Overview of the Jiangmen Underground Neutrino Observatory (JUNO)

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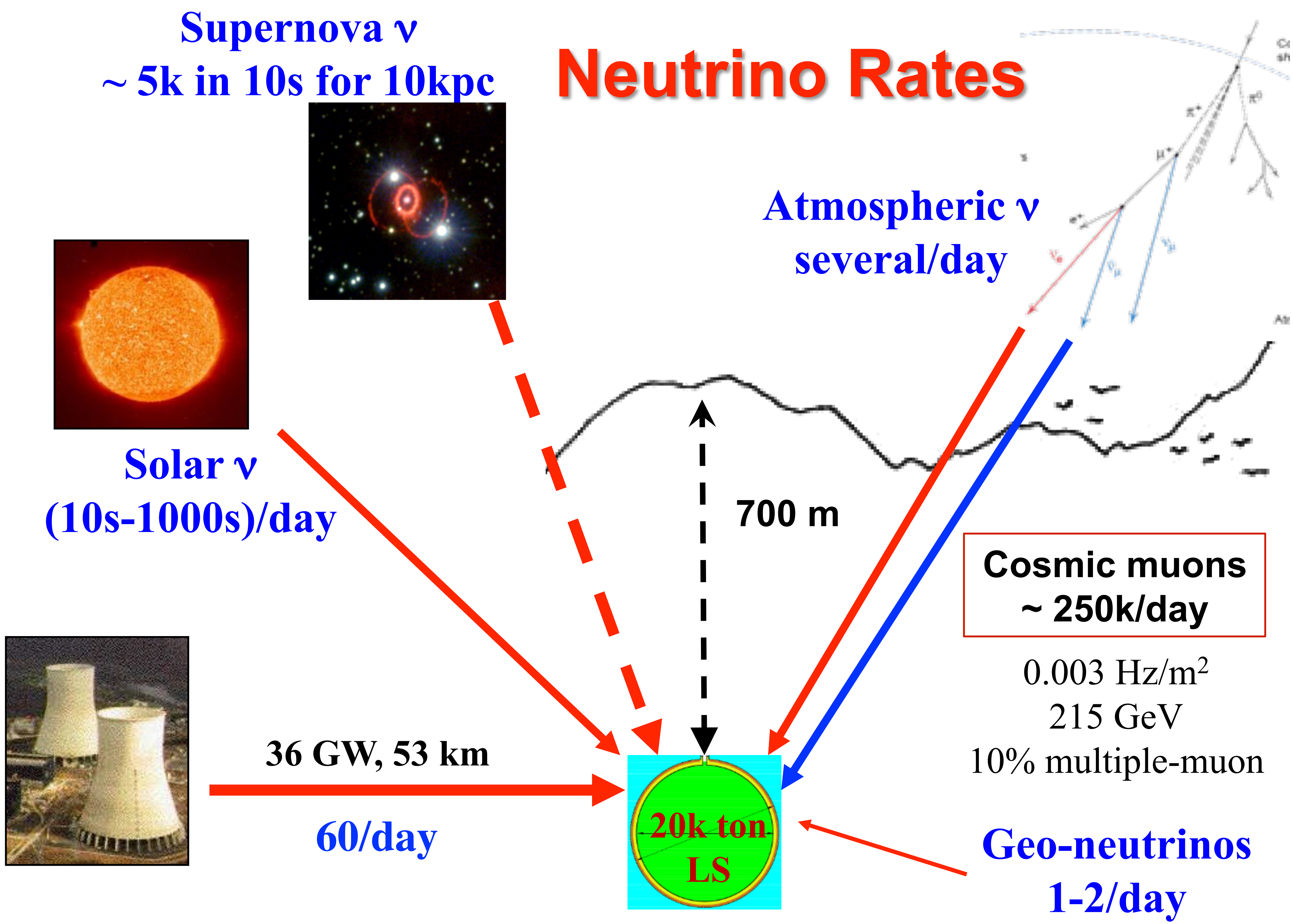
BROOKHAVEN NATIONAL LABORATORY

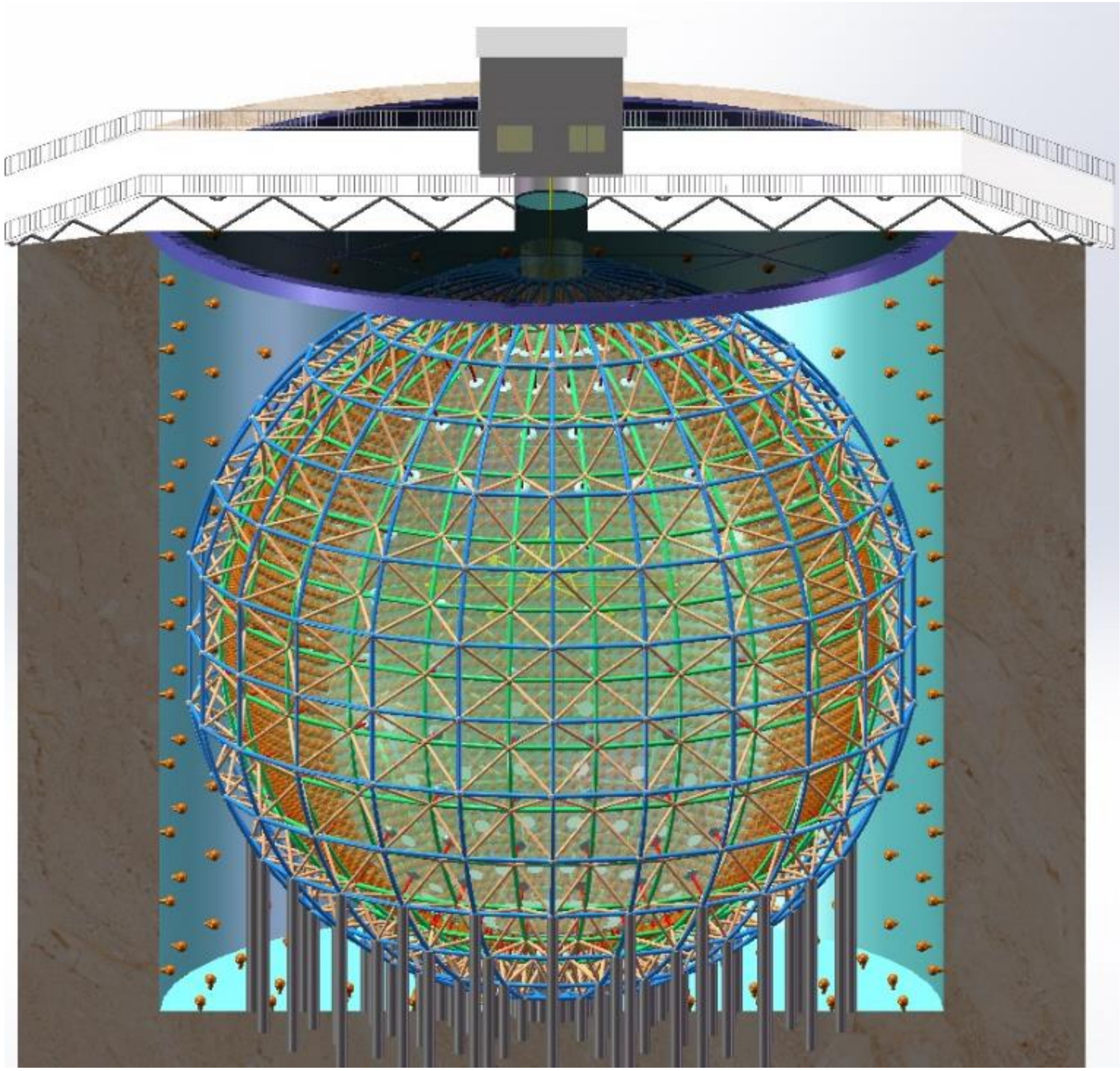
on behalf of the JUNO Collaboration

IPA 2015, Madison, 6 May 2015

JUNO: A Multi-purpose Neutrino Observatory



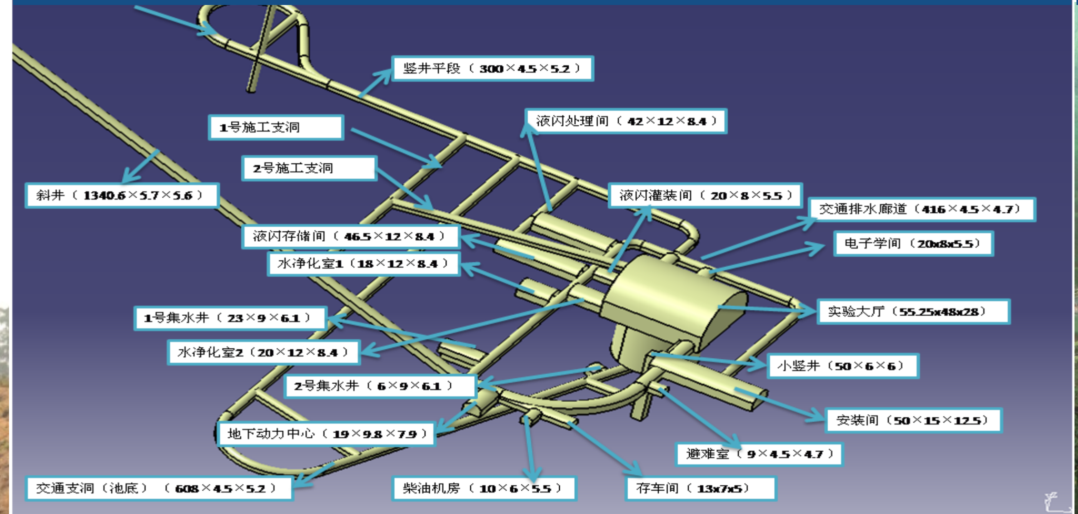
The JUNO Experiment



- **Key Features of the JUNO detector**
  - **Massive**: ~20 kton LS detector
  - **Underground**: ~1900 m.w.e
  - **Low threshold**: < ~0.5 MeV
  - **High resolution**: 3% / $\sqrt{E}$ (MeV)
  - **Precision energy scale**: < 1%

- Approved in Feb 2013 with ~300 M$ budget.
- Groundbreaking in Jan 2015. Expected data taking in 2020.

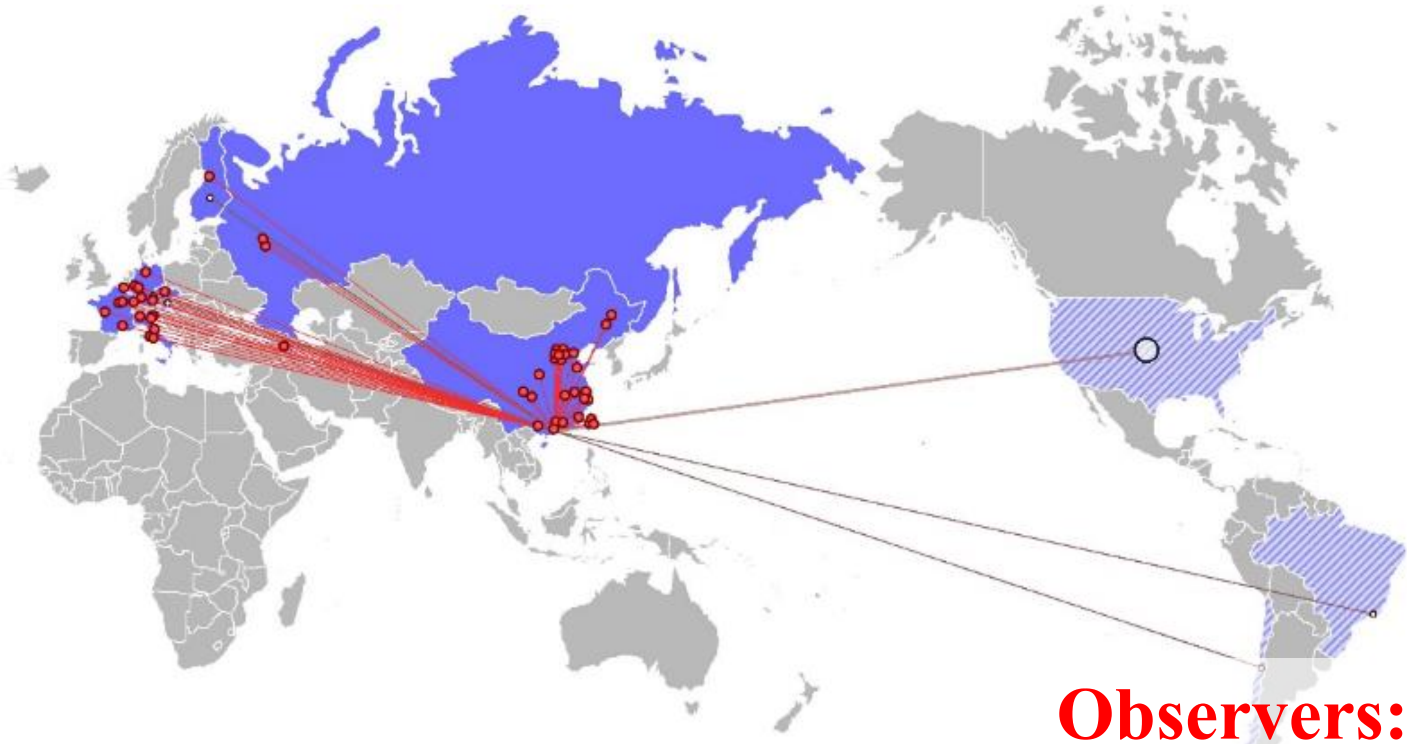
underground facilities



surface buildings

Ground Breaking Ceremony on 1/10/2015

JUNO Collaboration



Asia (28)

BNU
CAGS
CQ U
CIAE
DGUT
ECUST
Guangxi U
HIT
IHEP
Jilin U
Nanjing U
Nankai U
Natl. CT U
Natl. Taiwan U
Natl. United U
NCEPU
Pekin U
Shandong U
Shanghai JTU
Sichuan U
SYSU
Tsinghua
UCAS
USTC
Wuhan U
Wuyi U
Xiamen U
Xi'an JTU

Europe (23)

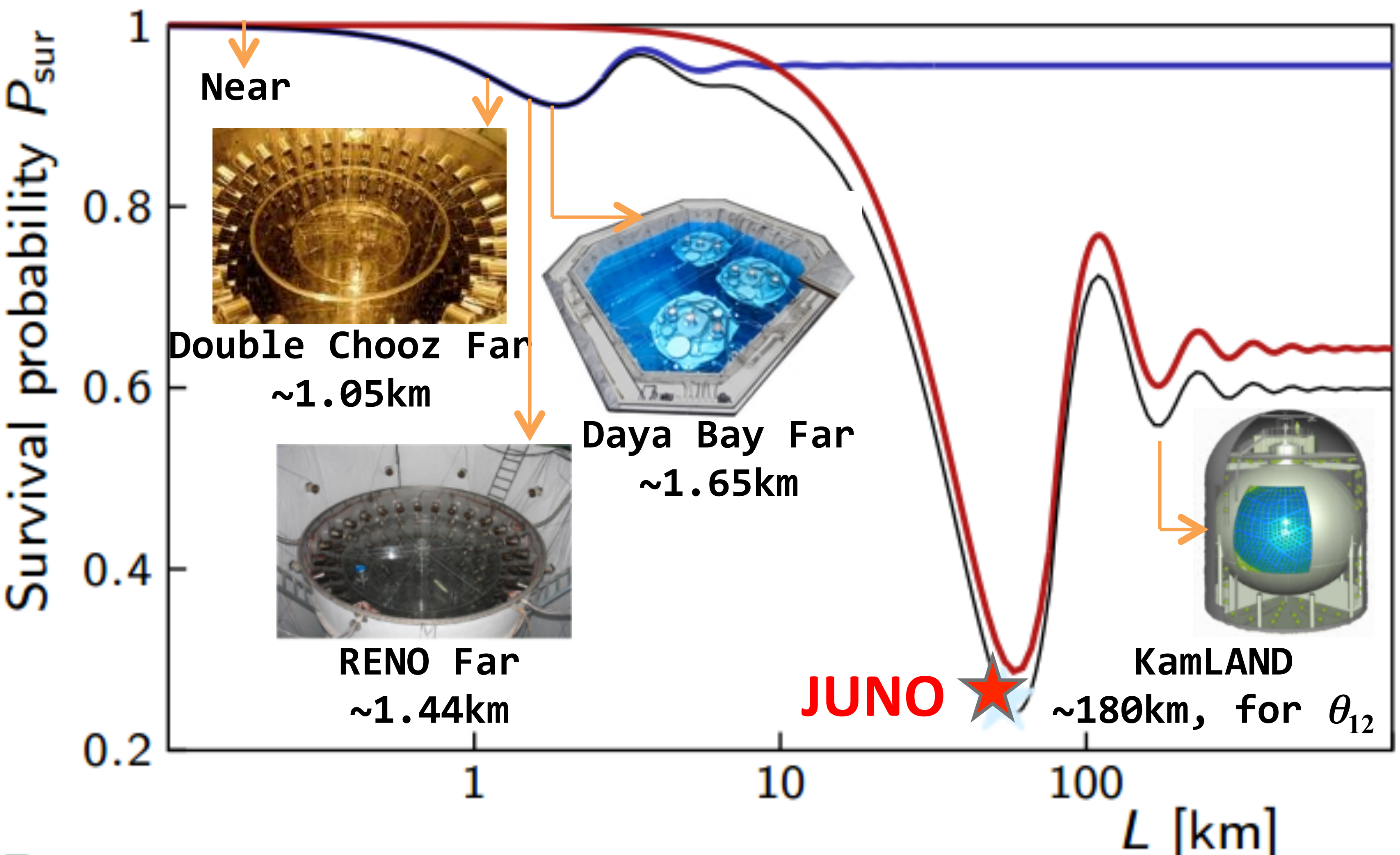
APC Paris
Charles U
CPPM Marseille
FZ Julich
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Padova
INFN-Perugia
INFN-Roma 3
IPHC Strasbourg
INR Moscow
JINR
LLR Paris
RWTH Aachen
Subatech Nantes
TUM
U.Hamburg
ULB
U Mainz
U Oulu
U Tuebingen
YPI Armenia

Observers:

US institutions
HEPHY Vienna
PUC Brazil
PCUC Chile
MPP Munich
Jyvaskyla U.

Reactor Neutrinos

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$



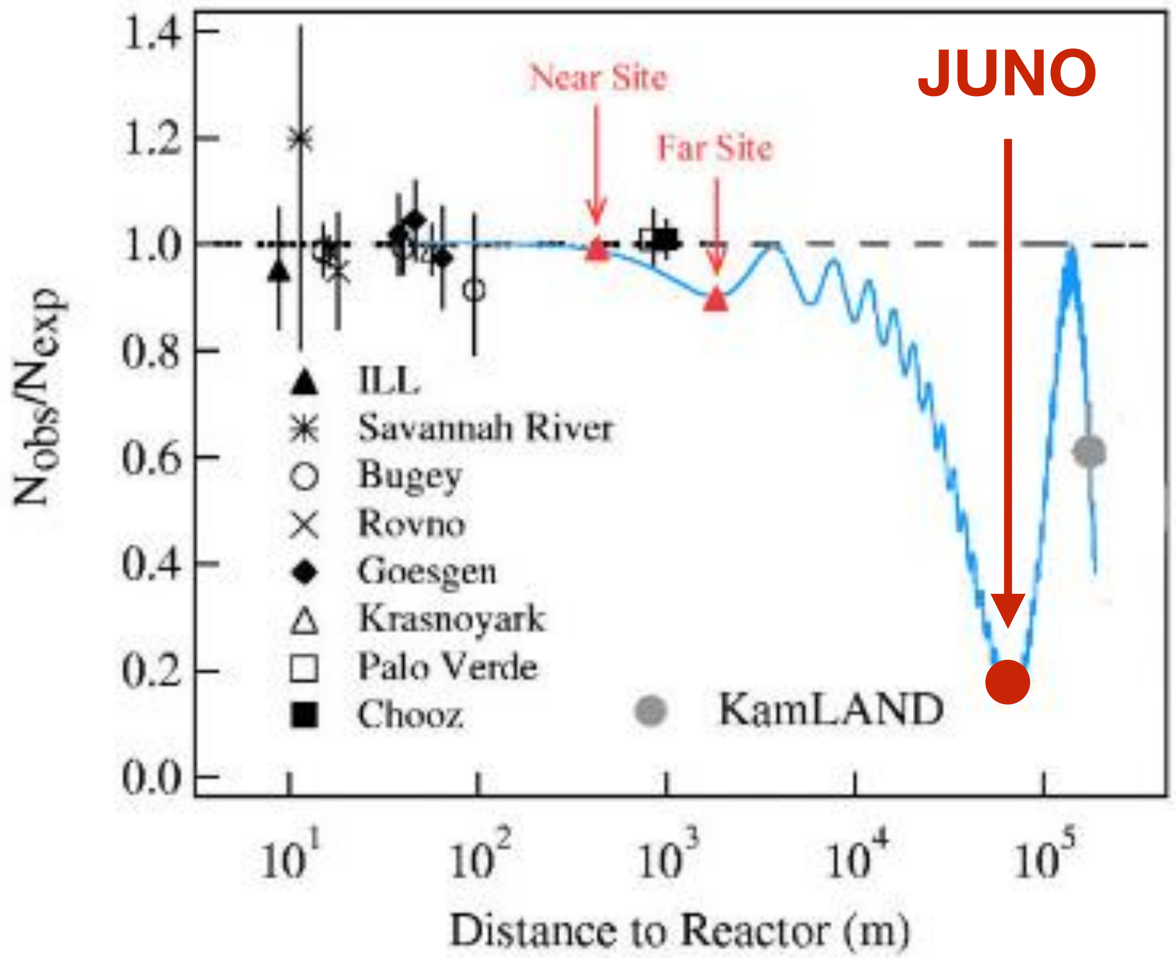
JUNO ~ 50 km

- both "solar" and "atmospheric" oscillations
  - Neutrino MH
  - Precision measurement of neutrino mixing parameters

Past

- "solar" oscillation: KamLAND ~ 180 km
- "atmospheric" oscillation: Daya Bay, RENO, Double Chooz ~ 2 km

Determine MH with Reactor Neutrinos



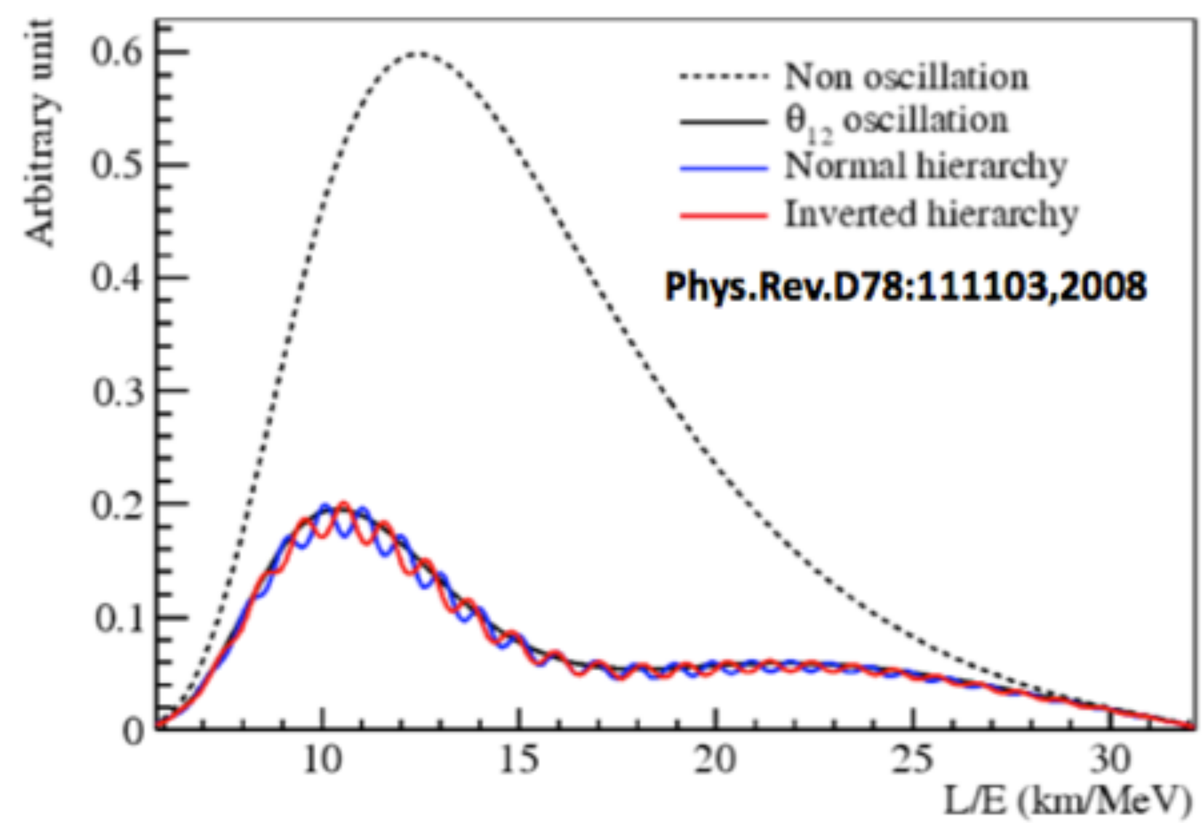
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$\frac{1}{2}\sin^2 2\theta_{13}\left[1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\cos(2|\Delta_{ee}| \pm \phi)\right]$$

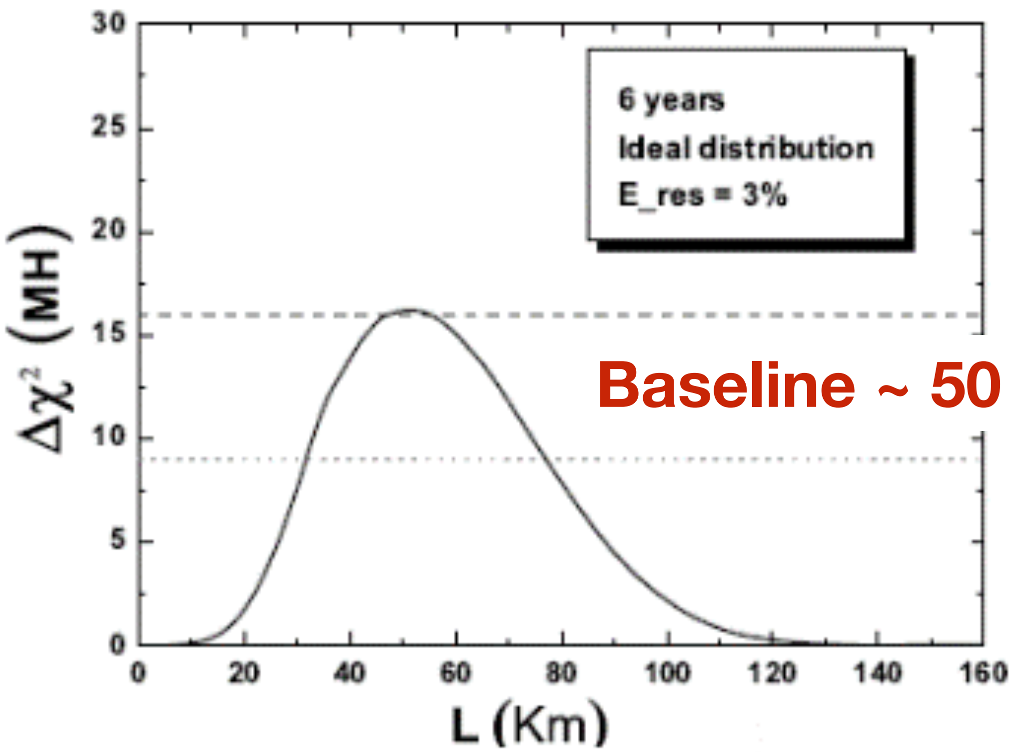
- **A fixed definition Δm^2_{ee}**
- **And an energy related phase shift ϕ**

Precision energy spectrum measurement interference between P_{31} and P_{32}
→ Relative measurement

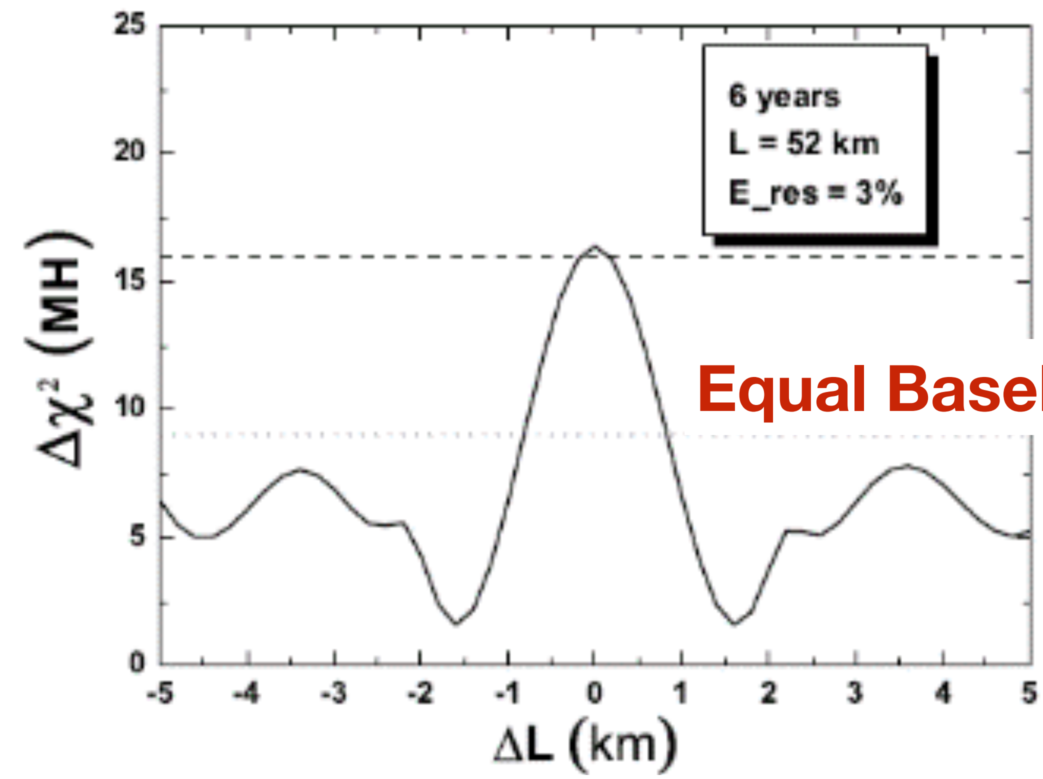
Further improvement with $\Delta m^2_{\mu\mu}$ measurement from accelerator exp.
→ Absolute measurement



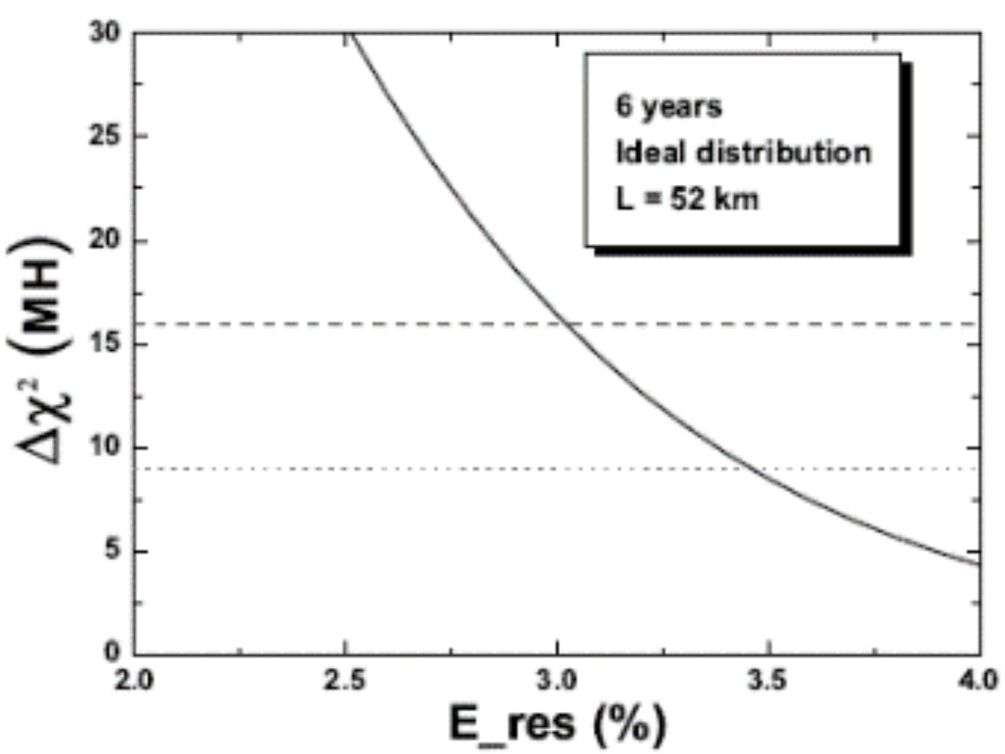
Requirement for MH Determination



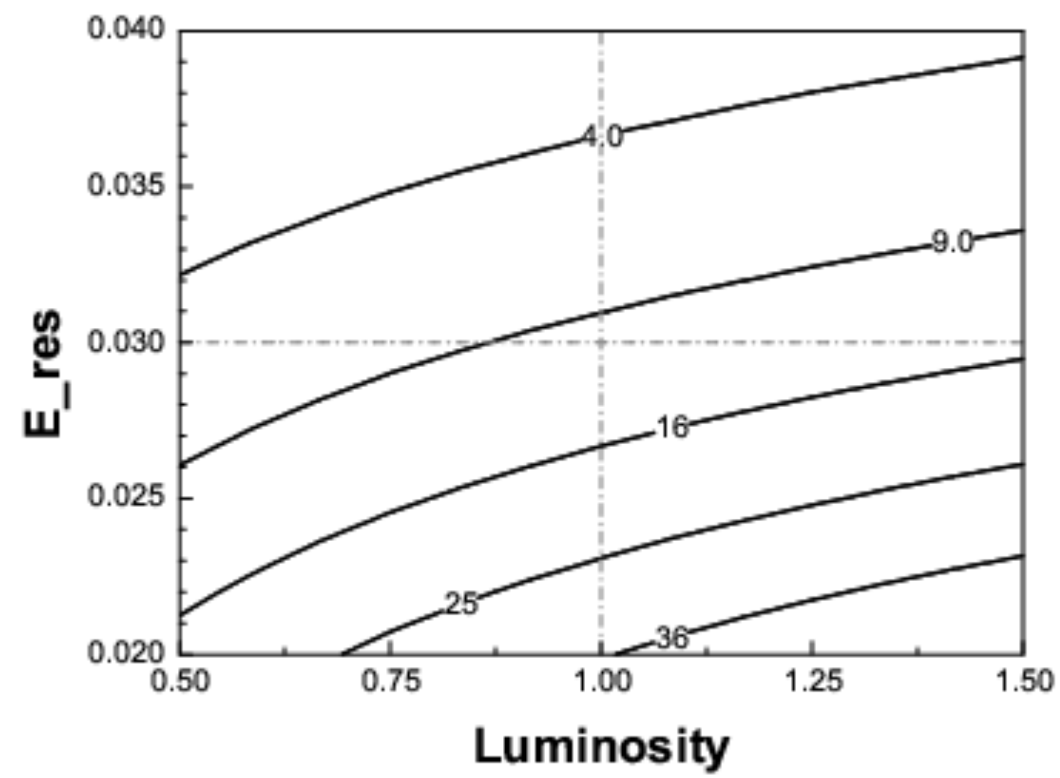
Baseline ~ 50 km



Equal Baselines



Energy resolution ~ 3%



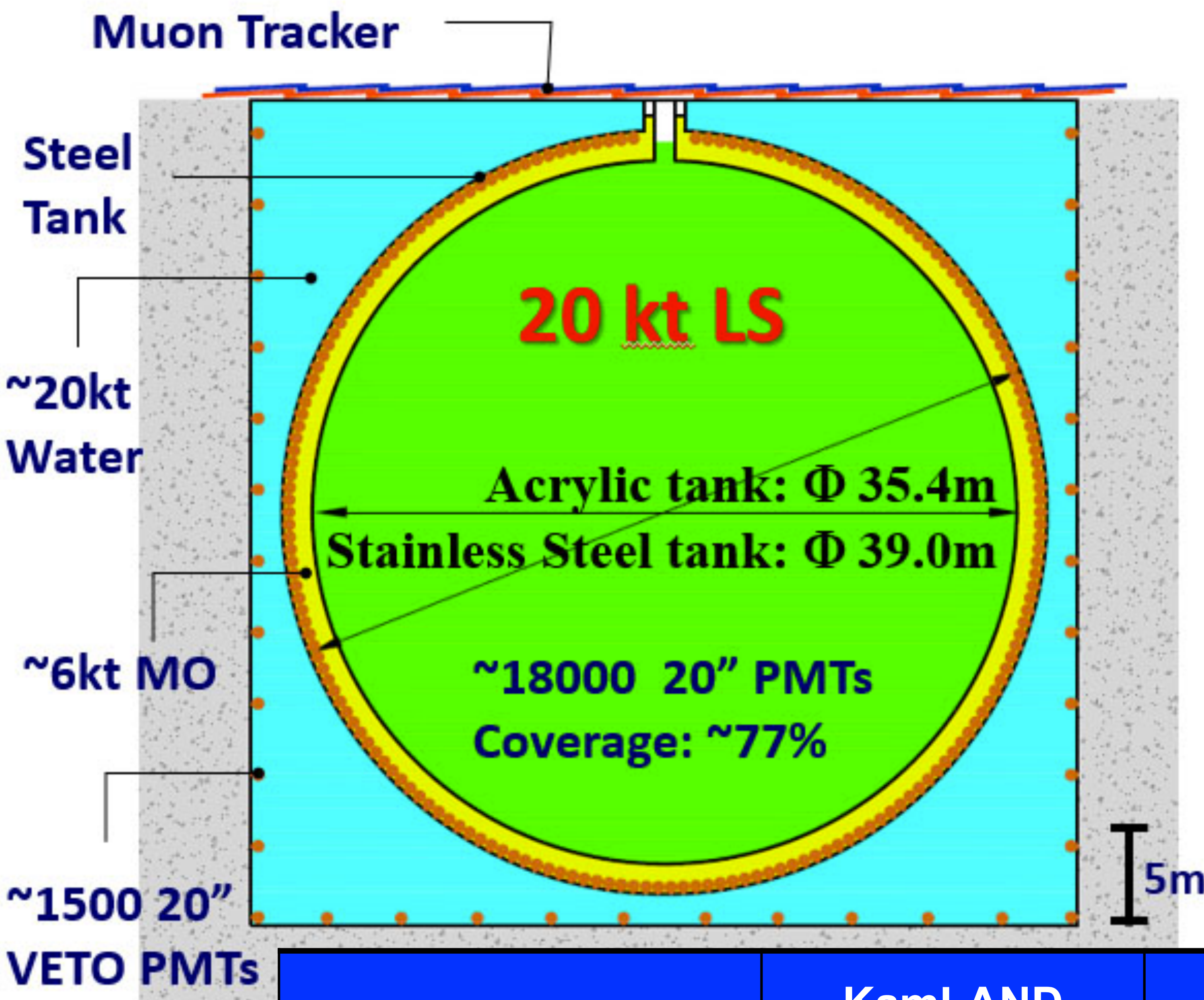
100k events = 20 kt x 35 GW x 6 yr
& minimal backgrounds

Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

High Resolution Large Scintillator Detector

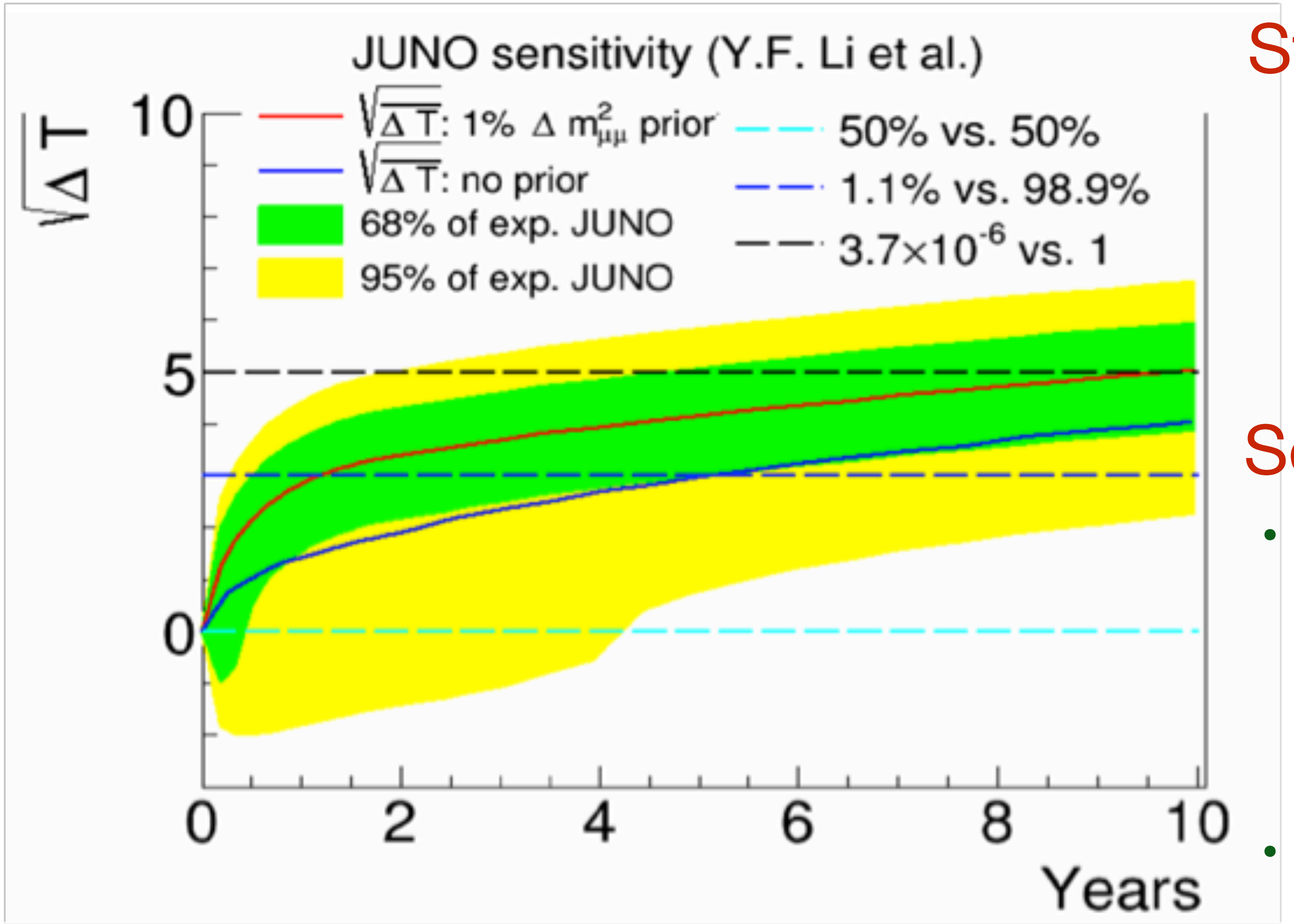


How to reach high resolution?

- Photocathode coverage: 77% with 20" PMTs
- High QE PMT: QE ~ 35%
- Highly transparent LS: atten. length ~ 30 m
- High light yield: optimize fluors

	KamLAND	BOREXINO	JUNO
LS mass	1 kt	0.5 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

JUNO MH Sensitivity



From Yufeng et al. PRD 88 013008 (2013)
Independently shown by arXiv:1307.7419

Standard inputs

- 100k events (6 years at 36GW)
- 3% @ 1MeV energy resolution
- 1% energy scale uncertainty
- realistic backgrounds

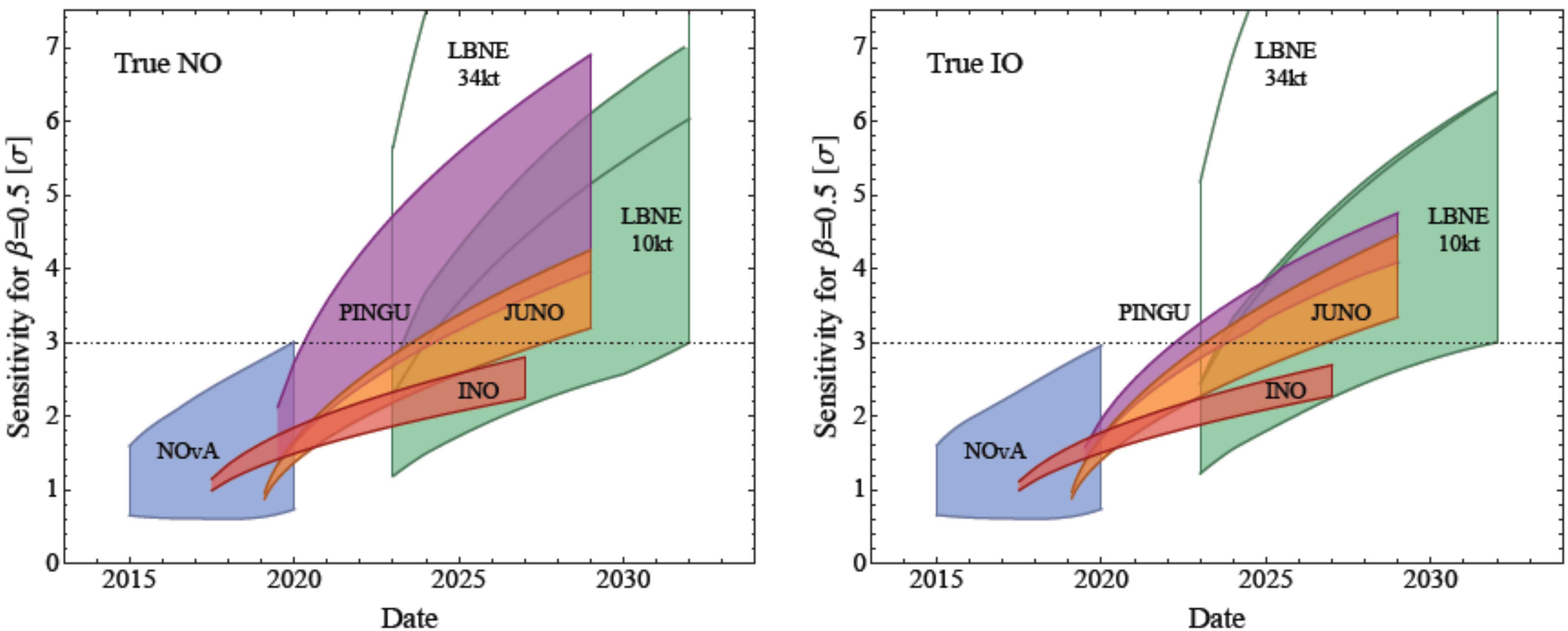
Sensitivity

- JUNO only
  - 50% chance to have 3σ or higher
  - 2.3% chance to have 5σ or higher
- JUNO + 1% $\Delta m^2_{\mu\mu}$
  - 84% chance to have 3σ or higher
  - 16% chance to have 5σ or higher

	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{\rm MH}$	+16	−4	−1	−0.5	−0.1	+8

Compared With Other MH Experiments

M. Blennow et al., JHEP 1403 (2014) 028



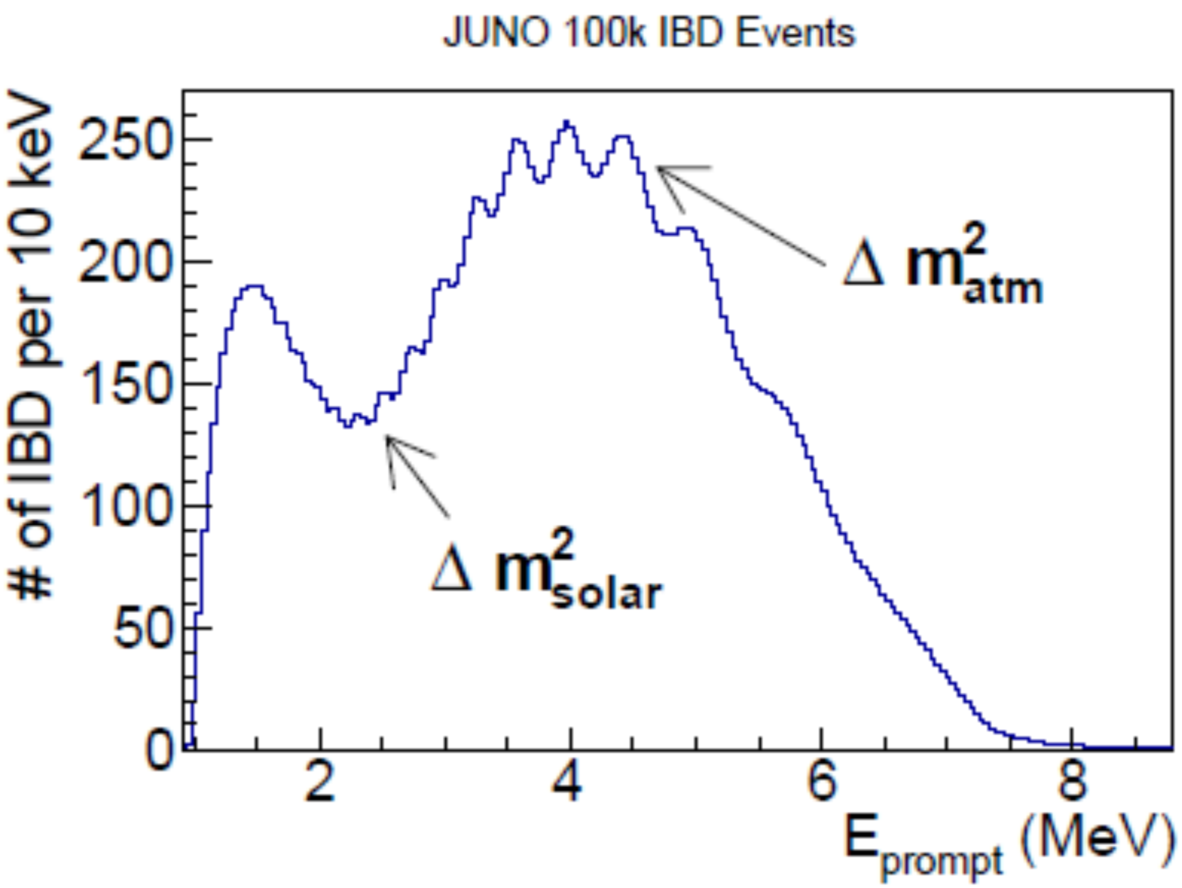
Δm^2_{31} **and** Δm^2_{32} **Interference (ϕ)**	Δm^2_{ee} **and** $\Delta m^2_{\mu\mu}$ **difference**	**Matter Effect**

Reactor — **atmospheric**

Independent of θ_{23}, CP phase, and matter effect

Accelerator

Precision Measurement of Mixing Parameters



	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°

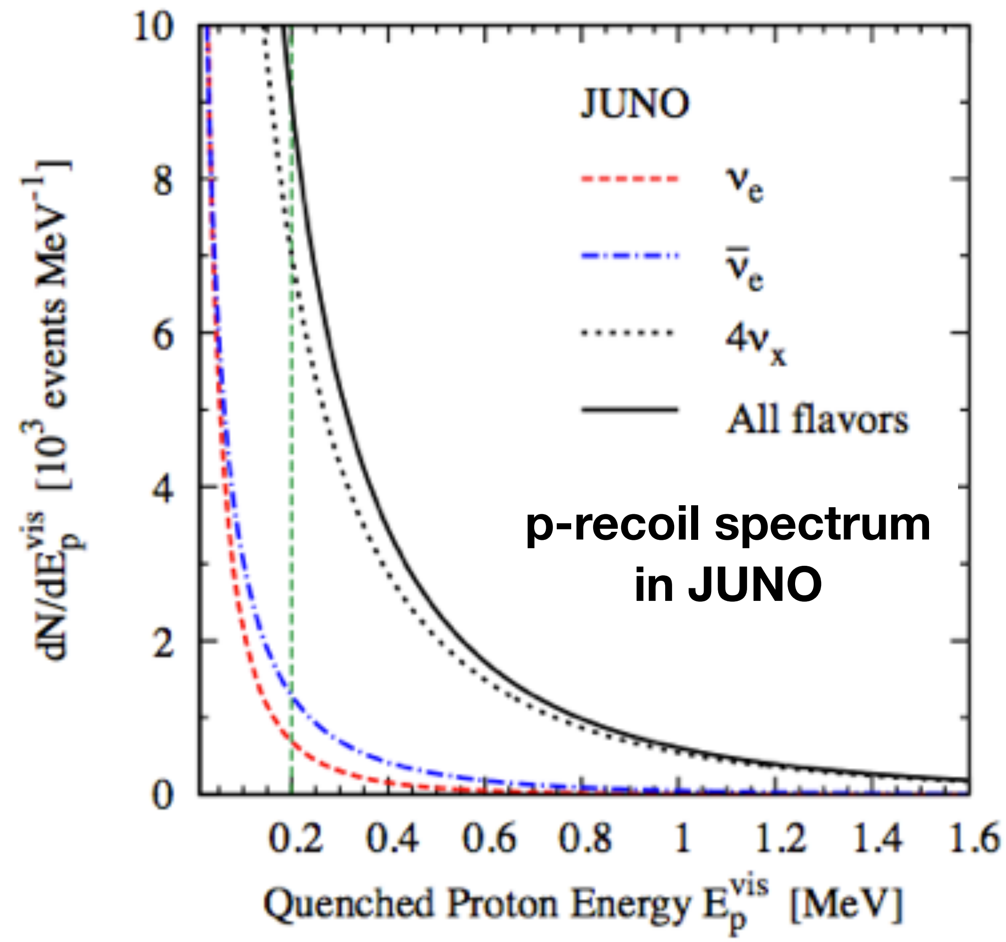
* 4σ requires 1% $\lvert\Delta m^2_{uu}\rvert$ ** Daya Bay reaches 3%

- First experiment to simultaneously observe "solar" and "atmospheric" oscillations
- First experiment to observe more than two cycles of neutrino oscillations

- Complementary to long-baseline accelerator program
- Probing the unitarity of U_{PMNS} to sub-percent!

Supernova Neutrinos

- For a typical 3x10^{53} erg core-collapse SN inside our galaxy (~10 kpc), JUNO will observe
  - ~5000 anti-electron-neutrinos via IBD
  - ~1200 all flavors via v-p scattering
  - ~1000 via other channels

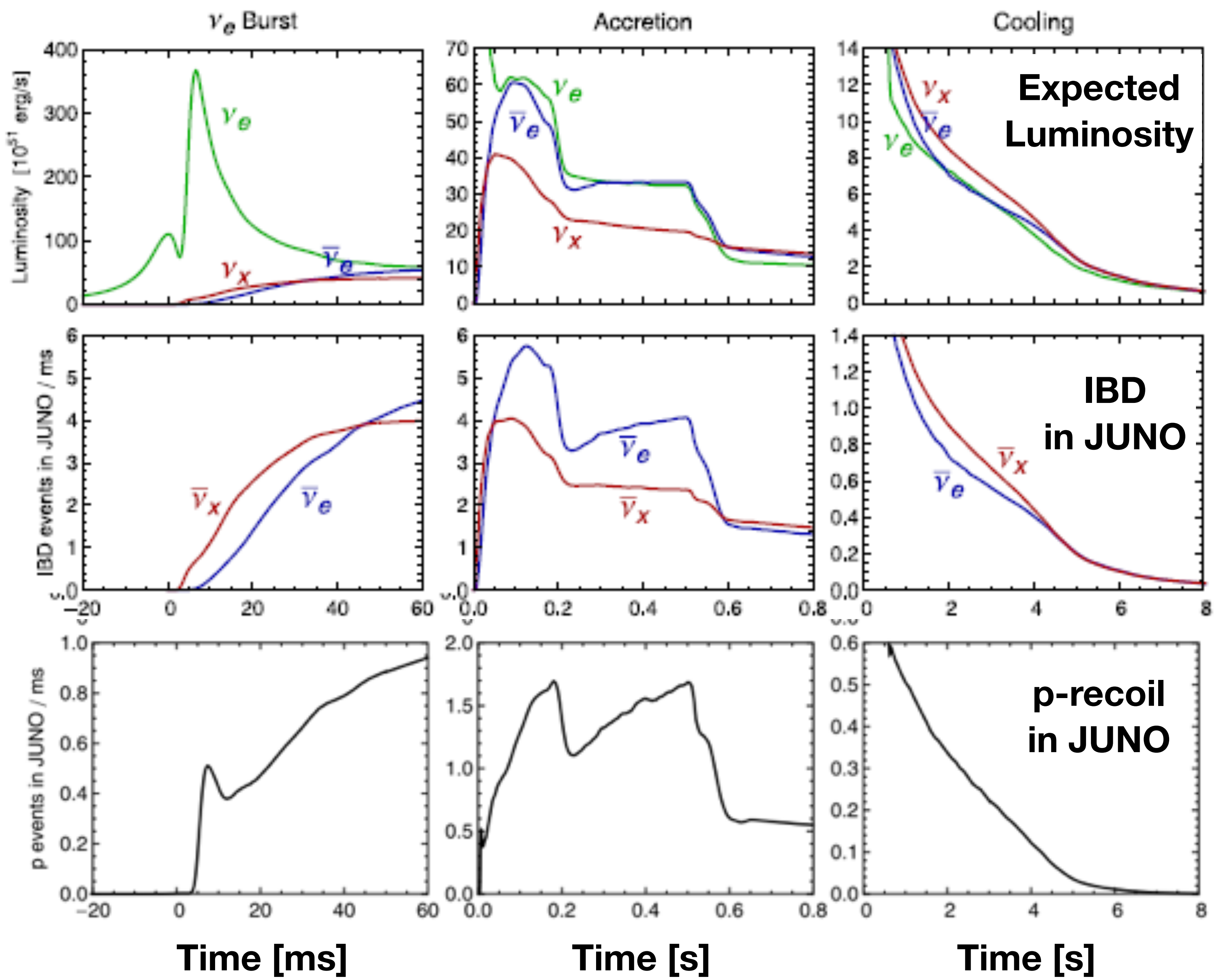


Estimated number of SN events in JUNO

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

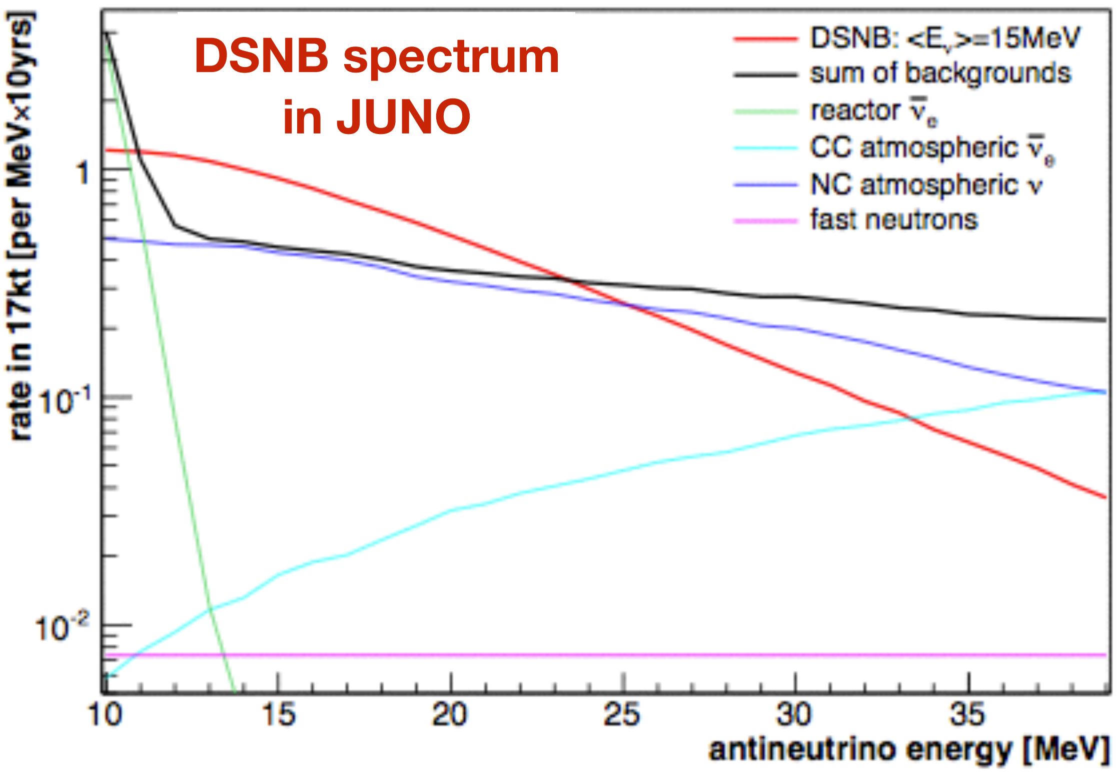
Supernova Neutrinos

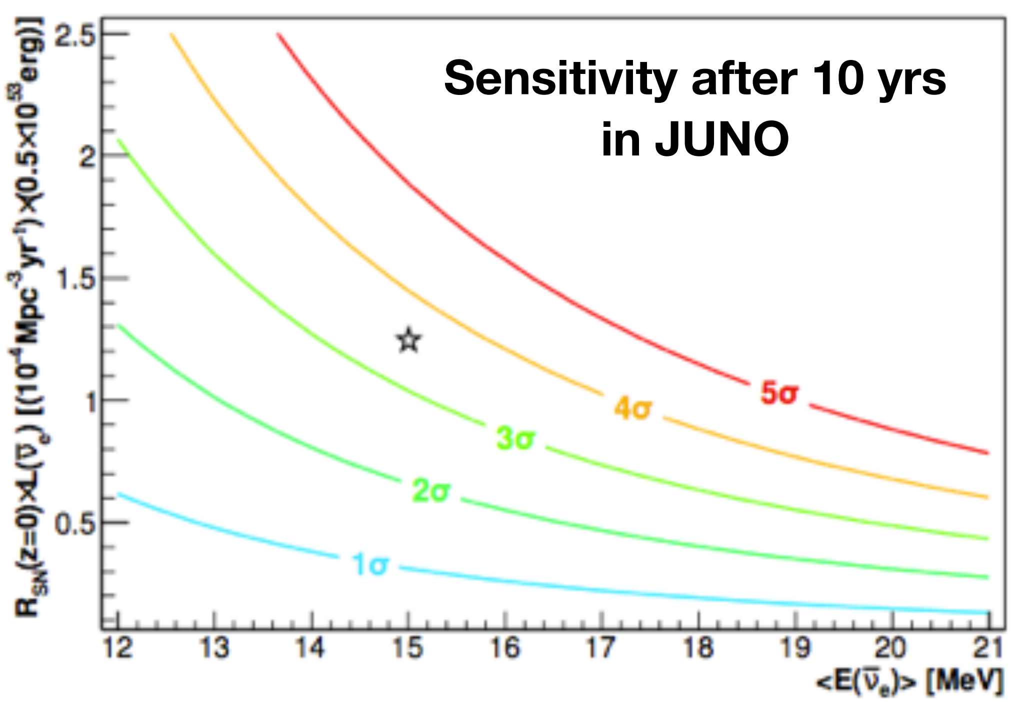
detection of “neutrino light curve” (and energy spectrum)



- Neutrino Mass
- Neutrino mass hierarchy
- Collective neutrino oscillation
- SN positioning
- Pre-SN neutrino (>1 day)
- SN nucleosynthesis

Diffuse Supernova Neutrino Background





- DSNB: Past core-collapse events
  - ⇨ Cosmic star-formation rate
  - ⇨ Core-collapse neutrino spectrum
  - ⇨ Rate of failed SNe

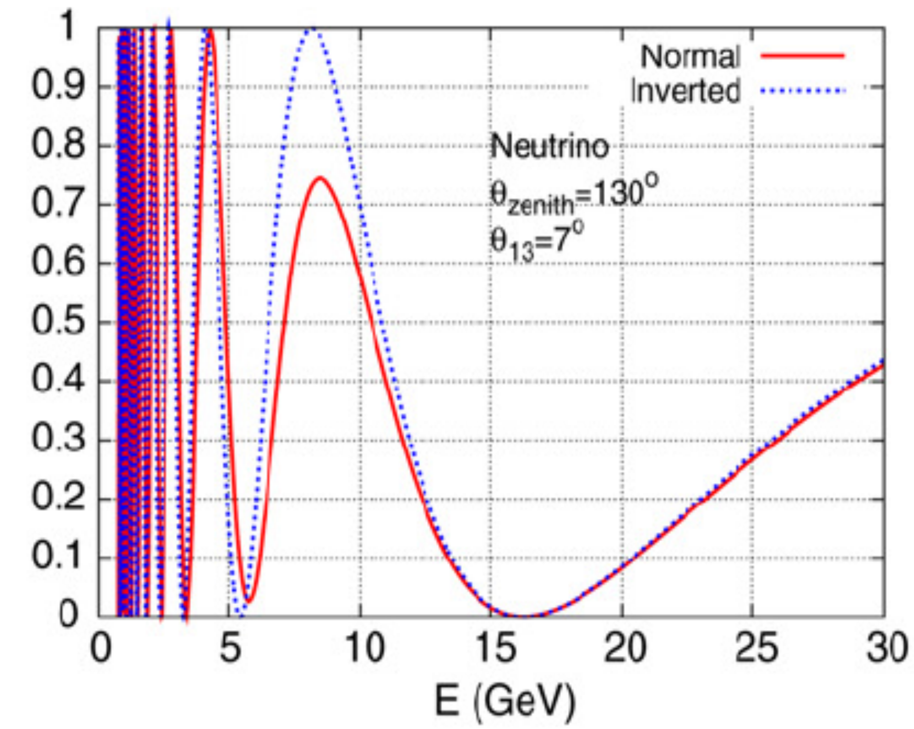
$$\frac{dF_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} = \frac{c}{H_0}\int_0^{z_{\max}} dz \frac{R_{\rm SN}(z)}{\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}} \frac{dN_{\bar{\nu}_e}(E'_{\bar{\nu}_e})}{dE'_{\bar{\nu}_e}}.$$

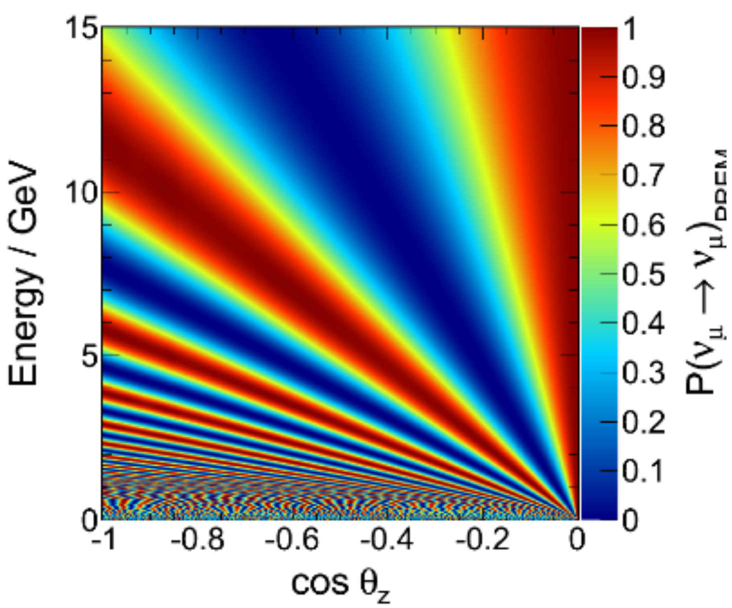
- Previously best limits from SK.
- Best sensitivity from IBD channel
- Largest background from atm. neutrino NC

Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e}\rangle = 12\,\mathrm{MeV}$	12.2	$\varepsilon_\nu = 50\,\%$	6.1
	$\langle E_{\bar{\nu}_e}\rangle = 15\,\mathrm{MeV}$	25.4		12.7
	$\langle E_{\bar{\nu}_e}\rangle = 18\,\mathrm{MeV}$	42.4		21.2
	$\langle E_{\bar{\nu}_e}\rangle = 21\,\mathrm{MeV}$	61.2		30.8
Background	reactor $\bar{\nu}_e$	1.6	$\varepsilon_\nu = 50\,\%$	0.8
	atm. CC	1.5	$\varepsilon_\nu = 50\,\%$	0.8
	atm. NC	716	$\varepsilon_{\rm NC} = 1.1\,\%$	7.5
	fast neutrons	12	$\varepsilon_{\rm FN} = 1.3\,\%$	0.15
	Σ			9.2

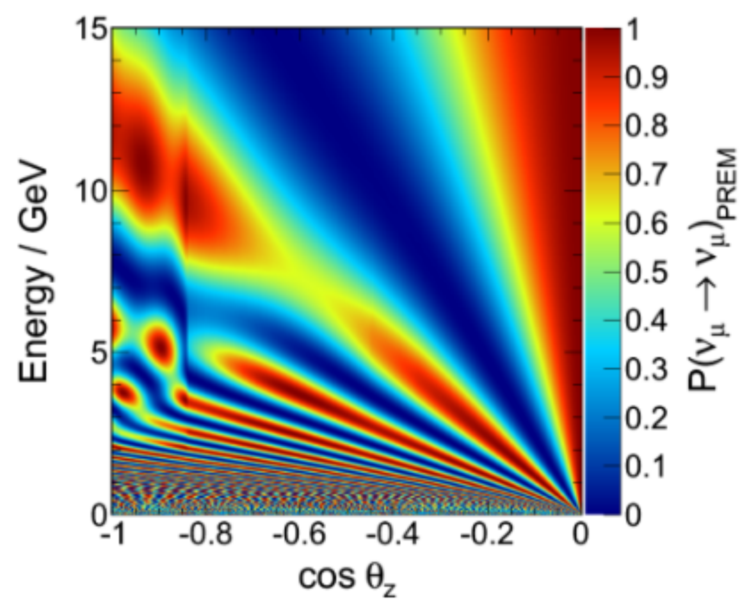
MH from Atmospheric Neutrinos

- Due to matter effect, oscillation probability of atmospheric neutrino when passing the earth depends on MH
- ~ 1900 (anti-)ν_μ and 1400 (anti-)ν_e events/year
- measure both lepton and hadron energy
    - Good tracking an energy resolution
- ~1 - 2σ MH sensitivity in 10 years

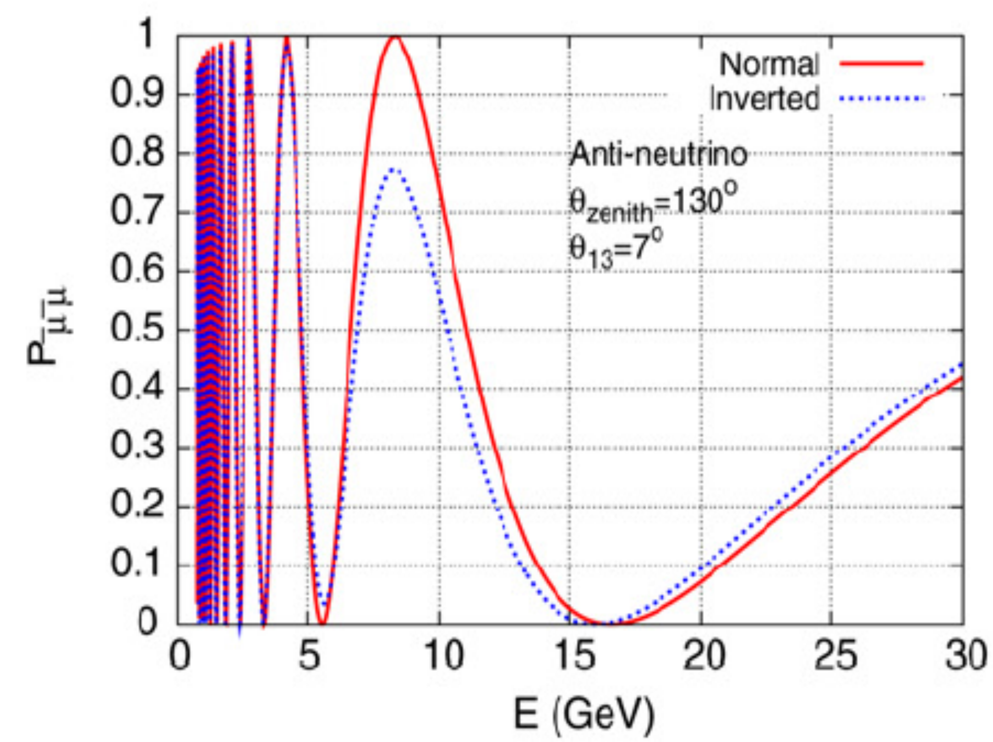




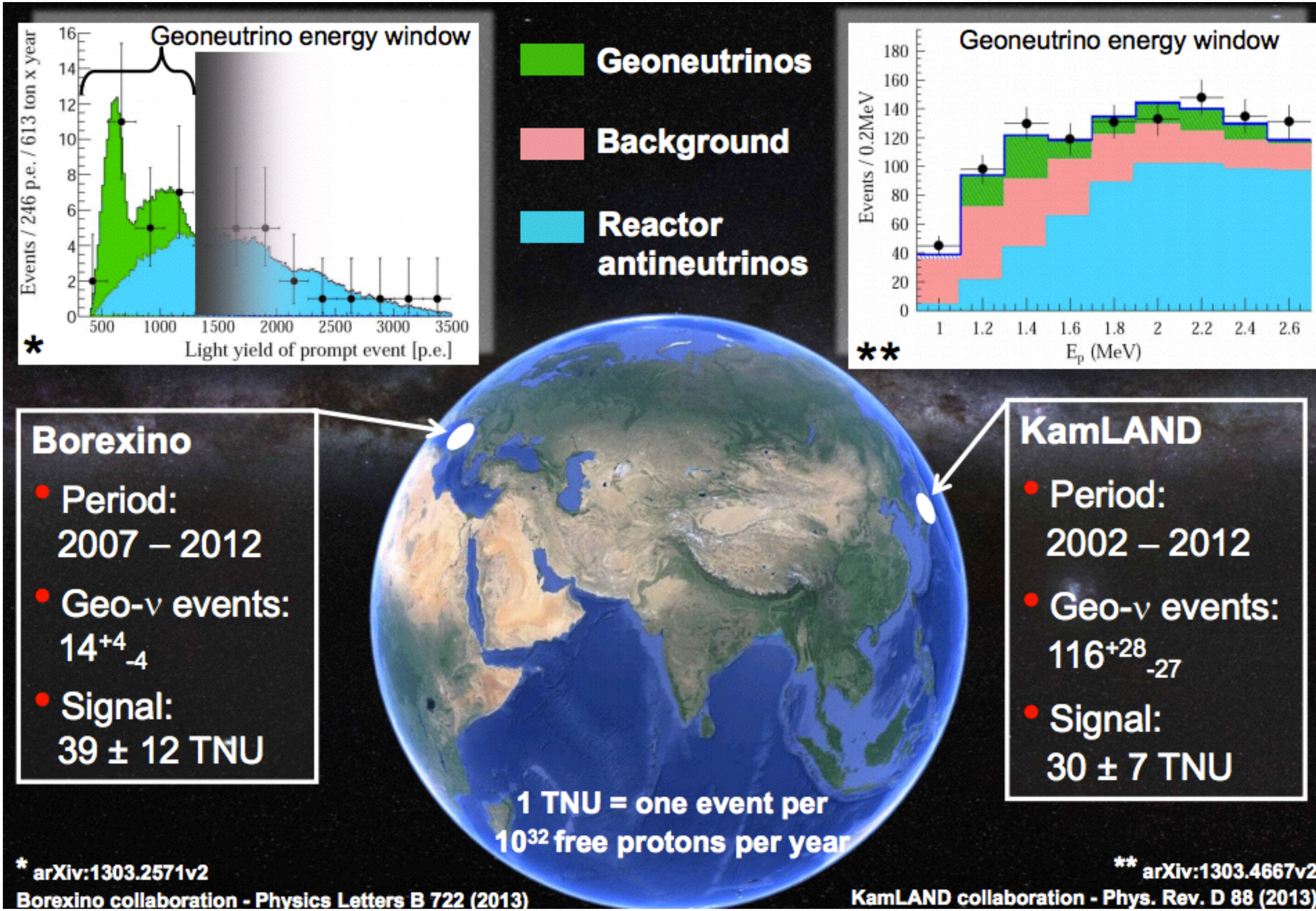
IH



NH



Geoneutrinos

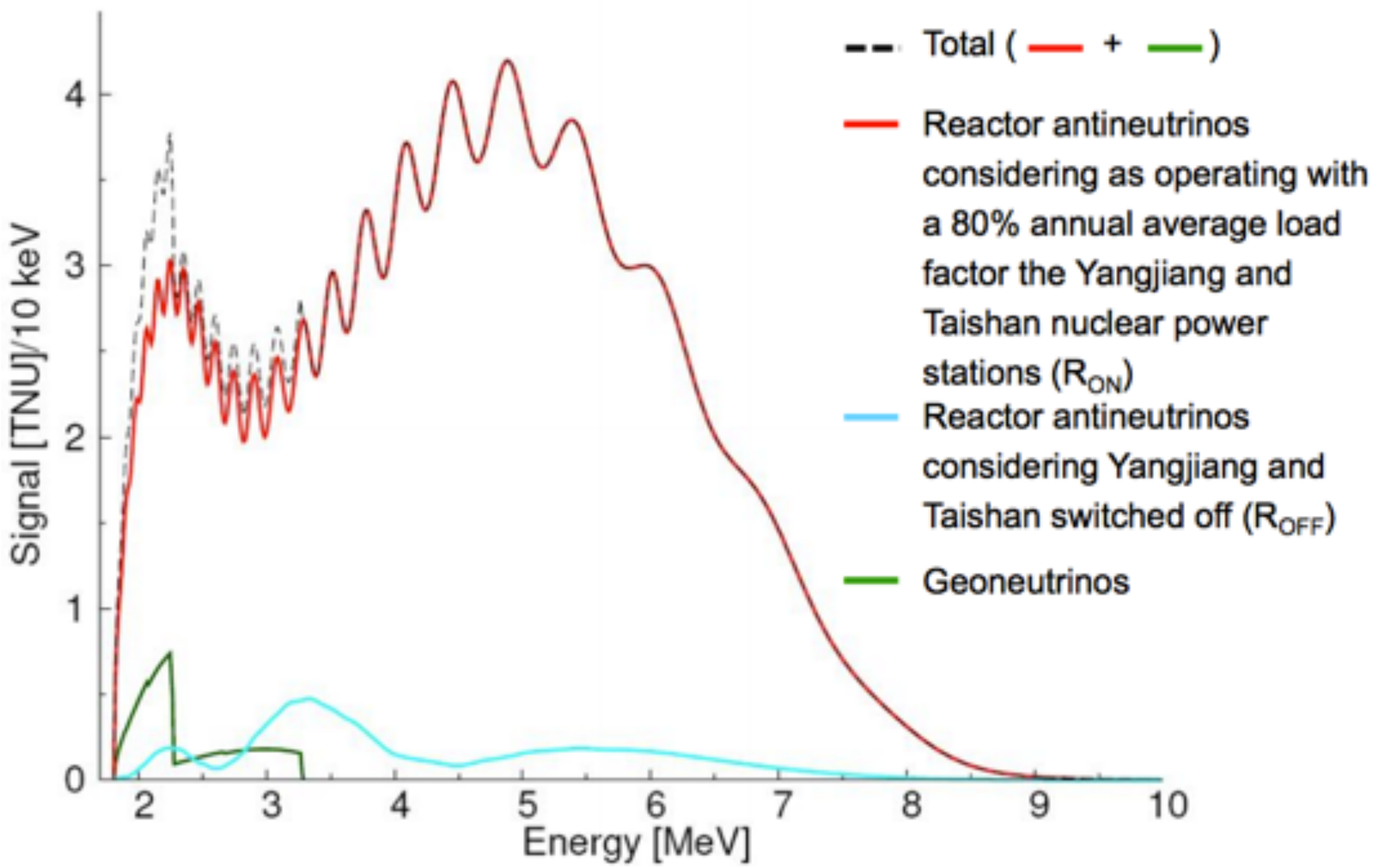


Geoneutrinos

- **Geo-neutrinos**
  - ⇨ Current results
    KamLAND: 30±7 TNU *(PRD 88 (2013) 033001)*
    Borexino: 38.8±12.2 TNU *(PLB 722 (2013) 295)*
    Statistics dominant
  - ⇨ Desire to reach an error of 3 TNU
  - ⇨ JUNO: ×20 statistics
    - Huge reactor neutrino backgrounds
    - Need accurate reactor spectra

expected signal & background

Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
$\boxed{\text{Reactors}}$	$\boxed{16100 \pm 900}$
Fast neutrons	3.65 ± 3.65
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4



combined fit of geoneutrino and reactor neutrino

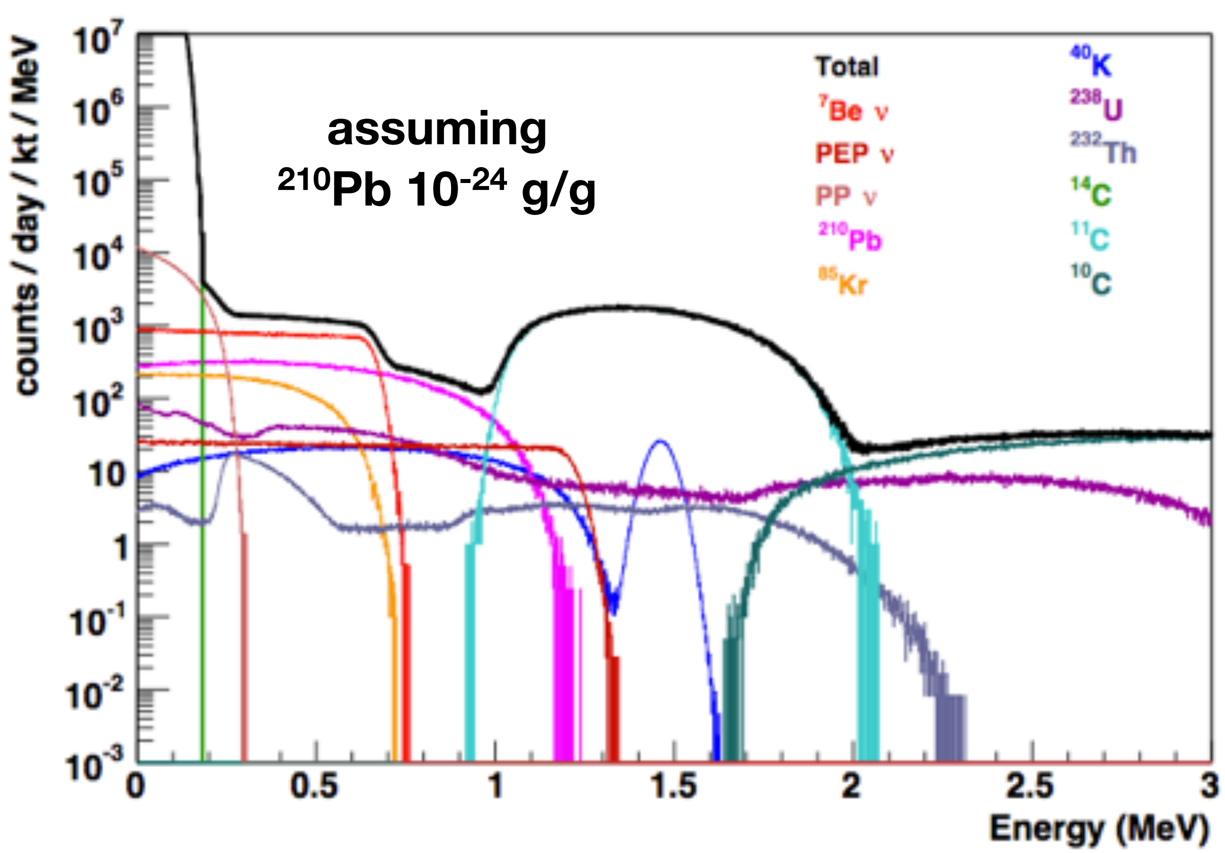
	Best fit	1 y	3 y	5 y	10 y
U+Th fix ratio	0.96	17%	10%	8%	6%
U (free)	1.03	32%	19%	15%	11%
Th (free)	0.80	66%	37%	30%	21%

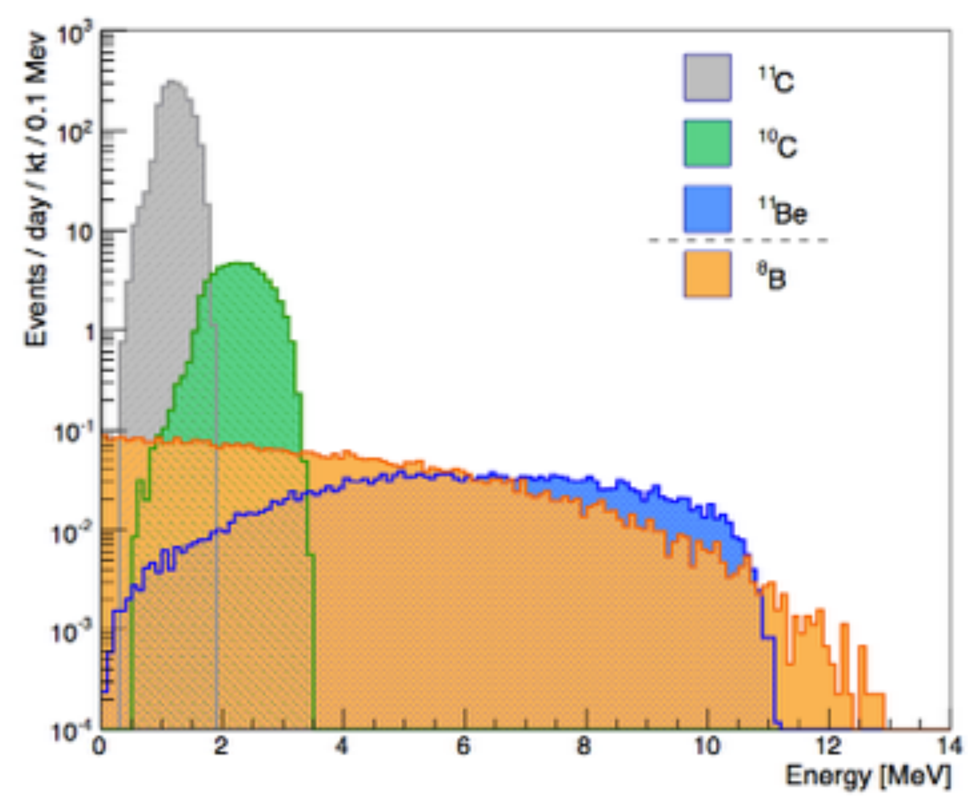
Solar Neutrinos

- Huge number of solar neutrinos, however is a challenging measurement
    - ^{7}Be (10^4 /day): low energy background purification
    - ^{8}B (100 /day): cosmogenic background tagging
    - Others are not practical to observe

LS impurity

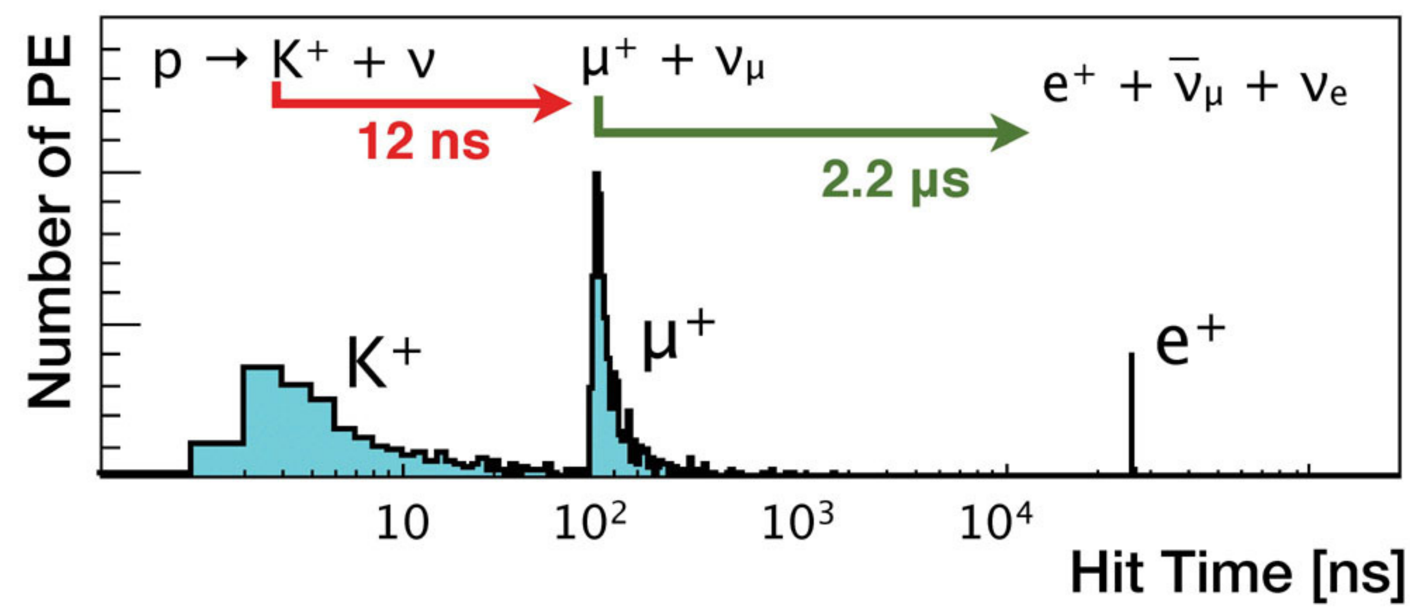
Liquid Scintillator	U238	Th232	K40	Pb210 (Rn222)	Ref.
No Distillation	10^{-15}	10^{-15}	10^{-16}	$1.4\cdot10^{-22}$	Borexino CTF, KamLAND
After Distillation	10^{-17}	10^{-17}	10^{-18}	10^{-24}	

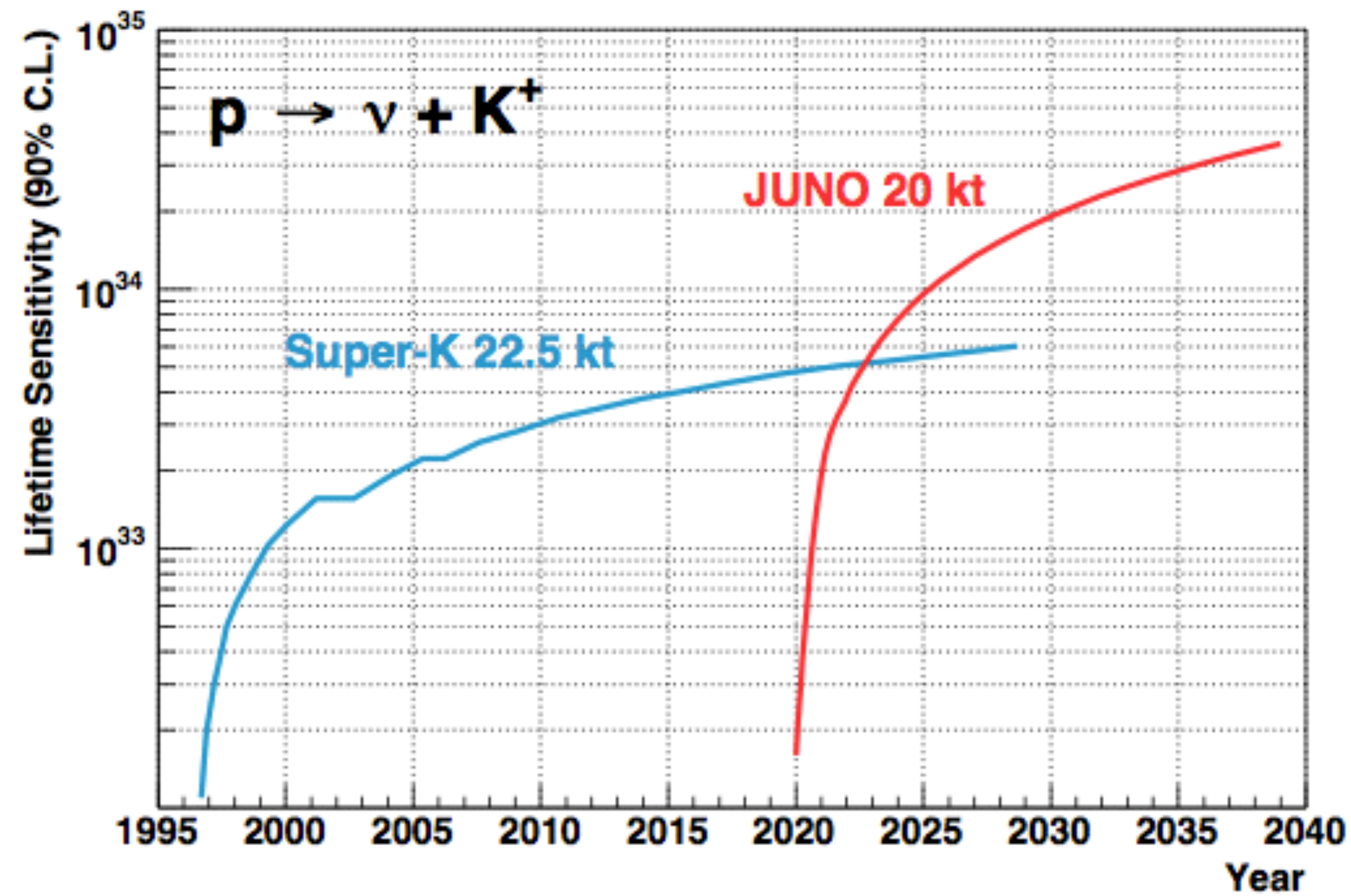




Proton Decay

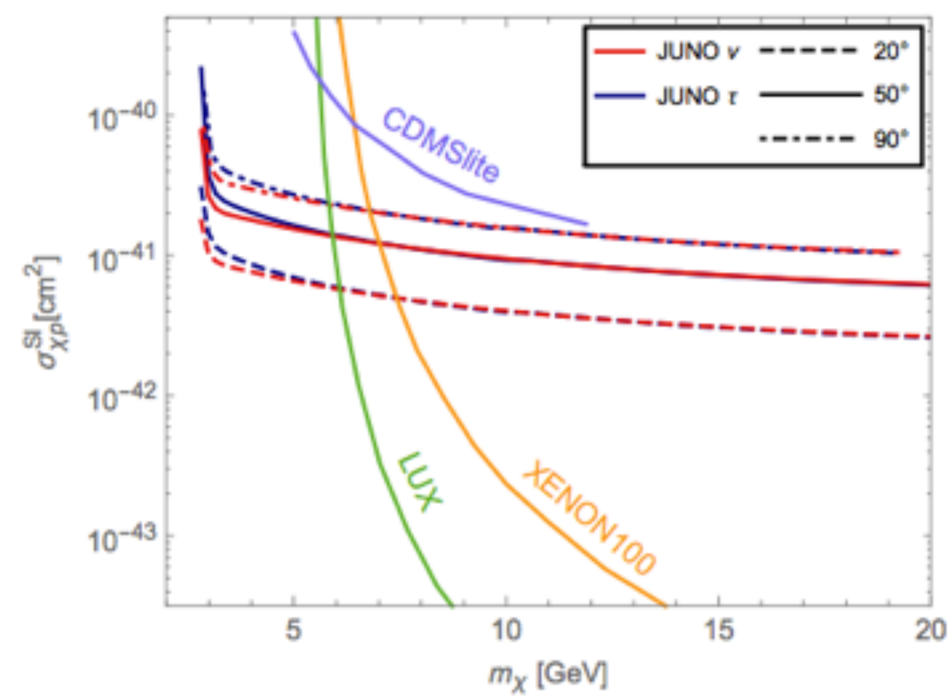
- Currently most lifetime limits set by SK
- JUNO (LS detector) is competitive in the $p \rightarrow K^+\overline{\nu}$ channel
  - high efficiency in detecting the K^+ (below Cherenkov threshold)
  - three-fold coincidence and pulse shape discrimination to reject background
    - ~0.05 bkgd/year from atm. neutrino





Other Physics

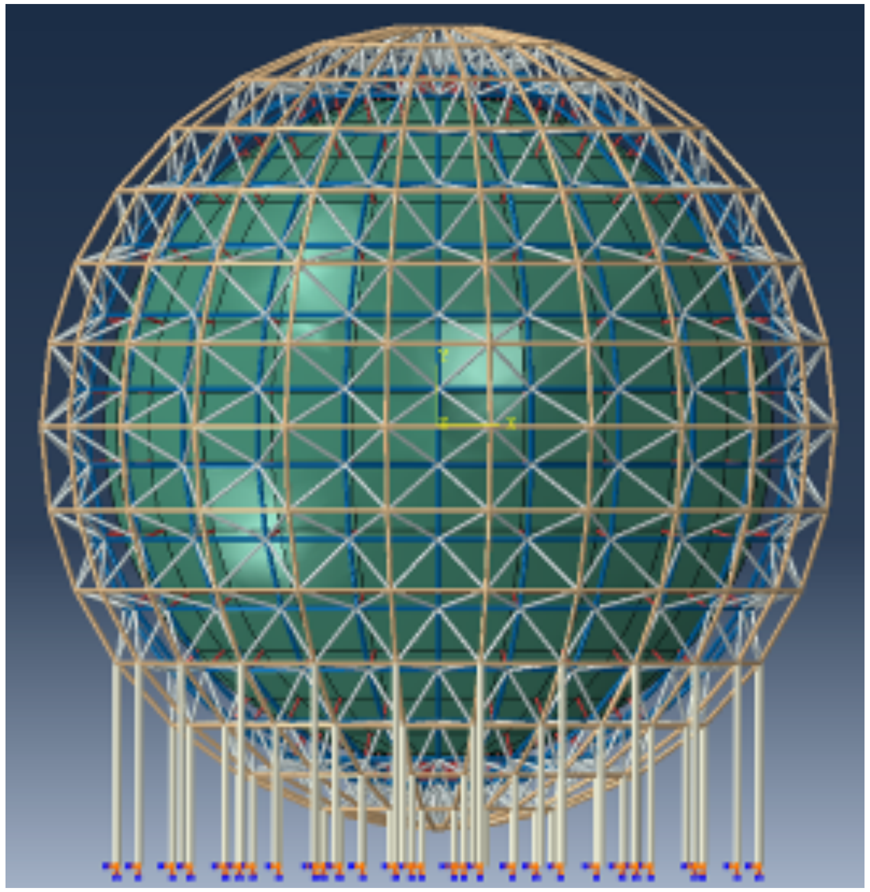
- Sterile neutrino searches
  - (anti-)ν source @JUNO
  - IsoDAR @JUNO (cyclotron-produced ^{8}Li antineutrino source)
- Indirect dark matter
  - dark matter annihilation inside the Sun
- Other Exotic searches
  - Nonstandard neutrino interactions
  - Lorentz-violating neutrino oscillation
  - Mass-varying neutrinos

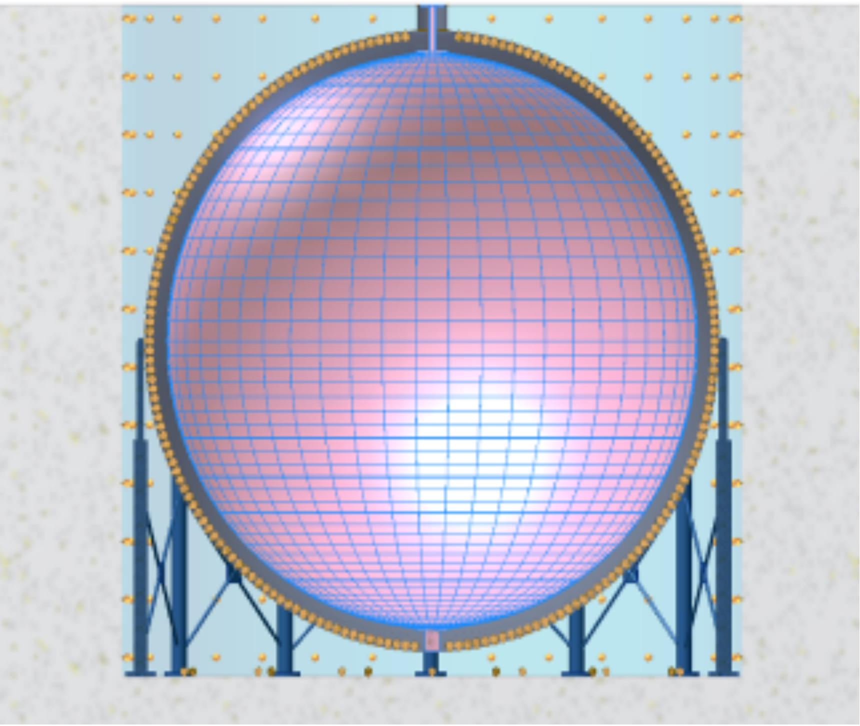


The JUNO Physics Book will be released in a few months.

JUNO Status - Central Detector

- Some basic numbers:
  - ⇨ Target: 20 kt LS
  - ⇨ Backgrounds/reactor signal: Accidentals (~10%), $^{9}Li/^{8}He$ (<1%), fast neutrons (<1%)
- A huge detector in a water pool:
  - ⇨ Default option: acrylic tank (D~35m) + SS truss
  - ⇨ Alternative option: SS tank (D~39m) + acrylic structure + balloon
- Challenges:
  - ⇨ Engineering: mechanics, safety, lifetime, …
  - ⇨ LS: high transparency, low background
  - ⇨ PMT: high QE, high coverage
- Design & prototyping underway



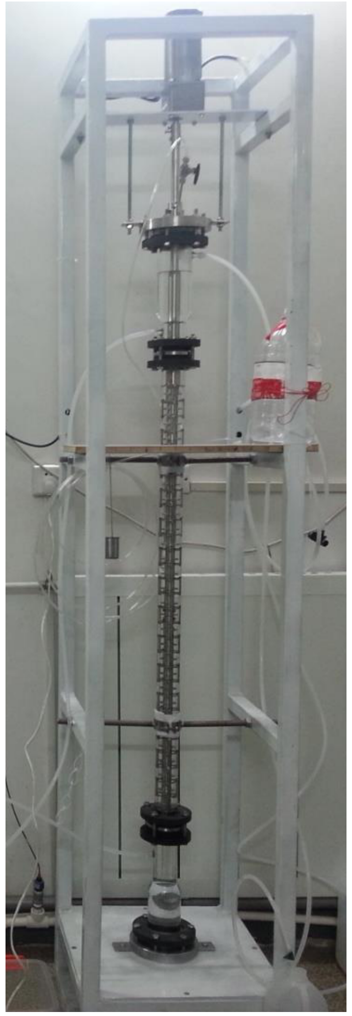


JUNO Status - Liquid Scintillator

- Recipe

  LAB+PPO+bisMSB (no Gd-loading)

- Increase light yield
  - ⇨ Optimization of fluors concentration
- Increase transparency
  - ⇨ Good raw solvent LAB
    - ➢ Improve production processes: cutting of components, using Dodecane instead of MO, improving catalyst, etc
  - ⇨ Online handling/purification
    - ➢ Distillation, Filtration, Water extraction, Nitrogen stripping, …
- Reduce radioactivity
  - ⇨ Less risk, since no Gd
  - ⇨ Instrinsic singles < 3Hz (above 0.7MeV), if ^{40}K/U/Th <10^{-15} g/g (TCF)

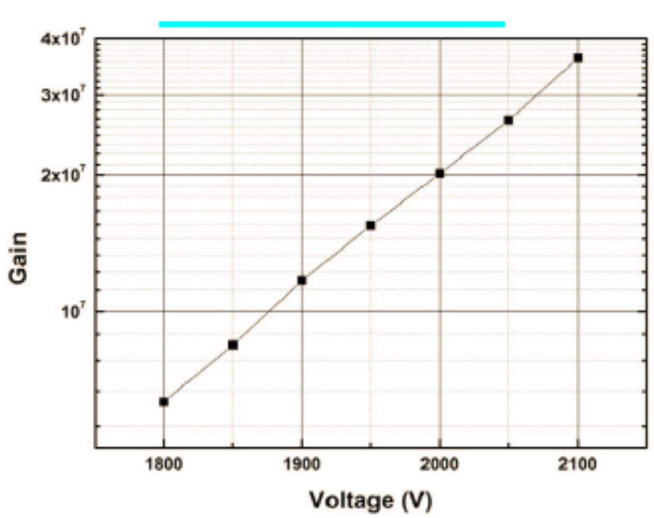


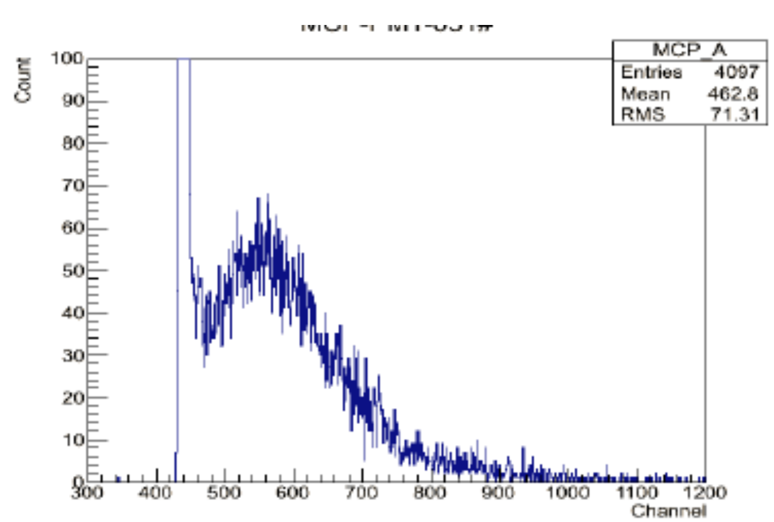
Linear Alky Benzene (LAB)	Atte. Length @ 430 nm
RAW (specially made)	**14.2 m**
Vacuum distillation	**19.5 m**
SiO_2 coloum	**18.6 m**
Al_2O_3 coloum	**25 m**

JUNO Status - High QE PMT

- High QE 20” PMTs under development:
  - **A new design using MCP: 4π collection**
- MCP-PMT development:
  - **Technical issues mostly resolved**
  - **Successful 8” prototypes**
  - **Many 20” prototypes**
- **Alternative options:** Hamamatsu or Photonics

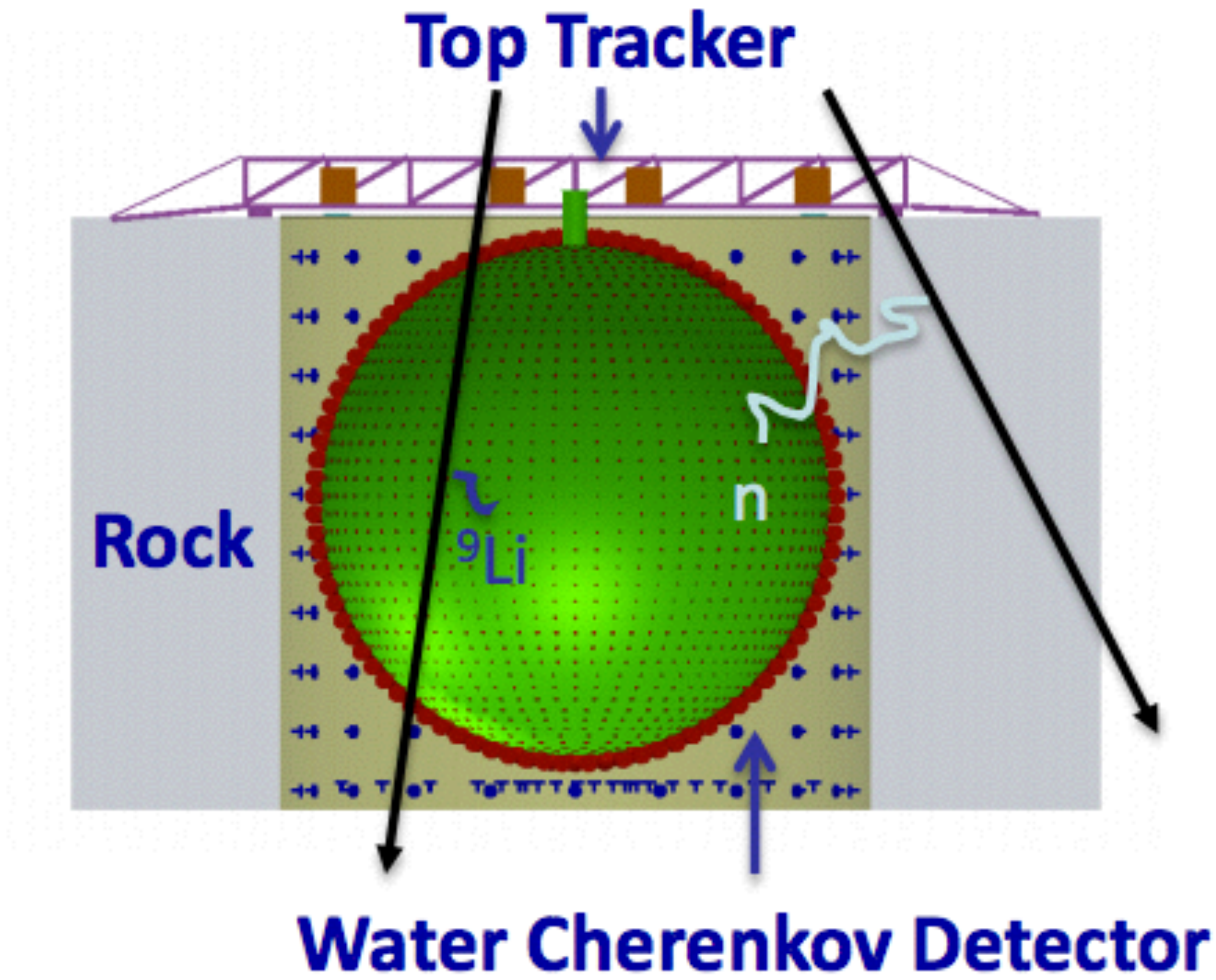
	R5912	R5912-100	MCP-PMT
QE@410nm	25%	35%	25%
Rise time	3 ns	3.4ns	5ns
Dark noise	1kHz	3.5kHz	2.2kHz
P/V of SPE	>2.5	>2.5	`~2
TTS	5.5ns	1.5 ns	3.5 ns





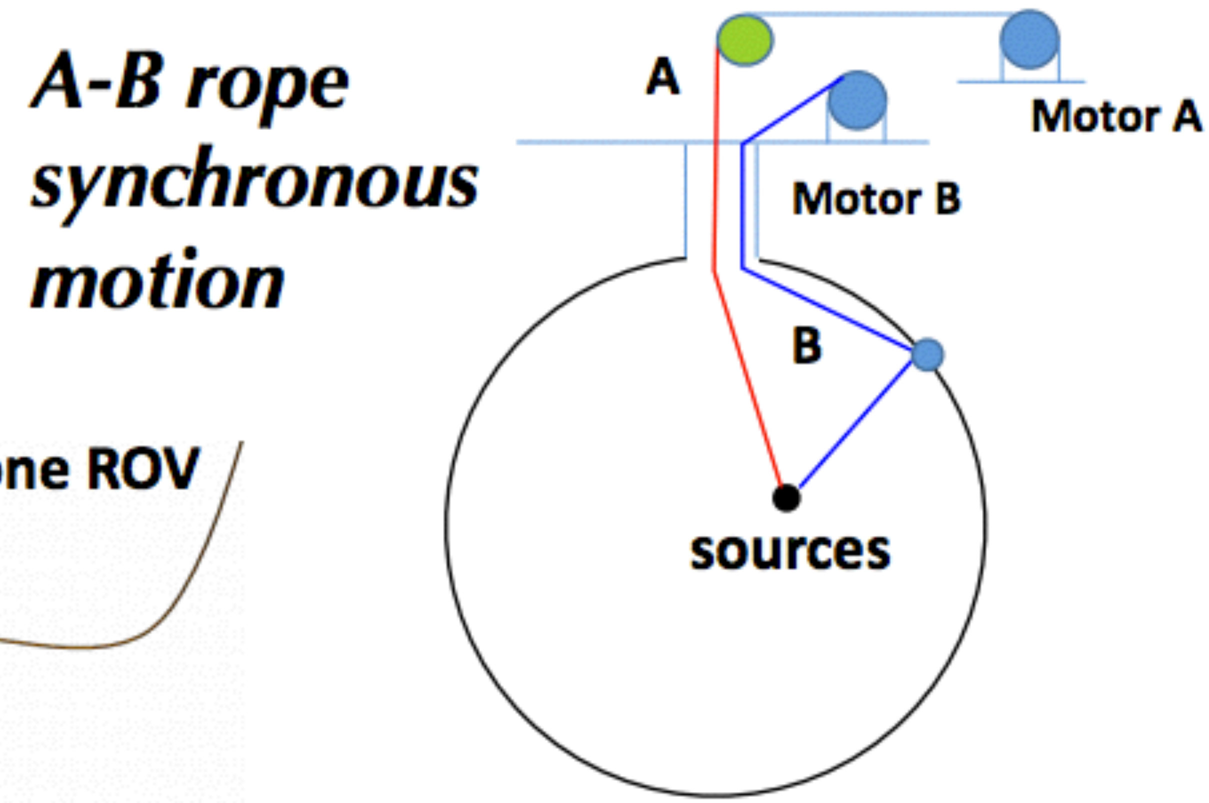
JUNO Status - Veto Detectors

- **Cosmic muon flux**
  - Overburden： ~700 m
  - Muon rate： 0.0031 Hz/m^2
  - Average energy： 214 GeV
- **Water Cherenkov Detector**
  - At least 2 m water shielding
  - ~1500 20”PMTs
  - 20~30 kton pure water
  - Similar technology as Daya Bay (99.8% efficiency)
- **Top muon tracker**
  - Muon track for cosmogenic bkg rejection
  - Decommissioned OPERA plastic scintillator
  - Possibly w/ RPC



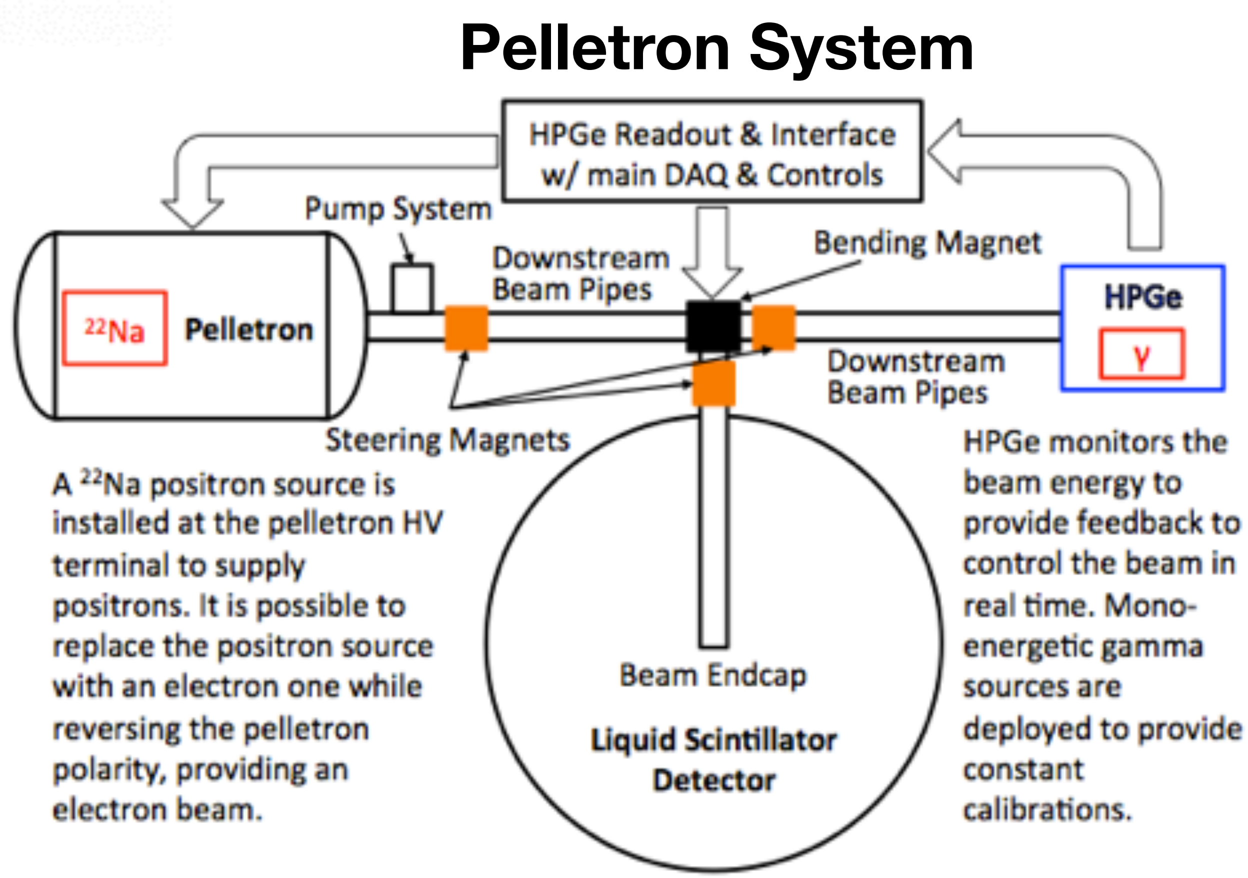
JUNO Status - Calibration System

- Regular central axis calibration system
- Off-axis rope system

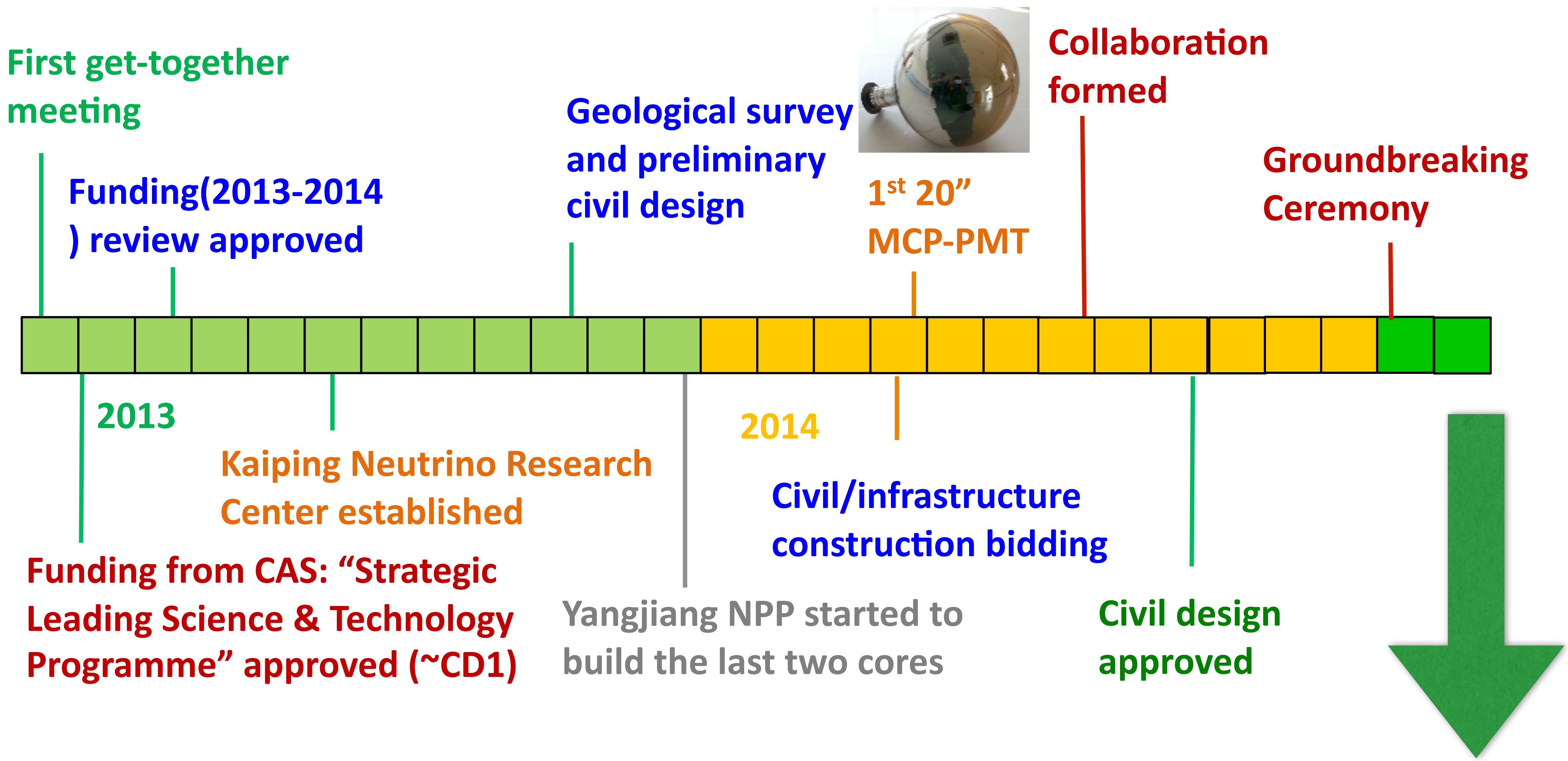


In consideration & design

- Remote Operated Vehicle 4π system
- Guide tube system near the boundary regions
- Pelletron accelerator system for precision e^+ calibration
- UV laser, diffuse isotopes, mini-balloon, positioning system etc.



Project Progress and Schedule



- Civil construction： 2015-2017
- Detector component production： 2016-2017
- PMT production： 2016-2019
- Detector assembly & installation： 2018-2019
- Filling & data taking： 2020

Summary

- JUNO is aiming to be a multi-purpose neutrino observatory
  - a comprehensive program with rich physic topics
    - Reactor neutrinos: MH, precision measurement of U_{PMNS}
    - SN, DSNB, atmospheric, solar, geo neutrinos, …
- A strong international collaboration has been established
- The JUNO project is progressing very well
  - Approved in Feb. 2013
  - Groundbreaking in Jan 2015
  - Physics book and CDR in a few months
  - Schedule: civil construction complete in 3 years, and data taking start in 6 years