The physics of JUNO

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INFN - Milano

Colloquium Prague ν 17
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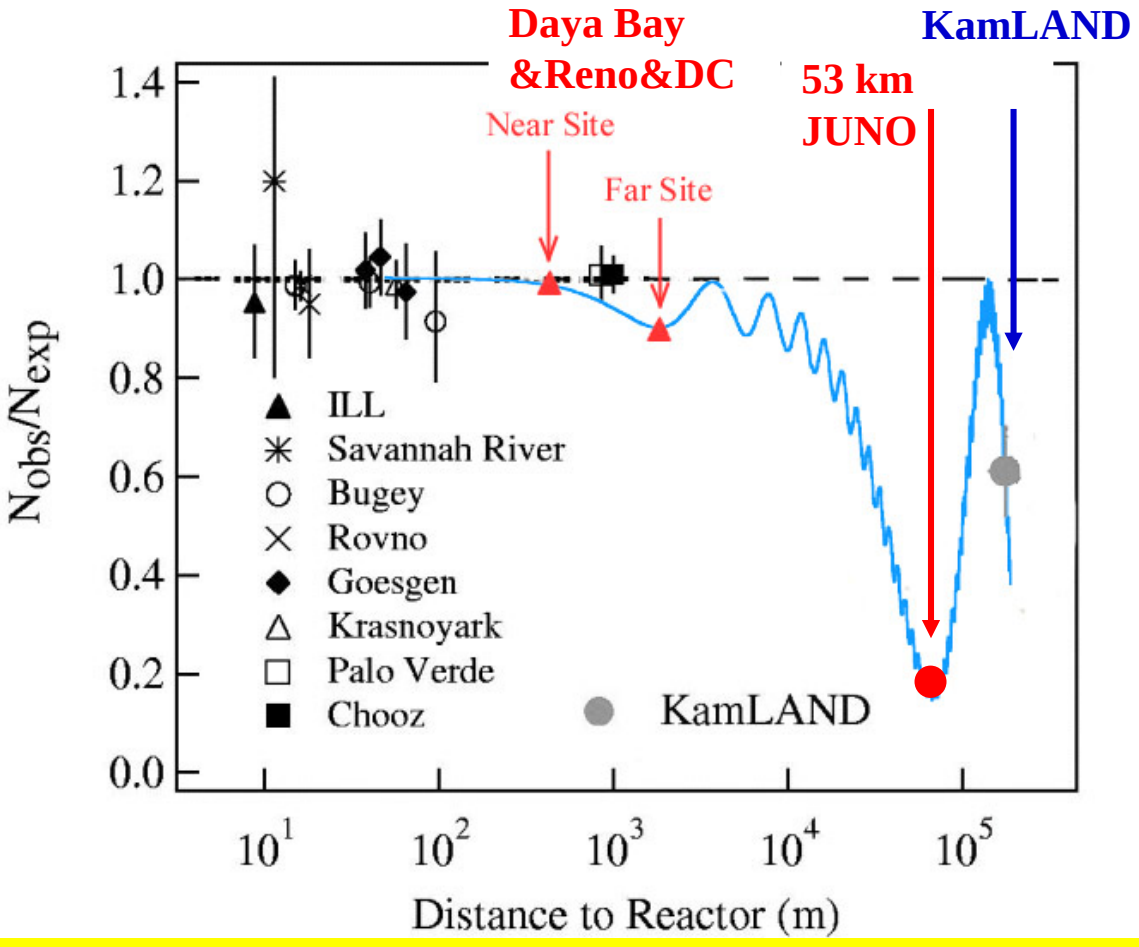
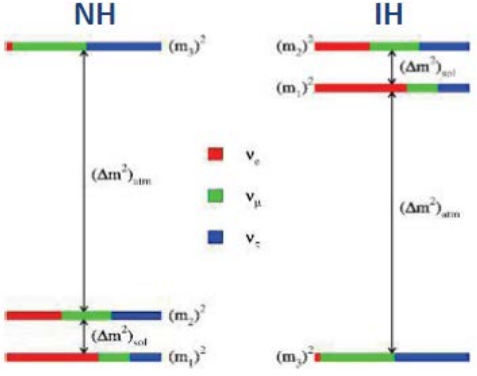
On behalf of the JUNO Collaboration

- Determination of the neutrino mass hierarchy with a large mass liquid scintillation detector located at medium distance – few tens of km – from a set of high power nuclear complexes
- Precise measurements of oscillation parameters
- Vast astroparticle program

JUNO physics summary



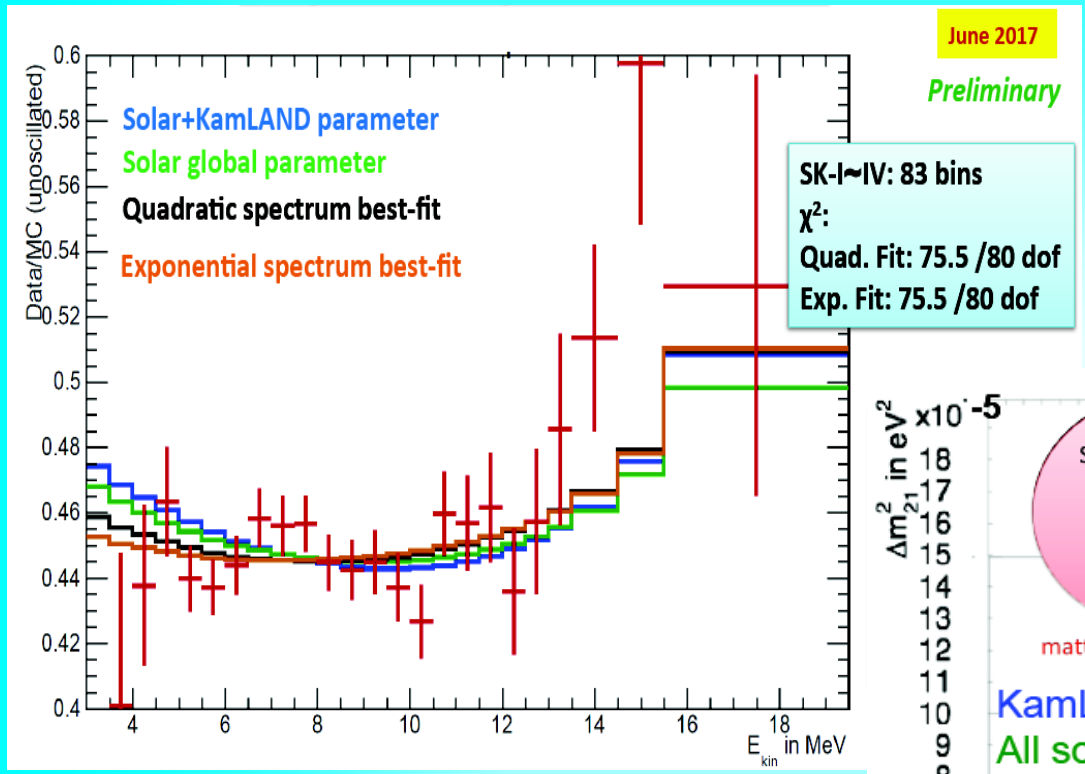
- 20 kton LS detector
- ~3 % energy resolution-the greatest challenge
- Rich physics possibilities
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 3 mixing parameters**
  - ⇨ **Supernovae neutrinos**
  - ⇨ **Geoneutrinos**
  - ⇨ **Diffuse Supernovae ν's**
  - ⇨ **Atmos&sol neutrinos**
  - ⇨ **Nucleon Decay**
  - ⇨ **Exotic searches**



Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)

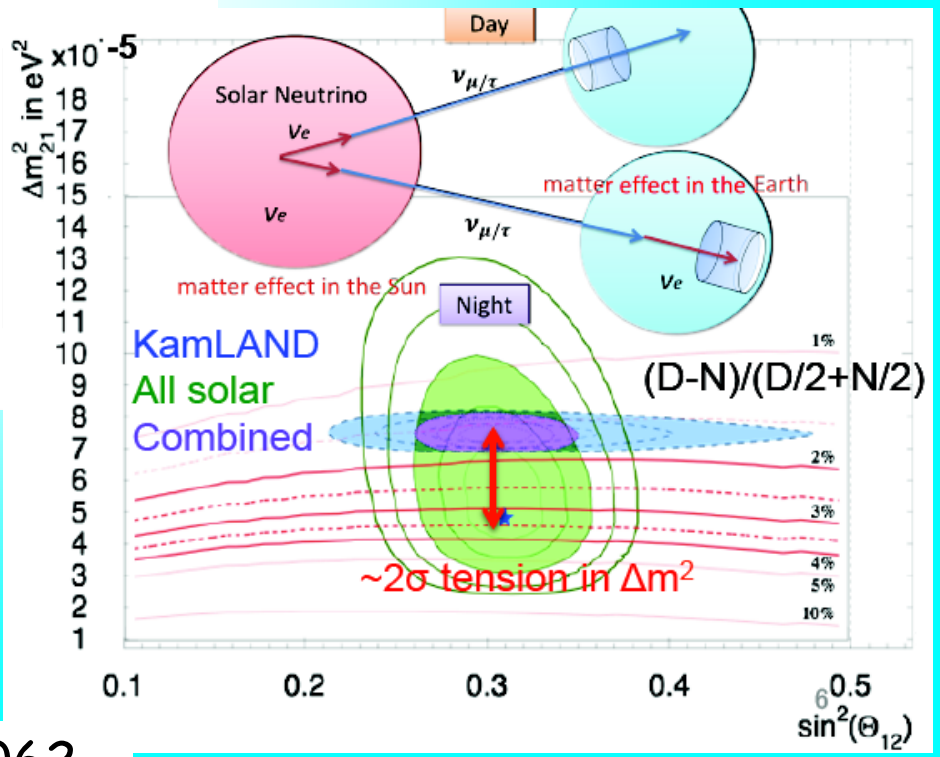
The tension between the solar and KamLAND Δm^2 has further boosted the importance of the precision Δm^2_{21} measurement

Super-Kamiokande results



A. Yu. Smirnov
Max-Planck Institute fuer Kernphysik, Heidelberg, Germany

Workshop on recent developments in Neutrino physics and astrophysics, Gran Sasso, September 7, 2017



SK-IV 18 events/day
+ 280 days until march 17,
E = 3.5 – 19.5 MeV
SK I – IV total 5480 days

Data/MC(no-osc) = 0.4486 +/- 0.0062

How things may develop

Value of Δm_{21}^2 fluctuates

Re-analysis of KamLAND with measured reactor neutrino spectra

JUNO: precise measurements of Δm_{21}^2 with 0.7 -1% accuracy

$$\sigma(\Delta m_{21}^2) = (0.05 - 0.07) \times 10^{-5}\ eV^2$$

Difference of solar and KamLAND

$$\Delta(\Delta m_{21}^2) = 2.5 \times 10^{-5}\ eV^2$$

If

$\Delta m_{21}^2(\text{JUNO}) = \Delta m_{21}^2(\text{solar})$ problem solved

$\Delta m_{21}^2(\text{JUNO}) = \Delta m_{21}^2(\text{KL})$ problem sharpens

Stronger bounds on NSI from COHERENT and other experiments

SNO+ spectrum measurements above 3 MeV (testin

Hyper-Kamiokande

Day-night asymmetry spectrum

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The physics with a large LS spherical detector

- LS large volume: ➔ for statistics
- High Light(PE) ➔ for energy resolution 1200 pe/MeV

Both crucial for the physics capabilities

Steel Truss

Holding PMTs

~20000 x 20”

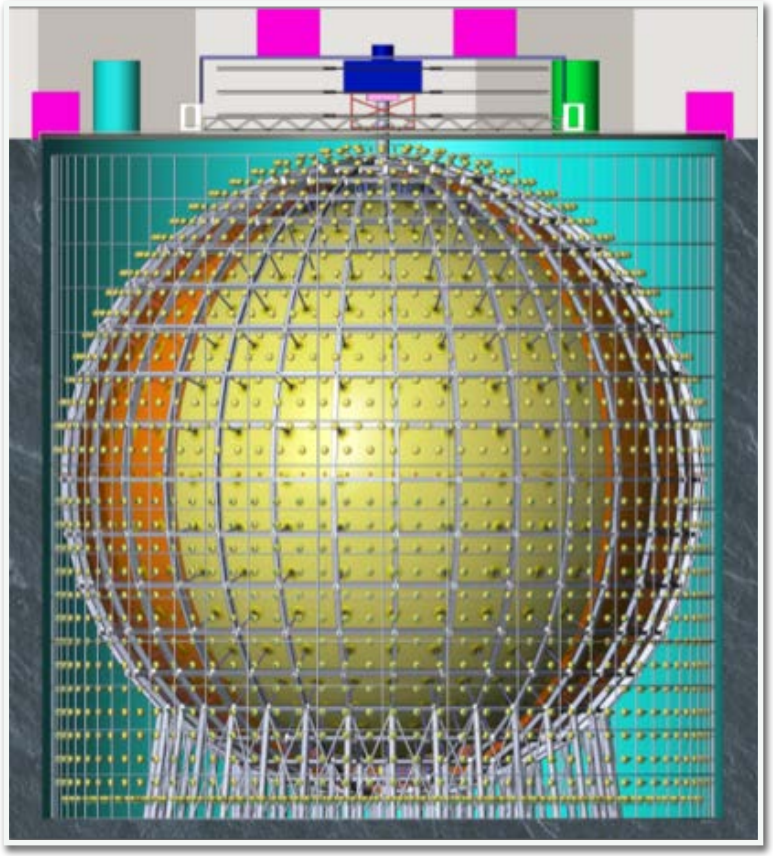
18000 Inner

2000 veto

~25000 x 3”

Acrylic Sphere

filled with 20 kt LS



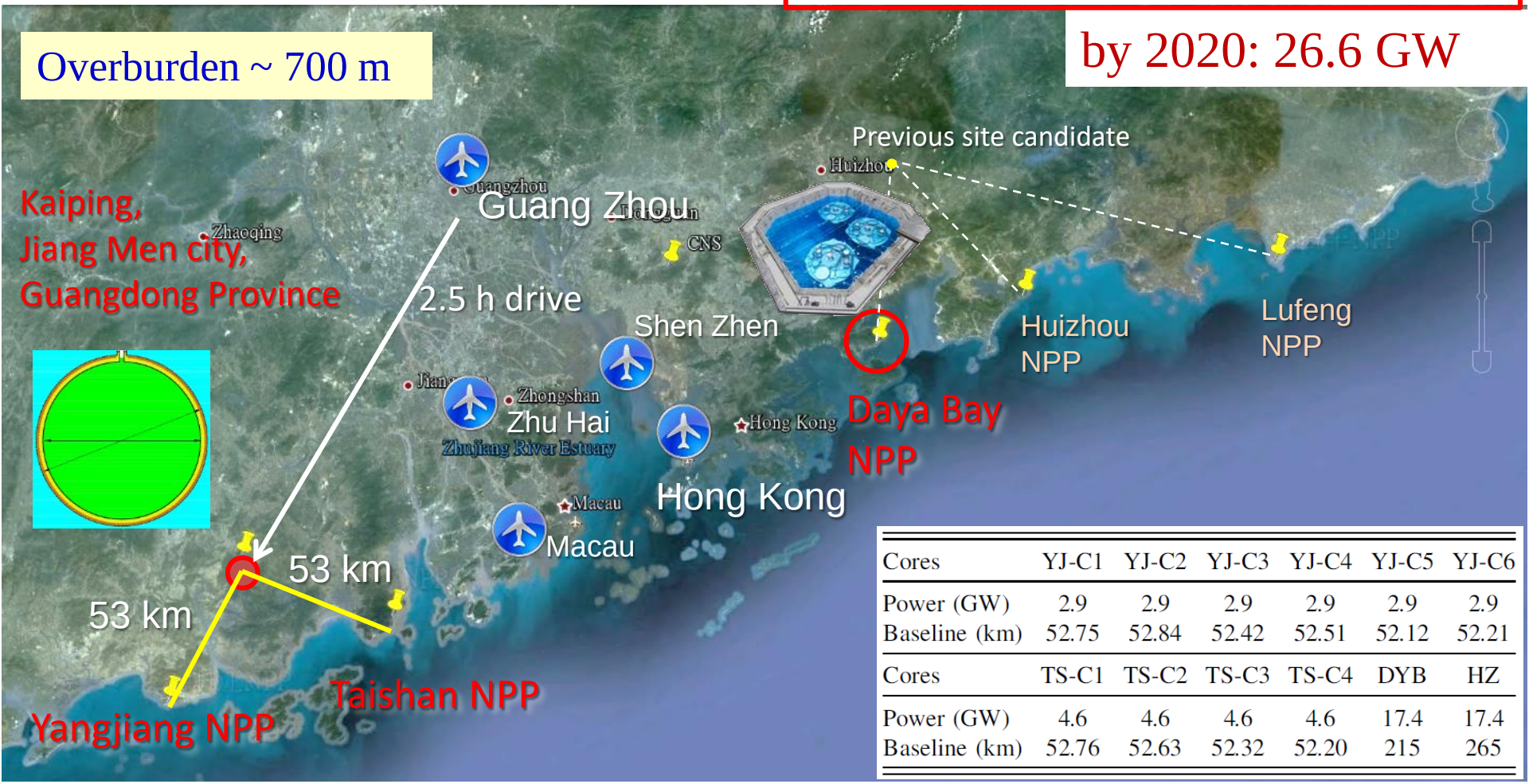
JUNO has been approved in China in Feb. 2013

Prospective and approved funding from several other countries:

- **Belgium**
- **Czechia**
- **Finland**
- **France**
- **Germany**
- **Italy**
- **Russia**
- **Taiwan**
- **Chile**
- **Brasil**
- **Thailandia**
- **Pakistan**

The importance of the location

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



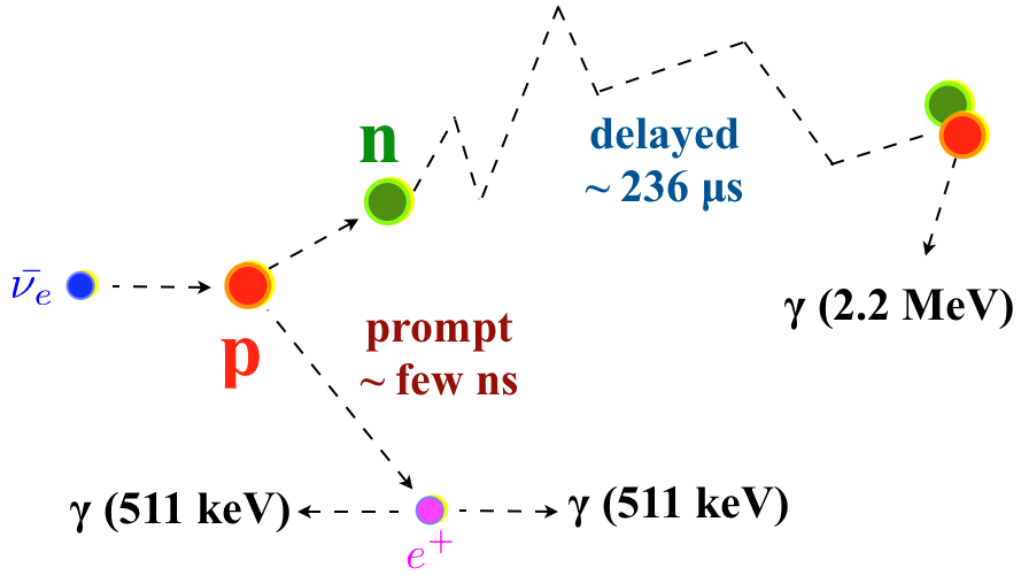
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

Methodology to infer the Mass Hierarchy

The determination of the mass hierarchy relies on the identification on the positron spectrum of the "imprinting" of the anti-ν_e survival probability

Detection through the classical inverse beta decay reaction

$$\bar{\nu} + p \rightarrow n + e^+ \quad E_\nu > 1.8 \text{ MeV}$$



The time coincidence between the positron and the γ from the capture rejects the uncorrelated background

The "observable" for the mass hierarchy determination is the positron spectrum
It results that $E_{vis}(e^+) = E(\nu) - 0.8$ MeV

Method from Petcov and Piai, Physics Letters B 553, 94-106 (2002)

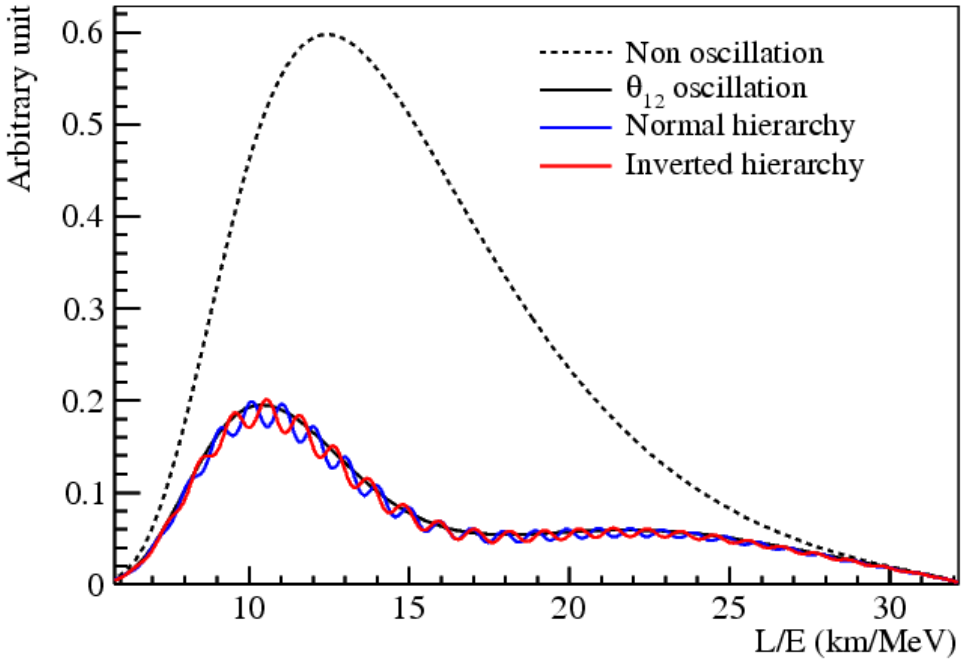
MH and Survival probability

arXiv 1210.8141

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i \frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$

$$= 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta_{21}) - \cos^2\theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta_{31}) - \sin^2\theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta_{32})$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$



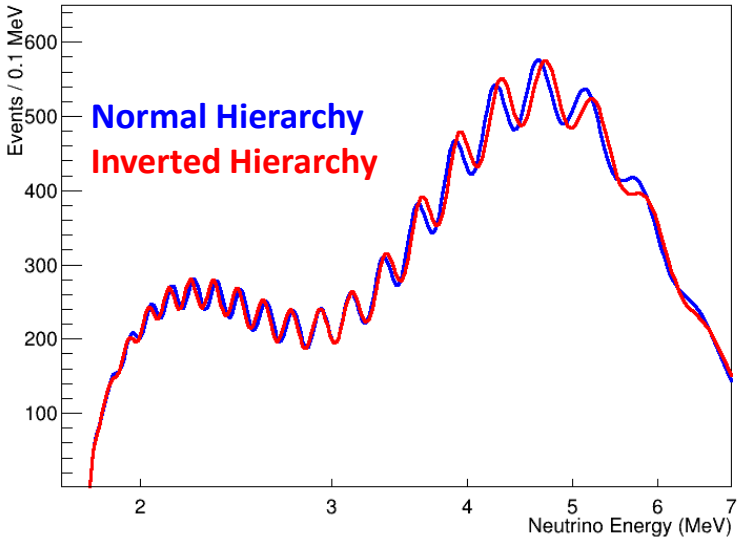
Or to make the effect of the mass hierarchy explicit, exploiting the approximation $\Delta m^2_{32} \approx \Delta m^2_{31}$:

$$P_{ee} = 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta_{21}) - \sin^2 2\theta_{13} \sin^2(|\Delta_{31}|) - \sin^2\theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta_{21}) \cos(2|\Delta_{31}|) \pm \frac{\sin^2\theta_{12}}{2} \sin^2 2\theta_{13} \sin(2\Delta_{21}) \sin(2|\Delta_{31}|),$$

+ NH
- IH

The big suppression is the "solar" oscillation → Δm^2_{21} , $\sin^2\theta_{12}$
The ripple is the "atmospheric" oscillation → Δm^2_{31} from frequency
MH encoded in the phase
"high" value of θ_{13} crucial

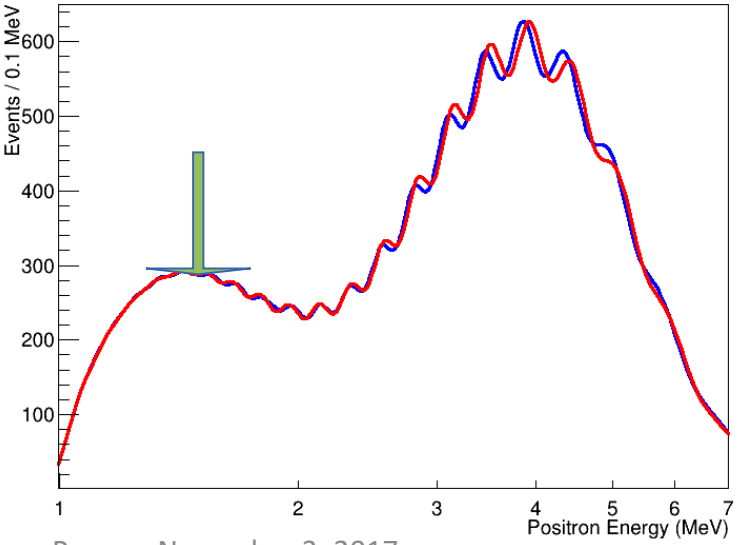
Neutrino & Positron Spectra



Spectrum in term of neutrino energy – no energy resolution

Replicating sensitivity study in arXiv 1210.8141

- Three neutrino framework (no effective Δm_{ee} $\Delta m_{\mu\mu}$)
- Baseline: 50 km
- Fiducial Volume: 5 kt
- Thermal Power: 20 GW
- Exposure Time: 5 years
- more pessimistic than the JUNO values ▶ used to be in sync with paper



Visible energy due to inverse beta decay

- E(vis) ~ E(ν) – 0.8 MeV
- Assuming 3% / sqrt(E) resolution
- Assuming negligible constant term in resolution

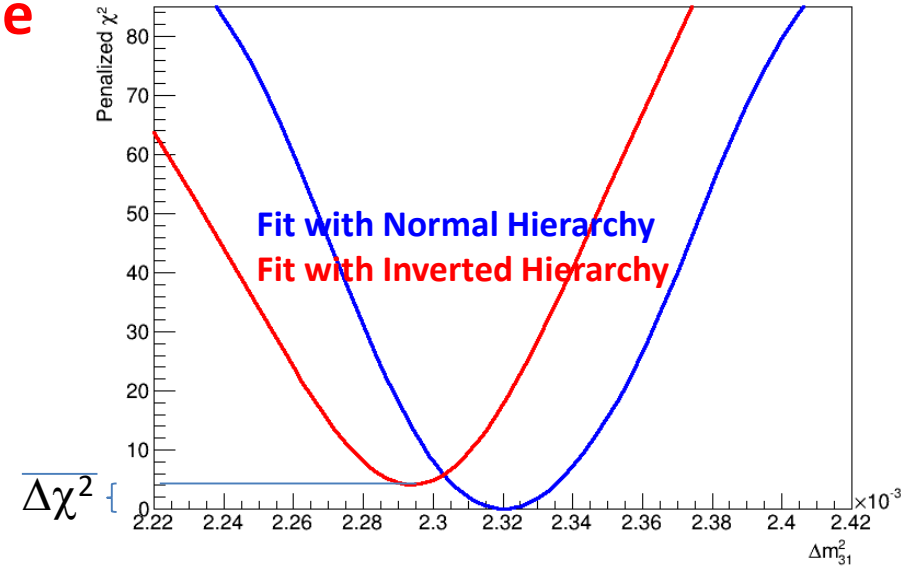
Spectrum in term of positron visible energy – with energy resolution

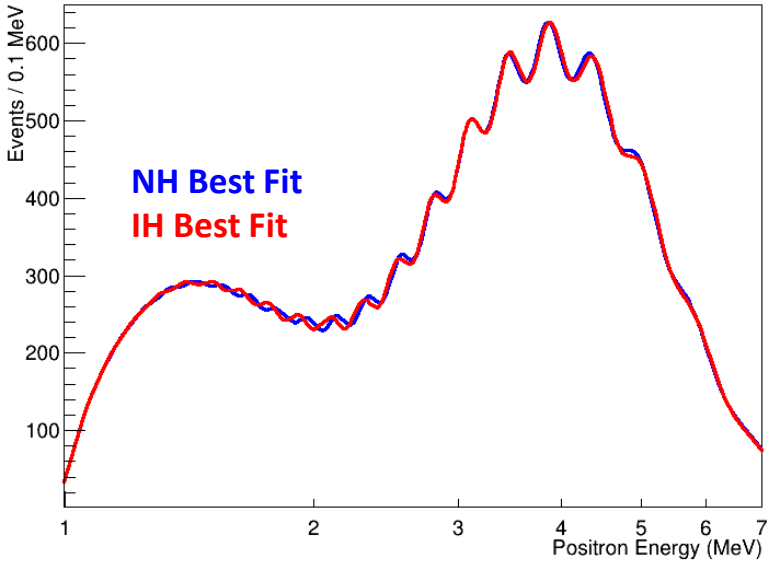
Example of χ^2 comparison – NH true

Numerical values as before
Scan of penalized (i.e. marginalized over the other minimization parameters) χ^2 vs. $|\Delta m^2_{31}|$

Case NH true- average spectrum
(no fluctuation –**Asimov data set**)
Test statistics → $\Delta\chi^2=\chi^2_{min}(NH) - \chi^2_{min}(IH)$

Fit NH minimum: 1.6 10^{-2} (practically 0)
FIT IH minimum: 4.0
$\overline{\Delta\chi^2}$ ~4.0



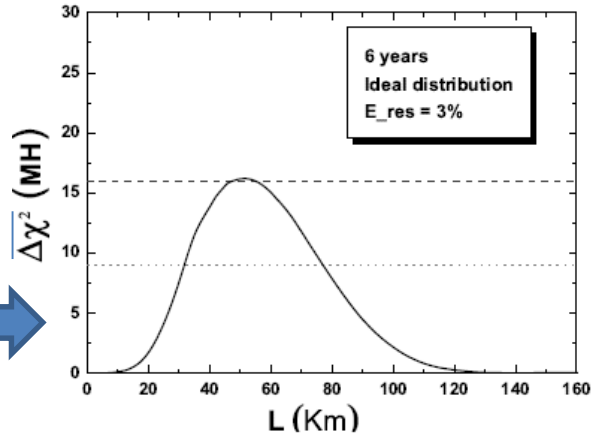


Comparison between IH/NH best fits
The best fit $|\Delta m_{31}|$ is different in the two cases

Fit almost succeeds in accommodating IH spectrum to NH data

The two solutions are fully degenerate but in a limited range of distances

Optimum distance to maximize $\overline{\Delta\chi^2}$

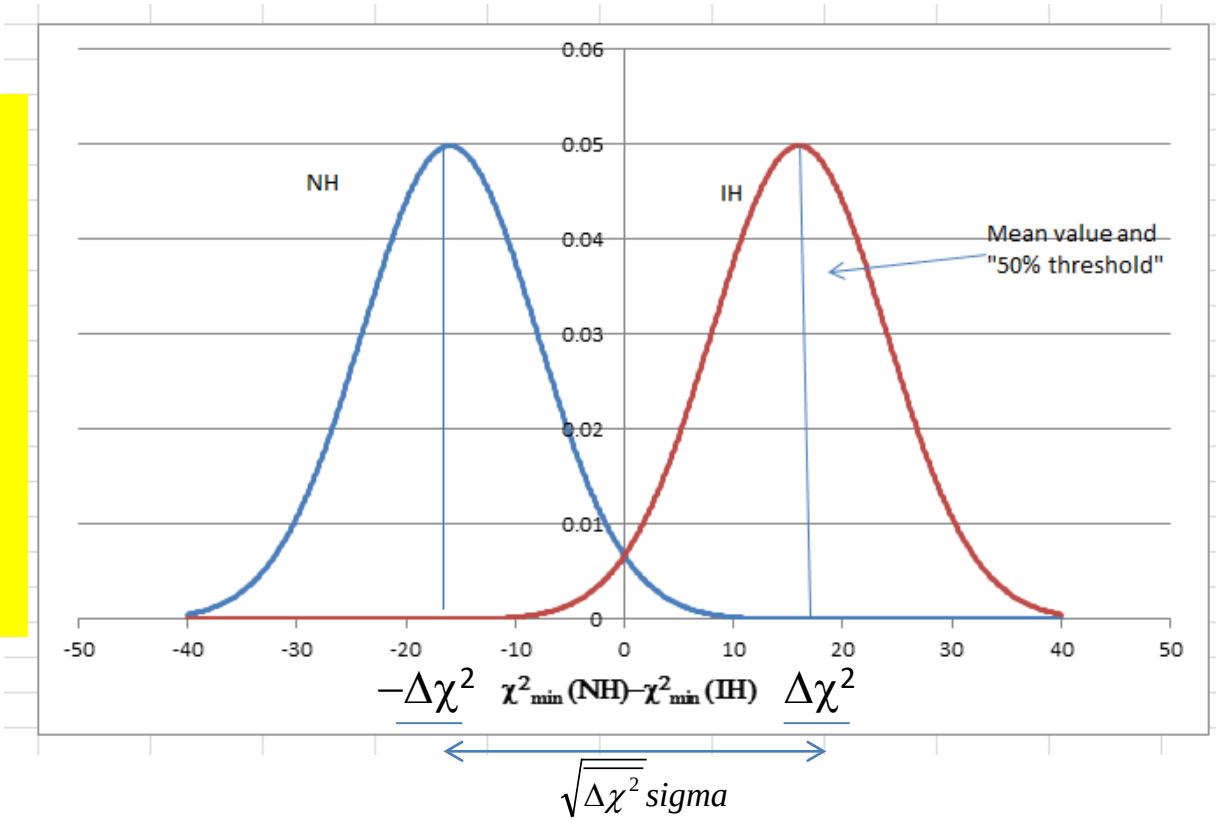


From arXiv:1303.6733v1 [hep-ex] JUNO
$\overline{\Delta\chi^2}$ can be as high as **16** @ 53 km

Distribution of test statistics and number of sigmas for discovery

- **Not unique answer**
- It depends upon the assumed framework (**frequentist or Bayesian**)
- However the actual information is fully encoded in the amount of overlap of the two Gaussian independently from how it is summarized as number of σ
- General result: sigma of each Gaussian = $2\sqrt{\Delta\chi^2}$ **arXiv: 1210.8141v2**

The mean value of the Gaussian curves is taken as representative of the **JUNO** capability at 53 Km arXiv:1303.673



The mean values of the two curves are displaced of exactly

$\sqrt{\Delta\chi^2}$ sigmas

Assumed in a frequentist framework as quantification of discovery capability

arXiv:1311.4076

Frequentist considerations for the number of σ

The special relation between sigma and mean value of the two distributions implies that the median sensitivity according to the frequentist framework is automatically equal to

$$\sqrt{\overline{\Delta\chi^2}}\,\sigma$$

This means that if the actual outcome of the experiment is more extreme than the expected mean value one get a positive indication for one of the two hierarchies (IH if the outcome is positive or NH if the outcome is negative) with a CL better than $\sqrt{\overline{\Delta\chi^2}}\,\sigma$ i.e. with a probability of making a mistake (type I error according to the statistical terminology) equal to the corresponding one-tailed p-value on the Gaussian curve

3 σ → p-value (1-0.9973)/2 instead of the standard 1-0.9973

In summary for JUNO

- If the outcome is as typically expected, the MH will be determined rather unambiguously
- Even better if there will be an upward fluctuation
- A downward fluctuation will produce an ambiguous result

With these characteristics JUNO can achieve a 4 σ sensitivity with the above meaning (spectrum with about 100000 events)

Baseline: 53 km

Fiducial Volume: 20 kt

Thermal Power: 36 GW

Exposure Time: 6 years

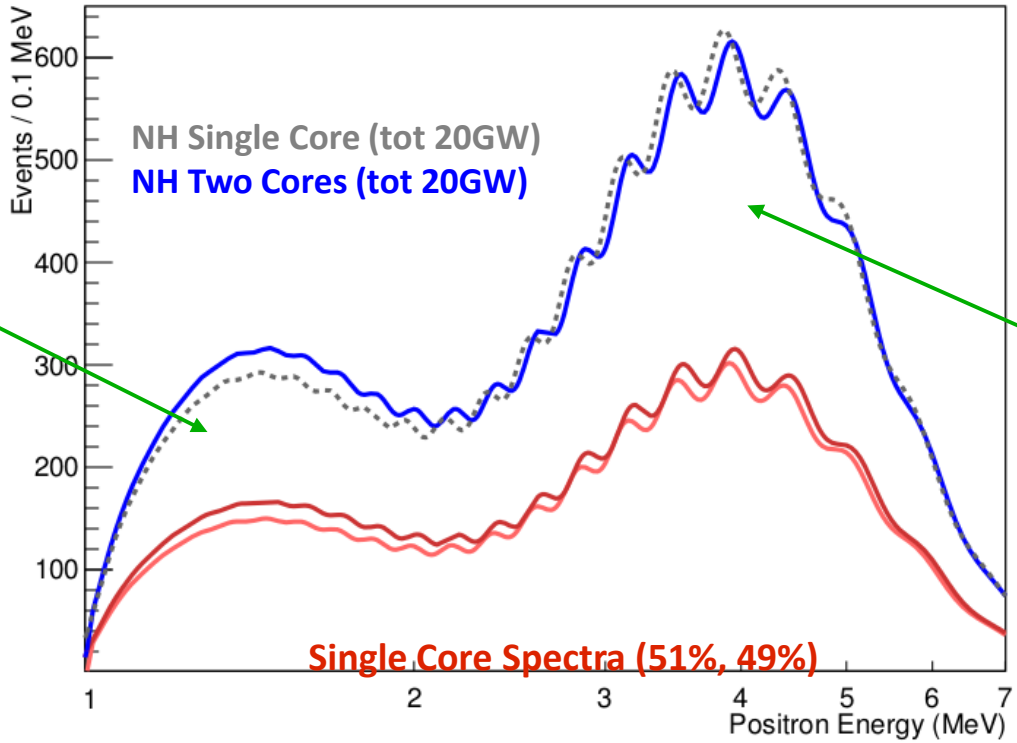
Proton content 12% in mass , en. res. 3%

Caveat: Multiple Cores

Reduction in sensitivity might arise from actual spatial distribution of nuclear reactor cores

Eg. two cores with 51% (49%) of tot. power, placed at 50 km (50.5km) distance from detector

Constructive Interference



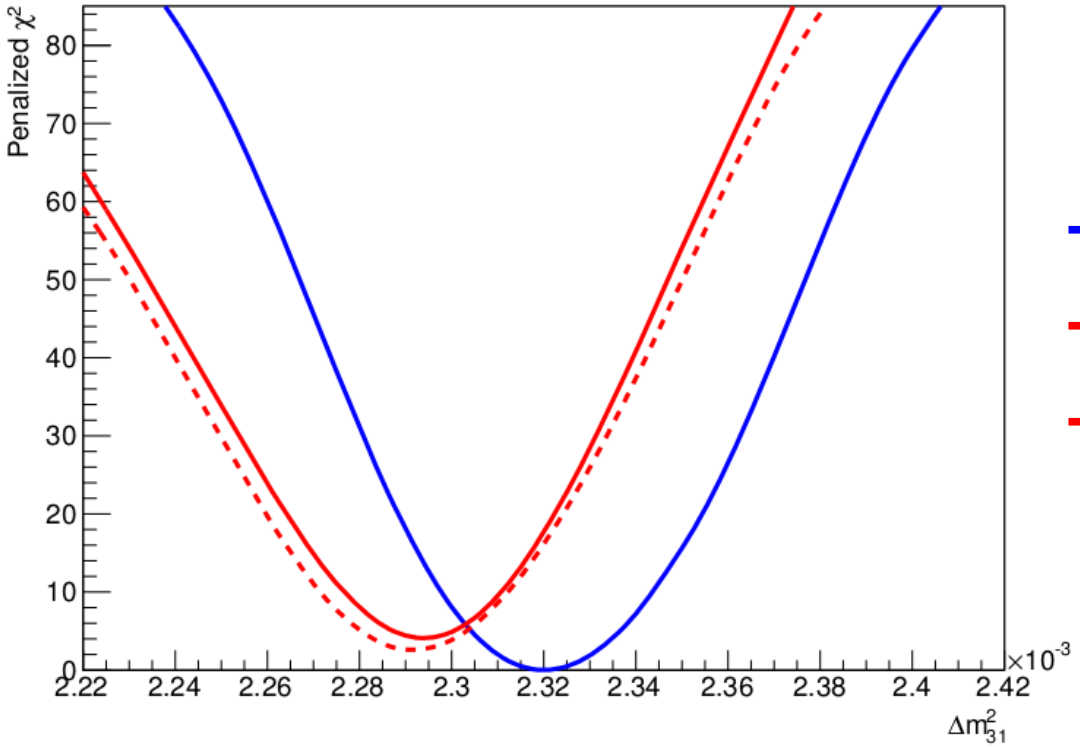
Destructive Interference

Baseline difference results in destructive interference in the most sensitive region of the spectrum

Important effect since JUNO will detect neutrinos several cores

Multiple Cores: χ^2

Sensitivity loss is measured through the new χ^2 minimum



Best Fit NH

Best Fit IH Two Cores

Best Fit IH Single Core

For JUNO this defines the location (only two reactors) and the maximum baseline difference : 500 m

$\overline{\Delta\chi^2}$ between IH and NH in this numerical exercise is reduced from 4.0 to 2.6

In the JUNO set-up the spread of the cores is 500 m $\rightarrow$ $\overline{\Delta\chi^2}$ reduction of about **4**

The other effects

- Adverse effects
  - Non linearity of the energy scale

  This clearly impacts the ability to distinguish the true from false Hierarchy since distorts the experimental spectrum, therefore a very careful calibration is required better than 1% arXiv:1307.7419v3, as well as the long term stability of the detector (Borexino experience very promising, this is what was accomplished in the bulk of the FV , anyhow this is a challenge due to the large dimensions)
  - Reactor shape uncertainty (1%)
  - The statistical and shape uncertainties of backgrounds

- Favorable element for analysis

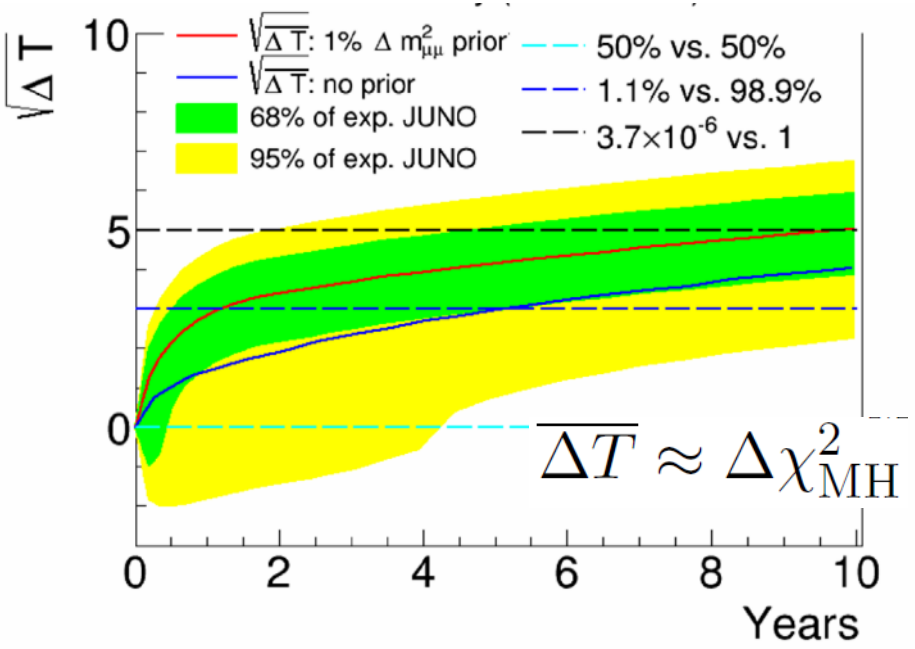
Improved knowledge of Δm_{31} by other experiments specifically T2K and NoνA ~1%

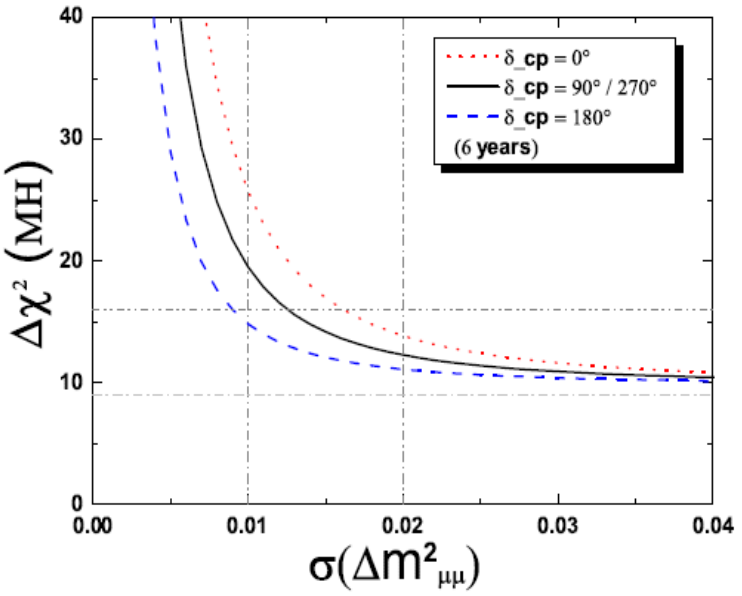
Exploited by adding a pull in the χ^2 definition thus increasing globally the $\Delta\chi^2$
This is better done using the effective parameter $|\Delta m|$

Summary of MH Sensitivity

	Relative Meas.	Use absolute Δm^2
Statistics only	4σ	5σ
Realistic case	3σ	4σ

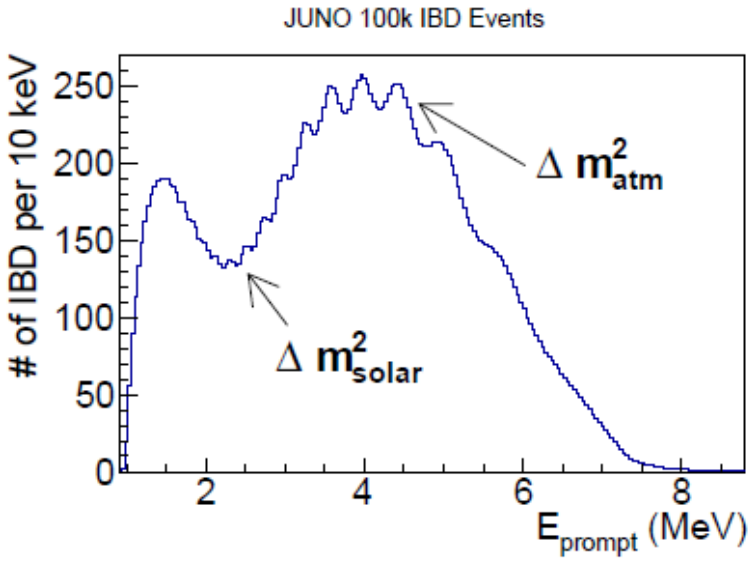
JUNO MH sensitivity with 6 years' data:





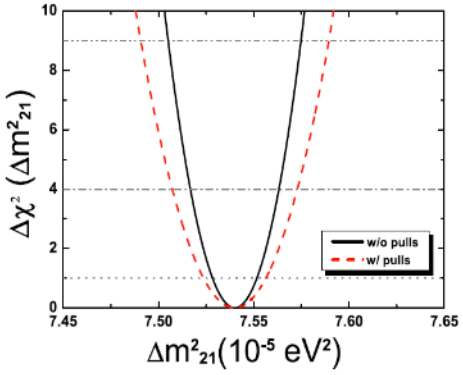
	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{\mathrm{MH}}$	+16	−4	−1	−0.5	−0.1	+8

Precision Measurements

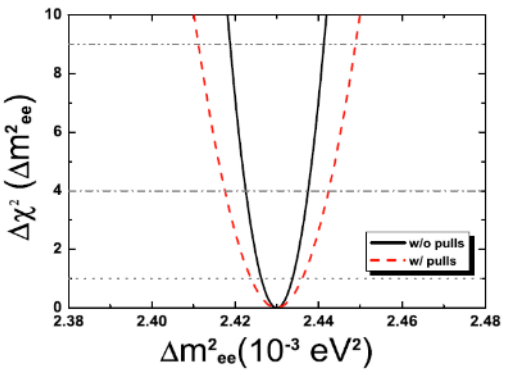


Probing the unitarity of U_{PMNS} to ~1%
more precise than CKM matrix elements !

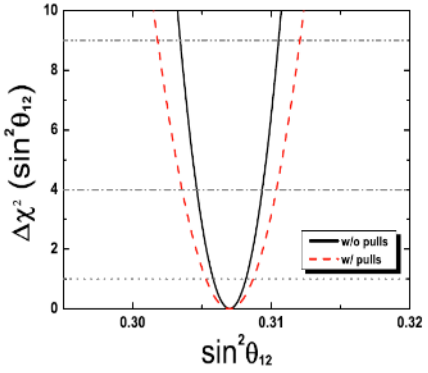
	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%



0.16%→0.24%

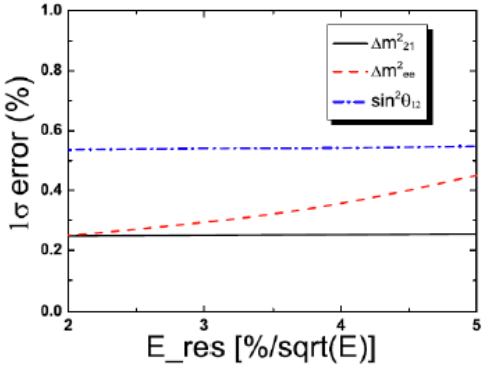


0.16%→0.27%



0.39%→0.54%

Correlation among parameters



E resolution

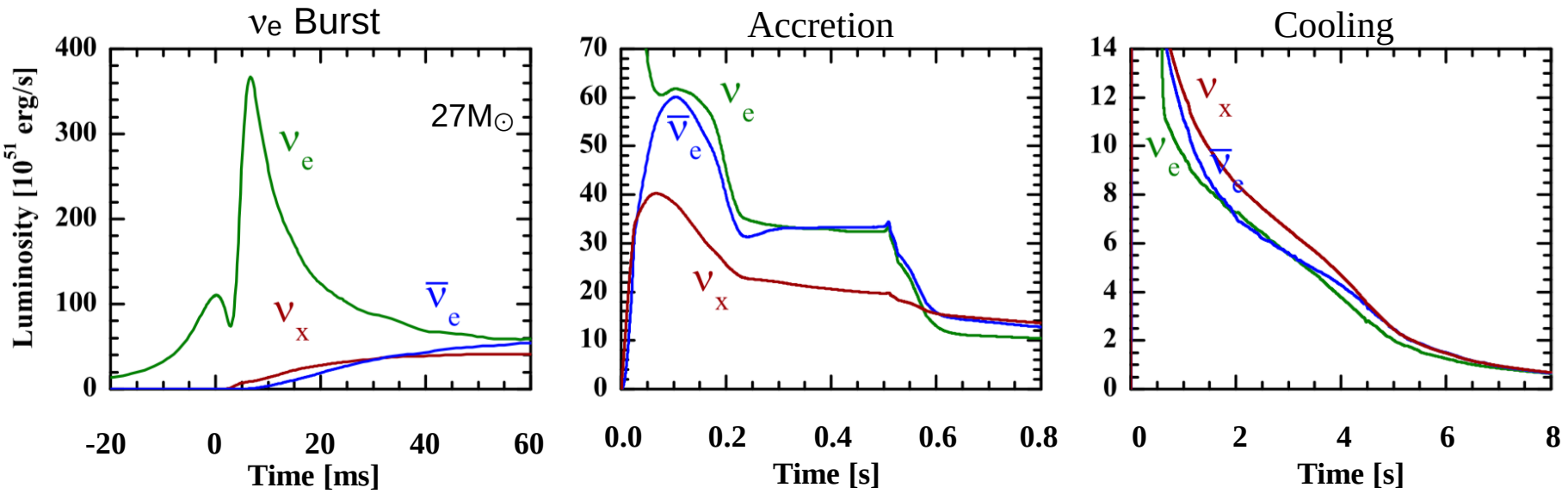
$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

Vast physics reach beyond Reactor Neutrinos

- **Supernova burst neutrinos**
- **Diffuse supernova neutrinos**
- **Solar neutrinos**
- **Atmospheric neutrinos**
- **Geo-neutrinos**
- **Sterile neutrinos**
- **Nucleon decay**
- **Indirect dark matter search**
- **Other exotic searches**

Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)

Supernova Neutrinos



Typical case :huge amount of energy (3×10^{53}erg) emitted in neutrinos at 10Kpc

3 phases equally important 3 "experiments" teaching us about astro- and particle-physics

Process	Type	Events $\langle E_\nu \rangle$=14MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	5.0×10^3
$\nu + p \rightarrow \nu + p$	NC	1.2×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	3.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.9×10^2
$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	1.1×10^2

NB Other $\langle E_\nu \rangle$ values need to be considered to get complete picture.

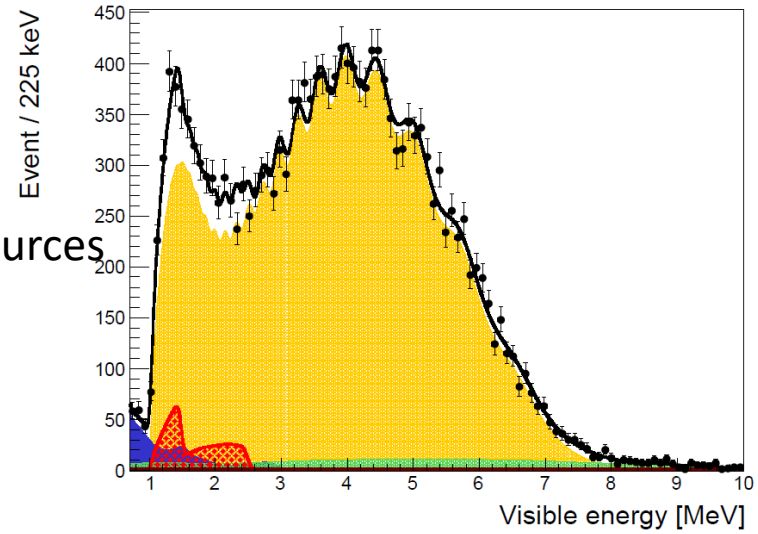
Bound on neutrino masses
Imprinting of the mass ordering
Collective neutrino oscillations
Constraining new physics

Expected events in JUNO for a typical SN distance of 10kpc

We need to be able to handle Betelgeuse (d~0.2kpc) resulting in ~10MHz trigger rate

Geo-neutrinos

- **Geo-neutrinos**
  - Current results
    KamLAND: 30 7 TNU
    Borexino: 43.5+11.8-10.4(stat)+2.7-2.4(sys) TNU
    id.031101
    Statistically dominated errors
  - More precise measurements for multiple geological insights Fraction of heat flow from radioactive sources
    nature of mantle convection
    energy needed to drive plate tectonics
  - JUNO 20 statistics
    - Huge reactor neutrino backgrounds
    - Need accurate reactor spectra



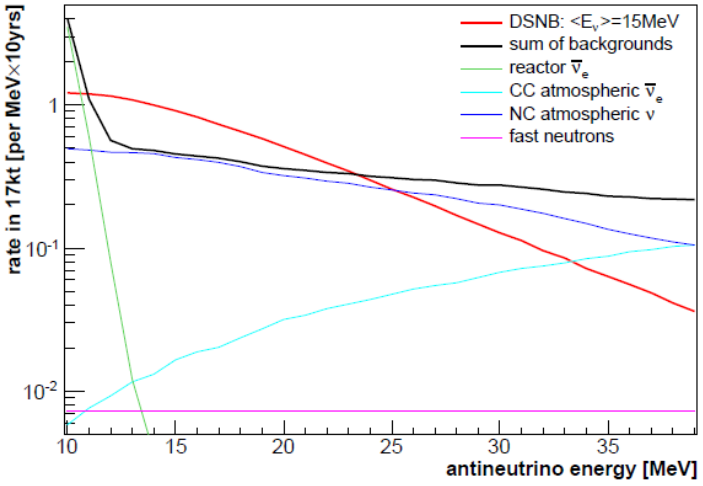
Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	3.65 ± 3.65
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4

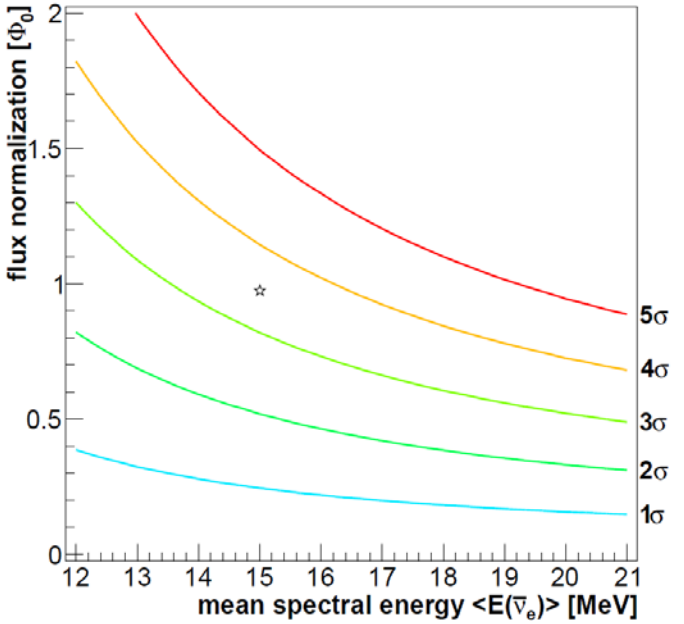
Chondritic ratio Th/U=3.9

Combined shape fit of geo-ν and reactor-ν

	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%

Diffuse Supernova Neutrinos





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

Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e} \rangle = 12\,\text{MeV}$	12.2	$\varepsilon_\nu = 50\,\%$	6.1
	$\langle E_{\bar{\nu}_e} \rangle = 15\,\text{MeV}$	25.4		12.7
	$\langle E_{\bar{\nu}_e} \rangle = 18\,\text{MeV}$	42.4		21.2
	$\langle E_{\bar{\nu}_e} \rangle = 21\,\text{MeV}$	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	$\varepsilon_{\text{NC}} = 1.1\,\%$	7.5
	fast neutrons	12	$\varepsilon_{\text{FN}} = 1.3\,\%$	0.15
	Σ			9.2

10 Years' sensitivity

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$
21 MeV	$6.9\,\sigma$	$7.3\,\sigma$	$6.2\,\sigma$	$6.4\,\sigma$

Solar Neutrinos

Fusion reactions in solar core: powerful source of electron neutrinos O(1-10 MeV)

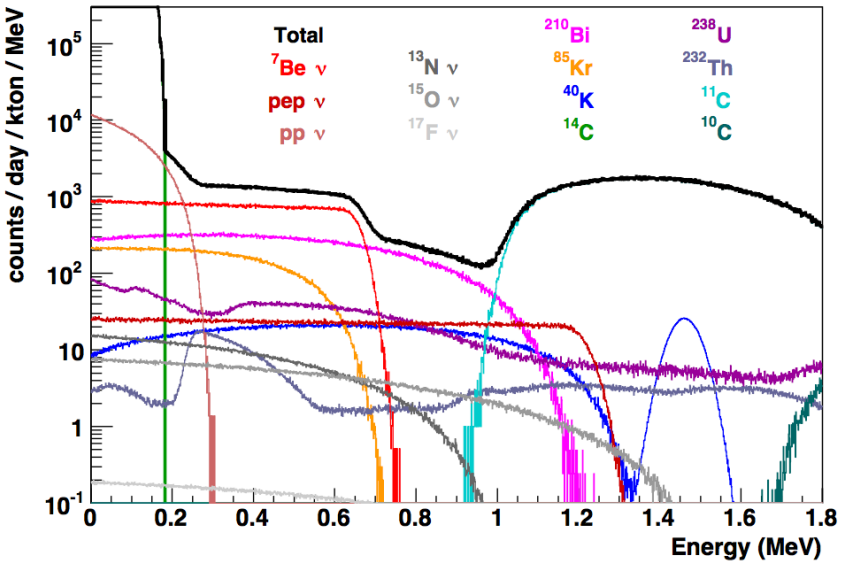
JUNO: neutrinos from ^{7}Be and ^{8}B reactions

Investigate MSW effect: Transition between vacuum and matter dominated regimes ^{8}B

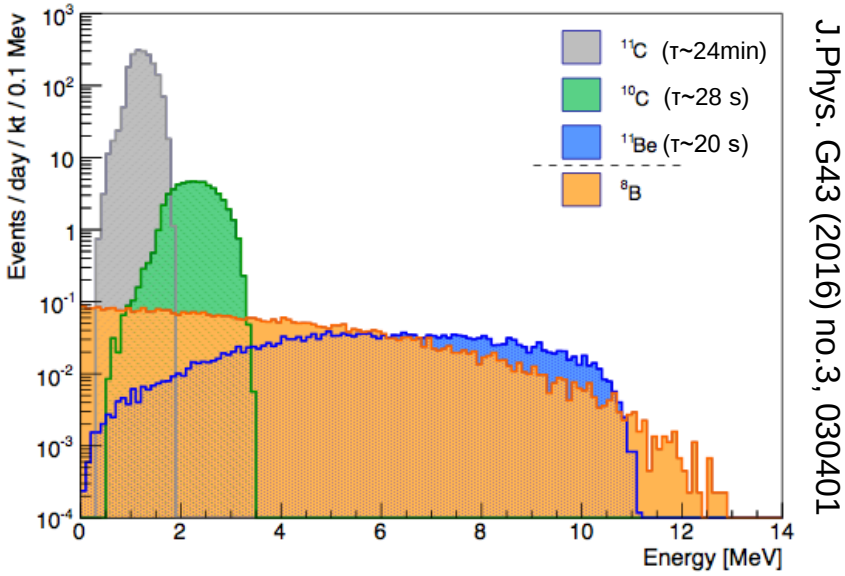
Constrain Solar Metallicity Problem: Neutrinos as proxy for Sun composition ^{7}Be

Radiopurity requirements for JUNO LS

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



Cosmogenic background for ^{8}B



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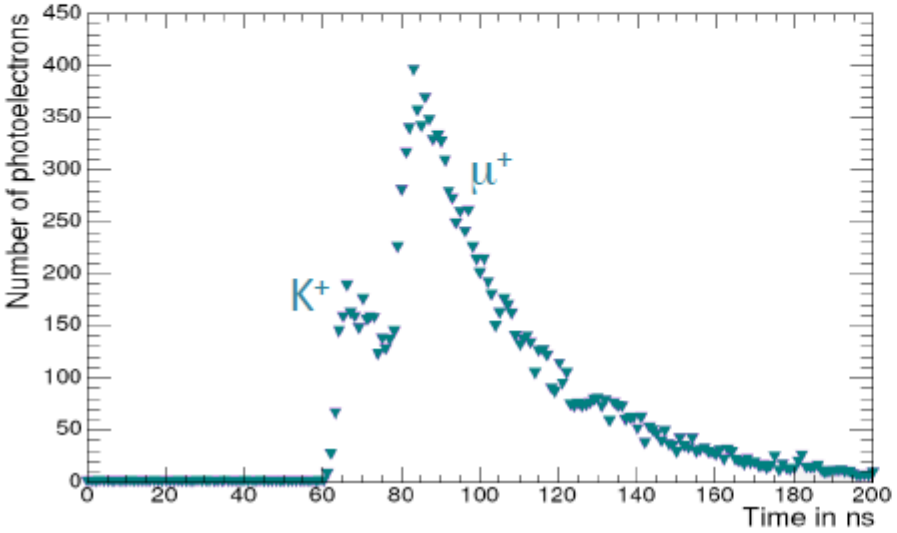
Proton decay into $K^+\bar{\nu}$



SUSY-favored decay mode

Signature $p \rightarrow K^+ \bar{\nu}$

$\hookrightarrow \mu^+\nu_\mu$ / $\pi^0\pi^+$

→ kaon visible in liquid scintillator!

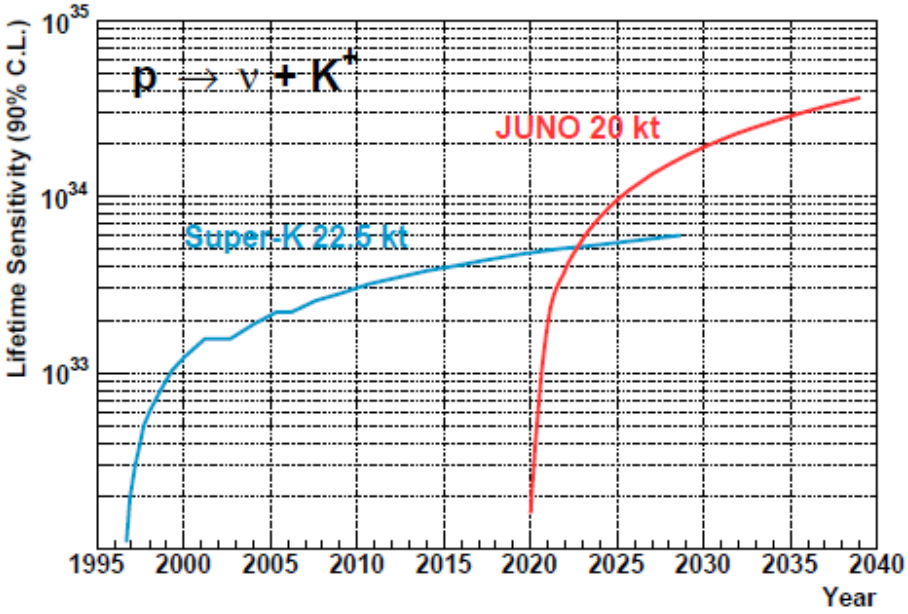
→ fast coincidence signature (τ_K = 13 ns)

→ signal efficiency: ~65% (atm. ν bg)

→ remaining background: <0.1 ev/yr

Limit if no event is observed in 10yrs (0.5 Mt·yrs):

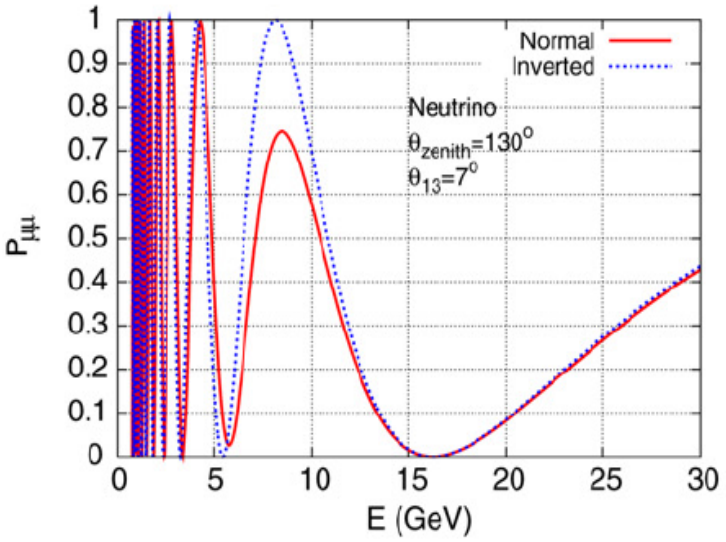
$\tau_p > 2 \times 10^{34}$ yrs (90%C.L.)

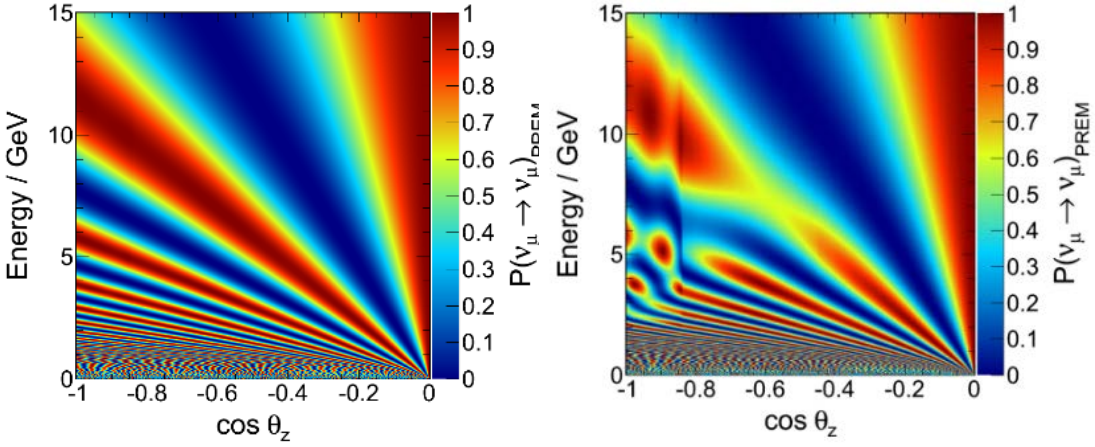


Mass Hierarchy from Atmospheric neutrinos

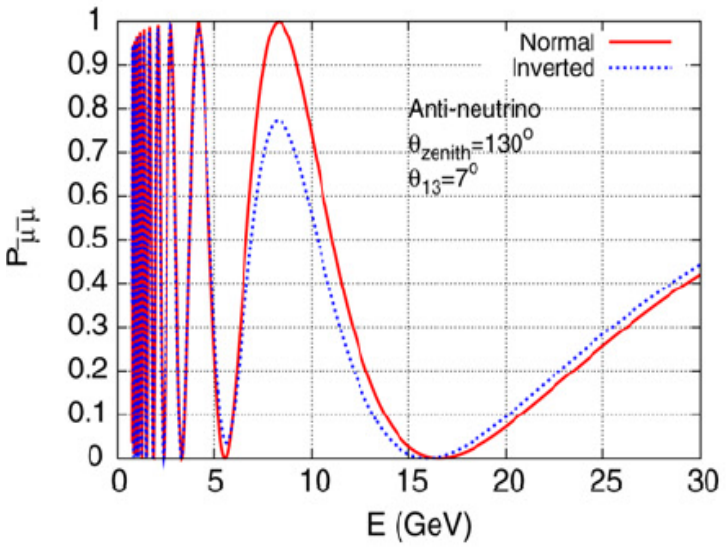
- Due to matter effect, oscillation probability of atmospheric muon neutrino when passing the Earth depends on mass hierarchy

- JUNO will have 1-2 σ sensitivity.
  - Measure both lepton and hadron energy
  - Good tracking and energy resolution





IH **NH**



Other physics at JUNO

1. **Introduction**
2. **Neutrino Mass Hierarchy**
3. **Precision Measurements of mixing parameters**
4. **Supernova burst neutrinos**
5. **Diffuse supernova neutrinos**
6. **Solar neutrinos**
7. **Atmospheric neutrinos**
8. **Geo-neutrinos**
9. **Sterile neutrinos** → Source, IsoDAR ν_e from ^{8}Li decay, superlight sterile based on the reactor spectrum study
10. **Nucleon decay**
11. **Indirect dark matter search** → muon neutrino events from DM annihilation channels
12. **Other exotic searches possible** → sub-leading oscillation effects pointing to new physics
13. **Appendix**

Yellow book

http://arxiv.org/pdf/1507.05613.pdf

Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)

Conclusions

The huge potential physics reach of a very large liquid scintillator detector close to high power nuclear cores - MH determination and beyond - makes JUNO very attractive and one of the pillars of the next round of massive detectors planned worldwide for the ultimate quest of the neutrino oscillation properties

JUNO will also deliver great results with its comprehensive and ambitious astroparticle program which completes and complements the neutrino oscillation investigation

JUNO will be definitively a cornerstone of the high precision neutrino studies era which will encompass the 2020 decade

Thank you