Spectrometry of the Earth core using Hyper-K

: Sensitivity study

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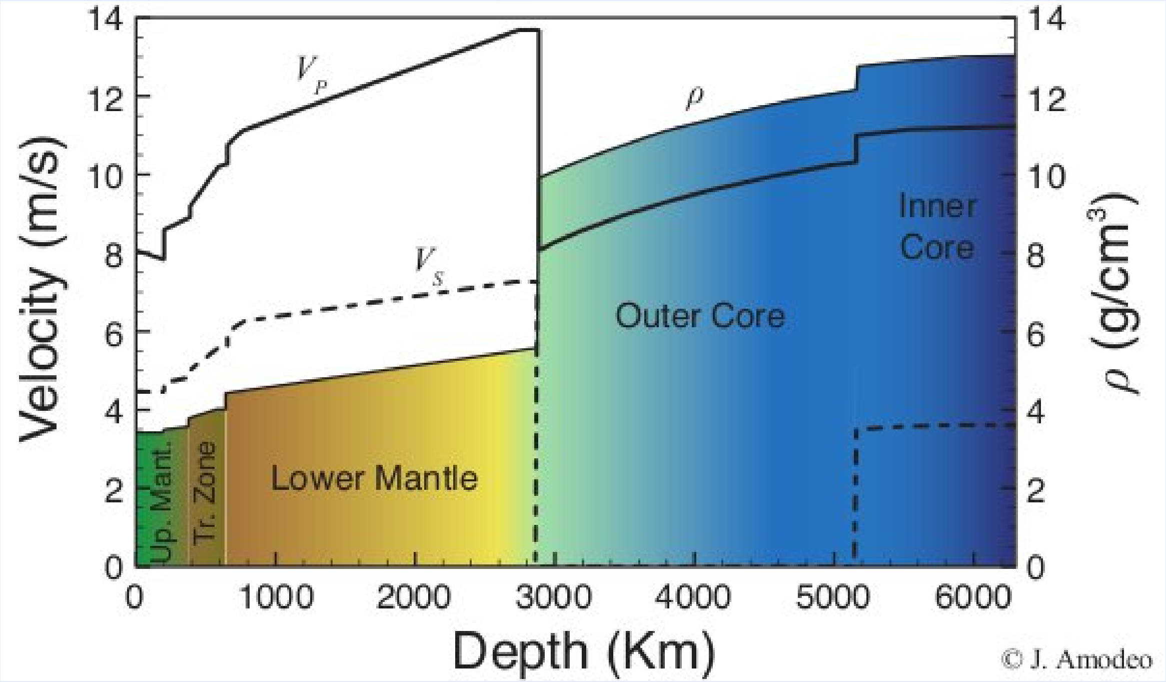
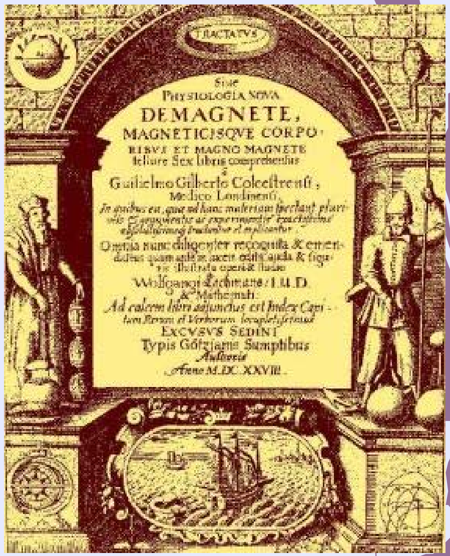
Current understanding

- Matter density profile is well known
  - Seismic measurement and free oscillation
- Outer core is assumed to be liquid iron (+Ni)
  - And some other light element
  - **But it's not measured**

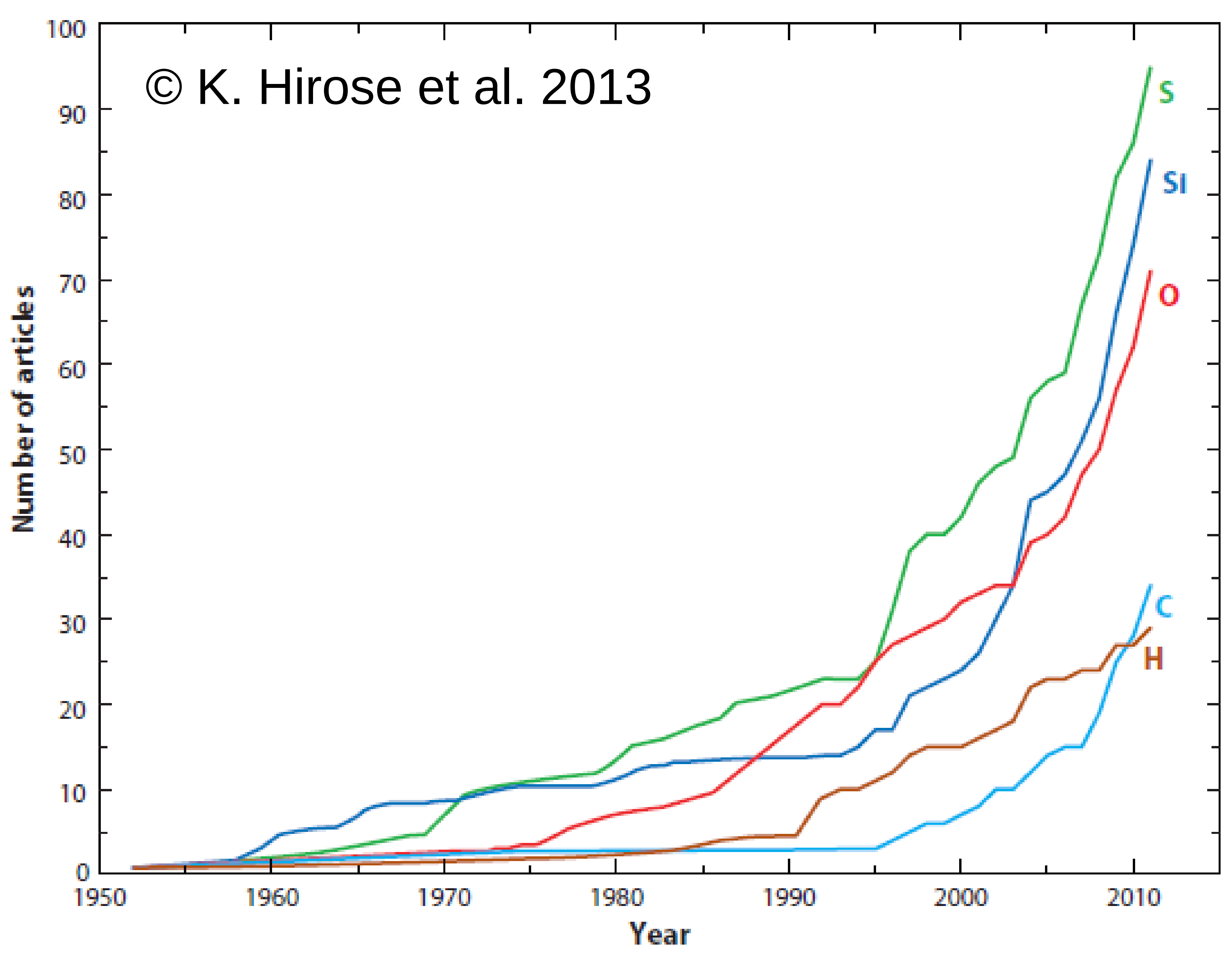


Why is light element important ?

- History of the Earth's evolution
- What is **the geomagnetic field** ? Who order it ?
  - W. Gilbert 1600
  - A. Einstein 1905
  - It requires the metal convection : dynamo theory
- Outer core composition is essentially important
  - Especially light component
  - Pure iron cannot maintain the convection
  - H? O? C? Si? S?



Cumulative number of articles



Neutrino physics to geophysics

- Neutrino oscillation probability depend on **electron density**, not matter density
- By using neutrino oscillation, we can measure the electron density of the medium
  - If we know the neutrino property very well
- We have the precise matter density of the earth
  - From seismic wave tomography and free oscillation
- Combining matter density and electron density, **we can measure the average chemical composition of the deep earth !**
  - Ratio of atomic number to mass number (Z/A)

Hypothesis

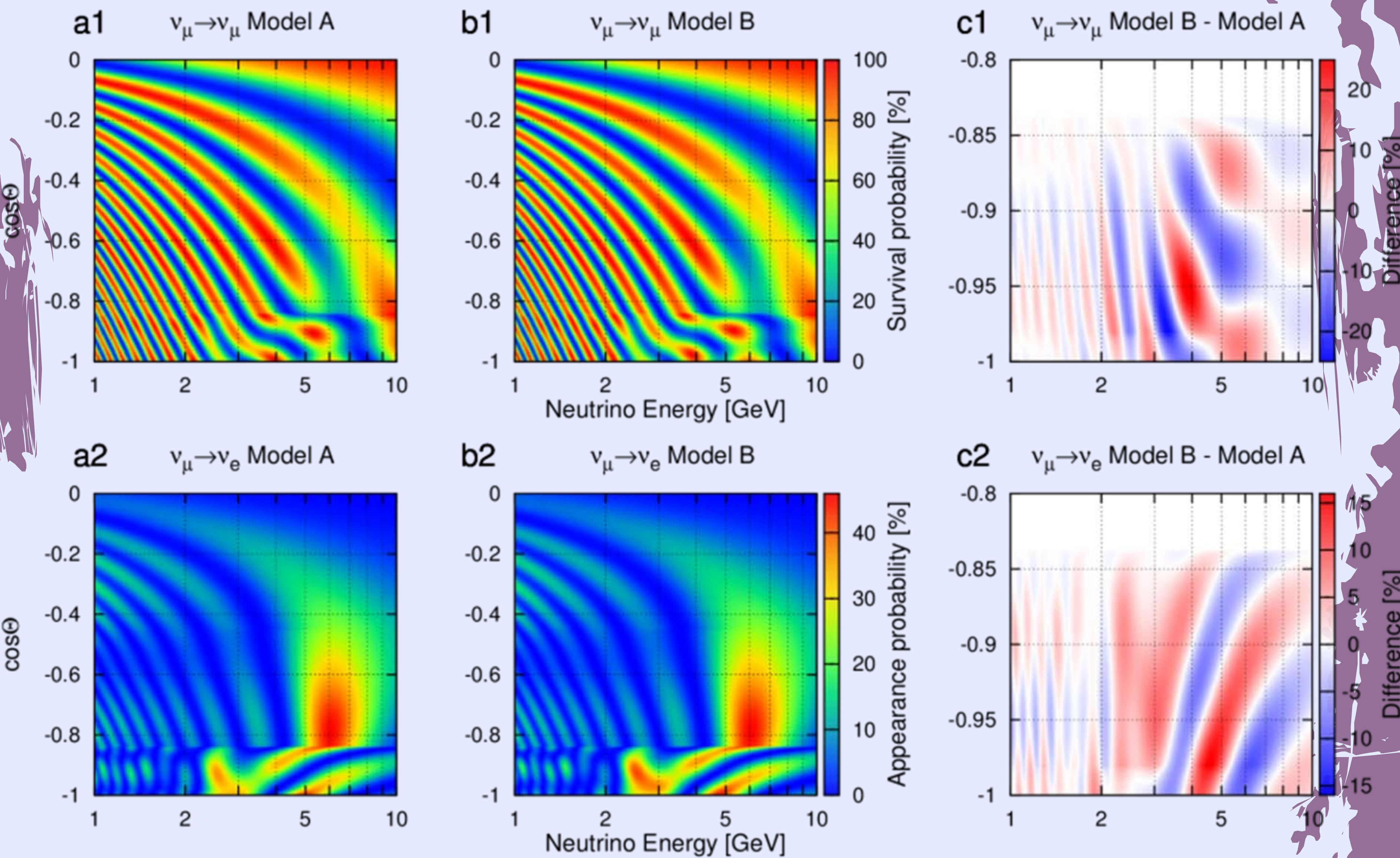
- Z/A ratio of materials
  - Fe :0.466, Light material :~0.5, Hydrogen :**1**
  - **More sensitive to Hydrogen**
- Matter density model : modified PREM
- Initial neutrino flux : Honda flux 2011
- Mantle is pyrolite (Z/A=0.496)
- Inner Core is Pure Iron (Z/A=0.467)
- **Z/A of outer core : free parameter**
- **Normal hierarchy**
- Oscillation parameter : Capozzi et al. 2014

$$\sin^2\theta_{12} = 0.308^{+0.017}_{-0.017} \qquad \delta_{CP} = 1.39^{+0.38}_{-0.27} \times \pi$$

$$\sin^2\theta_{13} = 0.0234^{+0.0020}_{-0.0019} \qquad \Delta m^2_{21} = (7.54^{+0.26}_{-0.22}) \times 10^{-5}$$

$$\sin^2\theta_{23} = 0.437^{+0.033}_{-0.023} \qquad \Delta m^2_{32} = (2.39^{+0.06}_{-0.06}) \times 10^{-3}$$

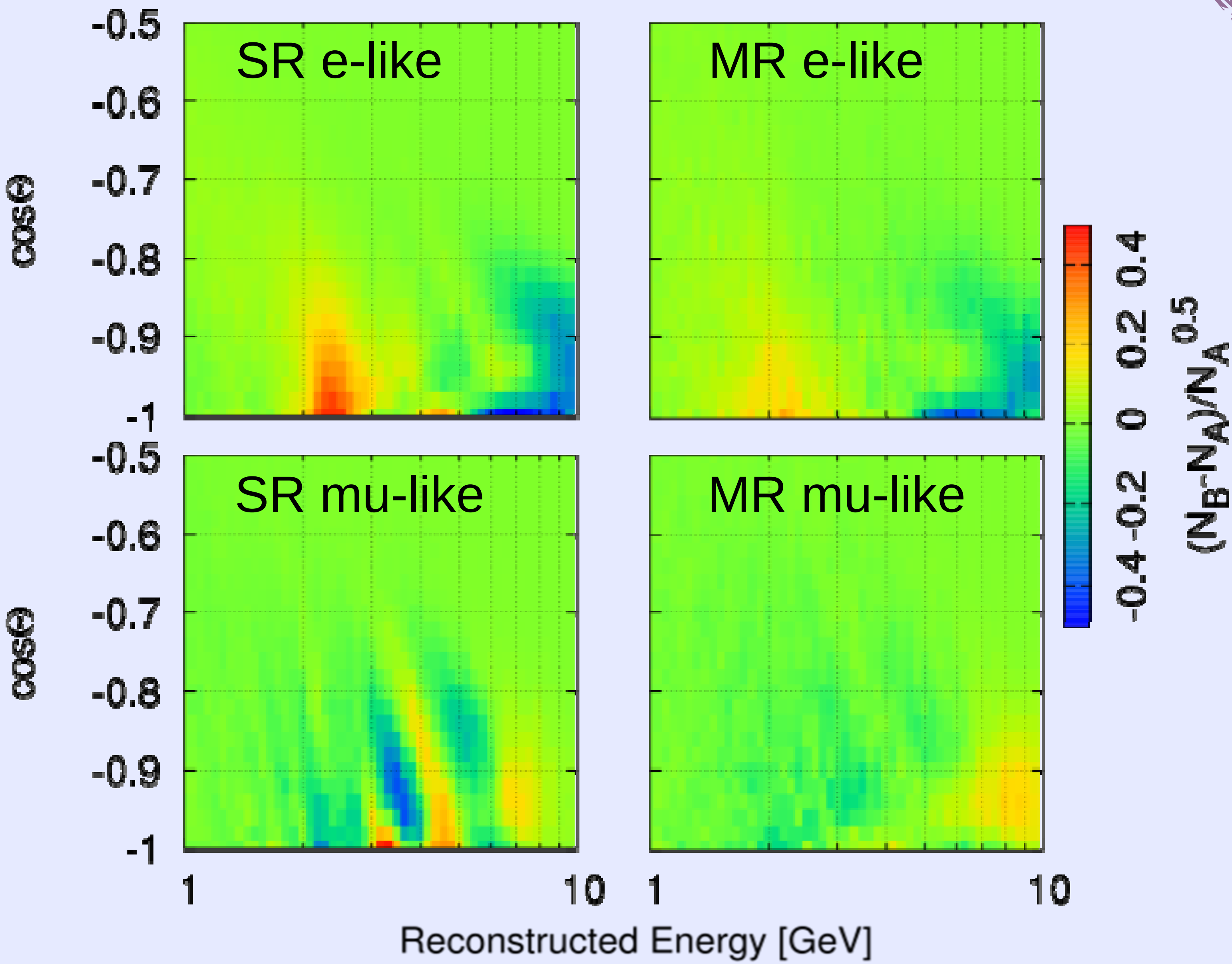
Oscillograms (Fe OC VS rock OC)



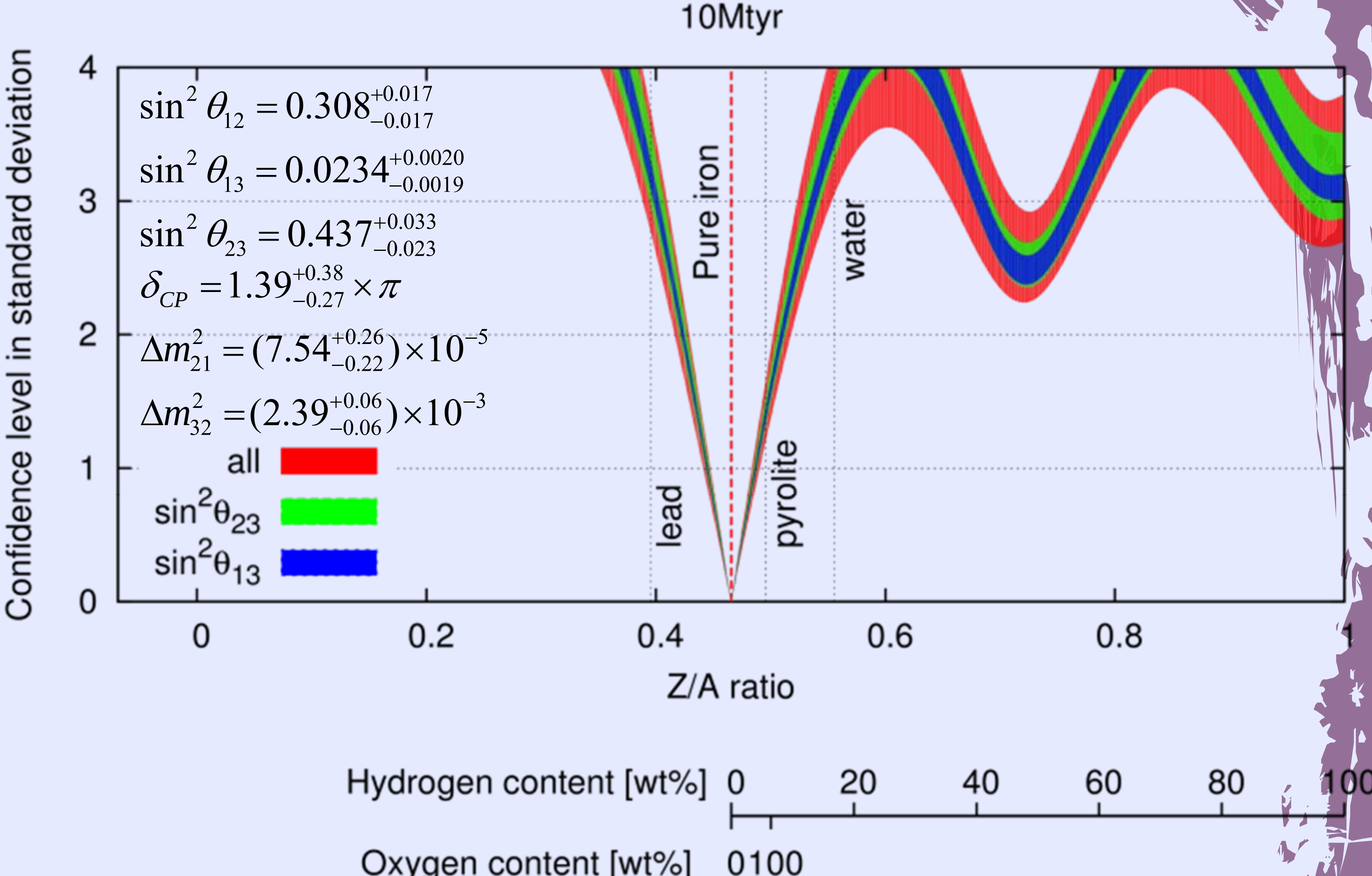
Sensitivity estimation

- Event template generation
  - Reconstructed SK-MC event : only 11.25Mt yr
    - Not enough for likelihood calculation using pseudo experiment
  - Event enhancement (1Gtyr)
    - Assume efficiency and resolution are independent to arrival direction
  - Calculate oscillation weight and add the weight to each bin
    - Bin size is 0.02 for $\log(P_{rec})$ and 0.02 for $\cos\vartheta_{rec}$
    - A template contain 4 event type : (SR mu, SR e, MR mu, MR e)
- P-value(confidence level) calculation
  - Generate likelihood ratio (LR) distribution
    - Generate pseudo experiments using 2 different templates A, B
  - Calculate the median of LR_B : M_B
  - Integrate $LR_A > M_B$

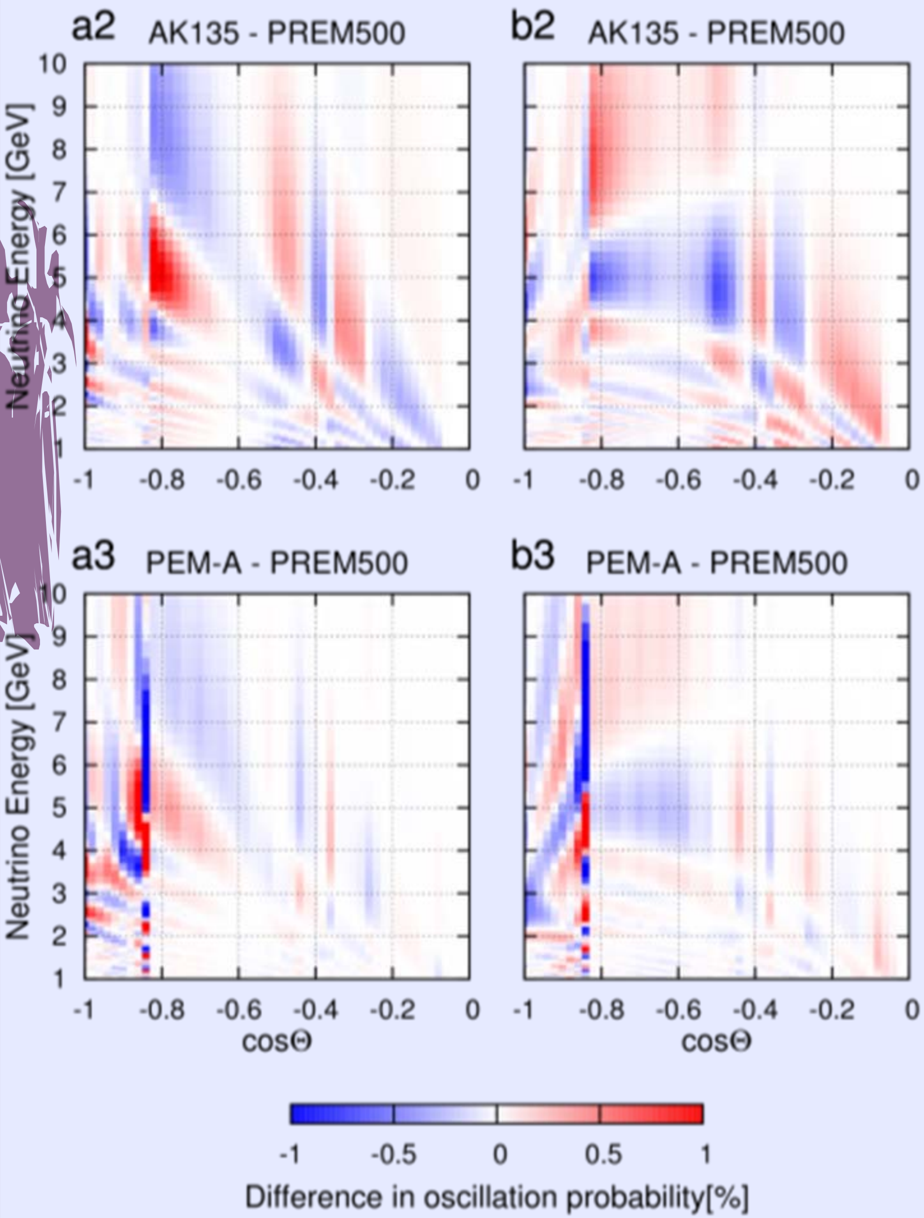
Significance map (Fe OC VS rock OC)

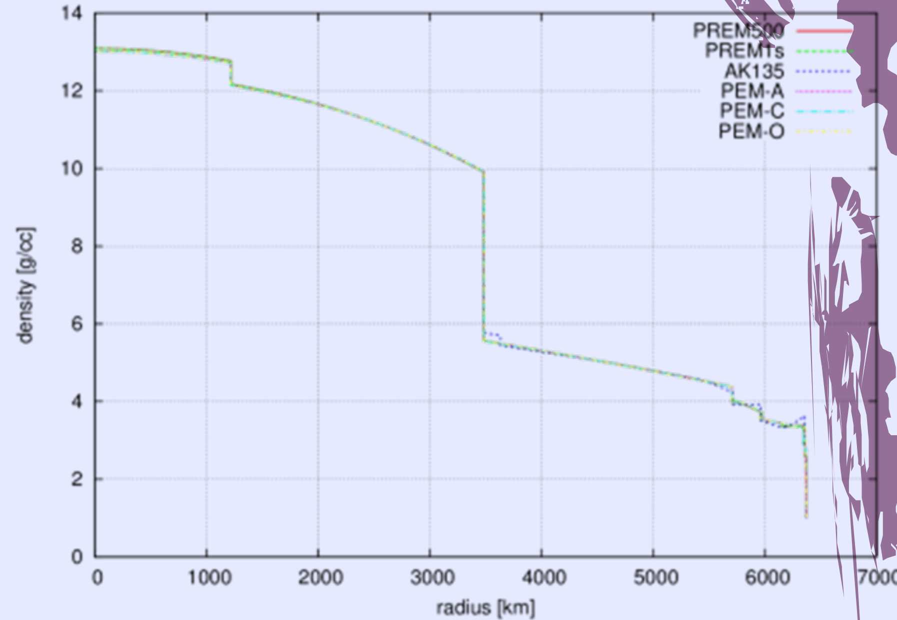


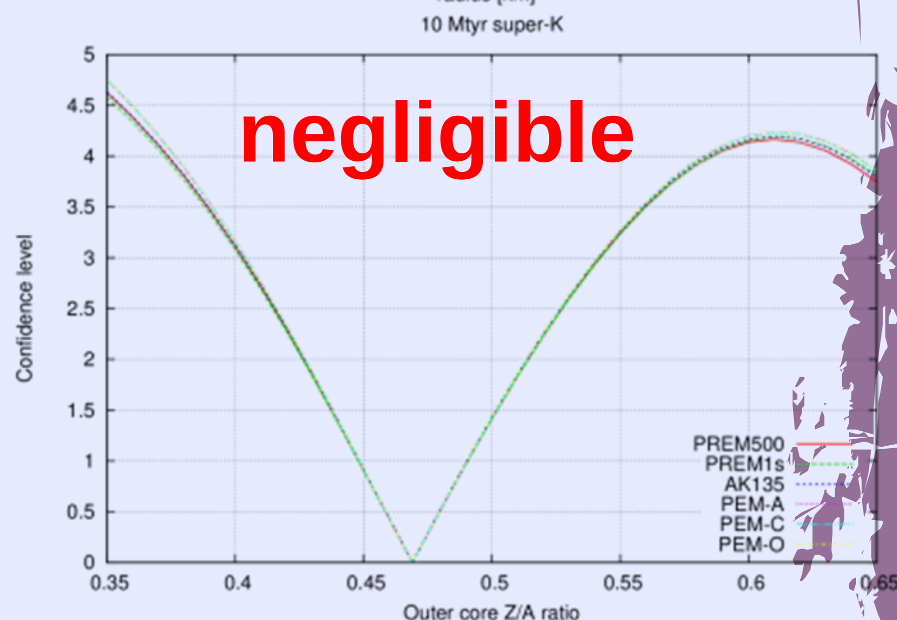
Expected sensitivity (HK 10Mtyrs)



Uncertainty from matter density model







TODO

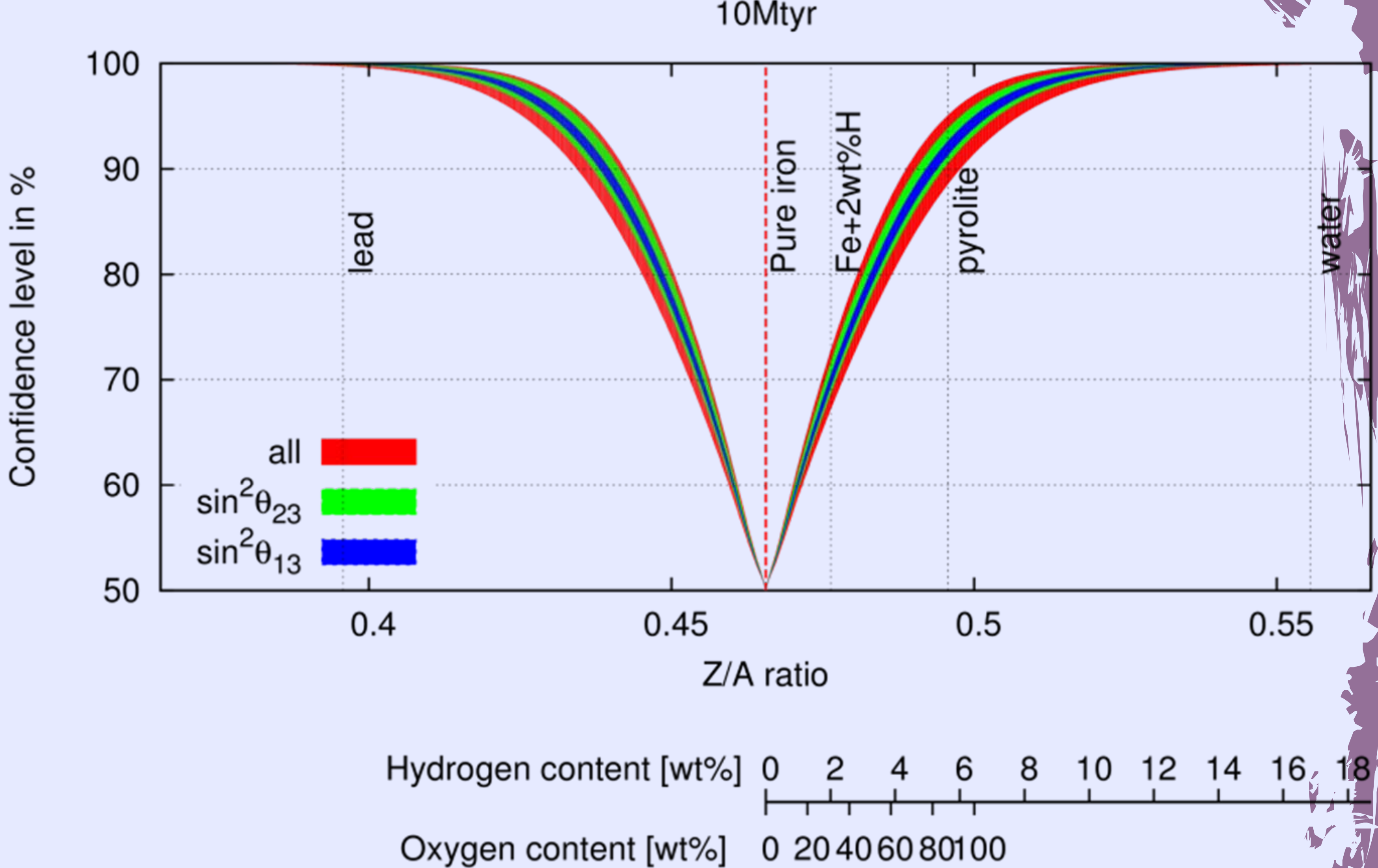
- Try fiTQun and add event classification
  - Currently single-ring e-like (SREL), MREL, SRML, MRML
  - Following classification can be tested
    - Single particle : e, μ, π^0
    - Double particle : eπ^0, μπ^0 , other
    - More than 2 particle
    - But this method increases MC sys. uncertainty
- Include upward muon event and PC event
- Systematic uncertainty estimation
  - Neutrino flux, Cross sections, Detector

Conclusion

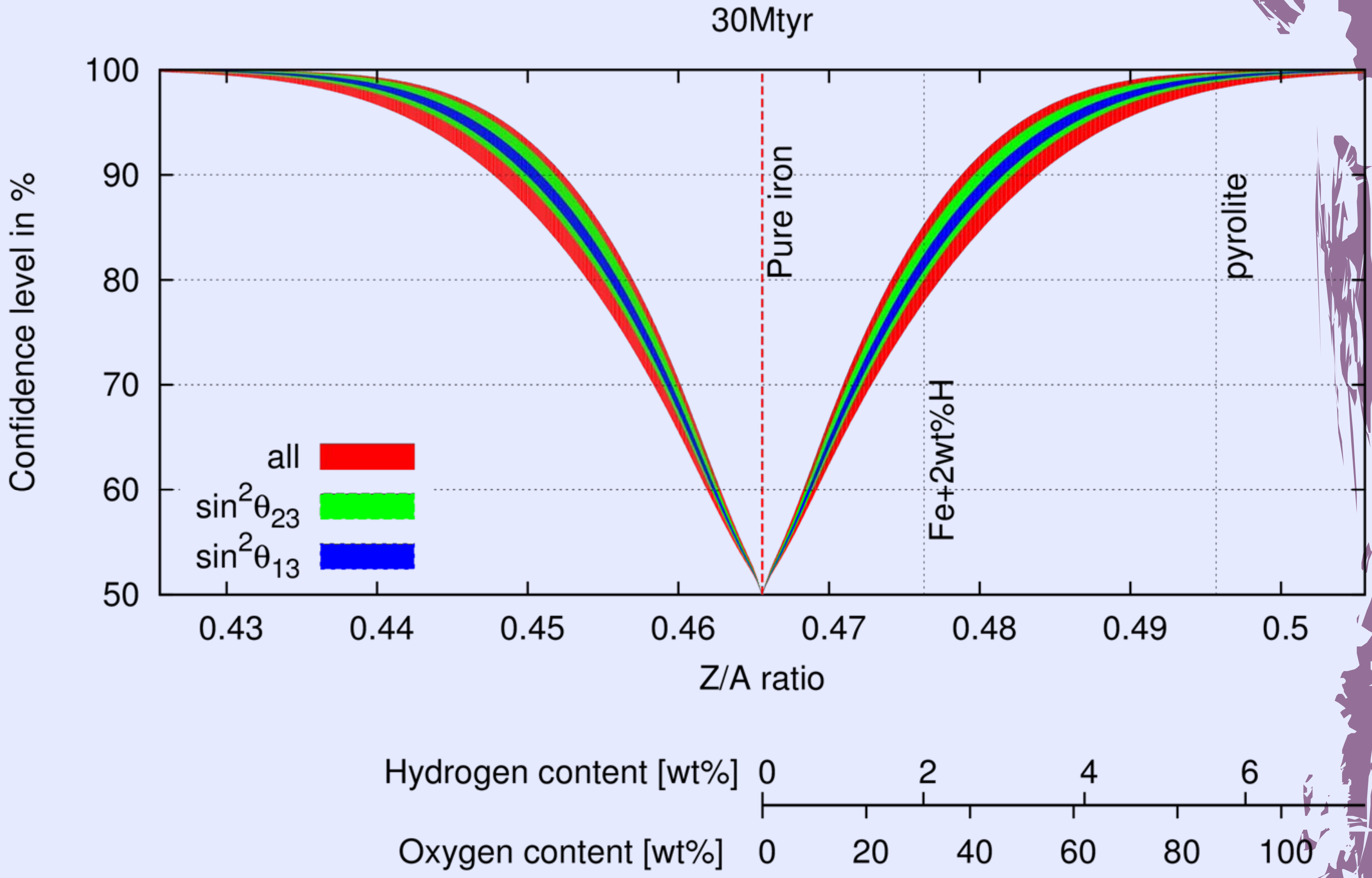
- Neutrino oscillation is applicable to geophysics
  - Only way to measure the chemical composition of the deep Earth
  - Larger detector volume is essentially important for this study
  - Sensitive energy range : **>2GeV**
  - **Precise oscillation parameter measurements are useful for geophysics**
- Uncertainty from matter density models is negligible
- Hyper-K can start spectrometry of the Earth
  - Fe, Pb, water can be resolved
  - Excludable Z/A range : 0.389>, 0.553< @3σ, 0.434>, 0.498< @90%
  - **Geophysicist's request : 0.466>, 0.472< @1σ**
  - **HK provides the first data point(s) of Z/A**
  - **Larger detector volume is essentially important**

Geophysicist meets physicists…

Expected sensitivity (HK 10Mtyrs)



Expected sensitivity (HK 30Mtyrs)



Event template generation

- Reconstructed SK-MC event : only 11.25Mt yr
  - Not enough for likelihood calculation using pseudo experiment
- Event enhancement (1Gtyr)
  - Assume det./reco. efficiency is independent to arrival direction
  - Select an event : (P_ν^0, Θ_ν^0,Φ_ν^0, P_{rec}^0, Θ_{rec}^0, Φ_{rec}^0)
  - Search 1Gt/11.25Mt(=888 events) : (P_ν^i, Θ_ν^i,Φ_ν^i, P_{rec}^i, Θ_{rec}^i, Φ_{rec}^i)
    - Same flavour and similar momentum
    - Maximum difference of momentum was 3% (1 – 10 GeV range)
  - Scale and scramble each event : (P_ν^0, Θ_ν^0,Φ_ν^0, $P_{rec}^i \times P_\nu^0 / P_\nu^i$, ϑ_{rec}^i, ϕ_{rec}^i)
  - Calculate oscillation weight : $P(x\rightarrow x)+P(x\rightarrow y)\ F_y(P_\nu^0, \Theta_\nu^0) / F_x(P_\nu^0, \Theta_\nu^0)$
  - Add the weight to correspond bin $M(P_{rec}^i \times P_\nu^0 / P_\nu^i, \vartheta_{rec}^i)$
    - Bin size is 0.02 for $\log(P_{rec}^i \times P_\nu^0 / P_\nu^i)$ and 0.02 for $\cos\vartheta_{rec}$
    - A template contain 4 event type : (SR mu, SR e, MR mu, MR e)

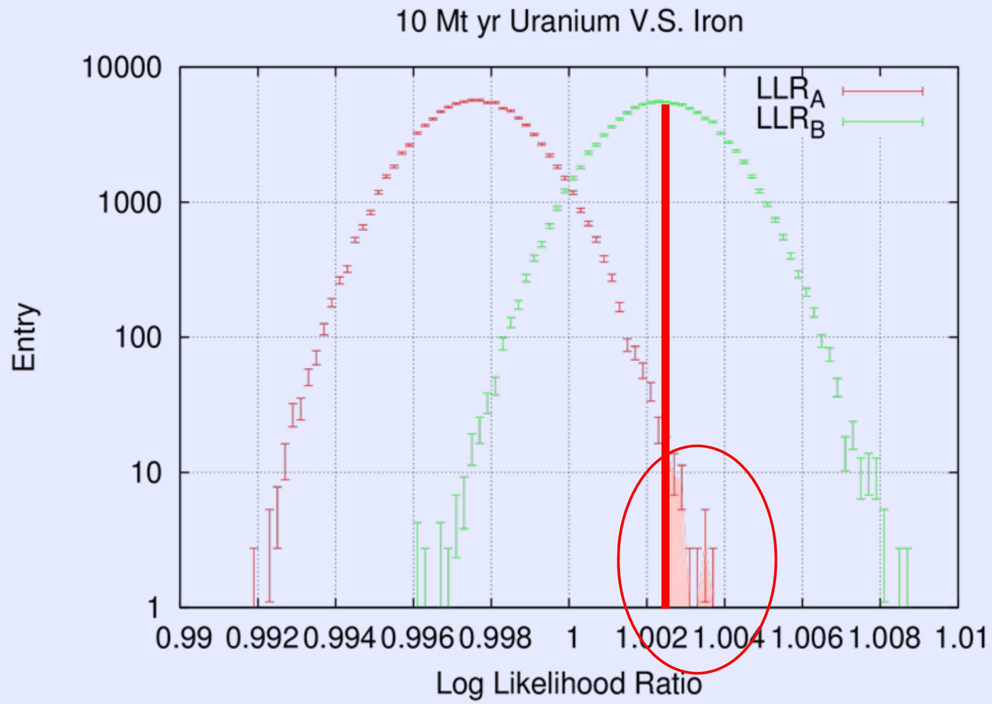
Log likelihood ratio (LLR) calculation

- Generate pseudo experiments using 2 different templates (m_A,m_B)
  - $N_A(E, \cos\Theta) \leftarrow \text{Poisson}(m_A(E, \cos\Theta))$
  - $N_B(E, \cos\Theta) \leftarrow \text{Poisson}(m_B(E, \cos\Theta))$
    - $m(E, \cos\Theta) = (\text{Mt yr})*M(E, \cos\Theta)$
  - 4 data set is created for each psuedo experiment
    - SR mu, SR e, MR mu, MR e
- $\ln L_{total} = \ln L_{SR\ mu} + \ln L_{SR\ e} + \ln L_{MR\ mu} + \ln L_{MR\ e}$

  $\ln L = \sum(N(P, \cos\Theta)\ln(m(P, \cos\Theta)) - m(P, \cos\Theta) - \ln(N(P, \cos\Theta)!))$
- Calculate log likelihood ratio
  - $LLR_A = \ln L(N_A, m_B) - \ln L(N_A, m_A)$
  - $LLR_B = \ln L(N_B, m_B) - \ln L(N_B, m_A)$

P-value (confidence level)

- Calculate the median of LR_B : $M(LR_B)$
- count the number of $LR_A > M(LR_B)$: N_{over}
- $P = N_{over} / N_{tot}$ determines the probability of 2 different model exclusion
- Actual calculation was done by convolution of probabilities
  - Not by MC



The Earth's core models

Model name	Z/A ratio	Si(wt%)	O(wt%)	S(wt%)	C(wt%)	H(wt%)	reference
Single light element model (maximum abundance)							
Fe+18wt%Si	0.4715	18	-	-	-	-	Poirier [28]
Fe+11wt%O	0.4693	-	11	-	-	-	Poirier [28]
Fe+13wt%S	0.4699	-	-	13	-	-	Li and Fei [5]
Fe+12wt%C	0.4697	-	-	-	12	-	Li and Fei [5]
Fe+1wt%H	0.4709	-	-	-	-	1	Li and Fei [5]
Multiple light elements model							
Allegre2001	0.4699	7	5	1.21	-	-	Allègre et al. [25]
McDonough2003	0.4682	6	0	1.9	0.2	0.06	McDonough [26]
Huang2011	0.4678	-	0.1	5.7	-	-	Huang et al. [27]