

# Introduction to the neutrino session

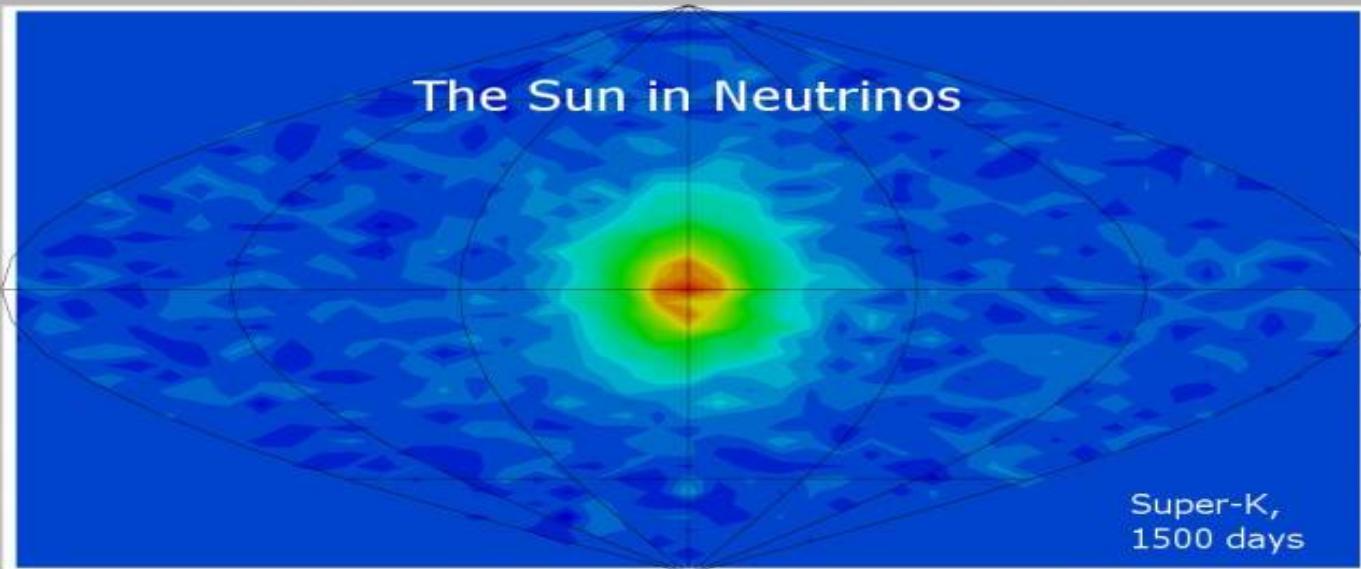
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(CNRS/Ecole polytechnique)

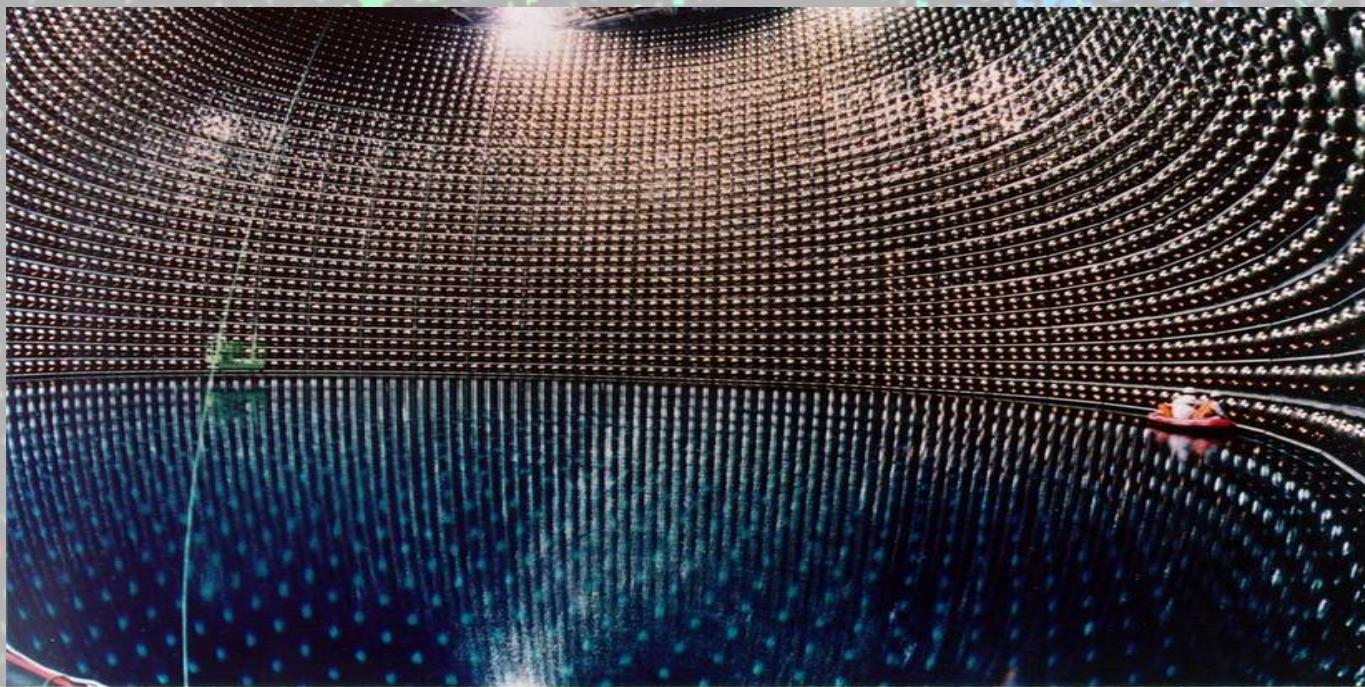
Journée de Rencontre Jeunes Chercheurs

2021/10/20

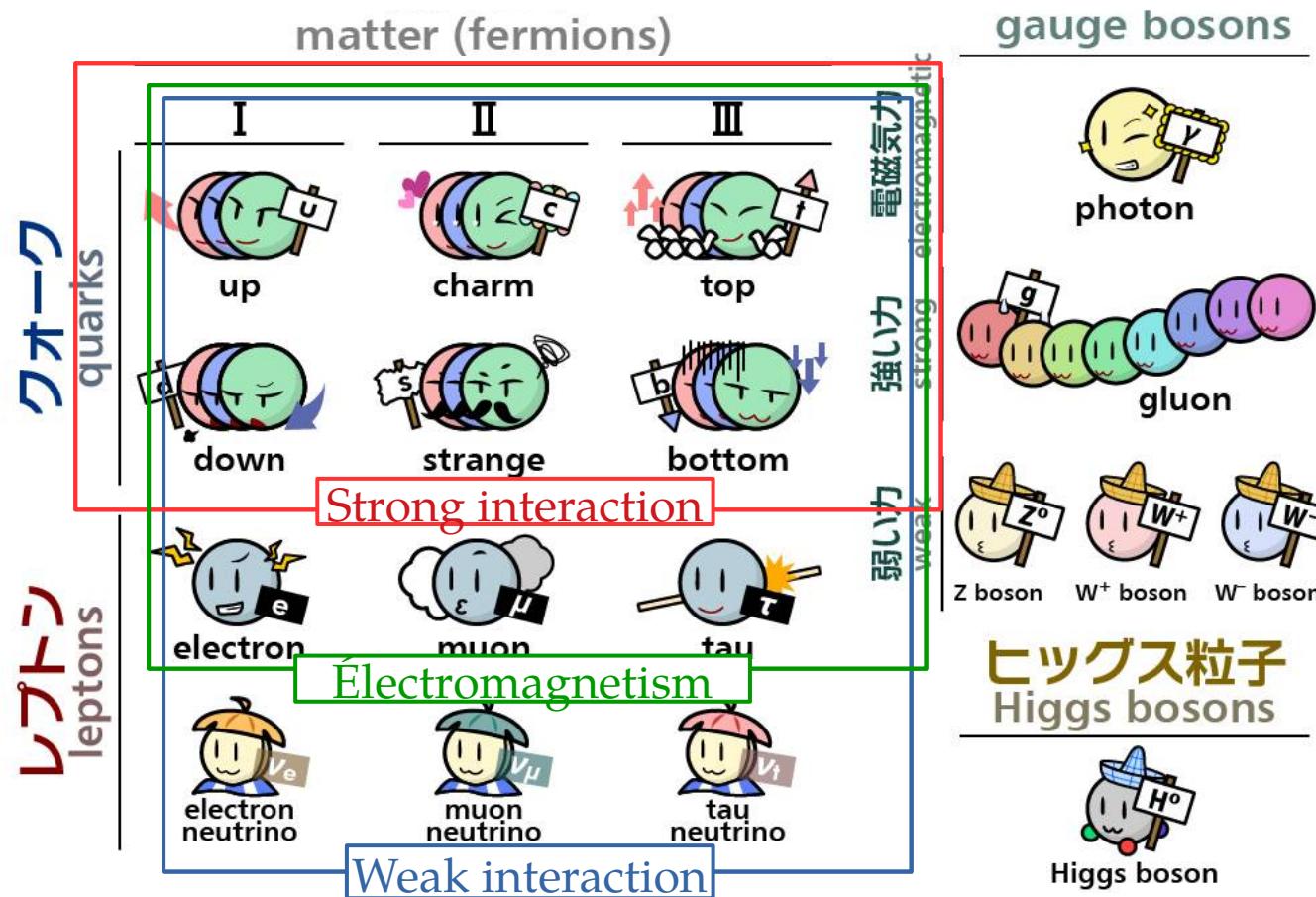




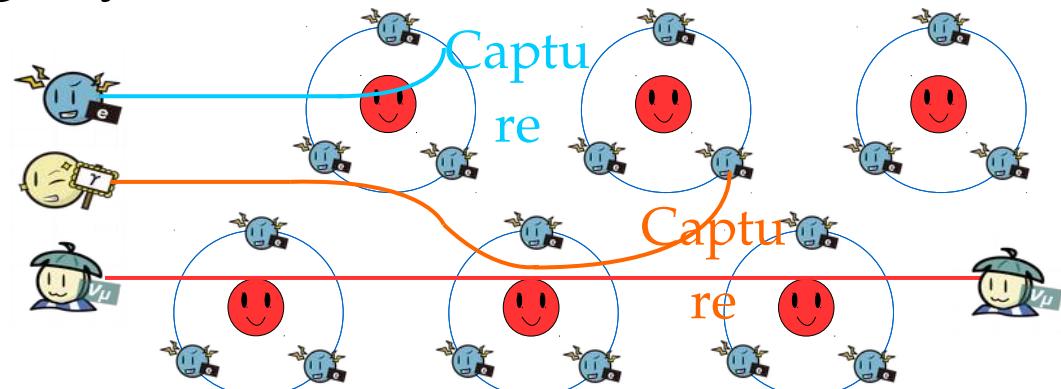
# I. Neutrino before 2000's



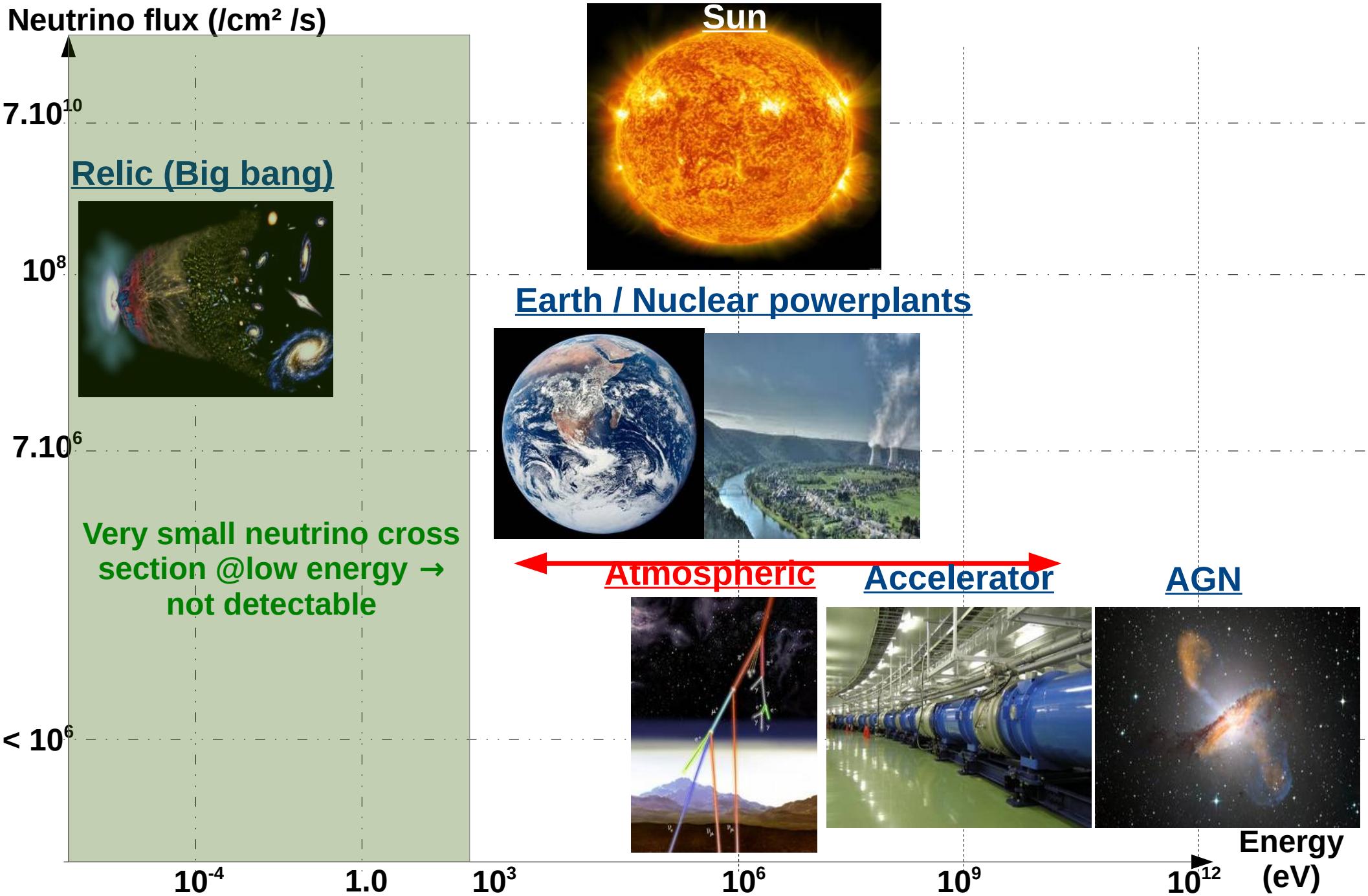
# Enter the matter



- Neutrinos : 50 % stopped by 1 light-year of lead ( $9.5 \times 10^{12}$  km)!!  
 → Easily crosses the Earth :  
 how to detect them ?



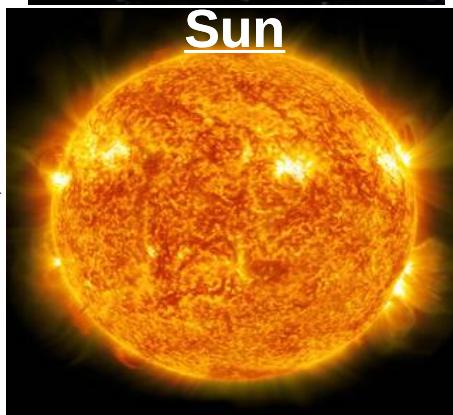
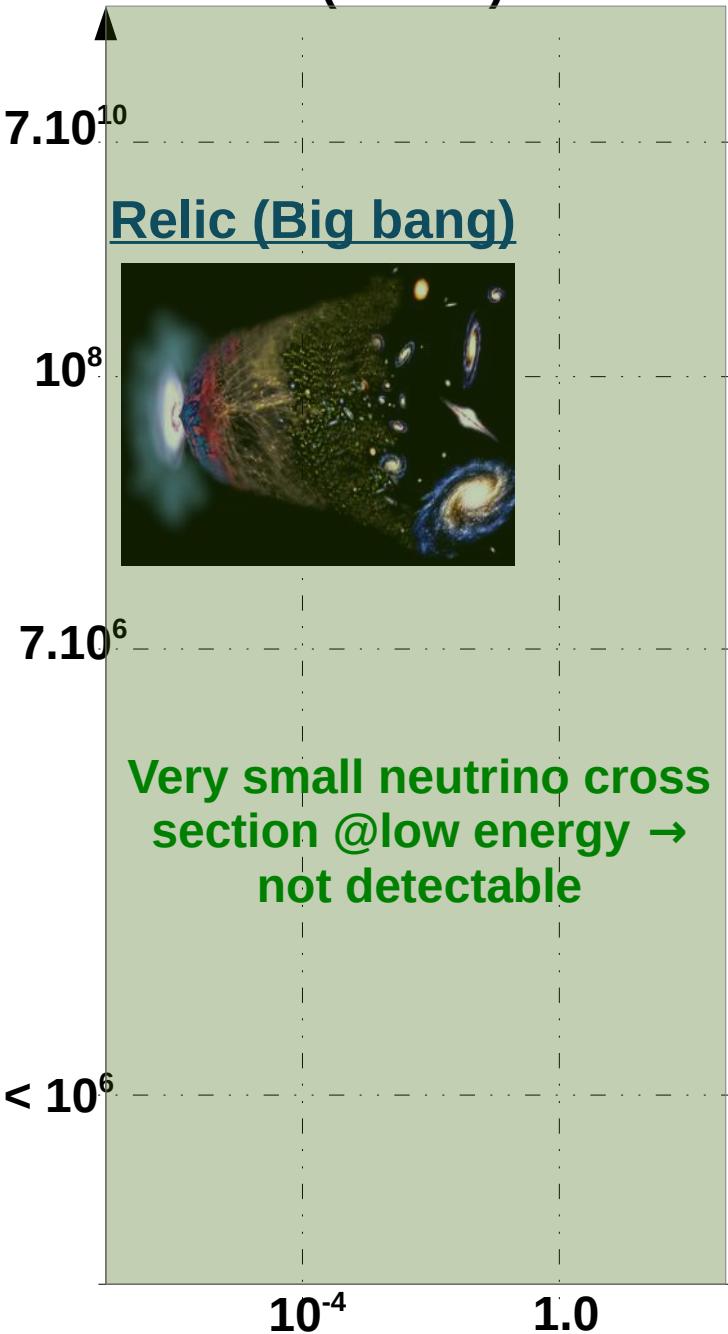
# Average fluxes on Earth



# Average Earth

SN1987 :  $10^{34}$

Neutrino flux ( $/\text{cm}^2/\text{s}$ )



Earth / Nuclear powerplants



Atmospheric Accelerator



AGN

Energy  
(eV)

# Selected discovery in neutrino physics



Pauli :  
Introduce neutrino  
to explain  $\beta$  spectrum  
(to save energy/spin  
conservation)

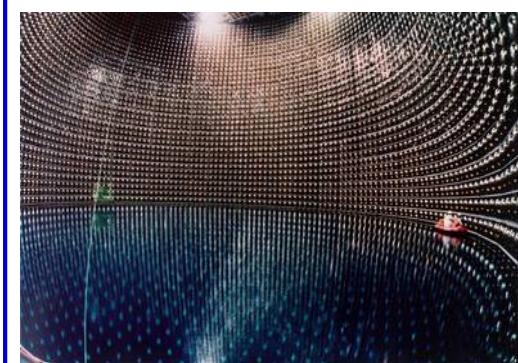


Reines & Cowan :  
Experimental  
detection of neutrino  
(Savannah River  
reactor)



@BNL :  
2 distinct  
neutrino  
families

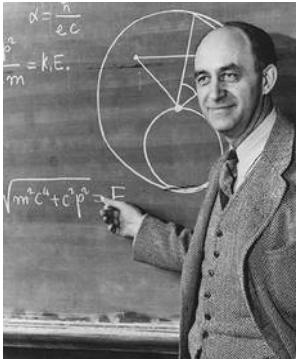
Davies@Homestake :  
First indication of solar  
neutrino deficit



@SK :  
Direct observation of  
neutrino oscillation  
(atmos.)

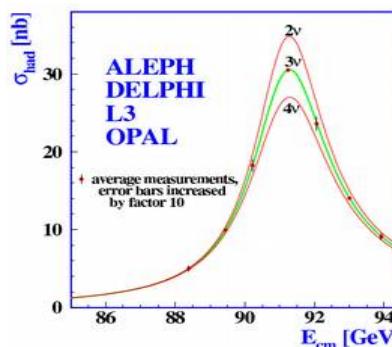
1930      1934      1956      1962      1967      1989      1998      2001

Fermi :  
Neutrino  
incorporated in a  
theory of weak  
interactions



Maki-Nakagawa-  
Sakata:  
Flavour states are  
superposition of mass  
states

@LEP :  
Only 3 active  
(Z int.) light  
(<45GeV)  
neutrino  
families

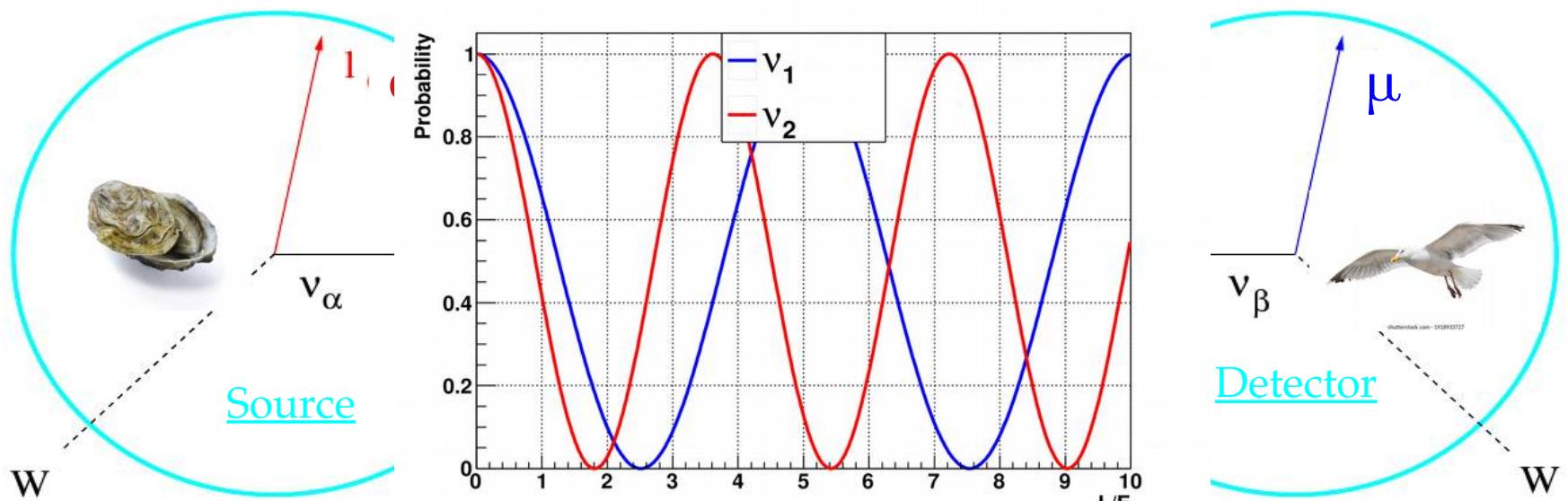


@SNO :  
Solar  
neutrino  
explained  
by  
oscillation

# Neutrino oscillation

- Flavour states (interact)  $(\nu_\alpha, \nu_\beta) \neq$  mass states (propagates)  $(\nu_1, \nu_2)$

→ Example :



$$|\nu_\alpha\rangle = \sum_j U_{\alpha j}^* |\nu_j\rangle$$

$$e^{-i(Et - p_j x)}$$

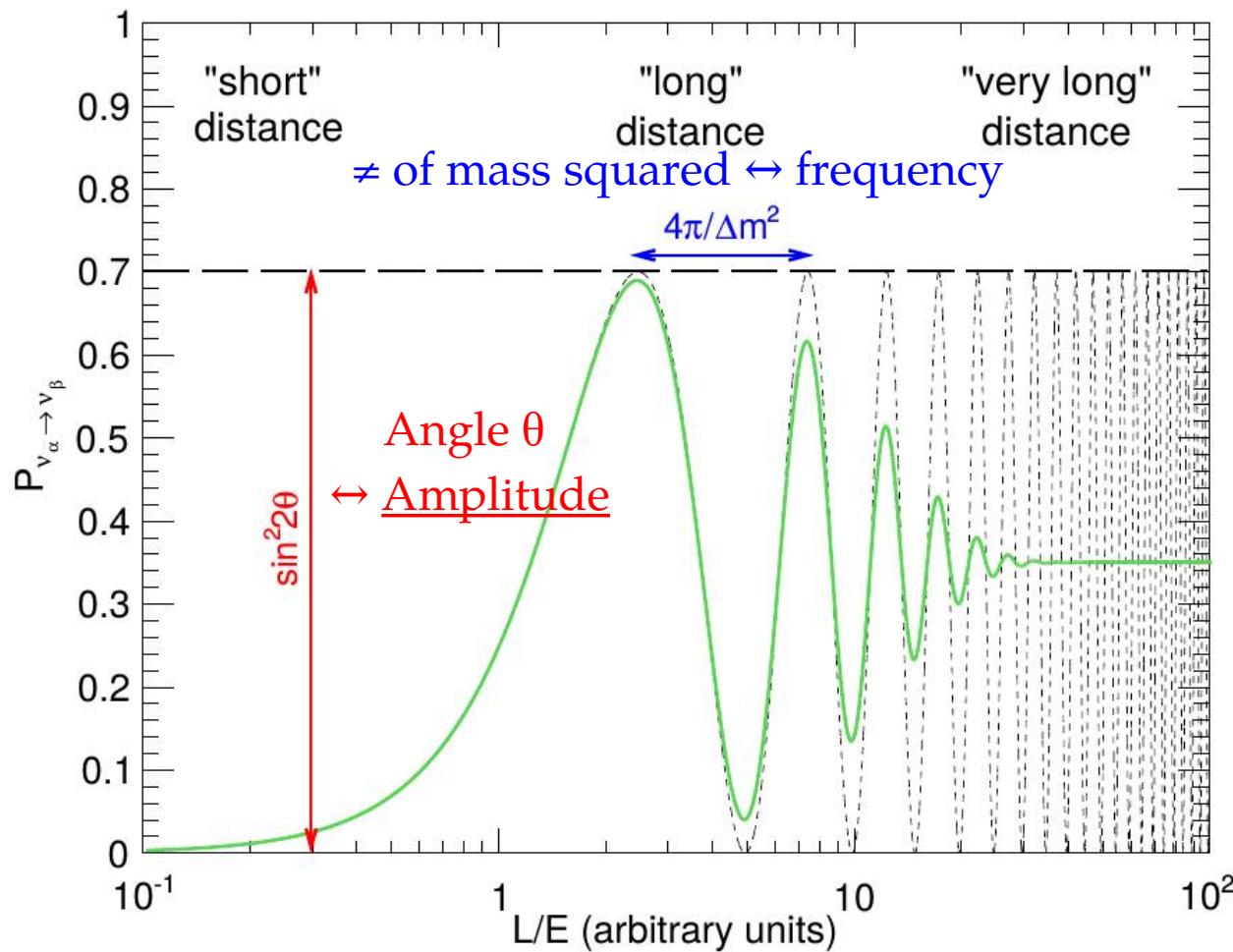
$$|\nu_\beta\rangle = \sum_k U_{\beta k}^* |\nu_k\rangle$$

- Oscillate if  $m_1 \neq m_2 \rightarrow E_1 \neq E_2$ .
- Oscillation goes in L/E :

$L$  = distance between source & detector.

$E$  = Neutrino energy. → Higher  $E$  needs longer  $L$  to oscillate.

# Neutrino oscillation in vacuum



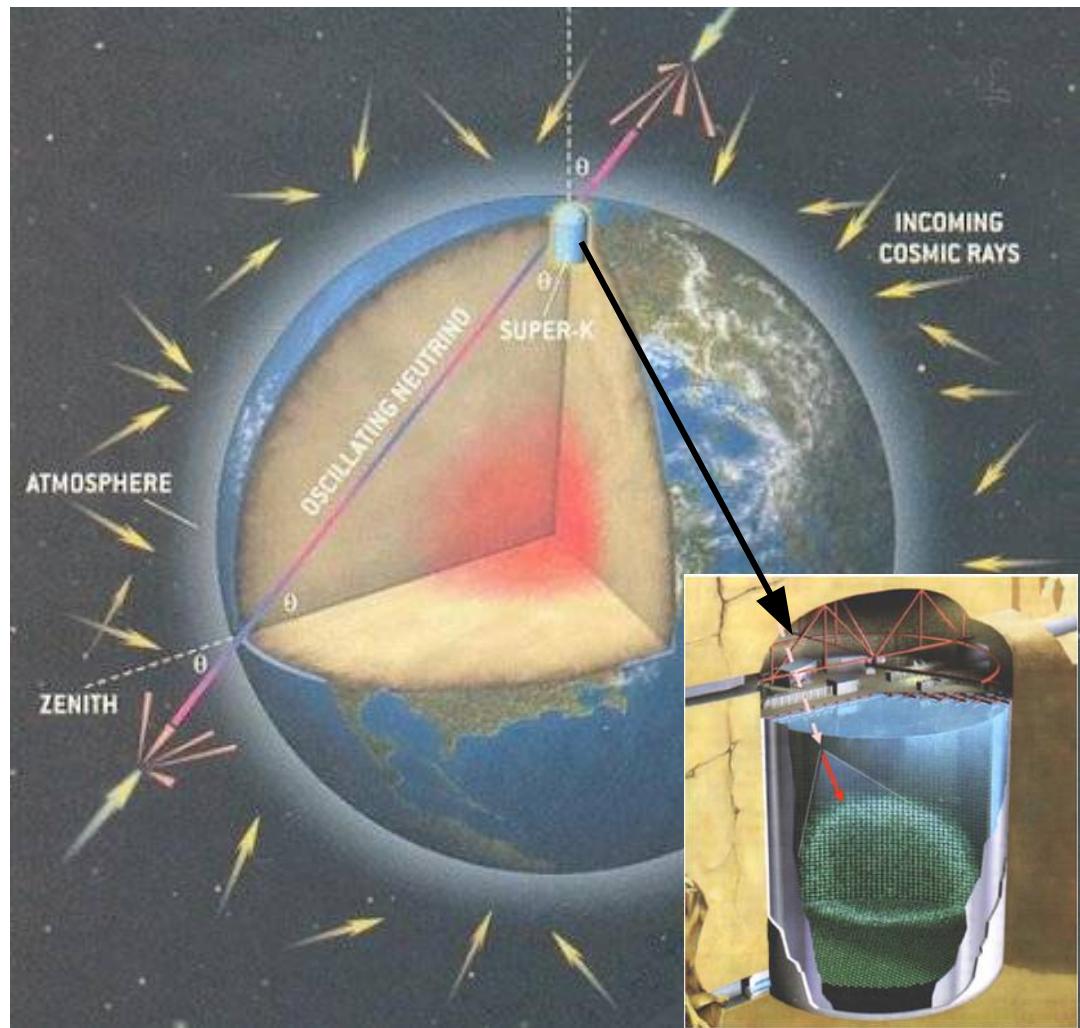
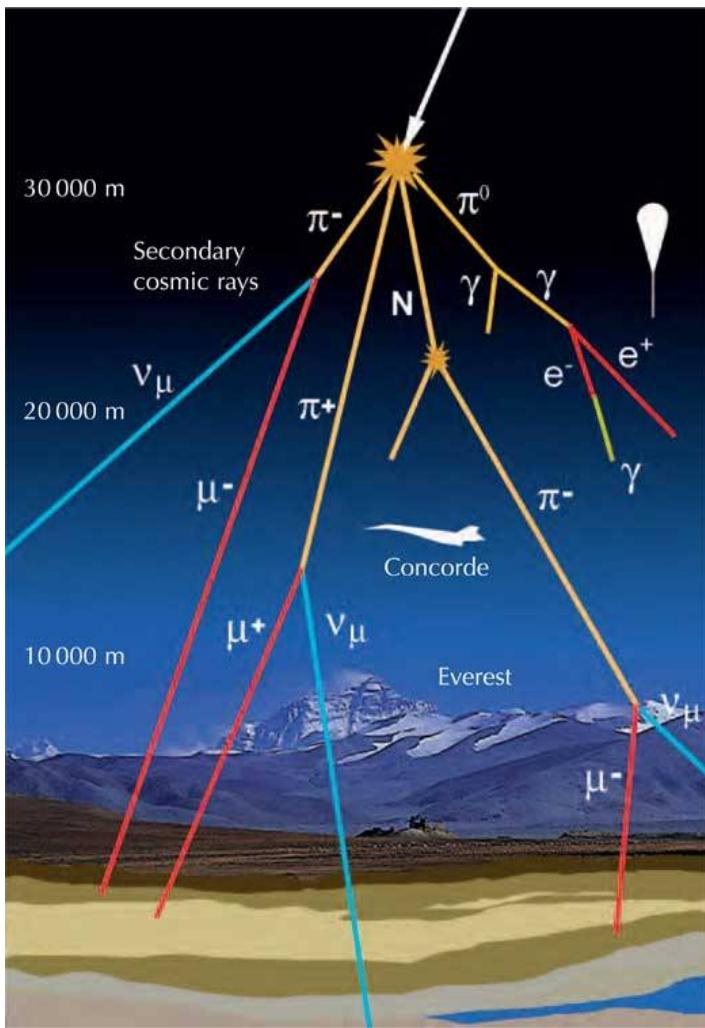
2 flavour approximation :

$$P_{\nu_\alpha \rightarrow \nu_\beta}(L, E) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$

- Oscillation in L/E.
- Frequency : determined by the mass square difference :  $\Delta m^2 = m_2^2 - m_1^2$
- Amplitude : determined by the mixing angle  $\theta$ .

# Atmospheric neutrinos in Super-K

- Neutrinos produced in cosmic ray decays.

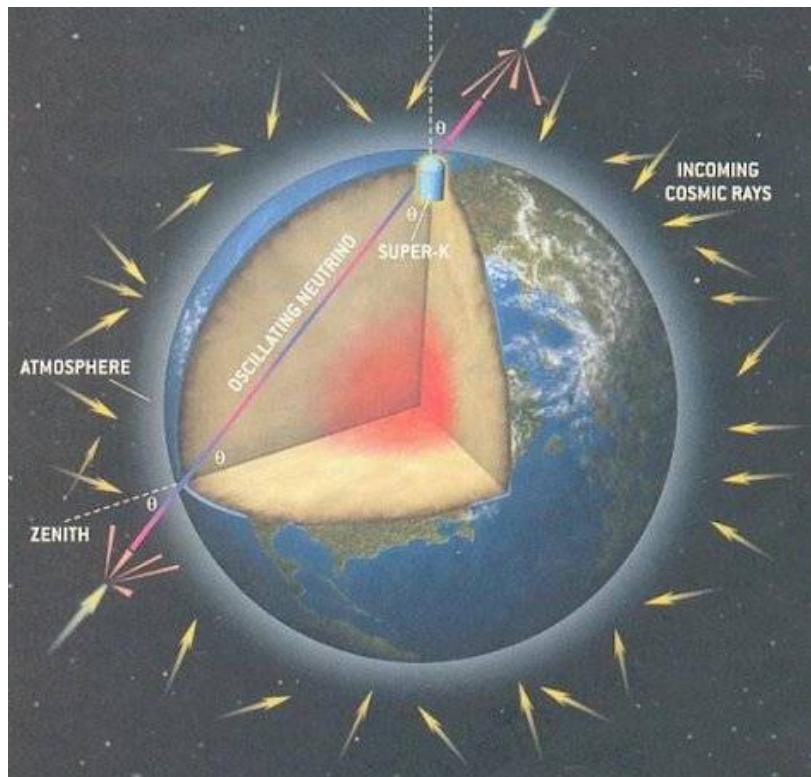


If no oscillations :

Atmospheric fluxes predicts  $\nu_\mu$  to  $\nu_e$  ratio,  $R = \frac{\phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu}}{\phi_{\nu_e} + \phi_{\bar{\nu}_e}} \approx 2$ .

$R$  should be independent from zenith angle as production is isotropic.

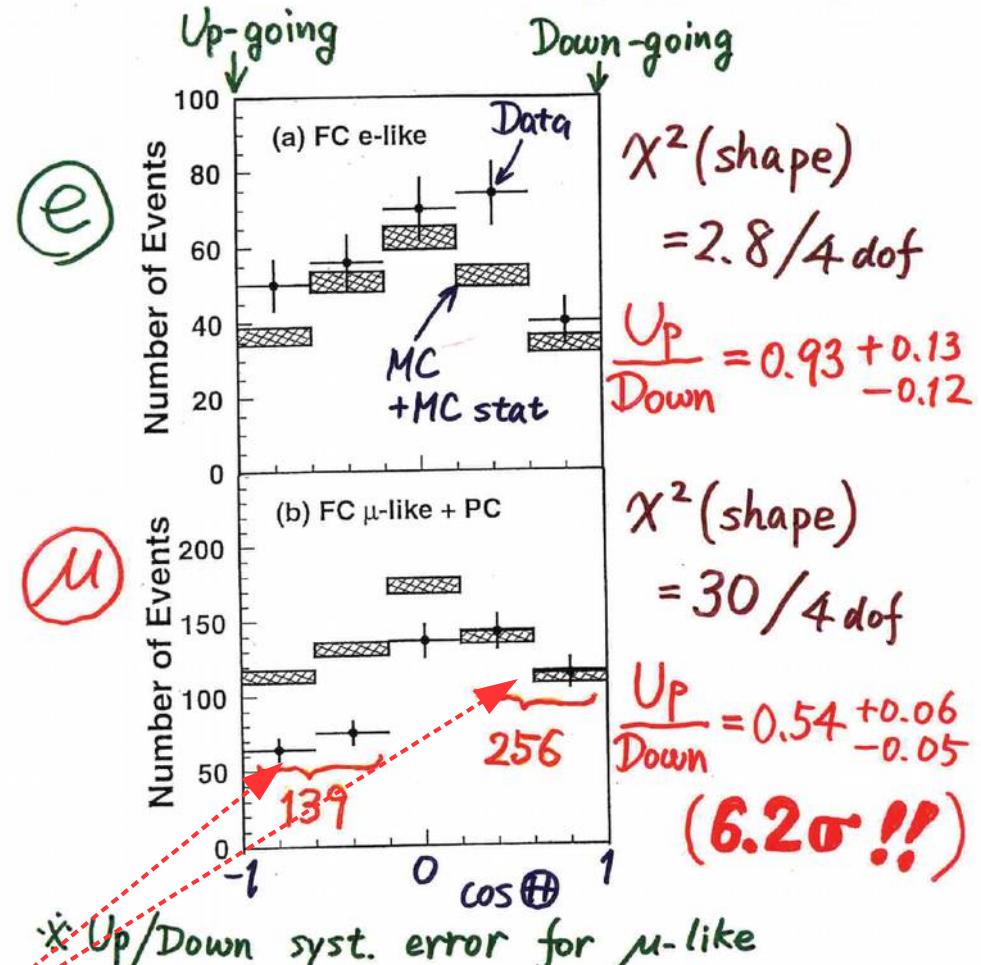
# Atmospheric neutrinos



## Observations :

- $R < 2$ .
- $R$  varies with zenith angle  
↔ L dependency
- A definite probe of  $\nu$  oscillation.

Zenith angle dependence  
(Multi-GeV)



\* Up/Down syst. error for  $\mu$ -like

Prediction (flux calculation .....  $\lesssim 1\%$ ,  
1km rock above SK .....  $1.5\%$ , )  $1.8\%$

Data (Energy calib. for  $\uparrow \downarrow$  .....  $0.7\%$ ,  
Non  $\nu$  Background .....  $< 2\%$ , )  $2.1\%$

## II. Neutrino oscillation in the current era

# As neutrinos have masses

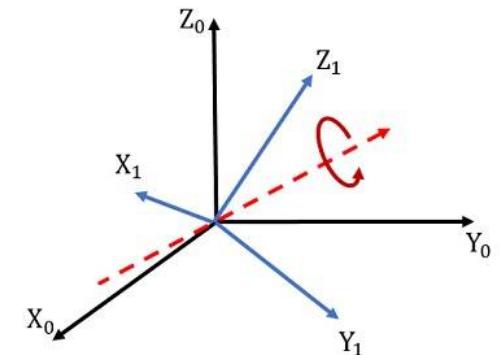
- In case of massless neutrinos, Lagrangian has V-A structure :

$$L_{int}^W = - \sum_{\alpha=e,\mu,\tau} \frac{g_w}{\sqrt{2}} ([\bar{\nu}'_\alpha] \gamma^\mu \frac{1}{2} (I - \gamma^5) [\alpha'] W_\mu^- + [\bar{\alpha}] \gamma^\mu \frac{1}{2} (I - \gamma^5) [\nu'_\alpha] W_\mu^+)$$

$\nu'_L \equiv \begin{pmatrix} \nu'_{eL} \\ \nu'_{\mu L} \\ \nu'_{\tau L} \end{pmatrix}$  ← Flavour  $\nu$  states      Flavour leptonic states →  $\nu'_R \equiv \begin{pmatrix} \nu_R \\ \nu_R \\ \nu_R \end{pmatrix}$

- If  $\nu$  has a Dirac mass :  $L_{mass}^D = \frac{m}{2} [\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L]$  w/  $m_i = \frac{g_i^\nu v}{\sqrt{2}}$  with  $i=1,2,3$

Mass  $\nu$  states →  $\nu_L = V_L^{\nu\dagger} \nu'_L \equiv \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$



- We introduce the rotation matrix  $V$  :  $V$  : mass states → flavour states.

- PMNS basically allows to rewrite the Lagrangian in mass basis :

$$L_{int}^W = - \sum_{\alpha=e,\mu,\tau} \sum_{i=1,2,3} \frac{g_w}{\sqrt{2}} ([\bar{\nu}^i U_{PMNS}^\dagger \gamma^\mu \frac{1}{2} (I - \gamma^5) [\alpha'] W_\mu^+ + h.c]) \quad w/ \quad U_{PMNS} = V_L^\nu V_L^{l\dagger}$$

- PMNS = rotation matrix to rewrite  $L$  from mass to flavour states.

# Three flavour neutrino oscillations

- 3 flavour eigenstates ( $\nu_e, \nu_\mu, \nu_\tau$ ) and 3 mass states ( $\nu_1, \nu_2, \nu_3$ ).  
 → PMNS symmetries allows to rewrite 3D matrix into three 2D rotations.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & e^{-i\delta} s_{13} \\ -e^{i\delta} s_{13} & 1 \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

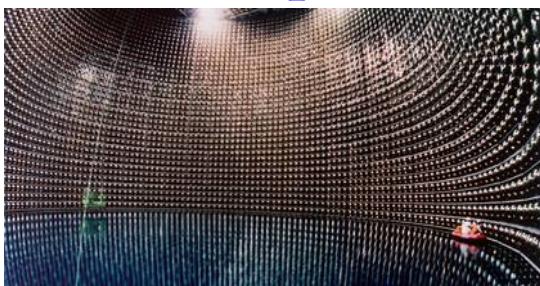
$c_{ij} = \cos \theta_{ij}$  and  $s_{ij} = \sin \theta_{ij}$

3 mixing angles:  $\Theta_{23}, \Theta_{13}, \Theta_{12}$

2 mass square differences :  $\Delta m^2_{32}, \Delta m^2_{21}$

1 Dirac CP violation phase:  $\delta_{CP}$

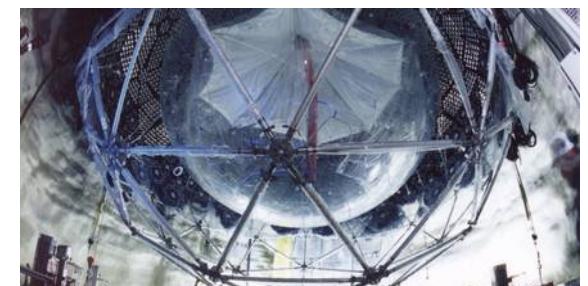
« Atmospheric »                                  « Reactor »                                  « Solar »



$\Theta_{23} = 45^\circ \pm 7^\circ$   
 $|\Delta m^2_{32}| = (232^{+12}_{-8}) \times 10^{-5} \text{ eV}^2$



$\Theta_{13} = 9.0^\circ \pm 2.9^\circ$



$\Theta_{12} = 33.9^\circ \pm 4.5^\circ$   
 $\Delta m^2_{12} = (7.50 \pm 0.20) \times 10^{-5} \text{ eV}^2$

# Open issues in neutrino oscillations

- Is CP violated in the neutrino sector ?

→ Is  $P(\nu_\alpha \rightarrow \nu_\beta) = P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$  ? Could explain why no anti-oyster.

→ Measure it in Long-Baseline experiments :

T2K/Nova today, Hyper-K ([Lucile's talk](#)), DUNE ([Pablo's talk](#))...

- What is the neutrino mass ordering : affect nucleosynthesis in SN...

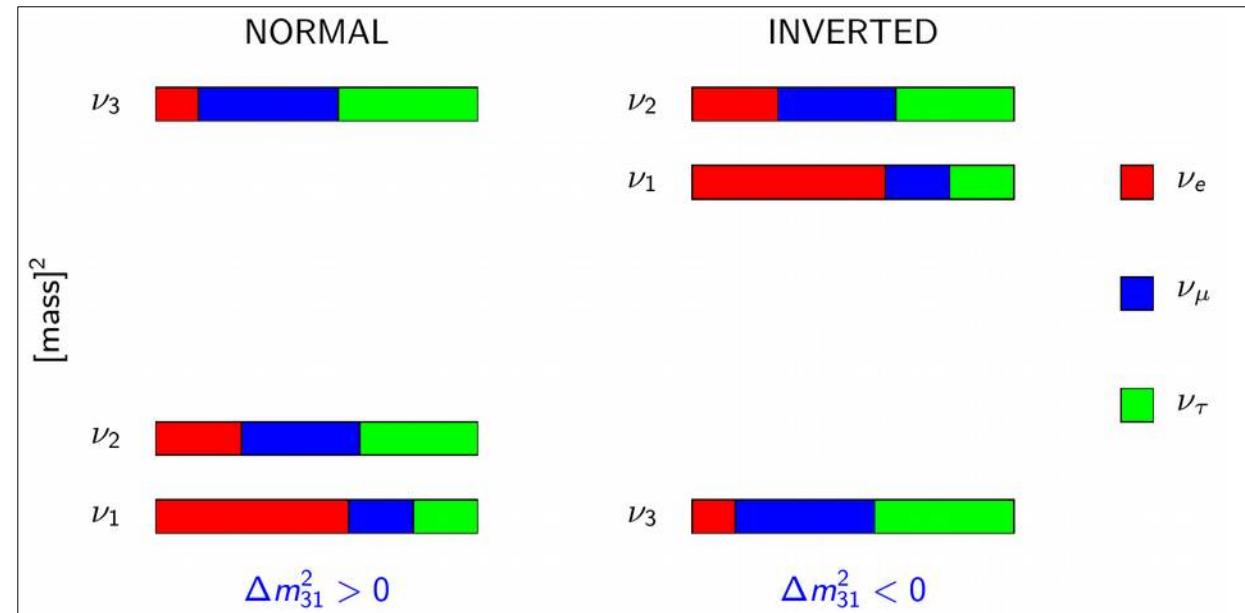
→ Oscillations in vacuum provides only  $|\Delta m^2|$ .

→ Matter effect in the Sun provides :  $m_2 > m_1$ .

→ 2 ways to measure it :

a. Matter effect in the Earth :  
Long-Baseline experiments.

b. Interférences : JUNO  
→ [Leonard's talk](#)

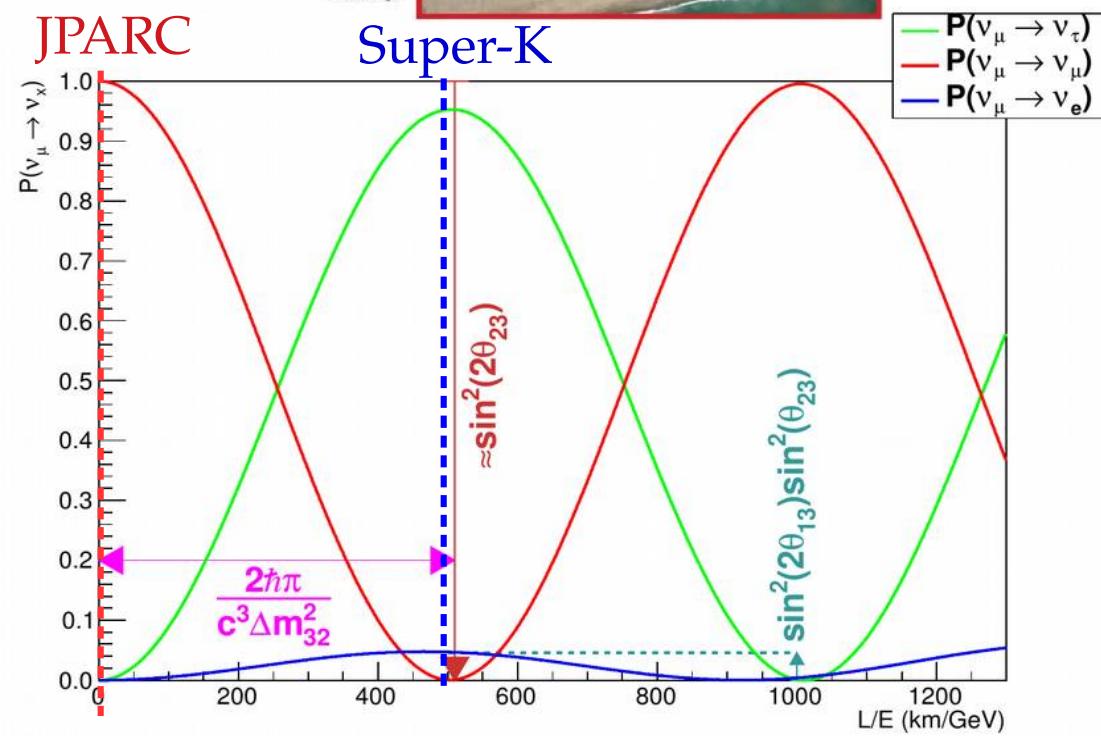


# The long-baseline experiments

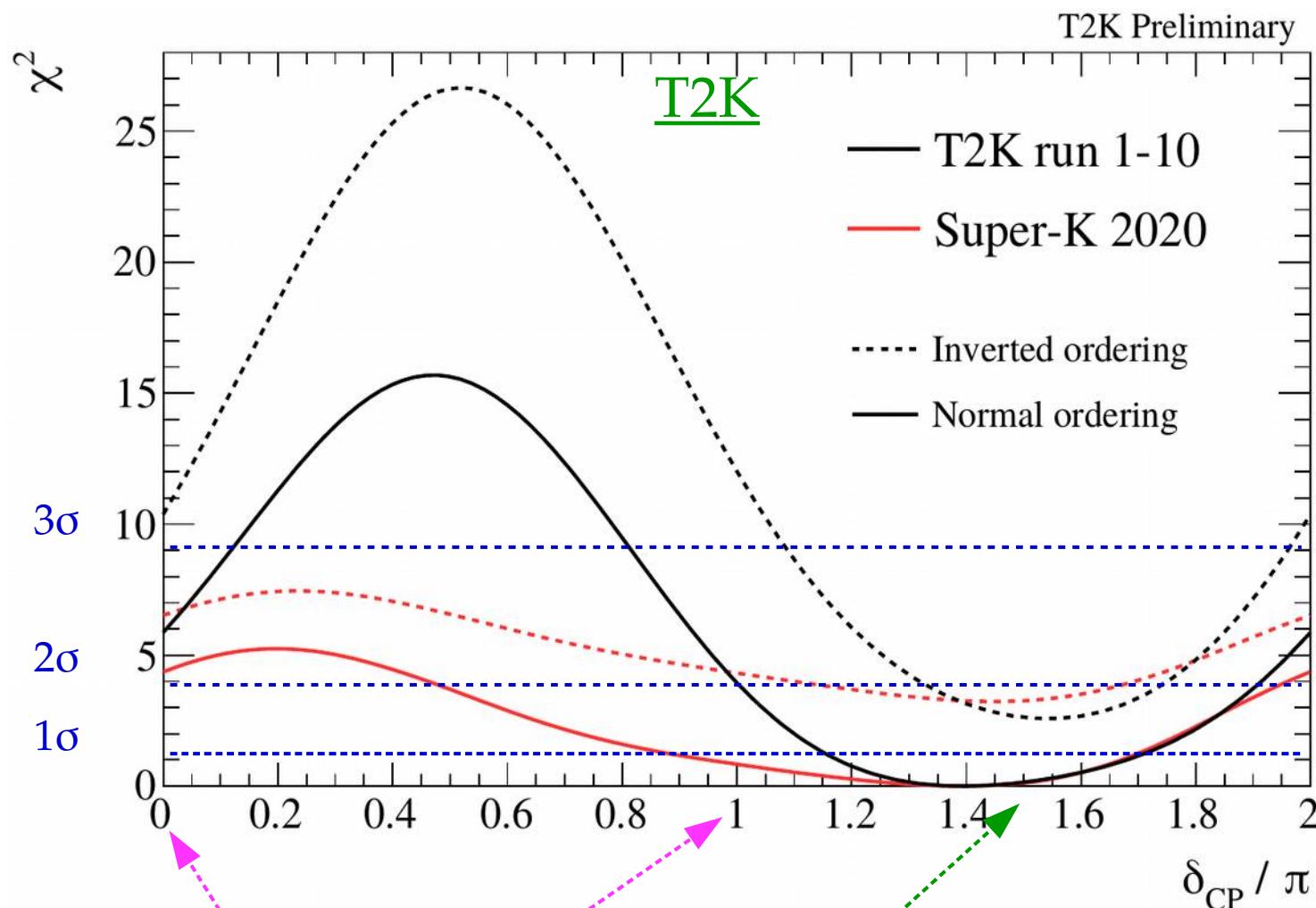
- All uses same method : focus on the T2K experiment in Japan.



- Intense  $\nu_\mu$  beam.
- Observe  $\nu_\mu$  disappearance and  $\nu_e$  appearance.
- Can select  $\nu$  or  $\bar{\nu}$ .



# $\delta_{\text{CP}}$ and mass-hierarchy

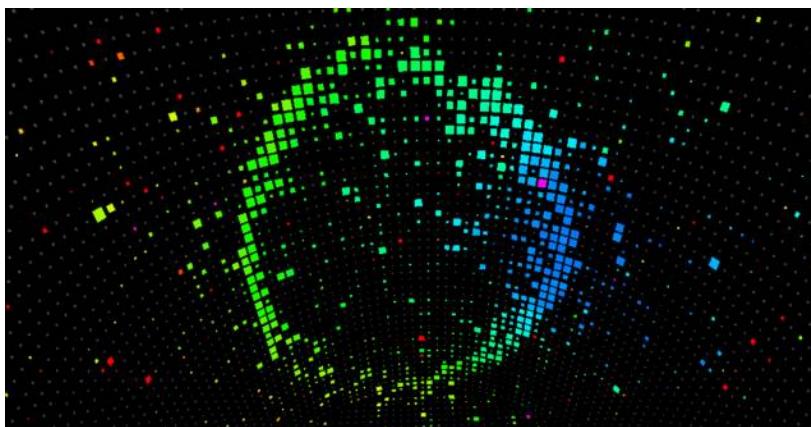
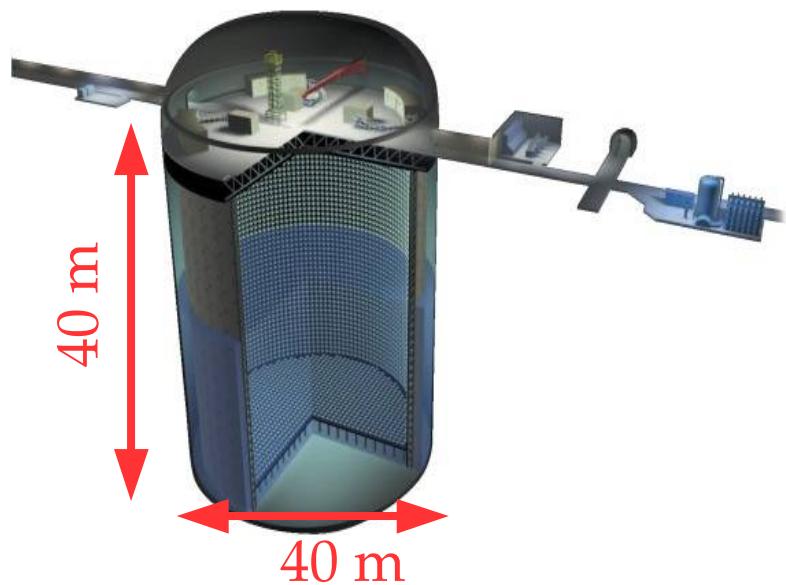


- Normal ordering favoured by T2K ( $1\sigma$ ) and SK ( $1.8\sigma$ ).
- CP conservation ( $\sin \delta_{\text{CP}} = 0$ ) excluded by T2K ( $2\sigma$ ) and SK ( $\sim 1\sigma$ ).  
→ Maximal CPV ( $\delta_{\text{CP}} = 3\pi/2$ ) favoured by T2K & SK, whatever MO.

# Next generation of experiments : Hyper-K

- Next generation of neutrino observatory in Japan → construction 2020-27  
→ A 260 kton water Cherenkov detector → Fiducial Mass  $\sim 8 \times$  SK.

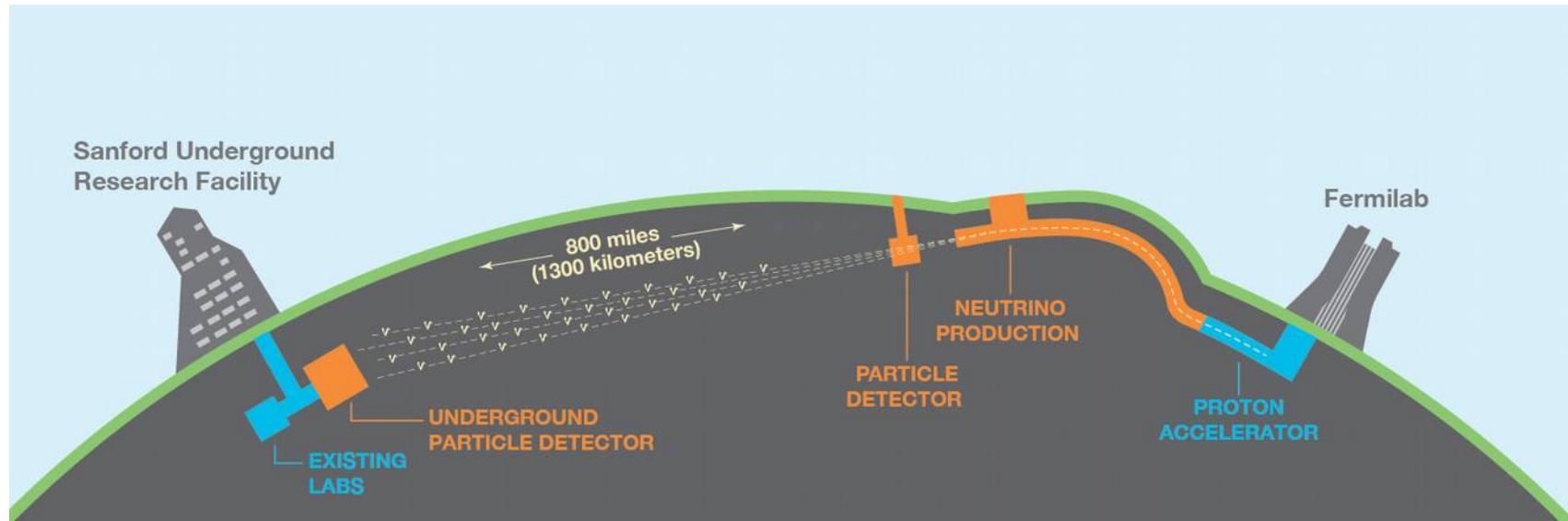
Super-Kamiokande



	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	11,129	40,000
Photo-coverge	40%	40% ( <b><i>x2 sensitivity</i></b> )
Mass / Fiducial Mass	50 kton / 22.5 kton	260 kton / 187 kton

# Next generation of experiments : DUNE

- DUNE is similar to T2K / HK, but in the USA  
→ Baseline is larger : L = 1300 km → Better for Mass Ordering.

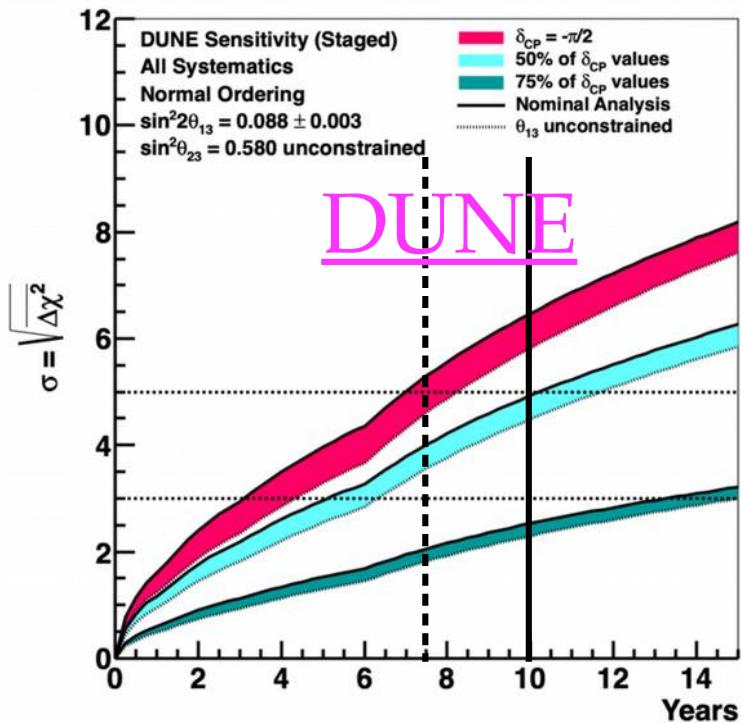
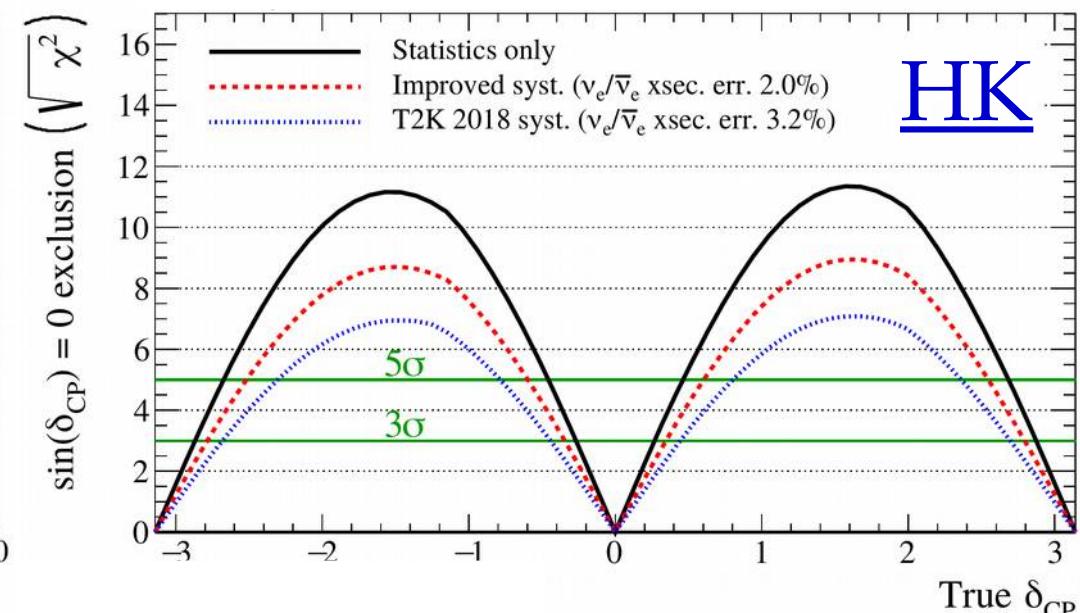
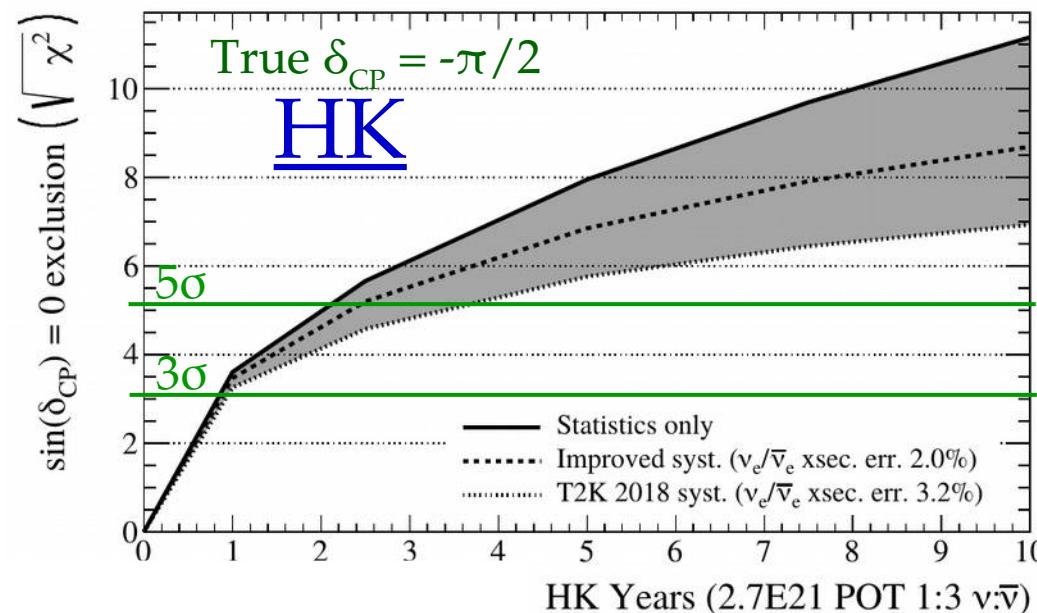


- Similarities and differences between Hyper-K and DUNE :

	HK	DUNE
Baseline	295 km	1300 km
Energy	600 MeV	Large Spectrum 0.8 → 6 GeV
Fiducial mass	190 kton	20 - 40kton
Technology	Water Cherenkov	Liquid Argon TPC
First data	2027	2029

# Sensitivity to CP violation

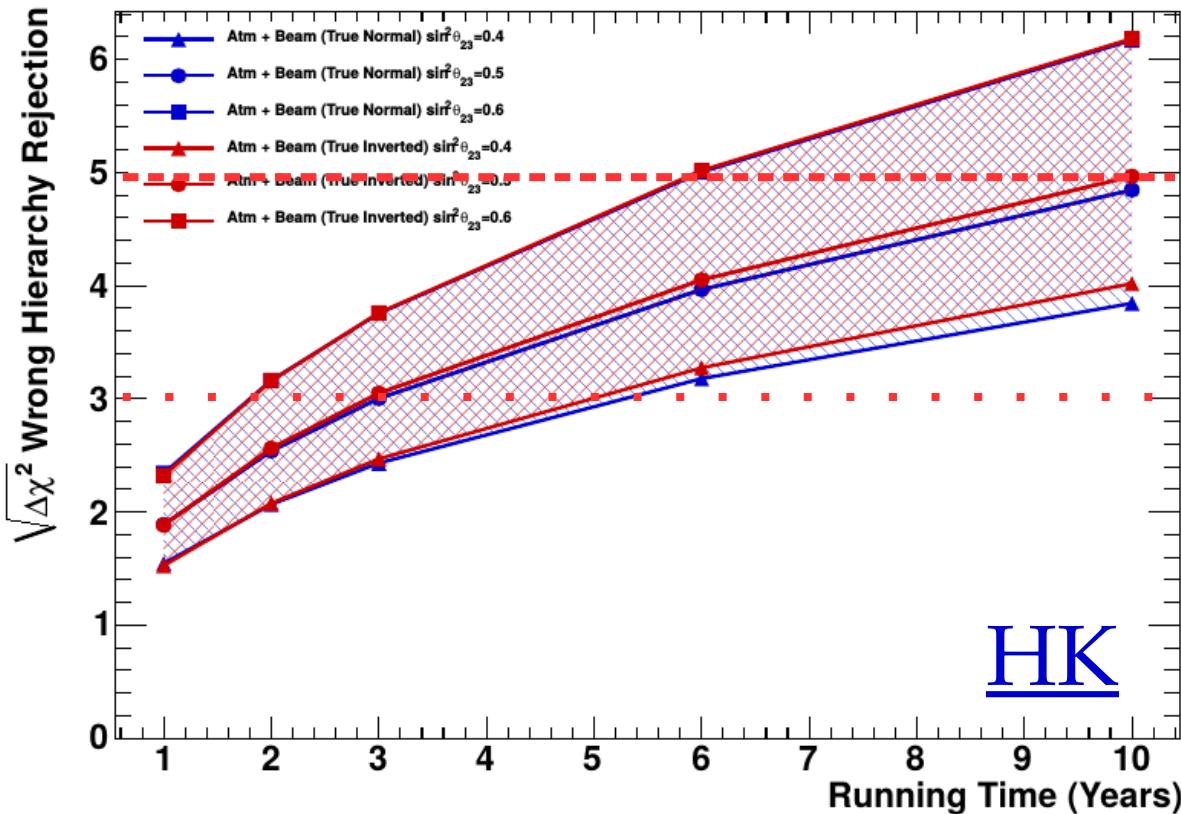
- Assuming a run  $\nu:\bar{\nu} = 1:3$  @1.3MW (can be adjusted).



- CPV  $5\sigma$  discovery (if  $\delta_{CP} = -\pi/2$ ) :  
→ 3 years for HK, 7 years for DUNE.
- Probing 50 % of  $\delta_{CP}$  phase space :  
→ HK needs 5 years, DUNE needs 10 years.
- HK & DUNE : world-best sensitivity to CPV.

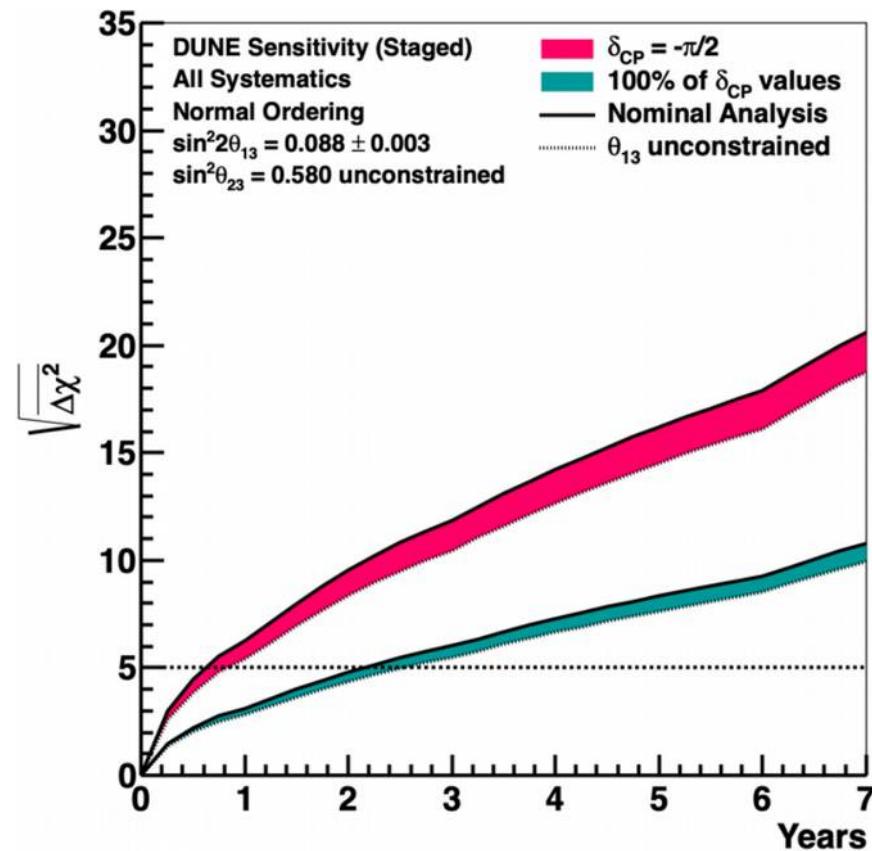
# Neutrino mass ordering

HK



HK

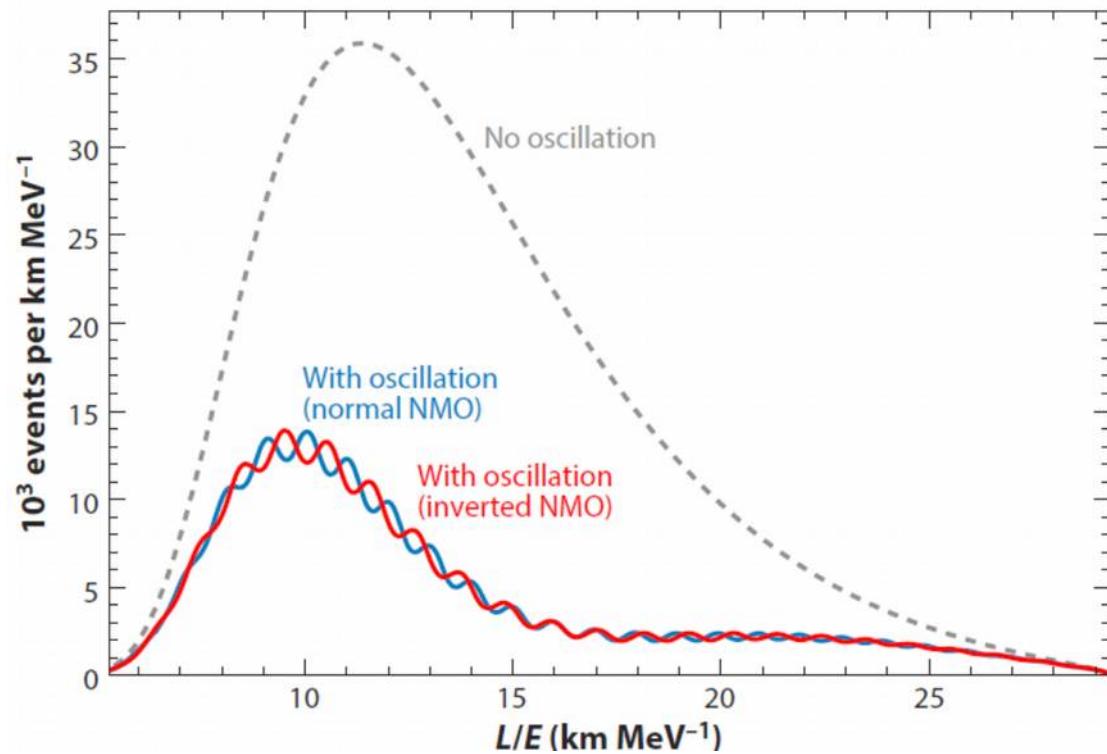
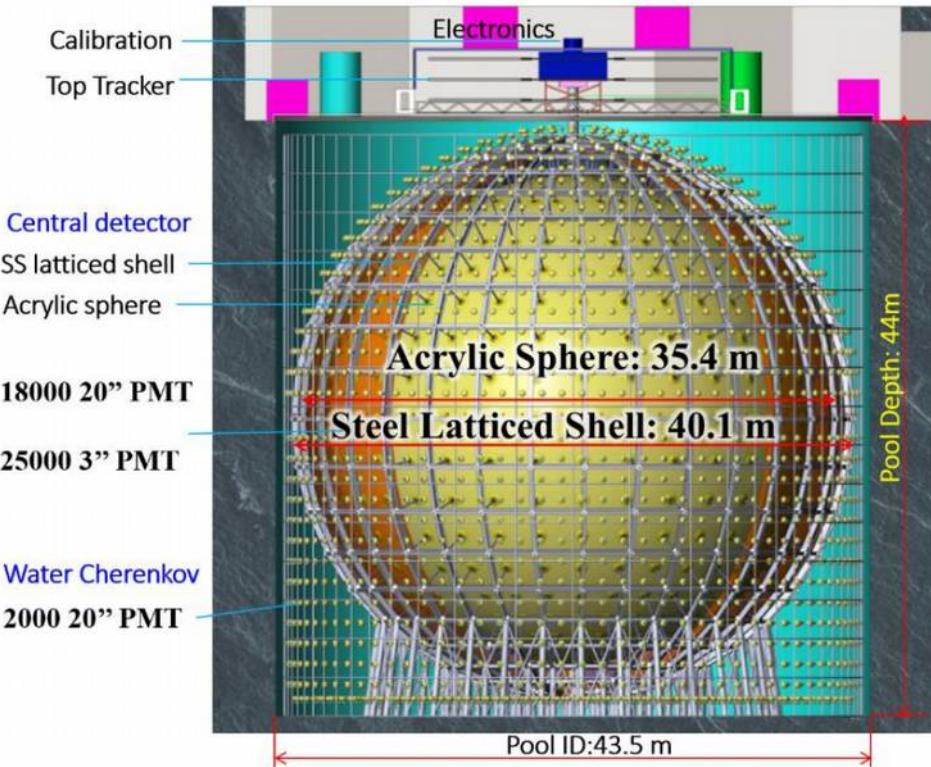
DUNE



- Mass ordering would be determined by :
  - HK after  $\geq 6$ -10 years via atmospheric.
  - DUNE : after 1-2 years (in  $\sim 2030$ 's)
  - DUNE : the best experiment to measure mass ordering at long-terms.
- See talks from Lucile Mellet (Hyper-K) and Pablo Kunze (DUNE).

# Measuring the mass hierarchy in JUNO

- JUNO : a 20 kton liquid scintillator detector in Jiangmen, China
- Multipurpose : mass ordering w/ reactor  $\nu$ , supernovae & solar  $\nu$ ...



- At large L/E : phase difference between  $\Delta m_{32}^2$  and  $\Delta m_{31}^2$  appears.

$$\begin{aligned}
 P(\bar{\nu}_e \rightarrow \bar{\nu}_e) &= 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta m_{21}^2 \frac{L}{4E} - \sin^2 2\theta_{13} \left( \cos^2 \theta_{12} \sin^2 \Delta m_{31}^2 \frac{L}{4E} + \sin^2 \theta_{12} \sin^2 \Delta m_{32}^2 \frac{L}{4E} \right) \\
 &\approx 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta m_{21}^2 \frac{L}{4E} - \sin^2 2\theta_{13} \sin^2 \Delta m_{ee}^2 \frac{L}{4E} \quad , \text{for } \Delta m_{12}^2 \ll \Delta m_{32}^2
 \end{aligned}$$

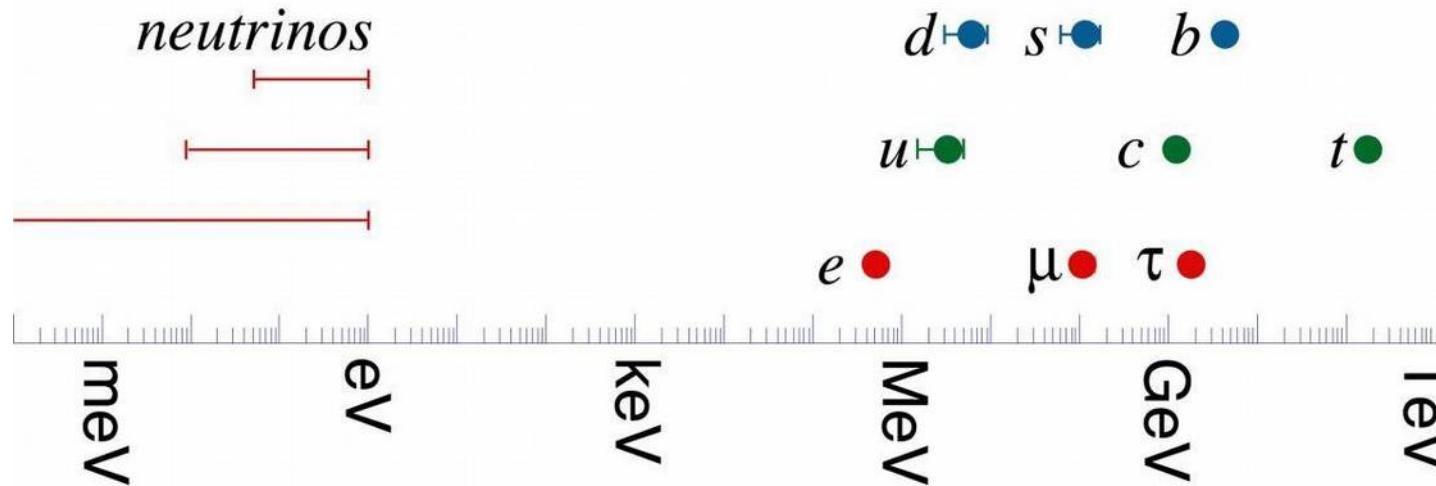
- JUNO : near future best detector to measure MO :  $4\sigma$  in 2027 (HK start)

→ See talk from Leonard Imbert and Victor Lebrin

### III. Neutrino masses

# Mass nature and absolute value

- Oscillation experiments provides  $\Delta m^2$  → What about absolute mass ?



- < 6 order of magnitude from other SM masses  
→ Hard to understand that Higgs coupling is so low for neutrinos...
- One possibility : nature of neutrino mass is different from other particles  
→ No  $\nu_R$  & no electric charge :  $\nu$  can be their own antiparticle  $\nu = \nu^c$   
→ In this situation, mass can arise from a Majorana term :

$$L_M^L = -\frac{1}{2} M_L (\bar{\nu}_L^c \nu_L + \bar{\nu}_L \nu_L^c)$$

$\Delta L = 2 \rightarrow$  Breaks lepton number conservation.

# Neutrinoless double beta decay

$$\mathcal{N}(A, Z) \rightarrow \mathcal{N}(A, Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

$$(T_{1/2}^{2\nu})^{-1} = G_{2\nu} |\mathcal{M}_{2\nu}|^2$$

second order weak interaction process in the Standard Model

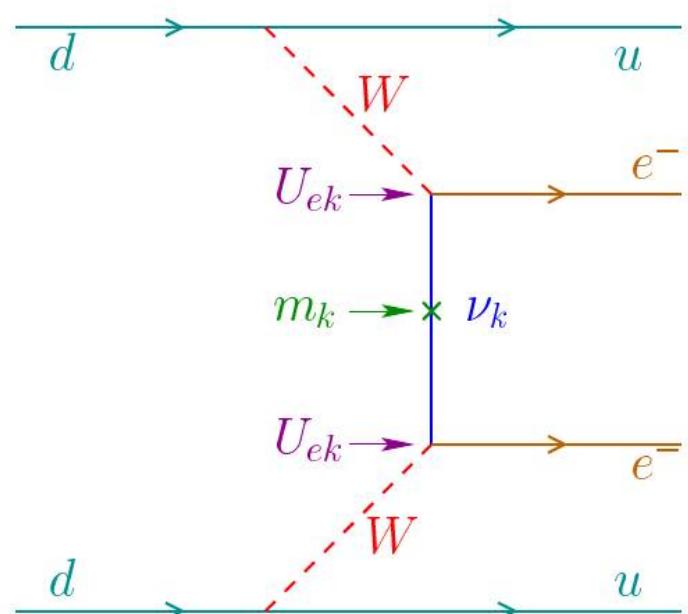
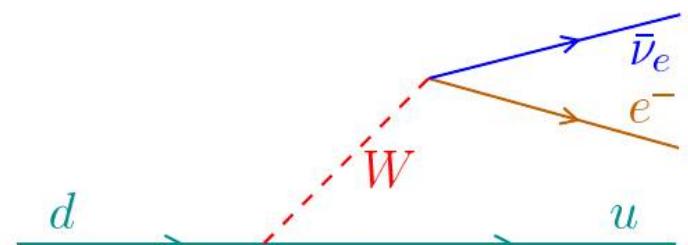
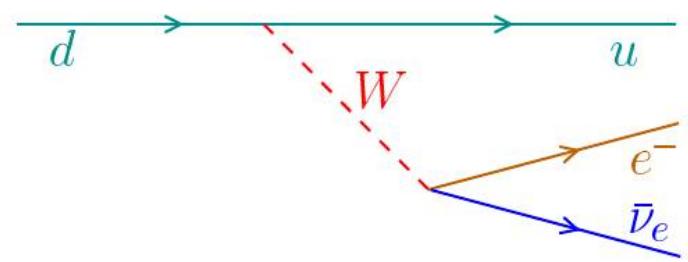
## Neutrinoless Double- $\beta$ Decay: $\Delta L = 2$



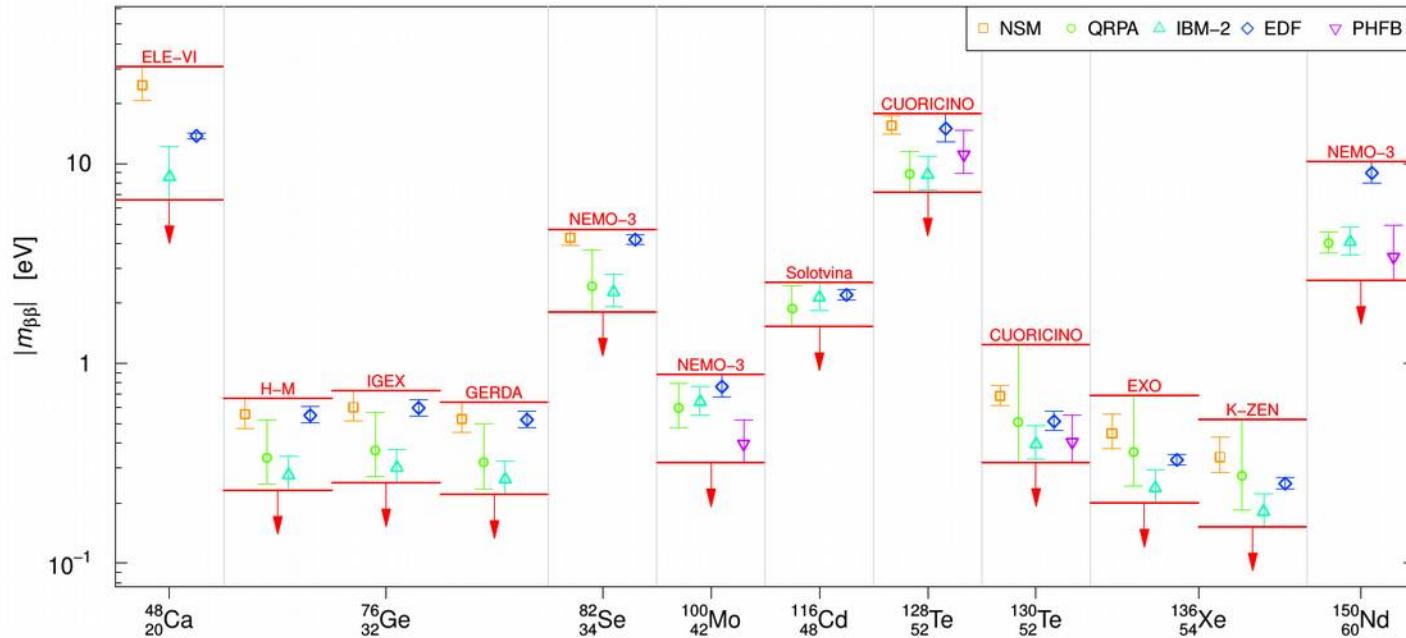
$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2$$

effective Majorana mass

$$|m_{\beta\beta}| = \left| \sum_k U_{ek}^2 m_k \right|$$



# Constraints from current experiments



New generation of experiments to reach a new milestone :

Super-NEMO : 100-140 kg of  $^{82}\text{Se}$

→ 90 % CL @ 50-100 meV

XENONnT :

6 tons of  $^{136}\text{Xe}$

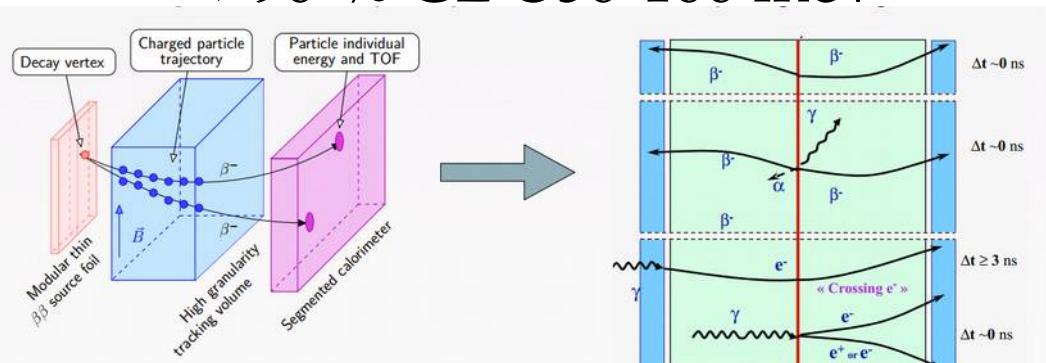
→ 90 % CL @ ? meV

→ Talk by Maxime Pierre

New concept : R2D2 :

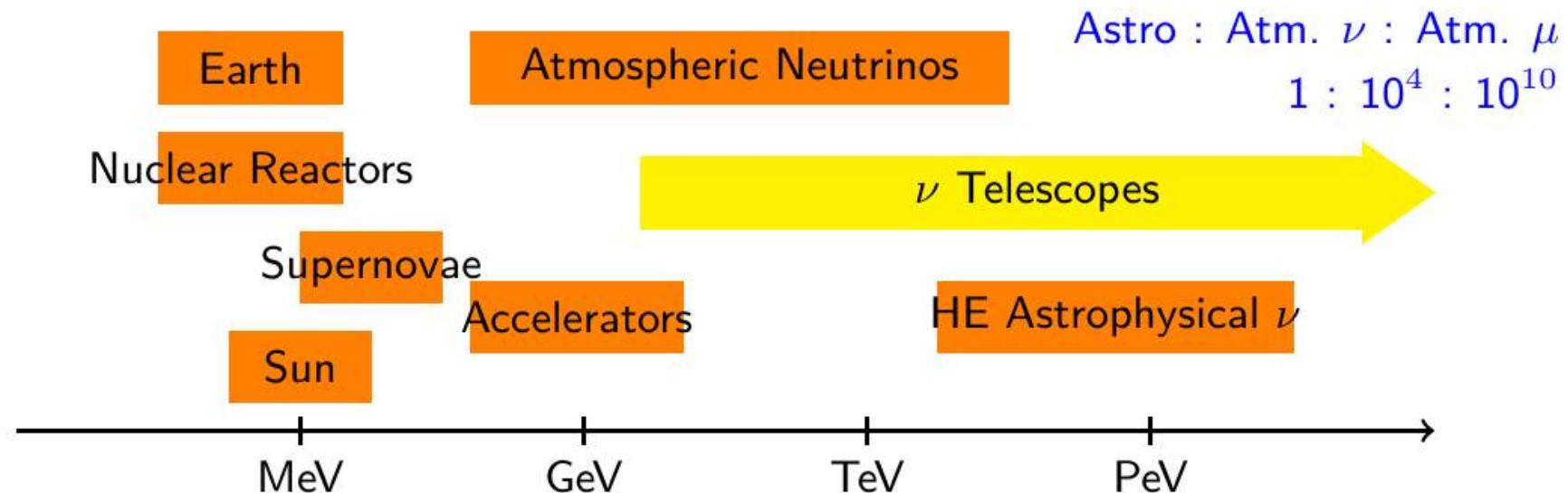
→ Talk by Vincent Cecchini

→ Talks by Malak Hoballah & Xalbat Aguerre



## IV. Astrophysics neutrinos

# Astrophysical sources of neutrinos

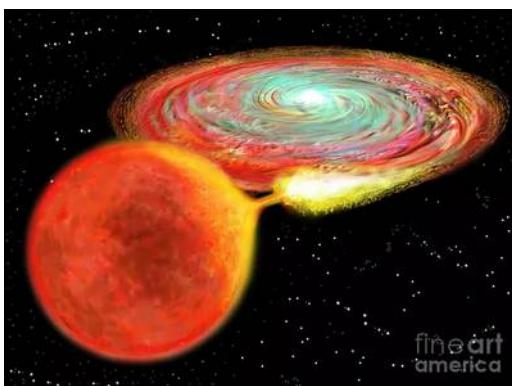


## Low energy : Supernovae

### Type II

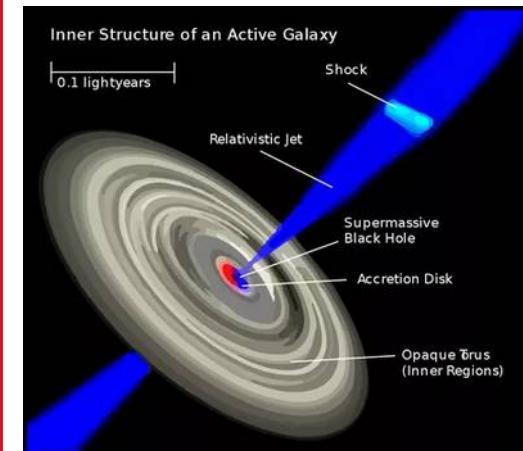


### Type I-A

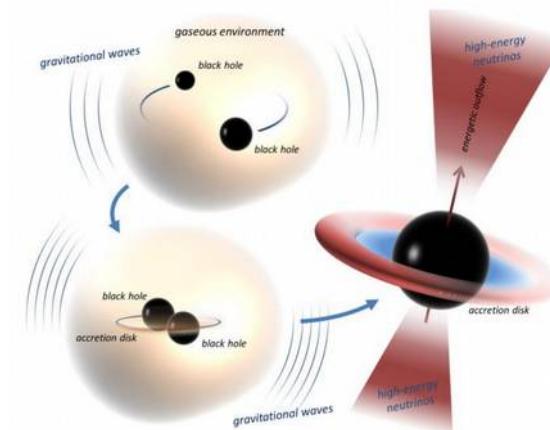


## High energy : Supernovae

### AGN :



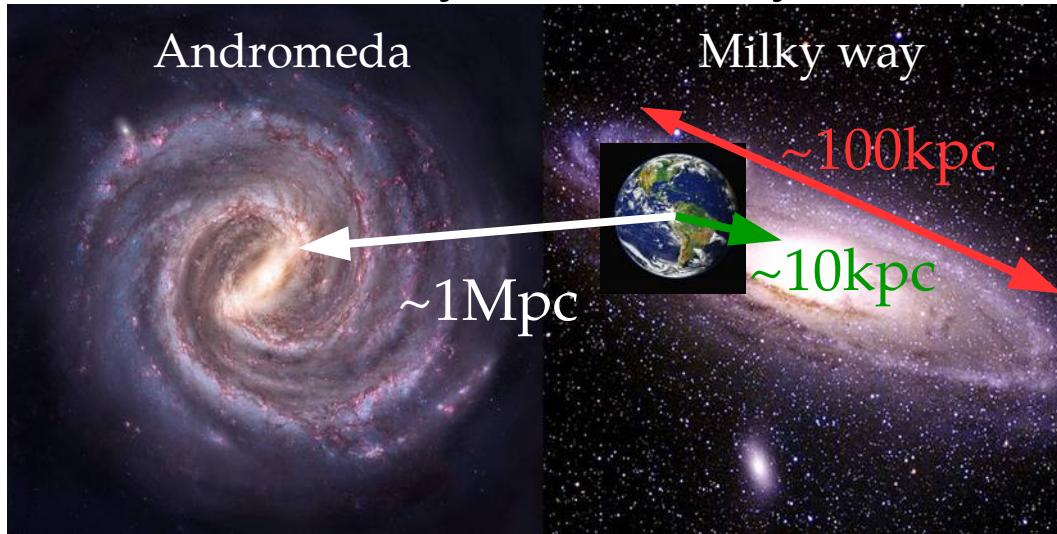
### Neutron stars/BH merger



# Supernovae neutrinos

- 99 % of SN energy emitted in  $\nu$  :

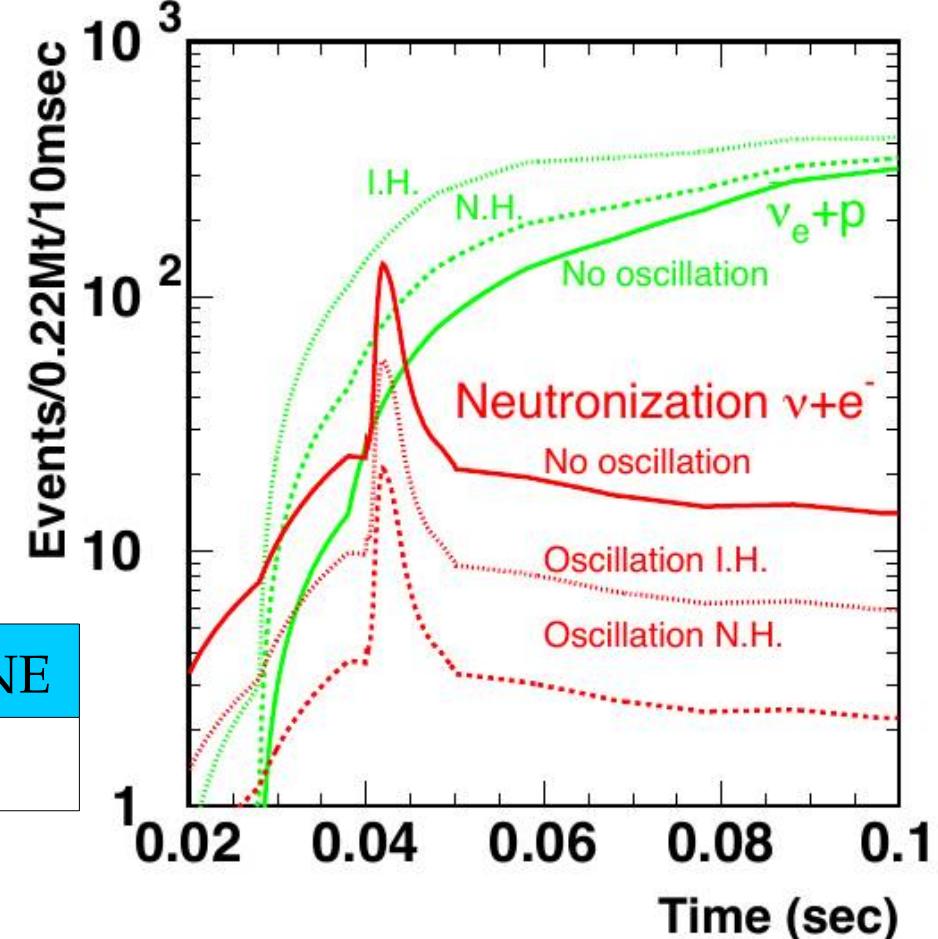
→ Detection very rare... only one 1987... an only ~10 events !



- For SN @galactic center (~10 kpc) :

	SK	JUNO	HK	DUNE
Nevents	8k	8k	60k	7k

→ At 1<sup>st</sup> order, only size matters !



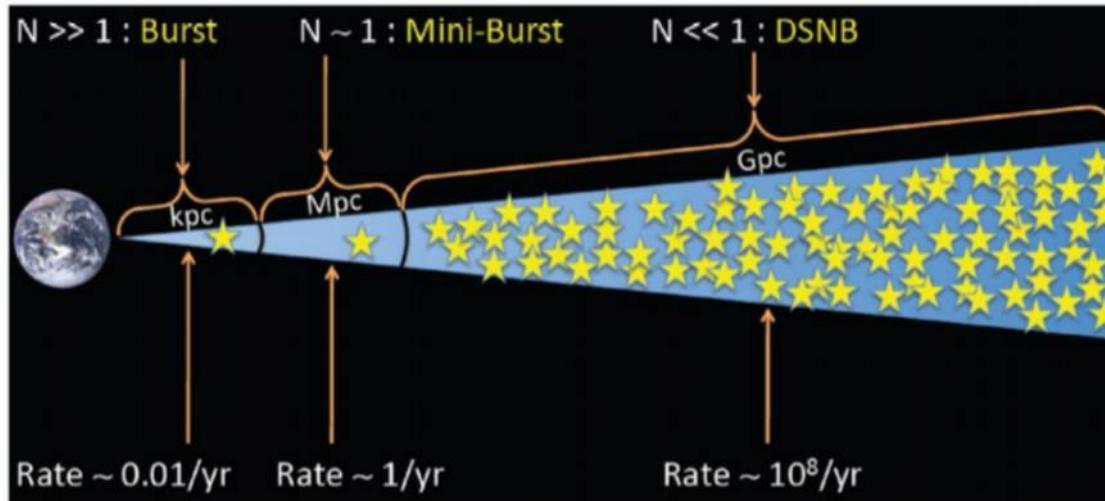
- Time&energy profile :

→ constrains SN-models w/ unprecedeted precision.

→ See talk by Victor Lebrin

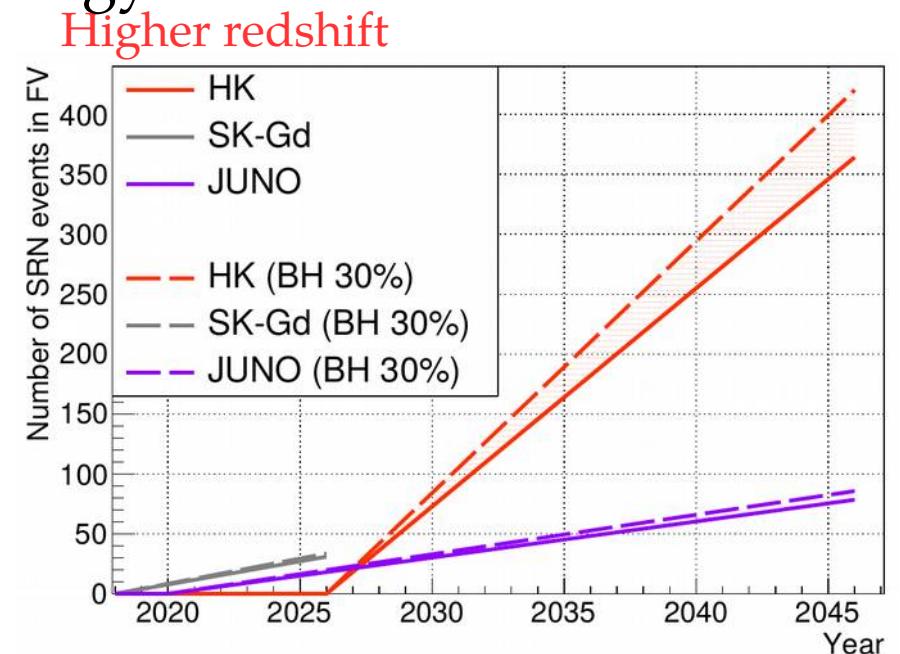
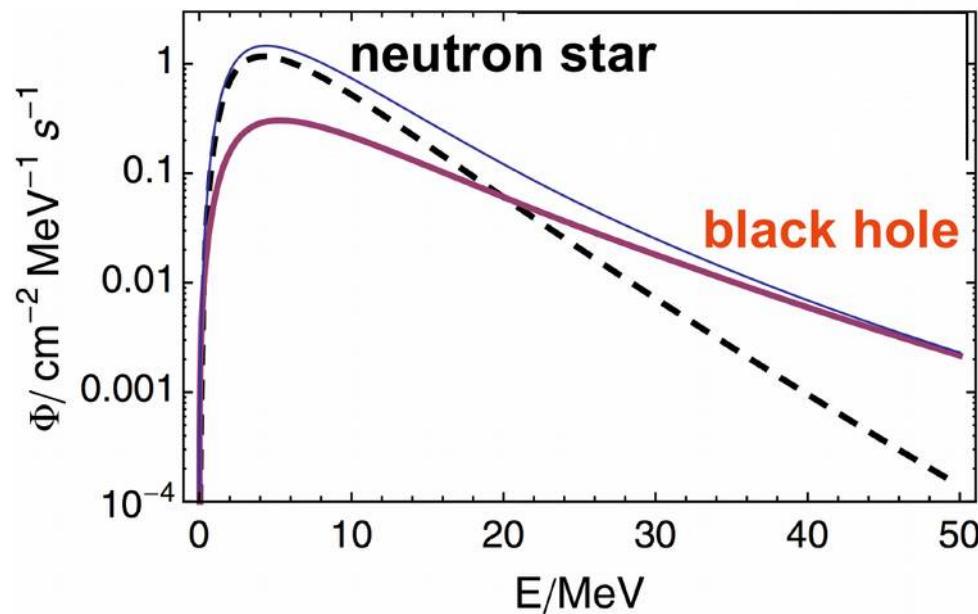
# Diffuse Supernovae Neutrino Background

- Sum of neutrinos emitted by all SN from the start of the universe.



- 1 SN/s in observable universe  
→ new constraints on cosmic star history
- 1<sup>st</sup> detection in SK-Gd & JUNO.

- Spectrum determined by HK : Low energy ↔ Probe older stars



- SK-Gd, JUNO & HK are the pioneer experiments of this domain !

# Conclusions

- Neutrino physics has known an incredible boost in the last 20 years  
→ PMNS matrix has been almost completed.
- Basically opened a new era : measure CPV in neutrino oscillation  
→ Could explain the matter/antimatter asymmetry.

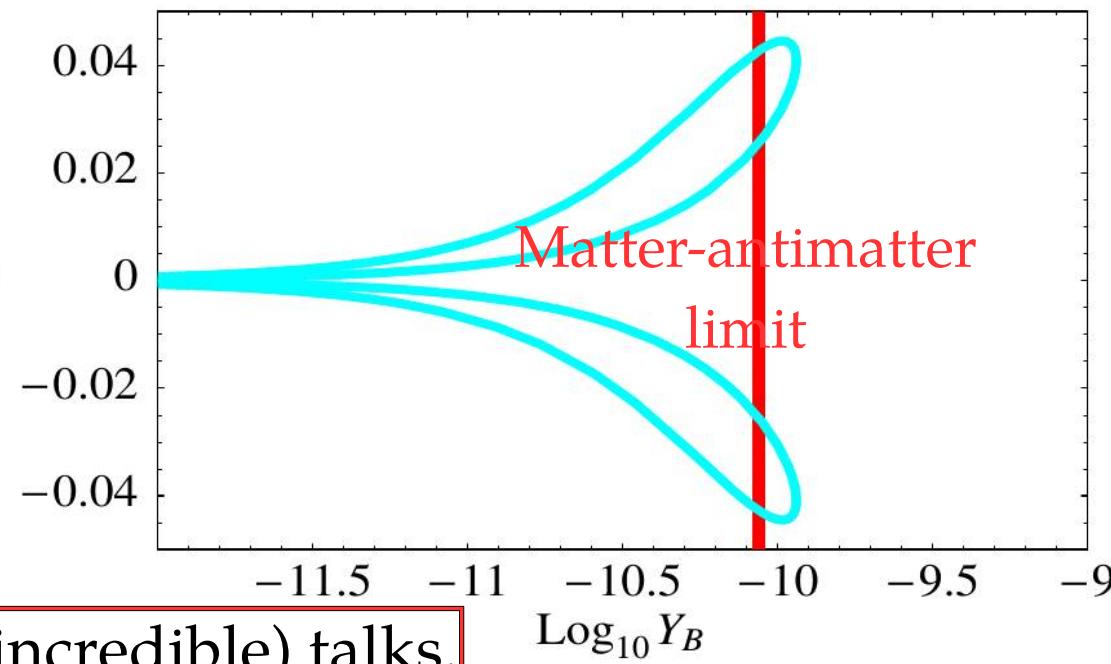


$$\Delta P = P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto J_{CP}$$

$$|Y_B| \cong 2.8 \times 10^{-13} |\sin \delta| \left( \frac{s_{13}}{0.2} \right) \left( \frac{M_1}{10^9 \text{ GeV}} \right)$$

- Large mysteries about nature of ν mass : Dirac or Majorana.

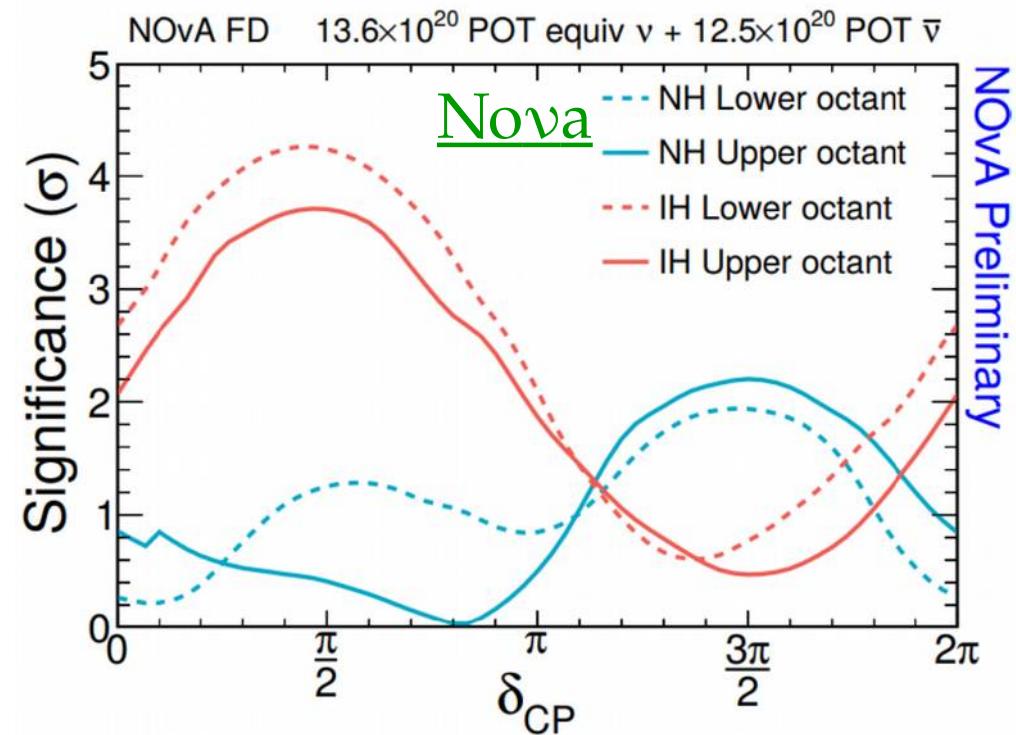
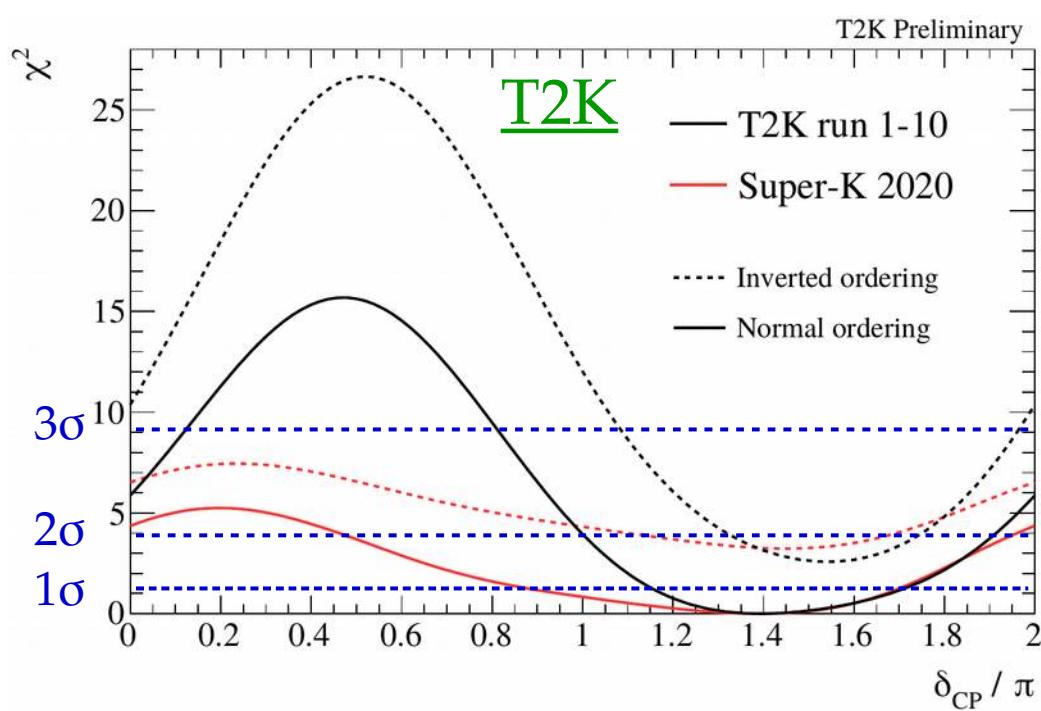
- ν astronomy started in 1987...  
... but is now reaching maturity  
w/ extra-large detectors.



- Please listen to all the incoming (incredible) talks.

# Additional slides

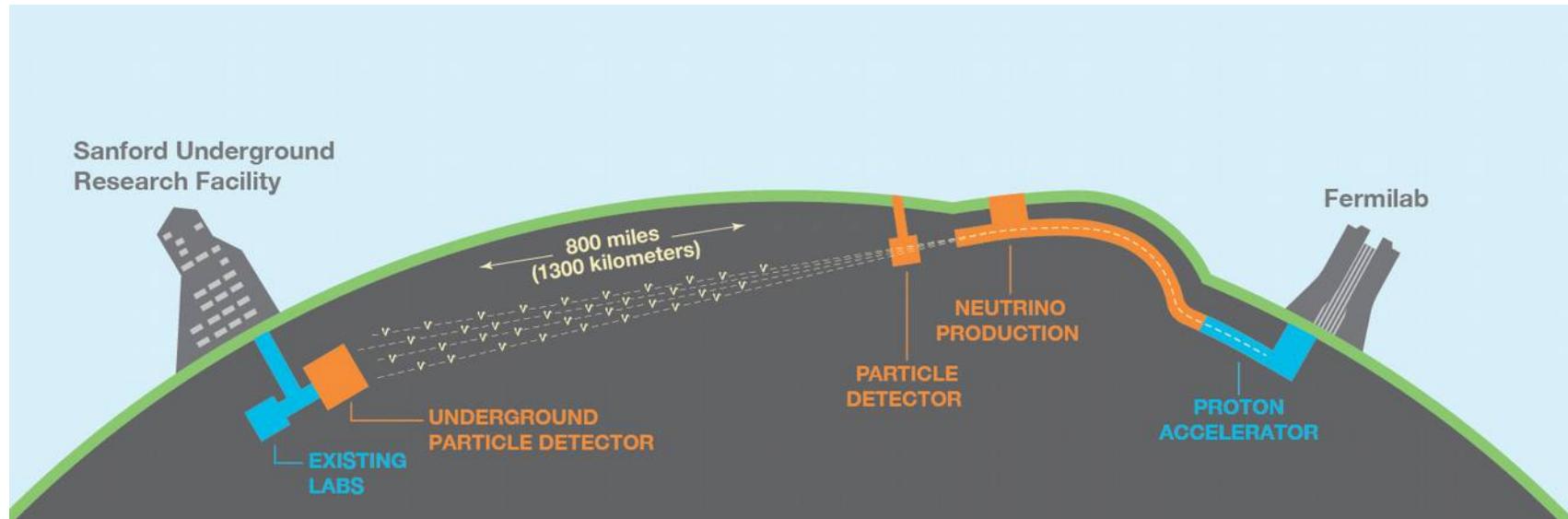
# $\delta_{\text{CP}}$ and mass-hierarchy



- Normal ordering favoured by T2K ( $1\sigma$ ) and SK ( $1.8\sigma$ ).  
→ Nova favours none significantly.
- CP conservation excluded by T2K ( $2\sigma$ ) and SK ( $\sim 1\sigma$ ).  
→ Maximal CPV ( $\delta_{\text{CP}} = 3\pi/2$ ) favoured by T2K & SK, whatever MO.  
→ Nova also favours  $\delta_{\text{CP}} = 3\pi/2$ , but if IO assumed...  
→ Nova largely compatible with CP conservation if NO.

# Next generation of experiments : DUNE

- DUNE is similar to T2K / HK, but in the USA  
→ Baseline is larger :  $L = 1300 \text{ km}$  → Better for Mass Ordering.

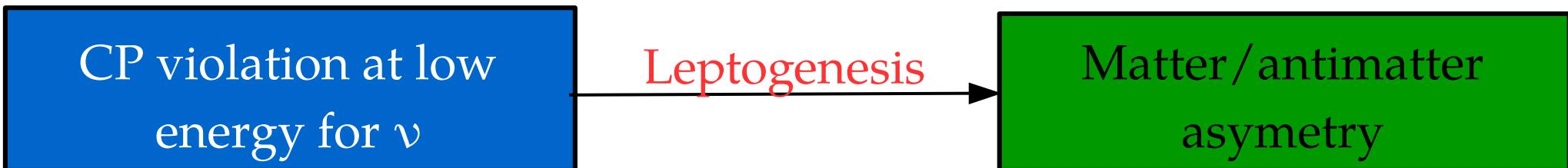


- Similarities and differences between Hyper-K and DUNE :

	HK	DUNE
Baseline	295 km	1300 km
Energy	600 MeV	Large Spectrum $0.8 \rightarrow 6 \text{ GeV}$
Fiducial mass	190 kton	20 - 40kton
Technology	Water Cherenkov	Liquid Argon TPC
First data	2027	2029

# Matter/antimatter asymmetry

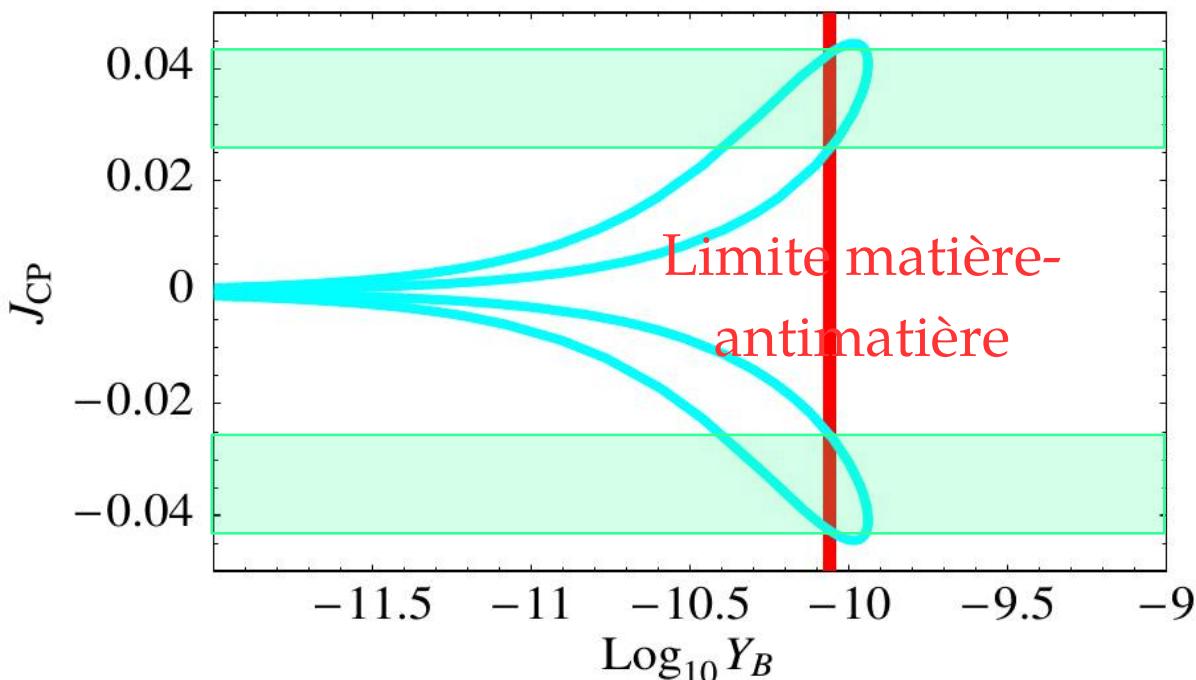
- CP violation in  $\nu$  maybe the key to matter/antimatter asymmetry  
→ Only in weak interactions. Too weak in quark sector.



$$\Delta P = P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto J_{CP}$$

$$|Y_B| \cong 2.8 \times 10^{-13} |\sin \delta| \left( \frac{s_{13}}{0.2} \right) \left( \frac{M_1}{10^9 \text{ GeV}} \right)$$

- First step is to actually measure if CP is violated...



Precision on  $\sin \delta_{CP}$   
↔ Precision on leptogenesis  
models

Lower limit for leptogenesis :  
 $|\sin \theta_{13} \sin \delta_{CP}| \geq 0.11$   
→  $|\sin \delta| \geq 0.78$

# Flavour symmetries

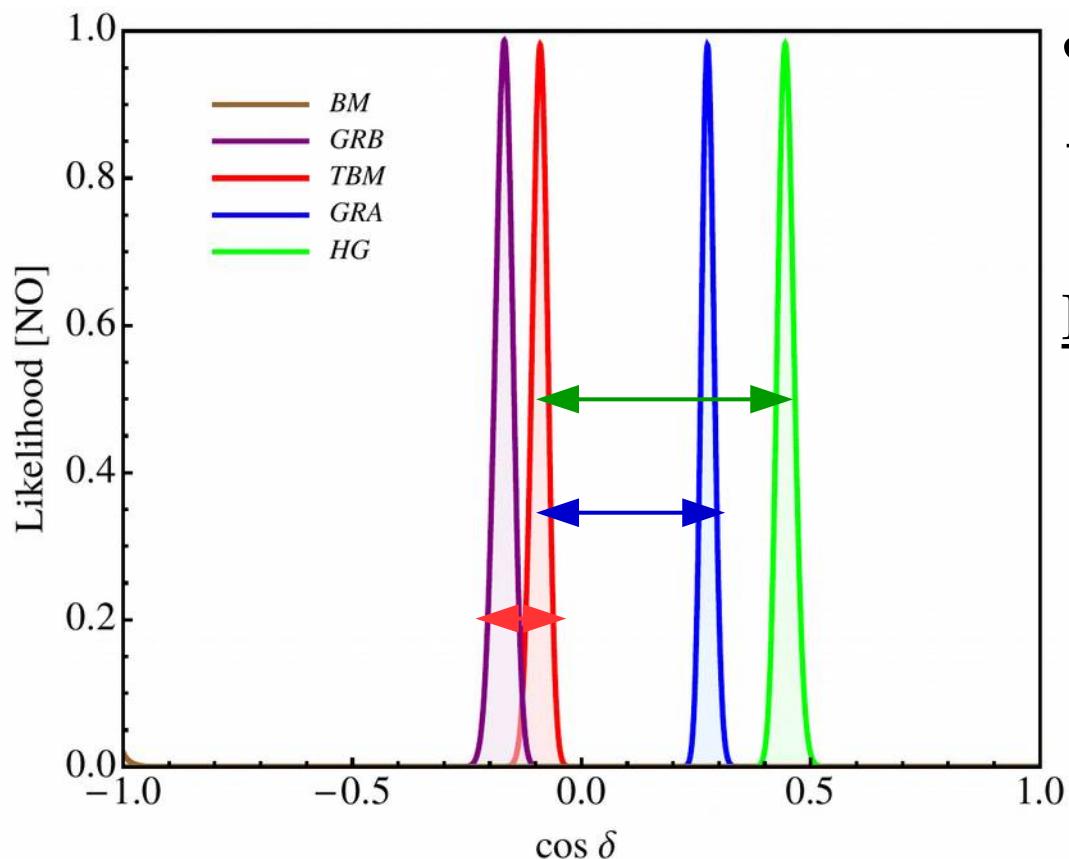
- Models of lepton flavour symmetries could be also tested

$$\begin{aligned} e &\leftrightarrow \mu \leftrightarrow \tau \\ \nu_e &\leftrightarrow \nu_\mu \leftrightarrow \nu_\tau \end{aligned}$$

$$\cos \delta = \frac{\cos 2\theta_{23} \cos 2\theta_{13}}{\sin 2\theta_{23} \sin \theta_{13} (2 - 3 \sin^2 \theta_{13})^{\frac{1}{2}}}$$

Lepton generation symmetric models

Links PMNS parameters



$\delta_{CP}$  = less well-known parameter  
→ Limits the model constraints.

Model separation requires :

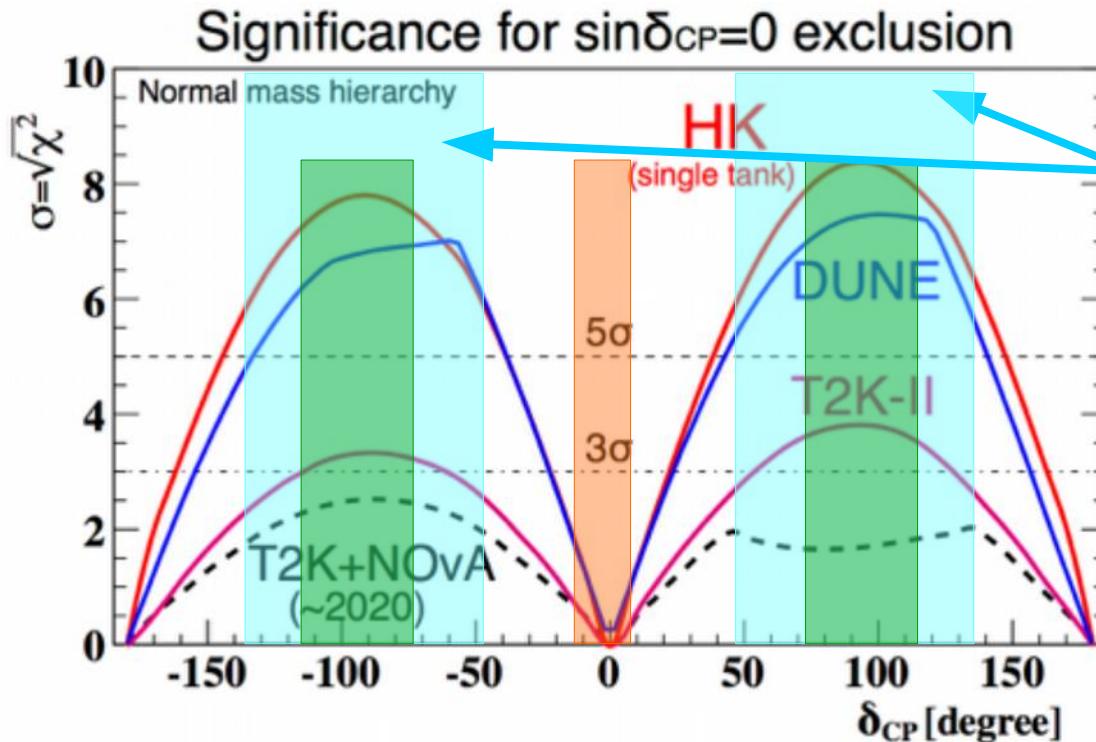
First séparation :  $\delta [\delta_{CP}] < 30^\circ$

Good separation :  $\delta [\delta_{CP}] < 23^\circ$

Great séparation :  $\delta [\delta_{CP}] < 5^\circ$

→ Precision of our experiments ?

# Leptogenesis scenarios

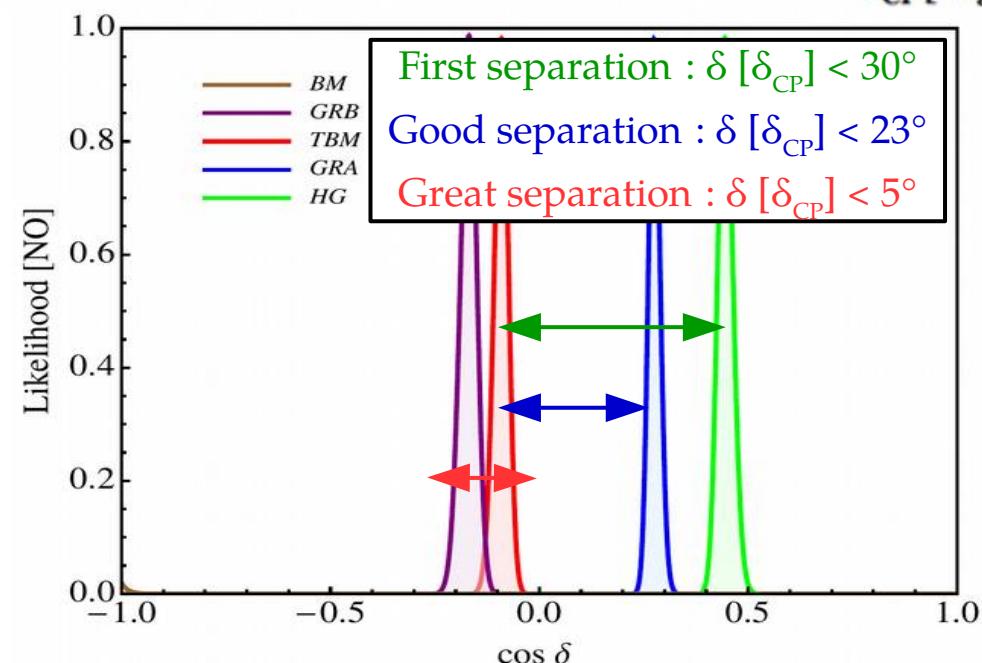


Lower leptogenesis limit :  $|\sin\delta| \geq 0.78$

HK/DUNE accuracies

- If  $\delta_{CP} = 0$
- If  $\delta_{CP} = -\pi/2$

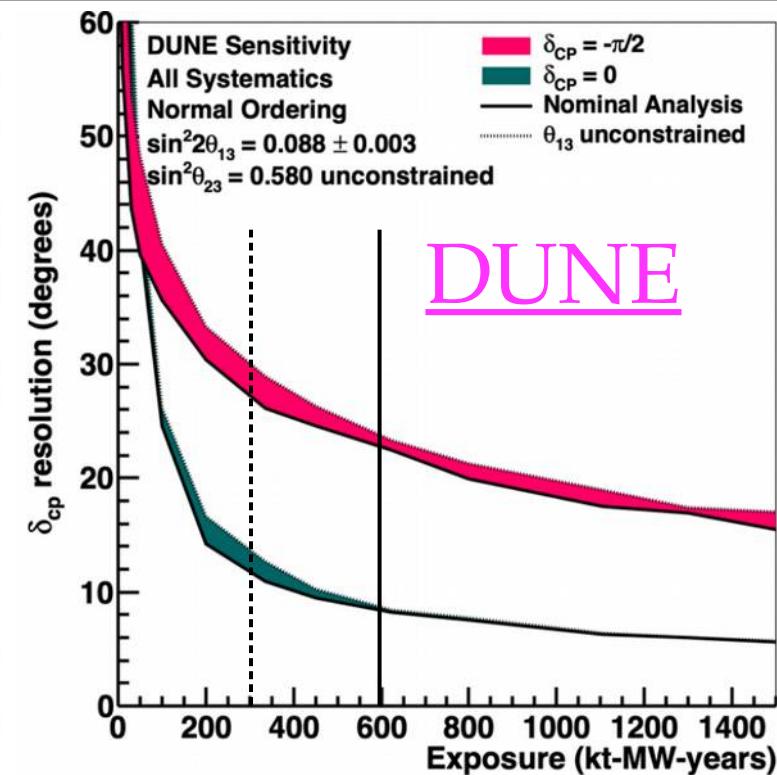
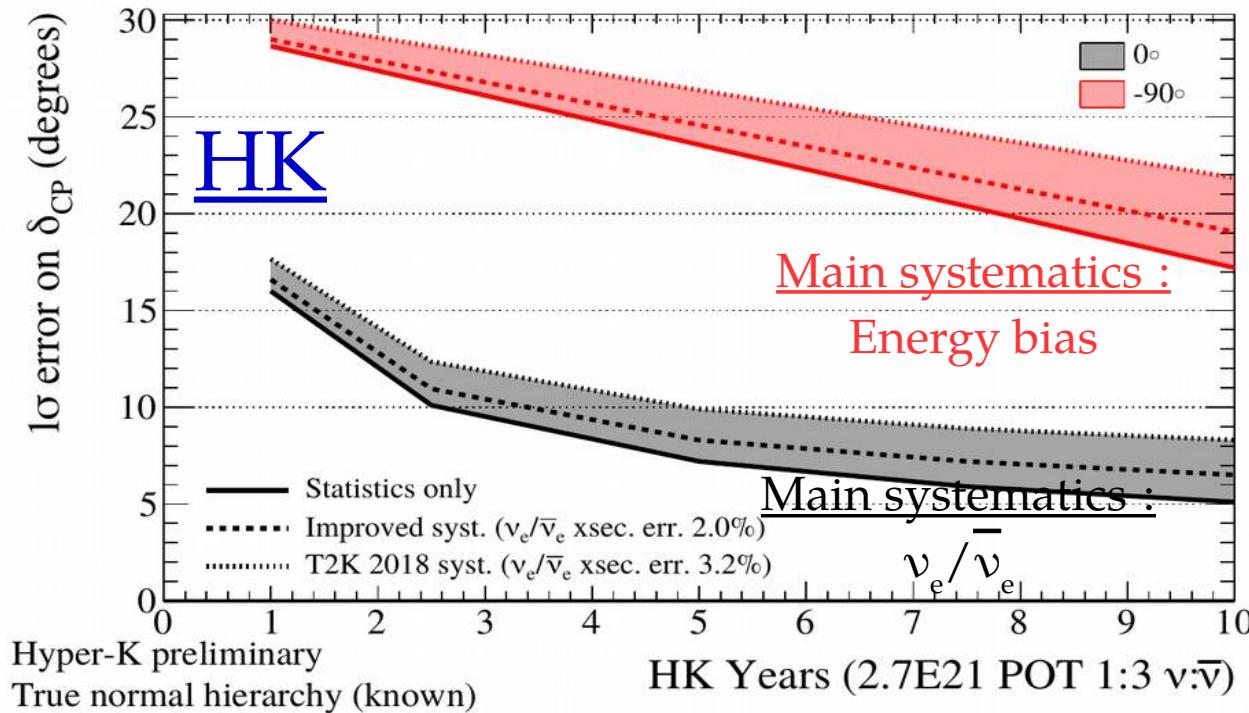
No CPV (Si  $\delta_{CP} = 0$ ) : Definitely exclude explanation of mat./antimat. asymmetry through Dirac CPV.



If CPV (i.e.  $\delta_{CP} = -\pi/2$ ) : Strong constraints on leptogenesis models.

HK ( $19^\circ$ ) & DUNE ( $24^\circ$ ) will provide « good » separation after 10 years  
 $\rightarrow$  Even better if  $\delta_{CP} = 0$ .

# Precision of $\delta_{CP}$ measurement



	5 years HK & DUNE	10 years HK & DUNE
CP conserved $\delta_{CP} = 0$	$8^\circ$ & $13^\circ$	$6^\circ$ & $9^\circ$
$\delta_{CP} = -\pi/2$	$25^\circ$ & $29^\circ$	$19^\circ$ & $24^\circ$

- World-leading sensitivity of HK and DUNE on  $\delta_{CP}$

→ Needs the two experiments to maximize impact on leptogenesis !