Geophysical and geochemical data for antineutrinos from reactors and the Earth

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Together with
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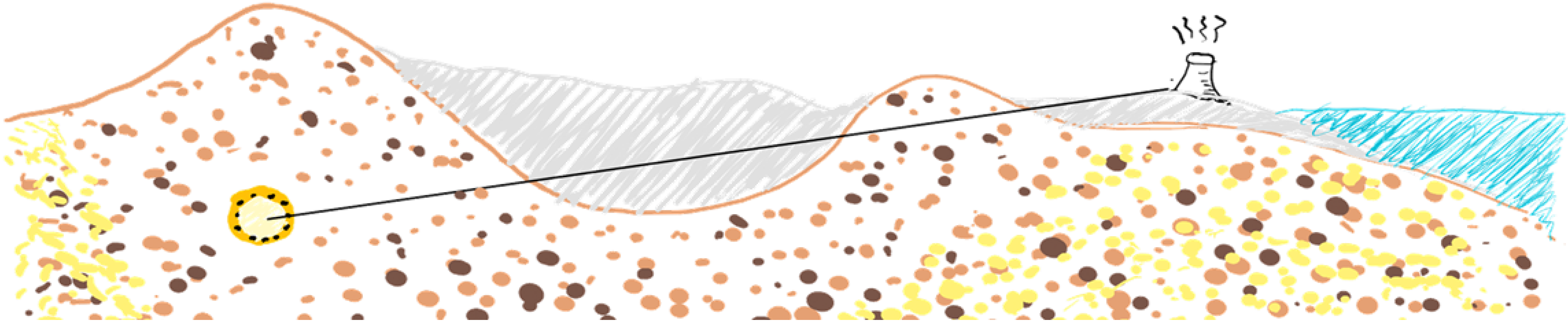
Michele Montuschi

Summary

- Neutrino oscillations in matter
- Rock samples from JUNO: density and composition
- Electron density from a reference rock
- Implications on reactor antineutrino spectrum



How does electron density affect neutrino oscillations?

$$P_{mat}^{3\nu} \simeq c_{13}^4 P_{mat}^{2\nu} + s_{13}^4 + 2 s_{13}^2 c_{13}^2 \sqrt{P_{mat}^{2\nu}}\, w \cos(2\Delta_{ee} + \alpha\varphi)$$

$$P_{mat}^{2\nu} = 1 - 4 \tilde{s}_{12}^2 \tilde{c}_{12}^2 \sin^2 \tilde{\delta}$$

- $\tilde{s}_{12}^2 \tilde{c}_{12}^2 = \frac{1}{4} \sin^2 2\tilde{\theta}_{12} \simeq \frac{1}{4} \sin^2 2\theta_{12} (1 - \mu_{12} \cos 2\theta_{12})^2$
- $\tilde{\delta} = \frac{\delta \tilde{m}^2 L}{4E} \simeq \delta m^2 (1 + \mu_{12} \cos 2\theta_{12}) \frac{L}{4E}$

$$\mu_{12} = \frac{2\sqrt{2} G_F N_e E}{\Delta m_{12}^2}$$

$s_{ij}^n = \sin^n \theta_{ij}$, $c_{ij}^n = \cos^n \theta_{ij}$

$\Delta_{ee} = \frac{[\Delta m^2 + \alpha/2 (c_{12}^2 - s_{12}^2) \delta m^2]\, L}{4E}$

$w \simeq 1 - 2{\Delta_{ee}}^2 \sum_n w_n \lambda_n^2$

$\sum_n w_n \lambda_n^2 = 2.16 \cdot 10^{-5}$

$\Delta m^2 = \frac{1}{2} |\Delta m_{31}^2 + \Delta m_{32}^2|$

$\delta m^2 = \Delta m_{21}^2$, $\delta = \frac{\delta m^2 L}{4E}$

$\alpha = 1$ if NH, $\alpha = -1$ if IH

$\varphi \simeq 2 s_{12}^2 \delta \left(1 - \frac{\sin \delta}{2\delta \sqrt{P_{vac}^{2\nu}}}\right)$

$G_F = 1.16637 \cdot 10^{-5}$ GeV^{-2}

From Capozzi et al., 2014

Electron density N_e

$$N_e(c,\rho) = \frac{\sum_i \rho_{Ox_i} f_i \frac{e^-{}_{Ox_i}}{N_{Ox_i}}}{\sum_i \rho_{Ox_i} f_i} \rho_{nat}$$

i: oxide index
ρ_{Ox_i}: density of the i-th oxide
f_i: weight fraction of the i-th oxide
$e^-{}_{Ox_i}$: number of electrons in the i-th oxide
N_{Ox_i}: number of nucleons in the i-th oxide
ρ_{nat}: average rock density

- Elements are considered in terms of **oxides**, compounds of one or more metallic elements combined with oxygen
- Generally, the ratio $e^-{}_{Ox_i}/N_{Ox_i}$ is **approximated** with 0.5. This gives the **simplified** formula $\mathbf{N_e(\rho) \simeq 0.5\, \rho_{nat}}$

"JUNO will make the first **precise** measurement of neutrino oscillations"

	Composition	ρ [g/cm³]	N_e [mol/cm³]
Capozzi et al., 2014	Not specified	2.6	1.3
Li et al., 2016	Not specified	2.6	1.3
Khan et al., 2020	Not specified	2.6	1.3
Our study	**We need more precise values**		

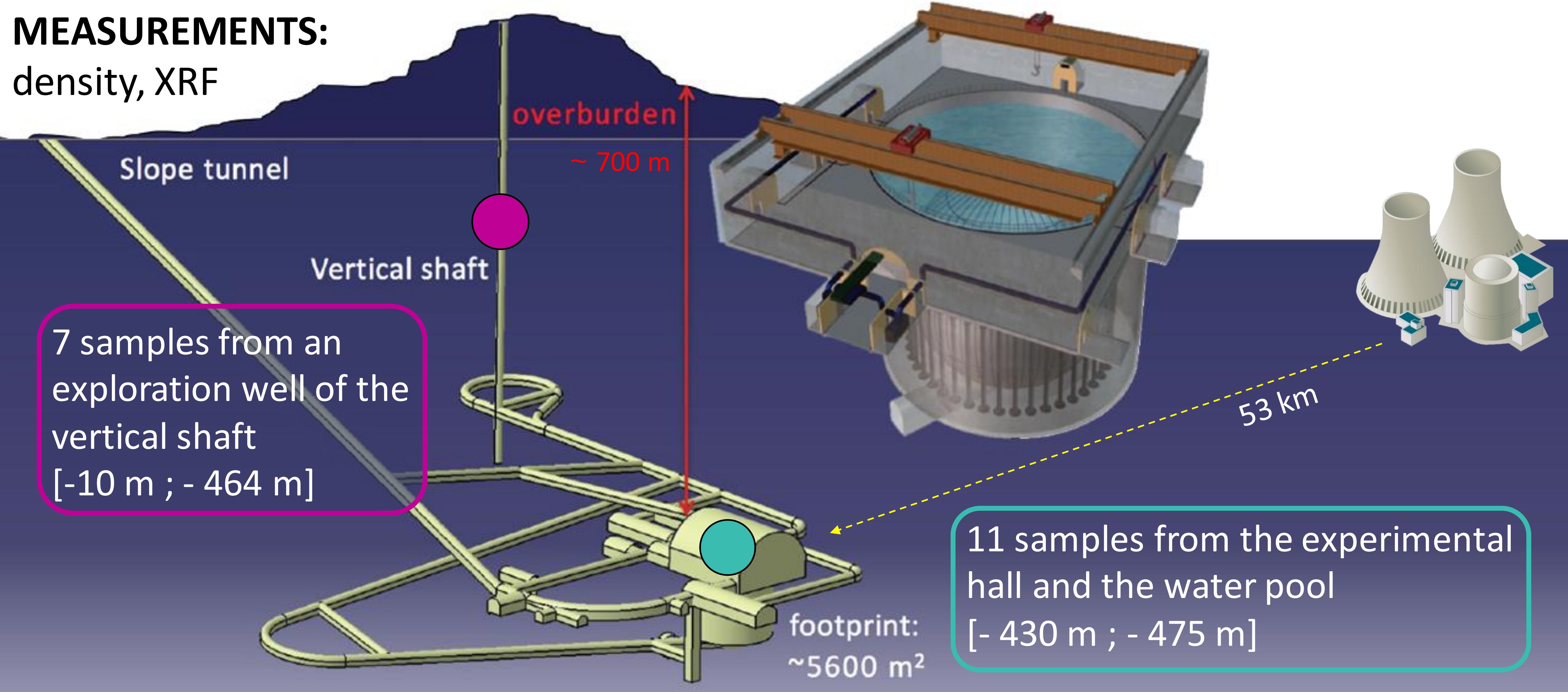
Rock samples from JUNO site

TOTAL NUMBER OF SAMPLES: 18

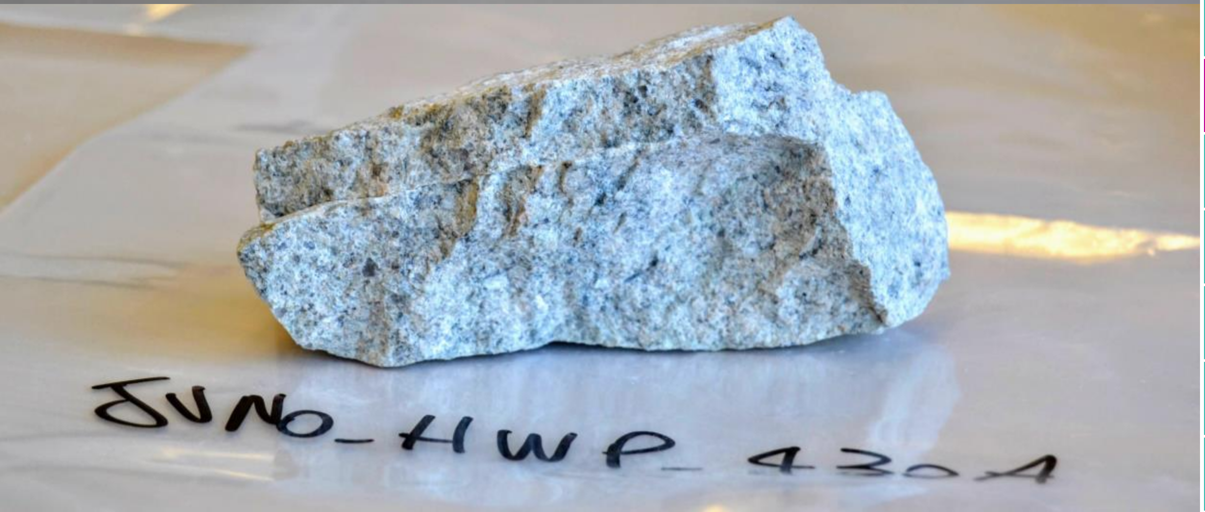
TYPE OF ROCK: GRANITES

MEASUREMENTS:

density, XRF



Rock samples' location



ID	Sample	Depth (m)	Notes
1	JUNO FRESH	10	Exploration well
2	JUNO ZK1 100	36	Exploration well
3	JUNO ZK1 200	64	Exploration well
4	JUNO ZK1 300	164	Exploration well
5	JUNO ZK1 400	264	Exploration well
6	JUNO ZK1 500	364	Exploration well
7	JUNO 2 HWP 430 A	430	Hall/water pool
8	JUNO 2 HWP 430 B	430	Hall/water pool
9	JUNO HWP 430 A	430	Lower part of the water pool
10	JUNO HWP 430 B	430	Above the water pool
11	JUNO HWP 460	460	Hall/water pool
12	JUNO 2 HWP 464	464	Exploration well
13	JUNO ZK1 600	464	Lower part of the water pool
14	JUNO HWP 465	465	Hall/water pool
15	JUNO 2 HWP 467	467	Hall/water pool
16	JUNO HWP 467	467	Lower part of the water pool
17	JUNO HWP 474	474	Hall/water pool
18	JUNO 2 HWP 475	475	Hall/water pool

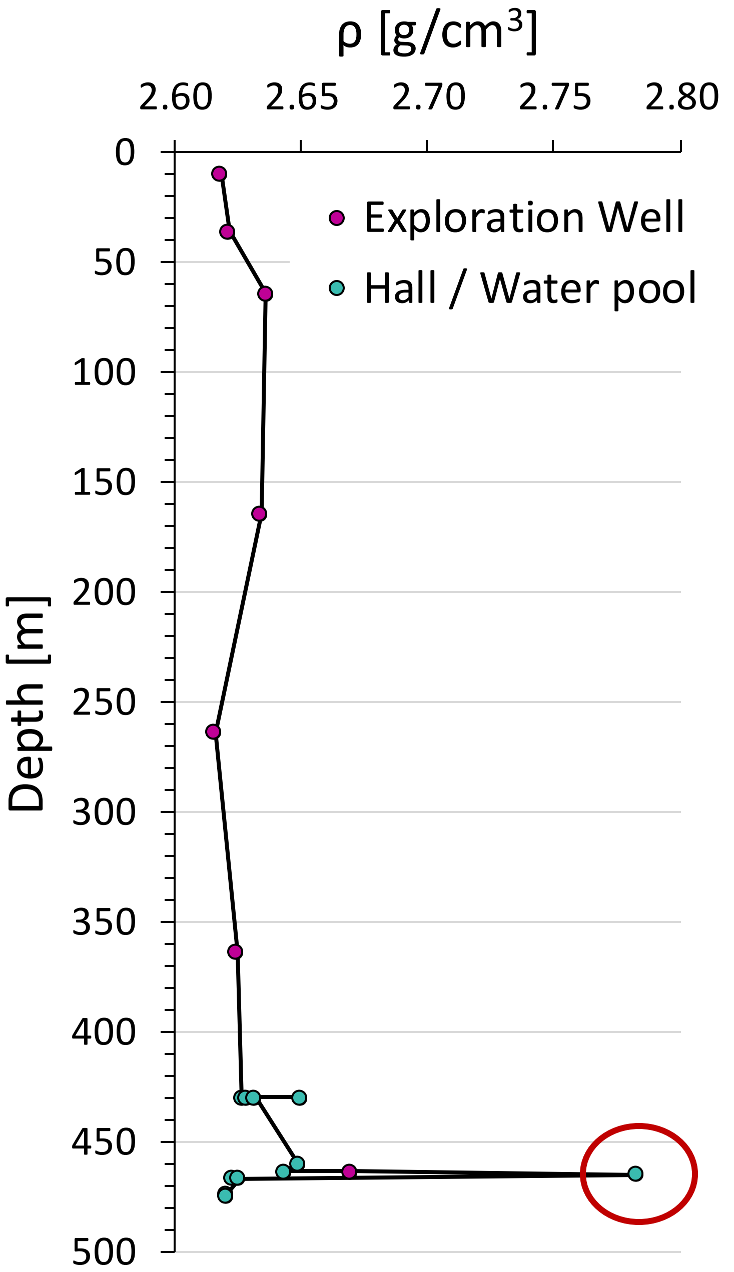
Results of density measurements

ID	Depth [m]	ρ [g/cm³]
1	10	2.6185
2	36	2.6218
3	64	2.6363
4	164	2.6344
5	264	2.6162
6	364	2.6251
7	430	2.6267
8	430	2.6284
9	430	2.6500
10	430	2.6319
11	460	2.6489
12	464	2.6438
13	464	2.6695
14	465	2.7832
15	467	2.6233
16	467	2.6257
17	474	2.6209
18	475	2.6205

- Experimental relative uncertainty ~ 10^{-4} g/cm^3
- **<ρ> = 2.6403 ± 0.0382 [g/cm³]**
- Std. dev. ~ 1.4% -> homogeneity

JUNO HWP 465

- The appearance of the rock is certainly different from the others. The darker color suggests that more **mafic minerals** are present



XRF technique for compositional analysis

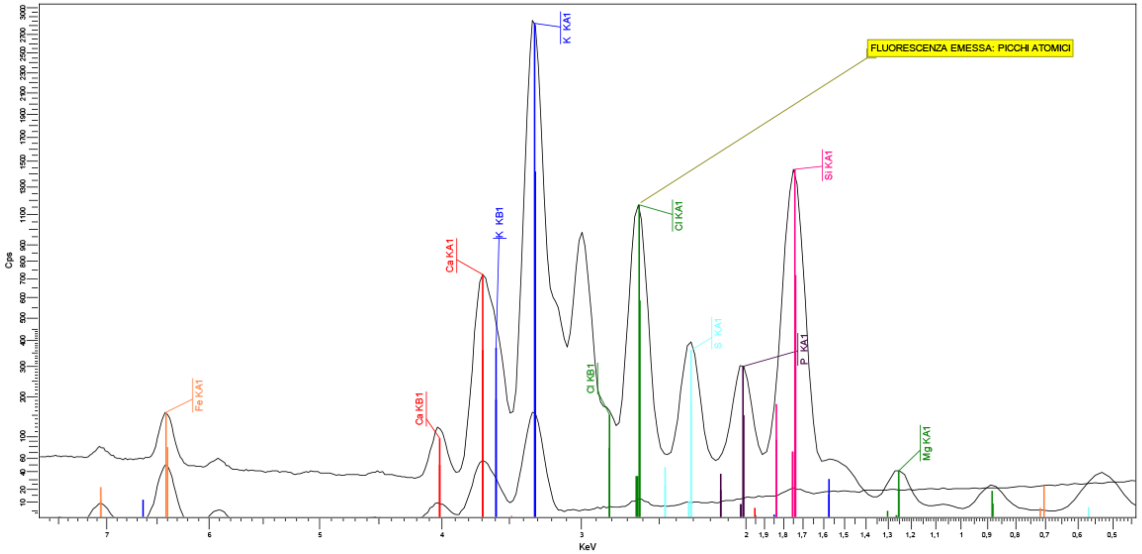
- The XRF technique (X-Ray Fluorescence) permits to identify the chemical elements constituting a sample thanks to the emitted X-rays following an induced atomic excitation.
- The **qualitative analysis** is made by **identifying** the X-emission lines associated with each element.
- The **quantitative analysis** requires a study of the **intensity** of the X-emission lines.
- The XRF technique permits to analyze both major and trace elements.

Major elements, expressed as equivalent oxides:

SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5

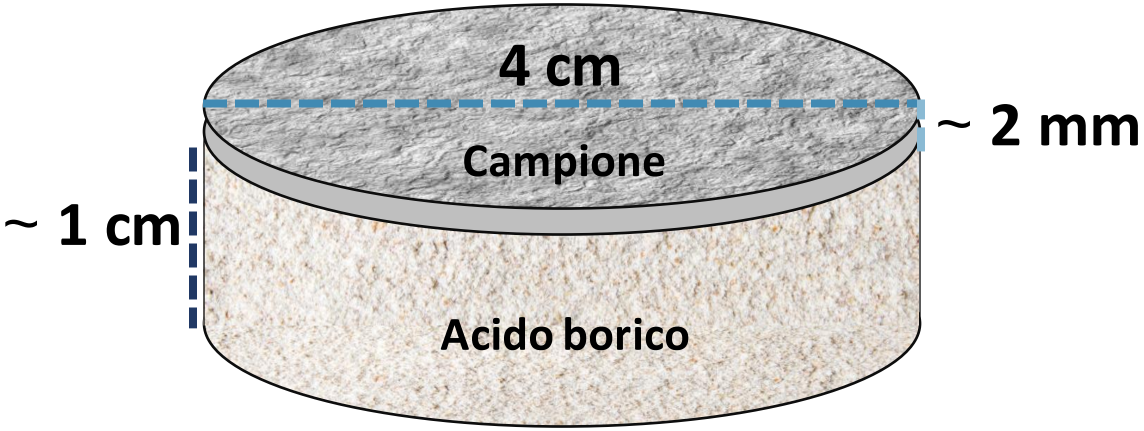
Trace elements (ppm or µg/g):

Ba, Ce, Co, Cr, Cu, Ga, Hf, La, Nb, Nd, Ni, Pb, Rb, Sc, Sr, Th, V, Y, Zn, Zr



Sample preparation

- **Shattering of the sample** by means of a hammer
- **Grinding of the sample** into small pieces
- **Redundant crushing** (grain size < 0.15 mm)
- **Paste preparation:** ~ 5 g of sample with organic glue
- **Press filling** with an additional ~20 g of boric acid
- **Compression** with a hydraulic press
- **Drying**



Results of XRF measurements

	Sample	Depth [m]	Si ± σSi [%]	Al ± σAl [%]	K ± σK [%]	Ca ± σCa [%]	Fe ± σFe [%]	S ± σS [ppm]	Mn ± σMn [ppm]	Zn ± σZn [ppm]	Pb ± σPb [ppm]
	JUNO_FRESH	10	35 ± 2	6.8 ± 0.4	3.7 ± 0.1	0.62 ± 0.02	0.8 ± 0.1	N/A	507 ± 60	30 ± 9	55 ± 12
	JUNO_ZK1_100	36	34 ± 2	7.0 ± 0.4	3.8 ± 0.1	0.76 ± 0.02	0.9 ± 0.1	441 ± 51	358 ± 58	27 ± 9	46 ± 12
	JUNO_ZK1_200	64	34 ± 2	7.1 ± 0.4	4.2 ± 0.1	0.60 ± 0.02	1.0 ± 0.1	723 ± 51	1574 ± 76	101 ± 12	115 ± 12
	JUNO_ZK1_300	164	34 ± 2	7.1 ± 0.4	3.9 ± 0.1	1.18 ± 0.03	0.9 ± 0.1	466 ± 51	565 ± 60	25 ± 9	51 ± 12
	JUNO_ZK1_400	264	34 ± 2	6.8 ± 0.4	4.0 ± 0.1	0.86 ± 0.02	0.7 ± 0.1	N/A	511 ± 56	44 ± 9	46 ± 12
	JUNO_ZK1_500	364	34 ± 2	7.2 ± 0.4	4.0 ± 0.1	0.56 ± 0.02	1.2 ± 0.1	1529 ± 57	643 ± 64	30 ± 12	55 ± 12
	JUNO_2_HWP_430_A	430	34 ± 2	7.2 ± 0.4	3.7 ± 0.1	0.64 ± 0.02	1.1 ± 0.1	532 ± 51	444 ± 58	27 ± 9	46 ± 12
	JUNO_2_HWP_430_B	430	34 ± 2	7.1 ± 0.4	3.8 ± 0.1	0.54 ± 0.02	1.0 ± 0.1	917 ± 51	474 ± 56	22 ± 9	44 ± 8
	JUNO_HWP_430_A	430	33 ± 2	7.7 ± 0.4	3.7 ± 0.1	0.77 ± 0.02	1.3 ± 0.1	463 ± 47	681 ± 56	103 ± 12	44 ± 8
	JUNO_HWP_430_B	430	34 ± 2	7.7 ± 0.4	3.9 ± 0.1	0.61 ± 0.02	1.0 ± 0.1	614 ± 49	494 ± 54	34 ± 9	48 ± 8
	JUNO_HWP_460	460	34 ± 2	7.5 ± 0.4	3.8 ± 0.1	0.73 ± 0.02	1.3 ± 0.1	594 ± 49	736 ± 62	35 ± 9	38 ± 8
	JUNO_2_HWP_464	464	34 ± 2	7.1 ± 0.4	3.7 ± 0.1	0.83 ± 0.02	1.3 ± 0.1	1506 ± 55	846 ± 62	182 ± 15	91 ± 12
	JUNO_ZK1_600	464	33 ± 2	7.6 ± 0.4	2.7 ± 0.1	0.64 ± 0.02	1.5 ± 0.1	5257 ± 70	3145 ± 98	78 ± 12	33 ± 12
	JUNO_HWP_465	465	32 ± 2	7.0 ± 0.4	3.4 ± 0.1	0.64 ± 0.02	4.2 ± 0.1	7584 ± 74	2779 ± 88	375 ± 21	88 ± 12
	JUNO_2_HWP_467	467	34 ± 2	7.4 ± 0.4	3.9 ± 0.1	0.63 ± 0.02	1.0 ± 0.1	662 ± 49	484 ± 58	24 ± 9	40 ± 8
	JUNO_HWP_467	467	34 ± 2	7.0 ± 0.4	3.7 ± 0.1	0.58 ± 0.02	1.0 ± 0.1	426 ± 49	496 ± 56	25 ± 9	39 ± 8
	JUNO_HWP_474	474	34 ± 2	6.9 ± 0.4	3.9 ± 0.1	0.57 ± 0.02	1.1 ± 0.1	482 ± 51	717 ± 62	30 ± 9	43 ± 8
	JUNO2_HWP_475	475	34 ± 2	7.0 ± 0.4	3.8 ± 0.1	0.79 ± 0.02	1.2 ± 0.1	451 ± 49	558 ± 60	27 ± 9	44 ± 12
	Average ± st.dev		**34 ± 1**	**7.2 ± 0.3**	**3.8 ± 0.3**	**0.70 ± 0.16**	**1.3 ± 0.8**	**1258 ± 1960**	**890 ± 801**	**68 ± 87**	**54 ± 22**

- Si, Al and K contents are **homogeneous**: relative standard deviation < 8 %
- Ca and Fe are less abundant and are characterized by higher variabilities
- Trace elements (S, Mn, Zn, Pb) present some relevant **outliers**

Anomalous samples

Sample	Depth [m]	Si ± σSi [%]	Al ± σAl [%]	K ± σK [%]	Ca ± σCa [%]	Fe ± σFe [%]	S ± σS [ppm]	Mn ± σMn [ppm]	Zn ± σZn [ppm]	Pb ± σPb [ppm]
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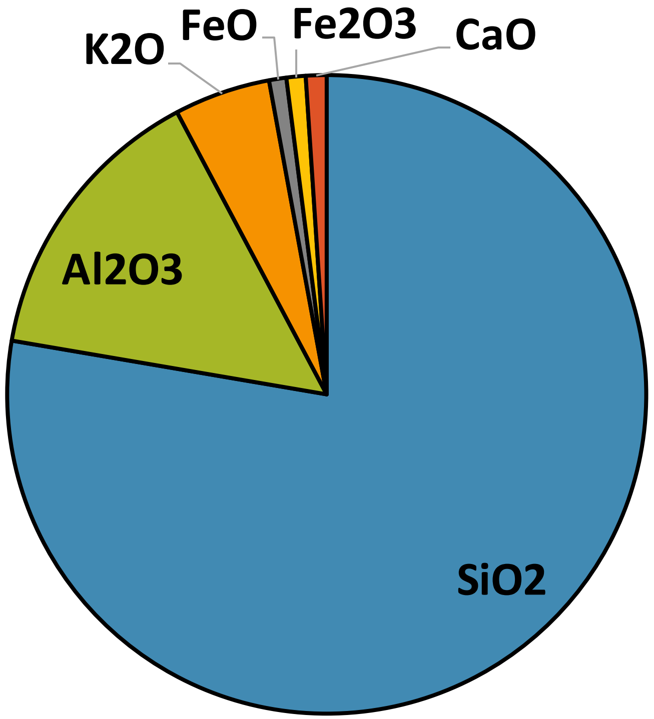
JUNO_HWP_474	474	34 ± 2	6.9 ± 0.4	3.9 ± 0.1	0.57 ± 0.02	1.1 ± 0.1	482 ± 51	717 ± 62	30 ± 9	43 ± 8
JUNO2_HWP_475	475	34 ± 2	7.0 ± 0.4	3.8 ± 0.1	0.79 ± 0.02	1.2 ± 0.1	451 ± 49	558 ± 60	27 ± 9	44 ± 12

- JUNO_2_HWP_464, JUNO_ZK1_600 and JUNO_HWP_465 (outliers) come from the same depth
- JUNO_HWP_465 is the already spotted **density outlier**
- JUNO_ZK1_600 is characterized by the presence of a **quartz vein**

Building a reference rock

- **Major elements**' average concentrations have been used to build a **reference rock** representative of the local rock composition
- The composition **in terms of equivalent oxides** have been obtained using the element-to-stoichiometric oxide **conversion factors** (CF)
- Fe concentration has been divided evenly between FeO and Fe_2O_3 oxides
- The sum of the obtained oxides equate to ~ 94 % so oxide concentrations have been **rescaled** to sum at 100%
- Trace elements have been **neglected**

Element	Element wt%	CF	Oxide	Oxide wt%	Normalized Oxide wt%
Si	34 ± 1	2.139	SiO_2	72	77
Al	7.2 ± 0.3	1.889	Al_2O_3	14	15
K	3.8 ± 0.3	1.205	K_2O	5	5
Ca	0.70 ± 0.16	1.399	CaO	1	1
Fe	0.65 ± 0.40	1.286	FeO	0.8	1
Fe	0.65 ± 0.40	1.430	Fe_2O_3	0.9	1

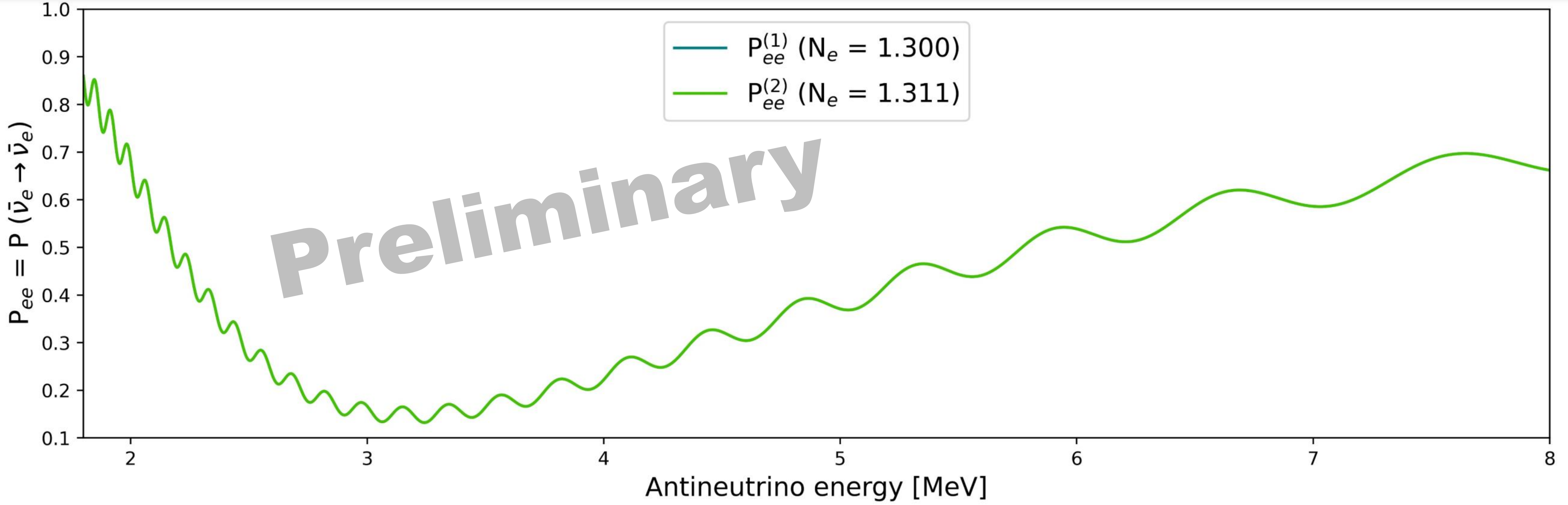


Electron density from geophysical and geochemical data

	Composition	ρ [g/cm^3]	N_e [mol/cm^3]
Capozzi et al., 2014	Not specified	2.6	1.3
Li et al., 2016	Not specified	2.6	1.3
Khan et al., 2020	Not specified	2.6	1.3
Our study	**Reference rock**	**2.640 ± 0.038**	**1.311**

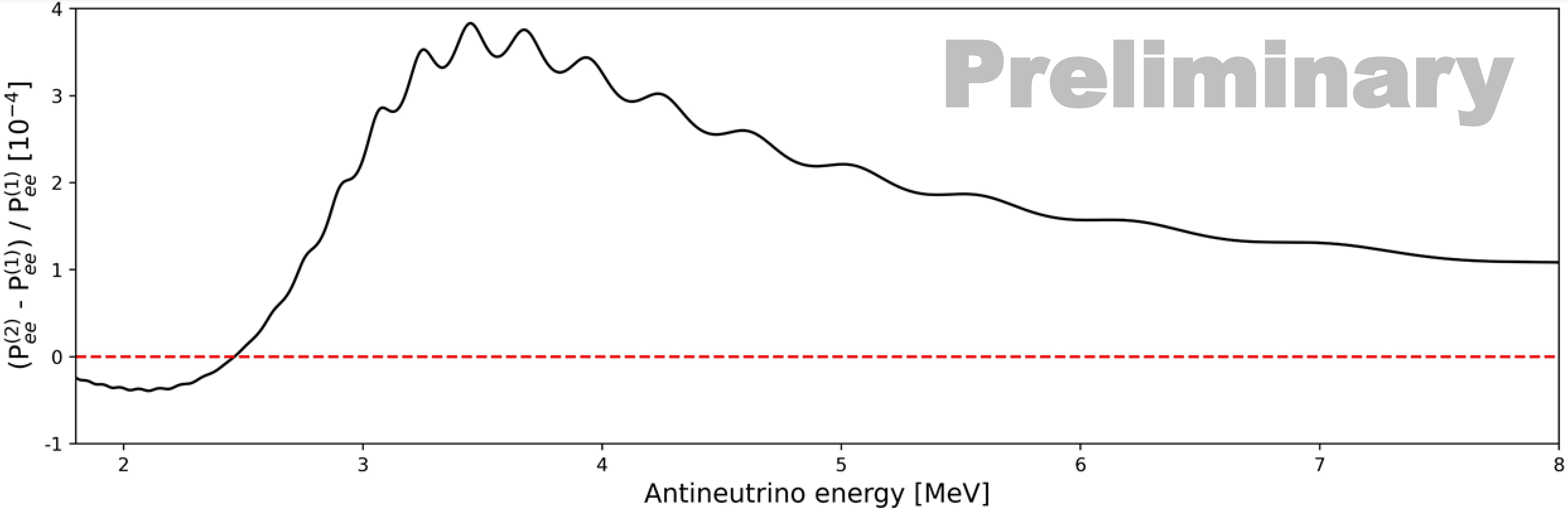
- Our estimations are based on geophysical and geochemical analysis of local rock samples
- Our density estimation differs from literature by 1.5%, **comparable with standard deviation**
- Estimation on N_e differs by 0.8% from literature
- With the complete measurement dataset, we will estimate the **uncertainty on N_e**

N_e and $\bar{\nu}_e$ survival probability in JUNO



- $\bar{\nu}_e$ survival probability as a function of antineutrino energy has been calculated for a **baseline L = 52.5 km** with **mixing parameters from ParticleDataGroup 2021**
- At this scale the effects of a different electron density are **not visible**

Impact of a precise N_e estimation



- The **relative difference** between $P_{ee}^{(2)}$(obtained with N_e = 1.311 mol/cm³) and $P_{ee}^{(1)}$ (obtained with N_e = 1.300 mol/cm³) is plotted as a function of antineutrino energy
- The maximum relative difference is of order of **$4 \cdot 10^{-4}$**, at ~ 3.5 MeV
- The **average** relative difference is **~ $1.7 \cdot 10^{-4}$**
- The effect of N_e obtained from geochemical and geophysical local data is small, but **should be considered for precise spectral calculation**

Conclusions and next steps

- We've made **density and compositional measurements** on 18 rock samples from JUNO site
- From measurement results we've estimated an **electron density of 1.311 mol/cm³**, to be compared with the value 1.300 mol/cm³ from literature
- This estimation modifies the $\bar{\nu}_e$ survival probability **at the order of 10^{-4}**
- Next steps are the **evaluation of N_e uncertainties** with a full dataset, the **characterization of rock and sediment types** crossed by antineutrinos and the **reconstruction of reactor $\bar{\nu}$ spectrum** in JUNO

Thank you