CAS Center for Excellence in Particle Physics

Self-assessment of Performance

From October 1, 2013 to September 30, 2014

WEILI ZHONG

11-21, 2014   Beijing

Basic Information

- I am in the *Neutrino and Dark Matter Frontier* division of CCEPP.
- I joined the neutrino group (led by Prof. Changgen Yang) of the *Particle Astrophysics Center* division of IHEP in March of 2012.
- I am interested in neutrino physics and dark matter detection.
- I am currently involved in:
  - **Daya Bay** reactor antineutrino experiment
  - **JUNO** reactor antineutrino experiment
  - **DarkSide** dark matter experiment for WIMP direct detection

Scientific Performance

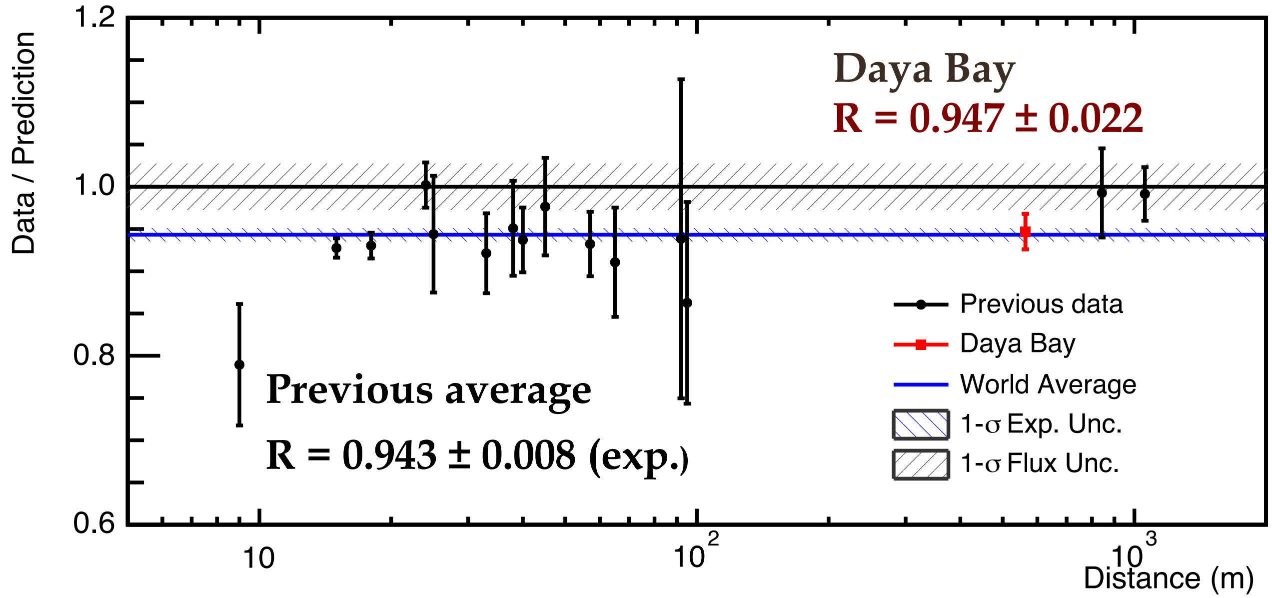
- The Daya Bay Experiment
  - The reactor antineutrino flux and spectrum
    - Preliminary results released at ICHEP'14
    - Collaboration Paper is drafted for review
- The JUNO Experiment
  - Yellow book
    - Chapter 2: Mass hierarchy & Chapter 9: Sterile neutrino
  - Reactor antineutrino spectrum prediction
  - Physics potential to light sterile neutrino
- The DarkSide Project
  - Prototype of liquid argon detector
  - Dark matter detection at CJPL

Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay

- Physics topics in Daya Bay:
  - Oscillation analysis: $\sin^2 2\theta_{13}$ and Δm^2_{ee}
  - Reactor analysis: absolute reactor antineutrino flux and spectrum
  - Supernova detection
  - New physics search: sterile neutrinos, CPT violation, etc…
- Organize analysis of Reactor flux and spectrum:
  - Convenors of Reactor Working Group: Karsten Heeger (Yale U.) and Weili Zhong
- Released the preliminary results of reactor analysis at ICHEP 2014
  - One of the highlights in ICHEP'14 experimental summary talk.

Absolute Flux Measurement (Neutrino 2014)

- Dataset: ~300,000 Inverse Beta Decay events (IBD) in 3 Antineutrino Detectors (AD) of two near sites.
- Absolute flux: $Y_0 = 1.553\times10^{-18}$ cm^2/GW/day or $\sigma_f = 5.934\times10^{-43}$ cm^2/fission
- Global comparison of measurement and prediction (Huber+Mueller model):



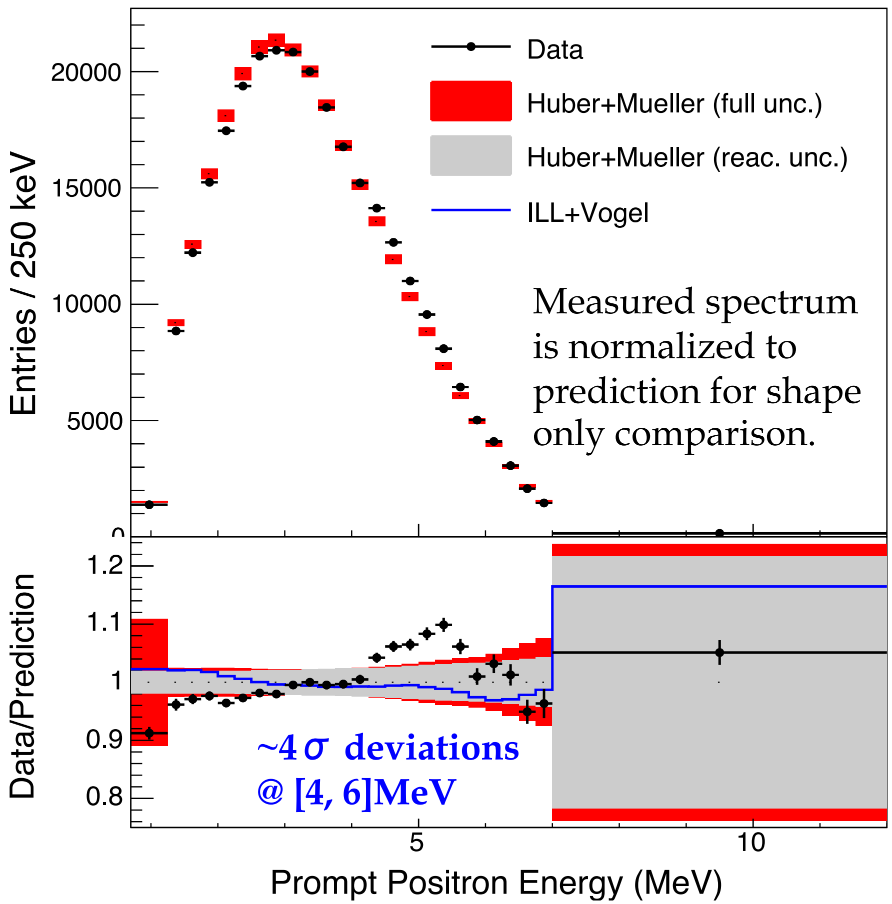
Data/Pred. (Huber+Mueller) 0.947 ± 0.022

Data/Pred. (ILL+Vogel) 0.992 ± 0.023

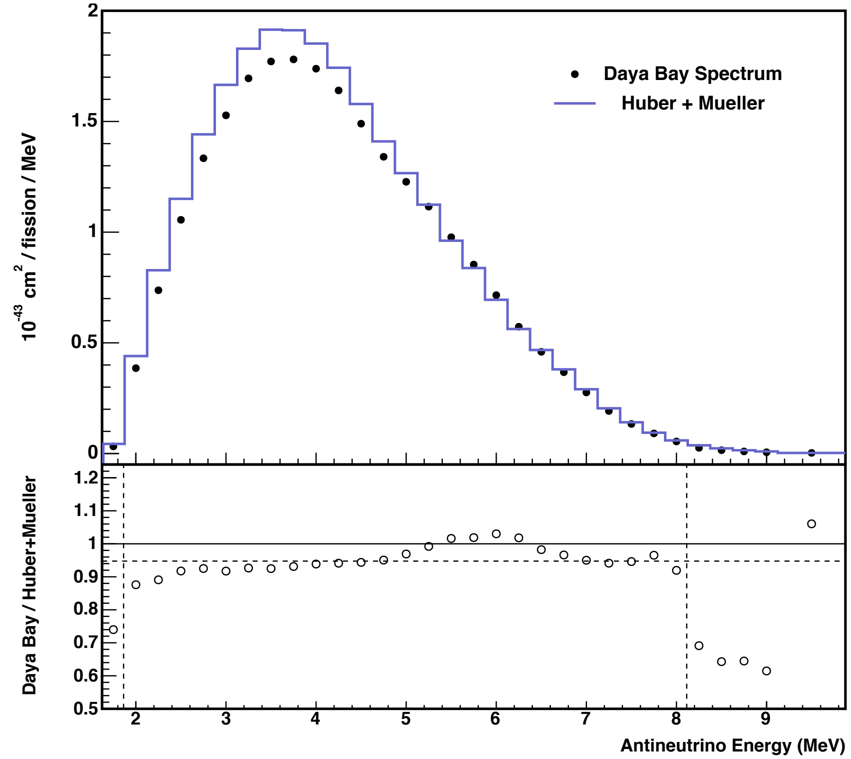
Daya Bay's reactor antineutrino flux measurement is consistent with previous short baseline experiments.

Absolute Spectrum Measurement (ICHEP 2014)

Positron spectrum



Antineutrino spectrum



Anti-ν spectrum could be used in place of flux models to predict spectrum for other reactor experiments.

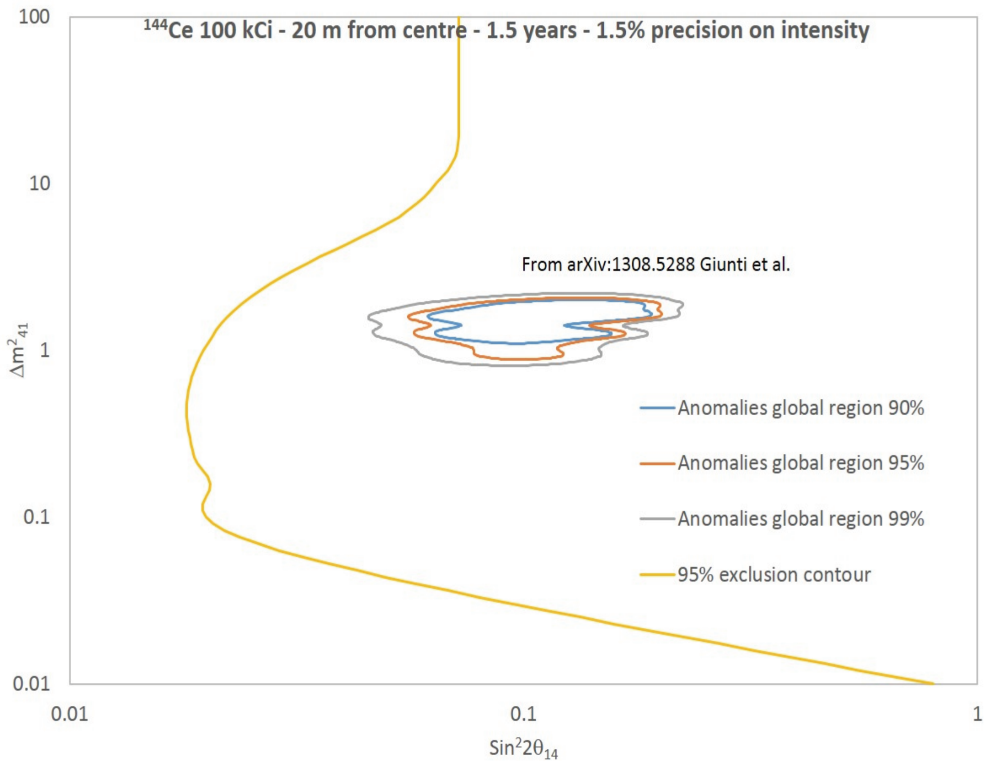
Collaboration paper is drafted, and will be sent to a larger audience for review around the end of this year.

Yellow Book of the JUNO Experiment

- The JUNO Experiment:
  - Primary physics goal: neutrino mass hierarchy
  - Other physics potentials:
    - Solar neutrinos,
    - Atmospheric neutrinos,
    - Supernova, sterile, geo-neutrinos,
    - Indirect dark matter searches…
- **Sterile Neutrino Chapter**
  - Two editors: Wang Meng (SDU) and Weili Zhong (IHEP)
  - A preliminary draft is complete. The polishing of the chapter is underway.

Physics Potential of JUNO

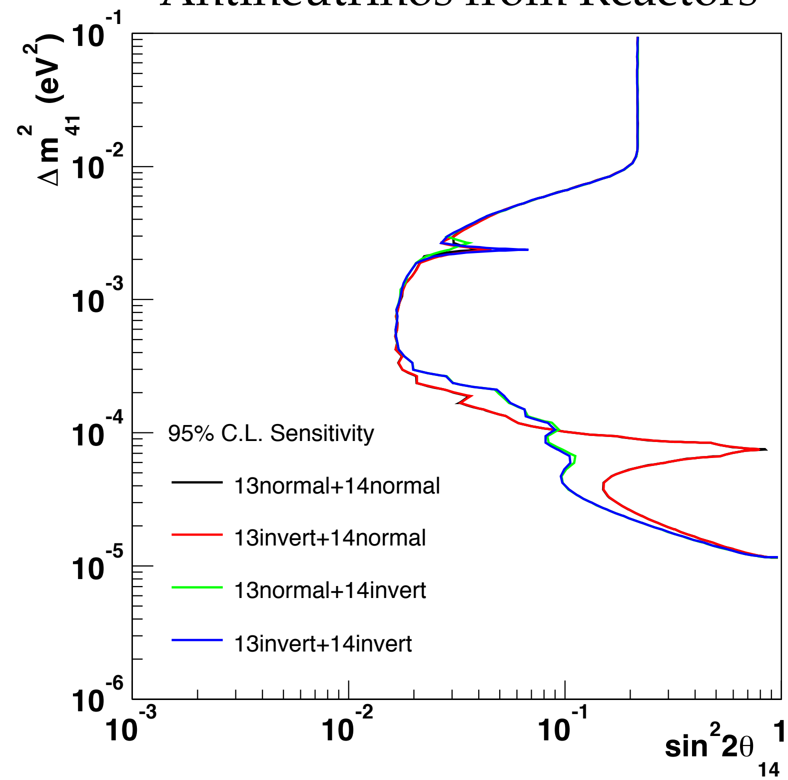
Antineutrinos from Strong Source



Baseline: a few meters to ~40 meters

Best sensitivity among all proposed similar experiments for sterile neutrino search

Antineutrinos from Reactors



Baseline: ~53km, from reactor to detector

No sensitivity at interested Δm^2_{new} (~1 eV^2) region.

Yellow Book of the JUNO Experiment

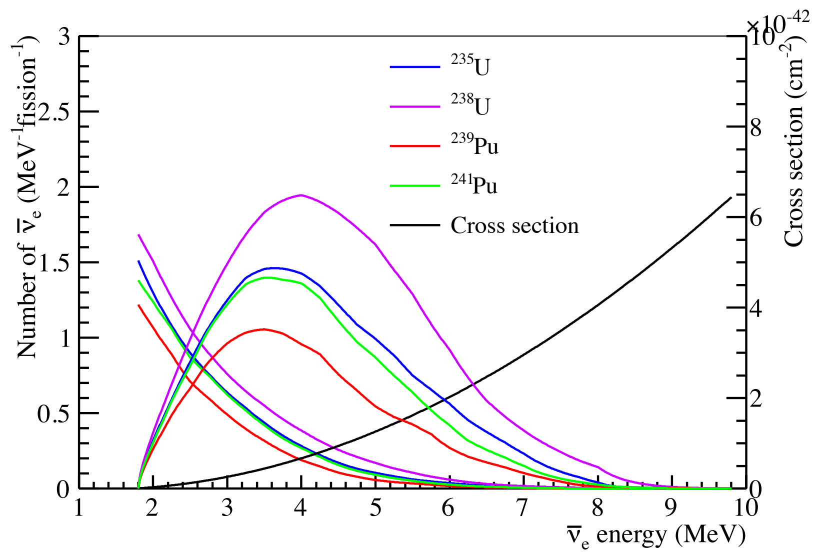
- **Mass Hierarchy (MH) Chapter**
  - Editor of Reactor Section. Preliminary draft of reactor section is finished, and reviewed by a limited audience.
  - Describes the spectrum prediction method currently in use for the MH sensitivity calculation: Reactor flux models
    - ILL + Vogel model, Huber + Mueller model

Antineutrino production at reactor:

$$\Phi(E_\nu) = \frac{W_{th}}{\sum_i f_i e_i} \cdot \sum_i f_i \cdot S_i(E_\nu)$$

Antineutrino detection at detector (w/o oscillation):

$$S(E_\nu) = \frac{1}{4\pi L^2} \cdot \Phi(E_\nu) \cdot \epsilon \cdot N_p \cdot \sigma(E_\nu)$$



Spectrum prediction with measurement of Daya Bay instead of with models

- Sensitivity of MH Determination:
  - Assume NH as true MH, and fit the spectrum with both false and true MH cases: $\Delta\chi^2 = \chi^2(\text{false}) - \chi^2(\text{true})$
  - relative measurement can reach a sensitivity of 3σ ($\Delta\chi^2 \sim 9$),
  - absolute measurement (with the constraint of $\Delta m^2_{\mu\mu} \sim 1\%$) can reach a sensitivity of 4σ ($\Delta\chi^2 \sim 16$).

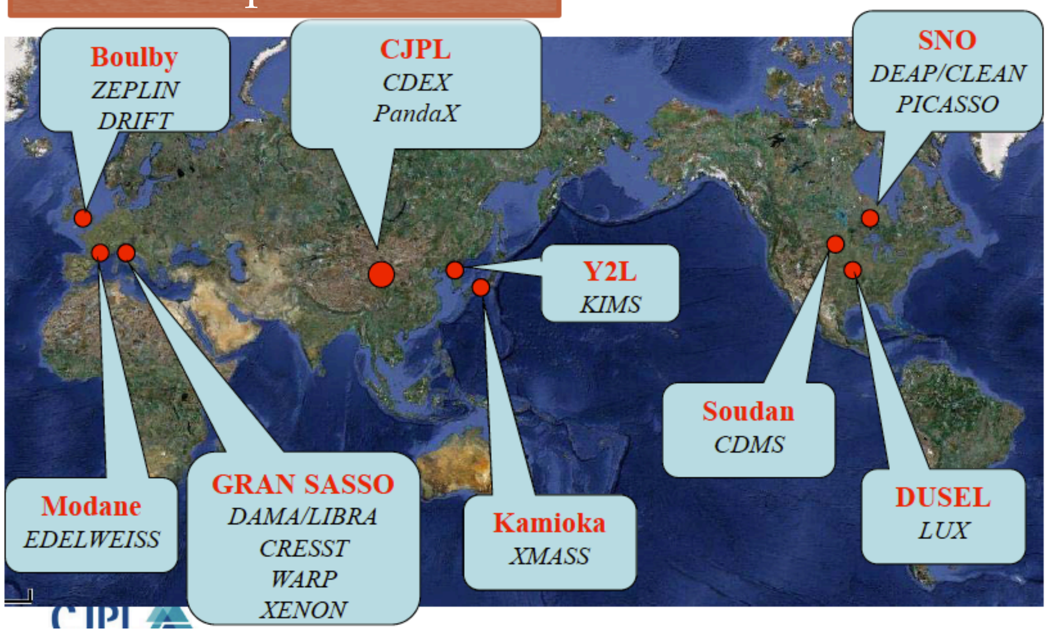
- Control reactor shape uncertainty at 1% level:
  - With 1% shape uncertainty $\Delta\chi^2$ degrades less than 1;
  - With 2% shape uncertainty $\Delta\chi^2$ degrades about 2.

- Shape uncertainty of prediction with current models can not reach 1% level
  - Treat Daya Bay as a 'near site' of JUNO: similar reactors, similar detector response, different baselines
  - Use measurement of Daya Bay to predict JUNO's observation: related work is underway.

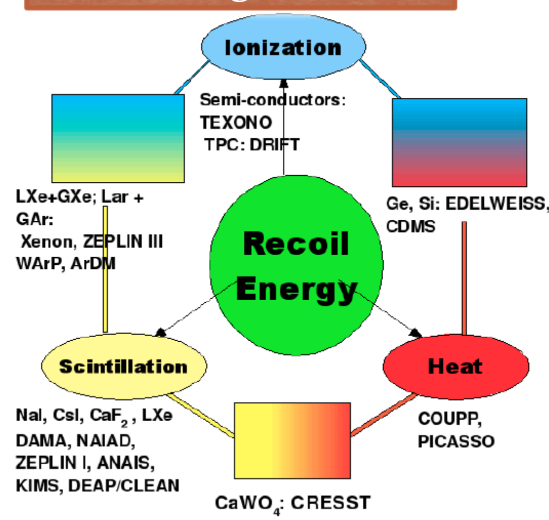
DarkSide Project

- WIMPs (GeV-TeV, 220 km/s, cross-section: ~weak interaction)
- Direct dark matter detection:
  - Elastic scattering of WIMPs and targets: measure recoil energy (1-100 keV)
  - DarkSide-3: Several-tens of tons Liquid Argon detector

A lot of experiments….



Multiple detection technologies…

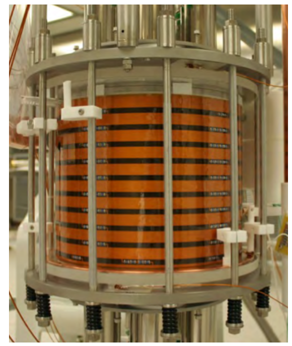


→ Zero-background experiment

A Liquid Argon Detector Prototype at IHEP

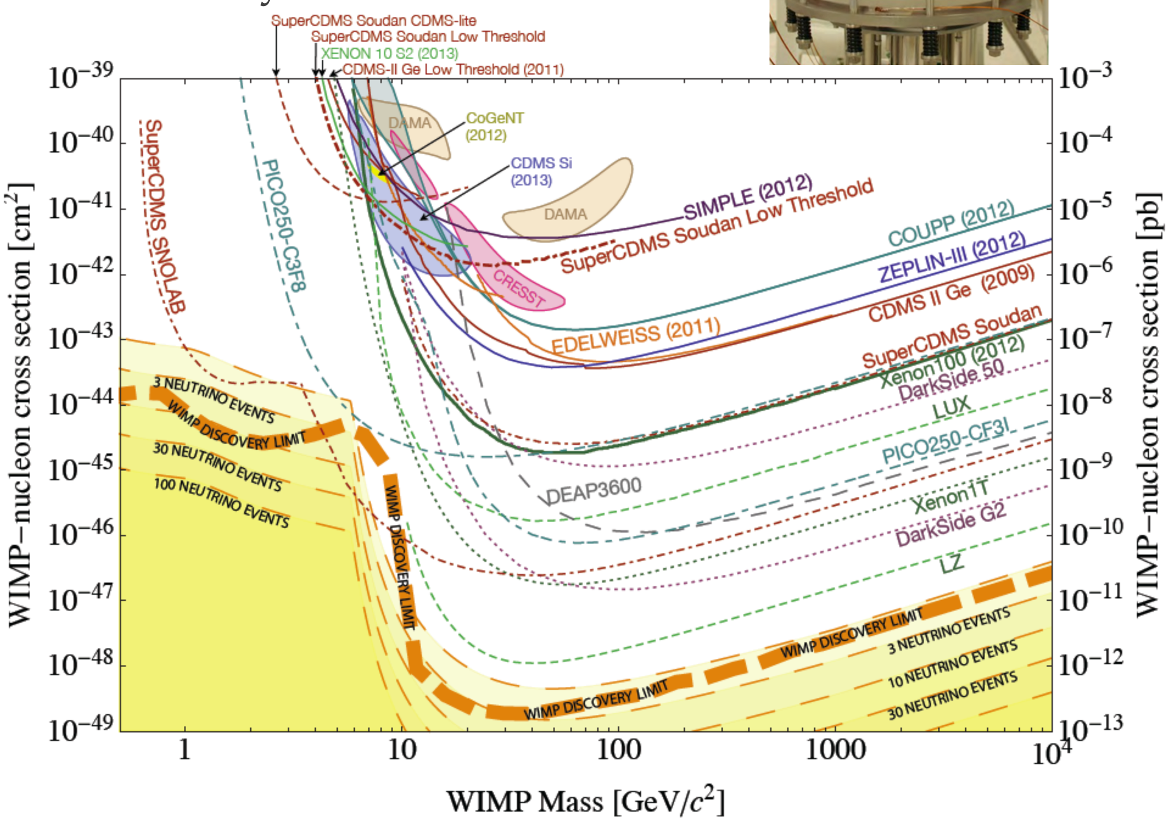
DarkSide-10: 10 kg
DarkSide-50: 50 kg
DarkSide-G2: 3.8 ton
DarkSide-G3: 20 – 50 tons

Darkside-10



A LAr detector (single phase) prototype is assembled at IHEP based purely on domestic industry

Sensitivity of DarkSide-G2:



Other Professional Performance

- Serving as a member of the speaker committee of the JUNO experiment
  - Discuss bylaws of the committee
  - Maintain webpage for conferences and speaker records
  - Select speakers for conference and workshop invitations

- Mentor three students from different institutes and universities
  - Qingwang Zhao (Ph.D. student of Prof. Jun Cao, IHEP), working on Daya Bay
  - Yanfei Zhao (M.D. student, NCEPU), working on Daya Bay
  - Chao Li (Ph. D. student of SDU), working on JUNO

Publications and Talks

- **Publications and preprints:**
  1. Search for a Light Sterile Neutrino at Daya Bay, DAYA-BAY Collaboration, Jul 27, 2014. 7 pp. arXiv:1407.7259
  2. The Muon System of the Daya Bay Reactor Antineutrino Experiment, Daya Bay Collaboration, Jul 1, 2014. 18 pp., arXiv:1407.0275
  3. Independent Measurement of Theta13 via Neutron Capture on Hydrogen at Daya Bay, Daya Bay Collaboration, Jun 25, 2014. 7 pp., arXiv:1406.6468
  4. Uncertainties analysis of fission fraction for reactor antineutrino experiments using DRAGON, X.B. Ma, L.Z. Wang, Y.X. Chen, **W.L. Zhong,** F.P. An. May 27, 2014. arXiv: 1405.6807
  5. Spectral measurement of electron antineutrino oscillation amplitude and frequency at Daya Bay, Daya Bay Collaboration, Phys.Rev.Lett. 112 (2014) 061801
  6. Assembly and Installation of the Daya Bay Antineutrino Detectors, **H.R. Band et al.** , ***JINST 8*** (2013) T11006
  7. Advantages of Multiple Detectors for the Neutrino Mass Hierarchy Determination at Reactor Experiments, Emilio Ciuffoli, Jarah Evslin , Zhimin Wang, Changgen Yang, Xinmin Zhang, **Weili Zhong** , ***Phys.Rev.D 89*** (2014) 073006
  8. Improved calculation of the energy release in neutron-induced fission, X.B. Ma, **W.L. Zhong**, L.Z. Wang, Y.X. Chen, J. Cao, ***Phys.Rev.C 88*** (2013) 1, 014605

- **Invited talks:**
  1. Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay

     ICHEP 2014, Valencia, Spain July 2 - July 9, 2014
  2. Latest Progress of the JUNO Experiment

     CPS Autumn Meeting 2014, Harbin, China September 12 - September 14, 2014

Expectations for the next review period

- The JUNO Experiment
  - Complete the prediction of the reactor antineutrino spectrum for mass hierarchy study and its uncertainty analysis;
  - Further study on sterile neutrino sensitivity;
  - Finalize the drafting of the sterile neutrino chapter and reactor section of the Yellow Book.

- The Daya Bay Experiment
  - Publish the PRL collaboration paper of the measurement of reactor antineutrino flux and spectrum;
  - Prepare the PRD collaboration paper of the reactor-related analyses;
  - Update the reactor-related analysis from 6AD to 8AD data.

- The DarkSide Project
  - Help assemble the two-phase liquid argon detector prototype at IHEP
  - Acquire more R&D experience of liquid noble detectors via contributing to the DarkSide project.

Backup

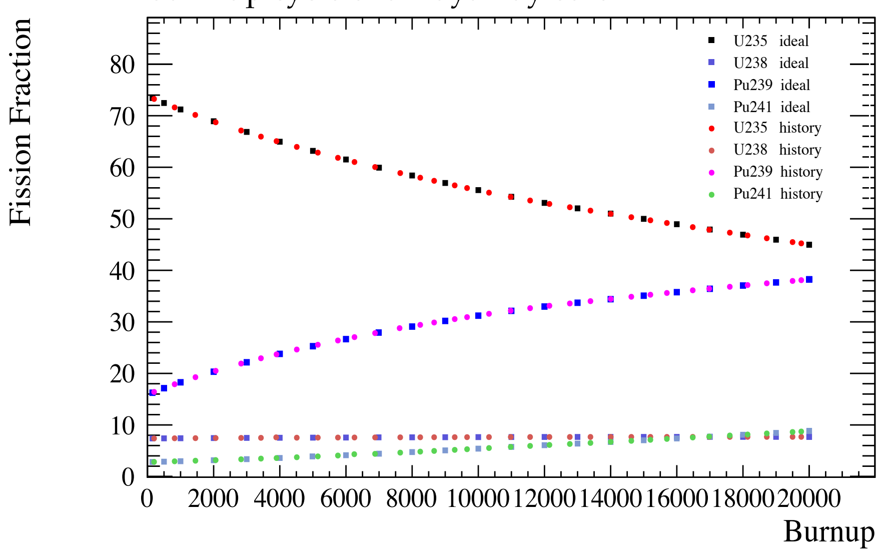
Reactor antineutrino Flux and spectrum

$$\frac{d^2N(E,t)}{dEdt} = \sum_i \left(\frac{W_{th}(t)}{\sum_j f_j(t)e_j} f_i(t)S_i(E)c_i^{ne}(E,t) \right) + S_{SNF}(E,t)$$

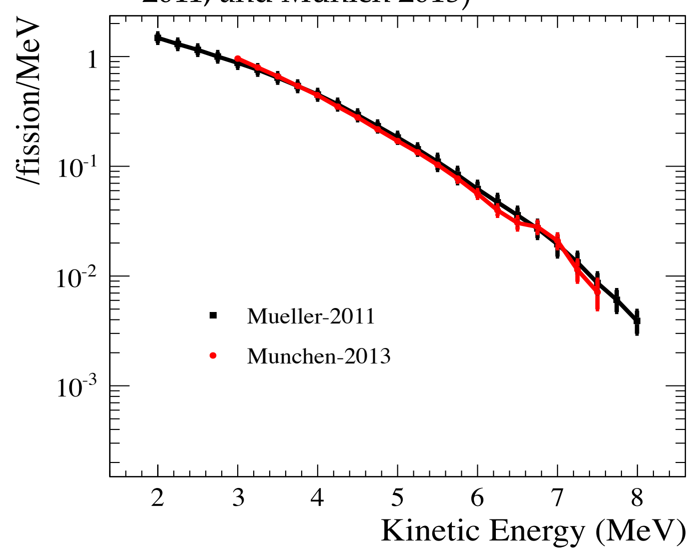
where W_{th} is reactor power, f_i are fission fractions, e_i are fission energies, S_i are isotope spectra, c_i^{ne} are off-equilibrium correction, S_{SNF} is correction from spent nuclear fuel.

- Weekly power and fission fractions are provided by Daya Bay nuclear power plant.
- New isotope ^{238}U spectrum (Munich) is used to build up Huber+Munich model.
  - R = Data (Daya Bay)/Prediction (Huber+Munich) = 0.948 ± 0.022

Fission fractions (%) of four isotopes in a typical burn-up cycle of a Daya Bay core



^{238}U spectrum comparison (Mueller 2011, and Munich 2013)



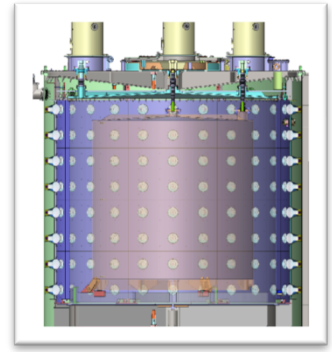
Flux and spectrum prediction

Reactor

Antineutrino production

$$\frac{d^2N(E,t)}{dEdt} = \sum_i \left(\frac{W_{th}(t)}{\sum_j f_j(t) e_j} f_i(t) S_i(E) c_i^{ne}(E,t) \right) + S_{SNF}(E,t)$$

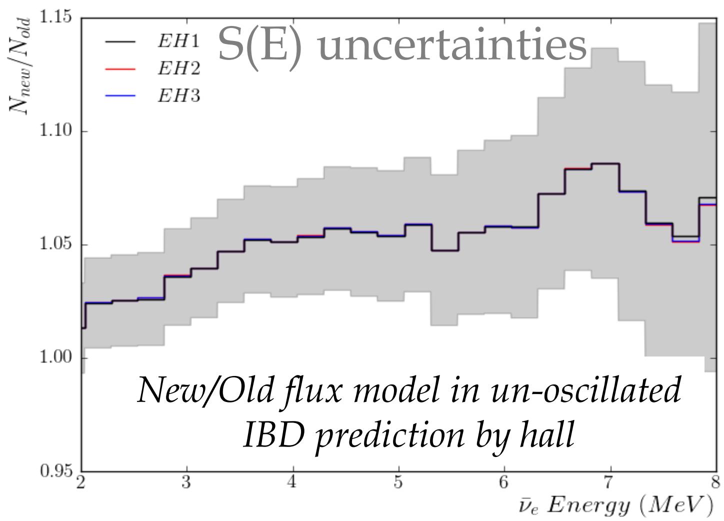
AD



Reactor Antineutrino Flux Model: isotope spectra $S_i(E)$

Old: ILL (^{235}U, ^{239}Pu, ^{241}Pu) + Vogel (^{238}U); New: Huber (^{235}U, ^{239}Pu, ^{241}Pu) + Mueller (^{238}U)

Reactor shape uncertainties



Reactor rate uncertainties

correlated			uncorrelated		
energy per fission	e	0.2%	power	W_{th}	0.5%
IBD reaction per fission	$S(E)$	3%	fission fraction	f	0.6%
			spent fuel	SNF	0.3%
			off-equilibrium	C^{ne}	0.3%
combined		3%	combined		0.9%

Other shape uncertainties

- 0.4%-1% due to **fission fraction** uncertainties (0.6%).
- <~3% spectral corrections from **spent nuclear fuel** (SNF) and **off-equilibrium** effects are applied at low energies (< ~4 MeV). 100% uncertainties are assigned to the bin-by-bin corrections.

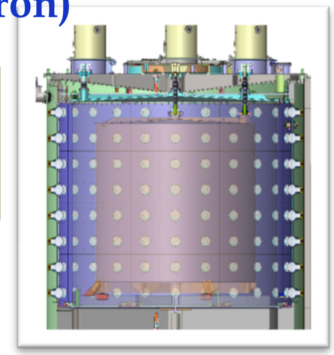
Flux and spectrum prediction

Reactor

Antineutrino detection (IBD positron)

$$S(E_{e^+}) = S(E_{\bar{\nu}_e})\sigma_{IBD}(E_{\bar{\nu}_e})N_p \cdot t_{live} \cdot \varepsilon_{m \cdot \mu} \cdot \varepsilon \cdot \text{Detector Response}$$

AD



Detection efficiency ε, and its uncertainty

	Efficiency	Correlated Uncertainty	Uncorrelated Uncertainty
Target protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.12%
Prompt energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined	80.6%	2.1%	0.2%

Detector efficiency is obtained from Full Detector MC simulation which is tuned with various data. Correlated uncertainties are obtained by comparison of MC and data.

An improved evaluation of the detection efficiency regarding Gd capture ratio, delay energy cut and spill-in effect, has been performed.

Detector Response is developed for spectral measurement.

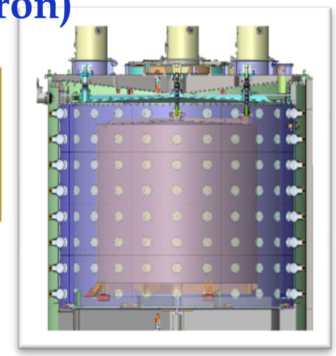
Flux and spectrum prediction

Reactor

Antineutrino detection (IBD positron)

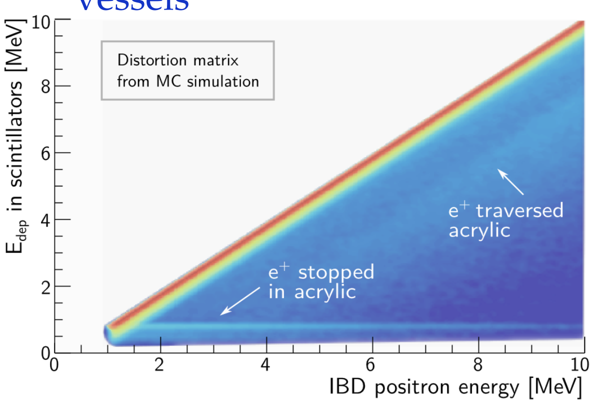
$$S(E_{e^+}) = S(E_{\bar{\nu}_e})\sigma_{IBD}(E_{\bar{\nu}_e})N_p \cdot t_{live} \cdot \varepsilon_{m\cdot\mu} \cdot \varepsilon \cdot \text{Detector Response}$$

AD

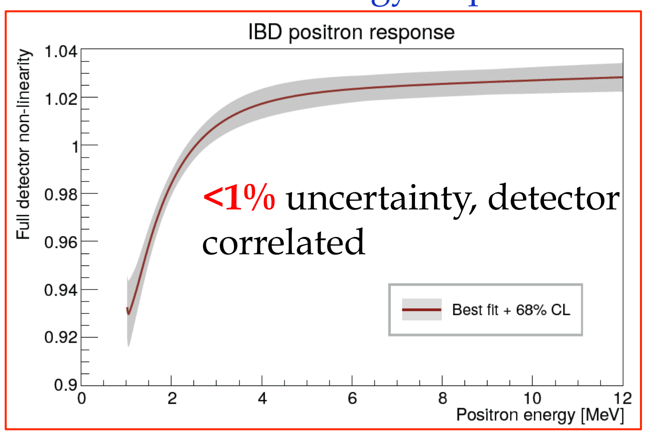


Detector response is obtained by adding detector effects step by step (energy losses → energy nonlinearity → energy resolution) based on calibration and MC simulation. An equivalent method of 'Full MC' including all detector effects together is also developed.

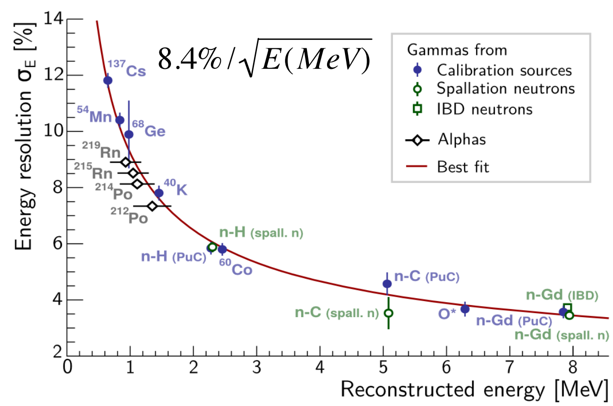
Energy losses in acrylic vessels



Nonlinear energy response

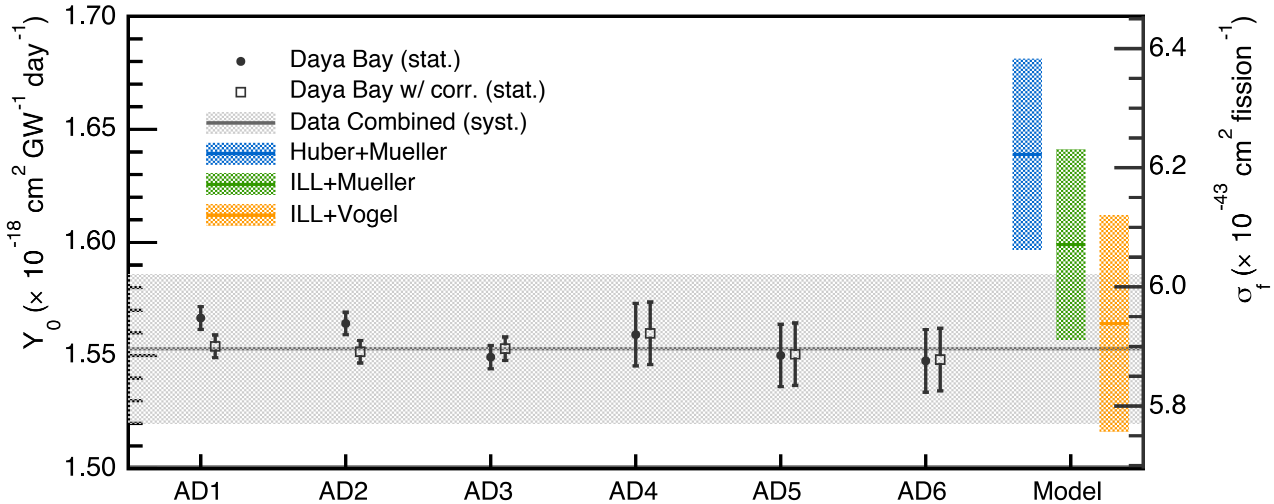


Energy resolution



Absolute Reactor Antineutrino Flux

- Measured IBD events (background subtracted) in each detector are normalized to *cm²/GW/day* (***Y_0***) and *cm²/fission* (***σ_f***).



3-AD (near sites) measurement:
$Y_0 = 1.553\times10^{-18}$

$\sigma_f = 5.934\times10^{-43}$

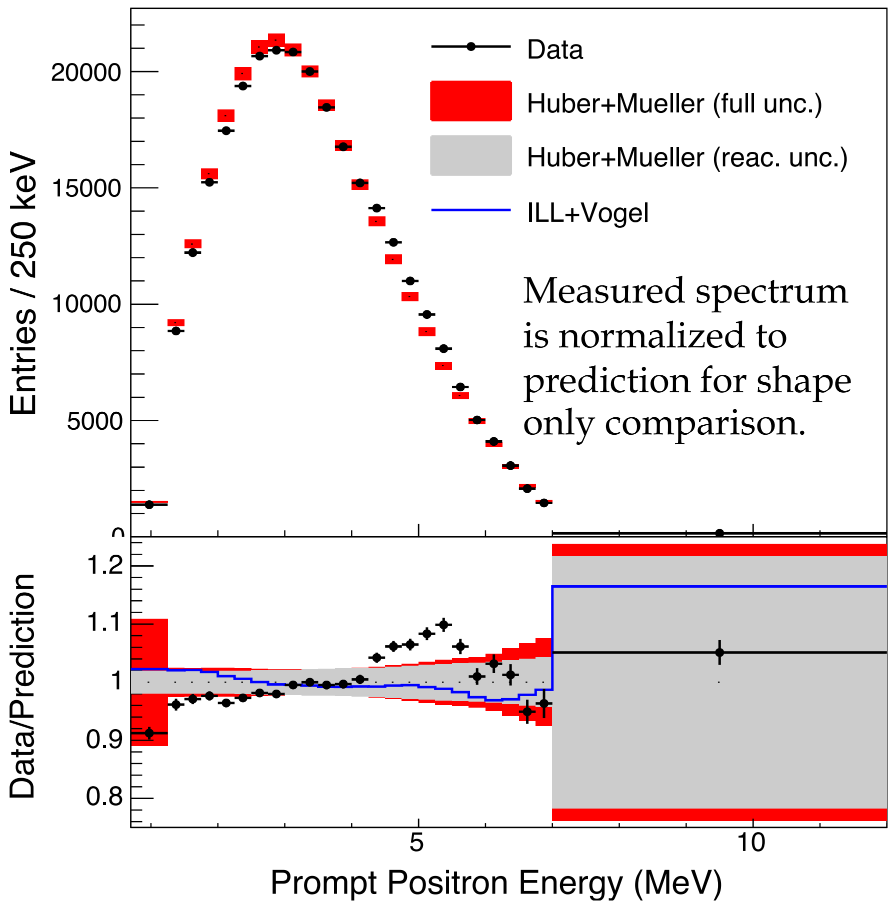
- Compare to reactor flux models: Measured / Predicted IBD candidates

Data/Prediction (Huber+Mueller)
0.947 ± 0.022
Data/Prediction (ILL+Vogel)
0.992 ± 0.023

	Uncertainty
statistics	0.2%
$\sin^2 2\theta_{13}$	0.2%
reactor	0.9%
detector efficiency	2.1%
combined	**2.3%**

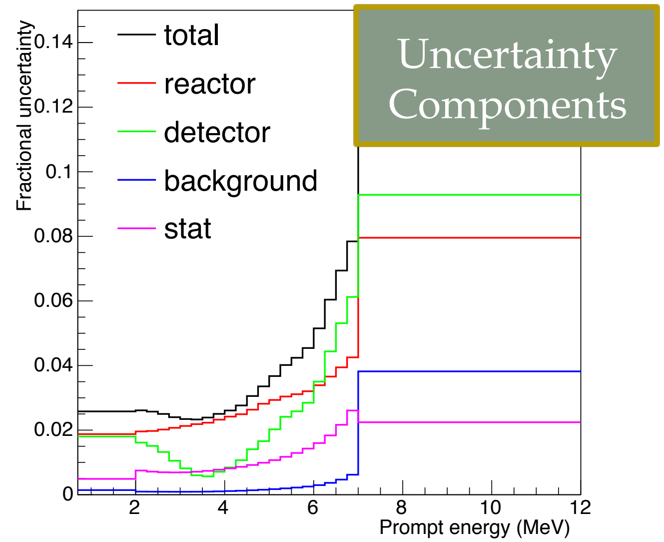
Absolute Spectrum Measurement

- The measured positron spectra of IBD events in the three near Hall ADs are combined and compared with the prediction of the same combination.



$$\chi^2 = (N_i^{obs} - N_i^{pred}) V_{ij}^{-1} (N_j^{obs} - N_j^{pred})$$

$$V = V_{stat} + V_{reactor} + V_{detector} + V_{bkgs}$$

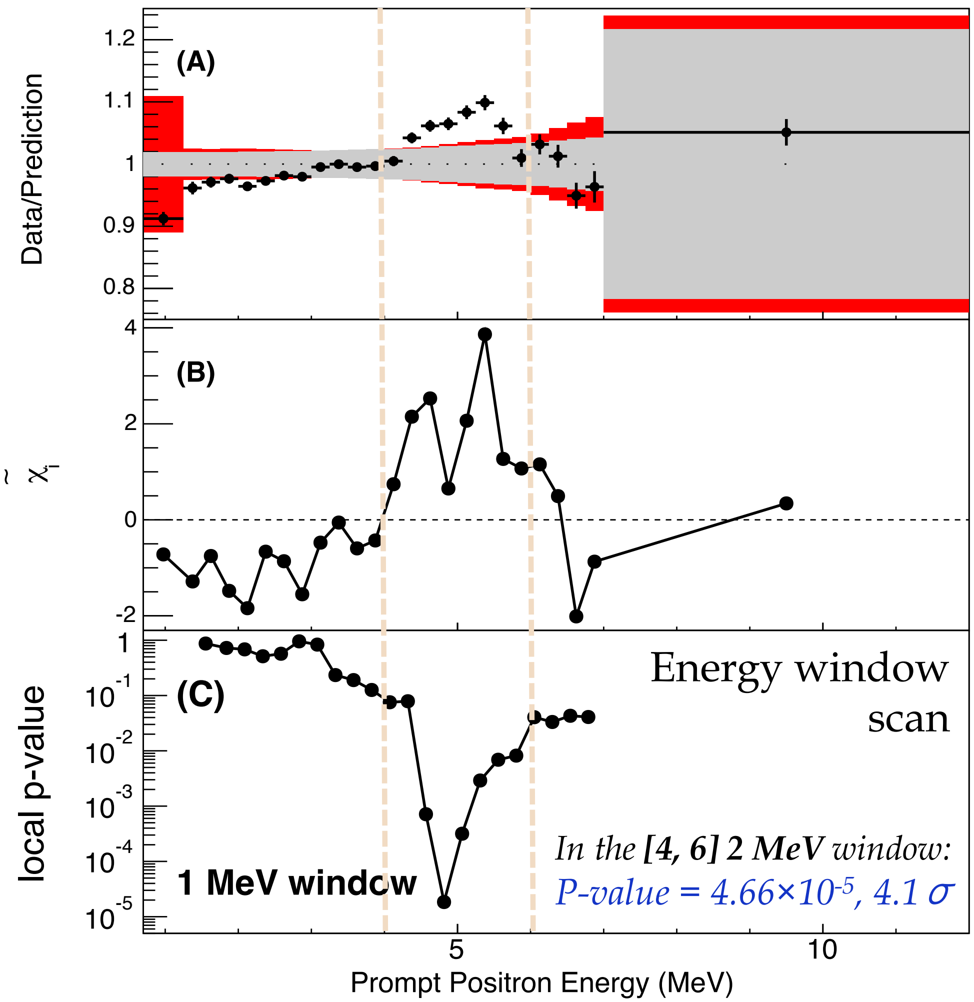


X^2 / ndf (0.7 < E < 12 MeV)

41.4/24

P-value = 0.015, 2.4 σ

Local significance of deviations



(A) Spectral comparison of data and prediction (Huber +Mueller)
(P-value=0.015, 2.4 σ)

(B) χ^2 contribution of each bin, evaluated by:

$$\tilde{\chi}_i = \frac{N_i^{obs} - N_i^{pred}}{|N_i^{obs} - N_i^{pred}|}\sqrt{\frac{1}{2}\sum_j (\chi_{ij}^2 + \chi_{ji}^2)}$$

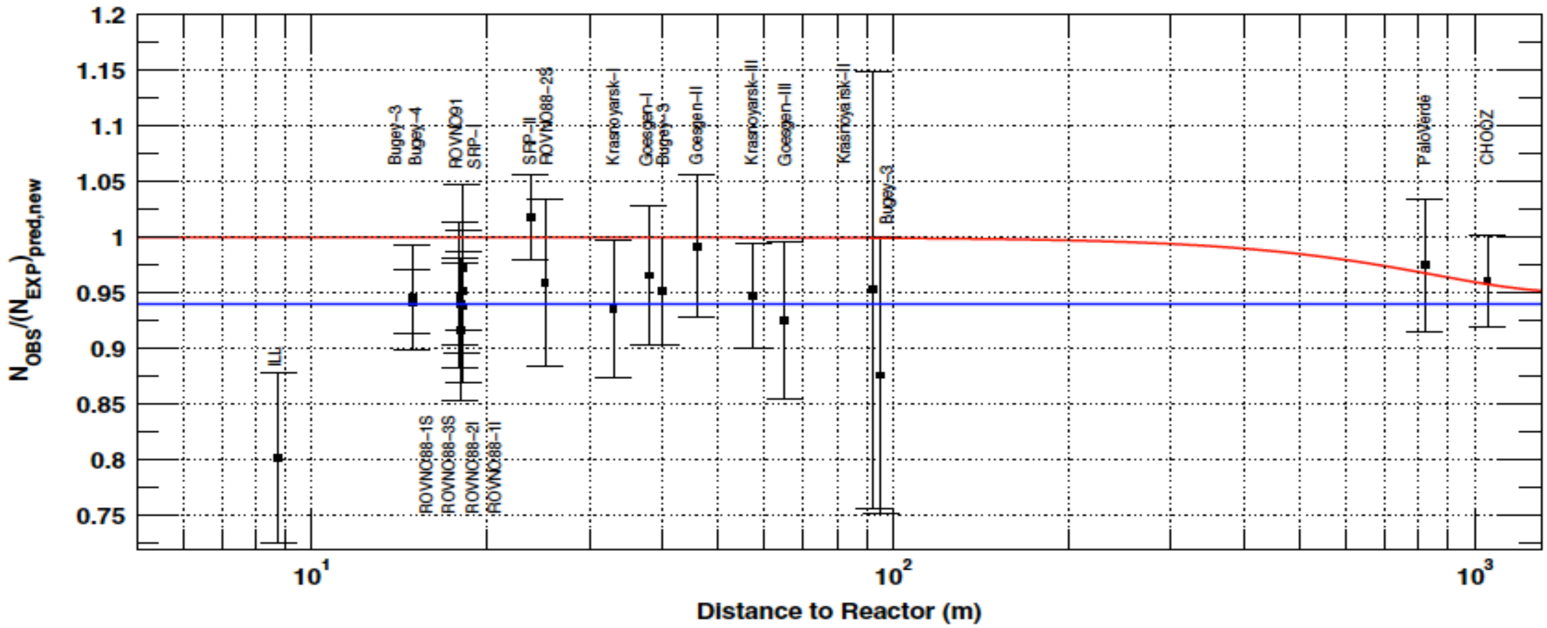
$$\textit{where } \chi_{ij}^2 = (N_i^{obs} - N_i^{pred})(V^{-1})_{ij}(N_j^{obs} - N_j^{pred})$$

(C) P-value of $\Delta\chi^2/\text{ndf}$ in a certain energy window (e.g. 1 MeV)

Introduce N (# of bins) nuisance parameters with no pull terms to oscillation fitter.

Expect the χ^2 difference after introducing the N nuisance parameters follows a χ^2 distribution with N-1 dof.

Reactor Antineutrino Anomaly



- Recalculation of reactor antineutrino flux & Reanalysis of the global reactor antineutrino experiment data in 2011.
- A nearly 3 σ indication of antineutrino disappearance at baseline of less than 100m.
- A possible explanation: mixing between electron antineutrino and a 4th flavor neutrino: "sterile"

Radioactive Sources – Antineutrino source

- Large Q-value and Long live-time
  - Combination of long live-time, low-Q, and short live-time, large-Q.
- ^{144}Ce – ^{144}Pr: SNF
- ^{106}Ru – ^{106}Rh: SNF
- ^{90}Sr – ^{90}Y: SNF
- ^{42}Ar – ^{42}K: too light to be produced in fission process. ^{42}Ar, needs two neutrino capture from stable ^{40}Ar, ^{42}Ar production is very difficult.

Radioactive Sources – Antineutrino source

Q-value of ^{90}Y is the lowest.

	^{144}Ce-^{144}Pr		^{106}Ru-^{106}Rh		^{90}Sr-^{90}Y		^{42}Ar-^{42}K	
$\tau_{1/2}$	285 d	7.2 min	372 d	30 s	28.9 y	64 h	32.9 y	12 h
Q_β (MeV)	0.319	2.996	0.039	3.54	0.546	2.28	0.599	3.52

Fission yield of ^{106}Ru is very low in ^{235}U.

	Cumulative fission yield (%)		
	$^{144}_{58}Ce$	$^{106}_{44}Ru$	$^{90}_{38}Sr$
^{235}U	5.50 (4)	0.401 (6)	5.78 (6)
^{239}Pu	3.74 (3)	4.35 (9)	2.10 (4)

Best choice: ^{144}Ce -^{144}Pr. (BoreXINO, CeLAND)

Source cooling and shielding

- Thermal heat issue
  - ^{144}Ce: ~7.5 W/kCi, 50 kCi is about 375 W.
  - It must be actively cooled.

- Radioactive background
  - 2.185 MeV gamma from ^{144}Pr decay: 0.7% decay branch.
    - 33cm W + 2cm Cu could reduce the gamma background by a factor of 2×10^{-10}.
  - Other possible gamma or neutrons from spent fuel
    - Can use PE or other material to shield neutrons.
    - Can use water for both cooling and shielding

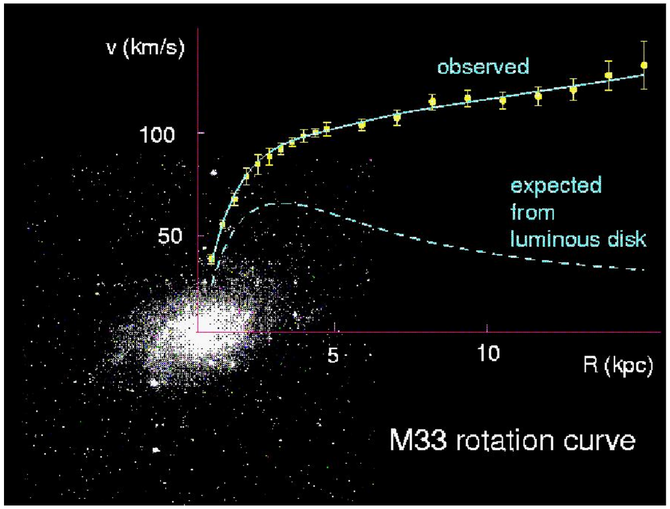
Weight and size of the source

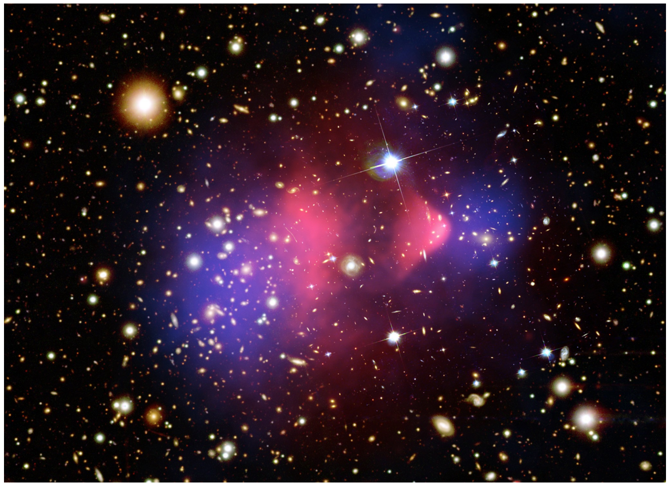
- 50 kCi ^{144}Ce is about 15 g
- There are ~100 g ^{144}Ce in one spent fuel rod
- Fuel Rod dimension: Φ=0.819 cm, L=366 cm, ρ=10.07 g/cm^3
- Spent fuel size we need: 28.9 cm^3, a ~3cm cube.
- Spent fuel weight: ~0.29 kg

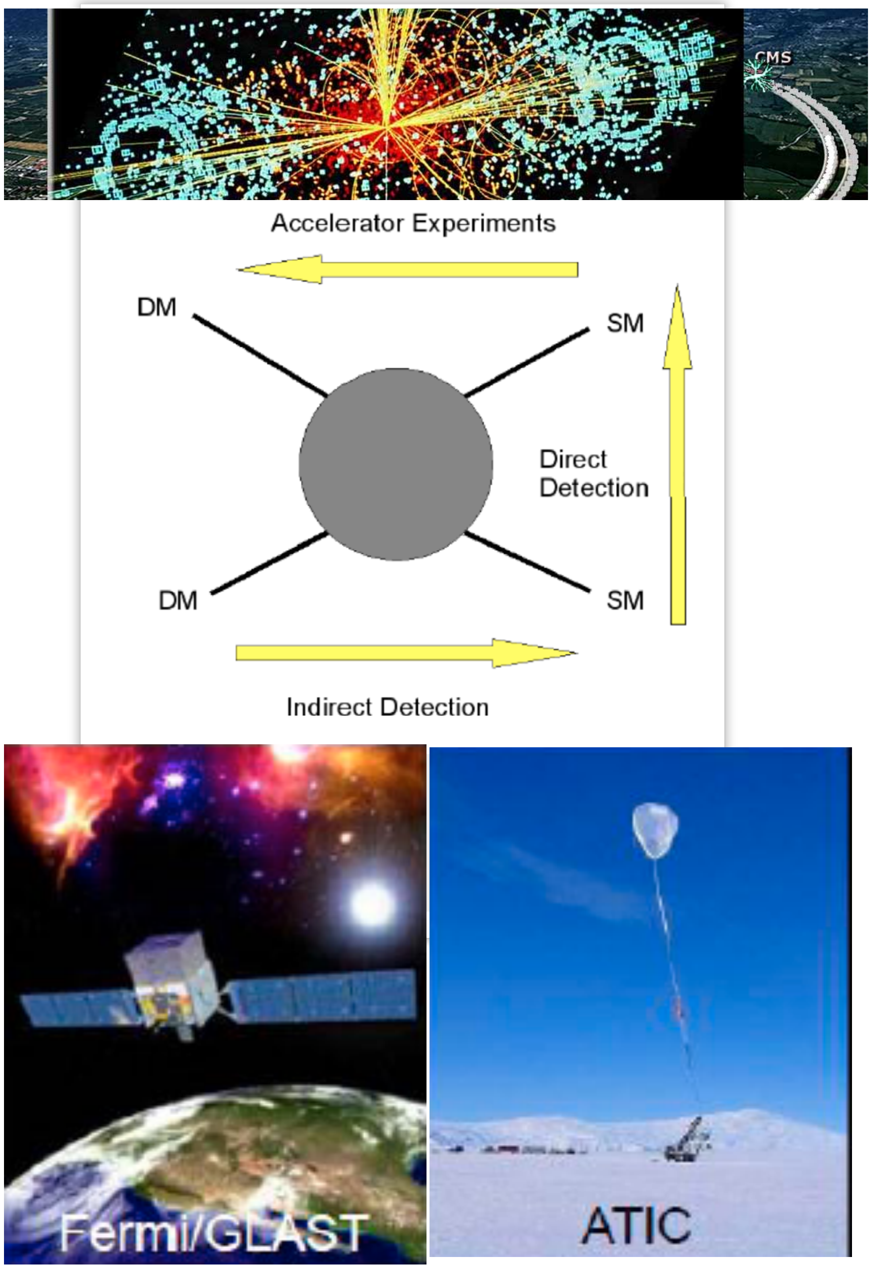
What is Dark Matter?

An entity that interacts gravitationally like ordinary matter, but can not be baryonic matter.

- Dark matter
  - Indirect evidence: rotational curves of spiral galaxies
  - Direct evidence: bullet cluster. Gravitational lensing
  - Distributed in galactic halos
- Candidates of dark matter
  - Weakly Interacting Massive Particle (WIMP).
  - All dark matter experiments now are searching for WIMPs.
- WIMP properties (from theory models)
  - **Assume** it is a relic from the Big Bang
  - **Assume** its mass is ~100GeV/c^2
  - **Assume** the interaction cross-section is close to the weak interaction…







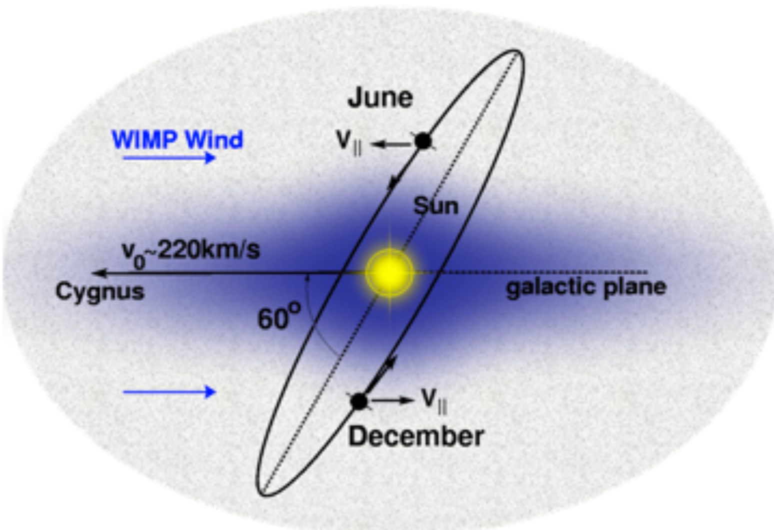
How to Detect Dark Matter?

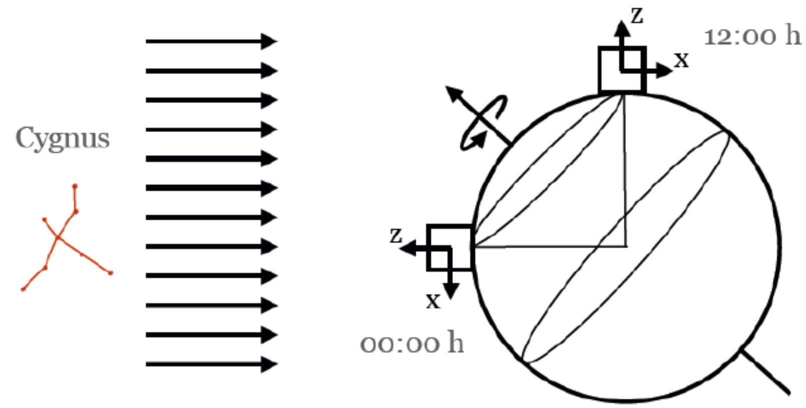
- Indirect detection:
  - Decays or annihilation of WIMPs: gammas
  - Annihilation of WIIMPs: particle-antiparticle pairs (neutrinos)
  - ***enormous background***..

- Accelerator experiments:
  - collide and annihilate known particles to obtain new, unknown particle
  - ***must be confirmed by separate experiments.***

- Direct detection:
  - WIMP ***elastic scattering*** off detector nuclei, transfer some of their kinetic energy…

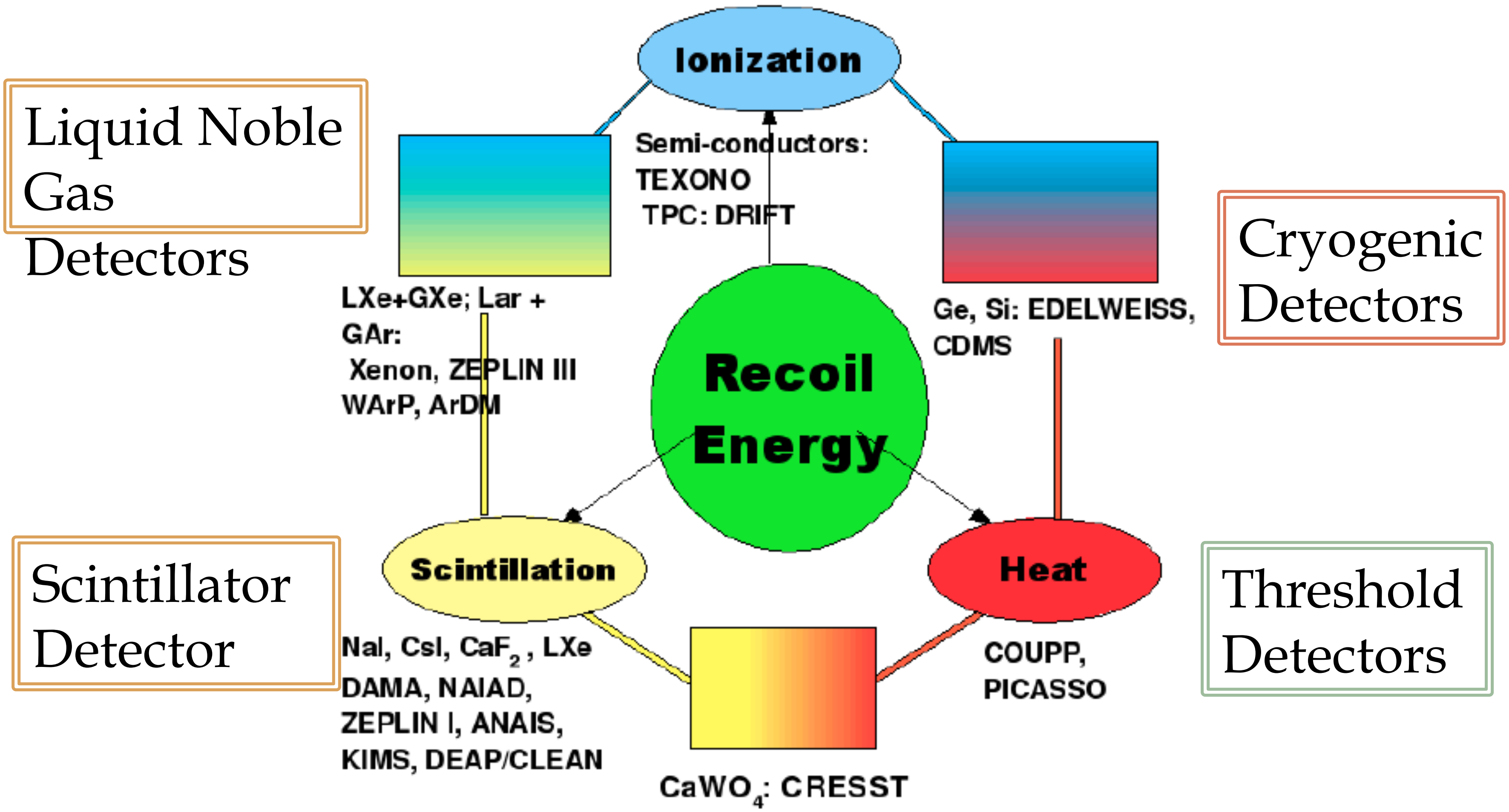
What is a dark matter signal for direct detection experiments?





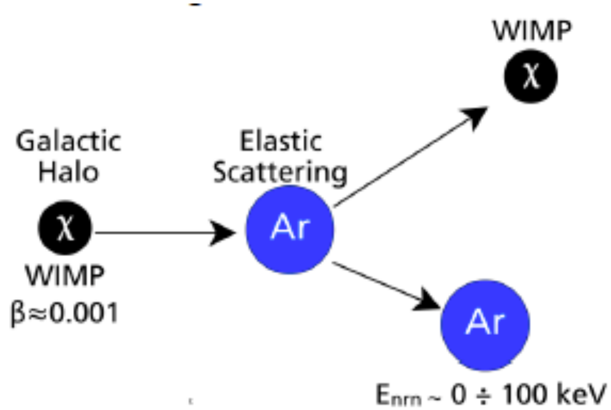
- Annual modulation
  - Sun revolves around the center of the galaxy
  - Earth revolves around the sun.
  - Magnitude of WIMP signal fluctuates annually.
- Daily modulation
  - Earth's rotation.
  - The direction of WIMPs detected in Lab. coordinate changes in one day.
  - **Condition: directional detector**

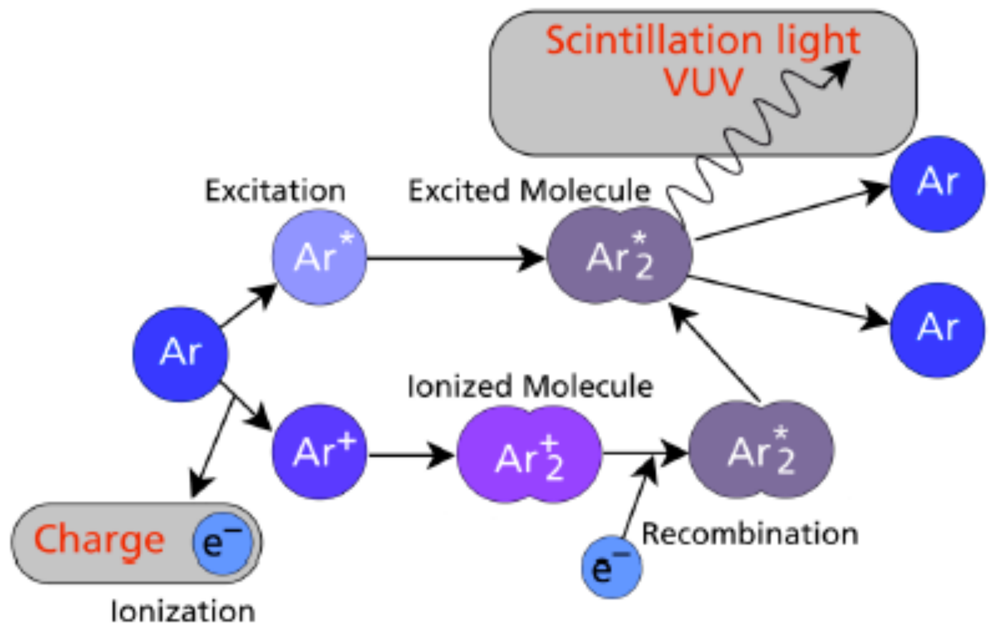
Interaction Channels



Liquid Noble Gas detectors

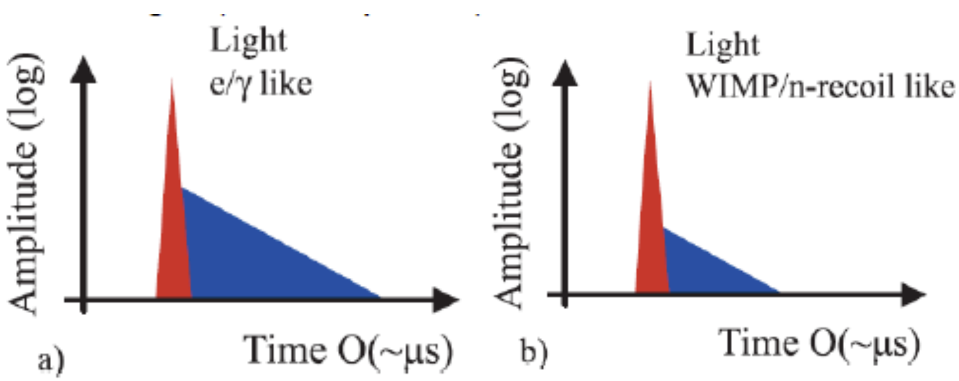
- Ionization: charge
- Excitation and ionization: scintillation light

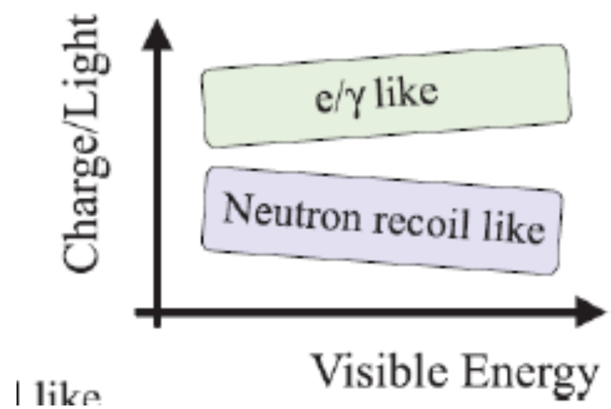




Liquid Noble Gas detectors

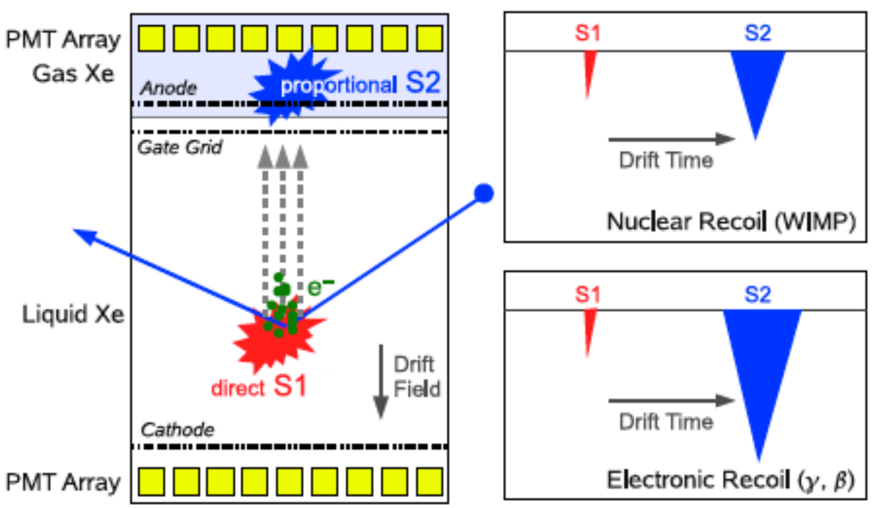
- Event selected by:
  - Charge/light ratio
  - Fast/slow component of scintillation light
- Single Phase detector: only collect scintillation light, fast/slow ratio
- Double phase detector: collect both charge and scintillation light, charge/light ratio.

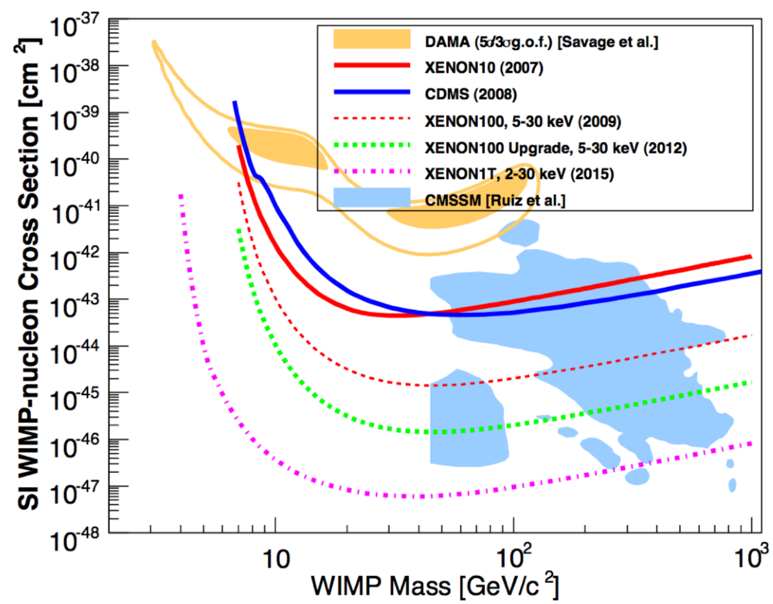




Double Phase Detector

- XENON-100
  - H 30.5cm x R 15.3cm, 62kg LXe target.
  - 24 PTFE panel as reflector and separate inner LXe target and outer LXe veto.
  - 11 days data: 2×10^{-45} cm^2 at 100GeV/c^2.
  - Ultimate goal: 10^{-47} cm2





Comparison of Ar and Xe

Property (unit)	Xe	Ar	Ne
Atomic Number	54	18	10
Mean relative atomic mass	131.3	40.0	20.2
Boiling Point T_b (K)	165.0	87.3	27.1
Melting Point T_m (K)	161.4	83.8	24.6
Liquid density at T_b (g cm^{-3})	2.94	1.40	1.21
Volume fraction in Earth's atmosphere (ppm)	0.09	9340	18.2
Cost/kg[a]	$1000	$2	$90
Scintillation light wavelength (nm)	175	128	78
Triplet lifetime (ns)	27	1600	15000
Singlet lifetime (ns)	3	7	<18
Electron mobility (cm^2 V^{-1} s^{-1})	2200	400	low
Scintillation yield (photons/keV)	42	40	30

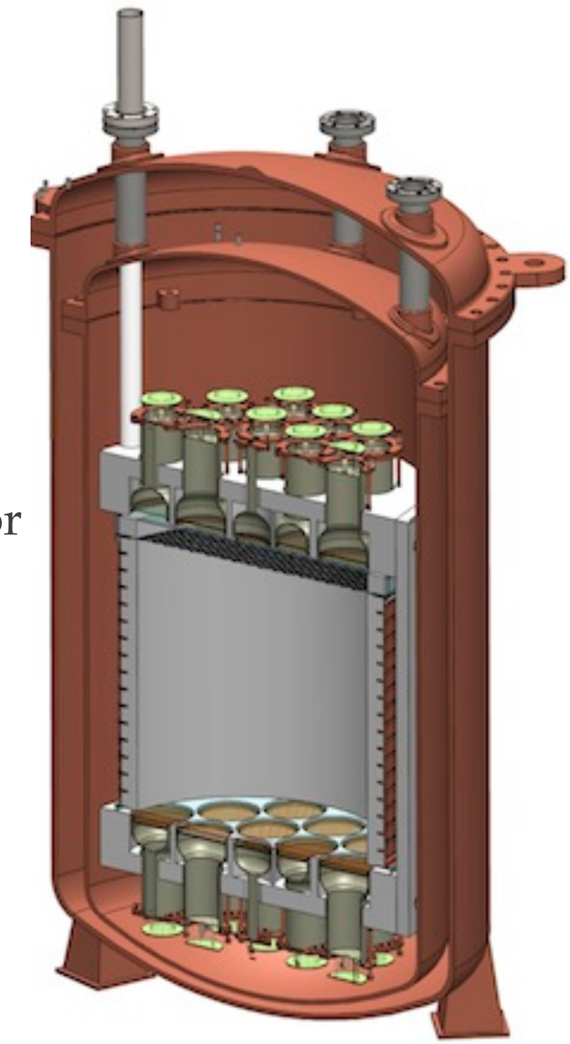
- Ar: cheaper, fast/slow components quite differ (single phase)
- Xe: atomic number is larger, electron mobility is larger, scintillation wavelength larger.

Background Reduction in DarkSide-50/G2

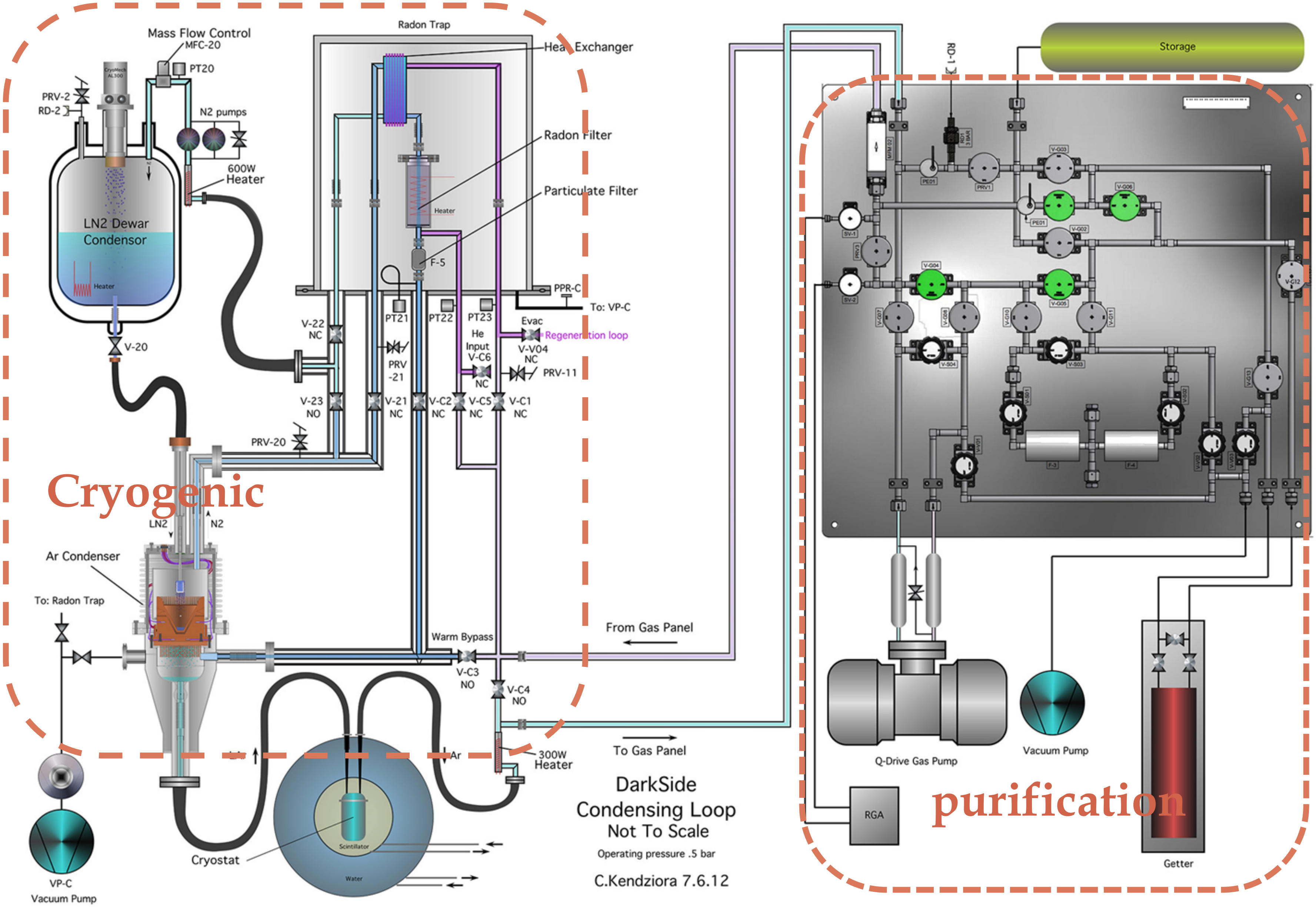
- Cosmogenic background
  - neutron veto & muon veto
- Radioactive background
  - Neutrons from radioactivity：neutron veto
  - Electron-like background
    - PSD of S1
    - S2/S1 ratio of LAr TPC
  - Neutron-recoil like background
    - Multiple interaction
  - Event positions in LAr TPC：remove surface events（α-n)
  - Clean room（Radon-free）
    - Assembly and installation: suppress background of Radon decay

LAr Detector of DarkSide-G2

- LAr TPC: DAr(suppress ^{39}Ar)
  - 1.5m×1.5m, 3.8ton target mass
  - PTFE cylindrical structure:
    - 278 4” low background PMT at top and bottom
    - Fused silica windows at top and bottom
  - Inner surface of PTFE: TPB wavelength shifter
  - Uniform electrical field:
    - Fused silica window: transparent ITO conductor
      - Top window: anode
      - Bottom window: cathode
    - PTFE outer surface: etched copper
  - Sensitive area:
    - Above grid: 2cm Gas Ar layer
    - Below grid: LAr (drift layer)
  - Electronic field:
    - Extraction field: 3.8kV/cm, Drift field: 1.0kV/cm



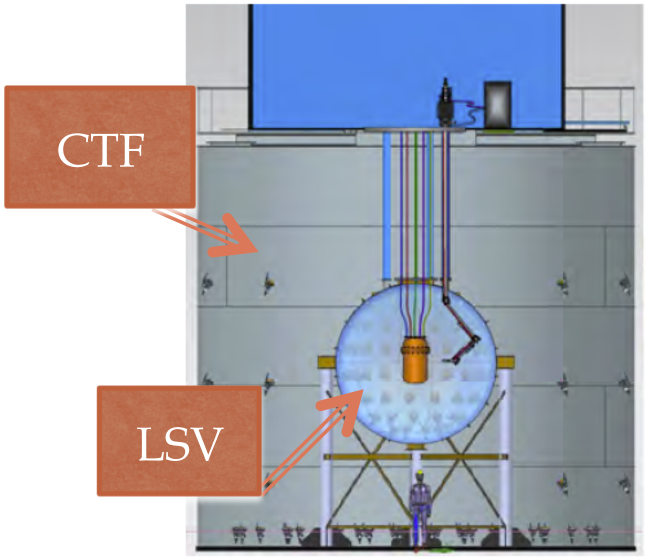
Cryogenic, circulation and purification system



Veto System

- Neutron Veto
  - Liquid scintillator detector
    - Tag and shield neutron and gamma
    - Boron liquid scintillator
  - Spherical Stainless Steel（LSV）
    - 4m diameter
    - 110 low bkg 8” PMT，7% coverage
    - Inner surface：Lumirror reflective film
- Muon Veto
  - Water Cherenkov detector
    - Detect Muon and secondary particles
  - Borexino CTF
    - 10m × 11m
    - 80 8”PMT：56 side，24 bottom
    - Inner surface： Tyvek film (IHEP)
- Efficiency of neutron veto：>99.5%

Veto system after installation



Calibration

- Calibrate and monitor detector performance
- Sources:
  - LAr TPC:
    - LY of electron-like events: ^{83}Rb - ^{83m}Kr (2.6hr, 9.4-32keV Auger e$^-$ and gamma)
    - Neutron energy scale and detection efficiency: AmBe
  - Veto system:
    - Uniformity and efficiency: AmBe
    - Double veto system efficiency: AmBe
- Neutron sources: customized d-d neutron generator (clean)
- Mechanic Design:
  - ARA mechanic arm
  - Reach all positions in LSV: accuracy ~1cm
  - Stored in CRH at the top of CTF