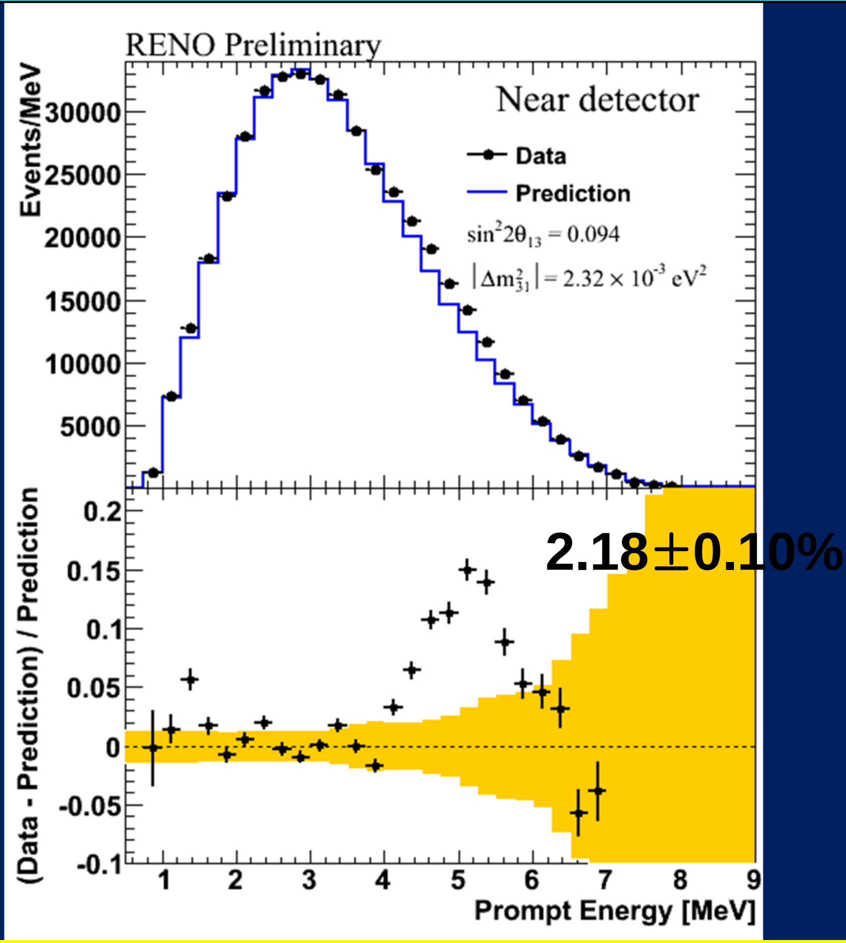


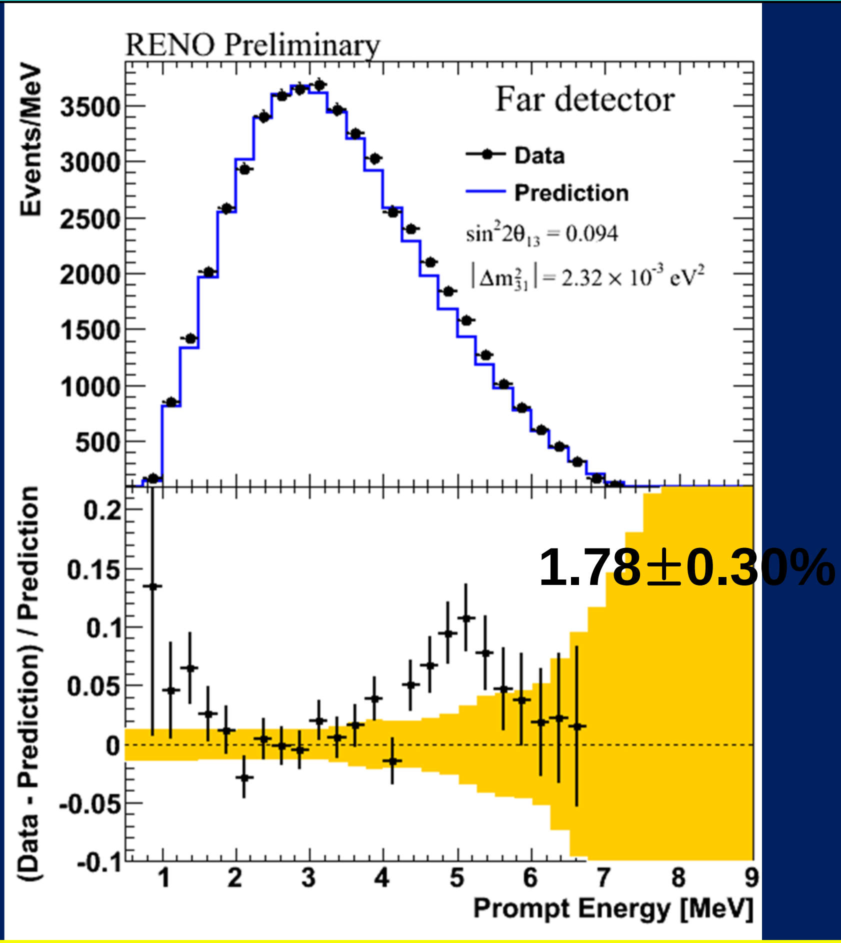




[Gariazzo, Giunti, Laveder, JCAP 1504 (2015) 023]

Observation of a New Reactor Neutrino Component at 5 MeV

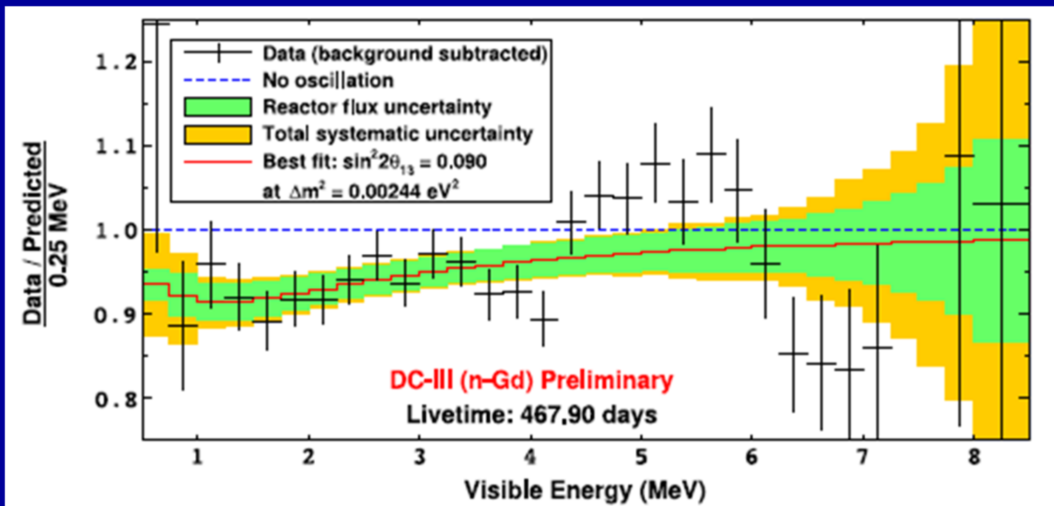




Fraction of 5 MeV excess (%) to expected flux [2011 Huber+Mueller]

- Near : 2.18 ± 0.40 (experimental) ± 0.49 (expected shape error)
- Far : 1.78 ± 0.71 (experimental) ± 0.49 (expected shape error)

The 5 MeV Excess Seen at Double-Chooz and Daya Bay



Double-Chooz, Neutrino 2014

Daya Bay, ICHEP 2014