ALHET: A Liquid HElium Time projection chamber

Junhui LIAO

“It is right to continue to challenge ΛCDM, but wrong to ignore the evidence from the abundance of tests.”
Prof. Jim Peebles (2019 Nobel laureate)

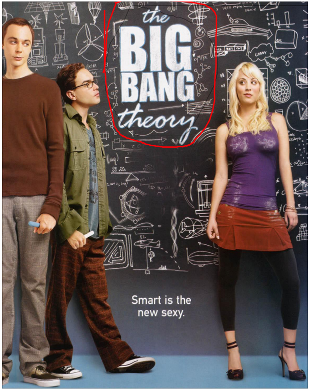
- “Astronomical evidence of many types, ..., all points to the existence of CDM particles. ... Alternative explanations involving modification of Einstein’s theory of GR have not been able to explain this large body of evidence across all length scales.” (1401.6085).
- WIMPs is the most promising DM candidate so far, although there exist other ones like Axion, etc.
  I will focus on WIMPs in this talk.
- Assuming the WIMPs mass is 10 GeV/c^2, roughly, ~ 10^8 WIMPs going through the cup per second.

Outline

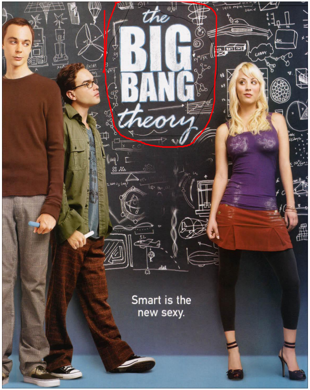
1. Understanding DM beyond gravitation with elementary physics
   - Where it all begins? The big bang theory
   - The strategies of DM detection
2. DM direct detection
   - A brief review of DM direct detection
   - DM direct detection: a multi-disciplines research
3. The ALHET
   - What is the ALHET and why
   - Possible analysis channels
   - Calibrations for the ALHET TPC prototype

Outline

Where it all begins? The big bang theory!

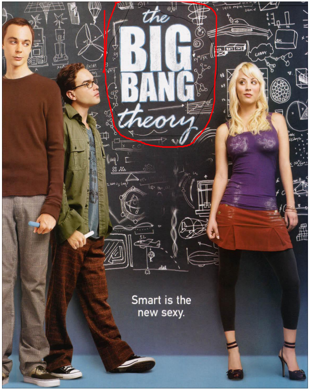


Where it all begins? The big bang theory!



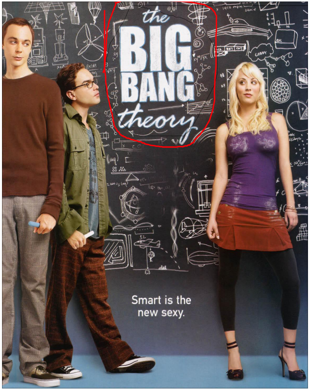
- Currently, most of serious physicists agreed the existence of DM. However, the evidence of DM from cosmology so far can only tell us that DM involves gravitation.

Where it all begins? The big bang theory!



- Currently, most of serious physicists agreed the existence of DM. However, the evidence of DM from cosmology so far can only tell us that DM involves gravitation.
- It is possible that DM only has gravitation with matter (no other interactions).

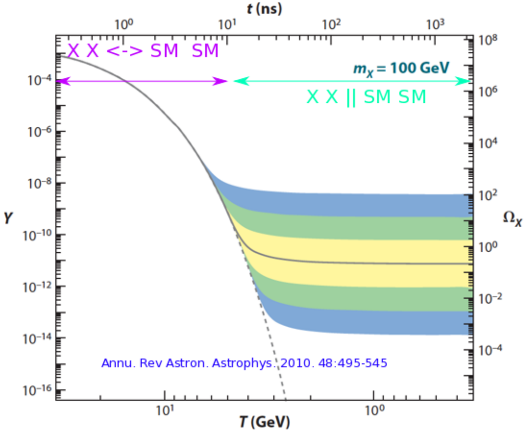
Where it all begins? The big bang theory!



- Currently, most of serious physicists agreed the existence of DM. However, the evidence of DM from cosmology so far can only tell us that DM involves gravitation.
- It is possible that DM only has gravitation with matter (no other interactions).
- One of the motivations for us to pursue a possible new fundamental interaction in between DM and matter beyond gravitation? The “WIMP miracle”.

The "WIMP miracle": The "biggest" and "smallest" physics are united

- Cosmology: The early Universe was dense and hot, DM and matter can annihilate to each other $\chi\chi \longleftrightarrow$ SM SM. As the Universe cooled down and expanded, DM can't annihilate to matter anymore therefore survived as the relic of the process. The observed Relic Density (RD) is, $\Omega_\chi \sim$ 0.12 (Planck results, 1807.06205).



- Particle physics:

  RD: $\Omega_\chi \propto \frac{1}{<\sigma v>} \sim \frac{m_\chi^2}{g_\chi^4}$.
  σv is the XS of the annihilation.
  The cosmology quantity, Ω_χ, can link to a particle physics quantity, g_χ, "naturally".
  Substituting $m_\chi \sim 100$ GeV, $g_\chi \sim 0.6 \rightarrow \Omega_\chi \sim$ 0.1 $\approxeq$ 0.12 !
- This is the so-called "WIMP Miracle": weak-scale particles (microscopic) make good cosmology DM candidate (macroscopic)!

Key events in the thermal history of the Universe

Event	time t	redshift z	temperature T
Inflation	10^{-34} s (?)	–	–
Baryogenesis	?	?	?
EW phase transition	20 ps	10^{15}	100 GeV
QCD phase transition	20 μs	10^{12}	150 MeV
Dark matter freeze-out	?	?	?
Neutrino decoupling	1 s	6×10^9	1 MeV
Electron-positron annihilation	6 s	2×10^9	500 keV
Big Bang nucleosynthesis	3 min	4×10^8	100 keV
Matter-radiation equality	60 kyr	3400	0.75 eV
Recombination	260–380 kyr	1100–1400	0.26–0.33 eV
Photon decoupling	380 kyr	1000–1200	0.23–0.28 eV
Reionization	100–400 Myr	11–30	2.6–7.0 meV
Dark energy-matter equality	9 Gyr	0.4	0.33 meV
Present	13.8 Gyr	0	0.24 meV

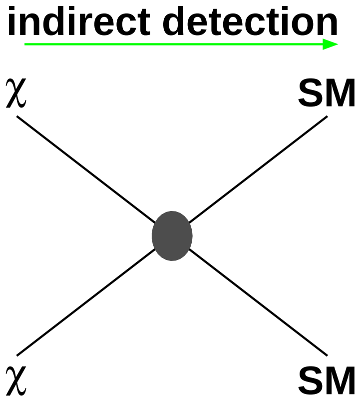
U. Cambridge cosmology

Outline

1. Understanding DM beyond gravitation with elementary physics
   - Where it all begins? The big bang theory
   - The strategies of DM detection
2. DM direct detection
   - A brief review of DM direct detection
   - DM direct detection: a multi-disciplines research
3. The ALHET
   - What is the ALHET and why
   - Possible analysis channels
   - Calibrations for the ALHET TPC prototype

Indirect detection

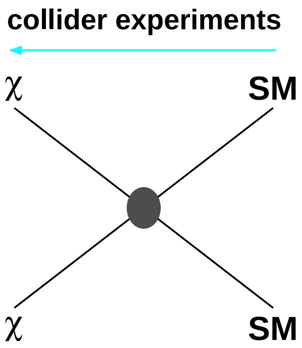
$\chi\chi \xrightarrow{\text{annihilate}}$ SM SM.



- $\chi\chi \to \nu$, from the Sun
  To measure: higher energy ν.
  Experiments: SuperK, IceCube.
  Status: no signal, limit $\sigma_A v \sim 10^{-23}$ cm^3 s^{-1}
- $\chi\chi \to e^+e^-$, in galaxies
  To measure: excess of e^+.
  Experiments: AMS, Fermi-LAT, PAMELA, DAMPE (Wukong).
  Status: no signal. Hard to rule out Pulsars (AMS02 take data until 2030).
- $\chi\chi \to \gamma$, in Milky Way.
  To measure: excess of γ.
  Experiments: Fermi-LAT, H.E.S.S.
  Status: no convincing signal ...

Collider experiments

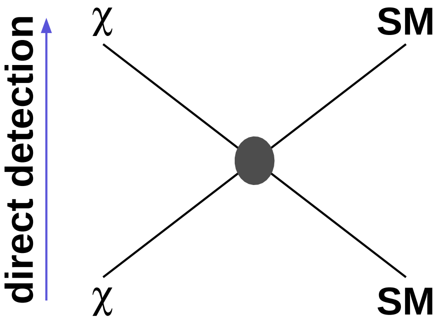
SM SM $\xrightarrow{\text{annihilate}} \chi\chi$



- SM SM $\xrightarrow{\text{heavy mediator}} \chi\chi$
  To measure: "missing energy".
  Experiments: ATLAS, CMS.
  Status: no signal.
  limits: $\sim (10^{-41} - 10^{-45})$ cm^2, channels dependent.
- SM SM $\xrightarrow{\text{mainly light mediator}} \chi\chi$
  To measure: other possible "hidden" sectors, like dark photon etc.
  Technology: beam hits on a fix target.
  Experiments: SHiP (https://ship.web.cern.ch/ship/), LDMX (sub-GeV, arXiv: 1808.05219)
  Status: construction or early stage of proposal.

Direct detection

χ + SM $\xrightarrow{\text{elastic Scattering}}$ χ + SM (This talk).



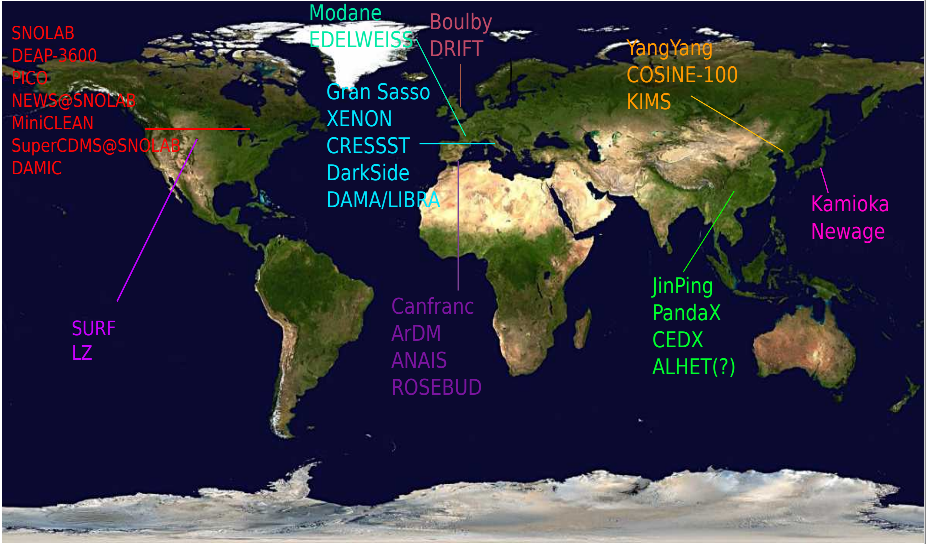
- Deep underground labs to block backgrounds due to cosmic rays.
- Very low background materials selected to build a detector system.
- Detector assembly under strict screening and dust control.
- Experiments globally (still active): ~ 20.
- Status: No signals. Lowest limits for high mass WIMPs: $\sim 4.0 \times 10^{-47}$ cm^2 at ~ 30 GeV, XENON 1T using LXe.
- Key technical challenge: the capability of discriminating NR (sig) from ER (bkg) events .

The feeling of DM (direct, indirect, and colliders) physicists

Outline

1. Understanding DM beyond gravitation with elementary physics
   - Where it all begins? The big bang theory
   - The strategies of DM detection
2. DM direct detection
   - A brief review of DM direct detection
   - DM direct detection: a multi-disciplines research
3. The ALHET
   - What is the ALHET and why
   - Possible analysis channels
   - Calibrations for the ALHET TPC prototype

DM direct detection experiments: a global view



Classify DM experiments

Table: 1. Physics motivation

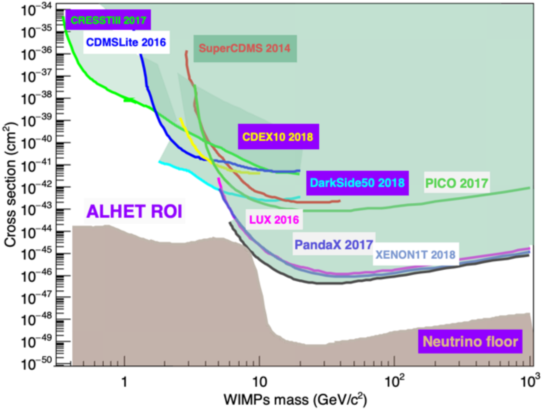
Low mass WIMPs	High mass WIMPs	Annual modulation	Directional detection
ALHET, CEDX, CRESST, DAMIC, Edelweiss, SuperCDMS.	ArDM, DarkSide, DEAP, LZ, PandaX, PICO, XENON.	ANAIS, COSINE-100, DAMA/LIBRA.	DRIFT, NEWAGE, NEWS.

Table: 2. Detector material or technology

LHe TPC	LAr TPC	LXe TPC	CsI/NaI	bolometric/SemiC	Bubble chamber	Gas
ALHET. UCB (Superfluid ^{4}He) Brown (Superfluid ^{4}He)	ArDM, DarkSide, DEAP.	LZ, PandaX, XENON.	ANAIS, KIMS, COSINE-100, DAMA/LIBRA.	CRESST, Edelweiss, SuperCDMS, CEDX, DAMIC.	PICO.	DRIFT, NEWAGE, NEWS.

The current limits of WIMPs direct detection

Upper limits on high mass WIMPs ($\mathcal{O}(100)$ GeV/c^2) is ~8 orders higher than low mass ($\mathcal{O}(1)$ GeV/c^2)! $\Rightarrow$ Physics motivation of the ALHET project.
Diversity is important (critical) for DM direct detection experiments.



Outline

Event rate

Standard Spin Independent (SI), (Kg day keV)$^{-1}$

- DM direct detection is a multi-disciplines research wrapping particle physics, nuclear physics, and astrophysics.
- $\frac{dE}{dR}_{SI} = \frac{\sigma^{SI}_{\chi p} A^2}{m^2_{red}(m_p)} \times N_T F^2_{SI}(E) \times \frac{\rho_\chi}{2m_\chi} \int_{v_{min}}^{\infty} \frac{f_1(v)}{v} dv$
- $\frac{\sigma^{SI}_{\chi p} A^2}{m^2_{red}(m_p)}$, particle physics.
  $\sigma^{SI}_{\chi p}$, cross-section of WIMPs and a proton; A, atomic number of target nucleus; $m_{red}(m_p)$, reduced mass of WIMPs and a nucleon.
  $N_T F^2_{SI}(E)$, nuclear physics.
  N_T, # of target nucleon per kg detector, $F^2_{SI}(E)$, form factor.
  $\frac{\rho_\chi}{2m_\chi} \int_{v_{min}}^{\infty} \frac{f_1(v)}{v} dv$, astrophysics.
  ρ_χ, observed dark matter mass density, a factor of 2 uncertainty. m_χ, mass of dark matter. v_{min}, minimum speed of WIMPs could deposit detectable energy, $f_1(v)$, local speed distribution of WIMPs (which is subject to be modified with more Gaia data.).
- Integrating event rate with ROI energy range (keV) and exposure (Kg day) to get # of events.

Event rate

Standard Spin Independent (SI), $(\text{Kg day keV})^{-1}$

- DM direct detection is a multi-disciplines research wrapping particle physics, nuclear physics, and astrophysics.
- $\frac{dE}{dR}_{SI} = \frac{\sigma^{SI}_{\chi p} A^2}{m^2_{red}(m_p)} \times N_T F^2_{SI}(E) \times \frac{\rho_\chi}{2m_\chi} \int_{v_{min}}^{\infty} \frac{f_1(v)}{v} dv$
- $\frac{\sigma^{SI}_{\chi p} A^2}{m^2_{red}(m_p)}$, particle physics.

  $\sigma^{SI}_{\chi p}$, cross-section of WIMPs and a proton; A, atomic number of target nucleus; $m_{red}(m_p)$, reduced mass of WIMPs and a nucleon.

  $N_T F^2_{SI}(E)$, nuclear physics.

  N_T, # of target nucleon per kg detector, $F^2_{SI}(E)$, form factor.

  $\frac{\rho_\chi}{2m_\chi} \int_{v_{min}}^{\infty} \frac{f_1(v)}{v} dv$, astrophysics.

  ρ_χ, observed dark matter mass density, a factor of 2 uncertainty. m_χ, mass of dark matter. v_{min}, minimum speed of WIMPs could deposit detectable energy, $f_1(v)$, local speed distribution of WIMPs (which is subject to be modified with more Gaia data.).
- Integrating event rate with ROI energy range (keV) and exposure (Kg day) to get # of events.

Event rate

Standard Spin Independent (SI), (Kg day keV)$^{-1}$

- DM direct detection is a multi-disciplines research wrapping particle physics, nuclear physics, and astrophysics.
- $\frac{dE}{dR}_{SI} = \frac{\sigma^{SI}_{\chi p} A^2}{m^2_{red}(m_p)} \times N_T F^2_{SI}(E) \times \frac{\rho_\chi}{2m_\chi} \int^\infty_{v_{min}} \frac{f_1(v)}{v} dv$
- $\frac{\sigma^{SI}_{\chi p} A^2}{m^2_{red}(m_p)}$, particle physics.
  $\sigma^{SI}_{\chi p}$, cross-section of WIMPs and a proton; A, atomic number of target nucleus; $m_{red}(m_p)$, reduced mass of WIMPs and a nucleon.
  $N_T F^2_{SI}(E)$, nuclear physics.
  N_T, # of target nucleon per kg detector, $F^2_{SI}(E)$, form factor.
  $\frac{\rho_\chi}{2m_\chi} \int^\infty_{v_{min}} \frac{f_1(v)}{v} dv$, astrophysics.
  ρ_χ, observed dark matter mass density, a factor of 2 uncertainty. m_χ , mass of dark matter. v_{min}, minimum speed of WIMPs could deposit detectable energy, $f_1(v)$, local speed distribution of WIMPs (which is subject to be modified with more Gaia data.).
- Integrating event rate with ROI energy range (keV) and exposure (Kg day) to get # of events.

Event rate

Standard Spin Independent (SI), $(\text{Kg day keV})^{-1}$

- DM direct detection is a multi-disciplines research wrapping particle physics, nuclear physics, and astrophysics.
- $\frac{dE}{dR}_{SI} = \frac{\sigma_{\chi p}^{SI} A^2}{m_{red}^2(m_p)} \times N_T F_{SI}^2(E) \times \frac{\rho_\chi}{2m_\chi} \int_{v_{min}}^{\infty} \frac{f_1(v)}{v} dv$
- $\frac{\sigma_{\chi p}^{SI} A^2}{m_{red}^2(m_p)}$, particle physics.
  $\sigma_{\chi p}^{SI}$, cross-section of WIMPs and a proton; A, atomic number of target nucleus; $m_{red}(m_p)$, reduced mass of WIMPs and a nucleon.
  $N_T F_{SI}^2(E)$, nuclear physics.
  N_T, # of target nucleon per kg detector, $F_{SI}^2(E)$, form factor.
  $\frac{\rho_\chi}{2m_\chi} \int_{v_{min}}^{\infty} \frac{f_1(v)}{v} dv$, astrophysics.
  ρ_χ, observed dark matter mass density, a factor of 2 uncertainty. m_χ , mass of dark matter. v_{min}, minimum speed of WIMPs could deposit detectable energy, $f_1(v)$, local speed distribution of WIMPs (which is subject to be modified with more Gaia data.).
- Integrating event rate with ROI energy range (keV) and exposure (Kg day) to get # of events.

EFT is a more complete description than the standard SI / SD

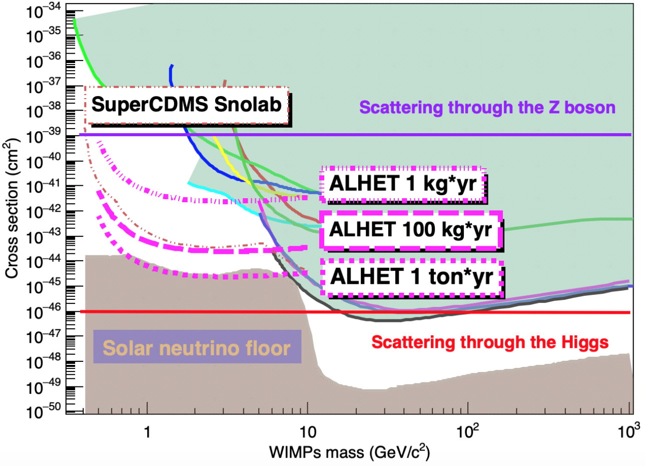
Considering or not the transferred momentum of a WIMPs-nucleon interaction.

- Left picture: a long wavelength → small momentum transfer. EFT and Standard SI/SD are the same for this kind of scattering.
- Right picture: a short wavelength → big momentum transfer. EFT fully characterizes all possible interactions in between the transferred momentum and ~ 0.1 c velocity nucleons, while standard SI/SD ignored it although a form factor is introduced to characterize the reduced recoil energy of the hit nuclei.
- (Atomium, 165 B × a single unit of iron crystal (Fe), Brussels, Belgium.)

Outline

Projected sensitivities of the ALHET under variant exposures

- With JUST 1 ton*yr exposure, ALHET can “touch down” the ^{8}B solar neutrino floor!



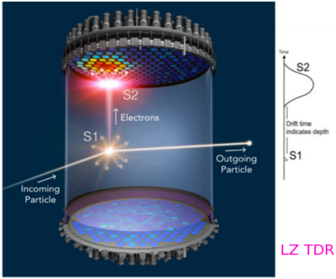
- The ROI of the ALHET: 10s MeV/c^2 - 10 GeV/c^2.
- The sensitivity of S2O analysis depends on data, so can’t project the limits on 10s MeV/c^2 - 100s MeV/c^2 here.
- Experiences from XENON and DarkSide-50, S2O could be sensitive to one order lower mass than S1/S2 and PSD.

Why liquid Helium? Very suitable for low mass WIMPs hunting!

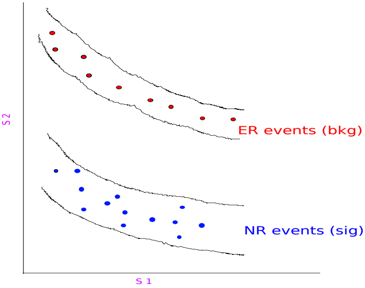
- Helium is the second lightest element: Hydrogen is the lightest element, but doesn't have most of the following advantages as Helium; even worse: no ER/NR discrimination → negative for setting limits and claiming a discovery.
- Instrumental-backgrounds free is achievable: Thanks to PSD + "S2/S1".
- High scintillation efficiency: 100% recombination efficiency at Zero E-field. ~ 25 eV excitation E to produce prompt scintillation light.
- The LHe is transparent for its scintillation: The peak wavelength of scintillation light, 80 nm (= 16 eV) < E difference of g-state to the 1st excited state, 20 eV.
- Low backgrounds due to neutrino-nucleus scattering: low nuclear mass; Low gammas: small # of electrons.
- High wavelength shifting Eff, ~ 97%: 80 nm, should use wavelength shift.
- High quenching factor (QF) at sub-keV ER: Measured lowest QF ~ 20% at 1.5 keVnr ER. A factor of ~ 100 better than H.
- No radioactive isotopes. Easy to be well purified.
- LHe is much cheaper than LXe: current price, ~ 1/5 of LXe.
- "Touch down" the ^{8}B ν floor: 1 t*y LHe TPC; (~ 1000 t*y LXe TPC atm ν).

Why “dual-phase TPC”? Setting most stringent limits in HM WIMPs!

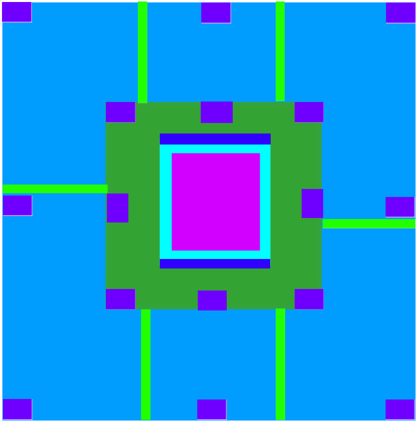
- A scintillation light (“S1”) in liquid and electroluminescence light (“S2”) in gas. Projecting the signal on the S1-S2 plan, layout of the events → ER or NR.
- Why it’s the best Tech: (1) having a fiducial volume with extremely low bkgs, (2) discriminate ER from NR events happened in this volume, (3) multiple analysis: PSD, S1/S2, S2O, (4) recycling and purifying, (5), online calibration, (6) scalability, (7), transplantation (EU→US→Asia, Ar→Xe→Ne→He.)



LZ TDR



The conceptual ALHET TPC (Inspired by DarkSide,LUX/LZ,XENON)

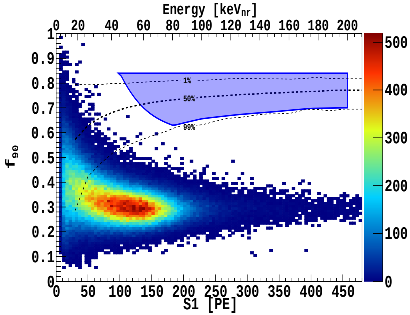


- For neutrons come from outside of the detector system, (a few meters) water tank can thermalize it, then being captured by ~ 0.5 m Gd-doped liquid scintillator and detected by surrounding PMTs (veto system).
- For neutrons from TPC (central detector) itself, an active self-shielding layer (cyan), fiducial volume (pink) and veto (green) compose to a triple veto to reject neutrons because neutrons can scatter multiple times while WIMPs can only do once due to a much smaller scattering XS.
- γ events in the fiducial volume can be rejected as bkg events by showing a different pulse shape with PSD analysis.

Outline

The analysis of PSD and PSD + S1/S2 in DS-50.

- Left plot: DS-50 demonstrated an instrumental bkg free search with the PSD only technique.
- Right plot: A better ER/NR discrimination with integrating S1/S2 analysis into PSD, DS-50.
- Both PSD and PSD + S1/S2 could be applied in the ALHET experiment.



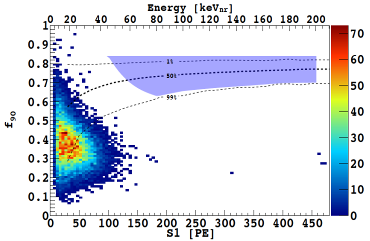
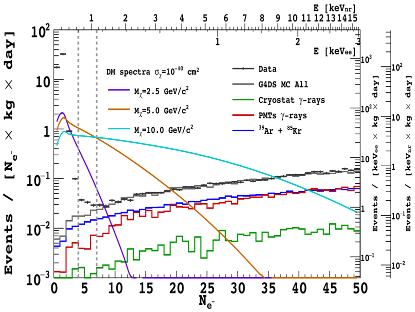
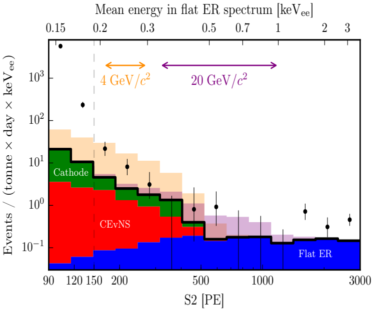


FIG. 12. Distribution of events in the f_{90} vs S1 plane that survive all analysis cuts and that in addition survive tightened radial and S2/S1 cuts (see text for details).

A (novel) DM analysis, S2O, in DS-50 and XENON-1T.

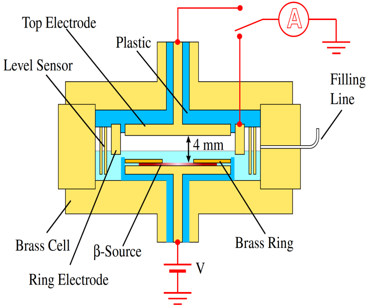
- Left plot: S2 Only (S2O) analysis with DS-50.
  W/ S2O, the limits of DS-50 extend to ~ 2 GeV/c^2, ~ one order lower than the analysis with PSD
- Right plot: S2 Only (S2O) analysis with XENON-1T.
  Similar extension of limits achieved in XENON-1T as DS-50.
- The S2O analysis could be applied in the ALHET experiment.

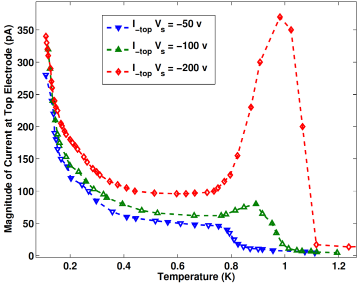




Brown Profs: G. Seidel, H. Maris, and R. Lanou

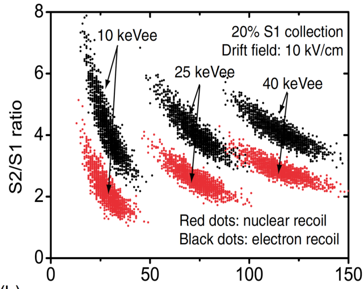
- George studied LHe a few decades, firstly proposed using LHe for DM hunting ~ 30 years ago (with other Profs), as a spin-off of the HERON experiment.
- Left plot: Typical apparatus used for LHe study (Sethumadhavan PhD thesis, Brown).
  Right plot: Electroluminescence in LHe under external field (Sethumadhavan PhD thesis, Brown) ⇒ S2 can be generated in a 2 mm helium gas layer.



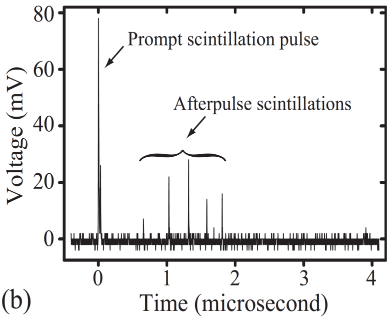


Prof. Dan McKinsey group(Yale →Berkeley)

- Dan has studied LHe a lot since he was a grad until now.
- Left plot: Simulation of Dan and his then-postdoc Guo ⇒ S1/S2 able to discriminate ER from NR events under reasonable assumptions.
  Right plot: Characterization the scintillation with βs ⇒ PSD capable of characterizing ER events.



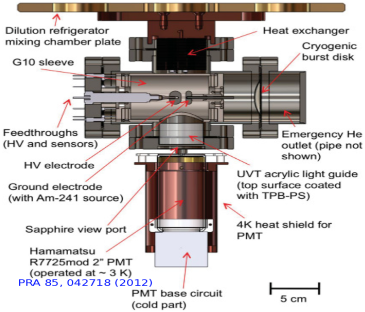
(b) PRD 87, 115001 (2013)



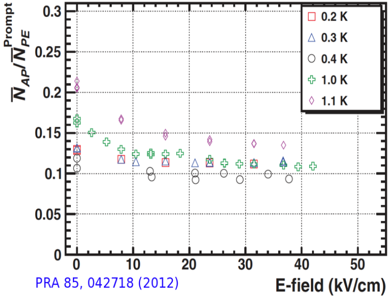
(b)

Dr. Takeyasu Ito (Neutron leader at LANL)

- Takeyasu group has studied LHe with the nEDM project at LANL.
- Left plot: A early version of apparatus for LHe study.
  TPB to shift wavelength from 80 nm to ~450 nm, the PMT operated at ~3 K.
  Right plot: Characterization of the timing with MeV α particles $\Rightarrow$ PSD capable of characterizing NR events in LHe.



PRA 85, 042718 (2012)

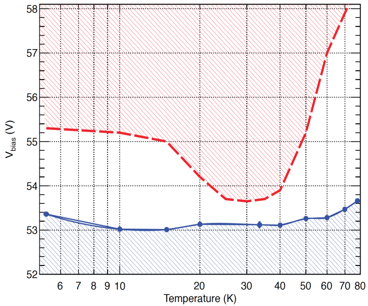


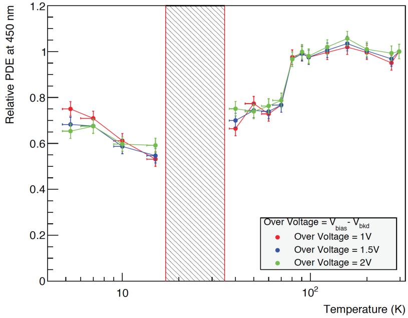
PRA 85, 042718 (2012)

SiPMs

Hamamatsu SiPMs

- Left plot: allowed working voltages range VS temperature.
- Right plot: The PDE at 5 K is ~ 70% of 300 K.
- The paper (Proc. IEEE Nucl. Sci. Symp. Med. Imag. Conf., pp. 1-6, Nov. 2014.) mentioned FBK SiPMs have similar performance.





Outline

1. Understanding DM beyond gravitation with elementary physics
   - Where it all begins? The big bang theory
   - The strategies of DM detection
2. DM direct detection
   - A brief review of DM direct detection
   - DM direct detection: a multi-disciplines research
3. The ALHET
   - What is the ALHET and why
   - Possible analysis channels
   - Calibrations for the ALHET TPC prototype

Calibrations decide the technical routine

- Cal-I: PSD calibration down to lowest possible ER and NR energy (include yield).
- Cal-II: Quenching factor calibration down to lowest possibly NR energy.
- Cal-III: W/ and W/O an electric field, S1/S2 analysis down to lowest possible ER and NR energy (including extraction efficiency of electrons).
- Cal-IV: Understanding the drift velocity of electron bubbles under external HV (10 kV/cm or higher).
- Cal-V: R&D on the construction of HV system (~ 500 kV or higher.)

Summary of the ALHET project

- Regardless of the discovery of WIMPs at high mass region $\mathcal{O}$ (100 GeV/c^2), the low mass WIMPs should still be investigated.
- Considering the null-WIMPs results on high mass region, low mass search is more urgent than ever.
- ALHET is an excellent experiment hunting for low mass WIMPs: helium is suitable for low mass WIMPs detection, TPC is the most convincing technology in the field of DM direct detection.
- Many dedicated calibrations are necessary.
- The ALHET project should be launched ASAP.

Summary of the ALHET project

- Regardless of the discovery of WIMPs at high mass region $\mathcal{O}$ (100 GeV/c^2), the low mass WIMPs should still be investigated.
- Considering the null-WIMPs results on high mass region, low mass search is more urgent than ever.
- ALHET is an excellent experiment hunting for low mass WIMPs: helium is suitable for low mass WIMPs detection, TPC is the most convincing technology in the field of DM direct detection.
- Many dedicated calibrations are necessary.
- The ALHET project should be launched ASAP.

Summary of the ALHET project

- Regardless of the discovery of WIMPs at high mass region $\mathcal{O}$ (100 GeV/c^2), the low mass WIMPs should still be investigated.
- Considering the null-WIMPs results on high mass region, low mass search is more urgent than ever.
- ALHET is an excellent experiment hunting for low mass WIMPs: helium is suitable for low mass WIMPs detection, TPC is the most convincing technology in the field of DM direct detection.
- Many dedicated calibrations are necessary.
- The ALHET project should be launched ASAP.

Summary of the ALHET project

- Regardless of the discovery of WIMPs at high mass region $\mathcal{O}$ (100 GeV/c^2), the low mass WIMPs should still be investigated.
- Considering the null-WIMPs results on high mass region, low mass search is more urgent than ever.
- ALHET is an excellent experiment hunting for low mass WIMPs: helium is suitable for low mass WIMPs detection, TPC is the most convincing technology in the field of DM direct detection.
- Many dedicated calibrations are necessary.
- The ALHET project should be launched ASAP.

Summary of the ALHET project

- Regardless of the discovery of WIMPs at high mass region $\mathcal{O}$ (100 GeV/c^2), the low mass WIMPs should still be investigated.
- Considering the null-WIMPs results on high mass region, low mass search is more urgent than ever.
- ALHET is an excellent experiment hunting for low mass WIMPs: helium is suitable for low mass WIMPs detection, TPC is the most convincing technology in the field of DM direct detection.
- Many dedicated calibrations are necessary.
- The ALHET project should be launched ASAP.

Caution! We are in the dark sector now!

Let's work hard and cross fingers !