JUNO

(solar$\oplus$atmospheric oscillations)

AAP-Conference @ APC (Paris, France)
December 2014

Anatael Cabrera

CNRS / IN2P3 @ APC (Paris)

Jiangmen Underground Neutrino Observatory

news!!!

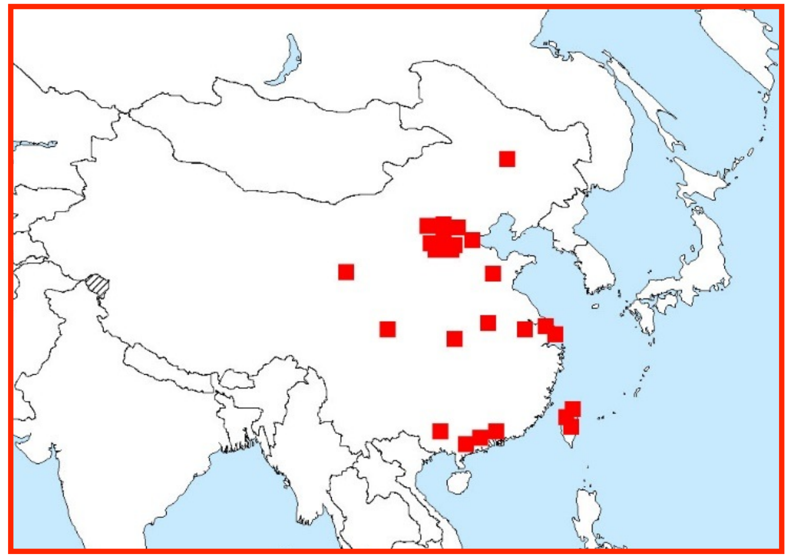
China to build a huge underground neutrino experiment

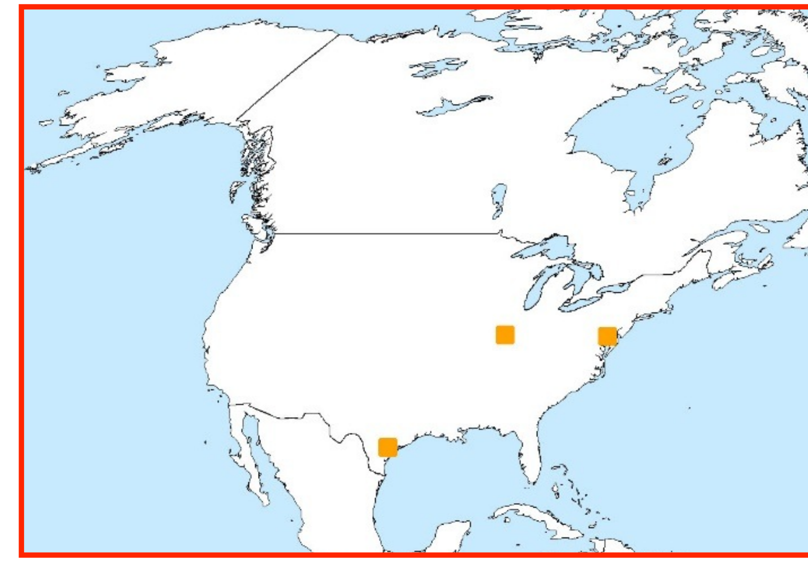
Mar 24, 2014 5 comments

Test site for the Jiangmen Underground Neutrino Observatory

"Work has started on a huge underground neutrino lab in China. The $330m Jiangmen Underground Neutrino Observatory (JUNO) is being built in Kaiping City, Guangdong Province, in the south of the country around 150 km west of Hong Kong. When complete in 2020, JUNO is expected to run for more than 20 years, studying the relationship between the three types of neutrino: electron, muon and tau."

JUNO Collaboration





Europe (20)

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

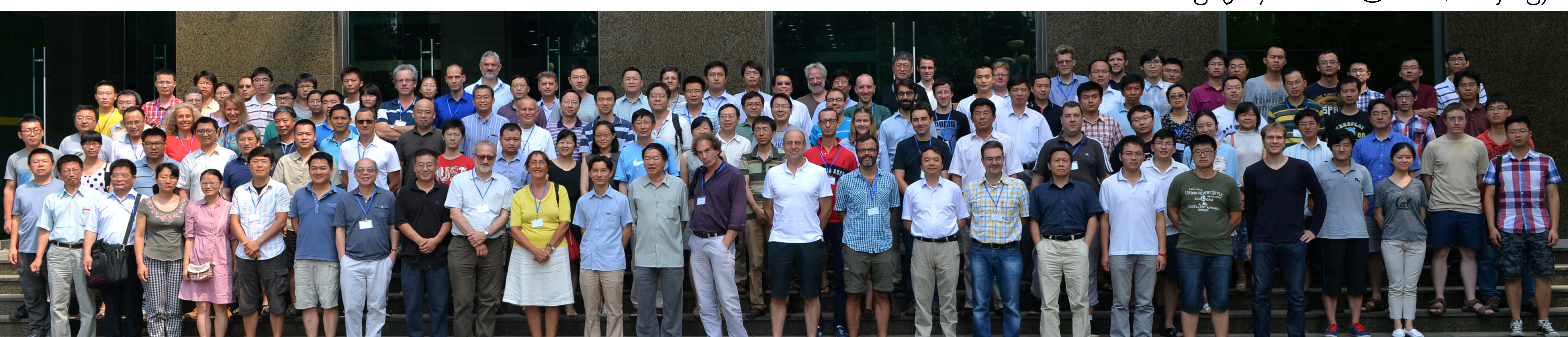
U. libre de Bruxelles (Observer)

Asia (25)

Beijing Normal U.
CAGS,
CIAE
DGUT
ECUST
Guangxi U.
IHEP
Jilin U.
Nanjing U.
Nankai U.
Natl. Chiao-Tung U.
Natl. Taiwan U.
Natl. United U.
NCEPU
Peking U.
Shandong U.
Shanghai JT U.
Sichuan U.
SYSU
Tsinghua U.
UCAS
USTC
Wuhan U.
Wuyi U.
Xi'an JT U.

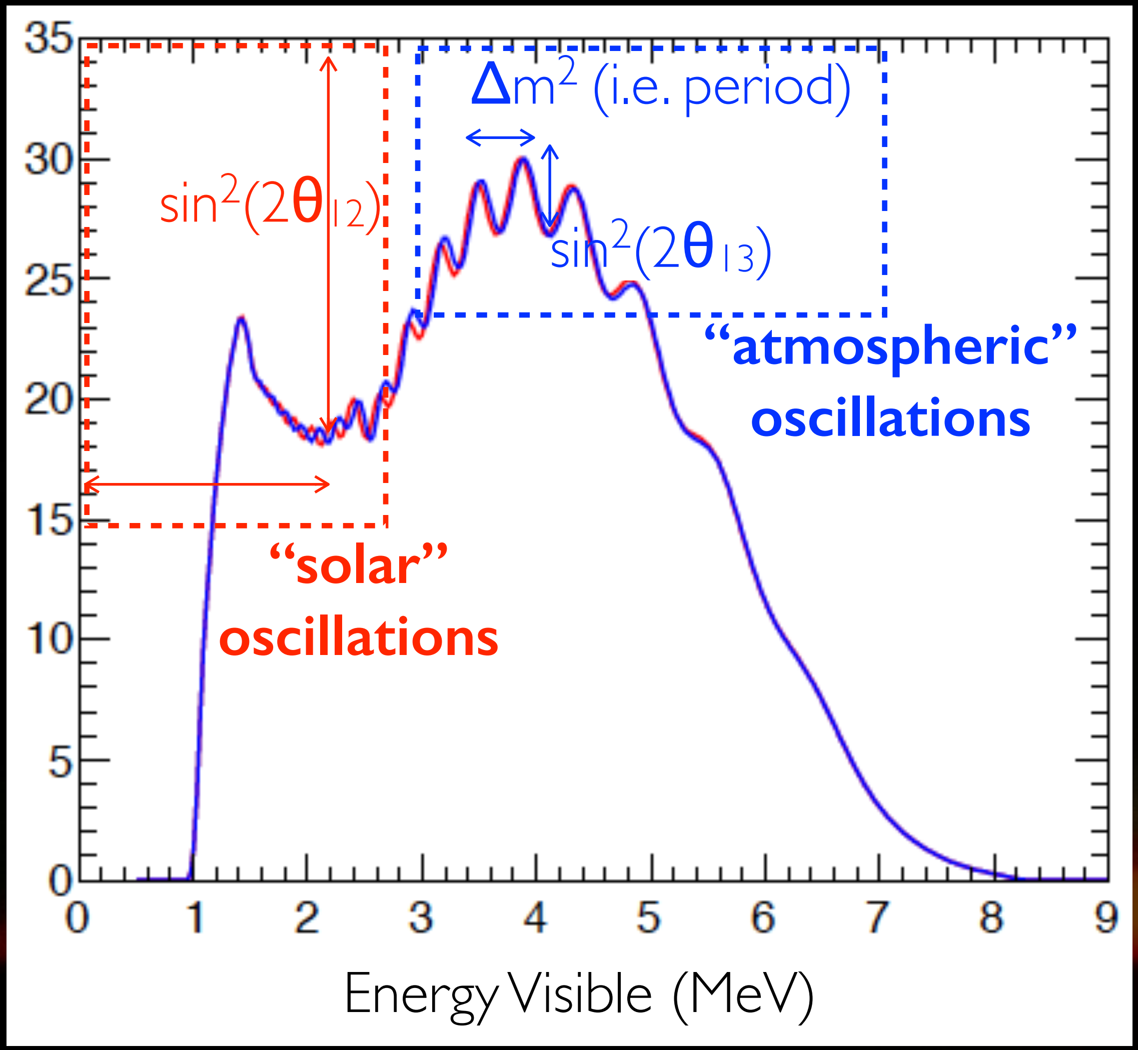
US-JUNO group holds an observer status in collaboration

1st Collaboration Meeting (July 2014 @IHEP, Beijing)



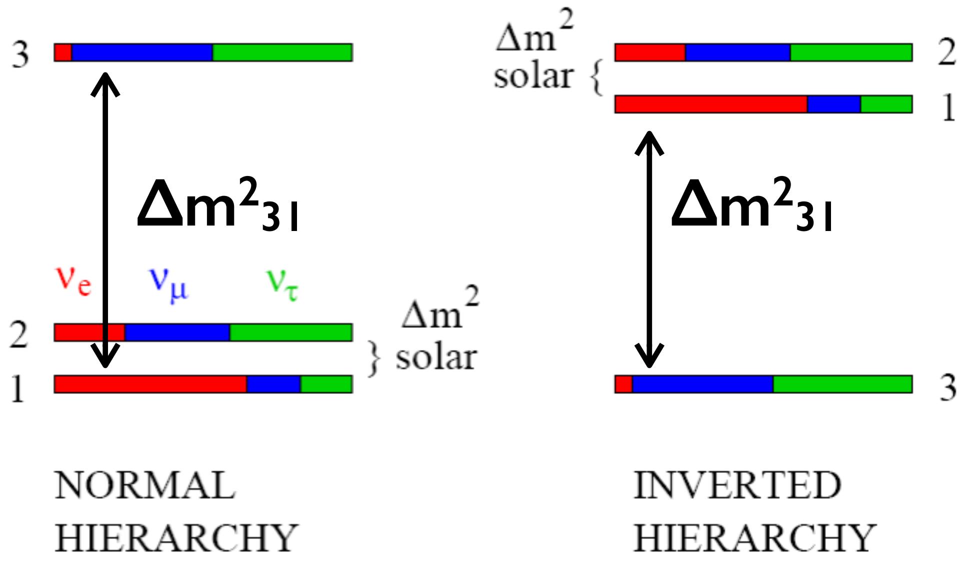
physics programme…

what to do with the largest LS detector in the world?



- (reactor-ν) **mass hierarchy (atmospheric)**…
  - subdominant (θ13 modulated) spectral distorsion
    - driven by Δm^2(atmospheric)
  - vacuum effect → no via matter enhance effects
    - complementarity to ORCA/PINGU, NOνA, LBN{A,Z}
- (reactor-ν) **solar δm2 & θ12 highest precision**…
  - needed for CP-violation (Jarlskog Invariant) → ambiguities
    - complementarity to T2K/NOνA & LBN{A,Z}
    - → no θ_{23}-octant or δ_{CP} ambiguities (not bad)
  - test: Solar (MSW) vs KamLAND (distorsion: not ideal baseline)
- (reactor-ν) **unique solar⊕atmospheric vacuum-oscillations fit**
- (supernova-ν) unique capabilities (size & observation: IBD, ν_e, ν_x)
- (proton-decay) unique capabilities (size & unique channels)
  - proton fraction larger in scintillator than water (up to 2x)
- (geo-ν) observation (reactor-ν large BG) → aid geo-physics
- other physics…
  - solar-ν, non-standard-interaction (different phase-space), etc

the gate to Mass Hierarchy is open…



$\Delta m_{31}^2(IH) \neq \Delta m_{31}^2(NH)$
$\Rightarrow$ **δ~3%** (i.e. $\delta m^2/\Delta m^2$)

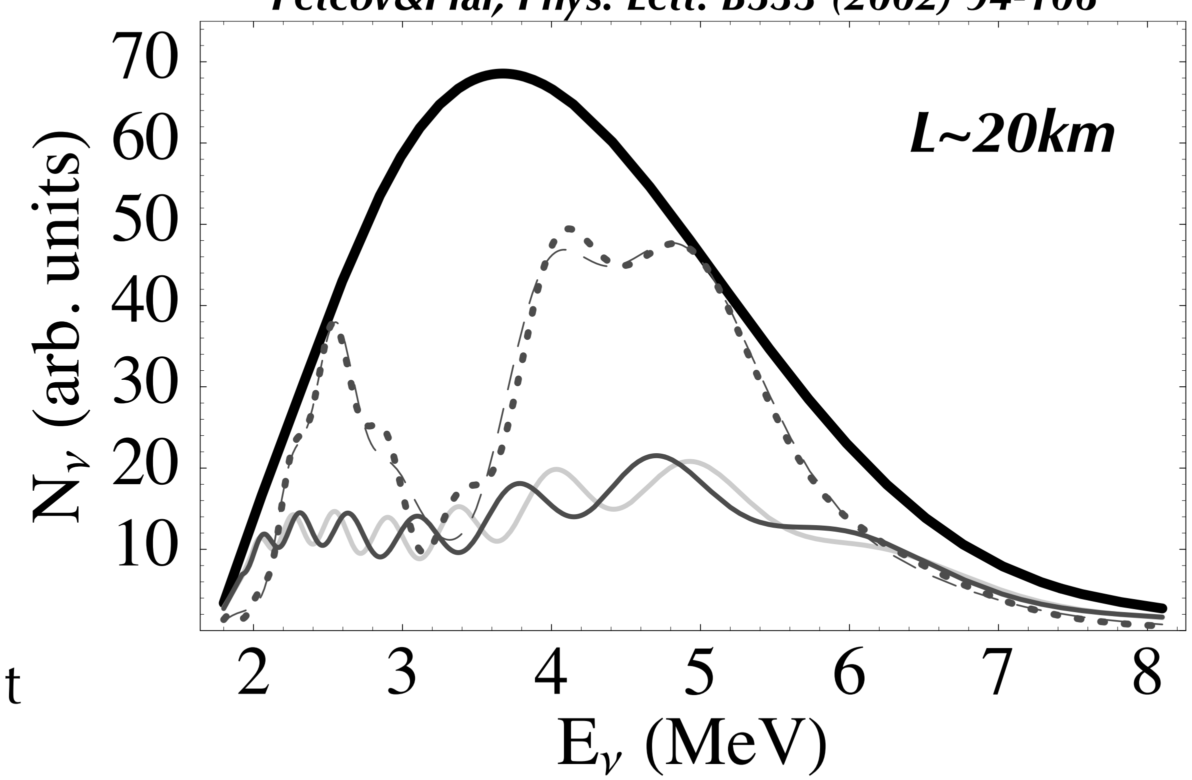
how to resolve neutrino mass hierarchy using reactor neutrinos?

- KamLAND (long-baseline) measures δm^2 very precisely
- DB/DC/RENO observe θ_{13} oscillation (T2K appearance too)
- reactor @ ~50km→ atmospheric & solar oscillations interference
- reactor oscillations follow Δm^2_{31}: difference (NH vs IV) is δm^2
  - vacuum oscillation energy distortion→ negligible MSW
  - sub-dominant oscillation (θ_{13} amplitude)→ ~3% resolution

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$
$$- \boxed{\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}$$

✓Mass hierarchy is reflected in the spectrum
✓Signal independent of the unknown δ_{CP} or θ_{23}-octant

Petcov&Piai, Phys. Lett. B533 (2002) 94-106



- Realization&Plausibility: L. Zhan et al, PRD.78.111103; J. Learned et al PRD.78.071302; and DYB/RENO

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Fourier analysis for Mass Hierarchy determination

- Treating L/E as the time domain, the frequency domain simply corresponds to Δm^2

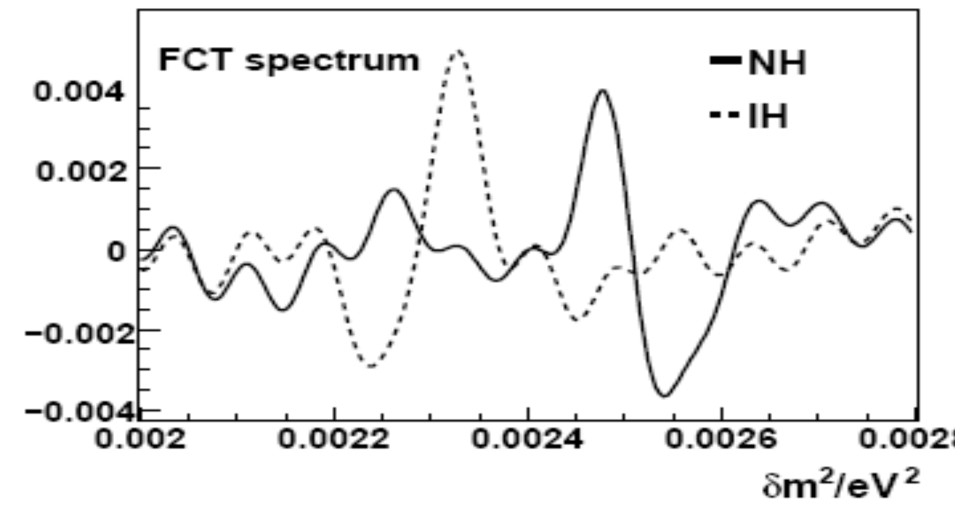
$$FST(\omega) = \int_{t_{min}}^{t_{max}} F(t)\sin(\omega t)\mathrm{d}t$$
$$FCT(\omega) = \int_{t_{min}}^{t_{max}} F(t)\cos(\omega t)\mathrm{d}t$$

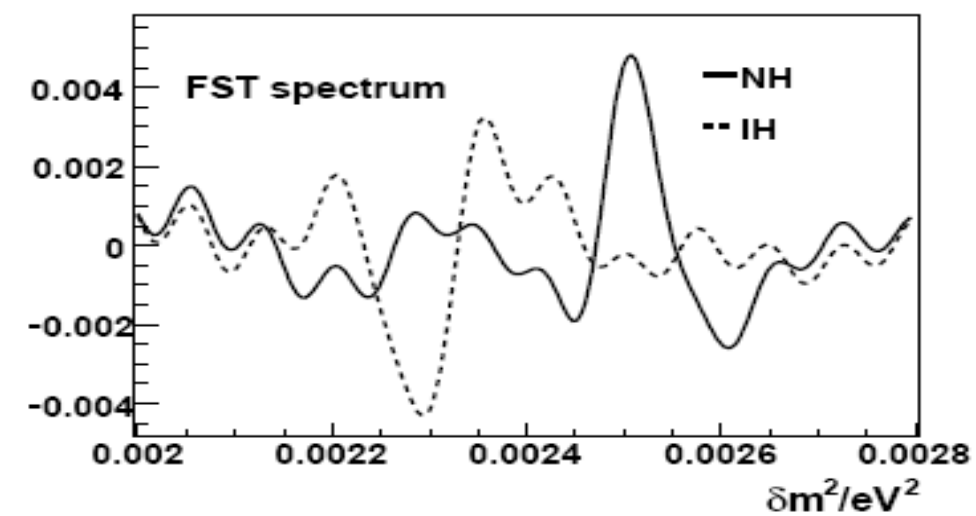
- In the Δm^2 domain, take Δm^2_{32} as the reference point,
  - NH: take "+" sign, the effective Δm^2 peaks on the right of Δm^2_{32}, then a valley
  - IH: take "-" sign, the effective Δm^2 peaks on the left of Δm^2_{32}, right to a valley

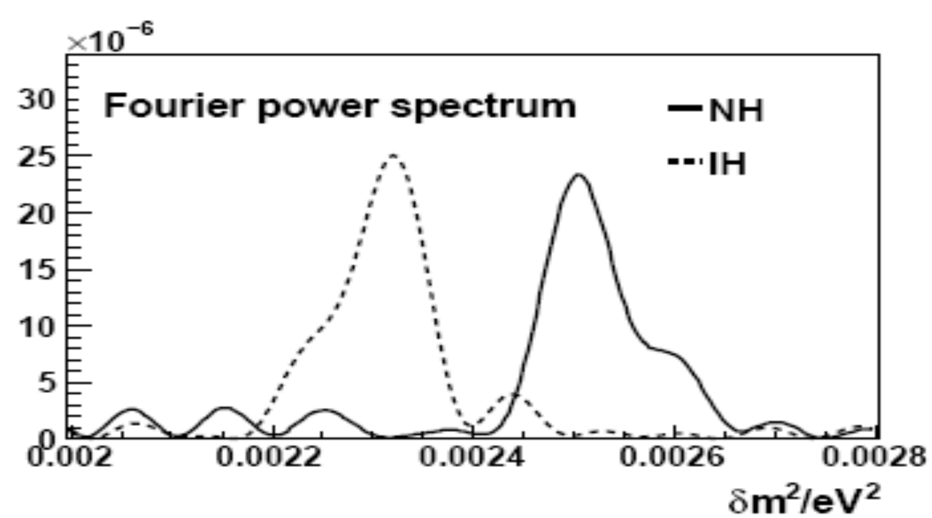
- Δm^2 spectra have very distinctive features for different hierarchies

L. Zhan et al., PRD78(2008)111103

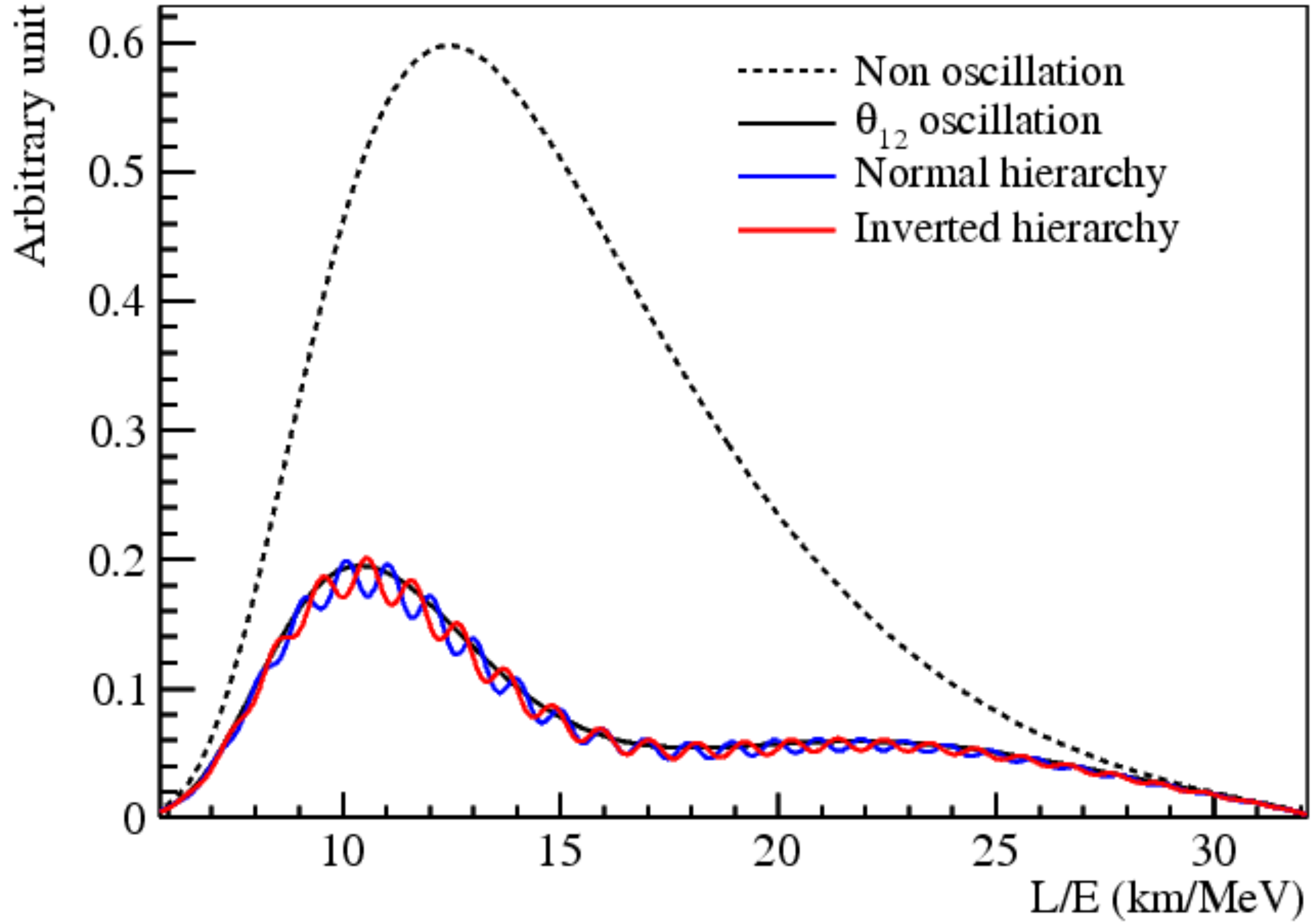
J. Learned et al proposed the FT power spectrum method 2006



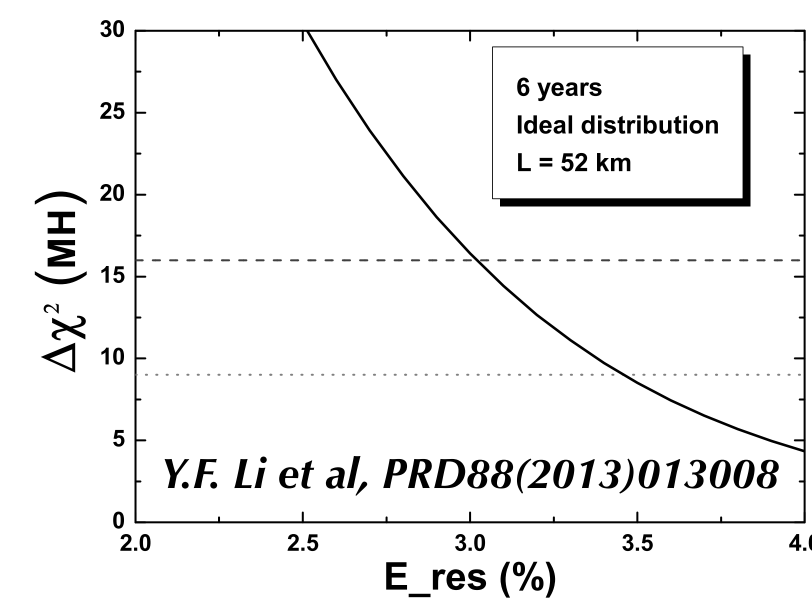




energy resolution of JUNO detector…



- the 3% requirement arises from ratio $\delta m^2/\Delta m^2$
  - i.e. the solar to atmospheric mass-squared difference
- need energy resolution ~ 3% @ 1MeV
  - stochastic term $(a/\sqrt{E}) \rightarrow a \leq 3\%$
  - non-stochastic term under investigation (next)



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energy scale accuracy (i.e. bias & systematics)…

S.J. Parke et al, Nucl.Phys.Proc.Suppl. 188 (2009)

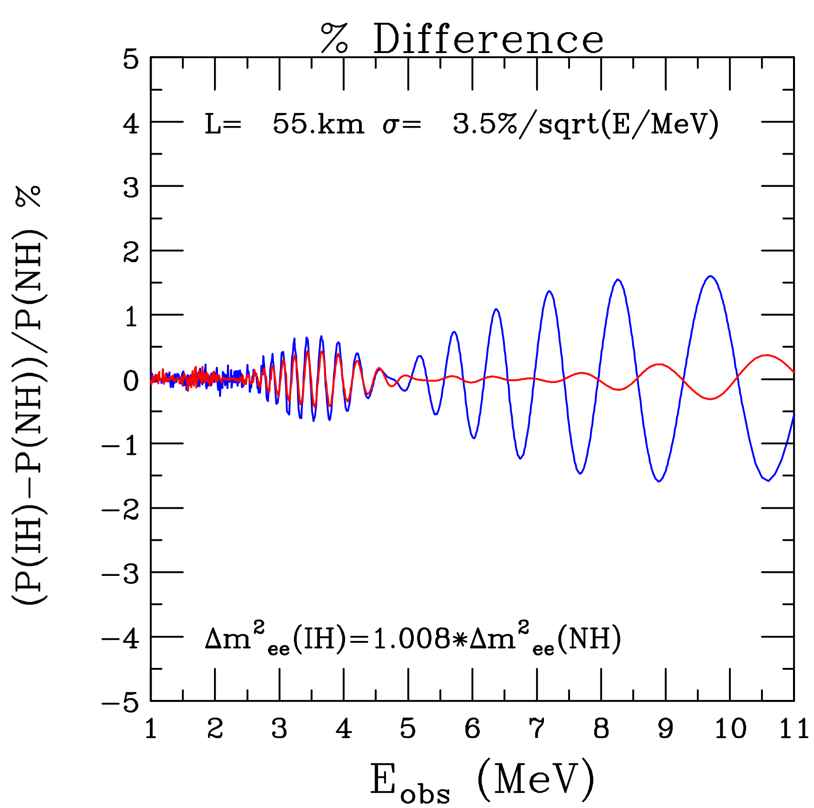
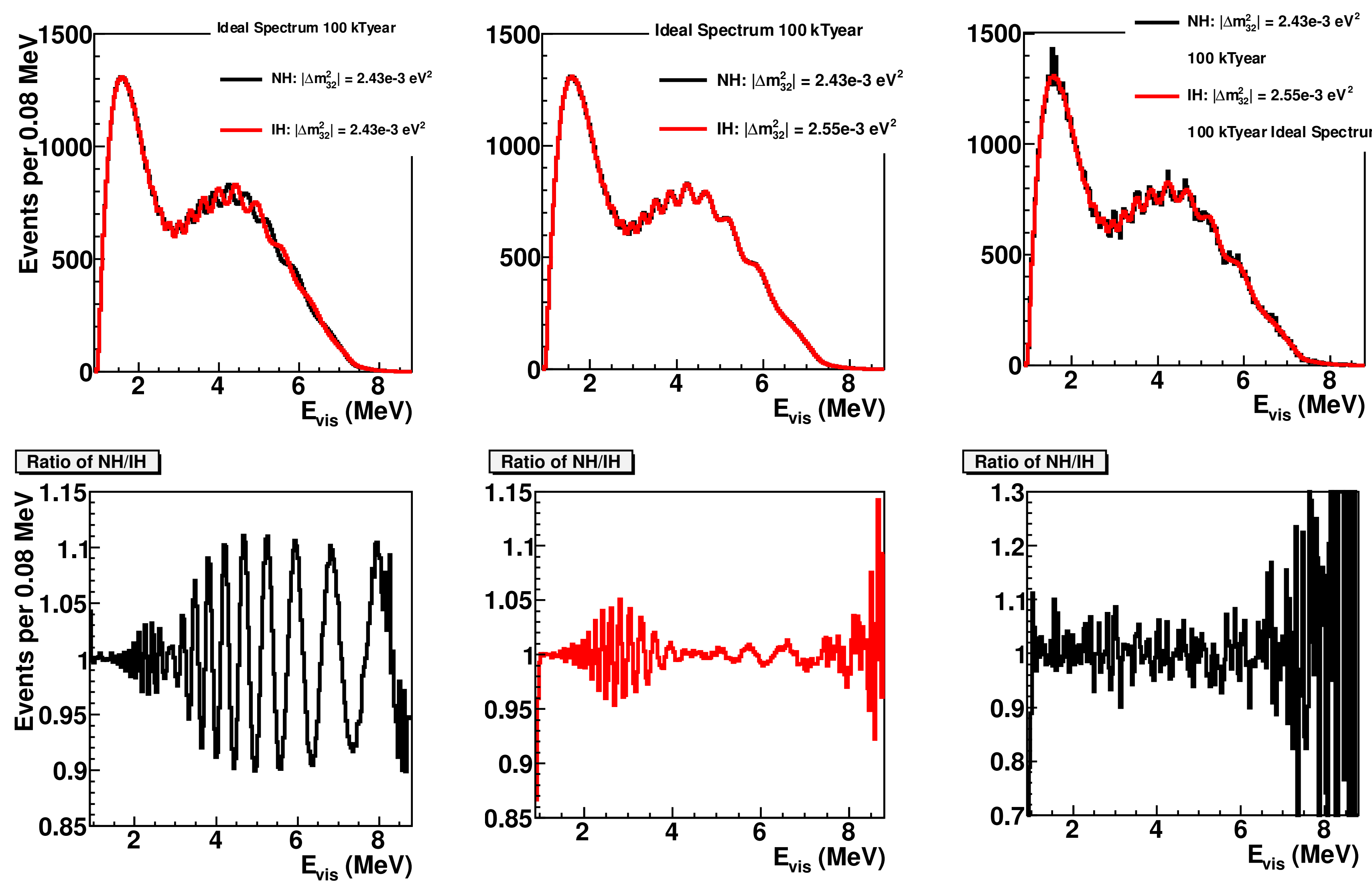


Figure 4. The percentage difference between the inverted hierarchy and the normal hierarchy. The blue curve is assuming $E_{obs} = E_{true}$ and maximum difference is less than 2%. Whereas for the red curve we have assumed that $E_{obs} = 1.015 E_{true} - 0.07$ MeV for the IH, so as to represent a relative calibration uncertainty in the neutrino energy. Here the maximum percentage difference is less than 0.5%.

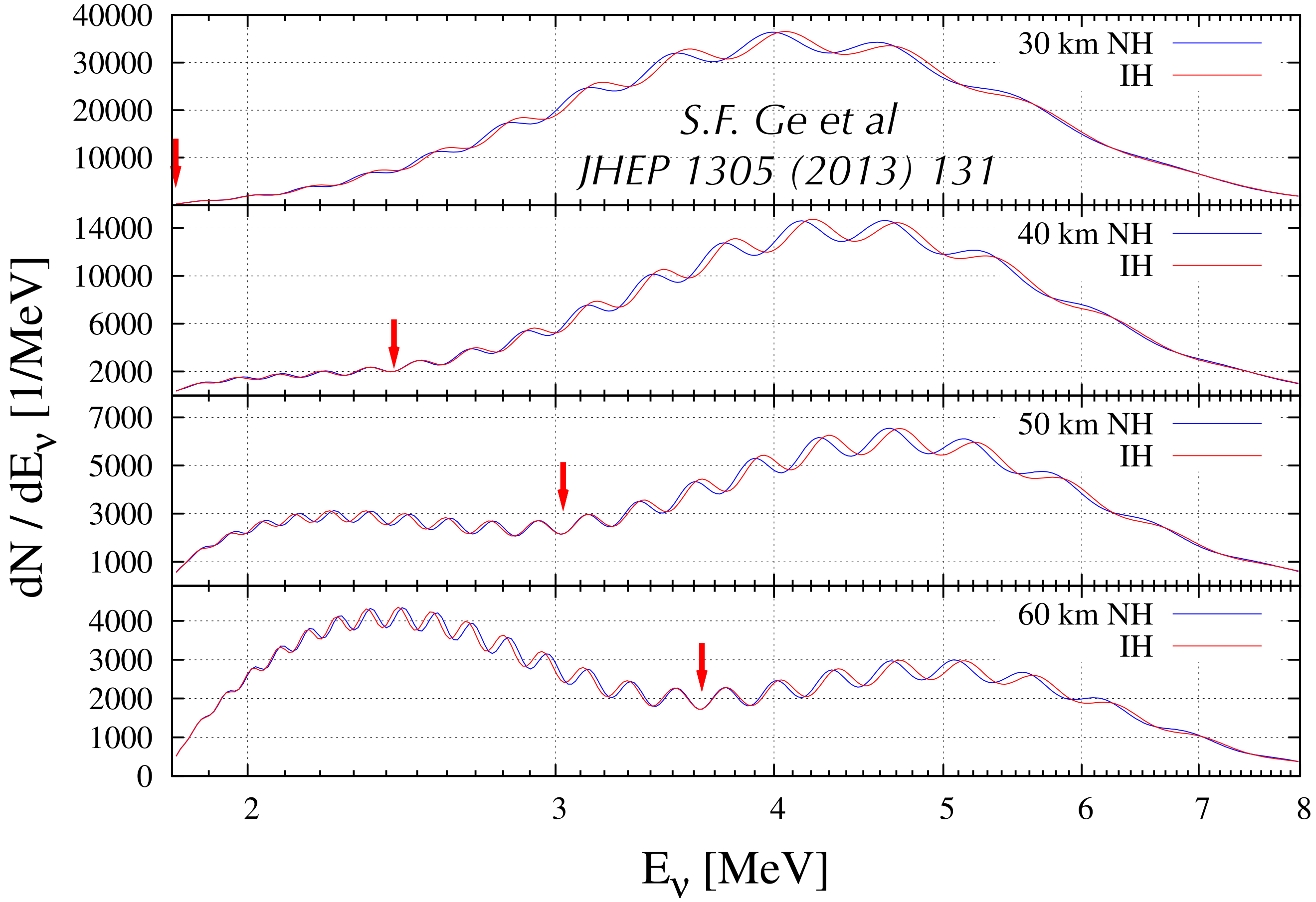
X. Qian et al, PRD87(2013)3, 033005

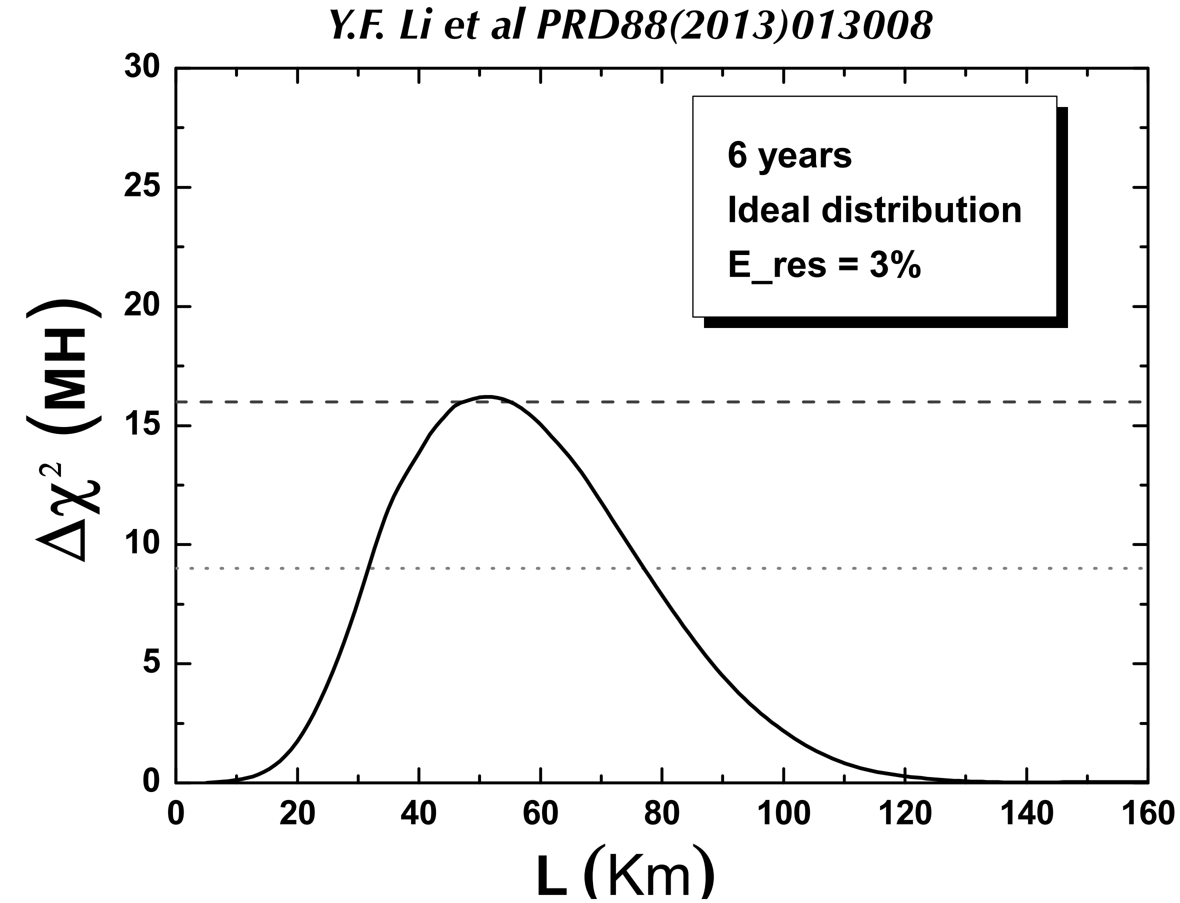


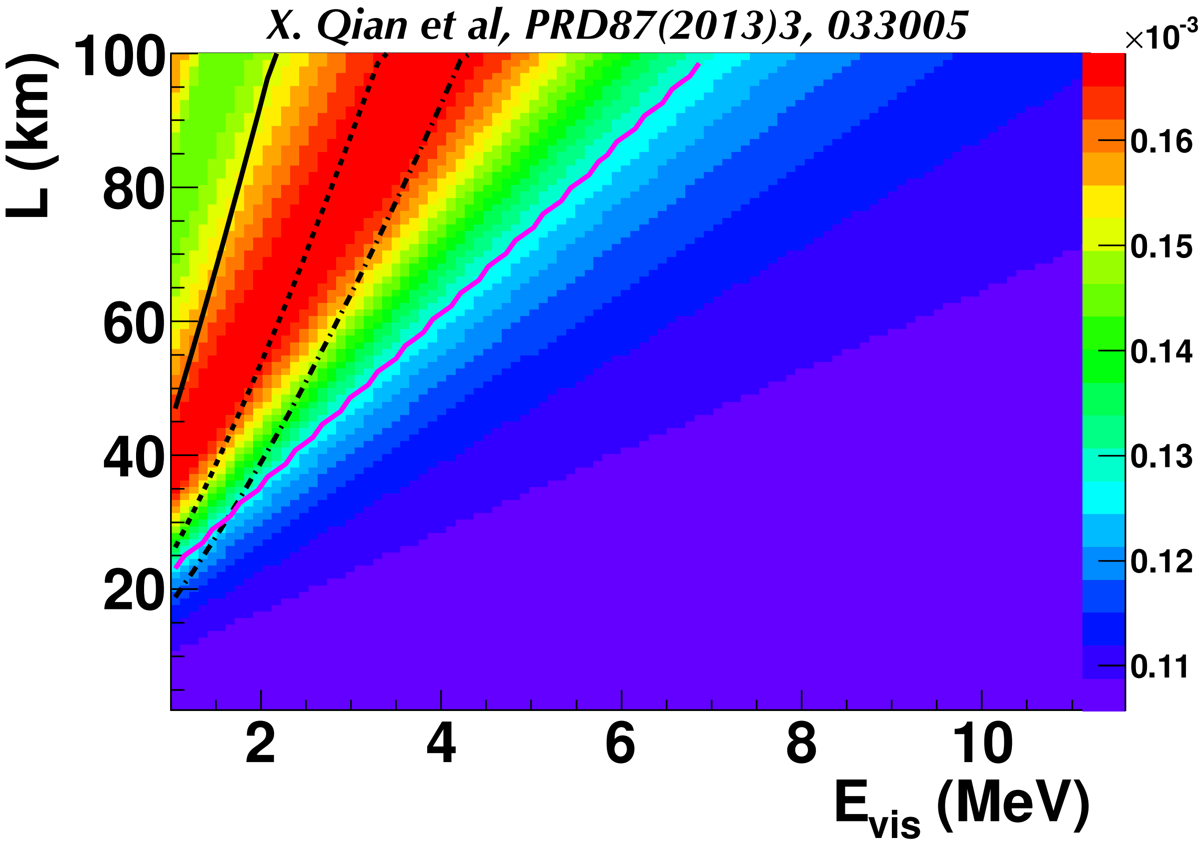
- if energy reconstruction→ **bias** or **non-linearity** residuals
  - ⇒ signals might disappear or wrong (solution)
- various studies show ≲**1% uncertainty is needed**

the detector: where?

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2\Delta_{21} + 2s_{13}^2 c_{13}^2 \sqrt{1 - 4s_{12}^2 c_{12}^2 \sin^2\Delta_{21}} \cos(2\Delta_{32} \pm \phi)$$



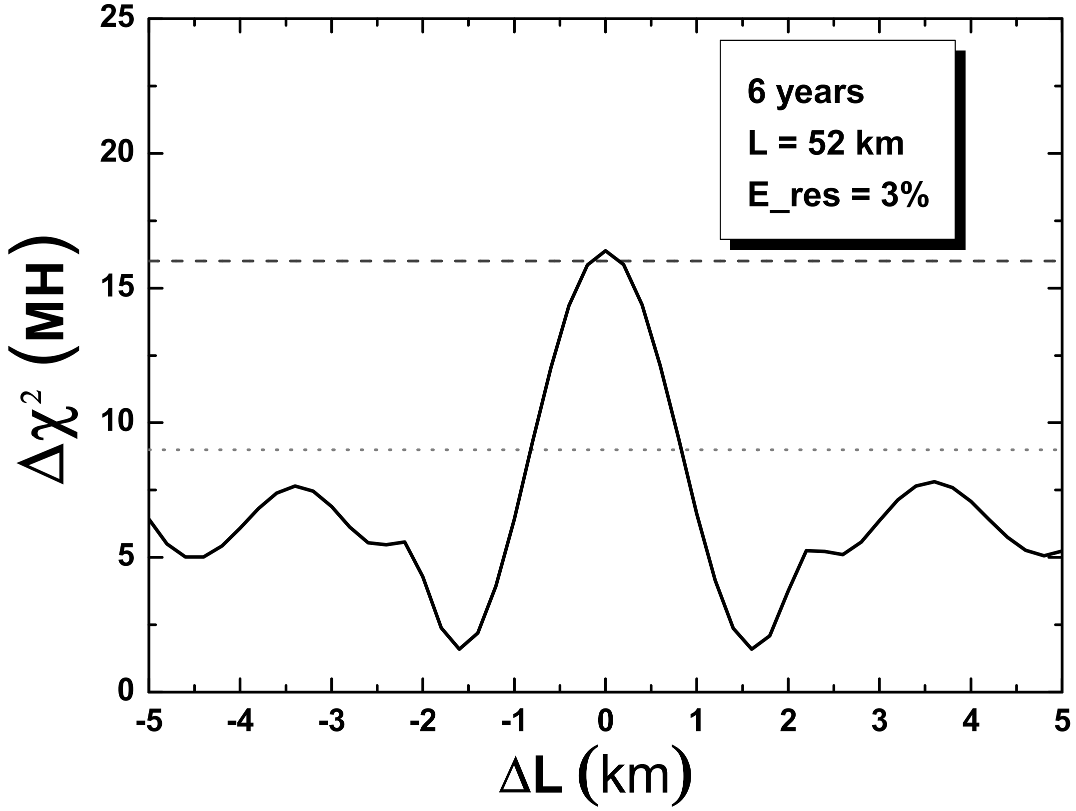


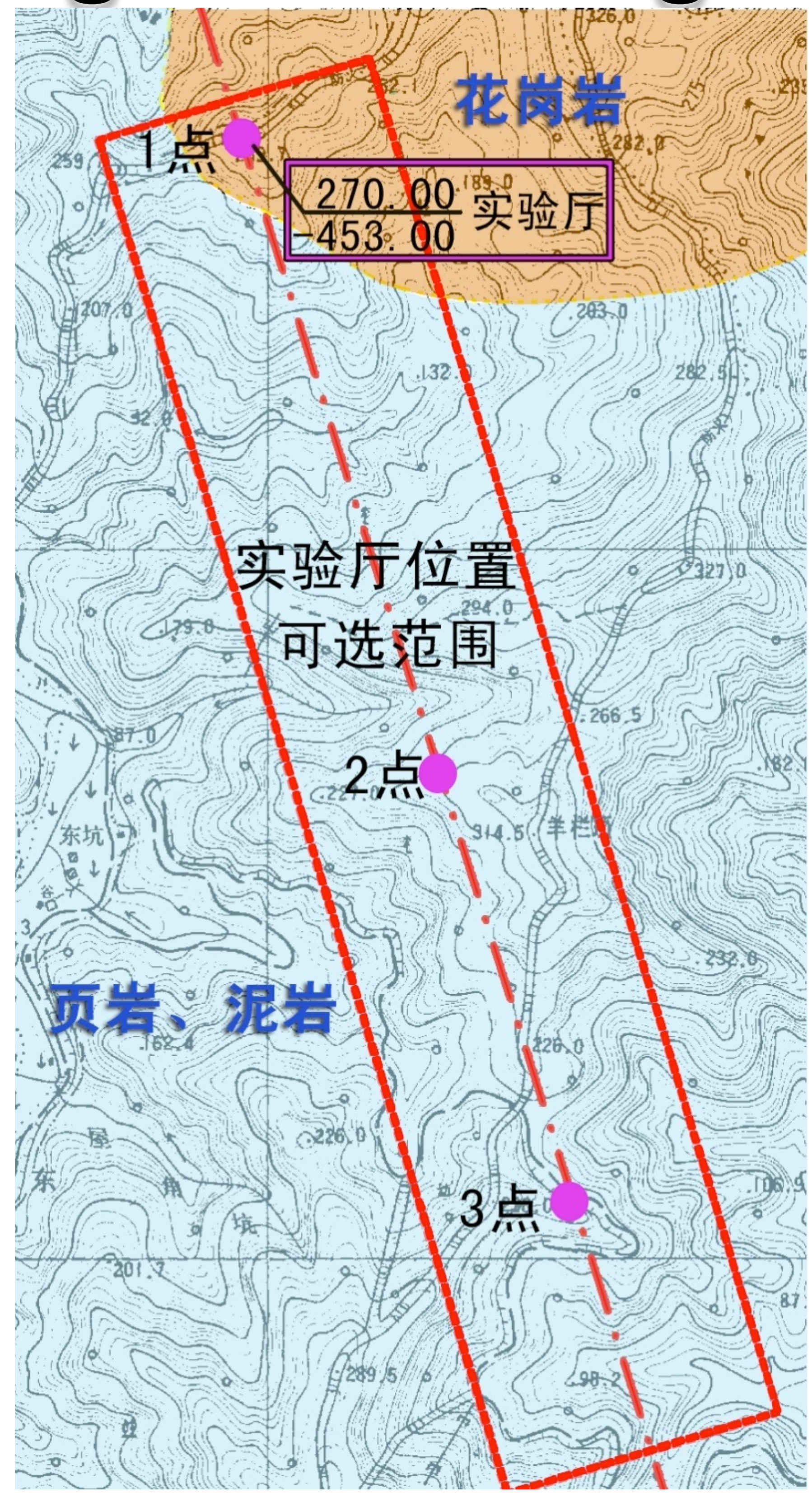


- The power lies in the contrast between the lower part and the higher part of the inverse beta decay spectrum
- The baseline needs to be 50km - 60km

the baseline design fine tuning…

Y.F. Li et al PRD88(2013)013008

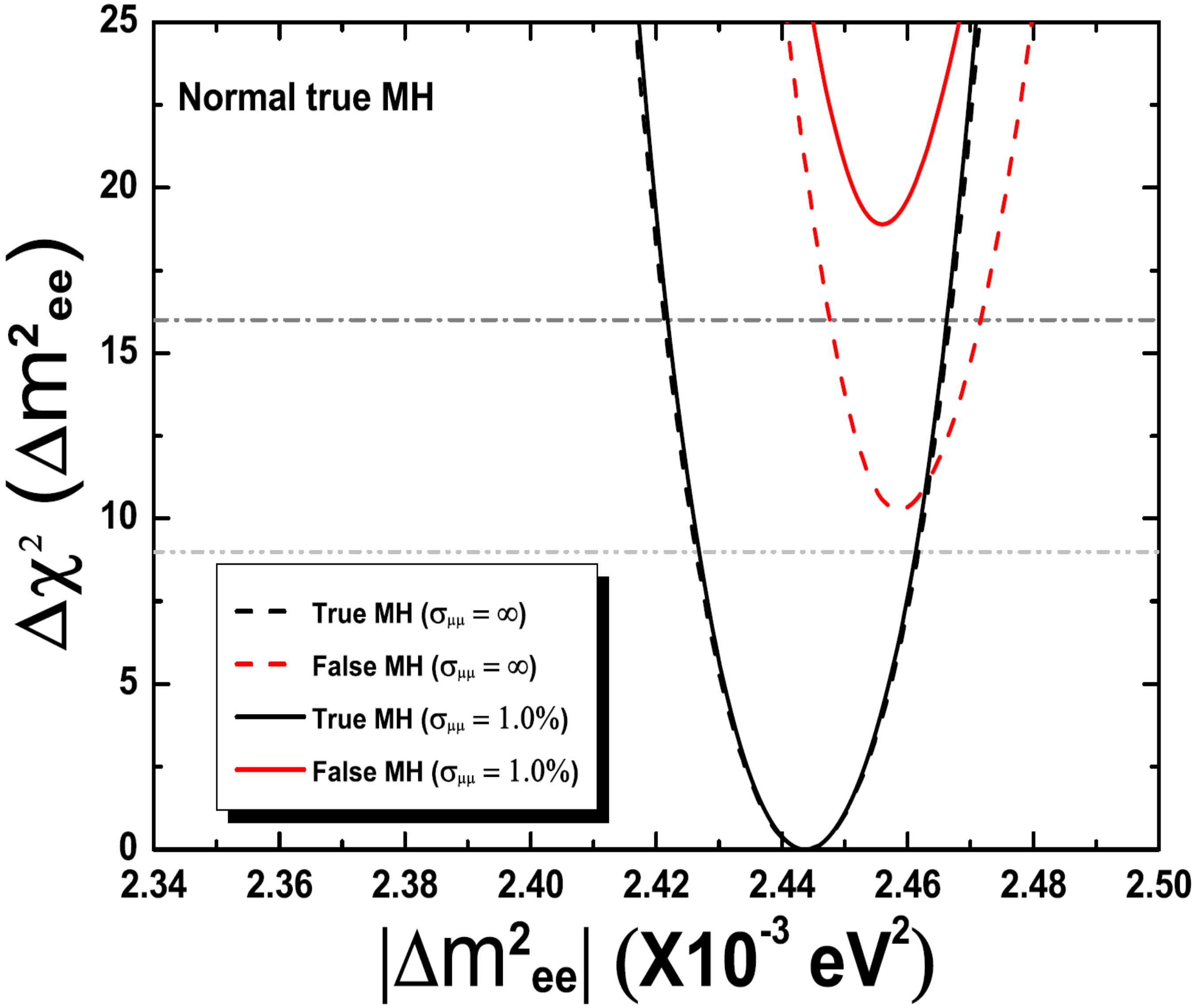




- reactor cores at the same power plant ~km apart
- If baselines shifted by half oscillation length
  - $\Rightarrow$ oscillation cancels (interference)
- design optimised: baseline differences $\leq$0.5km

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

Mass Hierarchy significance…



- ~3σ→ spectral measurement with no Δm^2 external constrain
- ~4σ→ external Δm^2 measured to ~1% error (ν_μ disappearance with ν-beam off-axis)

  - Δm^2 @~1% by T2K+NOvA
  - combined analysis [1312.1477]

ingredients…

✓Realistic reactor distributions considered

✓20kt valid target mass ⊕ 36GW reactor power ⊕ 6-years data

✓3% energy resolution ⊕ ~1% energy scale uncertainty assumed

neutrino oscillation precision before & after JUNO…

	Current	JUNO
δm^2	~3%	~0.5%
Δm^2	~4%	~0.6%
$\sin^2(2\theta_{12})$	~7%	~0.7%
$\sin^2(2\theta_{23})$	~15%	N/A
$\sin^2(2\theta_{13})$	~10%- ~4% (DYB)	~ 15%

after JUNO, the "Solar neutrino oscillation" parameters on the <1% level→ the "JUNO sector"?
(already worth the experiment)

when trying to measure/constrain δ_{CP}, all oscillation parameters matter! (**Jarlskog invariant: "*J*"**)

$$\Delta P_{\nu\bar{\nu}\,\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = -16 J_{\alpha\beta} \sin\Delta_{12} \sin\Delta_{23} \sin\Delta_{31}$$

$$J_{\alpha\beta} \equiv \Im(U_{\alpha1}U^*_{\alpha2}U^*_{\beta1}U_{\beta2}) = \pm J, \qquad J \equiv s_{12}c_{12}s_{23}c_{23}s_{13}c^2_{13}\sin\delta$$

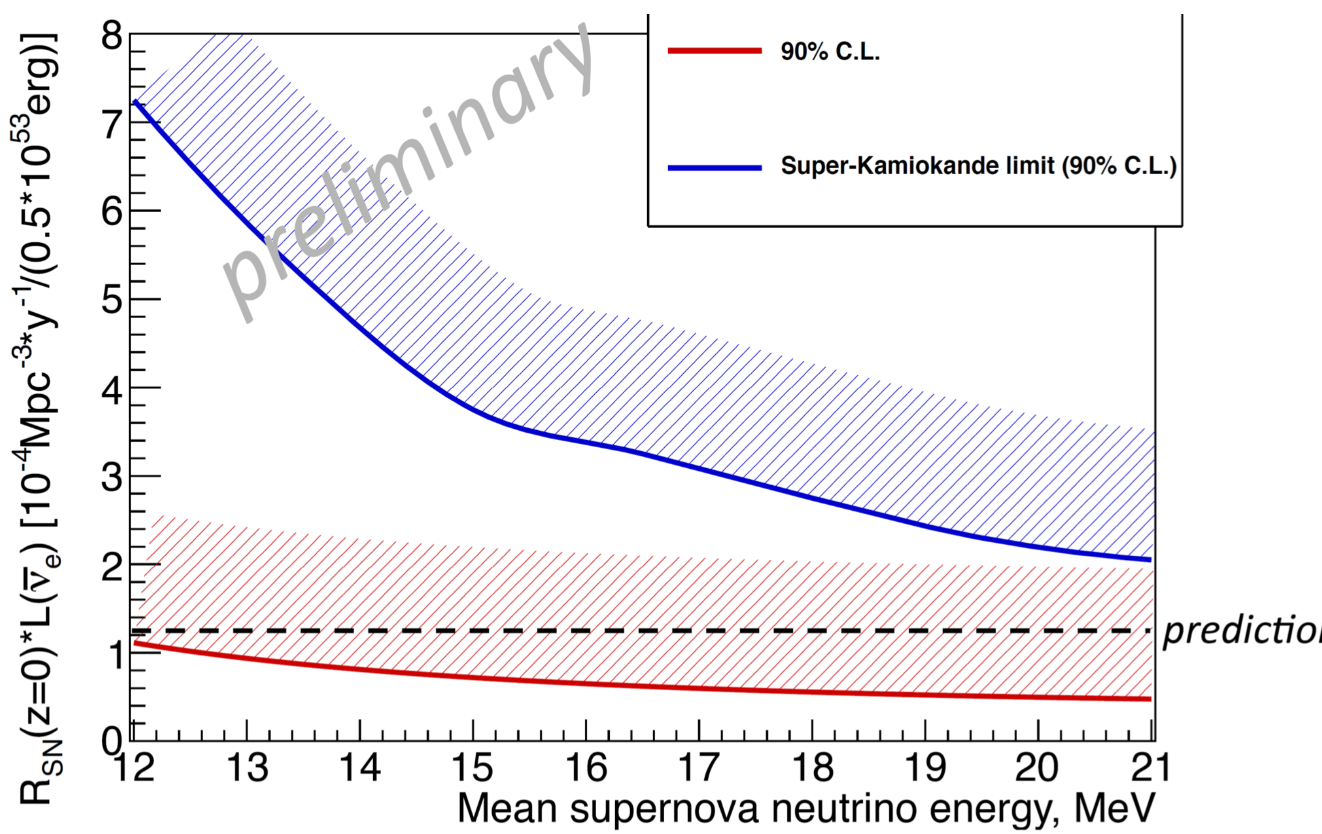
Other Physics Potential of JUNO

- supernova ν (core-collapse& diffused)
- proton decay
  - example: p ➞ K+ + anti-ν

$$\tau > 1.9 \times 10^{34} \text{ yr (90\% C.L.)}$$

- geo-ν's
  - KamLAND: 30±7 TNU [PRD 88 (2013) 033001]
  - Borexino: 38.8±12.0 TNU [PLB 722 (2013) 295]
  - JUNO (preliminary): 37±10%(stat)±10%(syst)TNU

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



- solar-ν: very demanding radioactivity control (à la Bx)➞ possible?
- atmospheric-ν: possible aid to Mass-Heirarchy? (à la ORCA/PINGU)
- unique E/L phase-scale explore: non-standard interactions, neutrino decay, etc

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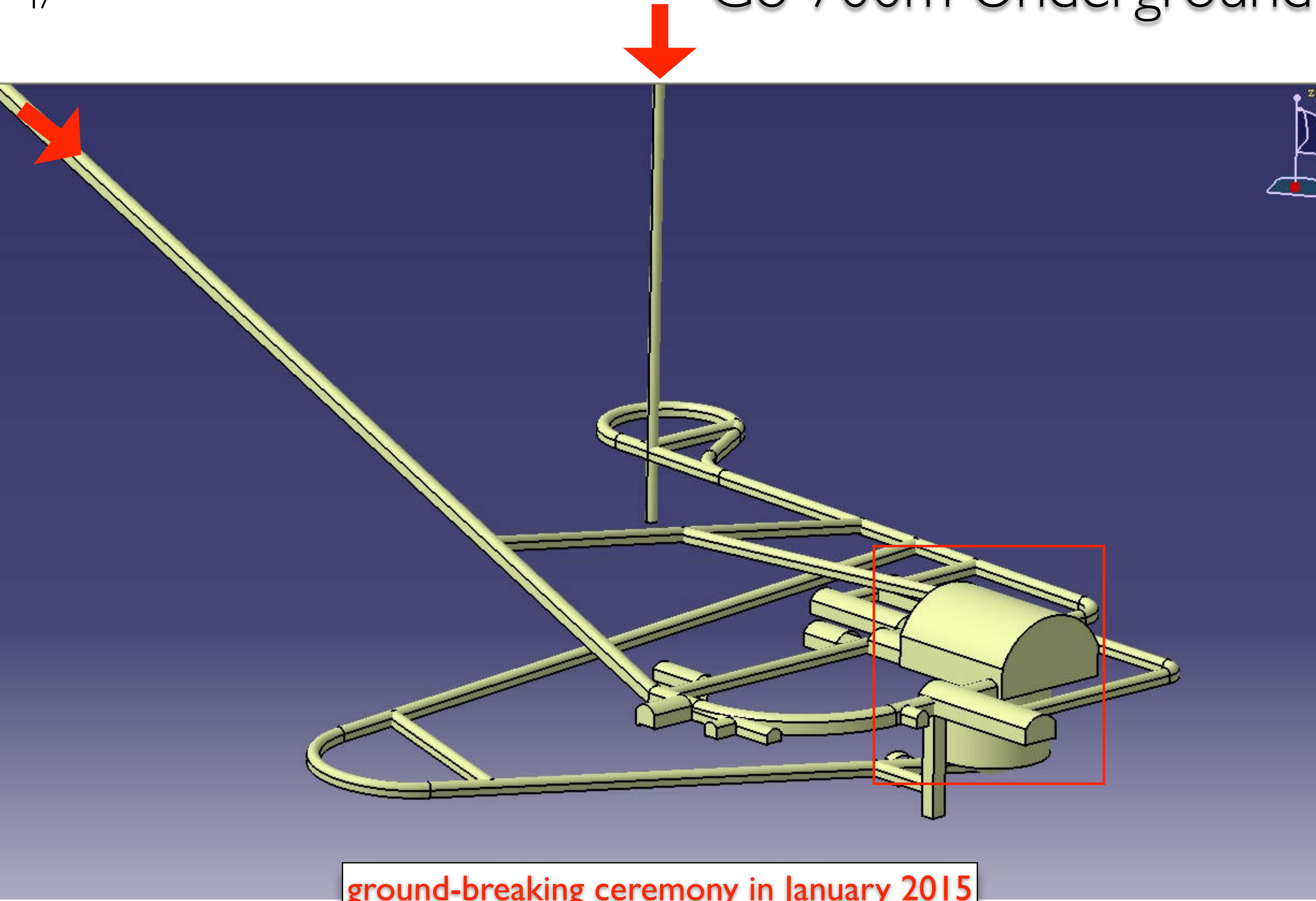
the detector…

A Medium-Baseline Reactor Neutrino Experiment

	Yangjiang	Taishan
Status	under construction	under construction
Power/GW	17.4	18.4

Go 700m Underground



ground-breaking ceremony in January 2015

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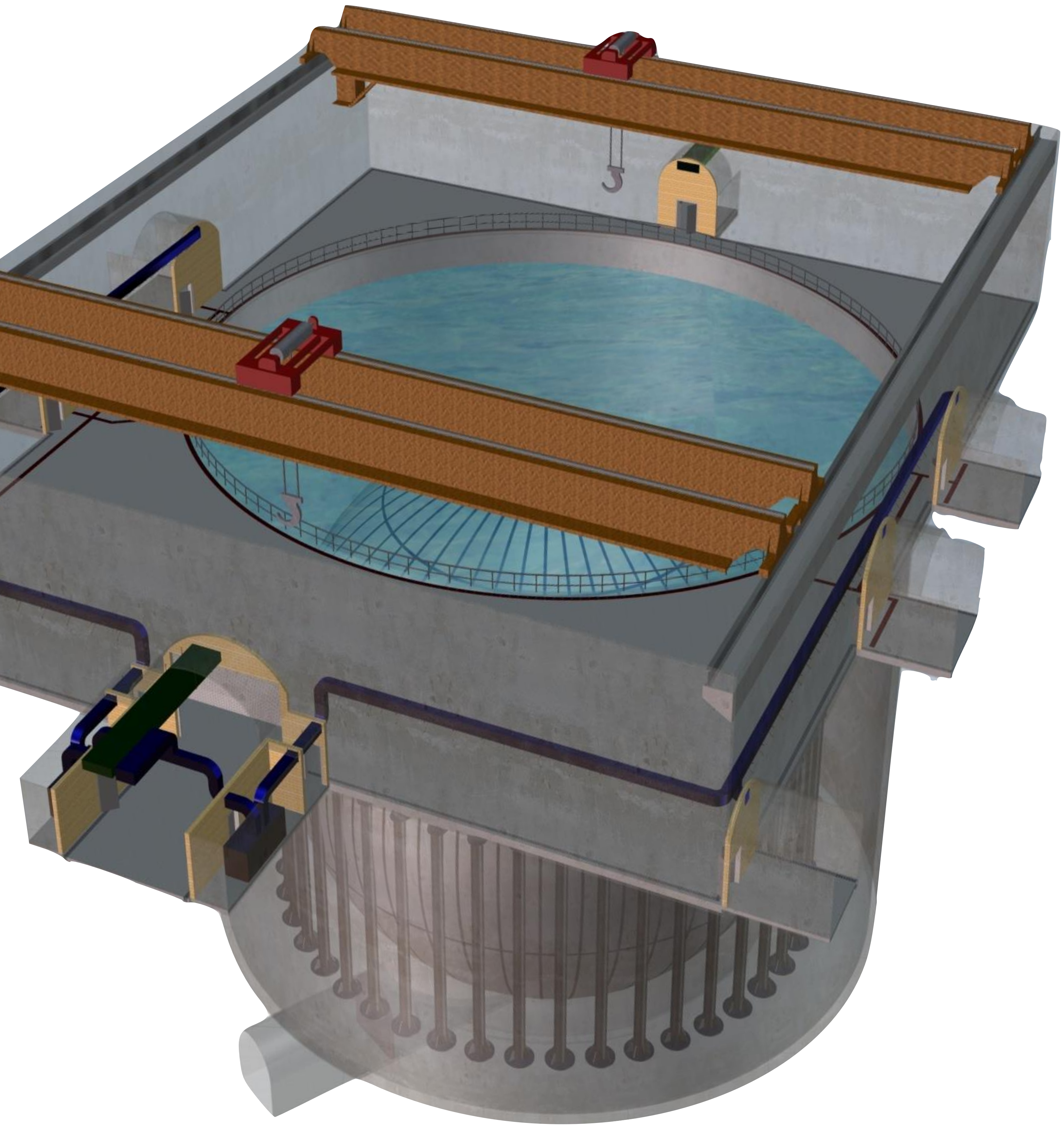
The Underground Detector System of JUNO



- JUNO detector major requirement (MH)
  - high precision calorimetry
    - largest light yield: ~1.2kPE/MeV
    - systematics control (transparent)
  - large (reactors @ ~50km)
    - → over-designed for all other physics
- ~20kt spherical liquid scintillator detector
  - ~1.5m of buffer (isolation + optics)
  - ~15k 20'' PMTs → ~80% photocathode
  - excellent μ-tracking resolution→^{9}Li+^{8}He
- cylindrical water pool system (surrounding)
  - passive shield: radioactivity
  - fast-n moderator
  - active fast-n detector (p-recoil)
  - muon active veto
- further top detector systems
  - stopping-muons & fast-neutrons
- →Borexino, DB, DC, KamLAND, SuperK, etc

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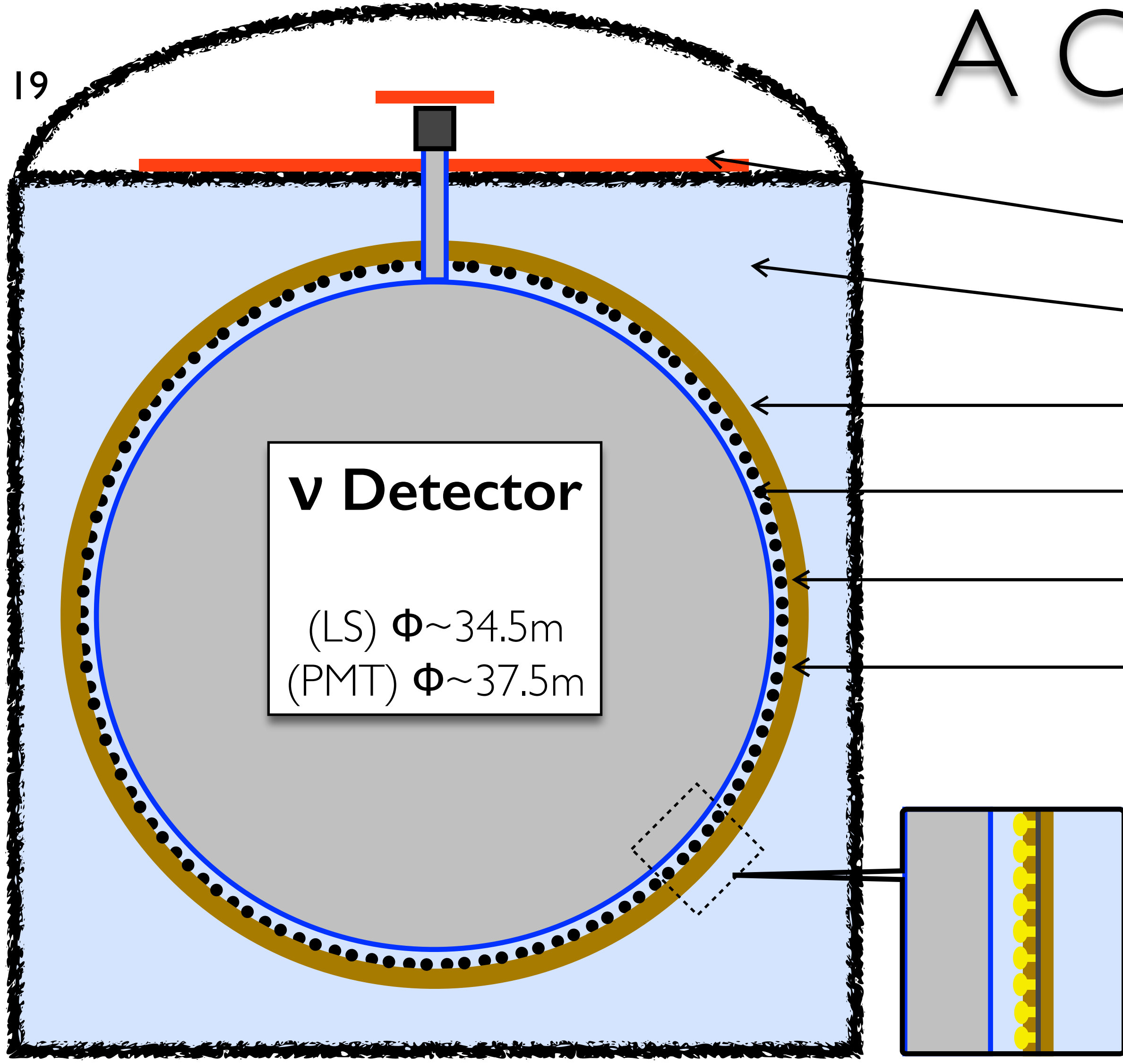
A Conceptual Design is Formed



- top μ detectors
- μ-veto detector & radioactivity shield
- Stainless steel tank or truss
- Water Cherenkov veto and radioactive
- Mineral oil or water buffer
- ~15000 20″ PMTs coverage: ~80%

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

stochastic term (→ ~1200PE/MeV)

non-stochastic terms (→systematics)

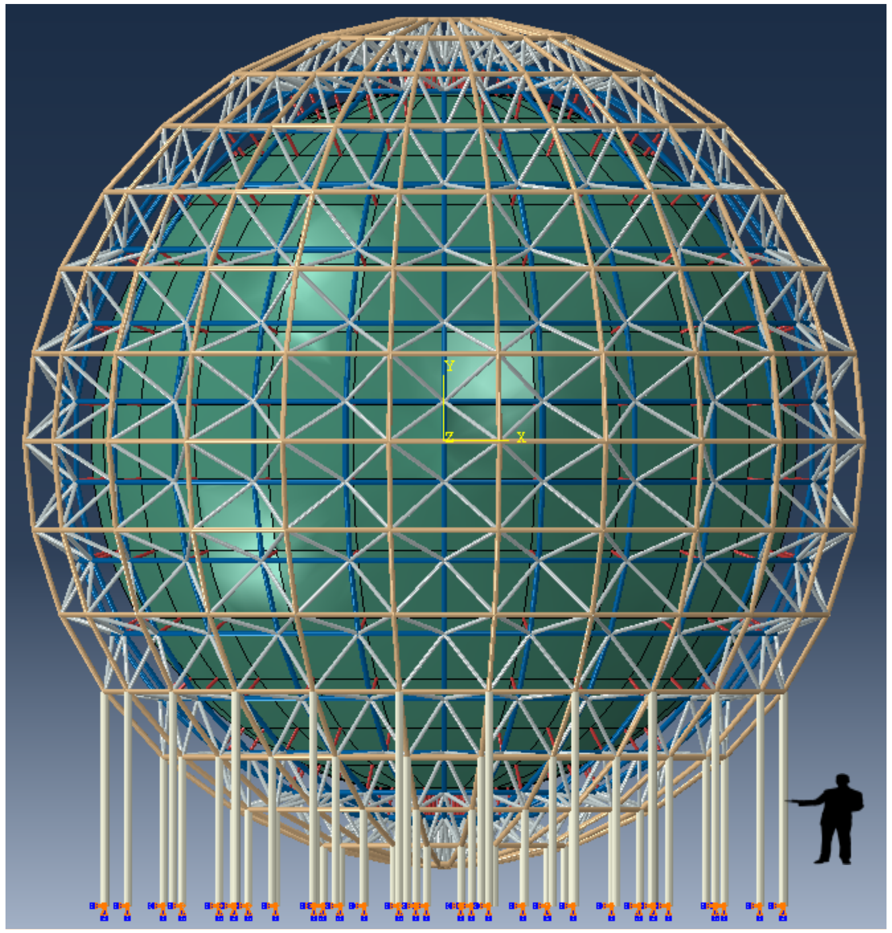
energy resolution is a design parameter (or milestone)

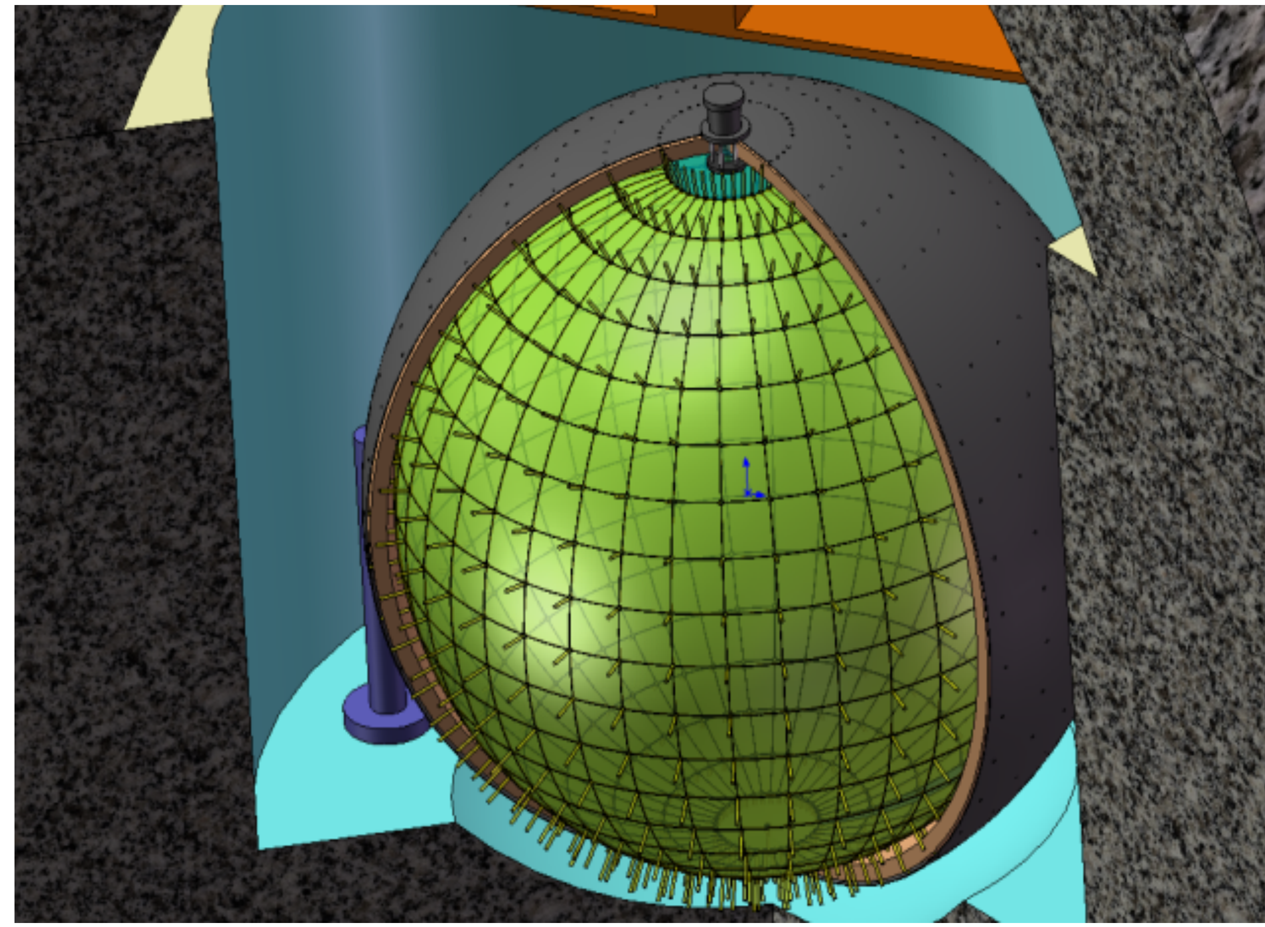
- **must reach ~3% @ 1MeV** (all terms)
  - highest calorimetry precision in LAND ever
- **huge light yield and maximal transparency**
  - highest light collection
  - highest photocathode coverage
  - high detection efficiency PMTs
- **detector uniform response & symmetrical** (sphere)
- **low electronics & light noise→ radio-purity**

resolution was far less demanding in past experiments

⇒ "softer" energy spectrum features

JUNO detector: two designs…





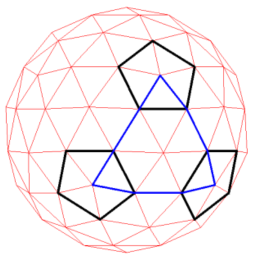
- **primary design**: a ~35m diameter **acrylic** sphere holds the LS
- stainless truss: mechanical supports to acrylic sphere and PMTs
- **water buffer volume**
- designing/improving details and interfaces with other components
- independent FEA calculations

- **backup**: a **balloon** holds the LS
- <u>acrylic panels</u> (not welded together like the sphere) + <u>stainless steel sphere</u> support the balloon and PMTs
- **oil/LAB buffer volume**
- leakage and dusts are the serious concerns

PMT arrangement & photocathode coverage

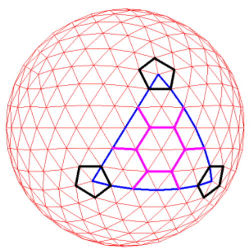
Polyhedral module layout method

others

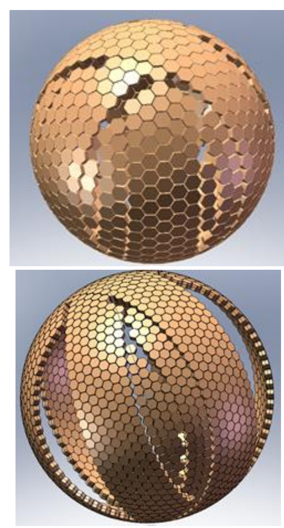


3 layers: 180 Triangles(or 12 Pentagons and 20 hexagons)

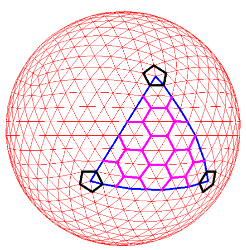
Football



6 layers: 720 Triangles(or 12 Pentagons and 110 hexagons)

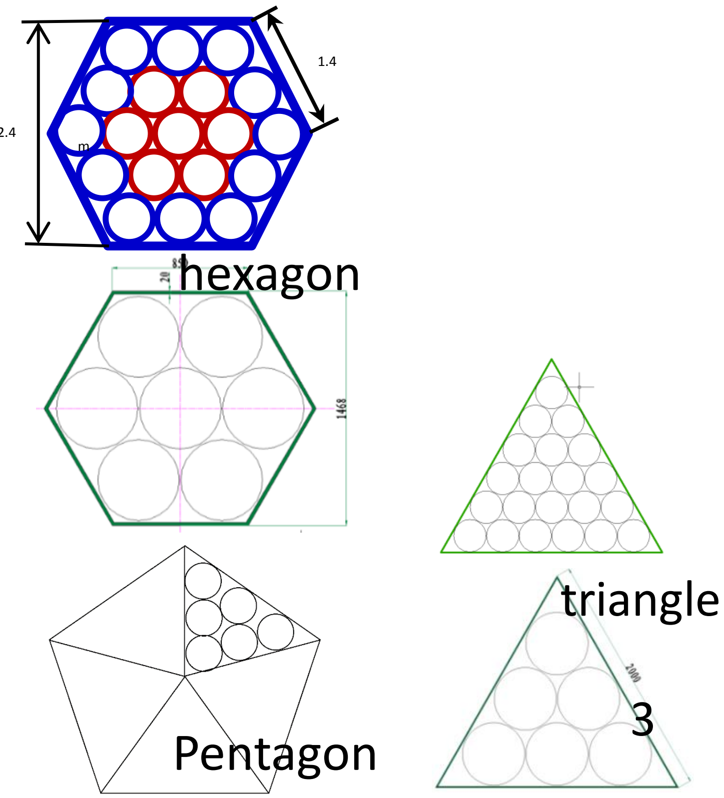


Volleyball-like

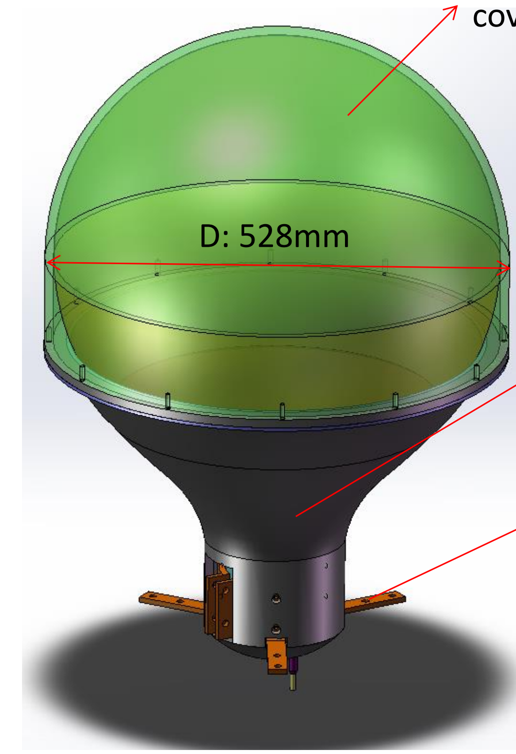


9 layers: 1620 Triangles(or 12 Pentagons and 260 hexagons)

module



Acrylic Transparent cover



Plastic caver

Fixation

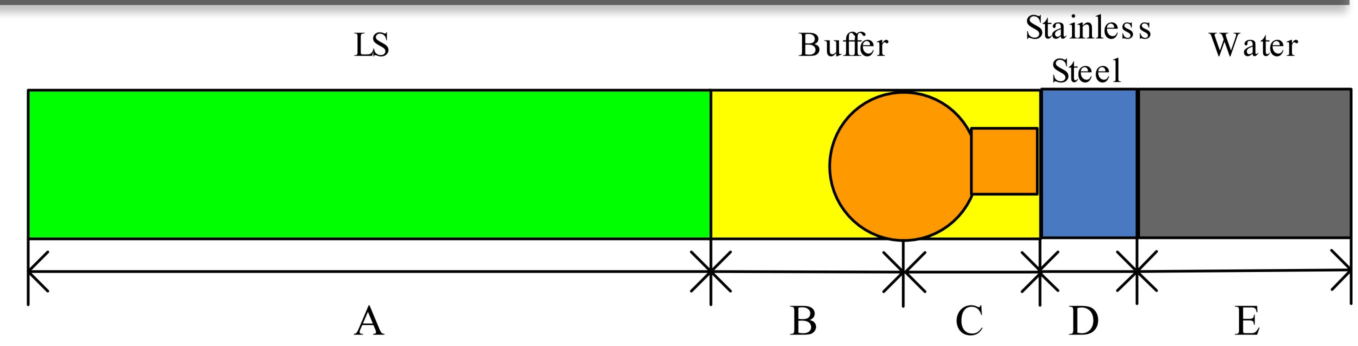
Conceptual explosion proof Structure of PMT

Scheme	**Acrylic vessel+steel space truss**	**stainless-steel tank + balloon with acrylic support**
Arrangement method	Layer-by-layer layout method: arrange PMT optimally then deleted PMT where bars occupied	9-layers' module layout method: 272 modules or 1620 installed cells
Radius & PMT No.	Radius has no influence to coverage R1: 18.7m PMT No. : 16918-616 coverage: 77.7 R2: 19.9m PMT No. : 19214-616 coverage: 77.9	Optimal radius: 18.7m PMT No. : 16520
Maximum coverage	**~77.9%-2.5%≈75.4%**	**~76.8%**

response simulation studies (preliminary)…

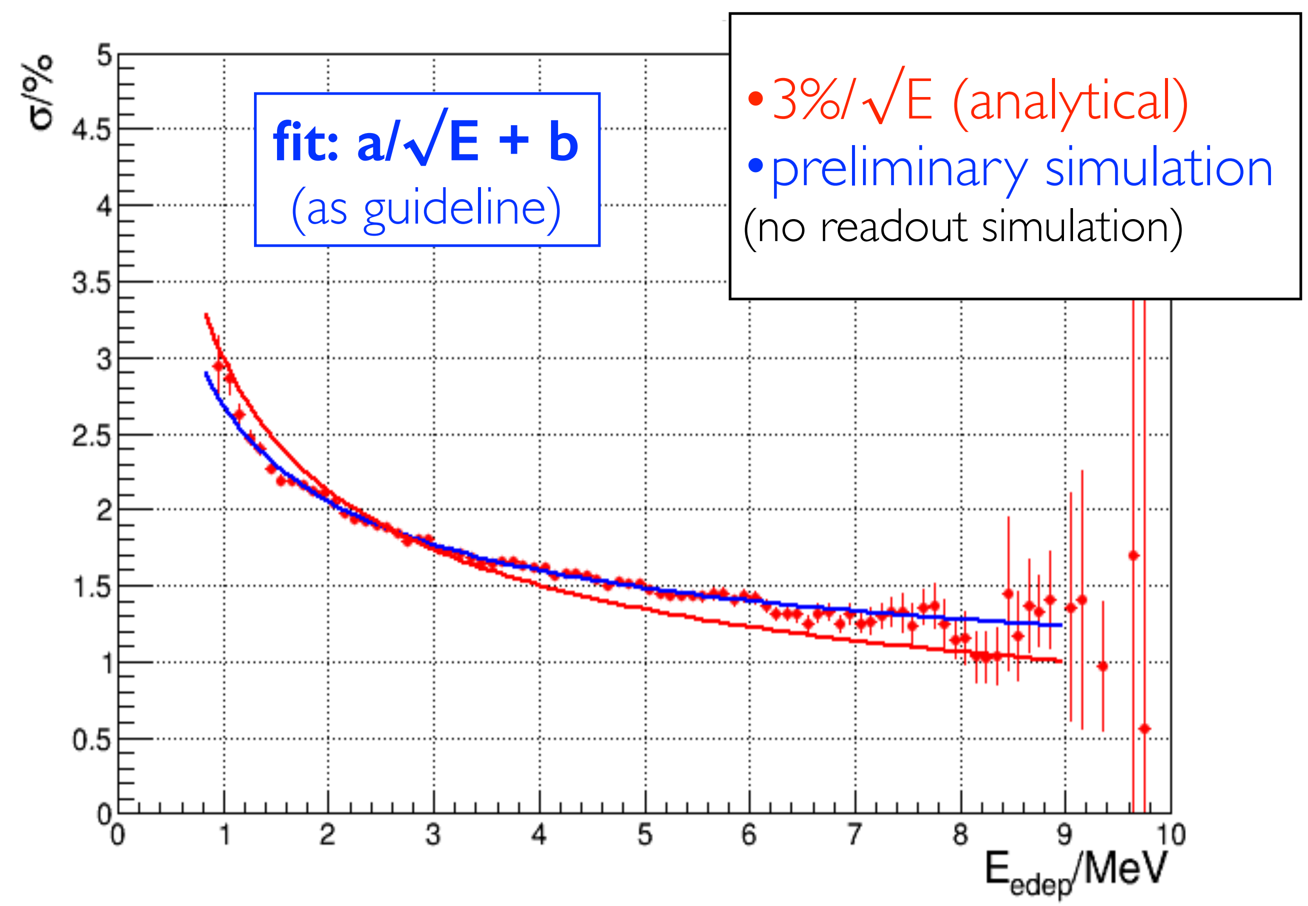
- large collaboration effort on high precision simulation (with readout, reconstruction, etc)→ a lot experience
  - investigate/optimise detector design & response control
- (main assumptions) QE @ ~35% + CE @ ~80% + light yield 10^4kγ/MeV + λ^{att}~20m [@430nm] + geometry

A=17.7m (LS)
B=(0.12+1.426+0.254)m=1.8m
C=0.45m
A+B=19.5m (position of PMT sphere center)
A+B+C=19.95m



major effort on high precision energy resolution understanding…

- full optical simulation (✓preliminary)
- full readout simulation (✗→soon)
- full position-reco (✓preliminary)
- full energy-reco (✓preliminary)
- full calibration (✗→soon)

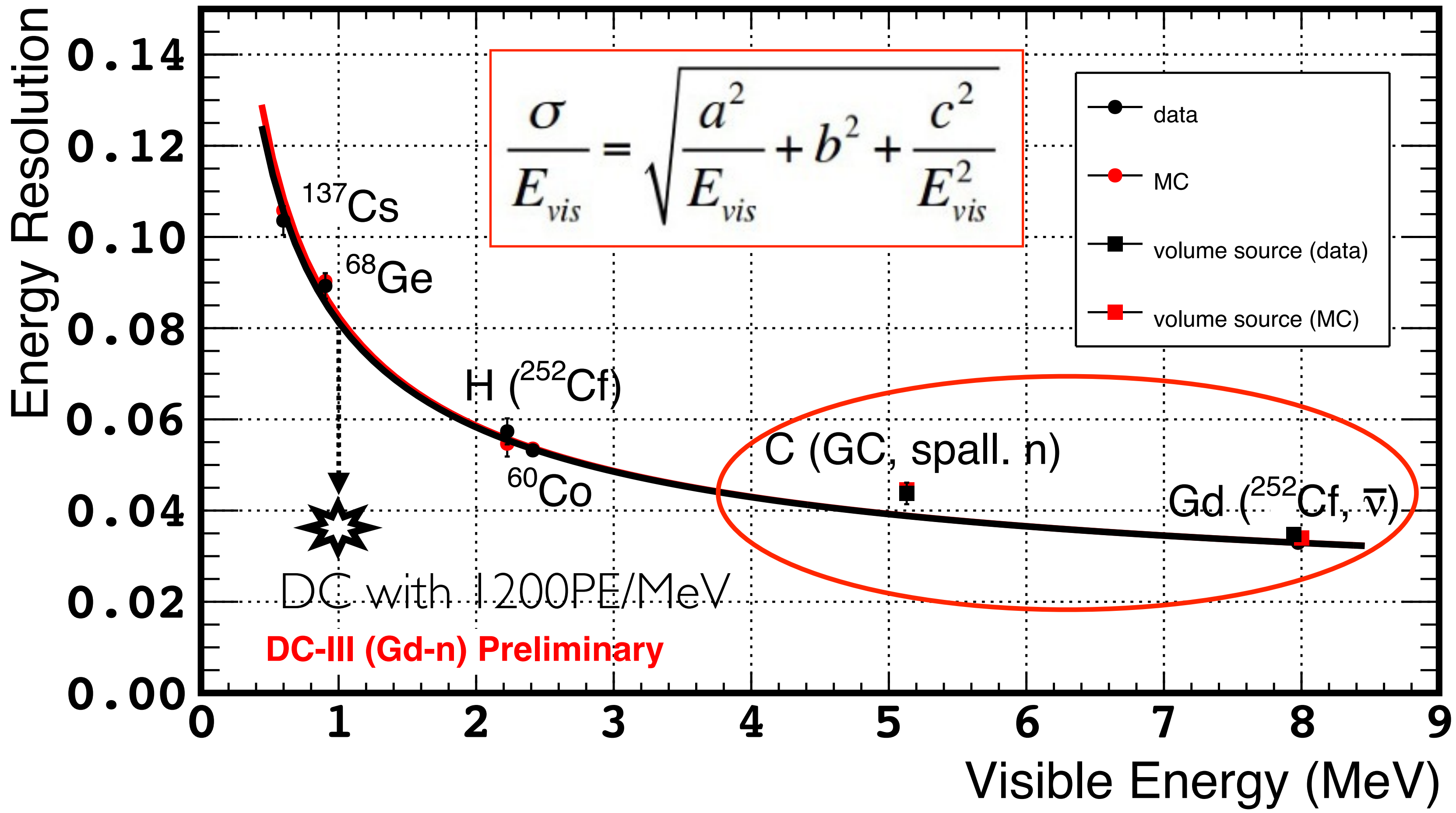


- both designs (full geometry, including structures)→ energy resolution is plausible (no showstopper)
- **≥1.1kPE/MeV** (enough light) [~75% coverage]→ **≤3% (stochastic-only)**
  - **how about non-stochastic terms contribution?** (under heavy investigation)

Anatael Cabrera (CNRS-IN2P3 & APC)

control energy resolution → DC as example…

arXiv:1406.7763



a: statistical term

b: constant term

c: e.g. electric noise

Data

a=0.0773±0.0025

b=0.0182±0.0014

c=0.0174±0.0107

MC

a=0.0770±0.0018

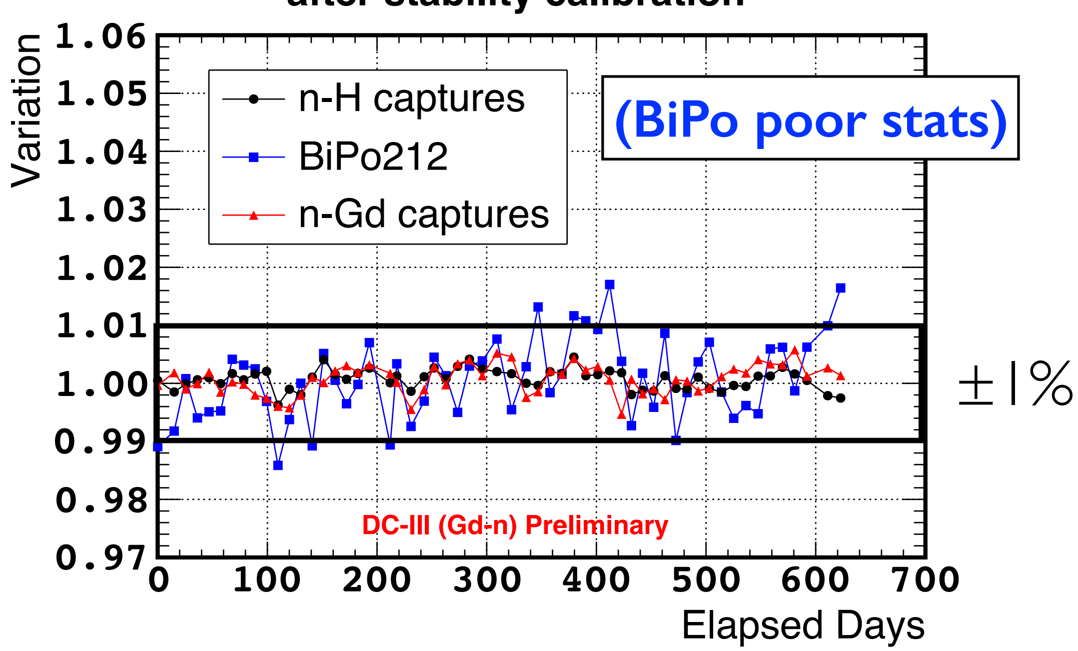
b=0.0183±0.0011

c=0.0235±0.0061

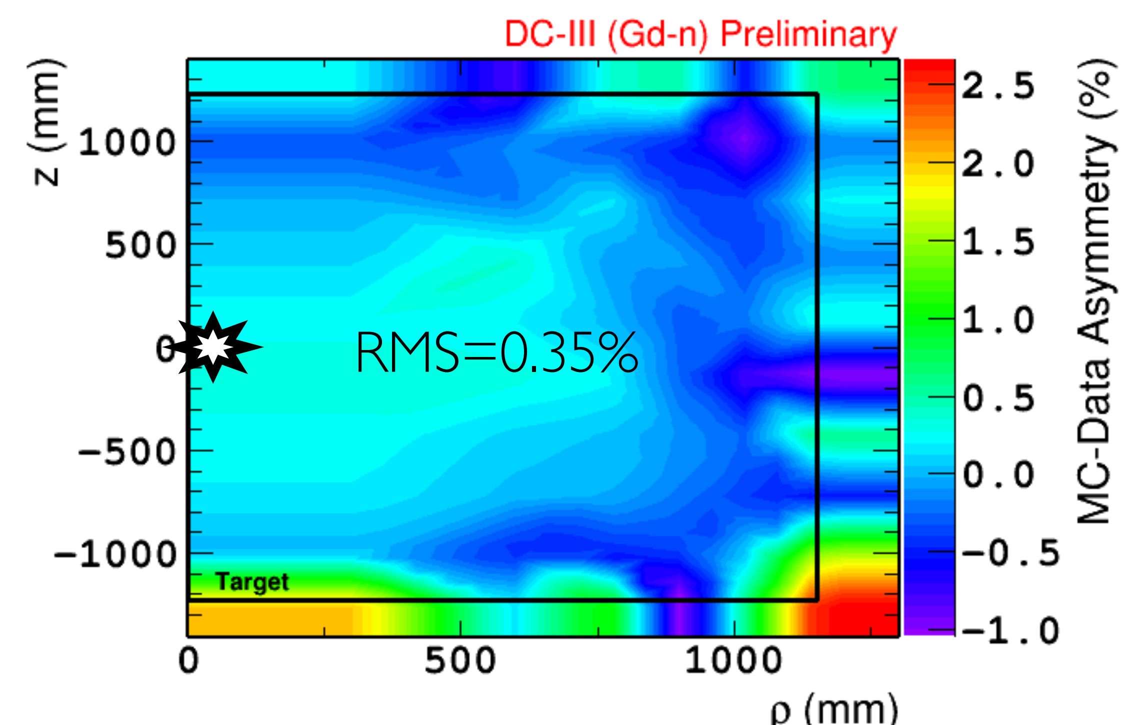
non-stochastic terms knowledge depends on confidence on Gd point (hard physics)

control of response stability

after stability calibration

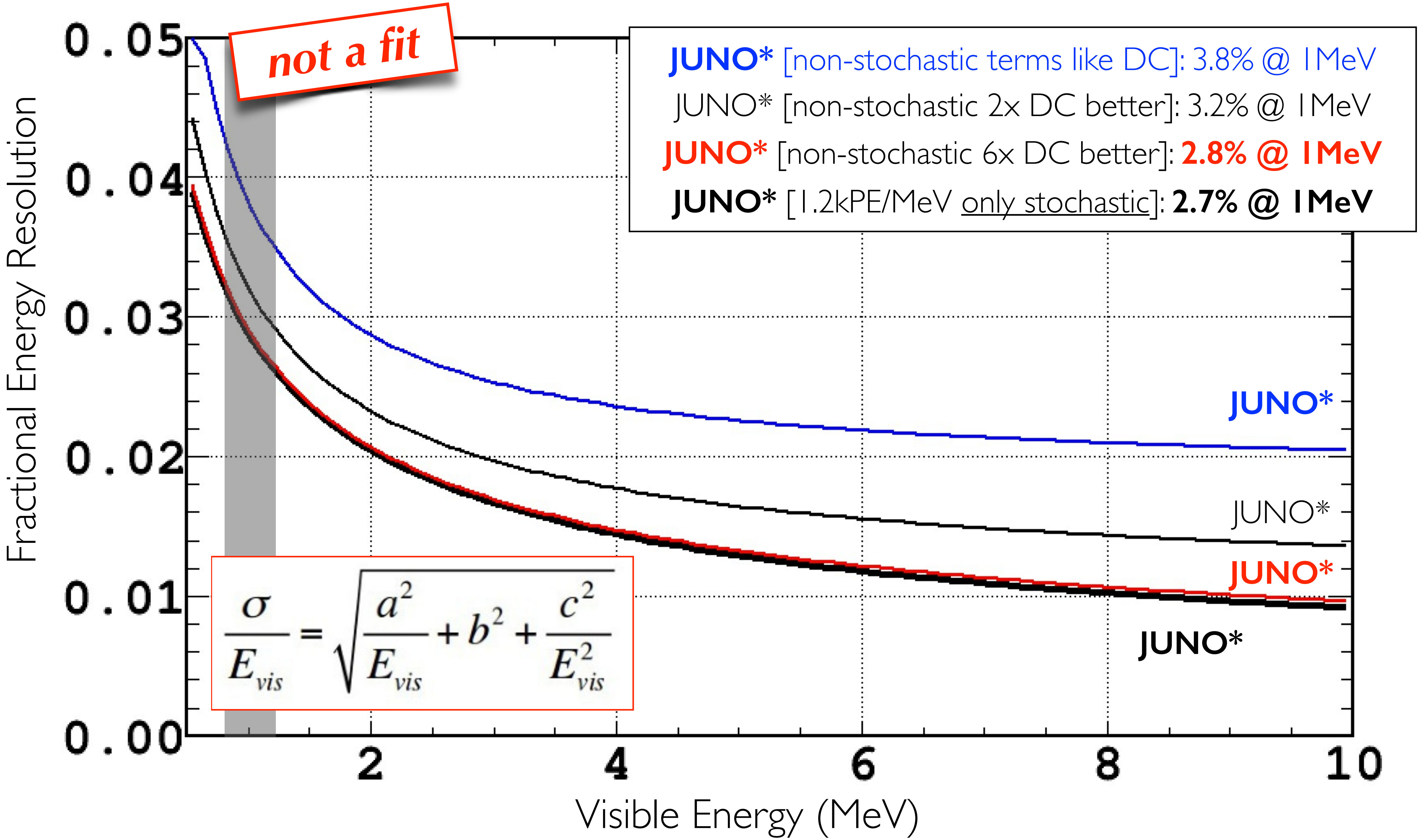


control of response uniformity



(extrapolation exercise) how far is ~3% @ 1MeV?

$\Delta m_{31}^2(IO) \neq \Delta m_{31}^2(NO) \Longrightarrow$ **δ~3%** (i.e. $\delta m^2/\Delta m^2$)

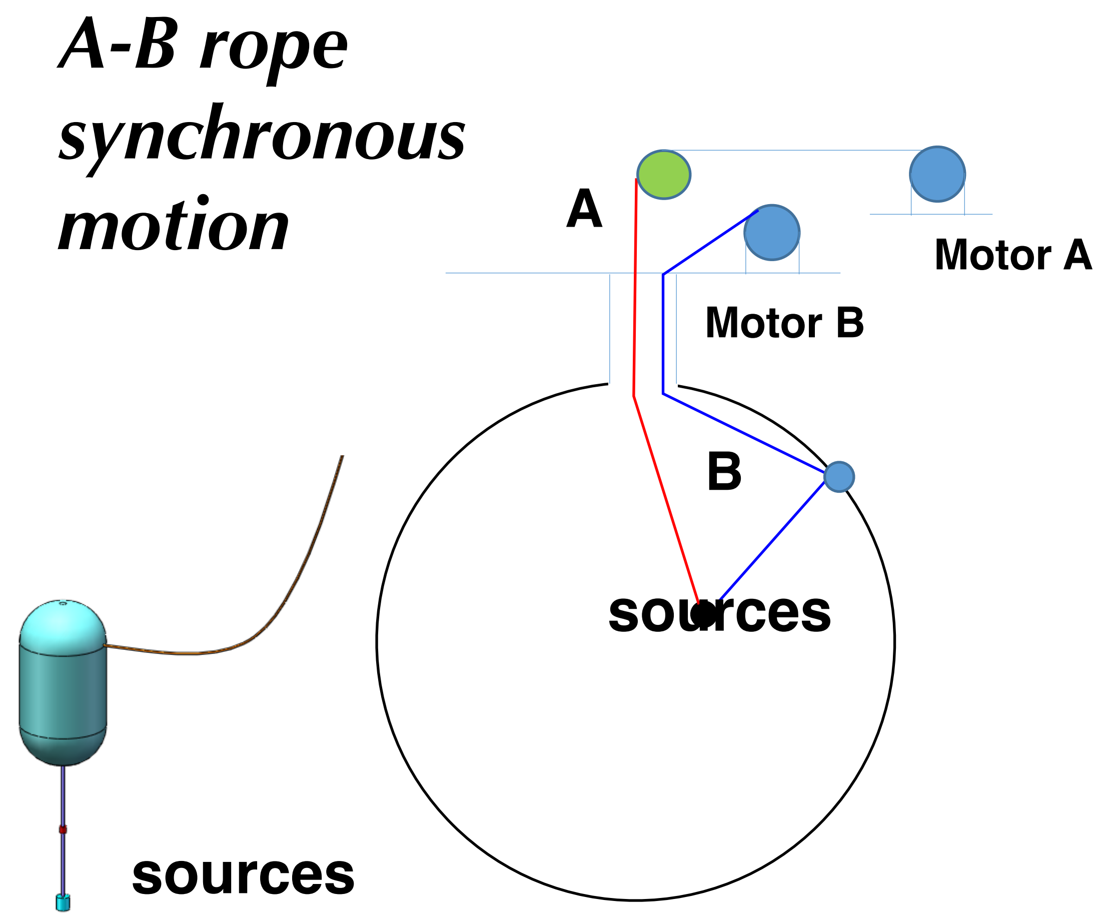


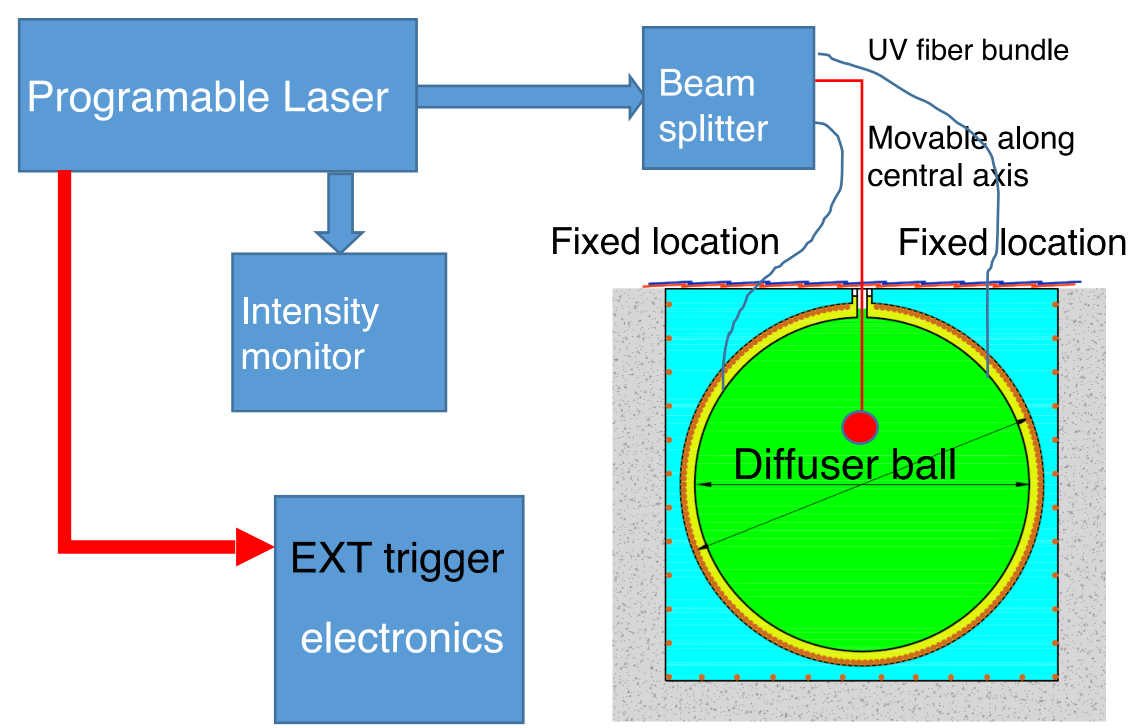
$$\frac{\sigma}{E_{vis}} = \sqrt{\frac{a^2}{E_{vis}} + b^2 + \frac{c^2}{E_{vis}^2}}$$

JUNO optimised for high precision calorimetry, unlike DC
(→much feedback from Borexino+DB+DC+KamLAND)

Calibration System Conceptual Designs

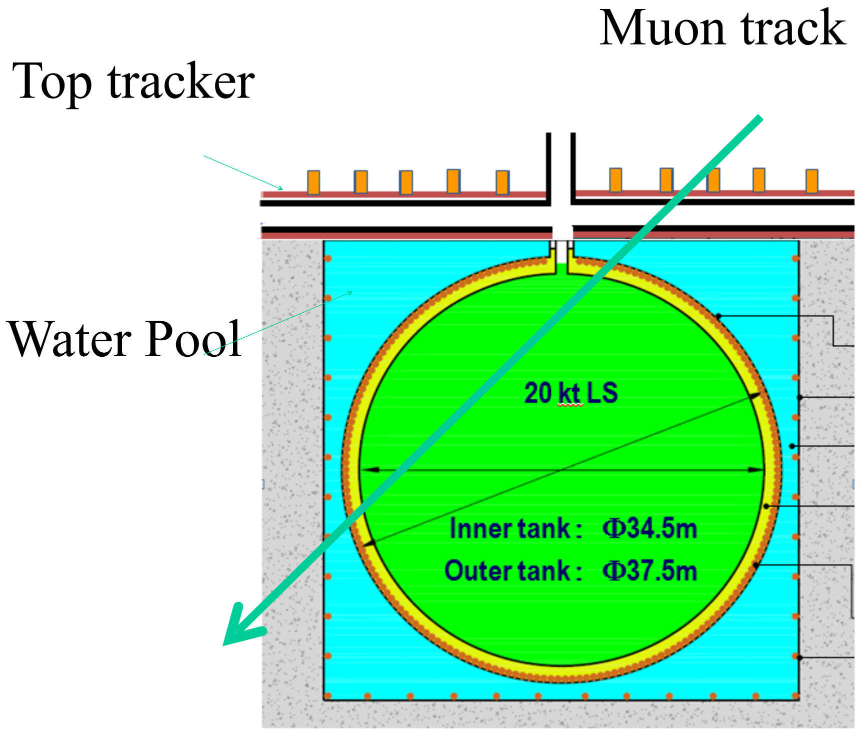
- high precision calorimetry
  - critical validation & cross-check
  - redundancy & 4π coverage
  - natural calibration: fast-n captures (after μ)
    - excellent readout behaviour upon μ
    - H-n & C-n (all the time & everywhere)
  - external calibration source: [0,10]MeV
- radioactive source calibration systems
  - z-axis calibration with high precision
    - spherical symmetry of response (→chimney)
  - rope system (off-z-axis deployment)
    - consider versatile system
  - guide tube system (off-z-axis deployment)
    - boundaries and near boundary regions
- short-lived diffusive radioactive sources
  - full volume response map calibration
- UV/blue laser systems
  - readout & scintillator monitoring/calibration *in situ*



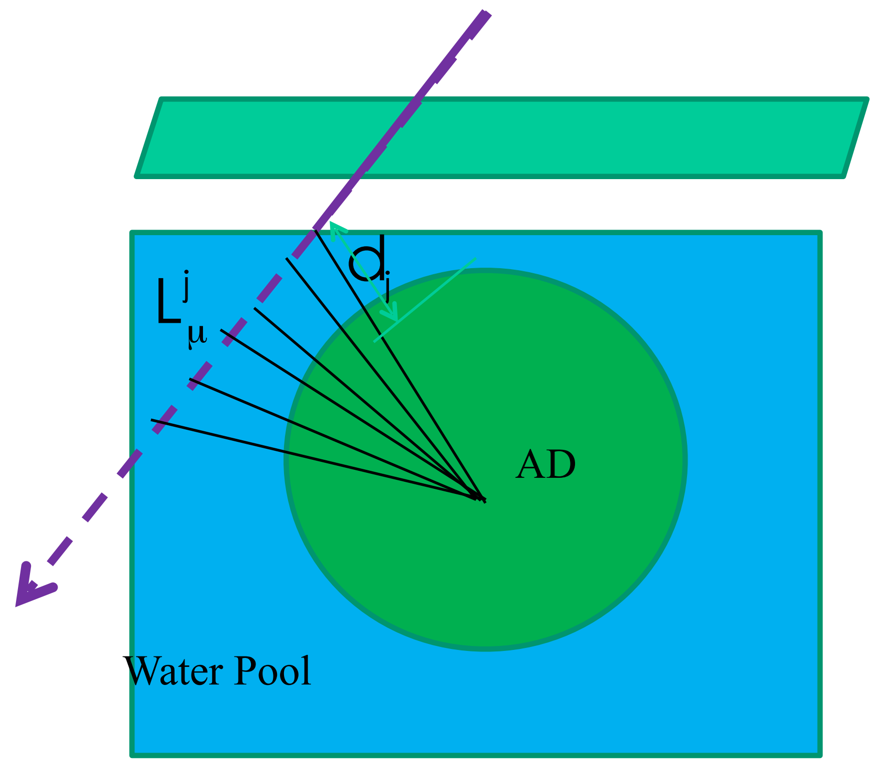


μ tracking & veto design⇒ all BGs linked to μ's…

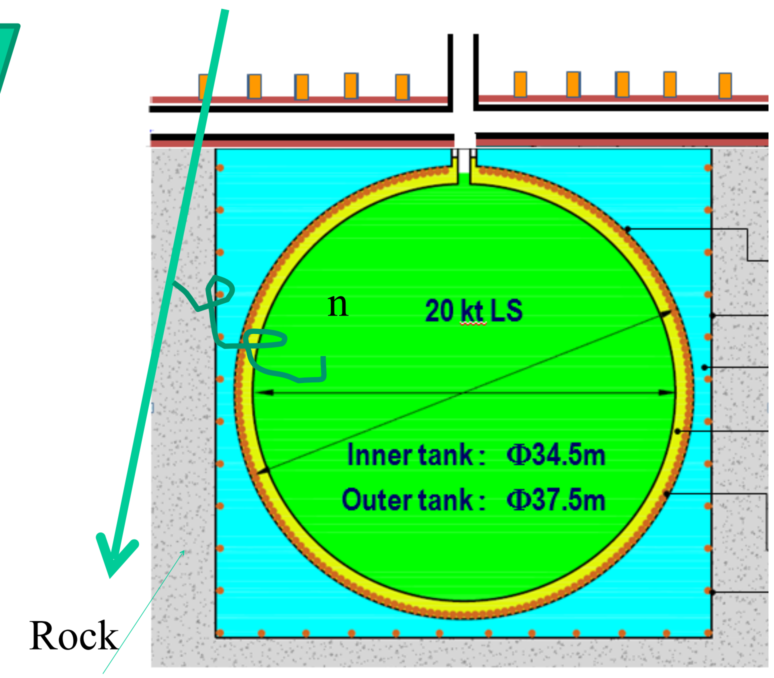
Central Detector muon



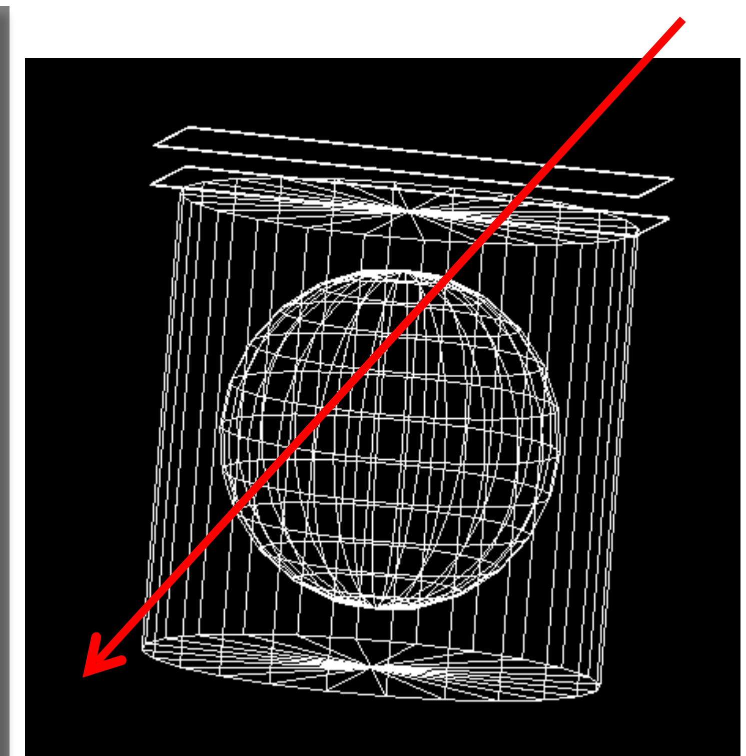
Water Pool muon



Rock muon



- not just a veto, but μ-tracking info→ better control of cosmogenic BG
- various designs and options for the Top Tracker (TT)
  - OPERA scintillator calorimeters will be moved to JUNO
  - RPCs are being considered
  - other optioncs considered (Ar gas TPCs, NOvA-LS tubes, etc)
- simulation and design are going through iteration
- Earth magnetic field shielding is being designed

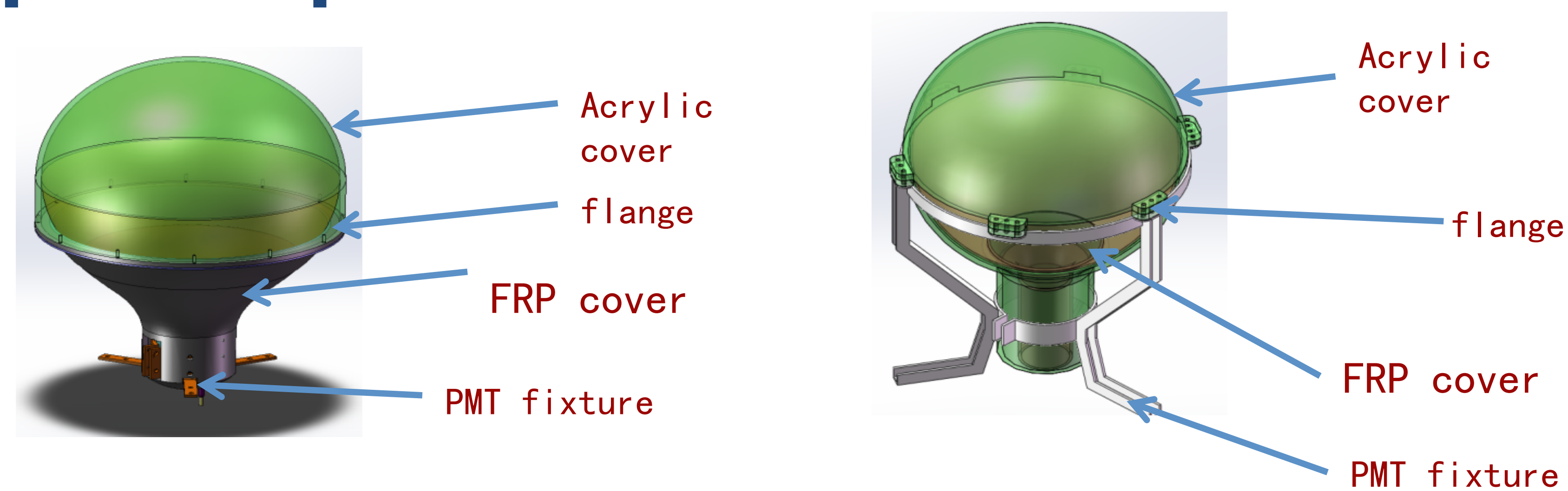


R&D status report…

- large PMT system
- liquid scintillator system

PMT implosion protection system…

Possible Implosion-proof structure



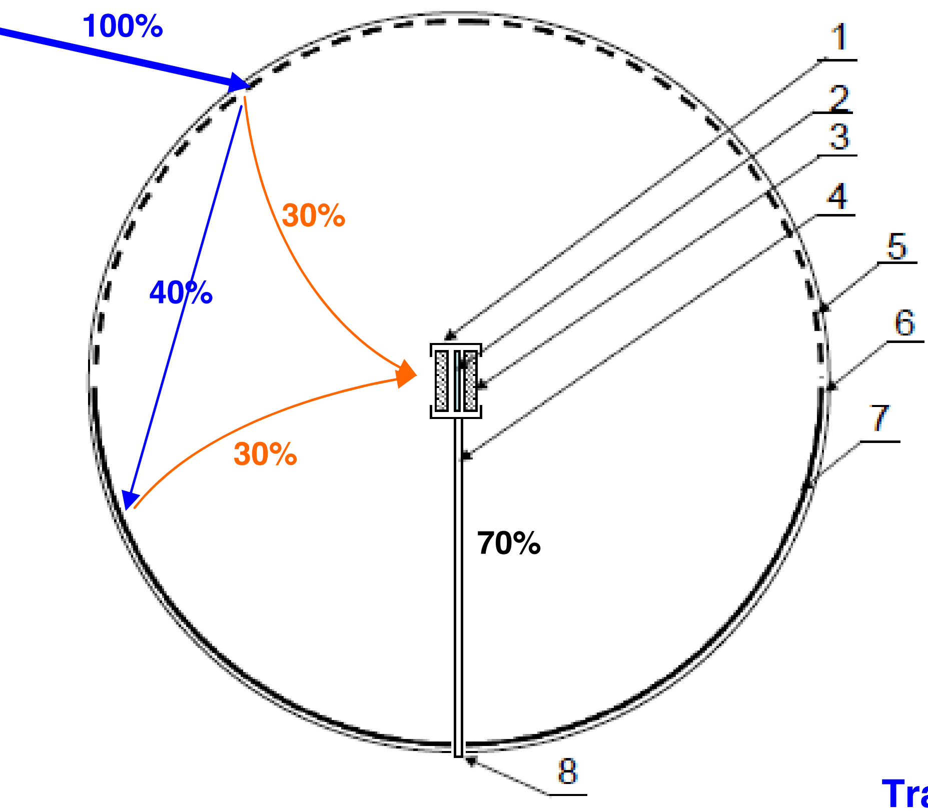
- two groups working on the implosion prevention design
  - calculation and experimentation (navy lab + university lab)
- (this year) finishing the shock-wave calculation & comparison to data
- (next year) chain reaction experimentation and iteration (design & experiments)

MCP-PMTs…

JUNO PMT Plan A progressing well

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain

2) Using transmission photocathode (front hemisphere) and reflection photocathode (back hemisphere) } **~ 4π viewing angle!**



1.Insulated trestle table

2.Anode

3.MCP dodule

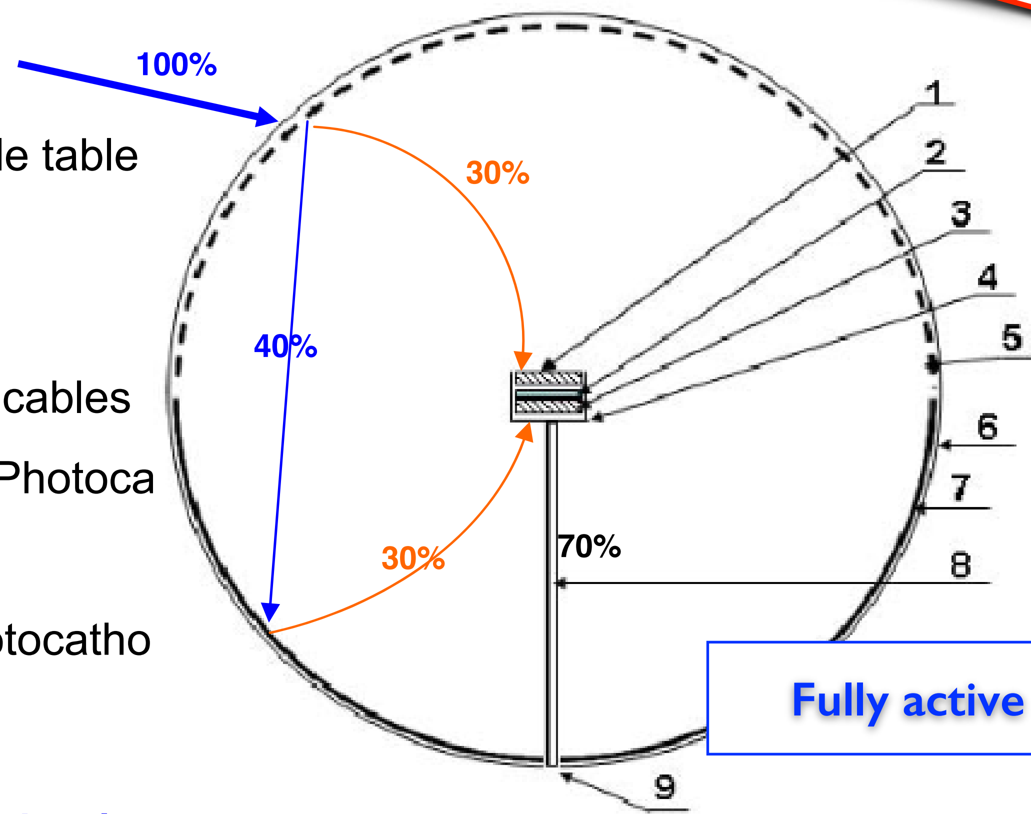
4.Bracket of the cables

5.Transmission Photoca

6.Glass shell

7.Reflection Photocatho

8.Glass joint



Fully active sphere surface

Transmission rate of the glass: 40%

Quantum Efficiency (QE) : of Transmission Photocathode 30% ; of Reflection Photocathode 30% ;

Collection Efficiency (CE) of MCP : 70%;

$$PD = QE_{Trans}*CE + TR_{Photo}QE_{Ref}*CE = 30\%*70\% + 40\%*30\%*70\% = 30\%$$

Photon Detection Efficiency: 15% → 30% ; ×~2 at least !

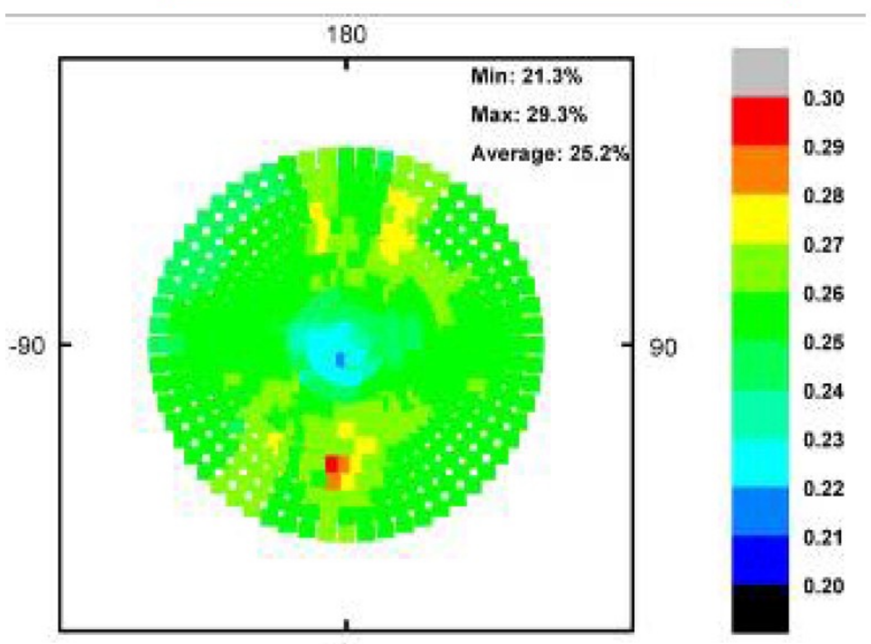
3 Plans in Parallel by Collaborators

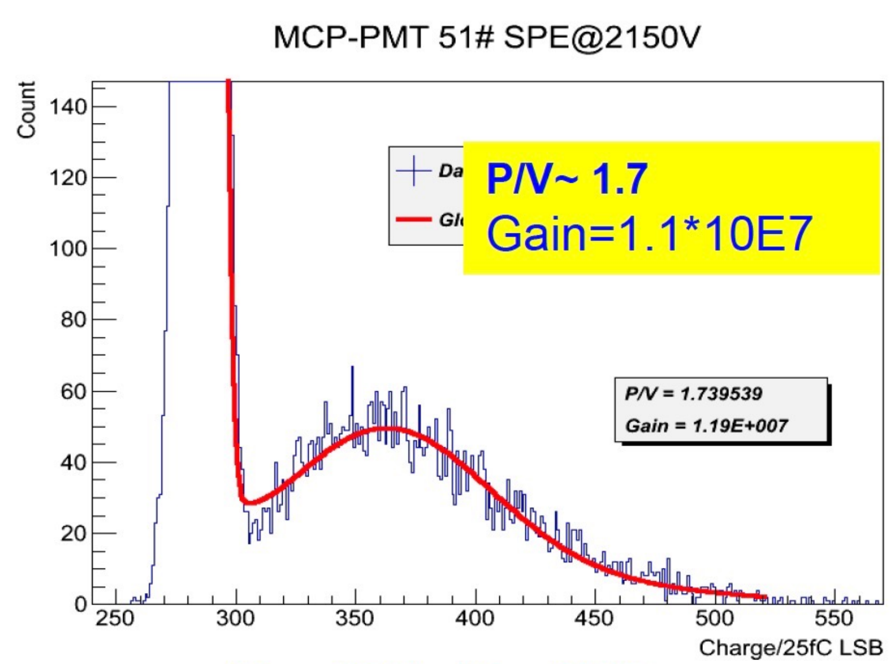
- **JUNO PMT plan B: Photonics China PMTs**
- **JUNO PMT plan C: new 20" Hamamatsu SBA high QE PMTs**

PMT R&D: further info…

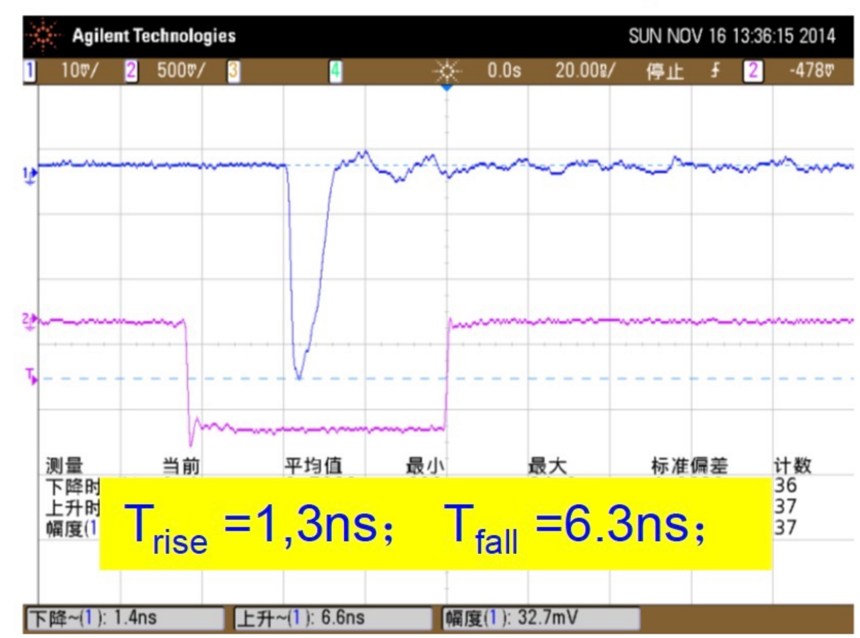
20 inch **sphere** Prototype 20 inch **ellipsoidal** Prototype

8"- MCP-PMT-035#





The SPE of the PMT



The signal of the 8 inch PMT

(a few examples)

Anatael Cabrera (CNRS-IN2P3 & APC)

MCP-PMT R&D summary…

	8" MPC-PMT	20" MPC-PMT
prototypes produced?	✓	✓
glass production	✓	✓
glass shape optimisation	on-going	on-going
low background glass	soon	soon
photocathode uniformity	✓ (under investigation→ quantification)	
QE⊗CE estimation	~25% ✓ (goal→ ~35%)	~22% ✓ (goal→ ~35%)
CE estimation	~60% (goal→ ~80%)	
MPC status	✓	✓
MPC location	several	several
signal optimisation	on-going (already reasonable)	
T-spread (TTS)	<20ns (<5ns)	
gain	10^7 @ ~2kV	
single-PE (P/V)	~2.5 (→improving)	~1.7 (goal→>2.5)
linearity studies	better than dynode-PMT (→ MPC)	
dark noise rate	O(5k s^{-1})	O(50k s^{-1})
JUNO benches @IHEP/@GS	✓/✓	✓/✗ (not yet)
status	working (not yet @ goals→ ongoing effort)	

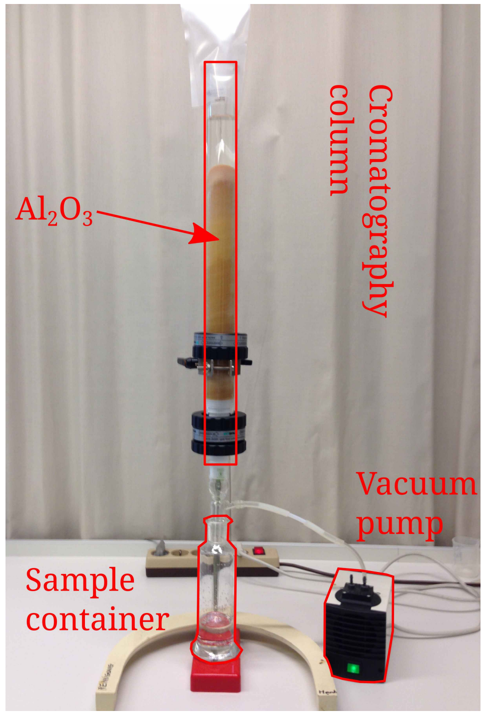
MCP-PMT (current knowledge) vs Hamamatsu…

➢ The performance of the 20 inch prototypes

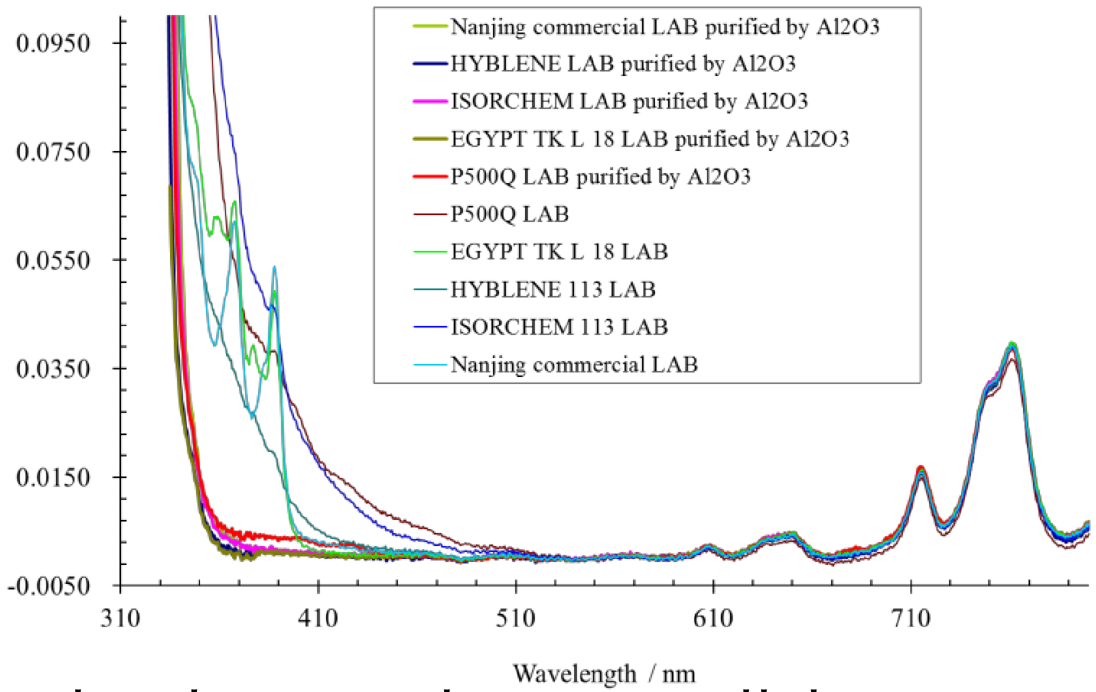
Characteristics	unit	R3600 (Hamamatsu)	MCP-PMT-20 (IHEP)	R12860 (Hamamatsu)	MCP-PMT-20 (IHEP)
ststus		Finished	Finished	Finished	Plan
size	inch	20	20	20	20
Spectral Response	nm	300~650	300~650	300~650	300~650
Photocathode Material	--	Bialkali-HQE	Bialkali	Bialkali-HQE	Bialkali
Electron Multiplier	--	Dynode	MCP	Dynode	MCP
Gain	--	$\geq 1 \times 10^7$	$\geq 1 \times 10^7$	$\geq 1 \times 10^7$	$\geq 1 \times 10^7$
Photocathode mode	**--**	**transmission**	**reflection + transmission**	**transmission**	**reflection + transmission**
Quantum Efficiency（400nm）	**%**	**25**	**22 (?)**	**32**	**35 (?)**
Electron Multiplier Collection efficiency	**%**	**～90%**	**～60%**	**～90%**	**～80%**
Anode Dark Count	**Hz**	**~50K**	**~60K**	**~50K**	**~50K**
Glass	**--**	**HARIO-32**	**Low-Potassium Glass-**	**HARIO-32**	**Low-Potassium Glass-**

Liquid Scintillator purification (radioactivity & transparency)

- key points about liquid scintillator
  - light yield
  - optical transparency
  - radioactive purity
- key technique under R&D: **purification**
  - expertise from Borexino on board
  - several samples & techniques under evaluation
    - up to λ^{att}~25m achieved(!!)

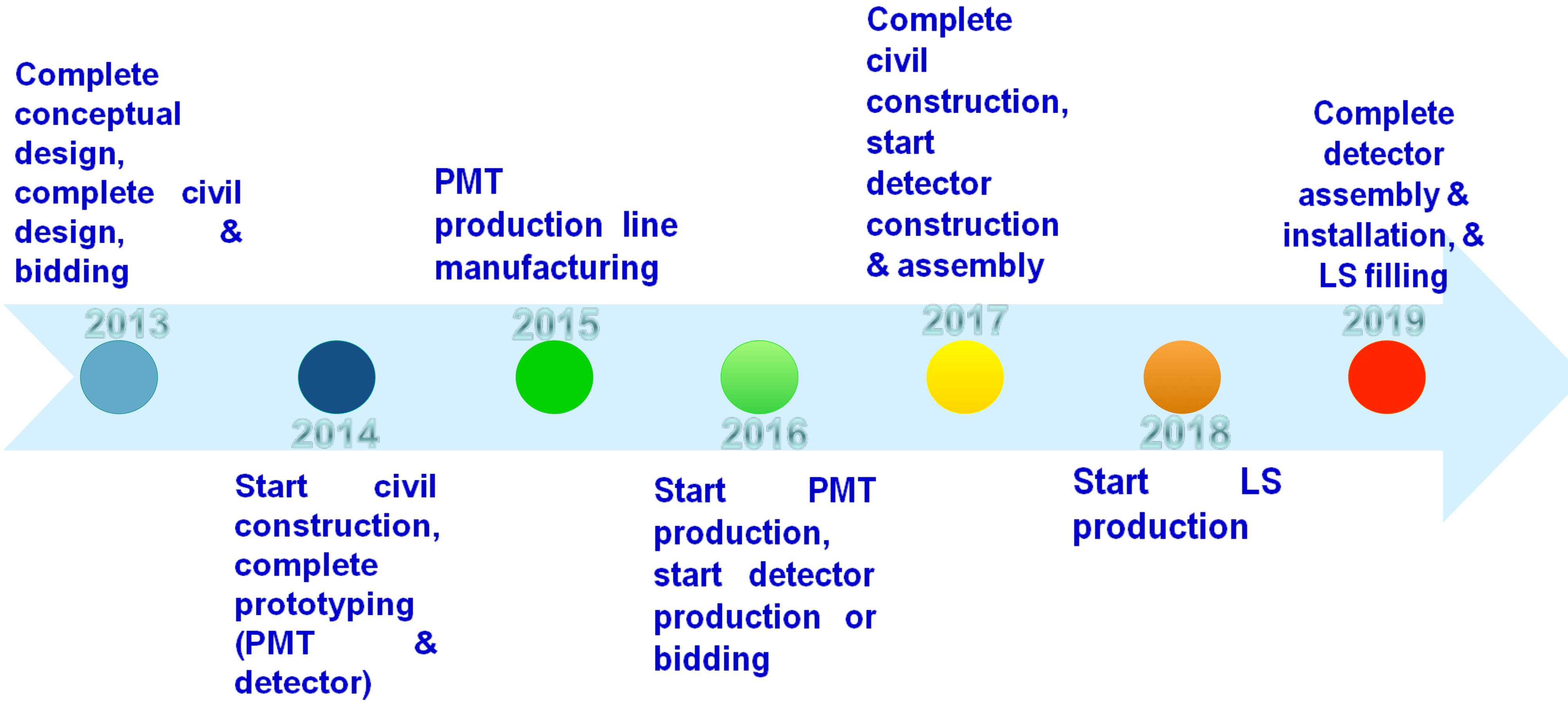


- Column purification
  - Various packing materials
- Vacuum Distillation (V.D.)
  - Single stage V.D. in the lab at IHEP
  - Multi-stage V.D. in the lab at IHEP
  - Molecular distillation (commercially available)
  - Real boiling point distillation (commercially available)



- Our Italian, Russian and German collaborators are also doing studies in parallel. We all see space for improvements and R&D activities are ongoing

conclusion…



- JUNO unprecedented large & high precision calorimetry liquid scintillator detector
- main physics topics: high precision neutrino oscillation with reactor-ν…
  - (atmospheric) Mass-Hierarchy without MSW enhancement (complementary to other approaches)
  - (solar) ≤1% high precision solar terms → needed for CP-violation determination (complementarity)
  - (non-reactor ν's) exciting program with unique and leading physics capabilities [→ fantastic detector]
- JUNO international collaboration (since July 2014) & funded in China→ data taking by ~2020
- JUNO R&D (PMTs & scintillator) excellent progress→ consistent with proposed schedule