Constraint on Neutrino Decay with Medium-Baseline Reactor Neutrino Oscillation Experiments

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Outline

Introduction

Current bounds on neutrino lifetime

Why JUNO/RENO-50 can do a good job?

Analysis Procedure

Results

Summary

Introduction

Open Questions in Neutrino Physics

Dirac or Majorana?

Mass Ordernig (Normal or Inverted)?

Neutrinos violate CP?

if θ_{23} is maximal, if not, which octant?

what is the origin of neutrino masses?

Introduction

Open Questions in Neutrino Physics

Neutrinos have some non-standard (or exotic) properties beyond the standard 3 falvor scheme?

For example,

Sterile Neutrinos

Non-standard Interactions (Irina's talk)

magnetic moment

Lorentz/CPT violation (Enrioc's talk)

Mass varying neutrinos

Neutrino decay

decoherence

Introduction

Do neutrinos decay?

Since we know that their masses are different and flavors do not conserve, in principle, they could decay

Introduction

Radiative decay like $\nu_i \to \nu_j + \gamma$

can be induced by the effective Lagrangian,

$$\mathcal{L} = \frac{1}{2}\bar{\nu}_i \sigma_{\alpha\beta}(\mu_{ij} + \epsilon_{ij}\gamma_5)\nu_j F^{\alpha\beta} + \mathrm{h.c.}$$

μ_{ij} (ϵ_{ij}) : magnetic (electric) transition moment

$$\Gamma_{ij} = \frac{1}{\tau} = \frac{|\mu_{ij}|^2 + |\epsilon_{ij}|^2}{8\pi}\left[\frac{m_i^2 - m_j^2}{m_i}\right]^3$$

Cosmological bounds by Mirizzi et al, PRD76, 053007(2007)

$$\tau > \text{a few} \times (10^{19} - 10^{20})\ \mathrm{s}$$

too strong to be of practical interest!

we must consider "invisible" decays

We can consider generic interactions (couplings) between neutrinos and "Majoraon" which allows "fast" invisible neutrino decay

$$\mathcal{L} = g_{ij}\overline{\nu}_i\gamma_5\nu_j J + \text{h.c.}$$

J: Majoron (= golstone boson associated with the spontaenous breaking of the lepton number)

$$g_{ij} = U^T_{i\alpha}\, g_{\alpha\beta}\, U_{\beta j}$$

coupling in mass base   coupling in flavor base

According to Lessa & Peres, PRD75, 043001 (2007)

from decays of mesons and leptons

$$|g_{e\alpha}| < 5.5 \times 10^{-6}$$

$$|g_{\mu\alpha}| < 4.5 \times 10^{-5}$$

$$|g_{\tau\alpha}| < 5.5 \times 10^{-2}$$

at 90% CL.

Current bounds on neutrino lifetime

If i-th mass eigenstate can decay,

$$E_i = \frac{m_i^2}{2E} - i\frac{\Gamma_i}{2}$$

where,

$$\frac{1}{\Gamma_i} = \left(\frac{E}{m_i}\right)\tau_i$$: Lorentz dilated lifetime,

what we can constrain from experiments is **τ/m**

Current bounds on neutrino lifetime

Order of magnitude estimates

$$\Gamma\, L = \left(\frac{m}{\tau}\right)\left(\frac{L}{E}\right) \sim O(1)$$

Neutrino source	Typical L/E	τ/m [s/eV]
Accelerator	500 km / 1 GeV	$\sim 10^{-12}$
Atmospheric	10^4 km/ 1 GeV	$\sim 3 \times 10^{-11}$
Solar	1.5×10^8 km/5 MeV	$\sim 10^{-4}$
Supernova	10 kpc/10 MeV	$\sim 10^5$
AGN	100 Mpc/1 TeV	$\sim 10^4$

Current bounds on neutrino lifetime

(1) $\tau_1/m_1 \gtrsim 10^5$ s/eV (SN1987A)

Frieman, Haber & Freese, PLB200, 115 (1988)

(2) $\tau_2/m_2 \gtrsim 10^{-4}$ s/eV (Solar)

Beacom & Bell, PRD65, 113009 (2002)

(3) $\tau_3/m_3 \gtrsim 10^{-10}$ s/eV (Atmospheric)

Gonzalez-Garcia & Maltoni, PLB663, 405 (2008)

Oscillation Probability with decay effect

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$-s_{13}^4\left(1 - e^{-\Gamma_3 L}\right) - \frac{1}{2}\sin^2 2\theta_{13}\left[1 - \cos\left(\frac{\Delta m_{\mathrm{atm}}^2 L}{2E}\right) e^{-\frac{\Gamma_3 L}{2}}\right]$$

$$\Delta m_{\mathrm{atm}}^2 \equiv \Delta m_{32}^2 \approx \Delta m_{31}^2$$

Current bounds on neutrino lifetime

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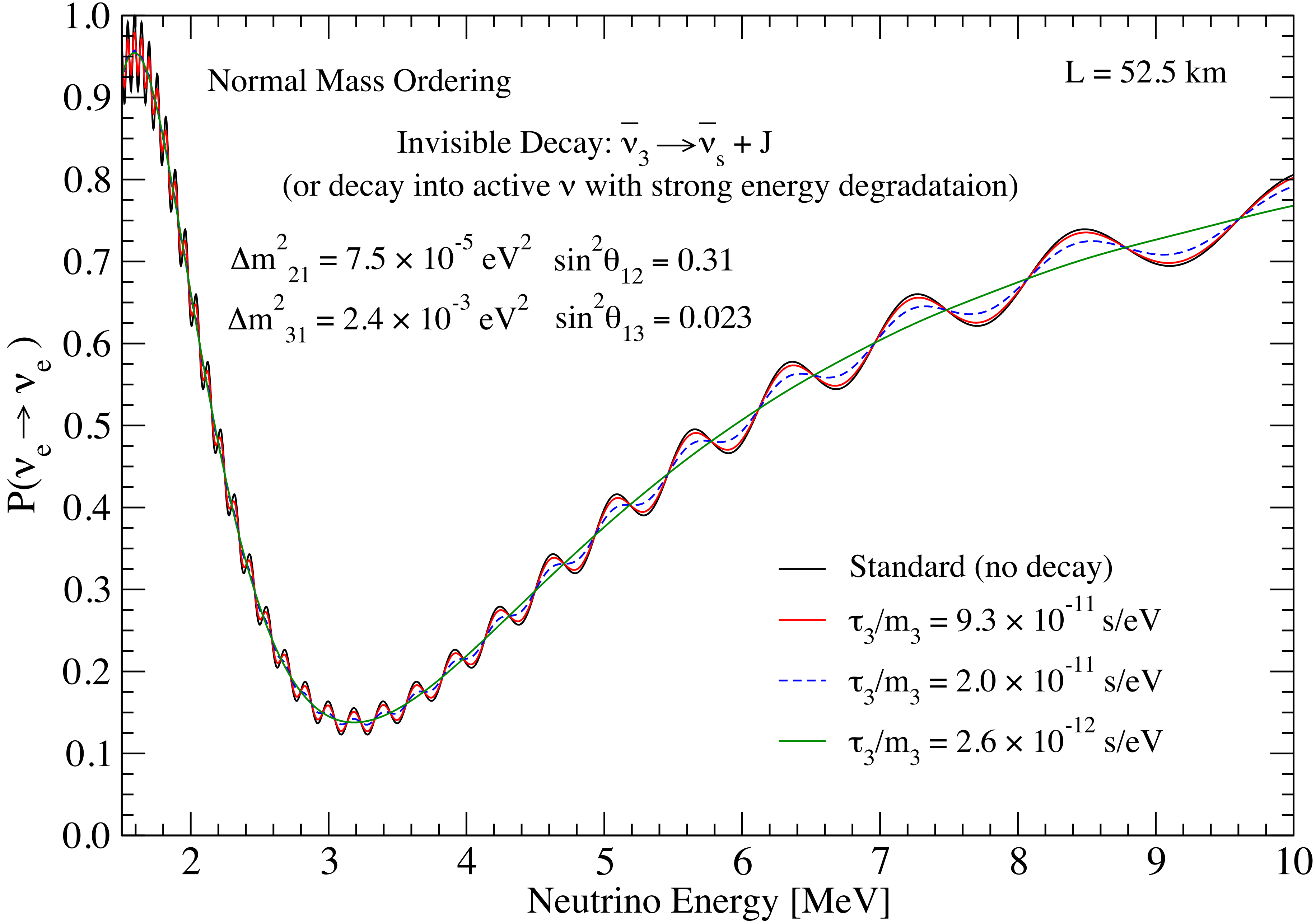
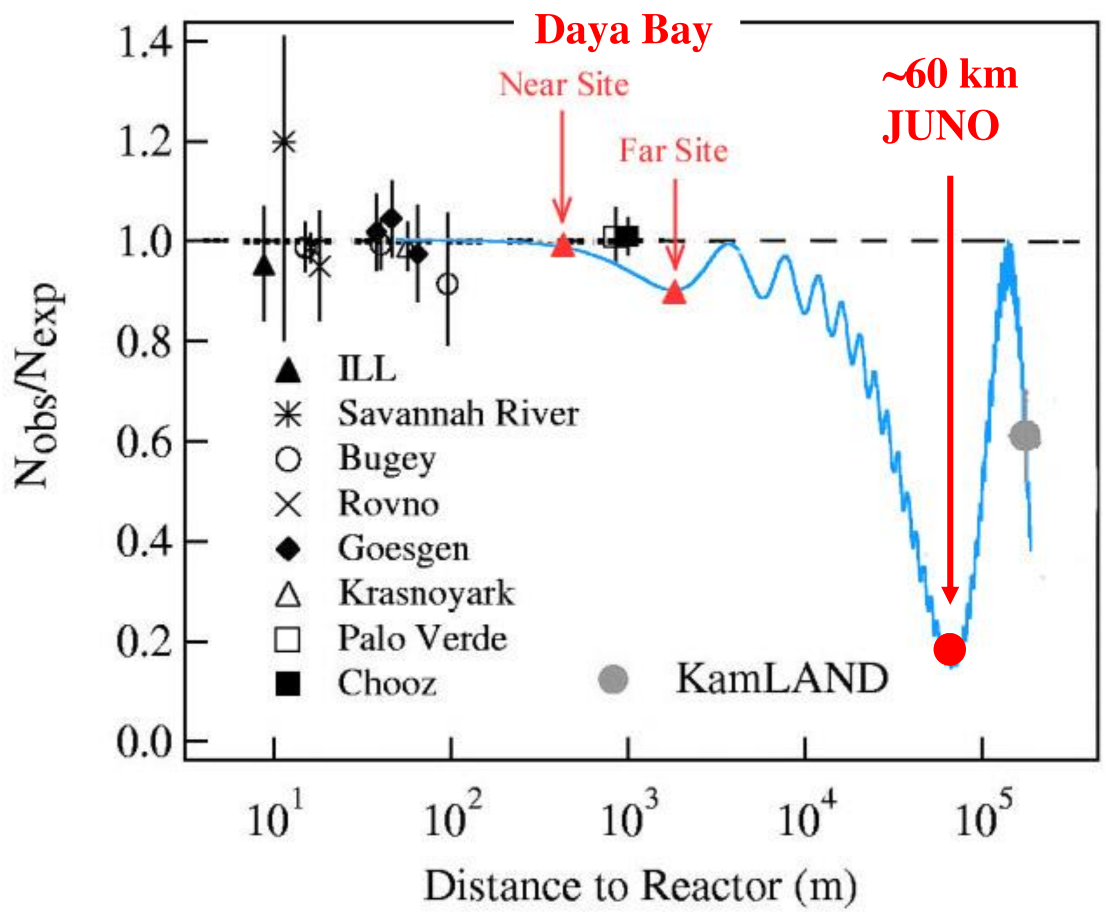
Atmospheric	10^4 km/ 1 GeV	$\sim 3 \times 10^{-11}$
Solar	1.5×10^8 km/5 MeV	$\sim 10^{-4}$
Reactor ($L \sim 1$ km)	1 km/5 MeV	$\sim 10^{-12}$
Reactor ($L \sim 50$ km)	50 km/5 MeV	$\sim 5 \times 10^{-11}$
Supernova	10 kpc/10 MeV	$\sim 10^5$
AGN	100 Mpc/1 TeV	$\sim 10^4$

Oscillation Probability with decay effect



JUNO Experiment

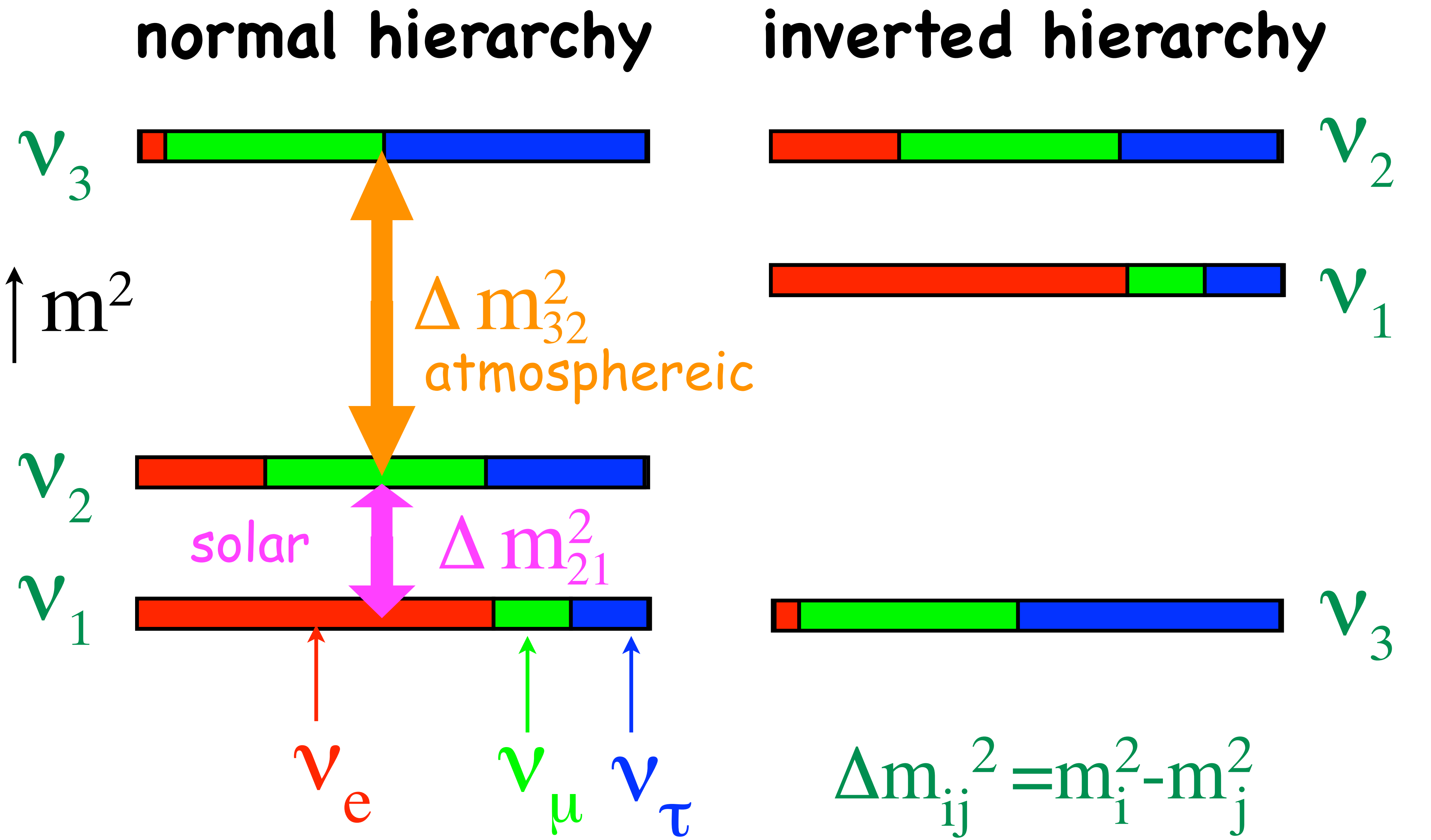
- Jiangmen Underground Neutrino Observatory (was Daya Bay II)
- Primary goals: mass hierarchy and precision meas.
  - 20 kton LS detector, 3%/$\sqrt{E}$ energy resolution
- Proposed in 2008, approved in Feb.2013. ~300M US$



- Rich Physics
  - Mass hierarchy
  - Precision measurement of mixing parameters
  - Supernova neutrinos
  - Geo-neutrinos
  - Solar neutrinos
  - Sterile neutrinos
  - Atmospheric neutrinos
  - Exotic searches

slide presented by Liangjian Wen at Neutrino 2014

Mass Spectrum: normal or inverted ?



Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

slide presented by Liangjian Wen at Neutrino 2014

How the event spectra look like at JUNO?

We compute the number of events induce by the inverse beta decay reaction $\bar{\nu}_e + p \to e^+ + n$

$$\frac{dN(E_{\text{vis}})}{dE_{\text{vis}}} = n_p t_{\text{exp}} \int_{m_e}^{\infty} E_e \int_{E_{\min}}^{\infty} dE \sum_{i=\text{reac,geo}-\nu} \frac{d\phi_i(E)}{dE} \epsilon_{\text{det}}(E_e) \times \frac{d\sigma(E_\nu, E_e)}{dE_e} P_i(\bar{\nu}_e \to \bar{\nu}_e; L_i, E) R(E_e, E_{\text{vis}})$$

n_p : number of free protons $\quad t_{\text{exp}}$: exposure

ϵ_{det} : detection efficiency

E_e : positron energy $\quad E$: neutrino energy

$d\sigma(E_\nu, E_e)/dE_e$: IBD cross section

$d\phi_i(E)/dE$: differential flux of reactor or geoneutrinos

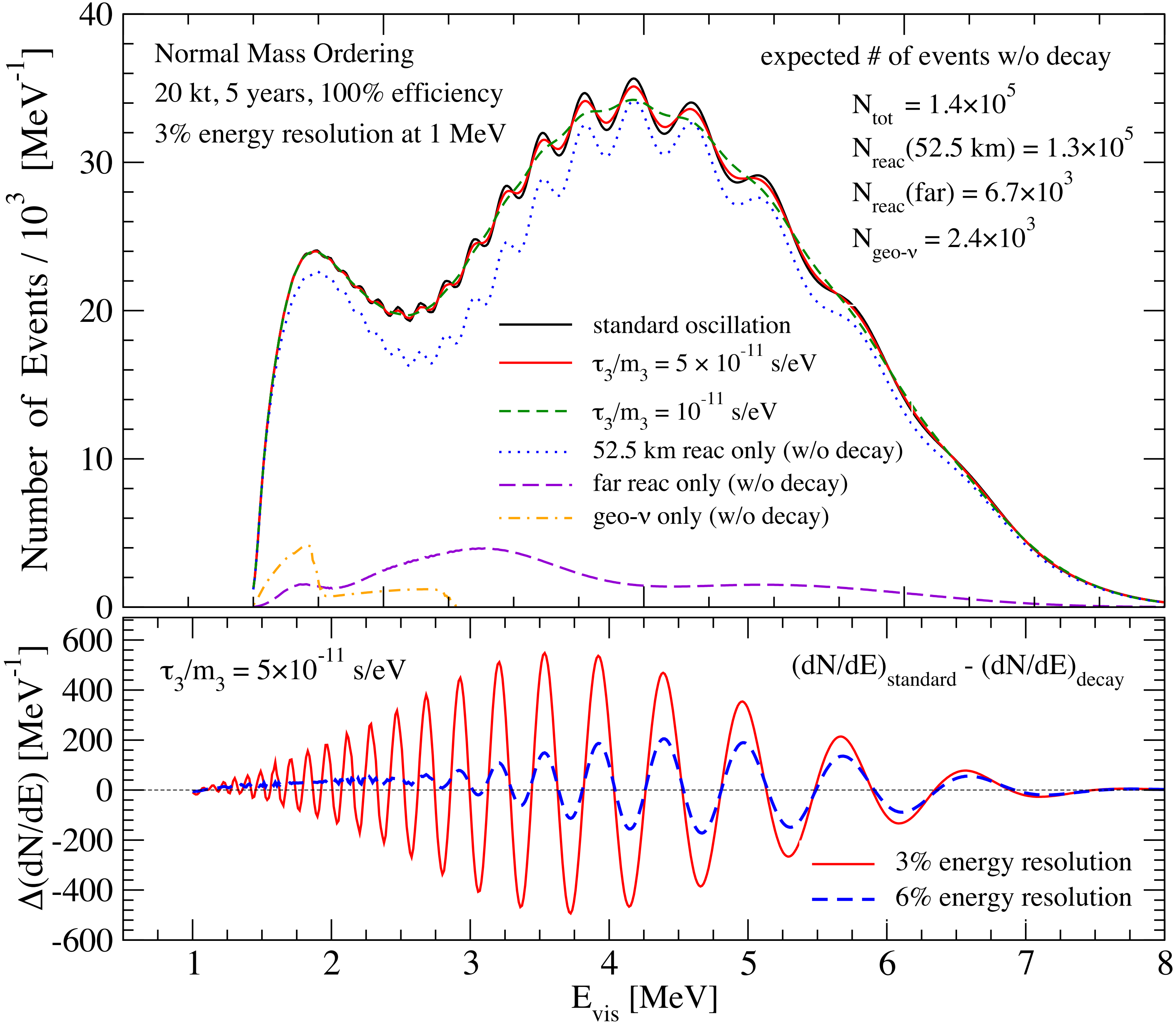
How the event spectra look like at JUNO?

Gaussian energy resolution fuaction

$$R(E_e, E_{\rm vis}) \equiv \frac{1}{\sqrt{2\pi}\sigma(E_e)} \exp\left[-\frac{1}{2}\left(\frac{E_e + m_e - E_{\rm vis}}{\sigma(E_e)}\right)^2\right]$$

$$\frac{\sigma(E_e)}{(E_e + m_e)} = \frac{3\%}{\sqrt{(E_e + m_e)/\mathrm{MeV}}}$$

How the event spectra look like at JUNO?



Analysis Procedure

$$\chi^2 \equiv \chi^2_{\text{stat}} + \chi^2_{\text{param}} + \chi^2_{\text{sys}}$$

$$\chi^2_{\text{stat}} \equiv \int_0^{E_{\text{vis}}^{\text{max}}} dE_{\text{vis}} \left(\frac{\dfrac{dN^{\text{obs}}}{dE_{\text{vis}}} - \displaystyle\sum_{i=\text{reac, U, Th}} (1+\xi_i) \dfrac{dN_i^{\text{fit}}}{dE_{\text{vis}}}}{\sqrt{\dfrac{dN^{\text{obs}}}{dE_{\text{vis}}}}} \right)^2$$

ξ_i : normalization parameters

Analysis Procedure

$$\chi^2_{\mathrm{param}} \equiv \sum_{i=1}^{4} \left(\frac{x_i^{\mathrm{in}} - x_i^{\mathrm{fit}}}{\sigma(x_i)} \right)^2$$

$$x_1 \equiv \sin^2\theta_{12},\ x_2 \equiv \Delta m^2_{21},\ x_3 \equiv \sin^2\theta_{13},\ x_4 \equiv \Delta m^2_{31}$$

$$\Delta m^2_{21}{}^{\mathrm{in}} = 7.50 \times 10^{-5}\mathrm{eV}^2, \quad \sin^2\theta_{12}{}^{\mathrm{in}} = 0.304,$$
$$\Delta m^2_{31}{}^{\mathrm{in}} = 2.46 \times 10^{-3}\mathrm{eV}^2, \quad \sin^2\theta_{13}{}^{\mathrm{in}} = 0.0218,$$

$$\sigma(\sin^2\theta_{12}) = 4.1\%,\ \sigma(\Delta m^2_{21}) = 2.4\%,$$
$$\sigma(\sin^2\theta_{13}) = 4.6\%,\ \sigma(\Delta m^2_{31}) = 1.9\%.$$

Analysis Procedure

$$\chi^2_{\rm sys} \equiv \left(\frac{\xi^{\rm fit}_{\rm reac}}{\sigma_{\xi_{\rm reac}}}\right)^2 + \left(\frac{\xi^{\rm fit}_{\rm U}}{\sigma_{\xi_{\rm U}}}\right)^2 + \left(\frac{\xi^{\rm fit}_{\rm Th}}{\sigma_{\xi_{\rm Th}}}\right)^2 + \left(\frac{\eta^{\rm fit}}{\sigma_{\eta}}\right)^2$$

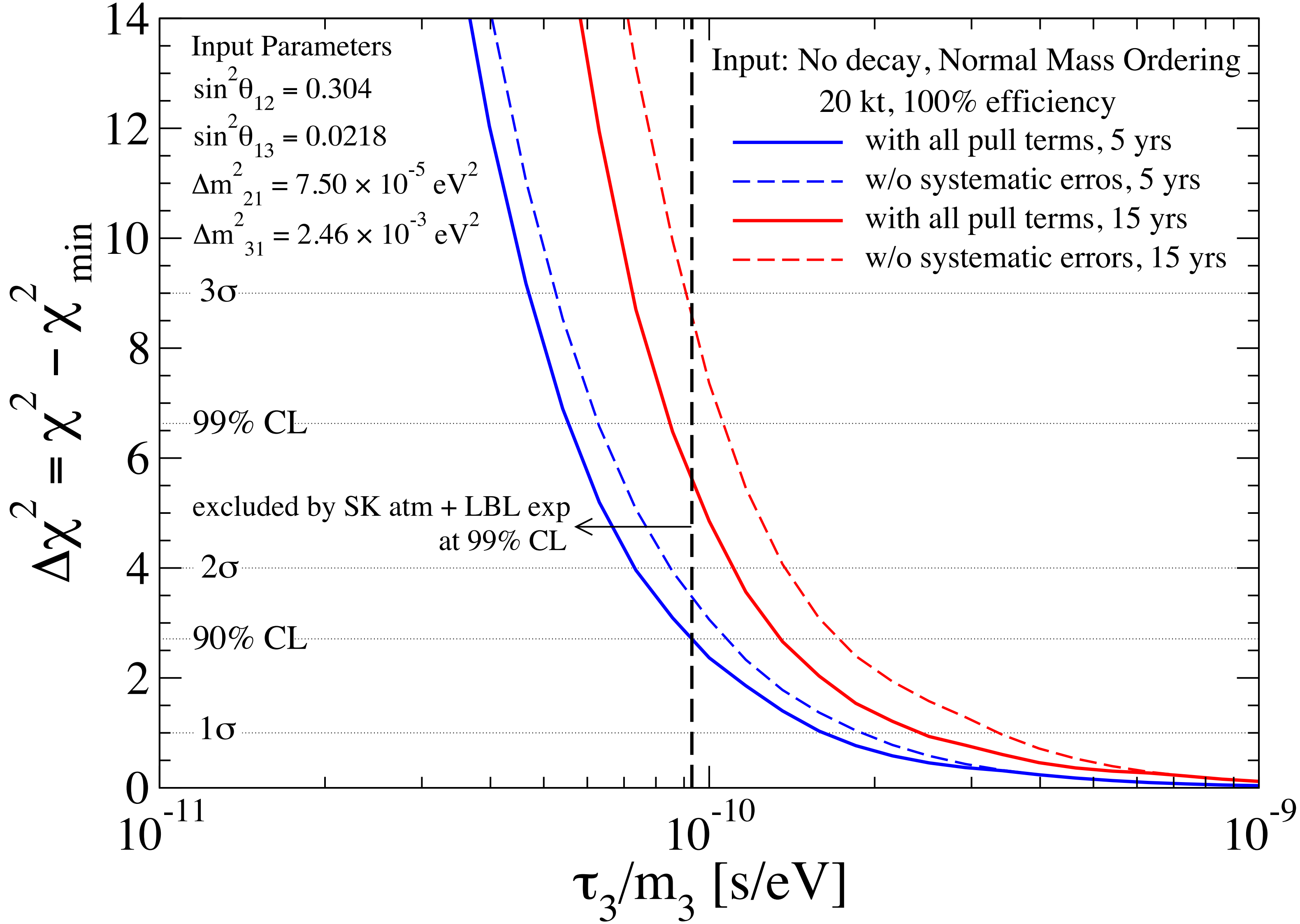
$\sigma_{\xi_{\rm reac}} = 3\%$: reactor flux normalization uncertainty

$\sigma_{\xi_{\rm U}} = \sigma_{\xi_{\rm Th}} = 20\%$: geoneutrino flux norm. uncert.

$$\frac{\sigma(E_e)}{(E_e + m_e)} = \frac{3\% \ (1+\eta)}{\sqrt{(E_e + m_e)/\mathrm{MeV}}}$$

$\sigma_\eta = 10\%$: energy resoluion normalization uncertainty

Sensitivity (expected bounds on lifetime)



$\tau_3/m_3 > 7.5\ (5.5) \times 10^{-11}$ s/eV at 95 (99)% CL for 5 yrs

$\tau_3/m_3 > 11\ (8.5) \times 10^{-11}$ s/eV at 95 (99)% CL for 15 yrs

Sensitivity (expected bounds on lifetime)

expected bounds in terms of couplings

$\tau_3/m_3 > 7.5\ (5.5) \times 10^{-11}$ s/eV at 95 (99)% CL

$\longrightarrow \quad \tau_3 > 7.5\ (5.5) \times 10^{-12}$ s $(m_3/0.1\text{eV})$

using the relation

$$\tau_3 \sim \frac{16\pi}{g_{s3}^2 m_3} \ (\text{assuming } m_3 \gg m_s)$$

$$\longrightarrow \quad g_{s3}^2 \lesssim 0.04\ (0.06) \left[\frac{0.1\text{eV}}{m_3}\right]^2$$

Impact of decay on mass hiearchy and oscillation parameter determinations

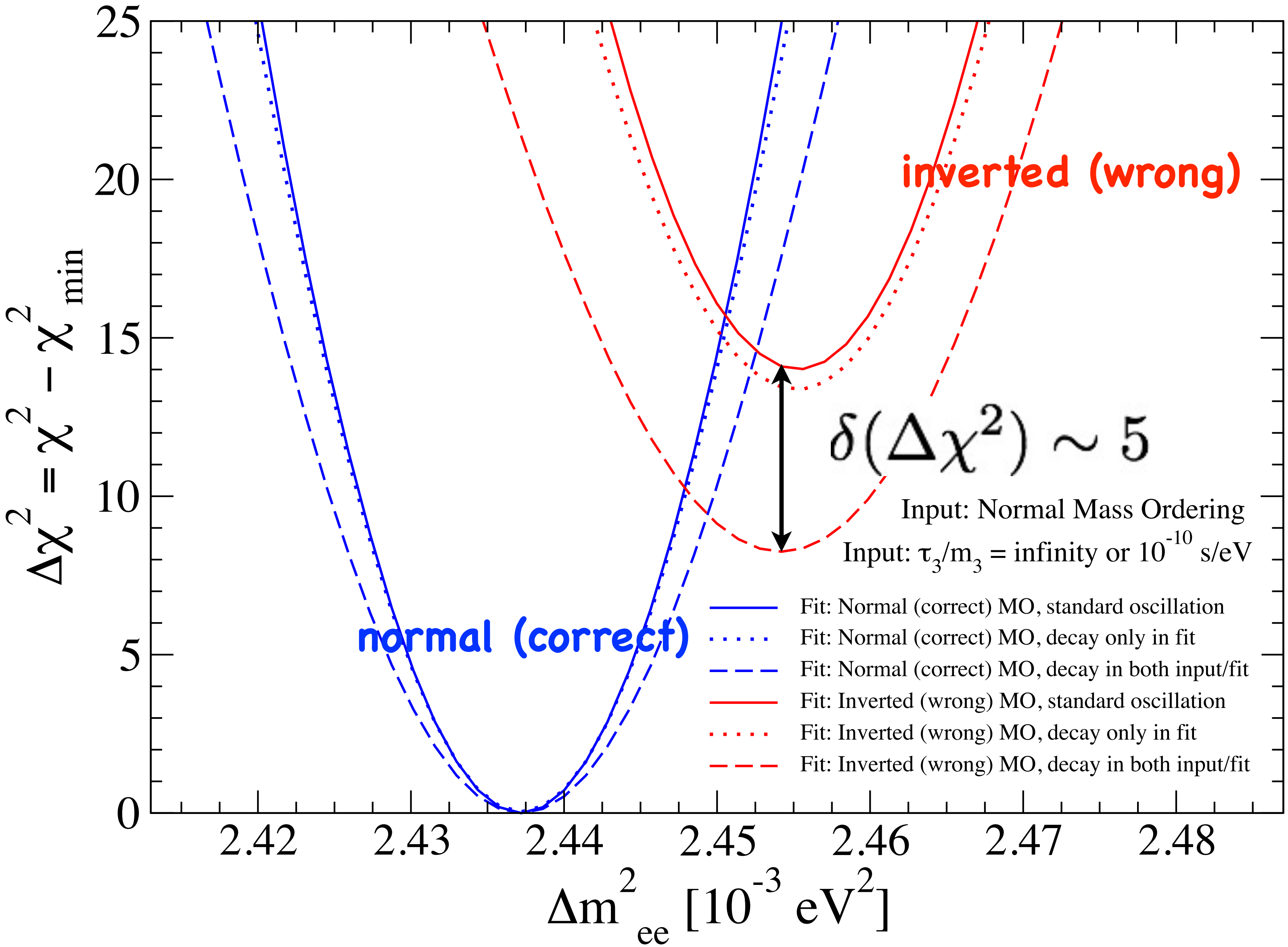
We consider (compare) three cases

(i) No Decay (standard oscillation fit)

(ii) No Decay for input but allowed in the fit

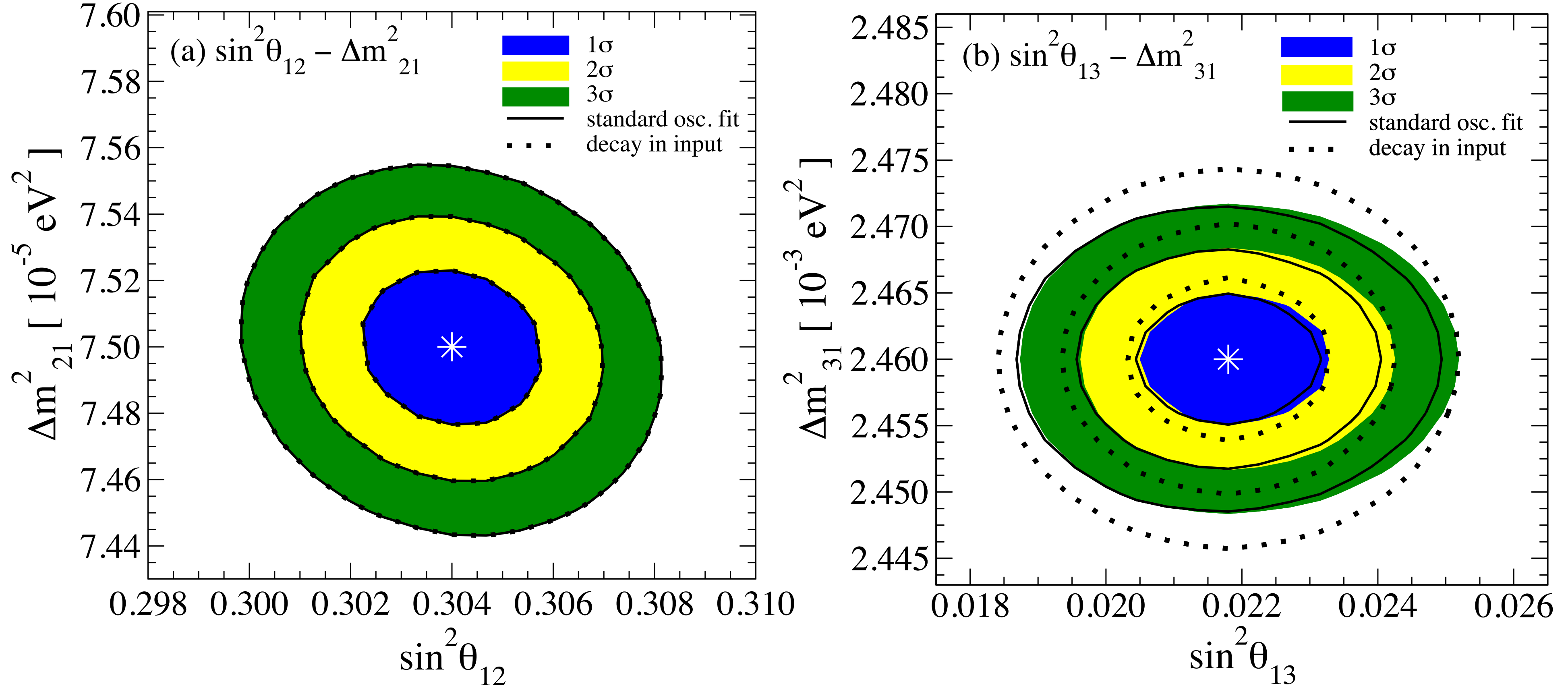
(iii) Assume Decay for input ($\tau_3/m_3 = 10^{-10}$ s/eV) as well as in fit

Impact of decay on mass hiearchy determination



large impact only when decay is considered for input

Impact of decay on oscillation parameter determinations



no (small) impact for solar (13 sector) parameter

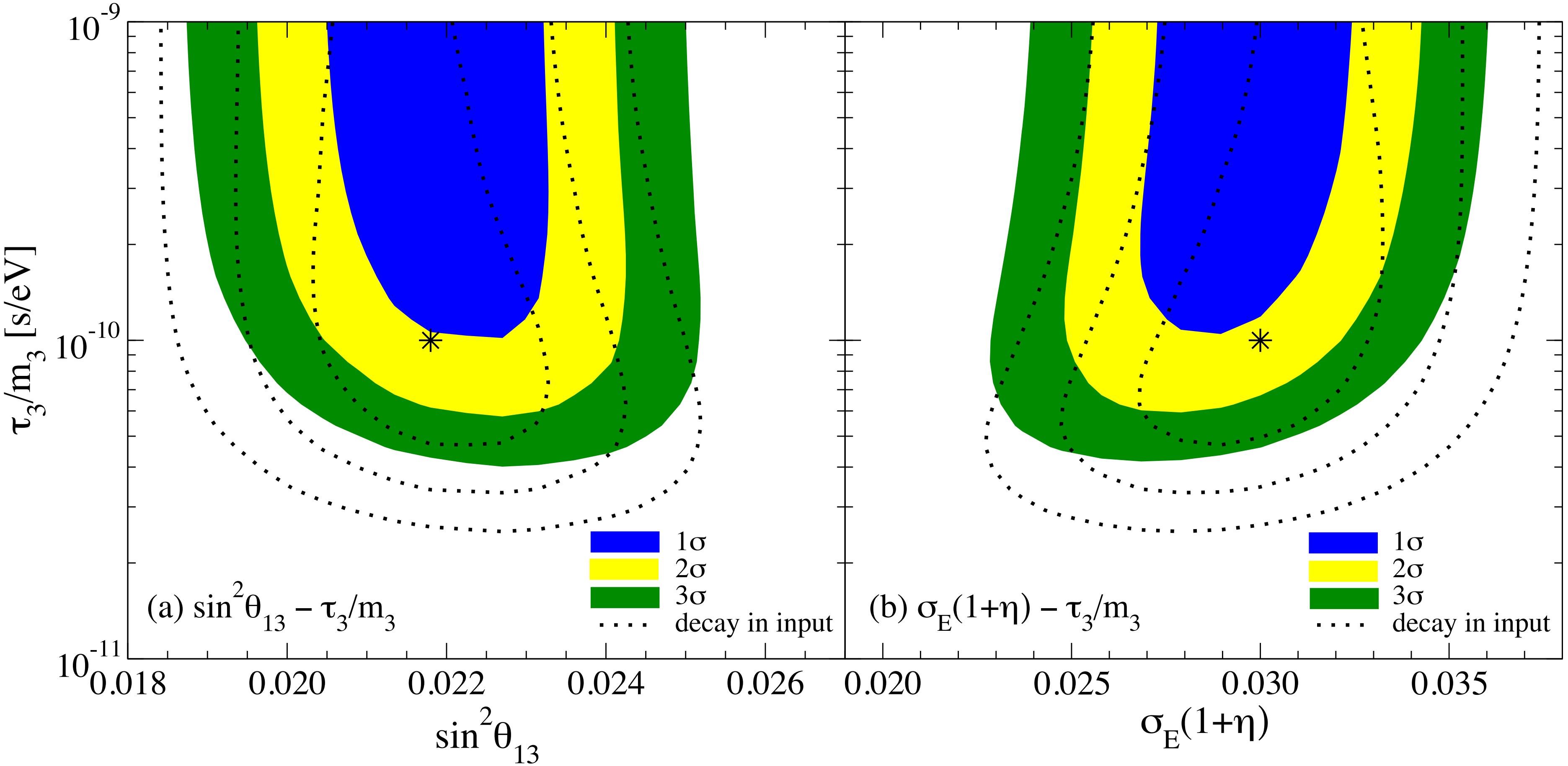
Impact of decay on oscillation parameter determinations

How precisely the parameters can be determined after 5 years of operation?

parameter	prior error (%)	fitted error (%)		
		(i)	(ii)	(iii)
$\sin^2\theta_{12}$	4.1	0.35	0.35	0.35
Δm^2_{12}	4.1	0.21	0.21	0.21
$\sin^2\theta_{13}$	4.6	3.7	3.8	4.3
Δm^2_{13}	1.9	0.12	0.12	0.16
$1+\xi_{\rm reac}$	3.0	0.50	0.50	0.51
$1+\xi_{\rm U}$	20	12	12	12
$1+\xi_{\rm Th}$	20	13	13	13
$1+\eta$	10	5.5	6.0	7.1

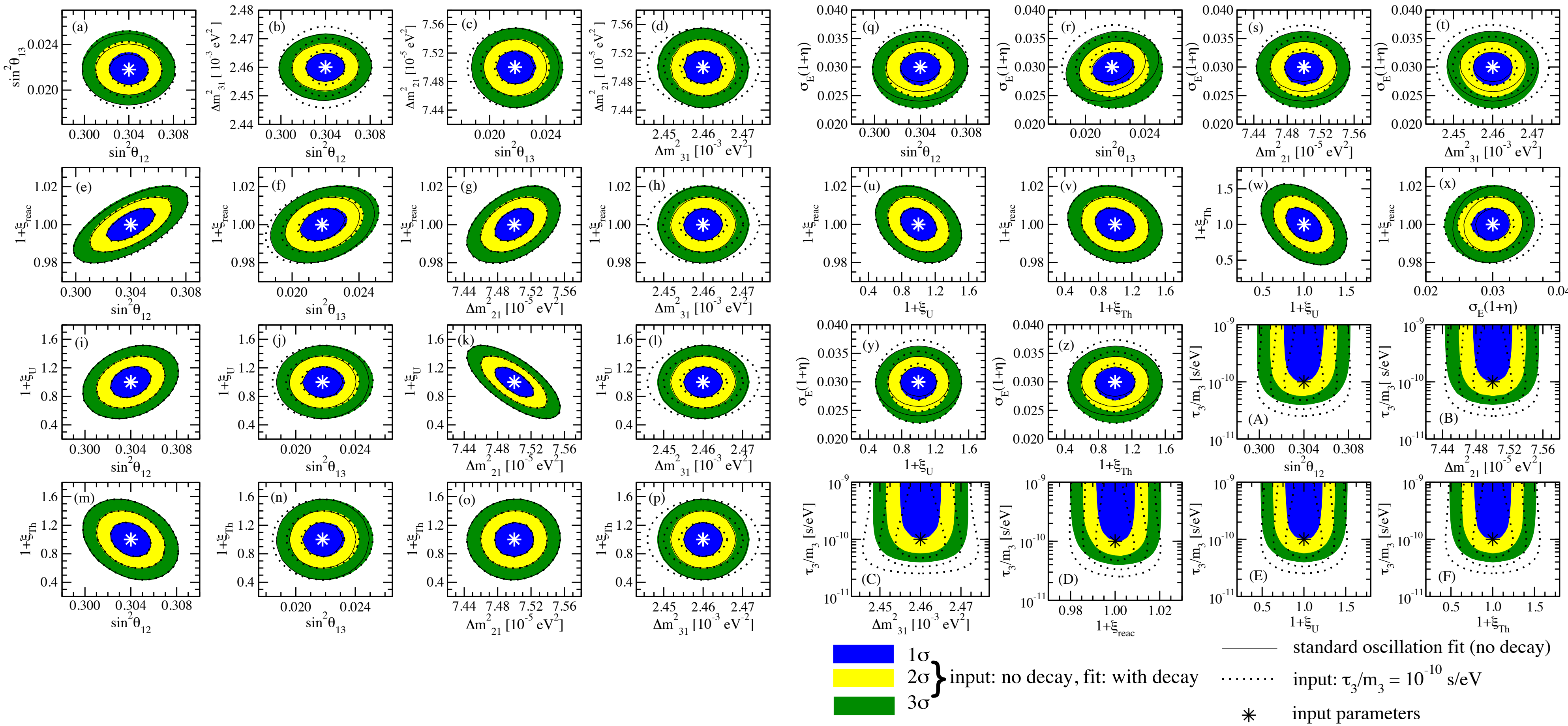
no strong impact of decay in general

correlation between decay and other parameters (2 examples)



no strong correlations between decay and other param

All the other combinations



no strong impact of decay

no strong newly induced correlation due to decay

Conclusions

Medium baseline ($\sim$50 km) reactor oscillation experiments can provide best limit on τ_3/m_3 among all experiments which utilize artificial neutrino sources

for 5 years of operation, JUNO can get bound as

$\tau_3/m_3 > 7.5\ (5.5) \times 10^{-11}$ s/eV at 95 (99)% CL

for 15 years of operation, JUNO can get bound as

$\tau_3/m_3 > 11\ (8.5) \times 10^{-11}$ s/eV at 95 (99)% CL

comparable to bounds by atmospheric neutrinos

Thank you very much
for your attention!