Direct Dark Matter Searches

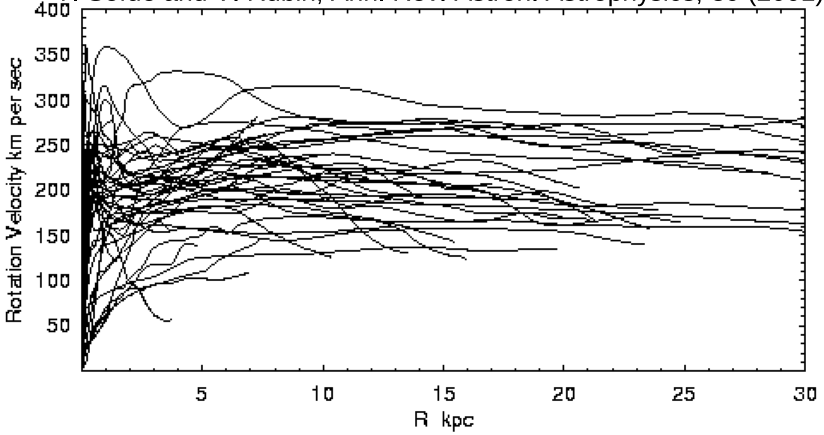
Y. Suzuki

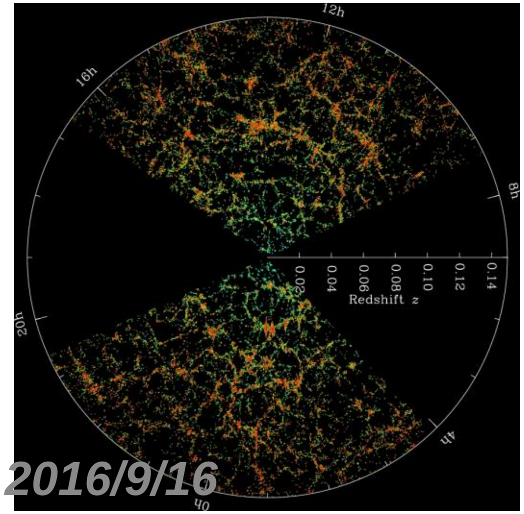
Kavli Institute for the Physics and Mathematics of the Universe, the University of Tokyo

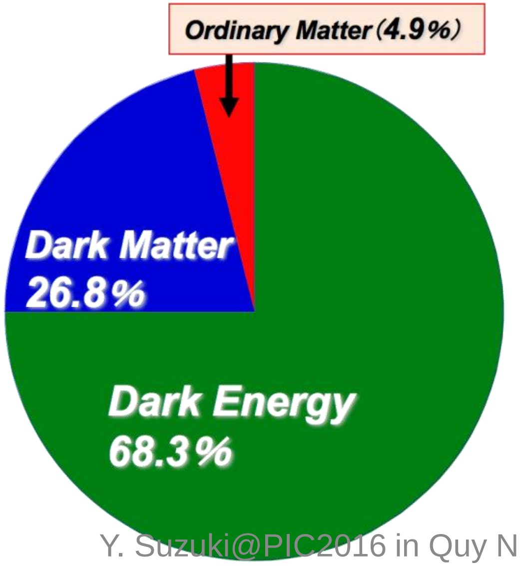
Evidence of Dark Matter (DM)

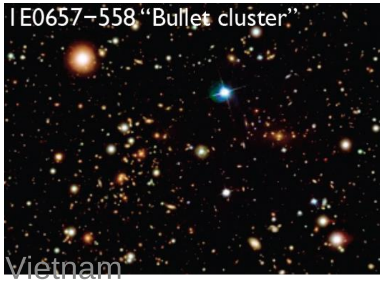
- DM exists
  - Gravitational Observations
    (Dynamical mass >> Luminous mass)
    - Cluster of galaxies
    - Rotation curves of galaxies
    - Gravitational lensing
  - Evidence by cosmological argument
    - Large Scale Structure
    - CMB + Supernovae

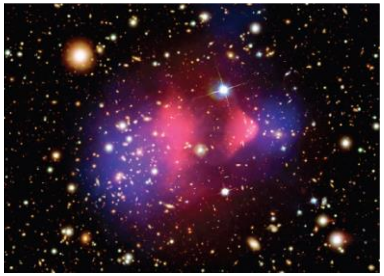
Y. Sofue and V. Rubin, Ann. Rev. Astron. Astrophysics, 39 (2001)











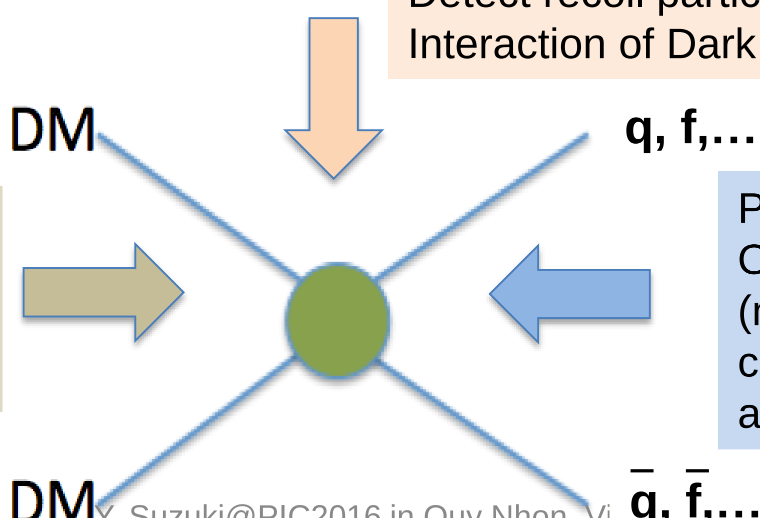
Detection of Dark Matter

- We know some nature of Dark Matter
  - Neutral
  - Stable (longer than the life time of the universe)
  - Cold (maybe warm: >3 keV/c^2 for structure formation) K.Abazajan,PRD73,063513.
  - Of very weak interaction [may be of no interaction other than Gravity]
- But we do not know what the dark matter is

➔ Important to detect Dark Matter by other than gravitational interactions

<u>Direct detection (DD) :</u>
Detect recoil particles produced by the Interaction of Dark Matter on ordinary matter

Indirect detection:
Detect secondary particles produced by annihilation of dark matter particles



Production of Dark Matter:
Observe dark matter particles (most likely missing energy) created by a high energy accelerator (like LHC):

Galactic Dark Matter

- Observe interactions of "Galactic Dark Matter" directly on target materials
- A simple model: Isothermal Halo Model (standard)
  - A single component isothermal sphere with a Maxellian velocity distribution

$$f(v)dv = \frac{4\pi v^2}{(v_0^2\pi)^{\frac{3}{2}}} e^{-\frac{v^2}{v_0^2}} dv$$

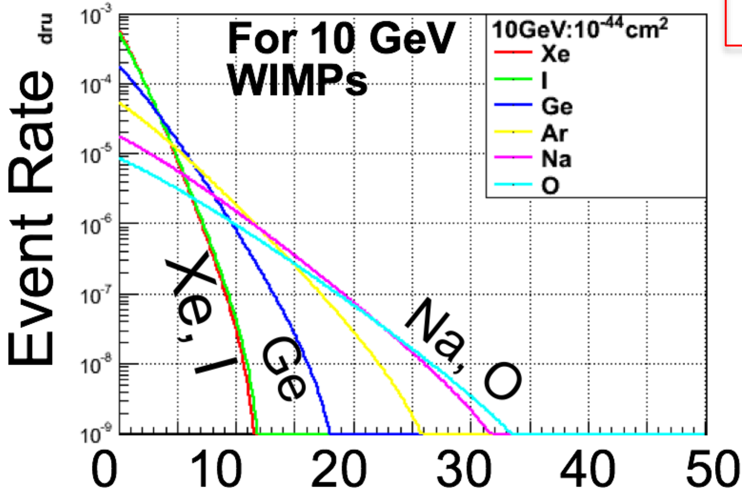
  - Typical values commonly used:

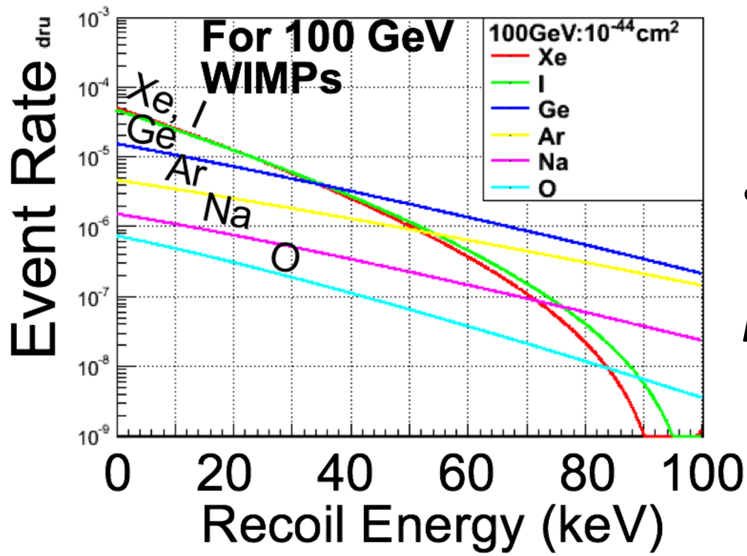
v_0 = 232 km/s, $<v^2>$ = 270 km/s, escape velocity = 550 km/s and density(ρ_x) = 0.3 GeV/cm^3

  - Values and uncertainty of these astrophysical parameters have been reevaluated and still under the discussion
- DM flux on the earth:

$$\phi \sim 10^5/cm^2/s \cdot (\frac{100GeV}{m_\chi})(\frac{\rho_\chi}{0.3GeV/cm^3})$$

Signal (Nuclear Recoil)





Nuclear Recoils if they interact coherently on the target material (WIMPs):

χ + A ➔ χ + A

$$\frac{\mathrm{d}R}{\mathrm{d}E_{nr}} = \frac{\rho_0}{m_A m_\chi}\int_{v_{min}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{nr}}(v, E_{nr})\,\mathrm{d}v$$

- Recoil energy 🡐 K.E. of DM

$$E_{nr} = \frac{M_\chi v^2}{2}\frac{4M_\chi M_A}{(M_\chi + M_A)^2}\frac{(1-\cos\theta)}{2}$$

need to detect low energy signals

$\lesssim$ a few 10s keV

For low mass WIMPs

- need to have lower threshold for high A target

Rare event rate

– Current best lower limit: a few x 10^{-46} cm^2 (@ 100 GeV/c^2 WIMPs)

⇔ ~ a few x 10^{-5} dru (ev/keV/kg/day)

~ a few events for 100kg, 100day, ΔE=10keV

Signal (e/γ events)

- Some dark matter particles other than WIMPs may produce e/γ signals
  - Axio-electric effect → electrons
    - for pseudo-scalar particles
    - ex. ALP (axion like particles)
    - E_e ~ mass of dark matter
  - Photo-electric effect → electrons
    - for vector particles (kinetic mixing)
    - ex. bosonic superWIMPs (vector)
    - E_e ~ mass of dark matter
  - Inelastic scattering of target material (ex. Xe detector (^{129}Xe))
    - 40 keV γ rays from de-excitation +NR
  - Luminous dark matter (PRD82, 075019)
    - Decay of DM in excited state
    - Mono-energetic γ-rays (in ~ keV?)
  - and so on....

$$\sigma_{abs} v \simeq \frac{3m_a^2}{4\pi\alpha f_a^2} \sigma_{photo}(\omega = m_a)c$$

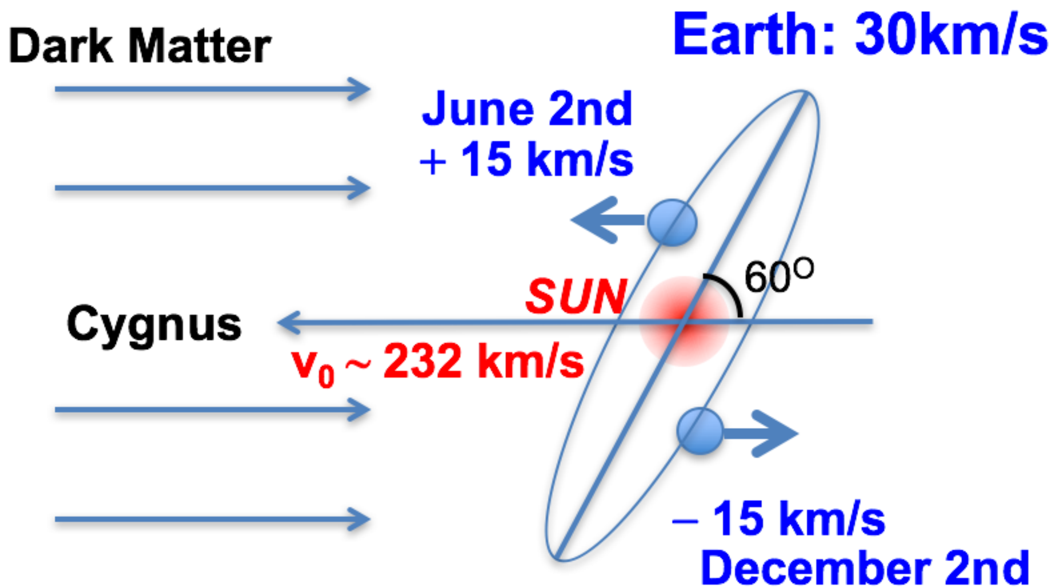
$g_{aee} = 2m_e/f_a$ axion coupling

$$\sigma_{abs} v \simeq \frac{\alpha'}{\alpha} \sigma_{photo}(\omega = m_V)c$$

α' effective coupling

There are varieties of DM interactions to produce e/γ signals.

Signal (Annual Variation)



- Expect annual modulation of the event rate

  ← Change of the rotation velocity of the earth due to the earth's revolution

$$v_E(t(\text{days})) \approx \left[232 + 15\cos\left(2\pi\frac{t-152.5}{365.25}\right)\right]\, km/s$$

- Expect O(a few ~ 10 %) modulation depending on models, energy threshold and so on

Requirements for DD Detectors

- low radioactive background
  - Material screening /purification
    - Remove U/Th, ^{40}K, ^{60}Co, ^{210}Pb(Surface)…and ^{222}Rn.
  - Shield /Veto (Active)
    - Cu/Pb/Teflon; Water tank
  - Cosmic muons /Cosmo-genic
    - Go underground

Note !
Shields are also background sources

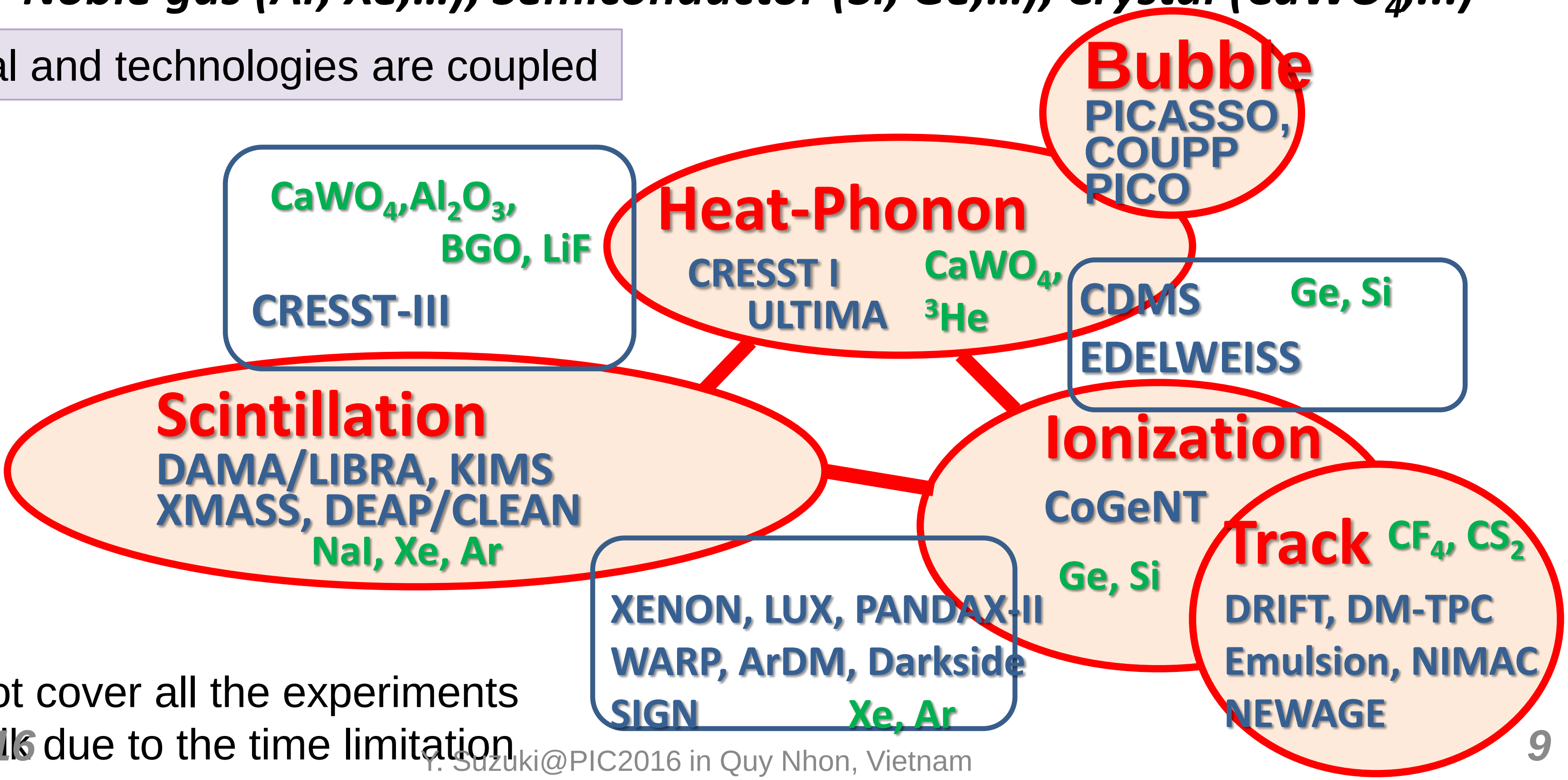
PMT (for example)
a few mBq/PMT
Cu bulk: ^{210}Pb
O(10mBq/kg)
Kr (Internal): ^{85}Kr
a few ppt
^{222}Rn (iternal):
~10μBq/kg

- Low energy threshold [Crucial for low mass WIMPs]
- large mass (especially for a "standard" WIMP search)
- Dark Matter detector ➔ Target ≡ Detector
  - Choice of target material determine the "experiment"
  - Different detector technology gives different way to reduce background

Choice of target material and technology

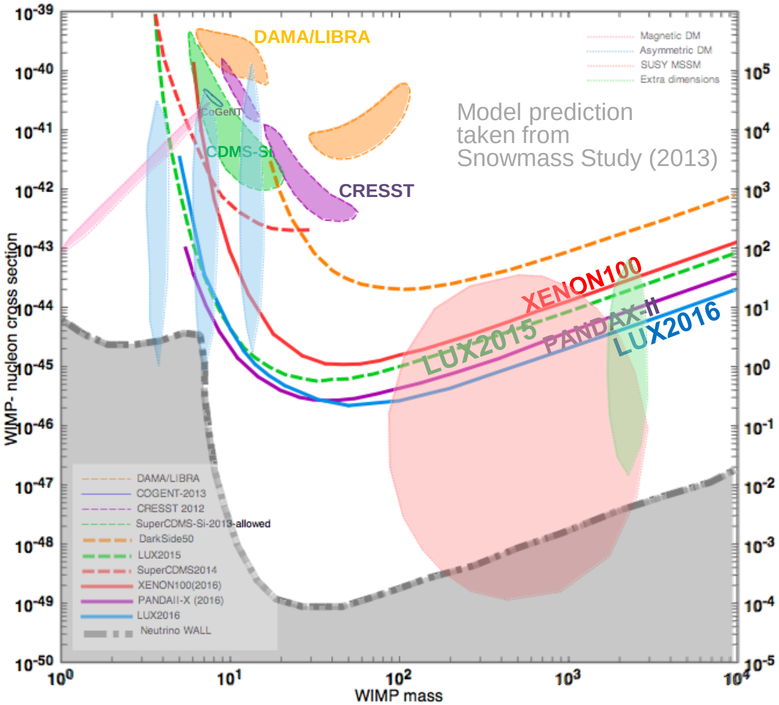
- ***Various Detection Technologies***
  - ***Scintillation, Heat-Phonon and Ionization***
  - ***Usually combined technologies to reduce backgrounds***
- ***Various material***
  - ***Noble gas (Ar, Xe,…), Semiconductor (Si, Ge,…), Crystal ($CaWO_4$,…)***

Material and technologies are coupled



Could not cover all the experiments in this talk due to the time limitation

Recent Results of Direct WIMPs searches



For "standard WIMPs" (a few 10s of GeV/c² ~ a few TeV/c² range):

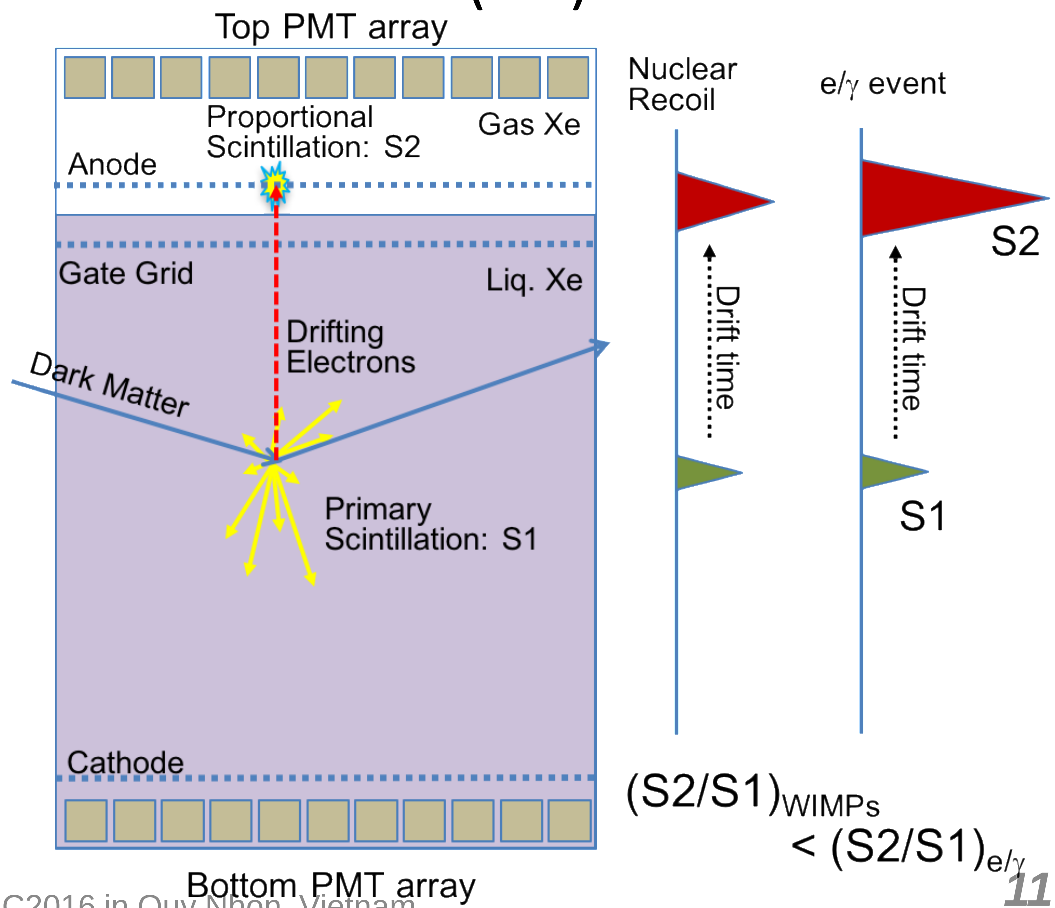
- Solid lines ⇔ New Results
- 3 experiments (in summer, 2016): XENON100, LUX, PANDAX-II, using <u>two phase liquid xenon technology</u>.

  ~ one order of magnitude improvement
- As usual for clarity not all the experimental results are shown

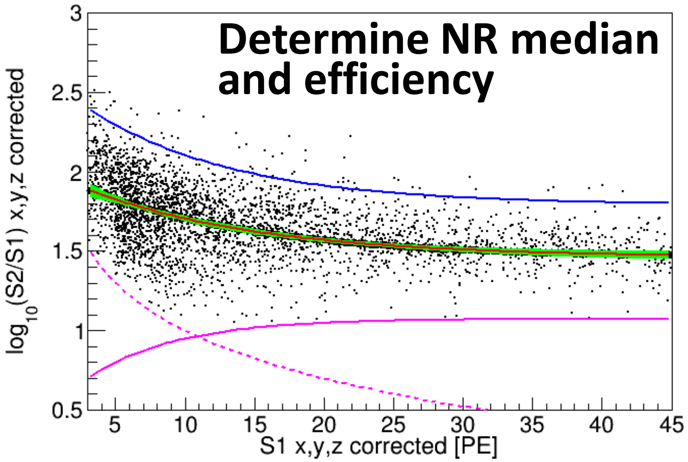
- No strong evidence or indication was found so far
- All earlier claims are less likely to be indications of WIMPs
- However, the DAMA/LIBRA modulation result remains as a mystery, which will be discussed later in talking about the low mass WIMPs.

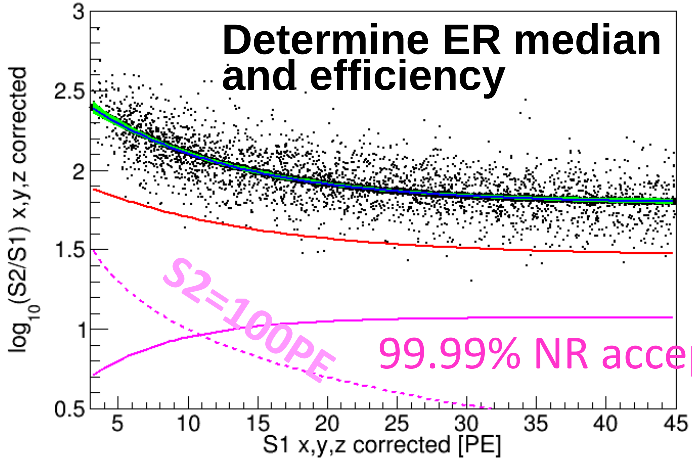
Two phase liquid xenon detector

- Why two phase detector (Advantage)
  - Scalable (larger mass)
  - Good background rejection
- Elastic scattering of DM → Nuclear Recoil (NR)
  - ➢ recombination: primary scintillation light (S1)
  - ➢ remaining ionization electrons to drift: proportional scintillation light (S2)
- More recombination for NR than e/γ events
- S2/S1 to separate NR from e/γ events



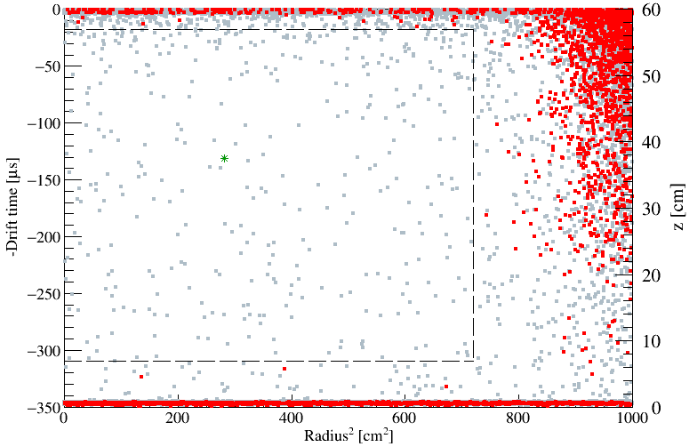
BG rejection





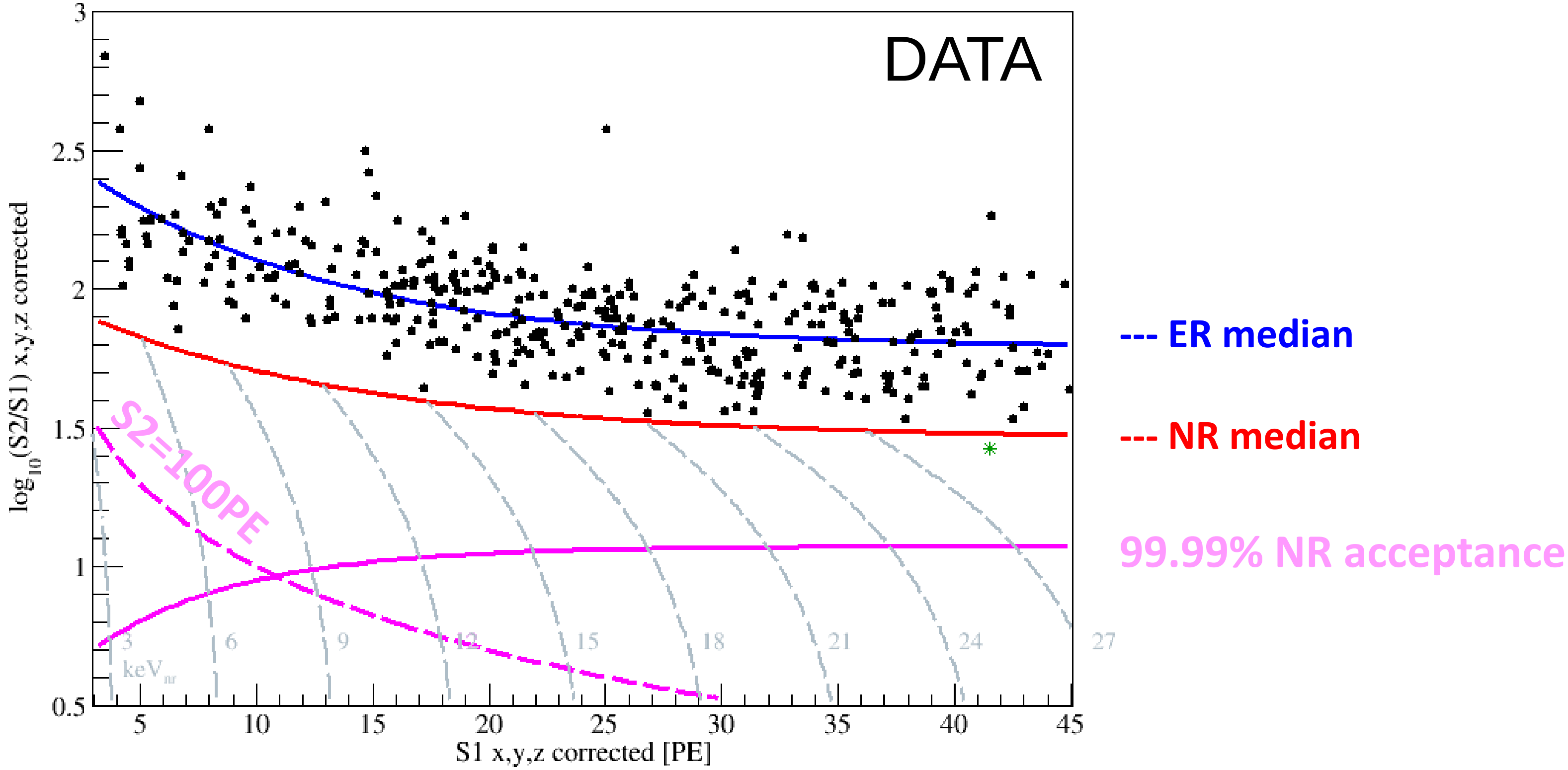
This shows how their BG rejection works!
(Example: PANDAX-II)

- NR Calibration (AmBe neutron source calib.)
  - ~3200 events
  - Determine NR median curve and detection efficiency
- Electron events calibration (Tritium (CH_3T))
  - ~2800 ER events
  - 14 events leaked blow NR median (0.5 ±0.1)%
  - ***1/200 rejection of e/γ events***
    - Gaussian exp: 0.55%



Gray: all events
Red: below NR median

BG level → Sensitivity

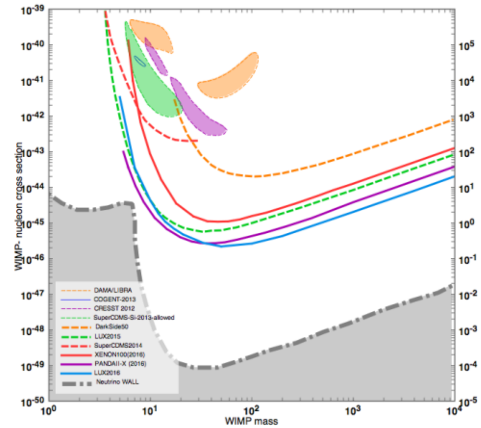


- Total 300 (kg) x 99 days [PANDAX-II]
  - 19.1 days with 15mdru + 79.6 days with 2 mdru
- 380 total events in FV
- 1 below NR median → 2.7 x 10^{-46}cm^2 @50GeV/c^2

dru: events/keV/kg/day

WIMPs & two phase liquid xenon detector

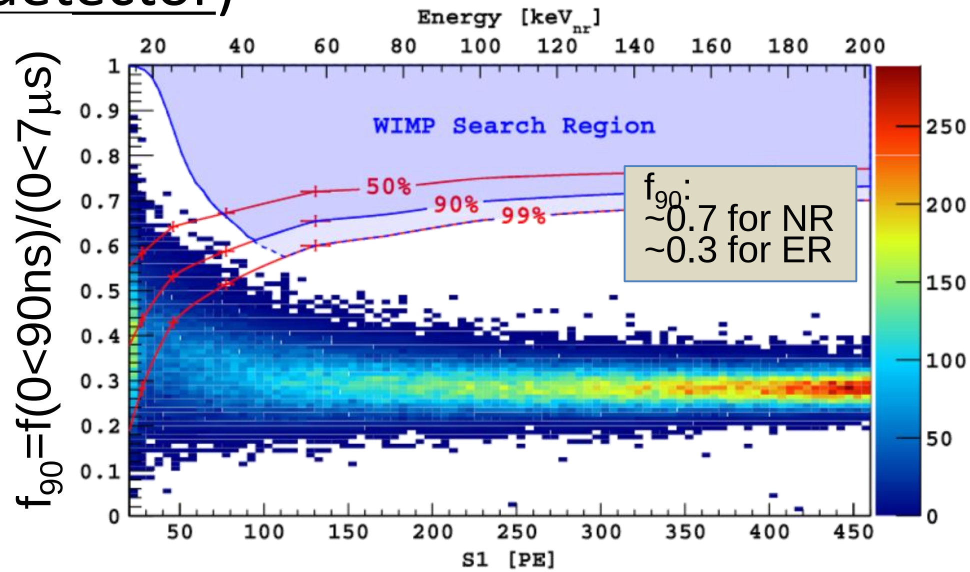
- The three experiments are compared in table
- Exposure, background, threshold and so on, determine the winner
- PANDAX-II can go further.



	XENON100 (completed)	LUX 2016 (completed)	PANDAX-II
FV (kg)	48 ~ 34 kg	99 ~ 107 kg	~300 kg
Live time	477 days	332 days	99 days
Exposure(kg*day)	17,500	32,000	30,000
BG in FV (mdru) NR+e/γ	5 - 22	3	2 -15
BG in FV (event #) NR+e/γ			380
BG (after selection of NR)	5	4~5 ?	1 (reject: 0.5%) ~ 10 μdru
Cross section limit (cm^2)	1.1 x 10^{-45}	2.2x 10^{-46} (50GeV)	2.7x 10^{-46}

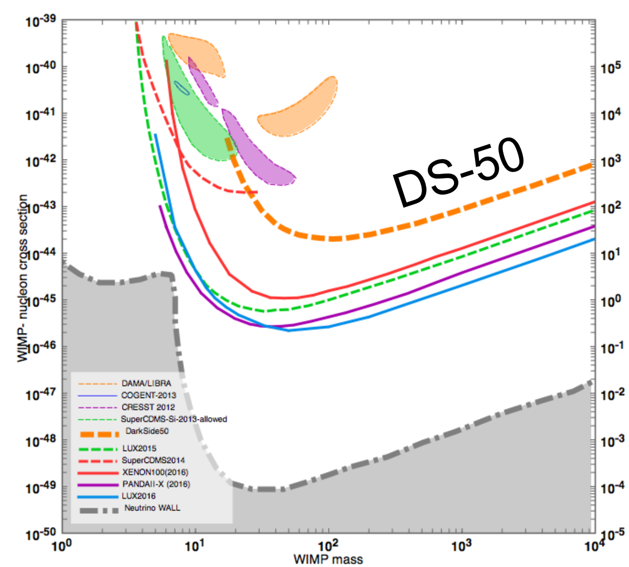
Other efforts for WIMPs [Liquid Ar]

- DarkSide (Double phase liq. Ar detector)
  - ***Advantage of Ar***
    - Inexpensive
    - Superb PSD: NR vs e/γ ➔ 10^7
      [7ns(NR) ⇔1.5 μs (e/γ)]
  - ***Disadvantage***
    - Contamination of ^{39}Ar
      - 269yr, 565keV
    - ~1 Bq/kg
  - Use underground Ar
    - But ^{40}Ar(n,2n)^{39}Ar even in undergr.
    - 1/1400 ^{39}Ar contamination
    - ~1 mBq/kg



- DS-50: 153kg UAr (50kg fid. Mass)
  - 2616 kg*day exposure

➔ A few x 10^{-44}cm
  - Relatively high energy threshold
  - Need more reduction of BG



Other efforts for WIMPs [Liquid Ar]

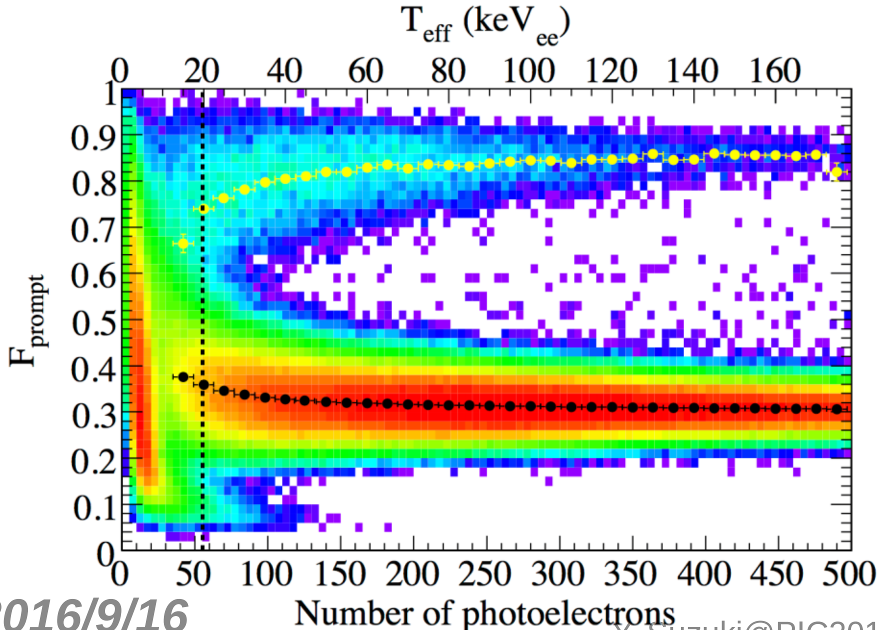
- DEEP3600 [Single phase liquid Ar Detectors]
- 1 ton fiducial (3.6t total); Ultraclean Acrylic Vessel
- e/γ events: ^{39}Ar ~1Bq/kg

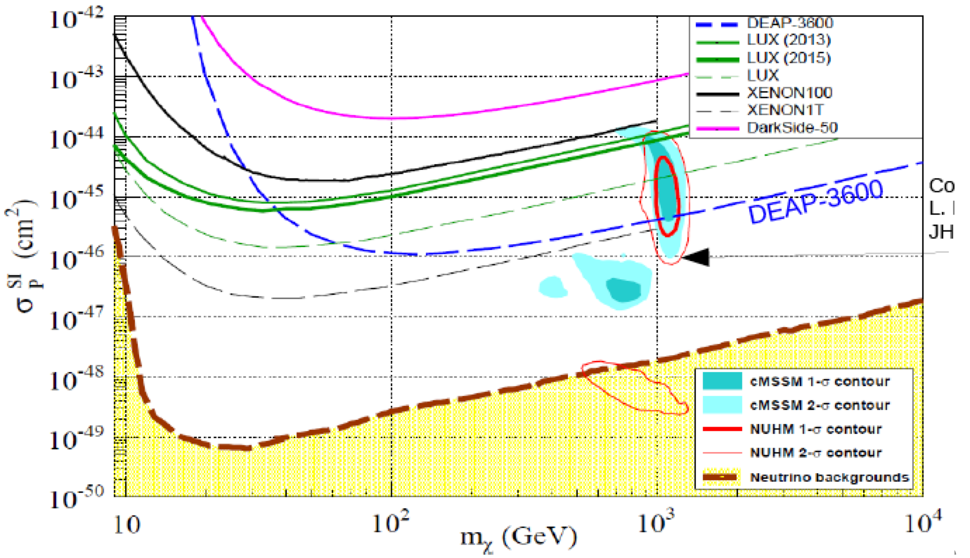
  PSD: ~10^{-10} Rejection

  $F_{prompt} = N_{prompt}/N_{total}$ (Prompt <150ns) to separate BG

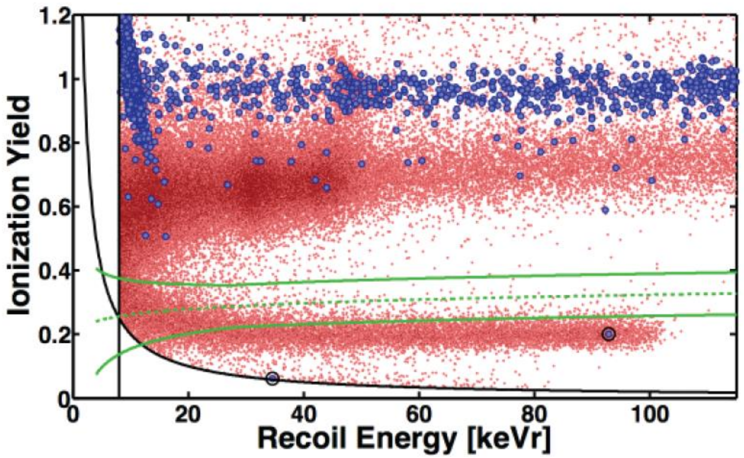
  F_{prompt} ~0.8 for NR and ~ 0.3 for e/γ
- Energy thresh: 20 keVee
- LAr filling completed at the end of July (2016) ➔ taking data

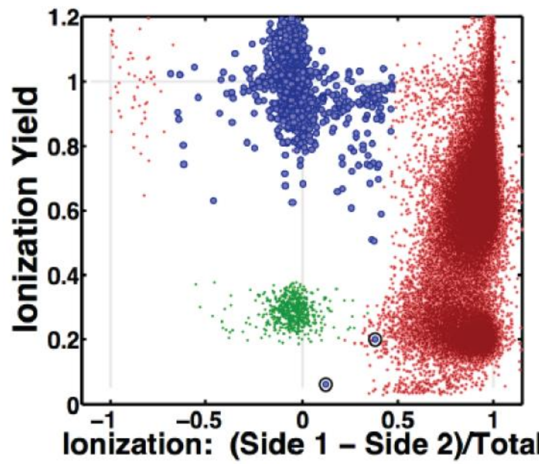
(S2/S1 does not give large rejection factor for 2 phase detector)



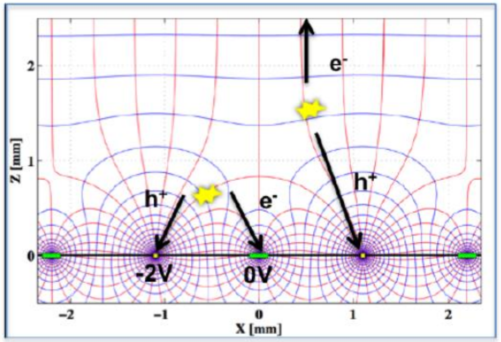


Comment on Ge detector





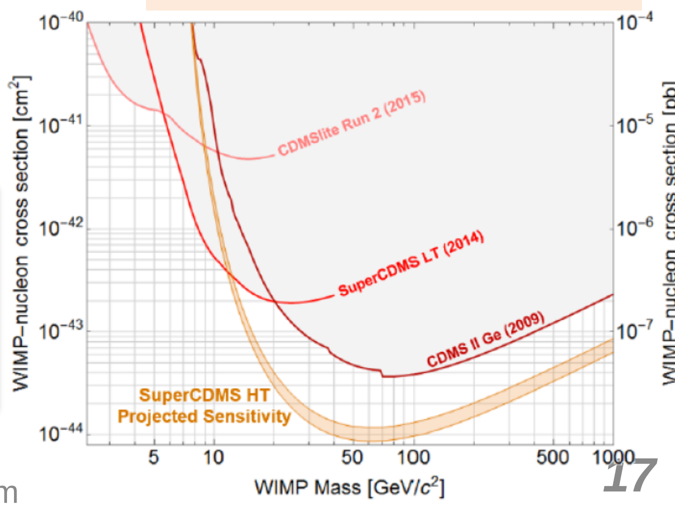
Charge symmetry



- Surface: detect both charges one side
- Bulk: charges drift across the crystal to both surface

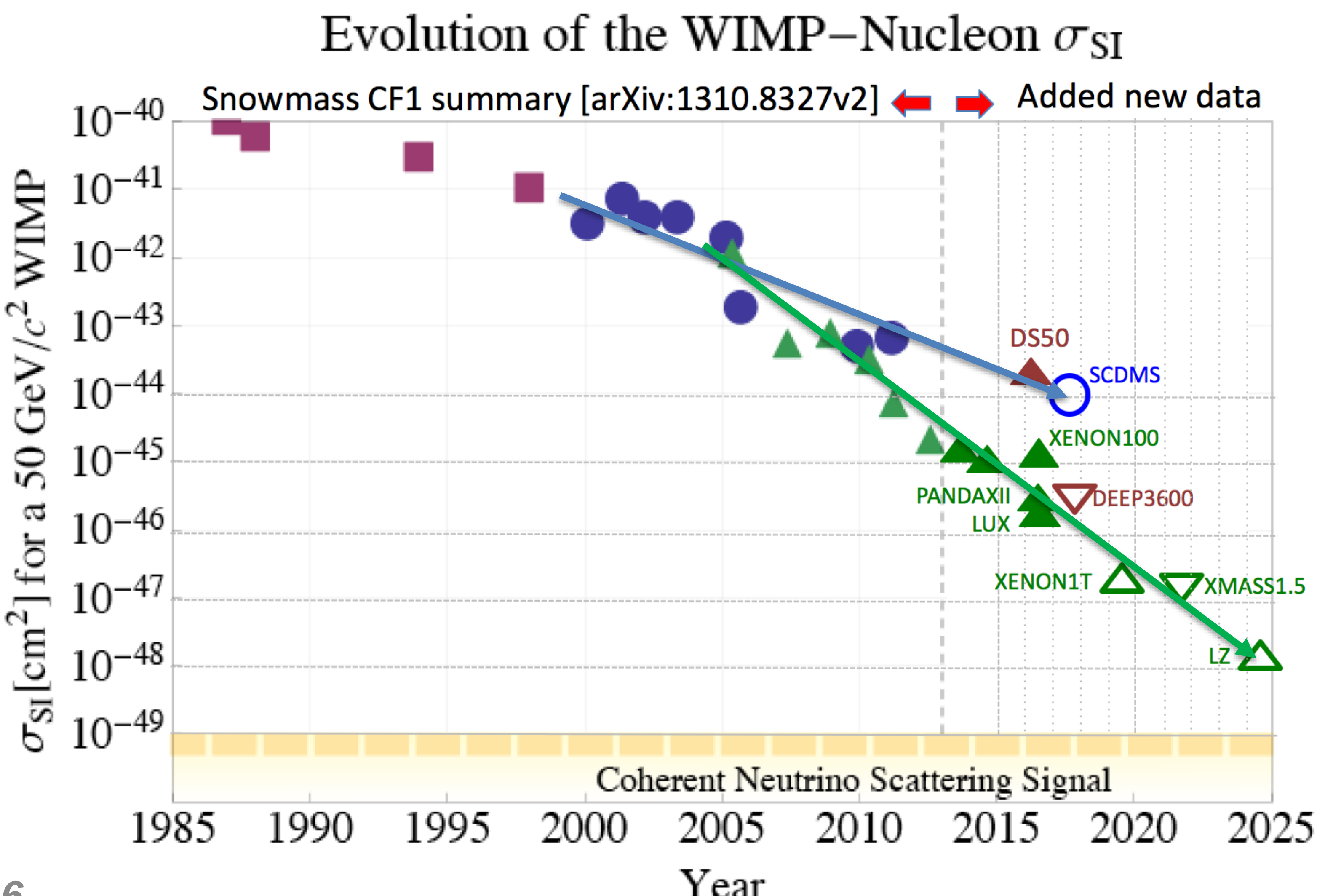
SuperCDMS (0.6kg x15 in 3 groups)

- Select 10 best detectors
- 1700 kg*day 50-60% fid. Vol efficiency
- Threshold: 7-15 keVnr
  - Result ➔ expected for O(10^{-44} cm^2)



Relatively high cost
→ Challenge to make a larger mass detector
➔go low mass region as a good low threshold detector

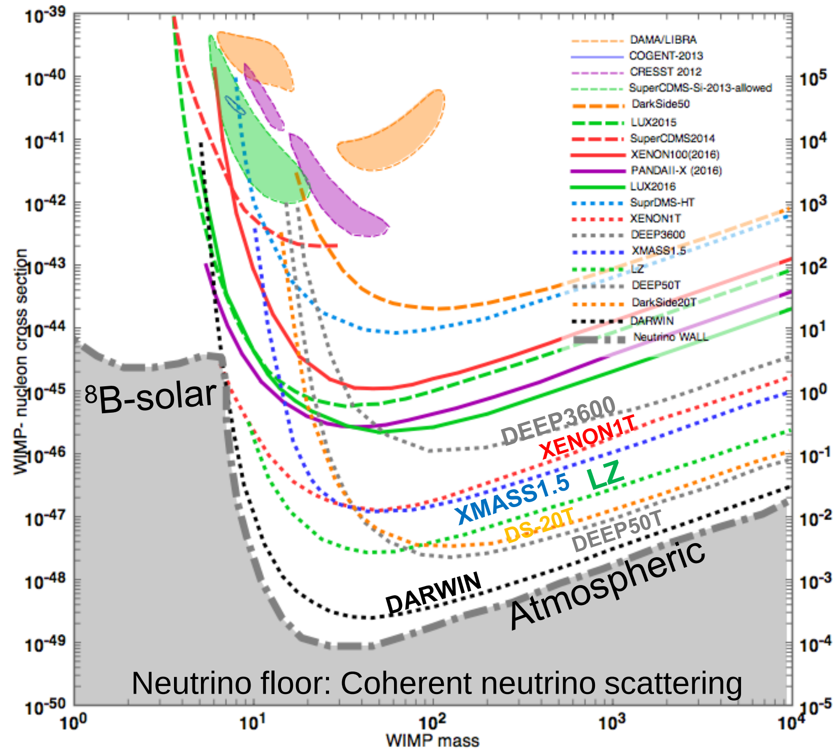
Past, present and future sensitivity



Future (Standard) WIMP search

Size and BG: imprtant factor

- 2 phase- Xenon
  - Xenon100→ **XENON1T(running)**
    →(XENONnT)
  - Lux+Zeplin → **LZ [5.6 ton]**
  - (Darwin[40 tons])
- 2 Phase-Argon
  - DS-50→ (DS-20K[20 ton])depleted Ar

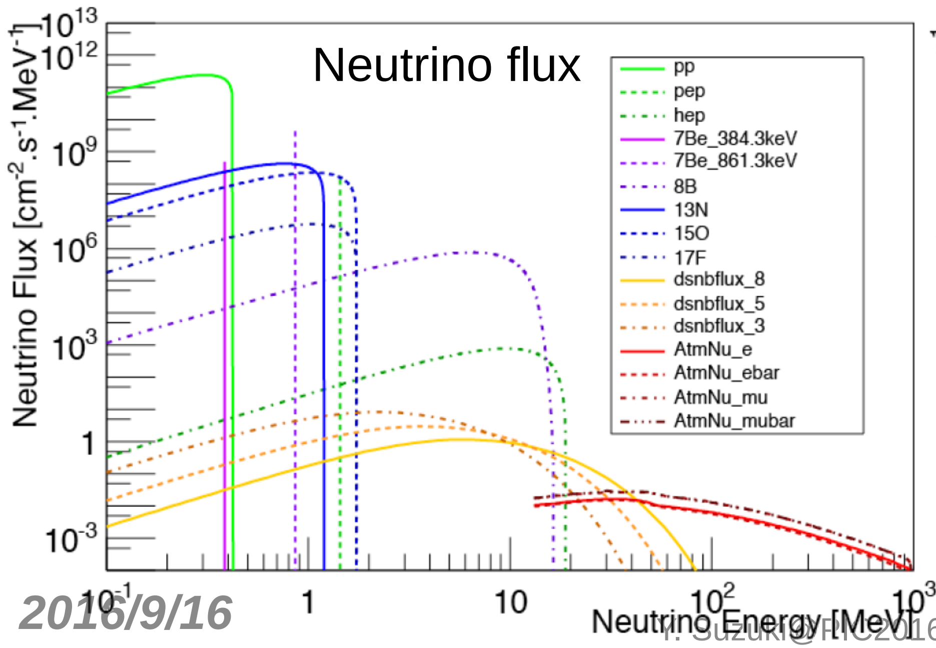


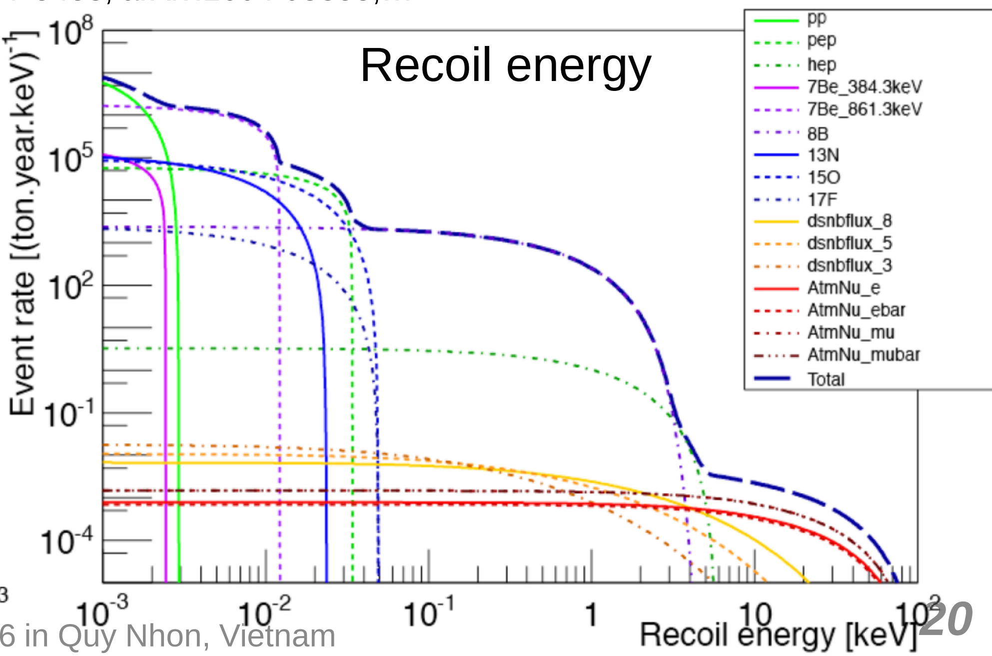
- Single phase- Argon
  - **DEEP3600[1 ton](running)**→ (DEEP-50T)
- Single phase- Xenon
  - **XMASS1.5 [6 ton]** → (XMASS-II[20ton])
  - XMASS1.5: fiducial mass 3 tons, BG Level 1x10^{-5} ~ 6x 10^{-6} dru, threshold 2keVee.

Neutrino floor

- This is the place where we start to see the coherent scattering of (solar/atmospheric/RSN) neutrinos on the target nuclei (irreducible background)
- Event rate depends on
  - Exposure, Target material, Threshold and so on
- Sensitivity: does not strongly depend on the energy resolution

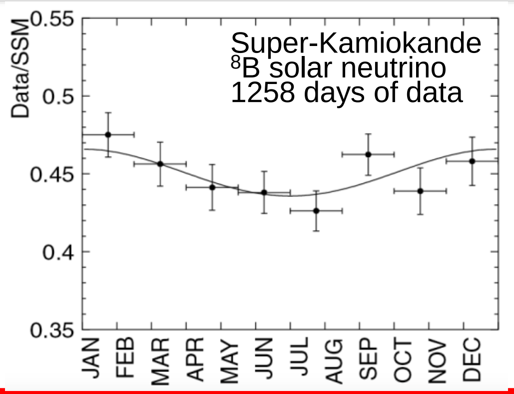
See for example arXiv:1307.5458, arXiv:1604.03858,….





Neutrino floor

- Way to overcome this limit
  - Discover DM before reaching to this floor !!
  - Annual modulation
    - Dark matter maximum:
      - June 2
    - Solar neutrino maximum:
      - 3~5th of January (perihelion)
      - ~7% annual modulation

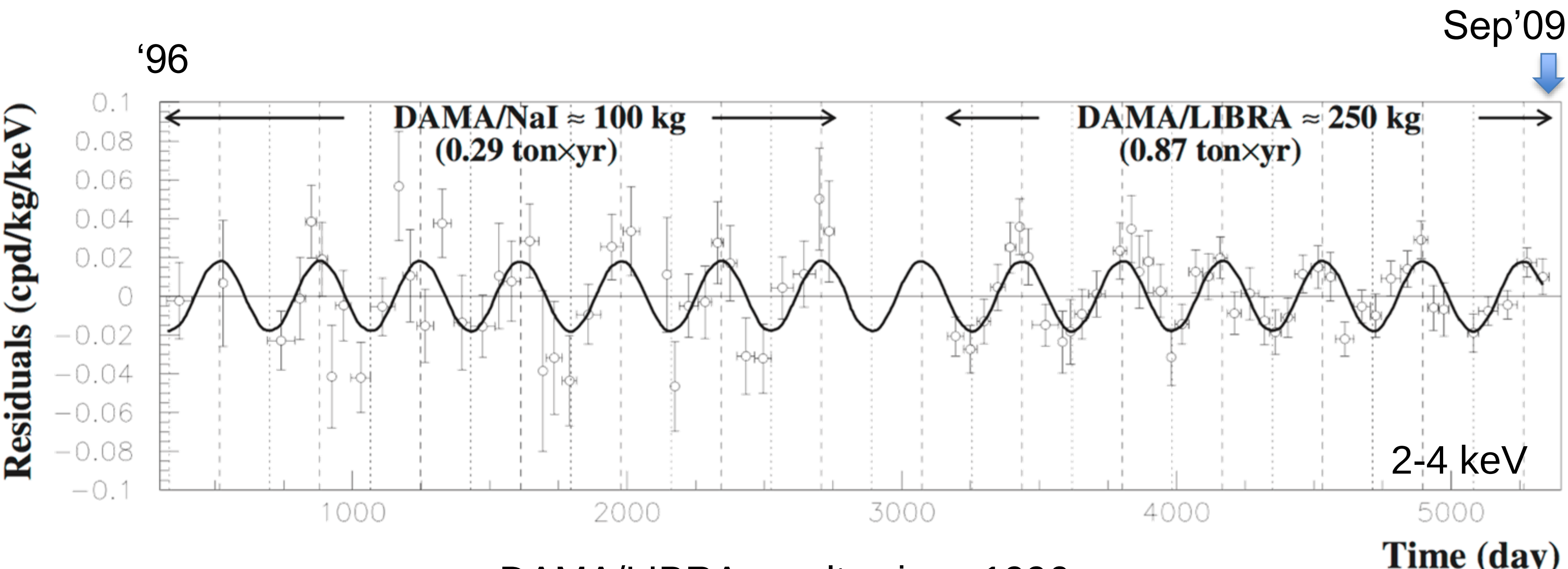


  - Directionality for dark matter recoil
    - Low density ⇔ large mass for WIMPs
      - Directionality: gas detector (a few ~ at most 10 atm)
      - example. Xenon
        - » 10 ton liq. Xenon → 3 m^3
        - » 10 ton gas xenon (10 atm) → 150 m^3
          - Huge, but may not be impossible

Low mass WIMPs search

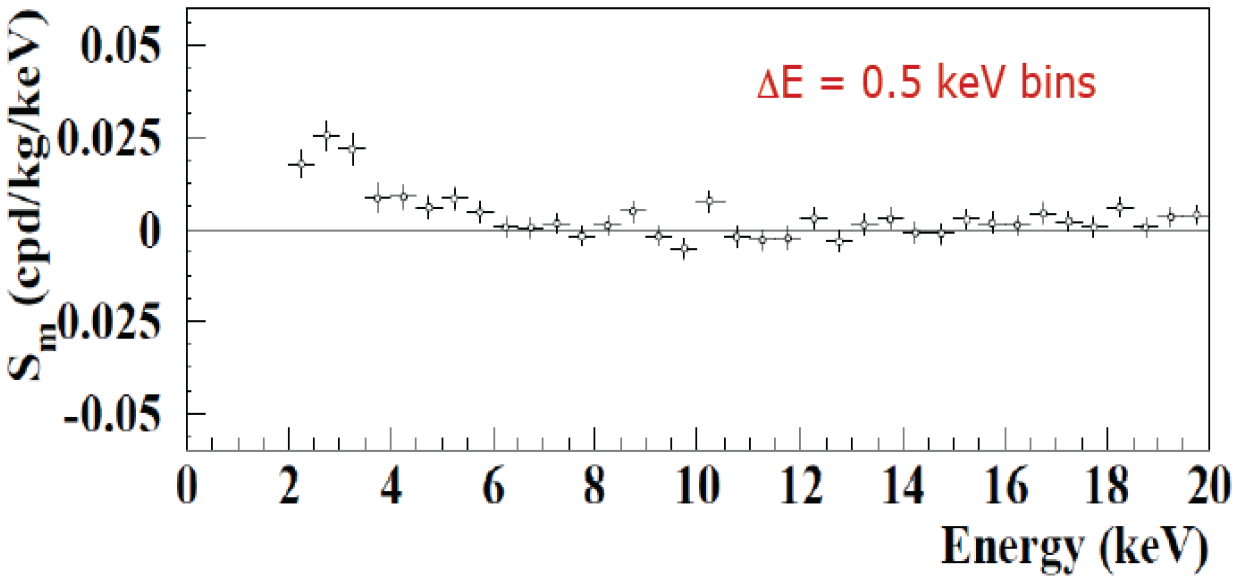
- No convincing direct evidence for WIMPs so far
- But there has been a persistent claim of a discovery of an annual modulation.

DAMA/LIBRA for 13 years of data (NaI: 100kg~ 250kg)



DAMA/LIBRA results since 1996

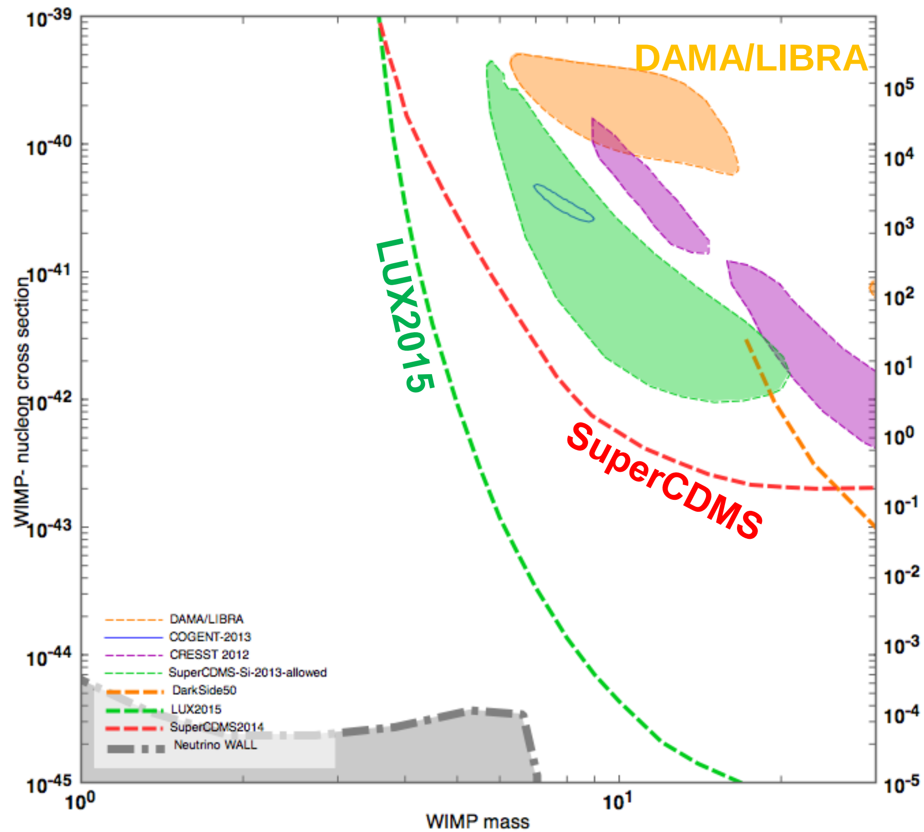
DAMA results



- Amplitude for 2~6 keV: 0.0116±0.0013 cpd/kg/keV (9.3σ)
- Note : they never claimed the discovery of "WIMPs"
- Possibility of electro-magnetic signals
- New Data: DAMA/LIBRA phase-II
  - New PMTs
  - Lower threshold below 2 keVee
  - They will present new data next year!!

Low mass situation

- DAMA/LIBRA annual modulation is persistent.
- Other "allowed regions" are getting weaker.
- 2 phase liq. xenon also set best limit for this region
  - They have a drastic change of the detection efficiency in low mass region
  - Large systematics

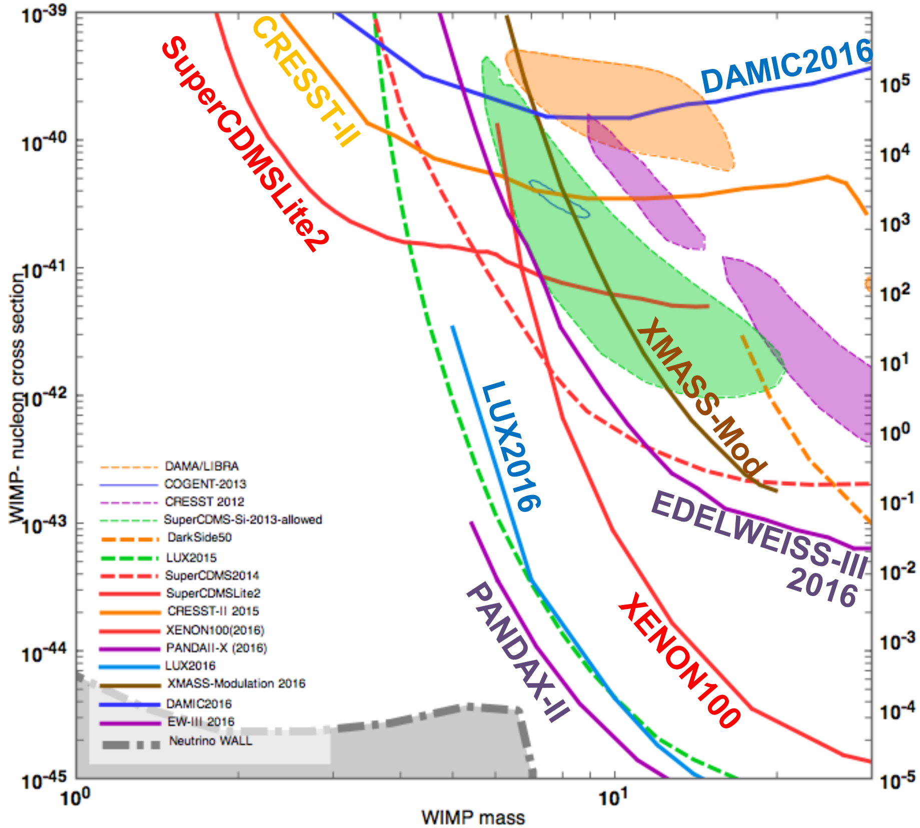


New approaches for low mass

- Both Ge detectors (SuperCDMS, EDELWEISS) and Crystal detector (CRESST)
  ➔ lowering energy threshold
  ➔ higher sensitivity for low mass
- New results from DAMIC (CCD) detector
- New modulation results of NR and e/γ events from XMASS

Low mass situation

- DAMA/LIBRA annual modulation is persistent.
- Other "allowed regions" are getting weaker.
- 2 phase liq. xenon also set best limit for this region
  - They have a drastic change of the detection efficiency in low mass region
  - Large systematics



New approaches for low mass

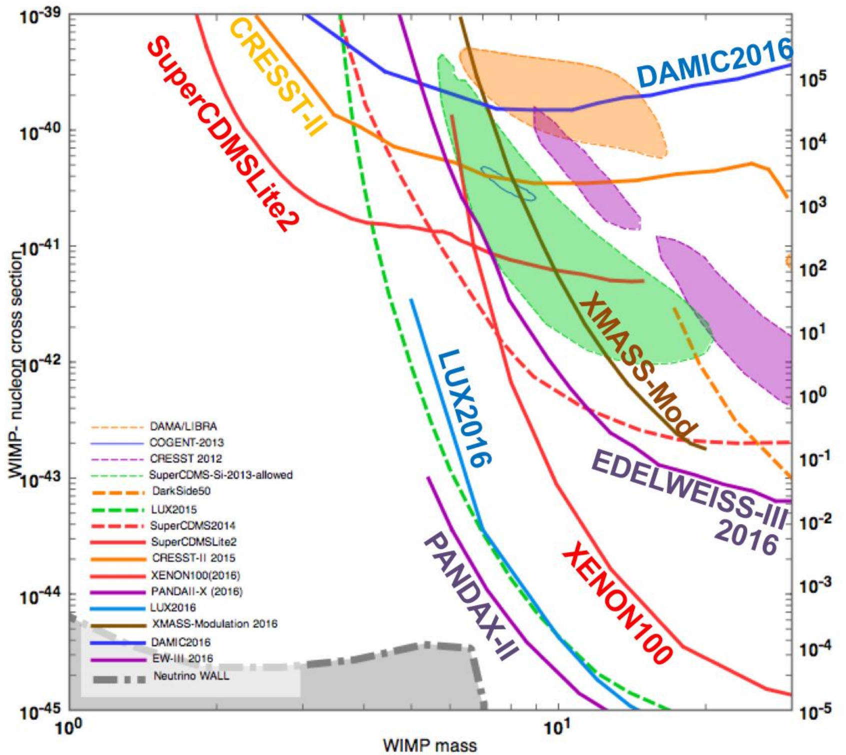
- Both Ge detectors (SuperCDMS, EDELWEISS) and Crystal detector (CRESST)
  - ➔ lowering energy threshold
  - ➔ higher sensitivity for low mass
- New results from DAMIC (CCD) detector
- New modulation results of NR and e/γ events from XMASS

New Rate Measurement

Ge detectors

- SuperCDMSLite (PRL116, 071301 (2016))
  (Low Ionization Threshold Experiment)
- Select one superCDMS detector
- <u>Operate with higher bias voltage to enhance phonon signal</u> (<u>Neganov-Luke effect</u>)
- Eth (ER): 56 eV
- Exposure 70 kg*day (2nd phase)
- New region 1.6 ~ 5.5 GeV/c^2

N-L effet
In incresing electric field, all the additional energy obtained by drifting electrons will be lost in a form of phonon



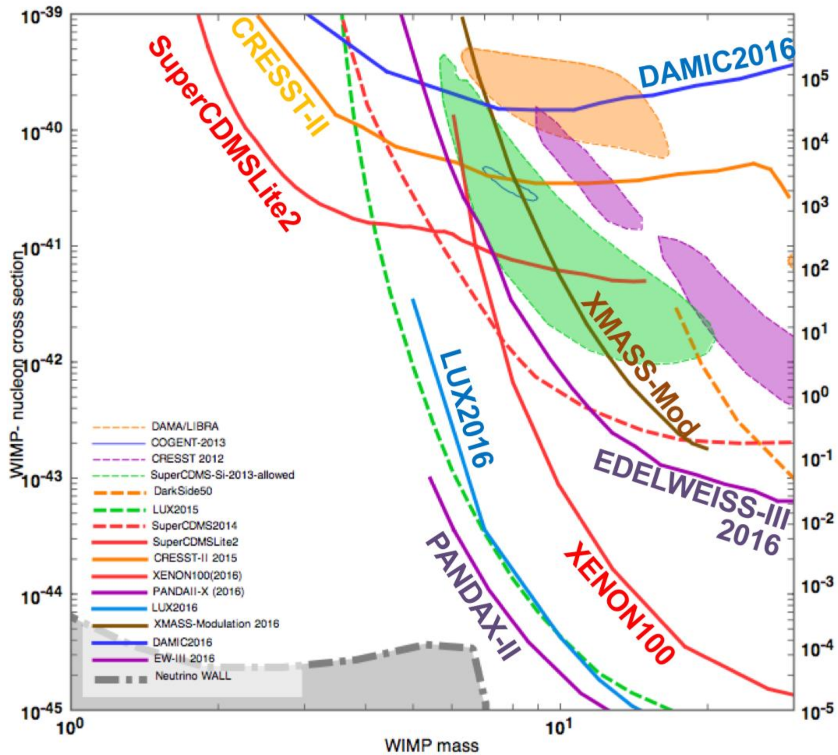
Simillar efforts by EDELWEISS-III

New Rate Measurement

CRESST ($CaWO_4$): phonon and Scintillation light

- Selected best crystal: 300 g
- Threshold: 307 eV
- Exposure 52kg*day, New window down to 0.5 GeV/c² (CRESST-II)

➔ Will use small size of detector 24g to decrease the capacitance to lower the energy threshold to 100 eV ($\Delta T=\Delta E/C$) and therefore increase the sensitivity for low mass DM

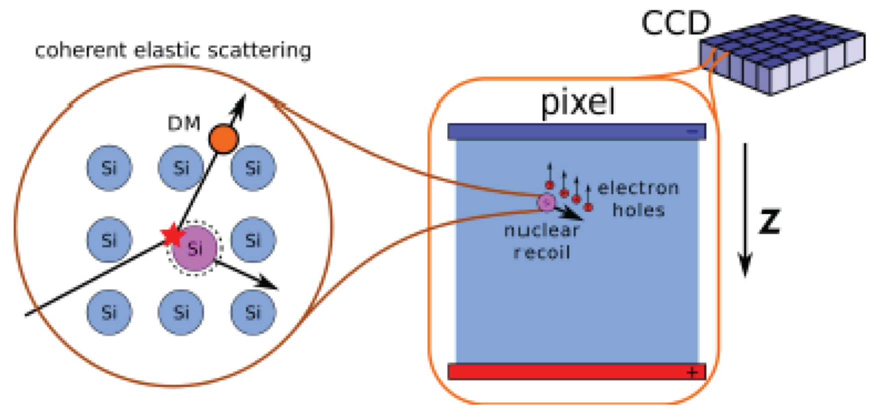


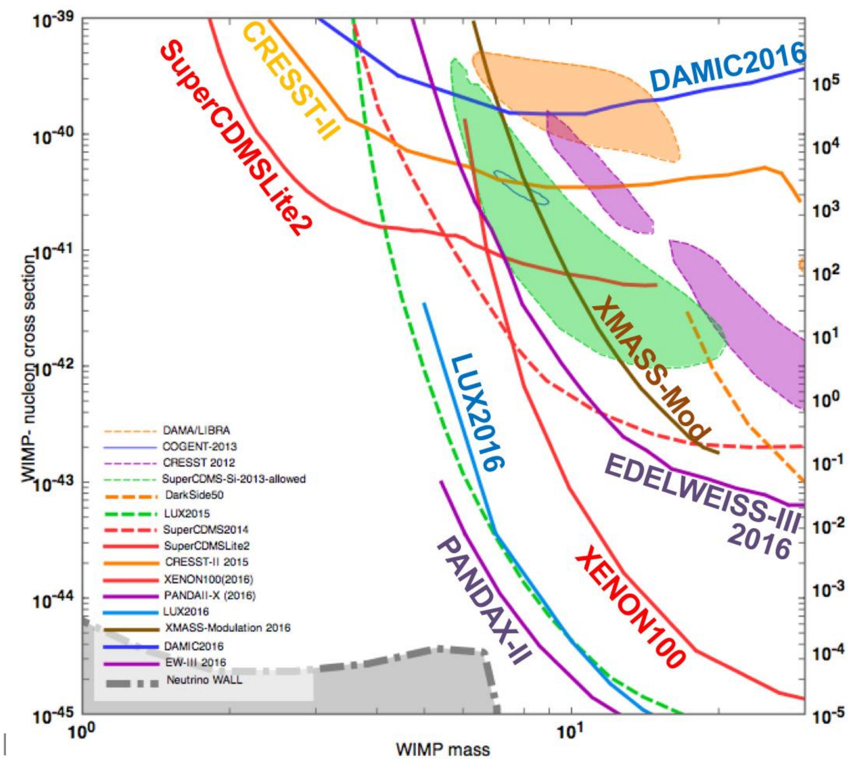
New Rate Measurement

DAMIC (Dark Matter in CCDs)

- CCDs: low noise ➔ low thresh.
  - Noise level: 1.8 electrons
    ➔ 5 sigma noise ➔ <u>40 eV</u>
- First result: 250μm thickness and 8 MPix, 1 g per CCD
  - Phys. Lett. B711, 264 (2012).
- DAMIC-100: 674 μm, <u>general CCDs,</u> 16M Pix, 5.6g per CCD
- 18 x 5.6 g = 100.8 g

- Start commissioning, in April 16
- 0.6 kg*day exposure

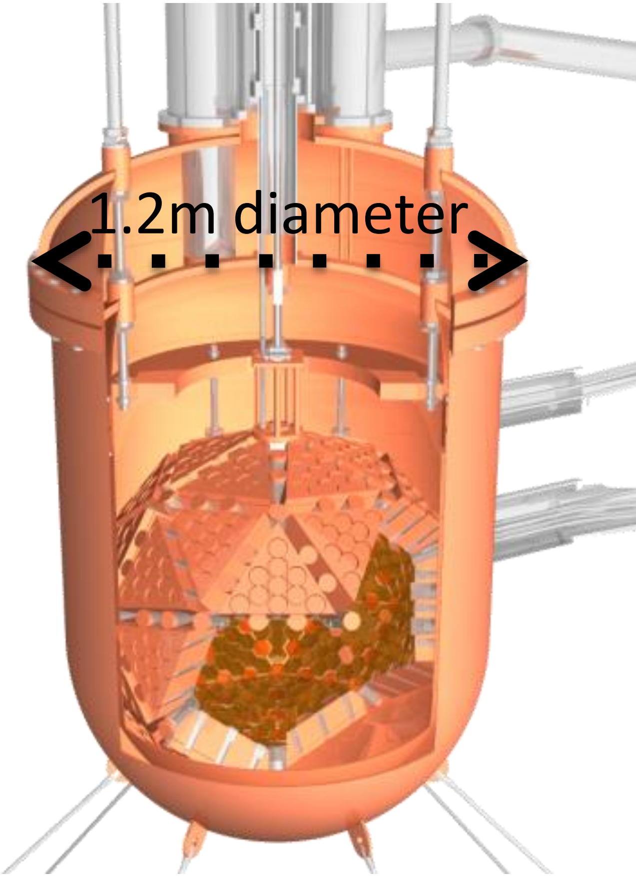




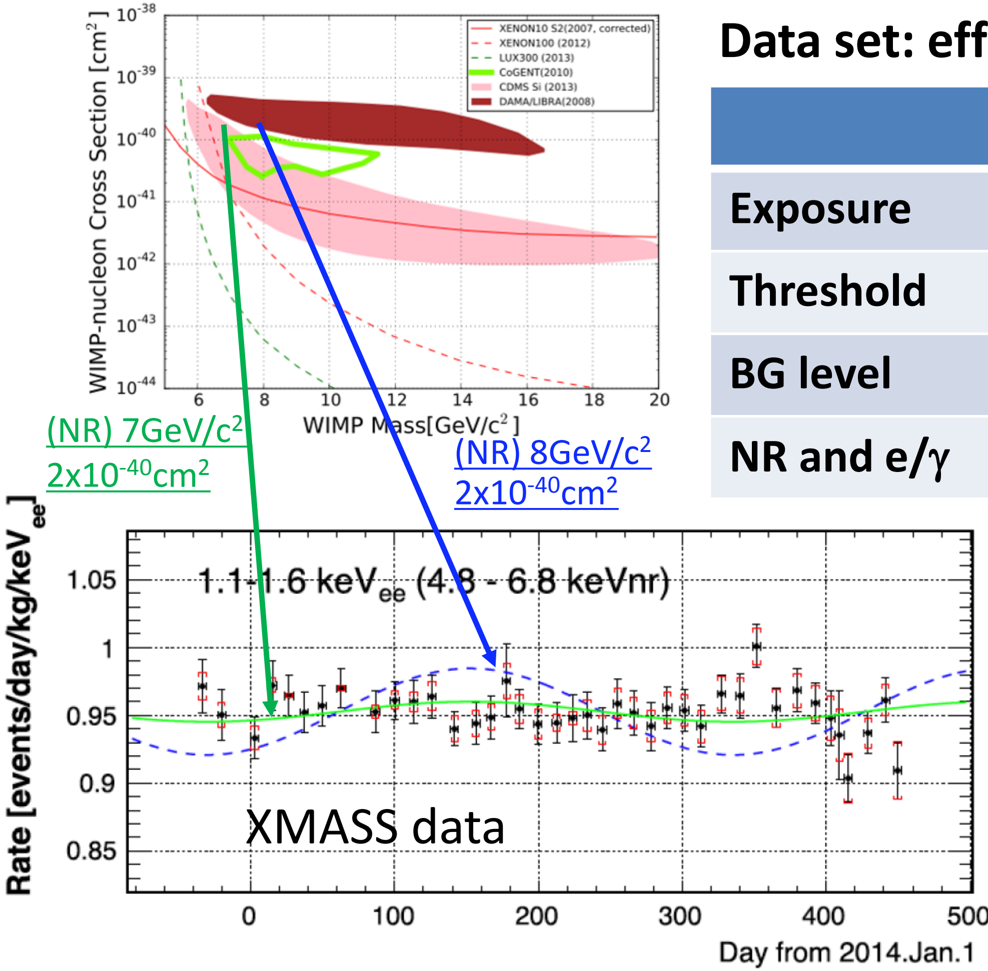
A search for modulation [XMASS-I]

Improtant to check DAMA results not only by ”rates”, but also by “modulation”.

- XMASS-I: single phase liquid xenon detector with inner mass of 835 kg
- 642 low BG PMTs covering ~62% of inner surface
- ~ 14 photo-electrons/keV(@122keV)
- Good for modulation study
  - Large mass, long exposure(> 1yr), low threshold
- Threshold for the modulation study:
  - 1.1 keVee (for this analysis)
    ← Scintillation efficiency in low energy
  - Could be lowered in future



XMASS-I
Low Mass Modulation Analysis



Data set: effective 359 days: [Dec-2013 ~ March-2015]

	XMASS	DAMA/LIBRA
Exposure	0.83 ton*yr (1yr)	1.33ton*yr (13yr)
Threshold	1.1keVee	2keVee
BG level	O(1 dru)	O(1 dru)
NR and e/γ	◎	◎

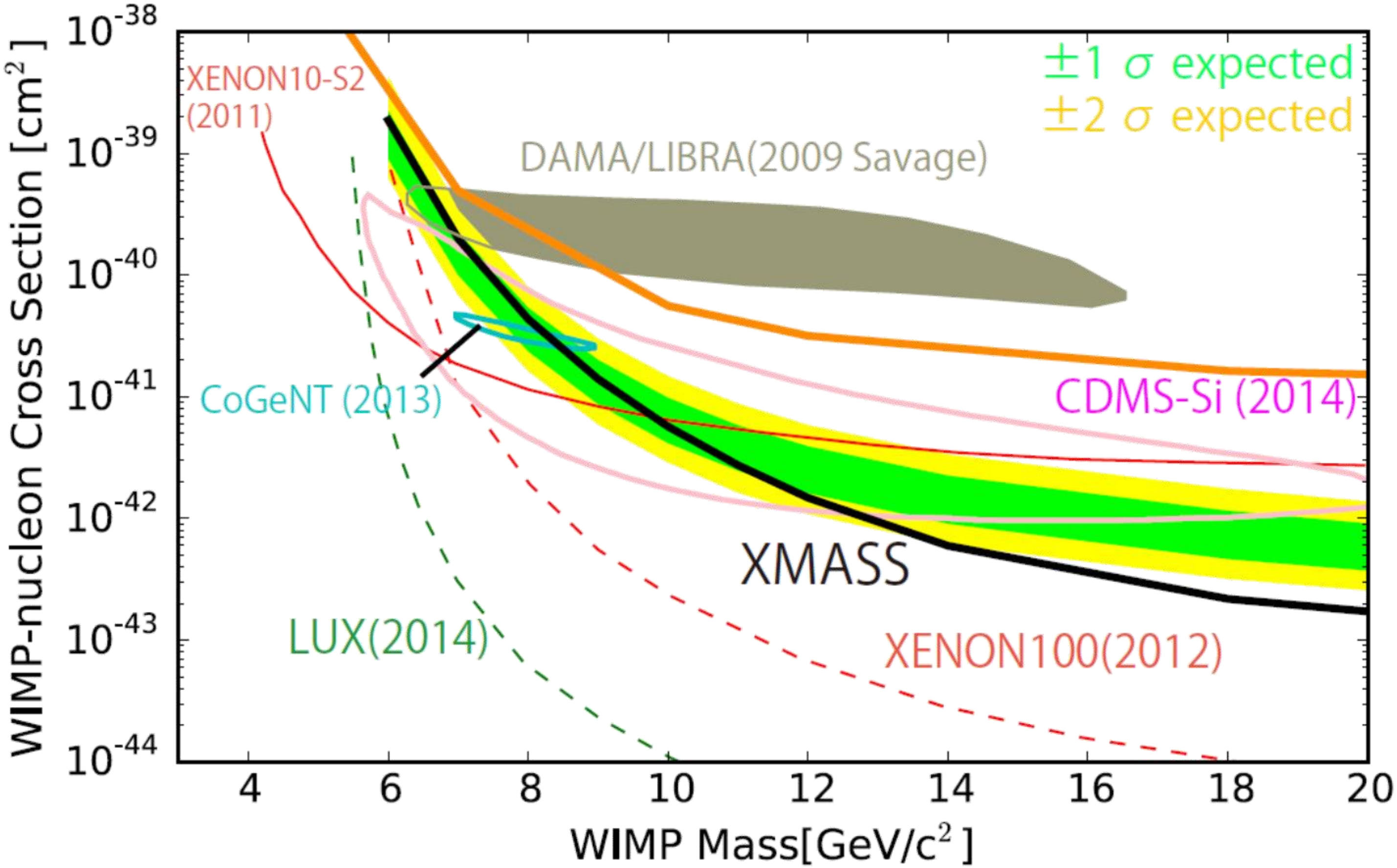
Fitting formula:

$$R^{ex}_{i,j} = \int_{t_j-\frac{1}{2}\Delta t_j}^{t_j+\frac{1}{2}\Delta t_j} \left(C_i + A_i \cos 2\pi \frac{(t-t_0)}{T} \right) dt$$

Δ_j: time bins ~ 10 days, t_0: 152.5 days
C_i: constant term, A_i: modulation amplitude
i: running over energy bins

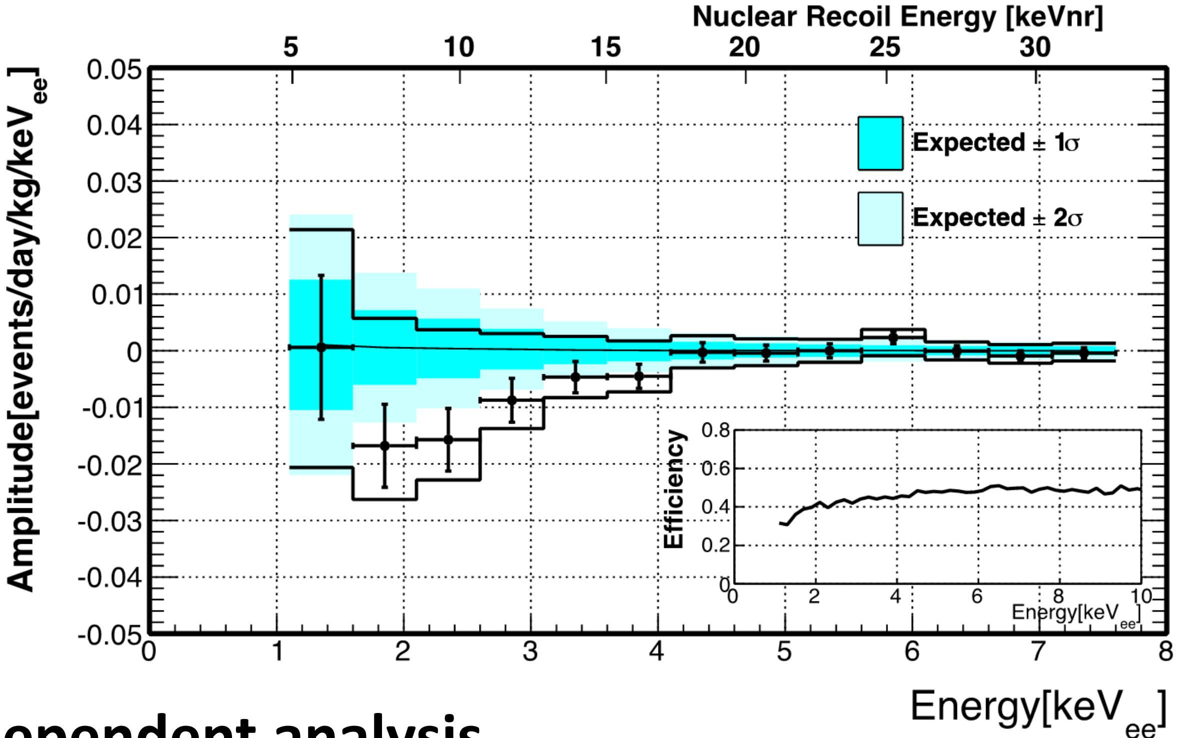
1) WIMPs analysis: A_i is constraint by the spectrum of WIMPs(m_χ): $A_i(m_\chi)$
2) model independent analysis: No constraint on A_i

XMASS low mass modulation
WIMP assumption



- Results for WIMP analysis (assuming NR and spectrum shape)
- Covered mass range between 6 and 20 GeV/c^2
- Exclude almost all the DAMA allowed region @90% confidence level

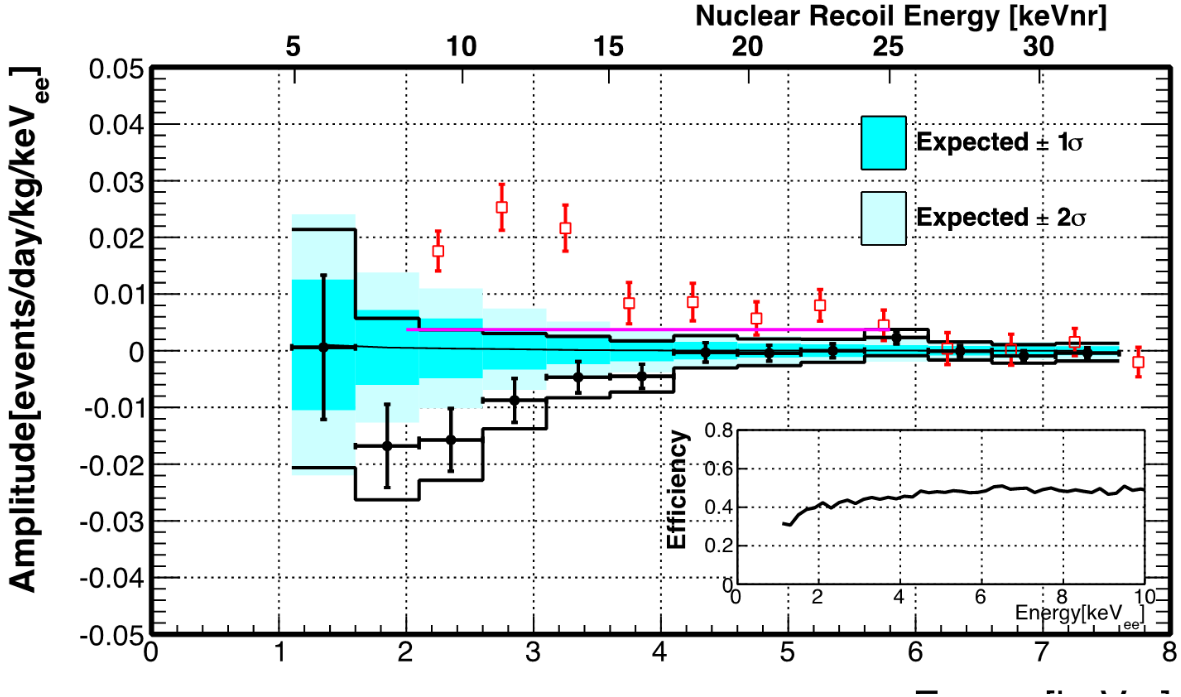
XMASS low mass modulation
DM model independent (e/γ signal)



Model independent analysis

- Not assuming WIMPs, no constraint on the spectrum shape
  - Includes both NR and e/γ signals
- Results ➔ Show weak negative correlation
- Two independent analyses, pull method & covariance matrix method, give similar results (1.8 ~ 2.5 σ level)

XMASS low mass modulation
DM model independent (e/γ signal)



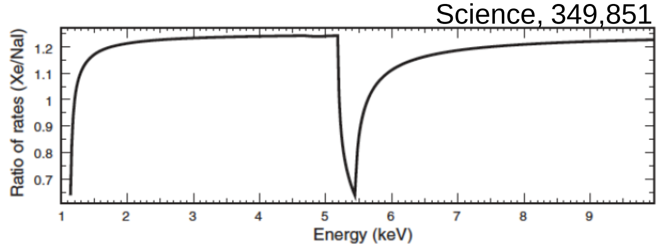
Model independent analysis

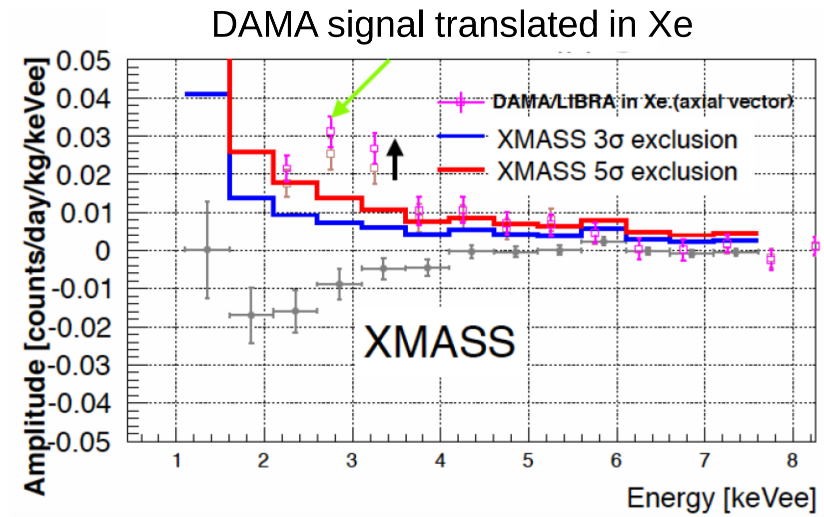
- Not assuming WIMPs, no constraint on the spectrum shape
  - Includes both NR and e/γ signals
- Results ➔ Show weak negative correlation
- Two independent analyses, pull method & covariance matrix method, give similar results (1.8 ~ 2.5 σ level)

DAMA results are simply overlayed in above figure (red poing).
In order to compare DAMA results to XMASS results, need a Model to translate.

Examples

- WIMP-Electron Scattering (J.Kopp et al. PRD80,083502(2009))
  - The whole recoil is absorbed by the electron that is then kicked out of the atom.
  - Xe(z=54) and I (Z=53) similar event rate, but
  - Atomic shell difference must be taken into account ➔ scale facctor

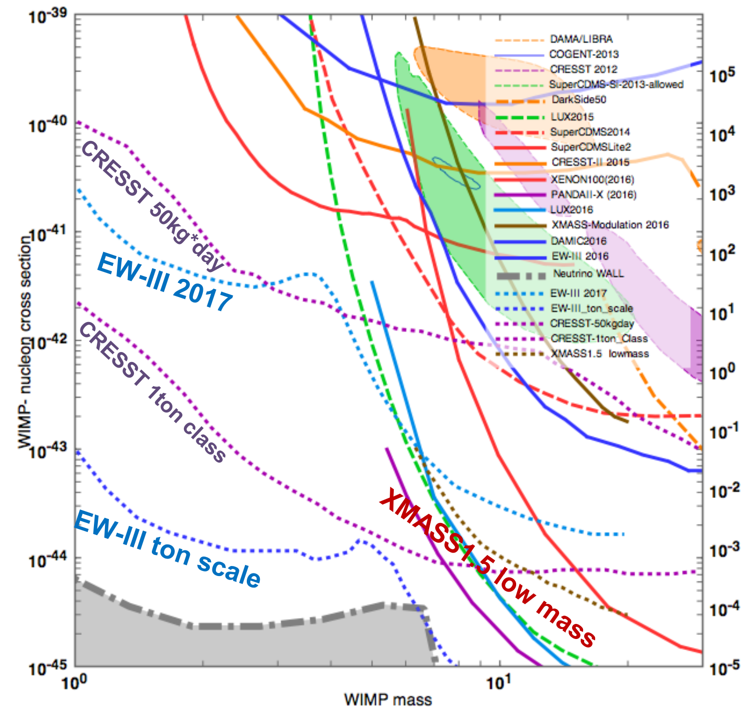




- Luminous Dark Matter (B. Feldstein et al., PRDD 82, 075019 (2010))
  - DM scattering in the Earth into the excited state and decaying back to the ground states
  - Emitting a single photon in the detector
  - Only the total <u>volume</u> affects the event rate
  - /kg ➔ /cm^3 : ρ(Xe)/ρ(NaI)= 2.88/3.67 = 0.78: scale factor to the DAMA data

Future of low mass

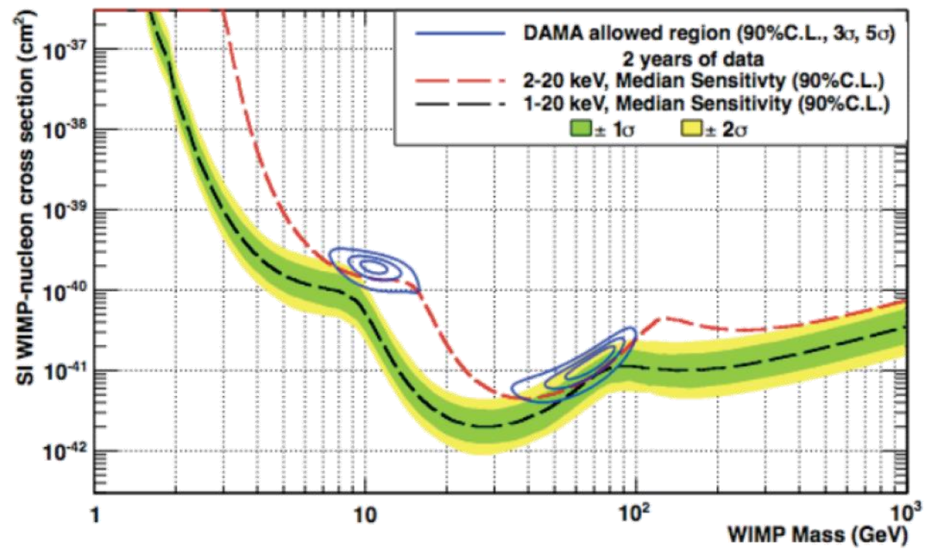
- XMASS1.5[6 ton] (Modulation)
  - Lower energy threshold:
    - ~1 keVee
  - Whole volume ← no vertex reconstruction
  - BG: expected to reduce to 1/500
    - BG < 10^{-2} dru
- Future Rate measurement
  - Efforts to reach lower energy threshold (Ge & Crystal)
- Future Modulation test by NaI
  - Many attempts



NaI experiments

Confirm/reject DAMA modulation data with same target material, NaI.

- COSINE-100 (Korea)
  = KIMS + DM-Ice
  - ~100 kg (8-18 kg each)
  - 2~4 dru @ 6keV
  - Will start soon



**Assumed 2 dru or 4 dru flat backgrounds depending on crystals.*

- ANAIS-112 (Canfranc)
  - 112.5 kg (proposal)
  - ANAIS-37 in progress
- SABRE (two locations: GranSasso & Australia)
  - 40~50 kg x 2 locations
  - In preparateion

BG ➔ easy to say, but difficult to achieve

DAMA K contamination: ~13 ppb in crystal

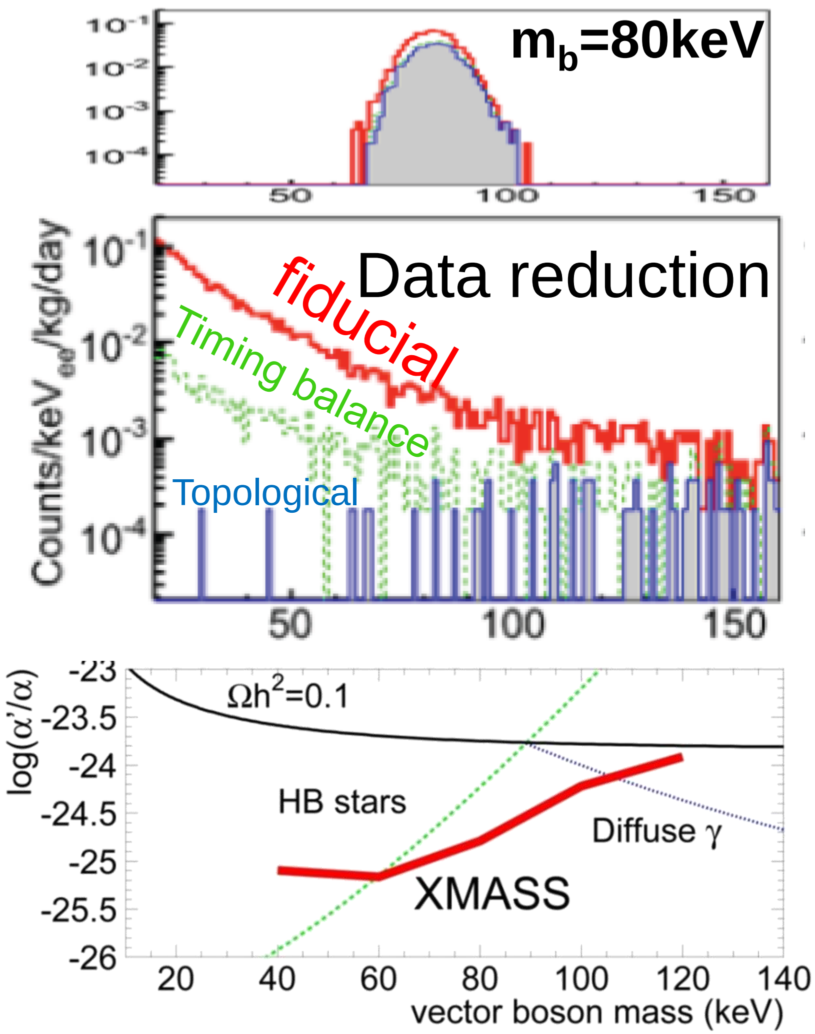
KIMS ~20 ppb,   ANAIS ~20 – 40ppb,   SABRE ~18ppb

Dark Matter searches other than WIMPs

***Bosonic Super-WIMPs** (e/γ signal)*

- Bosonic super-WIMPs in the mass range around 10s of keV.
  - thermally produced at the early universe
  - Energy scale is super-weak to prevent over-production
  - Can be hidden photons
- Why keV dark matter is interesting?
  - It may cure rich structures seen in a smaller scale than galaxy in a CDM simulation, which contradicts with the observation.
- Can be observed through the photo(axio)-electric effect
  - Search for mono energetic peak corresponding to a mass of the boson

Result from XMASS



- 166 days of data
- Mass range 40-120 keV
- Apply simple reduction cuts
- Remaining event rate: 3×10^{-4} /keVee/kg/day ← ^{214}Pb (^{222}Rn)
- For vector boson
  - First results from terrestrial experiment
  - Best limit of α'/α of the vector super-WIMPs (60~100 keV)
  - Rejected that all the dark matter is vector super-WIMPs
- For pseudo-scalar
  - Placed stringent limit
- Results demonstrate that single phase xenon detetor has high sensitivity for e/γ signals from Dark Matter

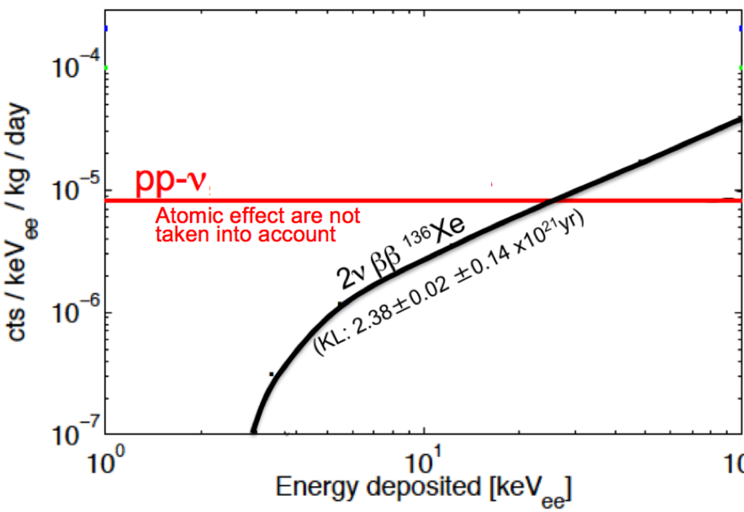
future

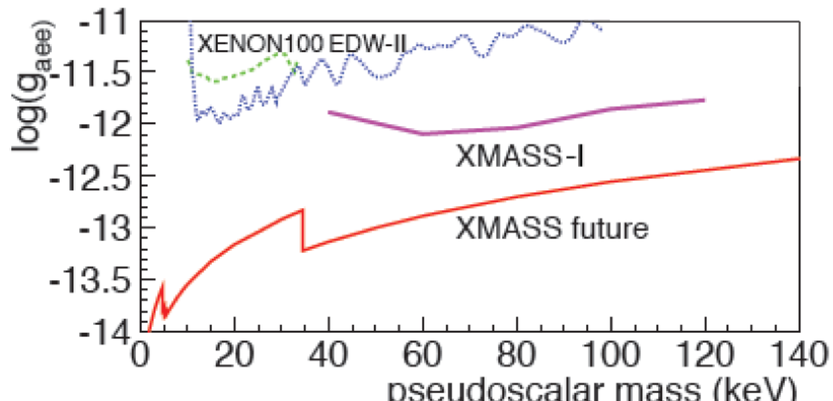
- BG determines future sensitivity
- For High energy e/γ O(10~100 keV)

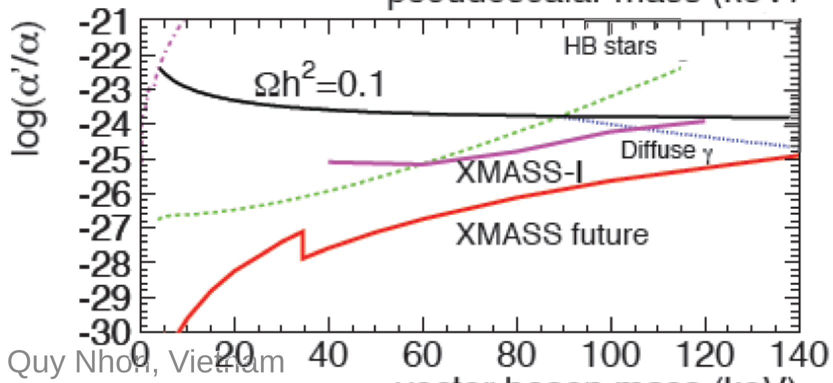
Need to reduce Rn

A few x 10^{-4} dru ➔ ~more than order reduction.

<u>pp-solar neutrino</u> and <u>^{136}Xe DB</u> (at 10^{-5} dru level) will be the ultimate BG







Summary

- Dark matter exists
- If dark matter interacts with us, we should not miss them.
- We need many「traps」as much as possible
- The best limit obtained for WIMPs search is

$$2.2 \times 10^{-46} cm^2 \ (2.2 \times 10^{-1} \ zb!!)$$

for spin independent cross sections at 50 GeV/c^2.

- Significant efforts have been made in exploring the low mass region.

Summary

- Standard search should continue, but
  - Complementary searches are also needed
    - e/γ signals are interesting
      - Hidden photons etc
- Hope we will detect them in near future. The task is very difficult, but extremely interesting and chances are everywhere
- Large DM search experiments becomes high risk and high return.
  - Need good by-products
    - WIMP search + Neutrinos, in ultimate DM detectors