The 19th International Workshop on Neutrinos from Accelerators (NUFACT2017)

25-30 September 2017
Uppsala University Main Building
Europe/Stockholm timezone

Physics prospects of the JUNO experiment

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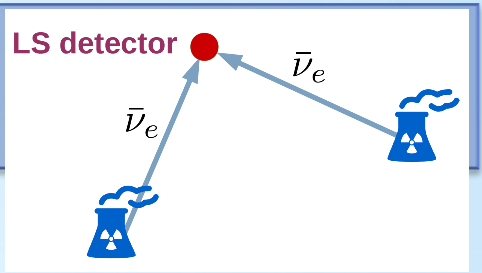
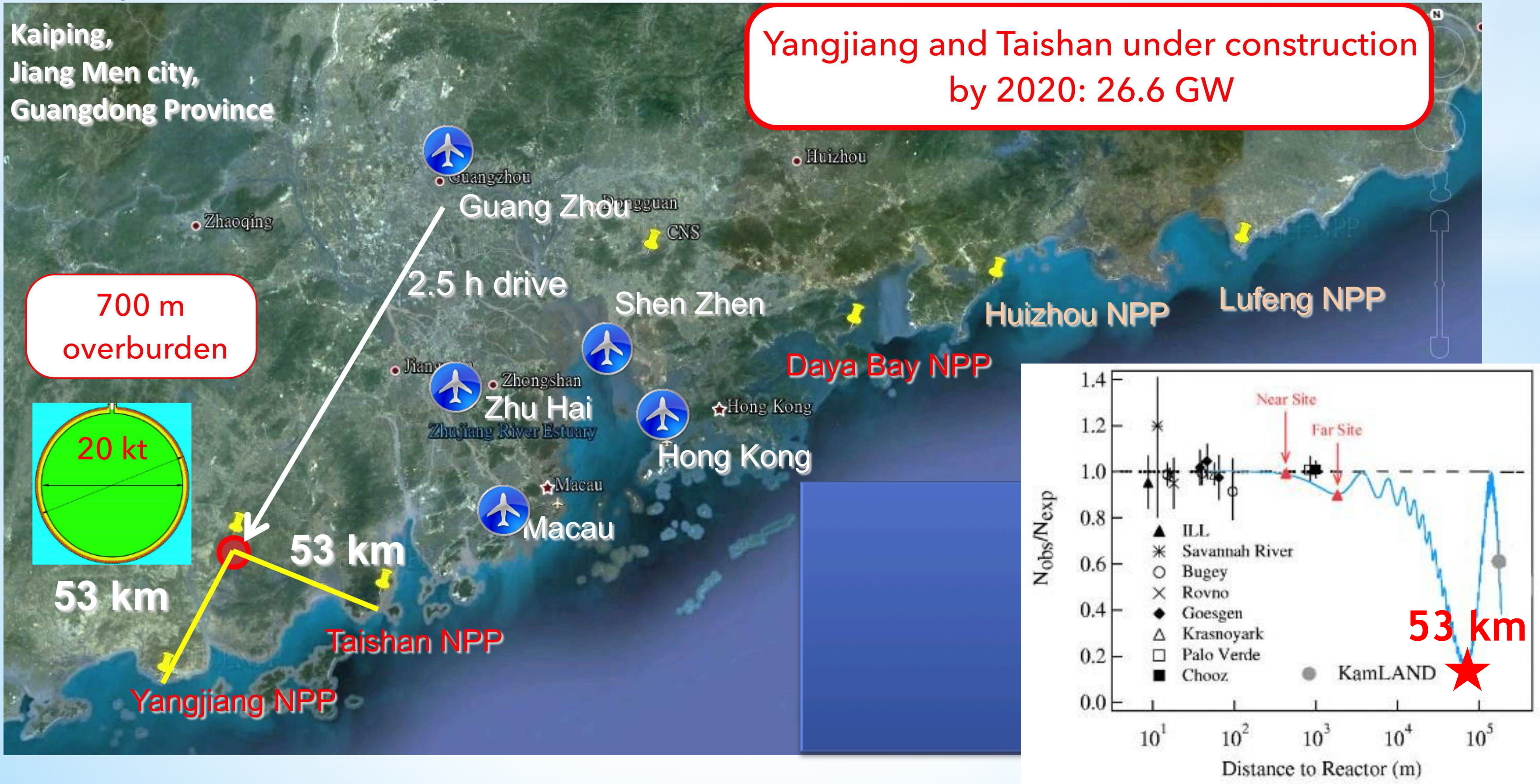
What is JUNO ?



JUNO = Jiangmen Underground Neutrino Observatory

- JUNO is a "medium-baseline" (53km) reactor neutrino experiment located in China, under construction (data taking foreseen in 2020)
- JUNO will be the largest Liquid Scintillator detector ever built (20kt)
- Goals : Measurement of the neutrino mass hierarchy (NMH) and oscillation parameters + astroparticle and rare processes

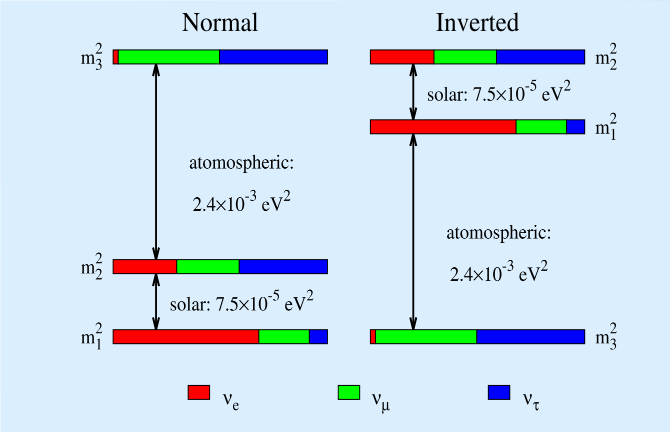


Neutrino Mass hierarchy (NMH)

The electron antineutrino survival probability in vacuum :

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

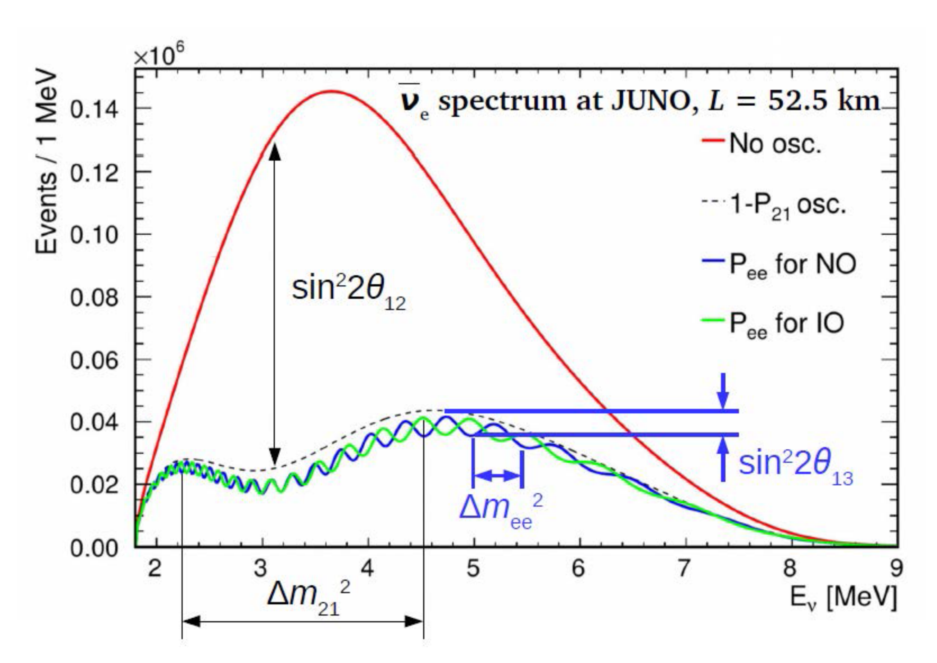


Depending on the NMH, the oscillation frequency differs :

$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \qquad \omega P_{31} > \omega P_{32} \\
\mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \qquad \omega P_{31} < \omega P_{32}
\end{aligned}
$$

The L/E spectrum contains the NMH information

JUNO antineutrino energy spectrum:



Key issues :

- energy resolution and energy scale
- Large statistics

JUNO Collaboration

72 institutes
553 members

EUROPE(30)

Armenia (1)
YPI Erevan
Belgium (1)
ULB Brussels
Czech (1)
Charles U.
Finland (1)
U. Oulu
France (6)
APC Paris
CENBG France
CPPM Marseille
IPHC Strasbourg
LLR Paris
Subatech Nantes
Germany (7)
FZ Julich
RWTH Aachen
TUM Munich
U Hamburg
IKP FZI Jülich
U Mainz
U Tuebingen
Latvia (1)
IECS Riga

Italy (8)
INFN Catania
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Bicocca
INFN-Padova
INFN-Perugia
INFN-Roma3

Russia (3)
JINR Dubna
INR Moscow
MSU Moscow
Slovakia (1)
Comenius U

ASIA(37)

China (33)

BISEE
BNU
CAGS
CQU
CIAE
DGUT
ECUST
Guangxi

HIT
IHEP
IMP
CAS
Jilin U
Jinan U
Nanjing U
Nankai U

Natl. CT U
Natl. Taiwan U
Natl. United U
NCEPU
Pekin U
Shandong U
Shanghai JTU
Sichuan U
SUT

Tsinghua
SYSU
UCAS
USTC
U. of S. China
Wuhan
Wuyi
Xiamen U
Xi'an JTU

Thailand SUT
Thailand CU
Thailand NARIT
Pakistan PINST

AMERICA (5)

PUCC Chile
UTFSM Chile
Maryland U
(2 groups)
UEL Brazil

Today's presentation

- *(Short introduction to) The JUNO detector*
- *The neutrino mass hierarchy measurement*
- *Other physics programs*

The JUNO detector

Only the general concepts here
Next talk : Design and Status of the JUNO experiment
by Pedro Ochoa

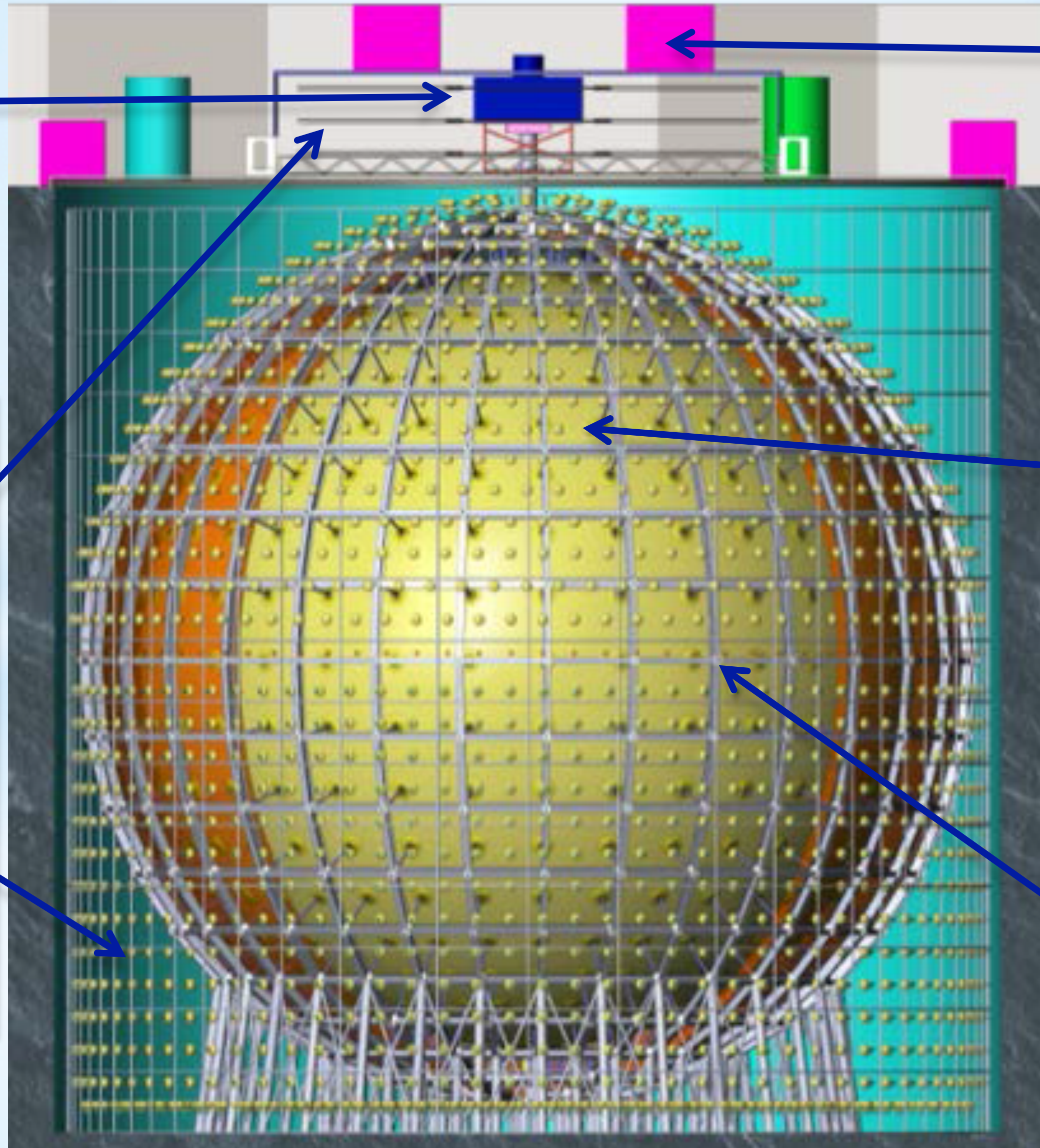
Detector design

Calibration
4-complementary calibration systems
(1D, 2D, and 3D)

Muon veto :

Top Tracker
(The OPERA TT is re-use as Top Tracker for JUNO)

Water Cherenkov Veto
20kt water and 2000 20” PMTs



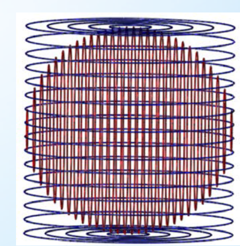
Electronics

Central detector :
Large volume of Liquid Scintillator (LS)
→ for the statistics

Acrylic sphere
(35.4 m diameter)
Filled with 20kt LS
18000 20” PMTs and 25000 3” PMTs
(double calorimetry)
High light coverage
→ for energy resol.

Stainless steel

Magnetic Field Compensating Coil



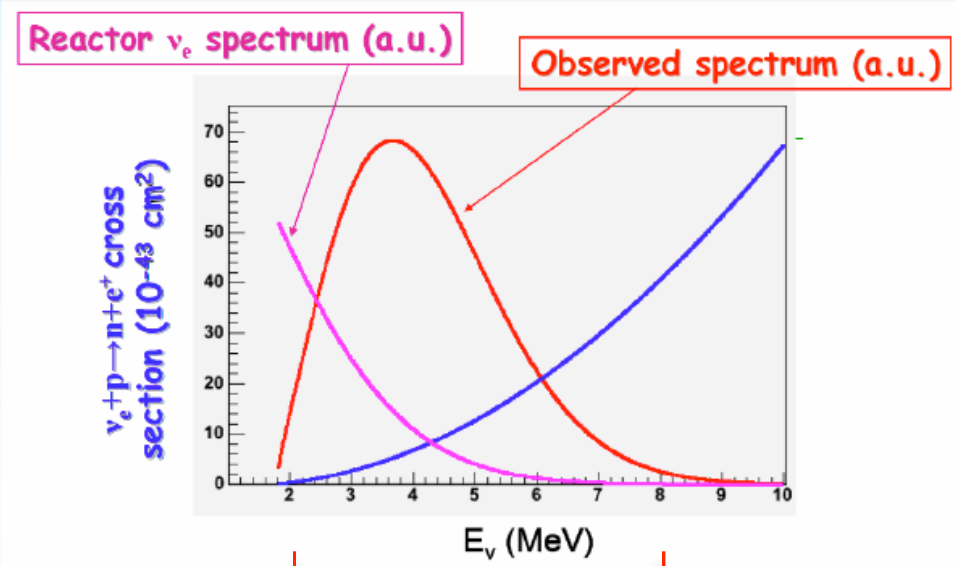
Neutrino detection

- Neutrinos are observed via **Inverse Beta Decay (IBD) :**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

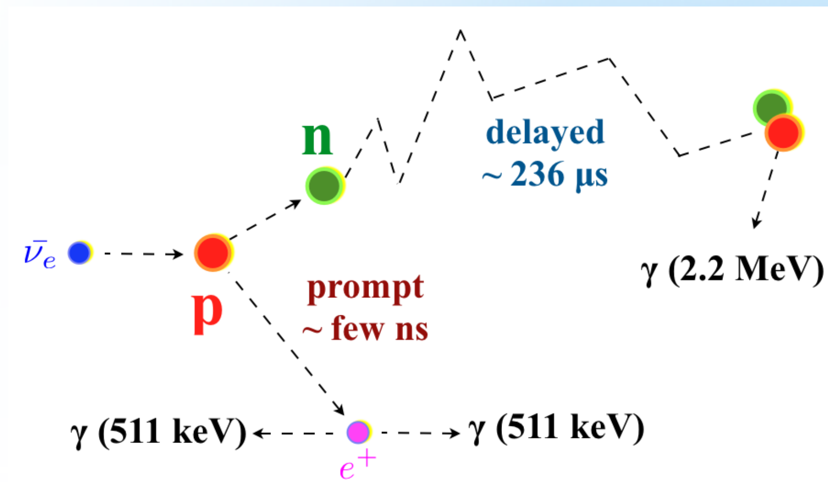
$$\tau \simeq 200\mu\text{sec} \quad \longrightarrow \quad n + p \rightarrow d + \gamma$$

$$E_{\bar{\nu}_e} \cong E_{e^+} + \underbrace{E_n}_{\text{30-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\text{1.8 MeV}}$$



→ E : (2 to 8) MeV

- **The signal signature is given by:**
  - Prompt photons from e+ ionisation and annihilation (1-8 MeV).
  - Delayed photons from n capture on Hydrogen (2.2 MeV).
  - Time (Δt~200 μs) and spatial correlation.



→ Very clean signature

Detector performance goals

	Daya Bay	BOREXINO	KamLAND	RENO-50	JUNO
Target Mass	20t	~300t	**~1kt**	**~18kt**	**~20kt**
PE Collection	~160 PE/MeV	**~500 PE/MeV**	~250 PE/MeV	**>1000 PE/MeV**	**~1200 PE/MeV**
Photocathode Coverage	~12%	**~34%**	**~34%**	**~67%**	**~80%**
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	**3%/√E**	**3%/√E**
Energy Calibration	~1.5%	**~1%**	~2%	**?**	**<1%**

→ An unprecedented LS detector !

The physics program

See JUNO Collaboration, Neutrino physics with JUNO, J. Phys. G 43 (2016) 030401

Selection cuts and background

Main backgrounds for the reactor neutrino oscillation analysis :

- **Cosmogenic** bg : in the LS, cosmic μ can interact with ^{12}C → radioactive isotopes as Lithium (^{9}Li), Helium (^{8}He). Can decay via (beta, neutron) → mimic antineutrino signal
- **Accidental bg**: mainly three types of random coincidence: (radioactivity, radioactivity), (radioactivity, cosmogenic isotope) and (radioactivity, spallation neutrons)

Expected rate of events per day :

For 36 GW thermal power, L= 53 km,
And with a 20-kton LS detector

Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α,n)
-	-	83	1.5	$\sim 5.7\times10^{4}$	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.8				

Applying the different selection cuts :
Fiducial volume, energy cut, time cut, vertex cut, muon veto

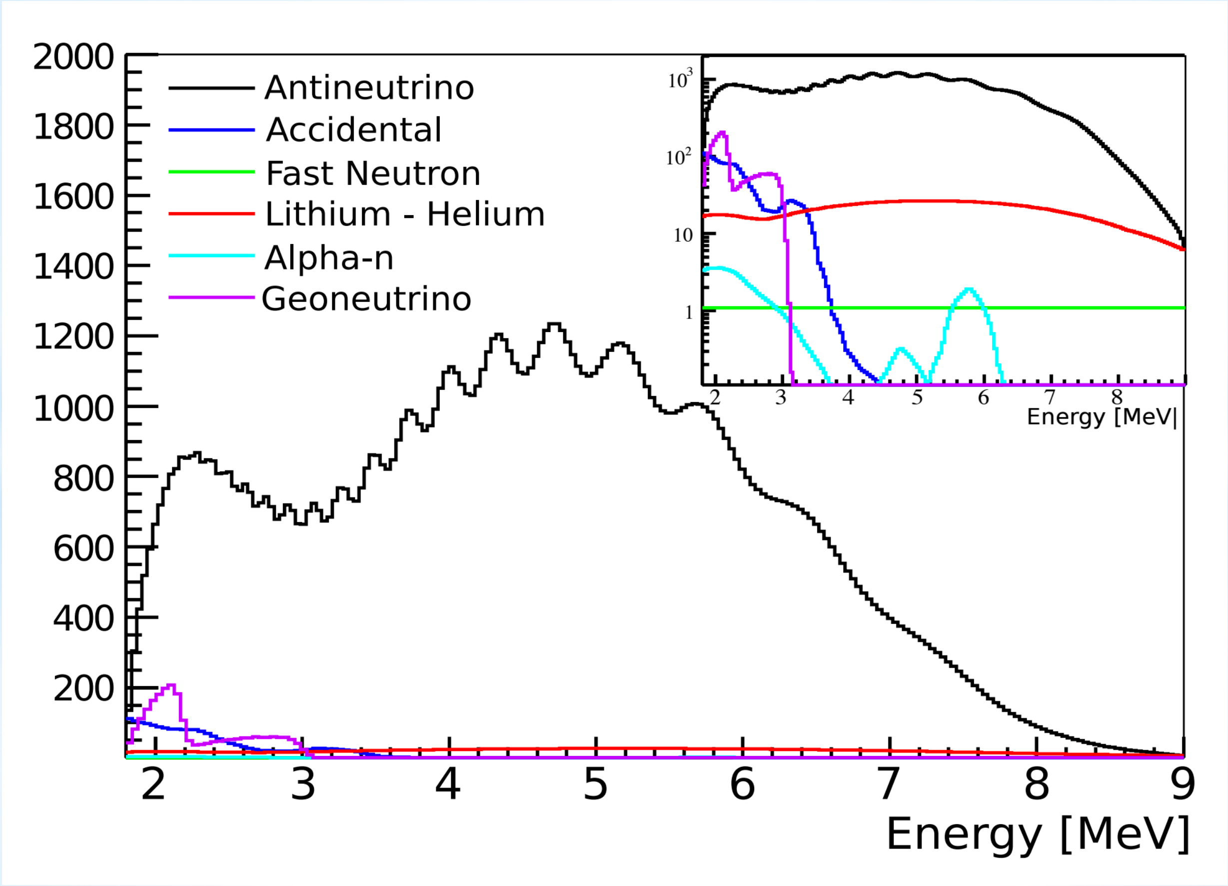
Signal rate : 60 events/day
Background rate : 3.8 events/day

(About 6% of background)

Selection cuts and background

[J. Phys. G 43 (2016) 030401]

Expected antineutrino signal spectrum
For the signal and the 5 kinds of backgrounds

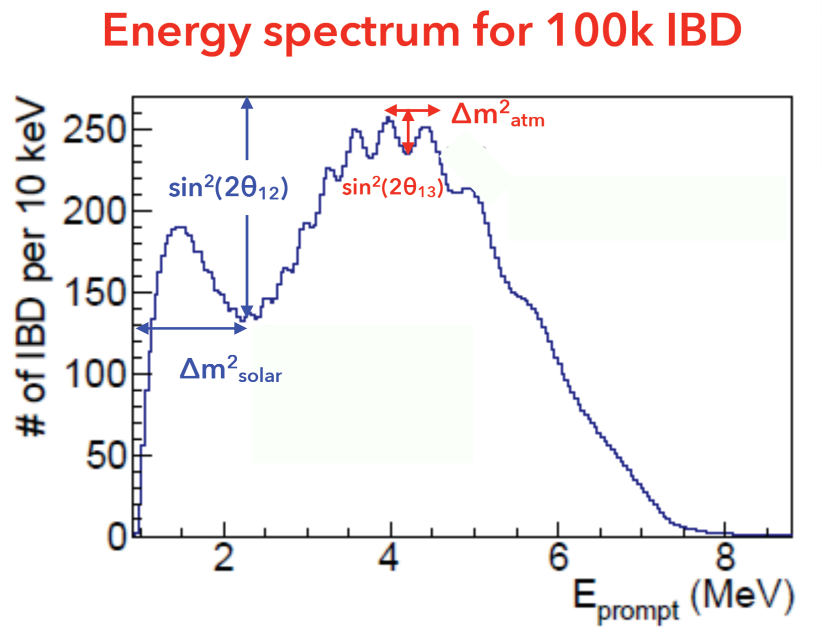


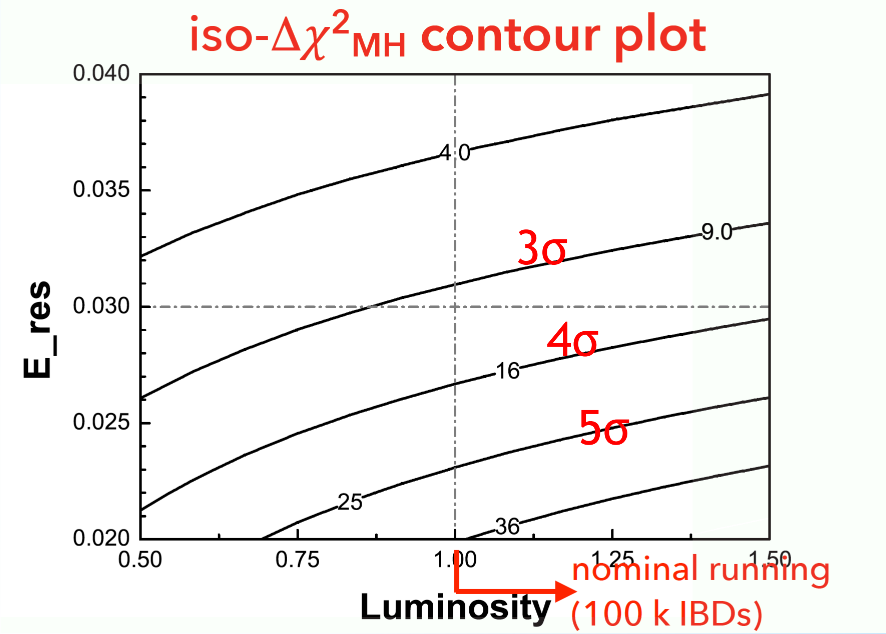
Nominal luminosity for six years of data taking (20 kt LS, and 36 GW reactor power)
→ a total of 100k IBD events
Assuming an energy resolution of 3%/√E

Neutrino oscillation parameters

[J. Phys. G 43 (2016) 030401]

- NMH : For σ(E) = 3% at 1 MeV → 3σ sensibility (ΔX=9) for 100 000 events (20Kt x 36 GW x 6 years of data taking)





- Three oscillation parameters :
  Δm^2_{12}, $|\Delta m^2_{ee}|$ and $\sin^2 2\theta_{12}$ can be measured with precision better than 1%
  → Probing the unitarity of U_{PMNS} to ~1% level

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

JUNO Physics goals

[J. Phys. G 43 (2016) 030401]

Neutrino oscillations - In the 3-flavour framework : 6 independent parameters

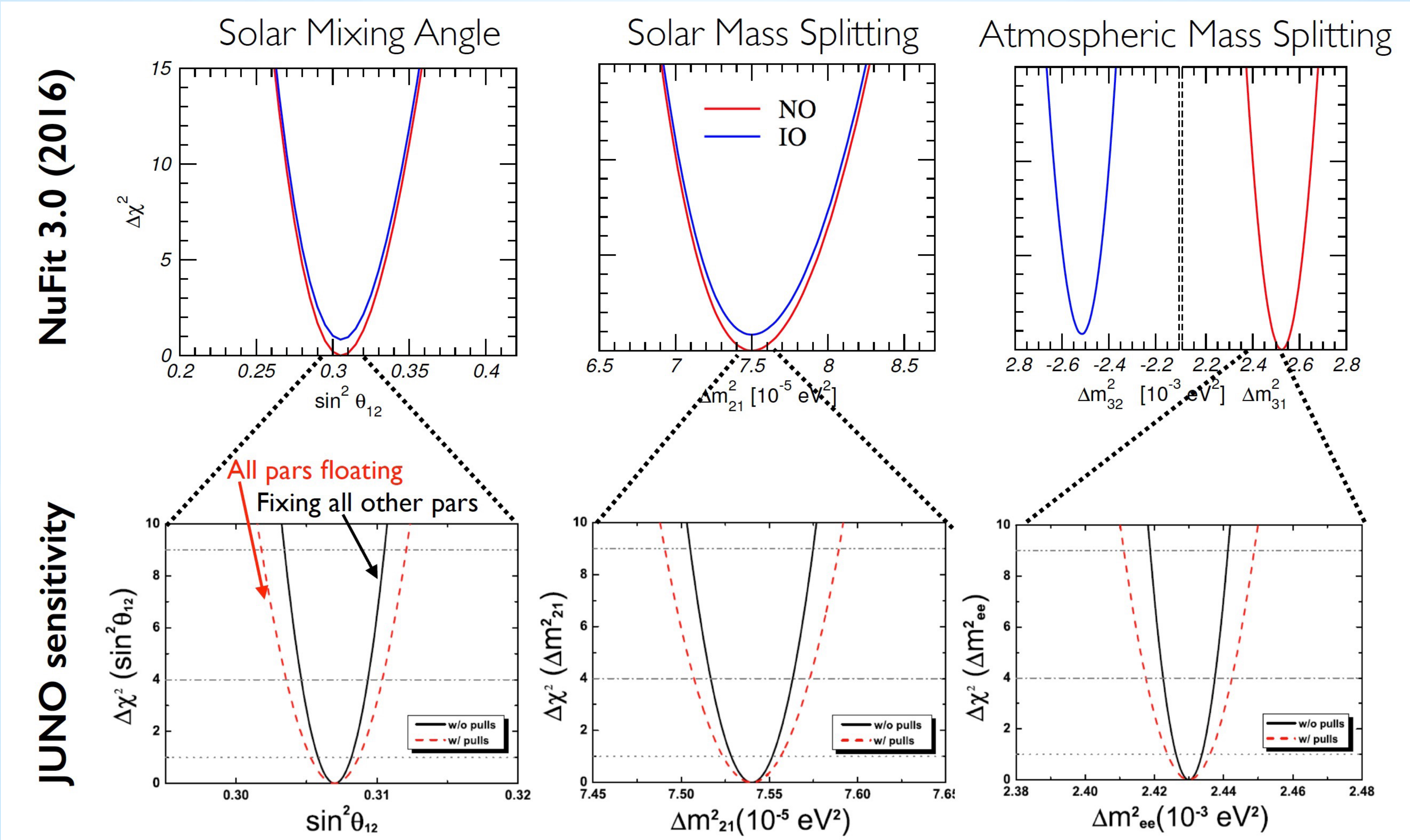
Current best estimation :

[F. Capozzi et al., arXiv: 1703.04471]

Parameter	Value		Uncertainty (1σ)	Expected JUNO precision :
	NH	IH		
$\sin^2\theta_{12}$	0.297		5%	< 1%
$\sin^2\theta_{13}$	0.0214	0.0218	4%	
θ_{23}	~45º		octant is unknown	
Δm^2_{21}	$7.37\cdot10^{-5}$ eV^2		2.3%	< 1%
$\lvert\Delta m^2_{31}\rvert$	$2.50\cdot10^{-3}$ eV^2	$2.46\cdot10^{-3}$ eV^2	2.5%, sign is unknown	sign
δ^{CP}	1.35	1.32	~50%	

JUNO Physics goals

[J. Phys. G 43 (2016) 030401]



$\sin^2(\theta_{12})$: 0.54%

Δm^2_{21}: 0.24%

Δm^2_{ee}: 0.27%

JUNO Physics goals

But also :

- TERRESTRIAL AND EXTRATERRESTRIAL NEUTRINO SOURCES:
  - Neutrino from supernova burst
  - Diffused supernova neutrino background (1-4 events/year)
  - Solar neutrinos
  - Atmospheric neutrinos
  - Geo-neutrinos

- EXOTIC PHYSICS:
  - Exotic searches as proton decay ($p \rightarrow K^+ + \bar{\nu}$)
  - Sterile neutrinos : using an artificial source close to or inside the LS
  - Indirect dark matter search
  - …

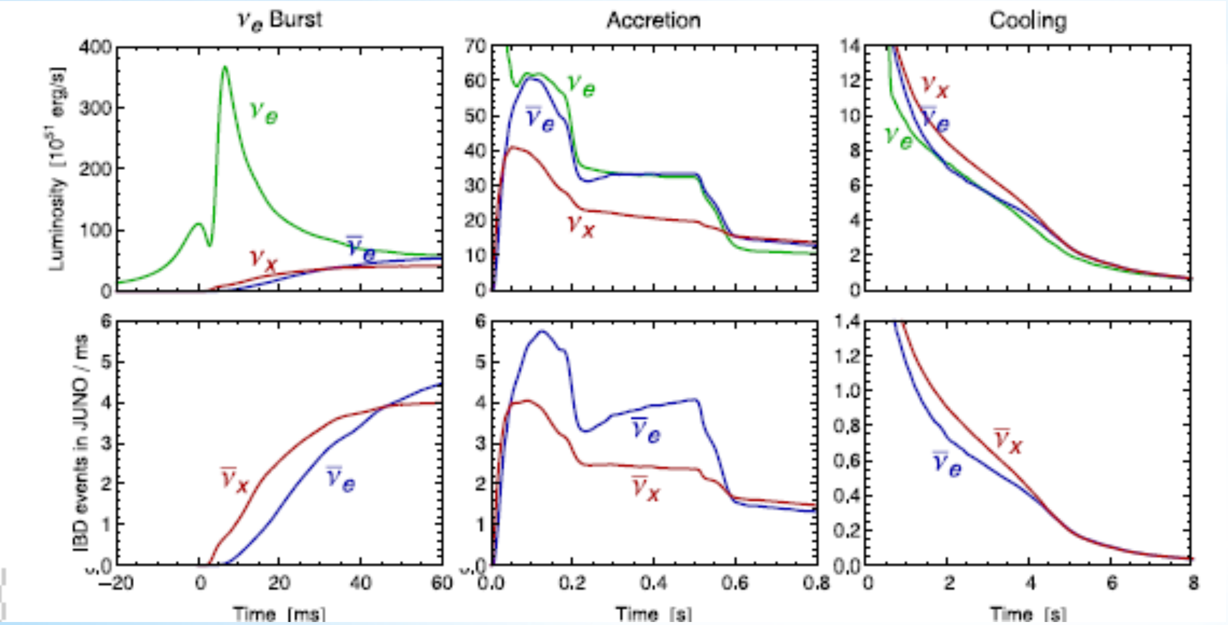
See : [J. Phys. G 43 (2016) 030401]

Neutrinos from supernova burst

[J. Phys. G 43 (2016) 030401]

- The galactic core-collapse SN rate is one every few decades → not to be missed
  The ν burst occurs several hours before the explosion and optical outburst → alert
- **Large amount of neutrino events :**
  ~10^4 for a burst@ 10 kpc
- **Short time:** ~10 seconds
- DAQ system adapted to detect SN
- Separate detection
  of ν_e, $\overline{\nu}_e$ and (ν_μ,ν_τ,$\overline{\nu}_\mu$,$\overline{\nu}_\tau$)

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2



Three phases of neutrino emission from a core-collapse SN

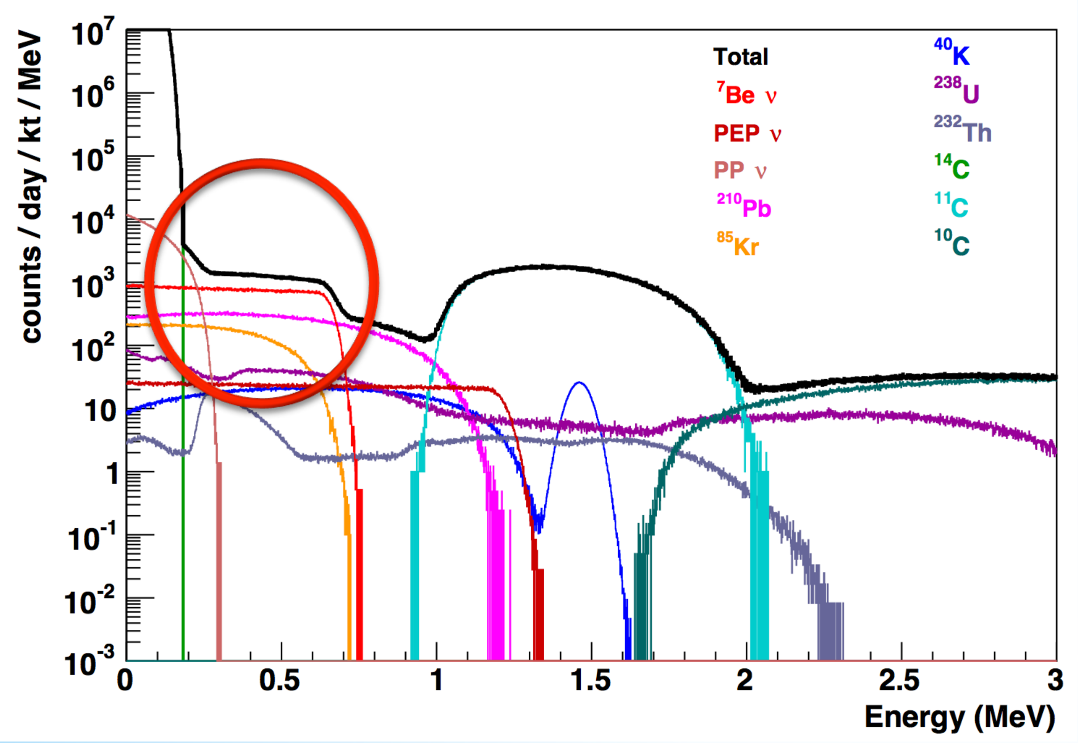
Physical outcomes:
- Models of SN burst - Pre-SN ν
- SN nucleosynthesis via ν_x spectra
- ν mass: < 0.83±0.24 eV at 95% CL [arXiv:1412.7418]
- Locating the SN: ~9°

Solar neutrinos

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$$

- Detection of solar neutrinos of all flavors through electron scattering → single flash light in JUNO
- Low level of intrinsic background is required

The expected single spectra :



Internal radiopurity requirement		
	baseline	ideal
^{210}Pb	5×10^{-24} [g/g]	1×10^{-24} [g/g]
^{85}Kr	500 [counts/day/kton]	100 [counts/day/kton]
^{238}U	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{232}Th	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{40}K	1×10^{-17} [g/g]	1×10^{-18} [g/g]
^{14}C	1×10^{-17} [g/g]	1×10^{-18} [g/g]
Cosmogenic background rate [counts/day/kton]		
^{11}C	1860	
^{10}C	35	
Solar neutrino signal rate [counts/day/kton]		
pp ν	1378	
^{7}Be ν	517	
pep ν	28	
^{8}B ν	4.5	
^{13}N/^{15}O/^{17}F ν	25/28/0.7	

The expected rate in JUNO

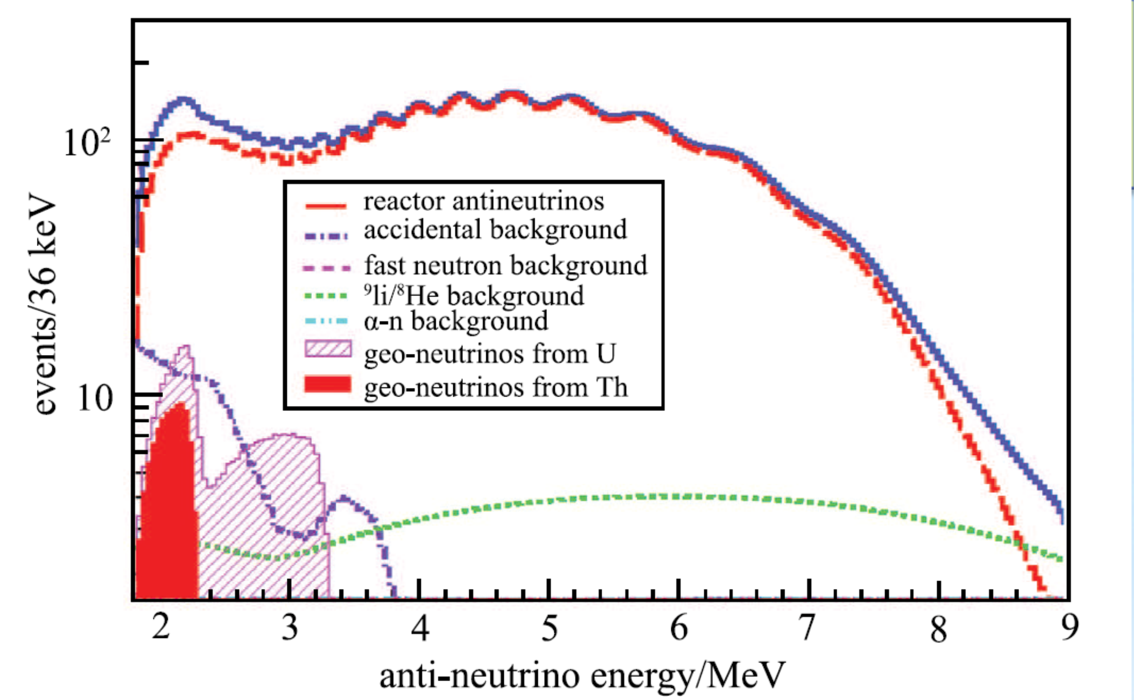
- Better understanding solar model:
  - ^{7}Be and ^{8}B spectra
  - Metallicity (discrimination of high and low Z version of the Solar Model)

[J. Phys. G 43 (2016) 030401]

Geo-neutrinos

- Detect the earth's emission of neutrinos (from U, Th)

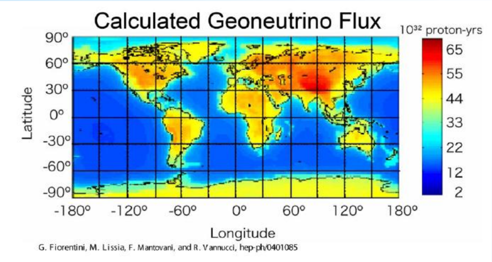
- **Current results :**
  - KamLAND: 30 ± 7 TNU [PRD 88 (2013) 033001]
  - Borexino: 43.5 ± 14.5 TNU [PRD 92 (2015) 031101]
  (Statistics dominant)



Chinese Phys. C40 N3 (2016) 033003

- **Goal** : to reach an error of 3 TNU
  Terrestrial Neutrino unit = 1IBD event/year/10^{32} protons (1kt LS)
- JUNO: x20 statistics
- But huge reactor neutrino bg
- Need accurate reactor spectra and accidental/Li/He bg under control

Source	[1.8-9.0] MeV ev/yr	[1.8-3.3] MeV ev/year	Uncertainty
geo	408	406	
reactor	16100	3653	±2.8%(rate)±1%(shape)
^{8}Li/^{8}He	657	105	±20%(rate)±10%(shape)
fast n	36.5	7.7	±100%(rate)±20%(shape)
αn	18.2	12.2	±50%(rate)±50%(shape)
accidental	401	348	±1%(rate)



Conclusions

- Neutrino sector : there are still key unknown parameters
  Key issues in our understanding of physics today

- JUNO experiment under construction - Important parameters are :
  the energy resolution/energy scale, and collecting large statistics

- JUNO will provide:
  - **First measurement of NMH** independent of the CP phase and matter effect
    First experiment to simultaneously observe "solar" and "atm" oscillations
    First experiment to observe more than two cycles of neutrino oscillations
  - **Precise measurements of $\sin^2 2\theta_{12}$, Δm^2_{12} , Δm^2_{ee} to < 1%**
    Probing the unitarity of U_{PMNS} to subpercent level
  - **Several other secondary physics goals and measurements**
    from terrestrial and extra-terrestrial neutrino sources
    (supernovae, solar, atmospheric, geo-neutrinos, …), also exotic physics
    (proton decay, sterile neutrinos, …)

→ Several key measurements,
20 years of copious physics with reactor neutrinos and beyond

- Complementary to long baseline accelerator program

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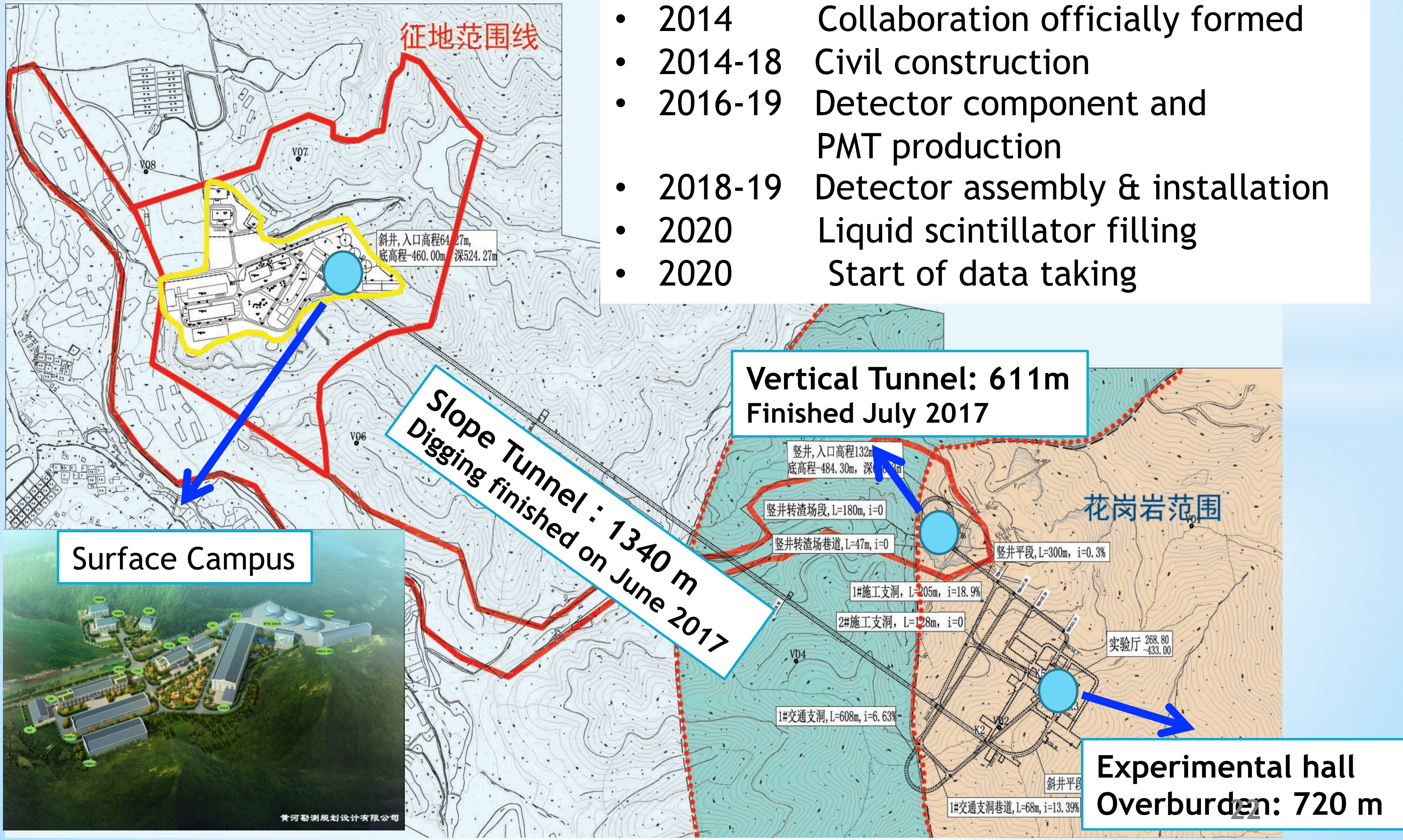
JUNO Timescale

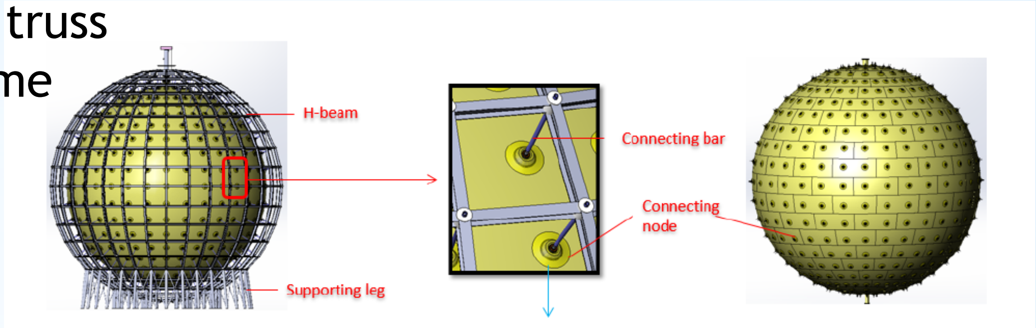
- 2013 Funding approved
- 2014 Collaboration officially formed
- 2014-18 Civil construction
- 2016-19 Detector component and PMT production
- 2018-19 Detector assembly & installation
- 2020 Liquid scintillator filling
- 2020 Start of data taking



JUNO detector main components

CDR http://arxiv.org/abs/1508.07166

- **Central detector :**
  Acrylic sphere and stainless steel truss
  Liquid Scintillator (LS) large volume
  -> for the statistics



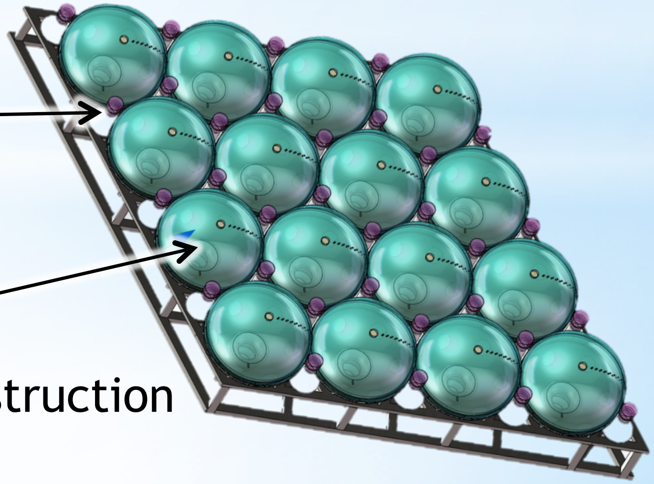
  Double calorimetry :

  → 18,000 large PMTs (20") → 75%
  → 25,000 small PMTs (3") → 2.5%

  High light coverage (78%)
  -> for the energy resolution

3" PMT

20" PMT



- **Muon veto** : use OPERA tracker layers
  Reject 50% of the muons
  Provide tagged muon sample to study muon reconstruction and bg contamination with the central detector

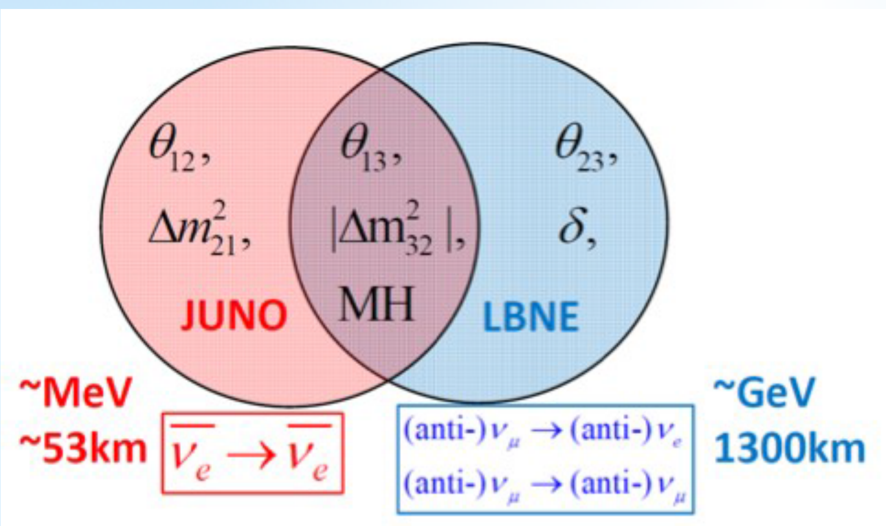
- **Calibration** : 4-complementary systems : Automatic calibration unit (1D- central axis scan), Cable loop system and guide tube calibration system (2D), remote operated vehicules (3D) – radiative sources (photon, positrons, neutrons)

Synergy with other experiments

Various projects seeking to resolve the neutrino mass hierarchy :

Two complementary methods

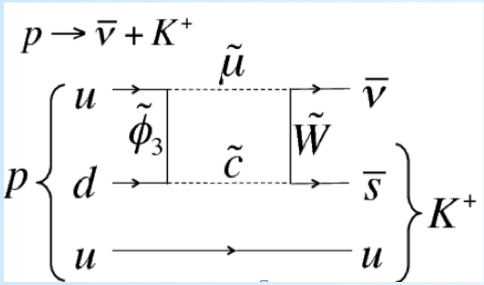
Experiment	Location	Method	Approved	Sensitivity	
PINGU	South pole	Matter effects: atmospheric ν		3…4σ in a few years	
ORCA	Mediterranean	Matter effects: atmospheric ν		3…4σ in a few years	
INO	India	Matter effects: atmospheric ν	✓	2σ in 10 years	
NOνA	U.S.	Matter effects: ν-beam	✓	0…3σ in 6 years	
Dune/LBNE	U.S.	Matter effects: ν-beam		>5σ in 6 years	**> 2028**
JUNO	China	3-flavor interference	✓	4σ in 6 years	**Data in 2020**
RENO 50	South Korea	3-flavor interference		4σ in 6 years	

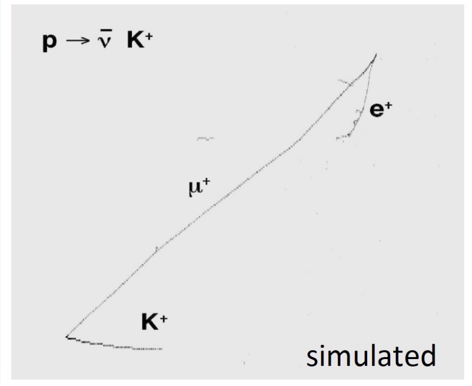


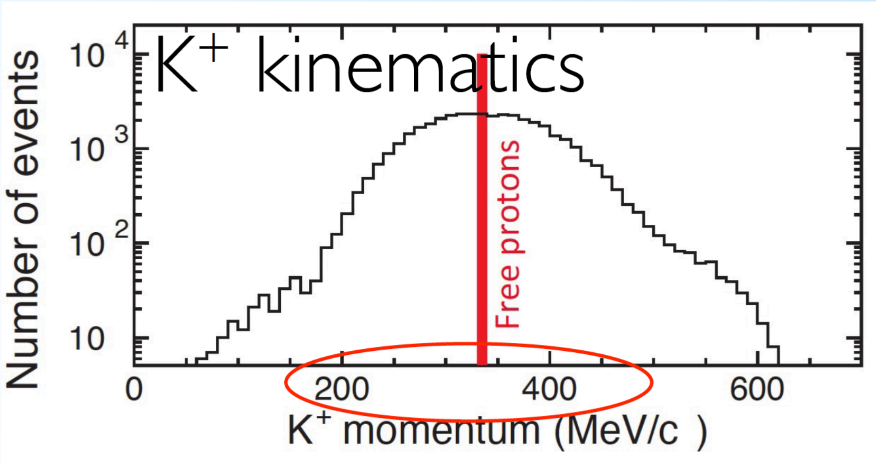
	JUNO	DUNE
$\sin^2 2\theta_{12}$	0.7%	
Δm^2_{21}	0.6%	
$\lvert\Delta m^2_{32}\rvert$	0.5%	0.3%
MH	3-4σ*	>5σ
$\sin^2 2\theta_{13}$	14%**	3%
$\sin^2\theta_{23}$		3%
δ_{CP}		10°

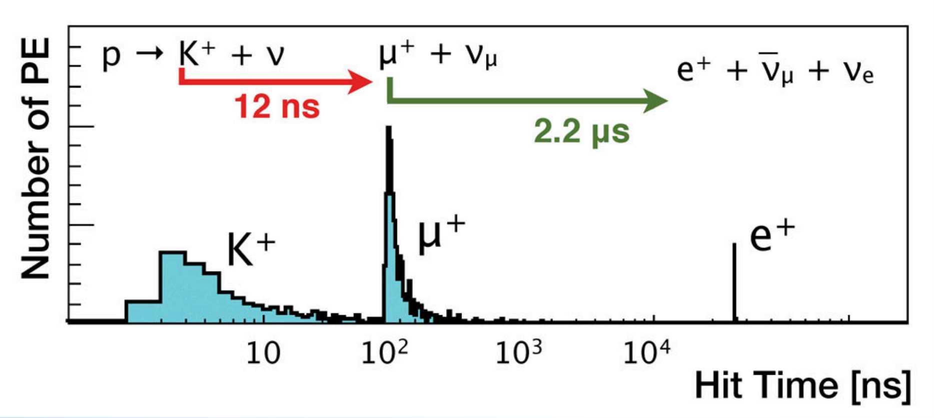
* 4σ requires 1% $|\Delta m^2_{uu}|$ ** Daya Bay reaches 3%

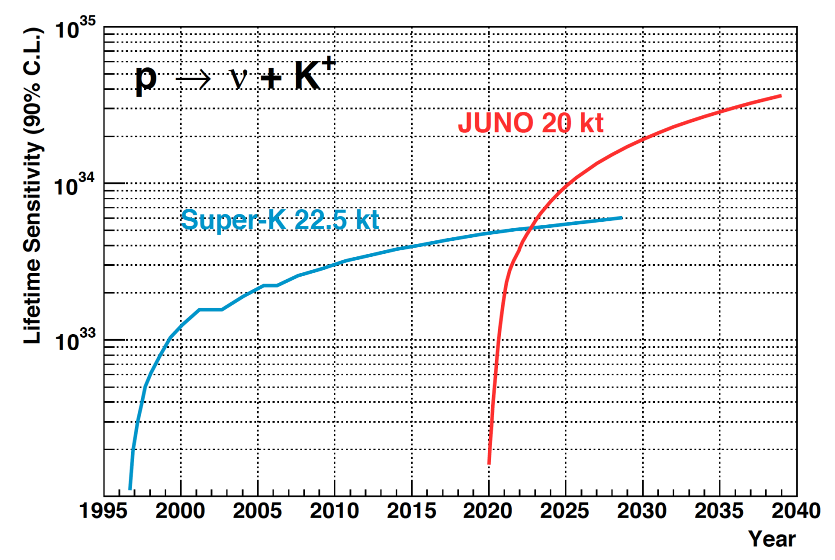
Proton decay via p → ν K









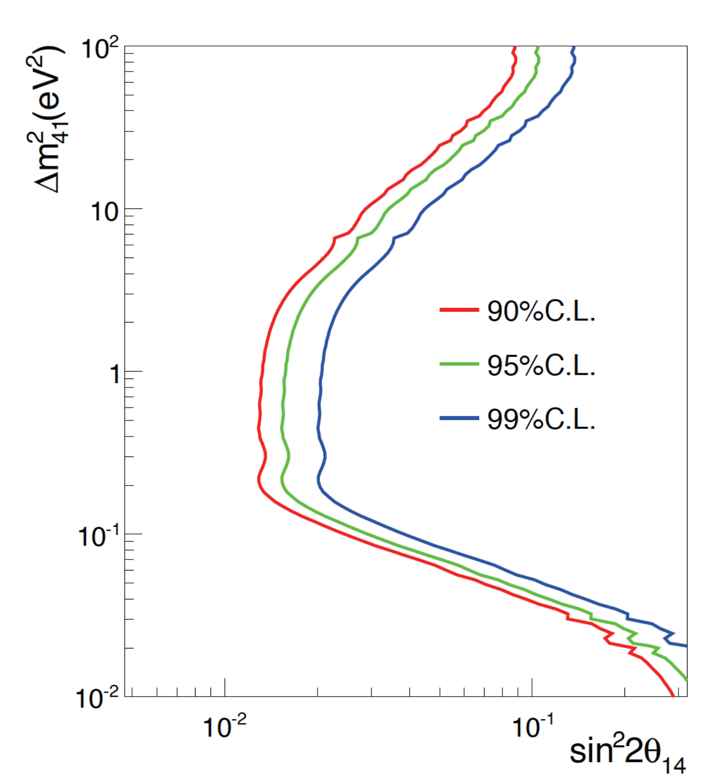


JUNO high efficiency :
- Large mass (like SK)
- Excellent timing → K+ decay signature
- Excellent dynamic →K+ mass reconstruction

Sterile neutrinos

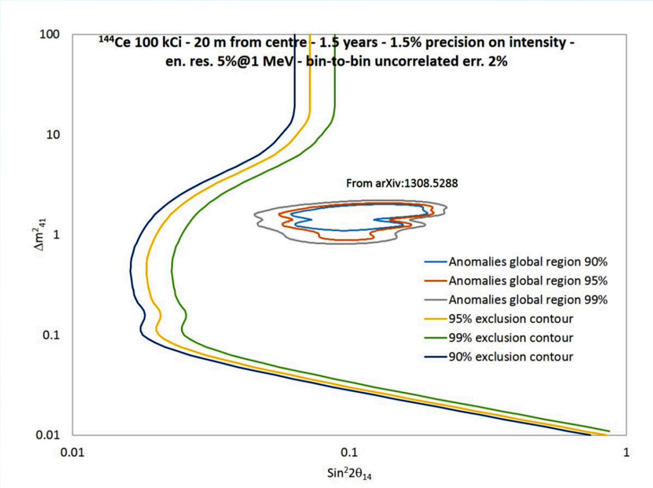
Sterile neutrinos : hypothesised gauge singlets in the SM
Do not participate to SM weak interaction but couple to active neutrinos via non-zero mixing between active and sterile flavors

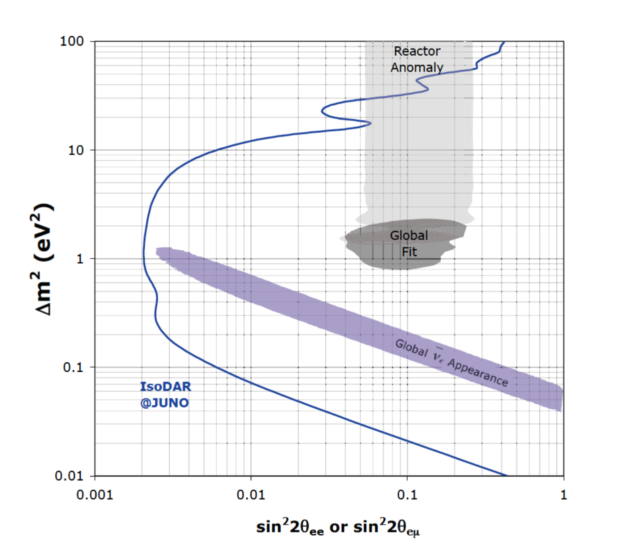
Sensibility of JUNO searches



50 kCi 144Ce source at the detector center (1-16 m)using 450-day data taking time

100 kCi 144Ce source outside of the detector vessel steel (20 m) 450-day data taking time

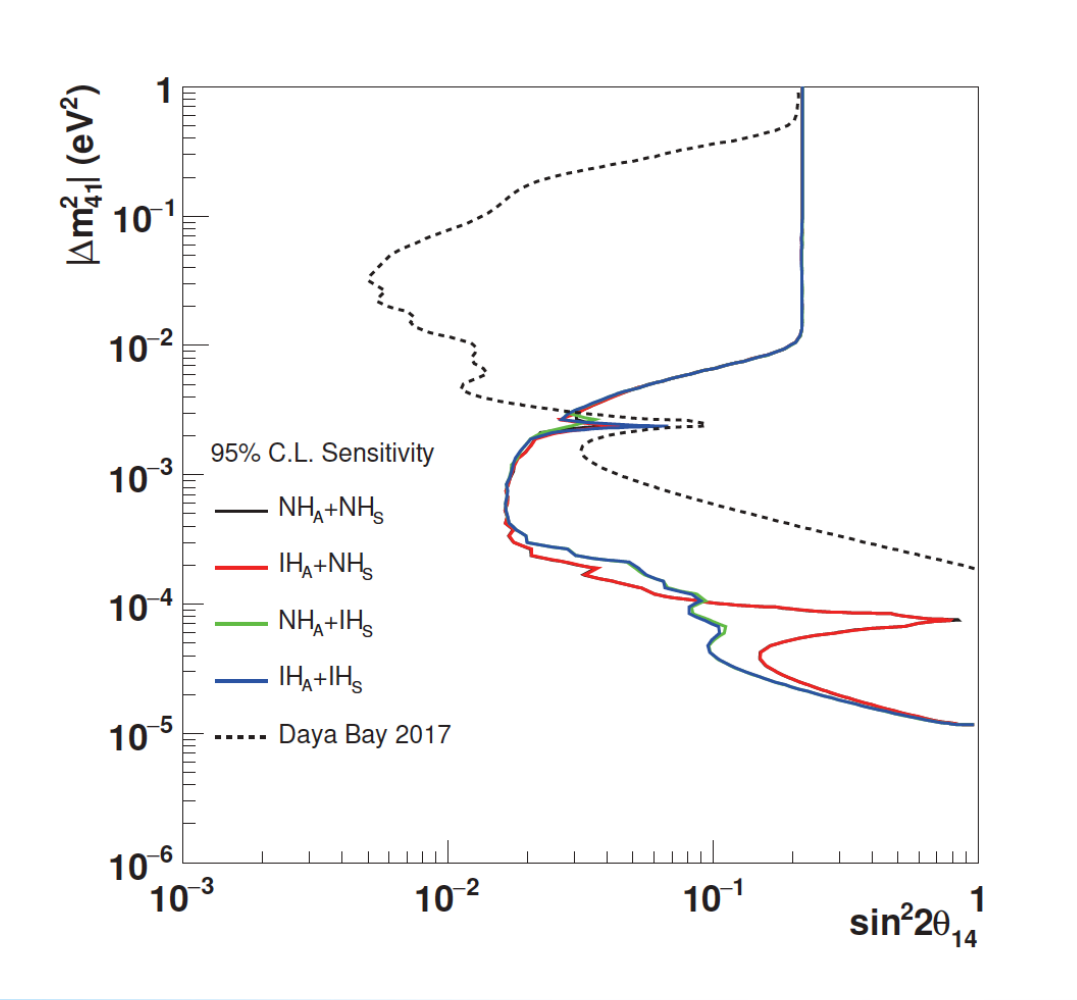




JUNO@IsoDAR
8 Li source
5 sigma contour
5 years data taking
source at the detector center (1-16 m)using 450-day data taking time

Sterile neutrinos

Sensibility of JUNO searches with reactor antineutrinos:



Sensitivities to super light sterile neutrinos :
Δm^2 of the order of 10^{-5} eV^2