Sources of background and veto strategies in the JUNO experiment

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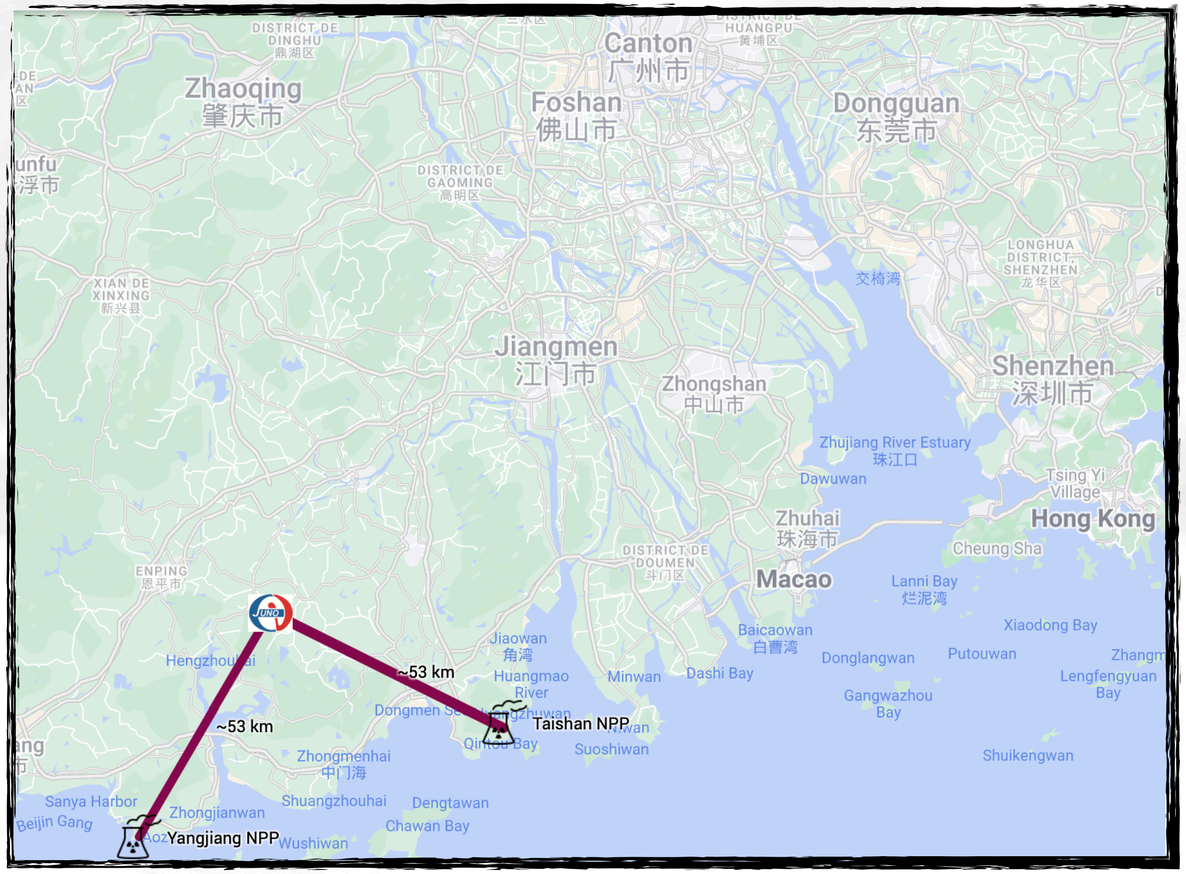
on behalf of the JUNO collaboration

Jiangmen Underground Neutrino Observatory

- The JUNO experiment:
  - multipurpose neutrino experiment
  - under construction at 53 km from Yangjiang and Taishan nuclear power plants (26.6 GW_{th}) in southeast China
  - ~650 m overburden ~ 2000 m.w.e
  - 20 kTon liquid scintillator (biggest ever built !)



- TAO detector:
  - Ancillary 1-ton detector at ~30 m from one of Taishan's reactor core to precisely measure antineutrino reactor spectrum

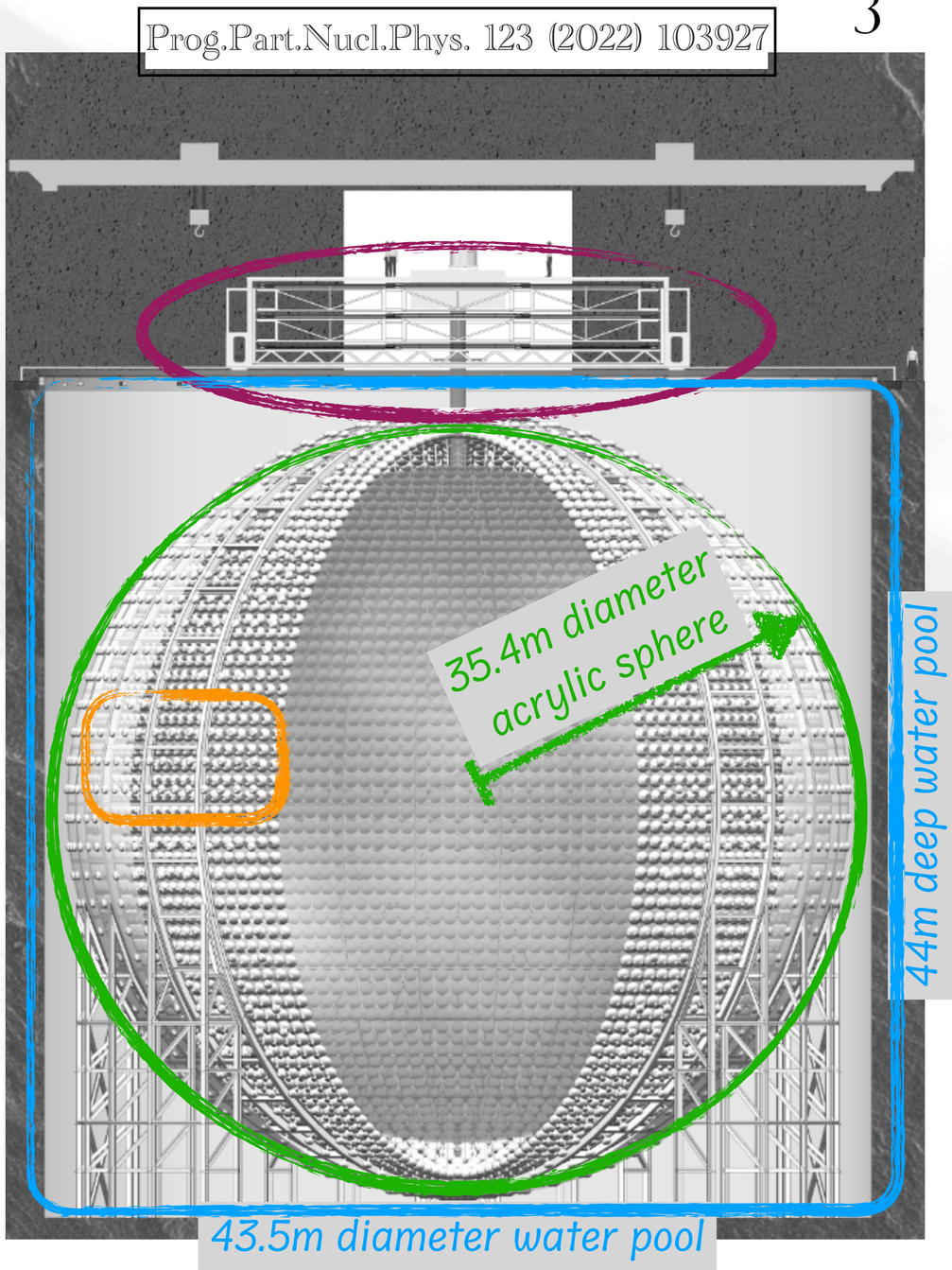
- The main purpose:
  - determination of neutrino mass ordering at 3σ level within 6 years of data taking

Detector design

- *Top Tracker (TT):*
  - *3 layers of plastic scintillator*
  - *2.6 × 2.6 cm² granularity*
  - *→ muon track angular resolution of 0.2°*

- *Water Cherenkov Detector (WCD):*
  - *43.5 × 44 m cylinder*
  - *35 ktons of ultrapure water*
  - *2400 20-inch PMTs*
  - *→ passive shielding against natural radioactivity from surrounding rock and fast neutrons from cosmic muons*
  - *Muon detection efficiency of 99.5 %*

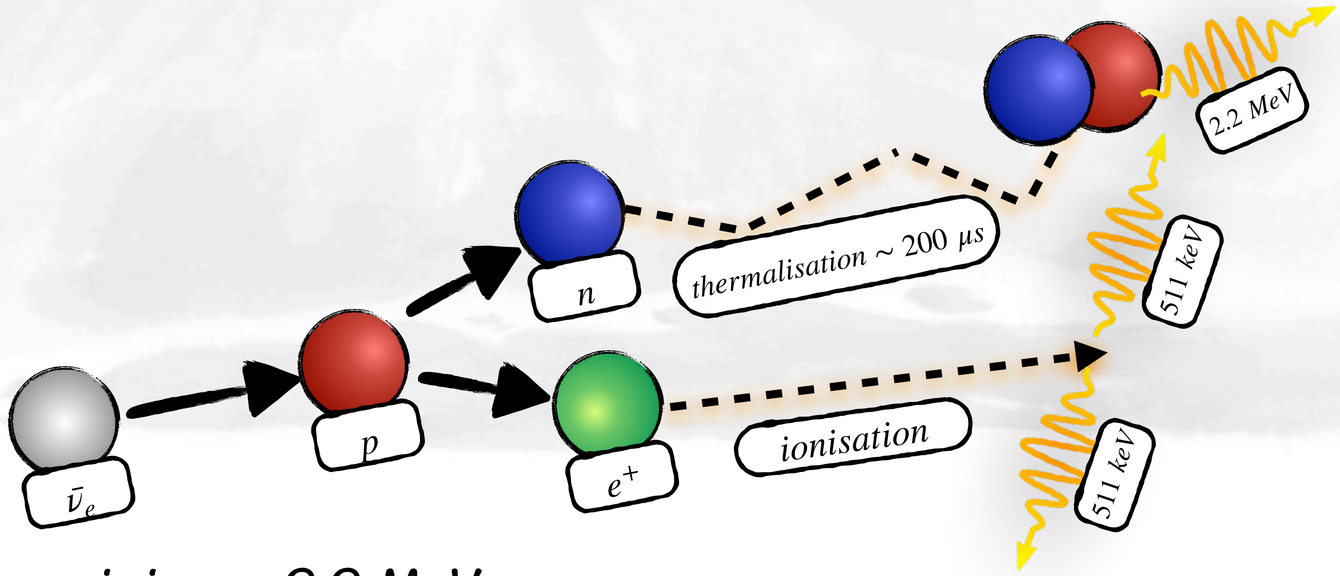
- *Central Detector (CD):*
  - *35.4 m diameter acrylic sphere (120 mm thick)*
  - *20 ktons of liquid scintillator*
  - *17 612 20-inch PMTs and 25 600 3-inch PMTs*
  - *→Energy resolution of 2.95%/$\sqrt{E}$*



Neutrino detection

- Reactor antineutrinos are observed by Inverse Beta Decay (IBD) resulting in a two fold signal:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$e^+ + e^- \rightarrow \gamma + \gamma \text{ (prompt)}$$
$$n + p \rightarrow d + \gamma \text{ (delayed)}$$

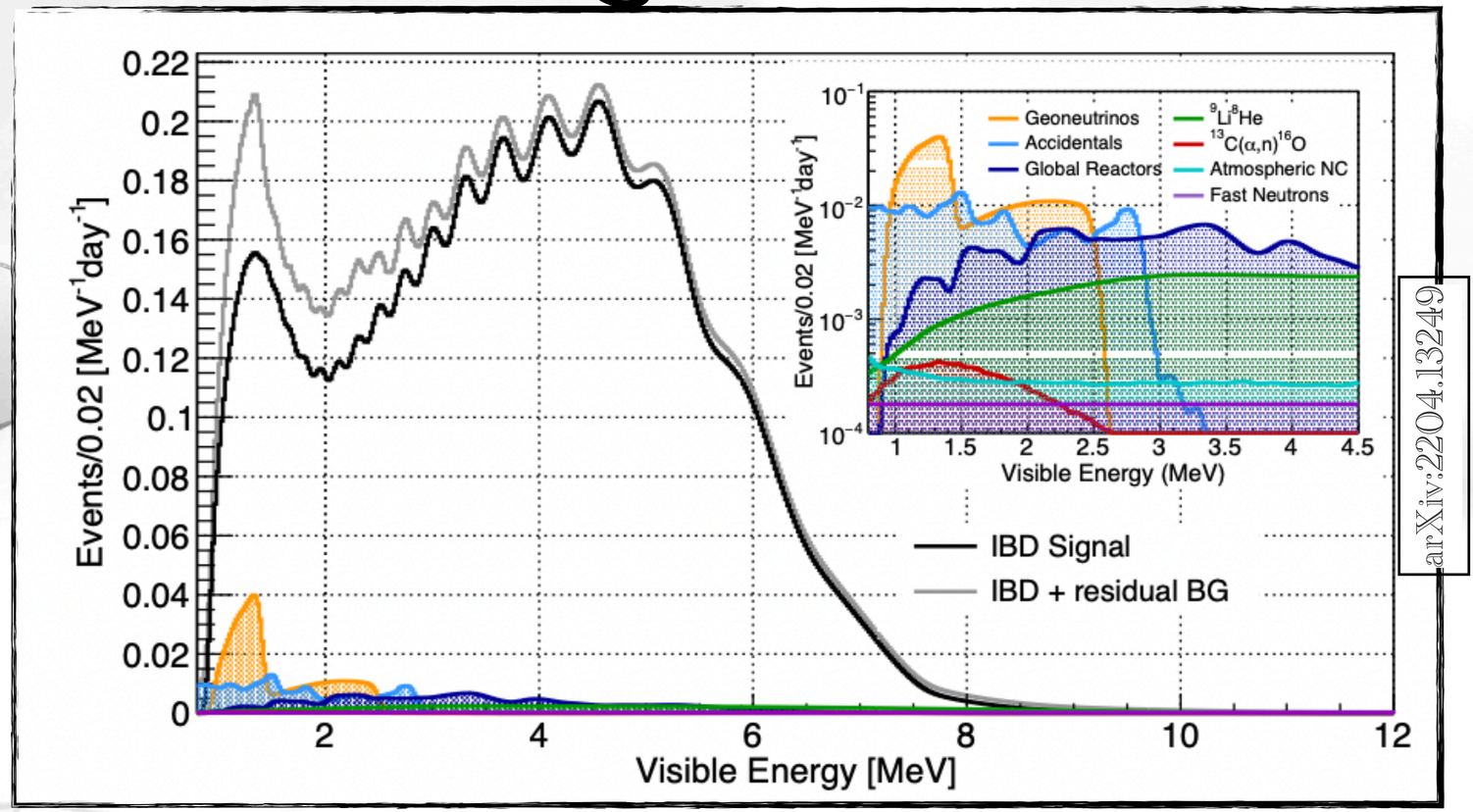


- Prompt signal: positron ionisation and annihilation with medium electron
- Delayed signal: neutron capture on hydrogen giving a 2.2 MeV γ

- Energy threshold for the IBD process is: $E(\bar{\nu}_e) > 1.8\ MeV$
- The neutrino energy is given by: $E_{vis} = E(e^+) = E(\bar{\nu}_e) - 0.8\ MeV$

Neutrino signal and background

- Visible energy spectrum from oscillated reactor $\bar{\nu}_e$
- Background contribution from 6 sources:
  - Accidental background
  - Cosmogenic background
  - Fast neutrons
  - $^{13}C(\alpha,n)^{16}O$
  - Geo-neutrinos
  - World reactors
  - atmospheric neutrinos
- Selection cuts:
  - Energy threshold: $E_{vis} > 0.7\ MeV$
  - Fiducial volume: $R < 17.2\ m$
  - Time correlation: $\Delta t_{p-d} < 1\ ms$
  - Spatial correlation: $\Delta \vec{R}_{p-d} < 1.5\ m$
  - Muon veto (temporal $\oplus$ spatial)



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		Rate [day^{-1}]						
Selection	IBD efficiency [%]	IBD	Geo-ν	Accidentals	Cosmogenics	Fast n	$^{13}C(\alpha,n)^{16}O$	World reactors
No cuts	100	57.4	1.5	5.7×10^4	84	-	-	-
All cuts	82.2	47.1	1.2	0.8	0.8	0.1	0.05	1

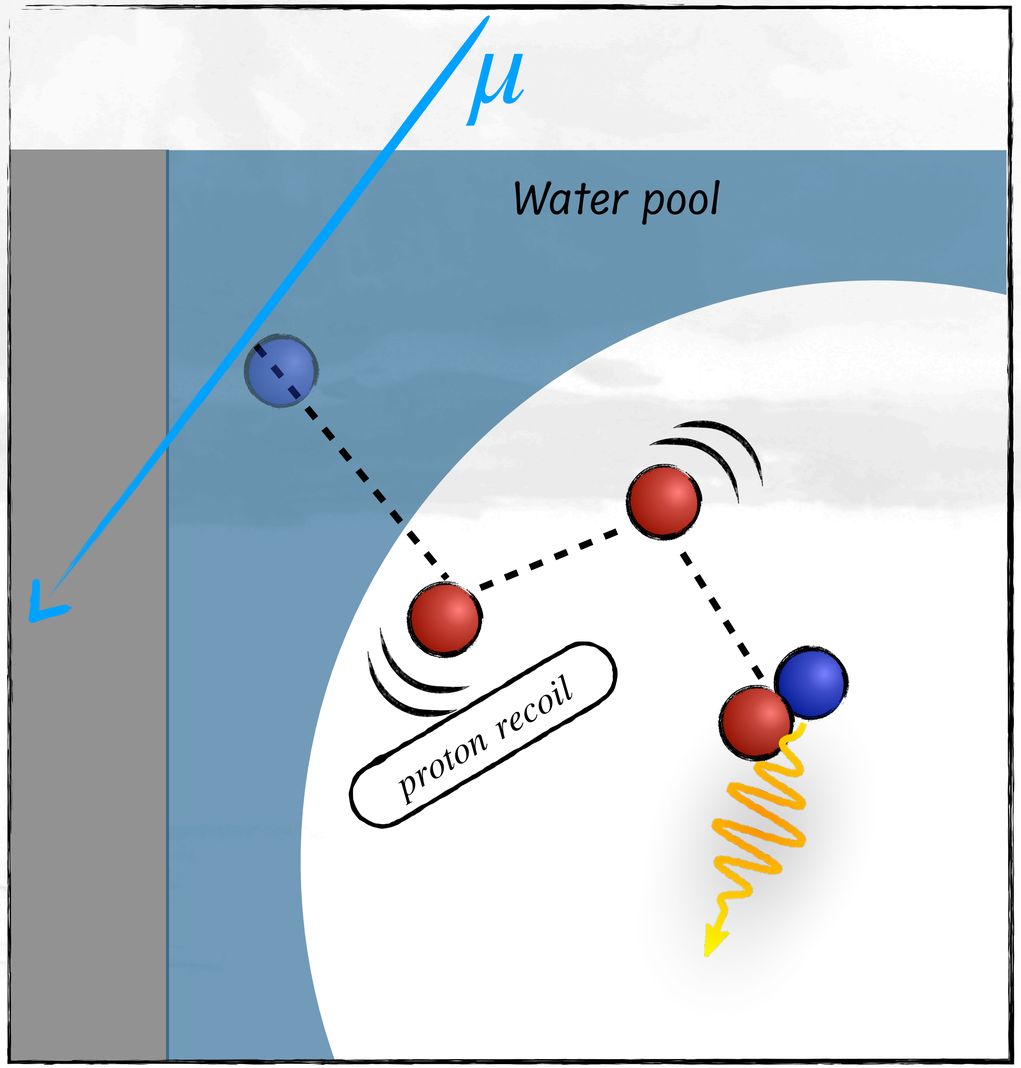
- After selection: ~47 signal events/day and ~4 background events/day

Accidental background

- Accidental background rate given by: $R_{acc} = R_p \times R_d \times \Delta t_{p-d}$
- Mainly given by 3 types of random coincidences:
  - (radioactivity, radioactivity)
    Singles rate ~7.6 Hz with 8% of delay-like events
    Prompt-delay time window ~1.0 ms: $R_{acc}^{rad,rad}$ ~ 410/day
    Spatial cut gives a reduction factor ~380 $\Rightarrow R_{acc}^{rad,rad}$ ~1.1 /day
  - (radioactivity, cosmogenics)
    Delay-like from cosmogenics ~340/day
    Rate after spatial and time correlation cuts $\Rightarrow R_{acc}^{rad,cosm}$ ~0.01 /day
  - (radioactivity, spallation neutrons)
    Spallation neutron rate ~1.8 Hz reduced to 45/day after muon veto $\Rightarrow R_{acc}^{rad,neut}$ negligible
- Total accidental rate after muon veto cut estimated to 0.8/day

Fast neutron background

- Muon passing through the rock surrounding WCD and corner clipping muons with short track in water are not tagged
- They produce fast neutrons which mimic IBDs:
  - scatter proton (prompt-like signal) while thermalising
  - captured on H after thermalisation (delay-like signal)
- Rate estimated by MC simulation to be ~0.1/day
- Prompt energy spectrum is flat
  ⇒ small impact on JUNO's sensitivity

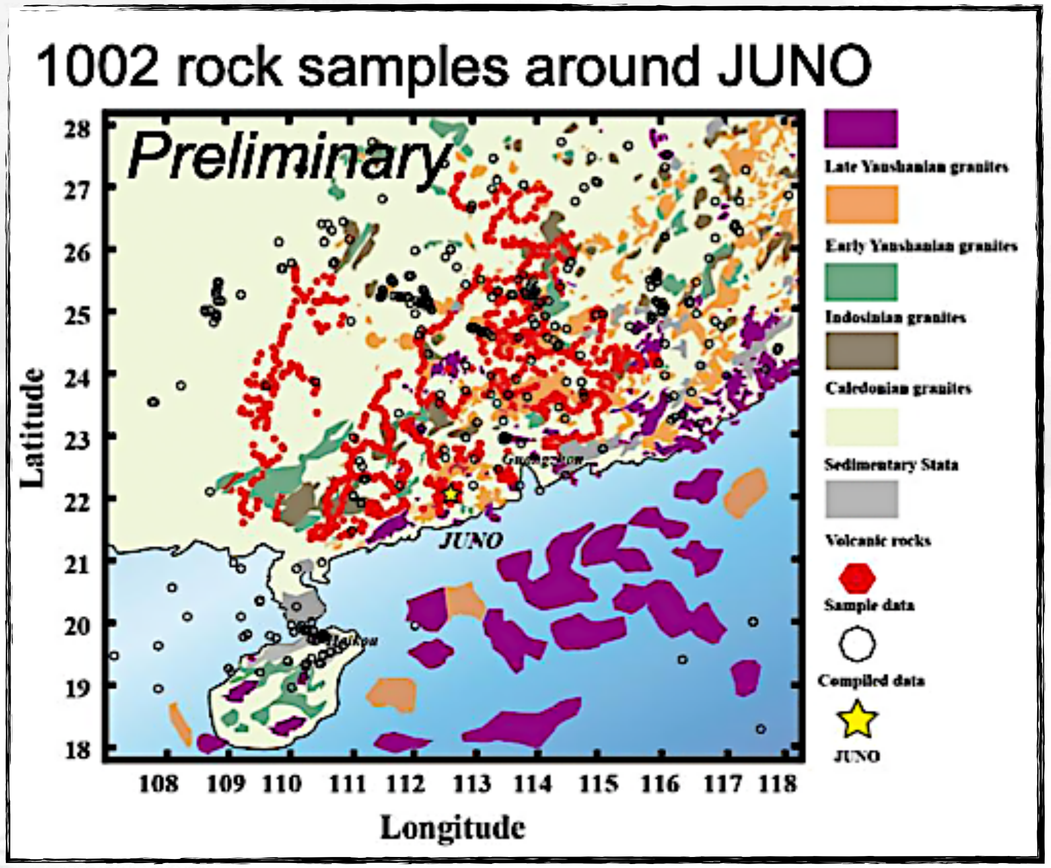


^{13}C induced background

- α from U and Th decay chain can interact with ^{13}C:
  $\alpha + ^{13}C \rightarrow ^{16}O + n$
- Prompt-like signal given by:
  - Proton recoils if the neutron is fast enough
  - de-excitation γ from ^{16}O
- Delay-like signal given by the neutron capture on H
- MC simulation gives a rate of 0.05/day after all selection cuts

Neutrino background (geo, reactors, atmospherics)

- $\bar{\nu}_e$ emitted in U and Th decay from the Earth constitute the geo-neutrino flux
- Rate of geo-neutrino interacting in JUNO estimated to 1.2/day after all selection cuts with a rate uncertainty of ~30%:
  - 18% for neutrino emitted in the crust and 100% for mantle
  - JUNO will be able to reduce the uncertainty on the geo-neutrino rate
- Energy spectrum shape of geo-neutrino known at 5% level
- Local geological studies ongoing to constrain crustal contribution and tackle largest uncertainty source



- Rate from world reactors estimated to ~1.0/day after all selection cuts
- Rate from atmospheric neutrino from simulation within the GENIE framework estimated to ~0.16/day a 50% shape and rate uncertainty considered for this background

Cosmogenic background

- Cosmogenic isotopes produced by muon showering in the LS
- Isotopes with $\beta - n$ decay mainly ^{9}Li and ^{8}He with half-lives of 178 ms and 119 ms resp. are sources of correlated background
- Production yields are extrapolated from KamLAND measurement with branching ratio to the $\beta - n$ decay:
  - 150 ^{9}Li /day (51% $\beta - n$ decay)
  - 50 ^{8}He /day (16% $\beta - n$ decay)

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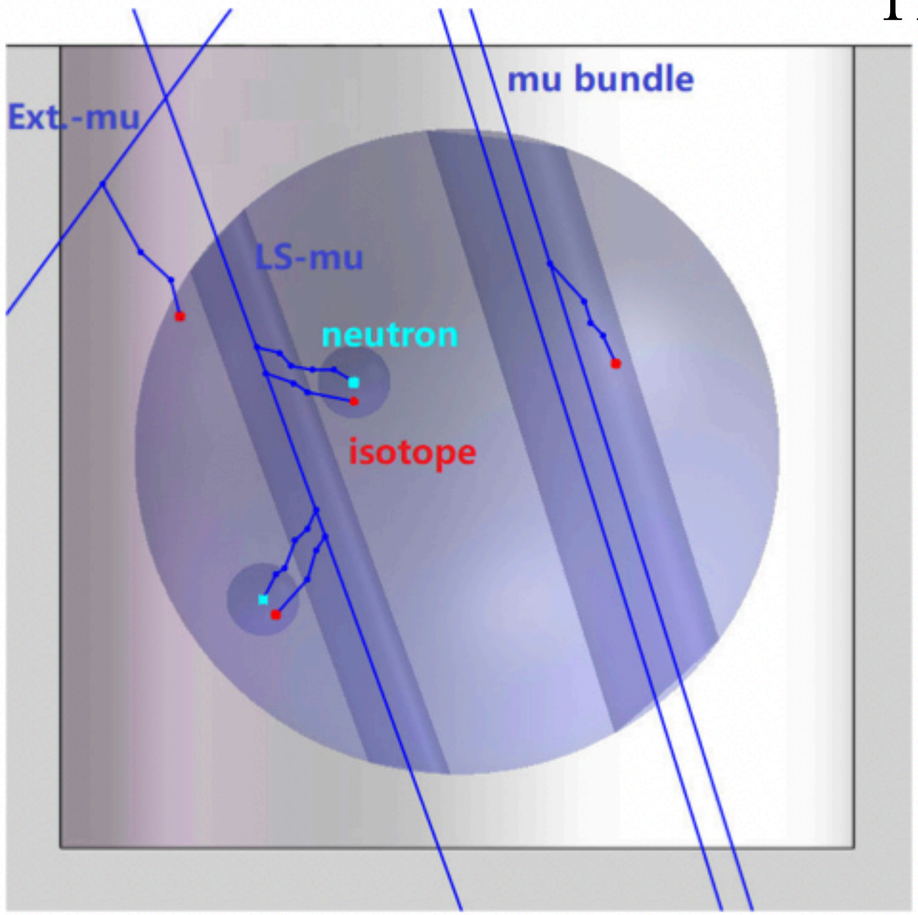
- Total rate of $\beta - n$ is 84/day reduces to 71/day after fiducial volume and space-time correlation cuts
- A dedicated muon veto has been designed to further reduce this background

Muon veto strategy

- 1ms veto on whole FV applied after μ passing through WCD or CD
  ⇒suppress spallation neutrons and short lived radioisotopes
- For well reconstructed single μ tracks in CD:
  - a 600ms, 400ms, 100ms veto applied on a 1m, 2m, 4m cylindrical volume around the muon track
- For muon bundle tracks (closer than 3m and parallel tracks)
  - single track reconstructed with larger dispersion
  - veto applied with cylinder radius enlarged according to the track dispersion
- For events with no track reconstructed
  - Occurs when more than 2 muons pass through the CD
  - 500ms veto over FV
- 1.2s veto on a 3m radius sphere around neutron capture events
- Muon veto strategy has an IBD selection efficiency of 91.6% while removing 98.8% of cosmogenic background



Muon multiplicity	Proportion [%]
1	91.9
2 (track separation > 3 m)	5.5
2 (track separation < 3 m)	0.6
≥3	2.0

Summary and Conclusion

- *JUNO is a large multipurpose liquid scintillator detector which main goal is to determine the neutrino mass hierarchy*
  - *the rate of signal event is estimated to be ~47 events/day*
- *In this talk we have assessed the main sources of background to the reactor antineutrino signal*
- *We have presented the dedicated muon veto strategy which have an IBD selection efficiency of 91.6% while removing 98.8% of the cosmogenic background (main correlated background)*
- *The rate of the various sources of background after all selection cuts is:*

Background	Rate (day^{-1})	Rate Uncertainty (%)	Shape Uncertainty (%)
Geoneutrinos	1.2	30	5
World reactors	1.0	2	5
Accidentals	0.8	1	negligible
$^{9}Li/^{8}He$	0.8	20	10
Atmospheric neutrinos	0.16	50	50
Fast neutrons	0.1	100	20
$^{13}C(\alpha,n)^{16}O$	0.05	50	50