Constraining Majorana CP phase in Precision Era of Cosmology and Double Beta Decay Experiment

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Based on Collab. with Hisakazu Minakata and Alexander A. Quiroga, arXiv: 1402.6014 [hep-ph] and its revised version, to appear

KITP, UCSB, December 15, 2014

Outline

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Assumptions and Analysis Procedure

Results I: Allowed Regions

Results II: CP Exclusion Fraction

Conclusions

Last ~15 years of Neutrino Physics was really exciting!

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Discovery of Neutrino Oscillation!

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was really exciting!

Discovery of Neutrino Oscillation!

↓

neutrinos have masses!

Mixing between 3 flavor of neutrinos

$$\text{flavor eigenstates} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_\nu \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \text{mass eigenstates}$$

$$U_\nu = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$$

atmospheric ν osc. (first matrix)

reactor ν osc. (second matrix)

solar ν osc. / reactor ν osc. (third matrix)

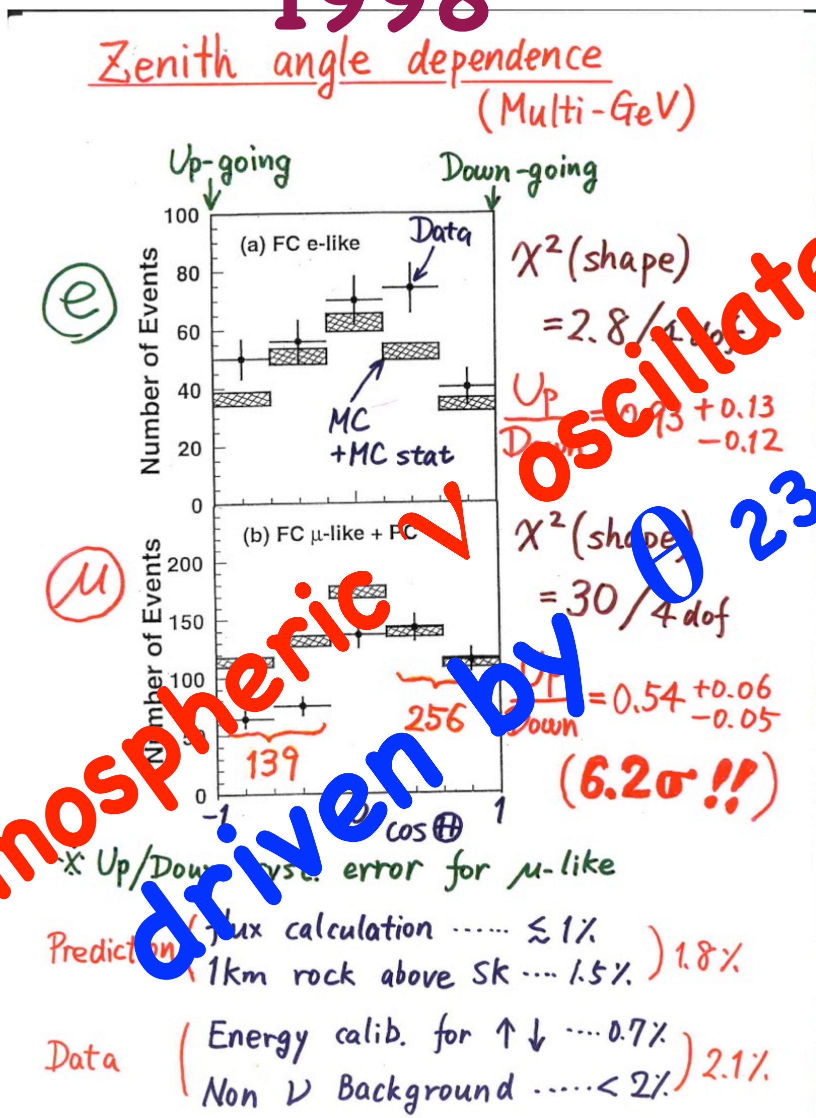
θ_{ij}: mixing angle δ: CP phase

for antineutrinos, $U_\nu \longrightarrow U_\nu^*$

Discovery of Neutrino Oscillation

Announced in "Neutrino '98" @Takayama, Japan

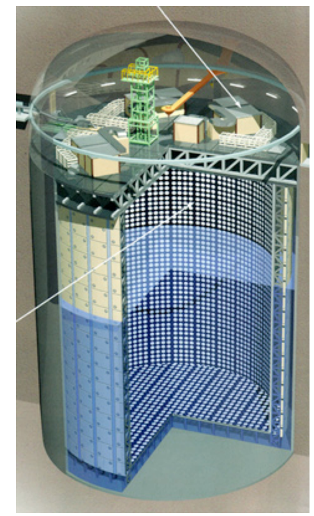
1998



atmospheric ν oscillate!

driven by θ_{23}

T. Kajita



Y. Totsuka
(1942-2008)

Super-Kamiokande Collaboration

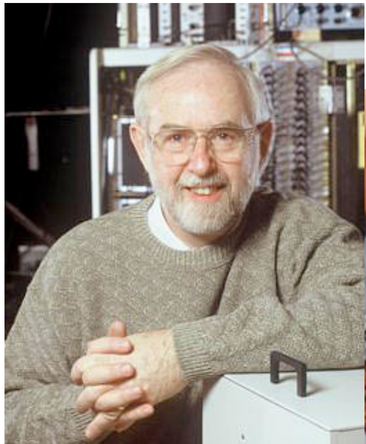
$$\nu_\mu \longleftrightarrow \nu_\tau$$

neutrinos change falvors !

confirmed also by accelerator neutrinos

Solar neutrinos also oscillate!

A. McDonald



$$\nu_e \longleftrightarrow \nu_{\mu,\tau}$$

A. Suzuki

driven by θ_{12} !

confirmed by reactor neutrinos!

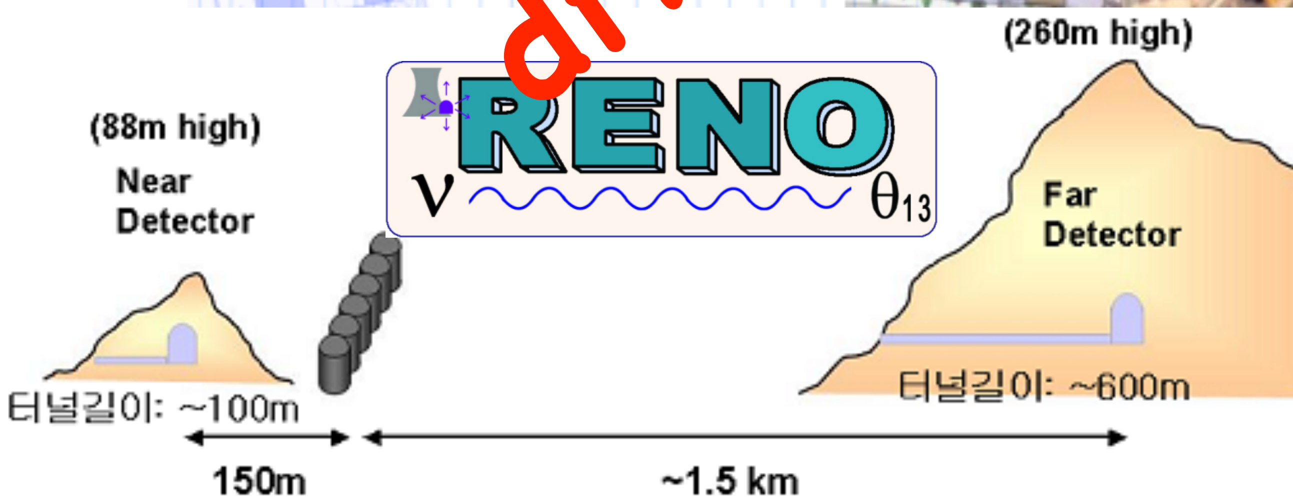
SNO

2002

KamLAND

Another type of oscillation observed by reactor experiments

driven by θ_{13} !



2011-2012

Mixing in the Quark Sector

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$V_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

Mixing in the Neutrino Sector

$$|U| = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

M.C.Gonzalez-Garcia et al, JHEP1411(2014)052

Very different from the CKM Matrix!

Thanks to the enourmous progress in neutrino physics after the discovery of neutrino oscillation by Super-Kamiokande collaboration, all the mixing angles are now measured!

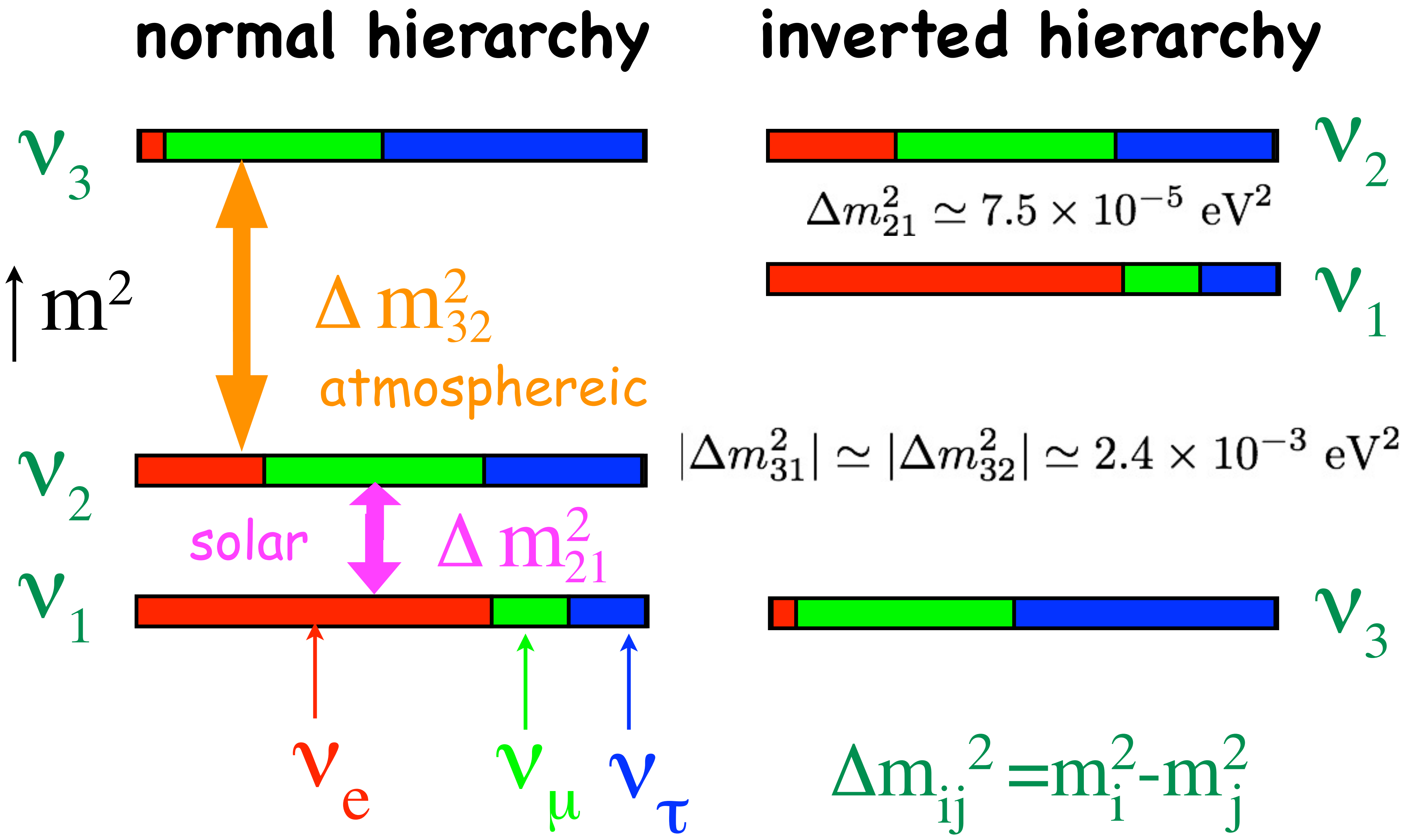
Unknowns of Oscillation paramters

mass ordering : $m_1 < m_3$ or $m_1 > m_3$?

Leptonic-Kobayashi-Maskawa CP phase

Hopefully, future oscillation experiments will eventually determine these unknowns

Mass Spectrum: normal or inverted ?



However, there are other open quetinos which can not be answered by oscillation experiments

Absolute Neutrino Mass Scale

Nature of Neutrinos, Dirac or Majorana?

However, there are other open quetinos which can not be answered by oscillation experiments

Absolute Neutrino Mass Scale

Cosmology, beta decay experiment

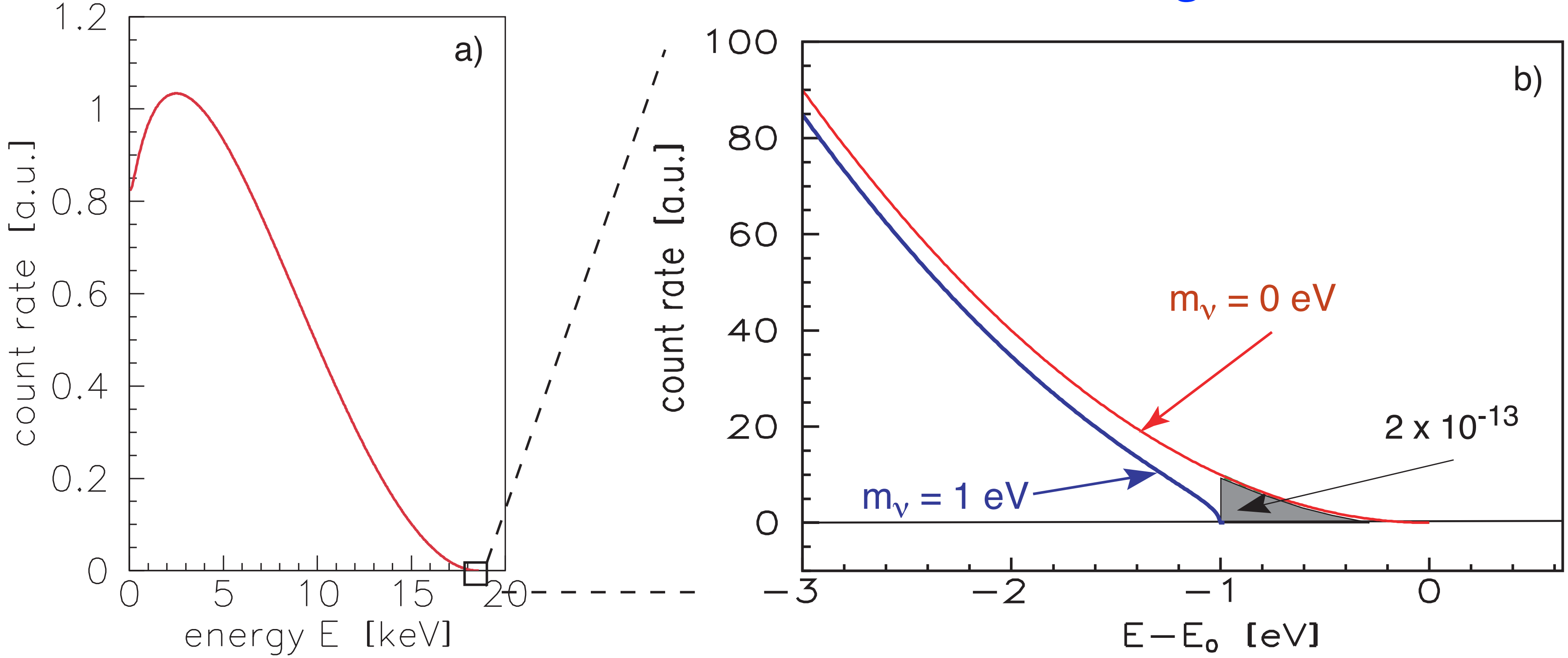
Nature of Neutrinos, Dirac or Majorana?

neutrinoless double beta decay experiment

Direct Measurement of Neutrino Mass

requires precise measurement of the end of the beta spectrum

$$^3H \rightarrow {}^3He + e^- + \overline{\nu}_e$$

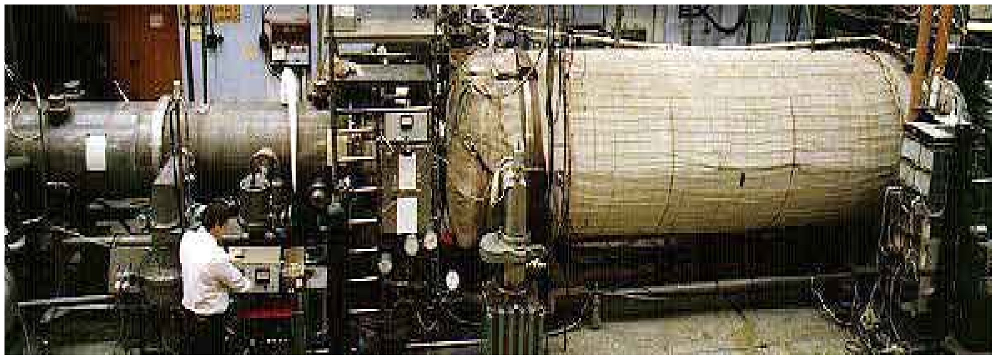


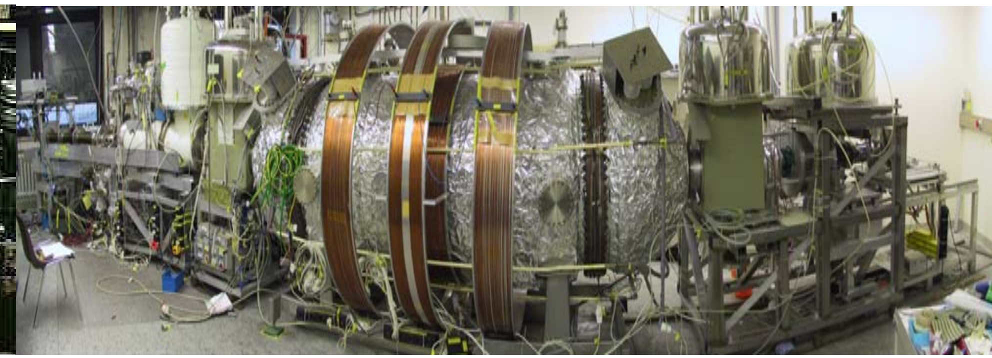
what can be actually measured is the effective mass,

$$m_\beta \equiv \left[m_1^2\,|U_{e1}|^2 + m_2^2\,|U_{e2}|^2 + m_3^2\,|U_{e3}|^2\right]^{\frac{1}{2}}$$

Status of previous tritium experiments

Mainz & Troitsk have reached their intrinsic limit of sensitivity





Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0 \text{ eV}^2$

$m_\nu \leq$ 2.2 eV (95% CL.)

Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1 \text{ eV}^2$

$m_\nu \leq$ 2.2 eV (95% CL.)

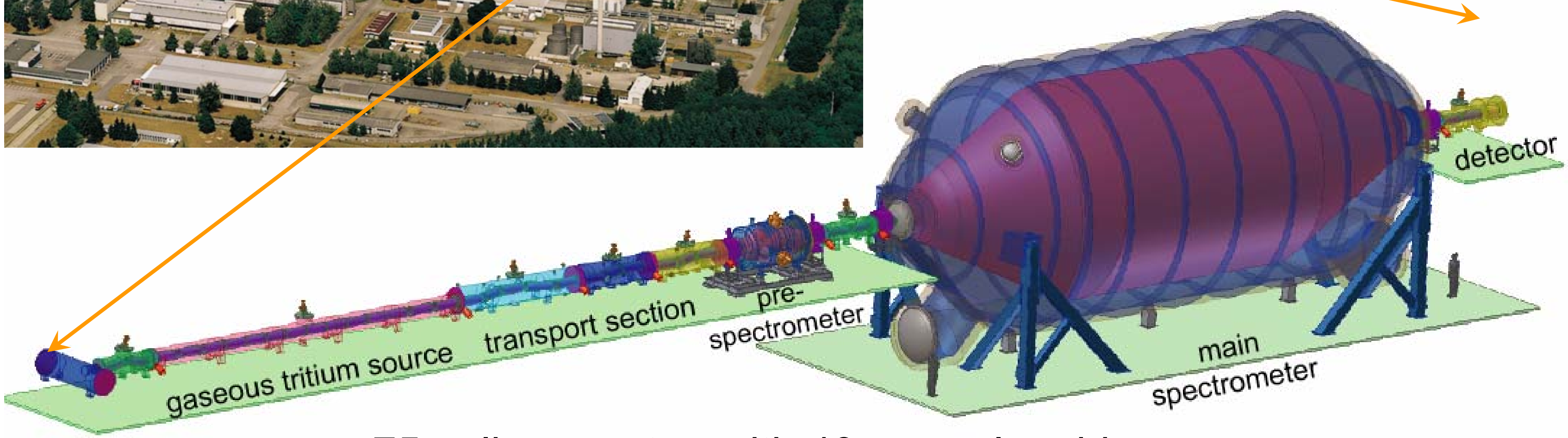
both experiments now used for systematic investigations

Karlsruhe Tritium Neutrino Experiment

KATRIN experiment

Karlsruhe Tritium Neutrino Experiment

at Forschungszentrum Karlsruhe
unique facility for closed T_2 cycle:
Tritium Laboratory Karlsruhe



~ 75 m linear setup with 40 s.c. solenoids

sensitivity: m_ν ~0.2 eV @90% CL

Cosmology may determine better neutrino masses

Neutrinos are the most abundant particles in the universe after photons

CνB

number density per falvor: $n_\nu = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T_\gamma^3 \sim 110/\mathrm{cm}^3$

for $m_\nu \ll T$: $\rho_\nu = \frac{7\pi^2}{120} T_\nu^4 = \frac{7\pi^2}{120} \left(\frac{4}{11}\right)^{4/3} T_\gamma^4$

for $m_\nu \gg T$: $\rho_\nu = m_\nu n_\nu \longrightarrow \Omega_\nu h^2 \simeq \frac{\sum m_{\nu_i}}{94\ \mathrm{eV}}$

From atmospheric neutrino data, we know that at least one of them > 0.05 eV

Cosmological Bounds on Neutrino Masses

Cosmology is sensitive to sum of the neutrino masses

$$\Sigma \equiv m_1 + m_2 + m_3$$

$$\Sigma < \begin{cases} 0.98 \text{ eV} & (\text{Planck} + \text{WMAP} + \text{CMB}), \\ 0.32 \text{ eV} & (\text{Planck} + \text{WMAP} + \text{CMB} + \text{BAO}), \end{cases}$$

at 95% CL (deviation from flatness was allowed)

by Ade et al [Planck Collaborataion], arXiv:1303.5076 [astro-ph.CO]

Indication of sub-eV neutrino masses?

According to recent work by Battye and Moss in PRL 112, 051303 (2014) [arXiv:1308.5870]

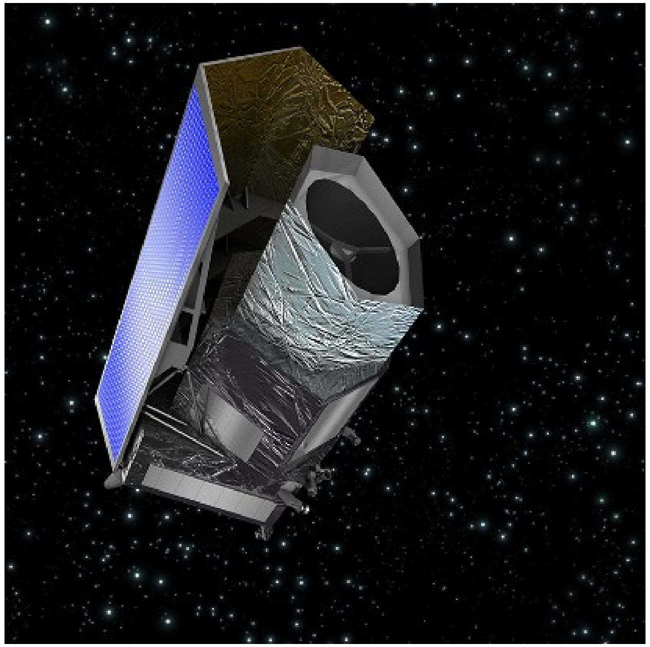
$\Sigma = 0.32 \pm 0.081$ eV is favored to decrease tension between CMB and lensing/cluster observations

However, see Leistedt et al, PRL113, 041301 (2014), arXiv:1404.5950 [astro-ph.CO]

Cosmology may determine better neutrino masses

Expected sensitivity...

ESA Euclid Misson



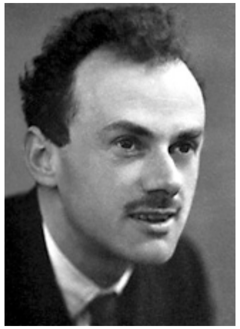
A **7-parameter forecast**: Hamann, Hannestad & Y[3]W 2012

Data	$10^3 \times \sigma(\omega_{\rm dm})$	$100 \times \sigma(h)$	$\sigma(\sum m_\nu)/{\rm eV}$
c	2.02	1.427	0.143
cs	0.423	0.295	0.025
cg	0.583	0.317	0.016
$\rm cg_l$	0.828	0.448	0.019
$\rm cg_b$	0.723	0.488	0.039
$\rm cg_{bl}$	1.165	0.780	0.059
csg	0.201	0.083	0.011
csgx	0.181	0.071	0.011
$\rm csg_b$	0.385	0.268	0.023
$\rm csg_b x$	0.354	0.244	0.022

c = CMB (Planck); g = Euclid galaxy clustering
s = Euclid cosmic shear; x = Euclid shear-galaxy cross

Most optimistic
Σm_ν potentially detectable at 5σ+ with Planck+Euclid (assuming nonlinearities to be completely under control)

Nature of Neutrinos: Dirac or Majorana ?



If neutrinos have masses, they can be either
Dirac or Majorana Fermions

Dirac Fermion: particles and anti-particles
are different, like electron

Majorana Fermion: particles and anti-particles are identical
(such particles can not have electric charge)

Possible Implications: Seesaw Mechanism, Leptogenesis

If neutrinos are Majorana particles,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_\nu \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_\nu = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

$$U_\nu \longrightarrow U_\nu \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{bmatrix}$$

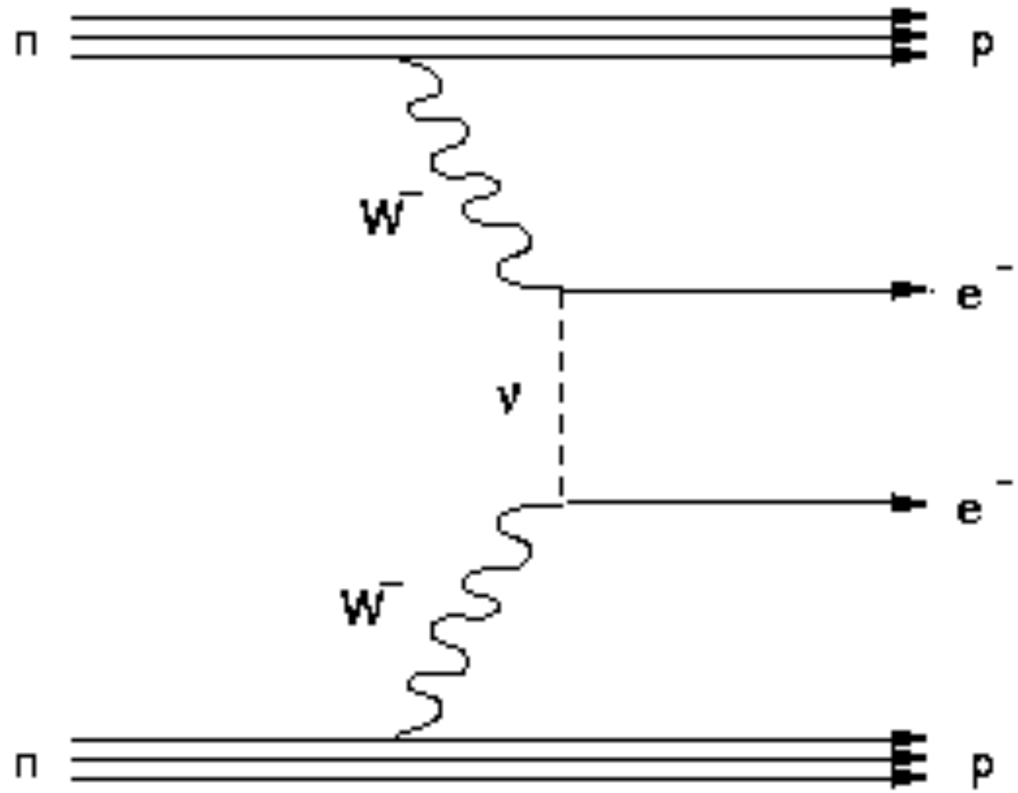
Majorana CP phases

Schechter & Vale, 1980, Bilenky, Hosek & Petcov, 1980

$\longrightarrow$ can not be measured by oscillation

How to test Majorana nature of neutrinos?

neutinoless double beta decay



violates lepton number by 2 units

decay rate ∝ effective neutrino mass

$$m_{0\nu\beta\beta} \equiv \left| \, m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 \mathrm{e}^{i\alpha_{21}} + m_3 |U_{e3}|^2 \mathrm{e}^{i\alpha_{31}} \right|$$

α_{21}, α_{31} : Majorana CP phases

Once the positive signal of neutinoless double beta decay will be observed, it is of great interest to measure also the Majorana CP phases

two main difficulties

1. uncertainty of nuclear matrix element

2. uncertainty of neutrino mass scale

What is actually measured is the decay rate or life time of the 0νββ decay

half life time

effective mass

$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu} \left| \mathcal{M}^{(0\nu)} \right|^2 \left(\frac{m_{0\nu\beta\beta}}{m_e} \right)^2$$

phase spcae factor

Nuclear Matrix Element (NME)

Problem: NME has a large uncertainty, typically factor of ~2 or more

Nuclear Matrix Element (NME)

Very difficult to compute due to many body nature of nuclear physics

results calculated by different models (methods) do not agree very well

Quasi-particle Rando Phase Approximation (QRPA)

Interacting Boson Model (IBM)

Nuclear Shell Model (NSM)

General Coordinate Method (GCM)

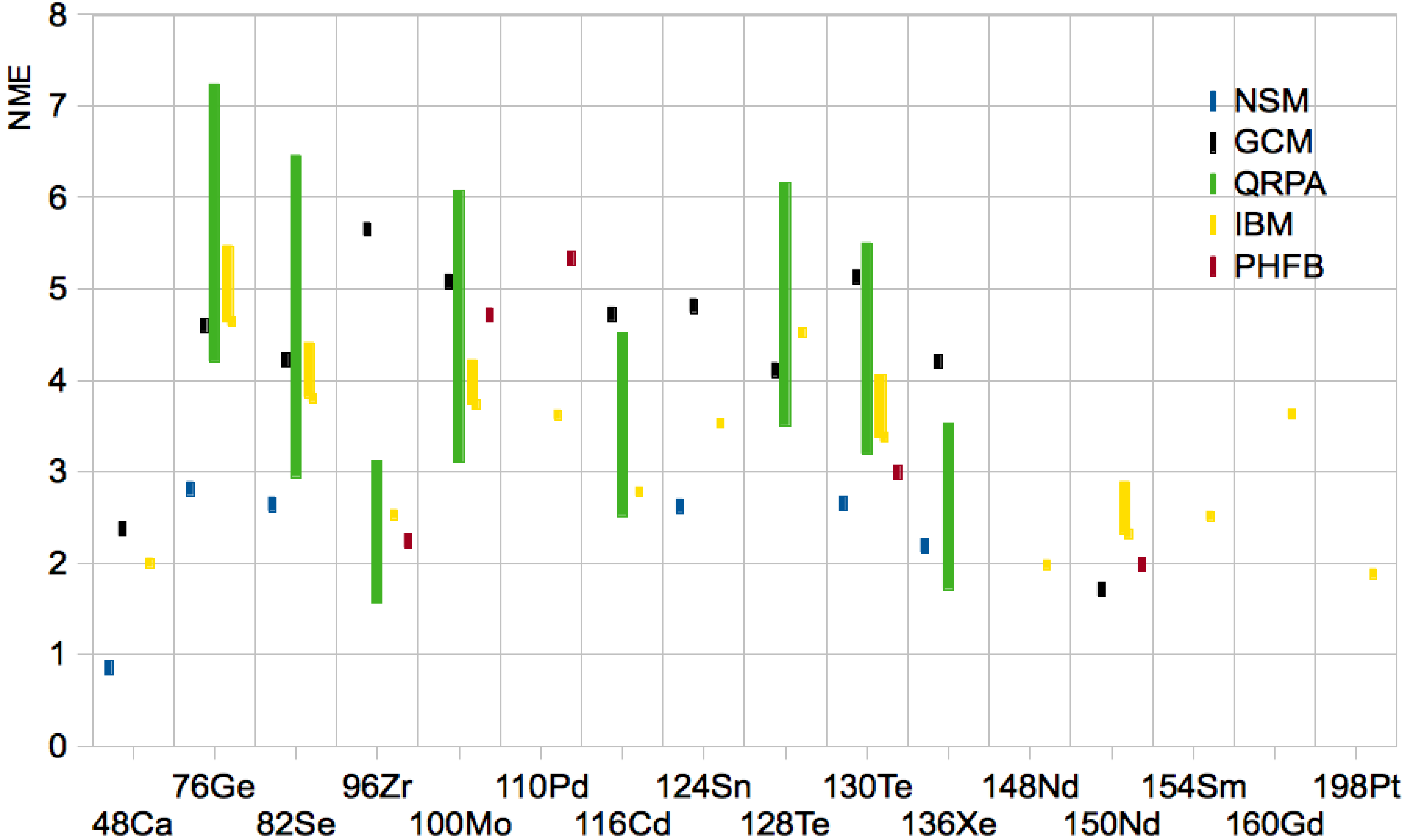
Other models (methods)...

NME values calculated by different models

Isotope	NSM[39]	GCM[42]	QRPA[56, 57, 58]	IBM[41]	PHFB[46]	
^{48}Ca	0.85	2.37		2.00		
^{76}Ge	2.81	4.60	4.20-7.24	4.64-5.47		
^{82}Se	2.64	4.22	2.94-6.46	3.81-4.41		
^{96}Zr		5.65	1.56-3.12	2.53	2.24	3.46
^{100}Mo		5.08	3.10-6.07	3.73-4.22	4.71	7.77
^{110}Pd				3.62	5.33	8.91
^{116}Cd		4.72	2.51-4.52	2.78		
^{124}Sn	2.62	4.81		3.53		
^{128}Te		4.11	3.50-6.16	4.52		
^{130}Te	2.65	5.13	3.19-5.50	3.37-4.06	2.99	5.12
^{136}Xe	2.19	4.20	1.71-3.53	3.35		
^{148}Nd				1.98		
^{150}Nd		1.71	3.45	2.32-2.89	1.98	3.70
^{154}Sm				2.51		
^{160}Gd				3.63		
^{198}Pt				1.88		

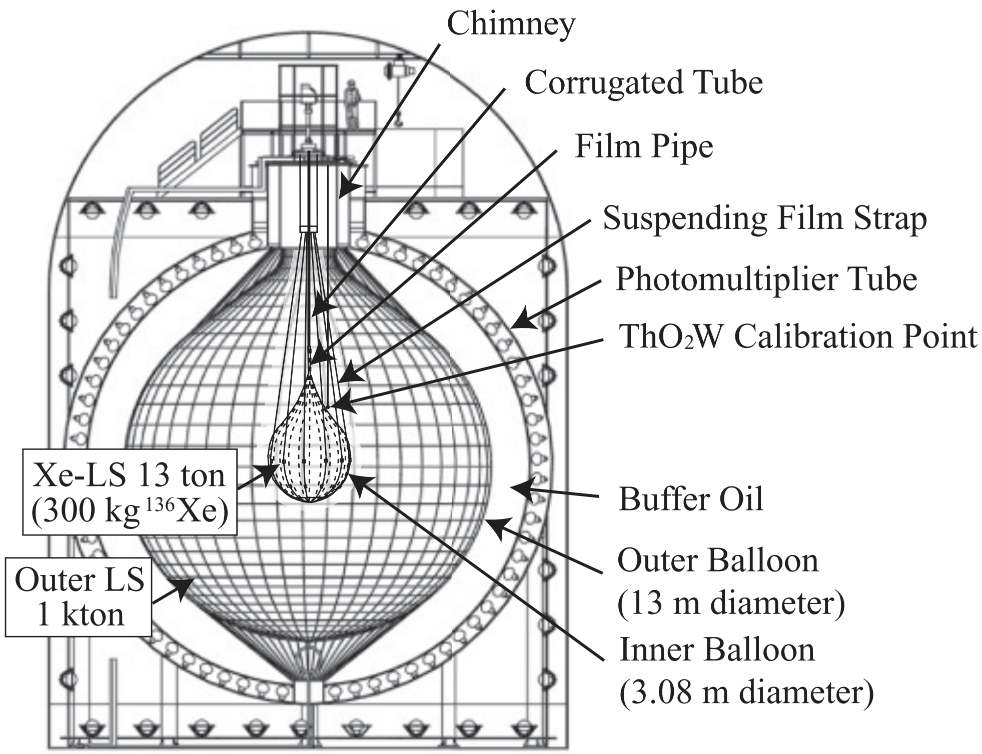
Cremonesi and Pavan, arXiv:1310.4692 [physics.ins-det]

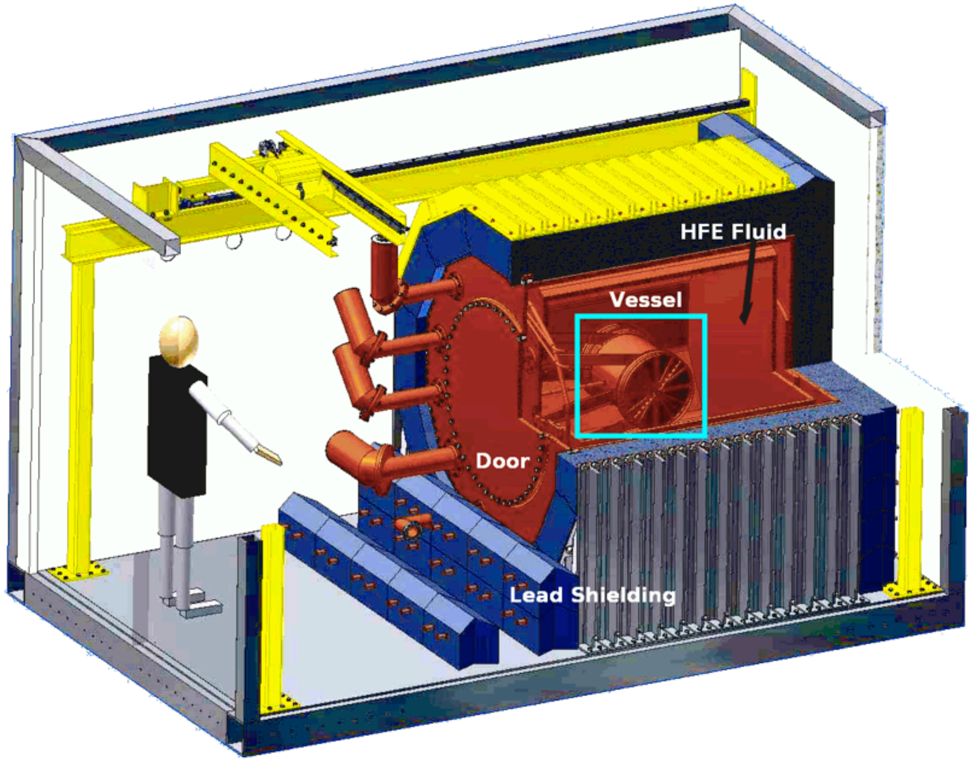
NME values calculated by different models



Cremonesi and Pavan, arXiv:1310.4692 [physics.ins-det]

Current bound on the effective Majorana mass





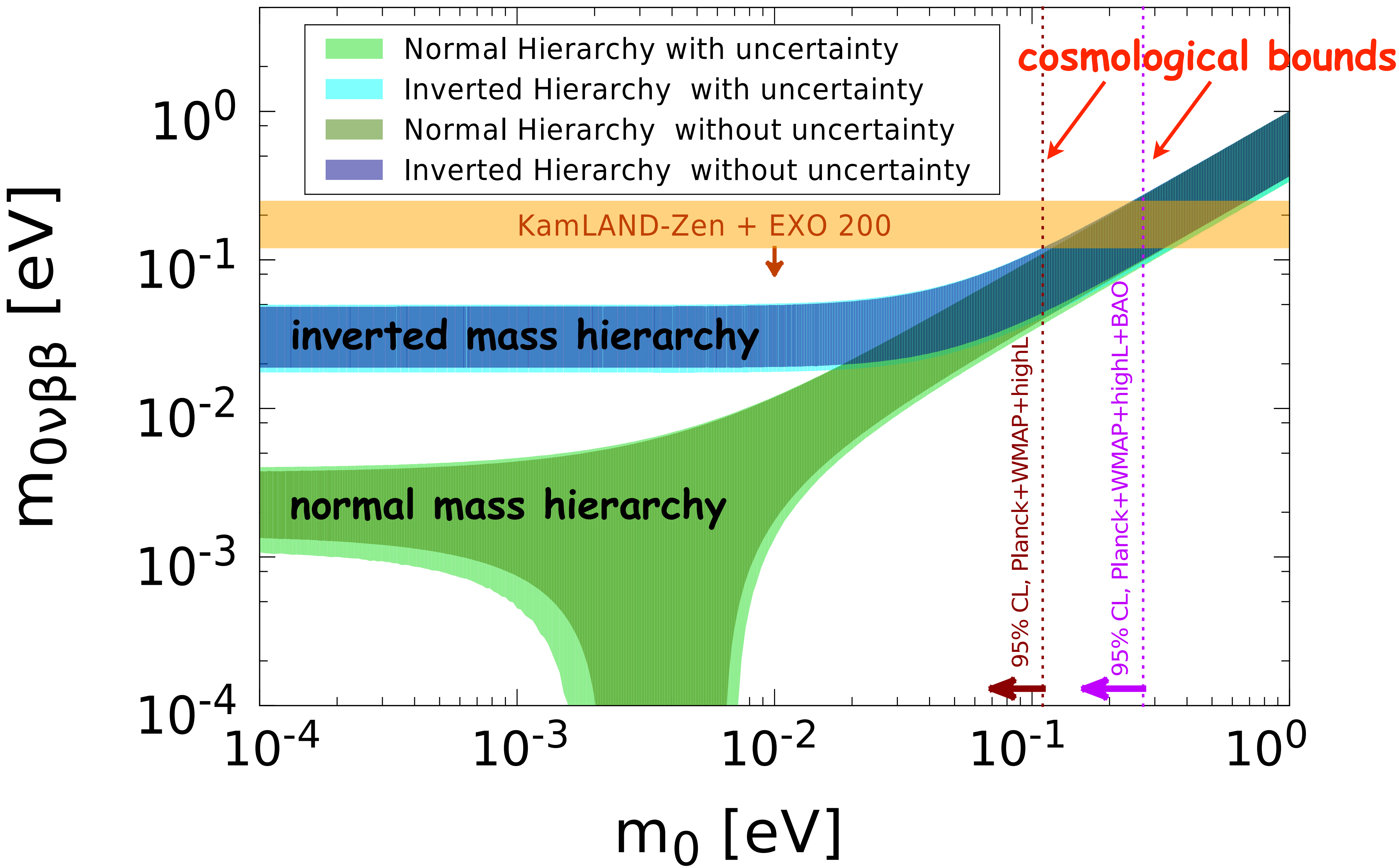
KamLAND-Zen detector **Exo-200 detector**

Exo-200: $T^{0\nu}_{1/2}(^{136}\text{Xe}) > 1.6 \times 10^{25}$ yr (90%CL)

KamLAND-Zen: $T^{0\nu}_{1/2}(^{136}\text{Xe}) > 1.9 \times 10^{25}$ yr (90%CL)

Combined: $m_{0\nu\beta\beta} < (0.12 - 0.25)$ eV (90%CL)

Effective Majorana Mass as a function of the lightest neutrino mass



$m_0 \equiv m_1$ **for normal hierarchy** $m_0 \equiv m_3$ **for inverted hierarchy**

Expected Sensitivities of some of the advanced 0νββ decay experiments

	Isotope	B_{iso}	FWHM (keV)	*Perf.*	*Sc.*	*Status*	$F^{0\nu}_{68\%C.L.}$ (5 yr)	$\lvert\langle m_\nu \rangle\rvert$
CUORE0[121]	^{130}Te	213	5.6	0.2	66	R	1.5	224
CUORE[119, 155, 156]	^{130}Te	29	5	27	1390	C	21	60
GERDA I[141]	^{76}Ge	21	4.8	9.2	119	R	9.4	165
GERDA II[136, 157, 158]	^{76}Ge	20/1.1	3.2	5.7/0.3	328	C	22/60*	107/65*
LUCIFER[133]	^{82}Se	1	20	4	125	D	17	74
MJD[142, 143, 144, 159]	^{76}Ge	0.9	4	0.4	238	C	4.4*	77*
SNO+[151]	^{130}Te	0.9	240	27	1253	D	2	62
EXO[99]	^{136}Xe	1.9	96	30	482	R	1.2	97
SND[110, 111, 112]	^{82}Se	0.6	120	18	23	D	3.3	166
SuperNEMO[110, 111, 112]	^{82}Se	0.6	130	20	366	D	13	85
KamLAND-Zen[147, 148]	^{136}Xe	7.4	243	243	1320	R	6.9	127
NEXT[109, 160]	^{136}Xe	0.8	13	5.4	165	D	1.6	82

in meV

Cremonesi and Pavan, arXiv: 1310.4692 [physics.ins-det]

Assumptions and Analysis Procedure

Observables we will consider

We will consider 3 observables which depends on the absolute neutrino mass scale

(1) $$m_{0\nu\beta\beta} \equiv \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}} \right|$$

to be measured by $0\nu\beta\beta$ decay experiment

(2) $$\Sigma \equiv m_1 + m_2 + m_3$$

to be measured by cosmological observations

(3) $$m_\beta \equiv \left[m_1^2 \, |U_{e1}|^2 + m_2^2 \, |U_{e2}|^2 + m_3^2 \, |U_{e3}|^2 \right]^{\frac{1}{2}}$$

to be measured by β decay expriment

In practice we can consider the lightest neutrino mass (m_0) as a relevant paramter determined by cosmology provided that we know the mass hiearchy,

For normal mass hierarchy

$$m_1 \equiv m_0, \quad m_2 = \sqrt{m_0^2 + \Delta m_{21}^2}\ , \quad m_3 = \sqrt{m_0^2 + \Delta m_{21}^2 + \Delta m_{32}^2}$$

For inverted mass hierarchy

$$m_1 = \sqrt{m_0^2 - \Delta m_{21}^2 - \Delta m_{32}^2}\ , \ m_2 = \sqrt{m_0^2 - \Delta m_{32}^2}\ , \quad m_3 \equiv m_0$$

From most updated global analysis

$$\Delta m_{21}^2 = 7.54 \times 10^{-5}\ \mathrm{eV}^2, \sin^2\theta_{12} = 0.308$$

$$\Delta m_{32}^2 = 2.40\ (-2.44) \times 10^{-3}\ \mathrm{eV}^2,\ \sin^2\theta_{13} = 0.0234\ (0.0239)$$

for normal (inverted) mass hierarchy

Capozzi et al, arXiv:1312.2878 [hep-ph]

Assumptions

Let us assume that neutrnio all the observables are measured with some uncetainties

$$m_{0\nu\beta\beta}^{\rm obs} = m_{0\nu\beta\beta}^{(0)} \pm \sigma_{0\nu\beta\beta} \longleftarrow \text{neutrinoless double beta decay}$$

$$\Sigma^{\rm obs} = \Sigma^{(0)} \pm \sigma_{\Sigma} \longleftarrow \text{cosmology}$$

$$m_{\beta}^{\rm obs} = m_{\beta}^{(0)} \pm \sigma_{\beta} \longleftarrow \text{tritium beta decay}$$

$$\sigma_\Sigma = 0.05 \text{ eV}, \quad \sigma_\beta = 0.06 \text{ eV}, \quad \sigma_{0\nu\beta\beta} = 0.01 \text{ eV}$$

Assumptions

Let us assume that neutrnio all the observables are measured with some uncetainties

$$m_{0\nu\beta\beta}^{\rm obs} = m_{0\nu\beta\beta}^{(0)} \pm \sigma_{0\nu\beta\beta} \longleftarrow$$ neutrinoless double beta decay

$$\Sigma^{\rm obs} = \Sigma^{(0)} \pm \sigma_\Sigma \longleftarrow$$ cosmology

$$m_\beta^{\rm obs} = m_\beta^{(0)} \pm \sigma_\beta \longleftarrow$$ tritium beta decay

to fully cover inverted hierarchy regime

$$\sigma_\Sigma = 0.05 \text{ eV}, \quad \sigma_\beta = 0.06 \text{ eV}, \quad \sigma_{0\nu\beta\beta} = 0.01 \text{ eV}$$

minimum of $\Sigma \sim \sqrt{|\Delta m_{32}^2|}$

KATRIN

Estimation of sensitivity for $m_{0\nu\beta\beta}$

$$m_{0\nu\beta\beta} = \frac{m_e}{\sqrt{T_{1/2}^{0\nu} G_{0\nu} \left|\mathcal{M}^{(0\nu)}\right|^2}}$$

signal

$$N_{0\nu\beta\beta} = \varepsilon_{\rm det} \frac{m_X N_A}{W_X} \left[1 - \exp\left(-\frac{t_{\rm exp} \ln 2}{T_{1/2}^{0\nu}}\right)\right] \simeq \frac{\varepsilon_{\rm det} N_A m_X t_{\rm exp} \ln 2}{W_X T_{1/2}^{0\nu}}$$

m_X : mass of isotope X

W_X : molecular weight of X

N_A : Avogadro's number

$\varepsilon_{\rm det}$: detection efficiency

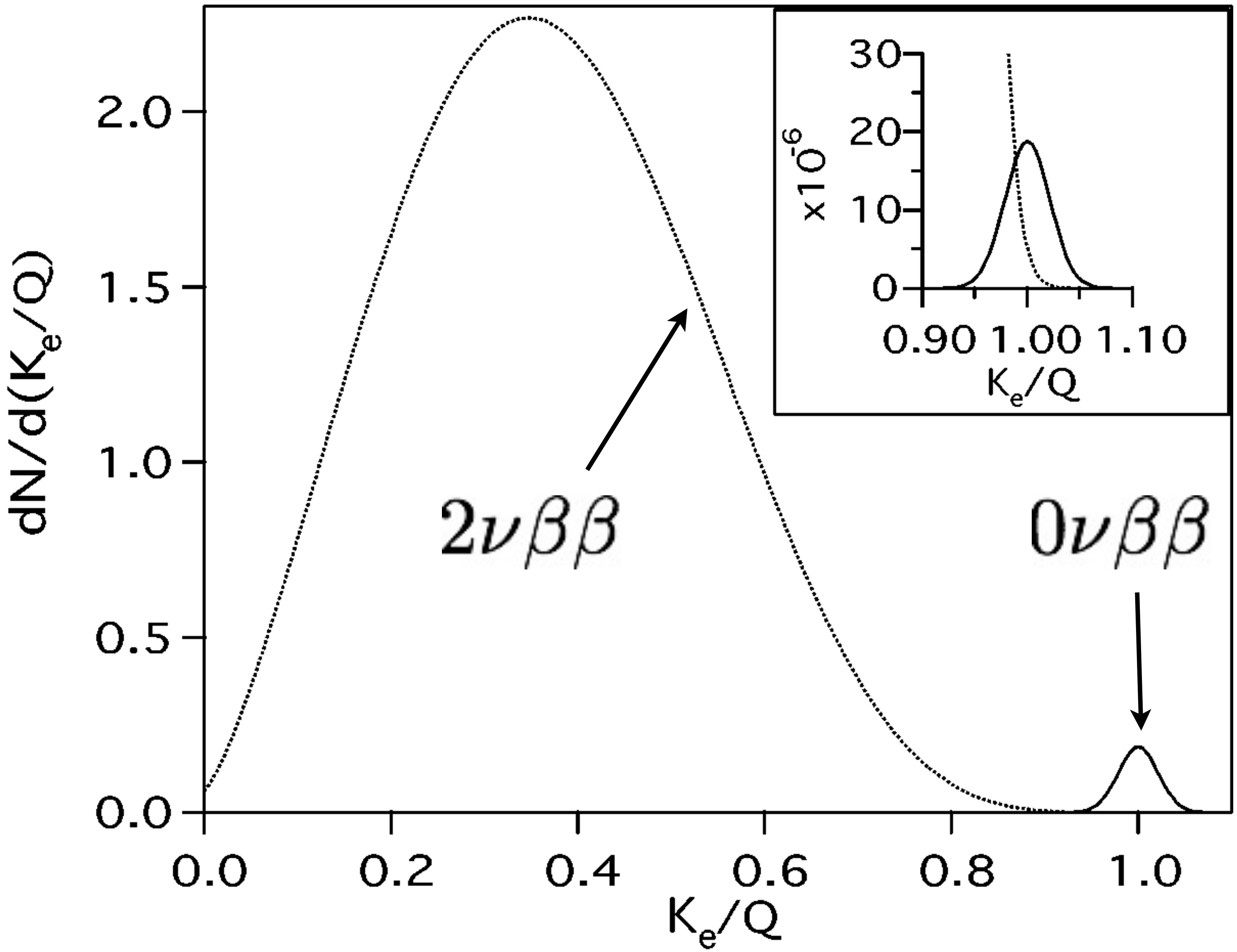
$t_{\rm exp}$: exposure of the experiment

$$N_{\rm BG} = b \Delta E m_X t_{\rm exp}$$: background

b : background count rate, usually measured in $\mathrm{keV^{-1}\ kg^{-1}\ yr^{-1}}$

ΔE : energy window (energy resolution)

Energy spectra for $2\nu\beta\beta$ and $0\nu\beta\beta$ decays



Estimation of sensitivity for $m_{0\nu\beta\beta}$

(1) Background dominated case

$$N_{0\nu\beta\beta} \sim \sqrt{N_{\mathrm{BG}}}$$

$$\longrightarrow \quad T_{1/2}^{0\nu} \sim \frac{\varepsilon_{\mathrm{det}} N_A m_X t_{\mathrm{exp}} \ln 2}{W_X \sqrt{b \Delta E m_X t_{\mathrm{exp}}}} = \frac{\varepsilon_{\mathrm{det}} N_A \ln 2}{W_X} \sqrt{\frac{m_X t_{\mathrm{exp}}}{b \Delta E}}$$

$$m_{0\nu\beta\beta}^{\min} \sim \frac{m_e}{\sqrt{G_{0\nu} \left|\mathcal{M}^{(0\nu)}\right|^2 \ln 2}} \left[\frac{W_X}{\varepsilon_{\mathrm{det}} N_A}\right]^{\frac{1}{2}} \left[\frac{b \Delta E}{m_X t_{\mathrm{exp}}}\right]^{\frac{1}{4}}$$

For ^{76}Ge

$$m_{0\nu\beta\beta}^{\min} \sim 0.12 \quad \left[\frac{5.0}{\mathcal{M}^{(0\nu)}}\right] \left[\frac{b}{0.01\ \mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr}}\right]^{\frac{1}{4}} \left[\frac{\Delta E}{3.5\ \mathrm{keV}}\right]^{\frac{1}{4}} \left[\frac{100\ \mathrm{kg} \cdot \mathrm{yr}}{\varepsilon_{\mathrm{det}}^2 \cdot m_{\mathrm{Ge}} \cdot t_{\mathrm{exp}}}\right]^{\frac{1}{4}} \mathrm{eV},$$

For ^{136}Xe

$$m_{0\nu\beta\beta}^{\min} \sim 0.24 \quad \left[\frac{3.0}{\mathcal{M}^{(0\nu)}}\right] \left[\frac{b}{0.01\ \mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr}}\right]^{\frac{1}{4}} \left[\frac{\Delta E}{100\ \mathrm{keV}}\right]^{\frac{1}{4}} \left[\frac{100\ \mathrm{kg} \cdot \mathrm{yr}}{\varepsilon_{\mathrm{det}}^2 \cdot m_{\mathrm{Xe}} \cdot t_{\mathrm{exp}}}\right]^{\frac{1}{4}} \mathrm{eV}$$

Estimation of sensitivity for $m_{0\nu\beta\beta}$

(2) Signal dominated case

$$T_{1/2}^{0\nu} = \frac{\varepsilon_{\rm det} n_X t_{\rm exp} \ln 2}{N_{0\nu\beta\beta}}$$

$$\longrightarrow \quad \delta(T_{1/2}^{0\nu}) \sim T_{1/2}^{0\nu} \frac{\delta(N_{0\nu\beta\beta})}{N_{0\nu\beta\beta}} \sim T_{1/2}^{0\nu} \frac{1}{\sqrt{N_{0\nu\beta\beta}}}$$

$$\delta(m_{0\nu\beta\beta}) \sim \frac{1}{2}\, m_{0\nu\beta\beta}^{(0)}\, \frac{\delta(T_{1/2}^{0\nu})}{T_{1/2}^{0\nu}} \sim \frac{1}{2}\, m_{0\nu\beta\beta}^{(0)}\, \frac{1}{\sqrt{N_{0\nu\beta\beta}}} \sim \frac{m_e}{2\sqrt{G_{0\nu}\left|\mathcal{M}^{(0\nu)}\right|^2 \varepsilon_{\rm det}(m_X N_A/W_X) t_{\rm exp} \ln 2}}.$$

For ^{76}Ge

$$\delta(m_{0\nu\beta\beta}) \sim 0.06 \left[\frac{100\ {\rm kg\cdot yr}}{\varepsilon_{\rm det}\cdot m_{\rm Ge}\cdot t_{\rm exp}}\right]^{\frac{1}{2}} \left[\frac{5.0}{\mathcal{M}^{(0\nu)}}\right] \ {\rm eV},$$

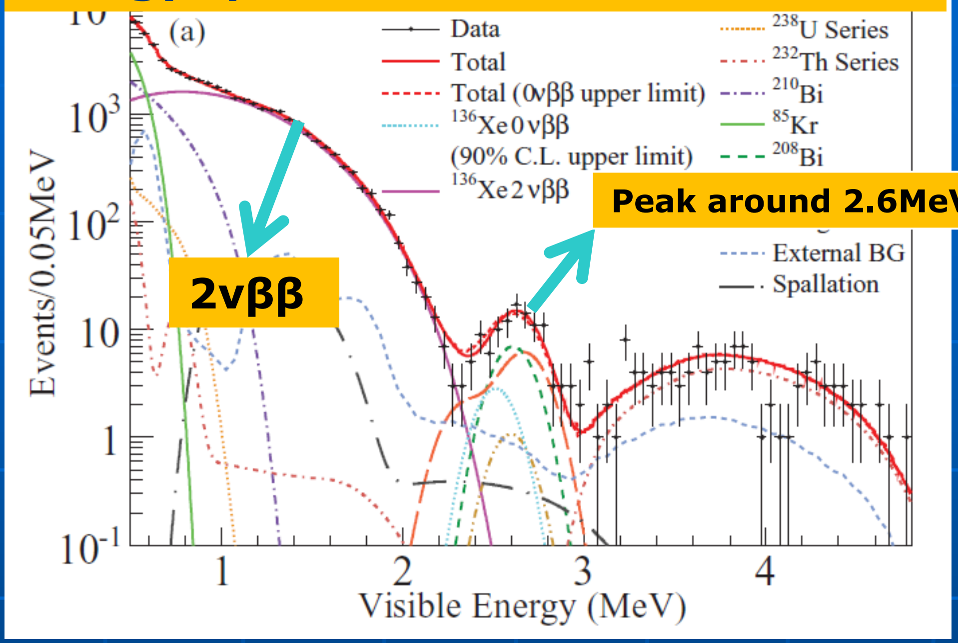
For ^{136}Xe

$$\delta(m_{0\nu\beta\beta}) \sim 0.04 \left[\frac{100\ {\rm kg\cdot yr}}{\varepsilon_{\rm det}\cdot m_{\rm Xe}\cdot t_{\rm exp}}\right]^{\frac{1}{2}} \left[\frac{3.0}{\mathcal{M}^{(0\nu)}}\right] \ {\rm eV}$$

Case of KamLAND-Zen

Result of 2νββ decay halflife

Energy spectrum after event selection



Event selection

- Fiducial cut : R<1.2m
- 2ms veto after muon
- remove consecutive events within 3ms for Bi-Po rejection(99.97% rejection for ^{214}Bi)
- Anti-nu CC reaction cut
- vertex-time-charge test to cut noise events

2νββ life

	exposure	2νββ life
1st result Phys.Rev.C85,045504(2012)	77.6days 129kg of ^{136}Xe	2.38 0.02(stat.) 0.14(sys.) 10^{21} yrs.
Updated Result arXiv:1205.6372	112.3days 125kg of ^{136}Xe	2.30 0.02(stat.) 0.12(sys.) 10^{21} yrs.

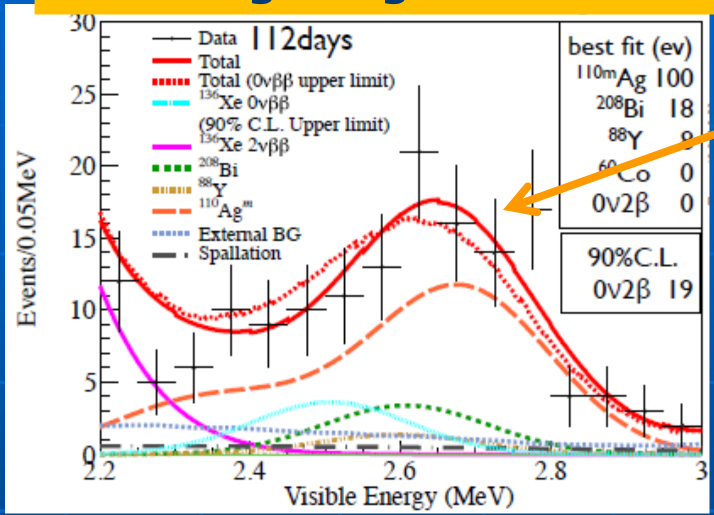
Consistent with the EXO-200 results arXiv:1205.5608
($T_{1/2}$=2.23   0.017(stat)   0.22(syst) 10^{21} years)

Case of KamLAND-Zen

Limit on 0νββ decay

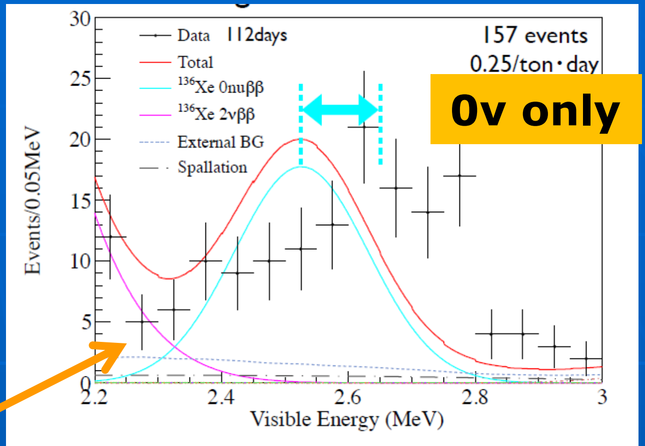
112.3days measurement

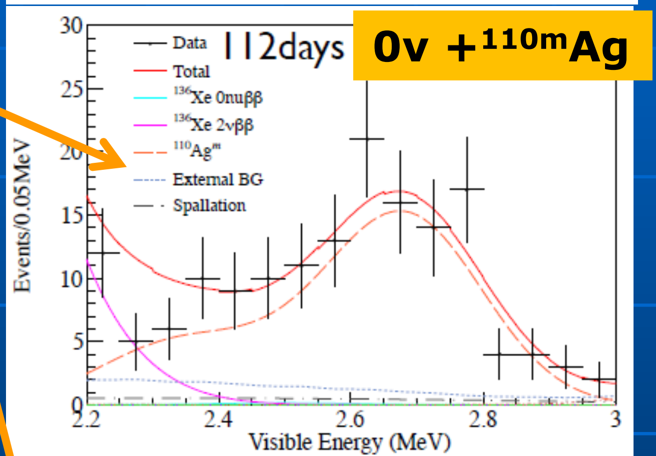
Including 4 b.g. candidates



E=2.2-3.0MeV

	χ^2
0ν + 4b.g. candidates	11.6
0ν only	85
0ν + ^{110m}Ag	13.1
0ν + ^{208}Bi	22.7
0ν + ^{88}Y	22.2
0ν + ^{60}Co	82.9

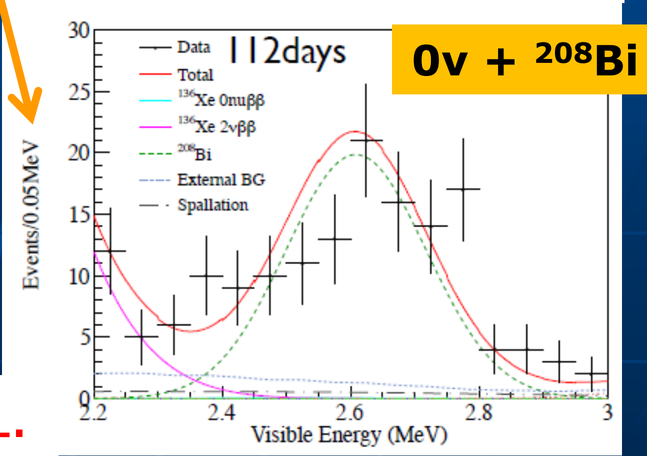




^{110m}Ag is favored to explain the 2.6MeV peak.

Lower limit for ^{136}Xe 0νββ decay half life

	exposure	0νββ limit
Updated Result arXiv:1205.6372	**112.3days 125kg of 136Xe**	**> 6.2 10^{24} yrs. (90% C.L.)**



Upper limit $\langle m_{\beta\beta} \rangle$<0.26~0.54 eV @90% C.L.

Definition of χ^2 function

$$\chi^2 \equiv \min\left\{\left[\frac{\Sigma^{(0)}-\Sigma^{\rm fit}}{\sigma_\Sigma}\right]^2+\left[\frac{m_\beta^{(0)}-m_\beta^{\rm fit}}{\sigma_\beta}\right]^2+\left[\frac{\xi\, m_{0\nu\beta\beta}^{(0)}-m_{0\nu\beta\beta}^{\rm fit}}{\sigma_{0\nu\beta\beta}}\right]^2\right\}$$

To take into account the uncertainty of the nuclear matrix element, we vary ξ

$$\xi \equiv \frac{\mathcal{M}_0^{(0\nu)}}{\mathcal{M}^{(0\nu)}}$$

reference NME value (known) — $\mathcal{M}_0^{(0\nu)}$

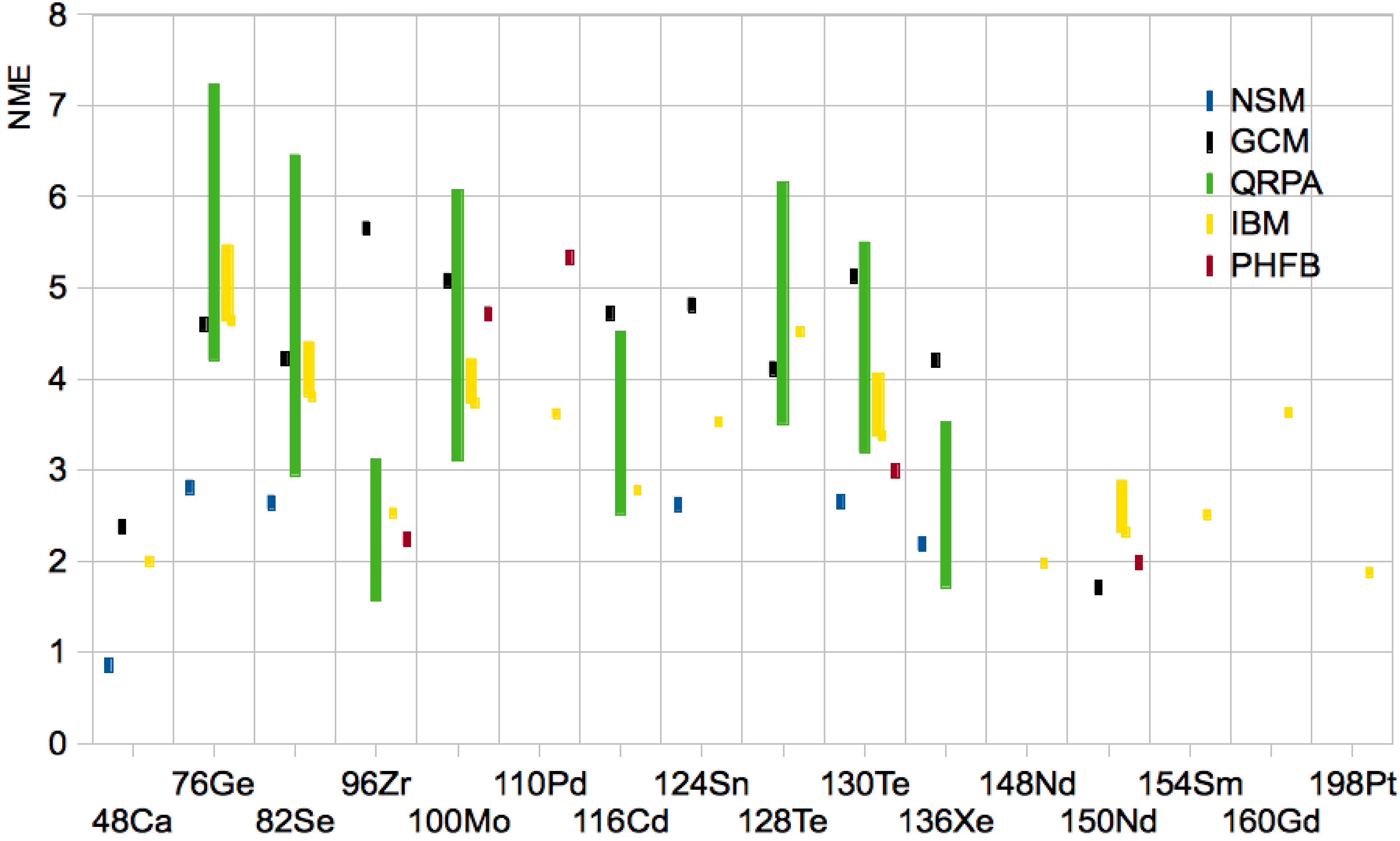
true NME value (unknown) — $\mathcal{M}^{(0\nu)}$

$$\frac{1}{\sqrt{r_{\rm NME}}} \leq \xi \leq \sqrt{r_{\rm NME}} \qquad r_{\rm NME} \equiv \mathcal{M}_{\rm max}^{(0\nu)}/\mathcal{M}_{\rm min}^{(0\nu)}$$

$$\mathcal{M}_{\rm min}^{(0\nu)} \leq \mathcal{M}^{(0\nu)} \leq \mathcal{M}_{\rm max}^{(0\nu)} \qquad \mathcal{M}_0^{(0\nu)} \equiv \left(\mathcal{M}_{\rm max}^{(0\nu)}\mathcal{M}_{\rm min}^{(0\nu)}\right)^{1/2}$$

we will consider $r_{\rm NME}$ = 2, 1.5, 1.3 and 1.1

NME values calculated by different models



Cremonesi and Pavan, arXiv:1310.4692 [physics.ins-det]

How can we measure Majorana CP phase?

in the degenerate regime,

$$m_{0\nu\beta\beta} \simeq c_{13}^2 m_0 \times \left[1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\alpha_{21}}{2}\right)\right]^{\frac{1}{2}}$$

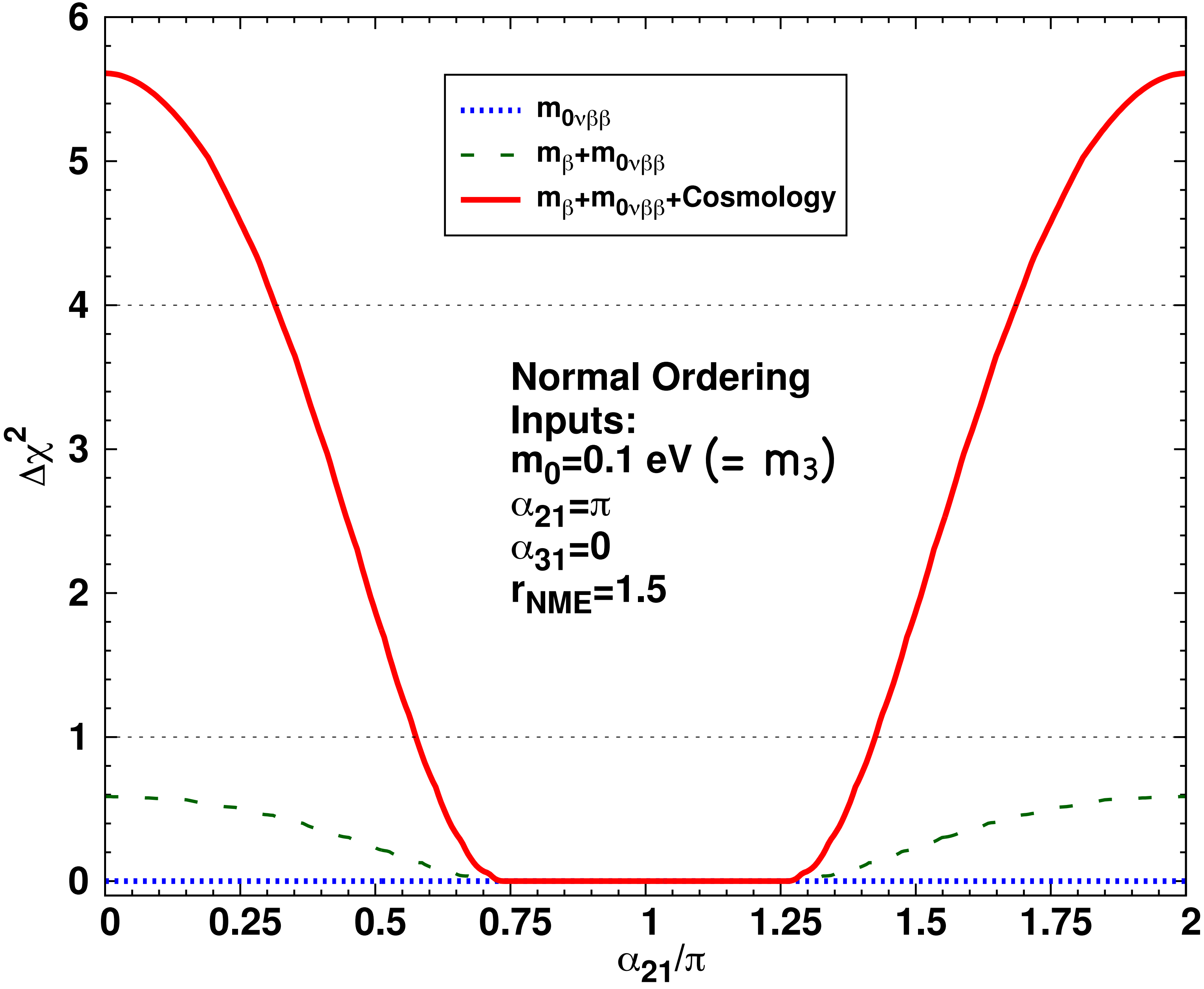
if m_0 is unknown, no matter how accurately $m_{0\nu\beta\beta}$ is measured (which is not possible due to NME uncertainty), it is impossible to determine (constrain) α_{21} !

↓

independent information on m_0 is needed,

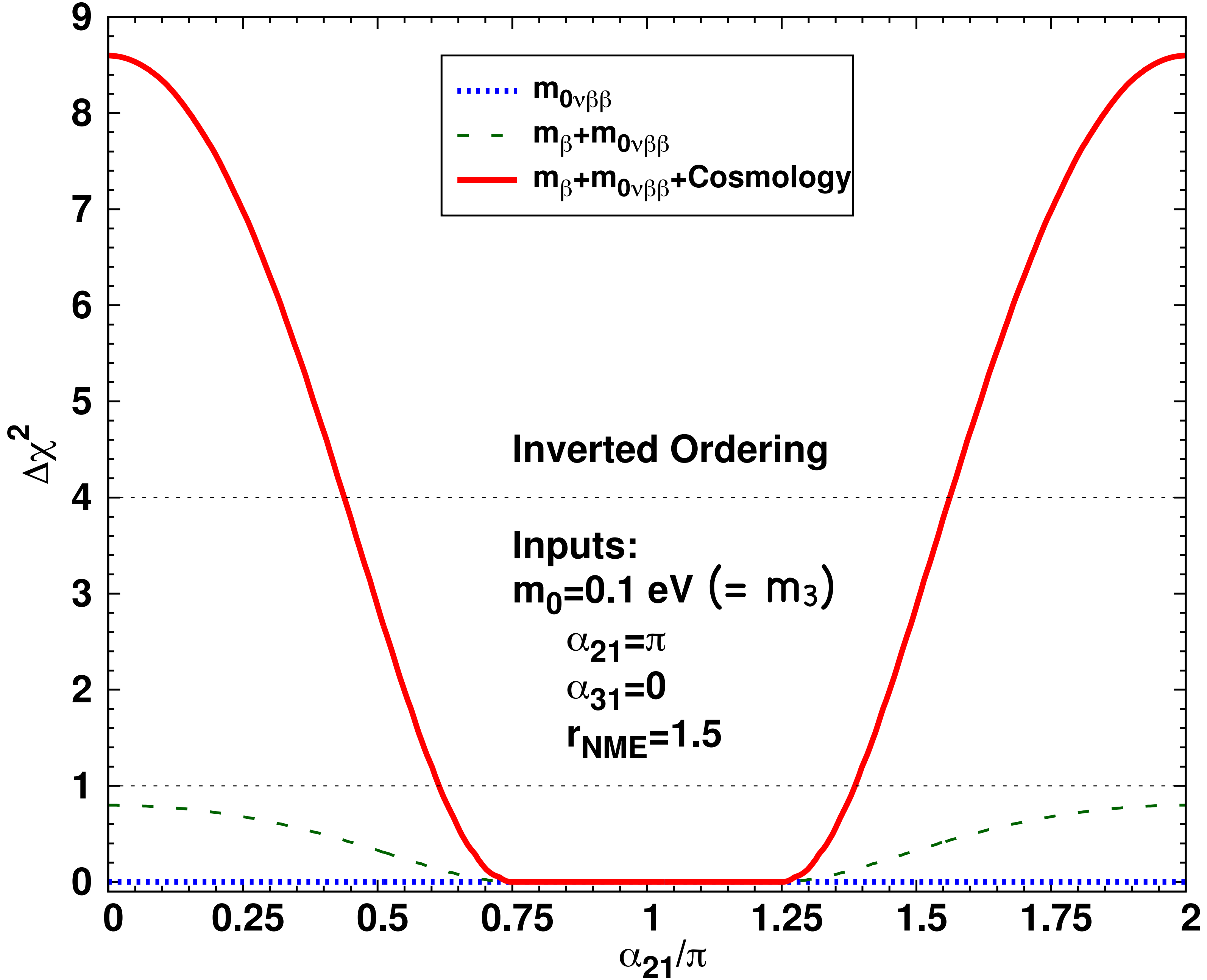
from cosmology and beta decay experiment

$\Delta\chi^2 \equiv \chi^2 - \chi^2_{\min}$ as a function of α_{21}



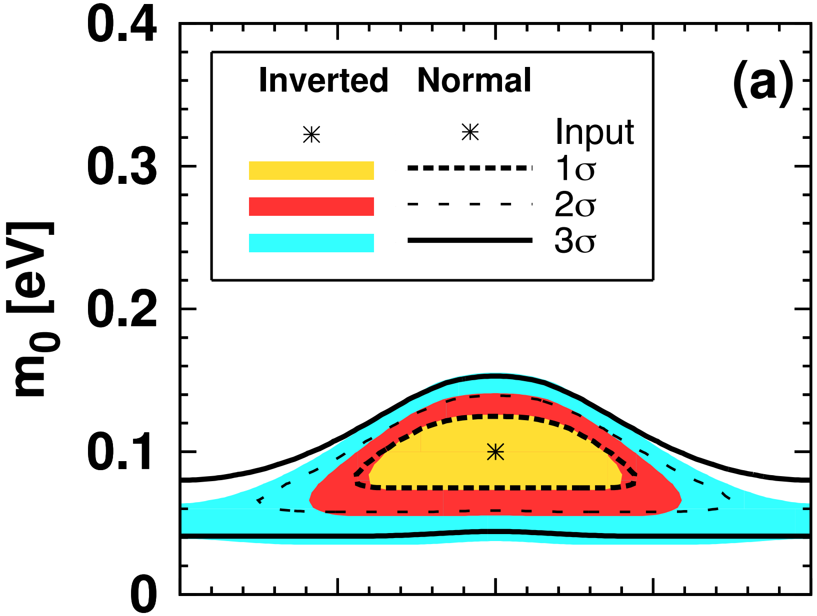
strong synergy of $0\nu\beta\beta$ with cosmology !

$\Delta\chi^2 \equiv \chi^2 - \chi^2_{\min}$ as a function of α_{21}



strong synergy of $0\nu\beta\beta$ with cosmology !

Allowed Regions (I)



Inputs:

r_{NME}=1.5

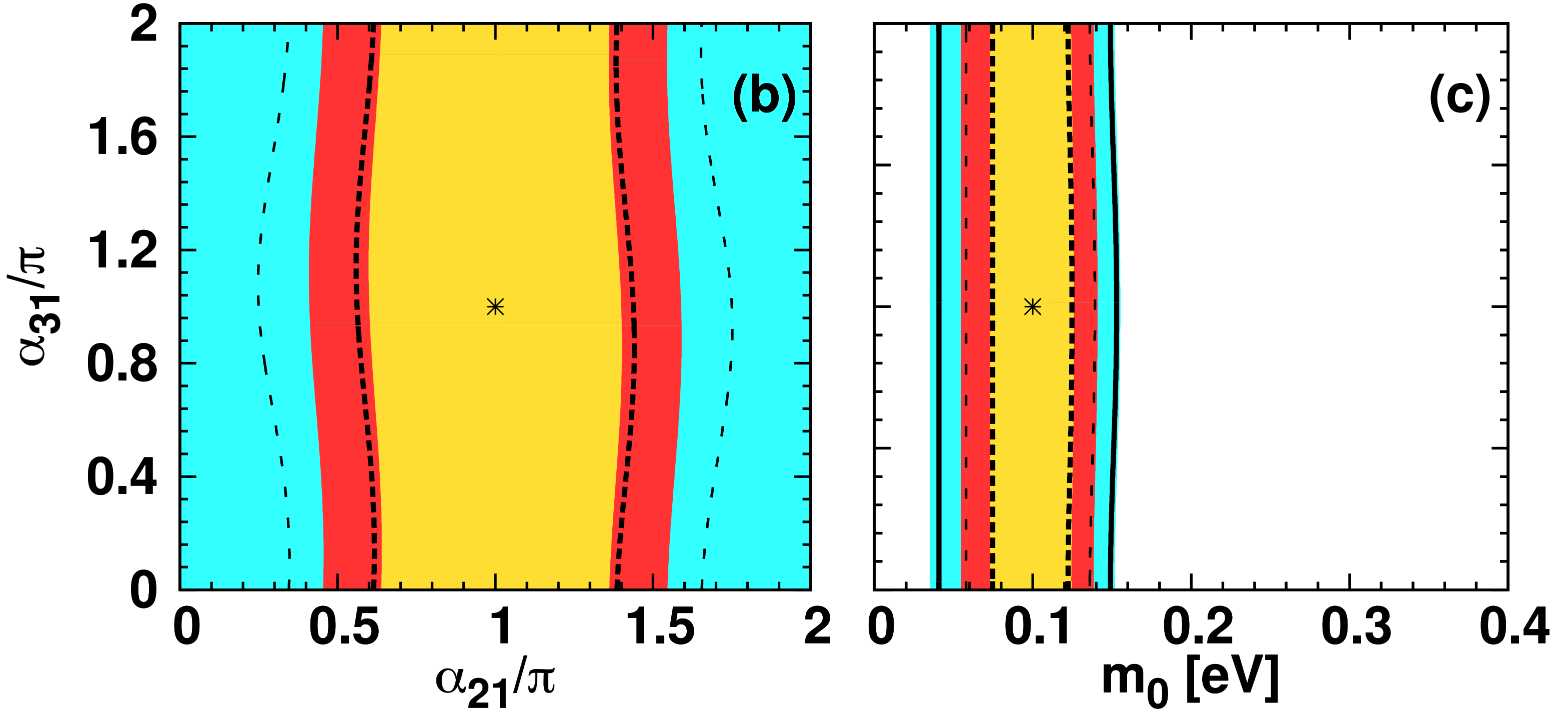
$m_{0\nu\beta\beta}$=0.041(0.036)± 0.01 eV

m_{β}=0.11(0.1) ± 0.06 eV

Σ= 0.32(0.31)± 0.05 eV

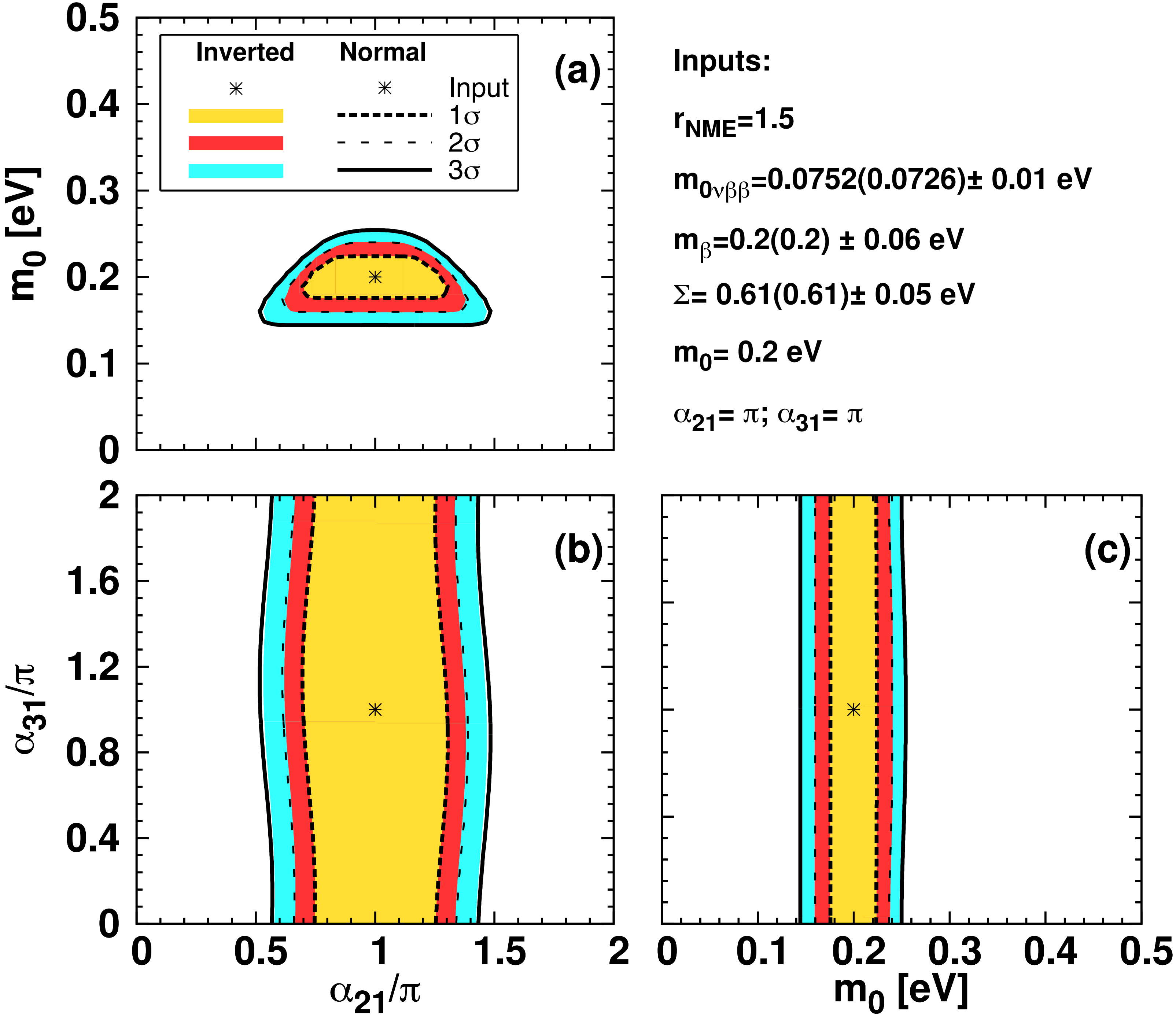
m_0= 0.1 eV

$\alpha_{21}=\pi$; $\alpha_{31}=\pi$



symmetric behaviours due to $m_{0\nu\beta\beta}(m_0, \alpha_{21}, \alpha_{32}) = m_{0\nu\beta\beta}(m_0, 2\pi - \alpha_{21}, 2\pi - \alpha_{32})$

Allowed Regions (II)



Inputs:

r_{NME}=1.5

$m_{0\nu\beta\beta}$=0.0752(0.0726)± 0.01 eV

m_{β}=0.2(0.2) ± 0.06 eV

Σ= 0.61(0.61)± 0.05 eV

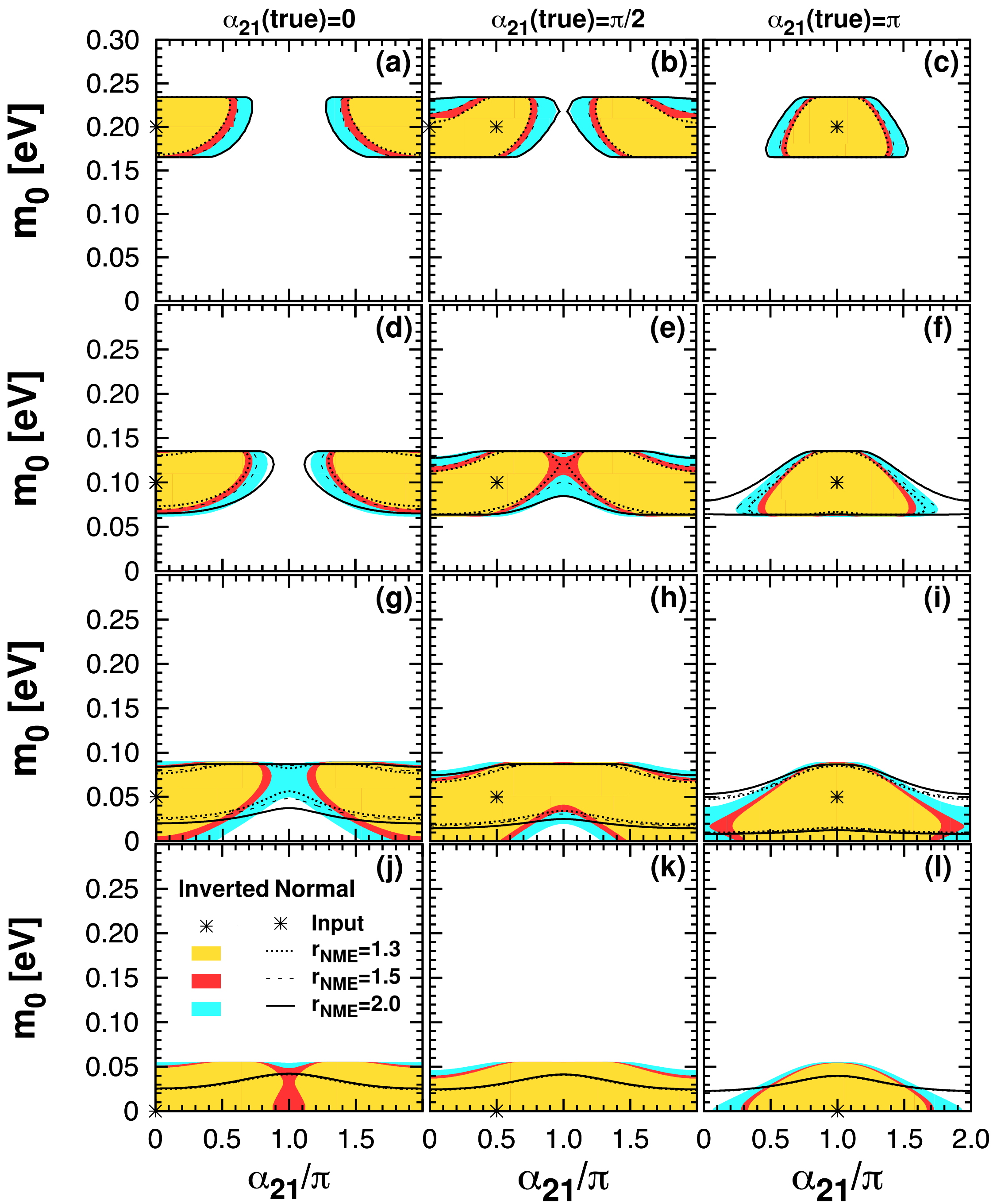
m_0= 0.2 eV

$\alpha_{21} = \pi$; $\alpha_{31} = \pi$

symmetric behaviours due to $m_{0\nu\beta\beta}(m_0, \alpha_{21}, \alpha_{32}) = m_{0\nu\beta\beta}(m_0, 2\pi - \alpha_{21}, 2\pi - \alpha_{32})$

Allowed Regions (III) $\alpha_{31}(\text{true}) = 0$

2 σ CL



$\longleftarrow m_0 = 0.2$ eV

$\longleftarrow m_0 = 0.1$ eV

$\longleftarrow m_0 = 0.05$ eV

$\longleftarrow m_0 = 0$ eV

symmetric behaviours due to $m_{0\nu\beta\beta}(m_0, \alpha_{21}, \alpha_{32}) = m_{0\nu\beta\beta}(m_0, 2\pi - \alpha_{21}, 2\pi - \alpha_{32})$

CP exclusion fraction, f_{cpx}

Machado et al, JHEP 1405, 109 (2014)
Winter, PRD70,033006(2004)
Huber et al, JHEP05,020 (2005)

what is f_{cpx} ?

For a given set of input (true) parameters,

$f_{cpx} \equiv$ fraction of CP phase which is exluded at certain confidence level

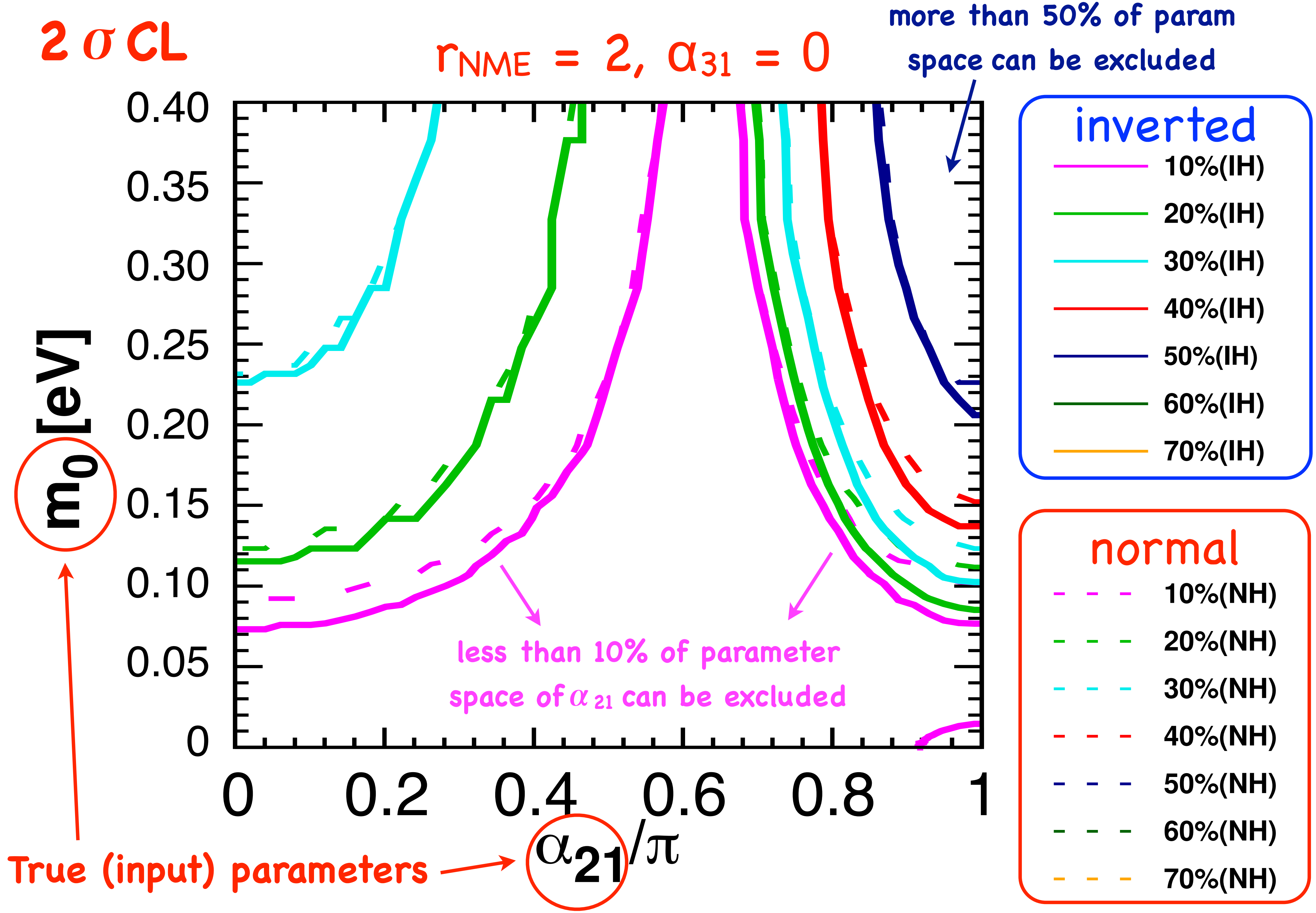
For example, if $0.2\pi \leq \alpha_{21} \leq 1.4\pi$

$f_{cpx} = 1-(1.4\pi-0.2\pi)/2\pi = 0.4$ (or 40%)

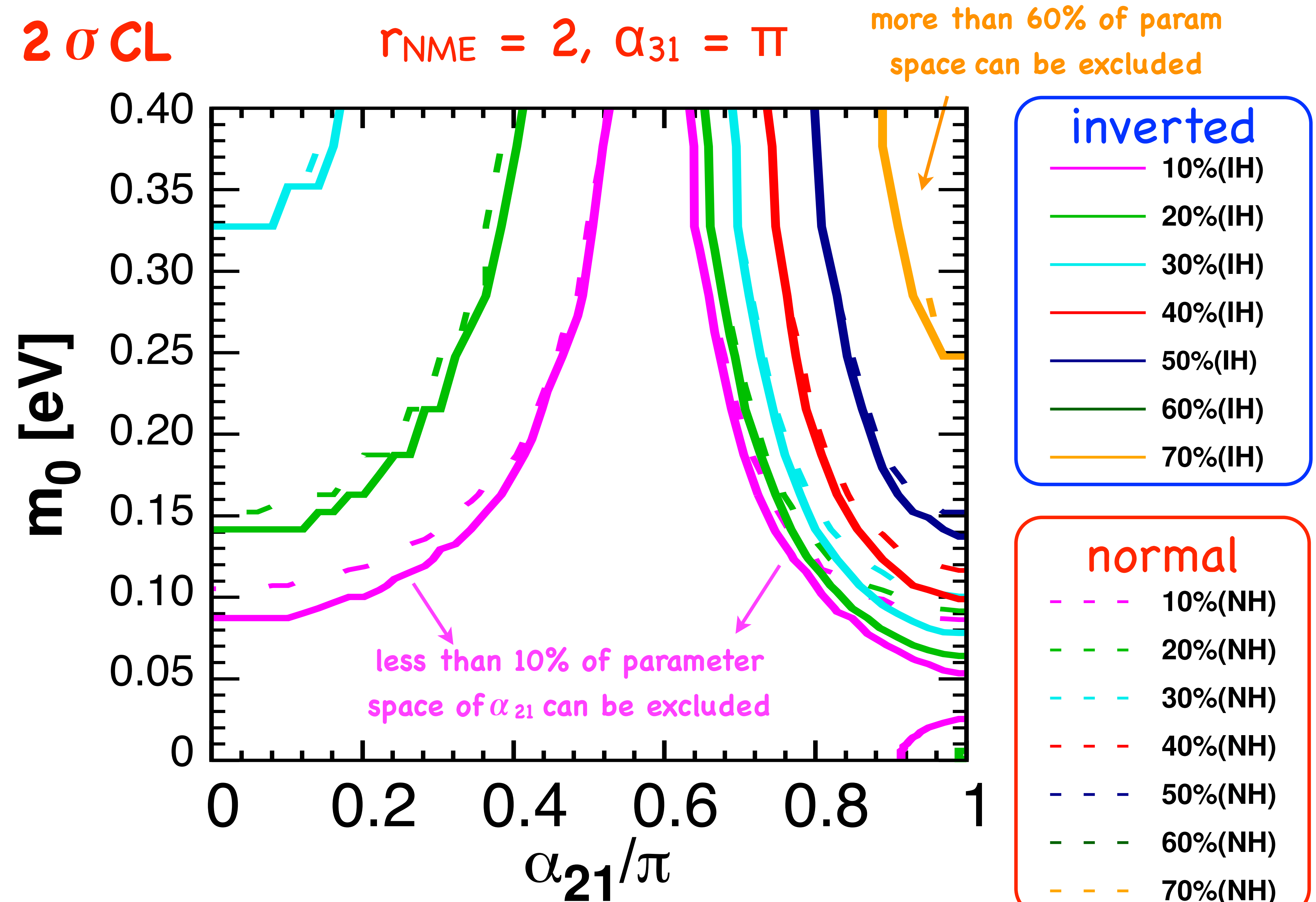
$f_{cpx} \equiv$ 1-(allowed fraction)

larger f_{cpx} $\longrightarrow$ better sensitivity

Iso-contours of CP exclusion fraction, f_{cpx}



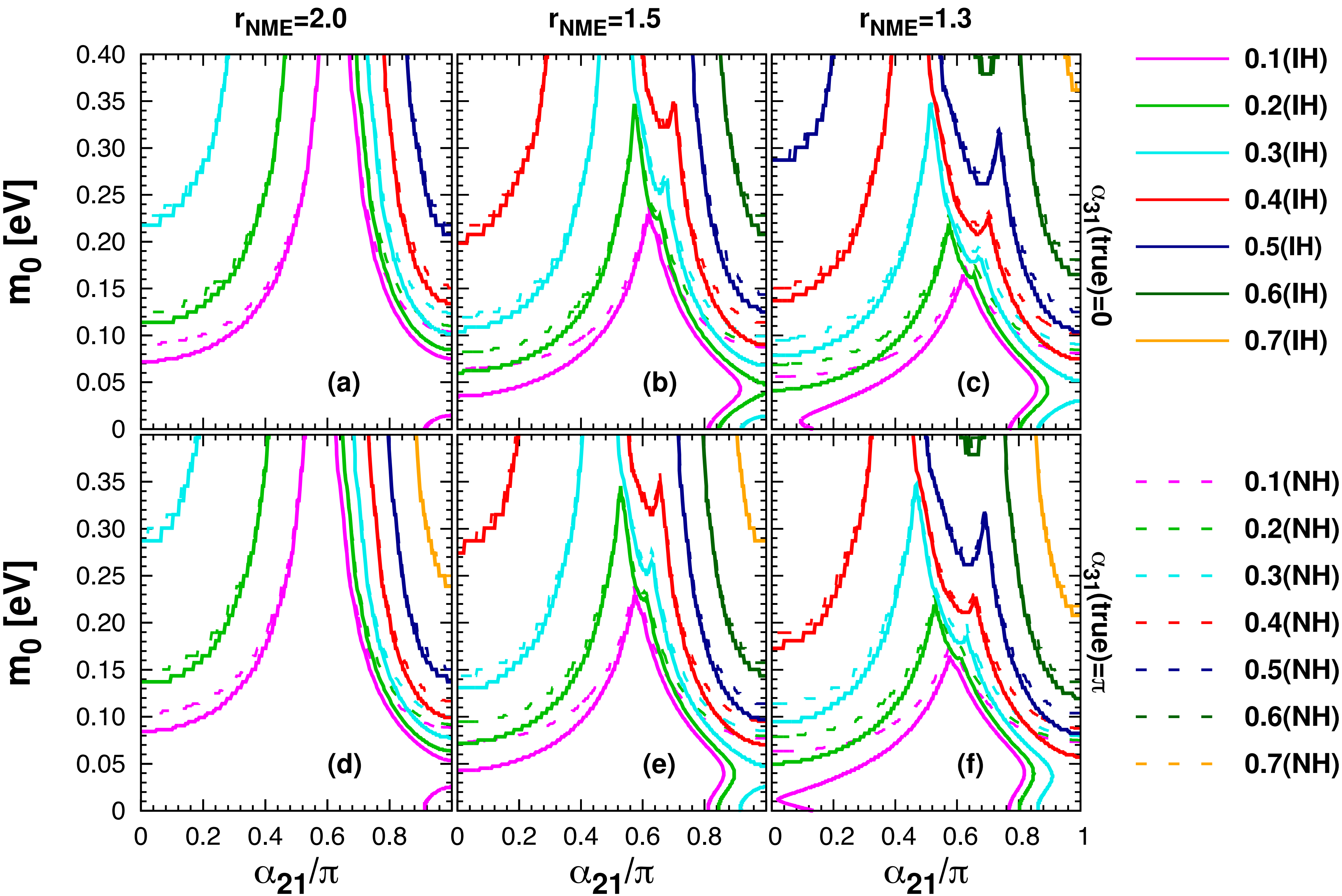
Iso-contours of CP exclusion fraction, f_{cpx}



Iso-contours of CP exclusion fraction, f_{cpx} (I)

$\sigma_\Sigma = 0.05$ eV, $\sigma_\beta = 0.06$ eV, $\sigma_{0\nu\beta\beta} = 0.01$ eV

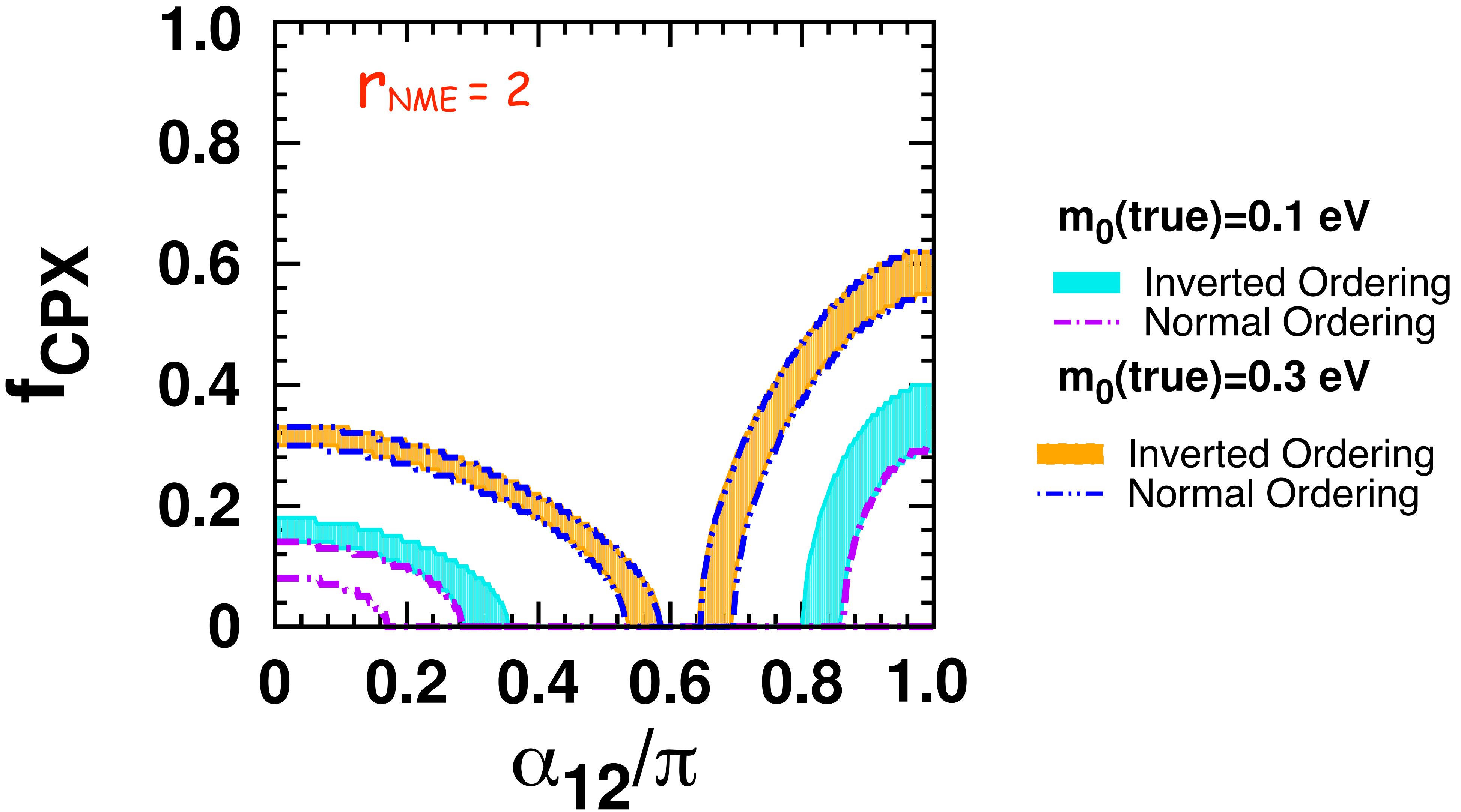
2 σ CL



for r_{NME} = 1.5, at m_0 = 0.1 eV, f_{cpx} = 10-50%

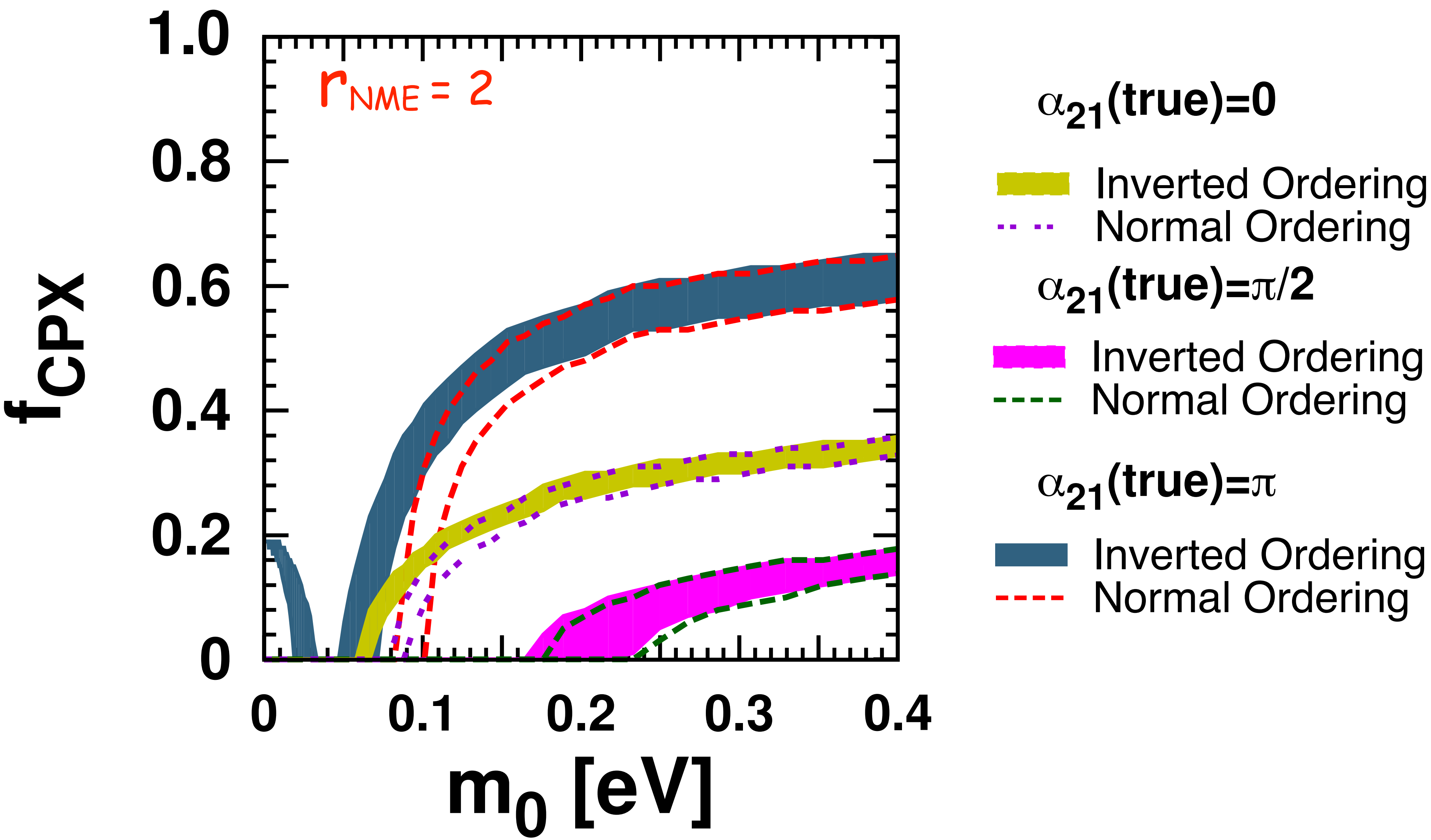
CP exclusion fraction, f_{cpx}, as a function of α_{21}

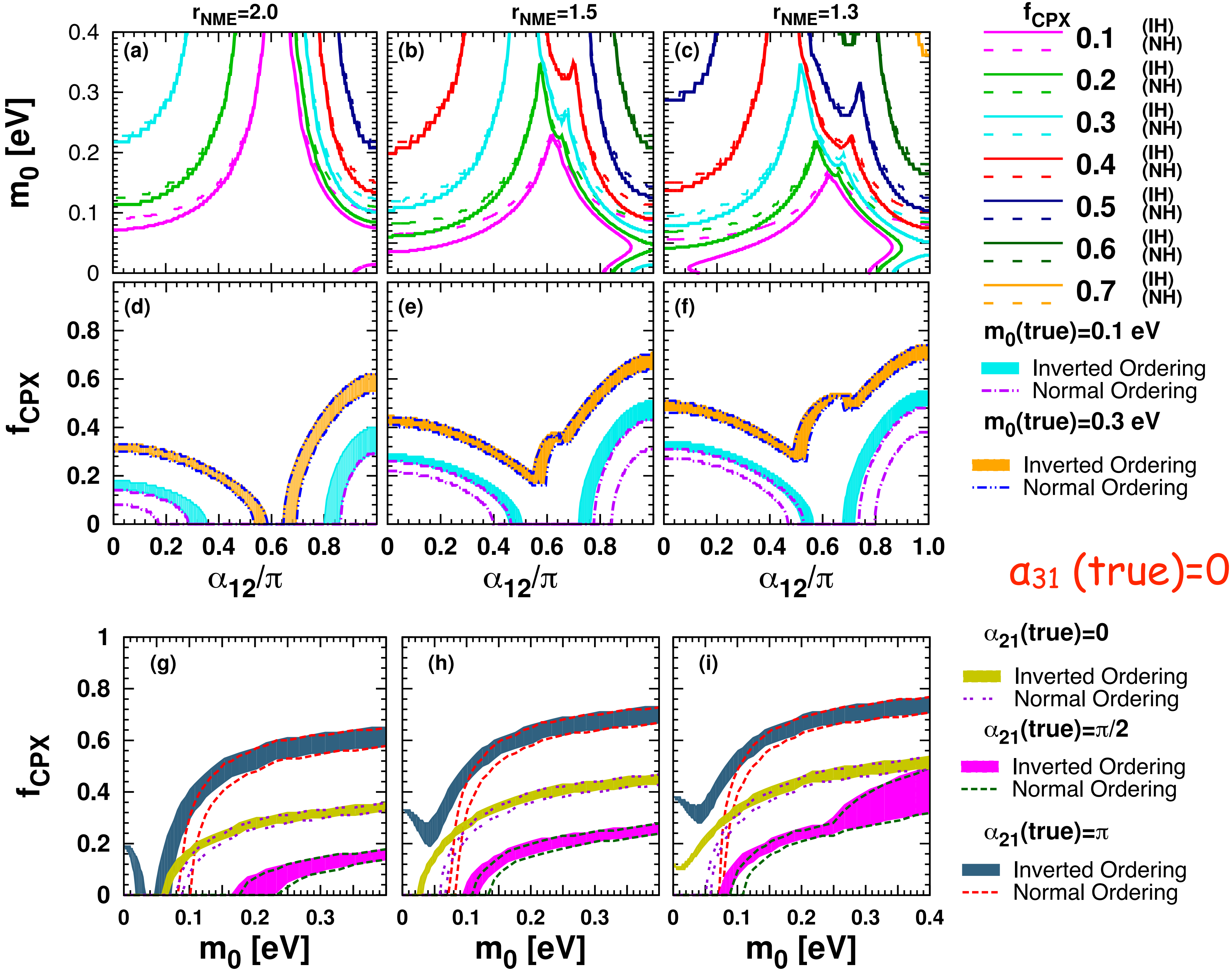
$\sigma_\Sigma = 0.05$ eV, $\sigma_\beta = 0.06$ eV, $\sigma_{0\nu\beta\beta} = 0.01$ eV **2 σ CL**



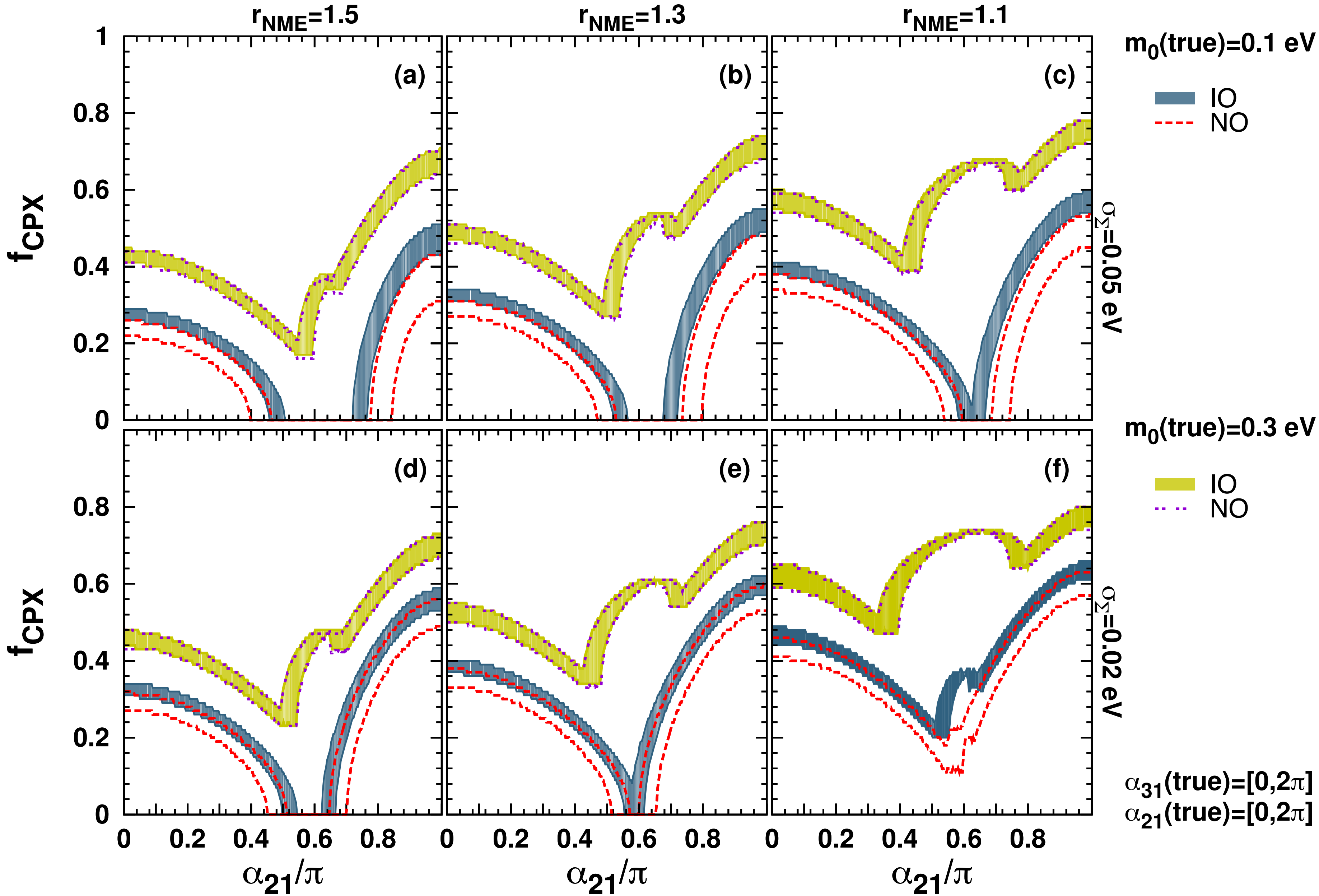
CP exclusion fraction, f_{cpx}, as a function of m_0

$\sigma_\Sigma = 0.05$ eV, $\sigma_\beta = 0.06$ eV, $\sigma_{0\nu\beta\beta} = 0.01$ eV **2 σ CL**

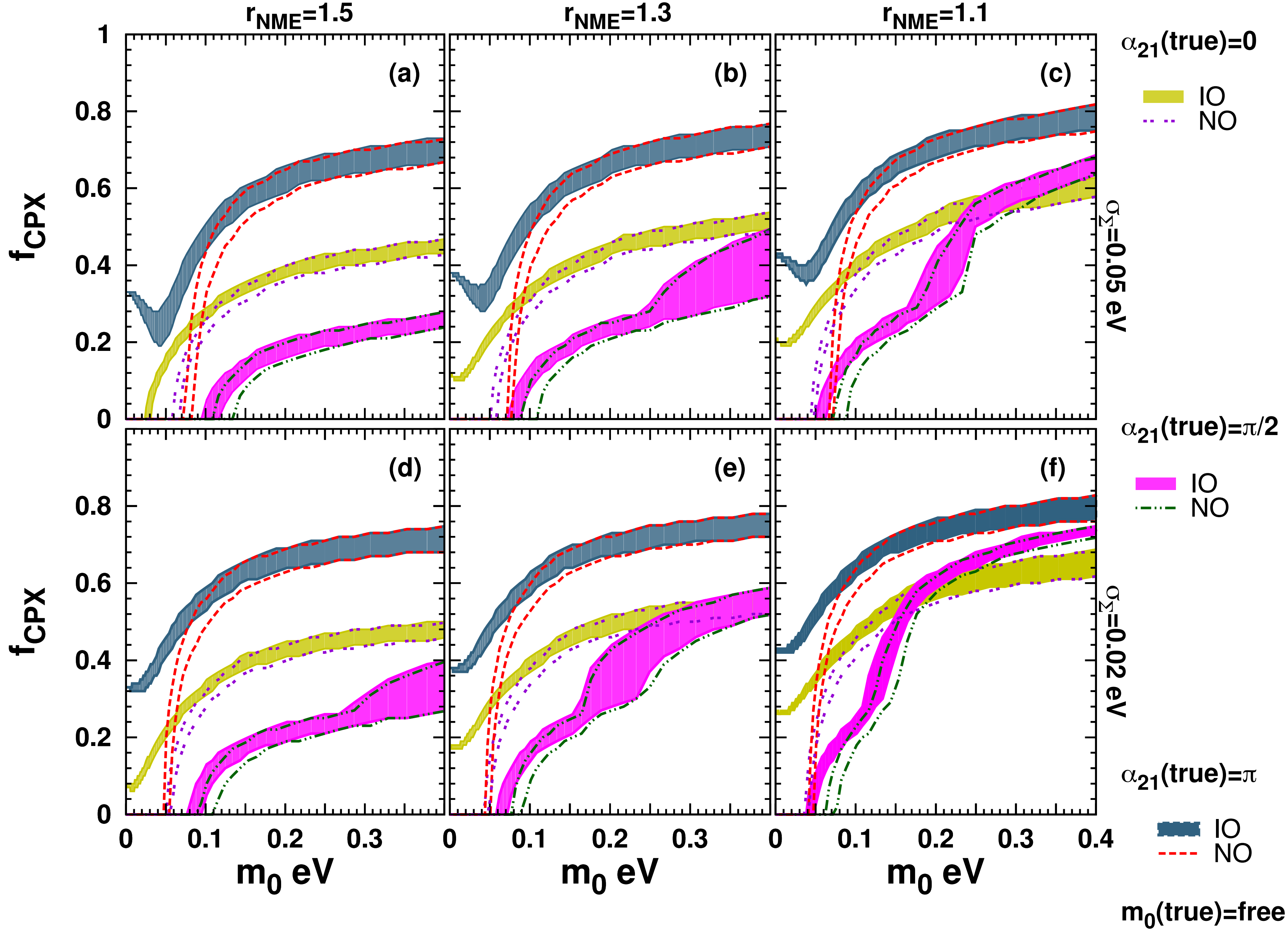




r_{NME}=2.0
r_{NME}=1.5
r_{NME}=1.3
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
m_0 [eV]
f_{CPX}
α_{12}/π
f_{CPX}
0.1 (IH) (NH)
0.2 (IH) (NH)
0.3 (IH) (NH)
0.4 (IH) (NH)
0.5 (IH) (NH)
0.6 (IH) (NH)
0.7 (IH) (NH)
m_0(true)=0.1 eV
Inverted Ordering
Normal Ordering
m_0(true)=0.3 eV
Inverted Ordering
Normal Ordering
α_{31} (true)=0
α_{21}(true)=0
Inverted Ordering
Normal Ordering
α_{21}(true)=$\pi/2$
Inverted Ordering
Normal Ordering
α_{21}(true)=π
Inverted Ordering
Normal Ordering



r_{NME}=1.5
r_{NME}=1.3
r_{NME}=1.1
m_0(true)=0.1 eV
IO
NO
σ_Σ=0.05 eV
m_0(true)=0.3 eV
IO
NO
σ_Σ=0.02 eV
α_{31}(true)=[0,2π]
α_{21}(true)=[0,2π]
(a)
(b)
(c)
(d)
(e)
(f)
f_{CPX}
f_{CPX}
α_{21}/π
α_{21}/π
α_{21}/π



r_{NME}=1.5
r_{NME}=1.3
r_{NME}=1.1
(a)
(b)
(c)
(d)
(e)
(f)
f_{CPX}
m_0 eV
0
0.2
0.4
0.6
0.8
1
0.1
0.3
α_{21}(true)=0
IO
NO
α_{21}(true)=π/2
IO
NO
α_{21}(true)=π
IO
NO
σ_Σ=0.05 eV
σ_Σ=0.02 eV
m_0(true)=free

Conclusions

We confirm very strong snergy of $0\nu\beta\beta$ and cosmological determination of neutrino masses

We identify the regions of sensitivity by using the CP exclusion fraction, f_{cpx}

assuming $\sigma_\Sigma = 0.05$ eV, $\sigma_\beta = 0.06$ eV, $\sigma_{0\nu\beta\beta} = 0.01$ eV

For m_0 = 0.1 eV, r_{NME} = 1.5,

$f_{cpx} < 50\%$ at 2σ

assuming $\sigma_\Sigma = 0.02$ eV, $\sigma_\beta = 0.06$ eV, $\sigma_{0\nu\beta\beta} = 0.01$ eV

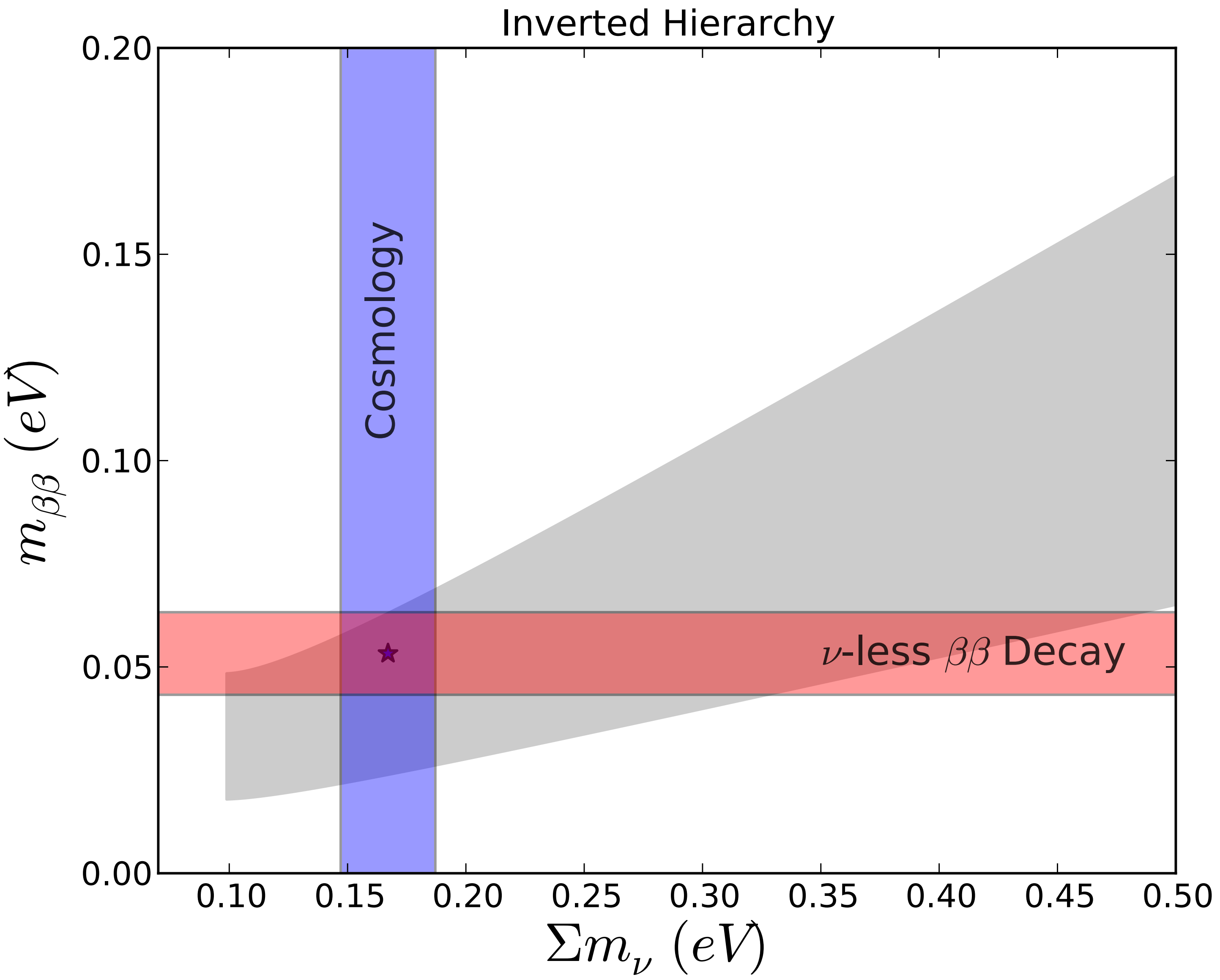
For m_0 = 0.1 eV, r_{NME} = 1.1,

$f_{cpx} < 60\%$ at 2σ

Thank you very much for your attention!

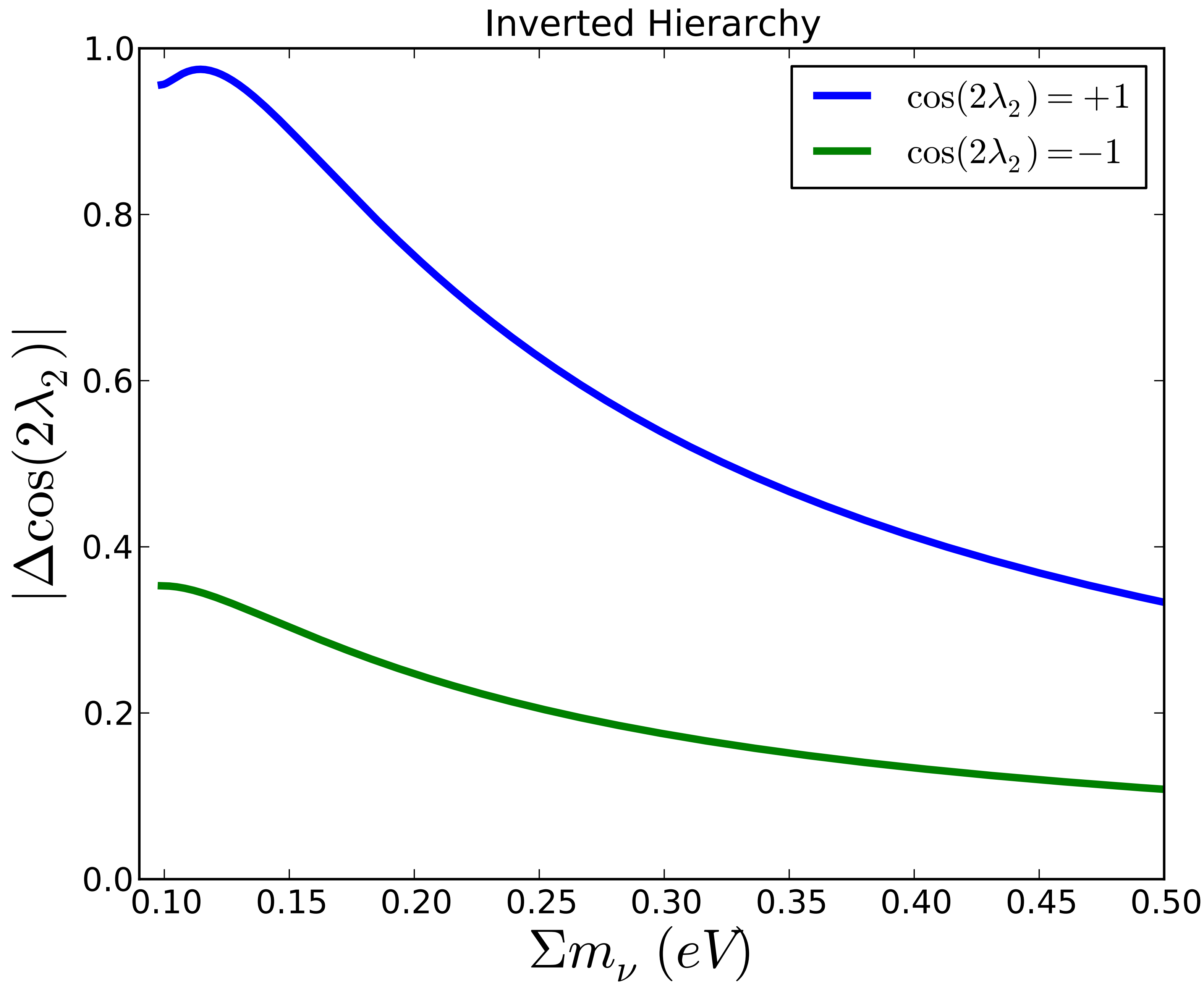
backup slides

Similar Work done by Dodelson and Lykken



Dodelson & Lykken, arXiv:1403.5173 [astro-ph.CO]

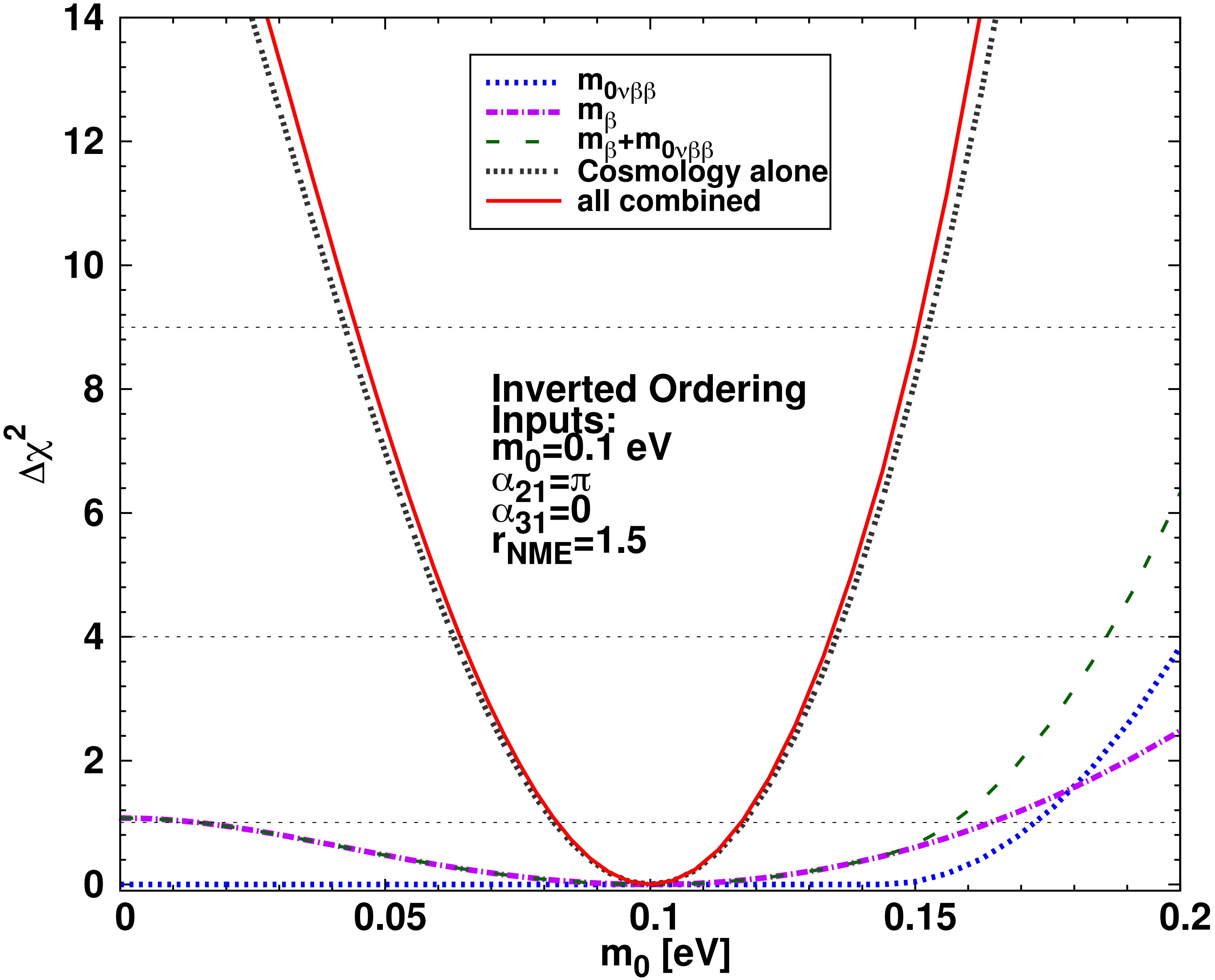
Projected 1 sigma error on $\cos(\alpha_{21})$



$2\lambda_2 = \alpha_{21}$

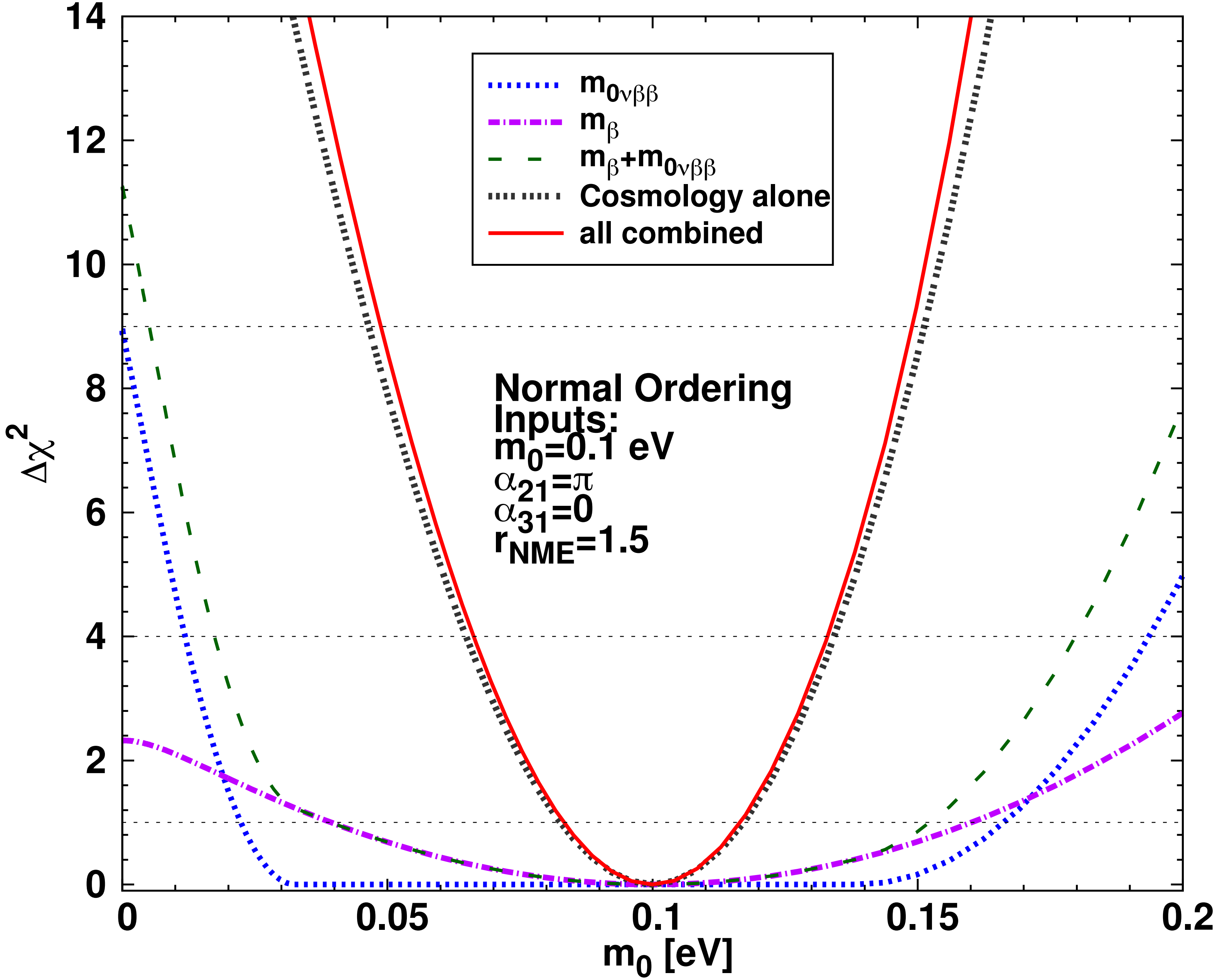
Dodelson & Lykken, arXiv:1403.5173 [astro-ph.CO]

$\Delta\chi^2 \equiv \chi^2 - \chi^2_{\rm min}$ as a function of m_0



cosmology dominates

$\Delta\chi^2 \equiv \chi^2 - \chi^2_{min}$ as a function of m_0



cosmology dominates