Neutrinos and antineutrinos in JUNO

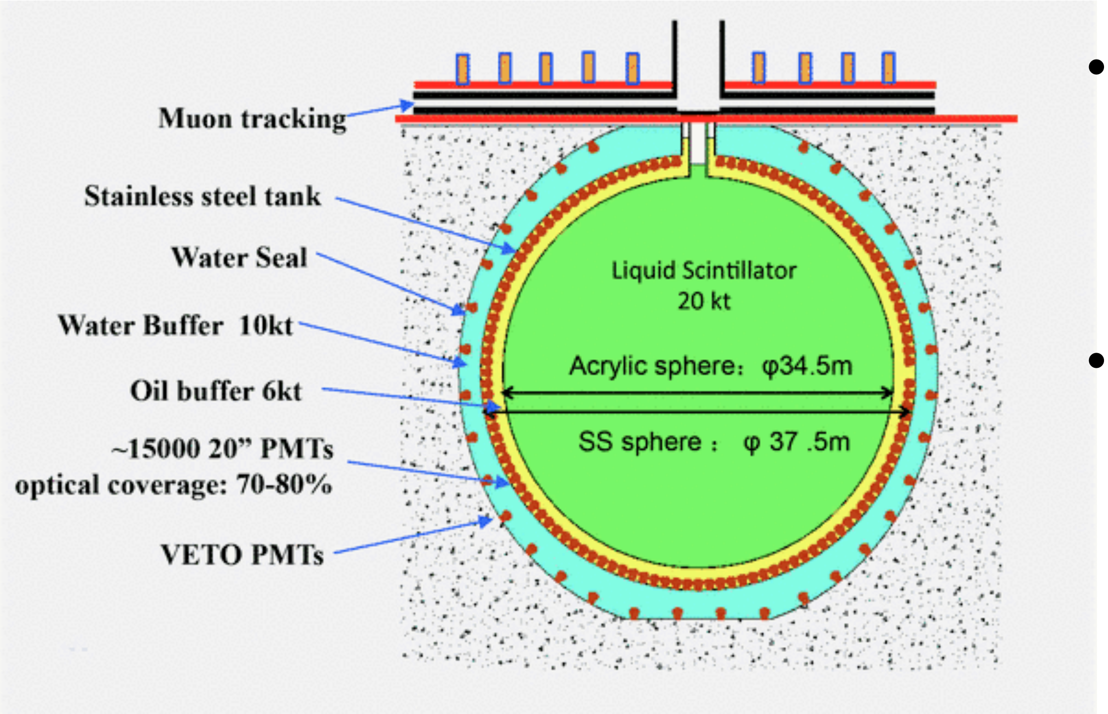
Livia Ludhova
for JUNO collaboration
INFN-Milano

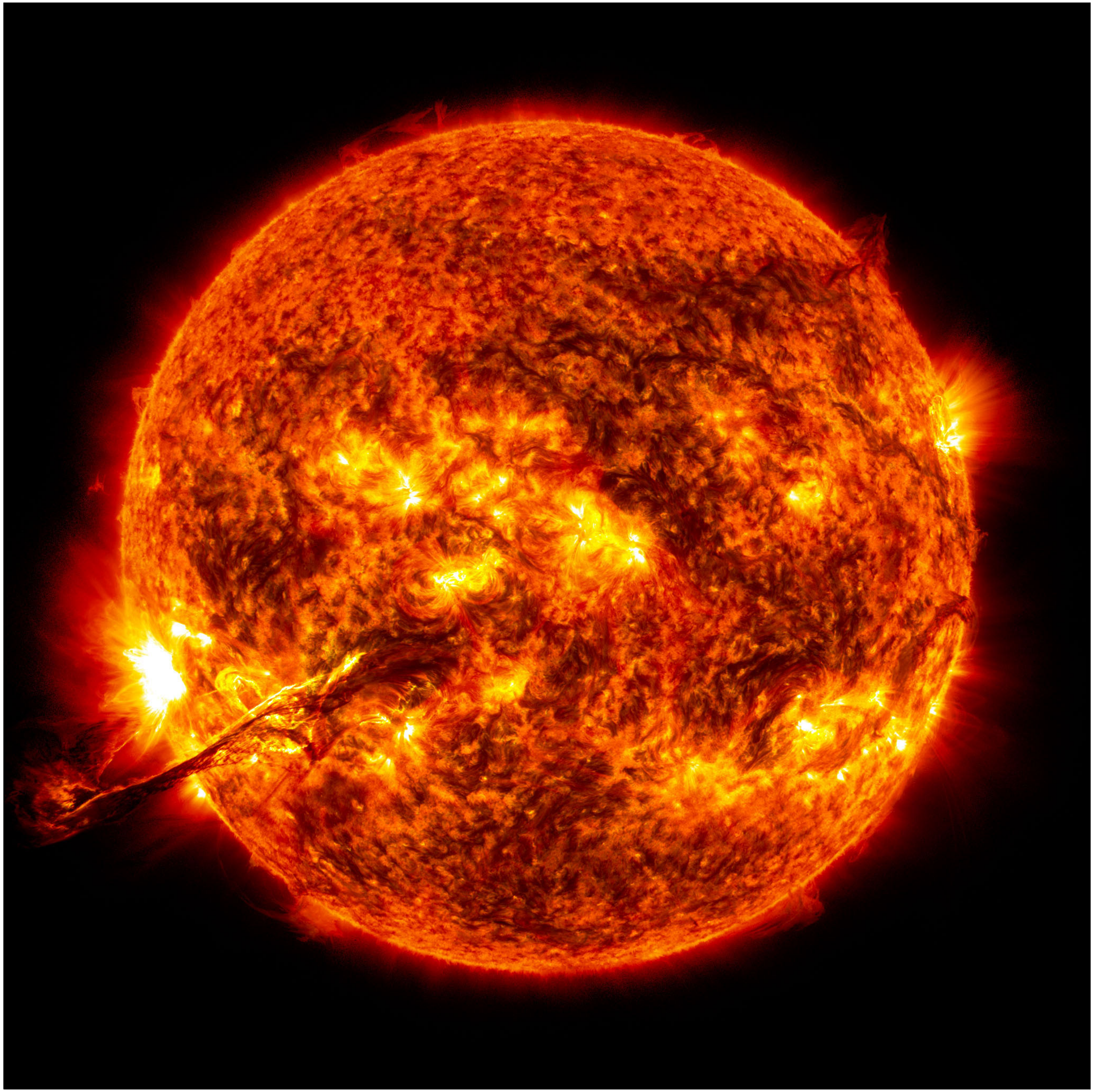
Outline…

1. JUNO in 1 slide;
2. JUNO and solar neutrinos;
3. JUNO and geoneutrinos;
4. Diffuse SN neutrinos in JUNO;

JUNO in China

- the site opening ceremony on January 9th 2015;
- to start DAQ in 2020;
- 20 kton of liquid scintillator 700 m deep;
- 3% energy resolution @ 1 MeV;
- main physics goal is to distinguish between the normal and inverted mass hierarchy;
- Other physics goals:
  - ✓ Geoneutrinos;
  - ✓ Solar neutrinos;
  - ✓ DSN @ SN neutrinos;





Why to measure solar ν's today ?

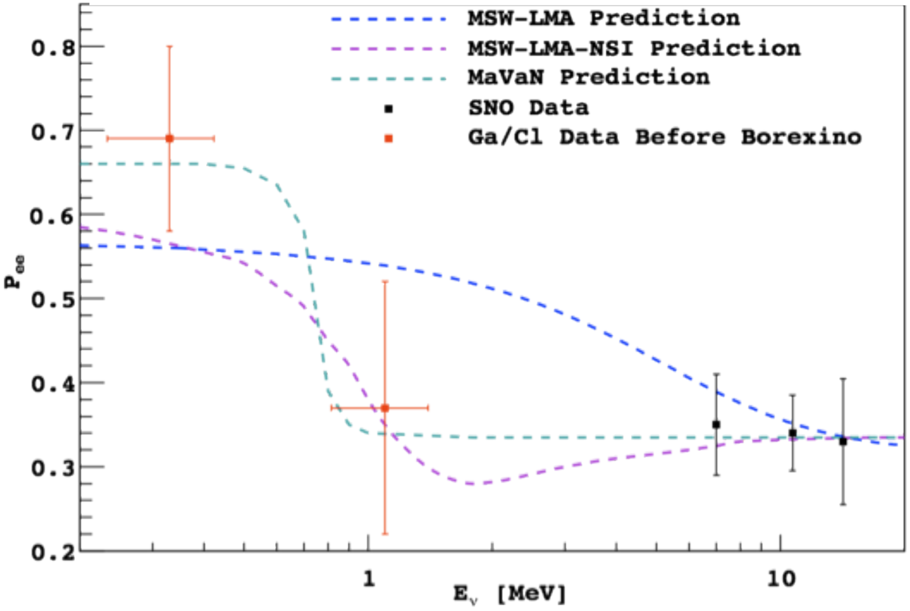
Neutrino Physics:

- MSW-LMA scenario is our current understanding of solar ν oscillations, but there is still room for exotic models (Pee versus energy);
- tension between best Δm^2 from solar and from KamLAND antineutrinos

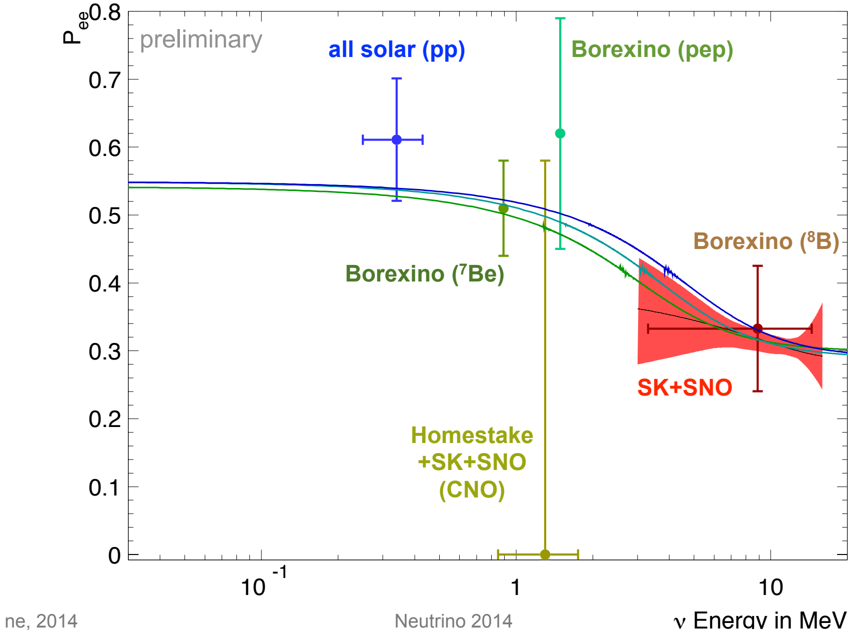
Solar Physics:

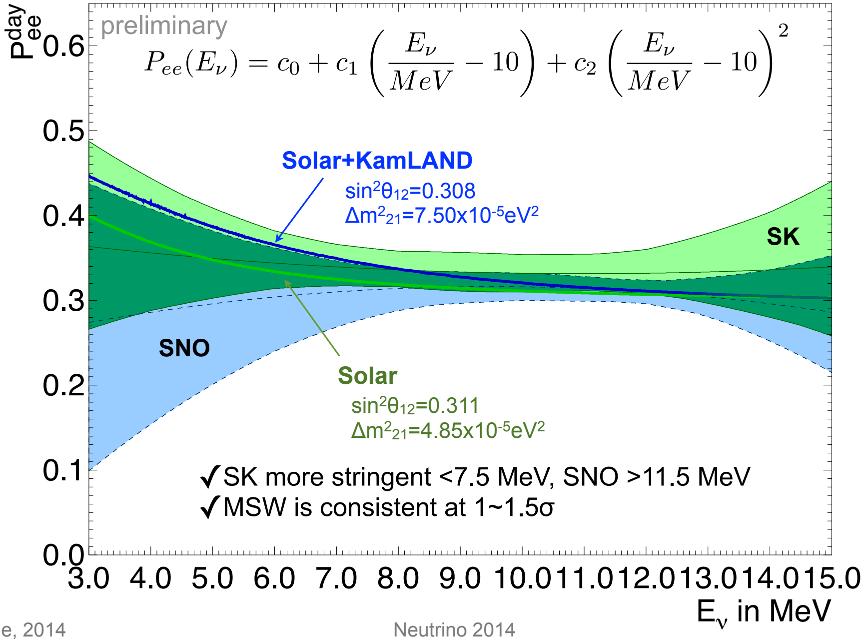
- metallicity problem: Low and High Metallicity models predict different neutrino fluxes!

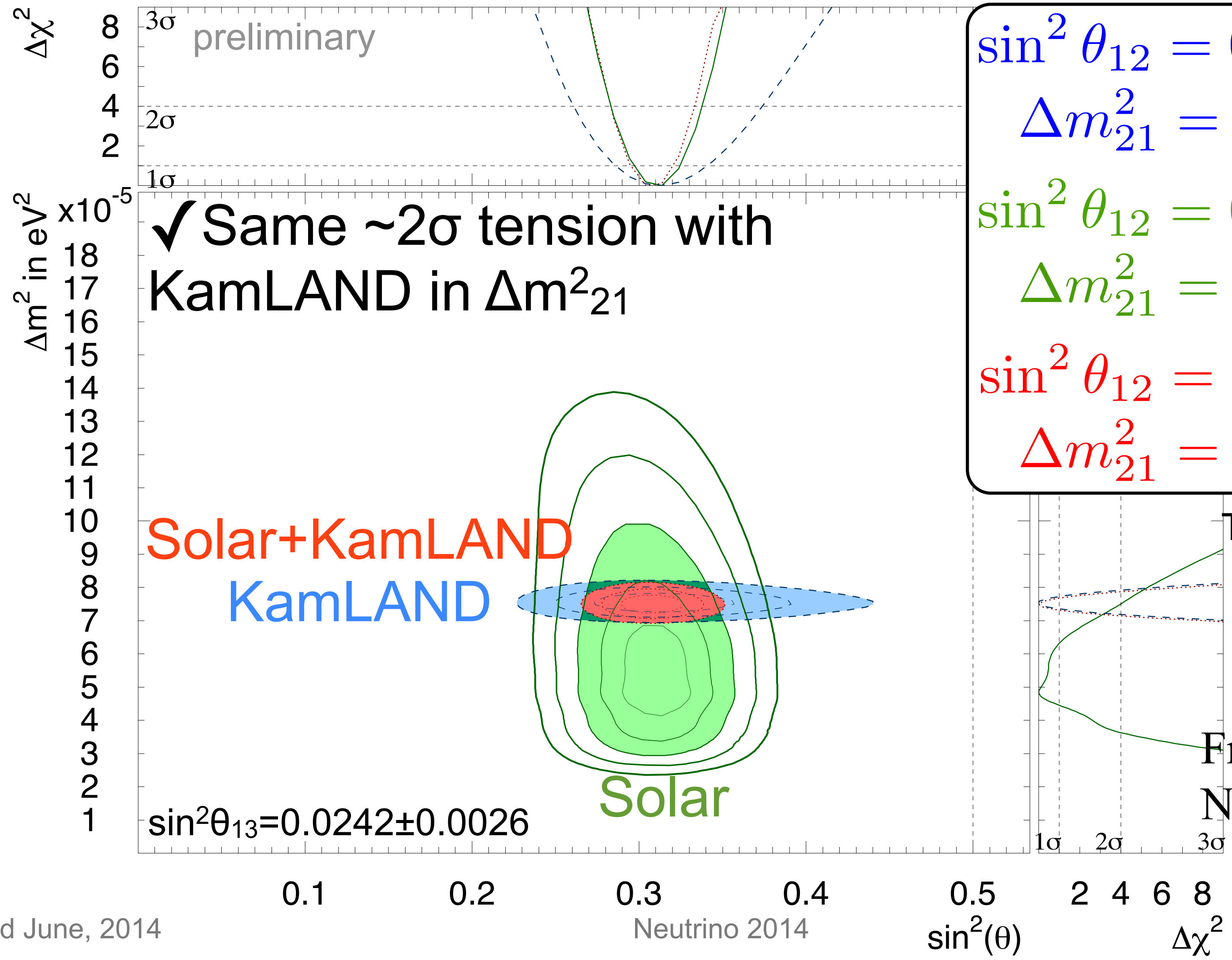
Before Borexino



NOW 2014







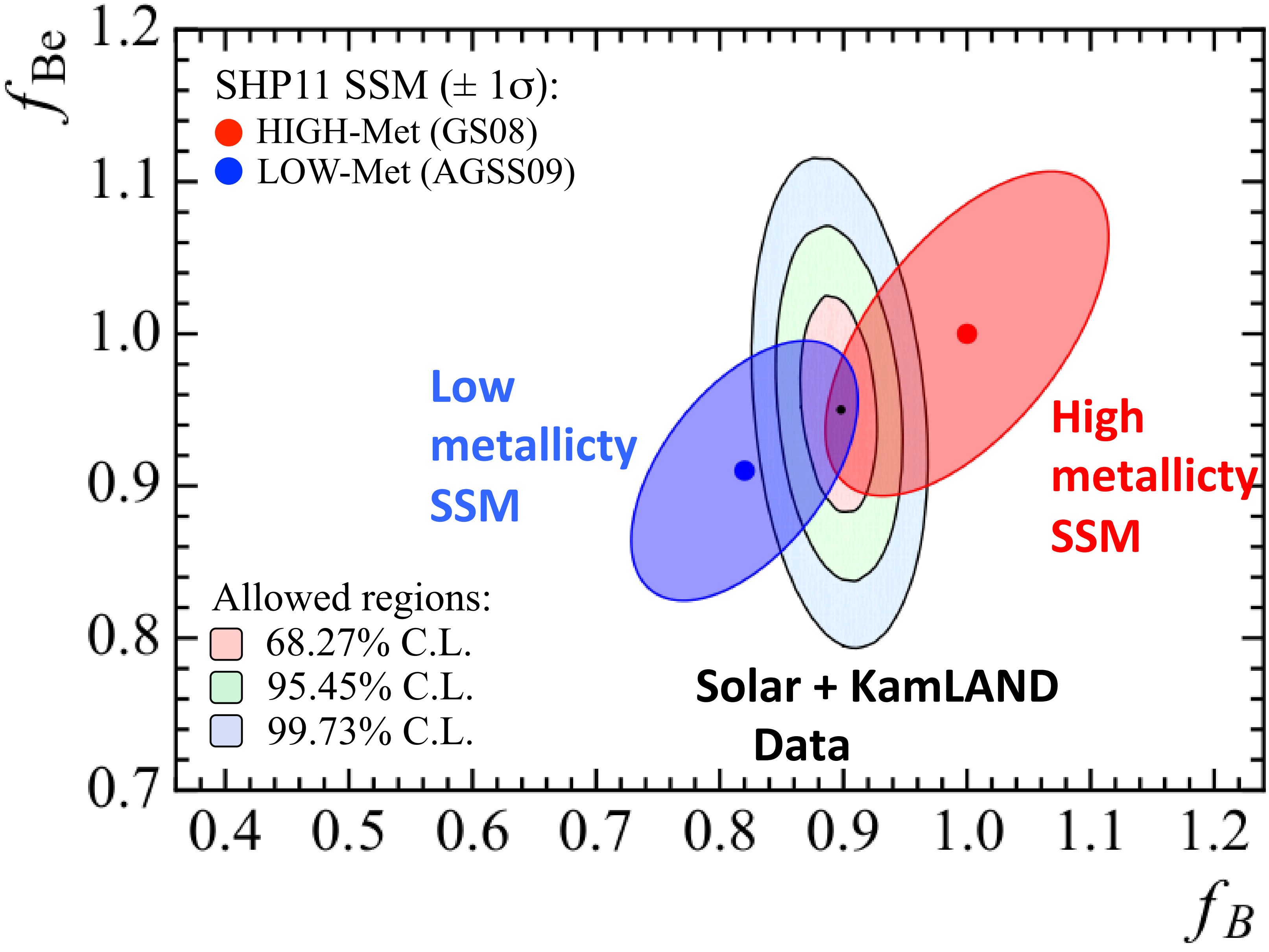
✓Same ~2σ tension with KamLAND in Δm^2_{21}

$\sin^2\theta_{13}=0.0242\pm0.0026$

$$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$$
$$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$$
$$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$$
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$$

The unit of Δm^2_{21} is 10^{-5} eV²

From SuperK Neutrino 2014



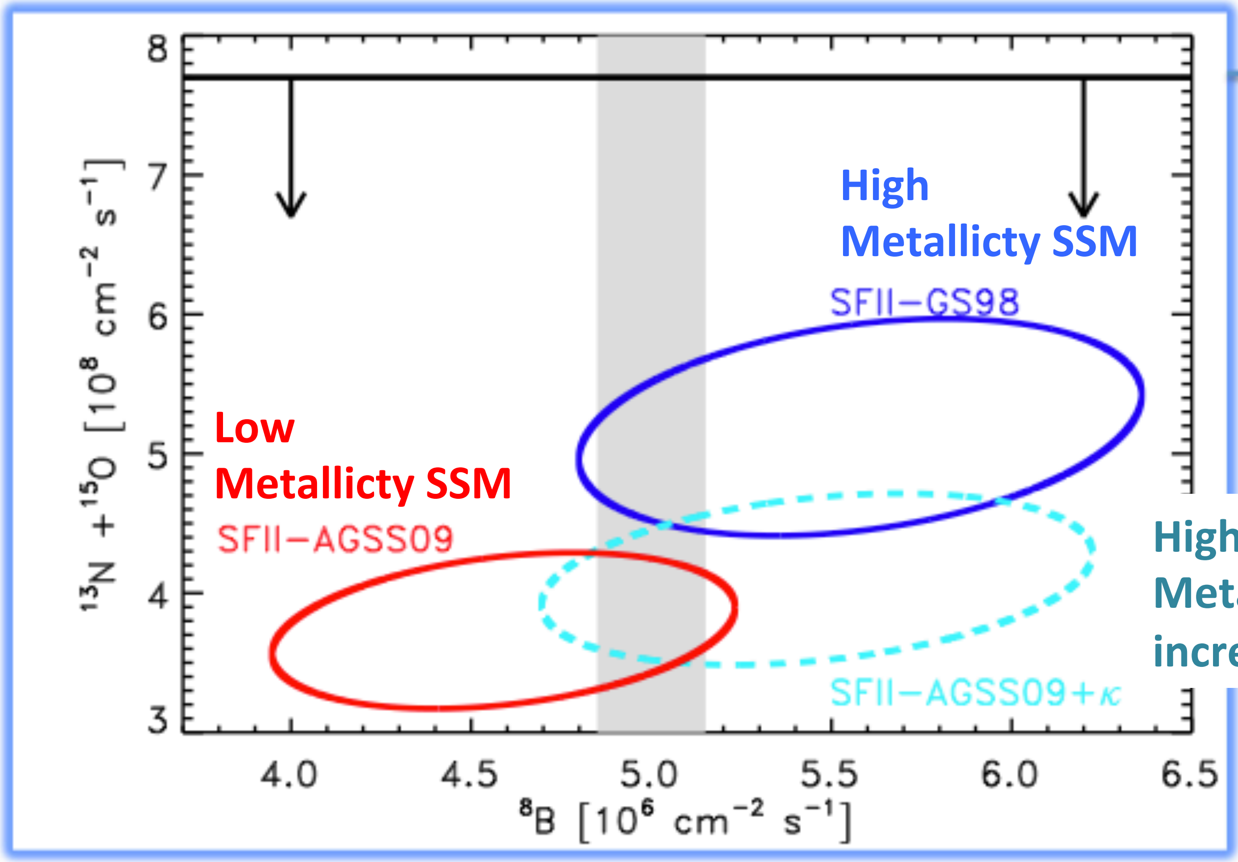
Low metallicty SSM

High metallicty SSM

Solar + KamLAND Data

=

All solar ^{8}B data



Upper limit by Borexino

High Metallicty SSM

Low Metallicty SSM

High Metallicty SSM + increased opacity

JUNO expected rates from solar neutrinos

Source	Rate [cpd/1kt]
pp	1337
^{7}Be [line 0.384 MeV]	19
^{7}Be [line 0.862 MeV]	475
pep	28
^{8}B	4.5
^{13}N	25
^{15}O	28
^{17}F	0.7

Background levels critical: use Borexino experience!

requiring at least 5 m distance from PMTs to fight external background-reduced FV

The latest High Metallicity SSM predicion

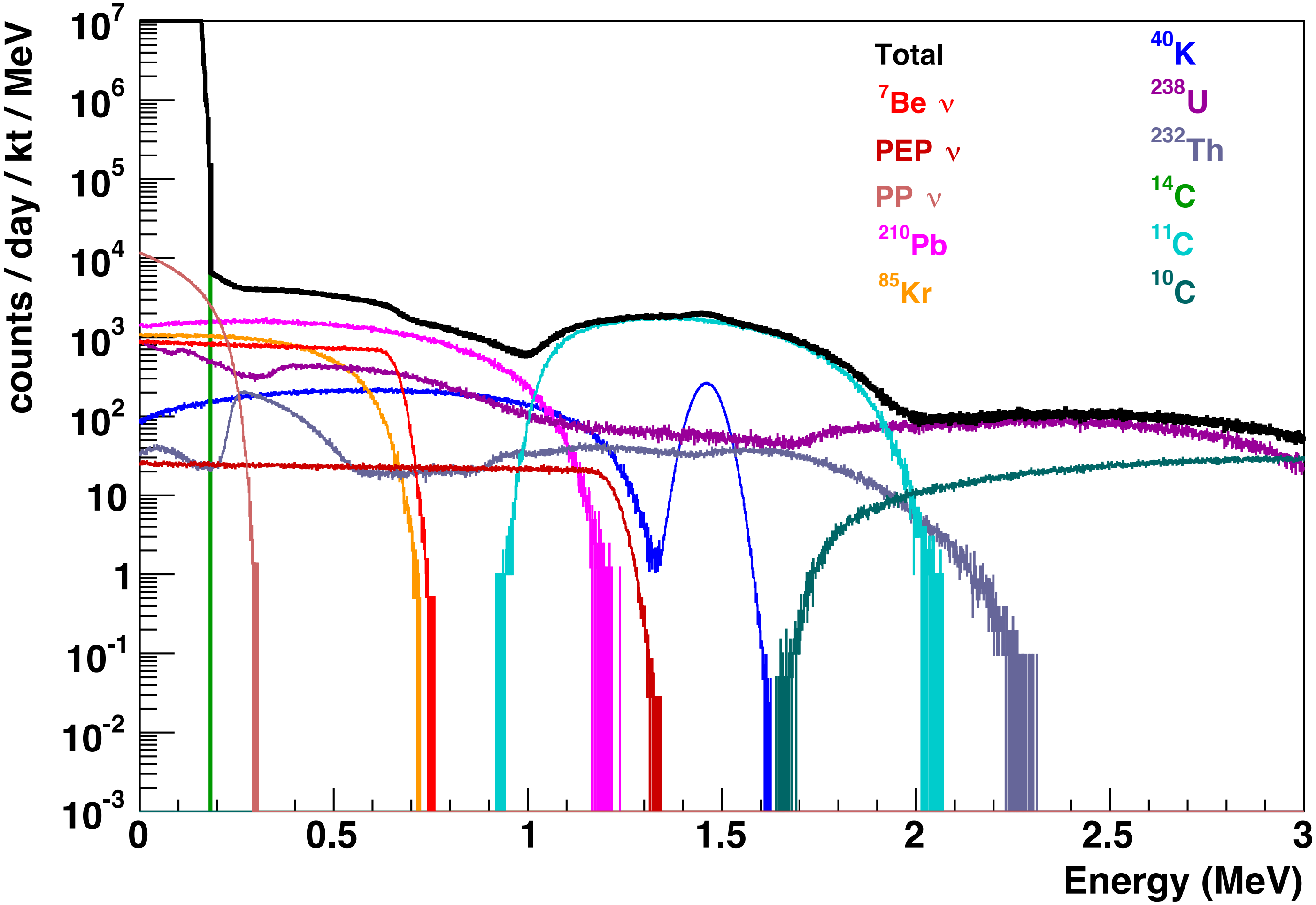
A.M.Serenelli, W. C. Haxton and C. Pena-Garay, Astroph. J. **743** (2011) 24.

The background levels required in JUNO for solar neutrino measurements < 1 MeV

Radio-Isotope		Concentration or Flux	
Name	Source	Typical	Required
^{14}C	intrinsic in LAB	$\sim 10^{-12}\ g/g$	$\sim 10^{-18}\ g/g$
^{238}U ^{232}Th	dust, metallic	10^{-5} - $10^{-6}\ g/g$	$< 10^{-16}\ g/g$
^{7}Be	cosmogenic	$\sim 3 \cdot 10^{-2}\ Bq/t$	$< 10^{-6}\ Bq/t$
^{40}K	dust, PPO	$\sim 2 \cdot 10^{-6}\ g/g$ (dust)	$< 10^{-18}\ g/g$
^{210}Po	surface cont. from ^{222}Rn		$< 7\ c/d/t$
^{222}Rn	emanation from materials, rock	$10\ Bq/l$ air, water 100-1000 Bq/kg rock	$< 10\ cpd/100t$
^{39}Ar ^{85}Kr	air, cosmogenic air, nuclear weapon	$17\ mBq/m^3$ (air) $\sim 1\ Bq/m^3$ (air)	$< 1\ cpd/100t$ $< 1\ cpd/100t$

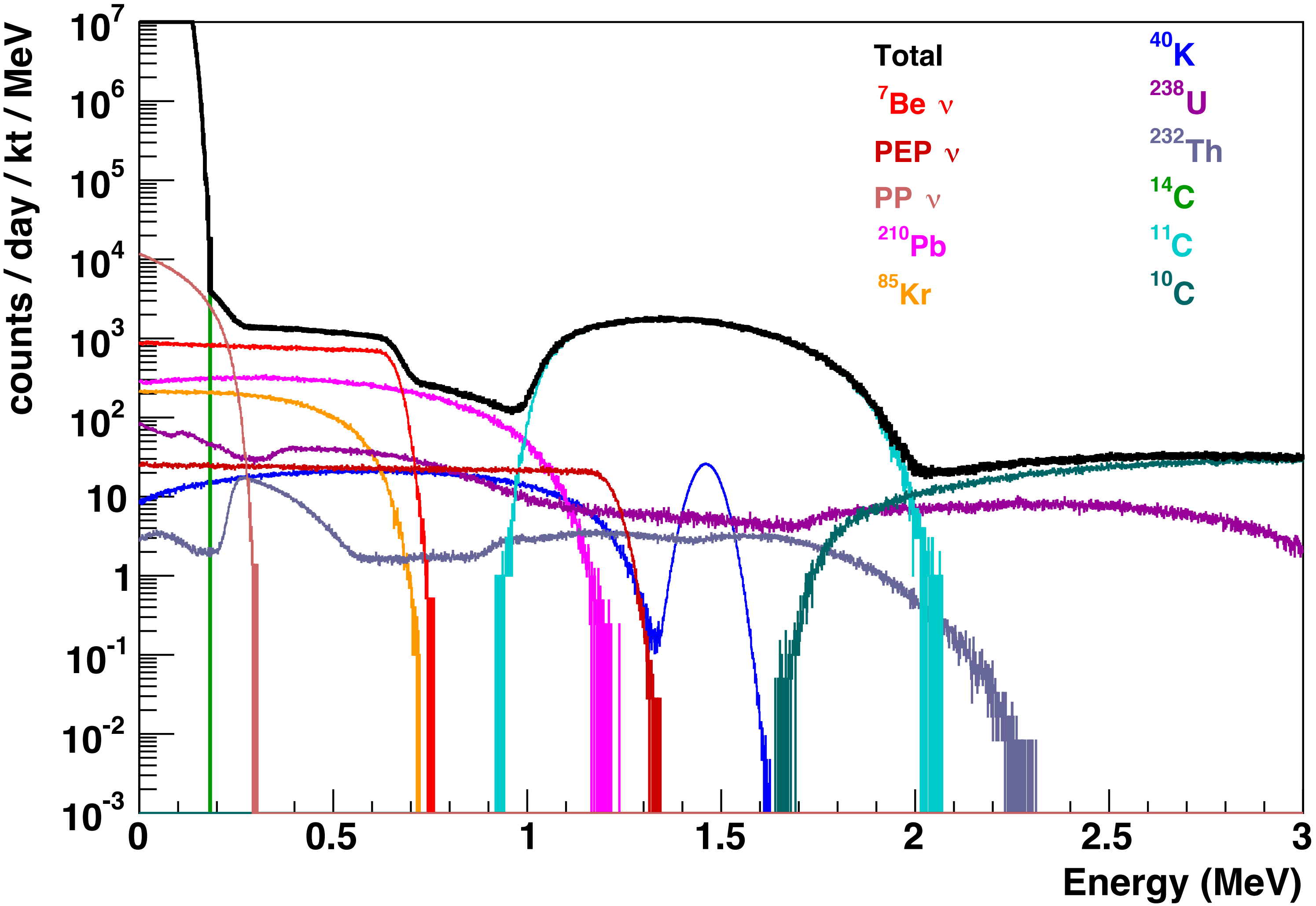
Expected JUNO $\beta + \gamma$ spectrum (assumed α's statistically subtracted), solar neutrinos + backgrounds

10^{-16} g/g/ ^{238}U and ^{232}Th, 10^{-17} g/g ^{40}K and ^{14}C, ^{85}Kr 500 cpd/kton, ^{210}Pb 5×10^{-24} g/g



Expected JUNO β + γ spectrum (assumed α' s statistically subtracted), solar neutrinos + REDUCED backgrounds

10^{-17} g/g/ ^{238}U and ^{232}Th, 10^{-18} g/g ^{40}K and ^{14}C, ^{85}Kr 100 cpd/kton, ^{210}Pb 1x10^{-24} g/g



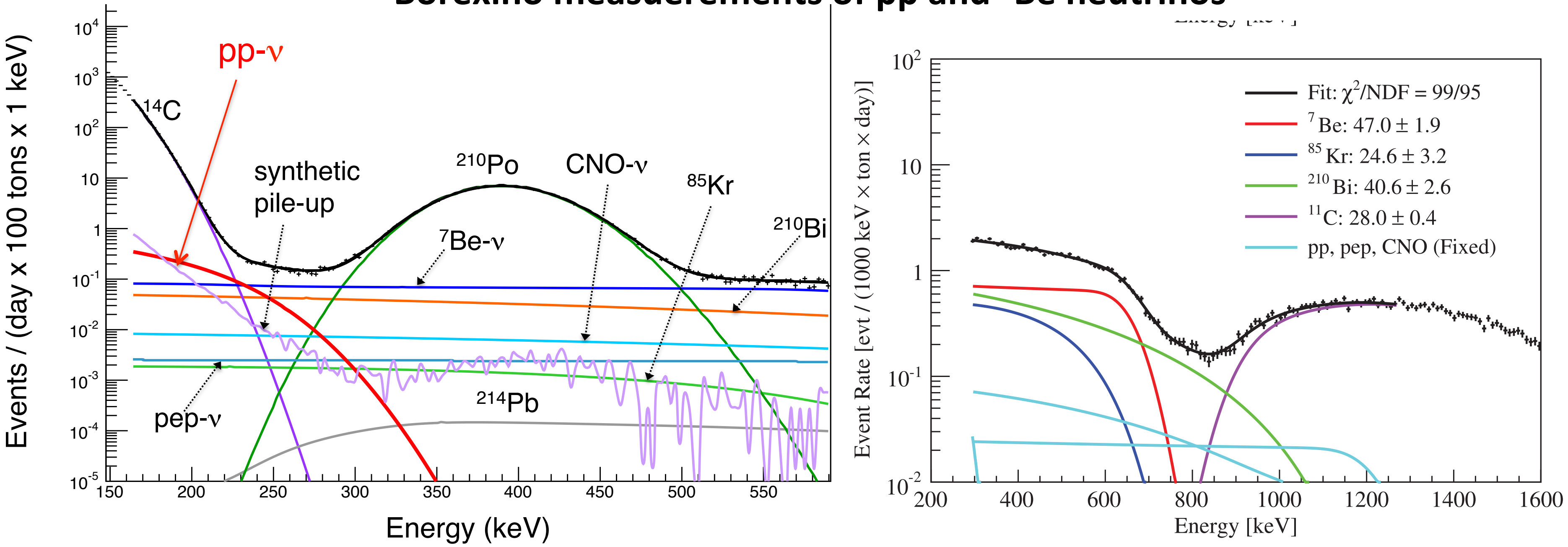
IF these background levels will be obtained,

then JUNO can with its

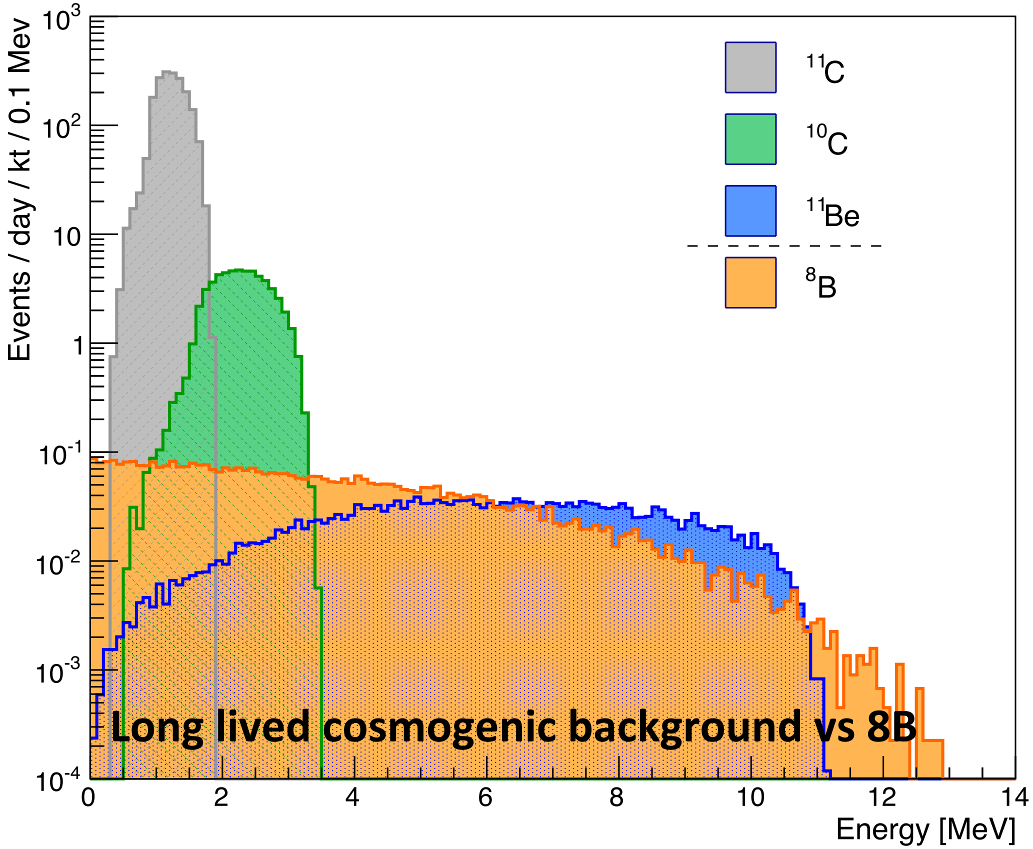
- ✓ high statistics
- ✓ excellent energy resolution measure

- ^{7}Be solar neutrinos with improved precision (currently, 5% precision from Borexino)
- pp solar neutrinos, since it can better distinguish better between ^{14}C and its pile-up (FADCs in JUNO!) and pp (currently, Borexino measured pp in 2014)
- Neutrino magnetic moment at low energies

Borexino measuerements of pp and ^{7}Be neutrinos



Towards ^{8}B solar neutrinos in JUNO…..



Long lived cosmogenic background, JUNO is only 700 m deep

External background (2.6 MeV ^{208}Tl gammas from PMTs), thus reduced FV ~9 kton

Reactor antineutrino scattering: at % level @ 3 MeV, statistical subtraction with high precision

Internal ^{208}Tl $\beta + \gamma$ up to 5 MeV (Bx: can be small, ^{212}Bi-^{212}Po tagging and stat. subtraction)

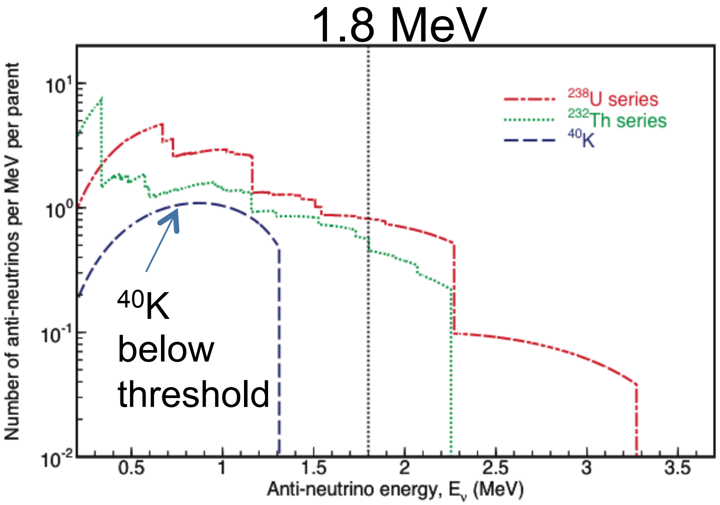
Isotope	Decay Type	Q-Value [MeV]	Life time	Yield [56, 57] 10^{-7} $(\mu\ g/cm^2)^{-1}$	Rate [cpd/ kt]
^{11}C	β^+	2.0	29.4 min	467	$1.8 \cdot 10^3$
^{10}C	β^+	3.7	27.8 s	14.1	54
^{11}Be	β^-	11.5	19.9 s	0.59	2.3

Geoneutrinos
antineutrinos from the decay of ^{238}U, ^{232}Th,^{40}K in the Earth

Abundance of radioactive elements fixes the amount of radiogenic heat (nuclear physics);
Mass and distribution of radiogenic elements → geoneutrino flux (cca 10^6 cm^{-2} s^{-1});
From measured geoneutrino flux to radiogenic heat….

Main goal: determine the contribution of the **radiogenic heat to the total surface heat flux**, which is an important margin, test, and input at the same time for many geophysical and geochemical models of the Earth;

Further goals: tests and discrimination among geological models, study of the mantle homogeneity, insights to the processes of Earth'formation…..



$$\bar{\nu} + p \rightarrow n + e^+$$

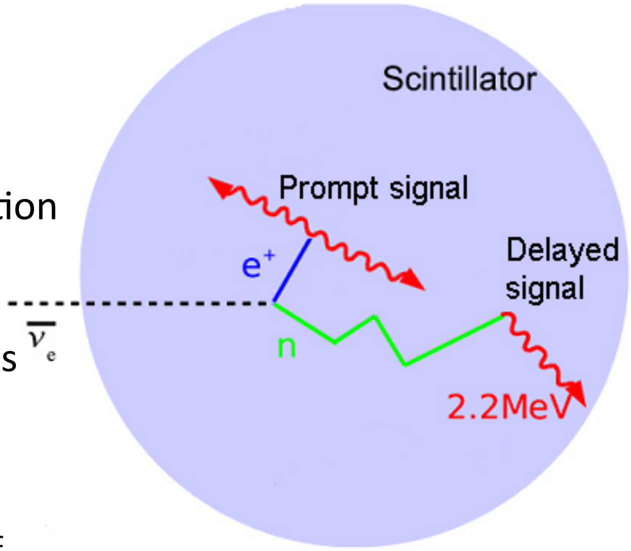
- "prompt signal"

e+: energy loss + annihilation

- "delayed signal"

neutron capture on protons after thermalization 2.2 γ

$E_\nu > 1.8$ MeV



Geoneutrino experimental results

KamLand (Japan)

- The very first investigation in 2005 (Nature 436 (2005) 499): CL < 2 sigma;
- Update in PRL 100 (2008): 73 +- 27 geo events
- high exposure: 99.997 CL observation in 2011 (Gando et al, Nature Geoscience 1205) **106^{+29}_{-28} geonu events detected;** (March 2002 – April 2009) 3.49×10^{32} target-proton year
- **PRD 88 (2013) 033001** **116^{+28}_{-27} geonu events detected;** (March 2002 – November 2012) 4.9×10^{32} target-proton year 0-hypothesis @ 2×10^{-6}

Borexino (Italy)

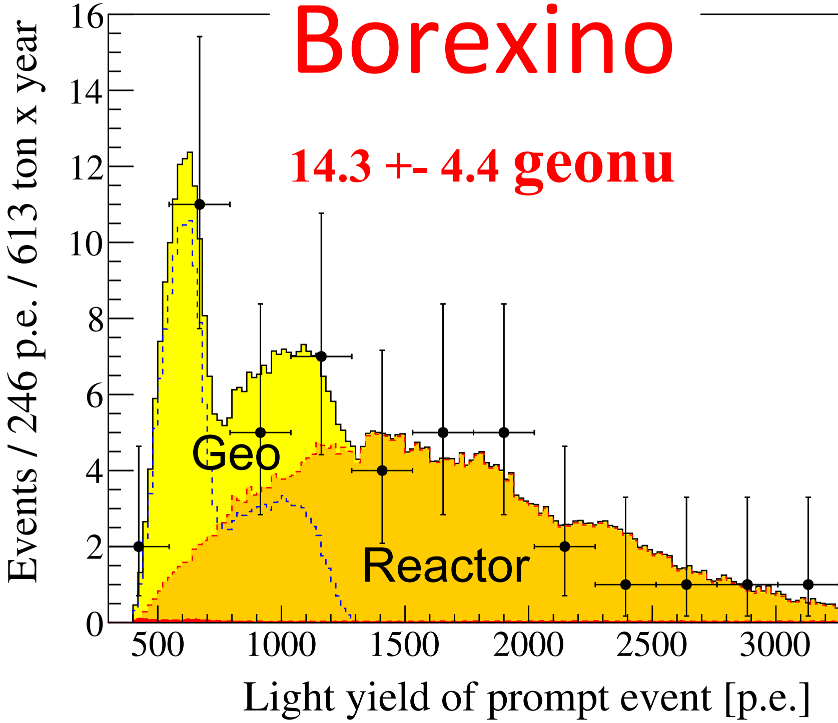
- small exposure but low background level: observation at 99.997 CL in 2010 (Bellini et al, PLB 687):

$9.9^{+4.1}_{-3.4}$ geonu events detected;
(December 2007 – December 2009)
Exposure 1.5×10^{31} target-proton year

- **PLB 722 (2013) 295–300:** **14.3 +- 4.4 geonu events;** (December 2007 – August 2012) 3.69×10^{31} target-proton year after cuts 0-hypothesis @ 6×10^{-6}

Borexino

14.3 +- 4.4 geonu

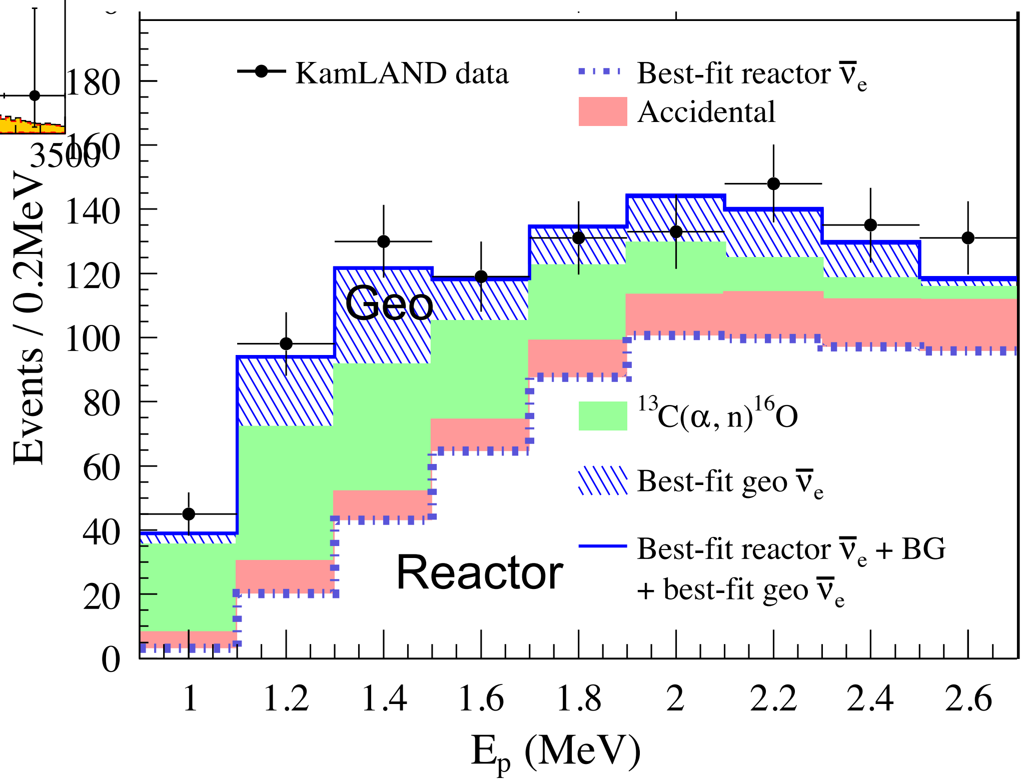


. Phys. Lett. B 722 (2013) 295-300

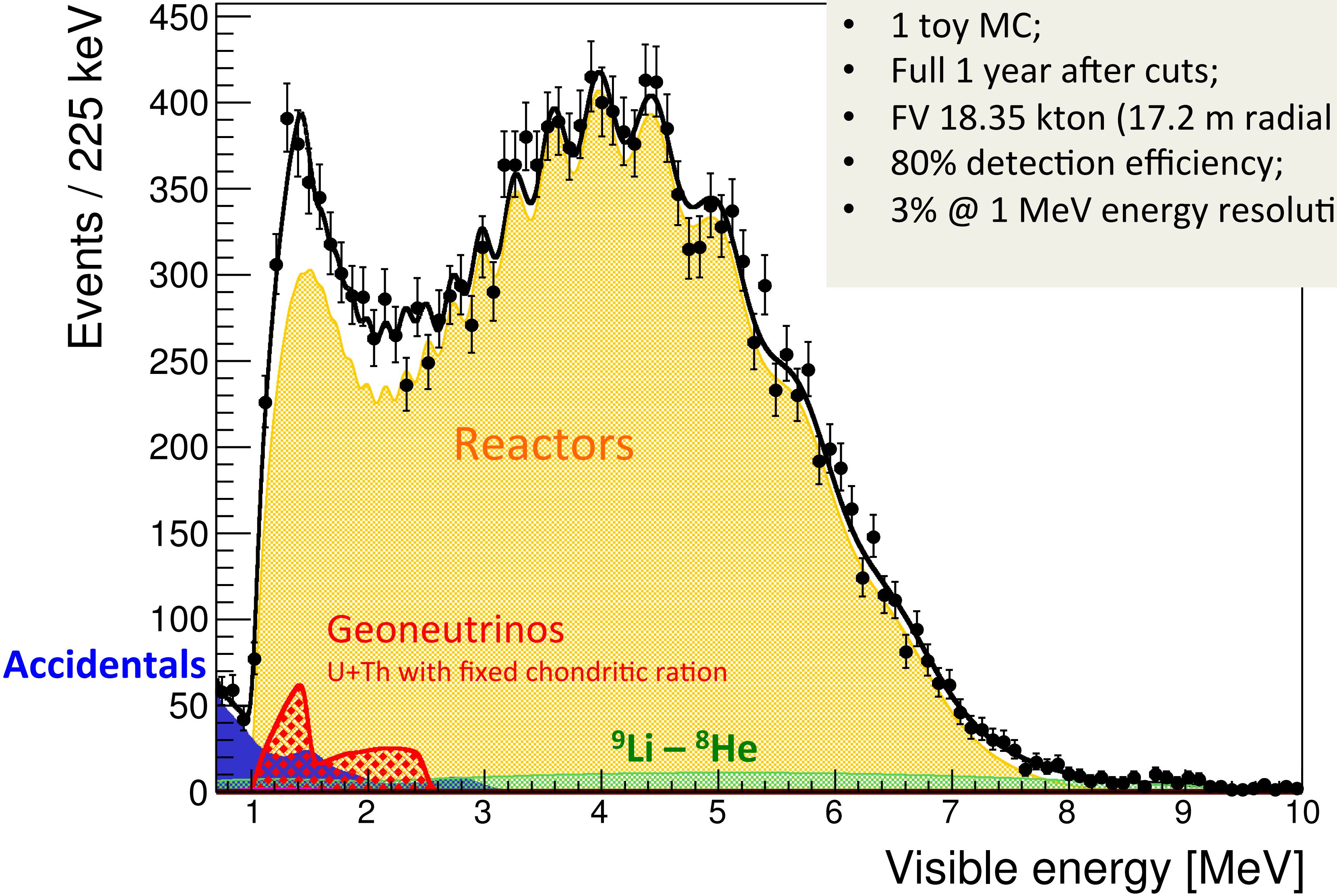
KamLAND

116 $^{+28}_{-27}$ geonu

. Phys. Rev. D 88 (2013) 033001



Simulated JUNO antineutrino spectrum (prompt energy) and the best fit



- 1 toy MC;
- Full 1 year after cuts;
- FV 18.35 kton (17.2 m radial cut)
- 80% detection efficiency;
- 3% @ 1 MeV energy resolution

Input for simulations: signal & background rates

- after cuts and vetos;
- FV 18.35 kton (17.2 m radial cut)
- 80% detection efficiency;

Expected signal
see talk of
Fabio Mantovani

Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	3.65 ± 3.65
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4

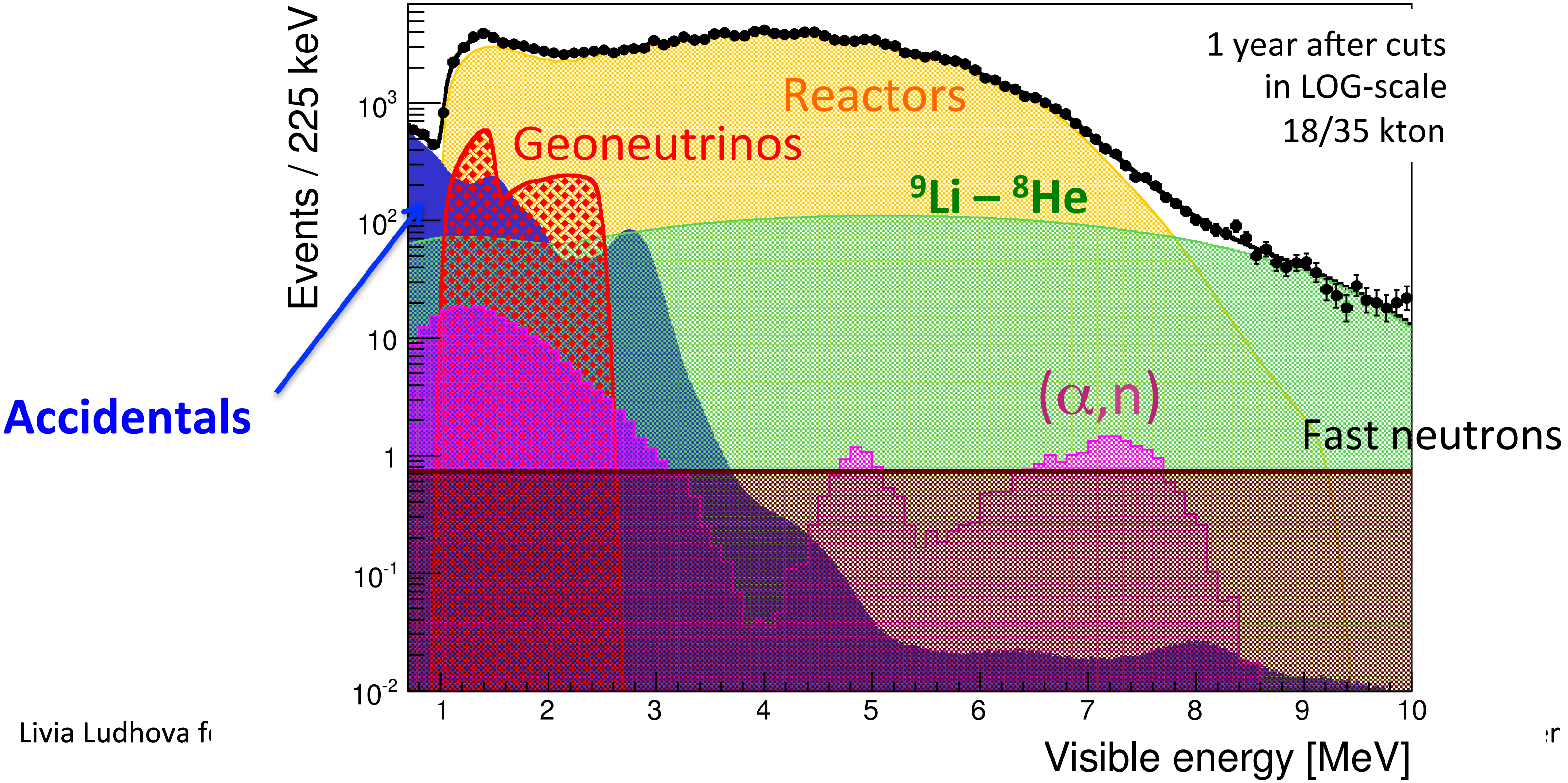
Fixed chondritic Th/U mass ratio of 3.9 (signal Th/U ~0.27)

Daya Bay spectral shapes

Non-antineutrino background rates in 0.7 – 12 MeV

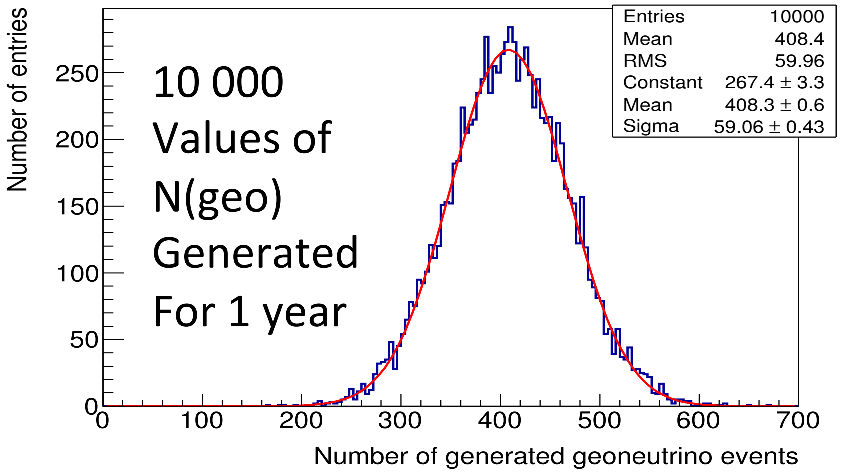
Background type	Rate after IBD+ muon cuts [events/day]	Uncertainty in Rate [%]	Uncertainty in Shape [%]
^{9}Li - ^{8}He (β + neutron decays)	1.8	20	10
Fast neutrons	0.01	100	20
Accidental events	1.1	1	negl.
^{13}C(α, n)^{16}O (acrylic vessel)	0.05	50	50
^{13}C(α, n)^{16}O (ballon)	0.01	50	50

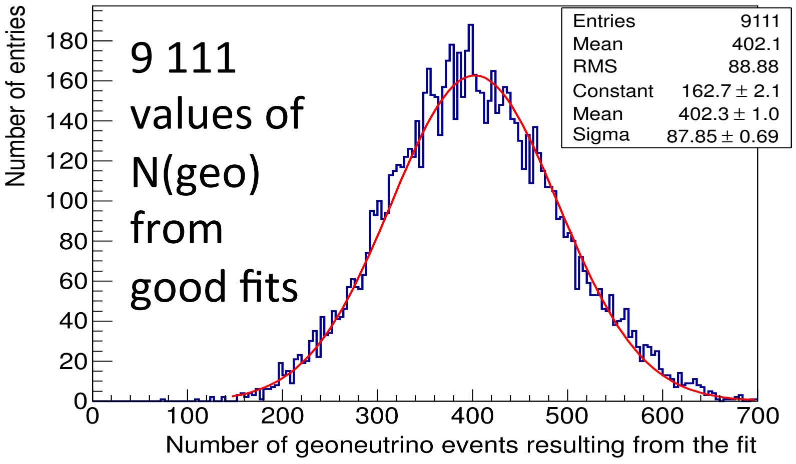
Cosmogenic production,
veto along muon tracks etc..
Reduced Li-He bgr from 80
To 1.8 events/day,
BUT 17% dead time

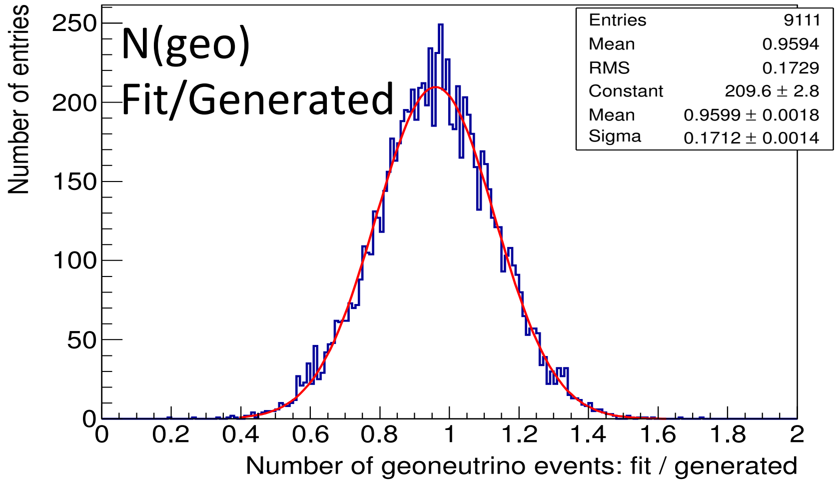


Toy MC was repeated 10 000 times for 1, 3, 5, and 10 years statistics

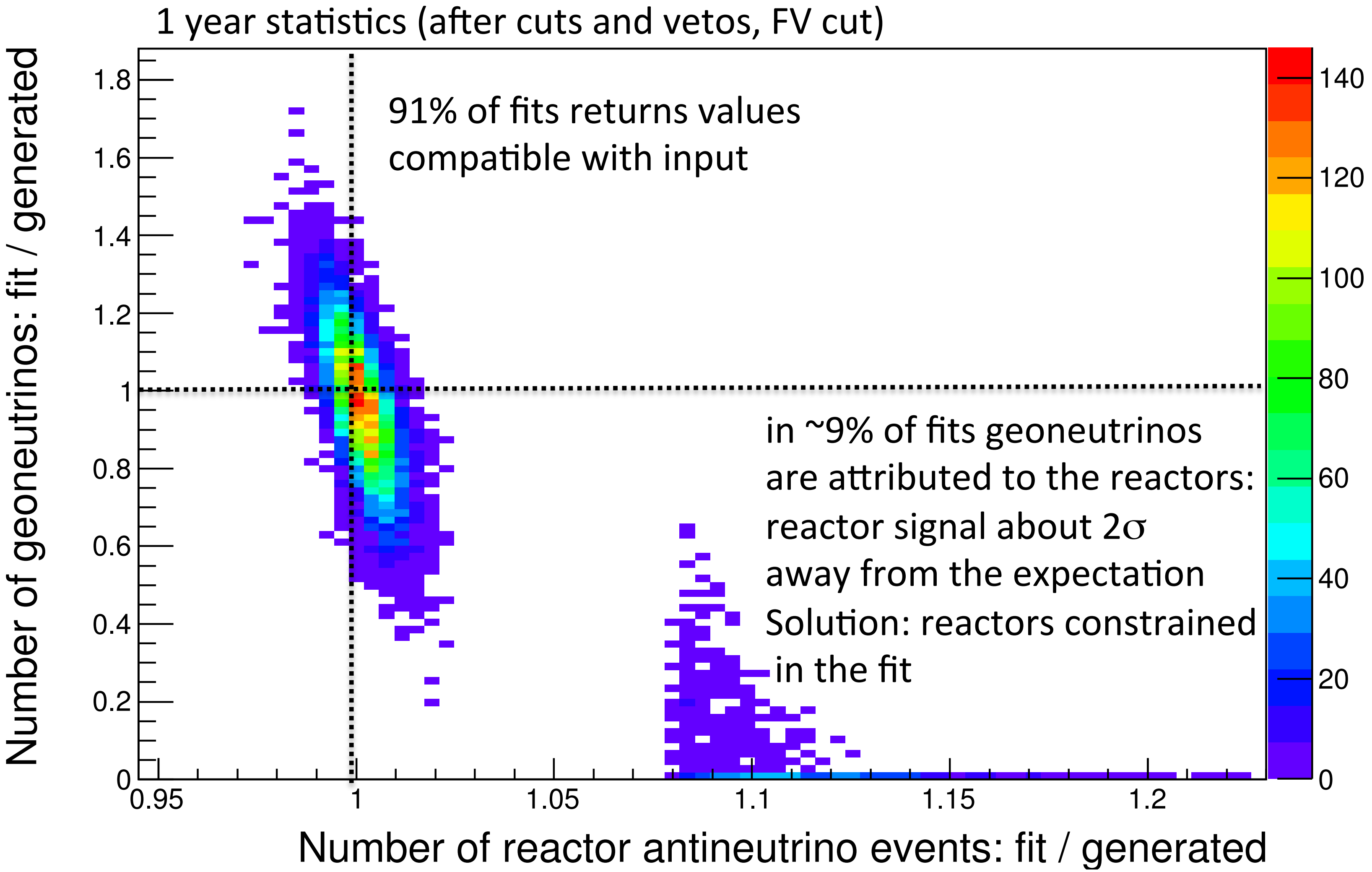
- Maximal likelihood fit;
- Geo and reactor signal free;
- Other backgrounds constrained within 1σ range;







Geoneutrino and reactor signals correlations


1 year statistics (after cuts and vetos, FV cut)

91% of fits returns values compatible with input

in ~9% of fits geoneutrinos are attributed to the reactors: reactor signal about 2σ away from the expectation

Solution: reactors constrained in the fit

Final results on the precision of JUNO geoneutrino measurement

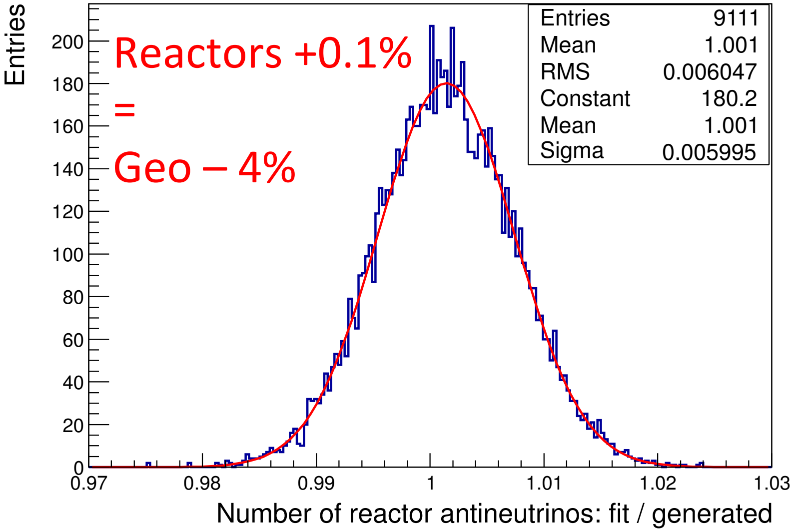
Number of years	U + Th (fixed chondritic Th/U ratio)
1	0.96 ± 0.17
3	0.96 ± 0.10
5	0.96 ± 0.08
10	0.96 ± 0.06

Better than the current data:
Borexino ~35-40%
KamLAND: ~25%

Mean and RMS of the Gaussian N(geo) fit/generated

The systematic shift of -4%
is mostly due to the correlations
with reactor antineutrino background
And does not dissapear with inctеased statistics

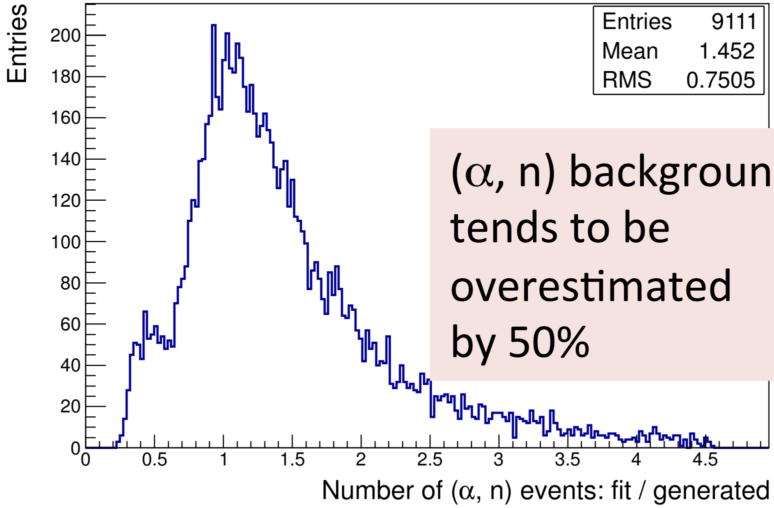
Background reconstruction: N fit / generated



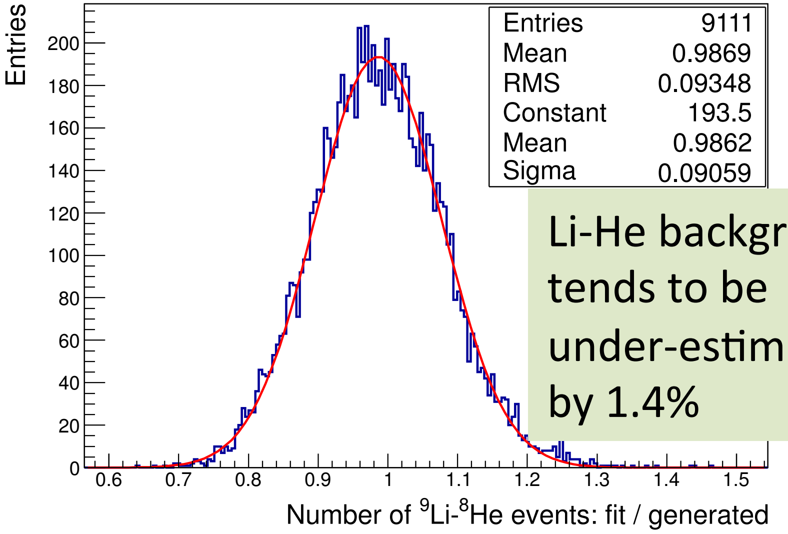
Reactors +0.1%

=

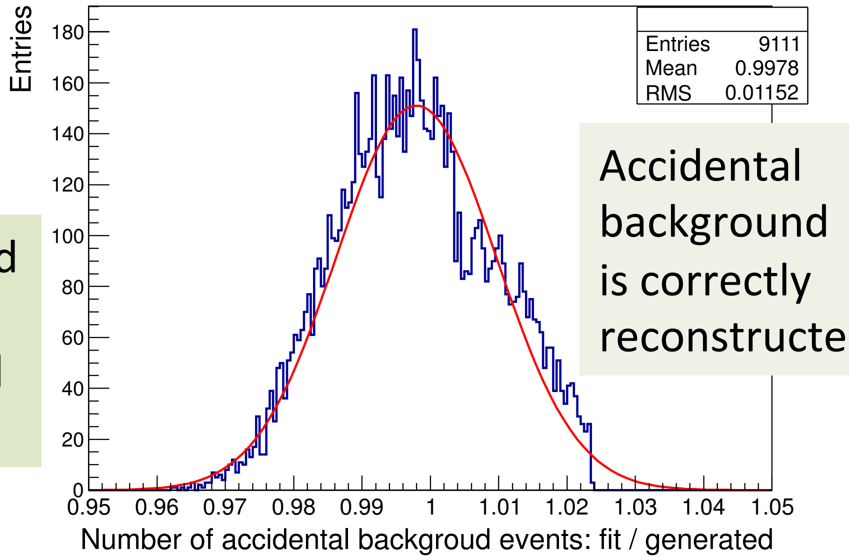
Geo – 4%



(α, n) background tends to be overestimated by 50%



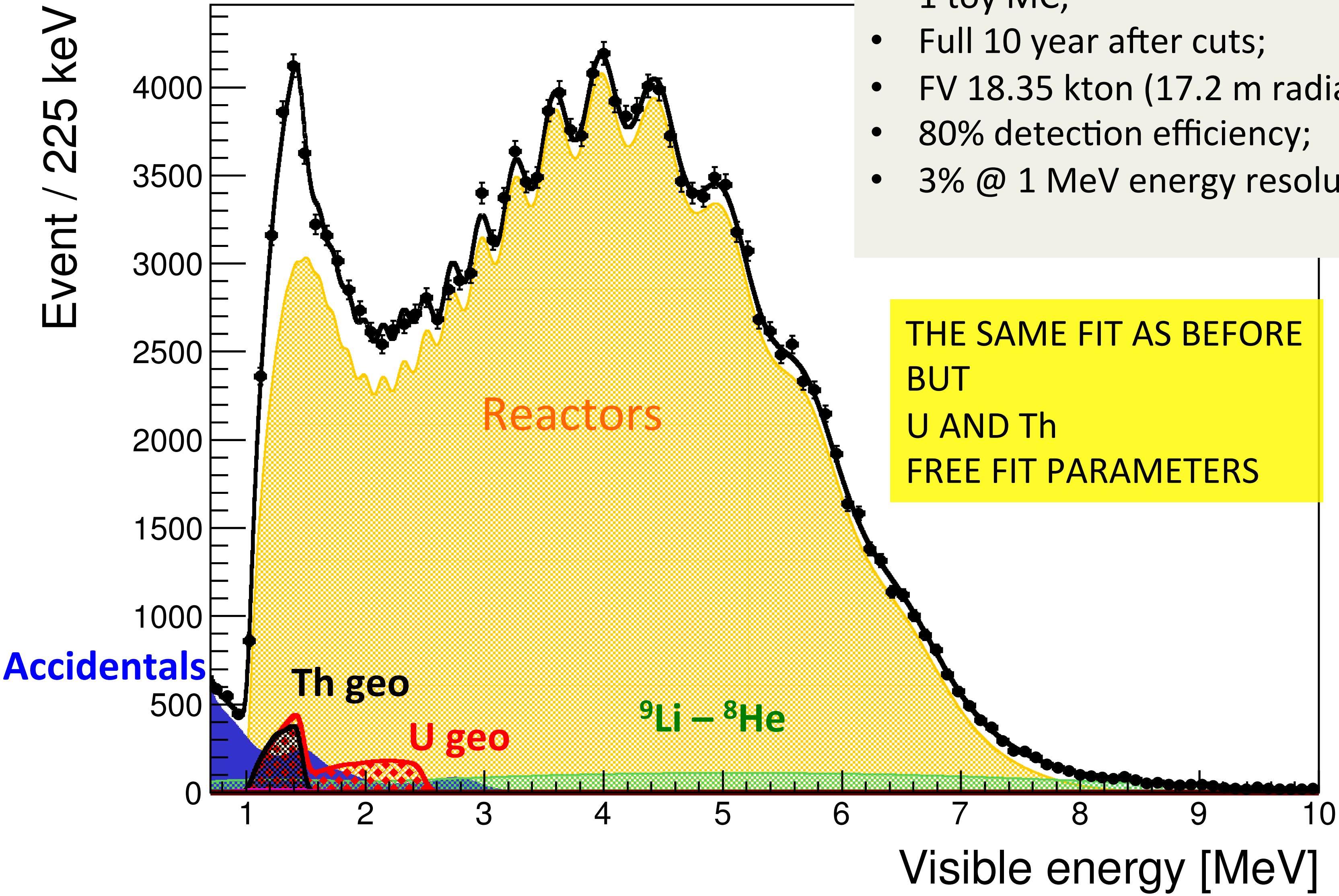
Li-He background tends to be under-estimated by 1.4%



Accidental background is correctly reconstructed

Simulated JUNO antineutrino spectrum (prompt energy) and the best fit WITH U and Th components free

- 1 toy MC;
- Full 10 year after cuts;
- FV 18.35 kton (17.2 m radial cut)
- 80% detection efficiency;
- 3% @ 1 MeV energy resolution



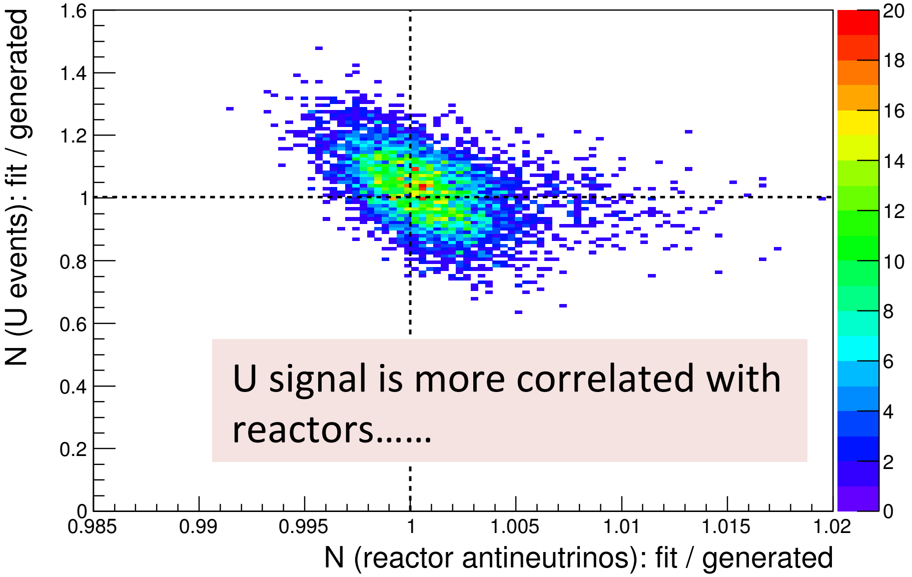
THE SAME FIT AS BEFORE
BUT
U AND Th
FREE FIT PARAMETERS

Precision of the reconstruction of the U and Th signals

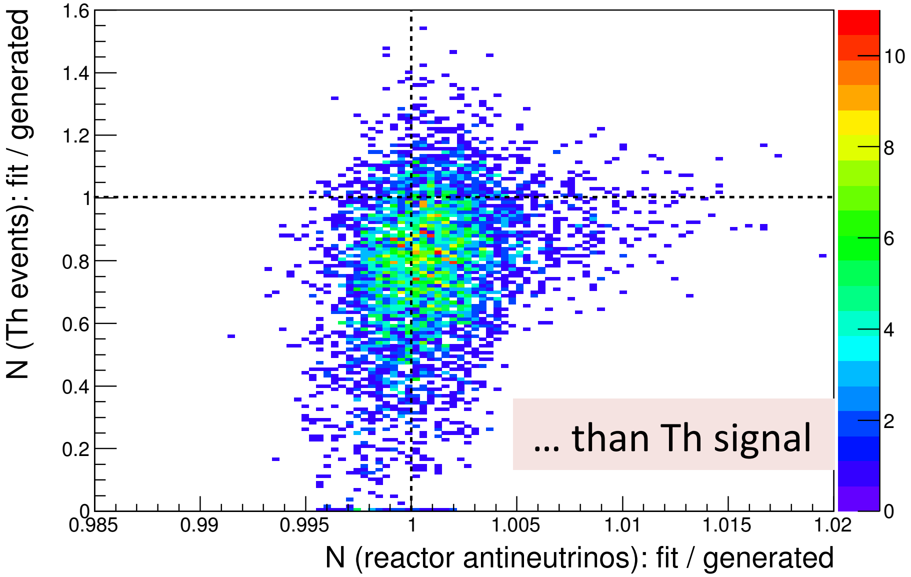
Number of years	U (free)	Th (free)
1	1.01 ± 0.32	0.79 ± 0.66
3	1.03 ± 0.19	0.80 ± 0.37
5	1.03 ± 0.15	0.80 ± 0.30
10	1.03 ± 0.11	0.80 ± 0.21

- 1 year poor precision but the RMS improves with statistics;
- Systematic 1-3% overestimation of the U signal;
- Systematic 20% underestimation of the Th signal;
- Systematics is due to the correlations;

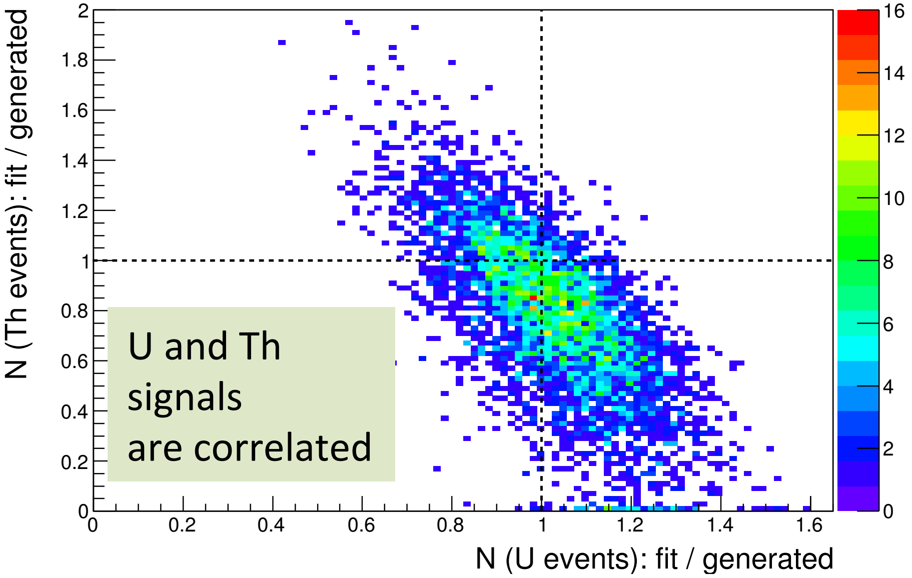
Correlations in 5 years livetime…..



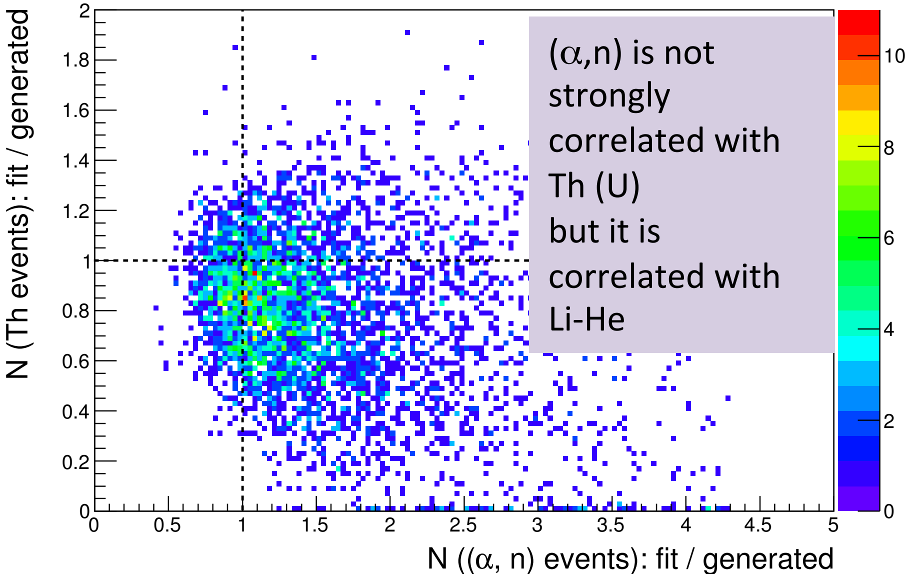
U signal is more correlated with reactors……



… than Th signal

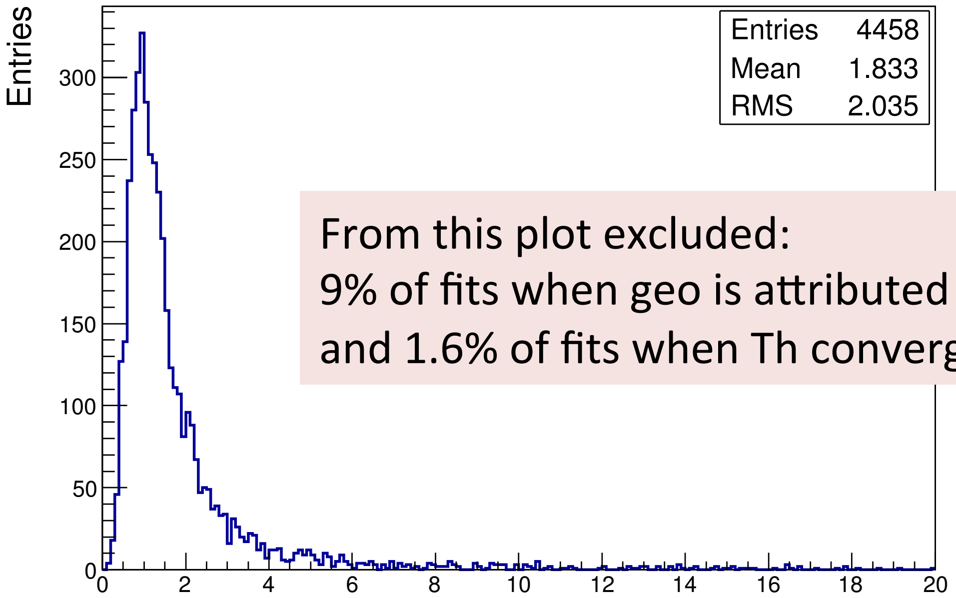


U and Th signals are correlated



(α,n) is not strongly correlated with Th (U) but it is correlated with Li-He

Reconstruction of U/Th ratio

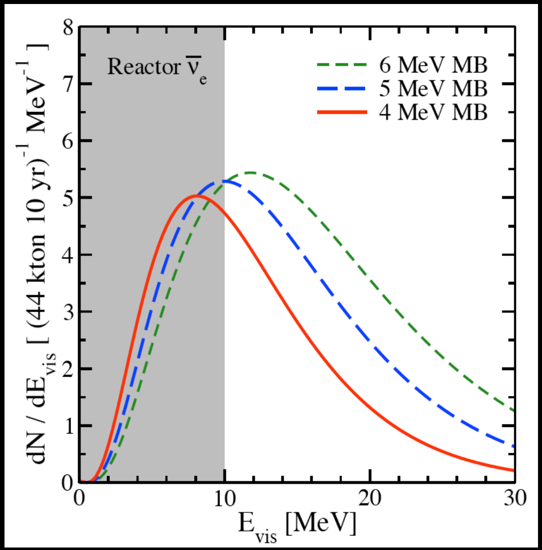


From this plot excluded:
9% of fits when geo is attributed to reactors
and 1.6% of fits when Th converges to 0

U/Th signal ratio: fit / generated after 3% years

Number of years	Peak position	Left RMS	Right RMS	Fits with Th(fit) = 0 [%]
1	0.66	0.18	2.6	7.0
3	0.92	0.18	2.2	1.6
5	1.0	0.15	1.7	0.5
10	1.1	0.14	1.2	0.2

Diffuse Supernova Neutrino Background



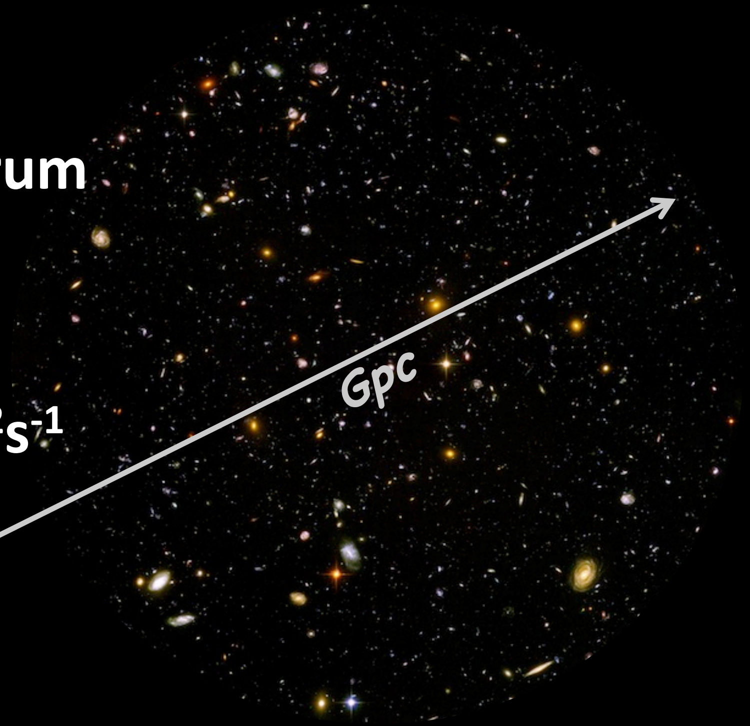
DSNB spectrum

averaged SN spectrum

redshifted by

cosmic expansion

anti-ν_e flux: 20 cm^{-2}s^{-1}



milky way

3 SN per 100yr

present ν detectors

neighbouring galaxy clusters

~1SN per year

single bursts need

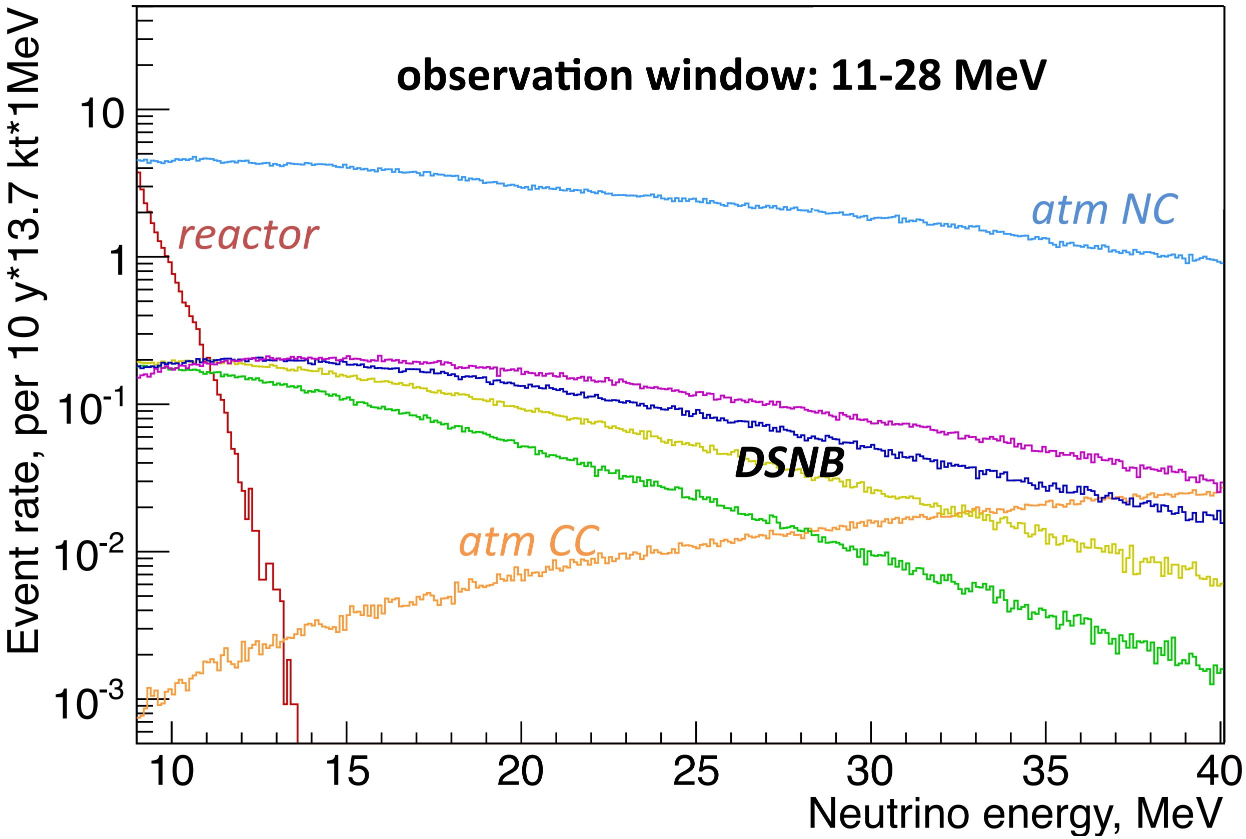
Mton++ detectors

DSNB

10^{8}SN per year

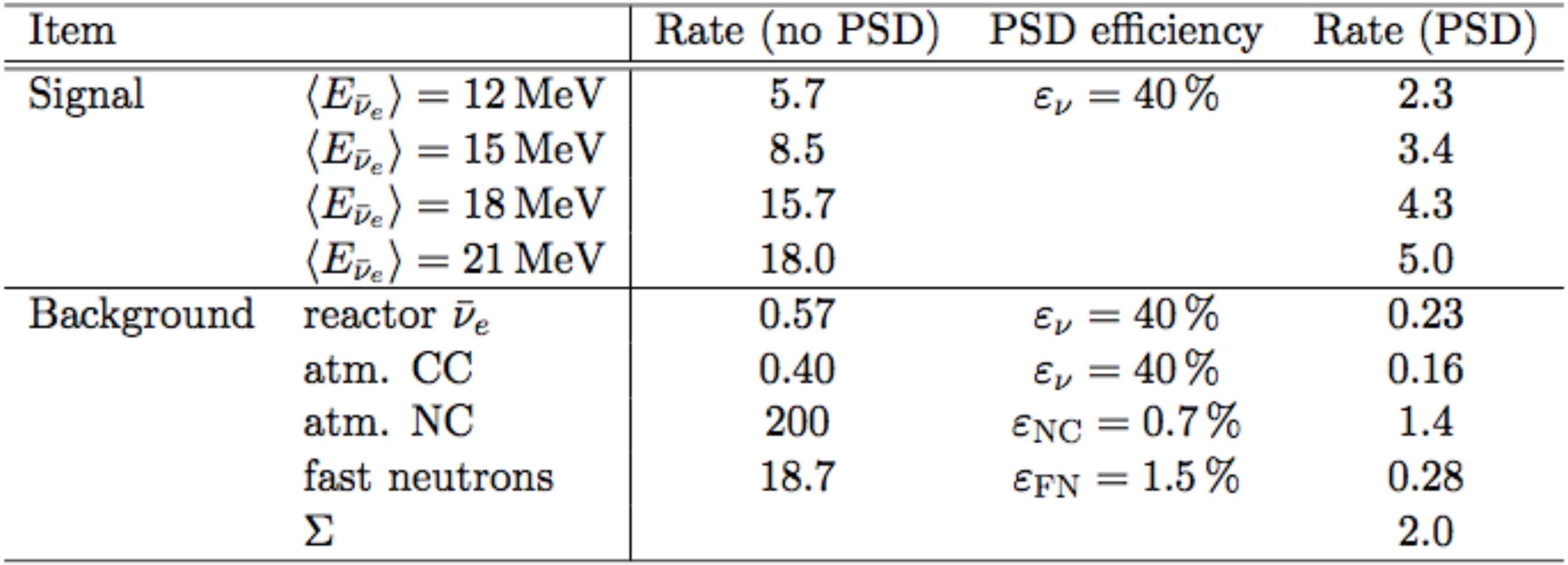
average flux

JUNO expected spectrum



- inverse beta decay, **rate: 3-6 yr^{-1}**
- irreducible backgrounds: reactor ν's and atm. ν CC reactions
- Atm NC and fast neutron's: cylindrical shielding and pulse-shape discrimination

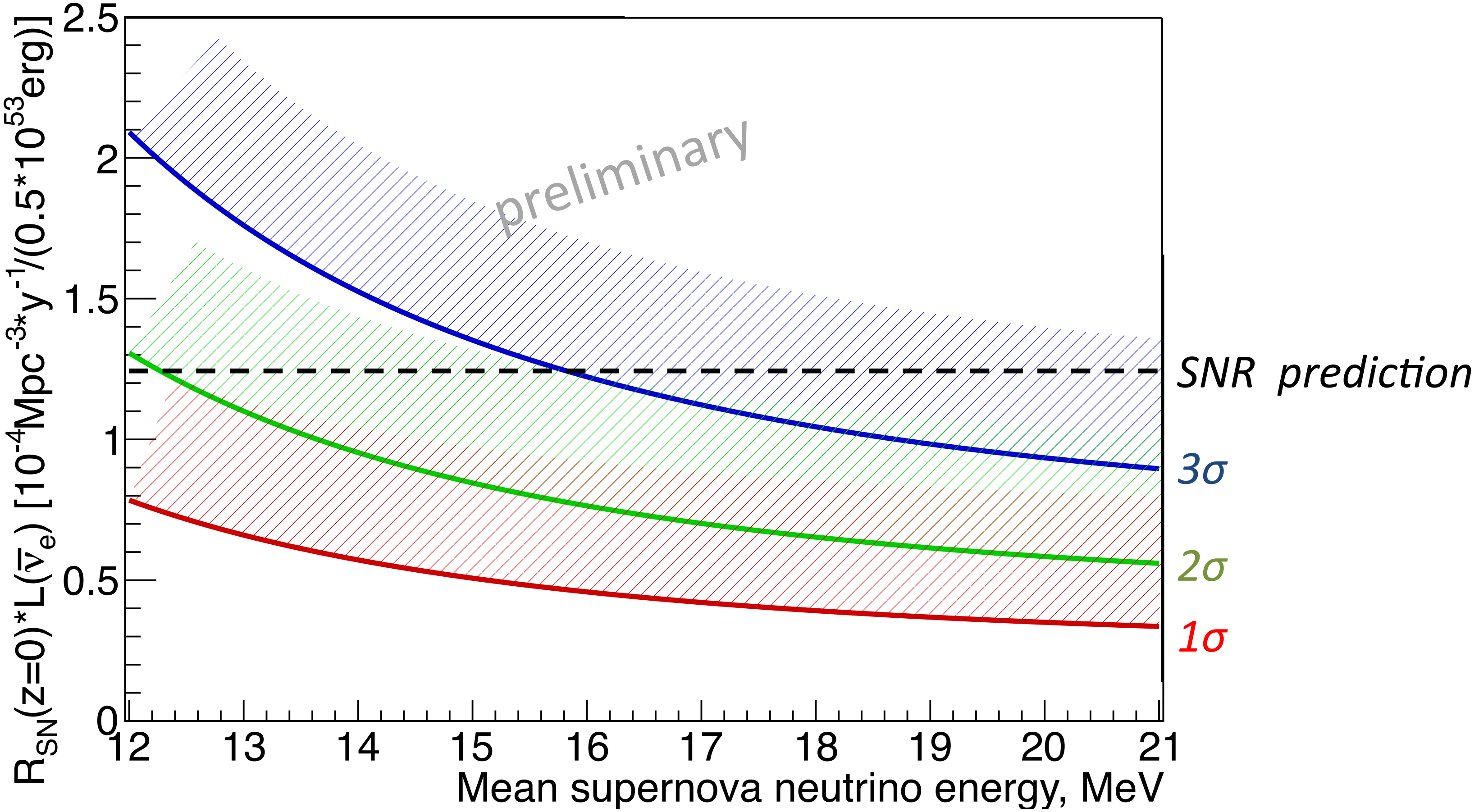
Expected Sensitivity after PSD



Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e} \rangle = 12\,\mathrm{MeV}$	5.7	$\varepsilon_\nu = 40\,\%$	2.3
	$\langle E_{\bar{\nu}_e} \rangle = 15\,\mathrm{MeV}$	8.5		3.4
	$\langle E_{\bar{\nu}_e} \rangle = 18\,\mathrm{MeV}$	15.7		4.3
	$\langle E_{\bar{\nu}_e} \rangle = 21\,\mathrm{MeV}$	18.0		5.0
Background	reactor $\bar{\nu}_e$	0.57	$\varepsilon_\nu = 40\,\%$	0.23
	atm. CC	0.40	$\varepsilon_\nu = 40\,\%$	0.16
	atm. NC	200	$\varepsilon_{\mathrm{NC}} = 0.7\,\%$	1.4
	fast neutrons	18.7	$\varepsilon_{\mathrm{FN}} = 1.5\,\%$	0.28
	Σ			2.0

→ *Signal-to-Background ratio better than 1*

JUNO discovery potential (10 years)



Conclusions & outlook

- the first 20 kton liquid scintillator detector will be constructed;
- the DAQ is expected for 2020;
- main goal: mass hierarchy and precision measurement of oscillation parameters;
- If low background levels: measurement of ^{7}Be, pp and ^{8}B neutrinos possible;
- Potential to measure geoneutrinos with a better precision than existing results;
- Potential to measure DSN and SN neutrinos;

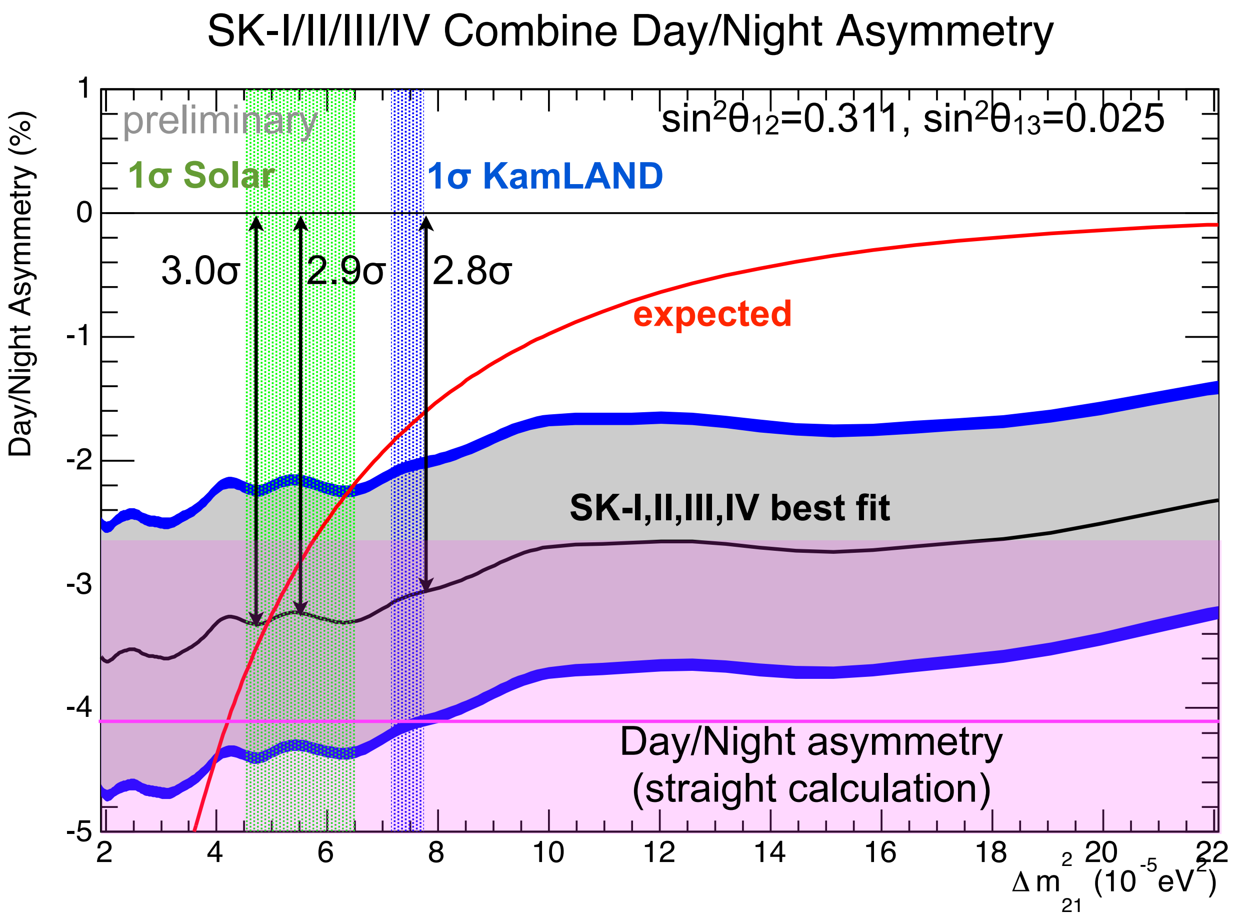
INFN with its experience in liquid scintillator techniuqe should take part in this game

Backup slides

15 years of work in one slide

Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final
Name	**Source**	**Typical**	**Required**	**Hardware**	**Software**	**Achieved**
μ	cosmic	~ 200 s^{-1} m^{-2} @ sea level	**< 10^{-10} s^{-1} m^{-2}**	underground water Cerenkov detector	Pulse shape analysis	**< 10^{-10} eff. > 0.9992**
γ	rock			water	fid. vol.	negligible
γ	PMTs, SSS			buffer	fid. vol.	negligible
^{14}C	intrinsic PC	~10^{-12} g/g	~10^{-18} g/g	selection	threshold	~ 2 10^{-18} g/g
^{238}U ^{232}Th	dust, metallic	10^{-5}-10^{-6} g/g	**< 10^{-16} g/g**	distillation, W.E., filtration, mat. selection, cleanliness	tagging, α/β	**1.6±0.1 10^{-17} g/g 5.1±1 10^{-18} g/g**
^{7}Be	cosmogenic	~3 10^{-2} Bq/t	< 10^{-6} Bq/t	distillation	--	not seen
^{40}K	dust, PPO	~2. 10^{-6} g/g (dust)	< 10^{-18} g/g	distillation,W.E.	--	not seen
^{210}Po	surface cont. from ^{222}Rn		**< 1 c/d/t**	distillation, W.E., filtration, cleanliness	fit	**May '07: 70 c/d/t Jan '10: ~1 c/d/t**
^{222}Rn	emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	< 10 cpd 100 t	N_2 stripping cleanliness	tagging, α/β	< 1 cpd 100 t
^{39}Ar	air, cosmogenic	17 mBq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	<< ^{85}Kr
^{85}Kr	air, nuclear weapons	~ 1 Bq/m^3 (air)	**< 1 cpd 100 t**	N_2 stripping	fit	**30 ± 5 cpd/100 t**

SuperKamiokande:Day-night variation of ^{8}B flux



Solar region

✓ differ from zero by 2.9~3.0σ

✓ agree with expect by 1.0σ

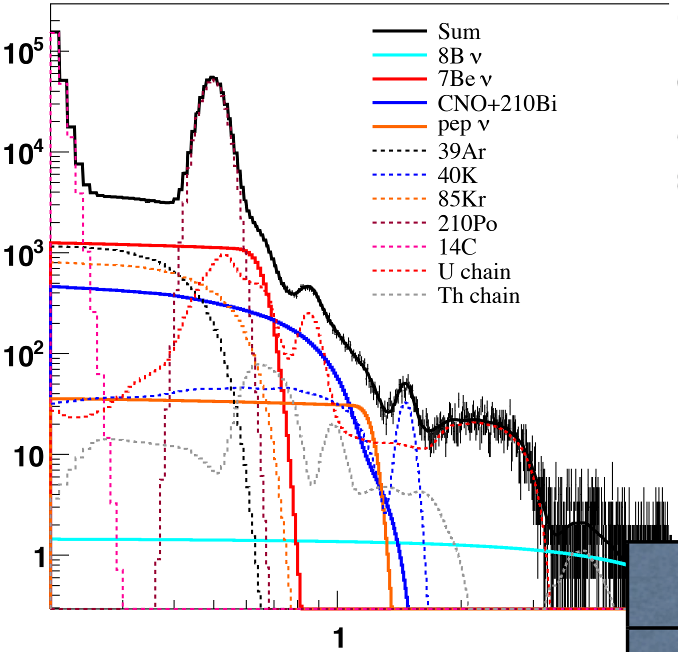
KamLAND region

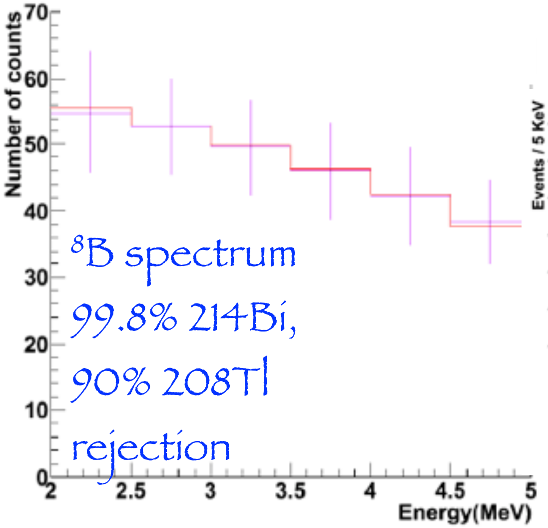
✓ differ from zero by more than 2.8σ

✓ agree with expect by 1.3σ

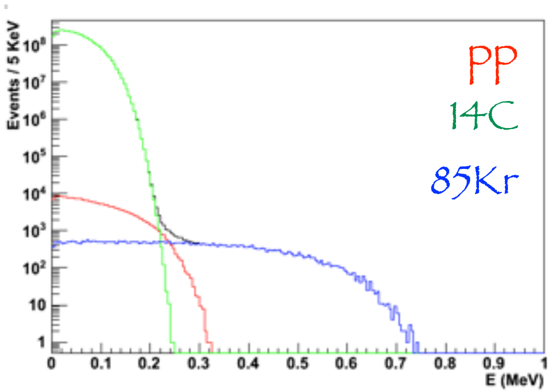
SNO+ Sensitivity

- 1 year livetime
- 50% fiducial volume (negligible external bkg)
- Assuming Borexino-level purification levels





^{8}B spectrum
99.8% 214Bi,
90% 208Tl
rejection



(pp dependent on ^{14}C, ^{85}Kr)
(CNO dependent on ^{210}Bi)

	pep	^{8}B	^{7}Be	pp	CNO
1 yr	9%	7.5%	4%	~ a few %	~ 15 %
2 yr	6.5%	5.4%	2.8%		

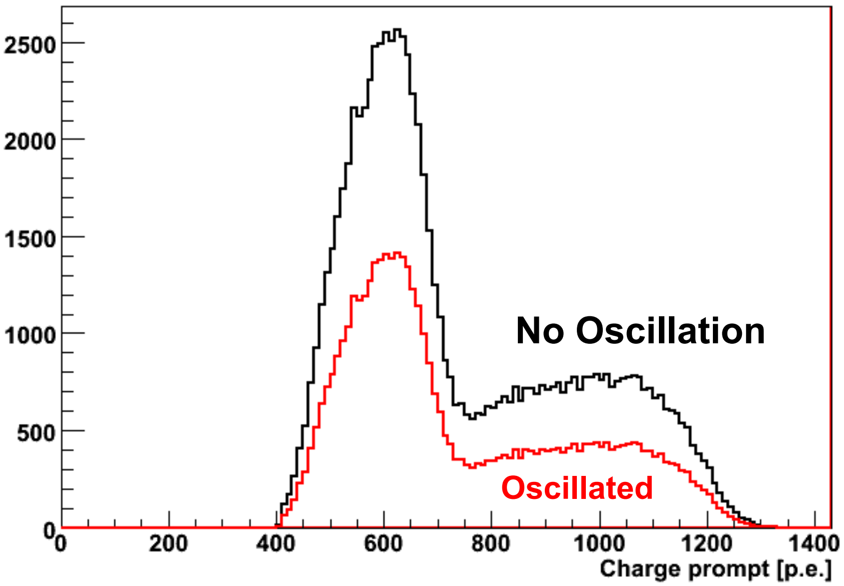
Effect of neutrino oscillations

$$P_{ee} = P(\overline{\nu}_e \to \overline{\nu}_e) = \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2 L}{4E}\right)\right) + \sin^4\theta_{13}$$

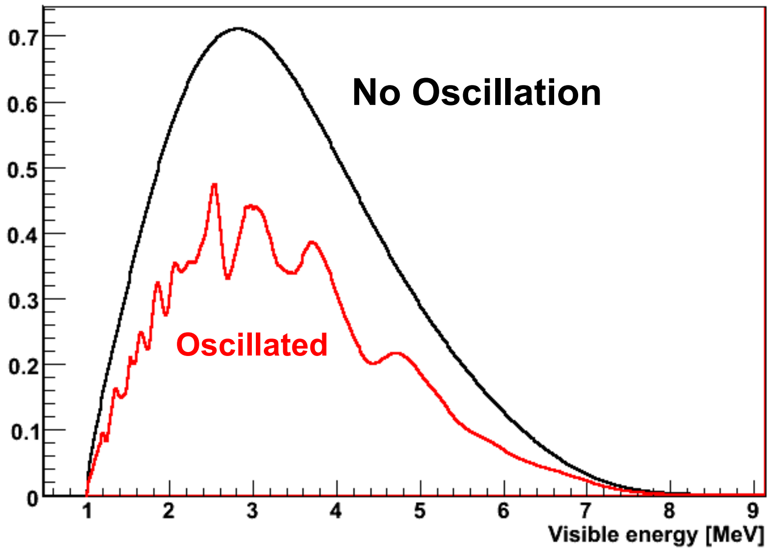
3 MeV antineutrino ..
Oscillation length of ~100 km

for geoneutrinos we can use average survival probability of 0.551 + 0.015 (Fiorentini et al 2012), but for reactor antineutrinos not!

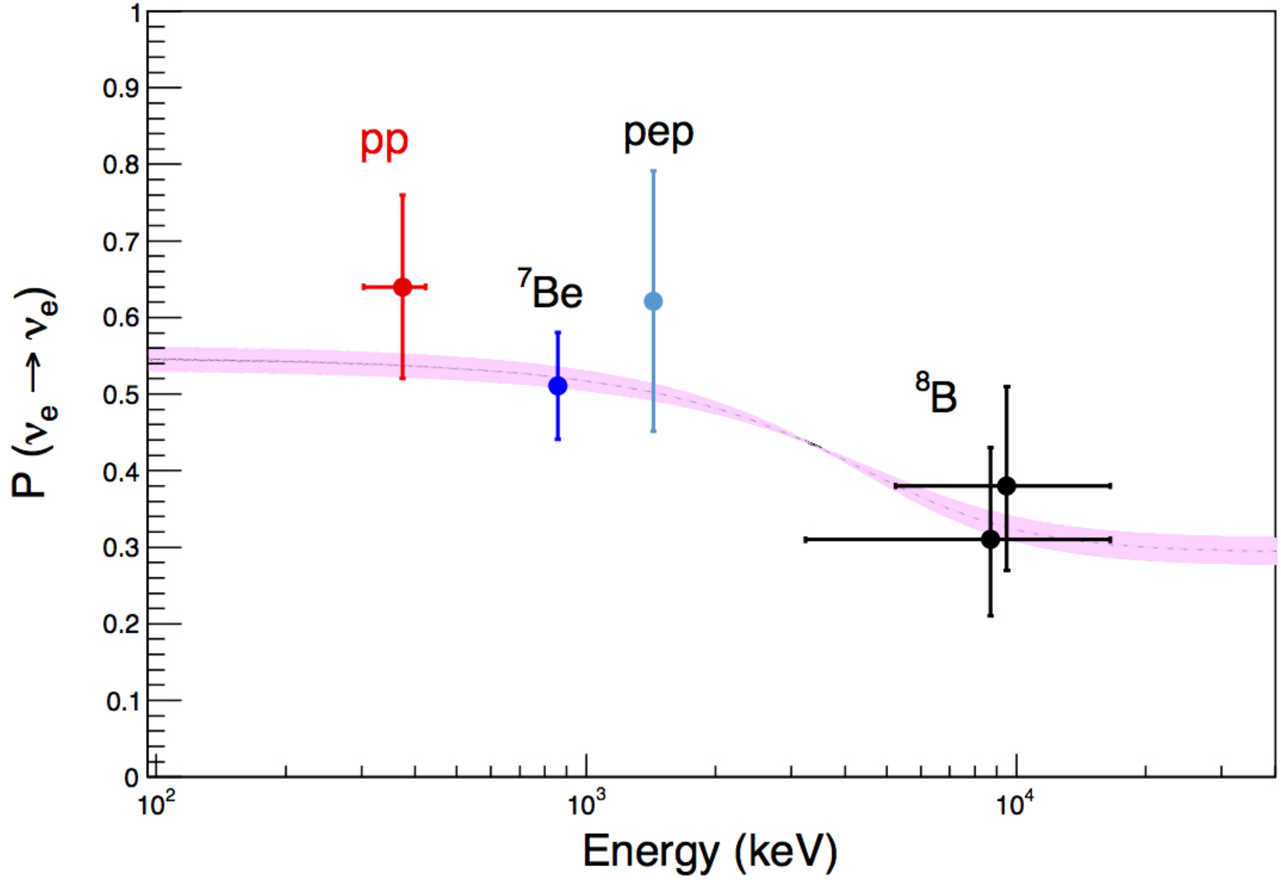
Geoneutrinos



Reactor antineutrinos at LNGS



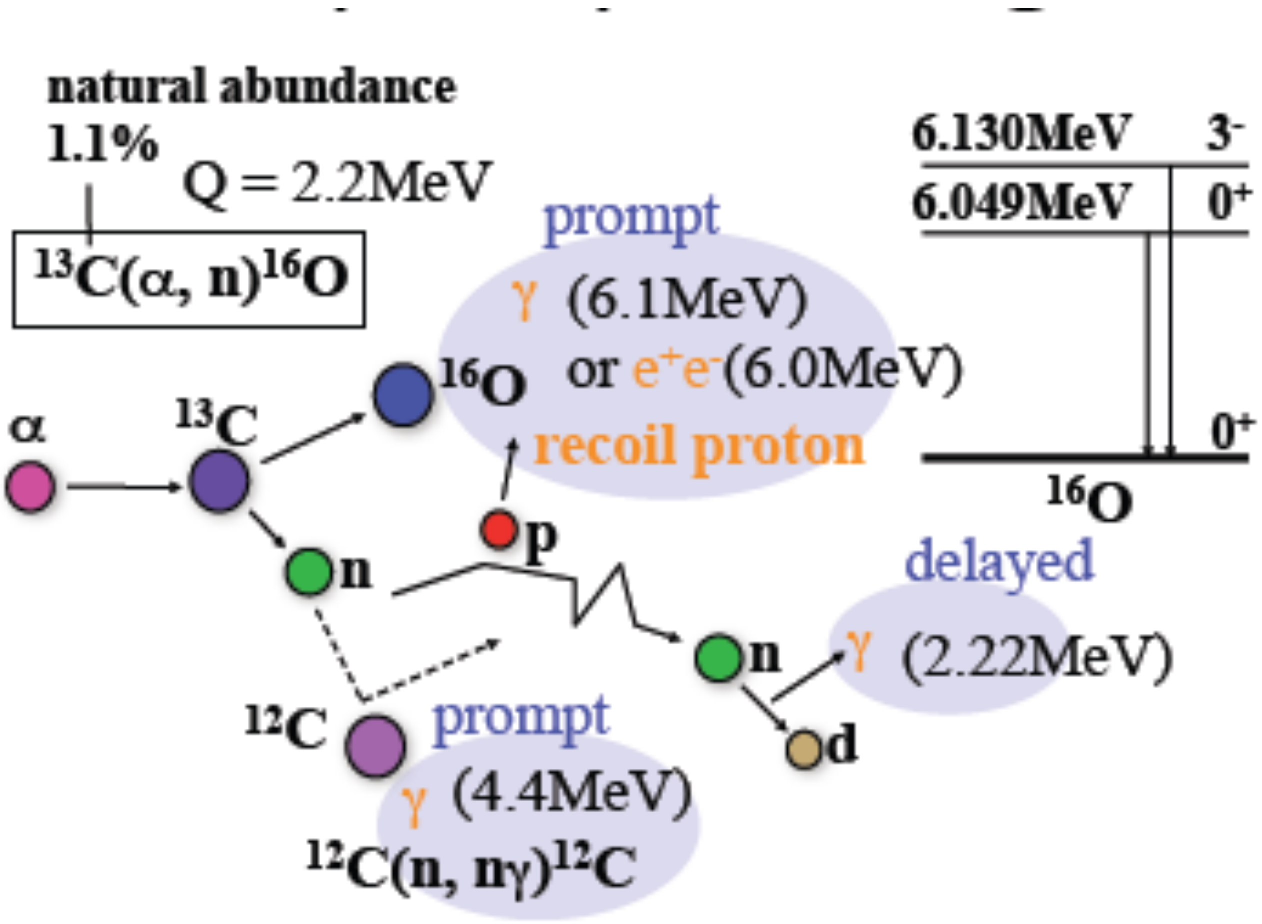
Borexino only 2014



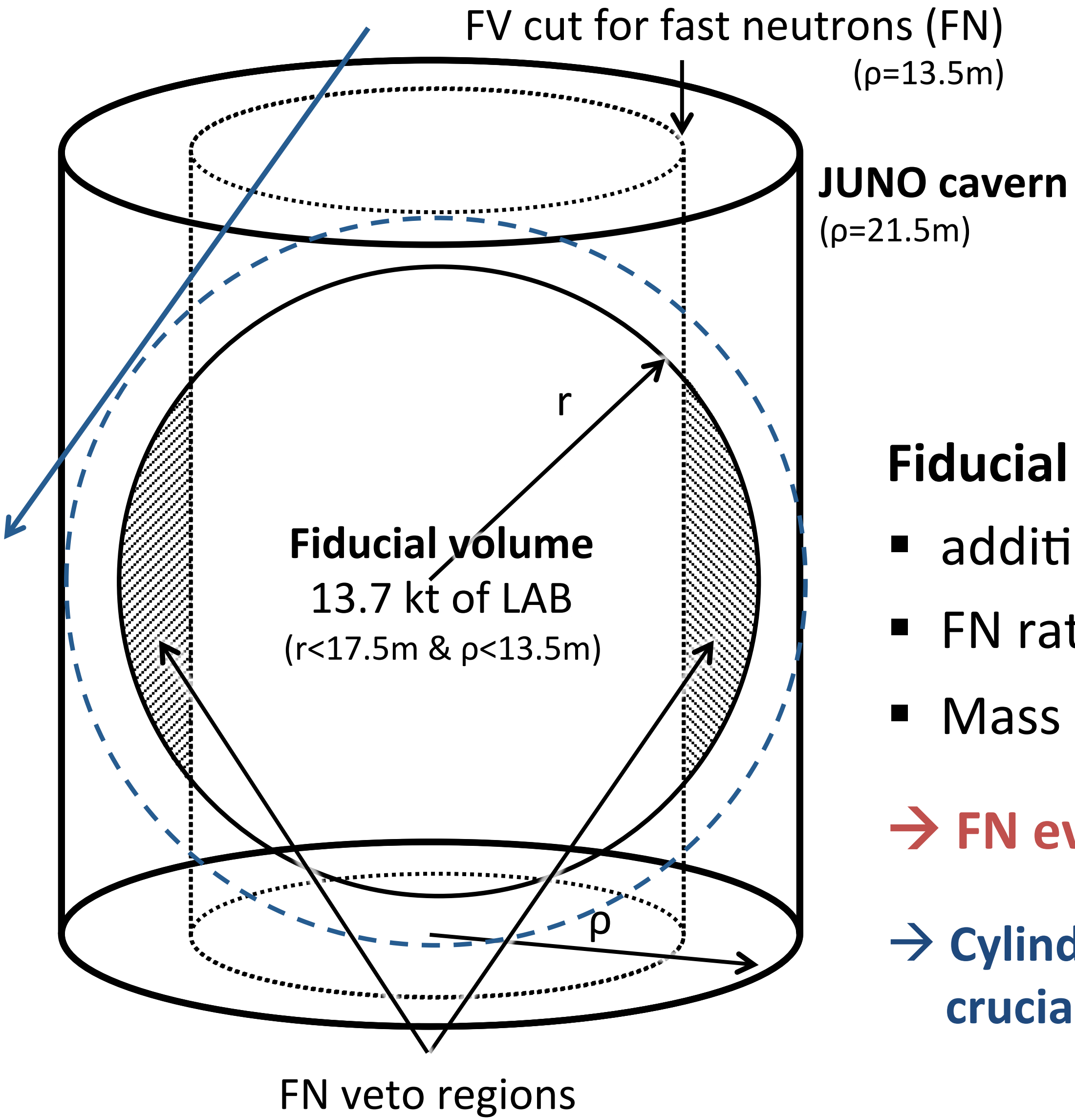
Nature 512 (2014) 383

$^{13}C(\alpha,n)^{16}O$

1) Isotopic abundance of ^{13}C: 1.1%
2) ^{210}Po contamination: **A_{Po}~ 12 cpd/ton**



FN Water Pool Shape



based on LENA MC study

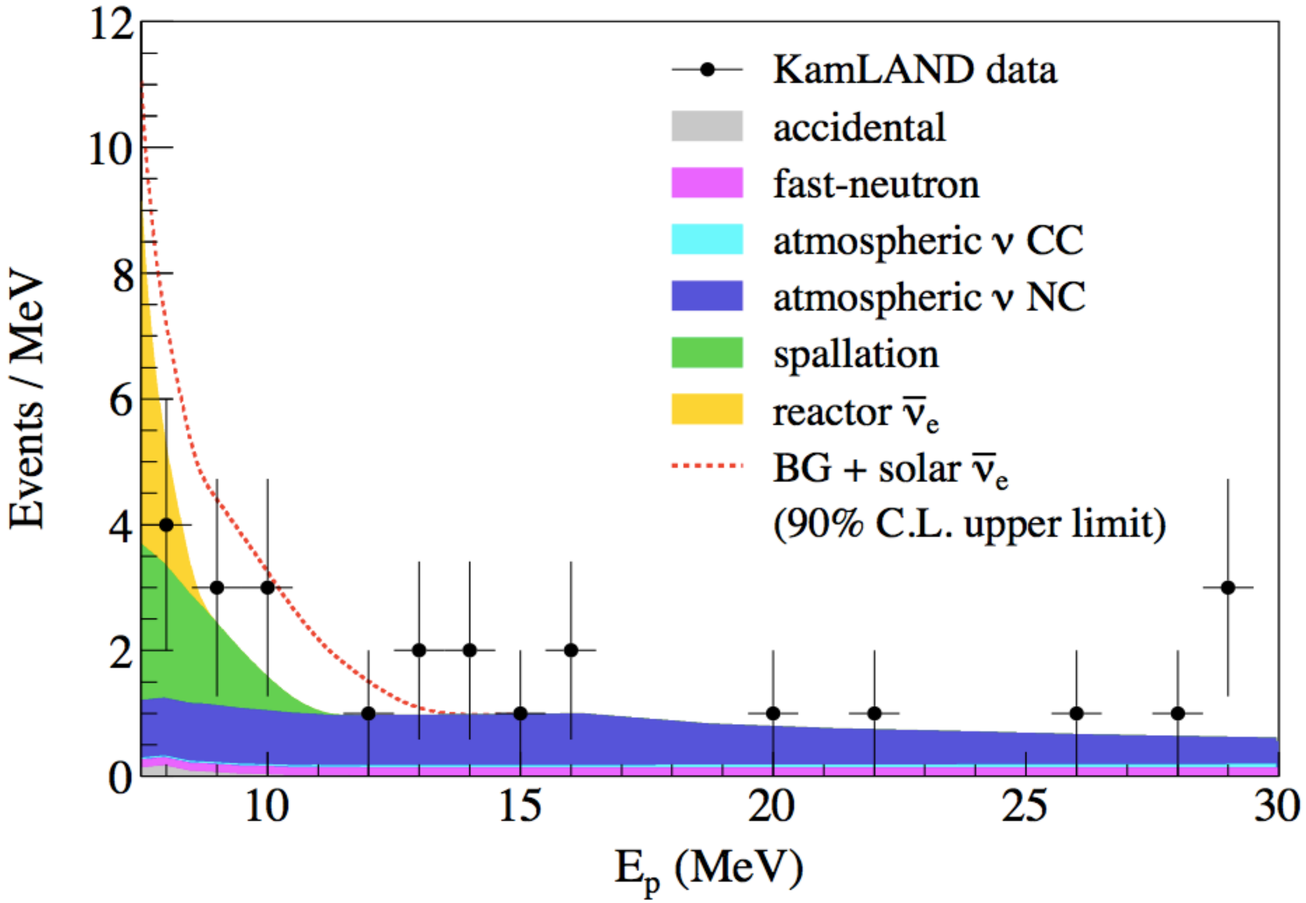
Fiducial volume cut

- additional shielding: 4 mwe
- FN rate reduction: x 500
- Mass reduction: x 1.5

→ **FN events in target: 19 yr^{-1}**

→ **Cylindrical shape of water pool is crucial for shielding inclined μ tracks**

Background measurements in KamLAND

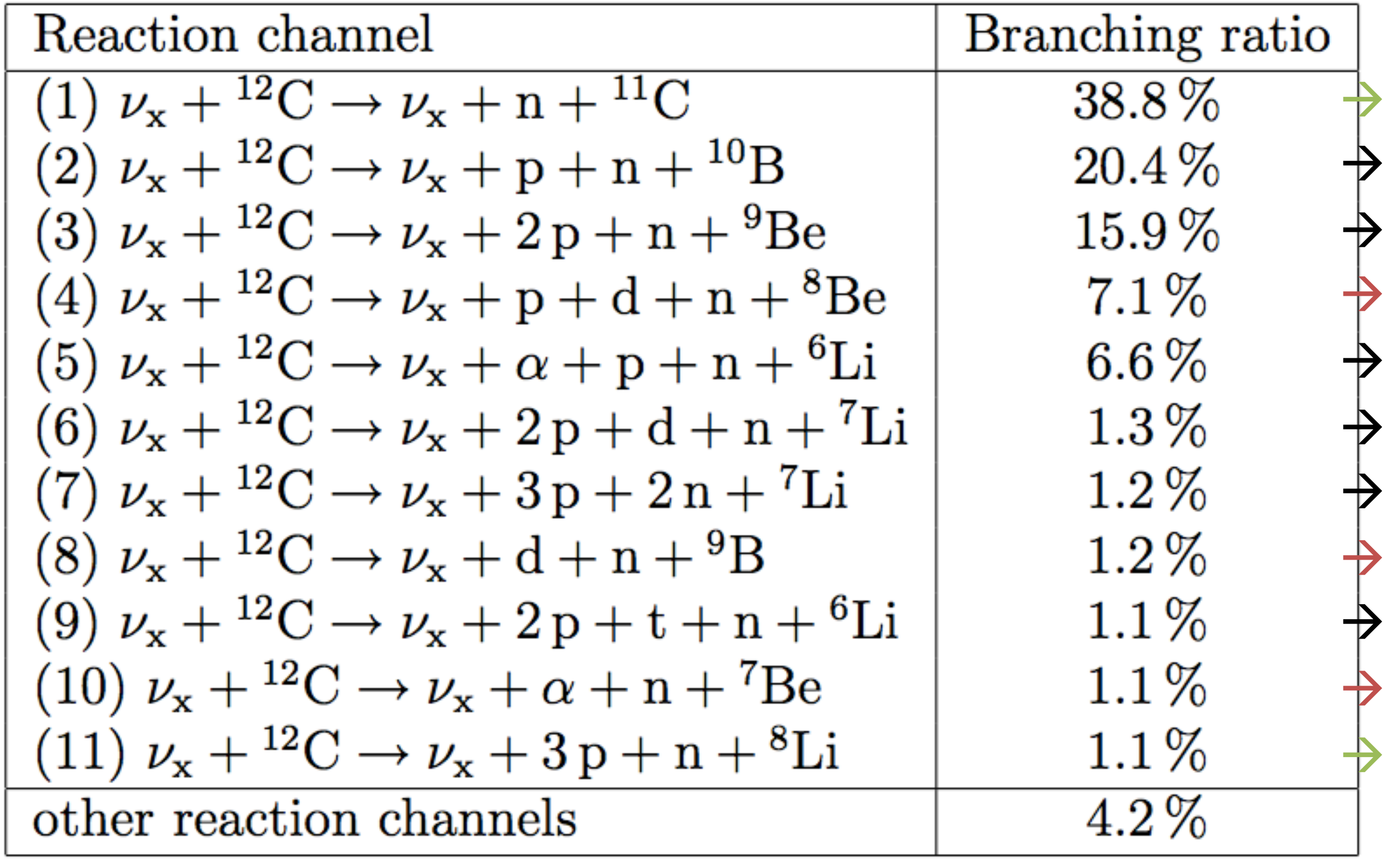


Primary backgrounds for 11 ÷ 28 MeV:

- fast neutrons
- atmospheric neutrino NC reactions

Atmospheric Neutrinos: NC Background

40% of events can be tagged by the decay of the final state isotope:



Reaction channel	Branching ratio	
(1) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + \mathrm{n} + {}^{11}\mathrm{C}$	38.8 %	→ *taggable*
(2) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + \mathrm{p} + \mathrm{n} + {}^{10}\mathrm{B}$	20.4 %	→ *stable*
(3) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + 2\,\mathrm{p} + \mathrm{n} + {}^{9}\mathrm{Be}$	15.9 %	→ *stable*
(4) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + \mathrm{p} + \mathrm{d} + \mathrm{n} + {}^{8}\mathrm{Be}$	7.1 %	→ *too fast*
(5) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + \alpha + \mathrm{p} + \mathrm{n} + {}^{6}\mathrm{Li}$	6.6 %	→ *stable*
(6) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + 2\,\mathrm{p} + \mathrm{d} + \mathrm{n} + {}^{7}\mathrm{Li}$	1.3 %	→ *stable*
(7) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + 3\,\mathrm{p} + 2\,\mathrm{n} + {}^{7}\mathrm{Li}$	1.2 %	→ *stable*
(8) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + \mathrm{d} + \mathrm{n} + {}^{9}\mathrm{B}$	1.2 %	→ *too fast*
(9) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + 2\,\mathrm{p} + \mathrm{t} + \mathrm{n} + {}^{6}\mathrm{Li}$	1.1 %	→ *stable*
(10) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + \alpha + \mathrm{n} + {}^{7}\mathrm{Be}$	1.1 %	→ *too long*
(11) $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + 3\,\mathrm{p} + \mathrm{n} + {}^{8}\mathrm{Li}$	1.1 %	→ *taggable*
other reaction channels	4.2 %	

→ NC background also removed by **Pulse Shape Discrimination**

Livia Ludhova for JUNO collaboration

INFN What's Next, Padova December 2nd, 2014