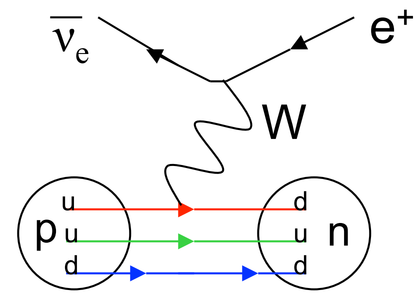

Geo-neutrino Observations

Can they transform geology?

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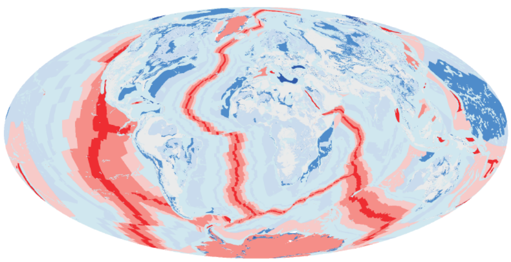
WHERE DISCOVERIES BEGIN

Hawai'i Pacific University

Planetary Energy Conservation

- **Terrestrial Power Balance**
  - $P_{surface} \approx P_{radiogenic} + P_{primordial}$



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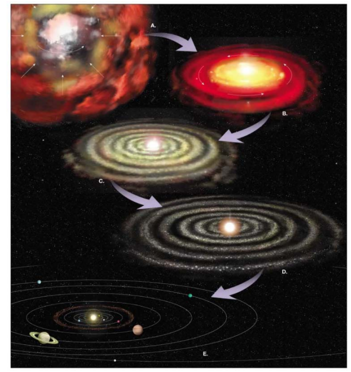


- **Present Status**
  - $P_{surface} = 47 \pm 3$ TW
    - » Davies and Davies 2010
  - $P_{radiogenic} = 9 - 27$ TW
    - » Ludhova & Zavatarelli 2013
  - $P_{primordial} = 20 - 38$ TW

Thermal Evolution and History of Earth

$$Aq = Mh - Mc(\partial T/\partial t)$$

Present temperature decrease rate:

$$\partial T/\partial t = Aq/Mc\ (Mh/Aq - 1) = 50 \text{ to } 150 \text{ K/Ga}$$

Rate of cooling poorly constrained

Present primordial heat loss rate:

$$Aq - Mh = 20 \text{ to } 38 \text{ TW}$$

Rate of primordial heat loss poorly constrained

Rates of cooling & primordial heat loss poorly constrained due to uncertainty of radiogenic heating

Motivating Geo-neutrino Observations

- **Questions to address:**
  - **How well does radiogenic heating need to be measured to transform geology?**
  - **Are there levels of precision (±7 TW? ±5 TW? ±3 TW?) for which major geological advances ensue?**
- **Answers to these questions guide geo-neutrino observational program**

Significant Geo-neutrino Observations

- ✓ **Geo-neutrinos: KamLAND (*Nature* 2005)**
- ✓ **Mantle geo-neutrinos: KamLAND + Borexino (*Phys Rev D* 2012)**

Pioneering detections followed by first constraints!

- ✓ **Radiogenic power constraint: KL + BX (*Adv. HEP* 2013)**
- ✓ **Th/U constraint: KamLAND (*Phys Rev D* 2013)**

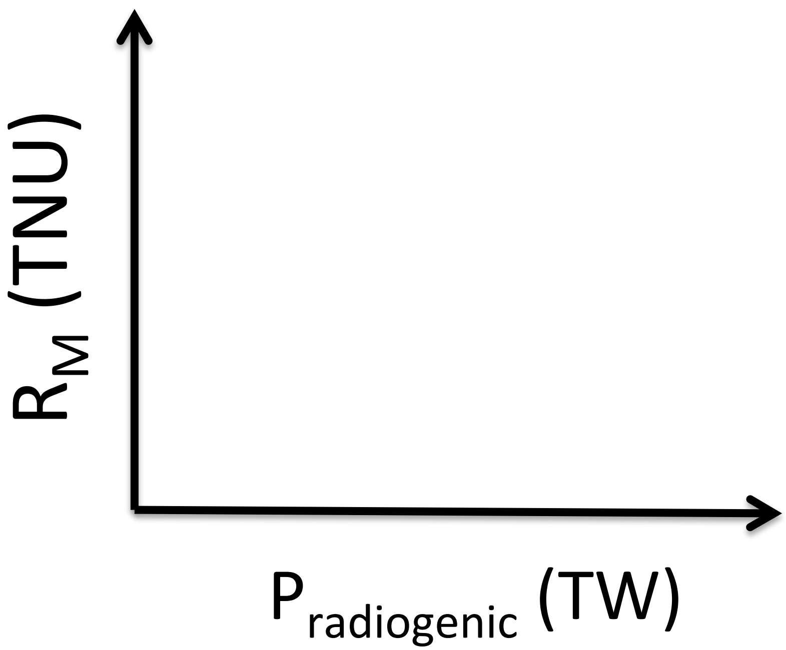
Fantastic! What is next?

- ? **Earth model resolution**
- ? **Constrain thermal evolution? Onset time of plate tectonics?**

Can geo-neutrino observations transform geology?

BSE Modeling

- **Model bulk silicate earth (BSE = mantle + crust)**
- **Calculate mantle geo-nu rate: $R_M = f(P_{radiogenic})$**
- **Simple and easy to change parameters**



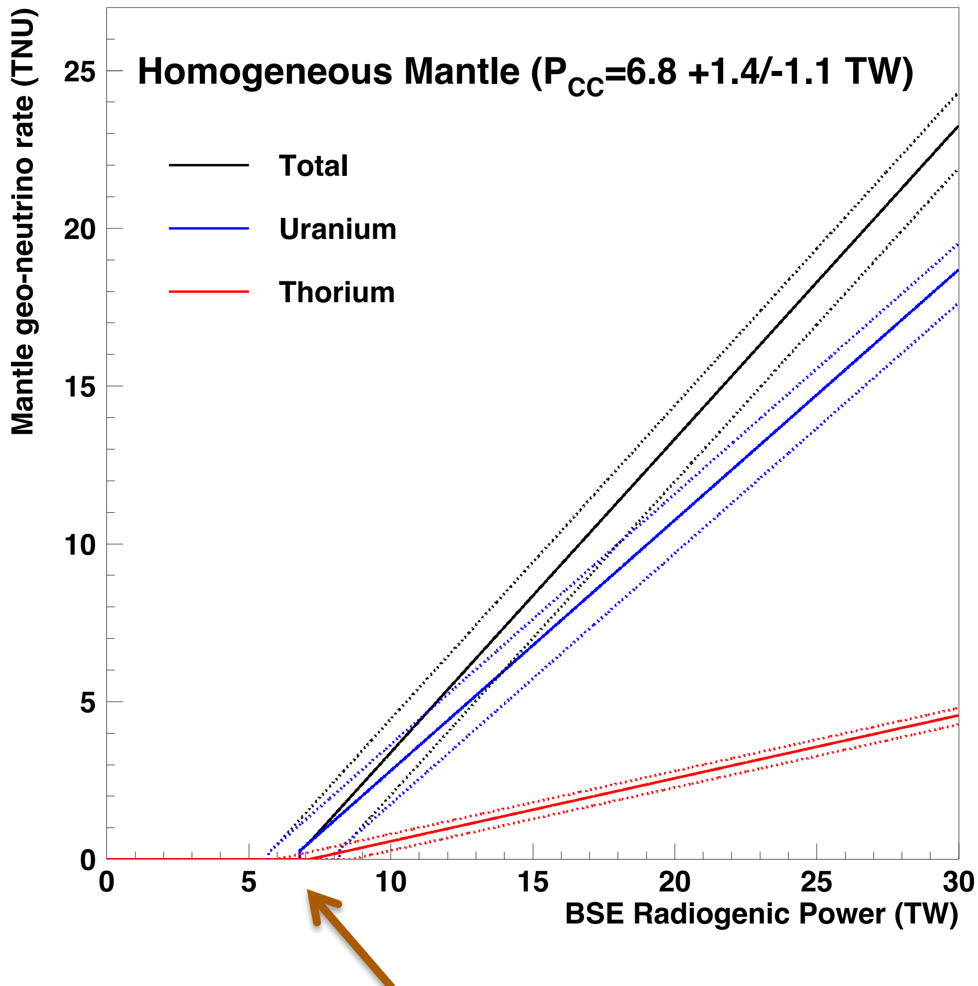
Fortran code

```
      program bse
      dimension gnurate(4000,2),twerror(4000)
c neutrino luminosity per unit mass of Th and U (#/kg/s)
      data rth/16.2e6/
      data rur/76.4e6/
c flux to rate conversion
      data f2rth/250000./
      data f2rur/76000./
c power per unit mass of Th and U (W/kg)
      data hth/26.3e-6/
      data hur/98.5e-6/
c average neutrino oscillation survival probability
      data pee/0.54/
c Huang et al. CC power (TW)
c      data pcc/6.8/
c      data pcc/8.2/
      data pcc/5.7/
c Workman and Hart DM power (TW)
      data pdm/2.0/
c Th/U for PM, CC, and W&H DM
      data thupm/3.9/
      data thucc/4.3/
      data thudm/2.5/
c geo-factors in kg/cm^2
      data geoman/1.177e6/
      data geoddp/0.292e5/
c masses in kg
      data assman/4.002e24/
      data assddp/0.132e24/
      alphth=rth*pee/hth/f2rth
      alphur=rur*pee/hur/f2rur
c      print *,alphth,alphur
      pccur=pcc/(1.+thucc*hth/hur)
      pccth=pcc-pccur
c      print *,pccur,pccth
      pdmur=pdm/(1.+thudm*hth/hur)
      pdmth=pdm-pdmur
c      print *,pdmur,pdmth
      r2hthman=alphth*geoman/assman
      r2hurman=alphur*geoman/assman
c      print *,r2hthman,r2hurman
      r2hthddp=alphth*geoddp/assddp
      r2hurddp=alphur*geoddp/assddp
c      print *,r2hthddp,r2hurddp
      r2hthdm=alphth*(geoman-geoddp)/(assman-assddp)
      r2hurdm=alphur*(geoman-geoddp)/(assman-assddp)
c      print *,r2hthdm,r2hurdm
```

BSE Power-Mantle Geo-neutrino Model

- **Model input**
  - **U, Th elemental heat generation per unit mass**
  - **U, Th elemental neutrino luminosity per unit mass**
  - **U, Th flux to signal conversion factors**
  - **$\langle P_{ee} \rangle = 0.54$**
  - **PREM mantle- seismic specification of ρ(r)**
  - **$P_M = P_{BSE} - P_{CC}$; $(Th/U)_{BSE} = 3.9$**
  - **$P_{CC} = 6.8$ +1.4/-1.1 TW ; $(Th/U)_{CC} = 4.3$**
  - **$P_{DM} = 2.0$ TW; $(Th/U)_{DM} = 2.5$**
  - **$P = P_U + P_{Th}$; P_K ignored (refine later)**

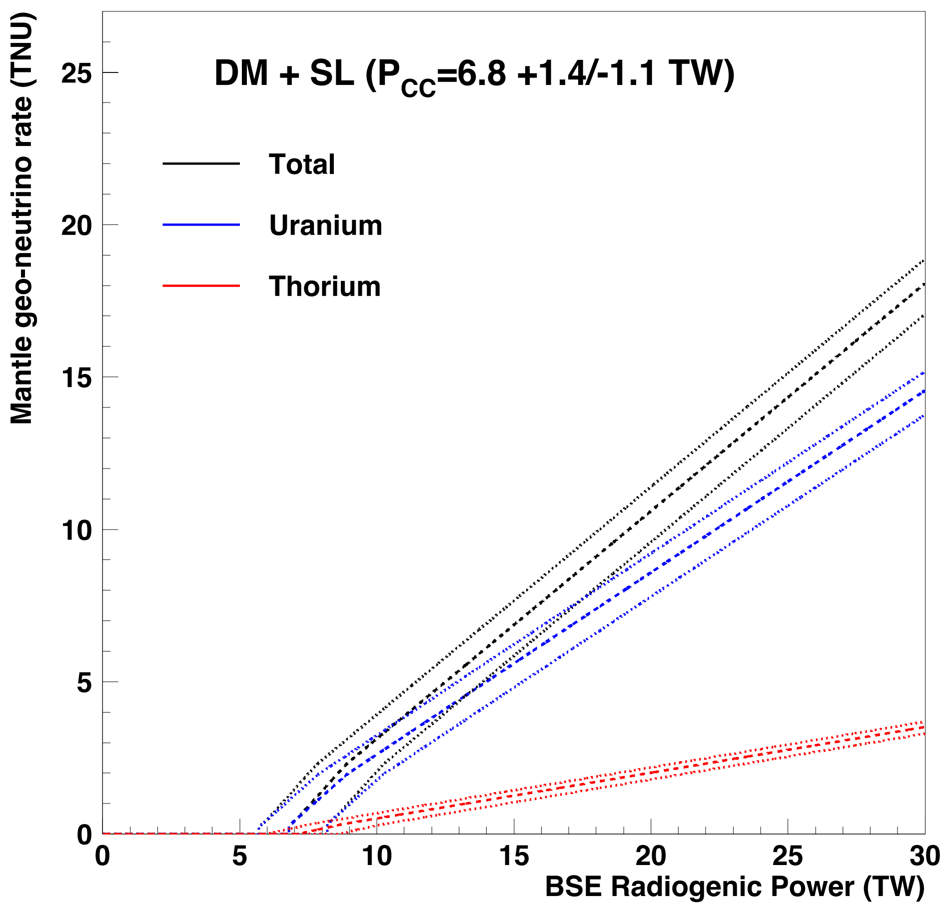
Homogeneous Mantle



P_{CC} = 6.8 +1.4/-1.1 TW

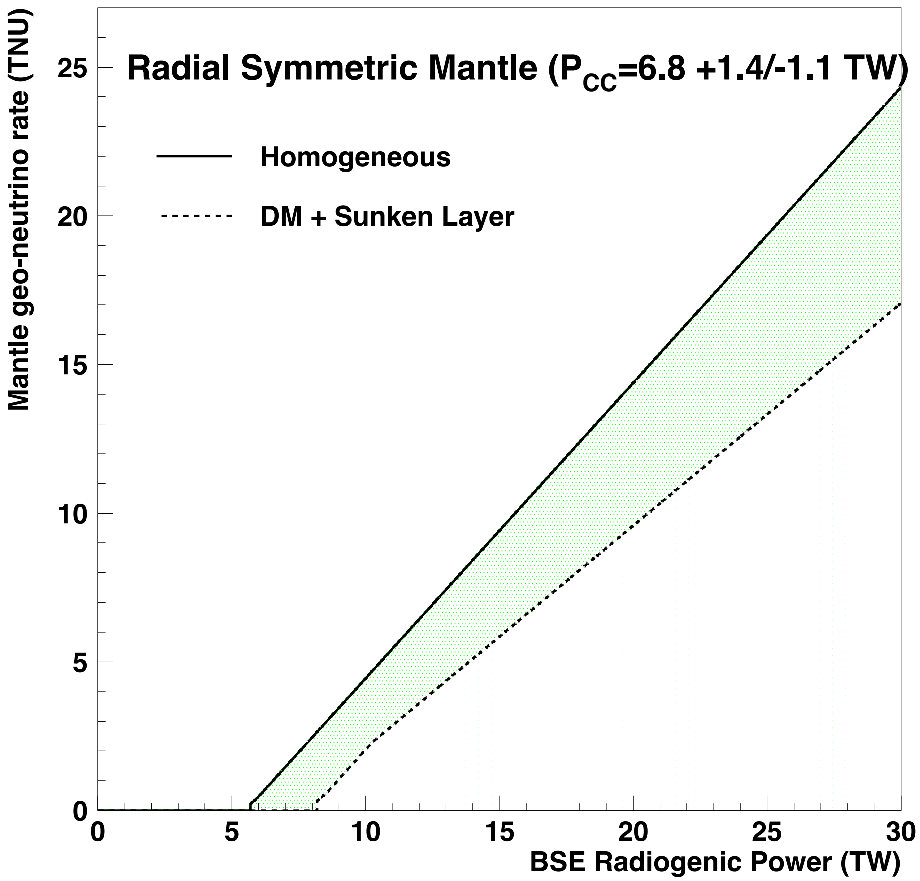
- $P_M = P_{BSE} - P_{CC}$
- Slope ~ 1 TNU/TW
- R_M ~ slope*($P_{BSE} – P_{CC}$)
- R_U ~ 4*R_{Th}
- Width of bands due to uncertainty in P_{CC}
- Max R_M for given P_{BSE}

Depleted Mantle + Sunken Layer



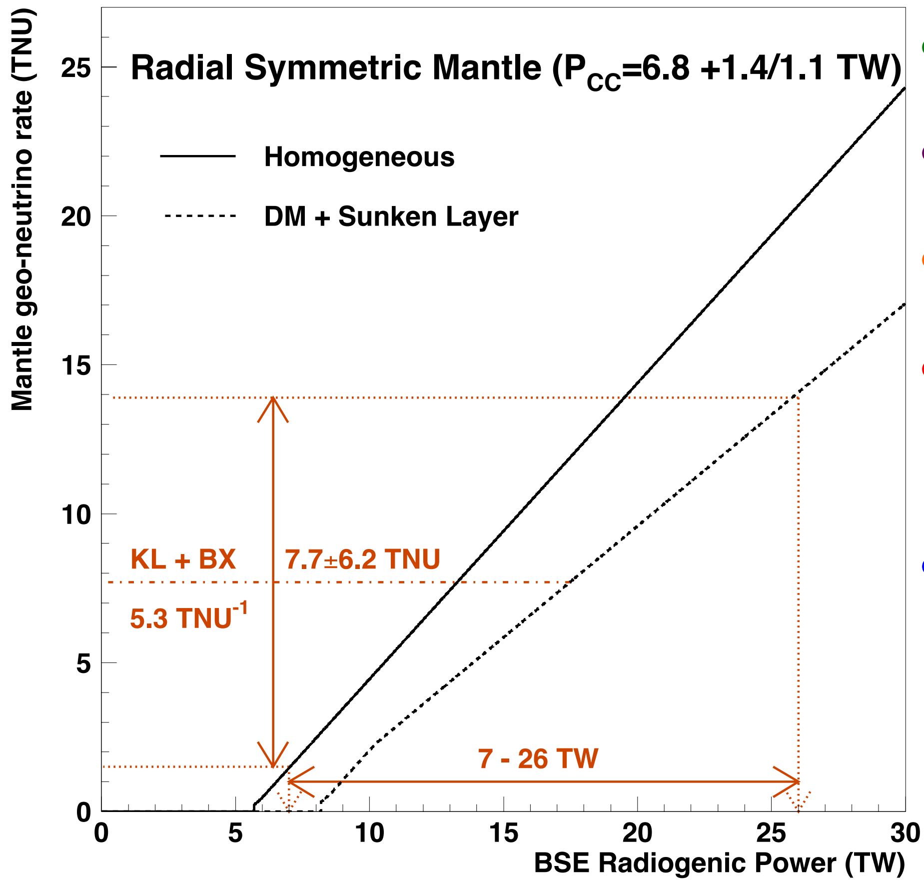
- $P_M = P_{DM} + P_{SL}$
- Sunken Layer is D"
  - r_{SL} = 3480 – 3630 km
- Depleted Mantle
  - P_{DM} = 2.0 TW
  - Th/U_{DM} = 2.5
- $R_U \sim 4*R_{Th}$
- $R_{DM+SL} < R_M$
- Slope ~ 0.8 TNU/TW

Model Signal-Power Allowed Region



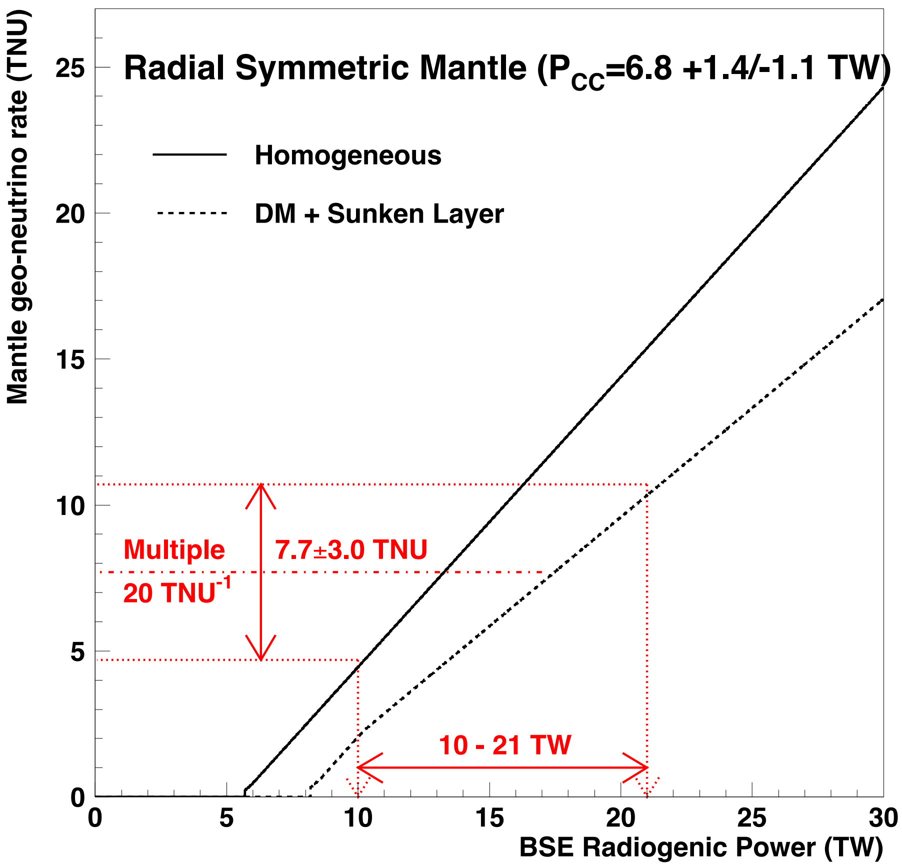
- Distribution of U, Th in mantle and uncertainty in P_{CC} affect geo-nu measurement of P_{BSE}
- Mantle R_{KL+BX}=7.7±6.2 TNU
- How does this geo-nu measurement constrain model P_{BSE}?

Geo-neutrino Constraint of Model P_{BSE}



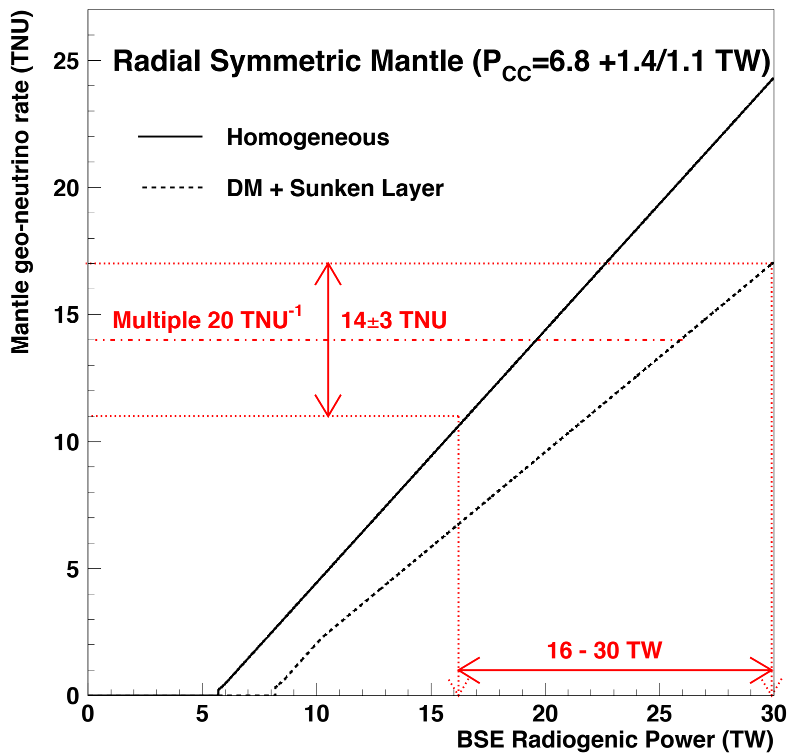
- KL + BX exposure 5.3 TNU^{-1}
- Mantle R_{KL+BX}=7.7±6.2 TNU
- Model P_{BSE} = 7 – 26 TW
- Power constrained but earth models not resolved
- What might we expect with future measurements?

Multiple (n=4) Continental Observatories



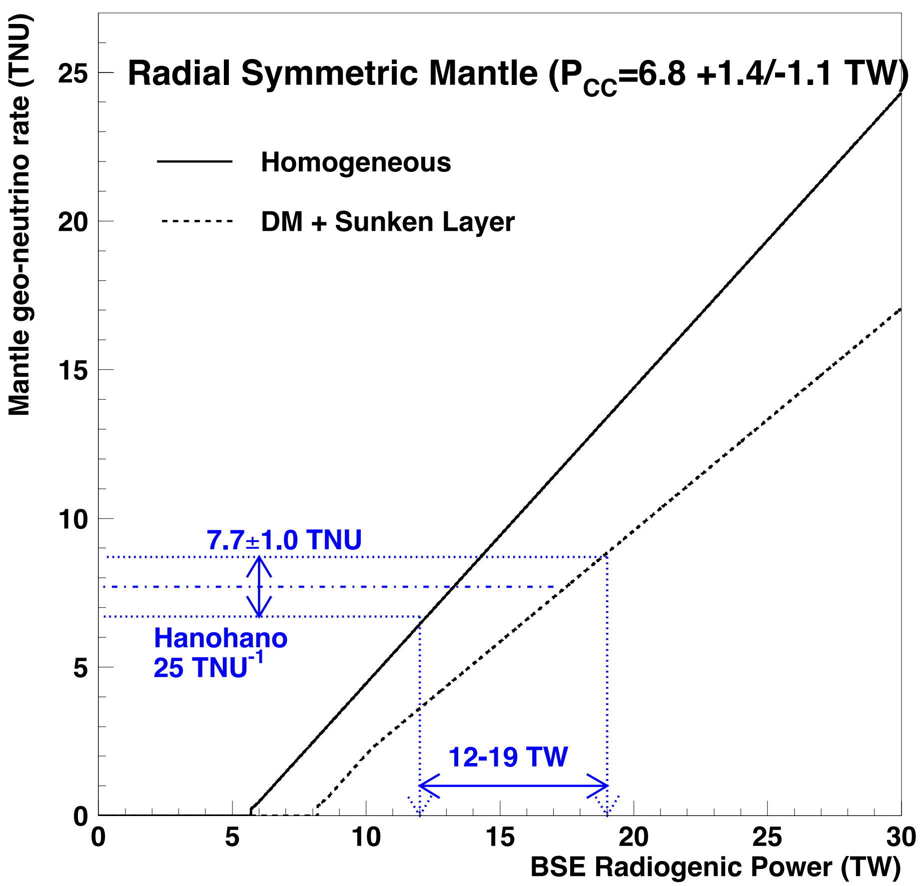
- Error on mantle R_{KL+BX} is ~½ stat and ~½ sys
  - 4x exposure reduces statistical error by 2
  - 4 independent obs. reduces systematic error by ~ 1/√4 = 2
- Should get to ±3 TNU
- Model P_{BSE} constraint depends on signal size
- If R=7.7±3.0, then model P_{BSE} = 10 - 21 TW
- Begin to resolve earth models?

Multiple (n=4) Continental: High R_M



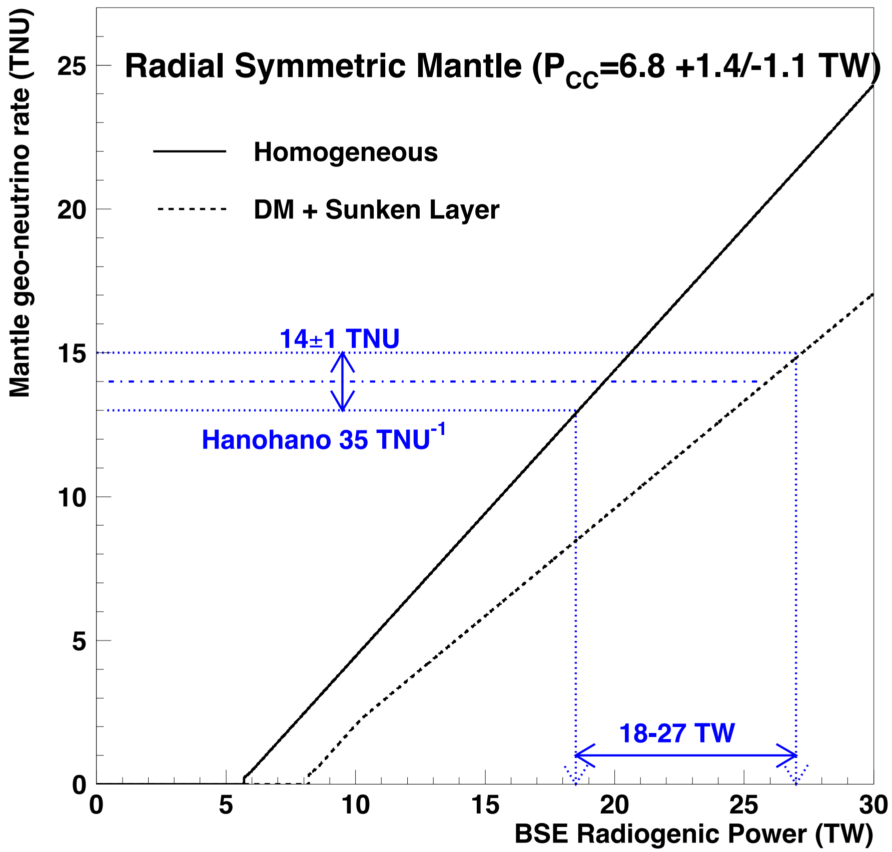
- **Higher signal increases value and range of P_{BSE}**
- **R_{KL+BX}(max) ~ 14 TNU**
- **R = 14 ± 3 TNU gives model P_{BSE} = 16 – 30 TW**
- **What improvement would oceanic observatory provide?**

Oceanic Observatory



- R_{CC} small can get ±1.0 TNU with 25 TNU^{-1}
- If R=7.7±1.0 TNU, then model P_{BSE} = 12 - 19 TW
- Begin resolve earth model
- However, due to unknown U, Th distribution and uncertainty in P_{CC} the factor of 3 reduction in δR compared with multi-continental reduces δP_{BSE} by ±2 TW and needs 25% more exposure
- If signal higher, it gets worse

Oceanic Observatory- High R_M



- If R_{KL+BX}(max) ~ 14 TNU
- To get ±1 TNU requires 35 TNU^{-1}
- If R=14±1 TNU, then model P_{BSE} = 18 - 27 TW
- This is better than multi-continental by ~±2 TW but requires 75% larger exposure

Results of Model BSE Study

δP_{BSE} grows with R_M

δP_{BSE}(8 TNU) = 10-21 TW
δP_{BSE}(14 TNU) = 16-30 TW

- **Multi-continental (n=4) mantle geo-neutrino measurement $\delta R=\pm3$ TNU**
- **$\delta R=\pm3$ TNU dominated by systematic error reduction of multi-continental δR requires *more observatories* not *more exposure***

δP_{BSE}(8 TNU) = 12-19 TW
δP_{BSE}(14 TNU) = 18-27 TW

- **Oceanic observatory can reduce δR significantly, reaching $\delta R=\pm1$ TNU**
- **Reduction in model δP_{BSE} is modest due to geological uncertainties**
- **Requires large exposure (>5 years of Hanohano)**

Model BSE Study Conclusions

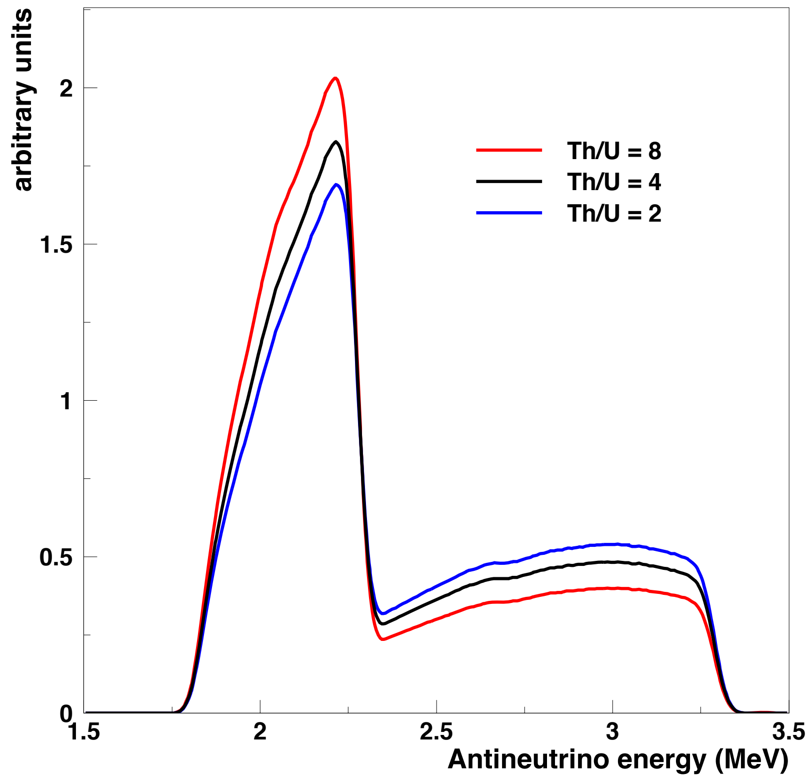
- **Model BSE study shows potential of geo-nu measurements to inform geology**
- **Geological uncertainties introduce systematic errors**
- **Effort to reduce geological uncertainties very helpful**
- **Refine model by explicitly including K but expect little change**
- **2-TW DM is lowest power predicted; effect of sunken layer decreases as DM power increases**
- **Model with P_{DM} = 6 TW would narrow allowed region**

Conclusions

- Will geo-neutrino observations transform geology?
- How well does radiogenic heating need to be measured?
- Outlook
  - **±10 TW present measurement**
  - **±7 TW possible with new observatories**
  - **±5 TW challenging**
  - **±3 TW extremely challenging**
  - **±1 TW improbable**

Thank You

Th/U by Geo-nu



arbitrary units
2
1.5
1
0.5
0
1.5
2
2.5
3
3.5
Antineutrino energy (MeV)
Th/U = 8
Th/U = 4
Th/U = 2