UNIVERSITY OF Southampton

Queen Mary University of London

Precision-Era Neutrino Studies at Super-K and Hyper-K

Susana Molina Sedgwick

Supervisors:
Francesca Di Lodovico, Stephen F. King

PPRC SEMINAR

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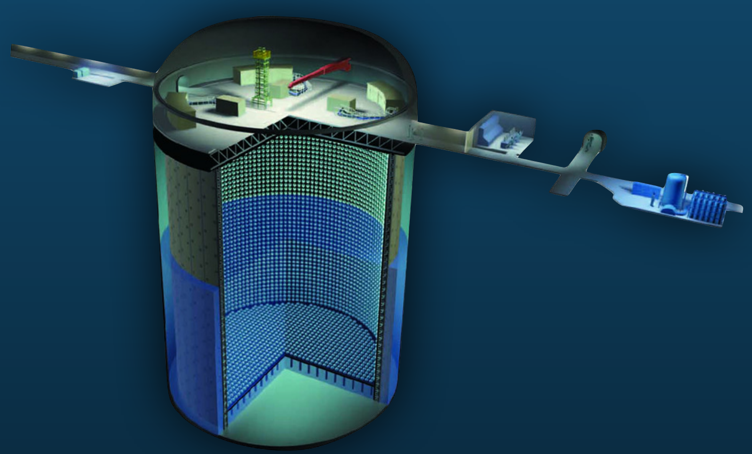
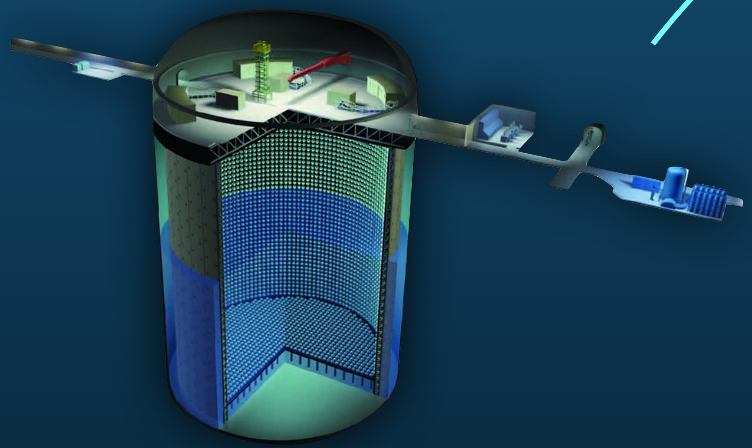


SK solar analysis



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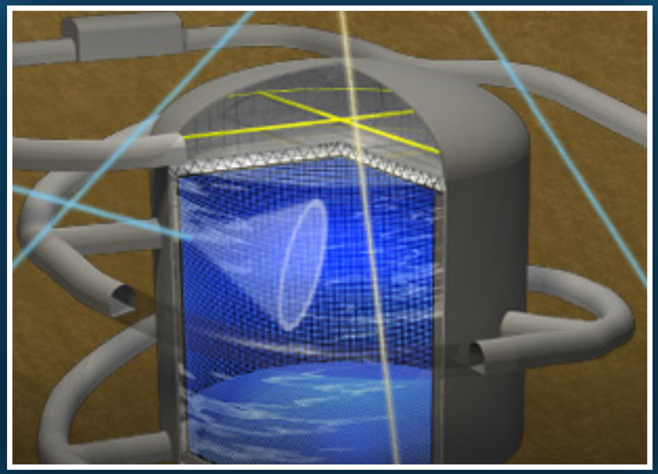
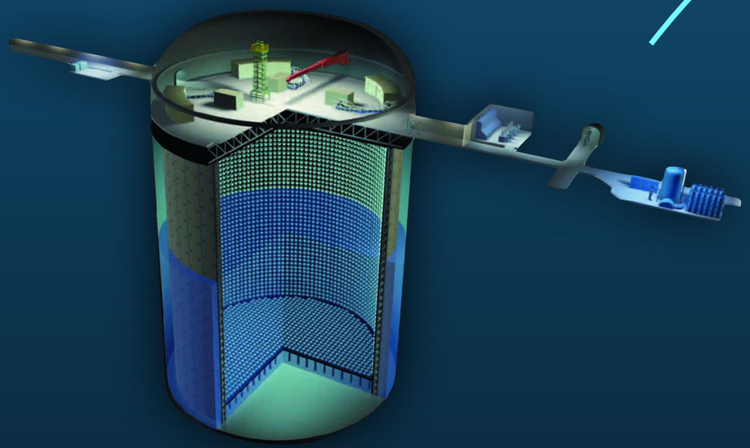
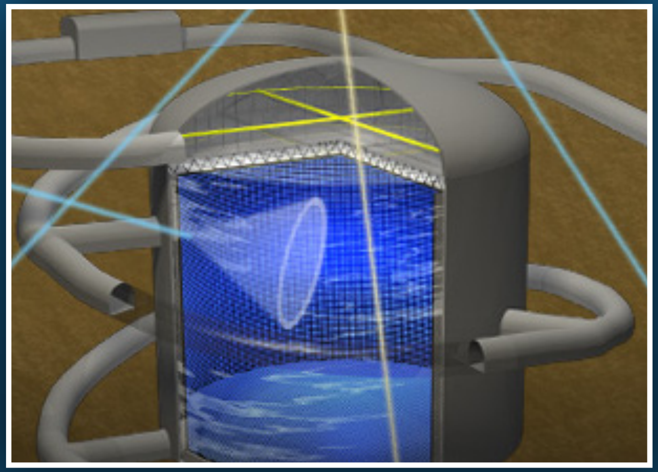


Matter effects at HK





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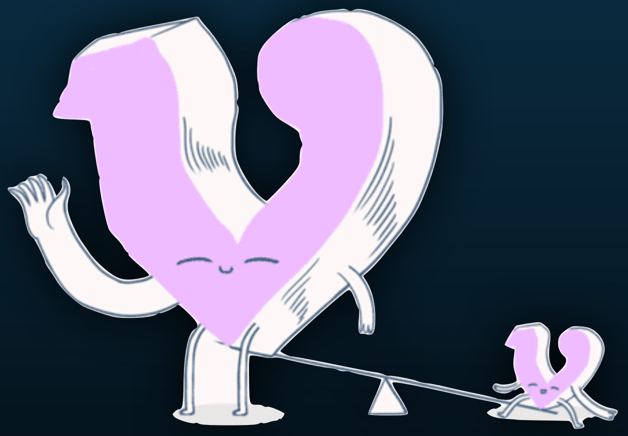
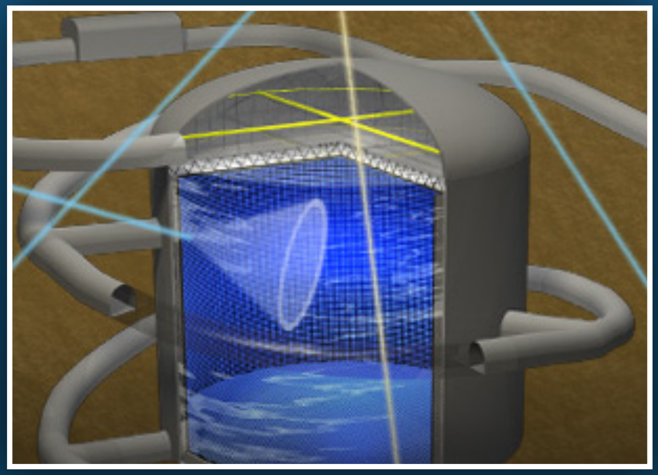


Littlest Seesaw



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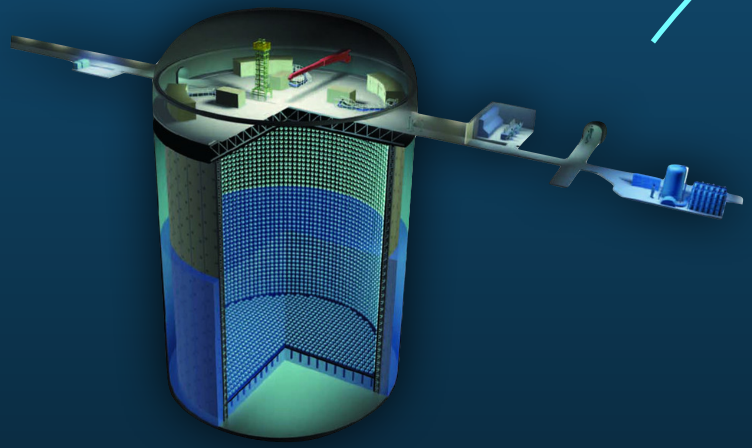

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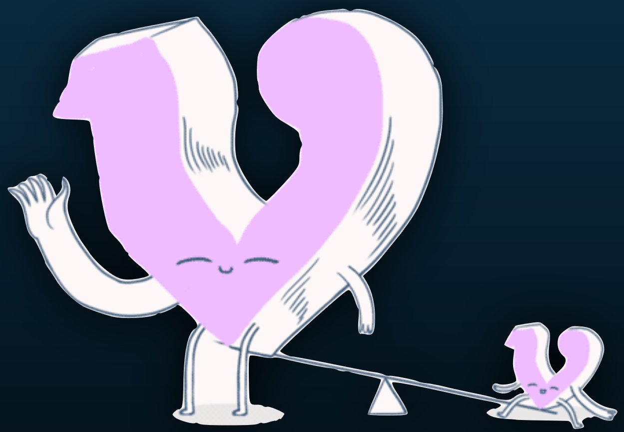

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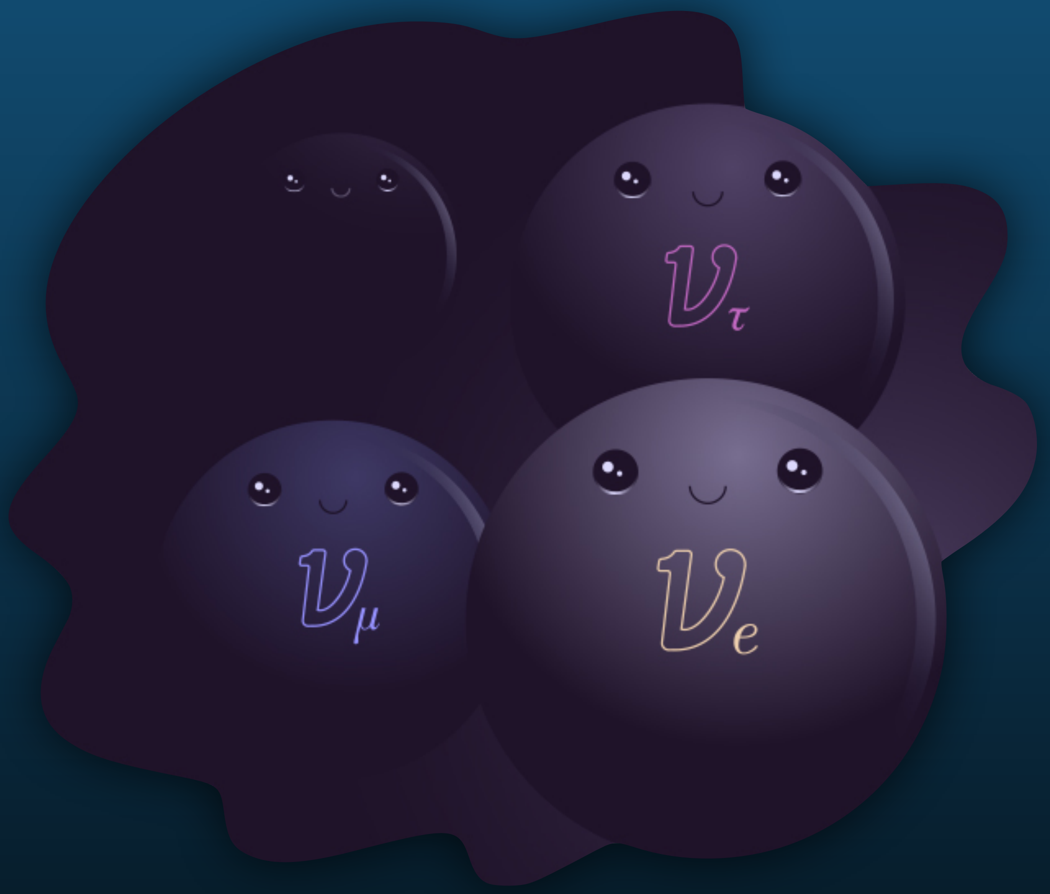
ν_τ
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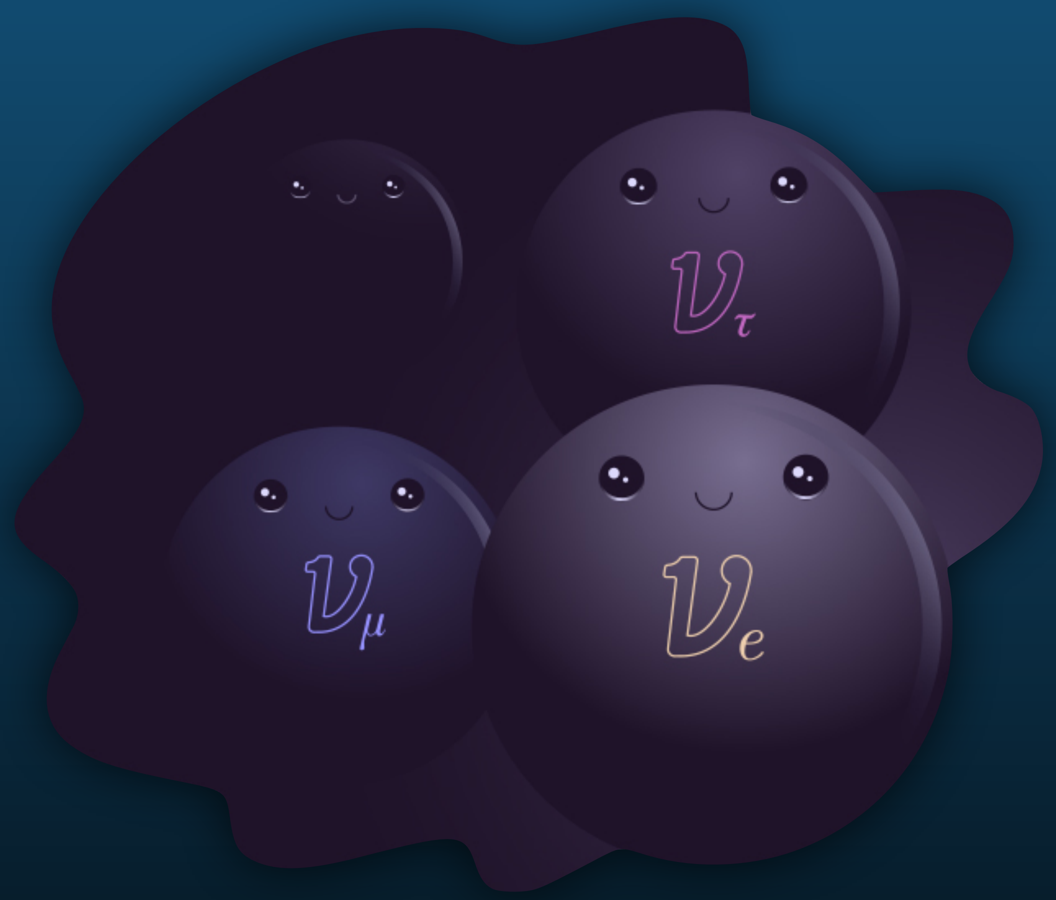
We know a lot about them!



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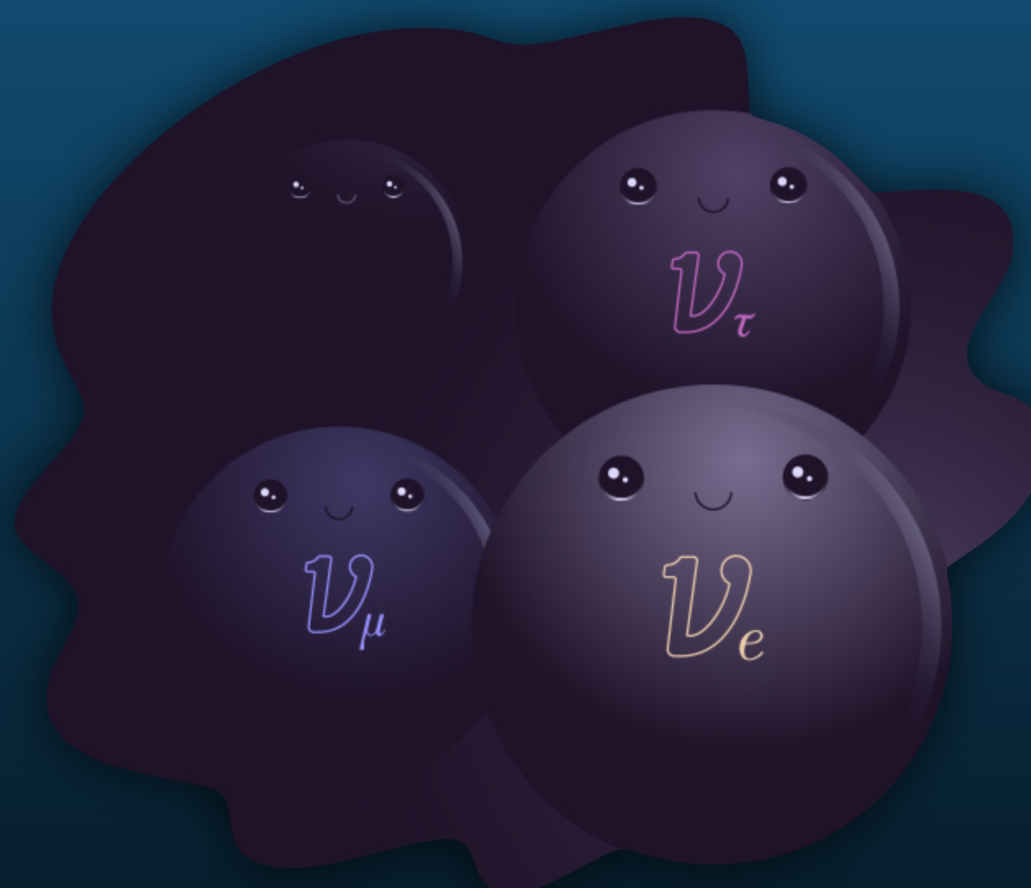
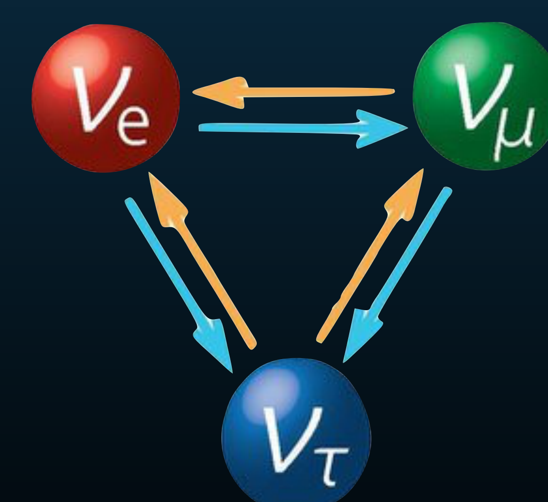
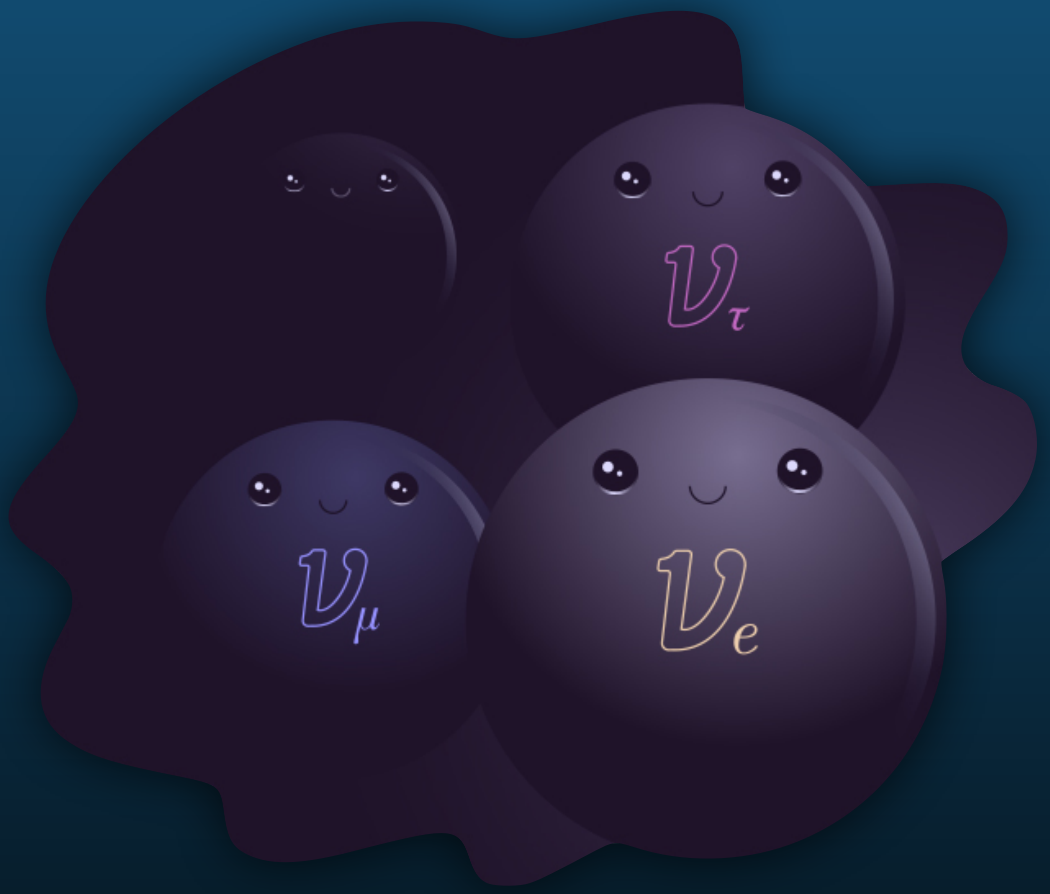
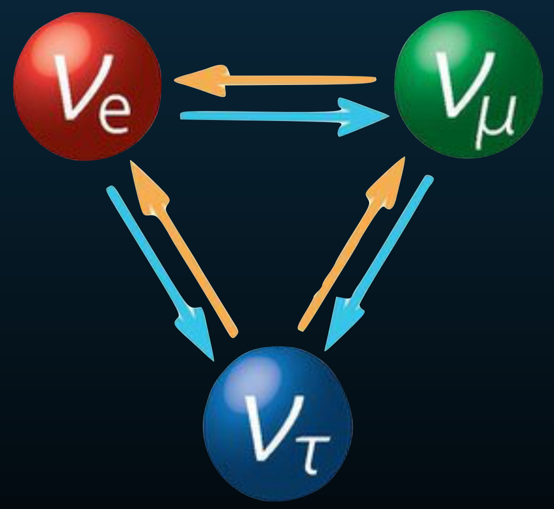




We know a lot about them!

They're important!





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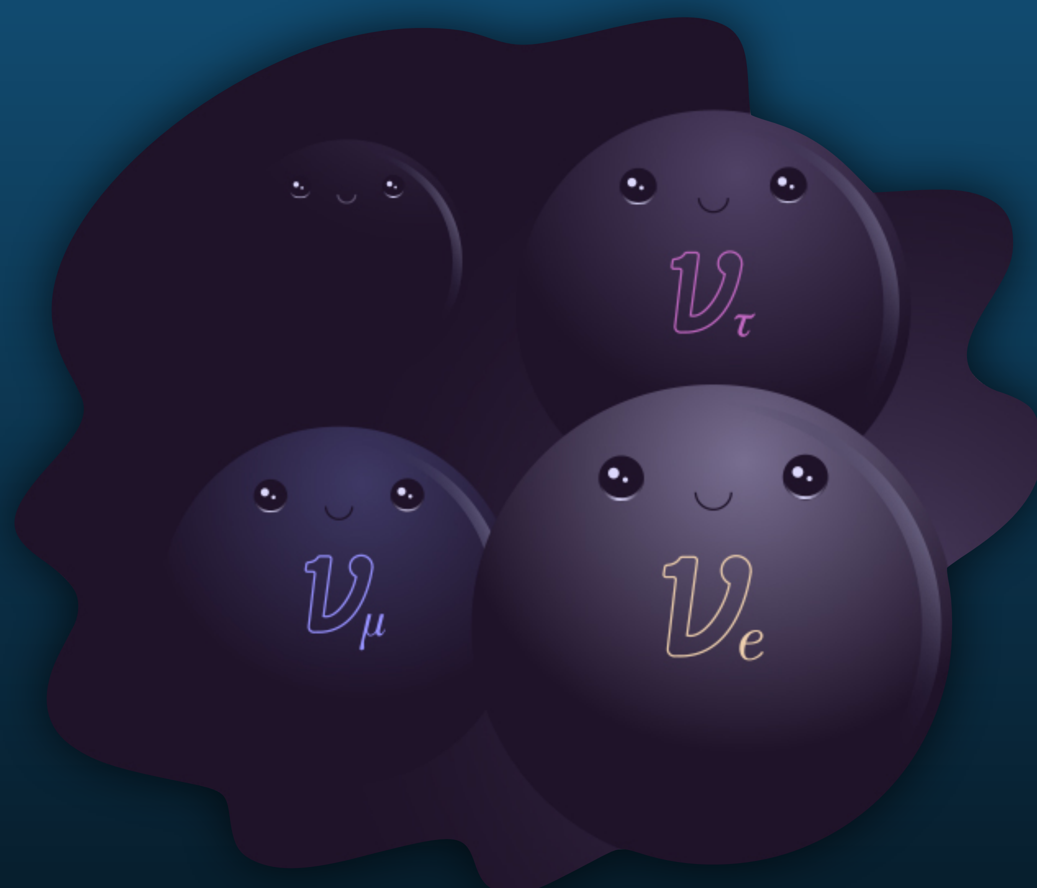

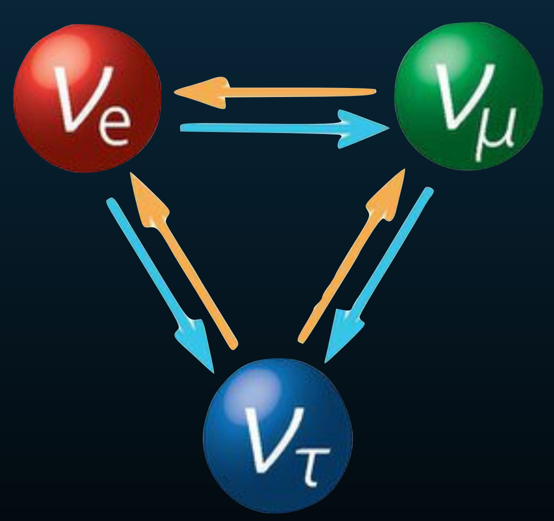

But there's still quite a few open questions…

Neutrino mixing matrix:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i$$

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

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- Three mixing angles:

  $\theta_{12}, \theta_{13}, \theta_{23}$

- 1 Dirac CP phase
- 3 masses (2 possible orderings)

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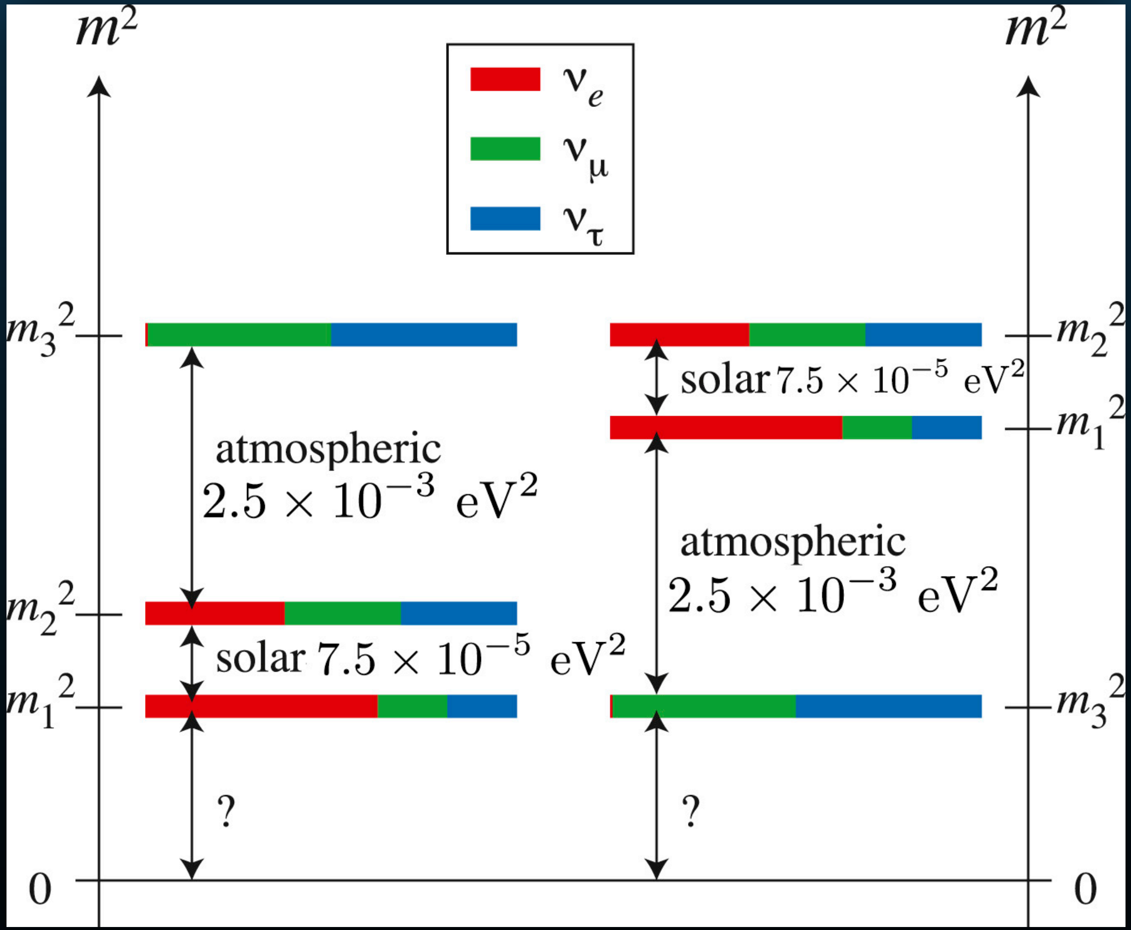

SUPER KAMIOKANDE

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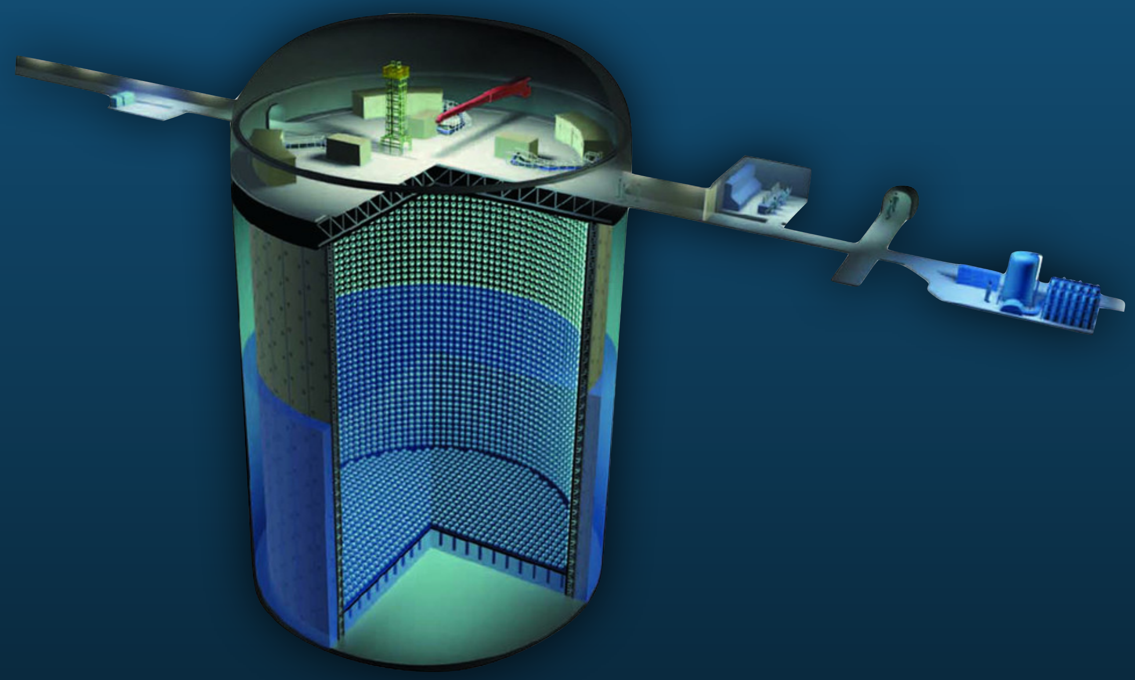

- Tank made of stainless steel
- ~ 50,000 tons of ultra pure water
- ~ 13,000 Photo-Multiplier Tubes (PMTs)

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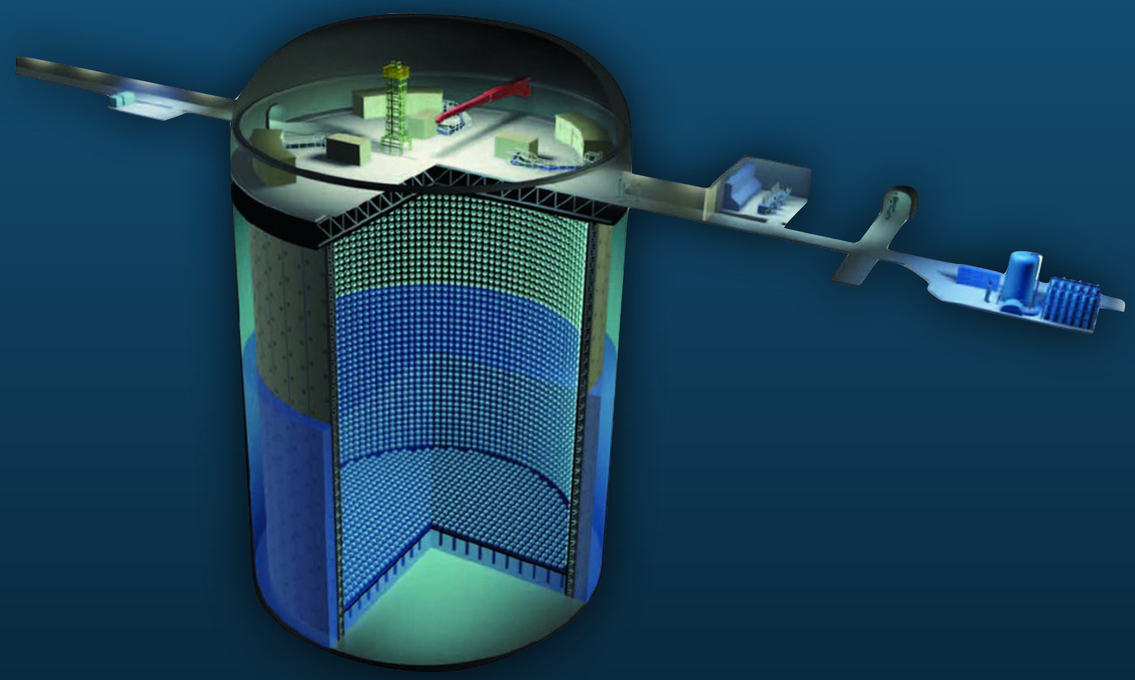

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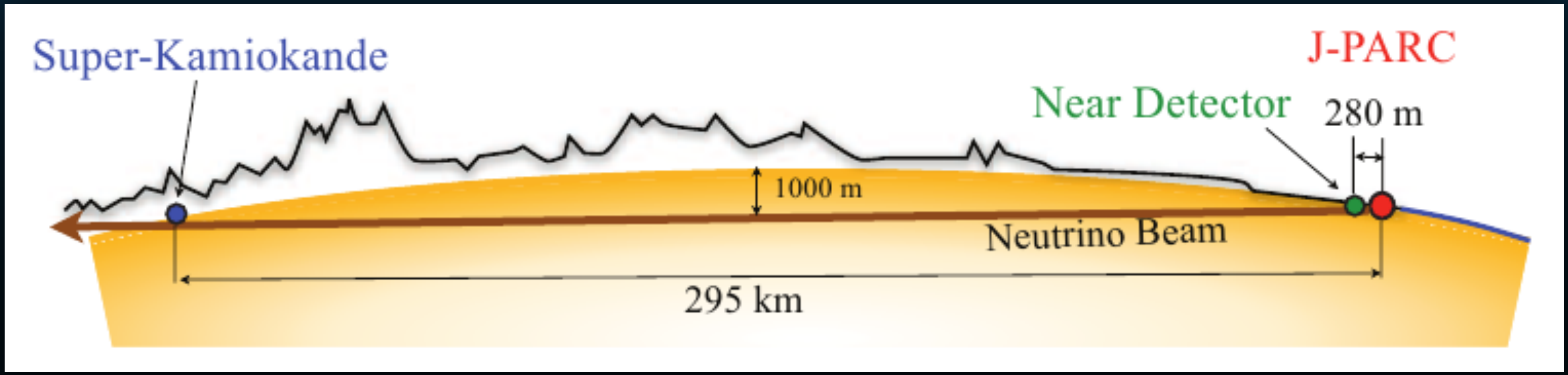

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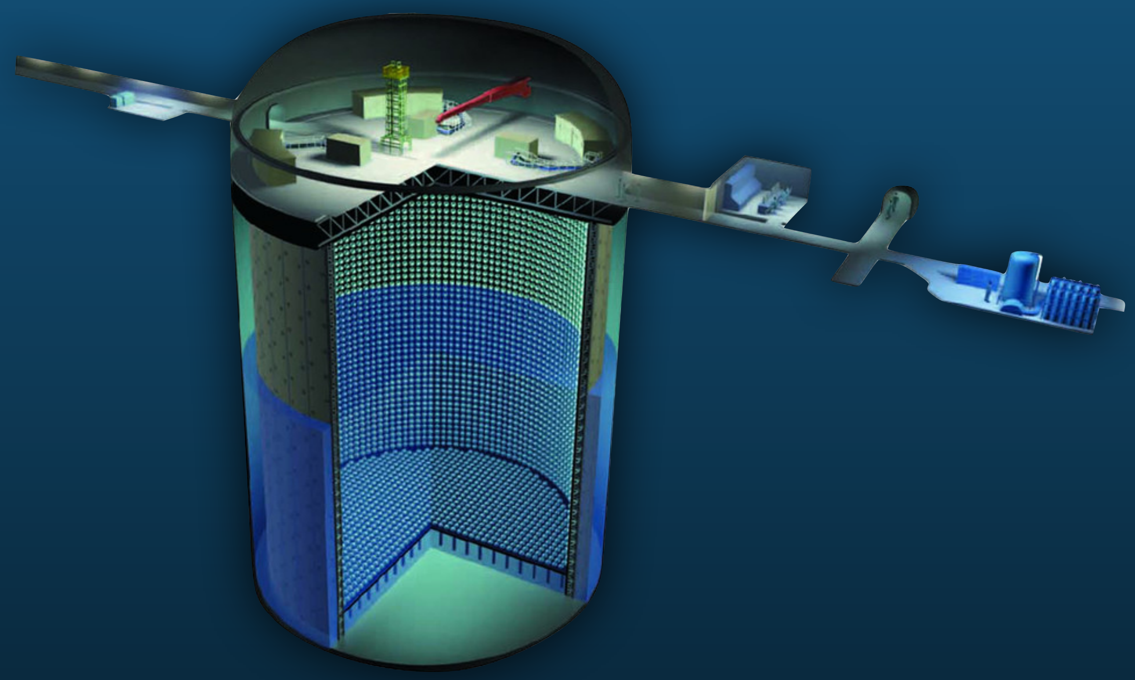

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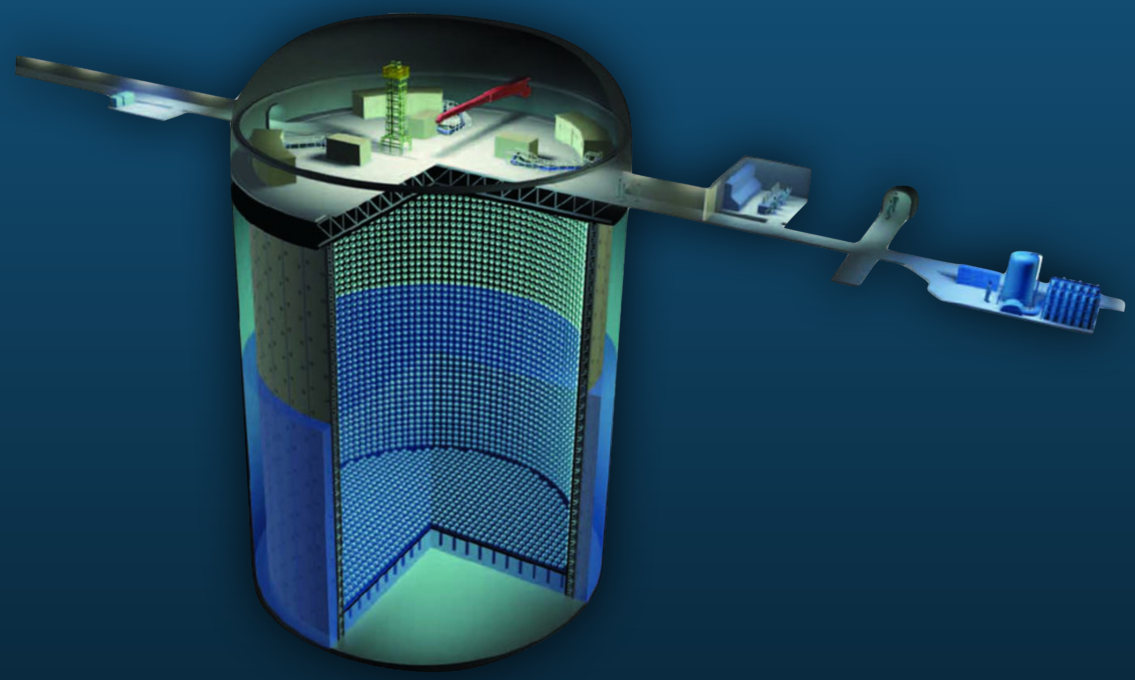

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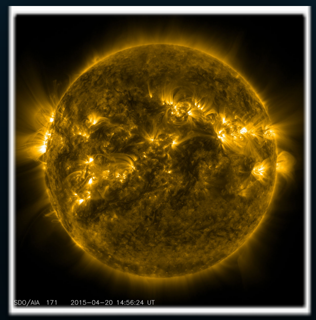

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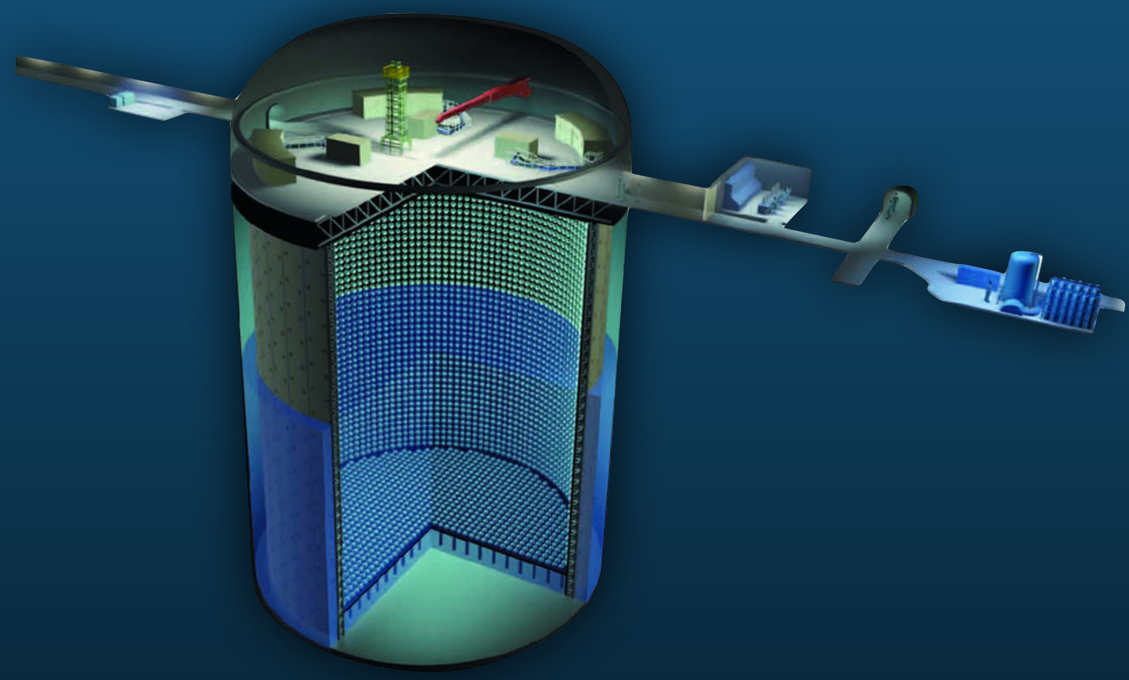

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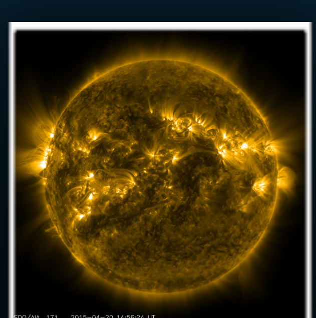

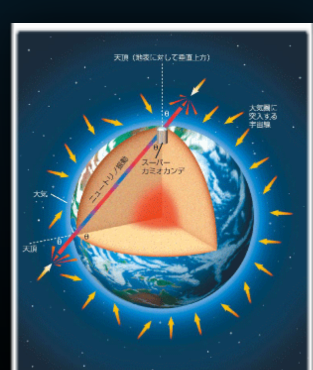

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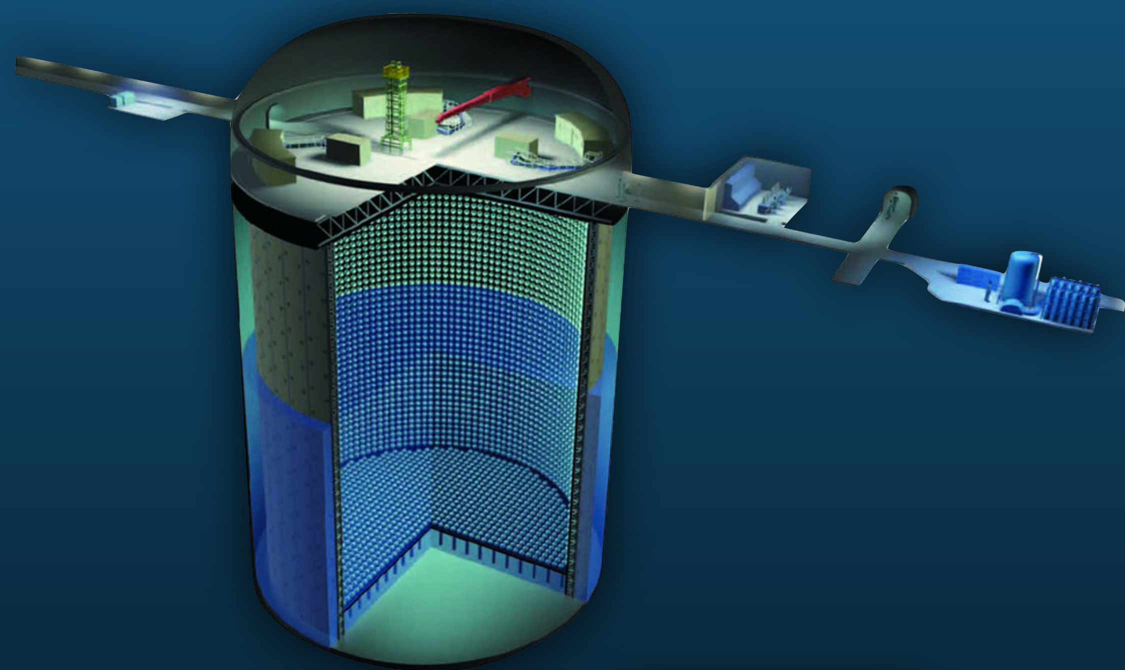

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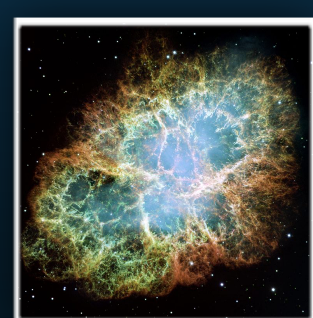

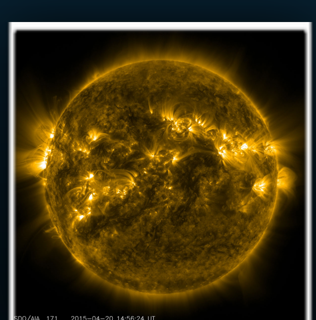

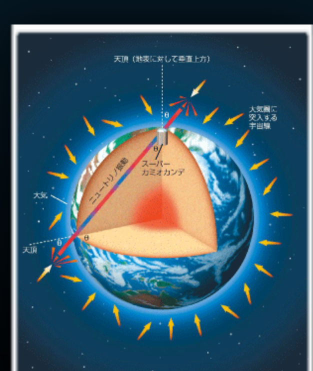

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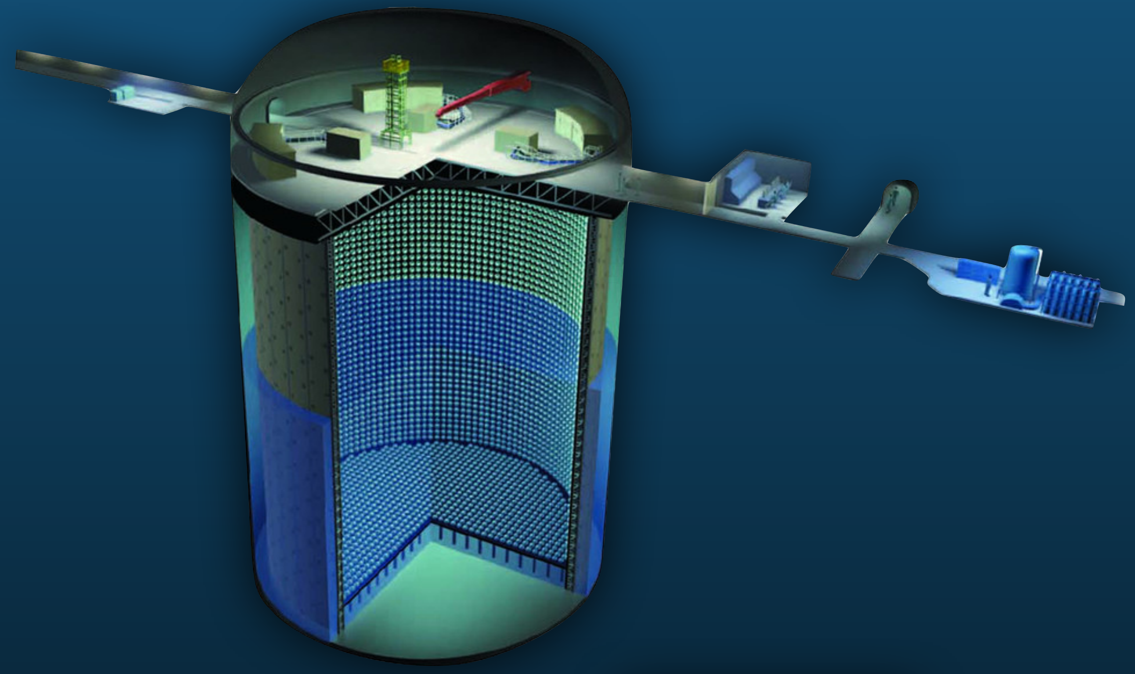

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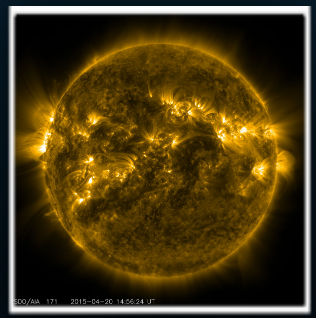

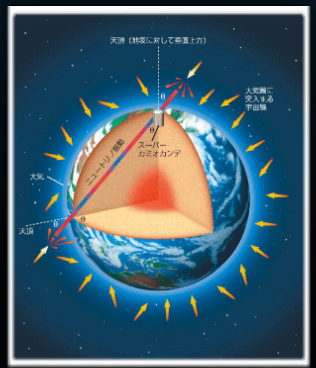

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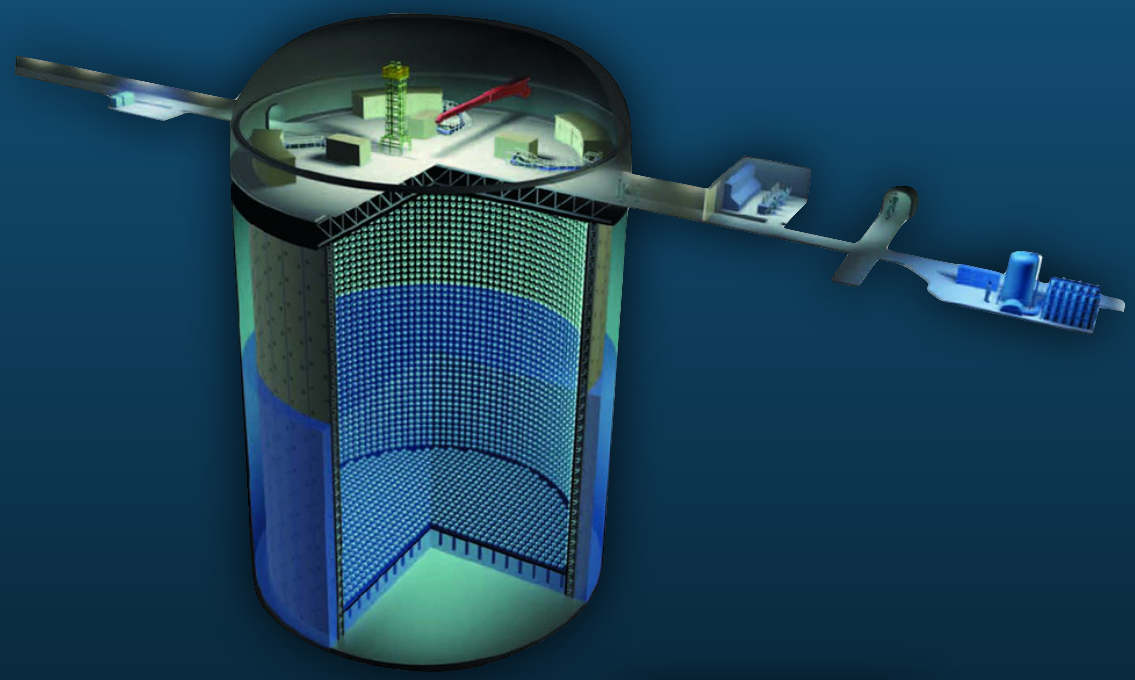

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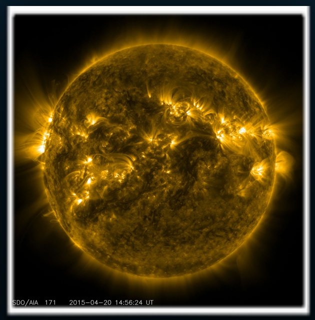

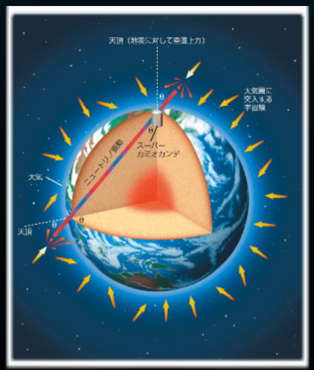

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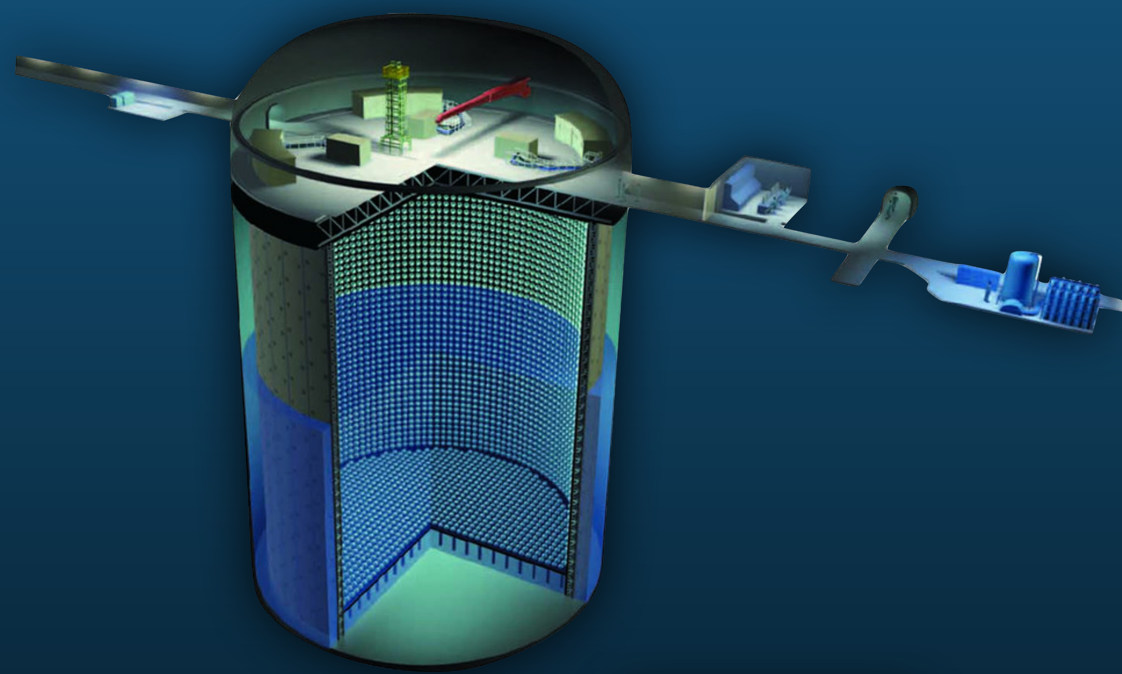

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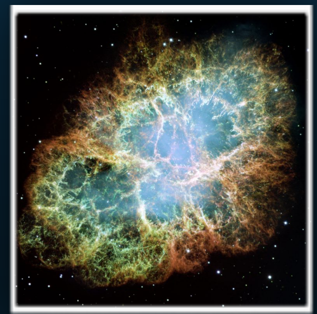

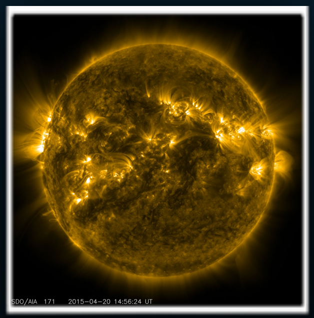

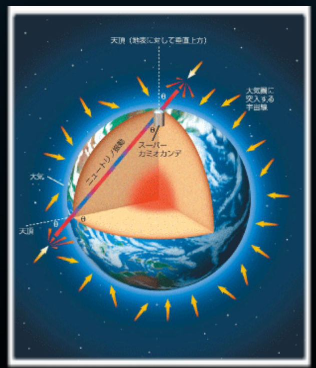

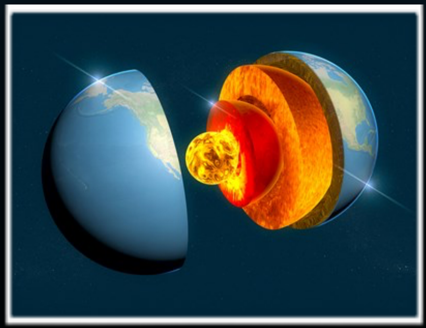

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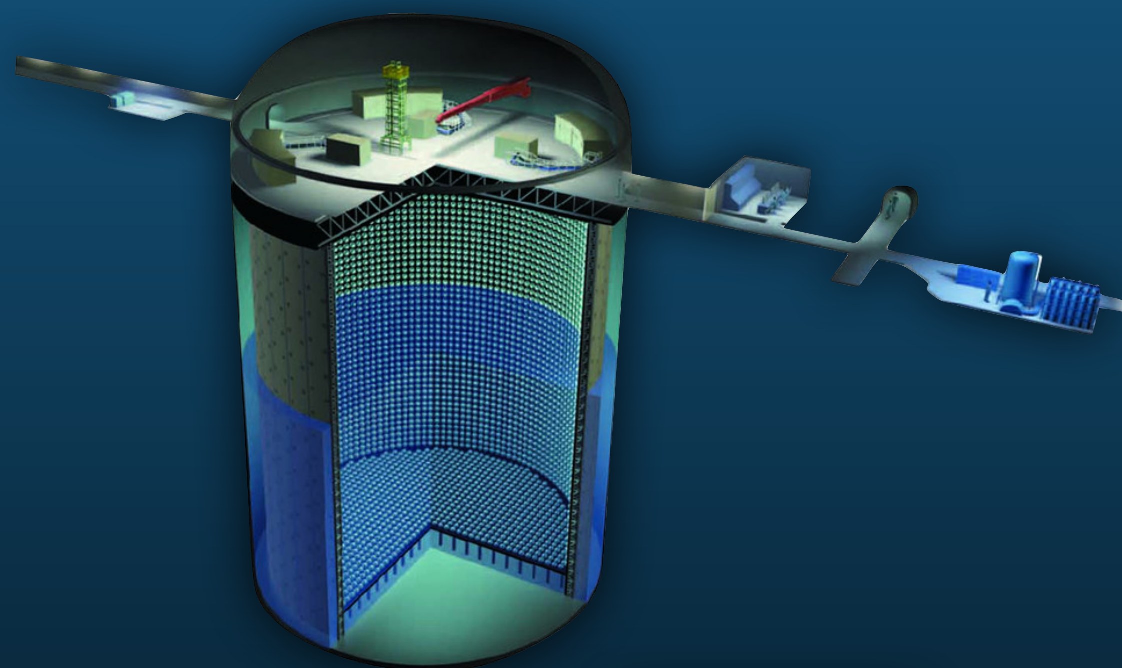

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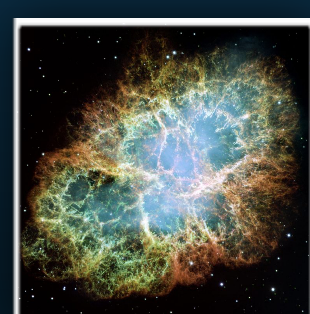

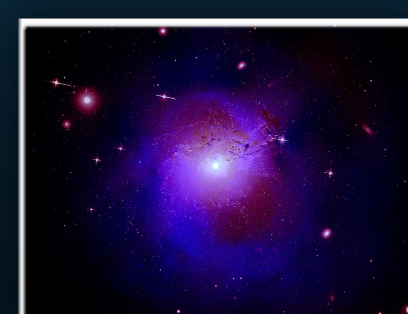

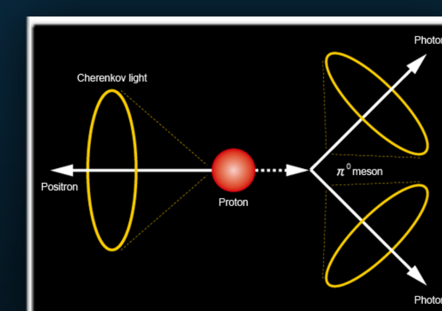

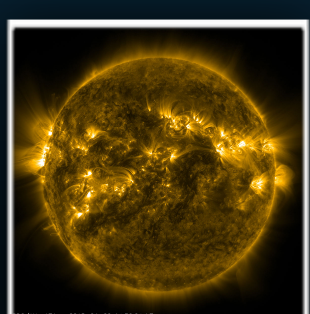

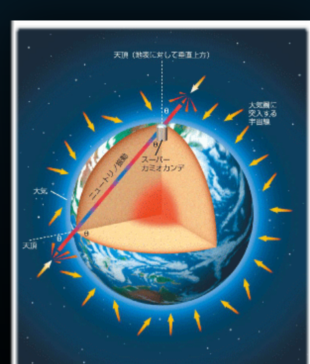

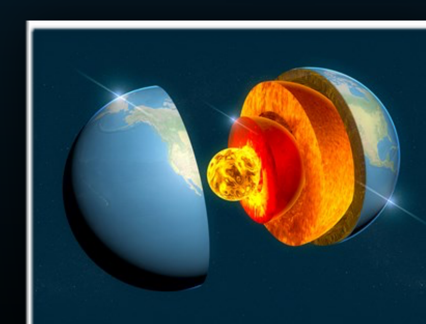

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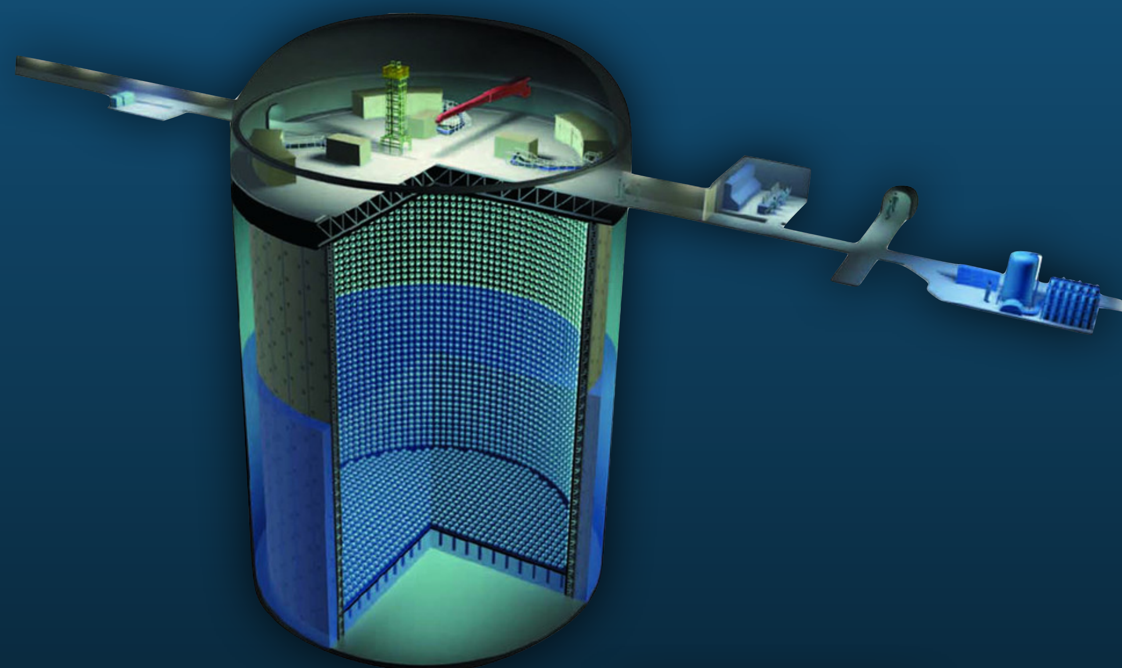

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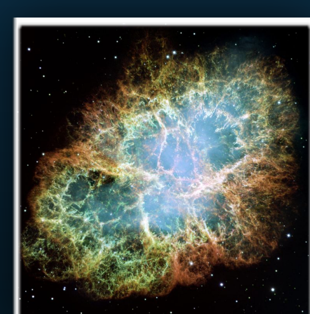

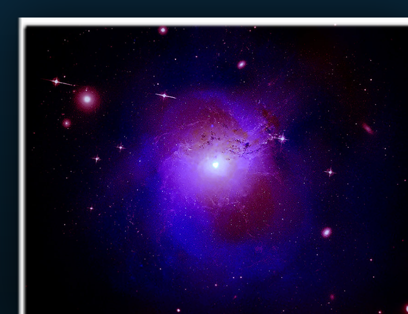

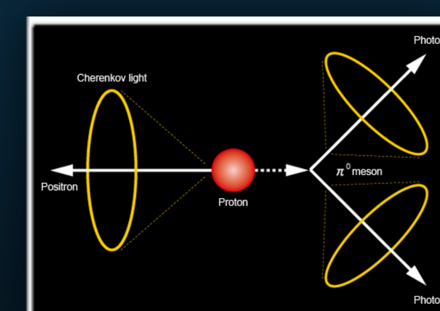

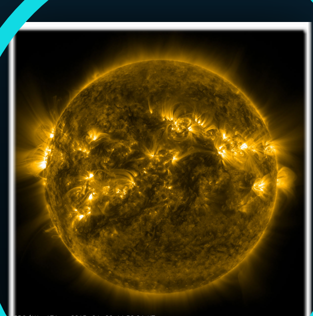

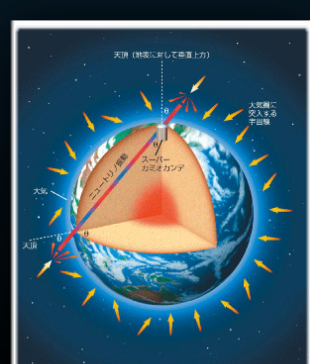

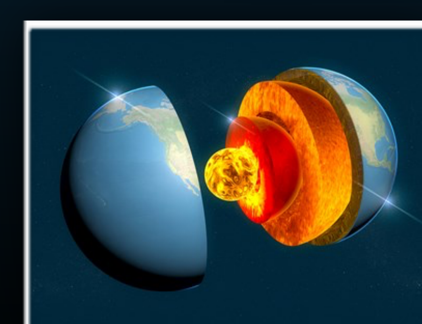

SEASONAL VARIATION

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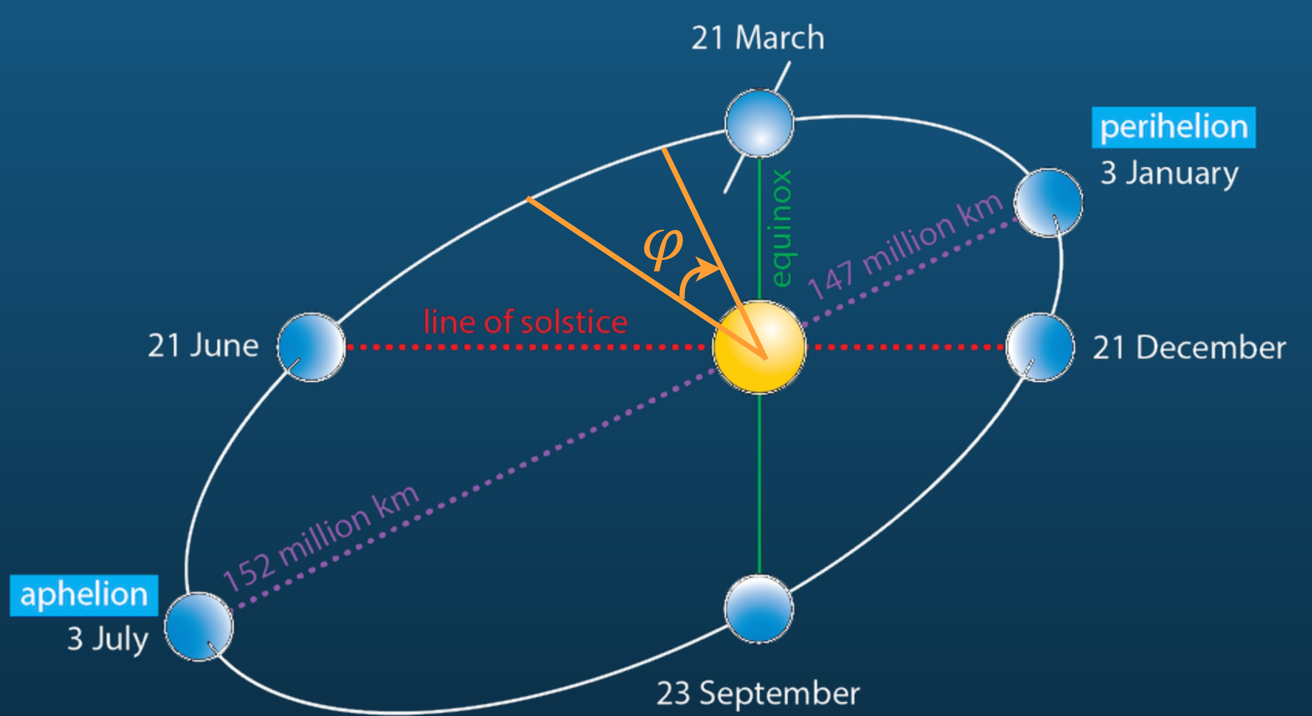
Expected variation in the solar neutrino flux depends on:

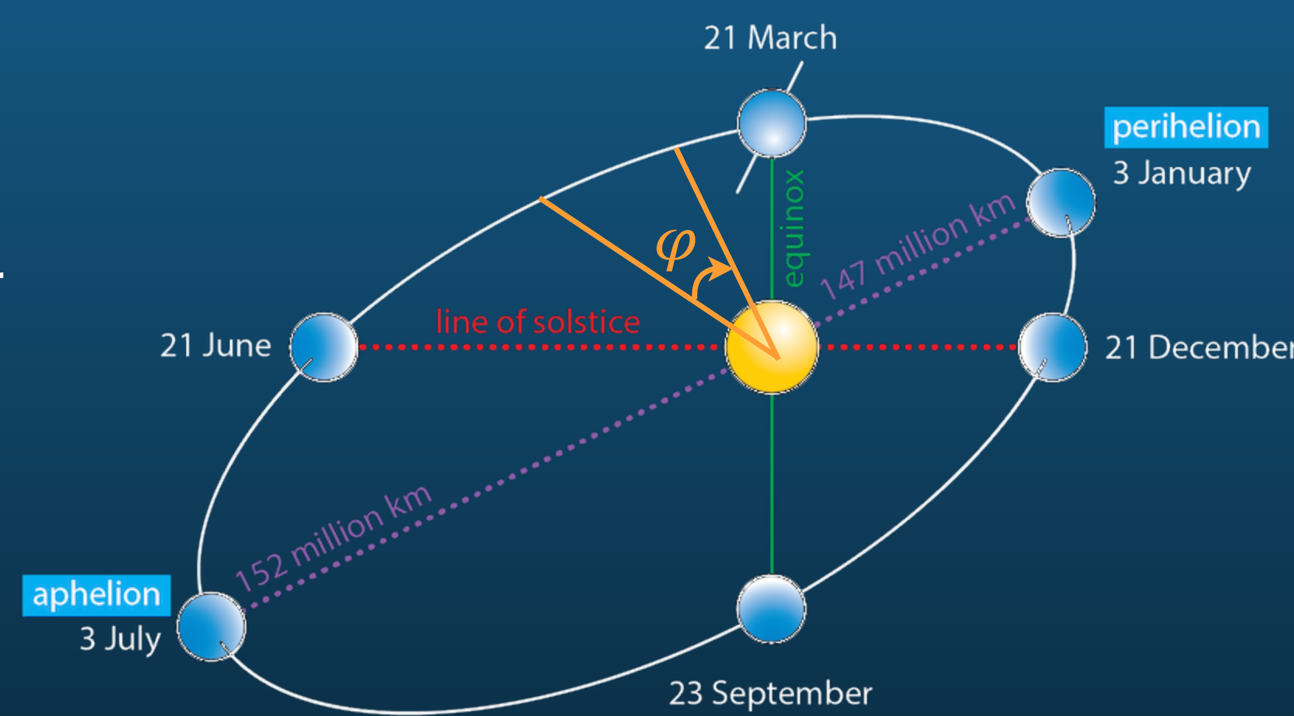
- Spherical symmetry: $1/r^2$

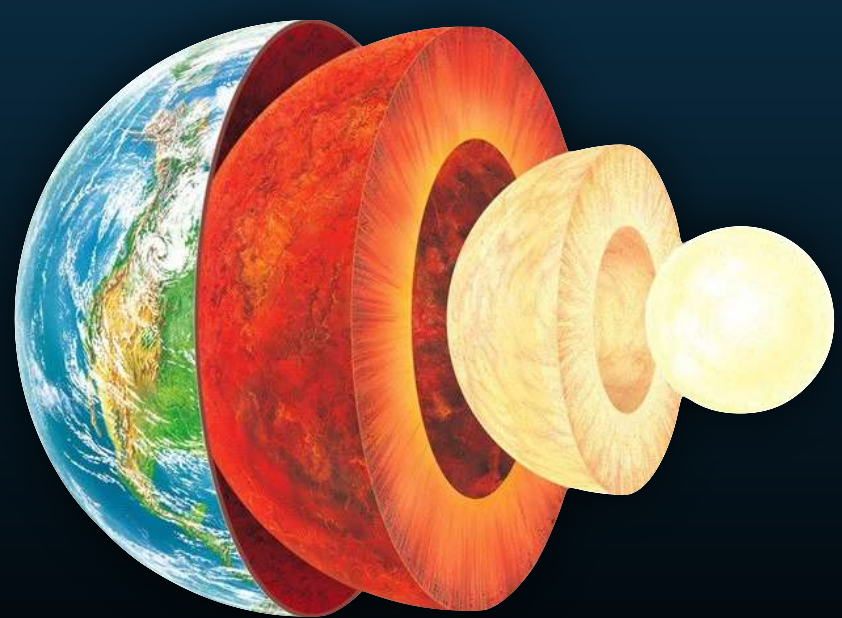


Seasonal Variation

Expected variation in the solar neutrino flux depends on:

- Spherical symmetry: $1/r^2$
- MSW effect





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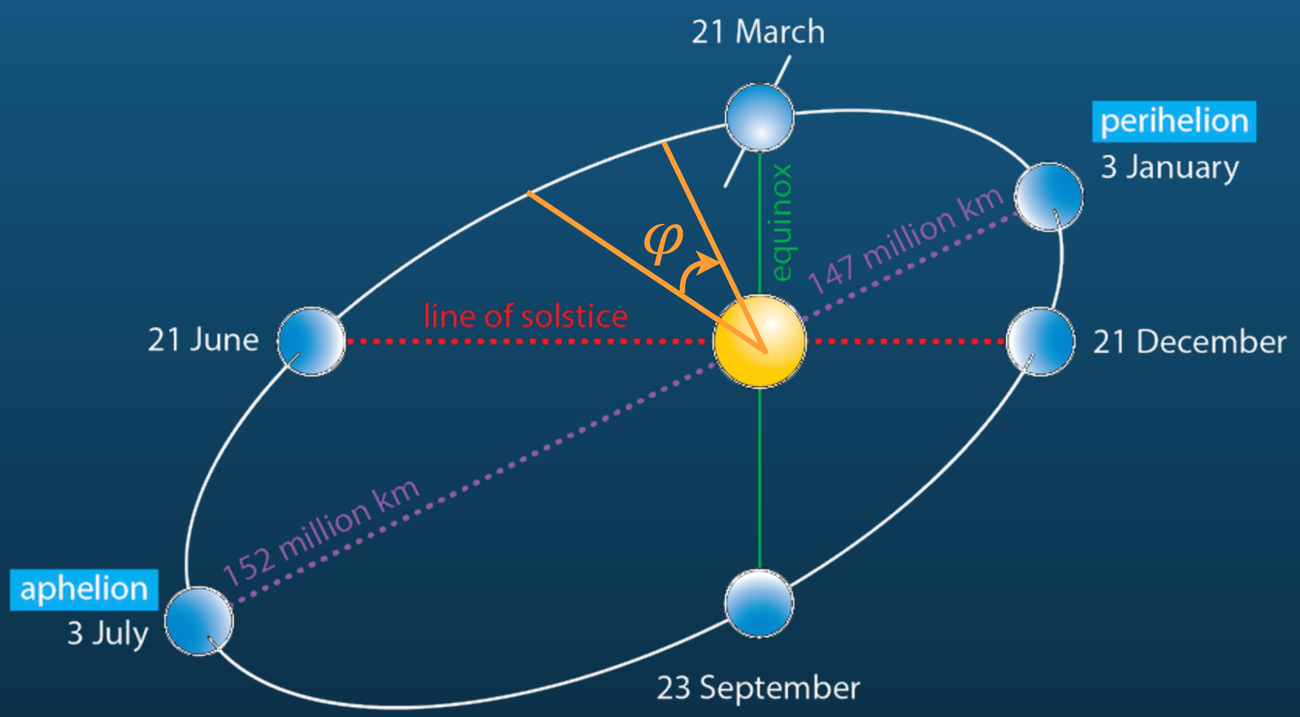

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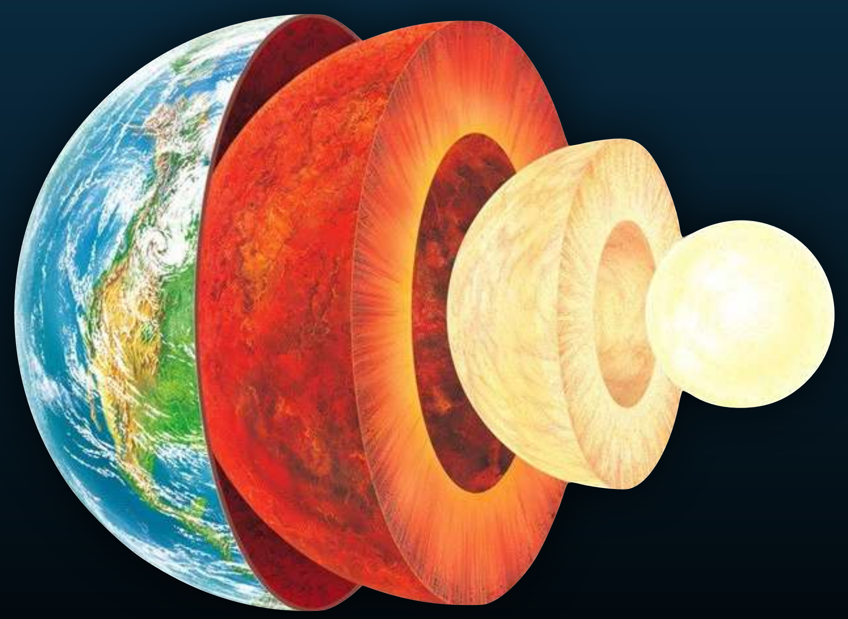
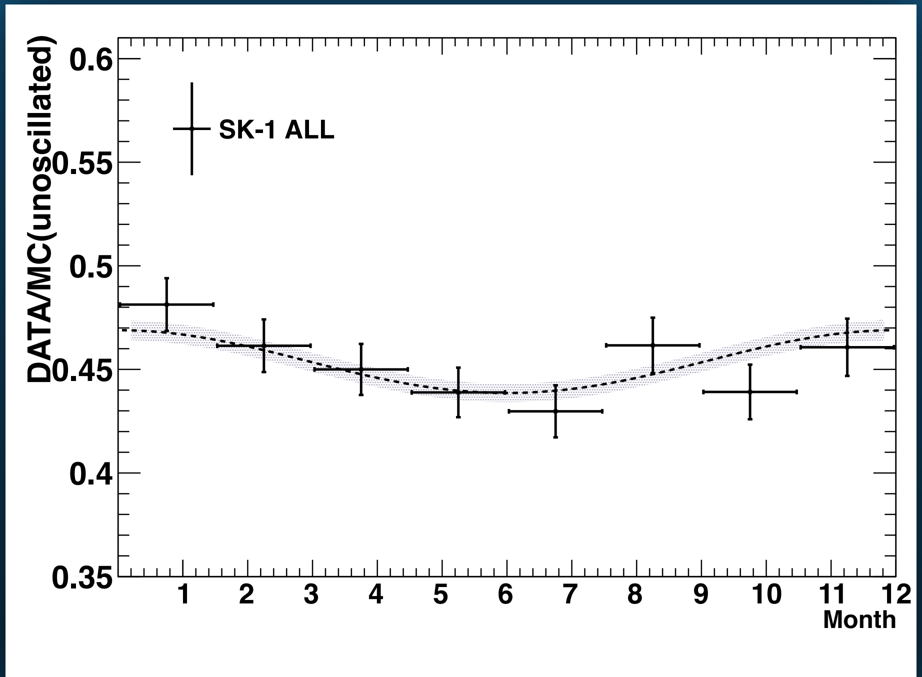


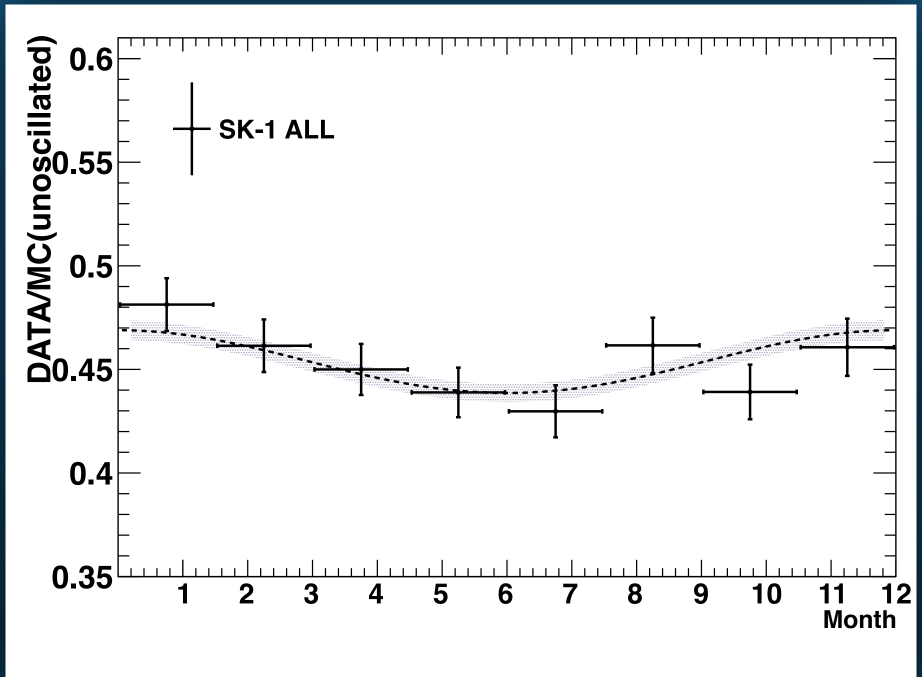
In phase
- SK-I: 1996 - 2001
- SK-II: 2002 - 2005

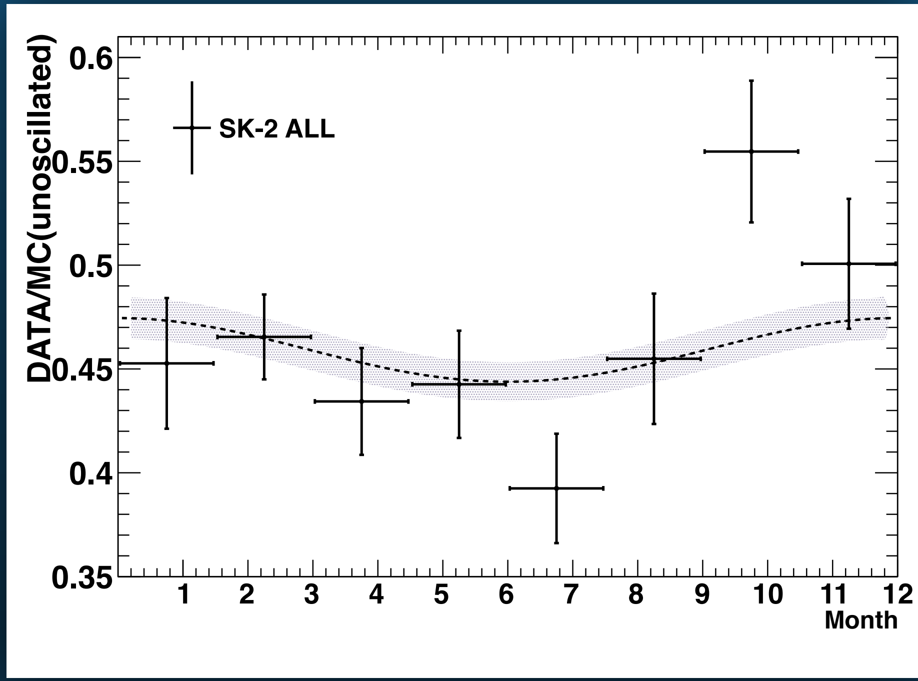
Out of phase
- SK-III: 2006 - 2008
- SK-IV: 2008 - 2019

SK-1


SK-1 ALL
DATA/MC(unoscillated)
0.6
0.55
0.5
0.45
0.4
0.35
1
2
3
4
5
6
7
8
9
10
11
12
Month

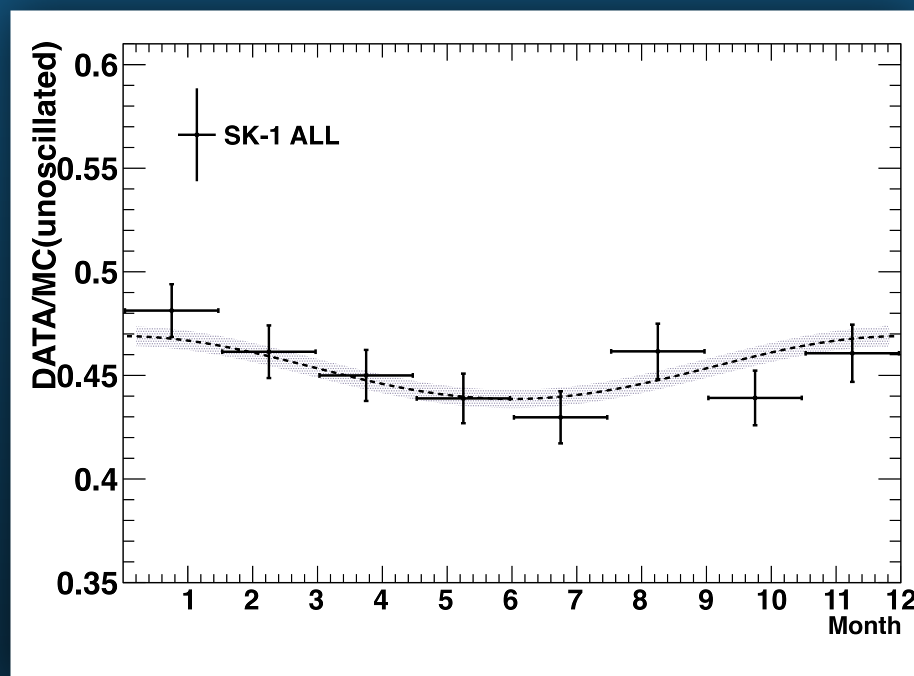
SK-I


SK-1 ALL
DATA/MC(unoscillated)
0.6
0.55
0.5
0.45
0.4
0.35
1 2 3 4 5 6 7 8 9 10 11 12
Month

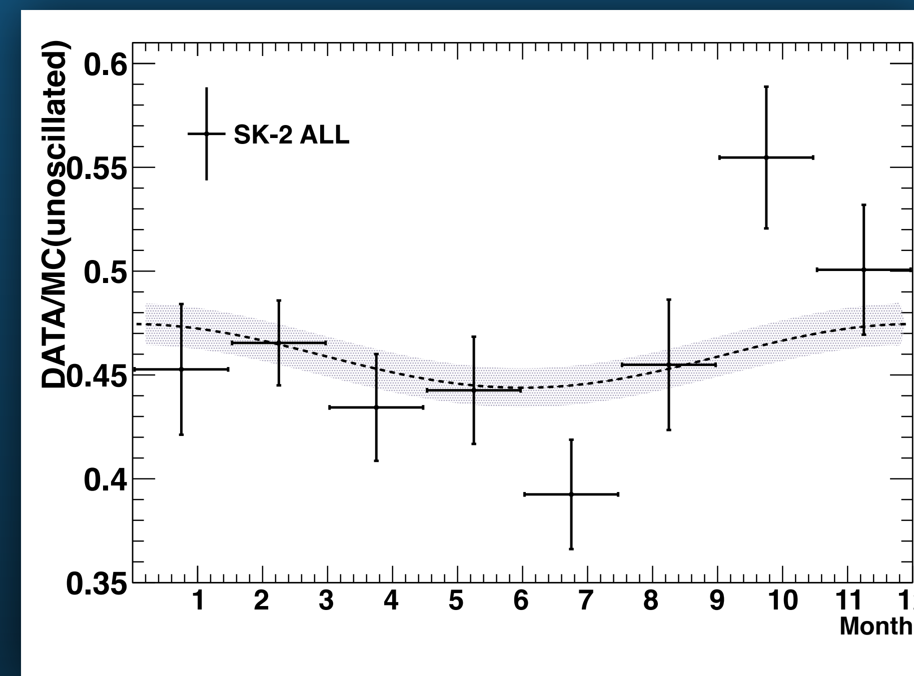

SK-2 ALL
DATA/MC(unoscillated)
0.6
0.55
0.5
0.45
0.4
0.35
1 2 3 4 5 6 7 8 9 10 11 12
Month

SK-II

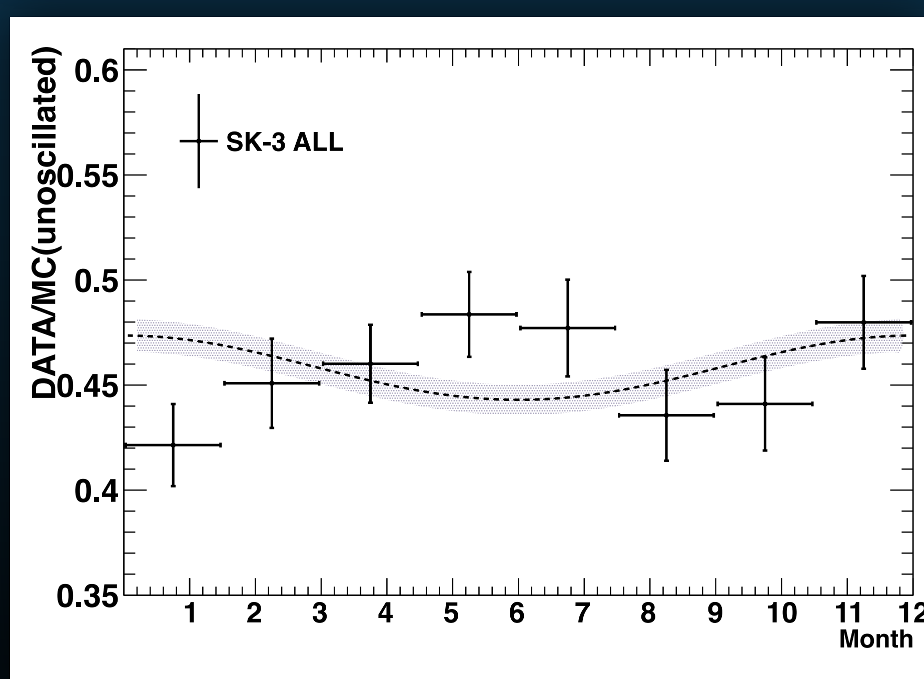
SK-I



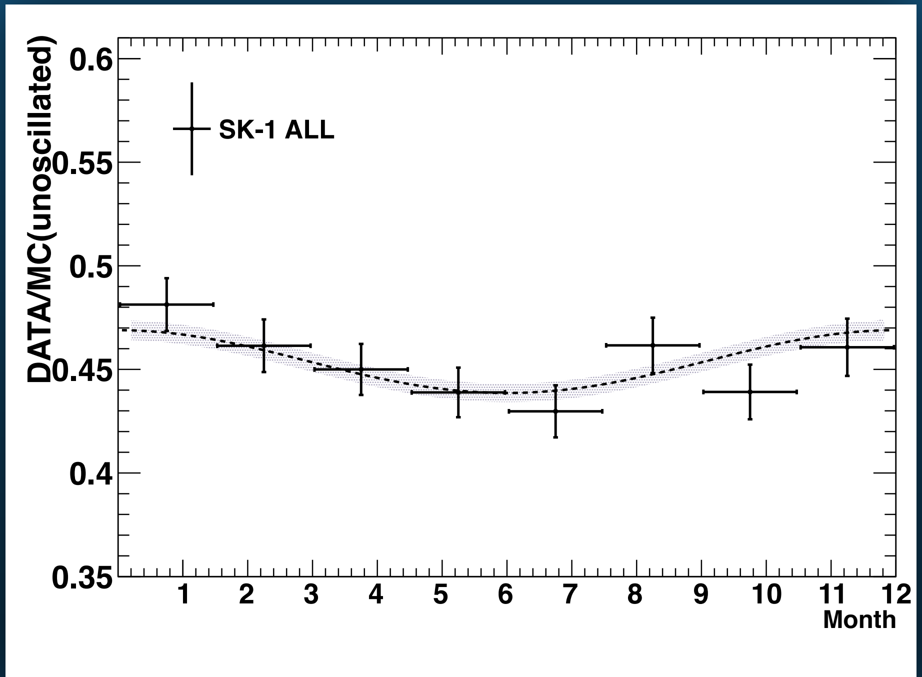
SK-II

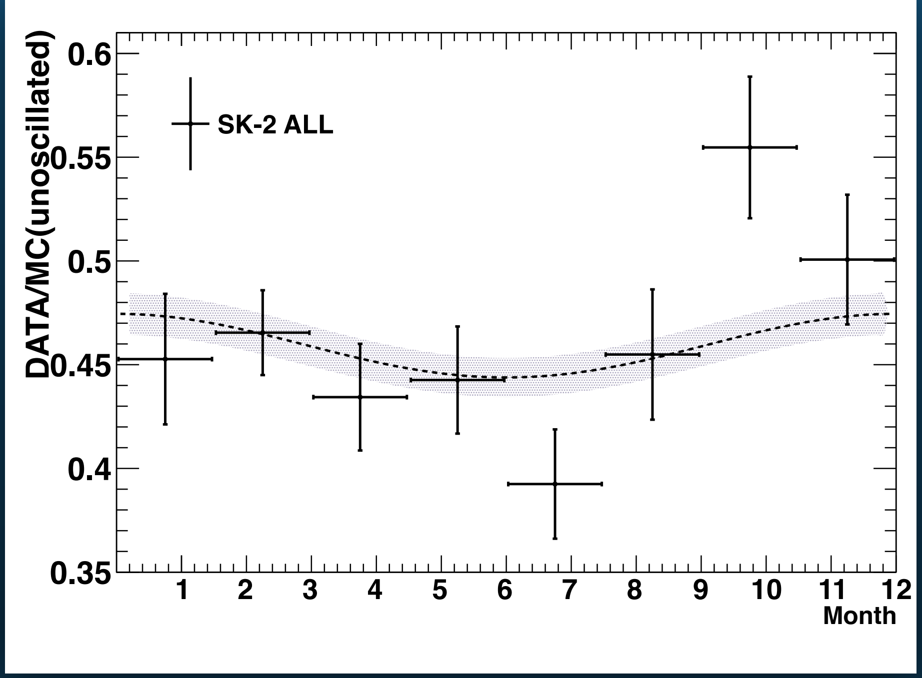


SK-III



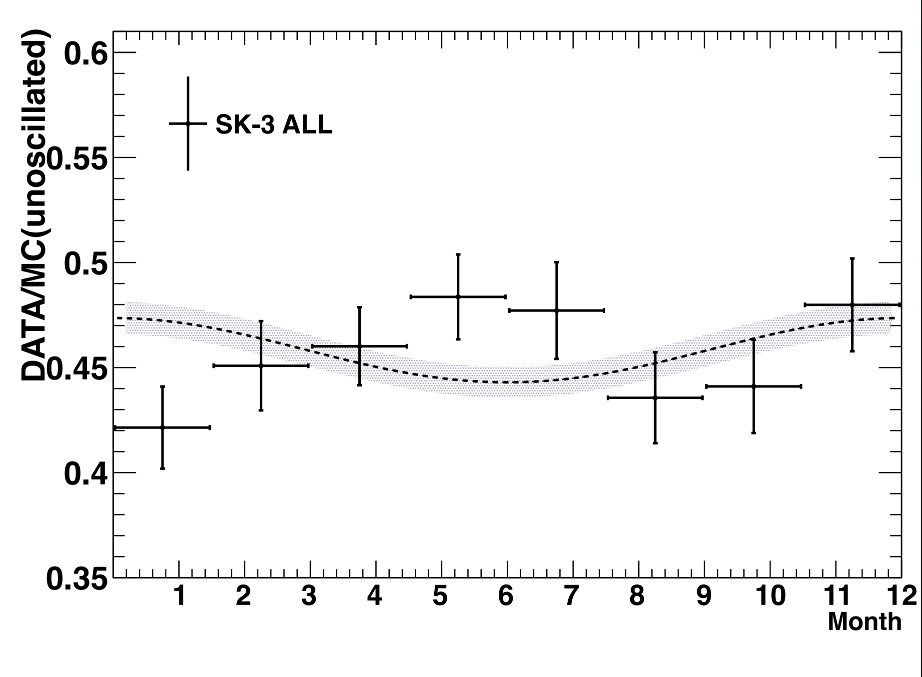
SK-I





SK-II

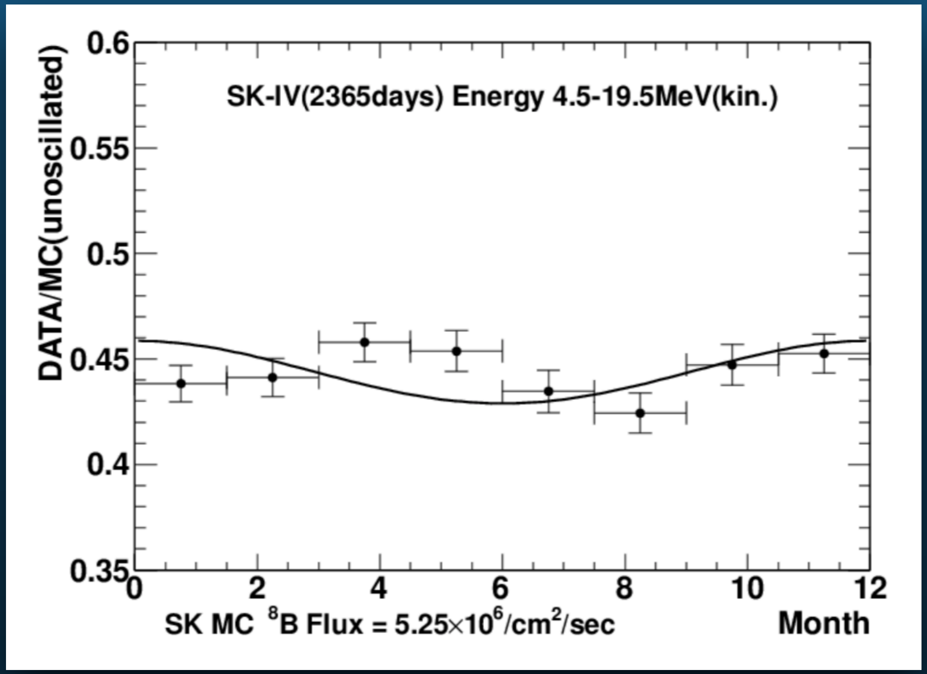
SK-III



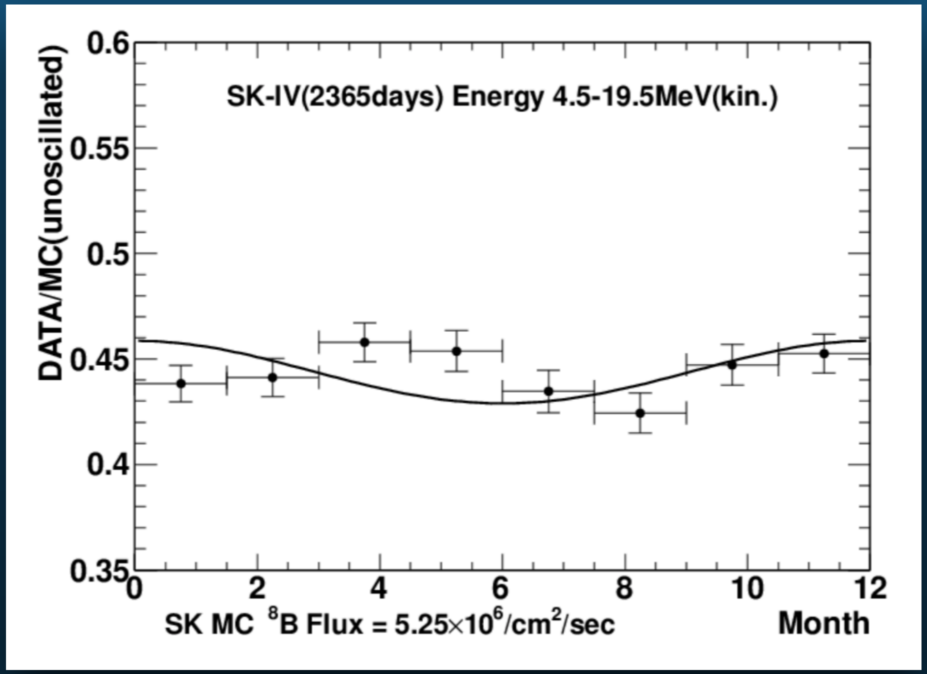
......

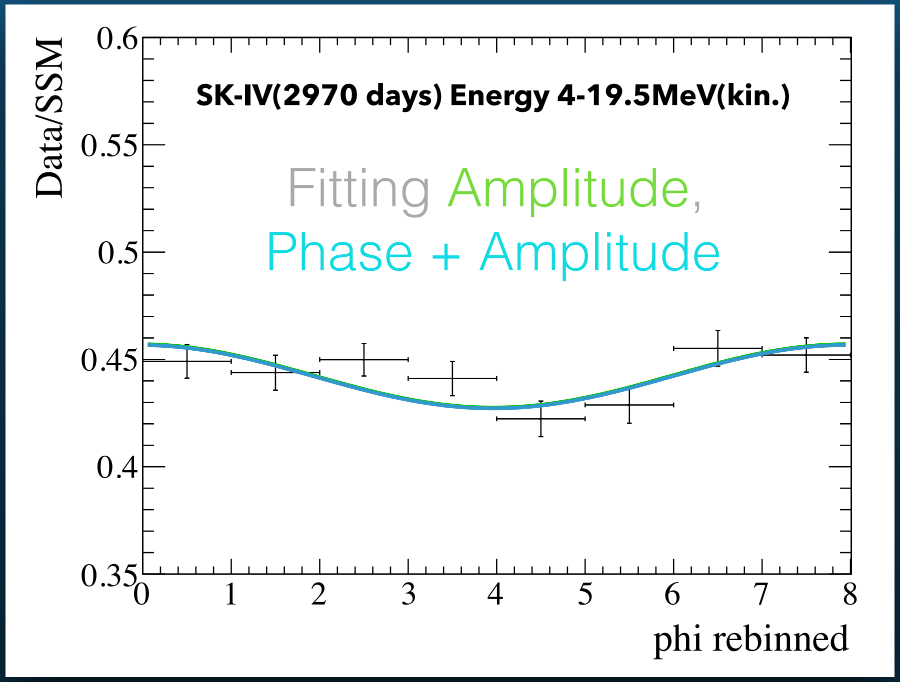
SK-IV

SK-IV

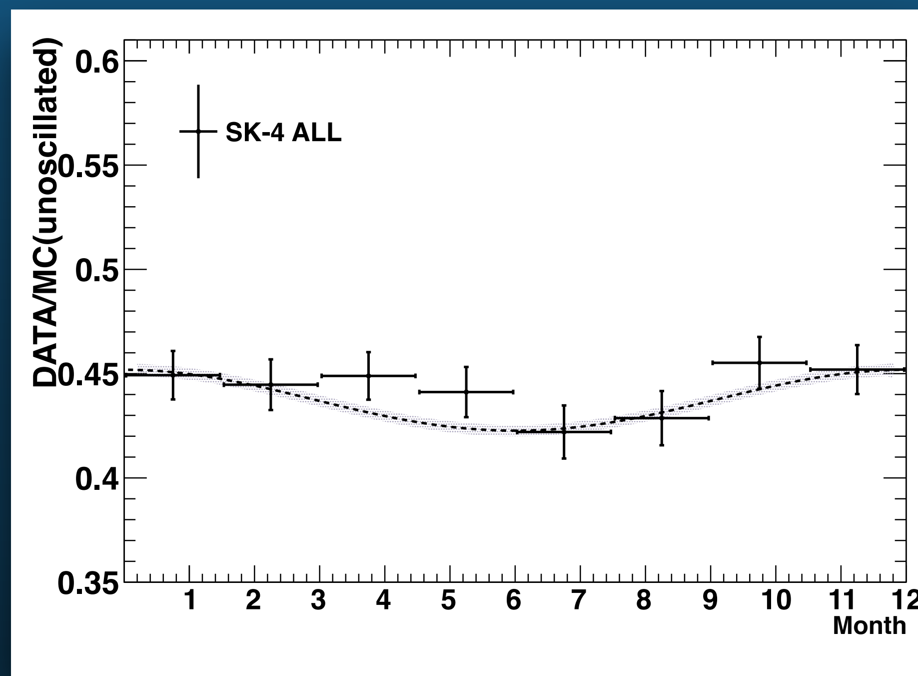

SK-IV(2365days) Energy 4.5-19.5MeV(kin.)
DATA/MC(unoscillated)
0.6
0.55
0.5
0.45
0.4
0.35
0
2
4
6
8
10
12
SK MC ^{8}B Flux = 5.25×10^6/cm^2/sec
Month

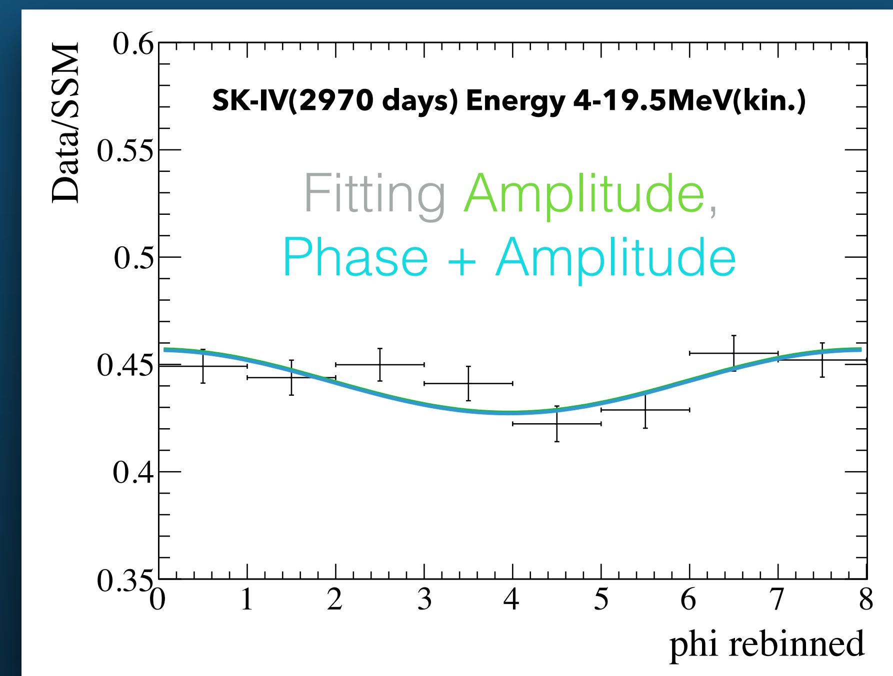
SK-IV


SK-IV(2365days) Energy 4.5-19.5MeV(kin.)
DATA/MC(unoscillated)
SK MC ^{8}B Flux = 5.25×10^6/cm^2/sec
Month

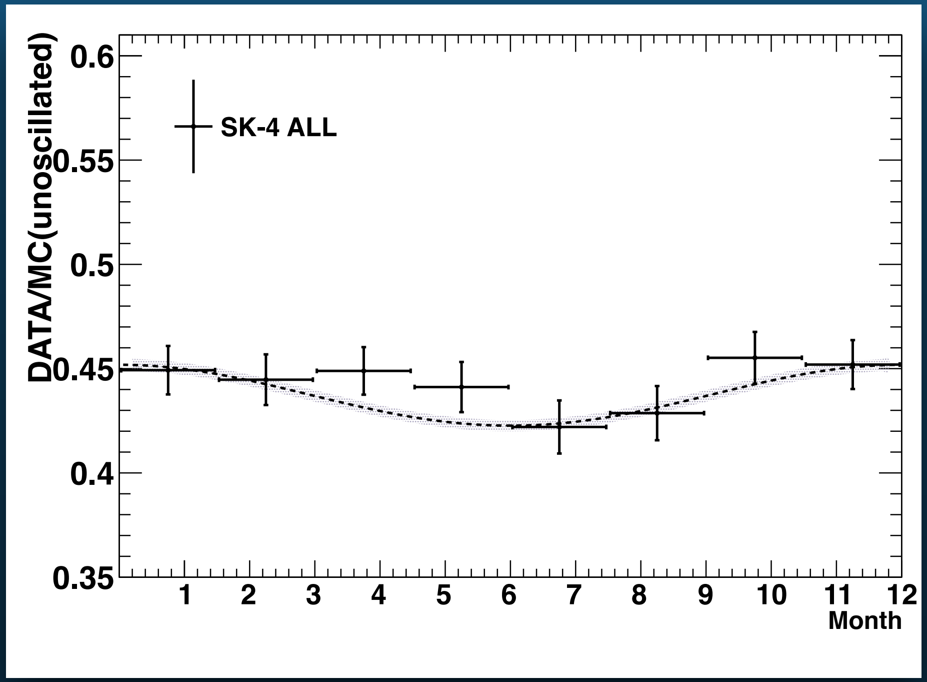

SK-IV(2970 days) Energy 4-19.5MeV(kin.)
Fitting Amplitude,
Phase + Amplitude
Data/SSM
phi rebinned

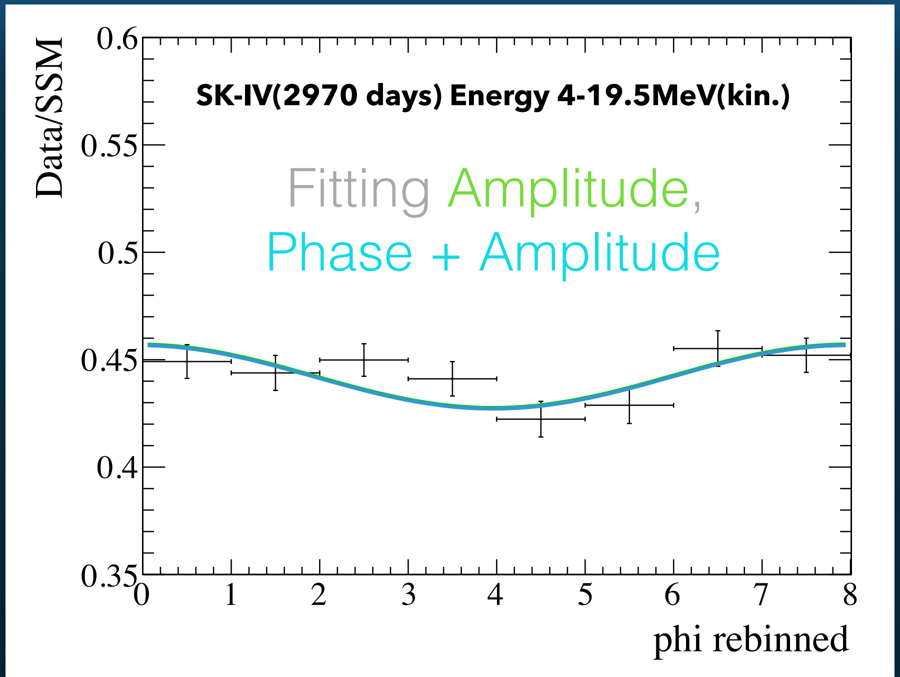
SK-IV


SK-4 ALL
DATA/MC(unoscillated)
0.6
0.55
0.5
0.45
0.4
0.35
1 2 3 4 5 6 7 8 9 10 11 12
Month

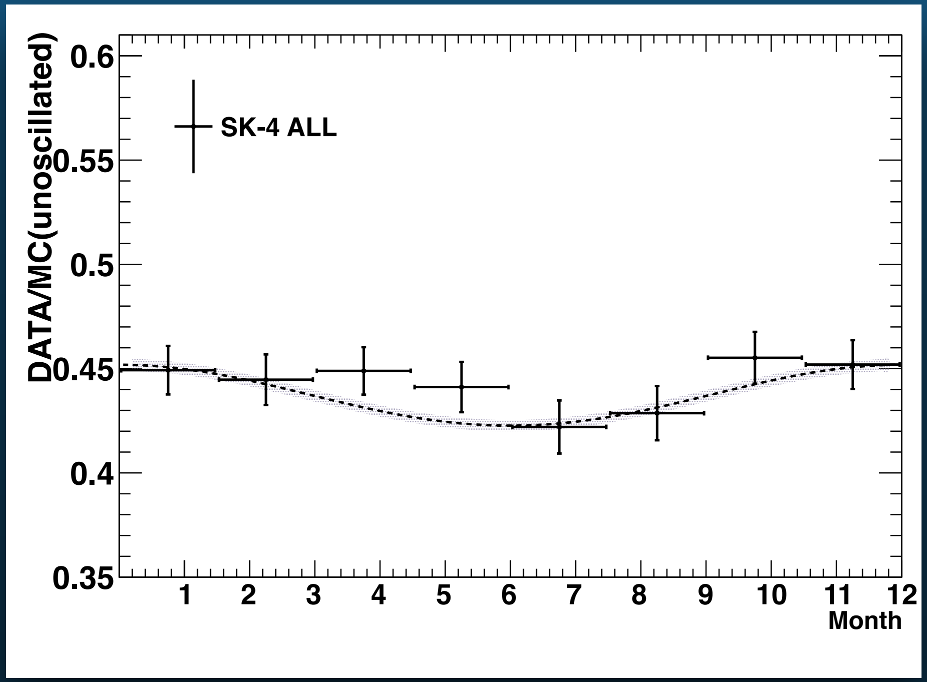

SK-IV(2970 days) Energy 4-19.5MeV(kin.)
Fitting Amplitude,
Phase + Amplitude
Data/SSM
0.6
0.55
0.5
0.45
0.4
0.35
0 1 2 3 4 5 6 7 8
phi rebinned

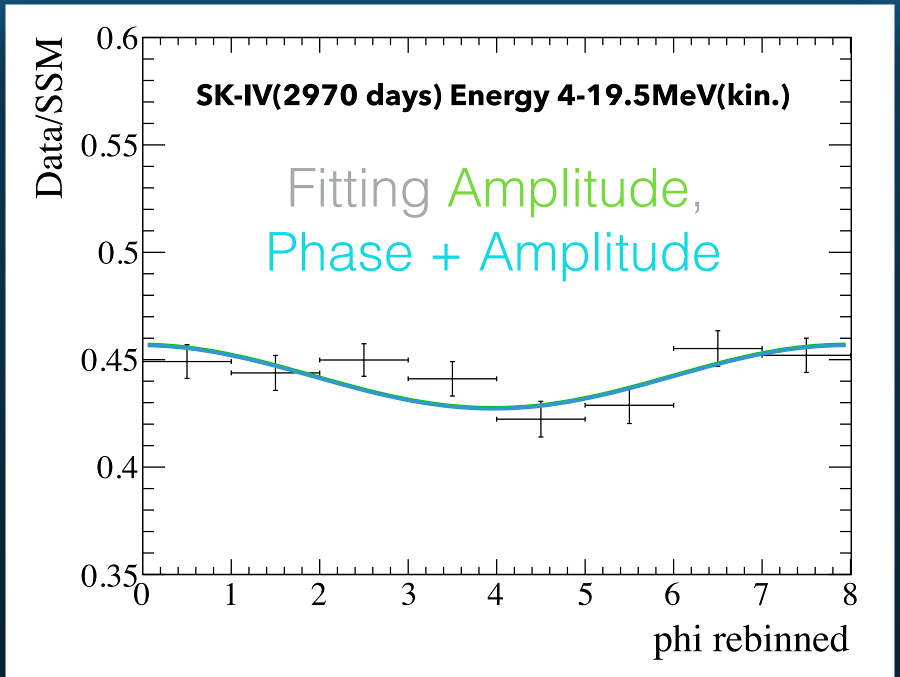
SK-IV


SK-4 ALL
DATA/MC(unoscillated)
Month


SK-IV(2970 days) Energy 4-19.5MeV(kin.)
Fitting Amplitude,
Phase + Amplitude
Data/SSM
phi rebinned

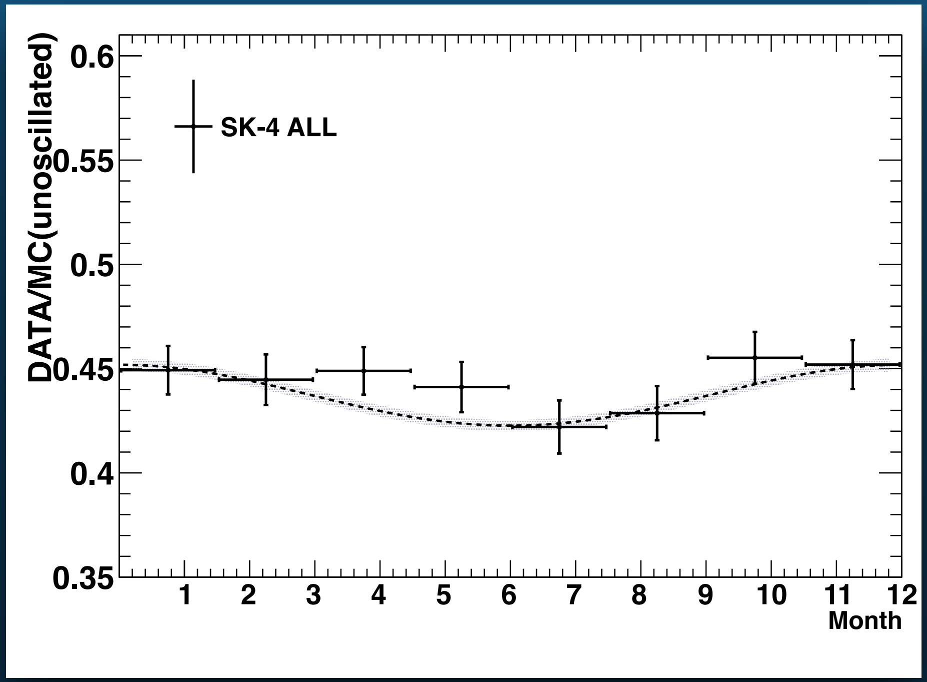
SK-IV

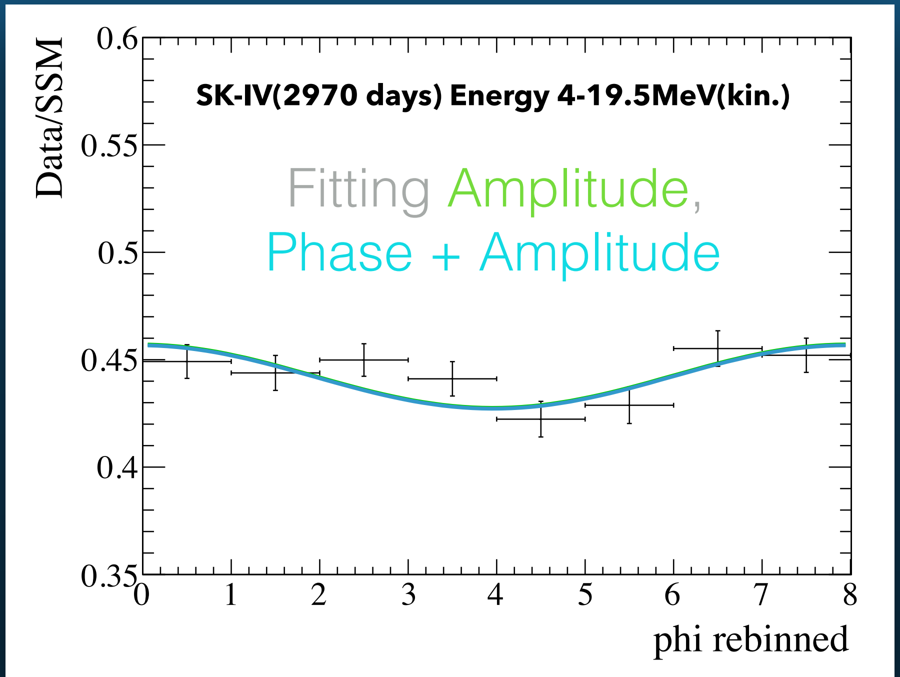




- The two methods now verify each other and function as a cross-check.

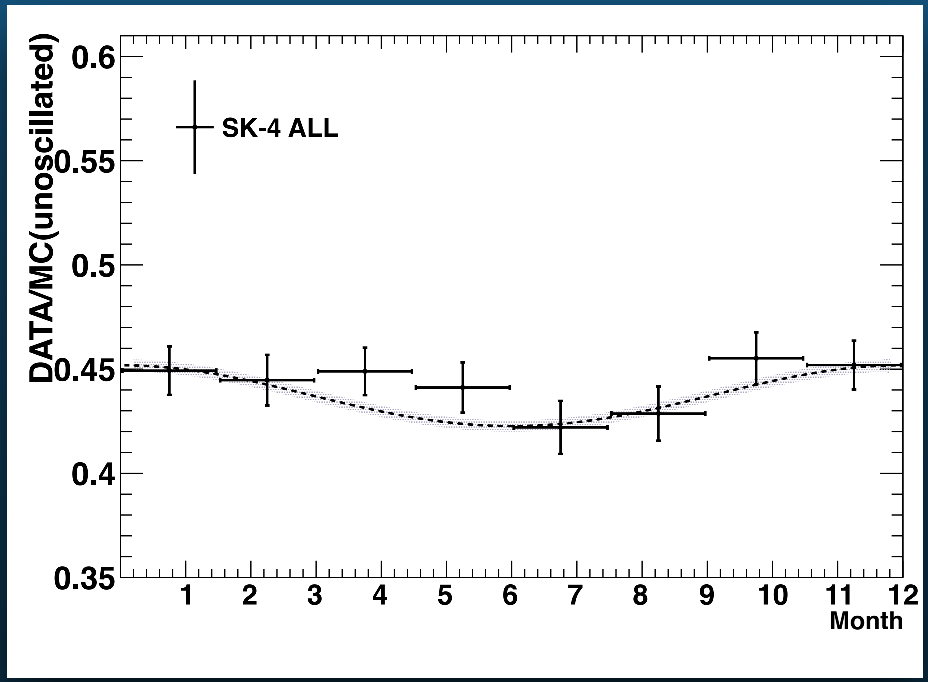
SK-IV

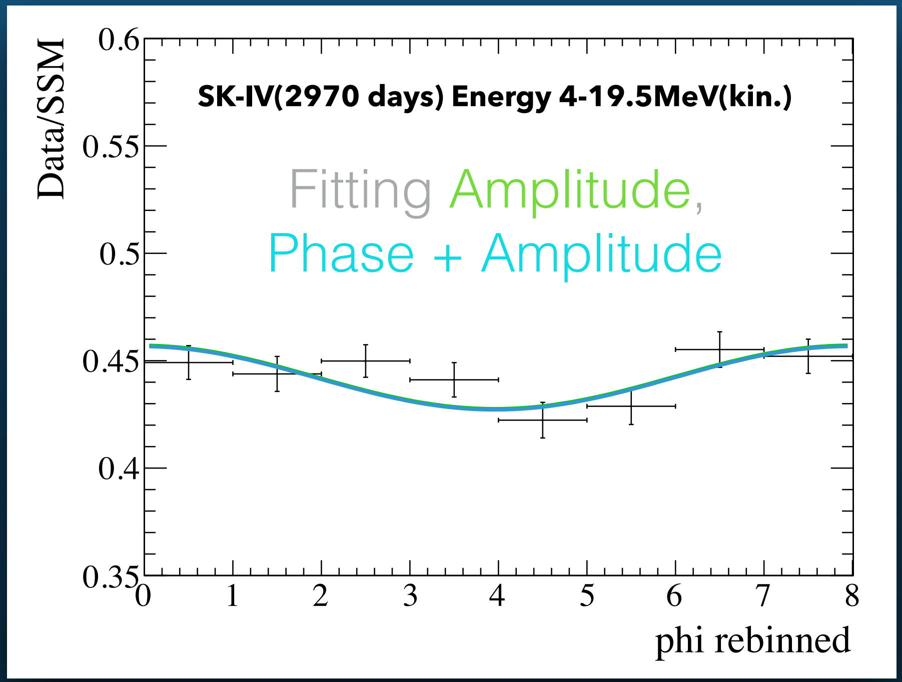




- The two methods now verify each other and function as a cross-check.
- SK-III reanalysis in progress.

SK-IV



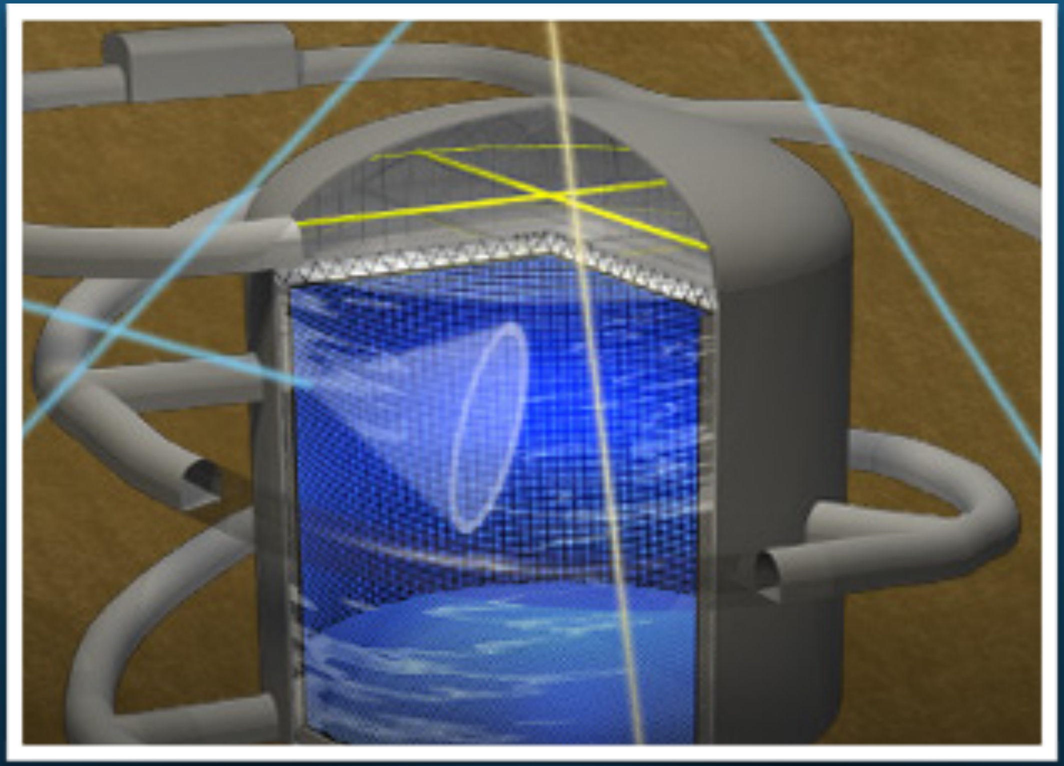


- The two methods now verify each other and function as a cross-check.
- SK-III reanalysis in progress.
- Possible applications to future direct dark matter experiments.

HYPER KAMIOKANDE

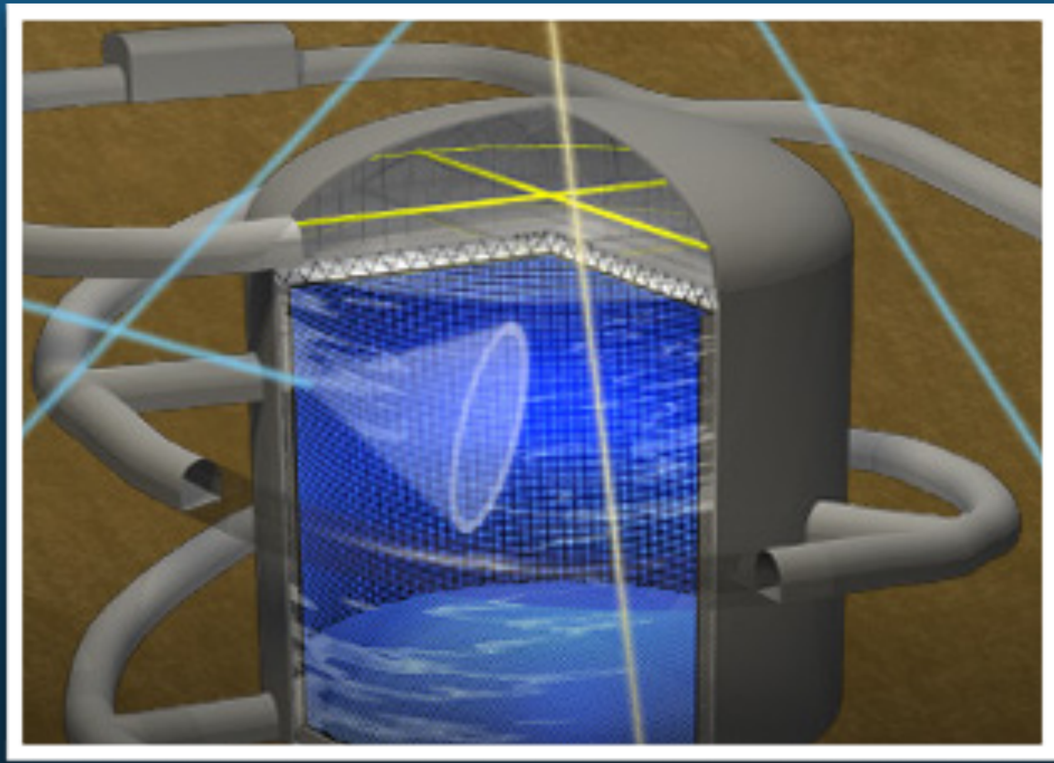
HYPER KAMIOKANDE

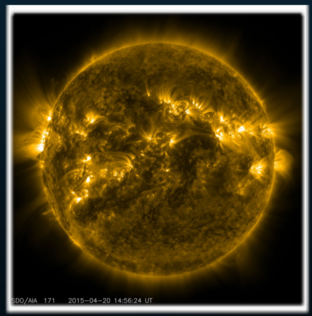
- 10x larger than Super-K
- Upgraded near + intermediate detector
- Multipurpose: huge research potential

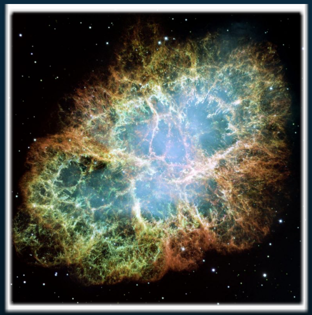


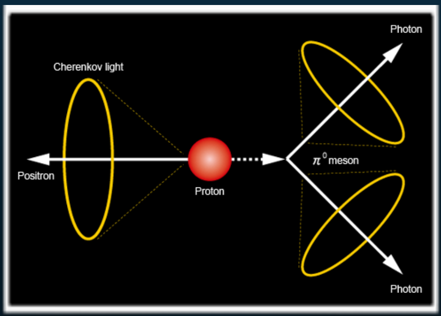
HYPER KAMIOKANDE

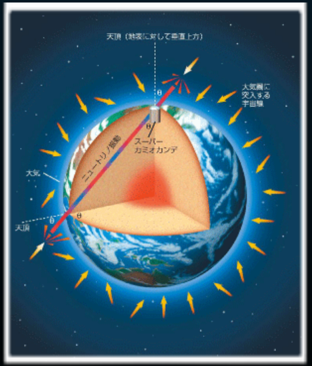
- 10x larger than Super-K
- Upgraded near + intermediate detector
- Multipurpose: huge research potential

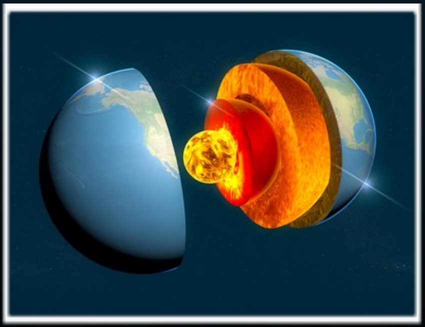






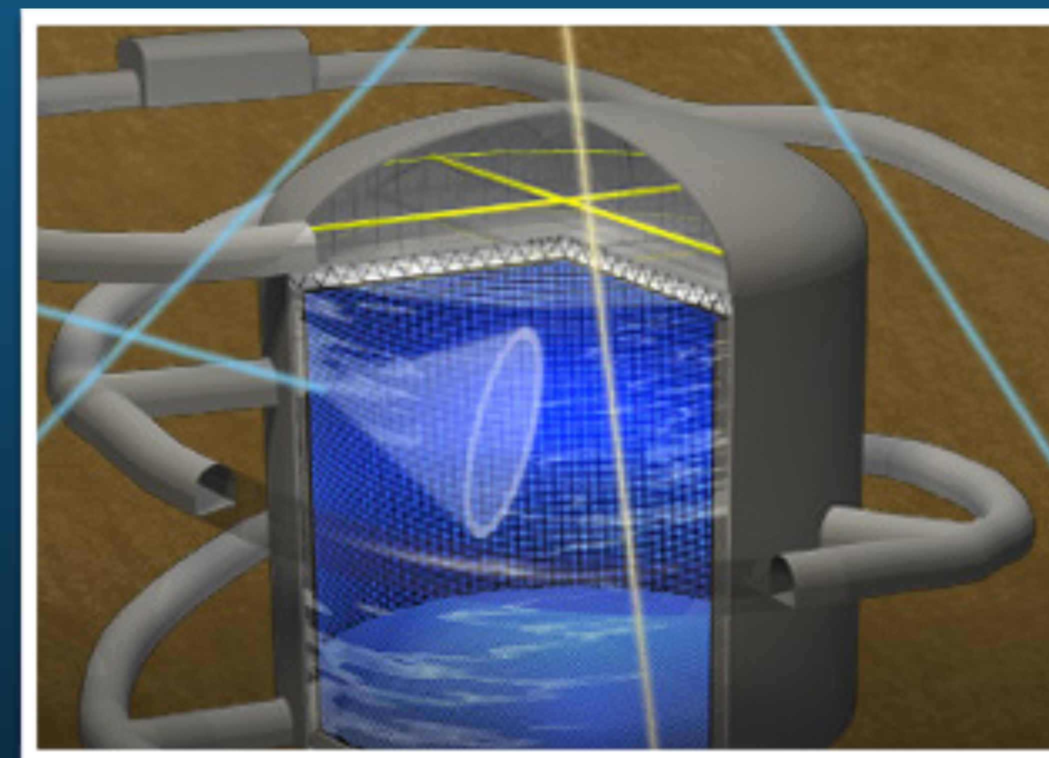


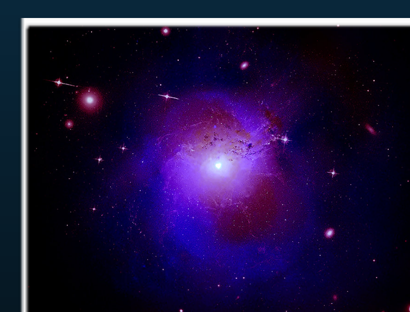


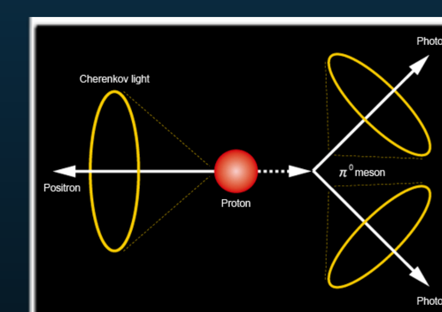


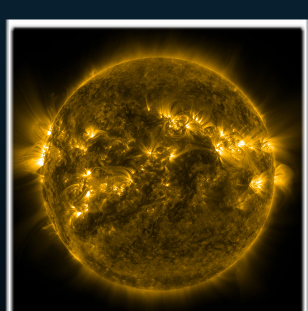
HYPER KAMIOKANDE

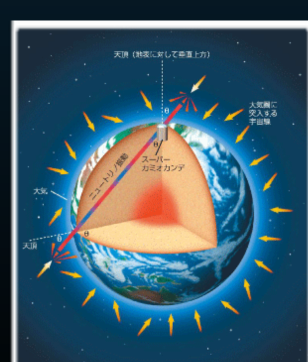
- 10x larger than Super-K
- Upgraded near + intermediate detector
- Multipurpose: huge research potential

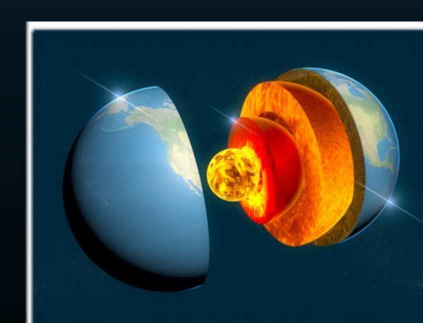






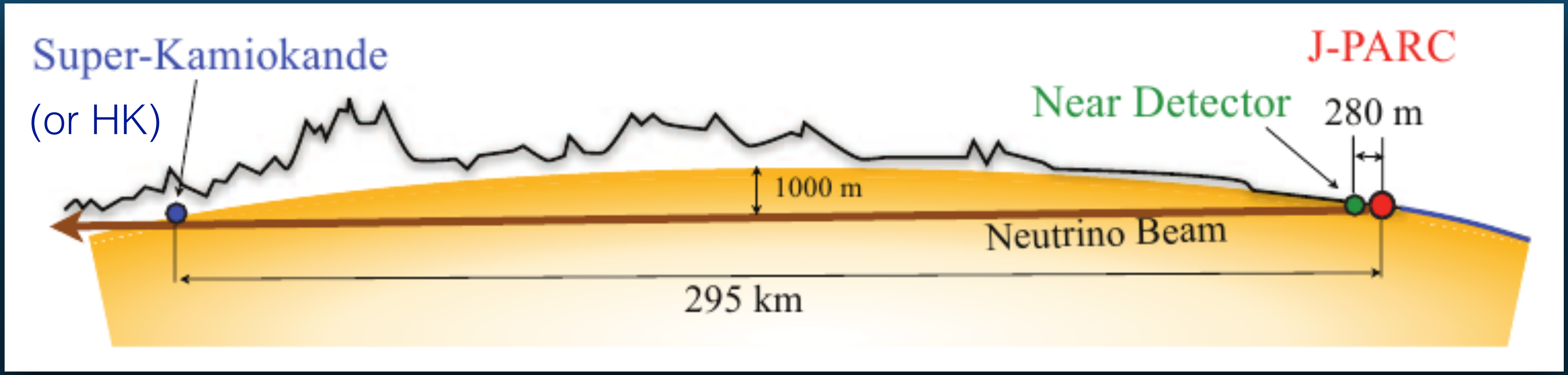




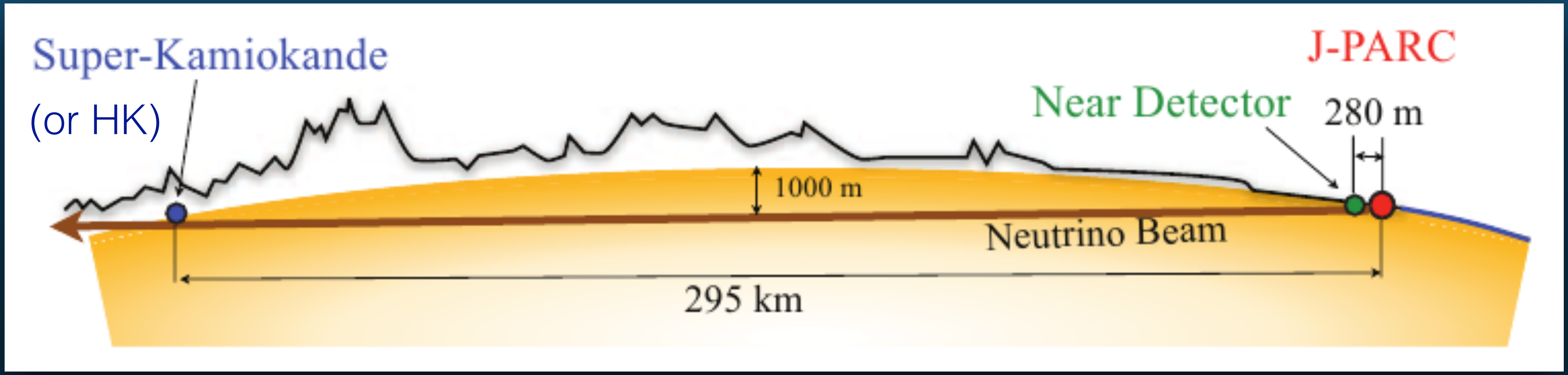


NEUTRINO OSCILLATIONS IN MATTER

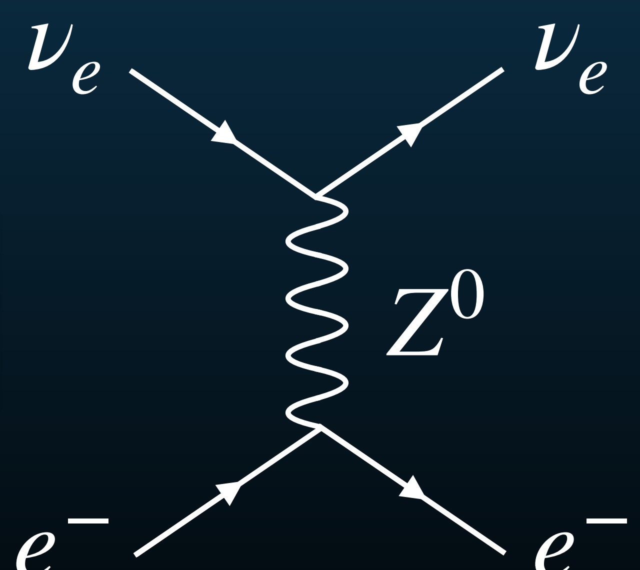
NEUTRINO OSCILLATIONS IN MATTER



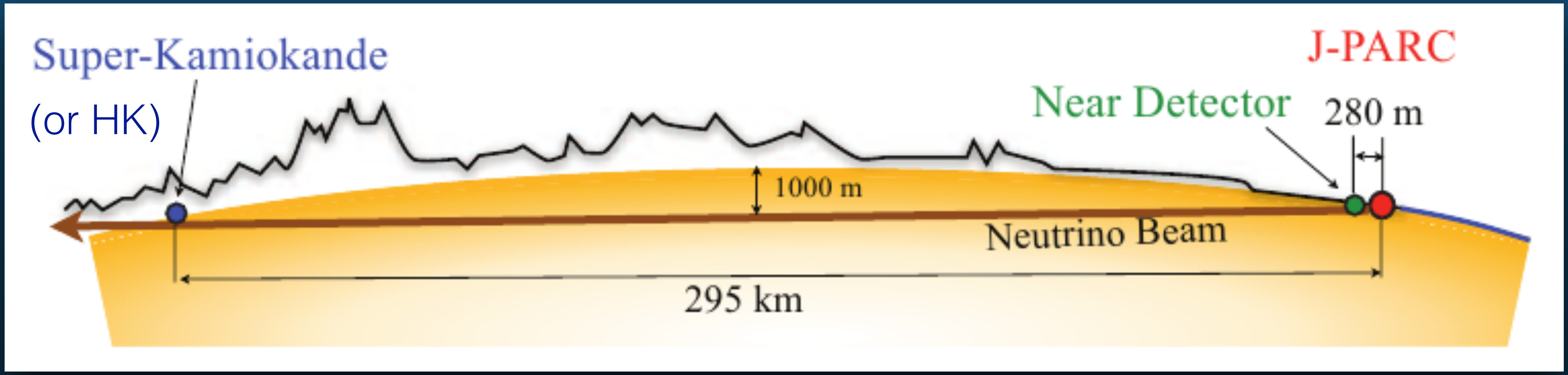
NEUTRINO OSCILLATIONS IN MATTER

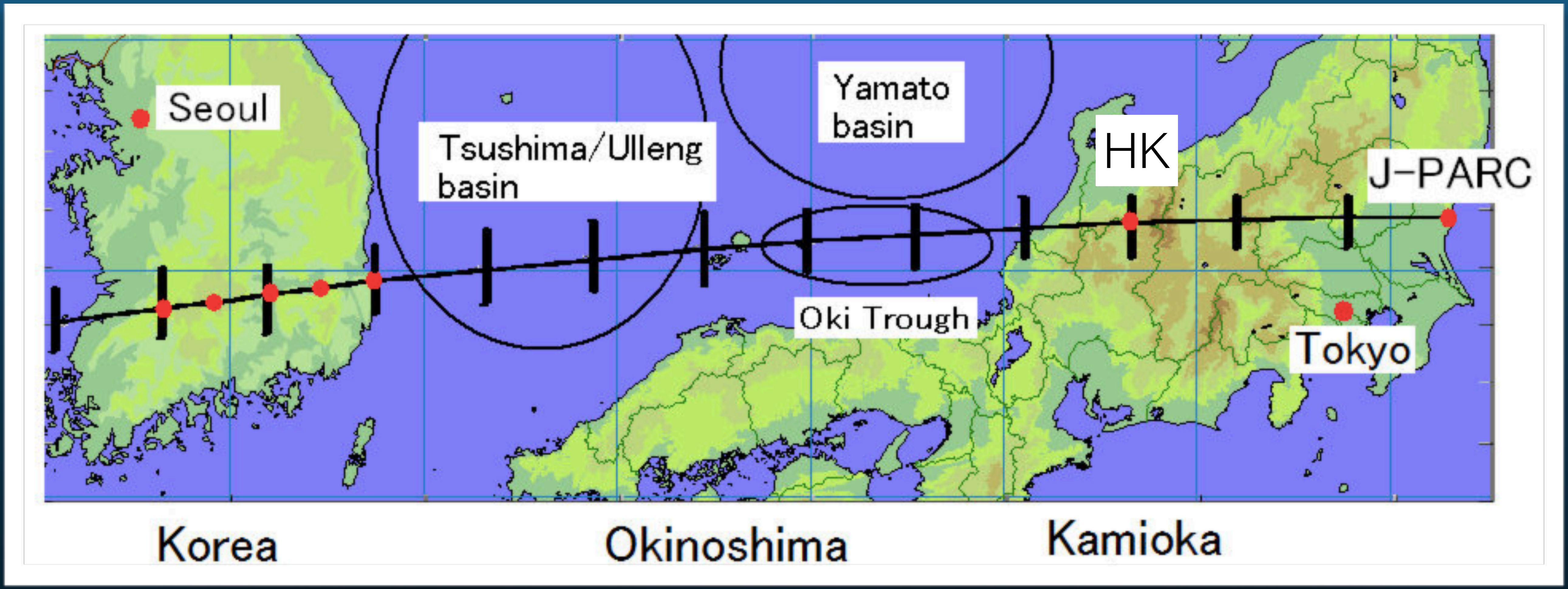


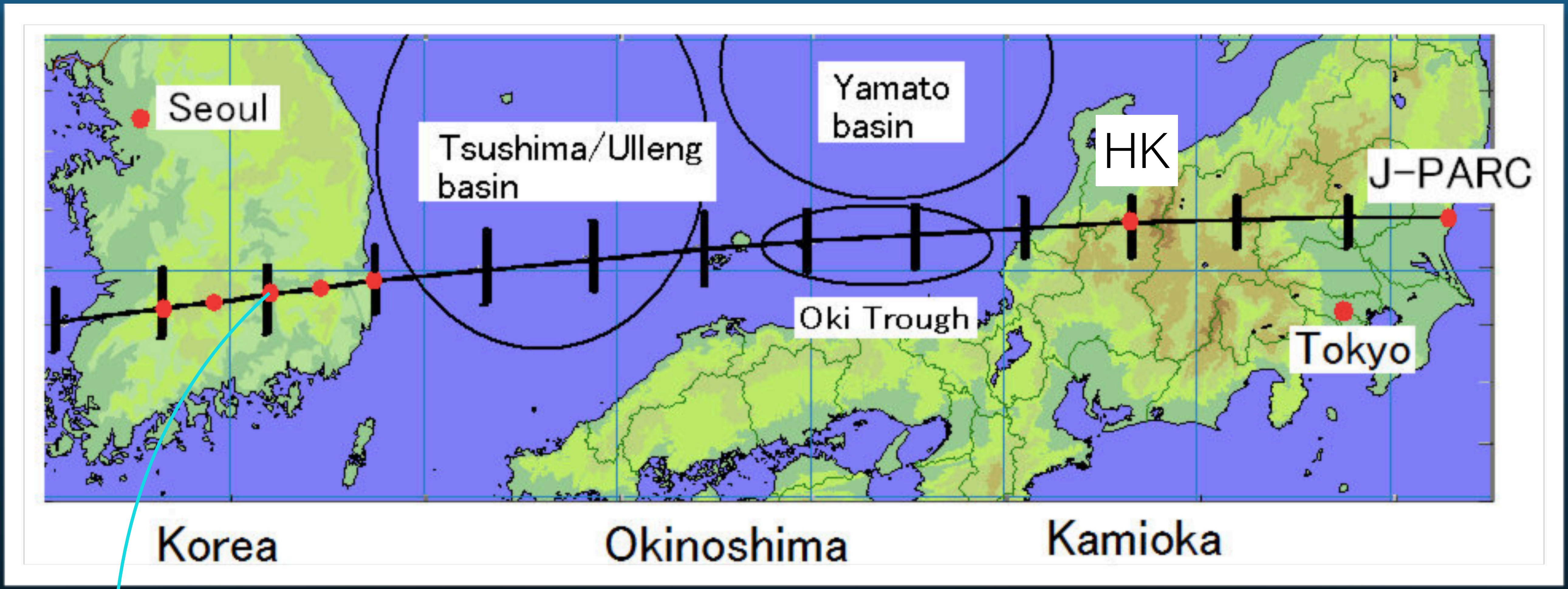
NC



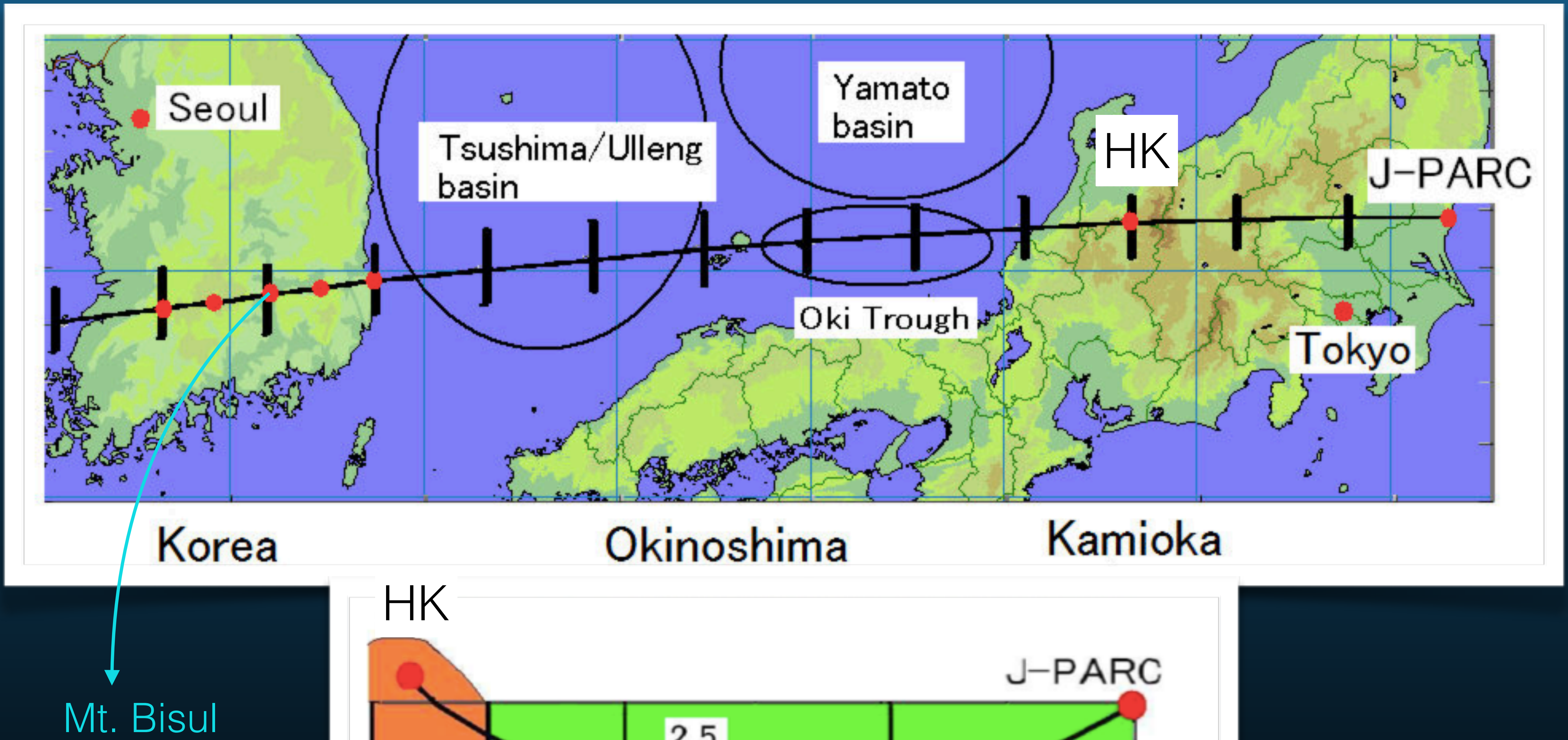
NEUTRINO OSCILLATIONS IN MATTER




Seoul
Tsushima/Ulleng basin
Yamato basin
HK
J-PARC
Oki Trough
Tokyo
Korea
Okinoshima
Kamioka


Seoul
Tsushima/Ulleng basin
Yamato basin
HK
J-PARC
Oki Trough
Tokyo
Korea
Okinoshima
Kamioka

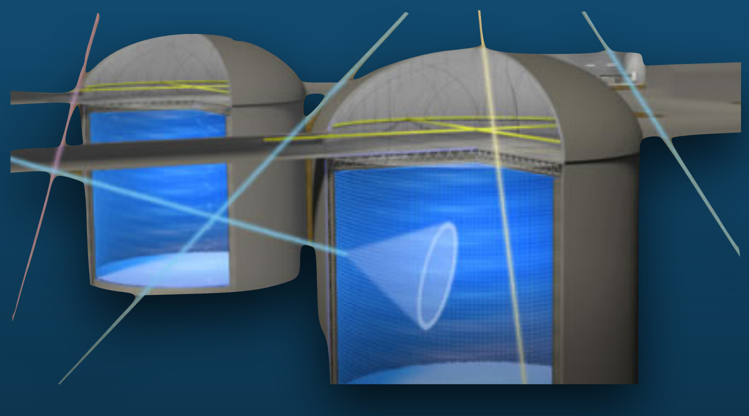
Mt. Bisul


Seoul
Tsushima/Ulleng basin
Yamato basin
HK
J-PARC
Oki Trough
Tokyo
Korea
Okinoshima
Kamioka
Mt. Bisul

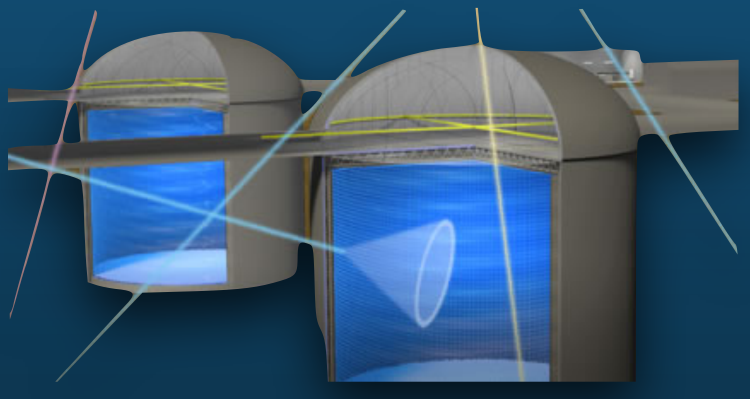

HK
J-PARC
2.5
2.8
2.8
1km
2km
295km
230km
210km
100km

HYPER-K KOREA

Hyper-K Korea



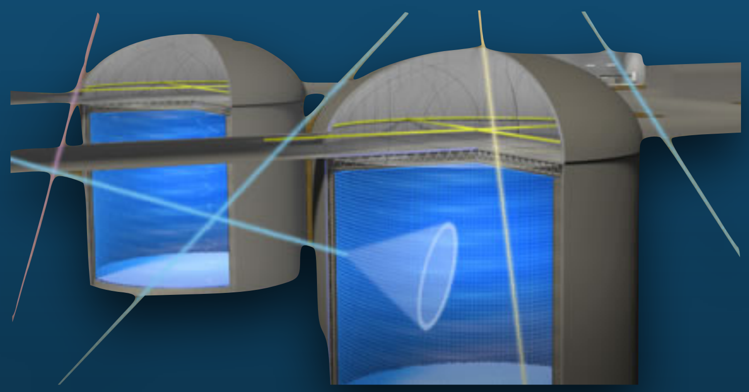
HYPER-K KOREA



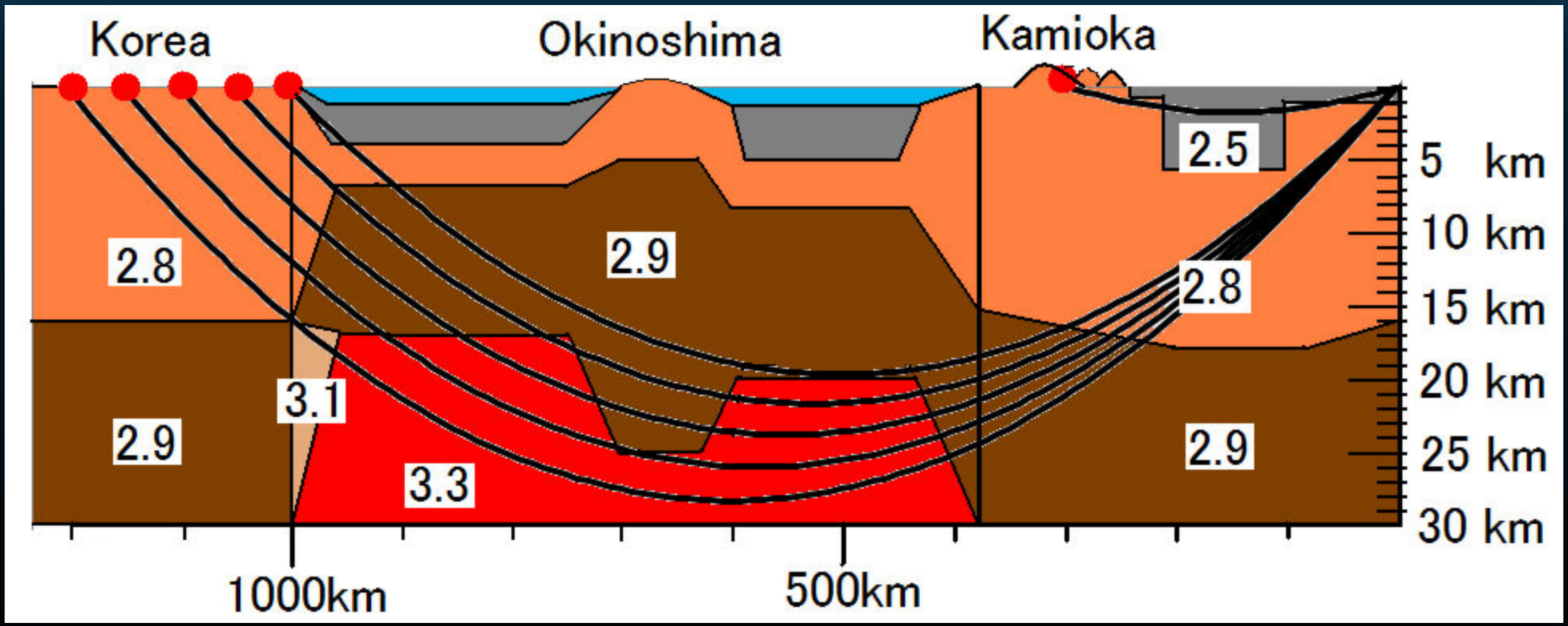
5 baselines

- 1000 km
- 1050 km
- 1100 km
- 1150 km
- 1200 km

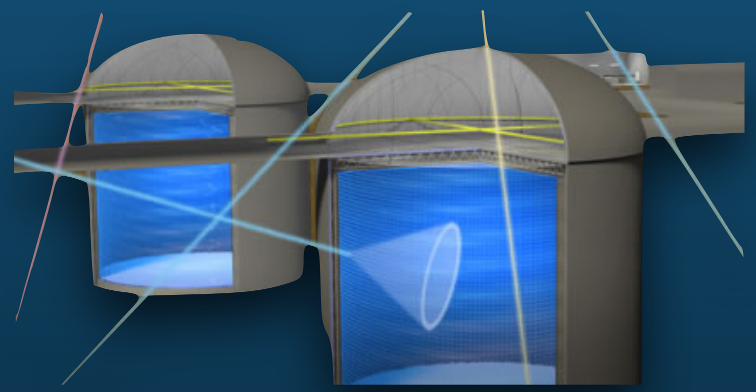
Hyper-K Korea



5 baselines
- 1000 km
- 1050 km
- 1100 km
- 1150 km
- 1200 km

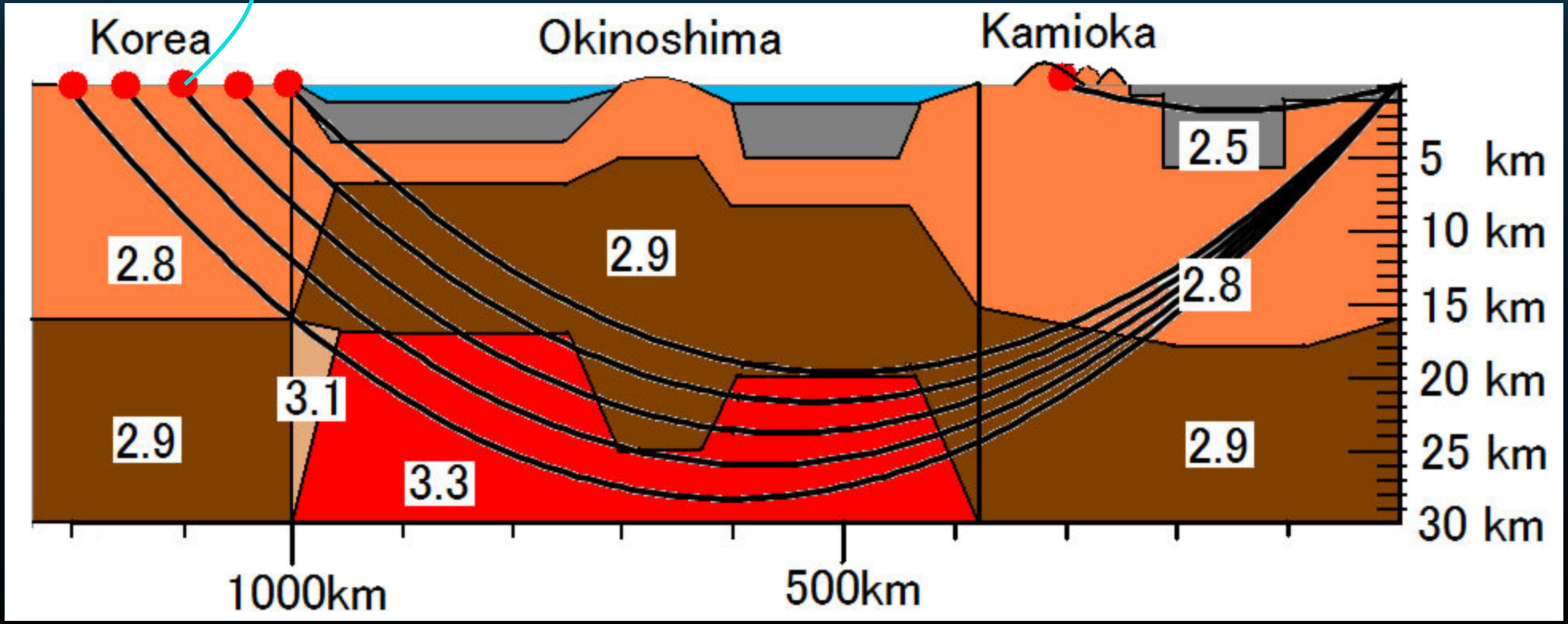


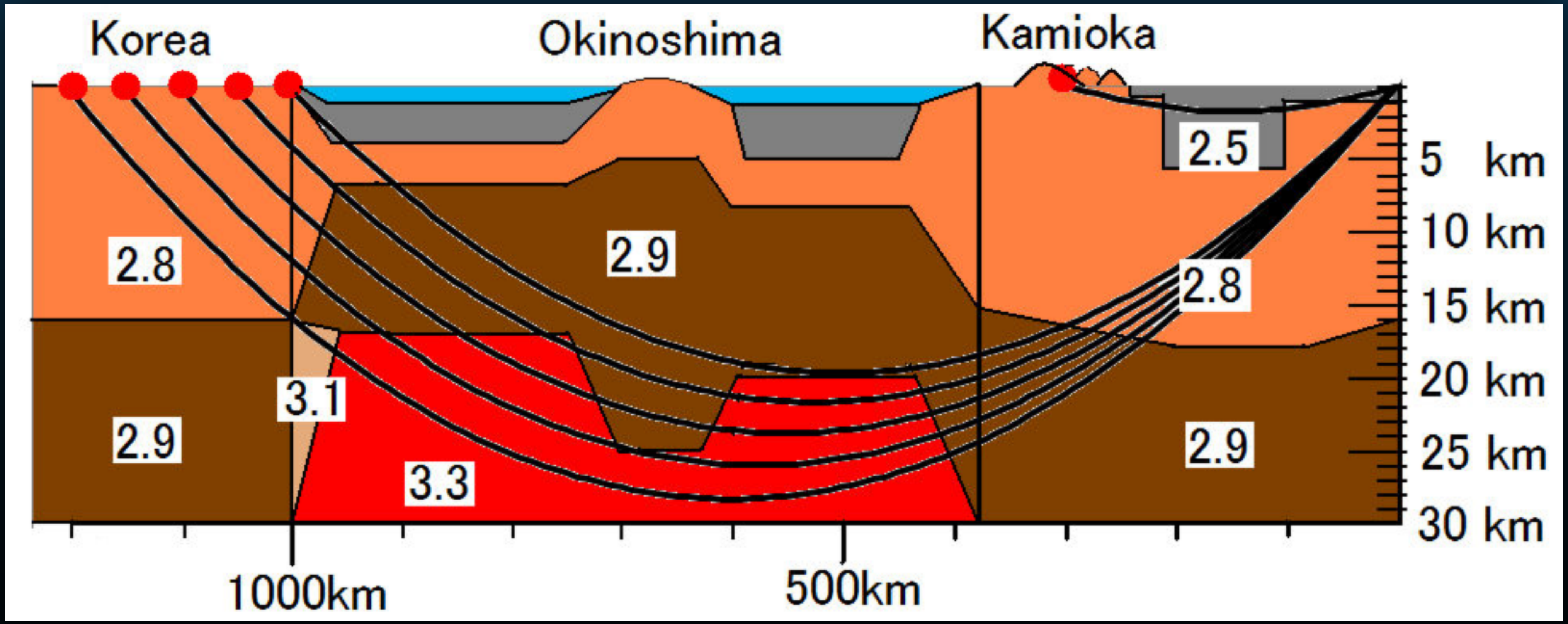
HYPER-K KOREA

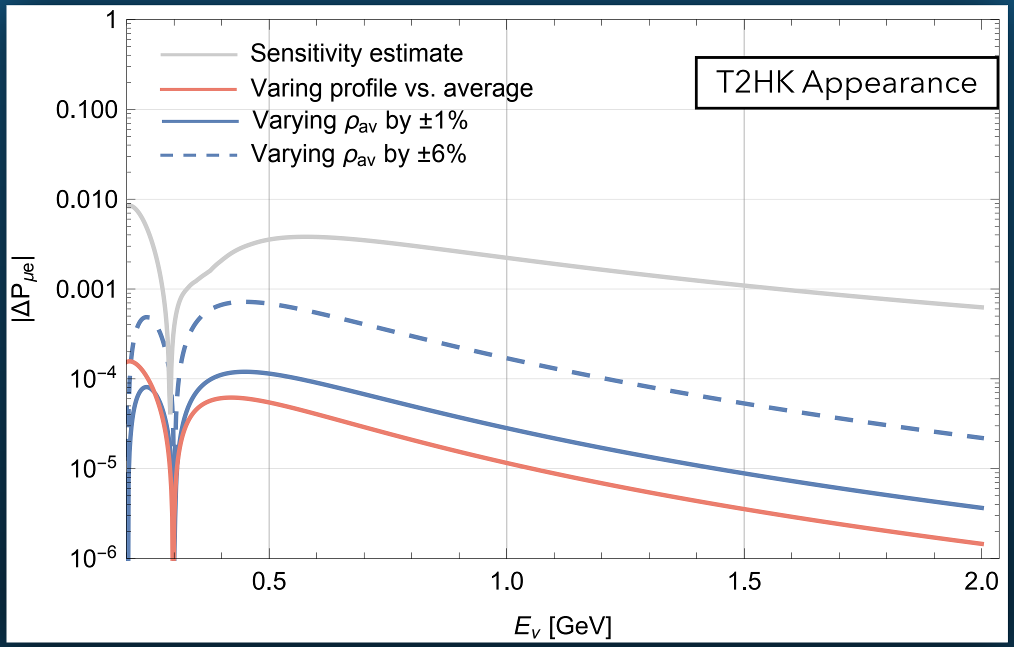


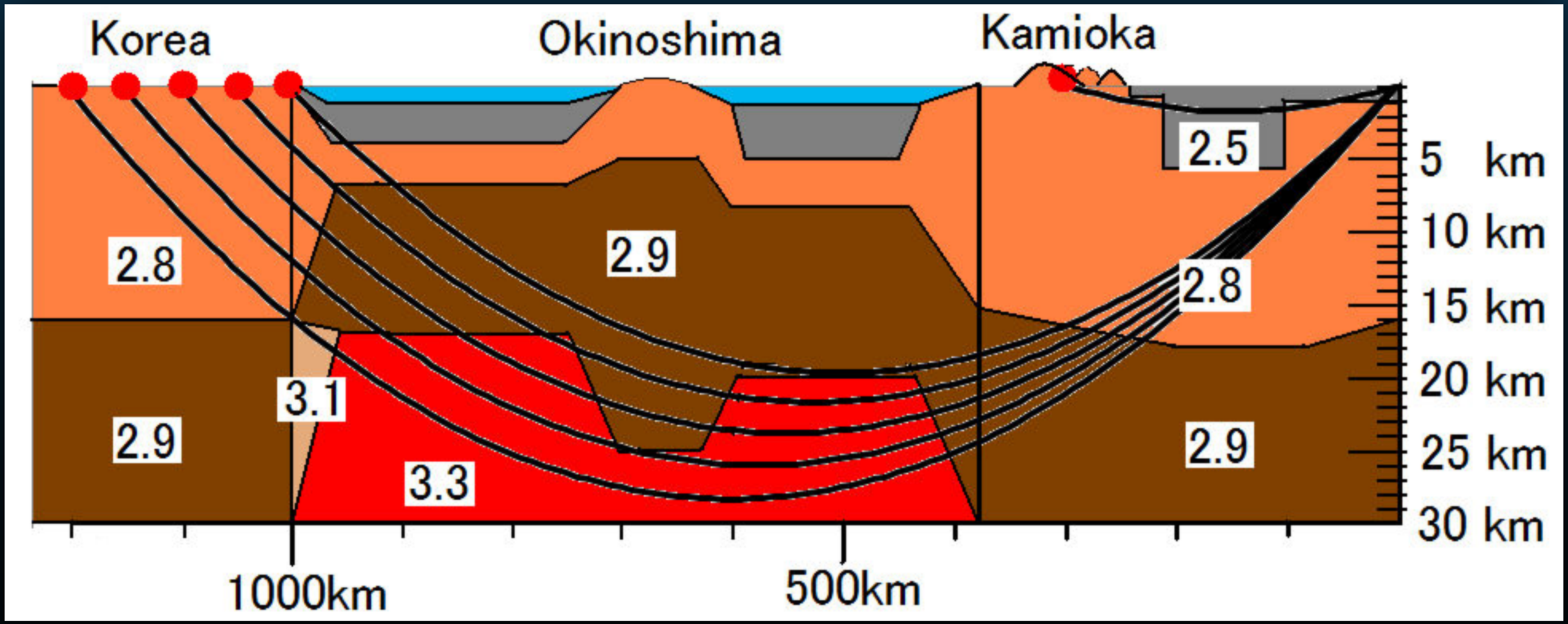
5 baselines
- 1000 km
- 1050 km
- 1100 km
- 1150 km
- 1200 km

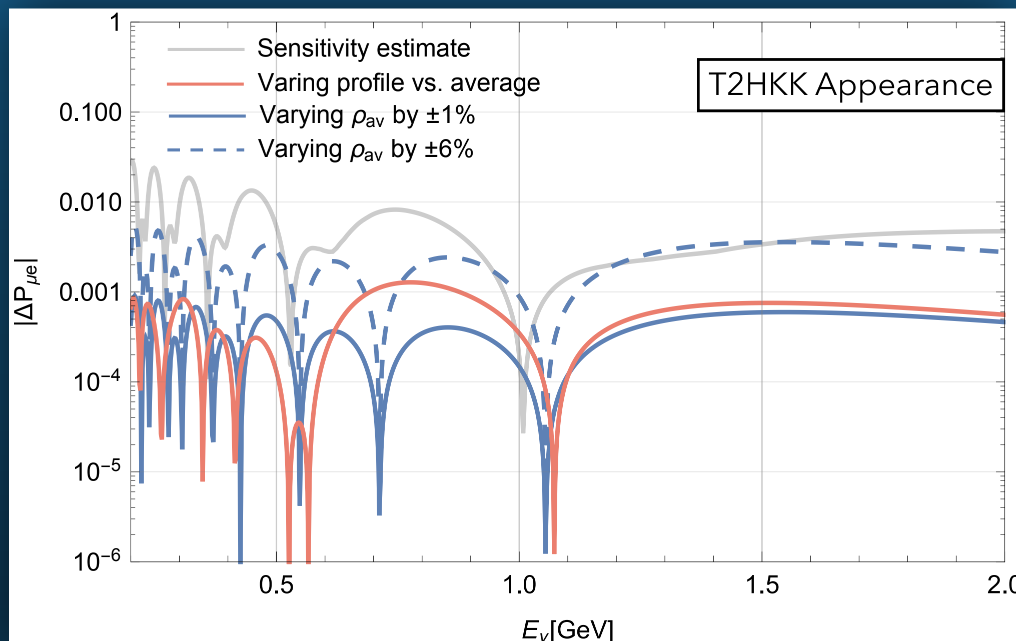
Mt. Bisul

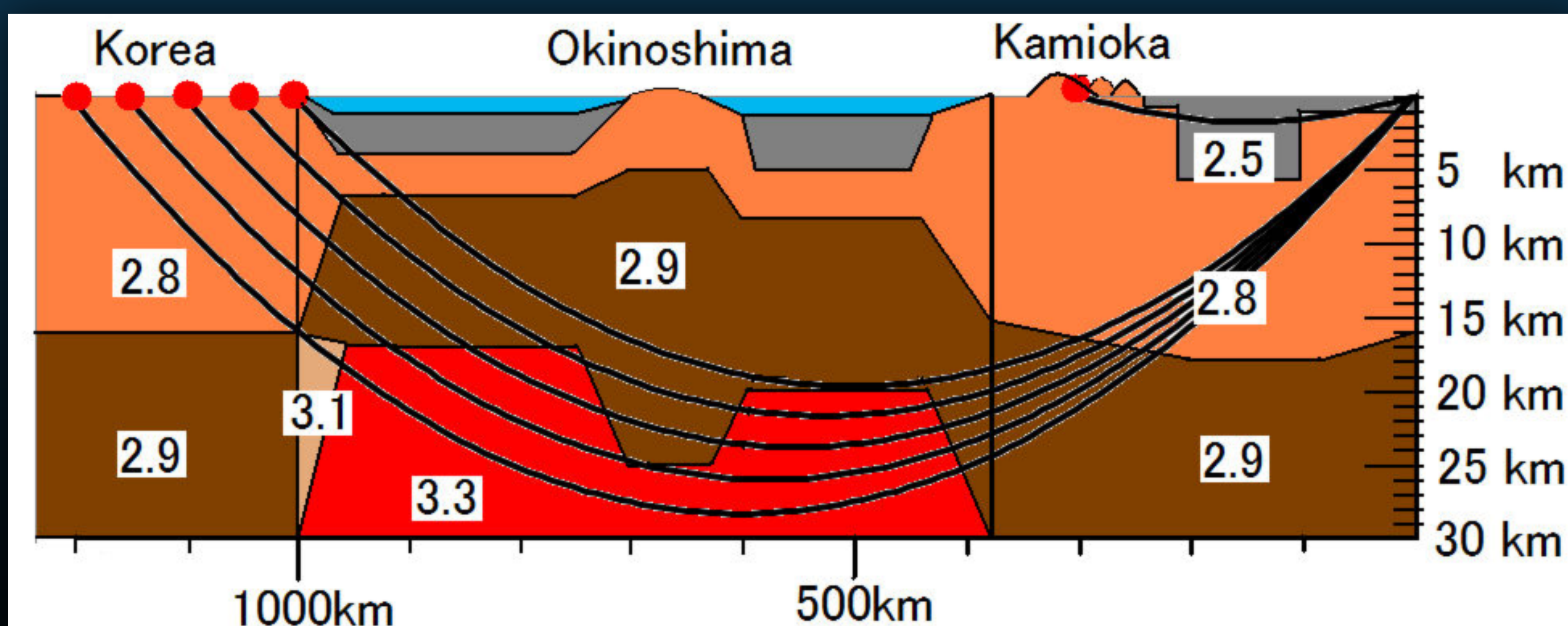


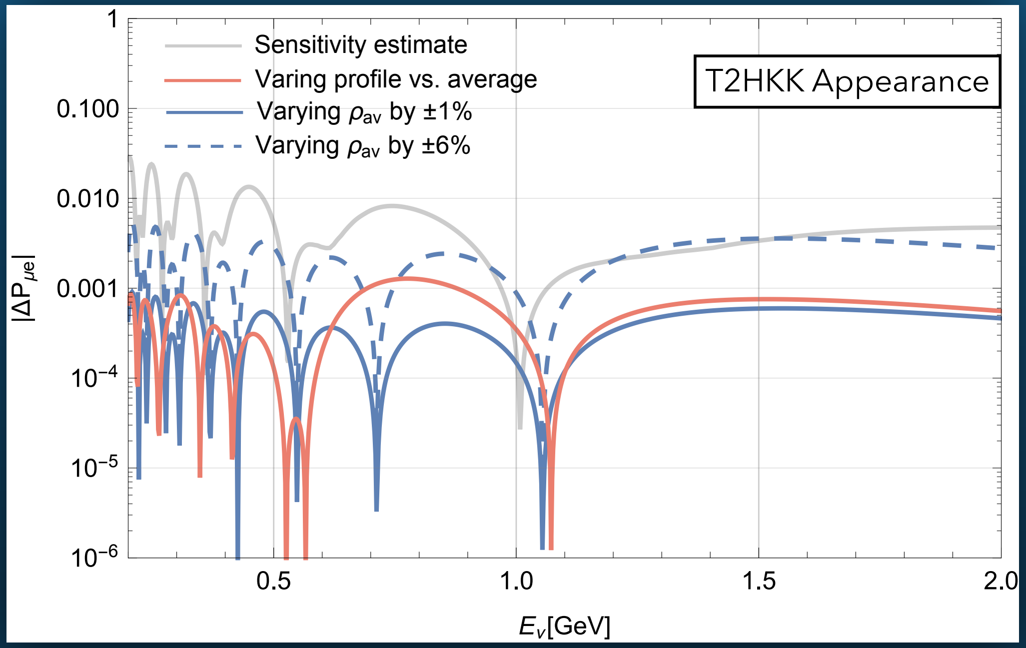

Korea
Okinoshima
Kamioka
2.5
5 km
10 km
15 km
20 km
25 km
30 km
2.8
2.9
2.8
3.1
2.9
3.3
2.8
2.9
1000km
500km

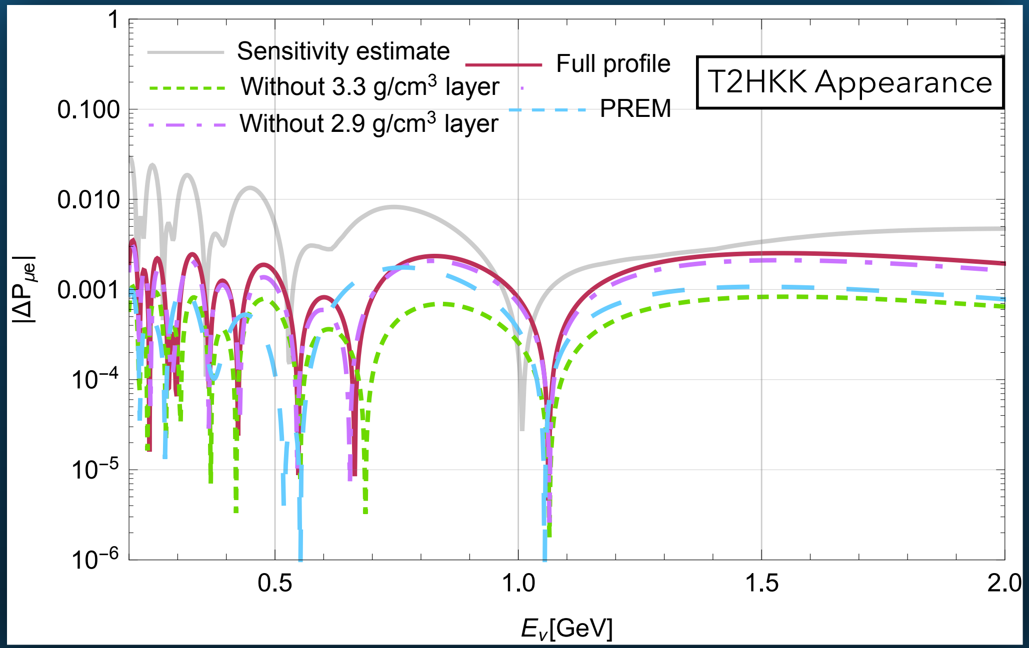

Sensitivity estimate
Varing profile vs. average
Varying ρ_{av} by ±1%
Varying ρ_{av} by ±6%
T2HK Appearance
$|\Delta P_{\mu e}|$
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
0.5
1.0
1.5
2.0
E_ν [GeV]

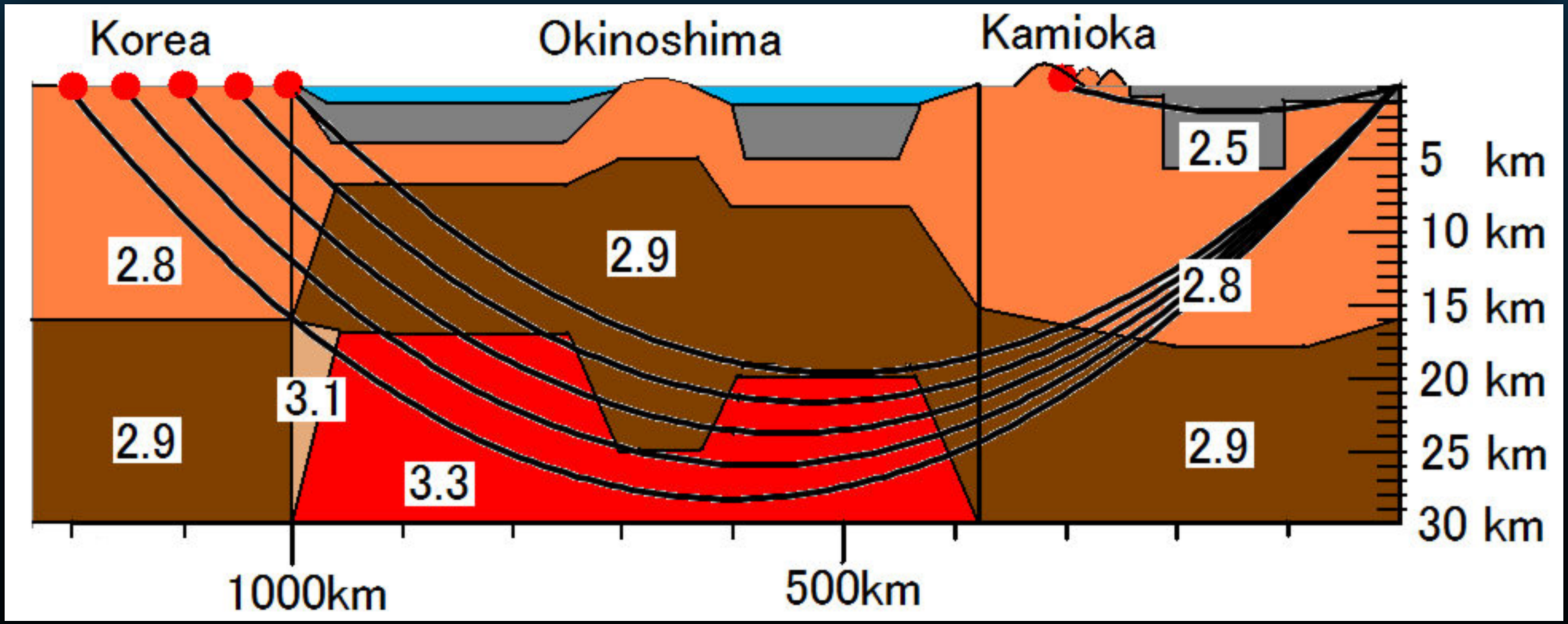

Korea
Okinoshima
Kamioka
2.8
2.9
3.1
3.3
2.9
2.5
2.8
2.9
5 km
10 km
15 km
20 km
25 km
30 km
1000km
500km

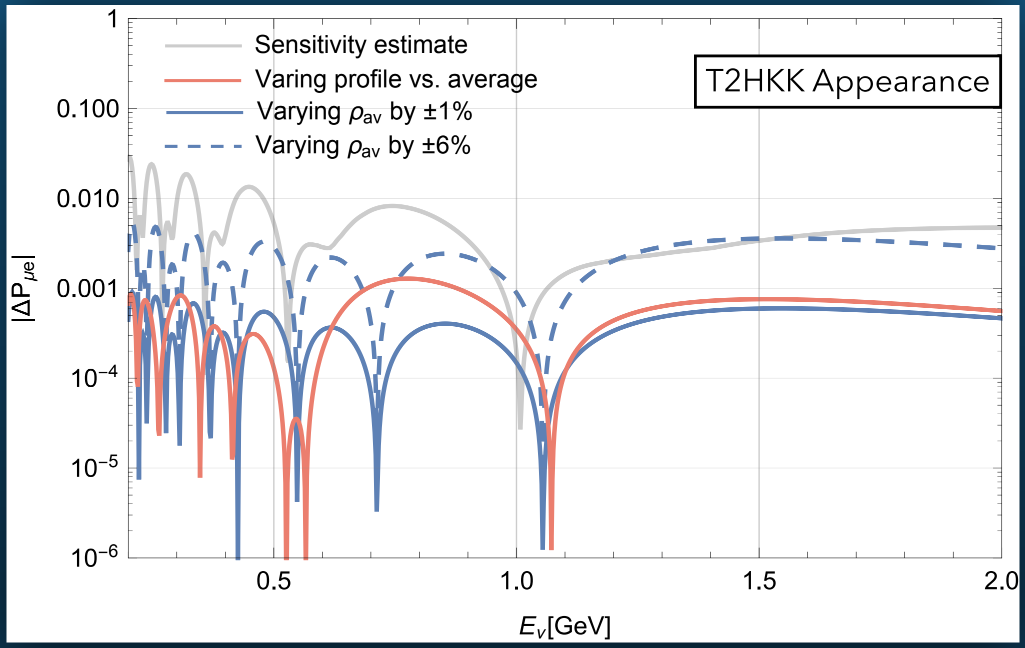

Sensitivity estimate
Varing profile vs. average
Varying ρ_{av} by ±1%
Varying ρ_{av} by ±6%
T2HKK Appearance
$|\Delta P_{\mu e}|$
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
0.5
1.0
1.5
2.0
E_ν[GeV]

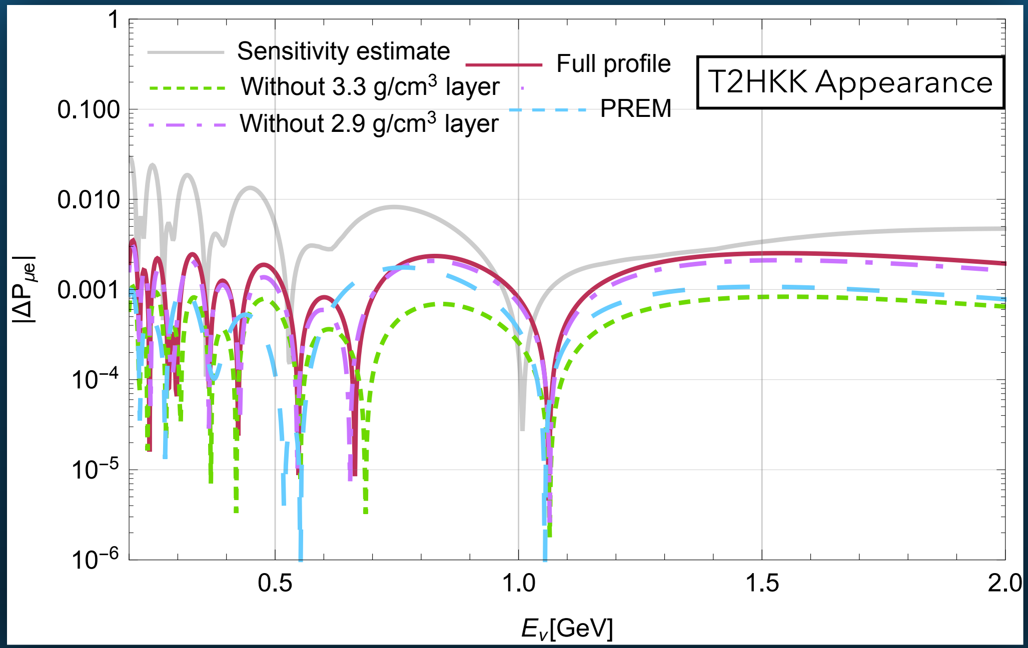

Korea
Okinoshima
Kamioka
2.5
2.8
2.9
2.8
2.9
3.1
3.3
2.9
5 km
10 km
15 km
20 km
25 km
30 km
1000km
500km

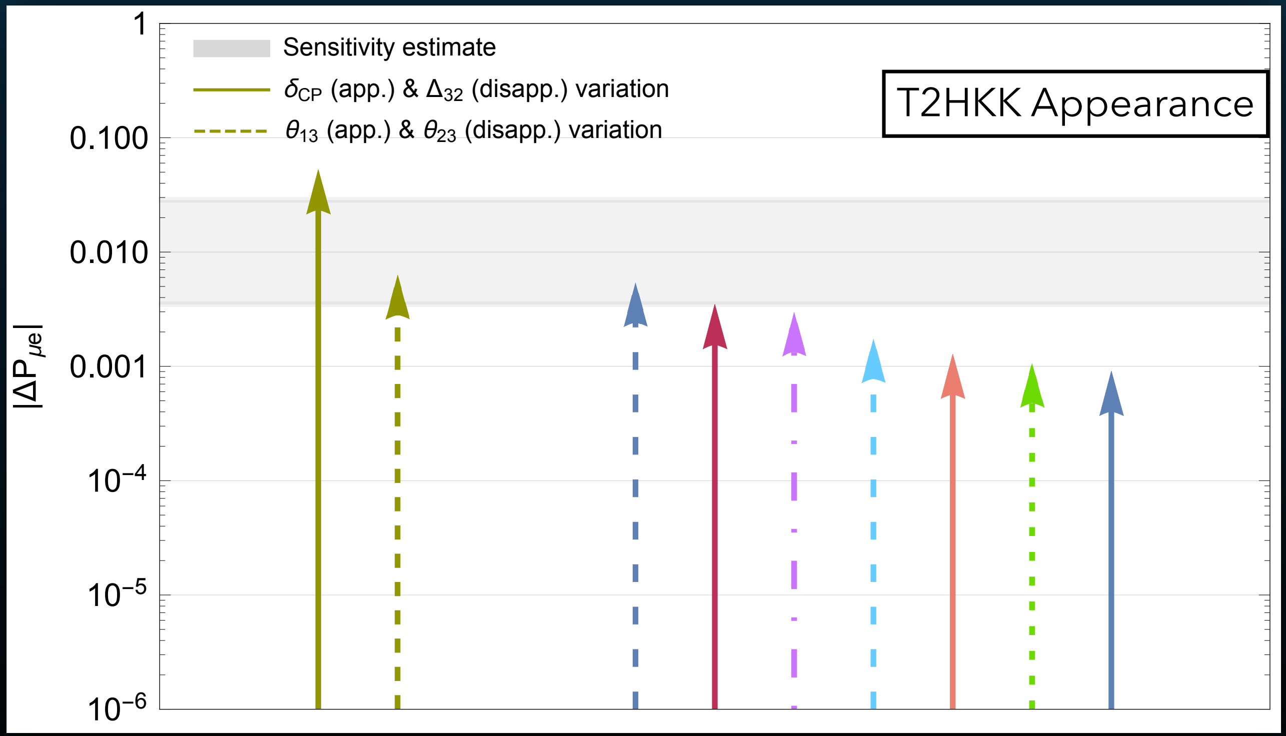

Sensitivity estimate
Varing profile vs. average
Varying ρ_{av} by ±1%
Varying ρ_{av} by ±6%
T2HKK Appearance
$|\Delta P_{\mu e}|$
E_ν[GeV]
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
0.5
1.0
1.5
2.0

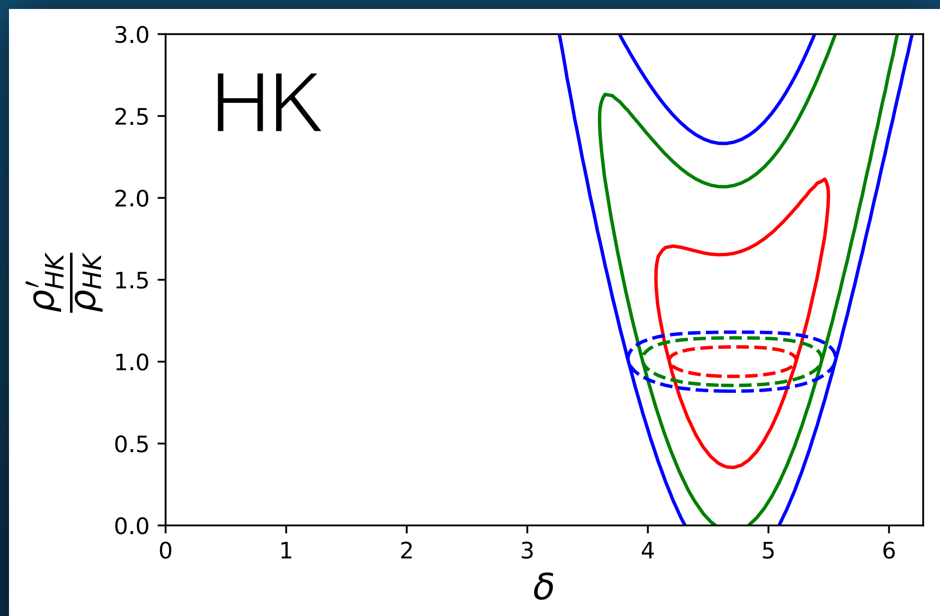

Sensitivity estimate
Without 3.3 g/cm³ layer
Without 2.9 g/cm³ layer
Full profile
PREM
T2HKK Appearance
$|\Delta P_{\mu e}|$
E_ν[GeV]
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
0.5
1.0
1.5
2.0

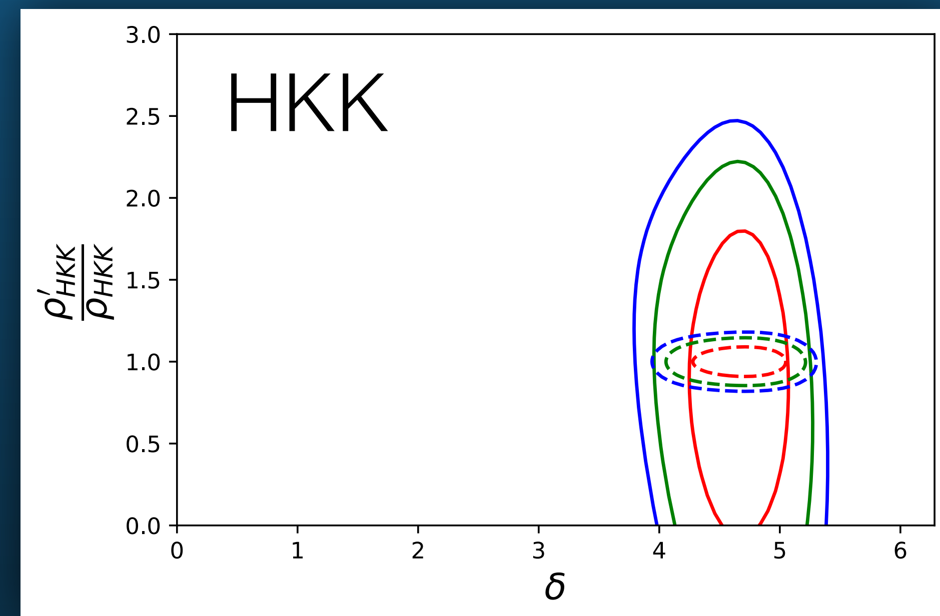

Korea
Okinoshima
Kamioka
2.5
2.8
2.9
2.9
2.8
3.1
2.9
3.3
2.9
5 km
10 km
15 km
20 km
25 km
30 km
1000km
500km

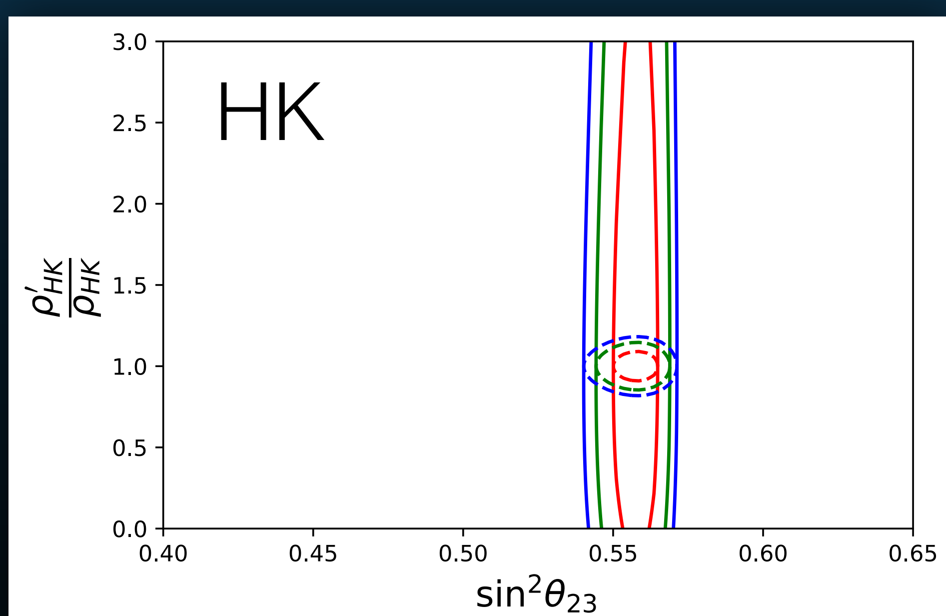

Sensitivity estimate
Varing profile vs. average
Varying ρ_{av} by ±1%
Varying ρ_{av} by ±6%
T2HKK Appearance
$|\Delta P_{\mu e}|$
E_ν[GeV]

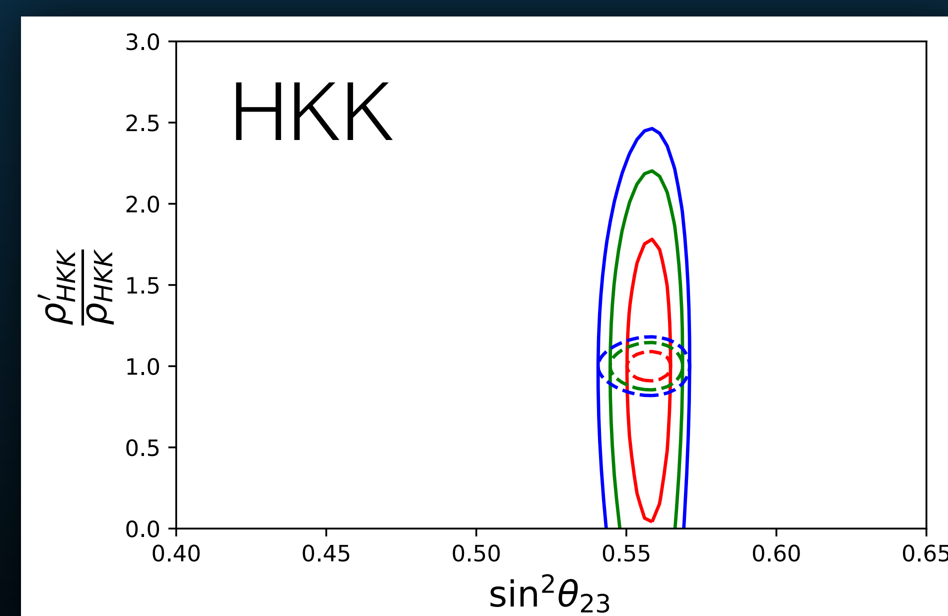

Sensitivity estimate
Without 3.3 g/cm^3 layer
Without 2.9 g/cm^3 layer
Full profile
PREM
T2HKK Appearance
$|\Delta P_{\mu e}|$
E_ν[GeV]


Sensitivity estimate
δ_{CP} (app.) & Δ_{32} (disapp.) variation
θ_{13} (app.) & θ_{23} (disapp.) variation
T2HKK Appearance
$|\Delta P_{\mu e}|$


HK
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$\frac{\rho'_{HK}}{\rho_{HK}}$
0
1
2
3
4
5
6
δ


HKK
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$\frac{\rho'_{HKK}}{\rho_{HKK}}$
0
1
2
3
4
5
6
δ


HK
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$\frac{\rho'_{HK}}{\rho_{HK}}$
0.40
0.45
0.50
0.55
0.60
0.65
$\sin^2\theta_{23}$


HKK
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$\frac{\rho'_{HKK}}{\rho_{HKK}}$
0.40
0.45
0.50
0.55
0.60
0.65
$\sin^2\theta_{23}$

LITTLEST SEESAW: SM extension with 2 new RHν singlets

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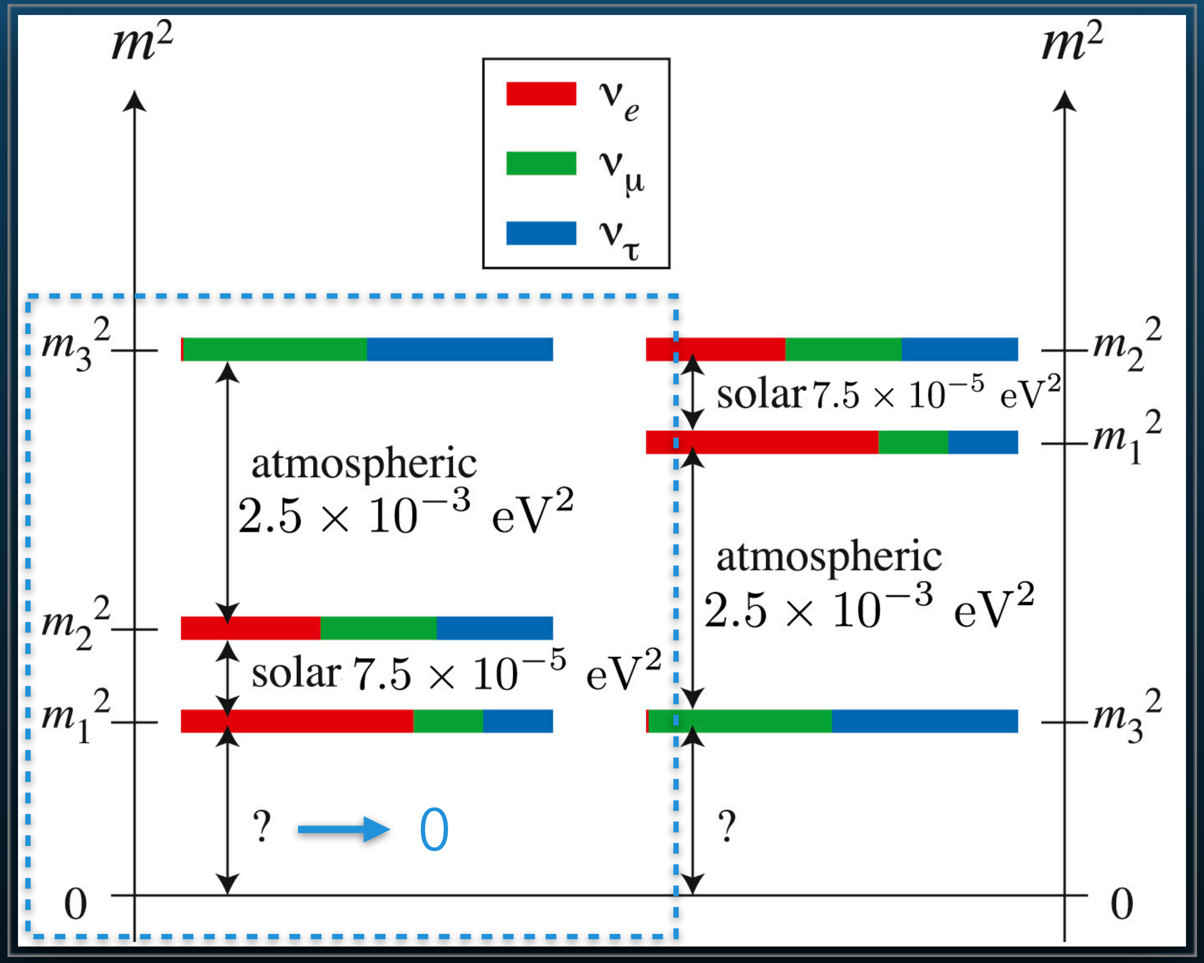
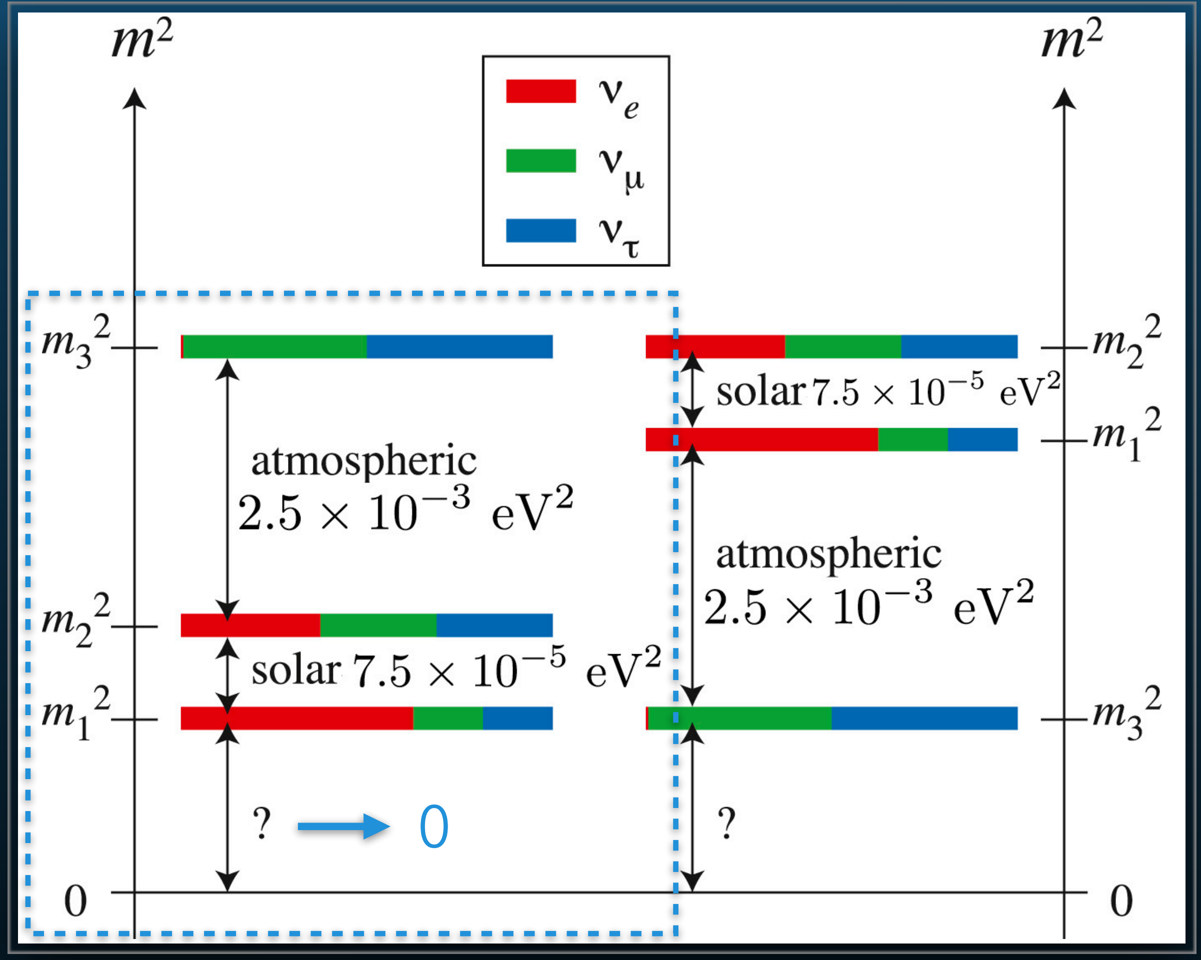


LITTLEST SEESAW: SM extension with 2 new RHν singlets

- *Renormalisation Group Evolution:* Evolve observables to low scales using RG running (REAP)
- *Leptogenesis:* Lepton asymmetry generated through decay of lightest RHν



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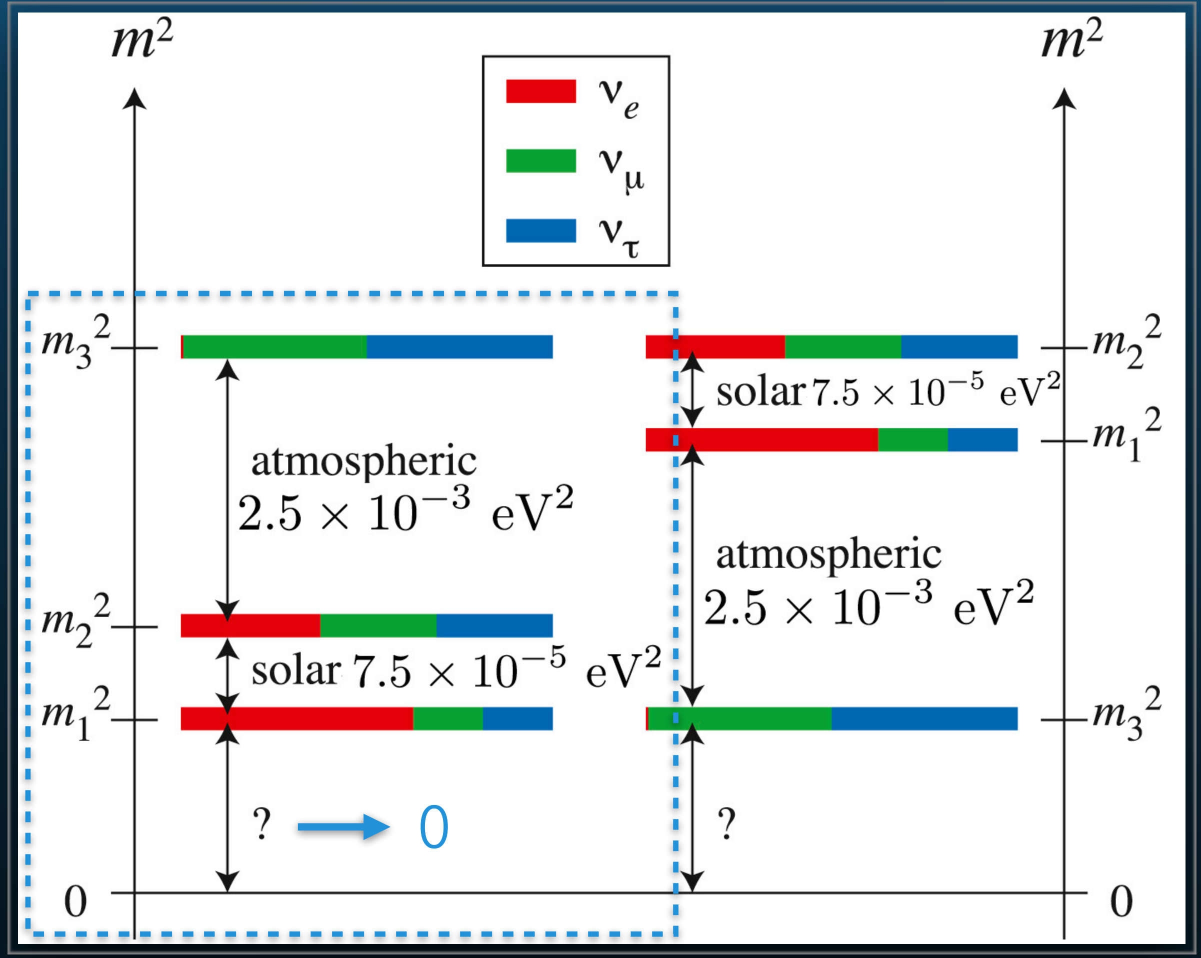

$$Y_{\Delta\alpha} = \eta_\alpha \epsilon_\alpha Y^{eq}_{N1} \quad \Rightarrow \quad Y_B = \frac{12}{37} \sum_{\alpha=e,\mu,\tau} Y_{\Delta\alpha}$$

2 cases: A, D $\Longrightarrow$ $Y_\nu^A = \begin{pmatrix} 0 & be^{i\eta/2} \\ a & nbe^{i\eta/2} \\ a & (n-2)be^{i\eta/2} \end{pmatrix}, \quad M_R^A = \begin{pmatrix} M_{atm} & 0 \\ 0 & M_{sol} \end{pmatrix}$

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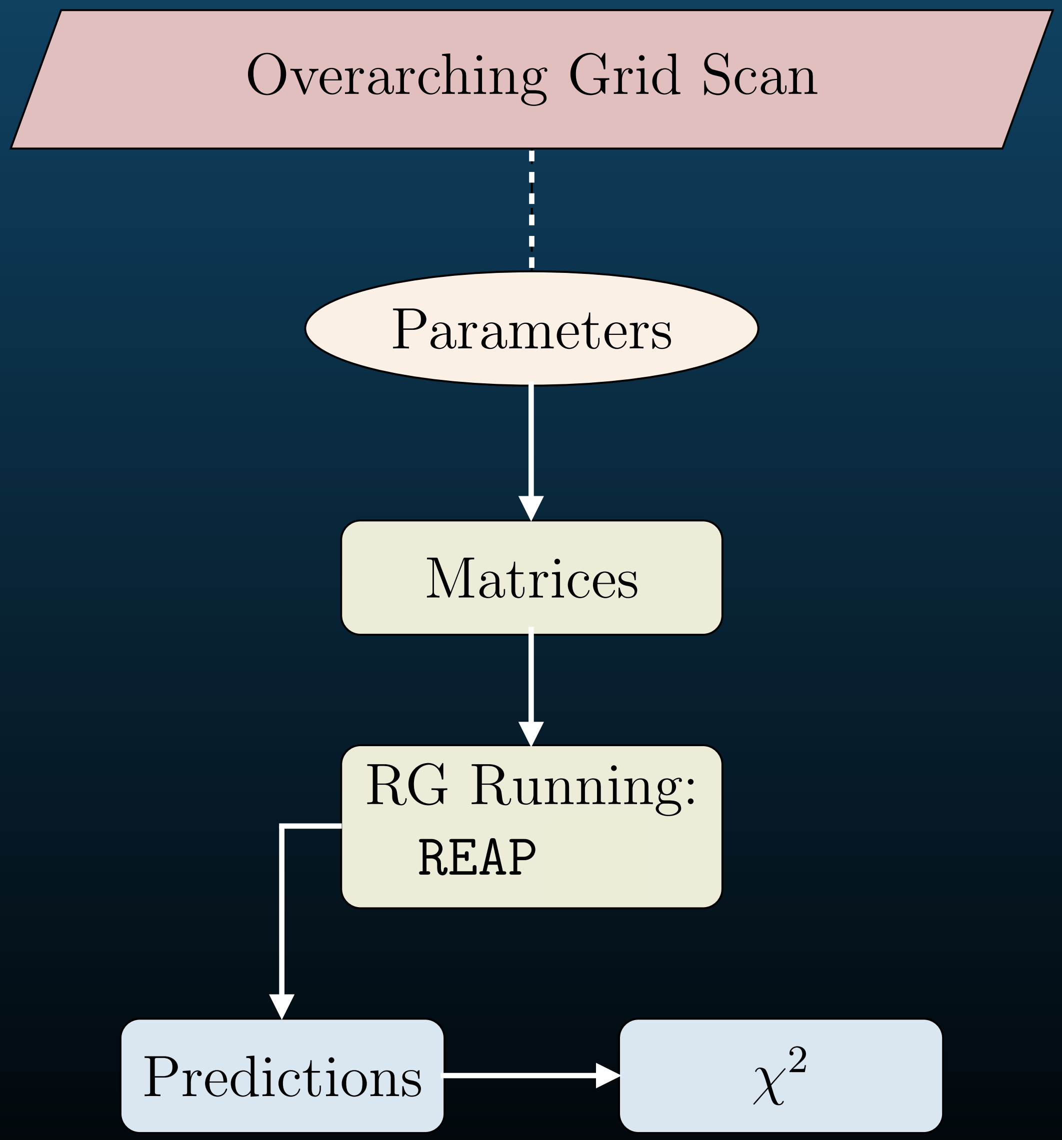
Method: Fit high scale parameters to low scale neutrino data and BAU from Leptogenesis (χ^2 analysis)



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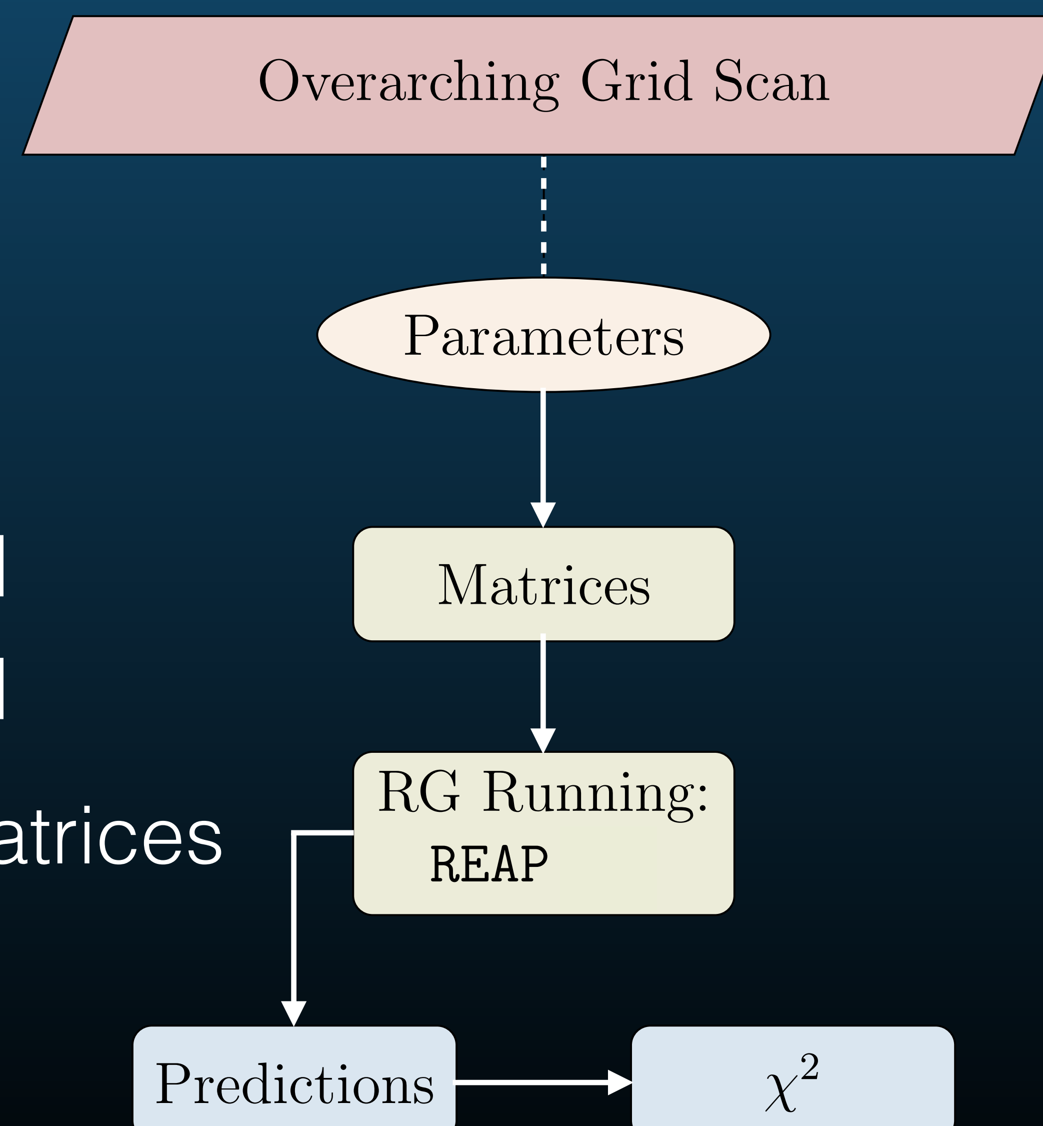
<u>Method:</u> Fit high scale parameters to low scale neutrino data and BAU from Leptogenesis (χ^2 analysis)

Scan over neutrino masses:

$$1.0 \times 10^9 \leq M_1 \leq 5.0 \times 10^{12} \quad \text{[GeV]}$$
$$5M_1 \leq M_2 \leq 1.0 \times 10^{16} \quad \text{[GeV]}$$

and *a*, *b* : free parameters in Yukawa matrices



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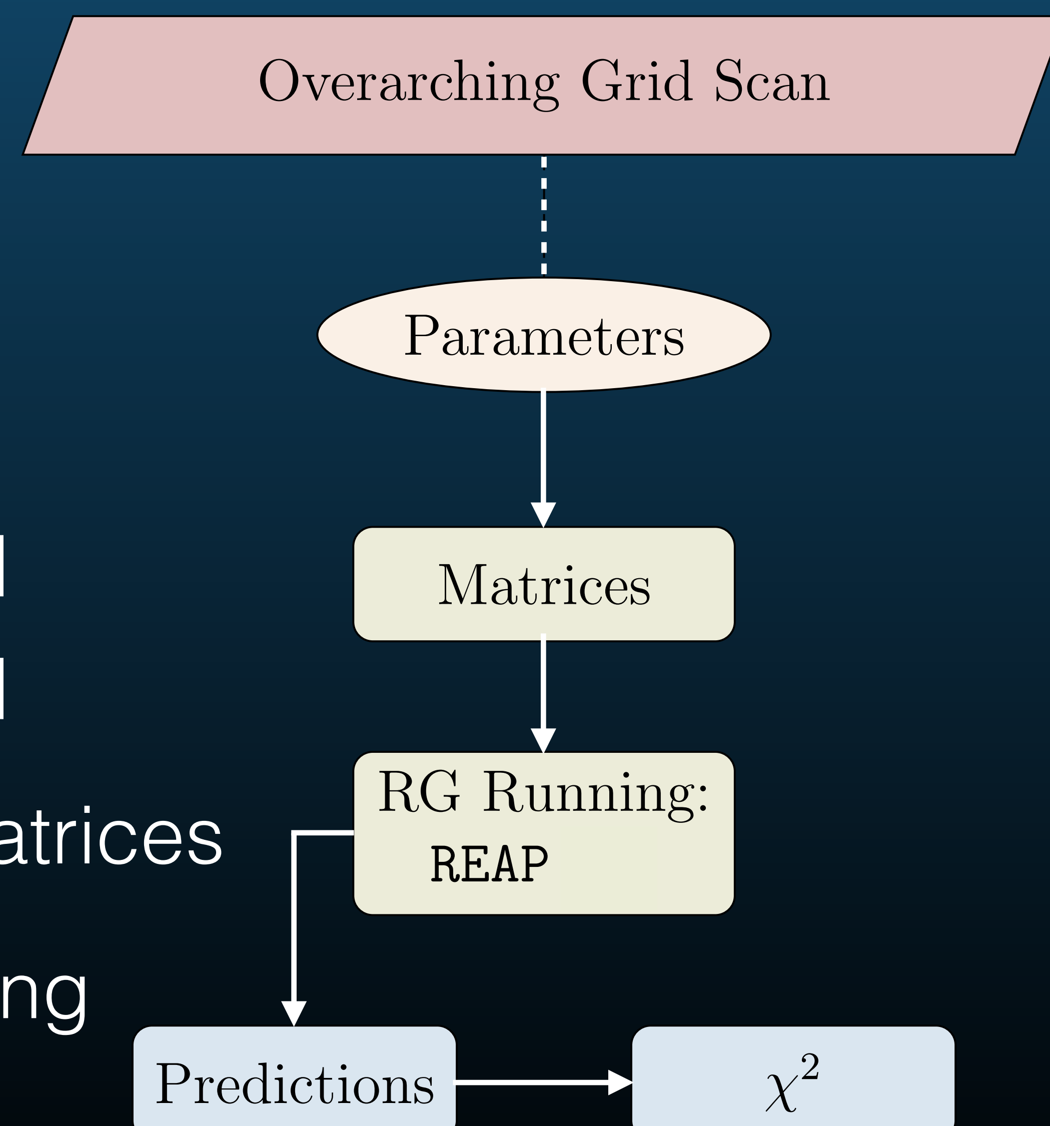

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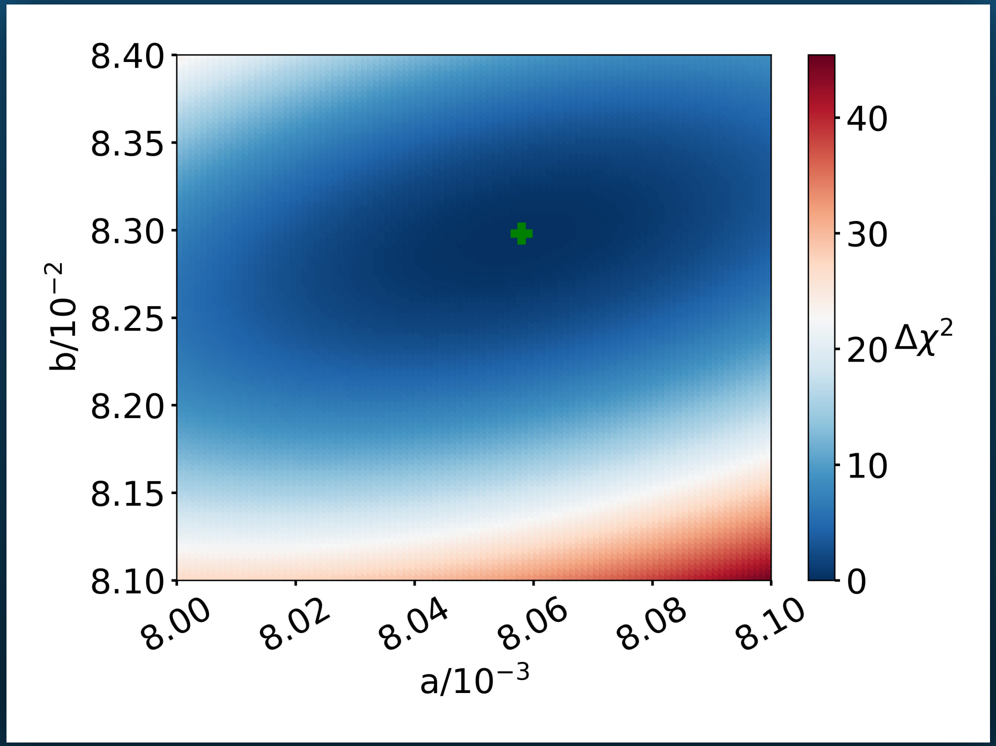
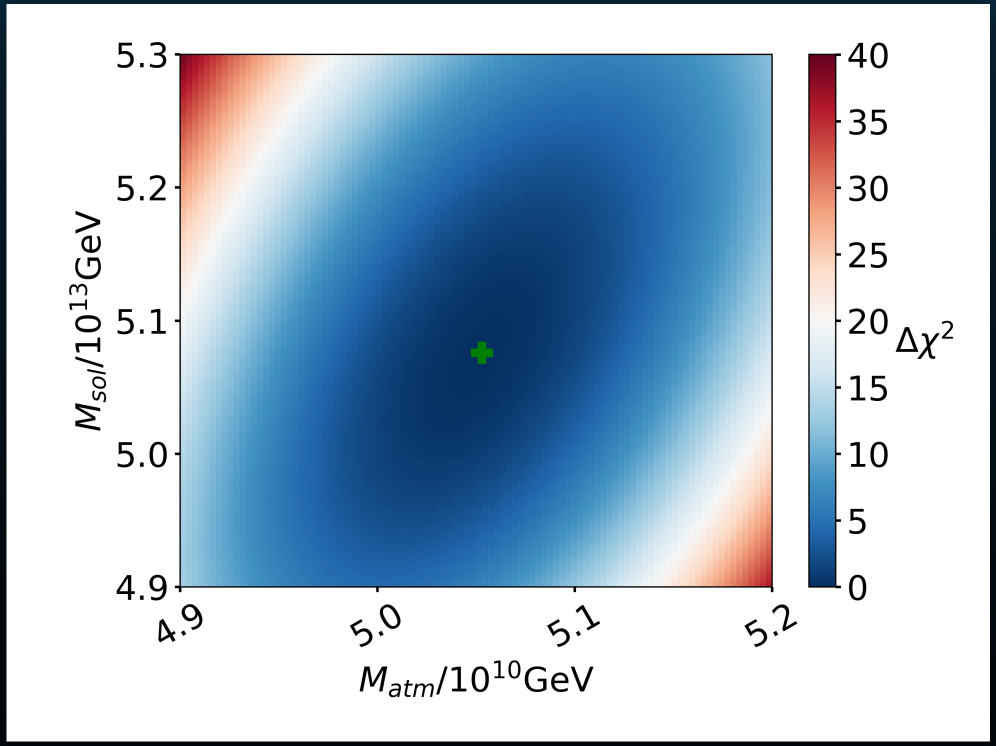
and *a*, *b* : free parameters in Yukawa matrices

$n = 3$
$\eta = \pm 2\pi/3$

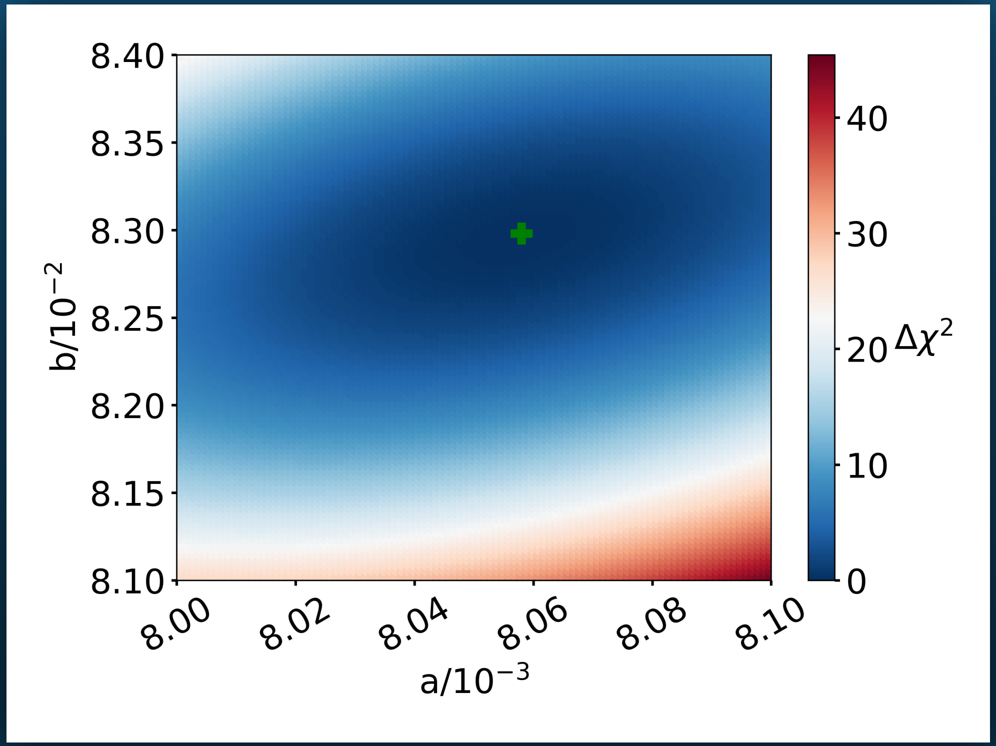
$\Longrightarrow$ 4-dimensional gridding

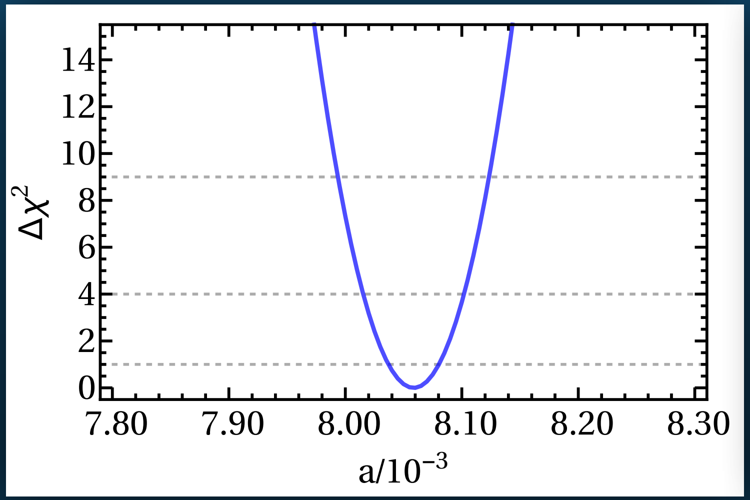
(Case A)

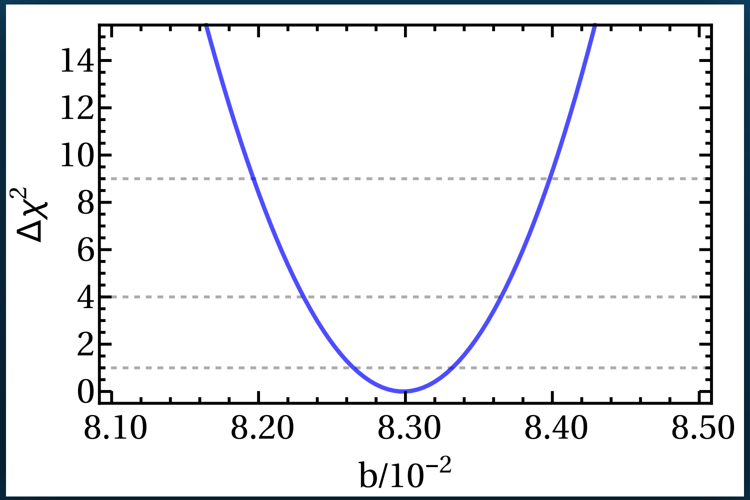

8.40
8.35
8.30
8.25
8.20
8.15
8.10
b/10^−2
8.00
8.02
8.04
8.06
8.08
8.10
a/10^−3
40
30
20
10
0
Δχ^2

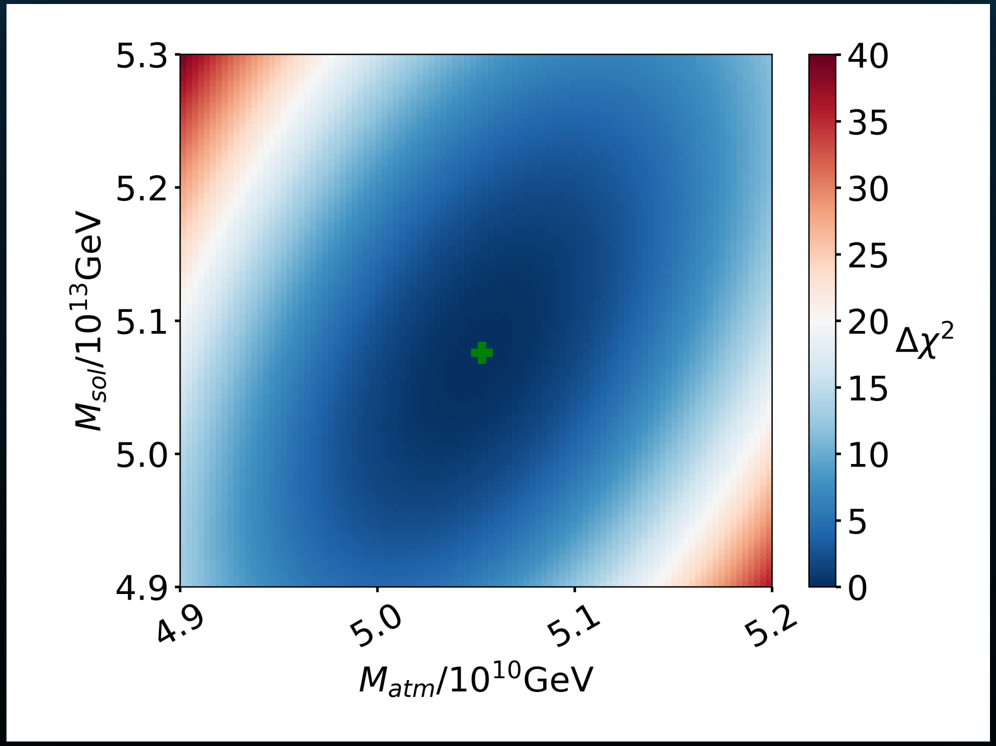

5.3
5.2
5.1
5.0
4.9
M_sol/10^13GeV
4.9
5.0
5.1
5.2
M_atm/10^10GeV
40
35
30
25
20
15
10
5
0
Δχ^2

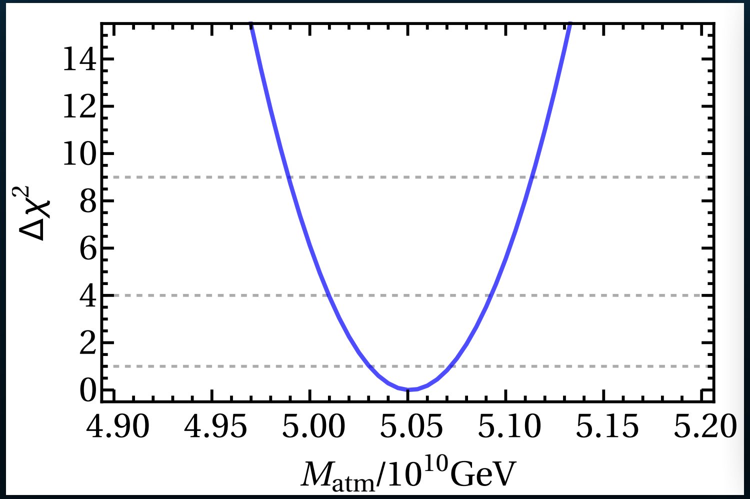
(Case A)

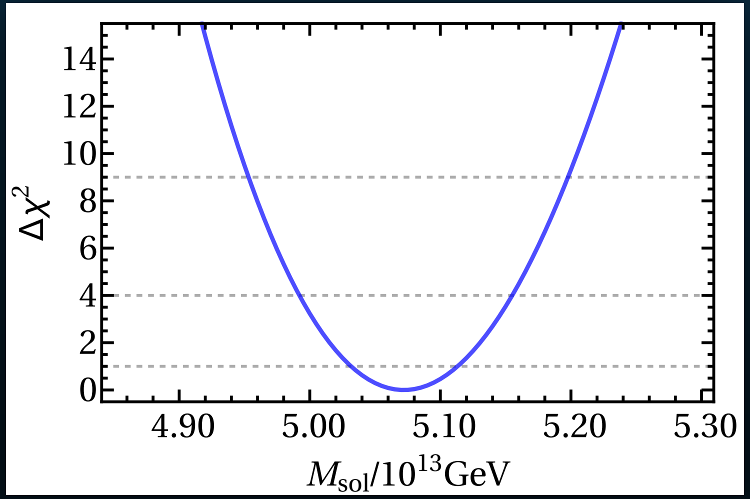

b/10^{-2}
a/10^{-3}
$\Delta\chi^2$


$\Delta\chi^2$
a/10^{-3}


$\Delta\chi^2$
b/10^{-2}


$M_{sol}/10^{13}$GeV
$M_{atm}/10^{10}$GeV
$\Delta\chi^2$


$\Delta\chi^2$
$M_{\rm atm}/10^{10}$GeV


$\Delta\chi^2$
$M_{\rm sol}/10^{13}$GeV

(Case A)

- LS highly predictive: 7 observables from 4 parameters
- Excellent fit; suggests $\delta \simeq -90°$; allows indirect prediction of RHν masses
- Withstands future test based on T2HK and DUNE sensitivity

	Case A	Case D
M_{atm} / GeV	5.05×10^{10}	1.36×10^{13}
M_{sol} / GeV	5.07×10^{13}	1.06×10^{10}
a	0.00806	0.135
b	0.0830	0.00116
χ^2 / d.o.f.	1.75 / 3	2.07 / 3

- LS highly predictive: 7 observables from 4 parameters
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	Case A	Case D
M_{atm} / GeV	5.05×10^{10}	1.36×10^{13}
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b	0.0830	0.00116
χ^2 / d.o.f.	1.75 / 3	2.07 / 3

Learn about high energies $\rightleftarrows$ Testable at low energies

We are living in a precision measurement era!

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THANK YOU

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THANK YOU