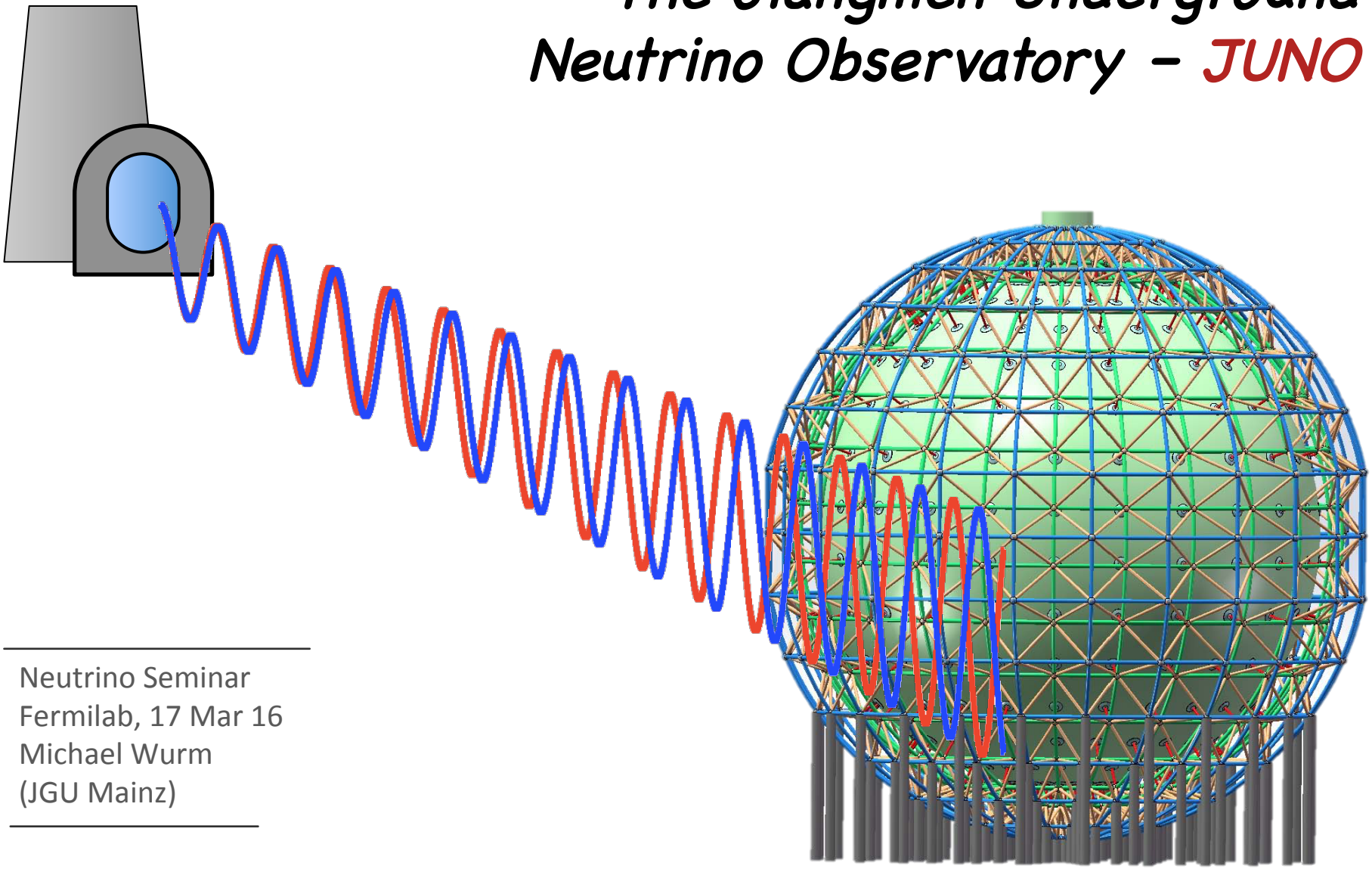
The Jiangmen Underground Neutrino Observatory – JUNO



Neutrino Seminar
Fermilab, 17 Mar 16
Michael Wurm
(JGU Mainz)

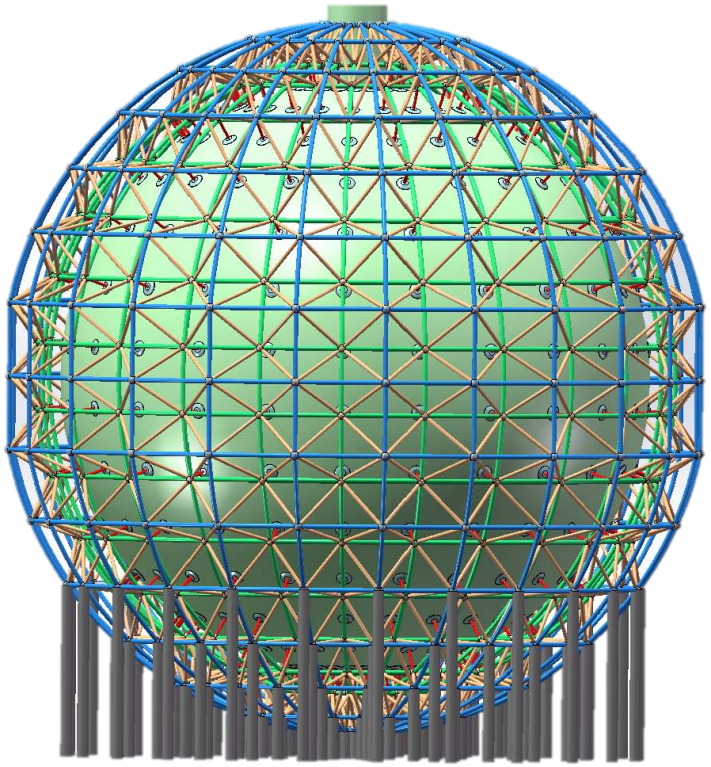
PRISMA

JUNO

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

JUNO in a nut-shell



JUNO characteristics

- liquid scintillator detector: 20ktons
- number of PMTs: 17,000 (20‘‘)
- energy resolution: 3% at 1MeV
- rock overburden: 700m
- distance to reactors: 53km

Physics objectives

- neutrino mass hierarchy
- sub-% measurement of solar oscillation parameters
- astrophysical neutrinos
- nucleon decay
- eV-scale sterile neutrinos

3-flavor neutrino mixing: status

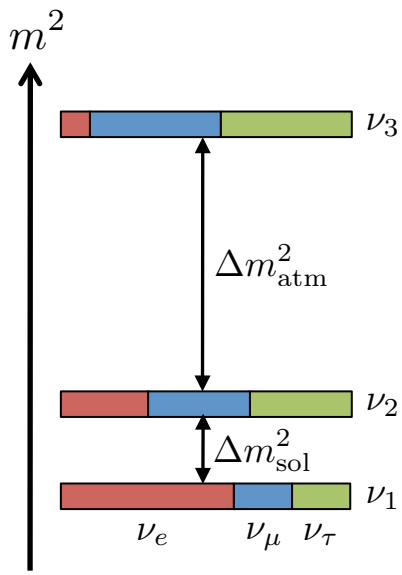
$$\mathbf{U_{3\times 3}} = \mathbf{U}_{\mathrm{PMNS}}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric mixing
(maximal 45°?)

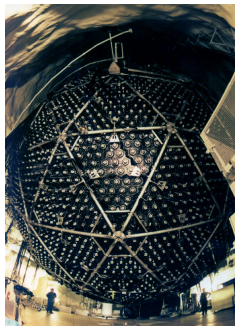
reactor mixing & CP violation
(small θ_{13}≈9°, δ?)

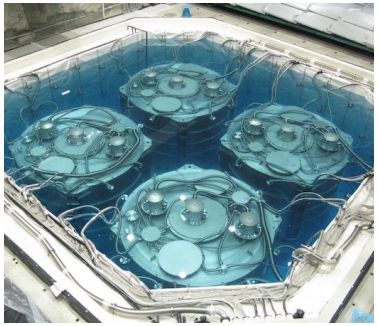
solar mixing
(large 33°)



mass squared differences :

- $\Delta m^2_{\mathrm{sol}} = \Delta m^2_{21}$ → *small splitting: +8x10^{-5} eV^2*
- $\Delta m^2_{\mathrm{atm}} = \Delta m^2_{32} \approx \Delta m^2_{31}$ → *large splitting: ±2.5x10^{-3} eV^2*

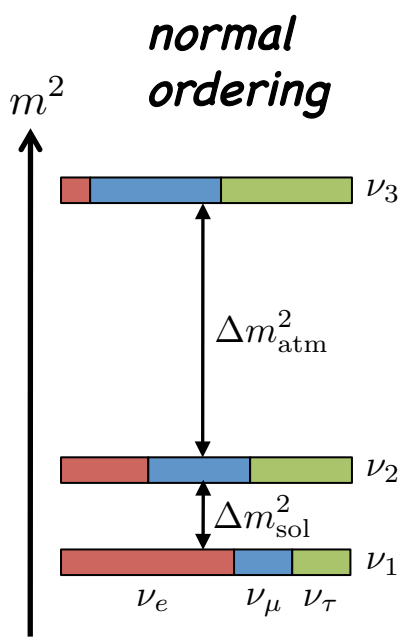




3-flavor neutrino mixing: open issues

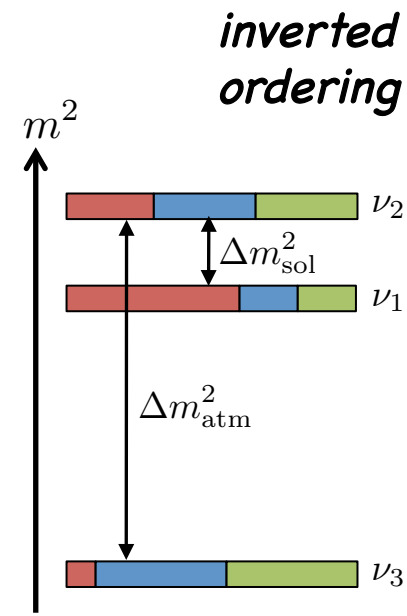
$$\mathbf{U_{3\times 3}} = \mathbf{U}_{\mathrm{PMNS}}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



What is the

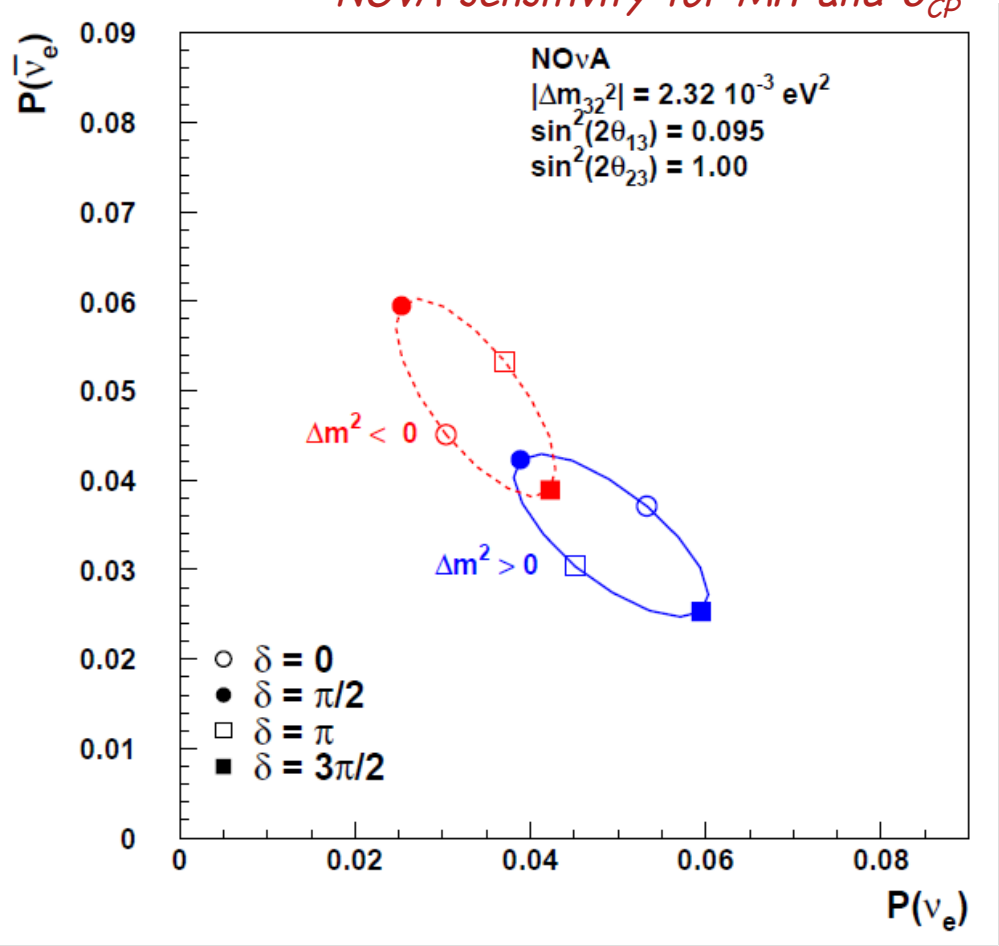
- **octant of θ_{23} ($\gtrless 45°$)?**
- value of **CP-phase?**
- **mass hierarchy?** (sign of $\Delta m^2_{\mathrm{atm}}$)



Why to measure the mass hierarchy?

- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**

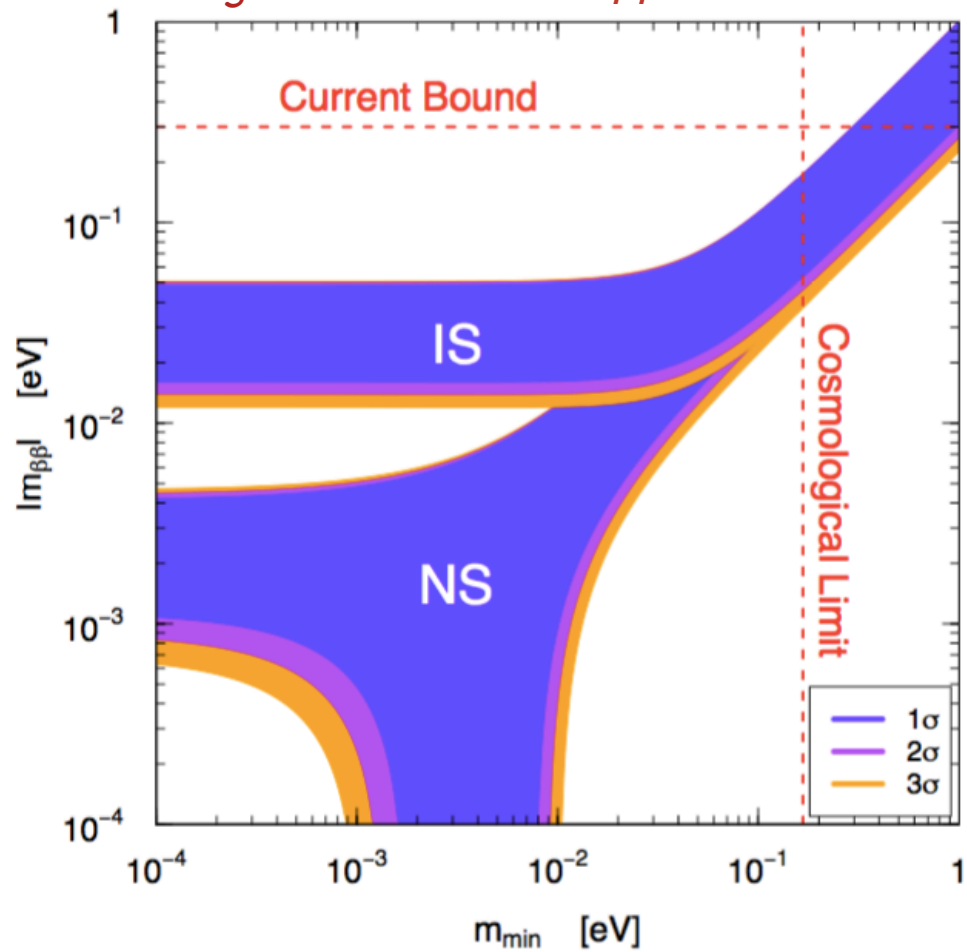
NOvA sensitivity for MH and δ_{CP}



Why to measure the mass hierarchy?

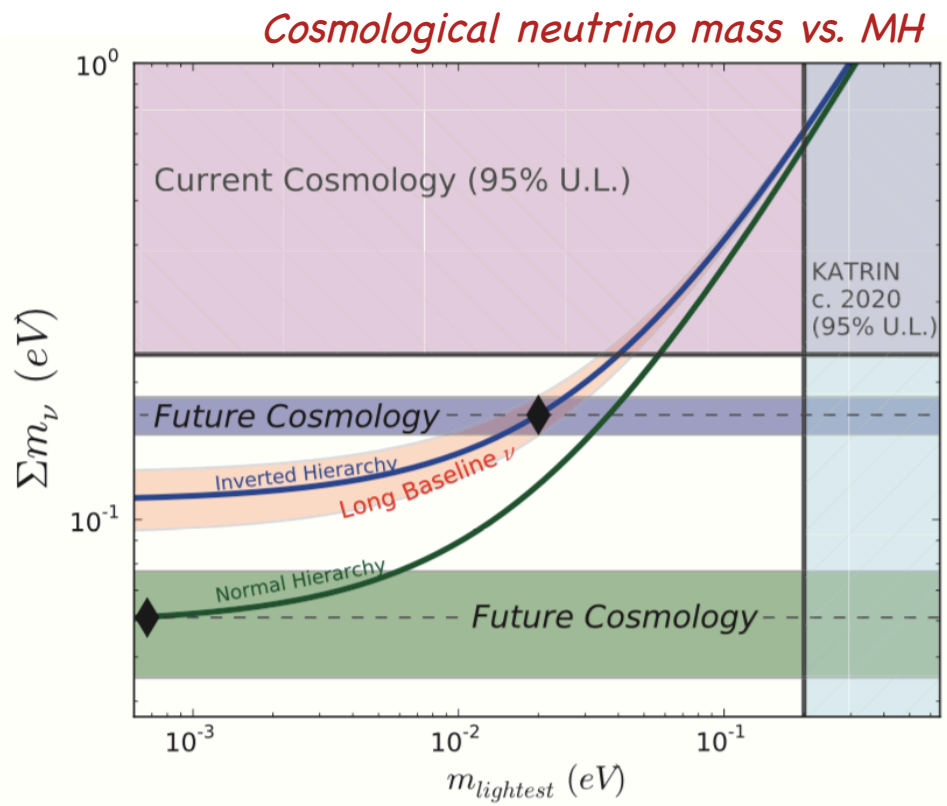
- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**
- target range for **sensitivity** of **0νββ decay** experiments

Lightest vs. effective ββ neutrino mass



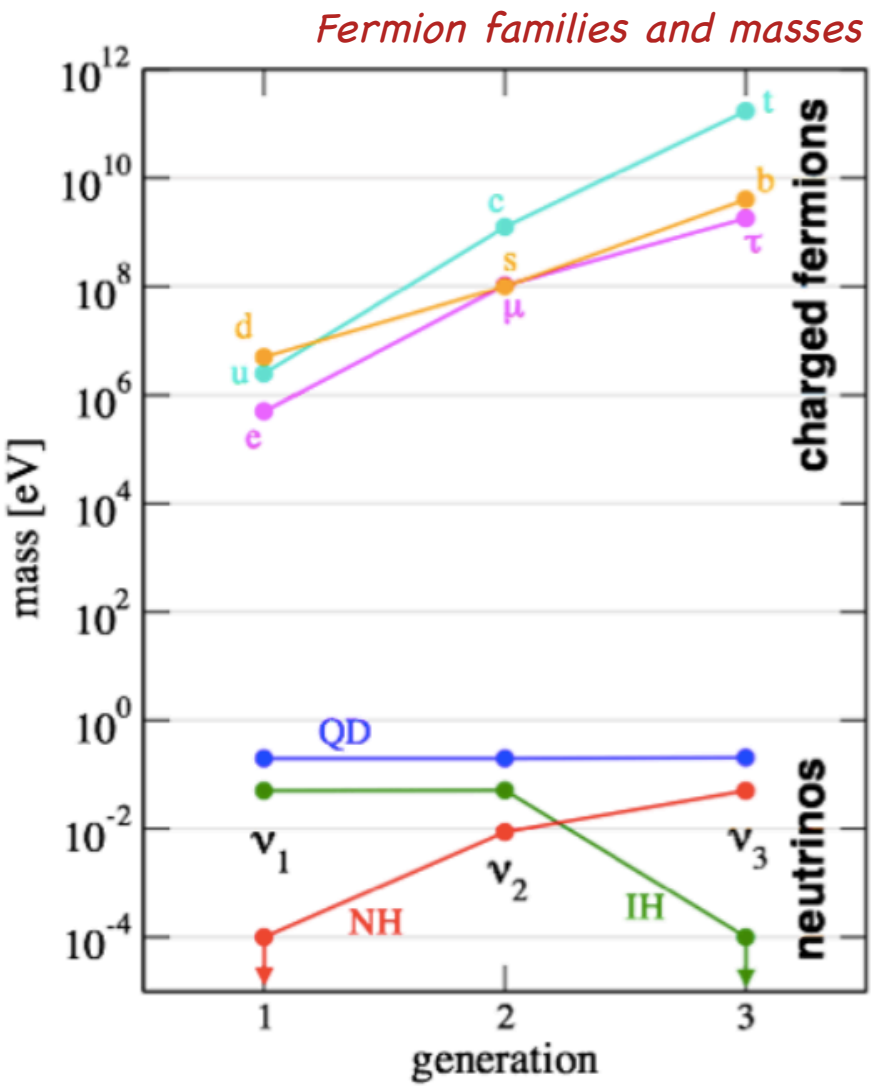
Why to measure the mass hierarchy?

- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**
- target range for **sensitivity** of **0νββ decay** experiments
- combination with **cosmology** might reveal **lightest neutrino mass**



Why to measure the mass hierarchy?

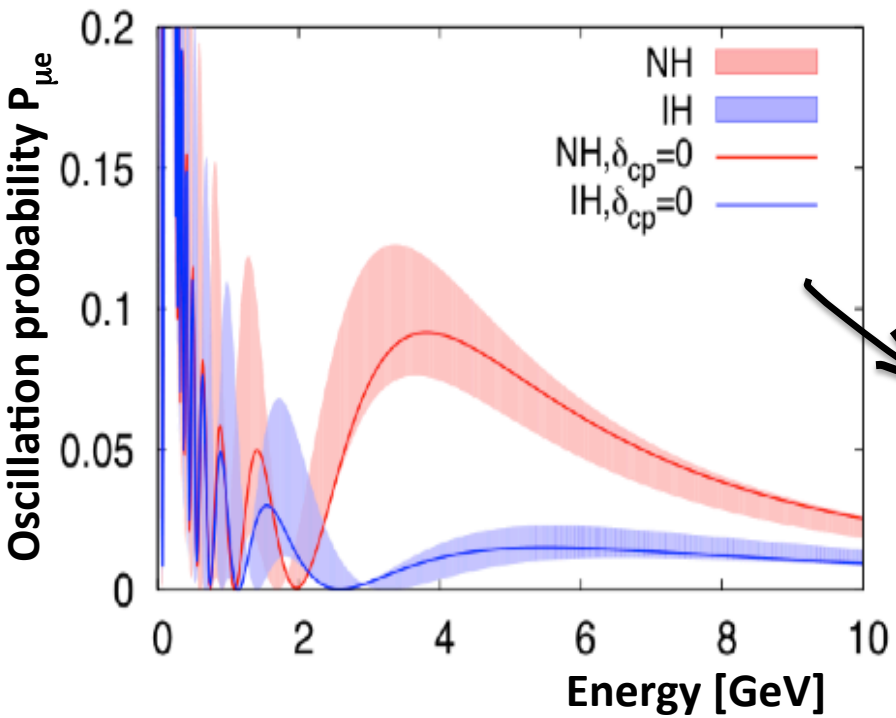
- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**
- target range for **sensitivity** of **0νββ decay** experiments
- combination with **cosmology** might reveal **lightest neutrino mass**
- important input for **model building**: inversion? degeneracy?



How to measure MH? – Matter effects

Oscillation probabilities of GeV neutrinos in Earth matter depend on MH

Oscillation probability $\nu_e \rightarrow \nu_\mu$ in a ν_μ-beam at 2300km



→ amplitude of matter effects increases with neutrino energy

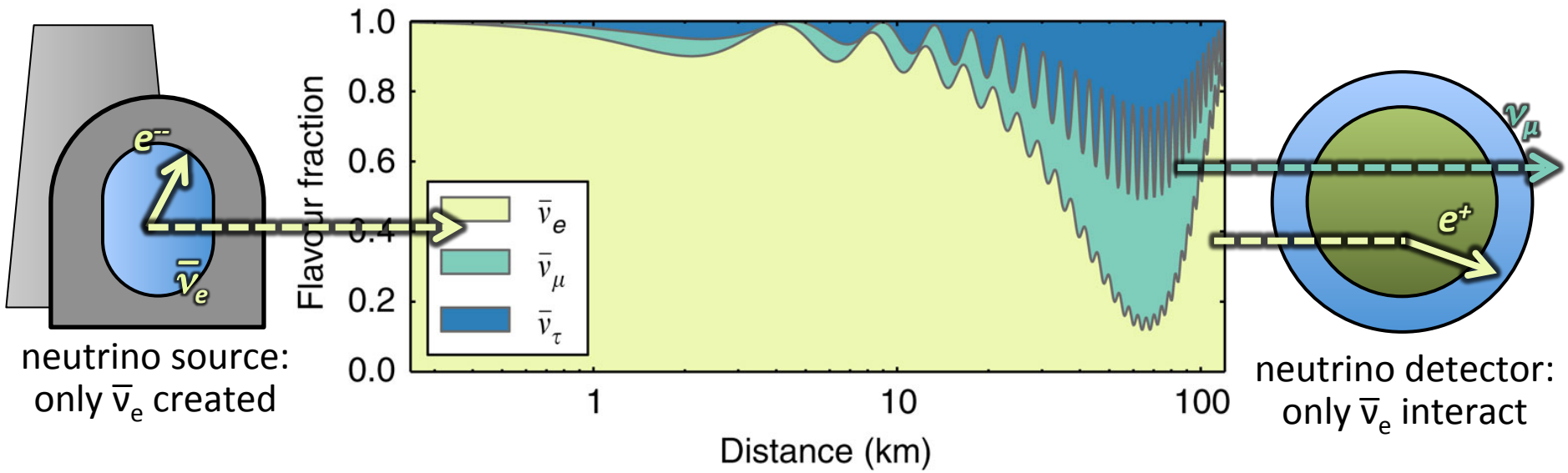
Two measurement modes:

- $\nu_\mu \rightarrow \nu_e$ appearance in a long-baseline neutrino beam: NOvA, DUNE
- $\nu_\mu \rightarrow \nu_\mu$ disappearance in atmospheric (anti-)ν oscillations: PINGU, ORCA, INO, Hyper-K

Reactor neutrino oscillation experiments

Common three-flavor reactor electron-antineutrino survival probability:

$$P_{ee} = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}}{4E}\right) - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4E}\right)$$



→ oscillation parameters are extracted from **ν_e disappearance pattern**

→ however, the formula above implicitly assumes $\Delta m^2_{31} = \Delta m^2_{32}$

How to measure MH? – Reactor neutrinos

[Petcov, Piai, hep-ph/0112074]

Survival probability

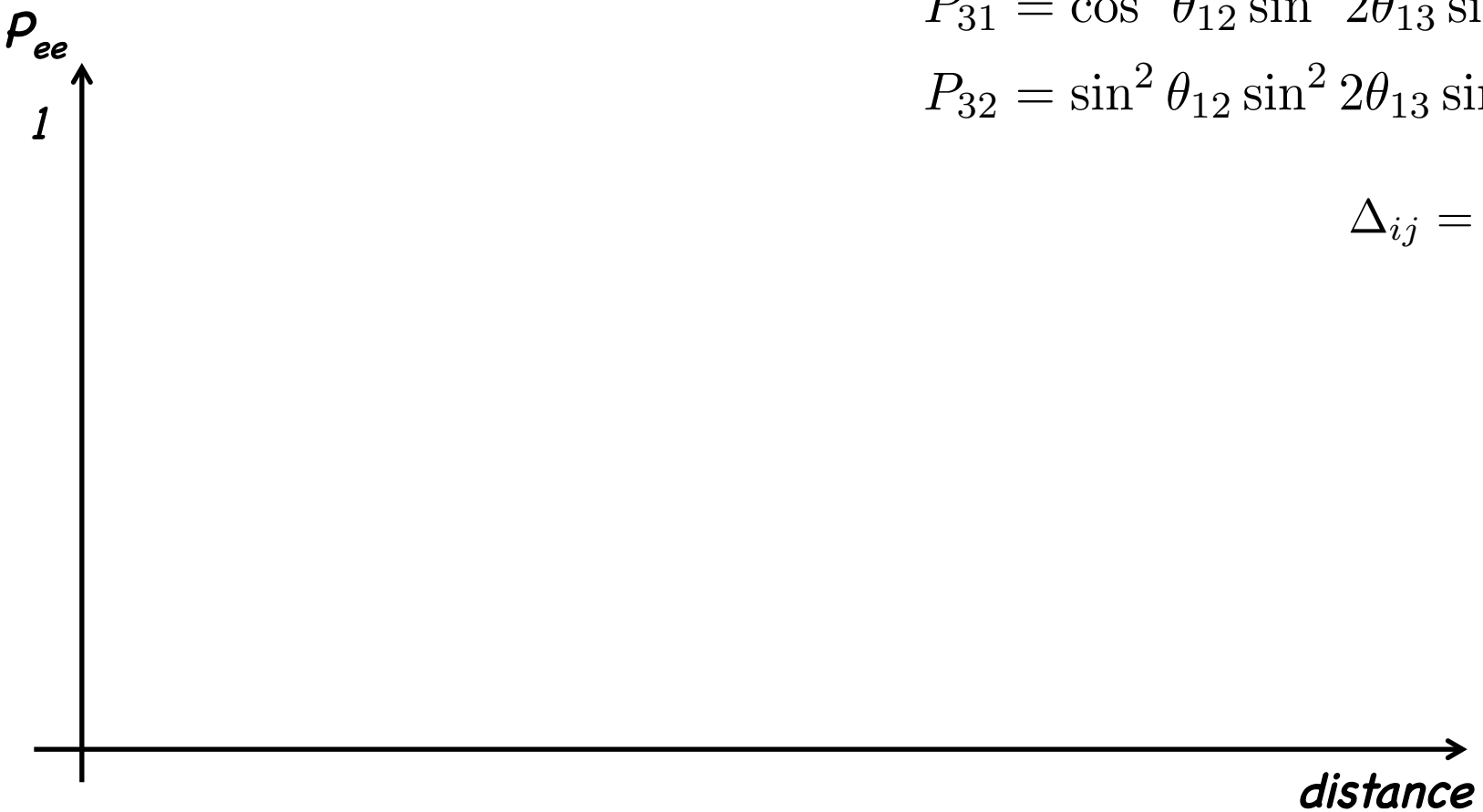
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$



How to measure MH? – Reactor neutrinos

Survival probability

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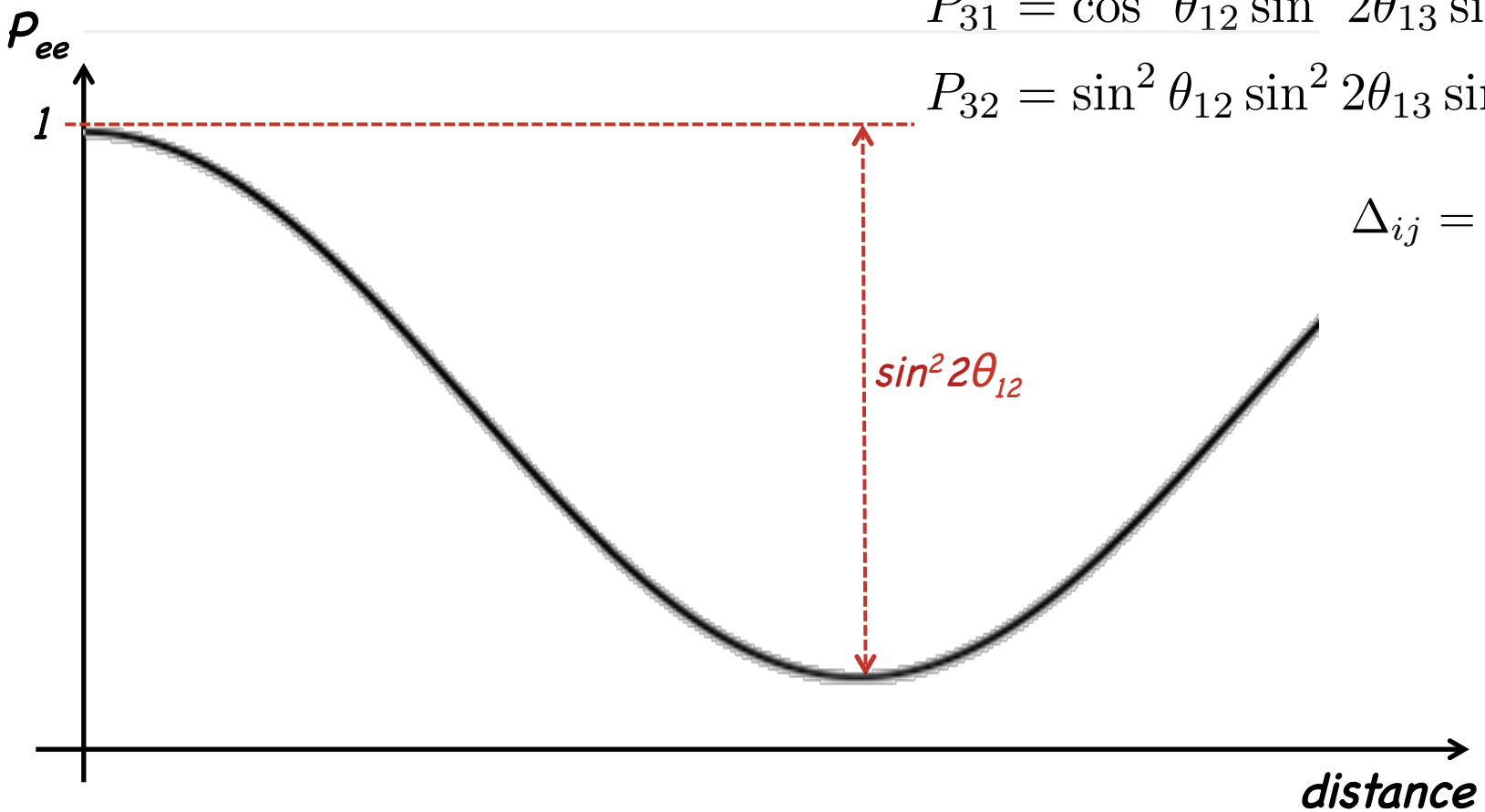

How to measure MH? – Reactor neutrinos

→ subdominant oscillation pattern depends on phase terms of P_{31}/P_{32}

→ depends on **relative sizes** of Δm^2_{32} and Δm^2_{31}

Survival probability

$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

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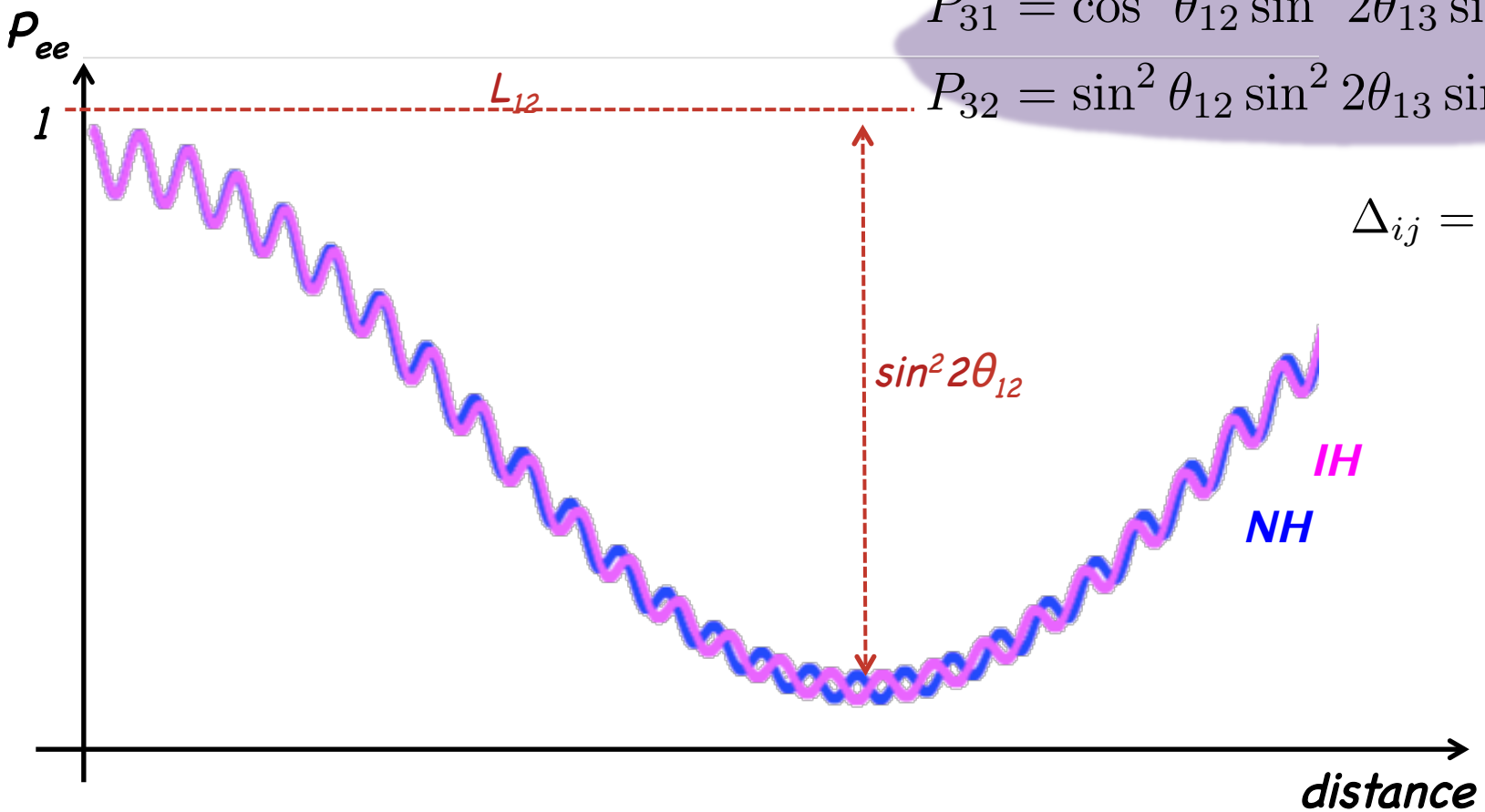
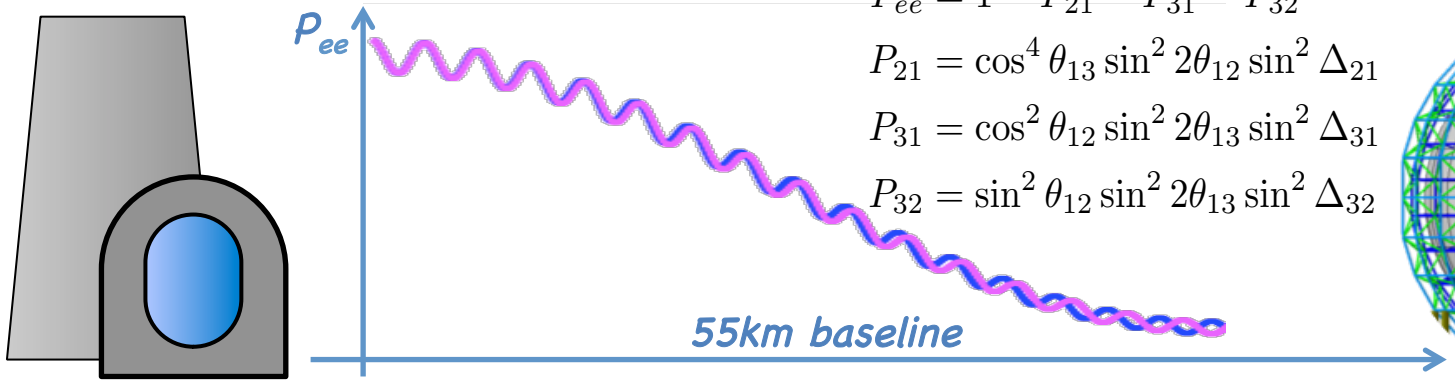


Reactor ν signal at 53km distance



$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
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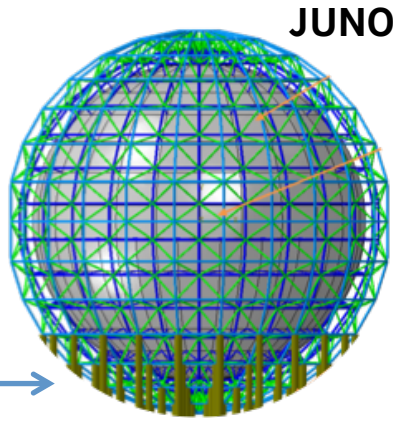
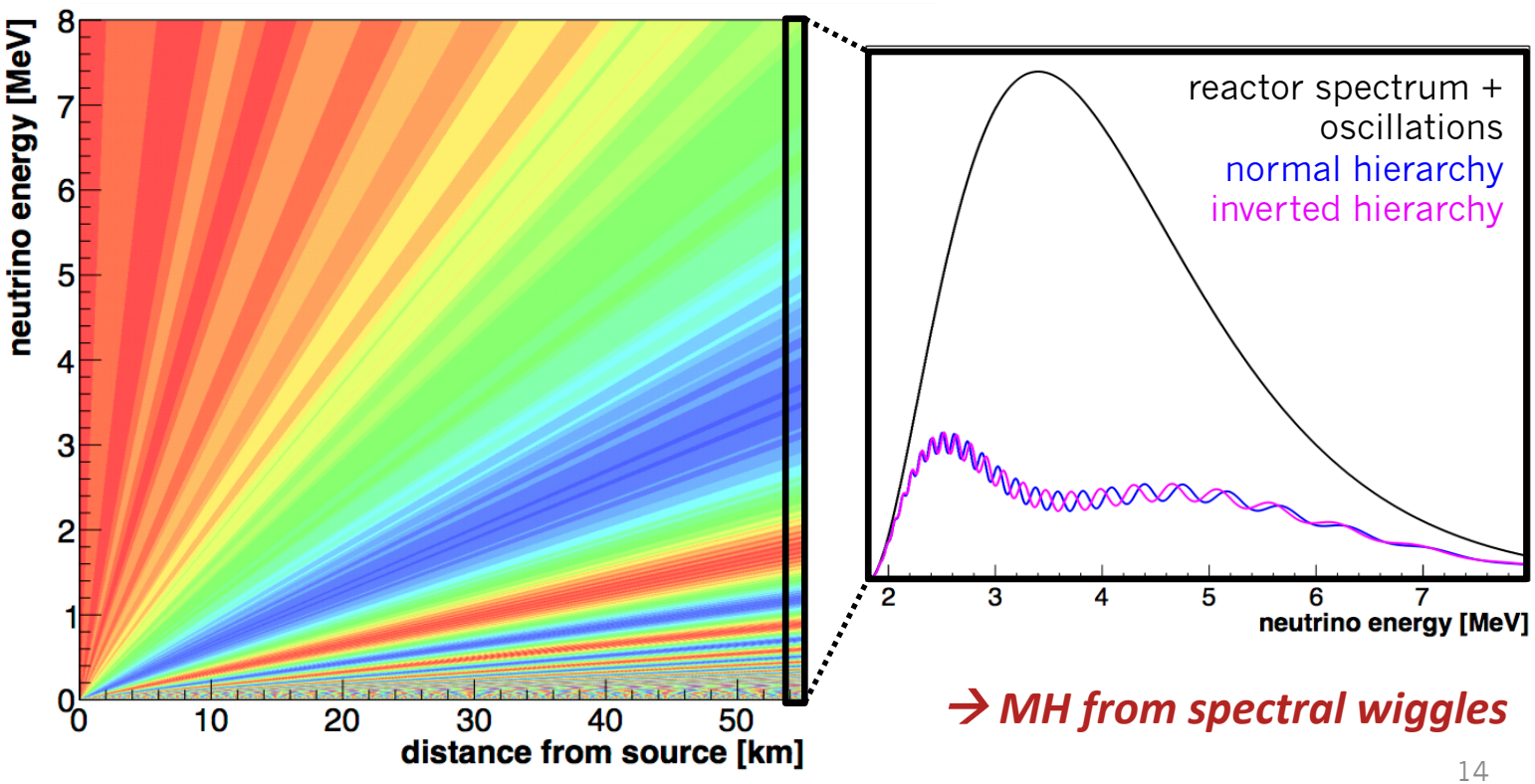


Nuclear reactors at
- *Yangjiang*
- *Taishan*
  (so. China)

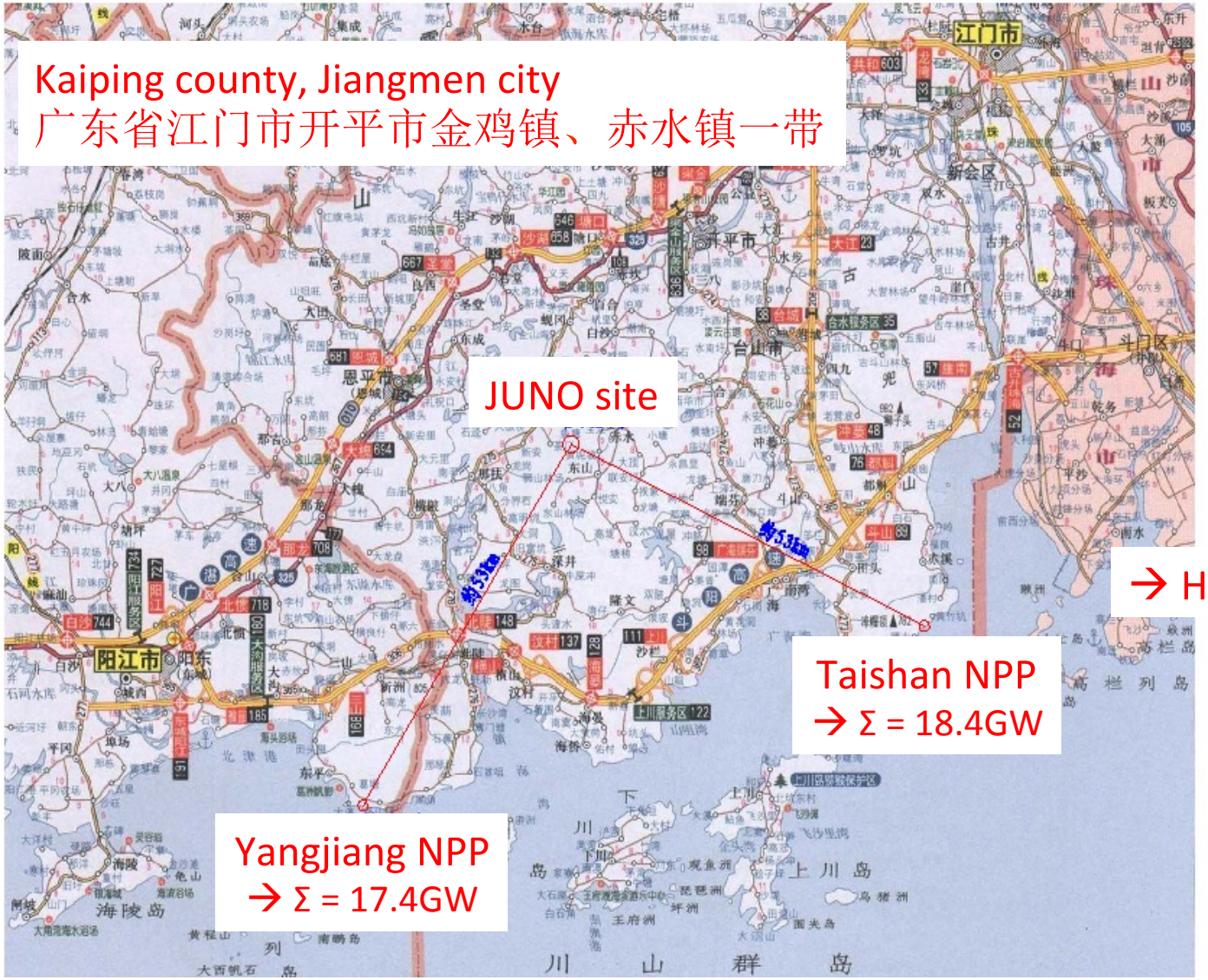
Total power:
38 GW



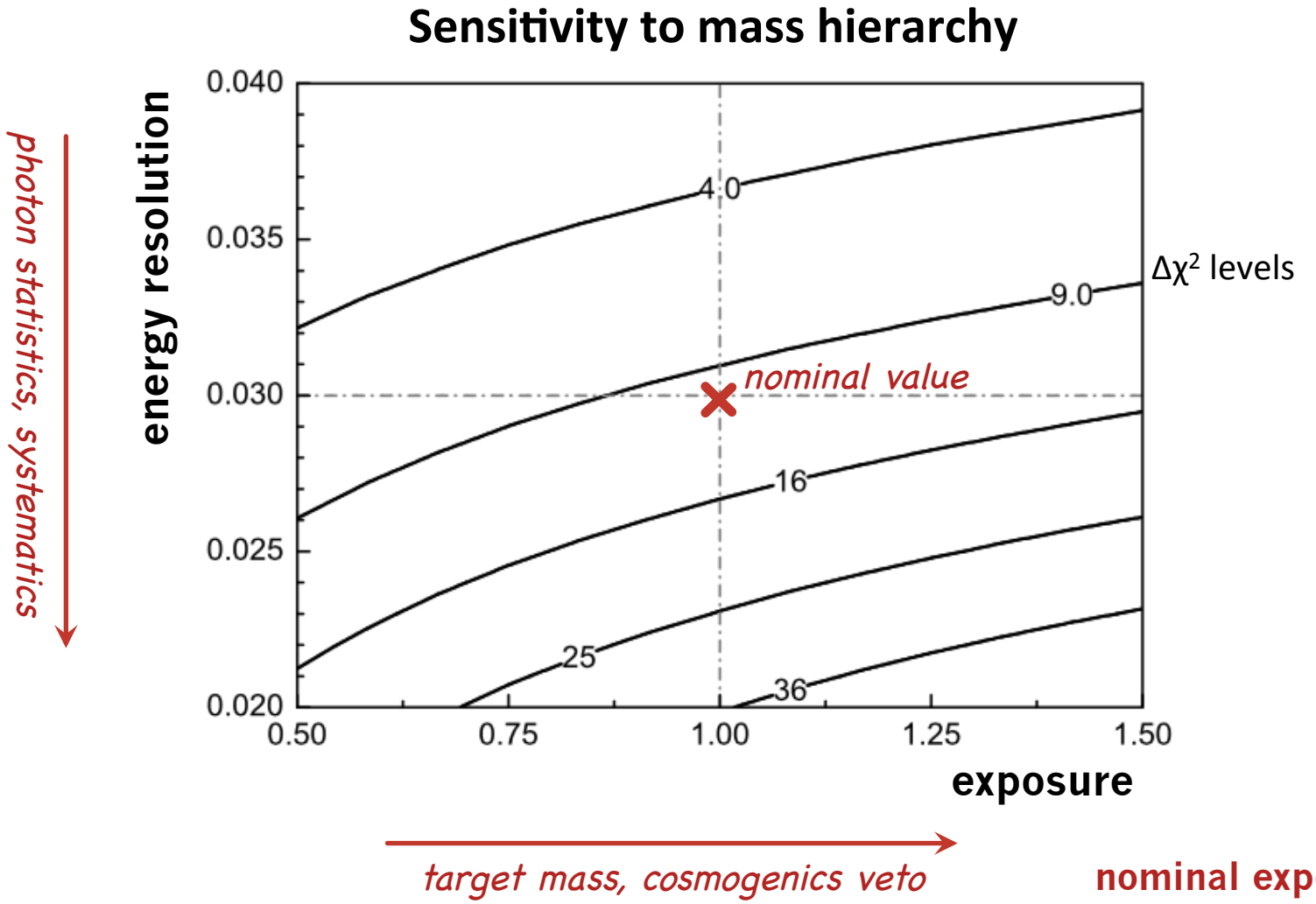
→ ***MH from spectral wiggles***

Experimental setup for reactor neutrinos

Experimental setup for reactor neutrinos



Sensitivity vs. energy resolution



nominal exposure

- 36 GW x 6 years x 20kt
- 80% IBD efficiency

Basic detector requirements for JUNO

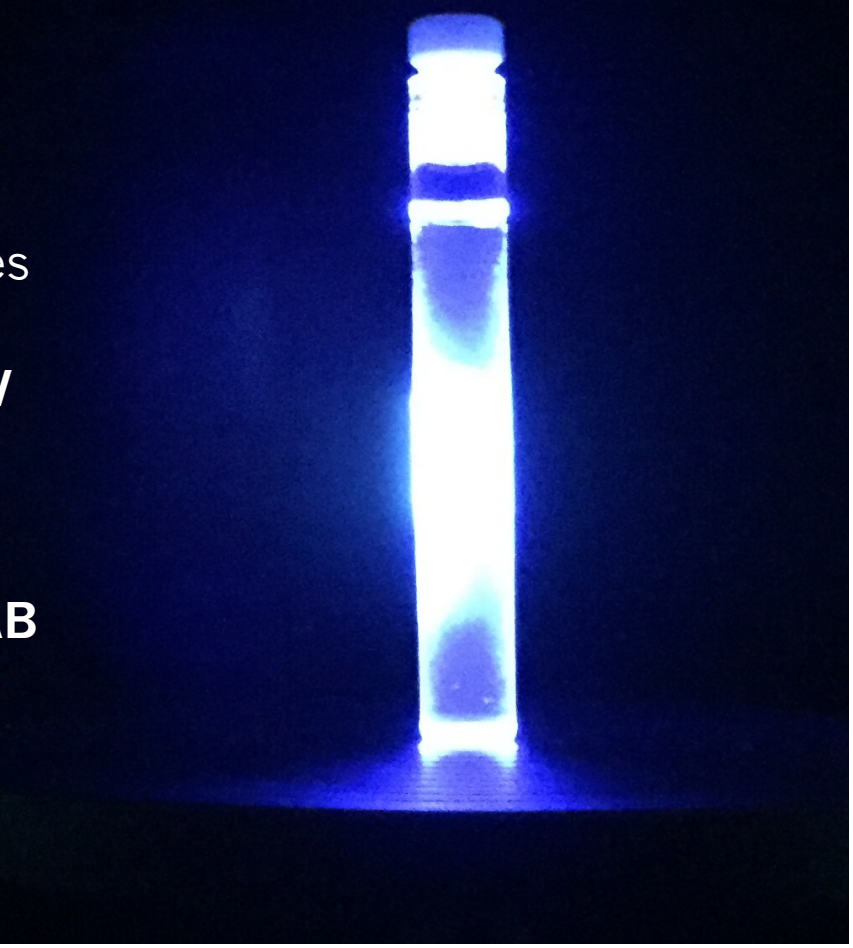
- reactor antineutrinos at MeV energies
  → **Liquid-scintillator detector**
  → Detection by inverse beta decay

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

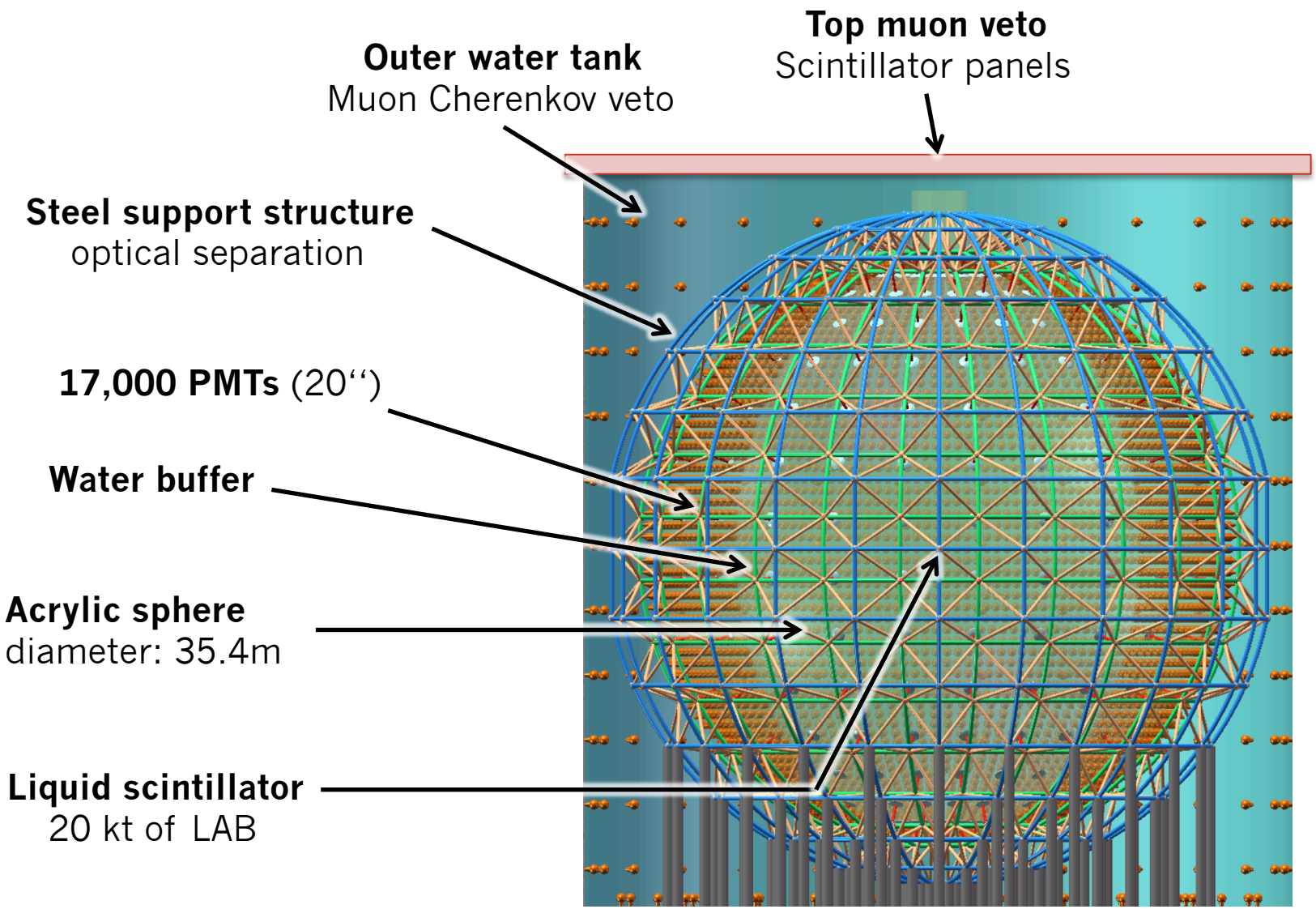
- signature in position of spectral wiggles
  → **~3% energy resolution** at 1 MeV
  → photoelectron yield: **~1,100 pe/MeV**

- large distance to source and high-statistics measurement
  → large target mass: **20 kilotons of LAB**

- cosmogenic background
  → rock overburden of **~700 m**



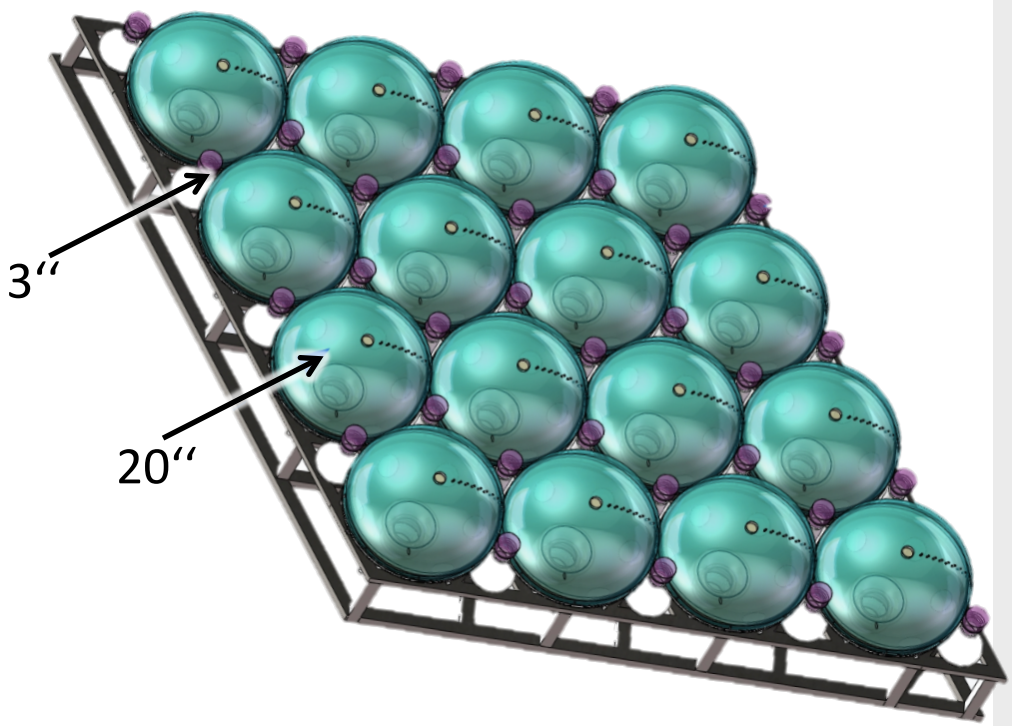
JUNO detector layout

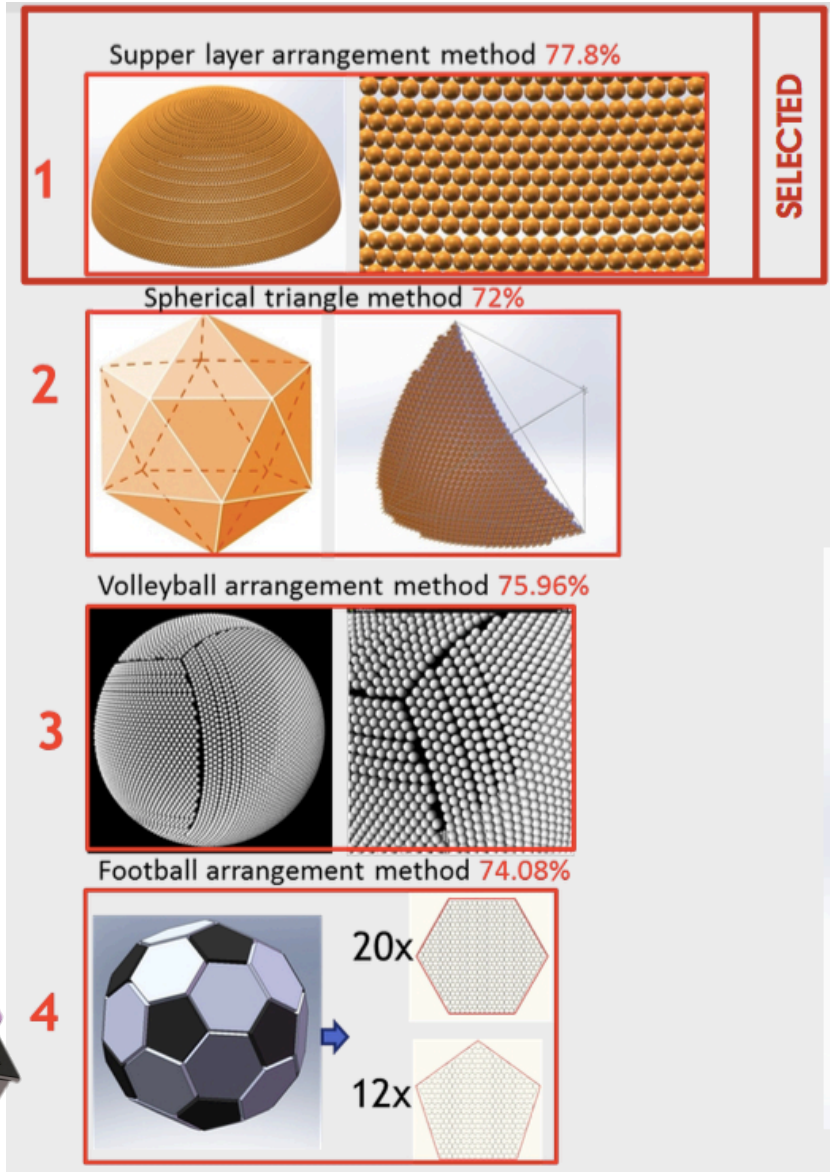


Light detection

Light collection required:

- optical coverage: 75%
  → 17,000 large PMTs (20‘‘)
  → additional small PMTs (3‘‘)
  (double calorimetry + timing)





Light detection

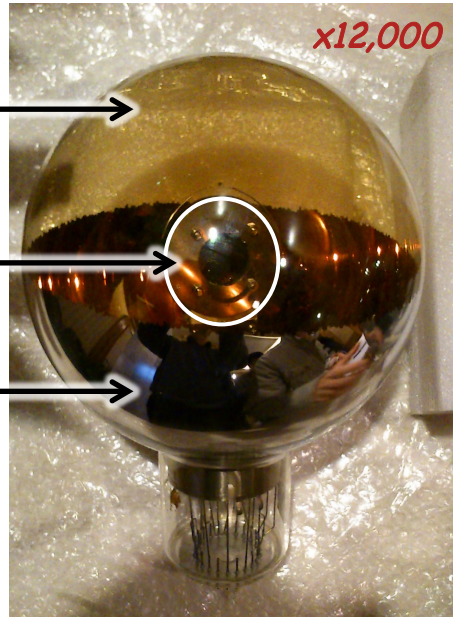
Light collection required:

- optical coverage: 75%
- quantum efficiency QE x collection efficiency CE = 35%

→ photons detected: ~26%

Hamamatsu R12860 (20"PMT)

Parameter	Hamamatsu 20"	new MCP-PMT
Photocathode	transmission	transmission + reflection
QE (400nm)	30%(T)	26%(T) + 4%(R)
relative CE	100%	110%
peak-to-valley ratio	>3	>3
transit time spread	~3ns	~12ns
dark rate	~30kHz	~30kHz
afterpulsing	10%	3%



MCP-PMT 8" prototype

JUNO's liquid scintillator

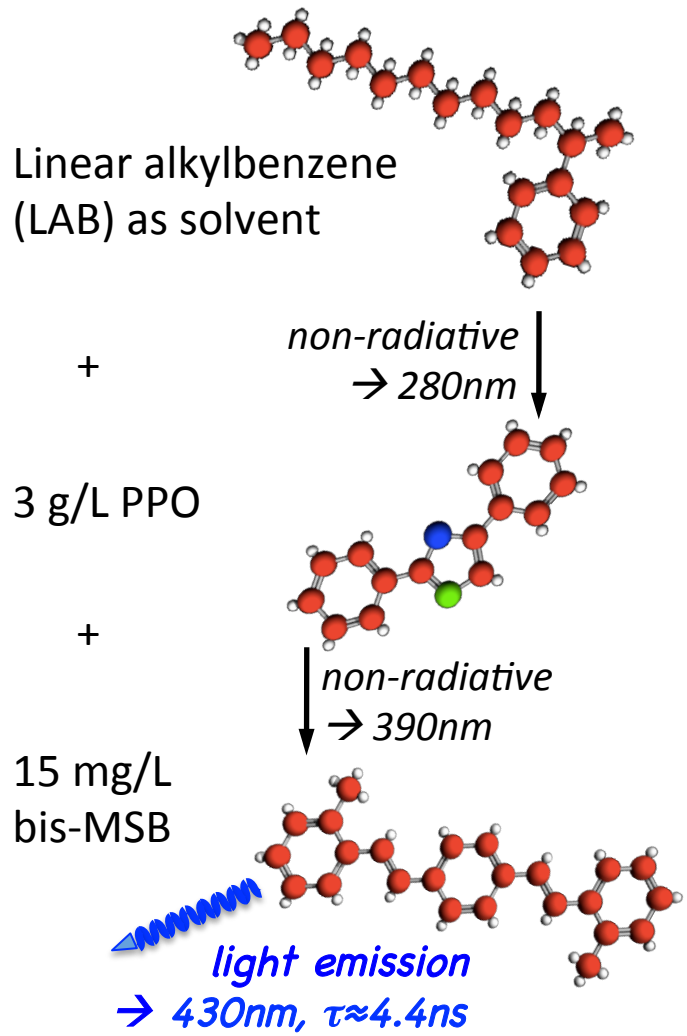
Required properties:

- Light transport over >17m
  → solvent LAB **very transparent**
  → no addition of gadolinium
  → Al_2O_3 column purification
- **High light yield**: >10^4 ph/MeV
  → pure LAB, no addition of paraffins
  → large fluor (PPO) concentration
- **Radiopurity**:
  → reactor neutrinos: <10^{-15} g/g in U/Th
  → solar neutrinos: <10^{-17} g/g
  → vacuum distillation

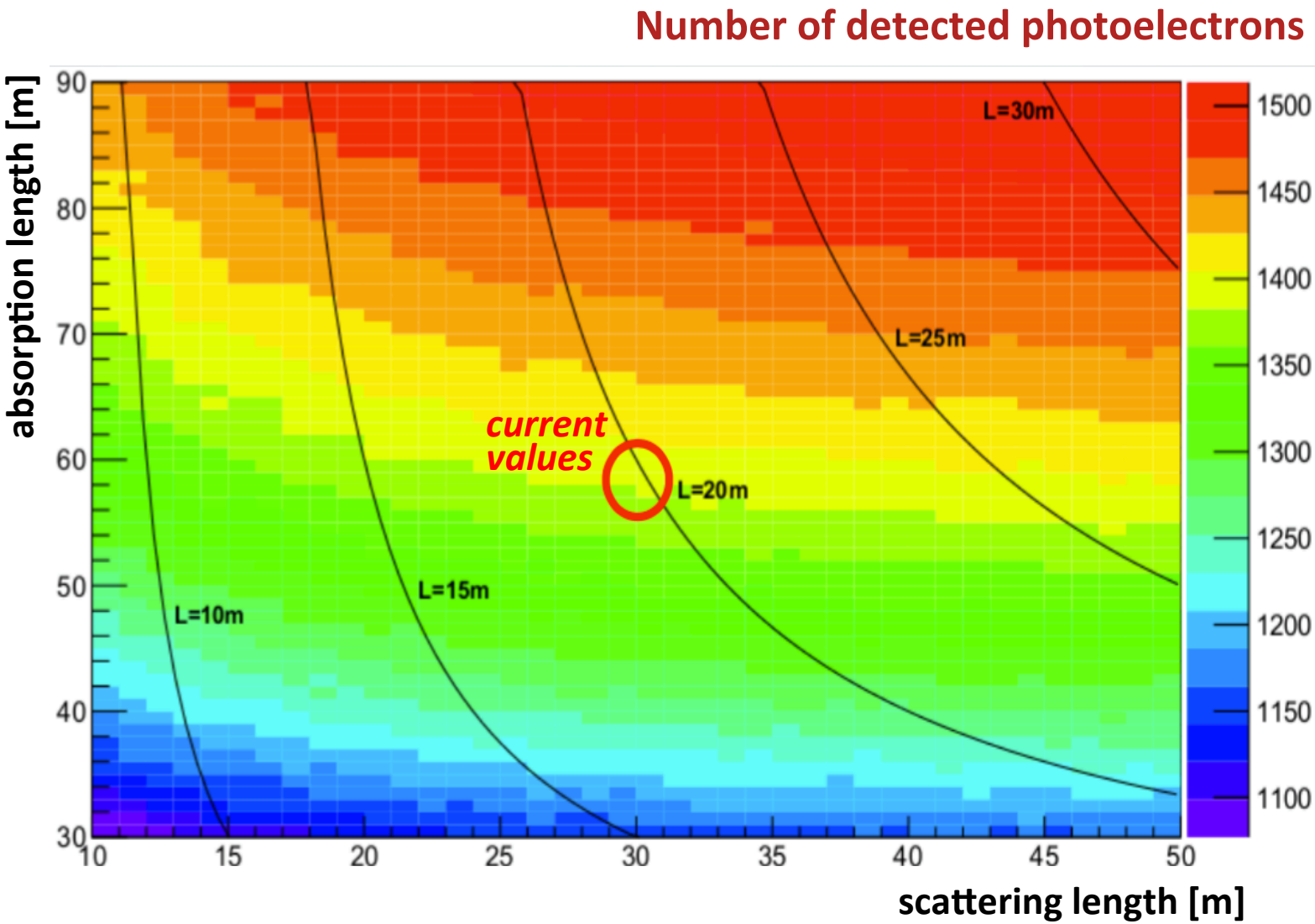
for free:

- Fast fluorescence times
  → **good spatial resolution**
- Good **pulse shaping** properties
  → background discrimination, e.g. e^+/e^-

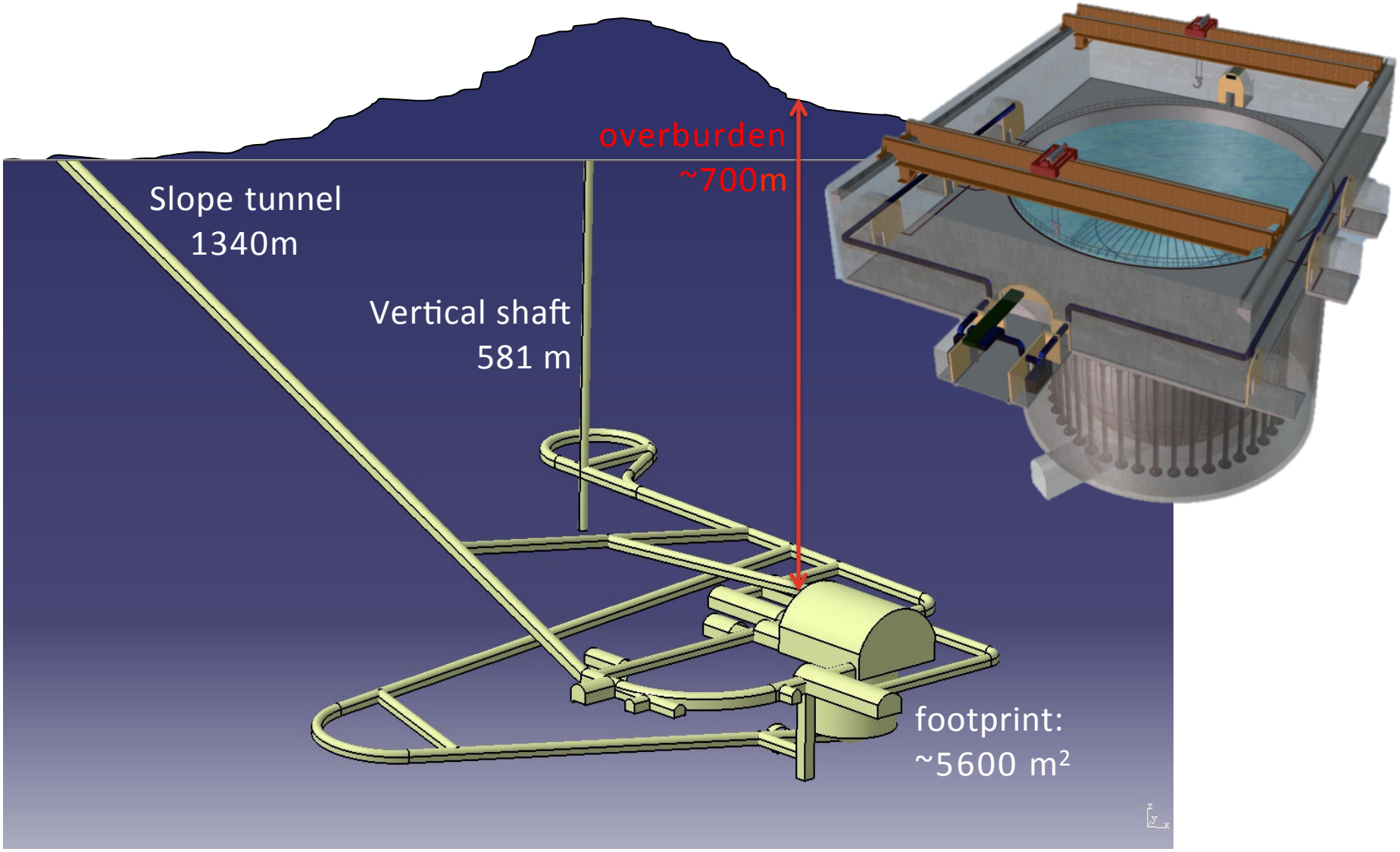
LENA-style liquid scintillator



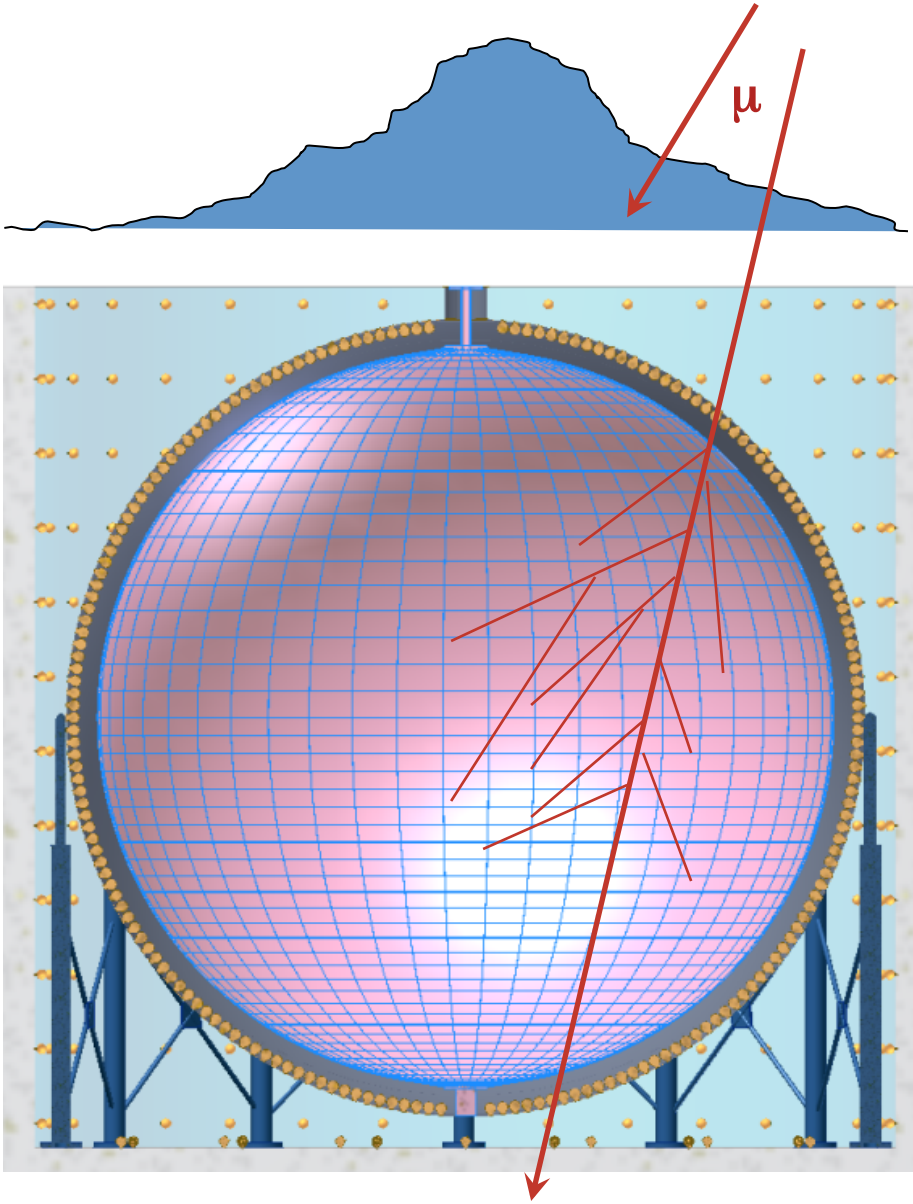
p.e. yield vs. scintillator transparency



Underground laboratory



Cosmogenic backgrounds



Cosmic background level

- rock shielding: 700 m
- μ rate in Central Detector: ~3 s^{-1}
- showering μ rate: ~0.5 s^{-1}

→ *radioisotopes from ^{12}C spallation*

Most dangerous: βn-emitters

- $^{9}Li \rightarrow {}^{9}Be + e^{-} + \nu_e$ [$\tau(^{9}Li)$~257ms]
  $\hookrightarrow 2\alpha + n$

→ prompt electron signal
+ delayed neutron capture

→ mimics neutrino (IBD) signature!

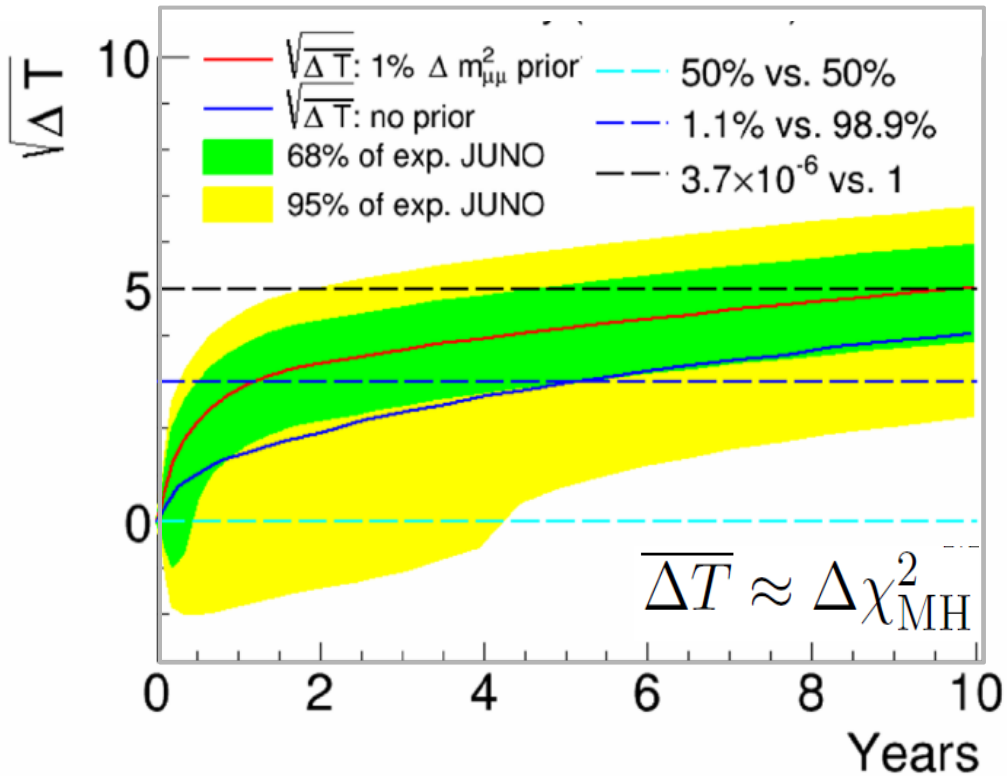
Expected ^{9}Li rate: ~70 d^{-1}

→ signal to background ~1:1

→ veto based on parent μ mandatory!

→ dead time introduced: ~20%

Sensitivity to mass hierarchy



Factors	$\Delta\chi^2$
Statistics only	+16
different core distances	-3
reactor background	-1.7
spectral shape	-1
S/B ratio (rate)	-0.6
S/B ratio (shape)	-0.1
information on $\Delta m^2_{\mu\mu}$	+8

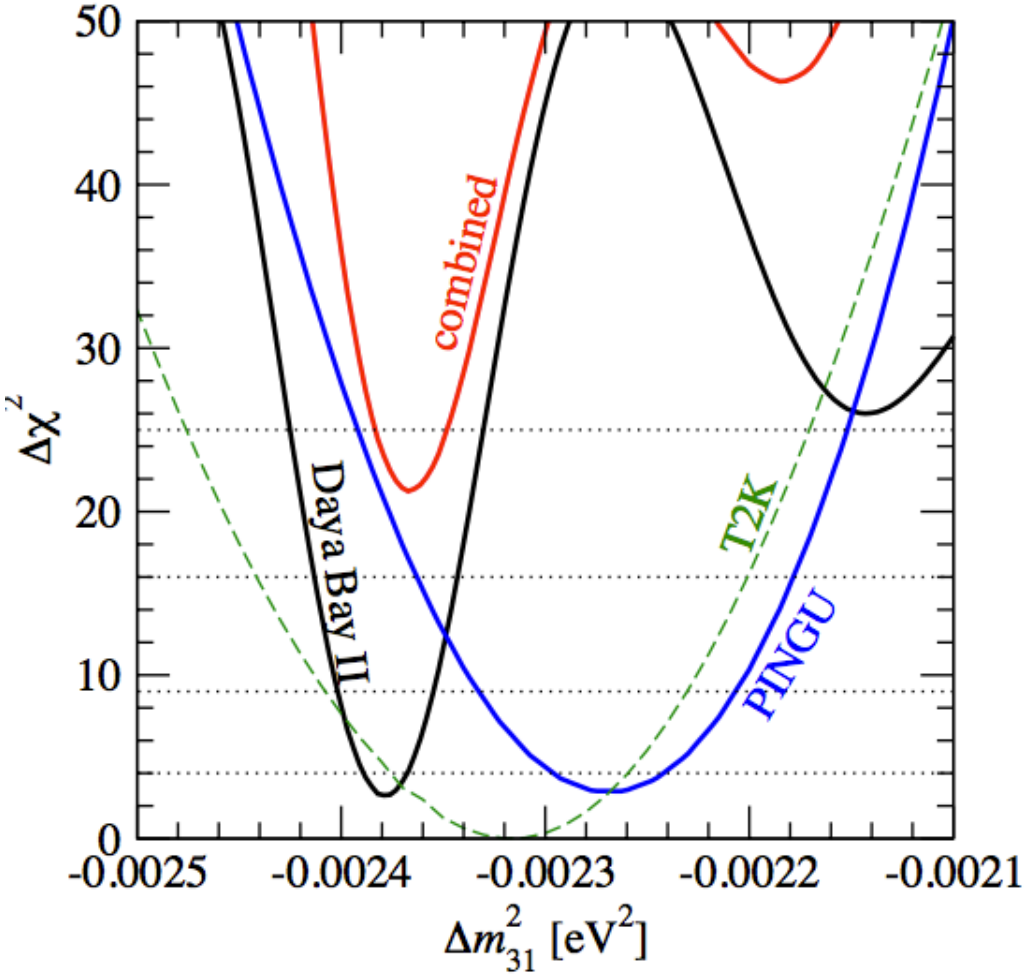
JUNO's expected sensitivity level

*(assuming **3% energy resolution**)*

- JUNO alone based on 6 years: ~3σ

+ precise data by T2K/NOvA on $\Delta m^2_{\mu\mu}$: **4σ**

Complementarity with other approaches



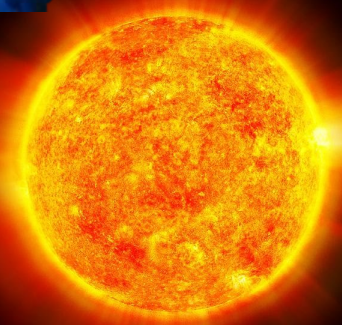
combine measurements of $|\Delta m^2_{31}|$ from PINGU and JUNO

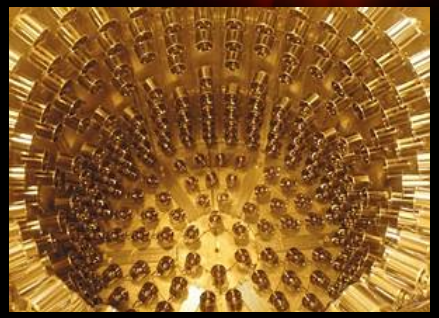
Blennow, Schwetz, arXiv:1306.3988

JUNO overall physics program

- Reactor neutrino oscillations
  - mass hierarchy
  - precise measurement of osc. parameters: Δm^2_{21}~0.6%, Δm^2_{ee}~0.4%, $\sin^2\theta_{12}$~0.7%
- Neutrinos from natural sources
  - Galactic Supernova neutrinos
  - Diffuse Supernova Neutrino Background
  - Solar neutrinos
  - Geoneutrinos
  - Neutrinos from dark matter annihilation
  - Atmospheric neutrinos
- Short-baseline oscillations (sterile ν's)
- Proton decay into $K^+\bar{\nu}$

→ *JUNO Yellow Book, arXiv:1507.05613*





Supernova neutrino detection in JUNO

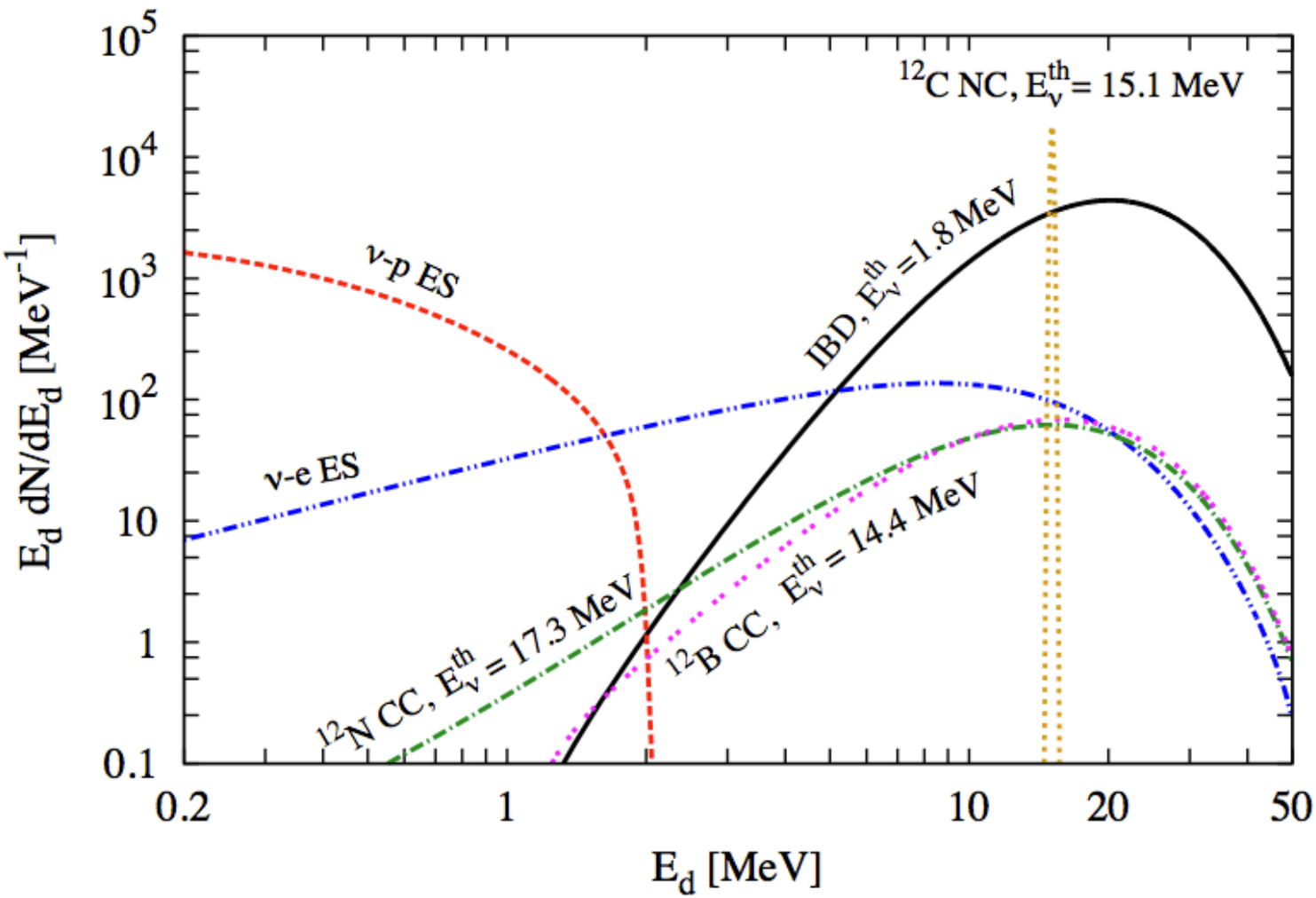
- Canonical core-collapse Supernova signal:
  - progenitor distance: 10 kpc
  - total energy: 3 x 10^{53} erg
  - equal flavor distribution
  - "pinched" Fermi-Dirac spectrum
  - symmetric neutrino emission

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	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	0.5×10^2	0.9×10^2	1.6×10^2
$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

- Total event number in 10 sec: 5.5 x 10^3 7.1 x 10^3 8.9 x 10^3

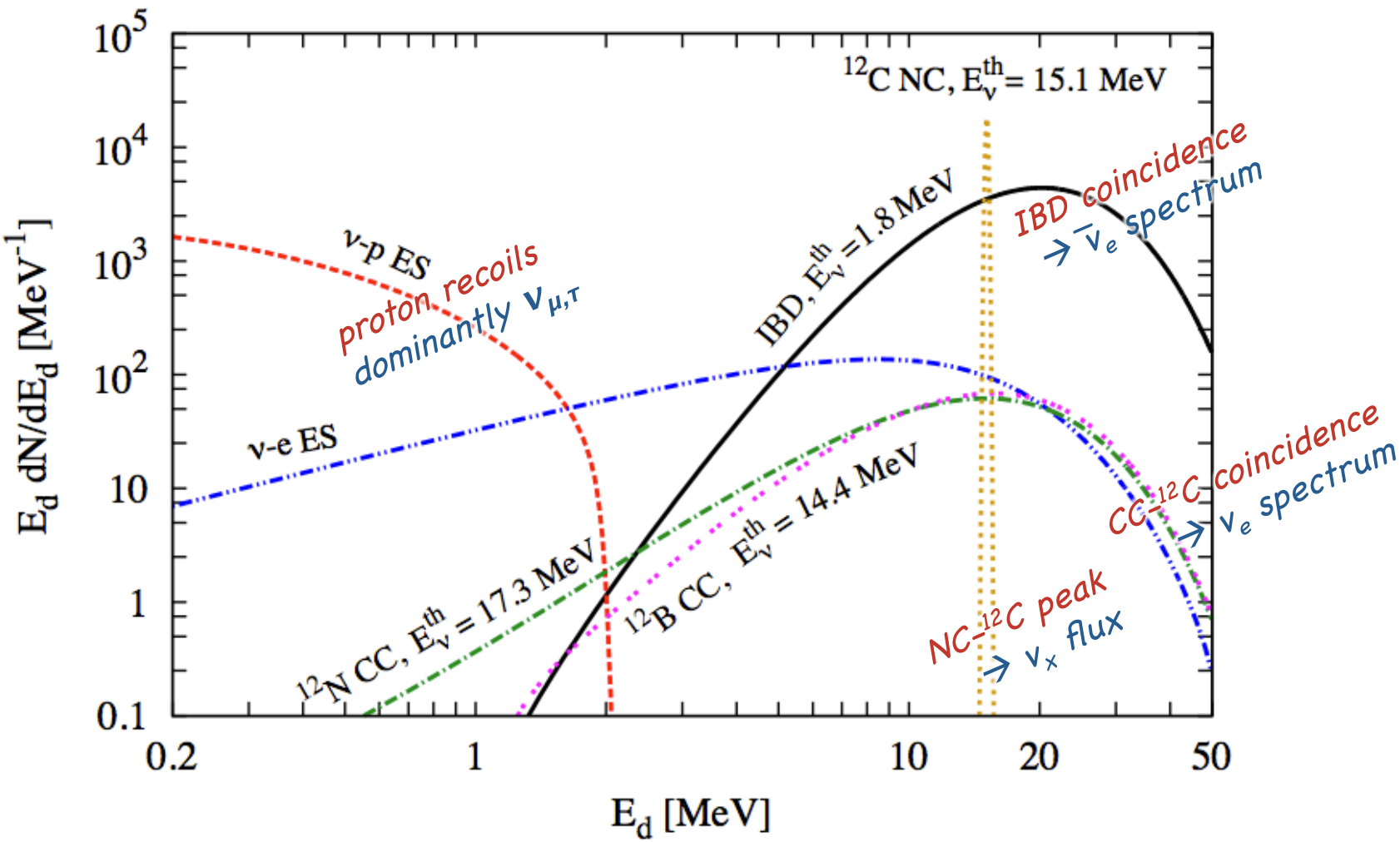
→ total signal rate comparable to Super-Kamiokande

Prompt event spectrum



→ CC channels (→ ν_e,$\underline{\nu}_e$) can be discriminated based on delayed signals

Prompt event spectrum



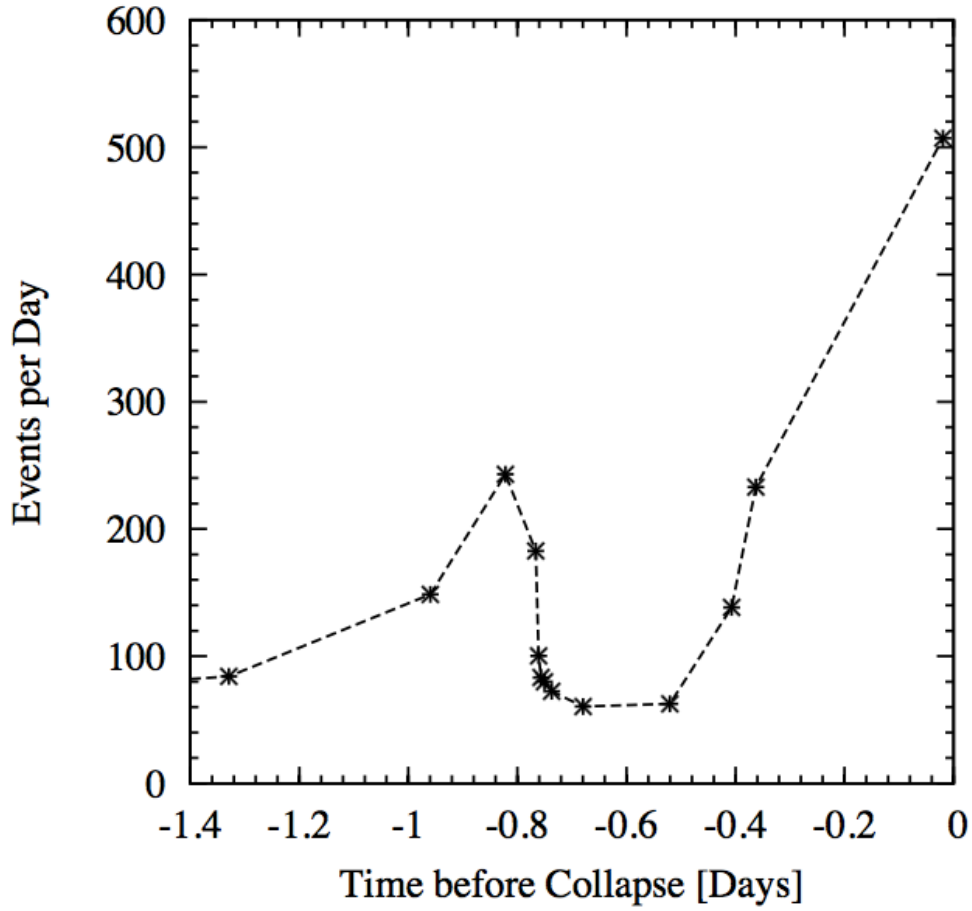
→ CC channels (→ ν_e,$\bar{\nu}_e$) can be discriminated based on delayed signals

→ JUNO permits energy- and flavor-resolved detection of the SN neutrinos!

Implications for astrophysics

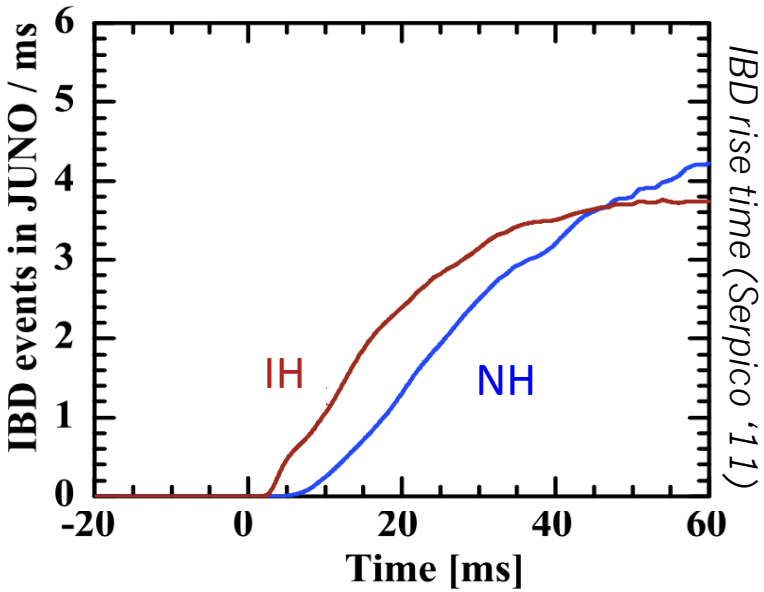
- Verification and details of the **core-collapse scenario**
- **Nature of the remnant** (neutron star vs. black hole)
- **Locating the SN** by IBDs angular resolution of ~9%
- Detection of nearby **pre-Supernova neutrinos**
- Coincidence with **gravitational waves**
- **Nucleosynthesis** ($\nu_{\mu,\tau}$ for ^{11}B, ^{7}Li)

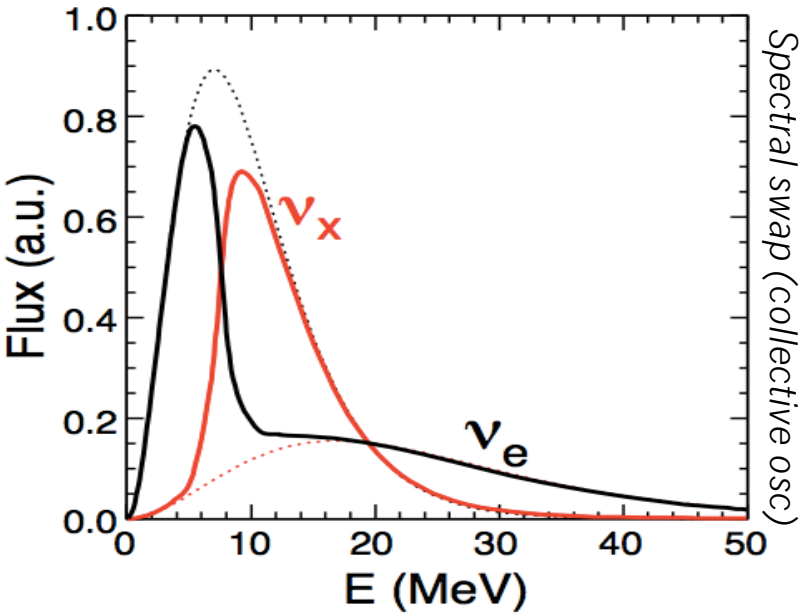
pre-SN antineutrino rates (progenitor: 20M$_\odot$, Si-burning, 200pc)



Implications for neutrino/particle physics

- **Absolute scale of neutrino masses**
  - from fitting the overall SN neutrino light curve: ~0.8 eV
  - cut-off by black-hole formation
- **Neutrino mass hierarchy**
  - Earth matter effect (if $E(\bar{\nu}_{\mu,\tau}) >> E(\bar{\nu}_e)$)
  - Suppression of neutronization burst
  - Rise time of the $\bar{\nu}_e/\bar{\nu}_x$ rates
  - Spectral swap in collective oscillations
  - ...
- **Presence of collective oscillations**
- **Exotic neutrino interactions**
- **Emission of exotic particles**
  - luminosity
  - duration of cooling phase

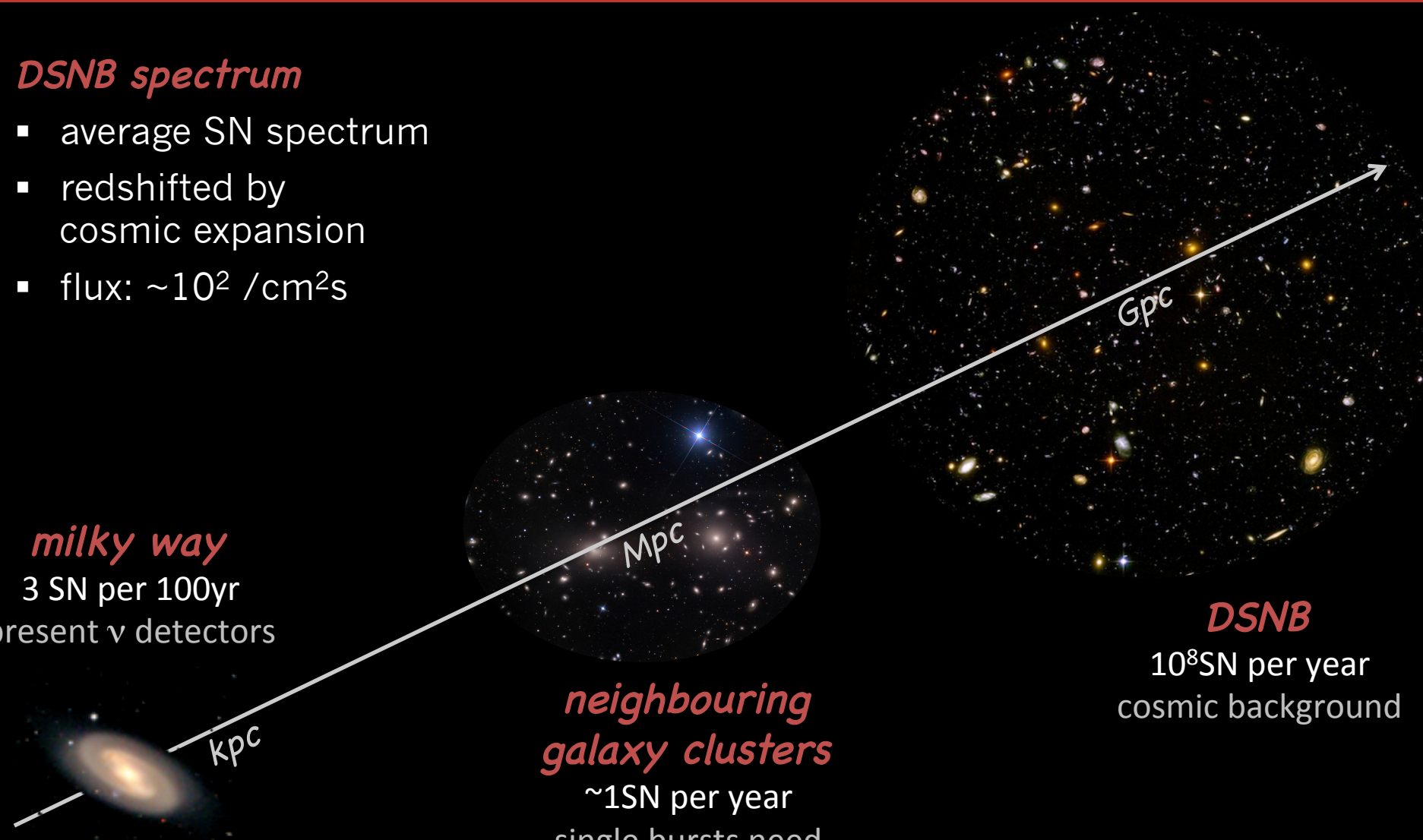




Diffuse Supernova Neutrino Background

DSNB spectrum

- average SN spectrum
- redshifted by cosmic expansion
- flux: ~10^2 /cm^{2}s



milky way

3 SN per 100yr

present ν detectors

neighbouring galaxy clusters

~1SN per year

single bursts need Mton++ detectors

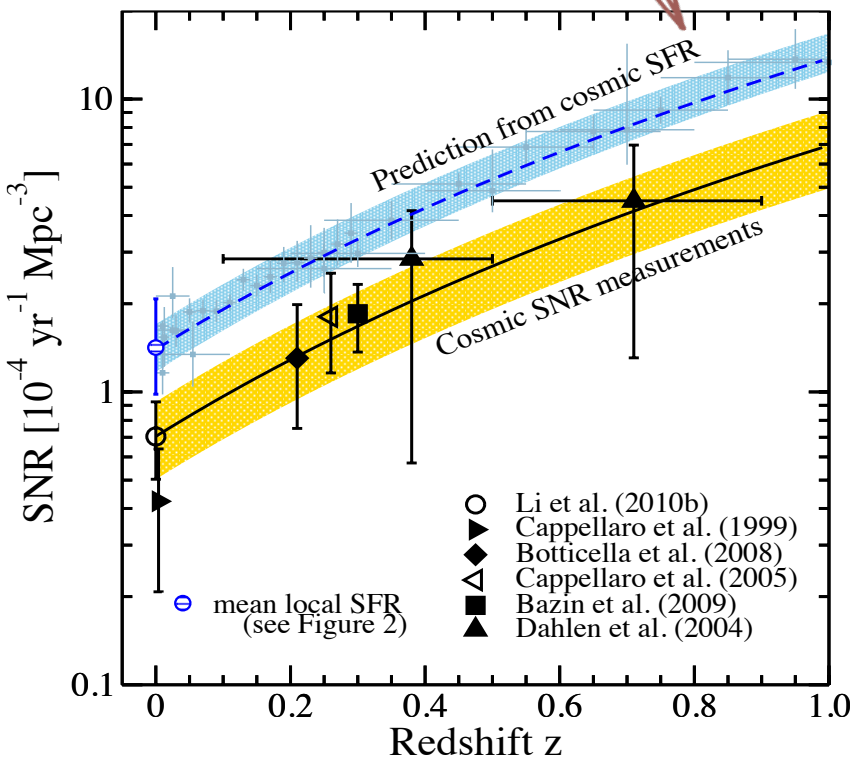
DSNB

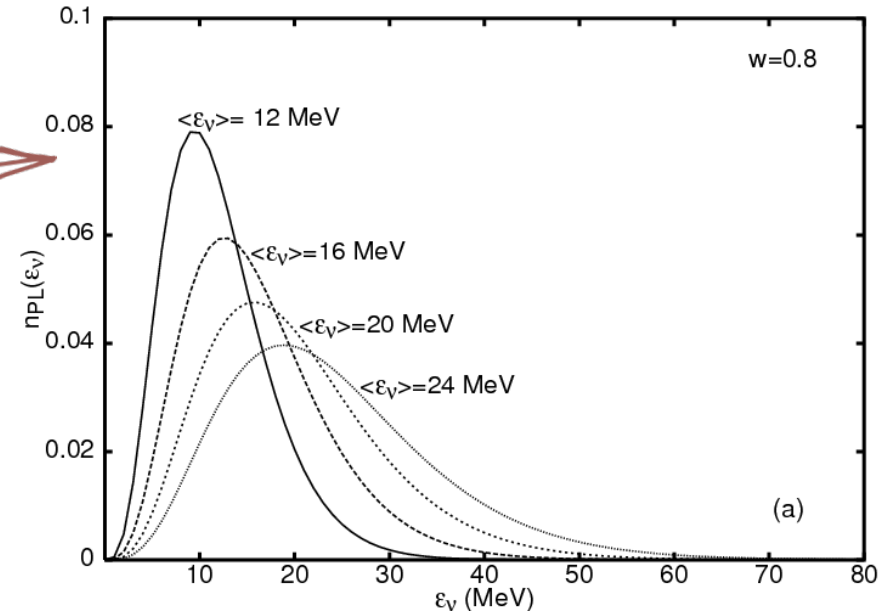
10^8SN per year

cosmic background

DSNB prediction

- DSNB depends on
  - SN neutrino spectrum, $<E_\nu>$
  - z-dependent SN rate, Φ_0 (or SFR and IMF)





Questions to be addressed:

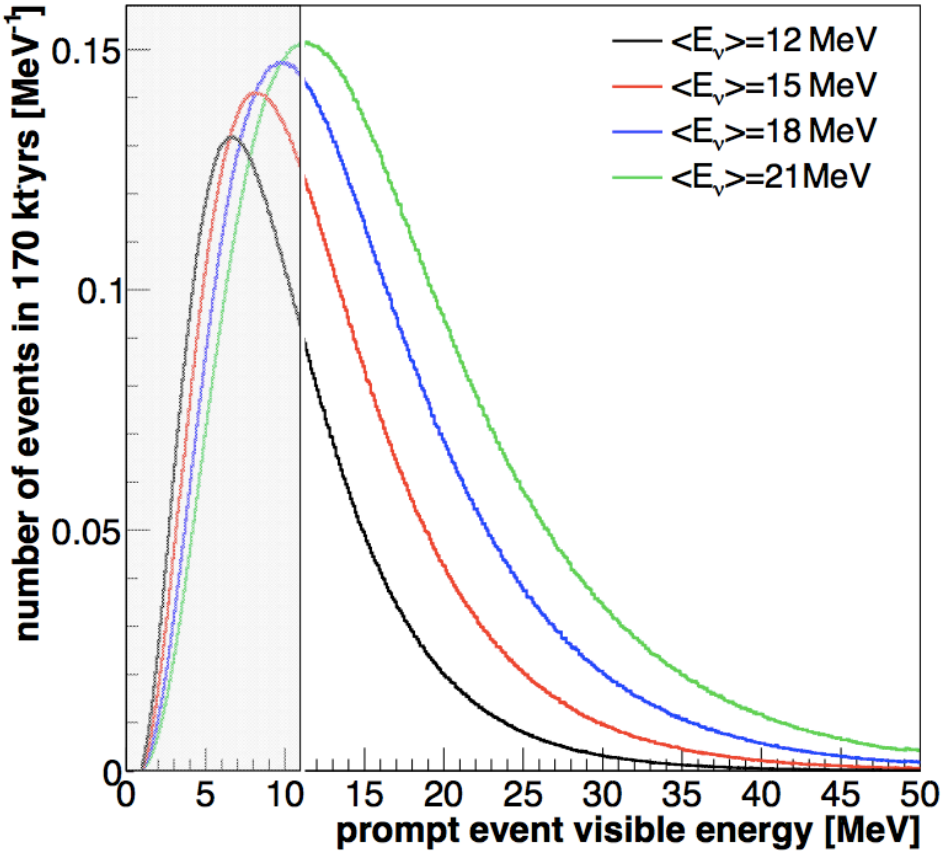
→ average SN ν spectrum

→ redshift-dependent SN rate

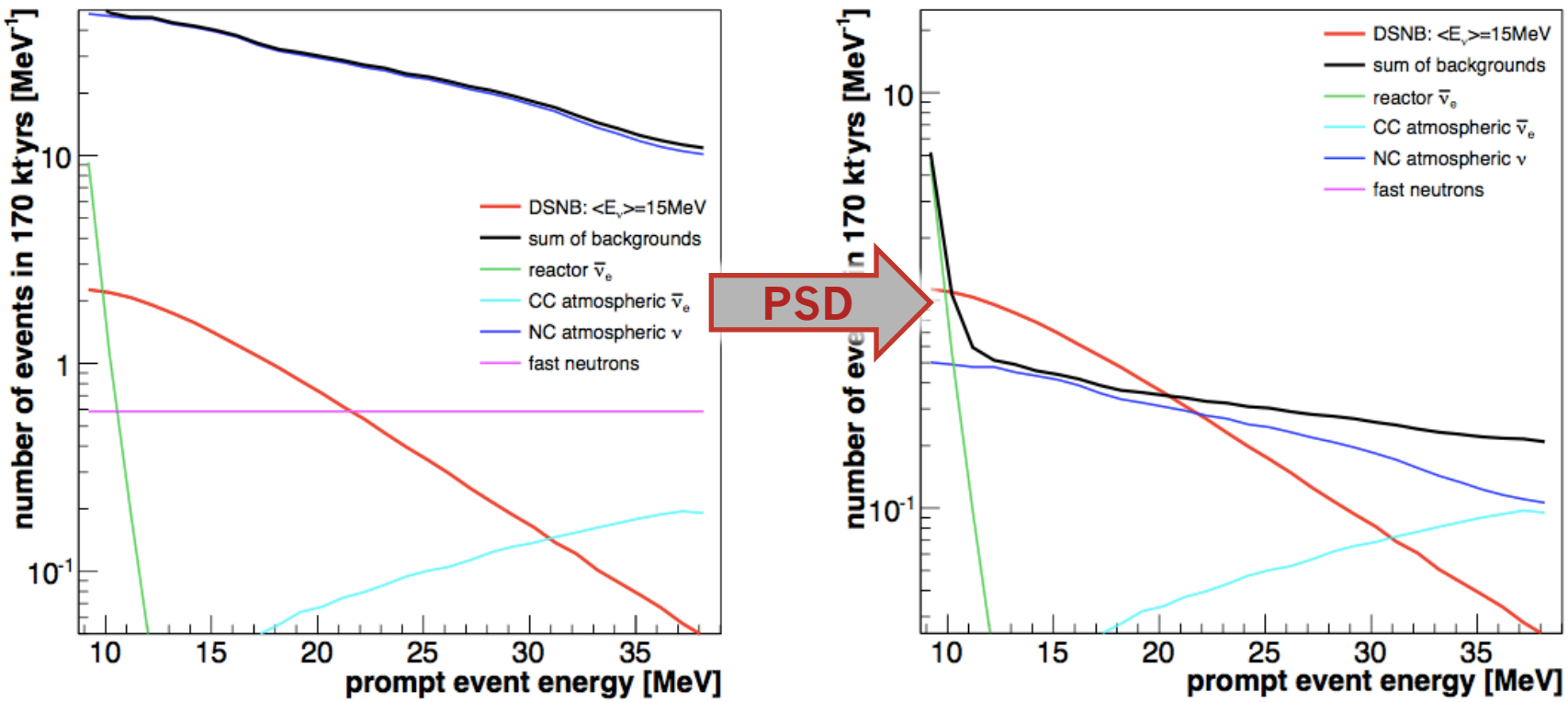
→ fraction of hidden SN

DSNB signal in JUNO

- DSNB depends on
  - SN neutrino spectrum, $<E_\nu>$
  - z-dependent SN rate, Φ_0 (or SFR and IMF)
- Detection via inverse beta-decay
  - 1 – 4 events per year
- coincidence signature
  - efficient suppression of single backgrounds
- remaining issue:
  - coincident backgrounds



Backgrounds to DSNB detection

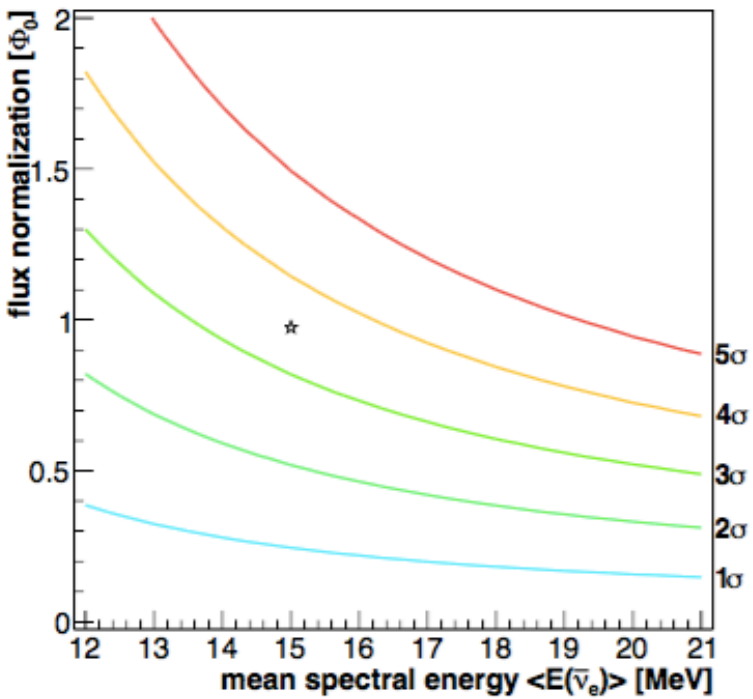


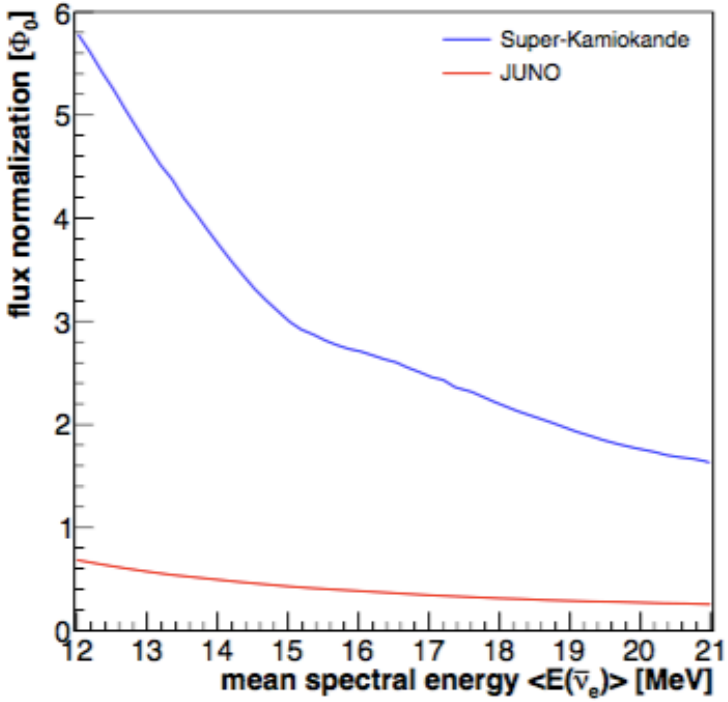
- **original spectrum**
  - atmospheric ν_μ-**NC**/CC
  - fast neutrons

  dominate the DSNB signal

- **after PSD**
  - atm. NC/FN greatly reduced
  - reactor & atmospheric IBDs define observation window

DSNB discovery/exclusion potential





- **Discovery potential**
  - esposure: 17kt x 10 yrs
  - syst. uncertainty on BG: 5%

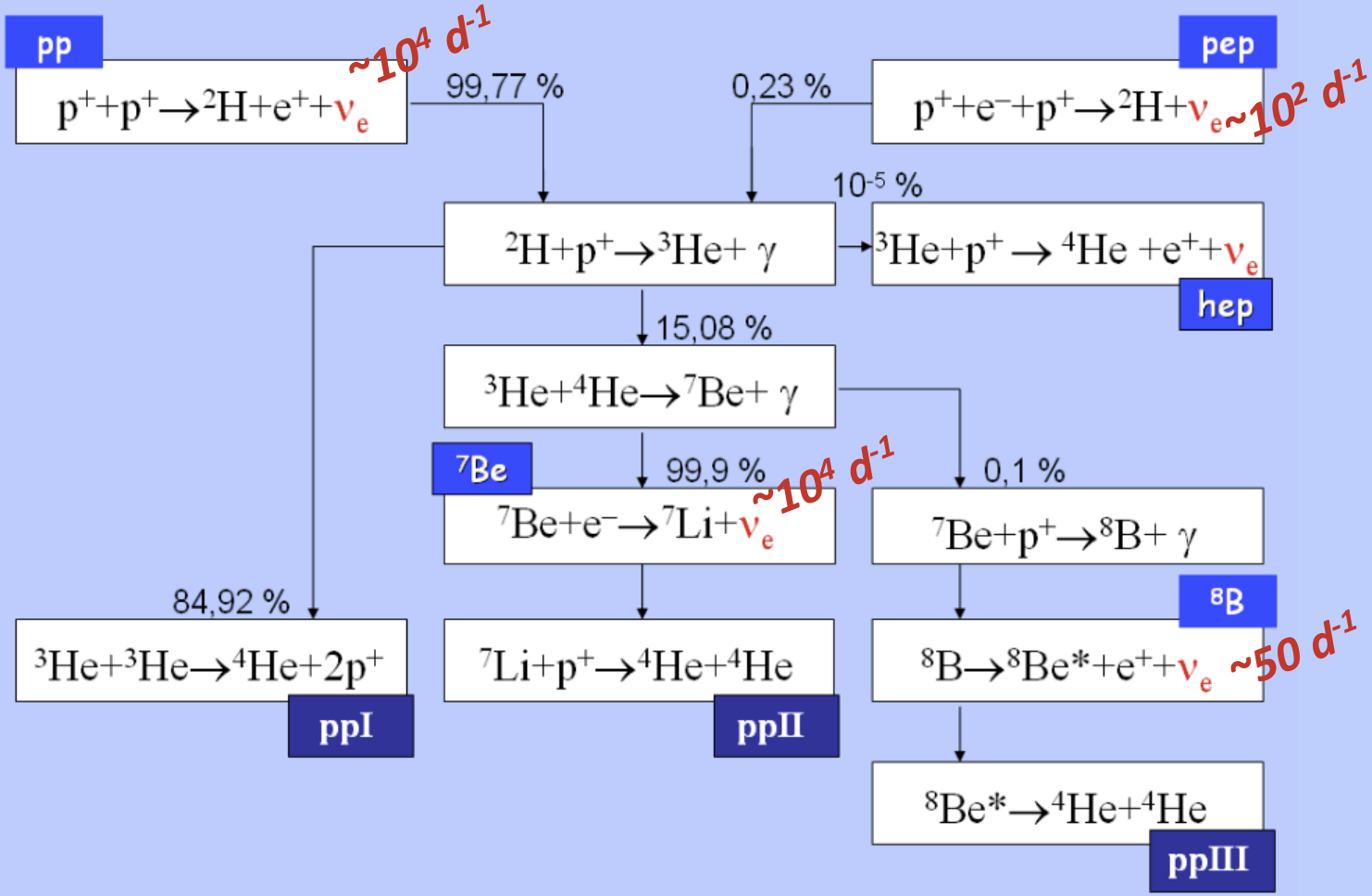
  → **possibly detection at 3σ level**

- **Exclusion plot**
  - same assumptions as before
  - only BG prediction detected

  → **significant improvement over current Super-K limit**

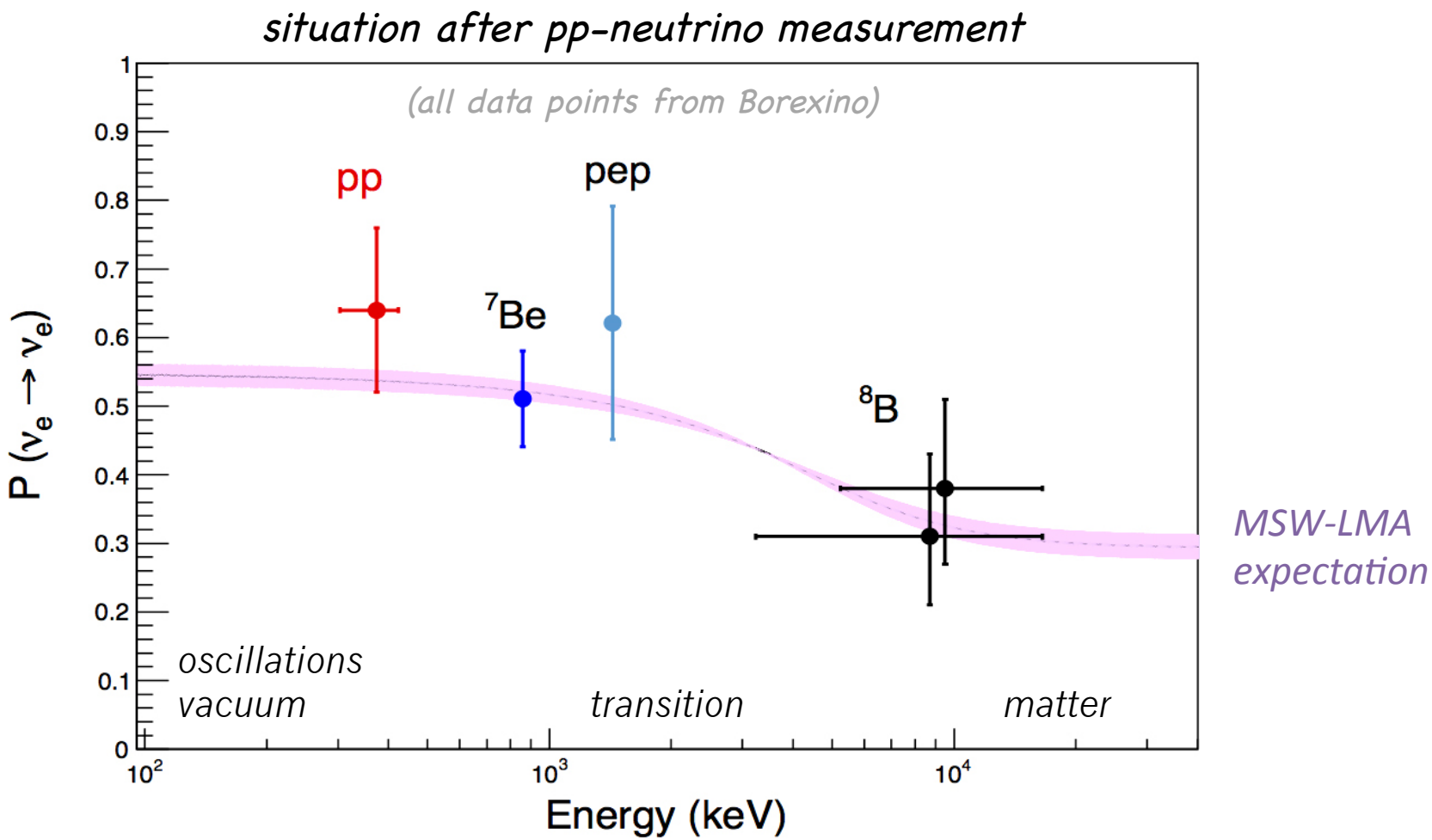
Solar neutrino detection in JUNO

Rates in 20 kt:



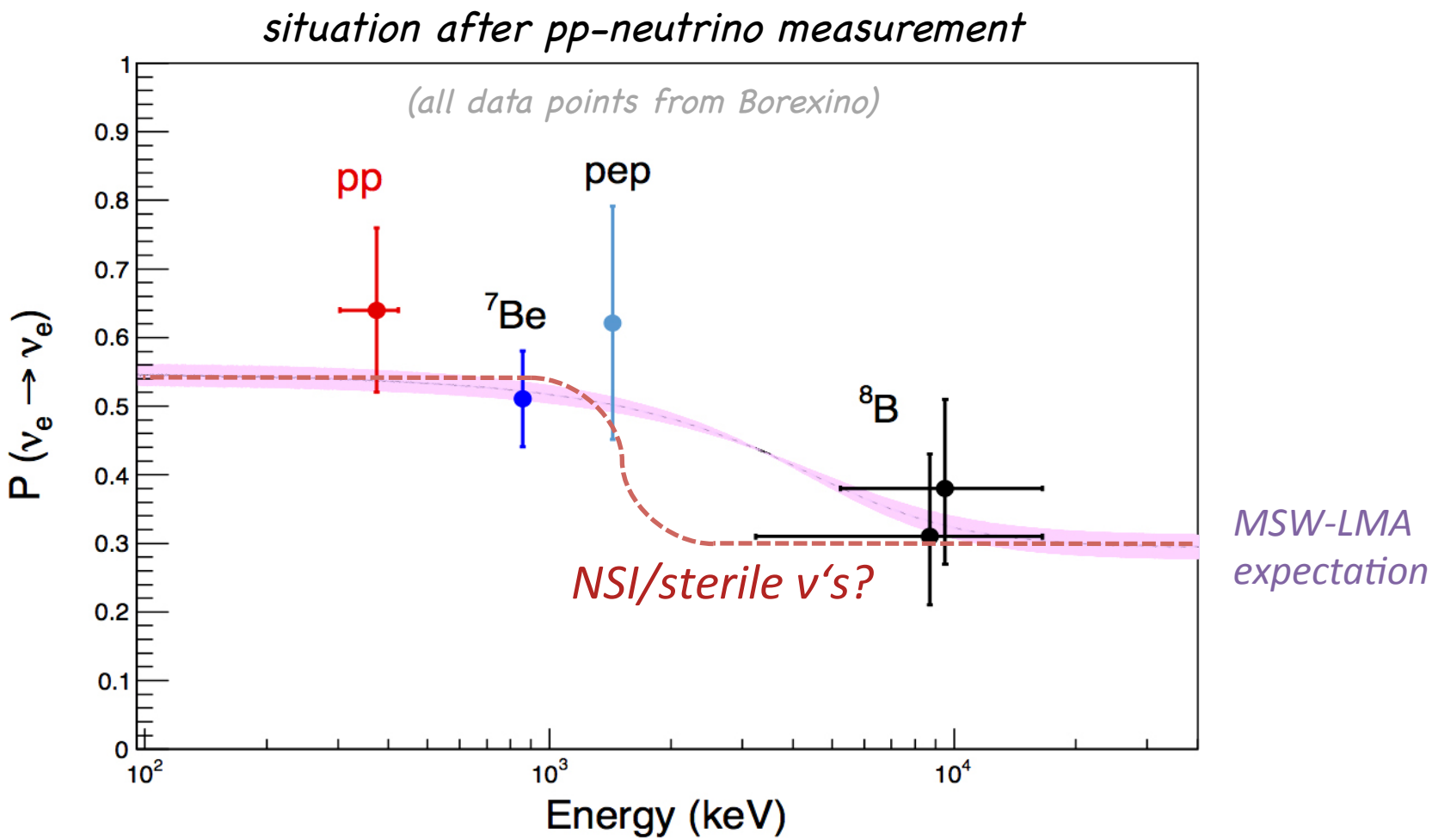
- great potential for precision spectroscopy of the solar spectrum
- largely depends on achieved internal/cosmogenic BG levels

Solar neutrinos – oscillation physics



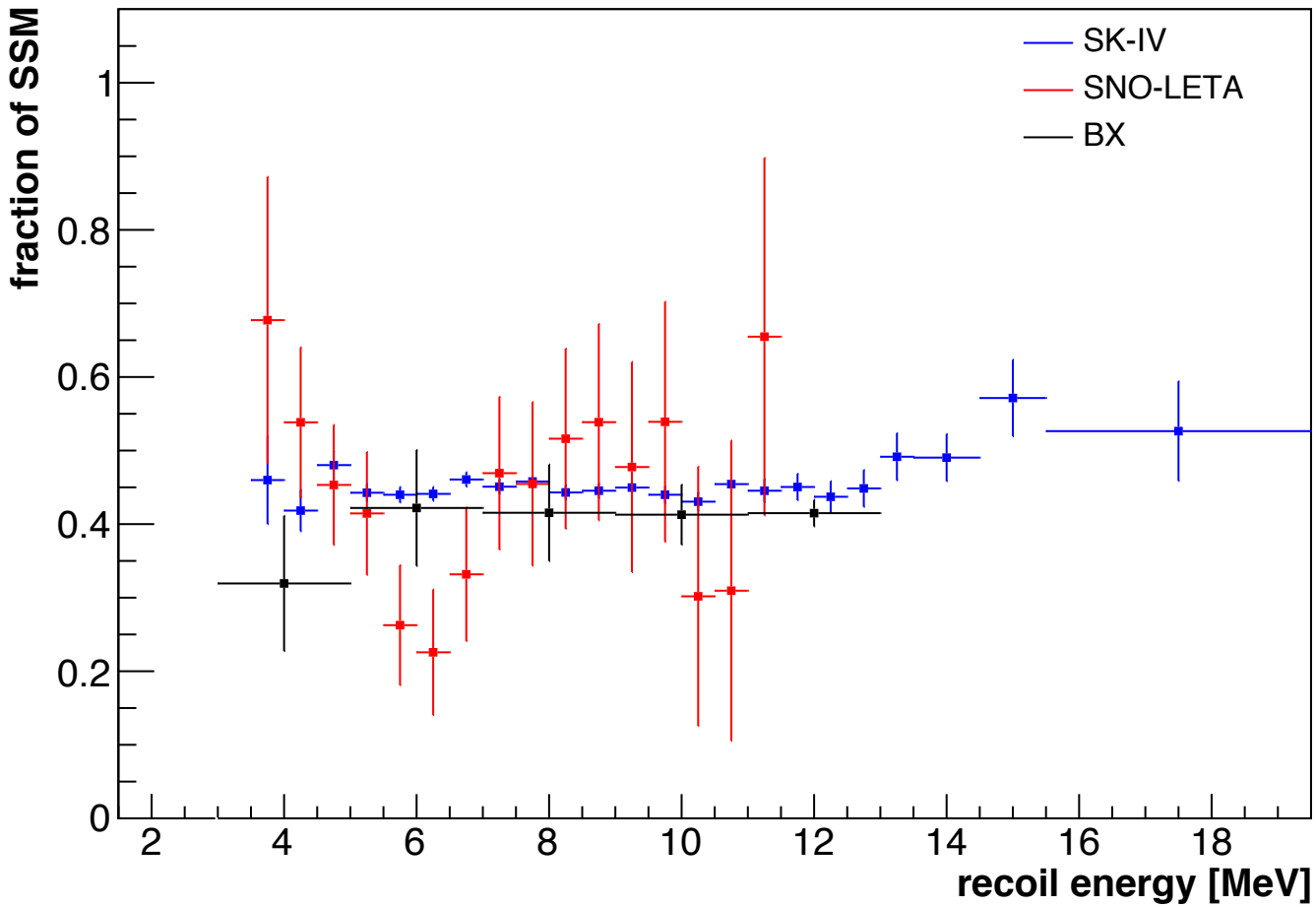
- so far, all data points compatible with MSW-LMA expectation
- scarce data in the transition region

Solar neutrinos – oscillation physics



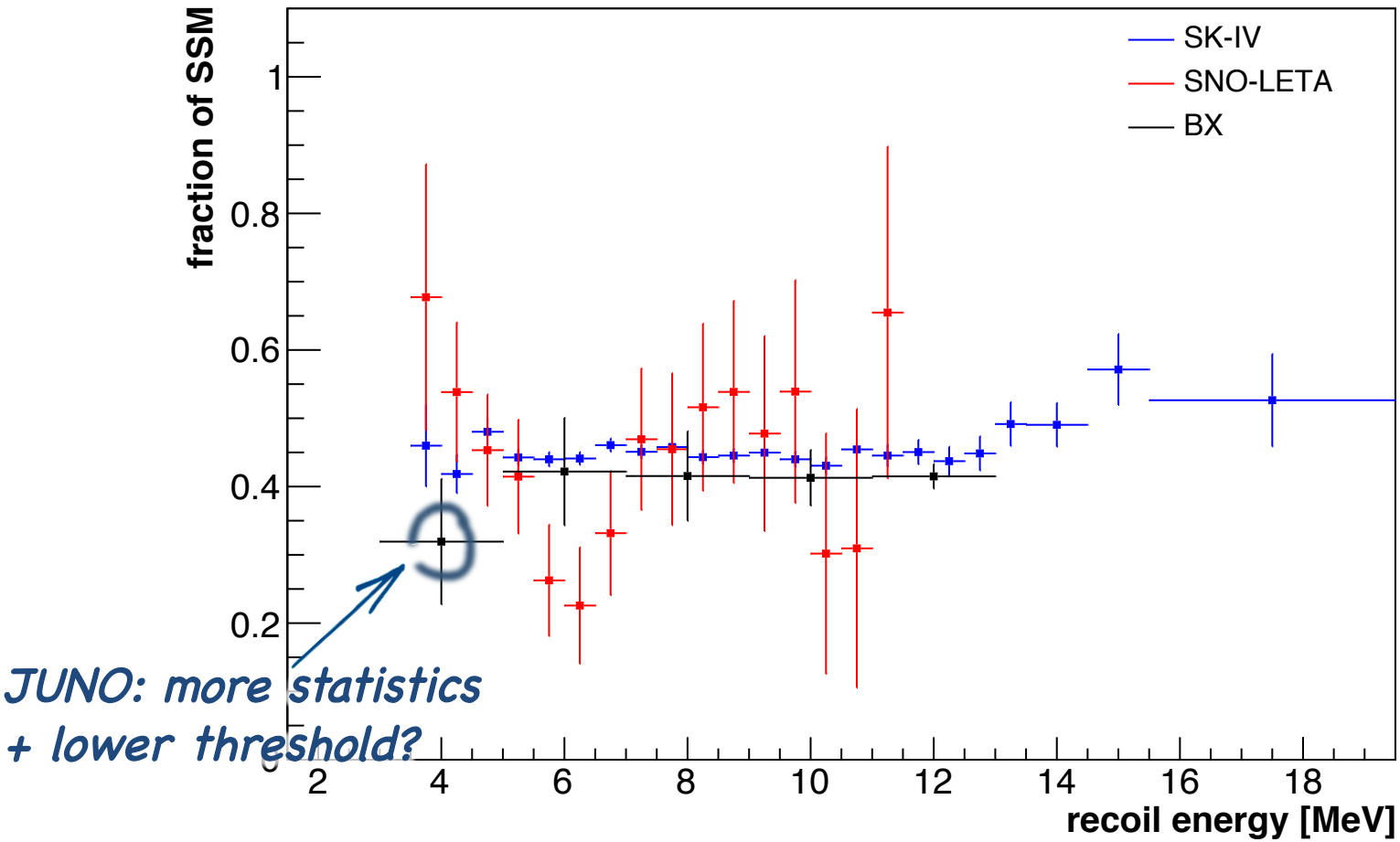
- so far, all data points compatible with MSW-LMA expectation
- scarce data in the transition region → **new physics?**

The (non-)existent ^{8}B upturn?



→ ES & CC-ν_e data (SNO) show no upturn on low-energy ^{8}B-ν's (but still compatible with MSW-LMA expectation at 2σ level)

The (non-)existent ^{8}B upturn?



→ ES & CC-ν_e data (SNO) show no upturn on low-energy ^{8}B-ν's (but still compatible with MSW-LMA expectation at 2σ level)

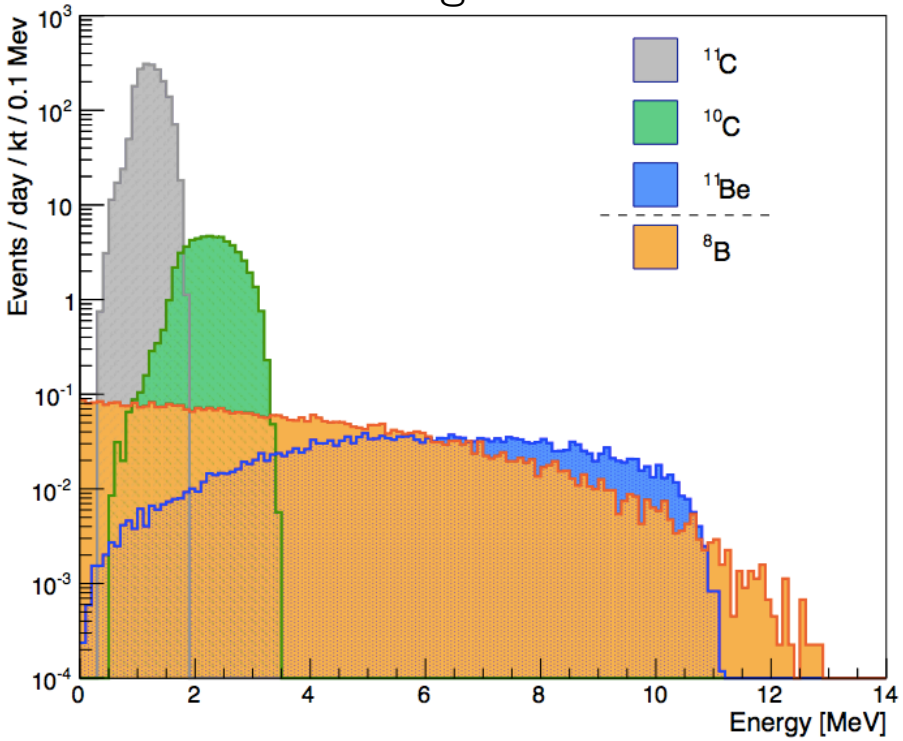
Potential for a low-E ^{8}B measurement in JUNO

^{8}B-ν's by elastic scattering

- large target volume
  - statistics: : ~2 (kt·d)$^{-1}$
  - stringent fiducial volume cut
    → effective reduction of external γ-background
- low overburden
  - large cosmogenic BG
  - reduction by factor 10-100?
    → threshold of 2 MeV
- internal radioactivity (^{208}Tl)?

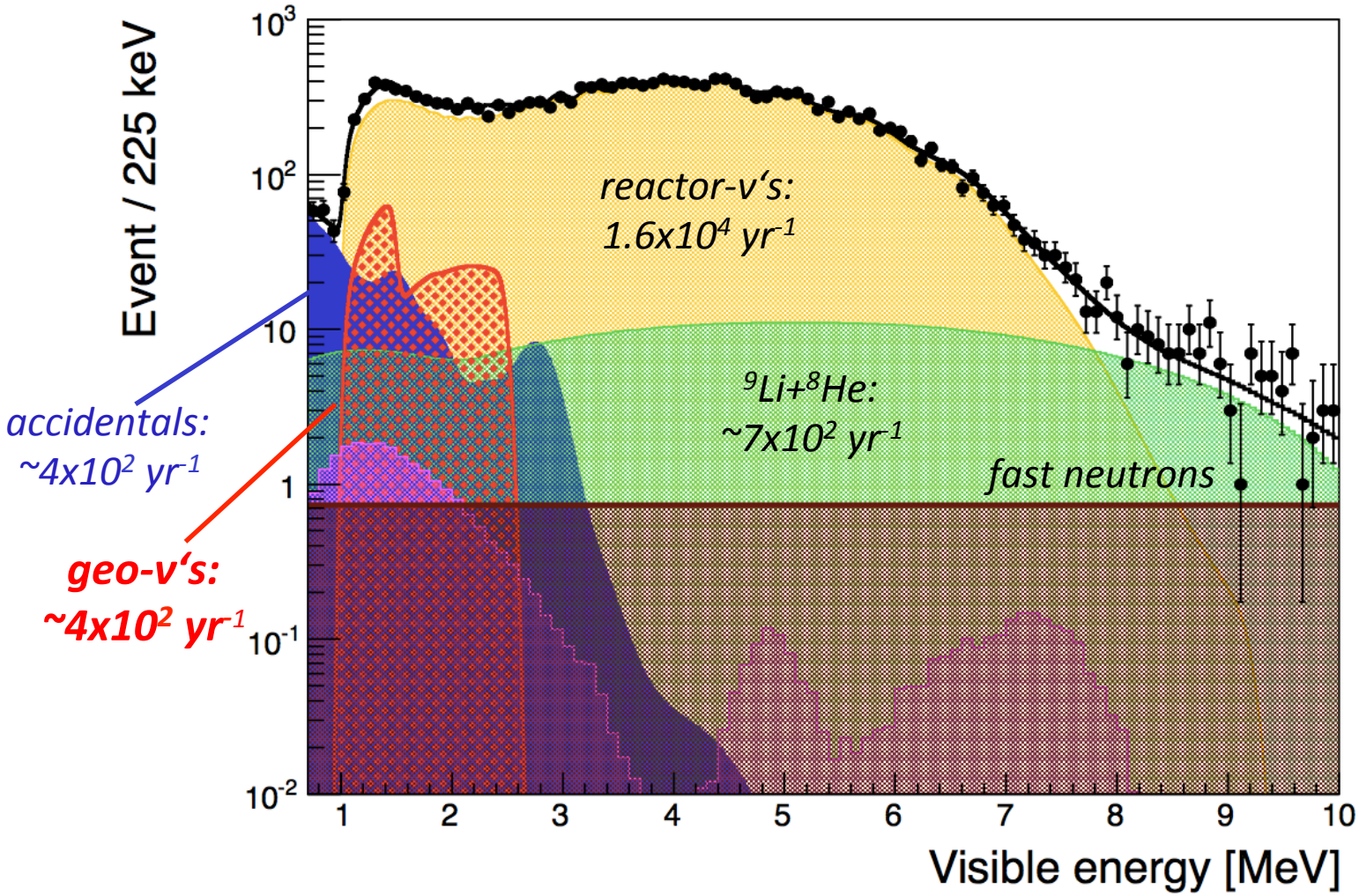
+ direct energy information from CC reaction on ^{13}C: ~25 (kt·yr)$^{-1}$

^{8}B-ν's & cosmogenic BGs in JUNO



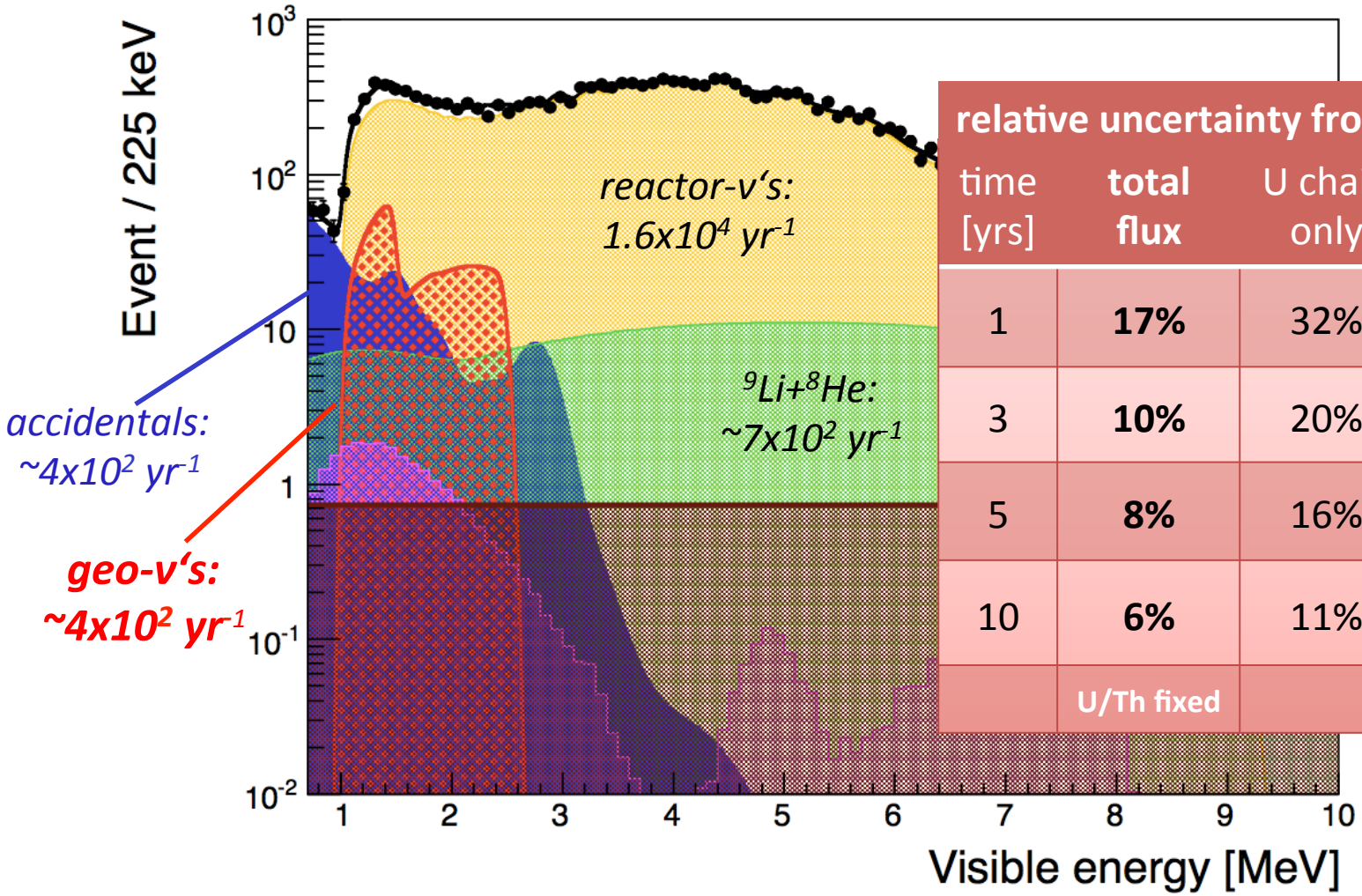
cf. LENA ^{8}B-paper arXiv:1408.0623

Geoneutrino signal in JUNO



- signal dominated by reactor neutrinos (+ other backgrounds)

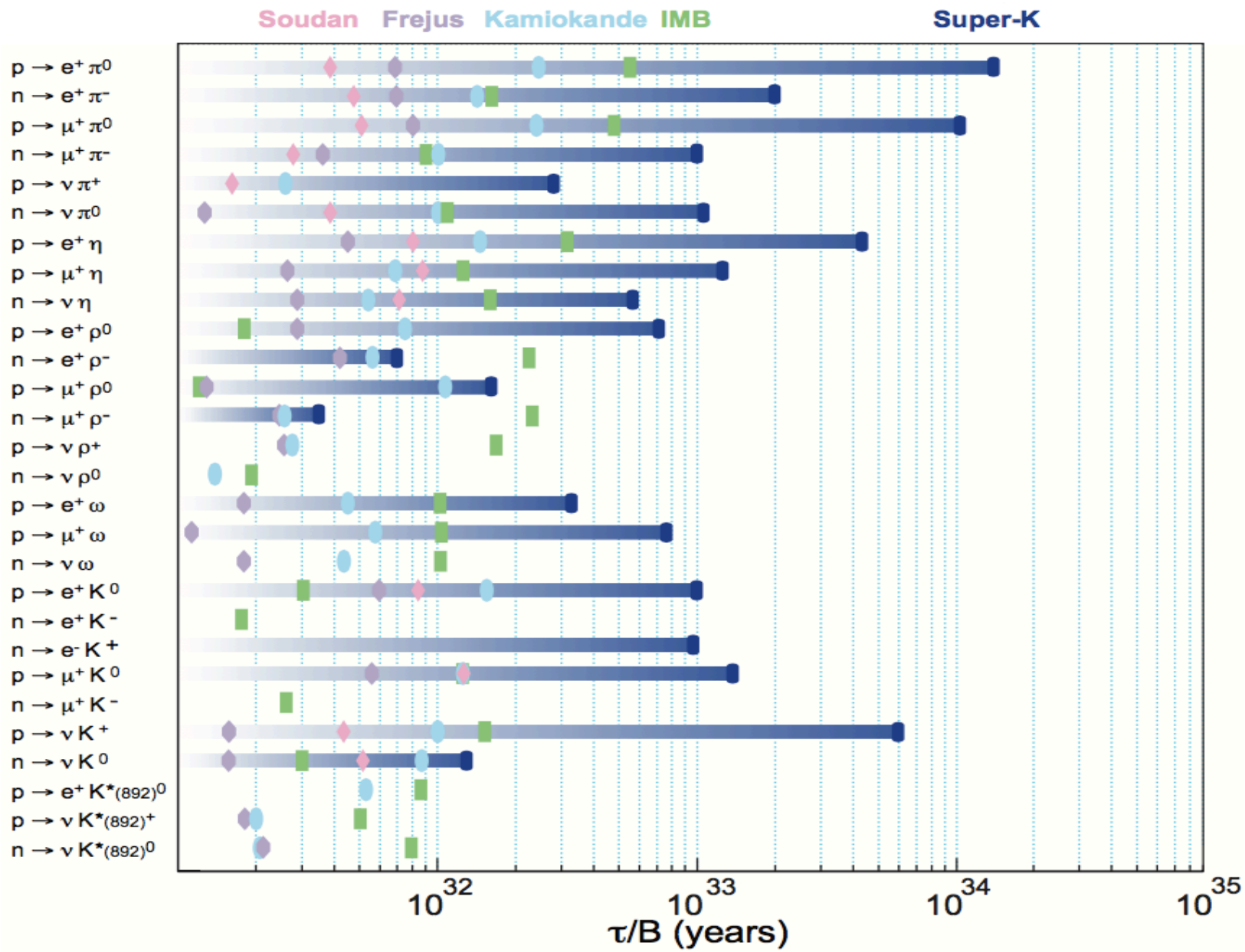
Geoneutrino signal in JUNO



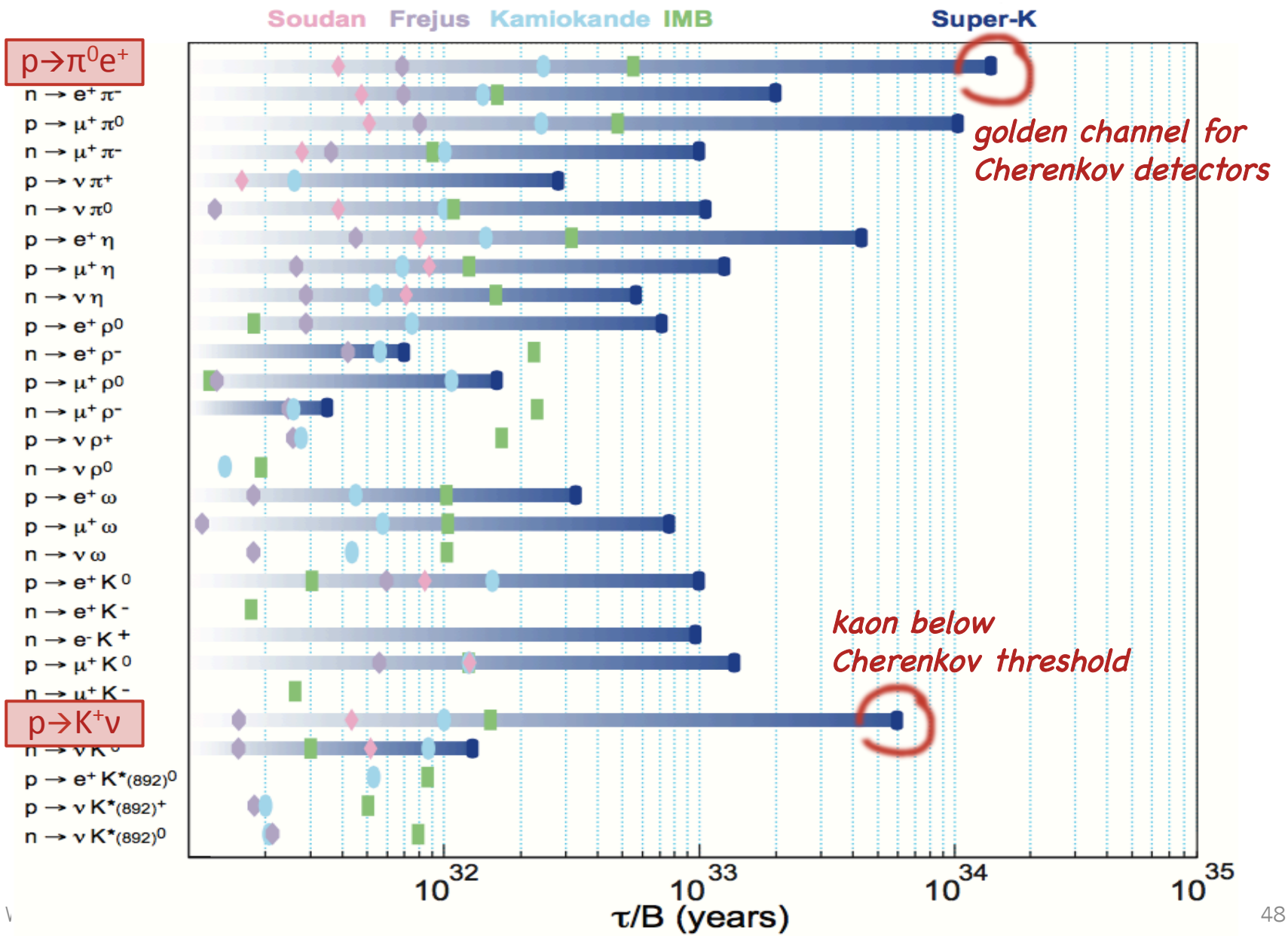
relative uncertainty from spectral fit			
time [yrs]	**total flux**	U chain only	Th chain only
1	**17%**	32%	60%
3	**10%**	20%	38%
5	**8%**	16%	28%
10	**6%**	11%	19%
	U/Th fixed		*syst. shifts*

- signal dominated by reactor neutrinos (+ other backgrounds)
- but: large statistics → information can be extracted by spectral fits

Current nucleon decay limits

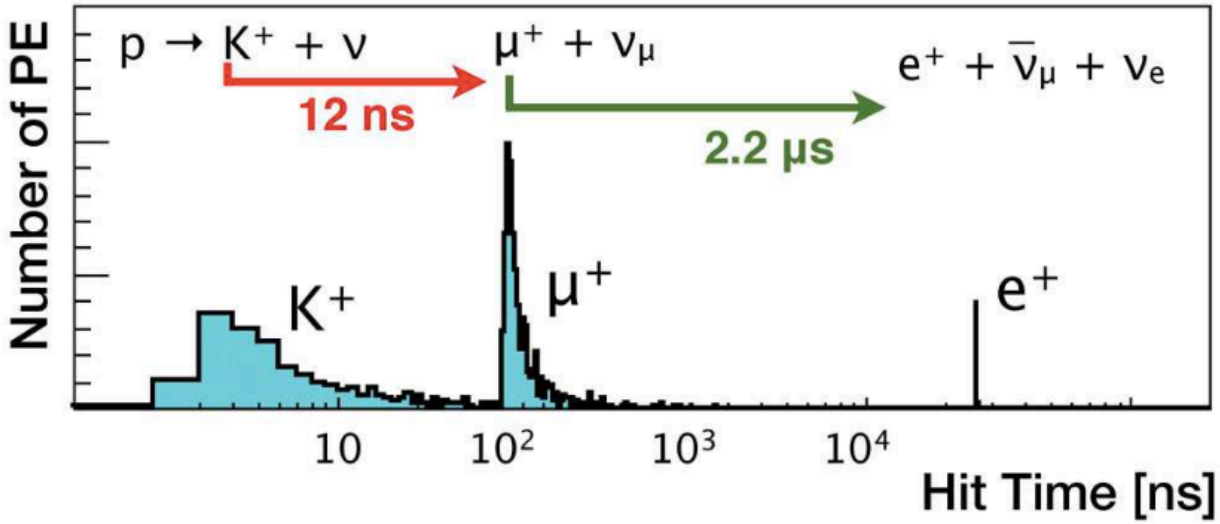


Current nucleon decay limits



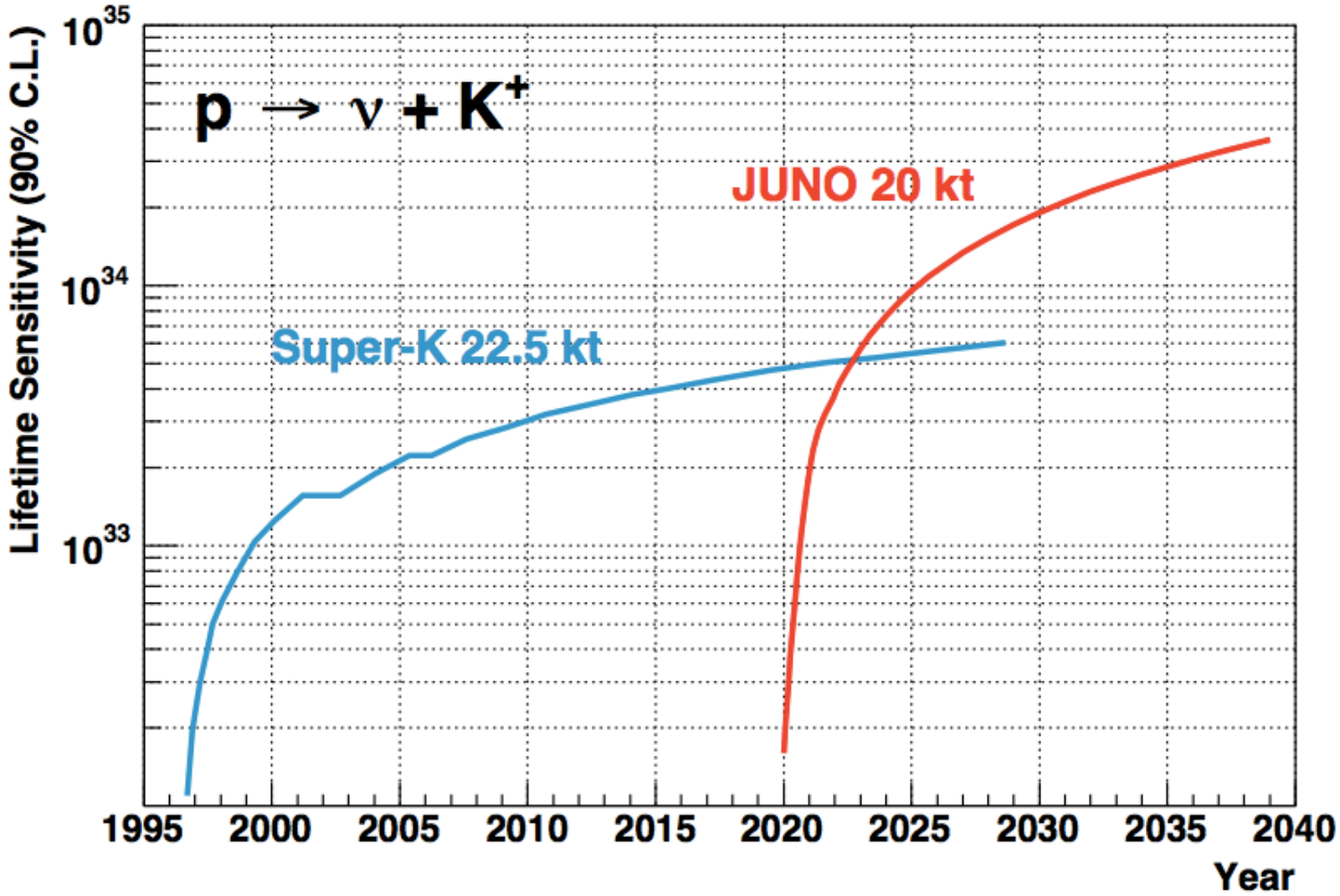
Nucleon decay search in JUNO

- **$p \rightarrow K^+\bar{\nu}$** is golden channel in liquid scintillator
- Distinctive double (triple) signature by kaon & decay products

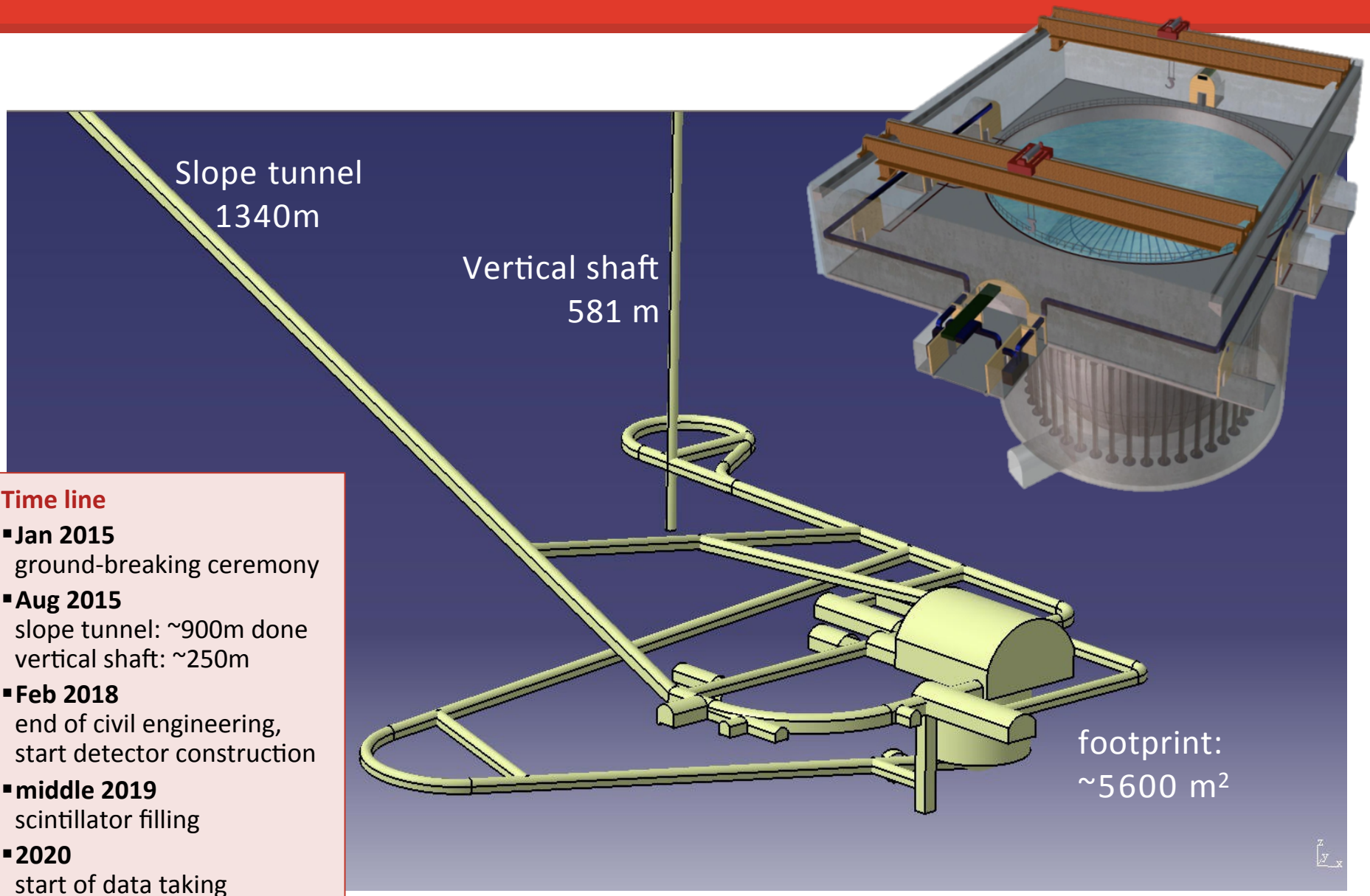


- Primary background: atmospheric neutrino reactions
- After discrimination cuts:
  - Detection efficiency: 65%
  - Remaining background: 0.05 yr^{-1}

Projected proton decay sensitivity



Schedule

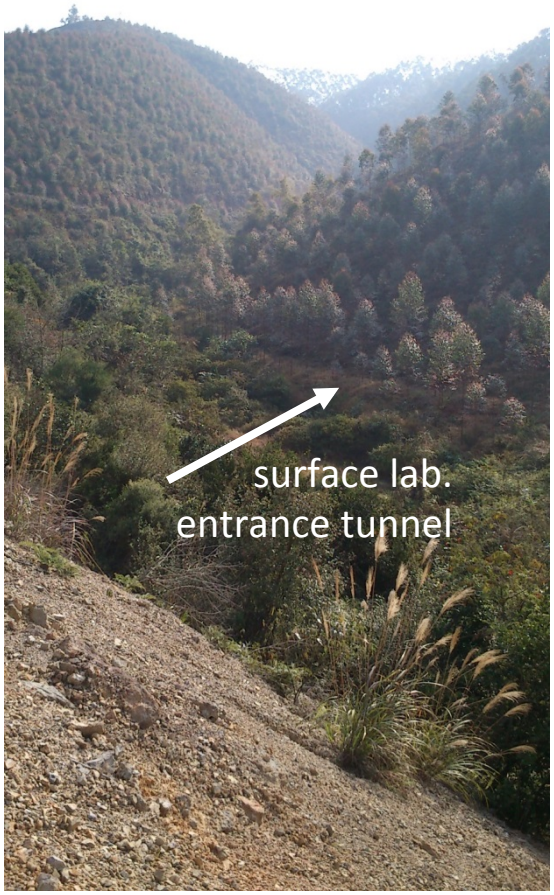


Time line

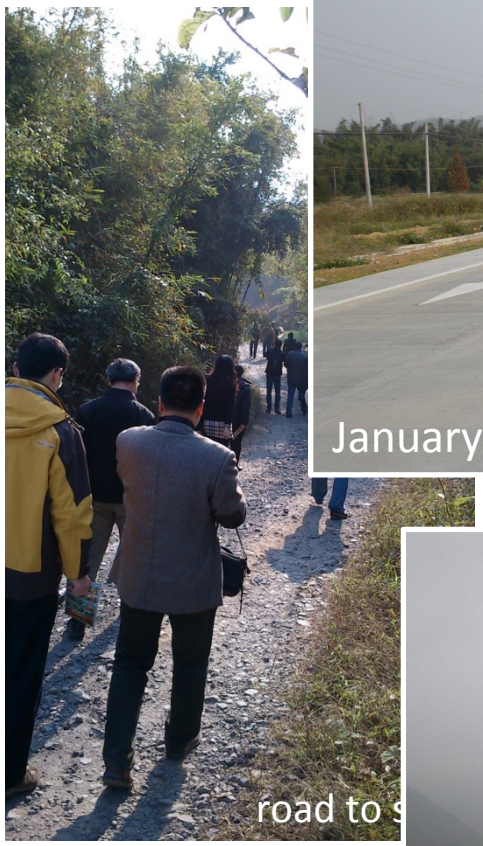
- **Jan 2015**
  ground-breaking ceremony
- **Aug 2015**
  slope tunnel: ~900m done
  vertical shaft: ~250m
- **Feb 2018**
  end of civil engineering,
  start detector construction
- **middle 2019**
  scintillator filling
- **2020**
  start of data taking

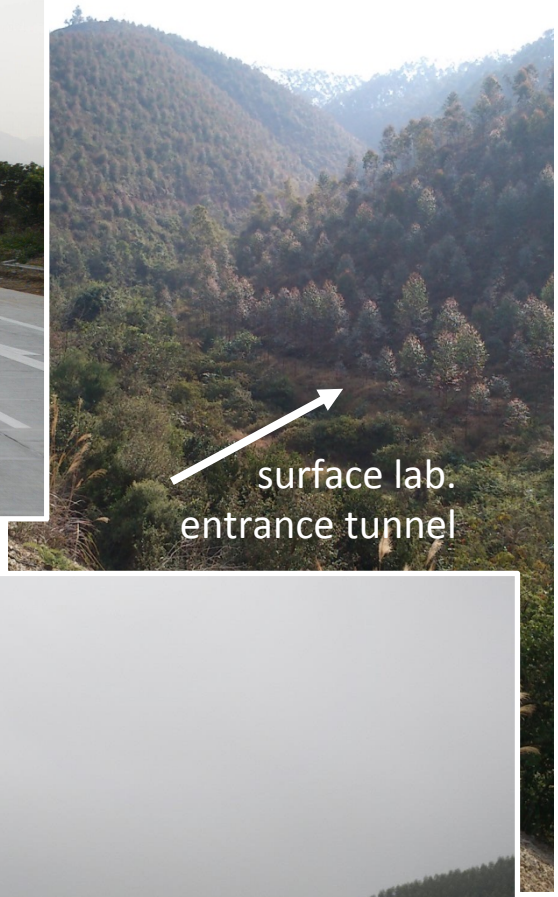
Slope tunnel

Surface facilities



Surface facilities





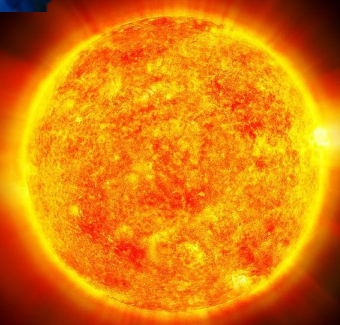
Surface facilities

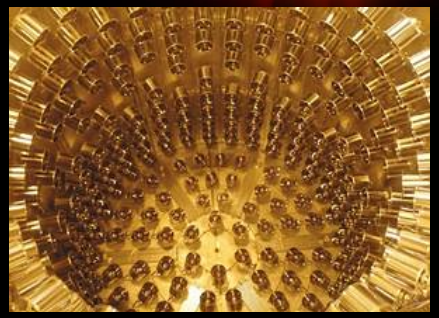
Conclusions

JUNO offers a rich physics program!

→ *Yellow Book, arXiv:1507.05613*

- **Reactor neutrino oscillations**
  - mass hierarchy
  - precise measurement of osc. parameters
- **Neutrinos from natural sources**
  - Galactic Supernova neutrinos
  - Diffuse Supernova Neutrino Background
  - Solar neutrinos
  - Geoneutrinos
  - Neutrinos from dark matter annihilation
  - Atmospheric neutrinos
- **Short-baseline oscillations** (sterile ν's)
- **Proton decay into $K^+\bar{\nu}$**





JUNO Collaboration

380 scientists, 60 institutions, 1/3 from Europe

Armenia, Austria, Belgium, Brazil, Chile, Chinese Republic, Czech Republic, Germany, Finland, France, Italy, Japan, Korea, Russia, Taiwan, and the United States

German institutes

RWTH AACHEN UNIVERSITY

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

JÜLICH FORSCHUNGSZENTRUM

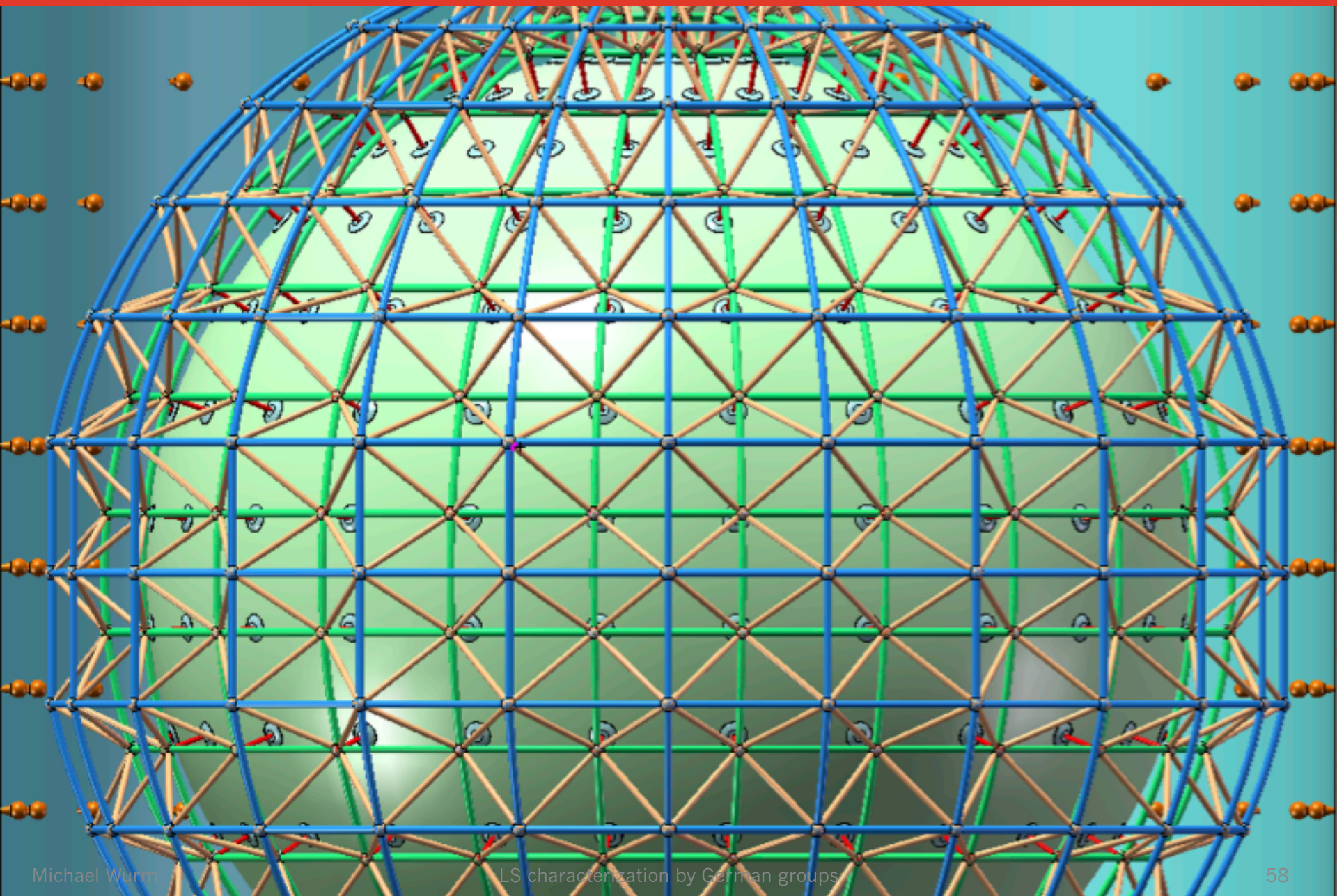
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Technische Universität München

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

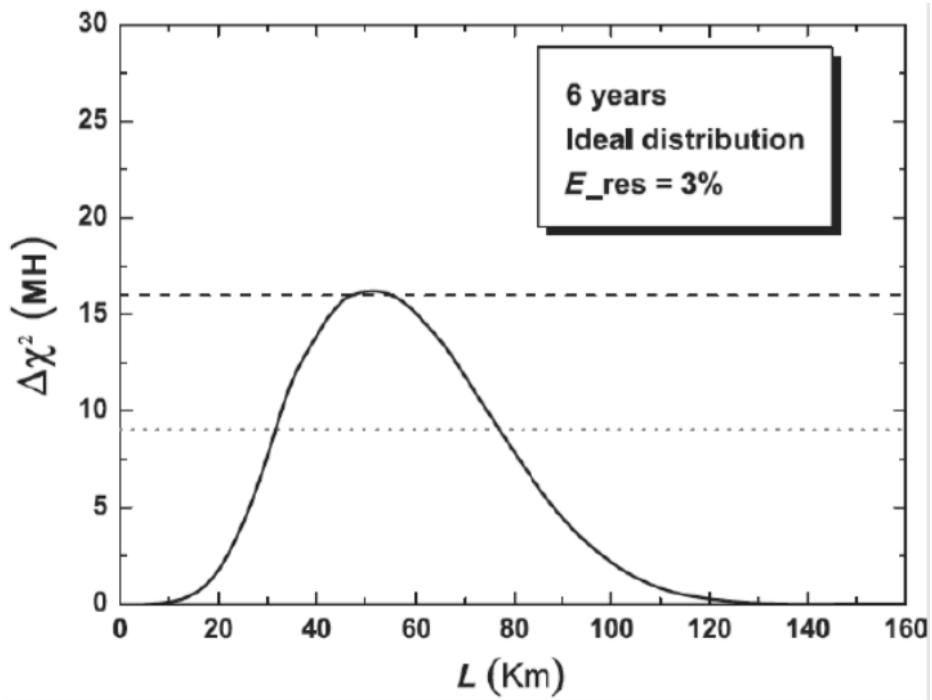
THANKS FOR YOUR ATTENTION!

Backup Slides

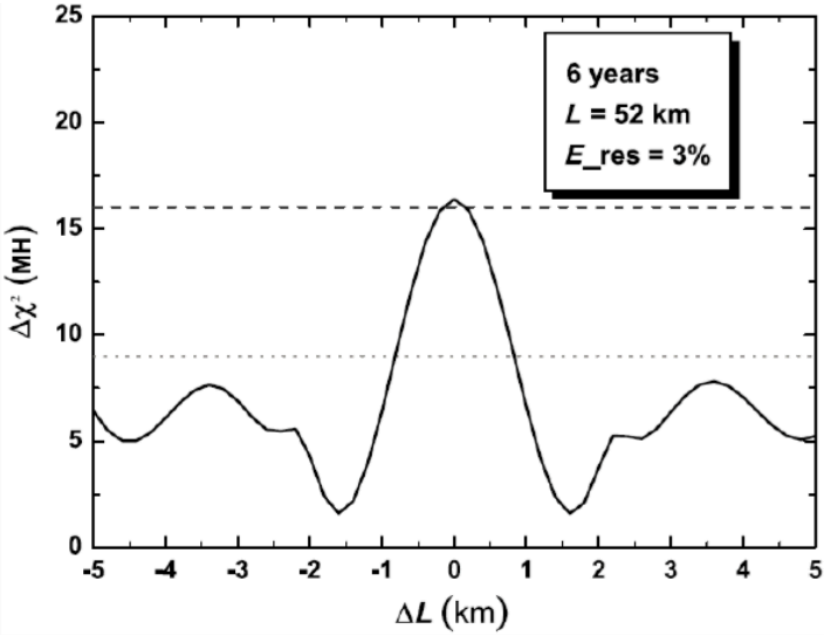


Optimum baseline

Baseline optimization



Difference between baselines to reactor complexes



Non-stochastic terms in E resolution

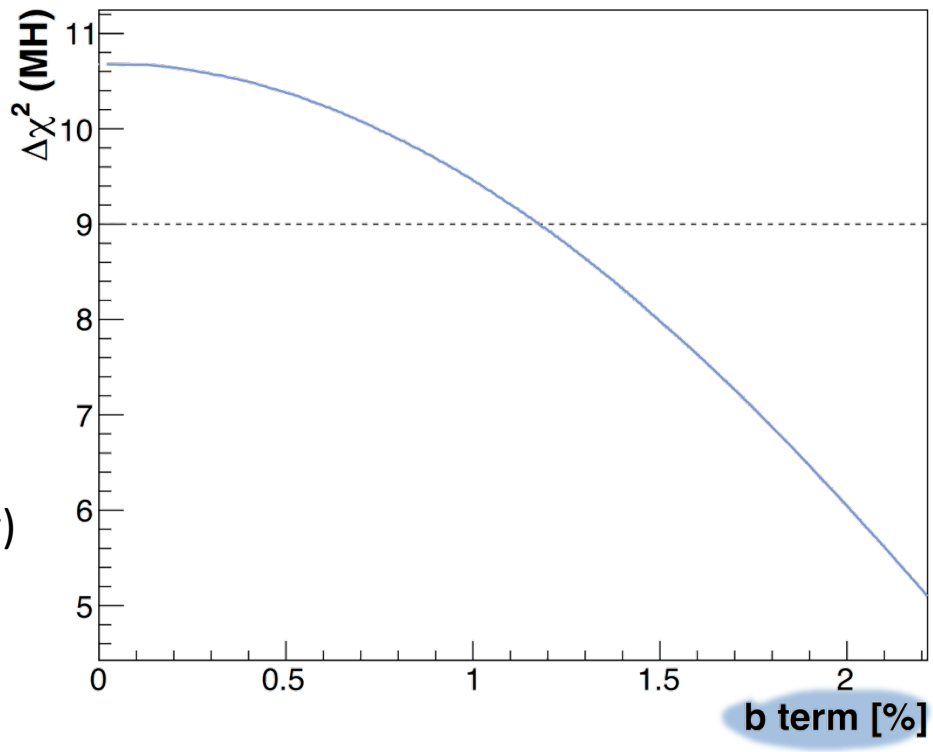
Energy resolution function

$$\frac{\Delta E}{E} = \sqrt{\frac{a^2}{E} + b^2 + \frac{c^2}{E^2}}$$

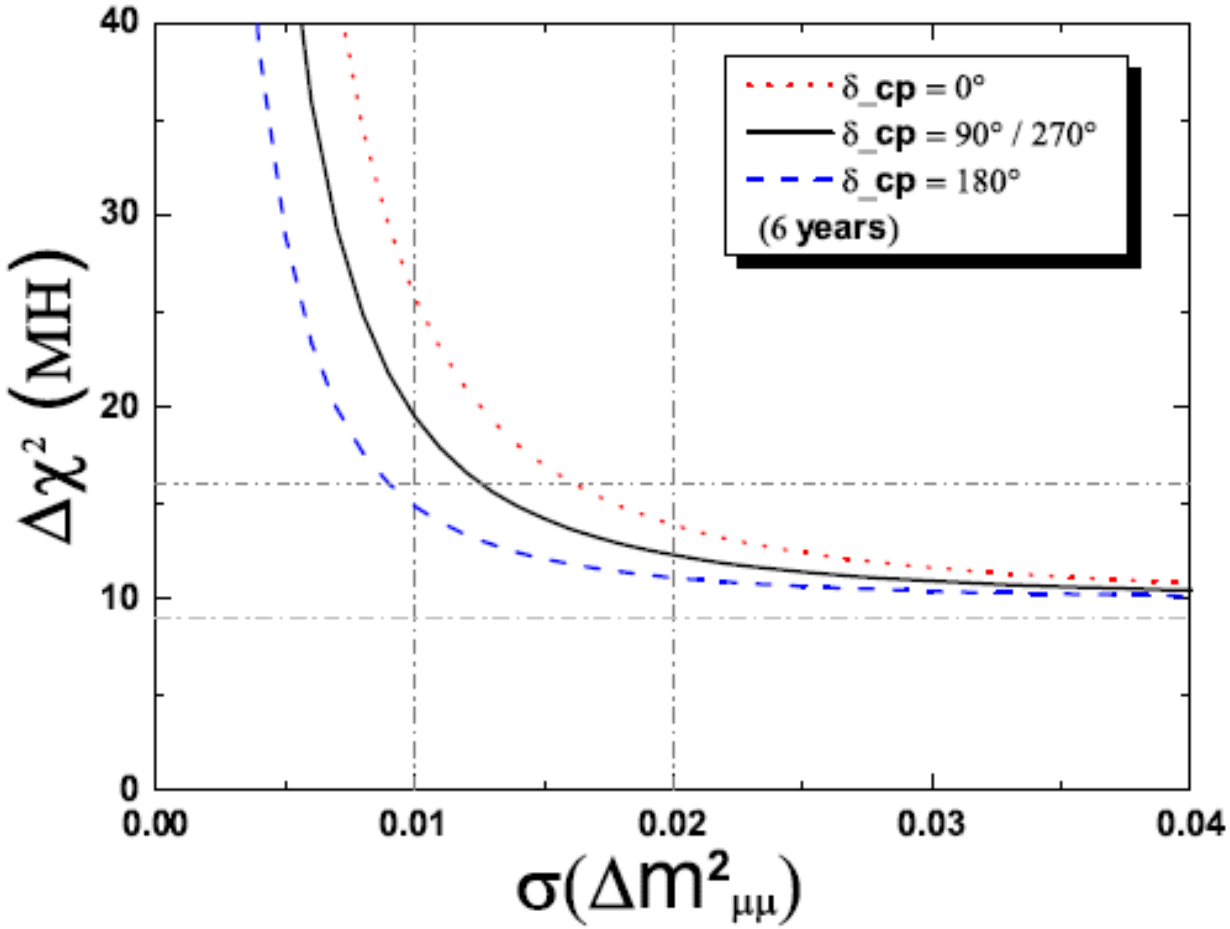
a term:
stochastic term (*photon statistics*)

b & c terms:
systematic contributions (*detector effects*)

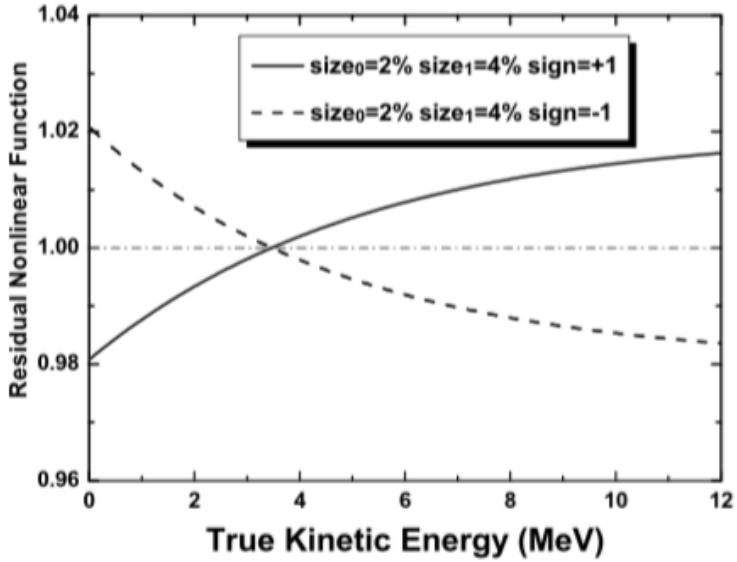
- PMT dark noise
- linearity of electronics
- position reconstruction uncertainty
- ...



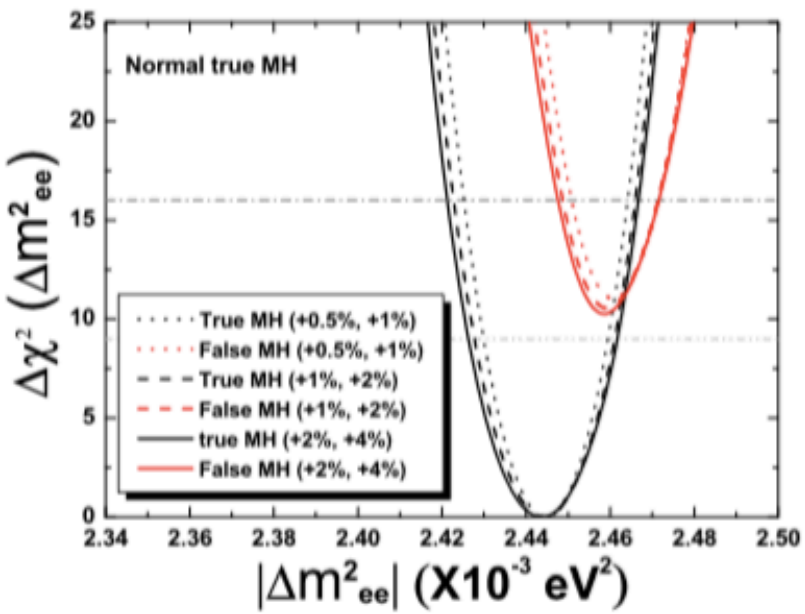
Influence of $\Delta m^2_{\mu\mu}$ accuracy



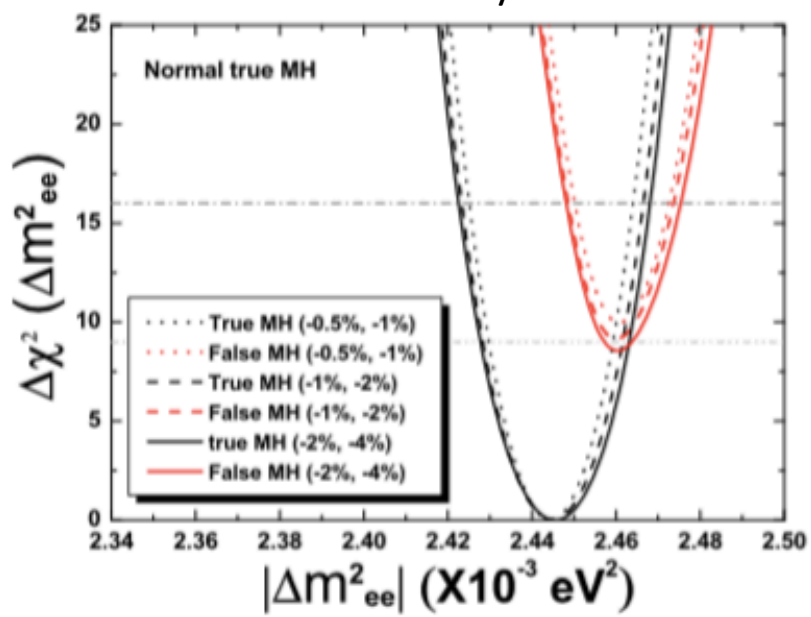
Influence of energy scale linearity



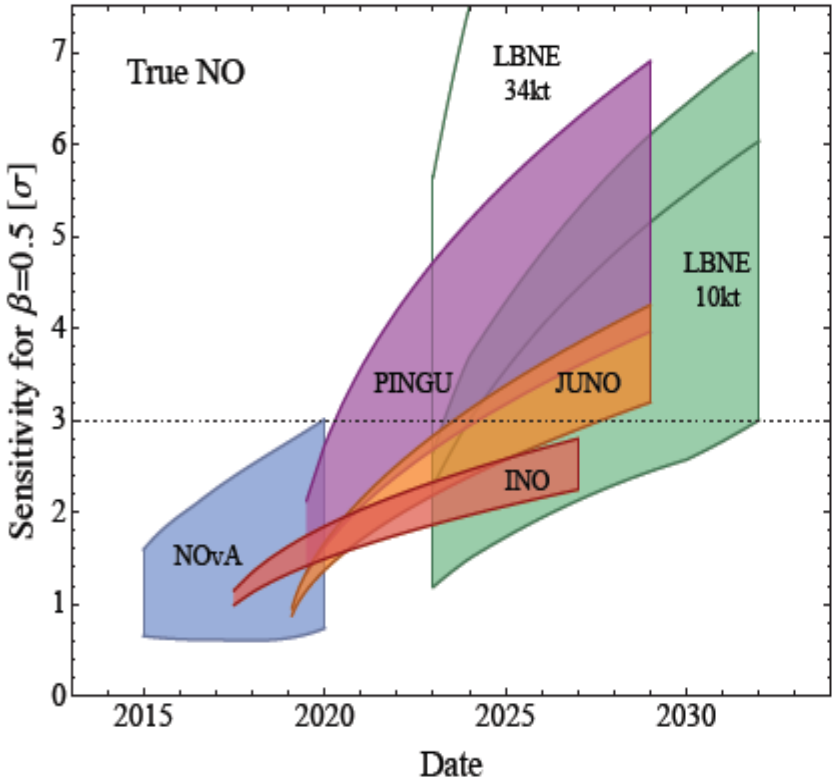
w/o self-calibration

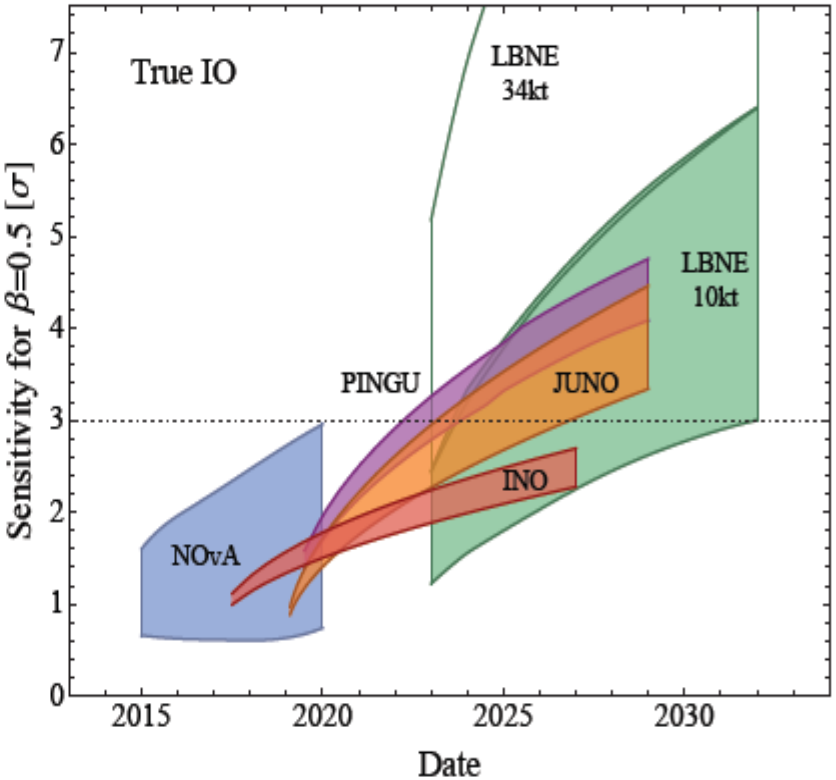


w/ self-calibration



Global effort on mass hierarchy





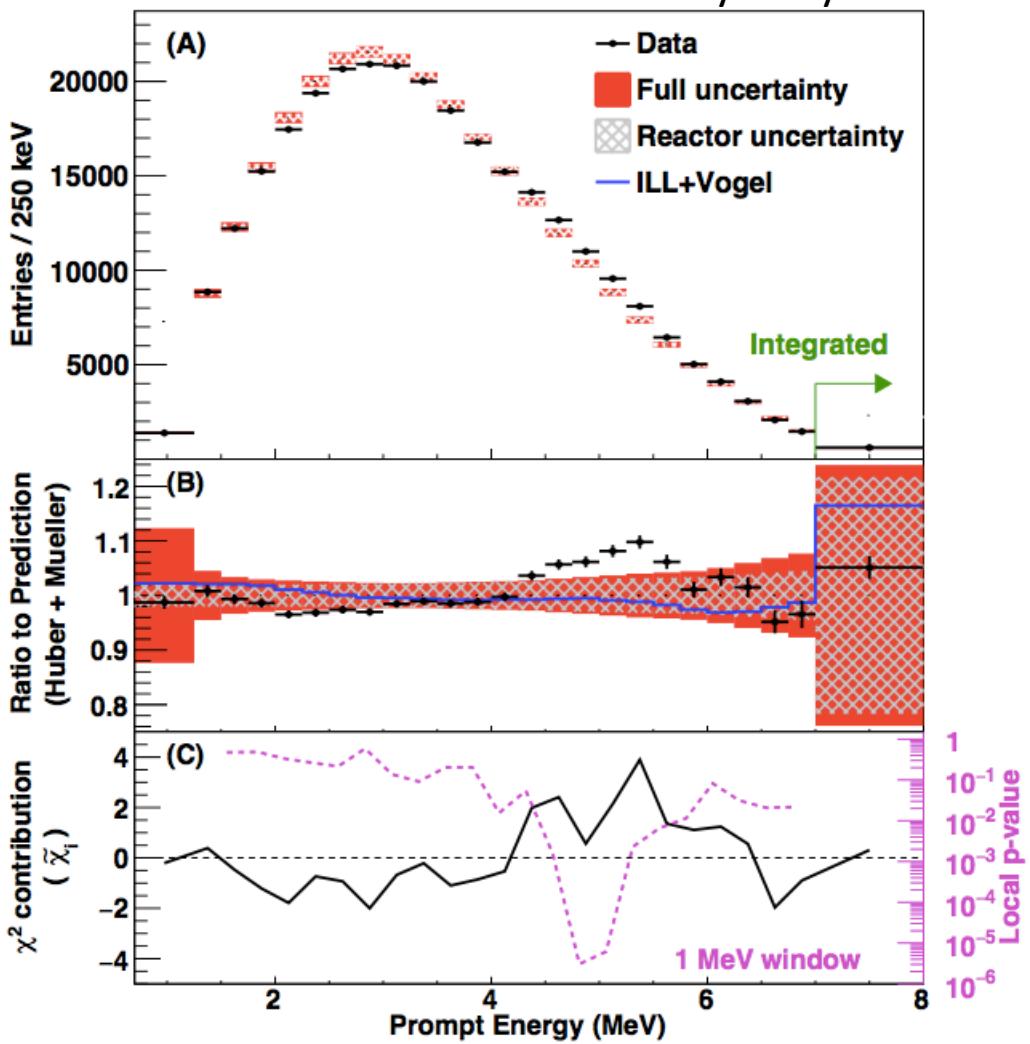
different techniques

- reactor neutrinos: JUNO
- atmospheric ν 's: INO,PINGU,ORCA
- long-baseline beam: LBNE→DUNE

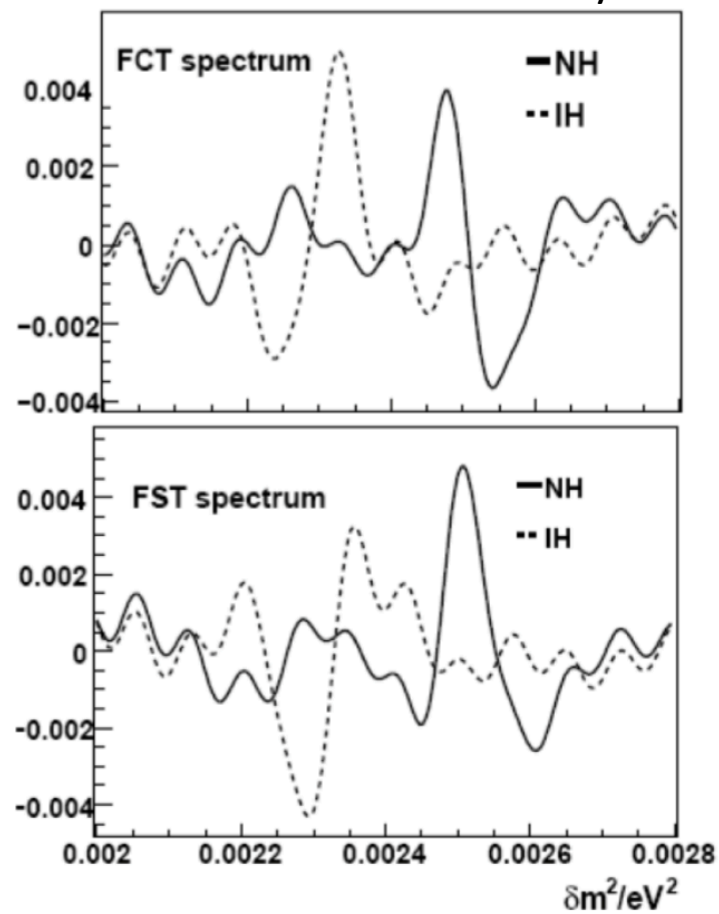
mode	**main uncertainties**
$\nu_e \rightarrow \nu_e$	energy res. (3-3.5%)
$\nu_\mu \rightarrow \nu_\mu$	value of θ_{23}=40-50°
$\nu_\mu \rightarrow \nu_e$	value of δ_{CP}

Reactor anomaly: 5 MeV bump

Daya Bay ND

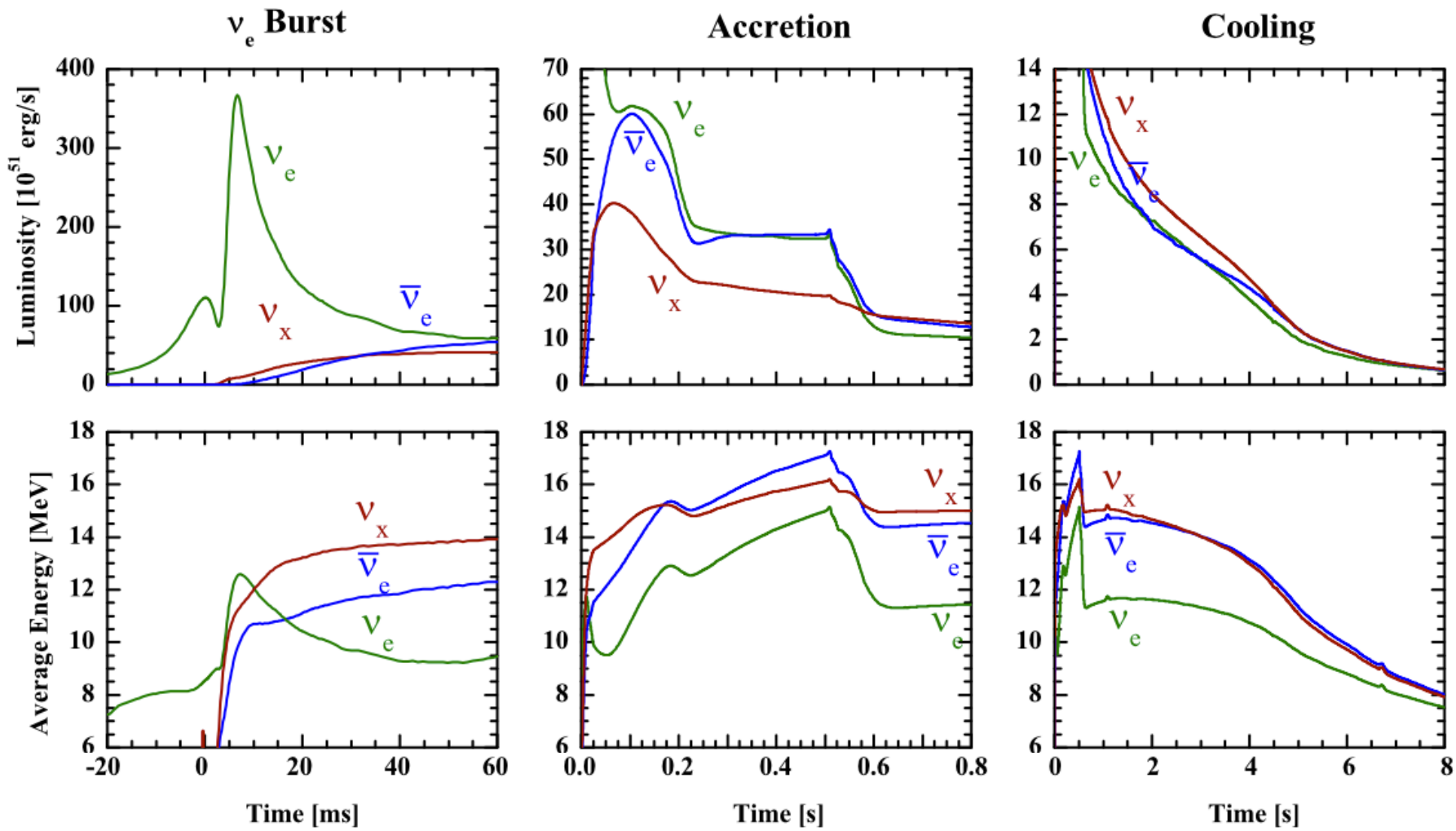


MH Fourier analysis



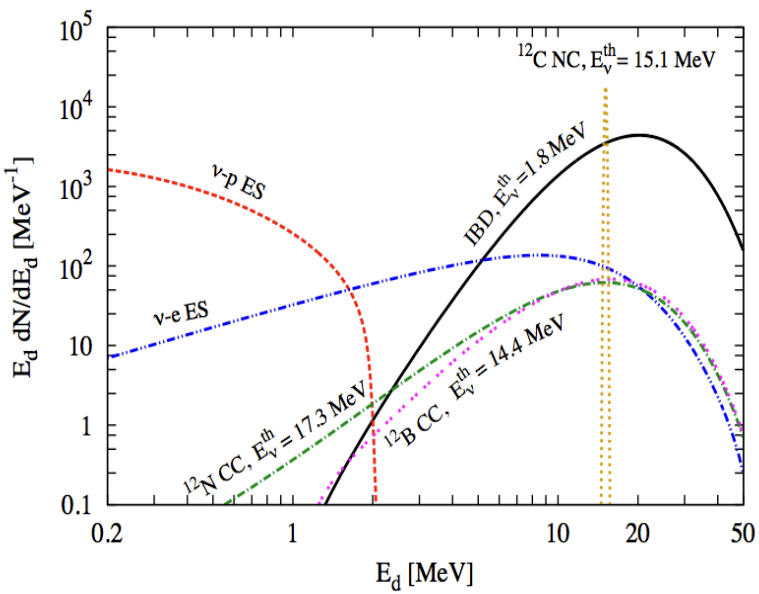
J. Learned et. al. Hep-ex/0612022

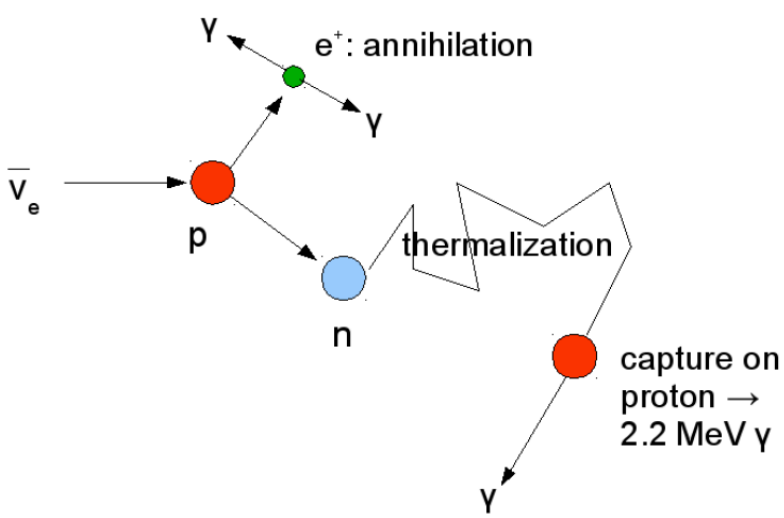
Supernova neutrino emission



based on spherically symmetric Garching model ($27M_\odot$, explosion triggered by hand after 0.5ms)

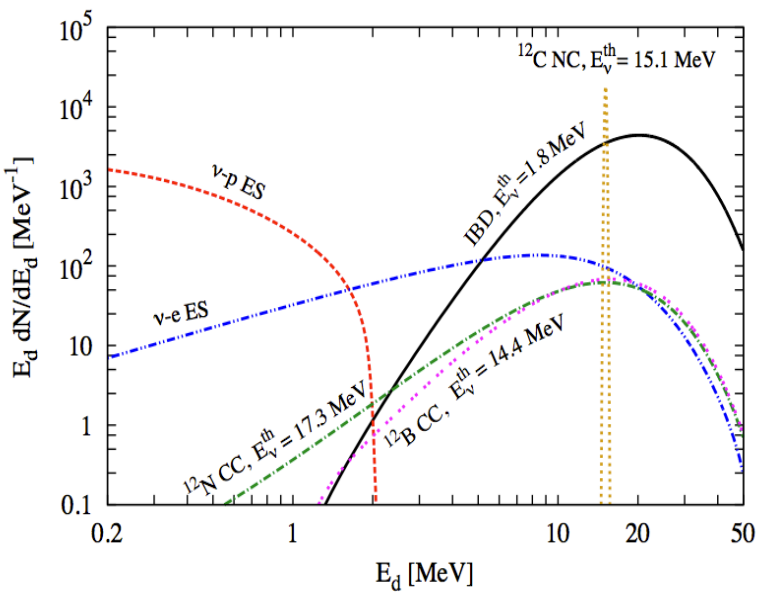
Inverse beta decay





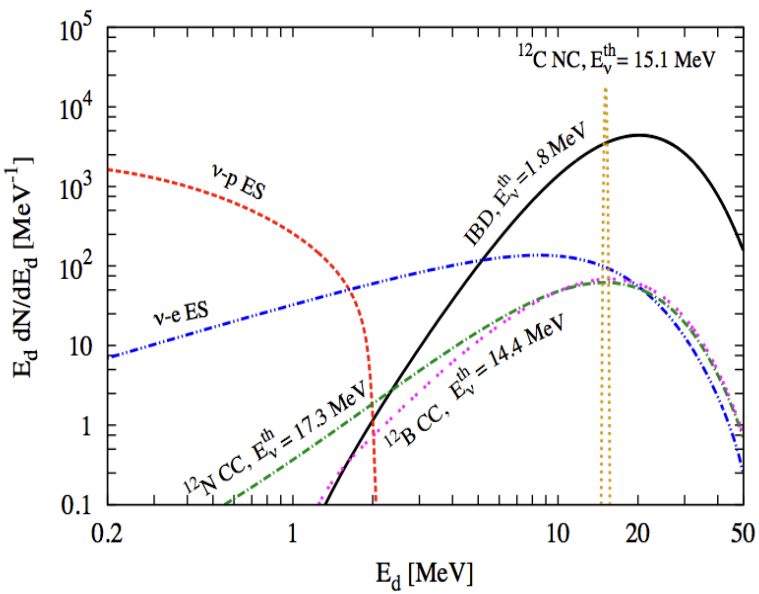
- Coincidence signal
  - $\bar{\nu}_e + p \rightarrow n + e^+$
  - $n + p \rightarrow d + \gamma$ [2.2 MeV]
- threshold: 1.8 MeV
- prompt event: energy info
- delayed event: tagging (~250μs)
- “Golden” channel: ~5000 events
- provides directionality:
  - average displacement of positron and neutron vertex
  - resolution: ~9°

Charged-current reactions on carbon



- Coincidence signal
  - $\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N} + e^-$
    ${}^{12}\mathrm{N} \rightarrow {}^{12}\mathrm{C} + e^+ + \nu_e$
  - $\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B} + e^+$
    ${}^{12}\mathrm{B} \rightarrow {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$
- thresholds: 17.3 MeV / 14.4 MeV
- prompt event: energy info
- re-decay half-lifes: 11 ms / 20 ms
  - event tagging is possible
  - channels can be separated by 2-dim fit to spectrum/dt
- information on ν_e spectrum!

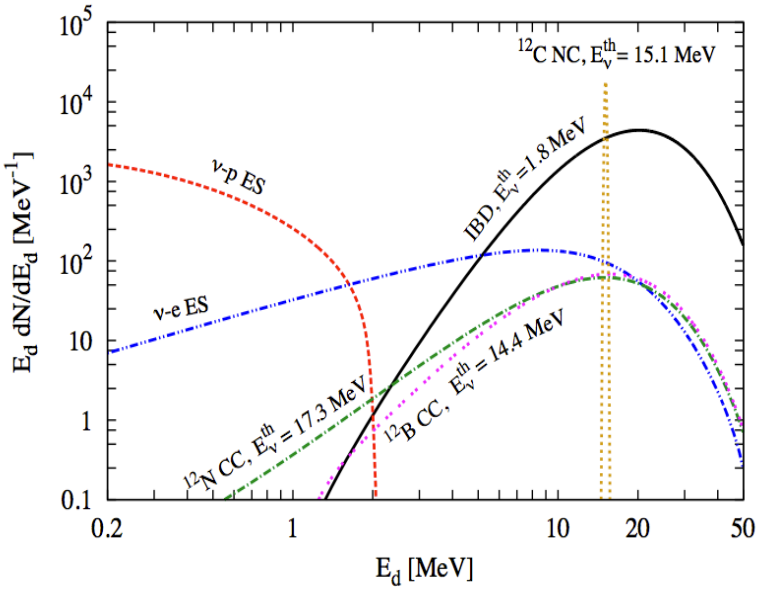
Neutral-current reaction on carbon



- In-elastic scattering
  - $\nu + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu$
  - ${}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma\ [15.1\,\mathrm{MeV}]$
- threshold: 15.1 MeV
- selection by HE gamma decay peak
- no energy information **but**
- cross-section identical for all flavors

→ flavor-independent flux information

Elastic scattering on electrons

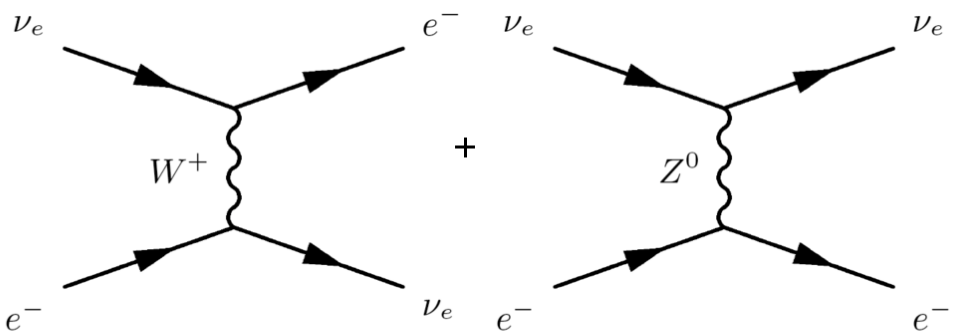


- Recoil electron from
  - $\nu + e^- \rightarrow e^- + \nu$
- no threshold
- some energy information
- no coincidence, broad spectrum

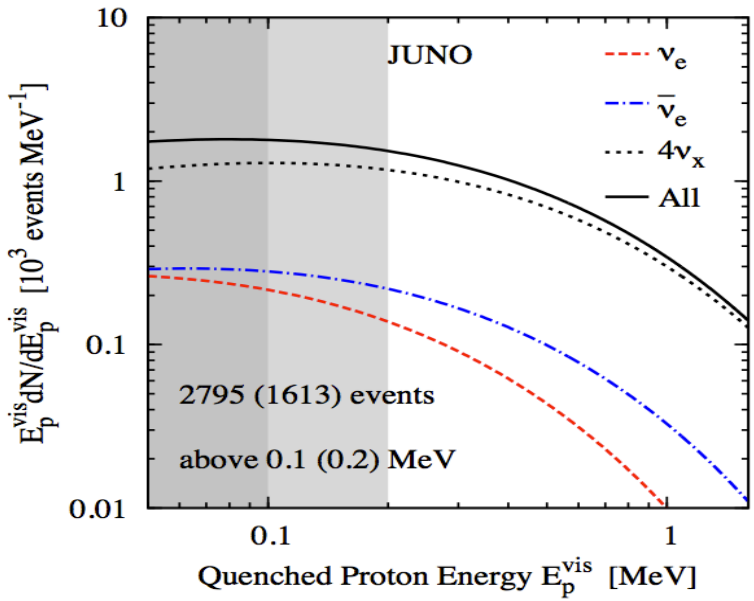
→ untagged events at high energies

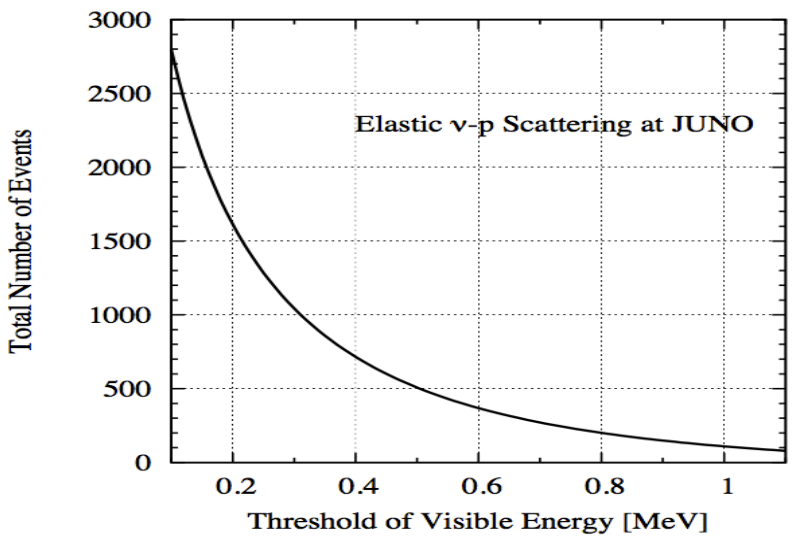
- largest cross-section for ν_e

→ spectral information for ν_e



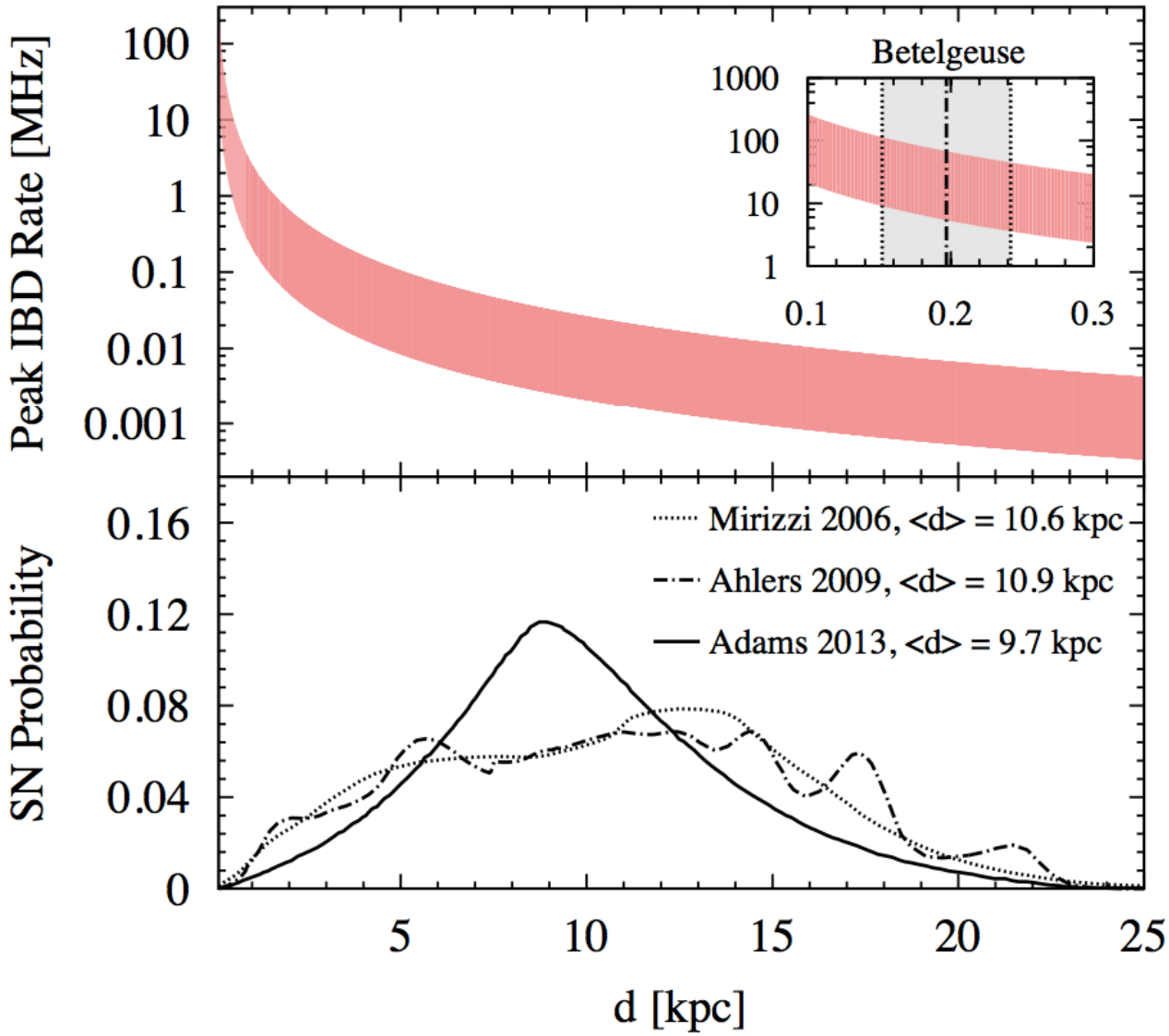
Elastic scattering on protons



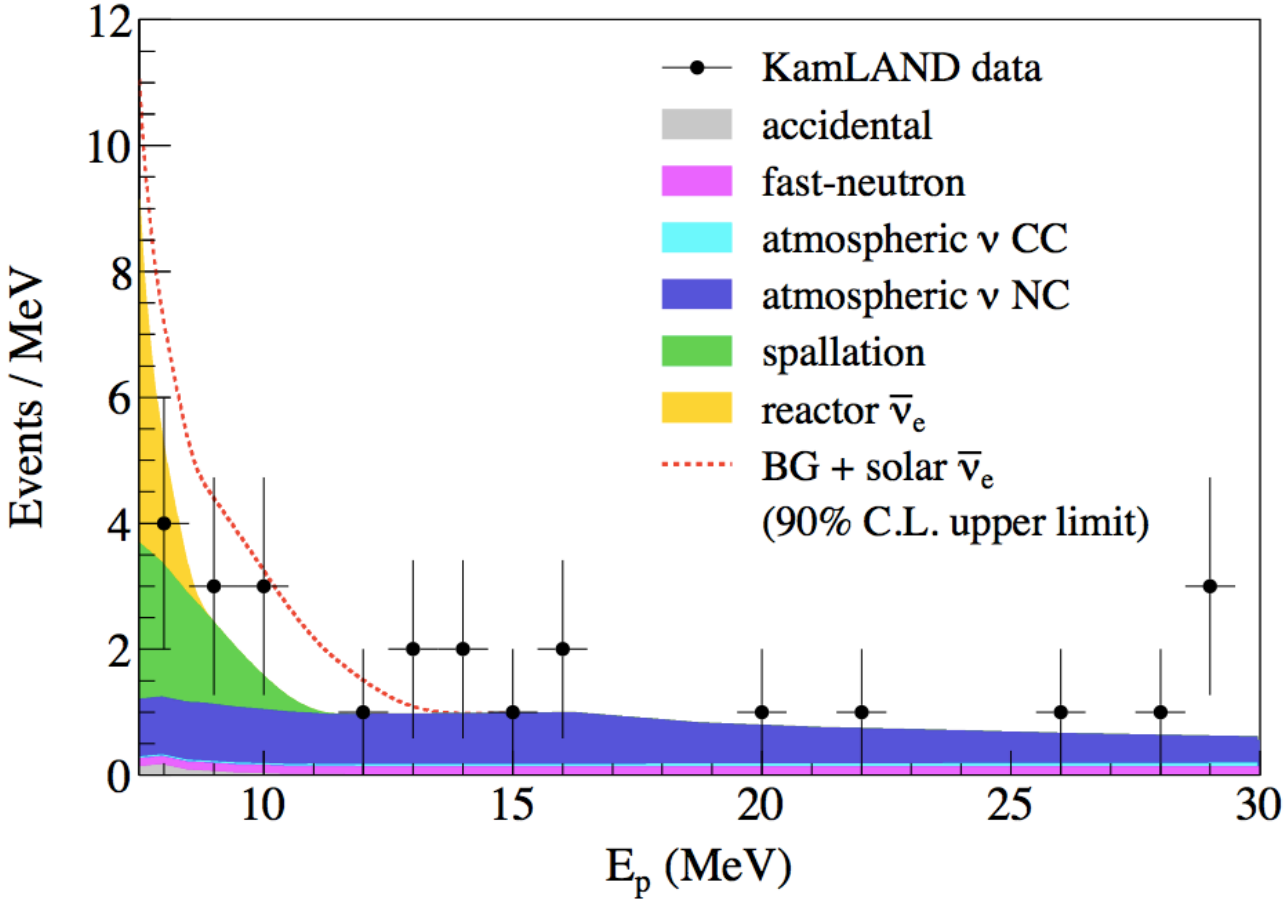


- Recoil protons from
  - $\nu + p \rightarrow p + \nu$
- cross-sections same for all flavors
  → rate dominated by ν_μ and ν_τ
- kinematics
  - no energy threshold, but
  - proton mass >> neutrino energy
    → inefficient energy transfer
- protons feature high dE/dx
  → quenched in liquid scintillator
- total reaction rate very sensitive to detection threshold
- depends on
  - trigger threshold (PMT dark rate)
    → selection by event topology
  - intrinsic rate of ^{14}C decays

Neutrino rates vs. SN distance



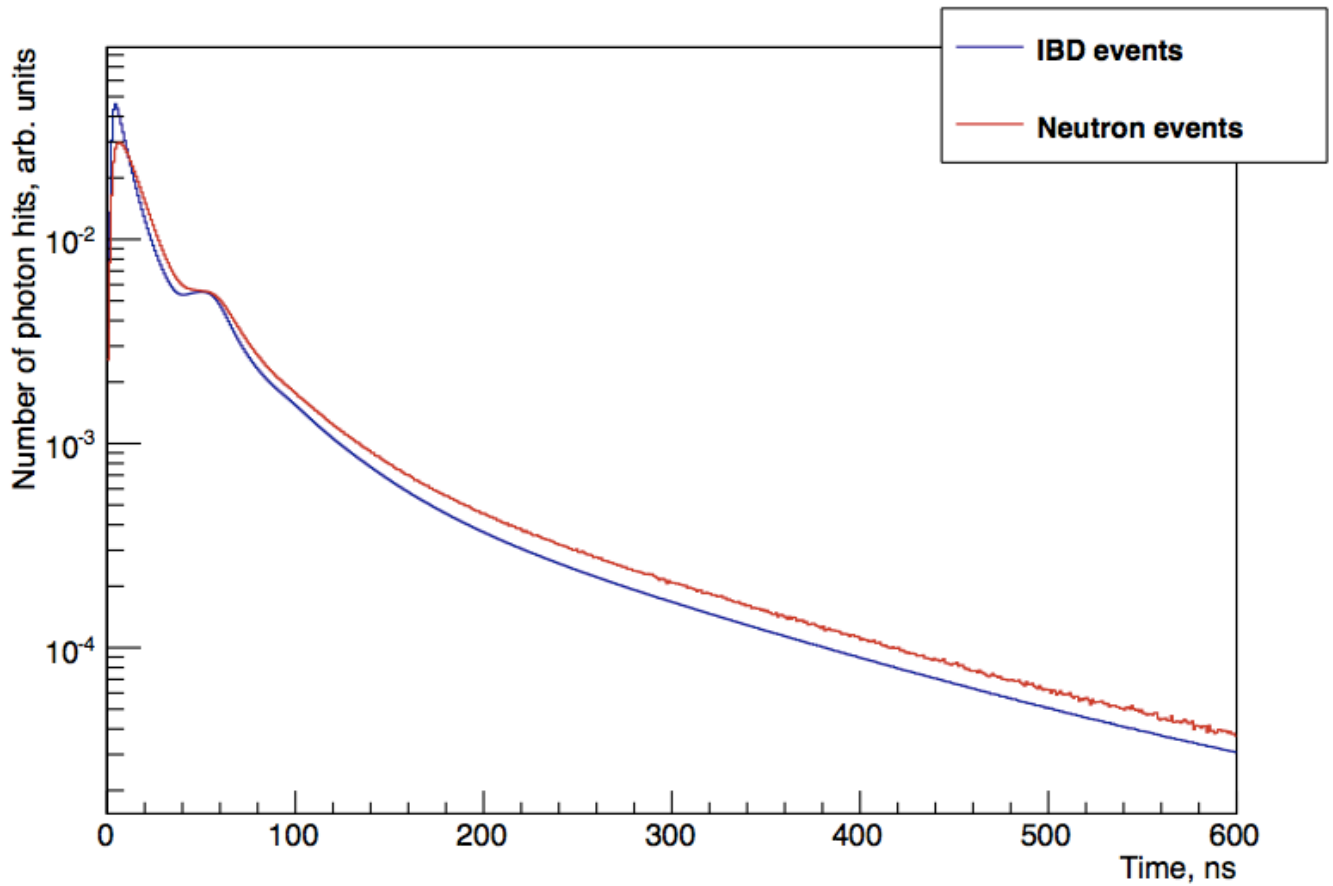
Background found by KamLAND



Primary backgrounds from 10 to 30 MeV

- **fast neutrons**
- **atmospheric neutrino NC reactions**

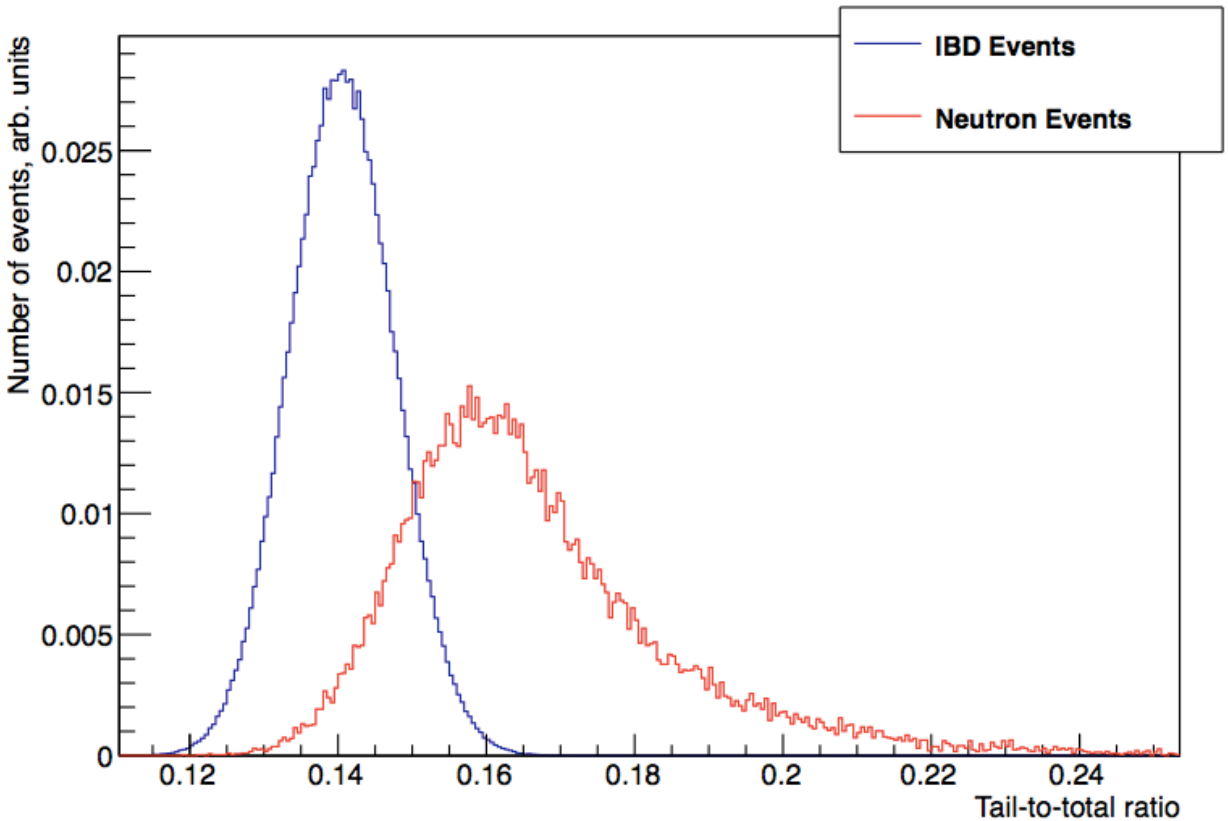
Pulse-shape discrimination (PSD) I



based on LENA MC:

- same scintillator (LAB + 3g/l PPO + 20 mg/l bisMSB)
- lower photoelectron yield: 250 pe/MeV
- better PMT timing: ~1ns (1 σ)

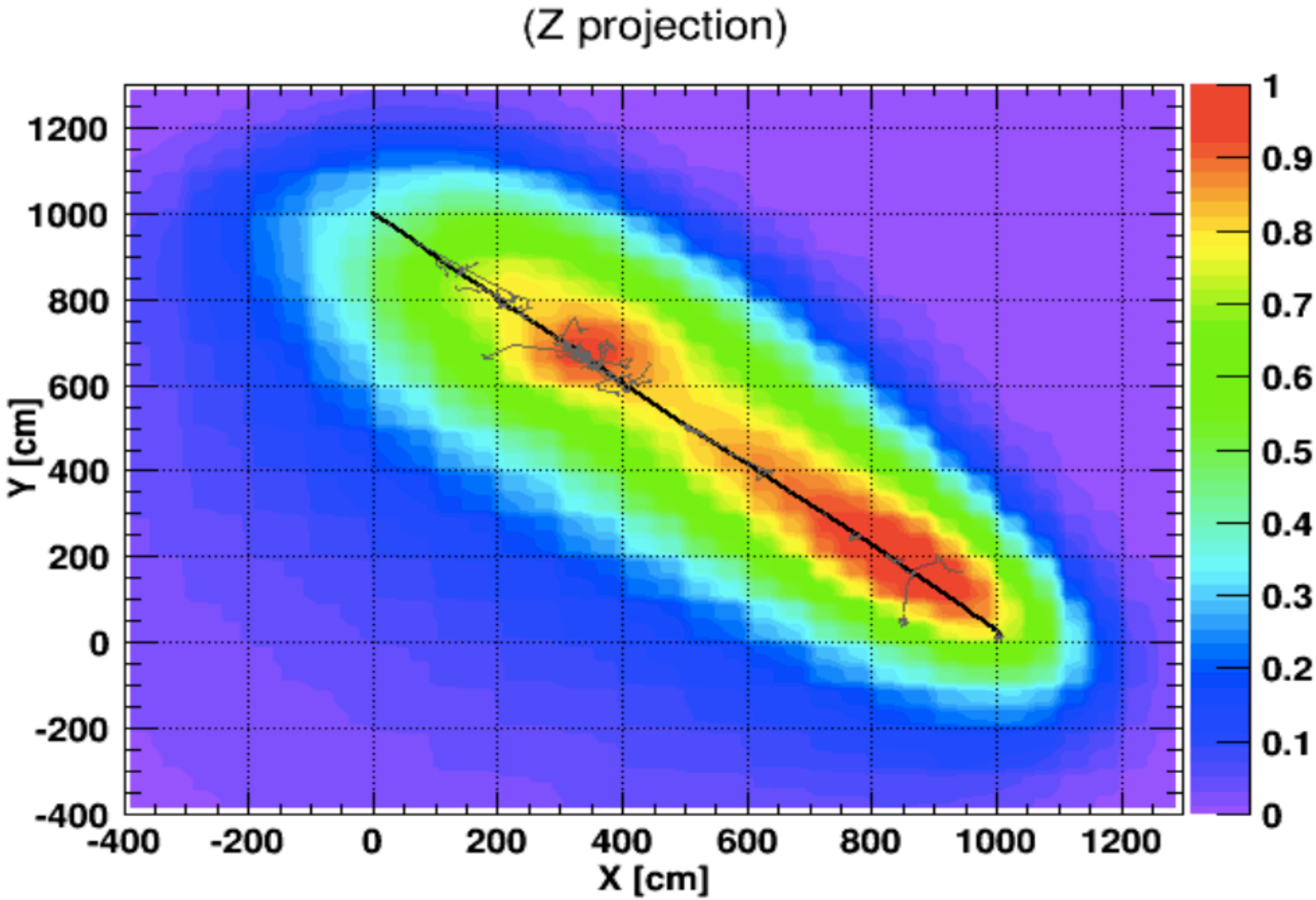
Pulse-shape discrimination (PSD) II



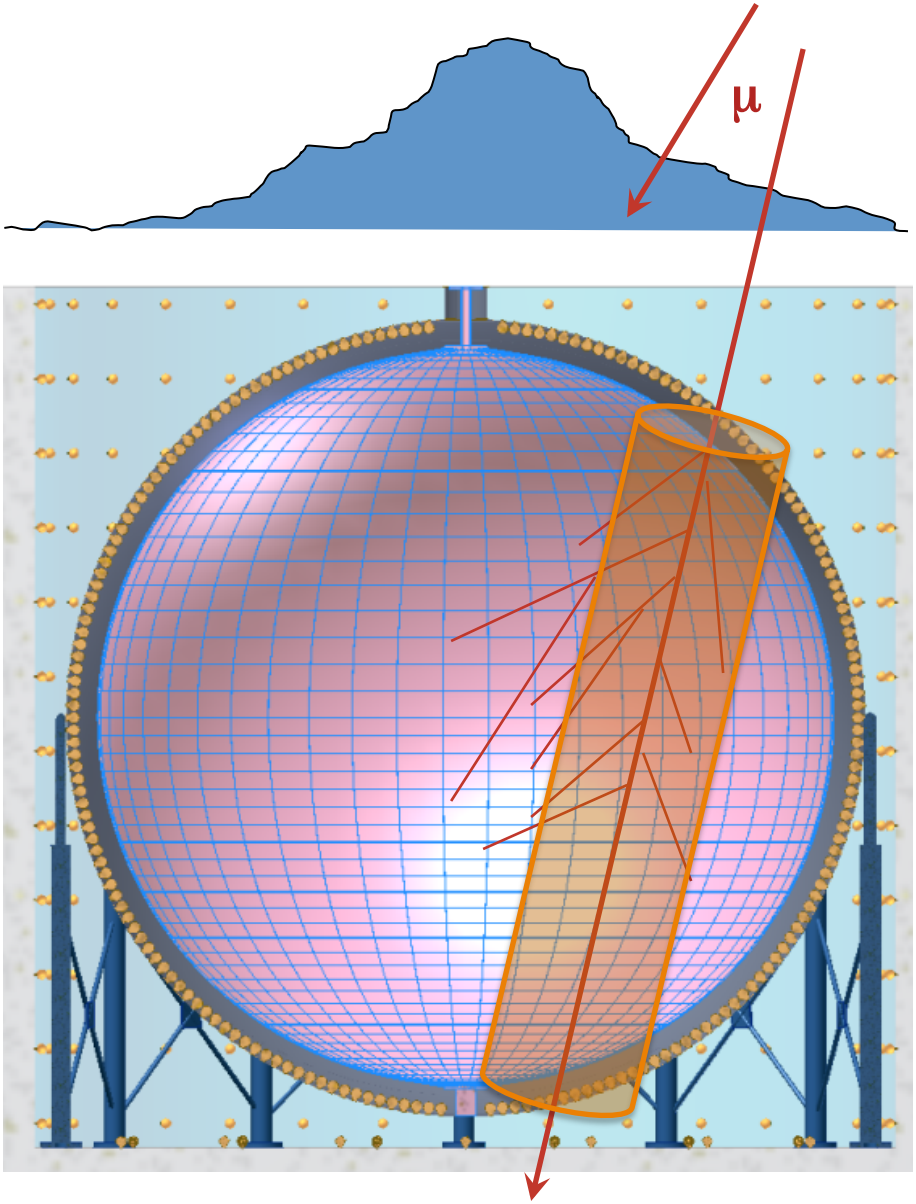
IBD Acceptance	FN Rejection
95%	15.7%
90%	8.2%
80%	4.8%
55%	2.2%
50%	1.9%
40%	1.5%

- based on tail-to-total ratio (&Gatti par)
- for 50% acceptance:
  DSNB rate: 0.7–1.9 yr^{-1}, BG rate: 0.6 yr^{-1}

Reconstruction of track topology in LS



Muon veto vs. live exposure



Loss in exposure induced by current veto strategy: **20%**
(time+cylindrical cut around μ track)

Strategies to recover exposure

- identification of showering muons
- μ track reco including local dE/dx
- tracking in muon bundles
- tagging based on neutron showers
- likelihood-based veto
- electron-positron discrimination

→ significant improvement expected

→ German groups can profit from considerable experience in Borexino, Double-Chooz, LENA ...