上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

PANDA X

Dark Matter Searches at PandaX

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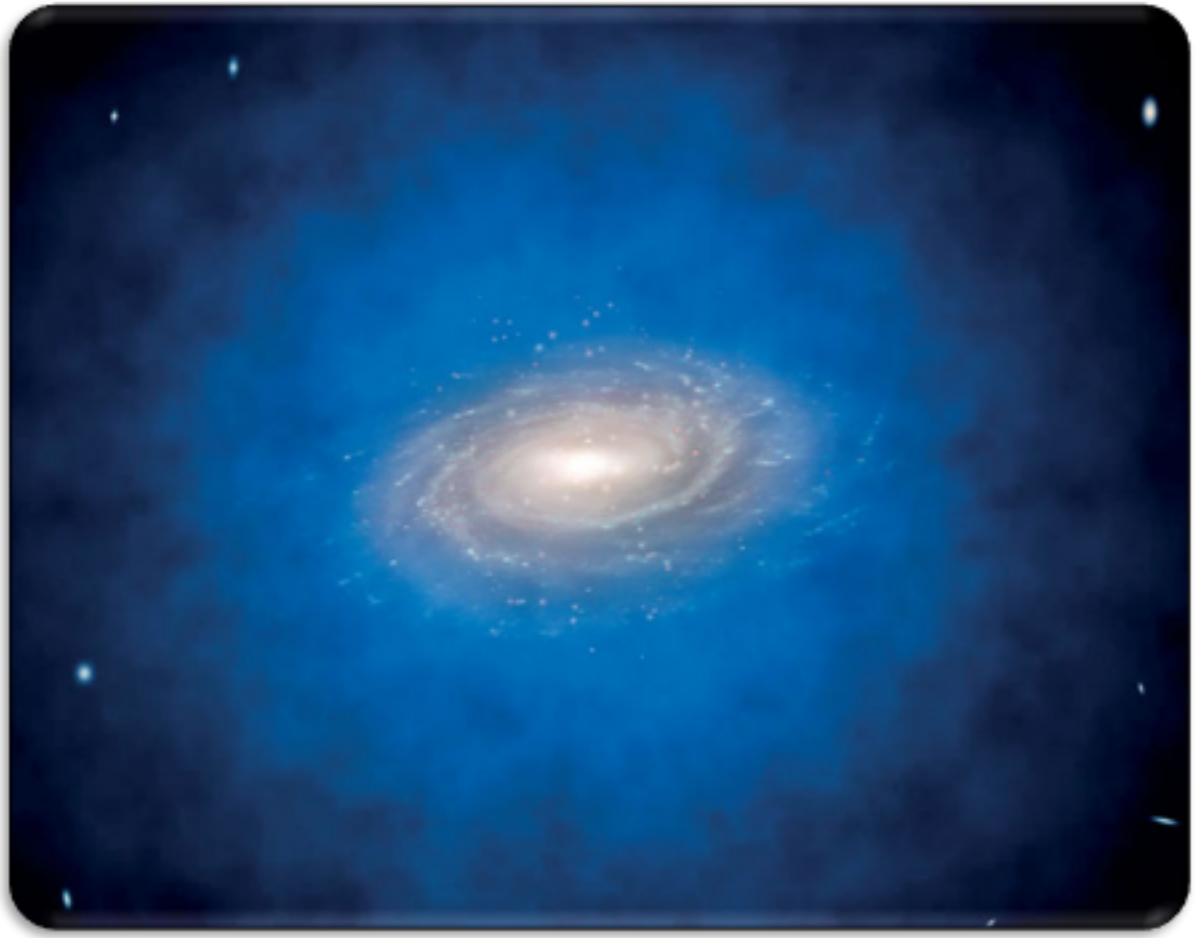
上海交通大学

2021-11-05 USTC

Dark Matter

- Strong evidences for the existence of dark matter
- The nature of dark matter is unknown



Dark Matter

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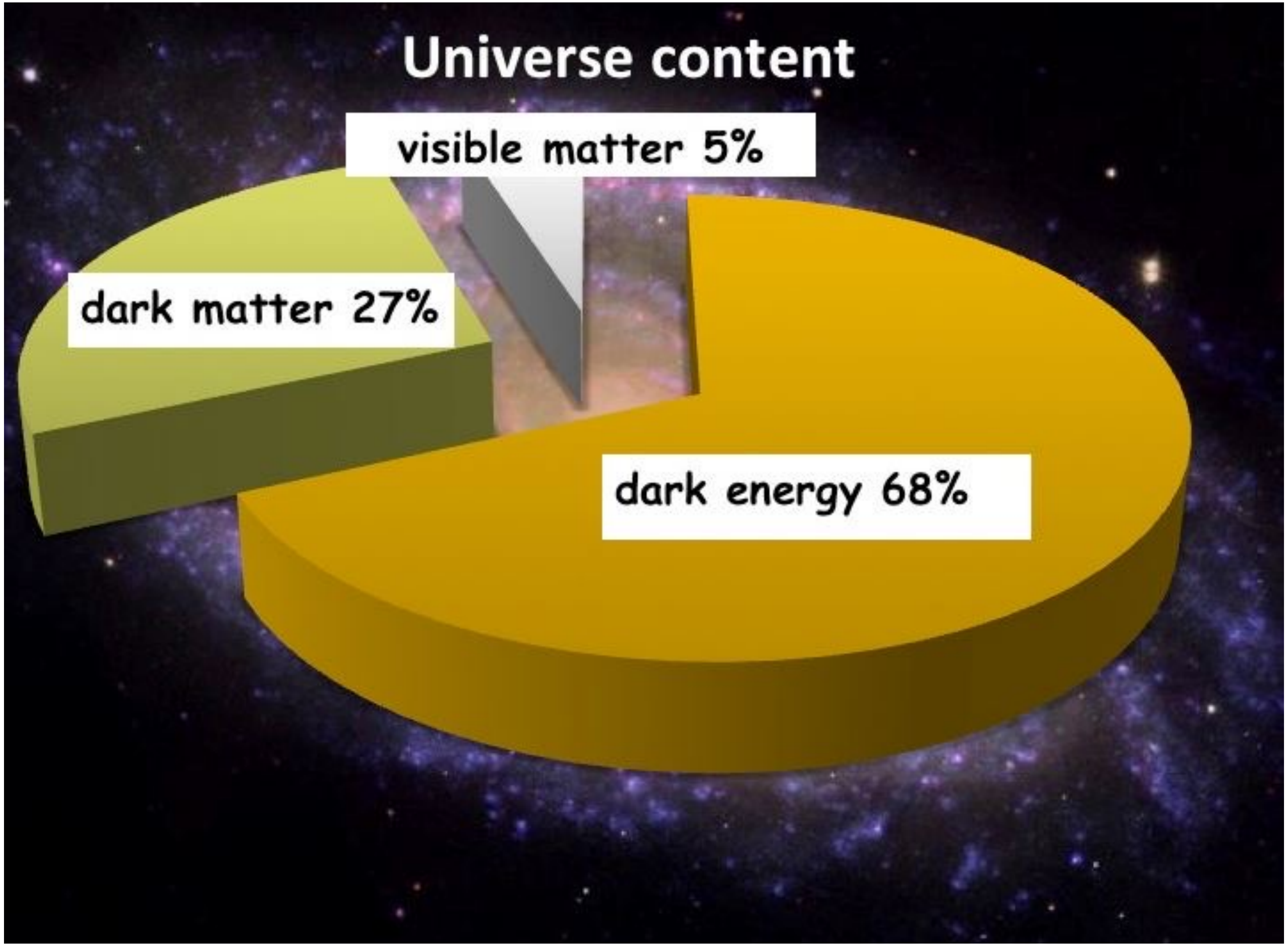
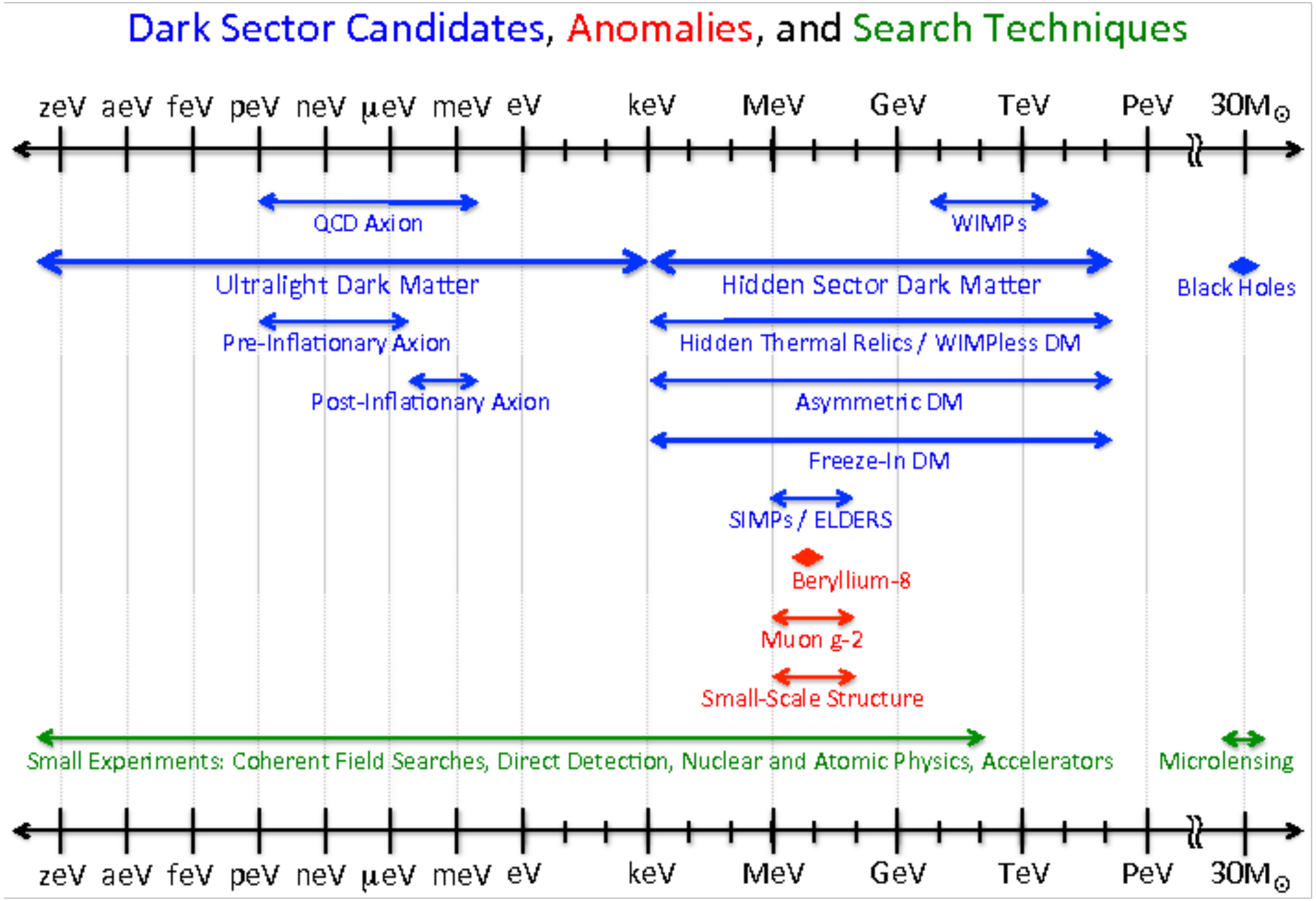


Universe content
visible matter 5%
dark matter 27%
dark energy 68%

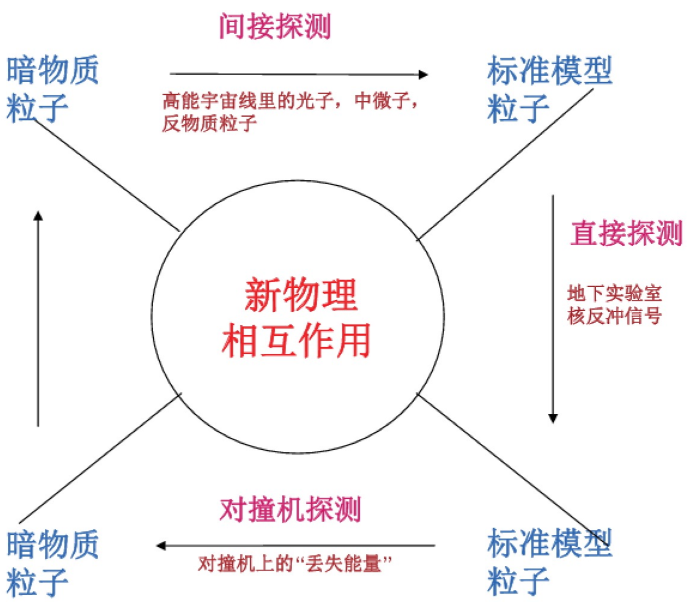
Dark Matter Candidates

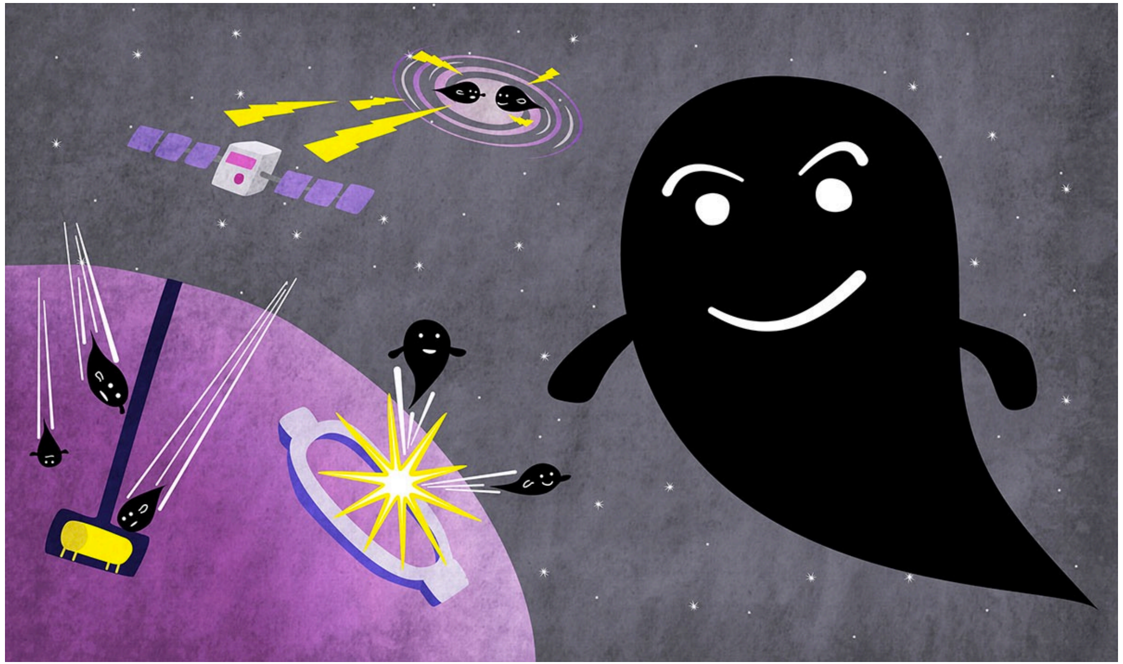
- WIMPs, Axions, ALPs, …: covering extreme large mass range

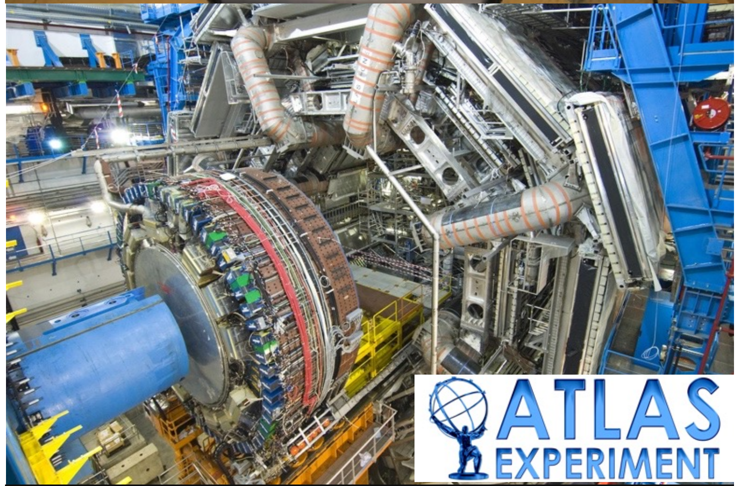


Dark Matter Detection

- General approaches
  - direct detection
  - indirect detection
  - collider search

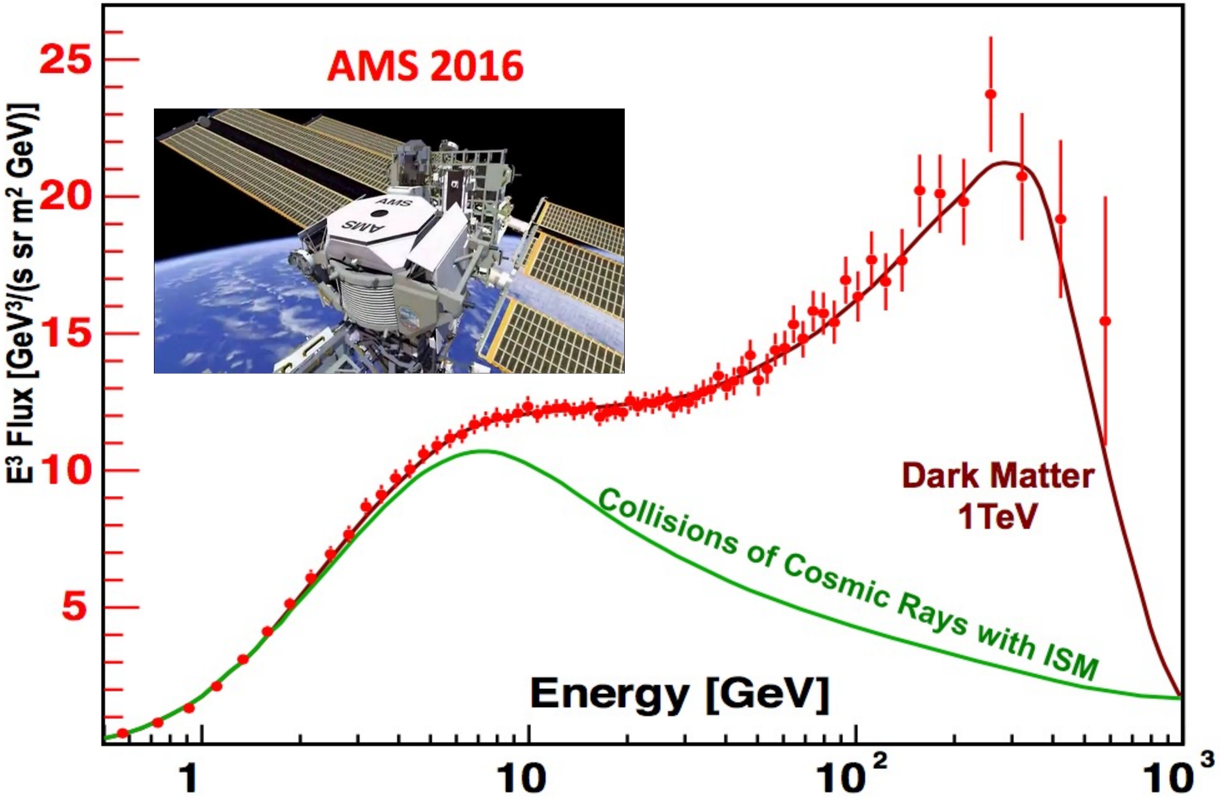


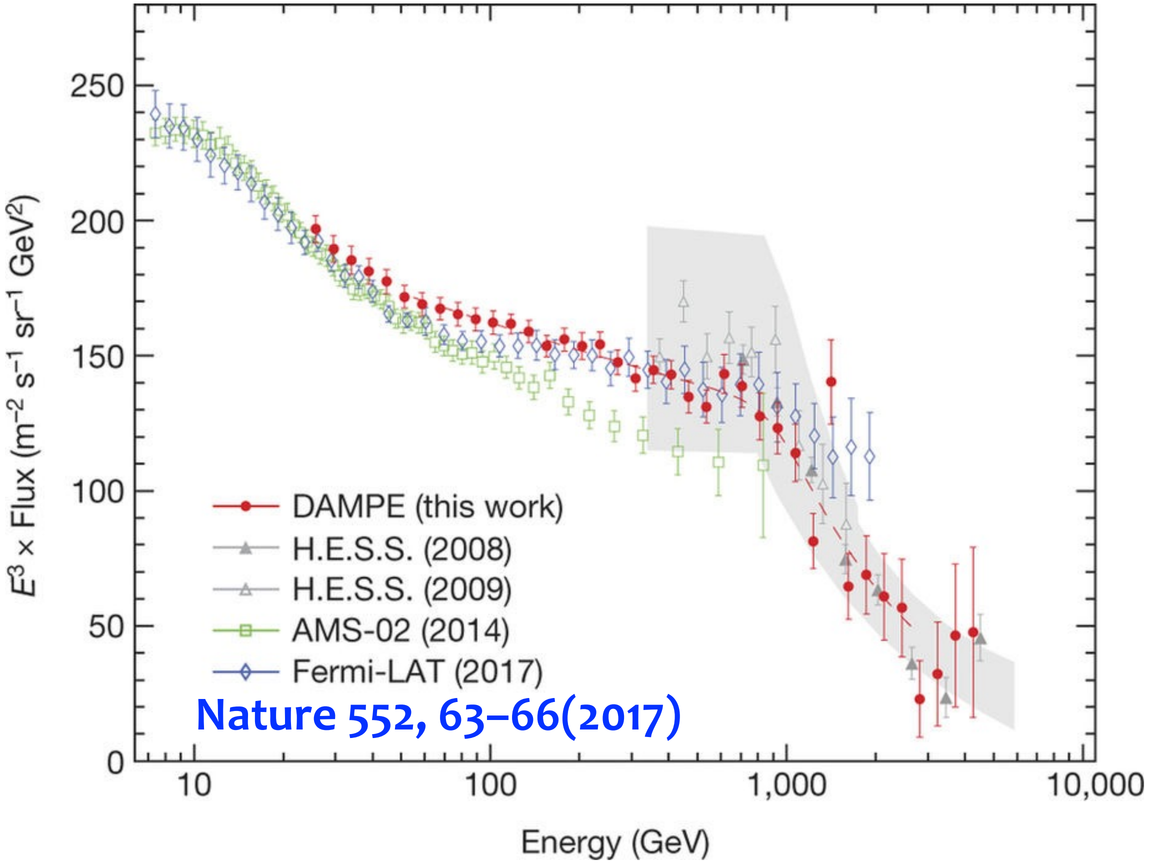




Indirect Detection

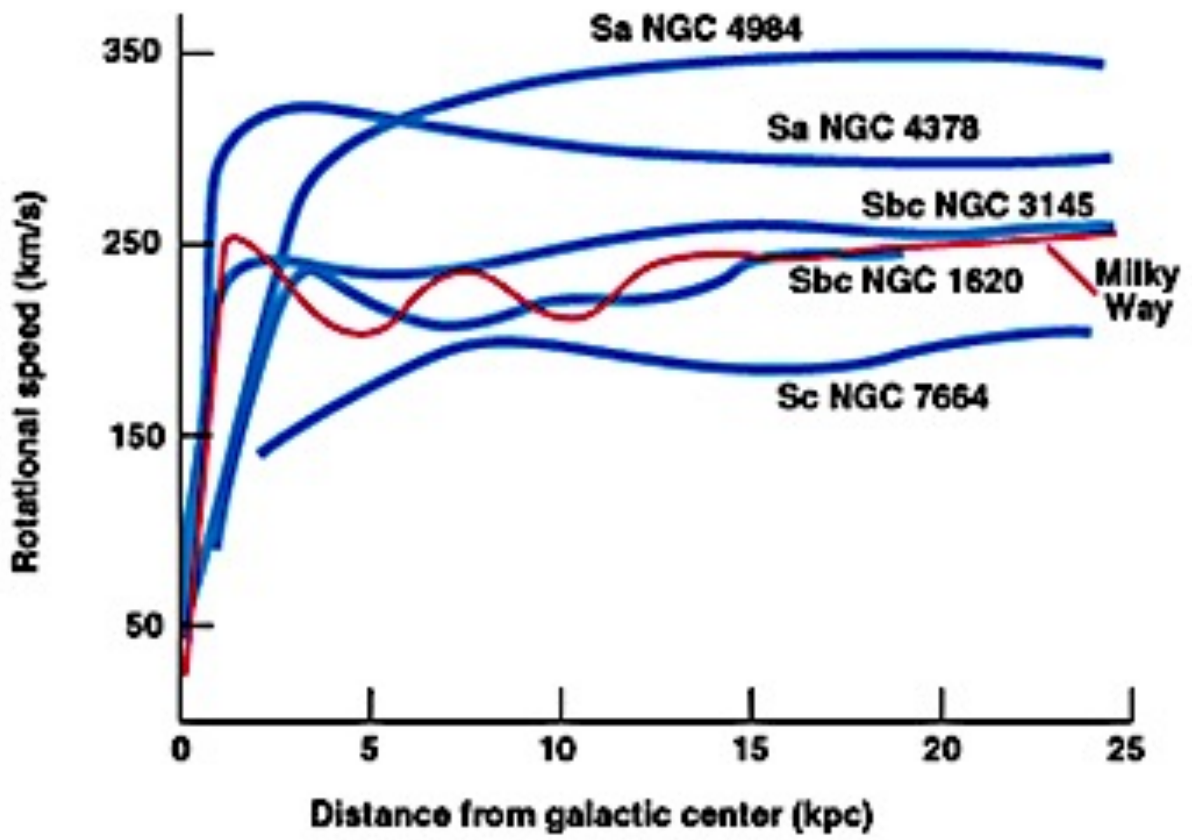
- AMS-02 experiment: positron spectrum
- DAMPE experiment: electron spectrum

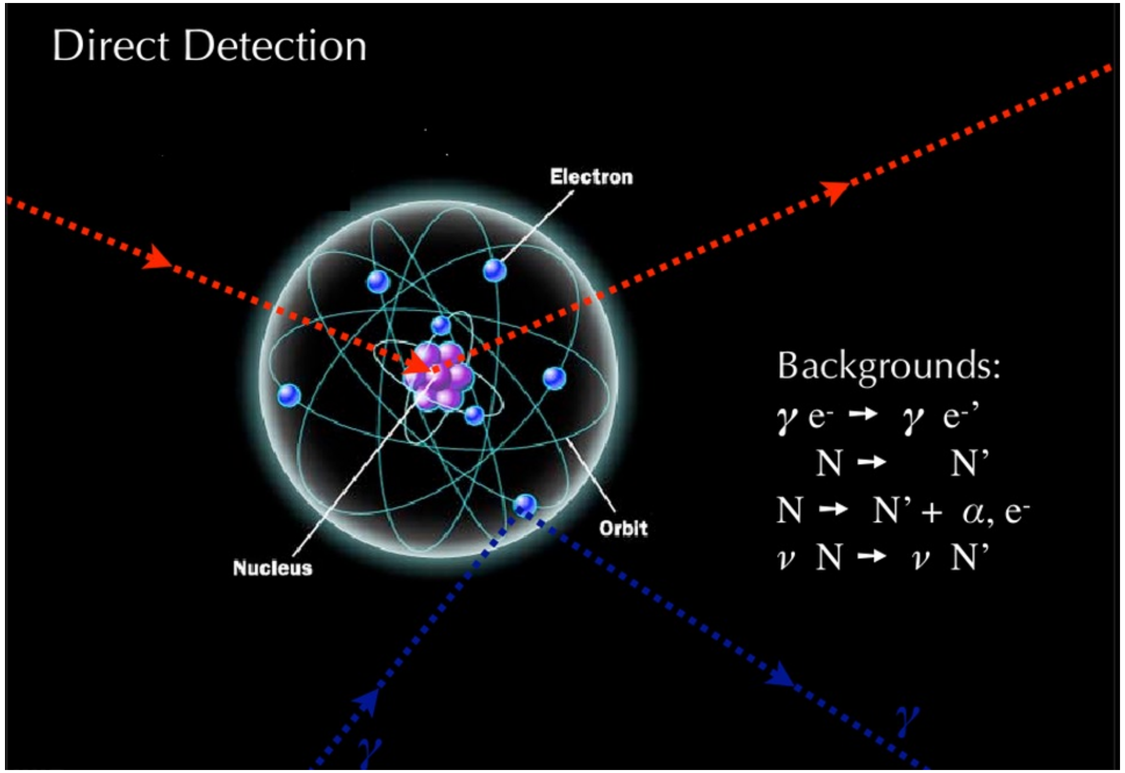




Direct Detection

- Near the Solar system， dark matter density 0.3 GeV/cm^3
- Every second, 100k dark matter particles (100 GeV/c^2) pass through 1 cm^2





DARK MATTER OVERVIEW: COLLIDER, DIRECT AND INDIRECT DETECTION SEARCHES - QUEIROZ, FARINALDO S. ARXIV:1605.08788

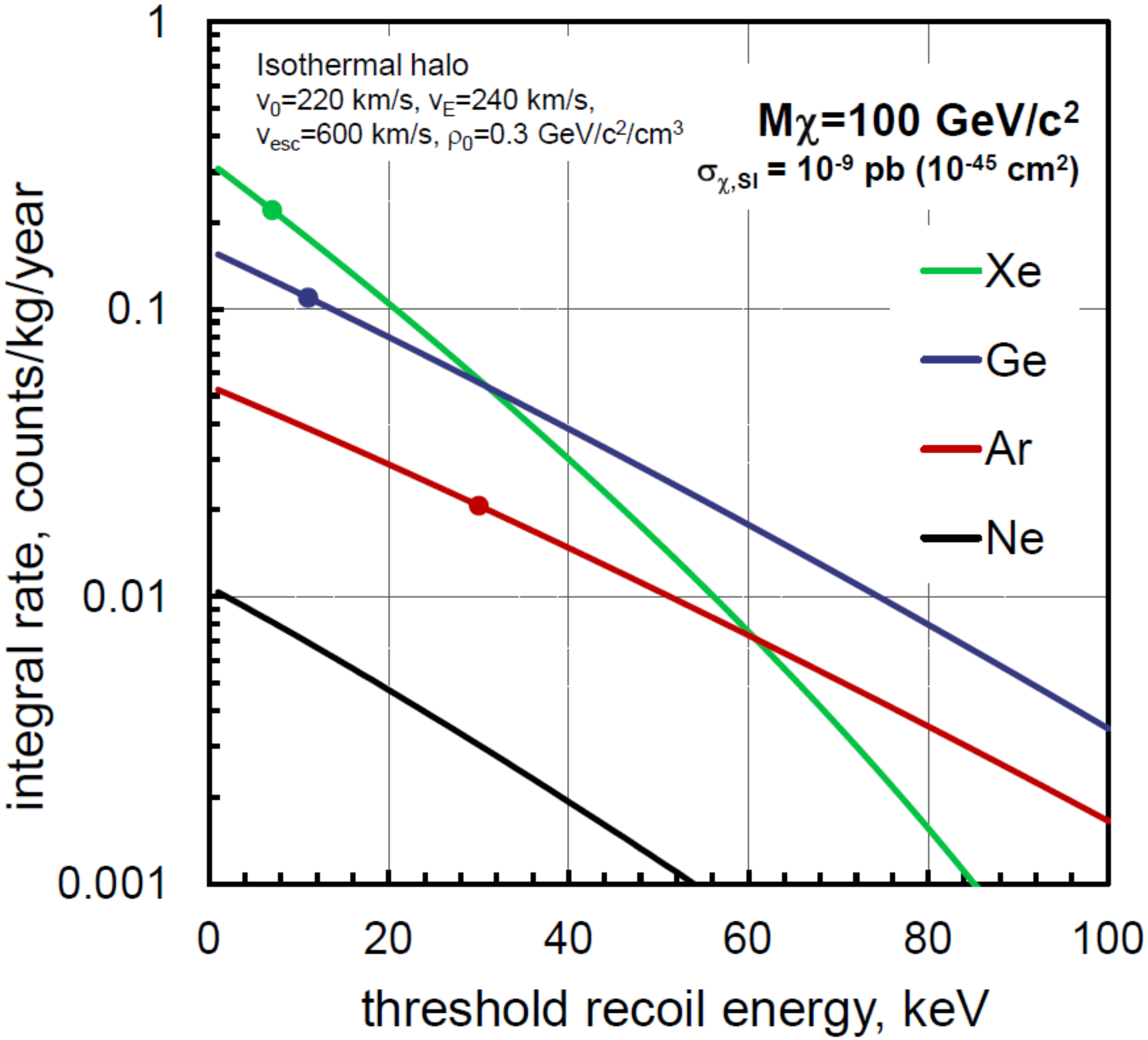
Dark Matter Signals

- Scattering cross section on nuclei
  - Spin-independent, $\propto A^2$, Form factor
  - Spin-dependent, spin structure factor

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N}\int_{v_{min}}^{v_{esc}} \frac{d\sigma_{\chi_N}}{dE_R}(v, E_R) v f(v) dv$$

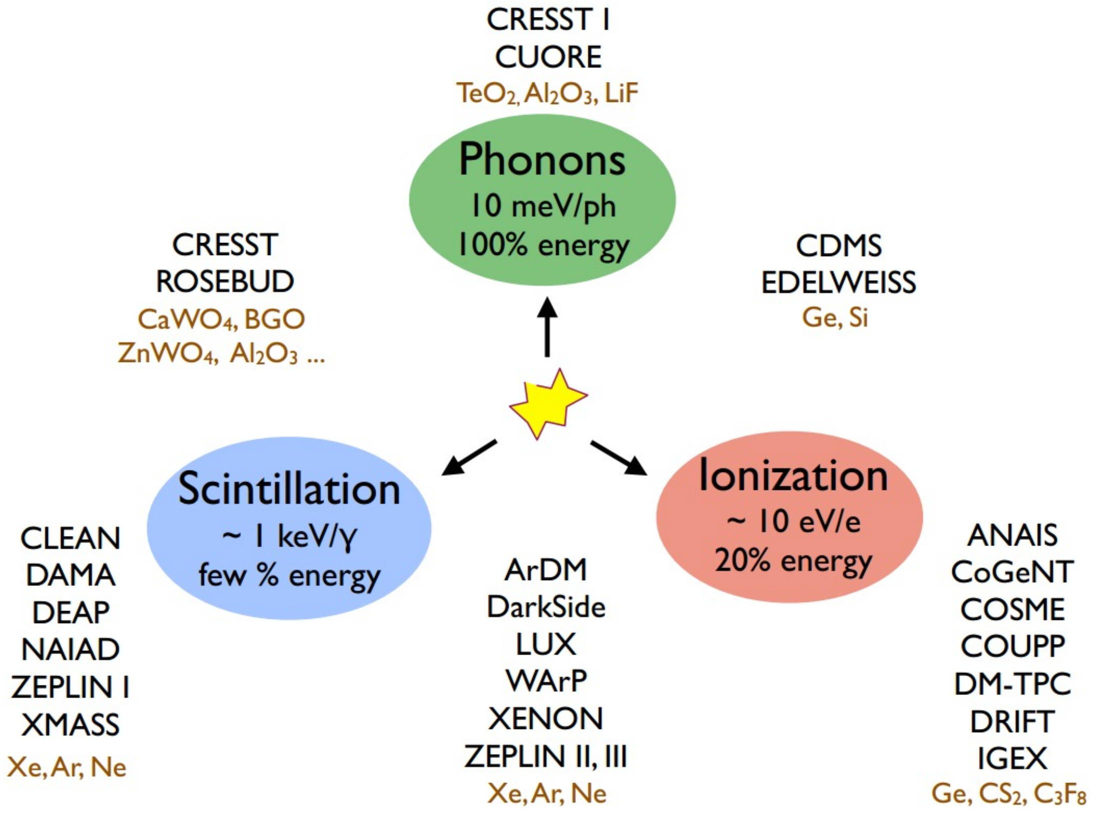
$$\frac{d\sigma_{\chi_N}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R))$$

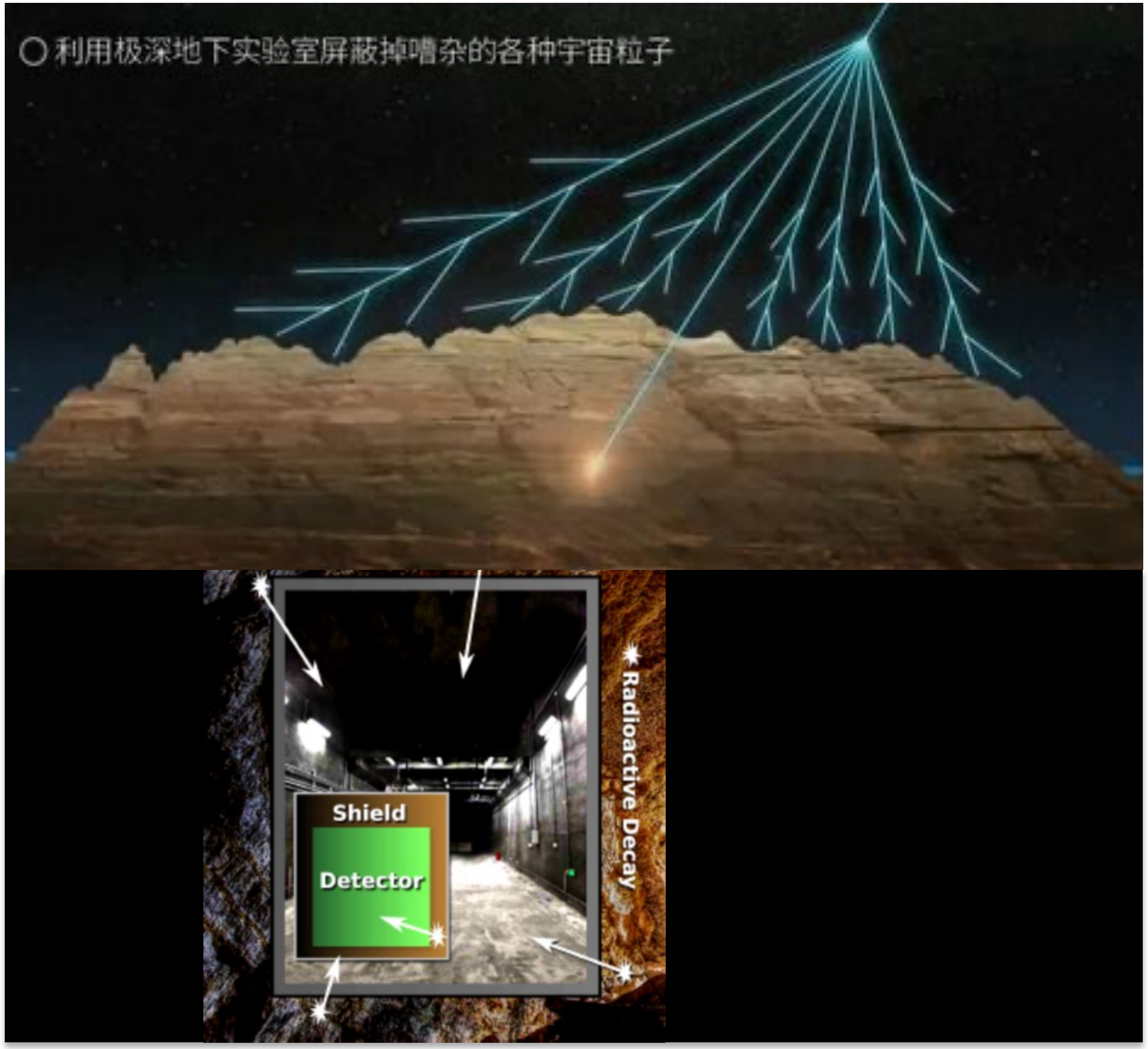
Recoil energy spectrum



Detection Strategy

- Recoil energy: light, charge, heat
- Large target: multi-tonne scale
- Underground laboratory

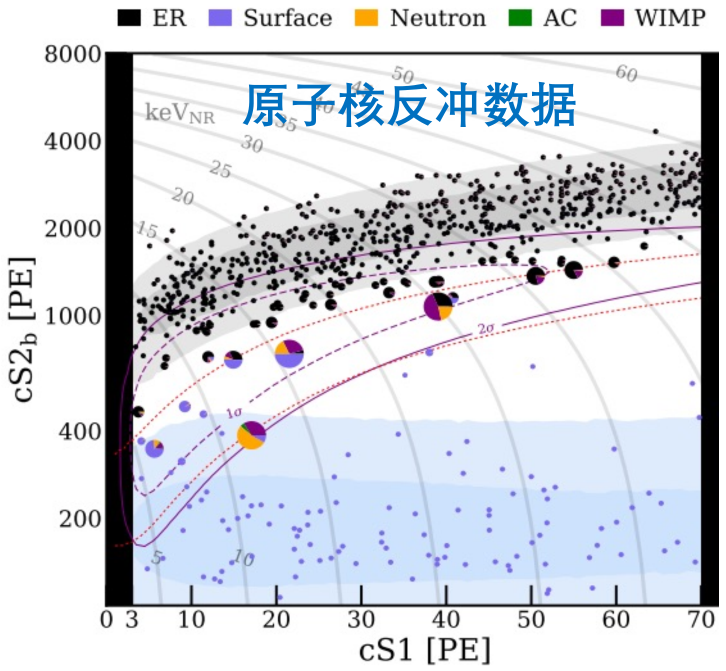




Excess in Xenon Detector

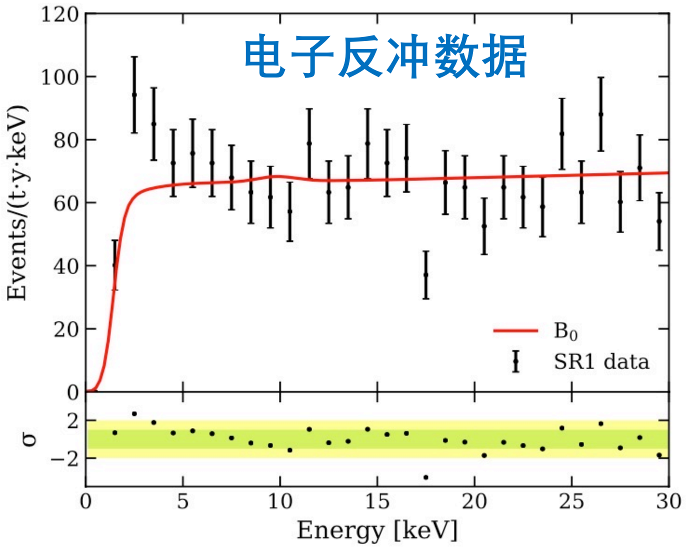
- XENON1T experiment，1 tonne-year exposure，some small excess in nuclear recoil signal region
  - fitted with WIMP of 200 GeV mass, 1.7 events

PRL 121, 111302 (2018)



- 0.65 tonne-year exposure，3σ excess in electronic recoil signal region
  - fitted with solar axion, etc

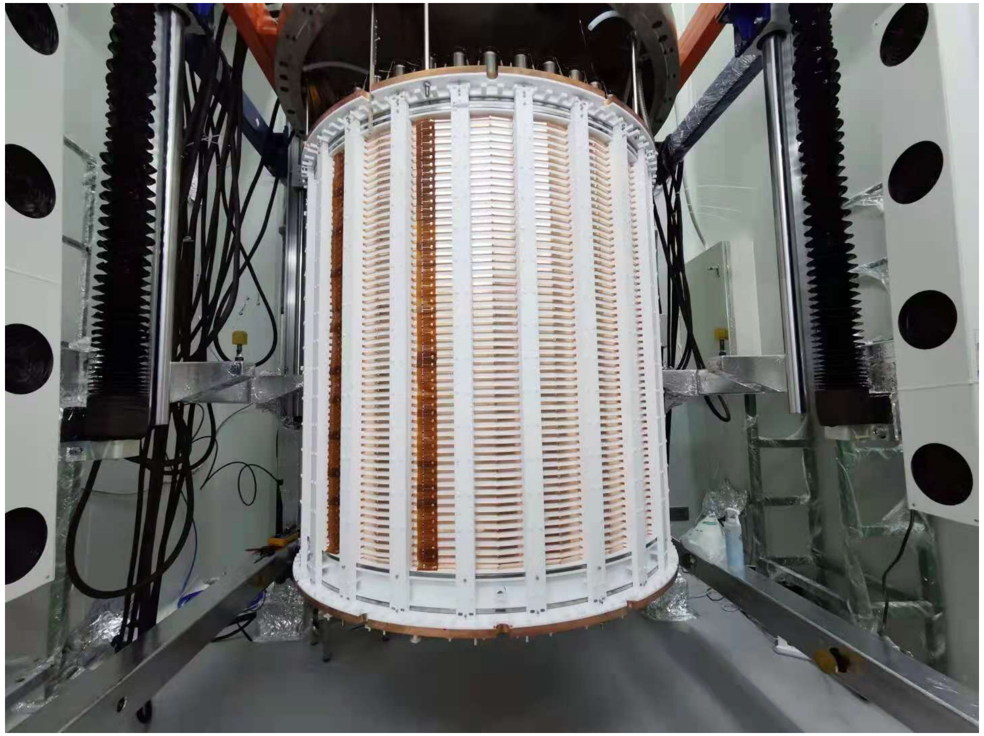
PRD 102, 072004 (2020)



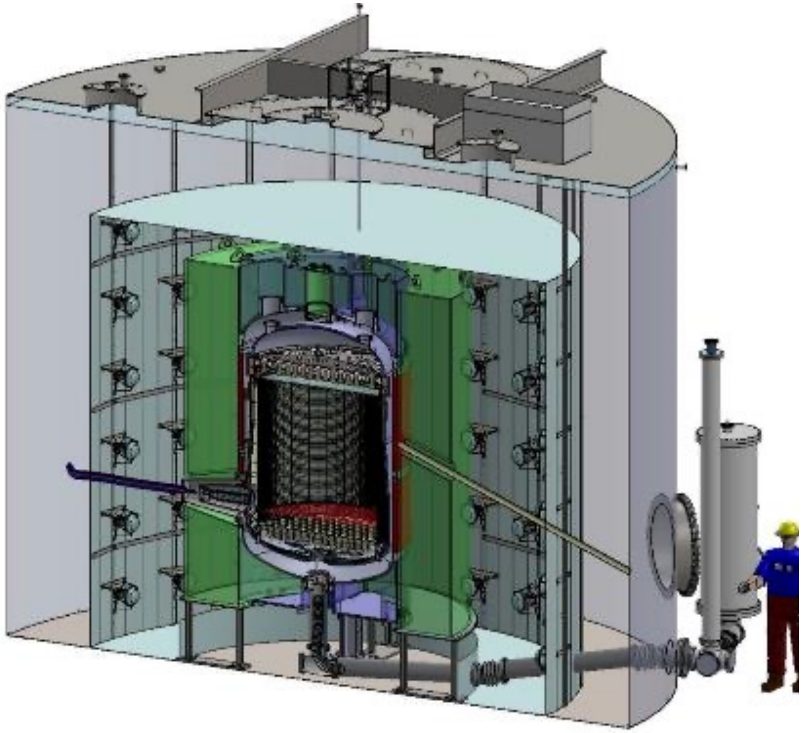
- Need further cross-check with more sensitive detectors

Multi-tonne Xenon Experiments

- PandaX-4T, XENONnT and LZ



PandaX-4T, 4 ton,
CJPL-II, China

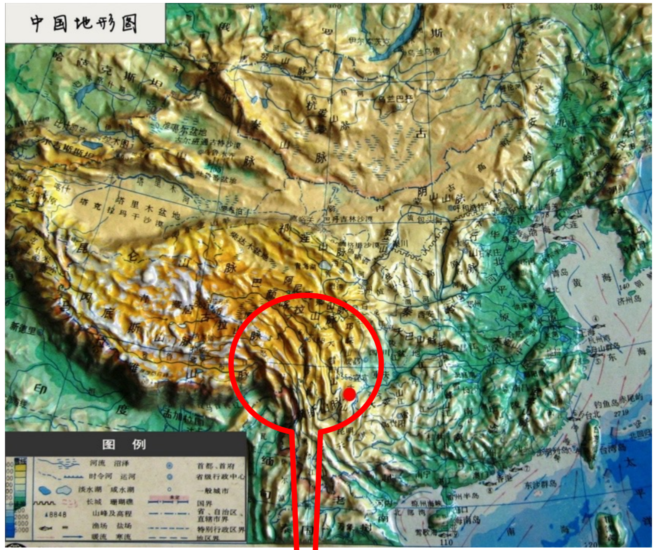


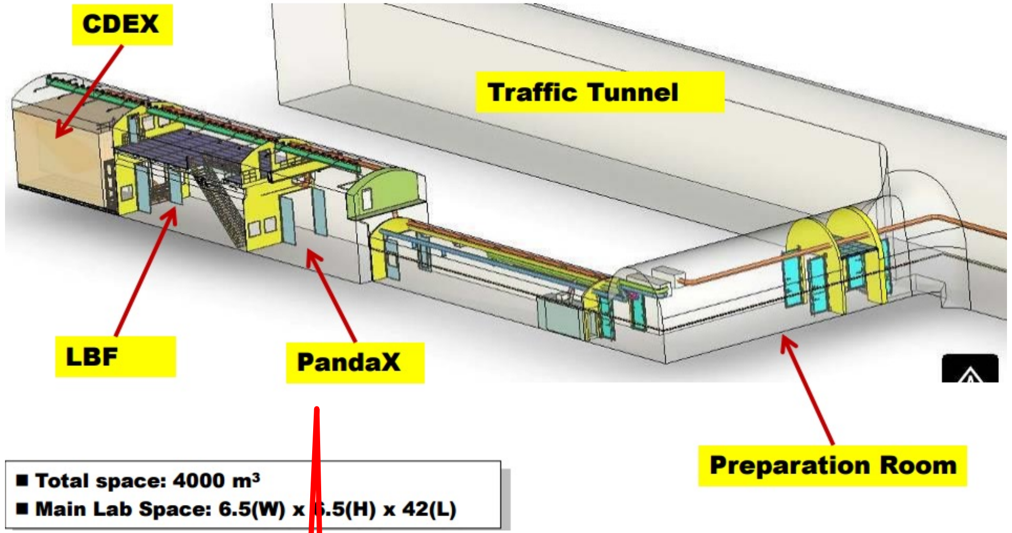
LZ, 7 ton,
Sanford Lab, US

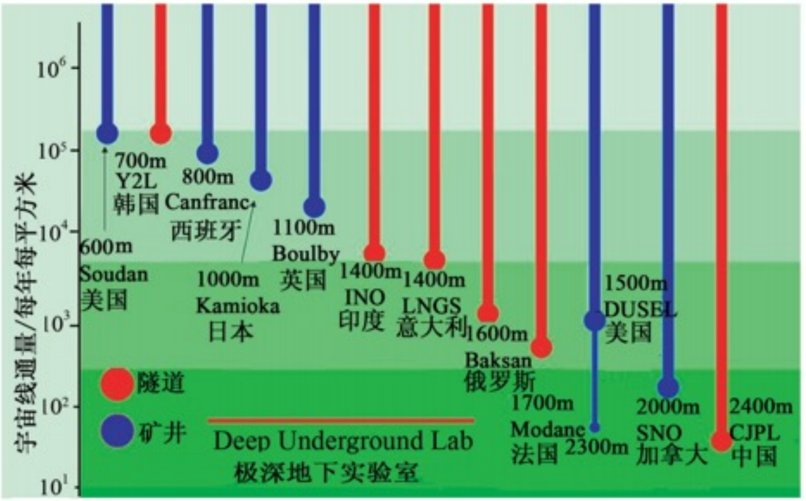
XENONnT, 6 ton
LNGS, Italy

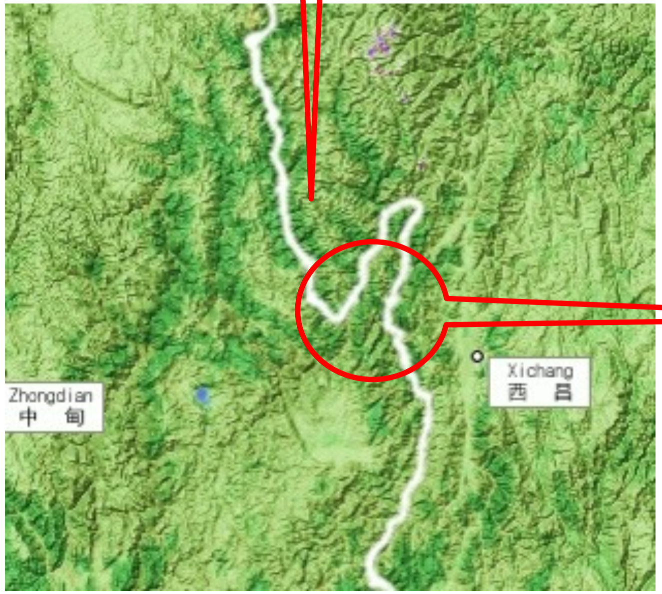
China Jinping Underground Laboratory (CJPL)

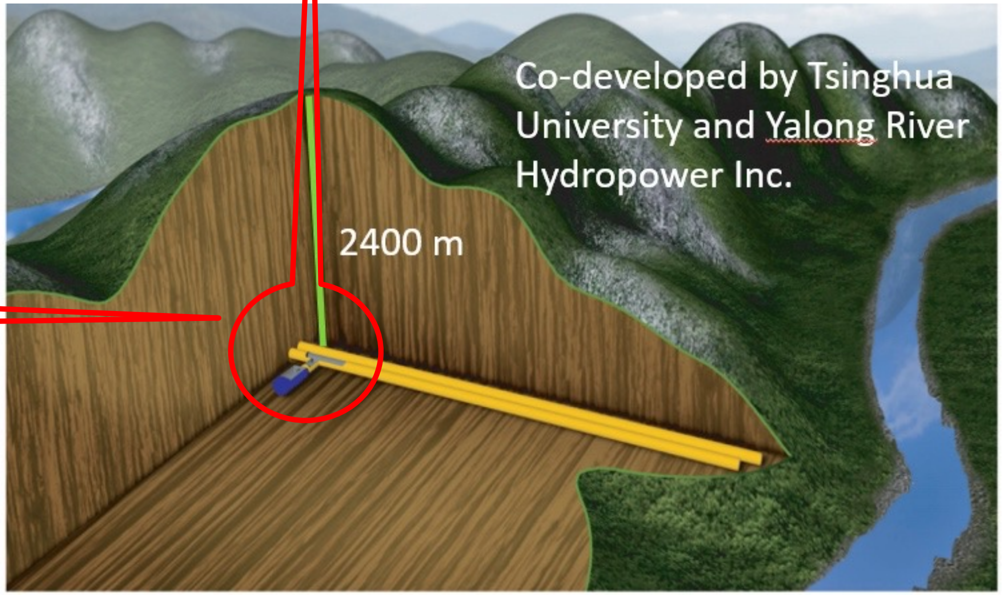
- Deepest
  - 6800 m.w.e.
  - < 0.2 muons/m^2/day
- Horizontal access
  - 9 km long tunnel







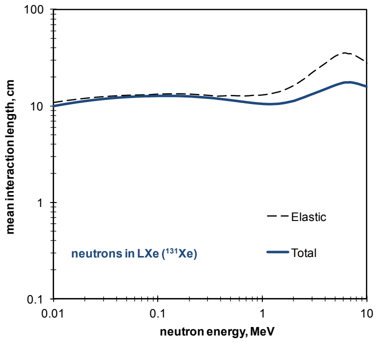


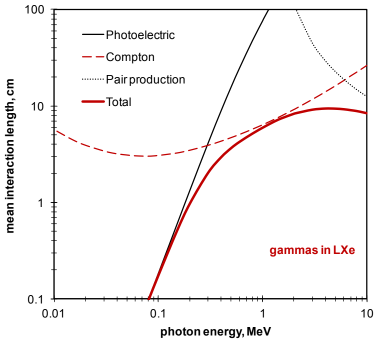


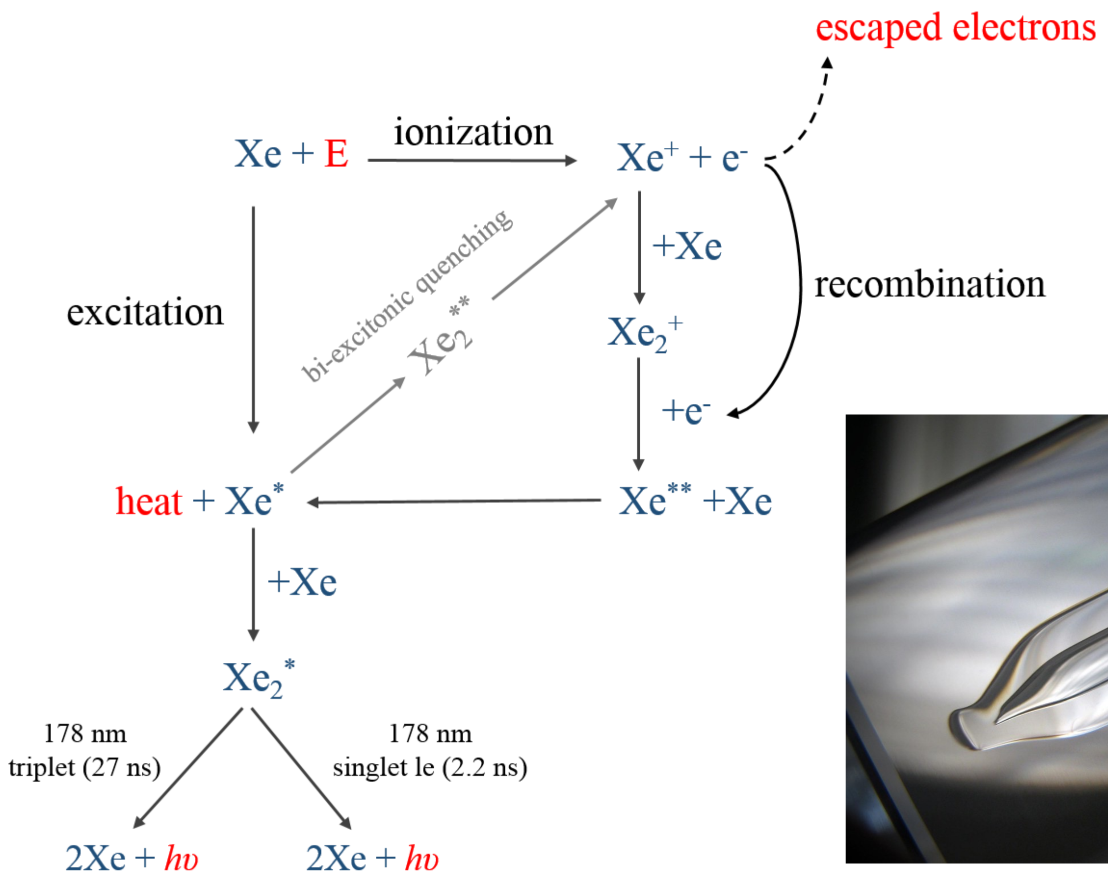
PandaX Collaboration

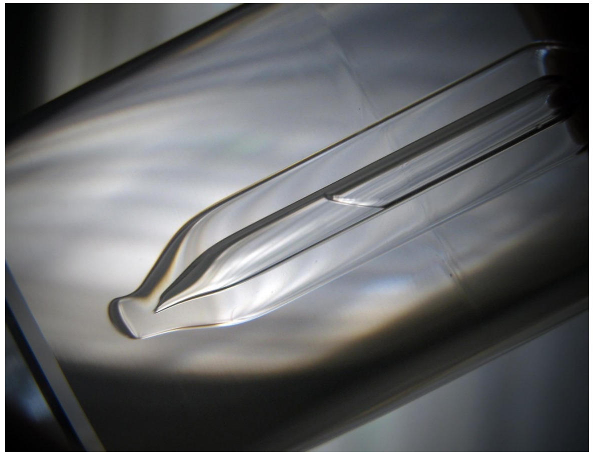
Xenon

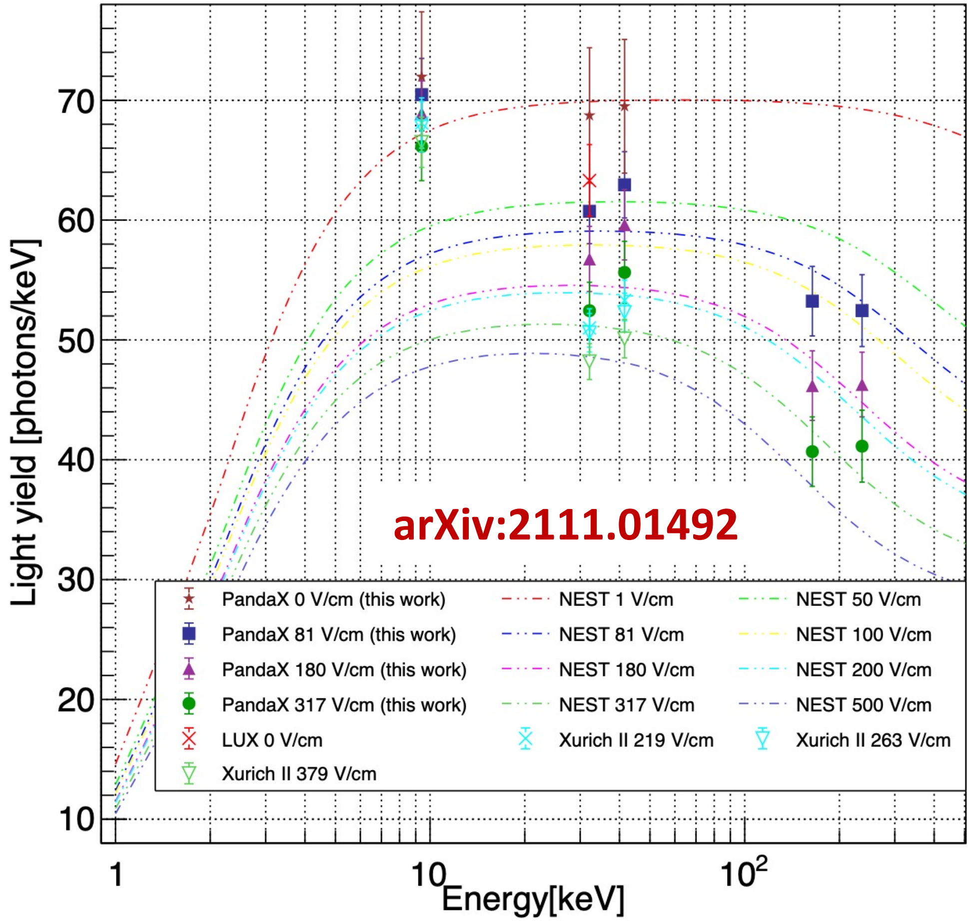
- Dense and homogenous
- Self-shielding
- High light and charge yields





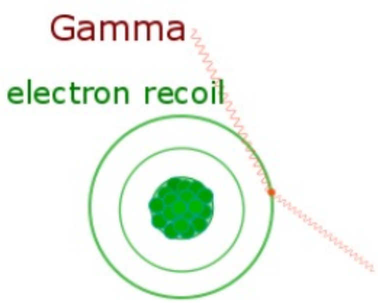


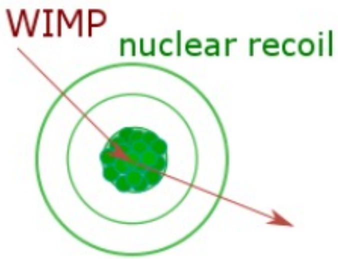




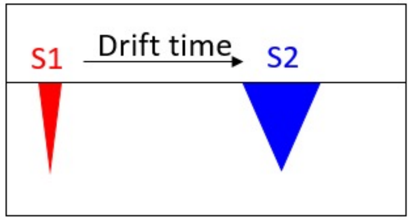
PandaX Detector

- Dual-phase xenon TPC
  - Large scale target
  - Precise energy and 3D-positon reconstruction
  - NR and ER discrimination power

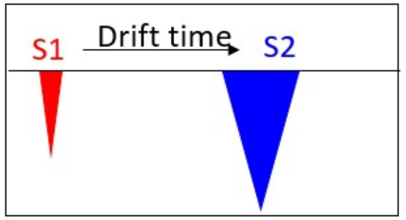




Dark matter: nuclear recoil (NR)

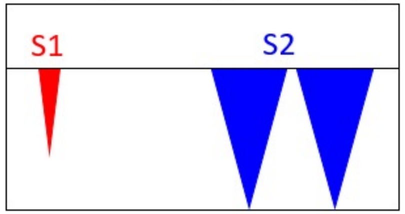


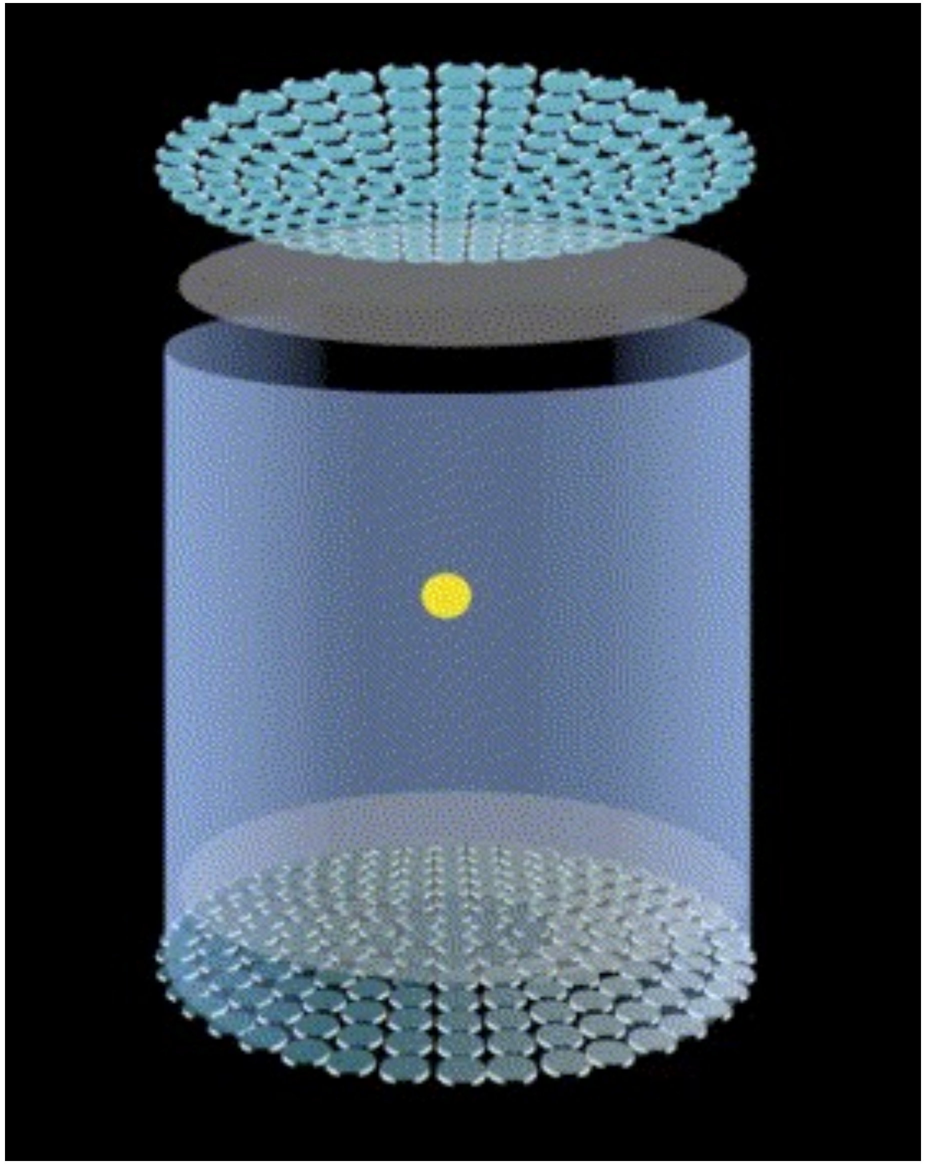
γ background: electron recoil (ER)



$(S2/S1)_{NR} \ll (S2/S1)_{ER}$

Multi-site scattering background (ER or NR)





PandaX Experiment

Collaboration formed

2009.3

2012.7

PandaX-I apparatus moved to Jinping

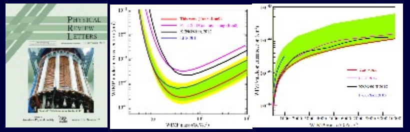
PandaX-I started

2014.3

2014.5-10

PandaX-I, 120 kg operation

PandaX-II, 580 kg operation

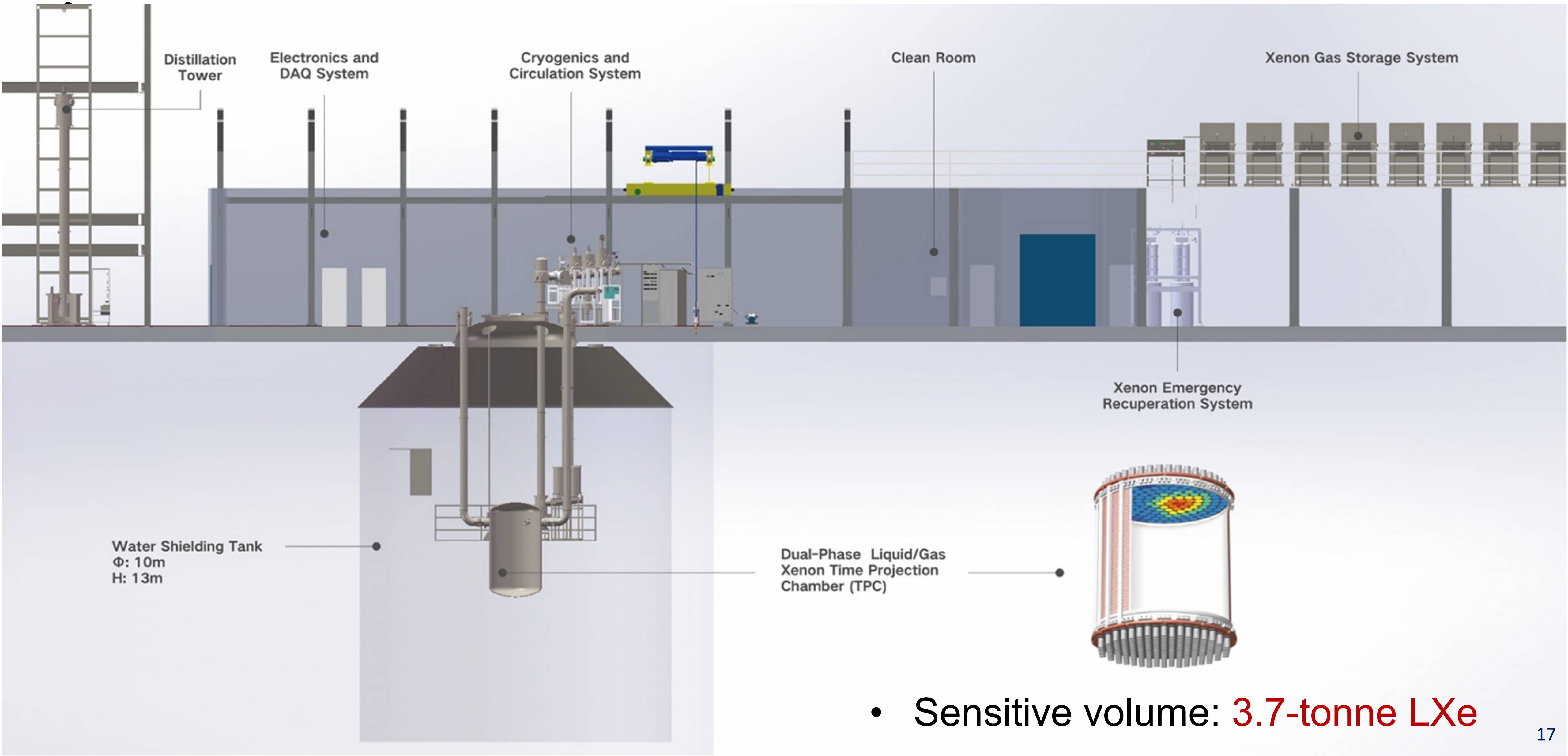


2016.7
-2019.7

2019.8-

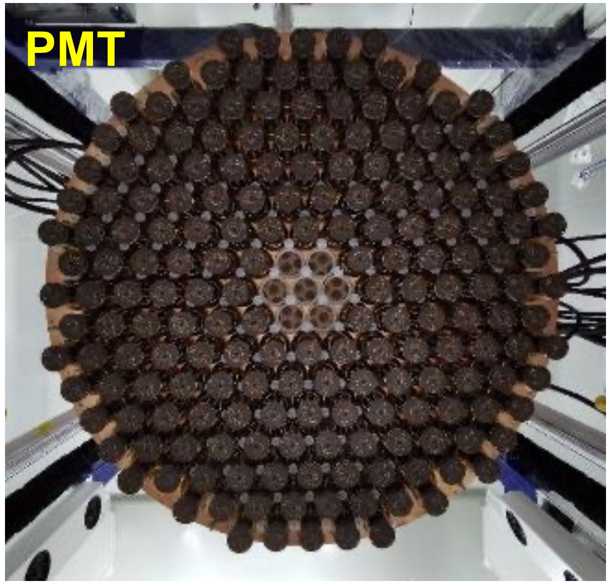
PandaX-4T moved to CJPL-II

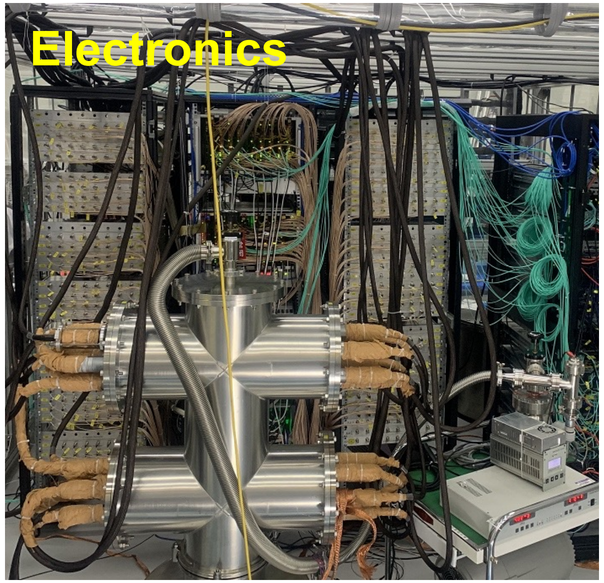
PandaX-4T @ CJPL-II

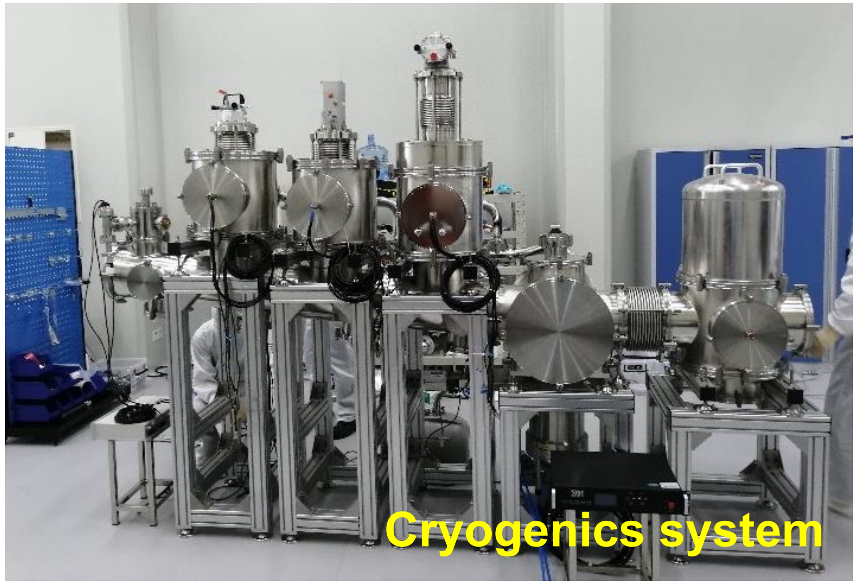


- Sensitive volume: 3.7-tonne LXe

PandaX-4T Subsystems







PandaX-4T Installation

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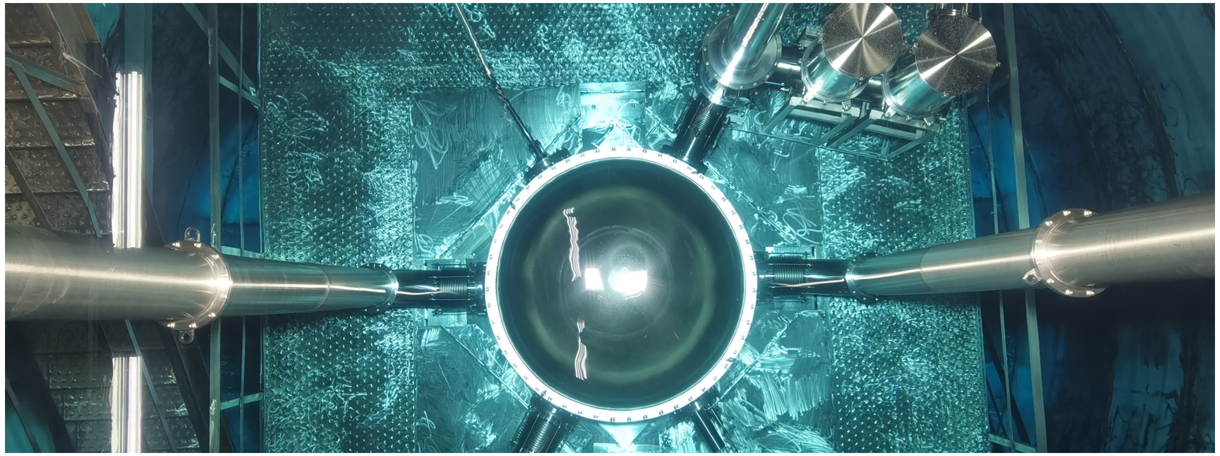
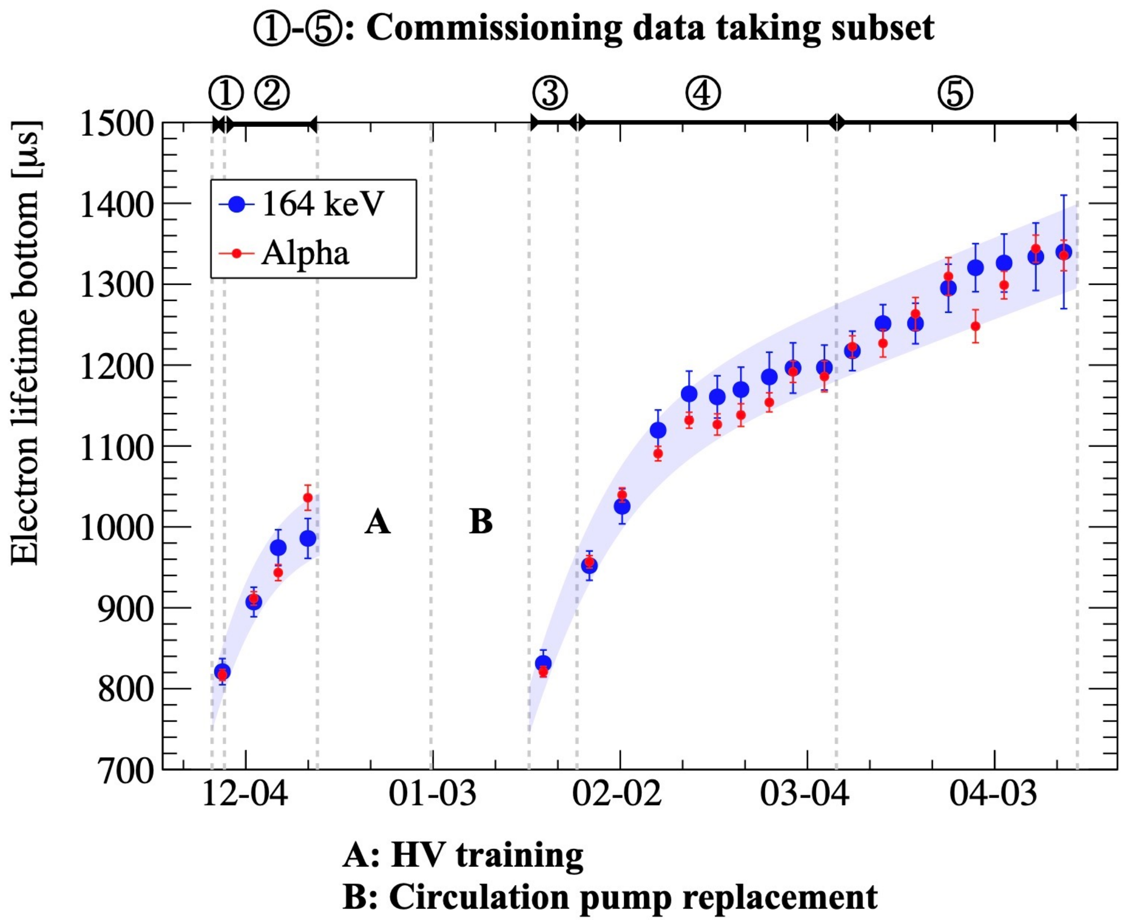
PandaX-4T commissioning

- Stable data running period: 95.0 calendar days

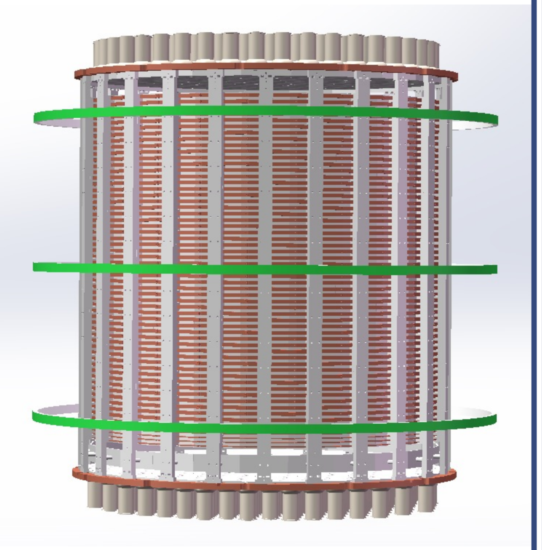


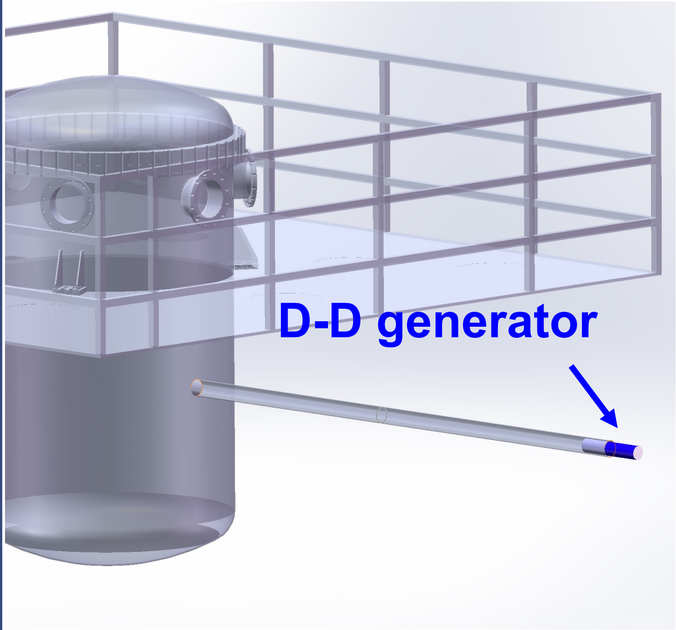


Calibration Methods

Gaseous source injection panel

Calibration tubes



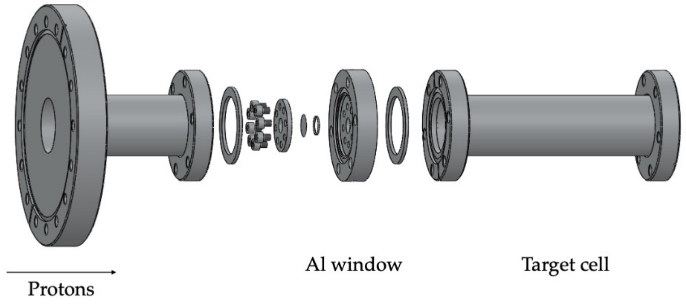


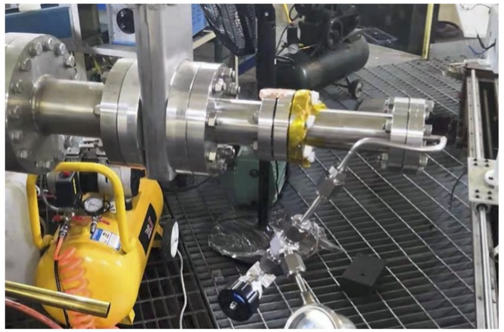
Calibration source	Position
$^{83m}Kr/^{220}Rn$	Injected from gas panel
^{241}Am-Be	Calibration tubes
D-D neutron	Beam pipe

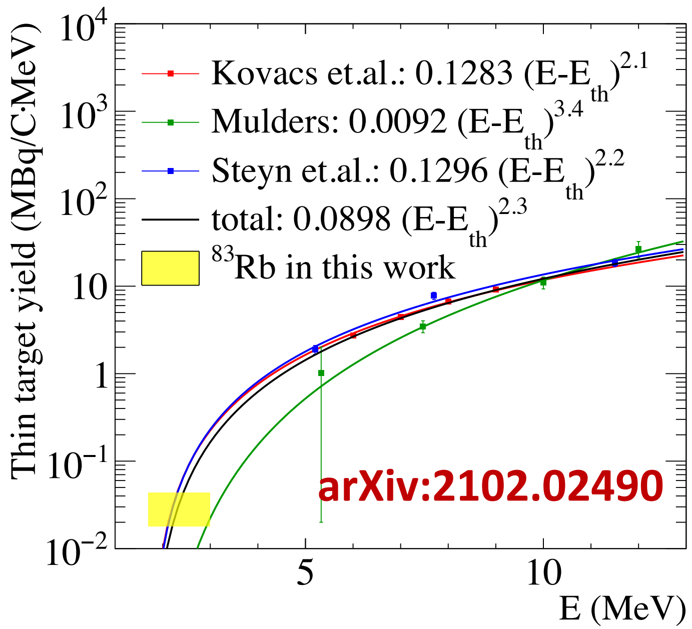
Internal Calibration Source

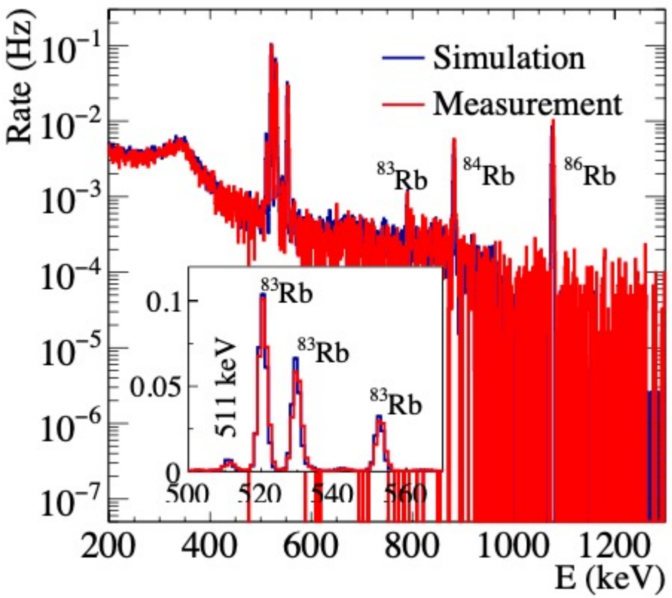
- Large size of TPC
  - External calibration sources can hardly produce events in the center
  - Internal calibration sources: ^{83m}Kr, ^{220}Rn
- ^{83m}Kr: proton beam bombarding ^{nat}Kr (p + ^{nat}Kr → ^{83}Rb → ^{83m}Kr)
  - optimal proton beam energy 20 MeV: limited access in China
  - successfully produced with 3.4 MeV: first measurement of the low energy yield

^{84}Rb threshold 3.46MeV



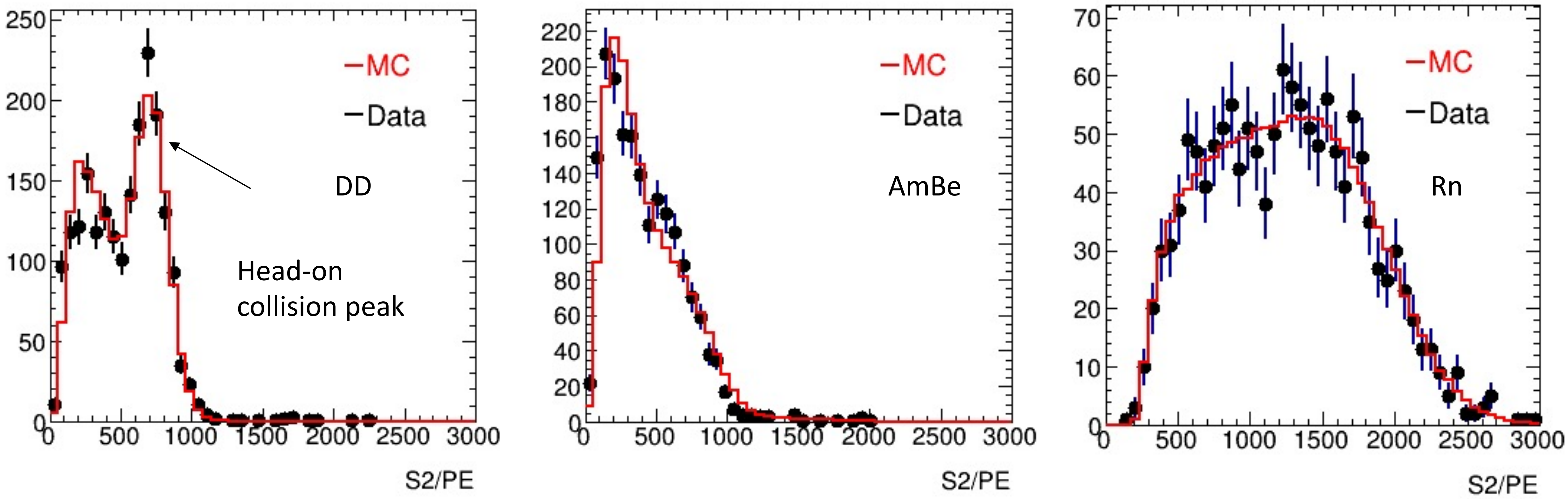






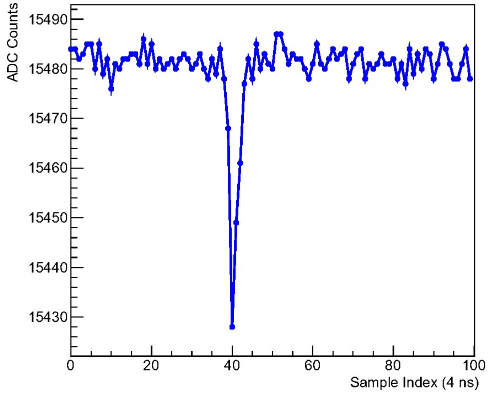
Detector Response Model

- Light/charge yield, as well as fluctuations
  - Deuteron-deuteron (DD) neutron data used together with AmBe
  - Rn data



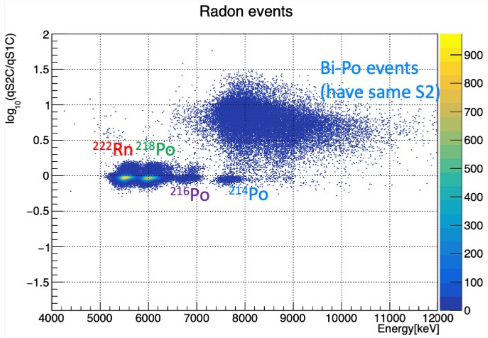
PandaX-4T Major Improvement

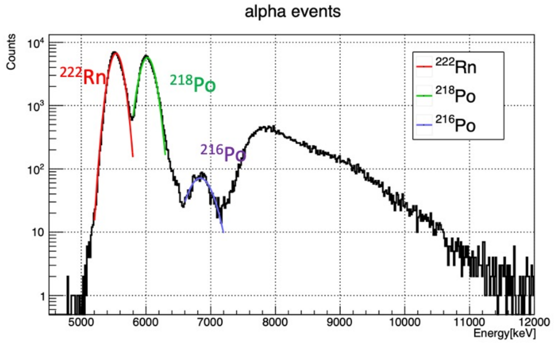
- **Triggerless DAQ**: low threshold
  - read out pulses above 20 ADC (~1/3 PE)
- **^{222}Rn**: ~ 5 uBq/kg
  - 1/6 of PandaX-II
- **^{85}Kr**: ~0.3 ppt mol/mol
  - 1/20 of PandaX-II

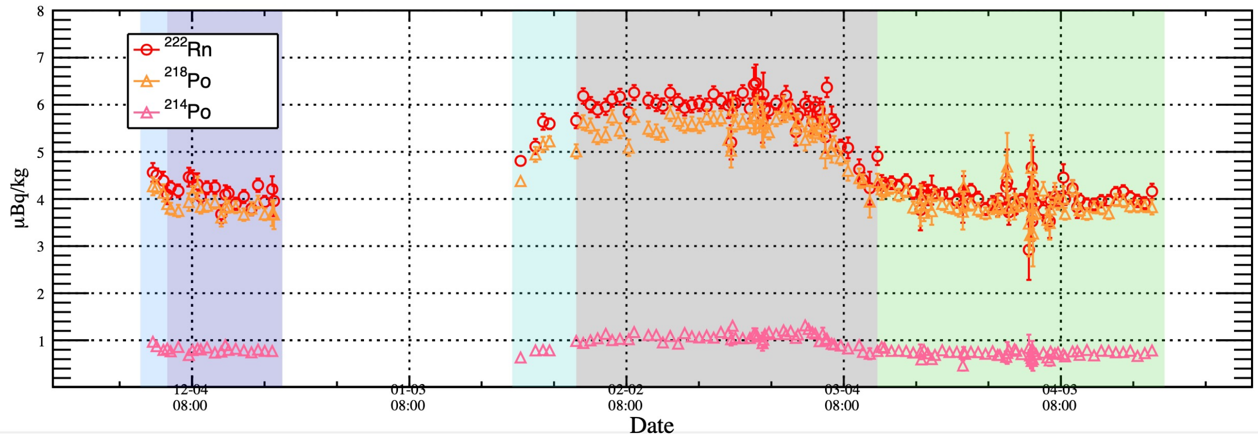


Typical single photon pulse

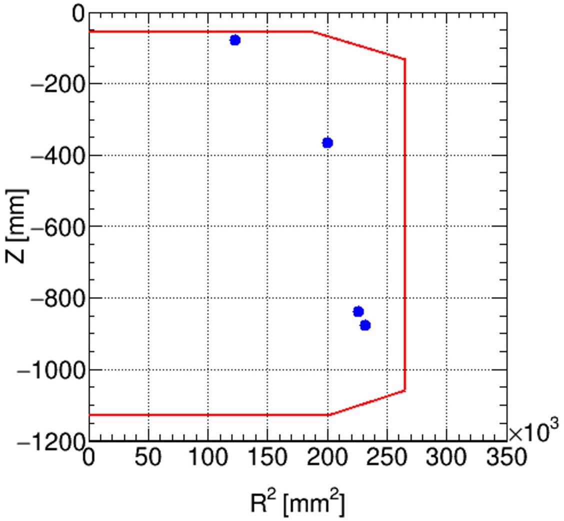
average single photon detection efficiency: 96%.





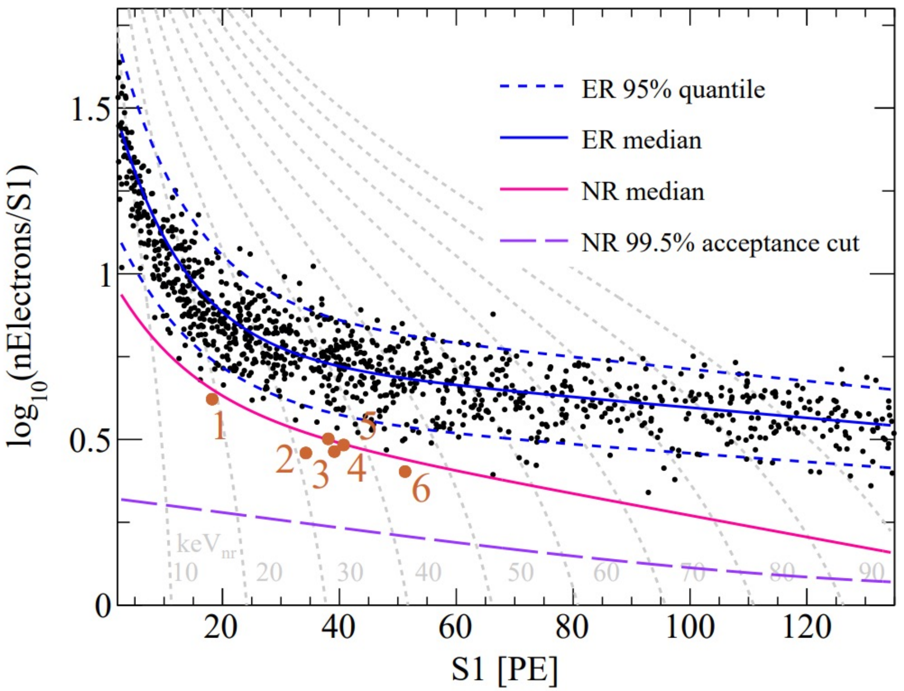


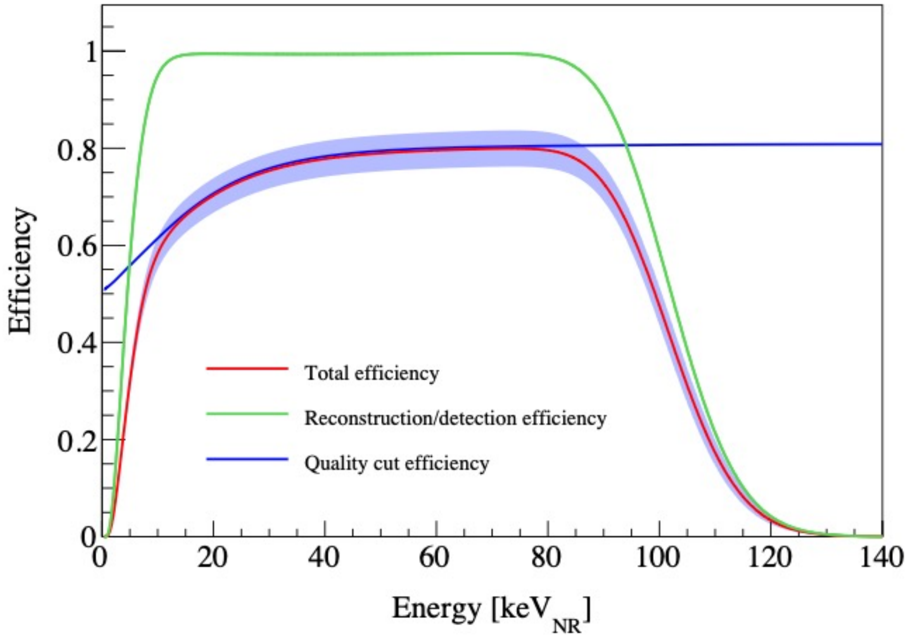
Vertex distribution of β-γ candidates

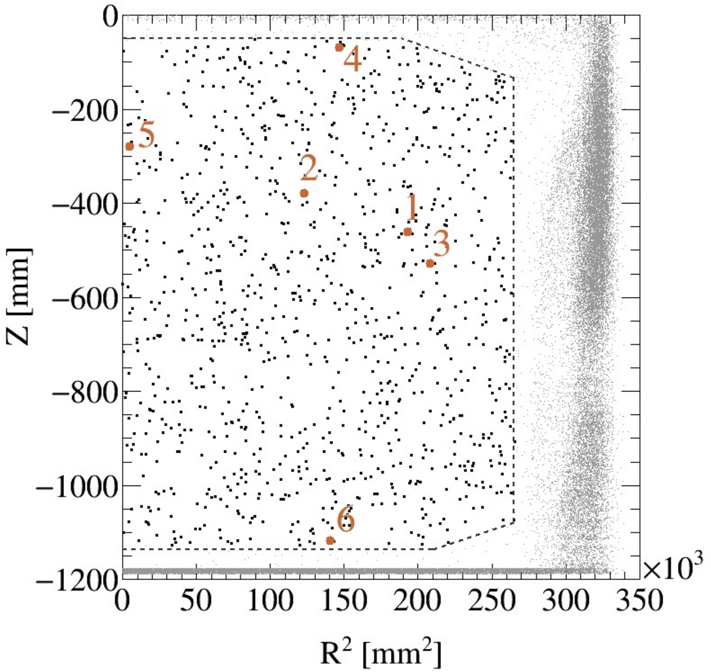


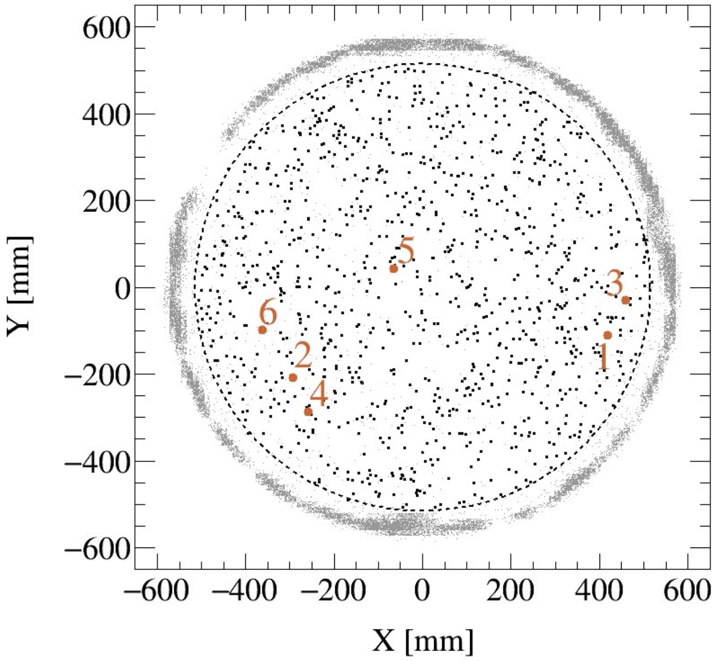
DM Candidates

- FV: 2.67 tonne
- Exposure: 0.63 tonne-year
- Candidates
  - **1058 candidates**
  - **6 below NR median line**



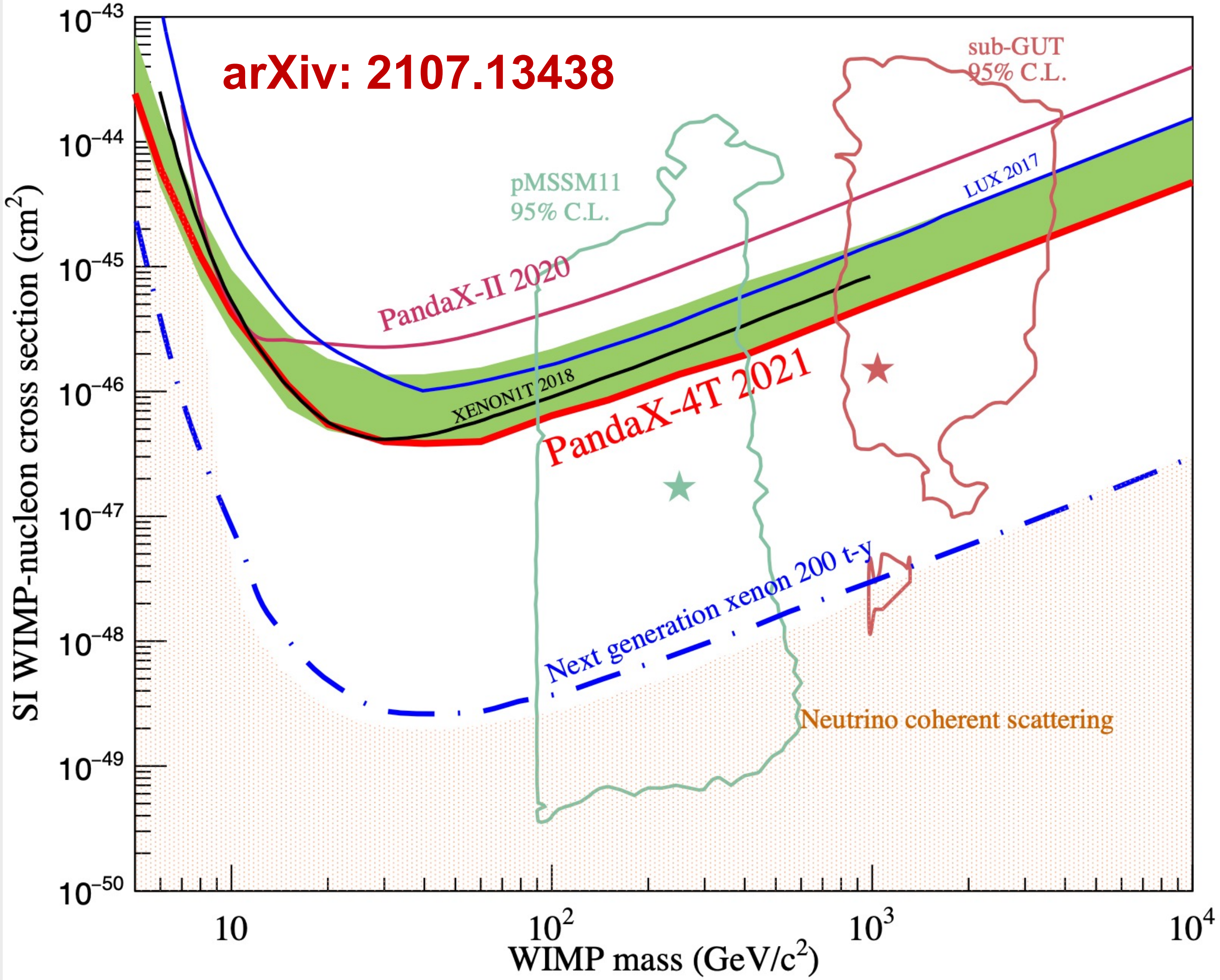






WIMP-nucleon SI exclusion limits

- Sensitivity improved from PandaX-II final analysis by 2.6 times at 40 GeV/c^2
- Dived into previously unexplored territory!
- Approaching the “low E” neutrino floor



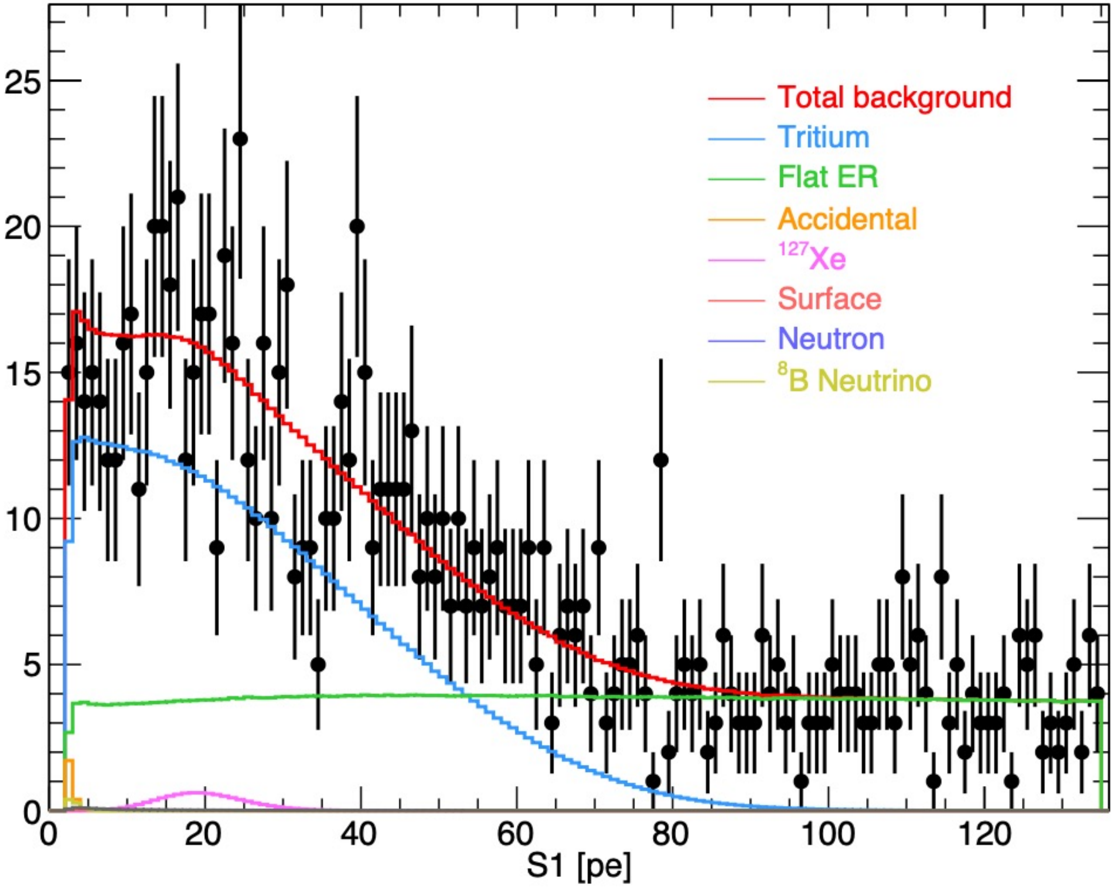
SUSY benchmark contours (MasterCode)

EPJC 78, no.3, 256 (2018), EPJC 78, 158 (2018)

Next Plan: Tritium Removal

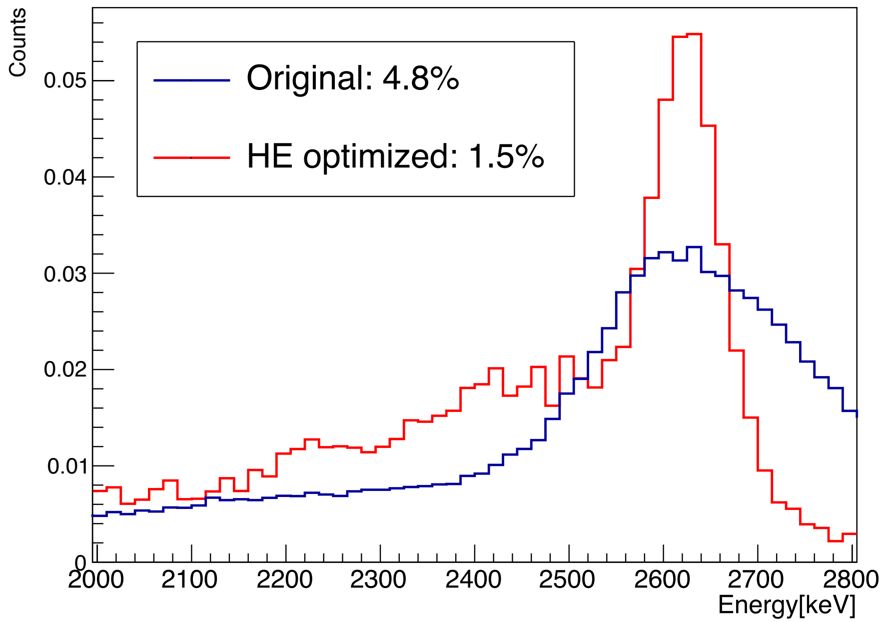
- Tritium spectrum identified in the data
- Likely originated from a tritium calibration at the end of PandaX-II
- Level floating in the final dark matter fit: ~ $5(0.3)\times10^{-24}$ (mol/mol)

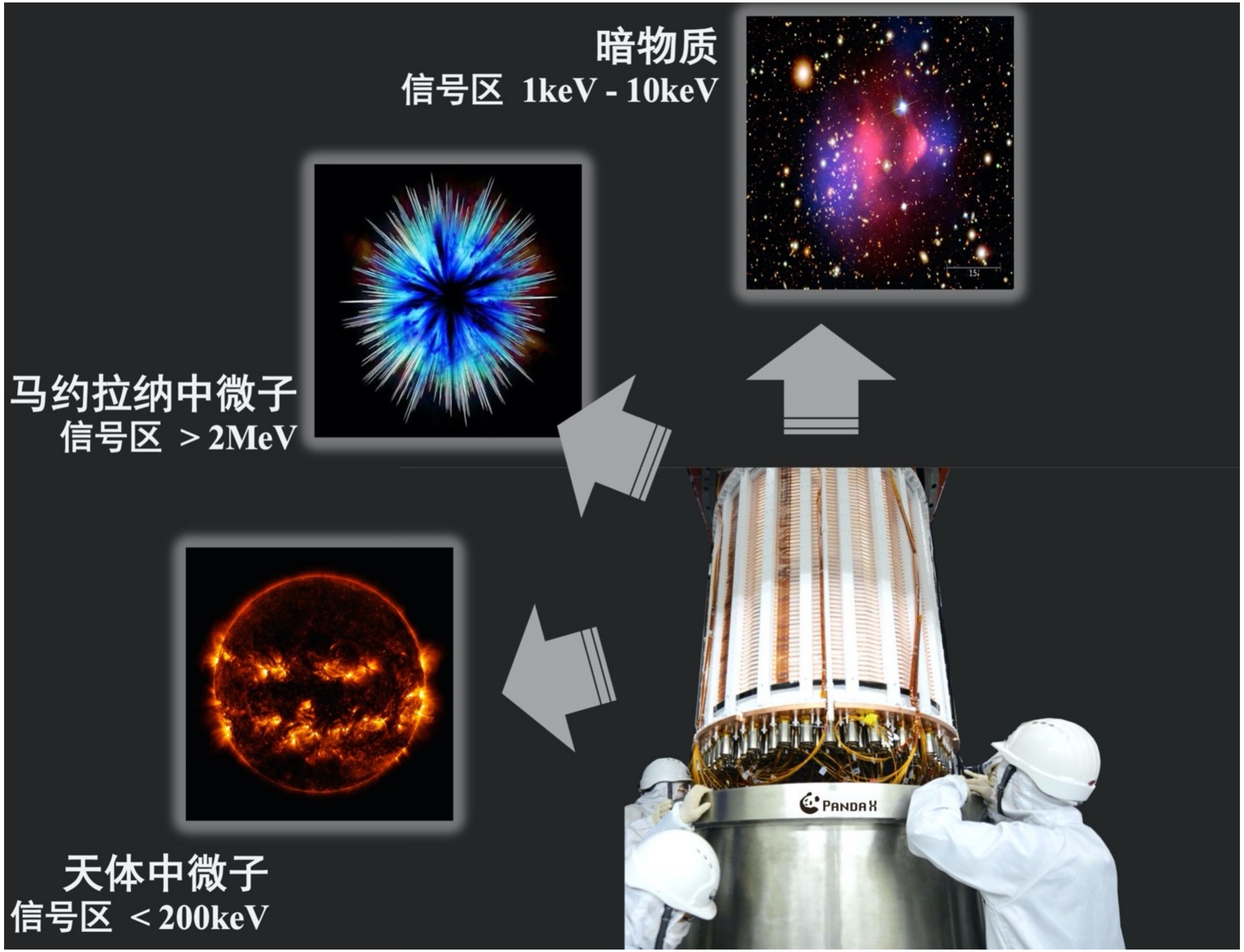
- **Xenon distillation to remove radioactive impurity like tritium**



Multiple Physics Tasks

- Energy 1-30 keVee
  - Dark Matter
- Energy < 200 keVee
  - Astro neutrinos
- Energy > 2MeVee
  - 0vDBD





Low Mass Dark Matter

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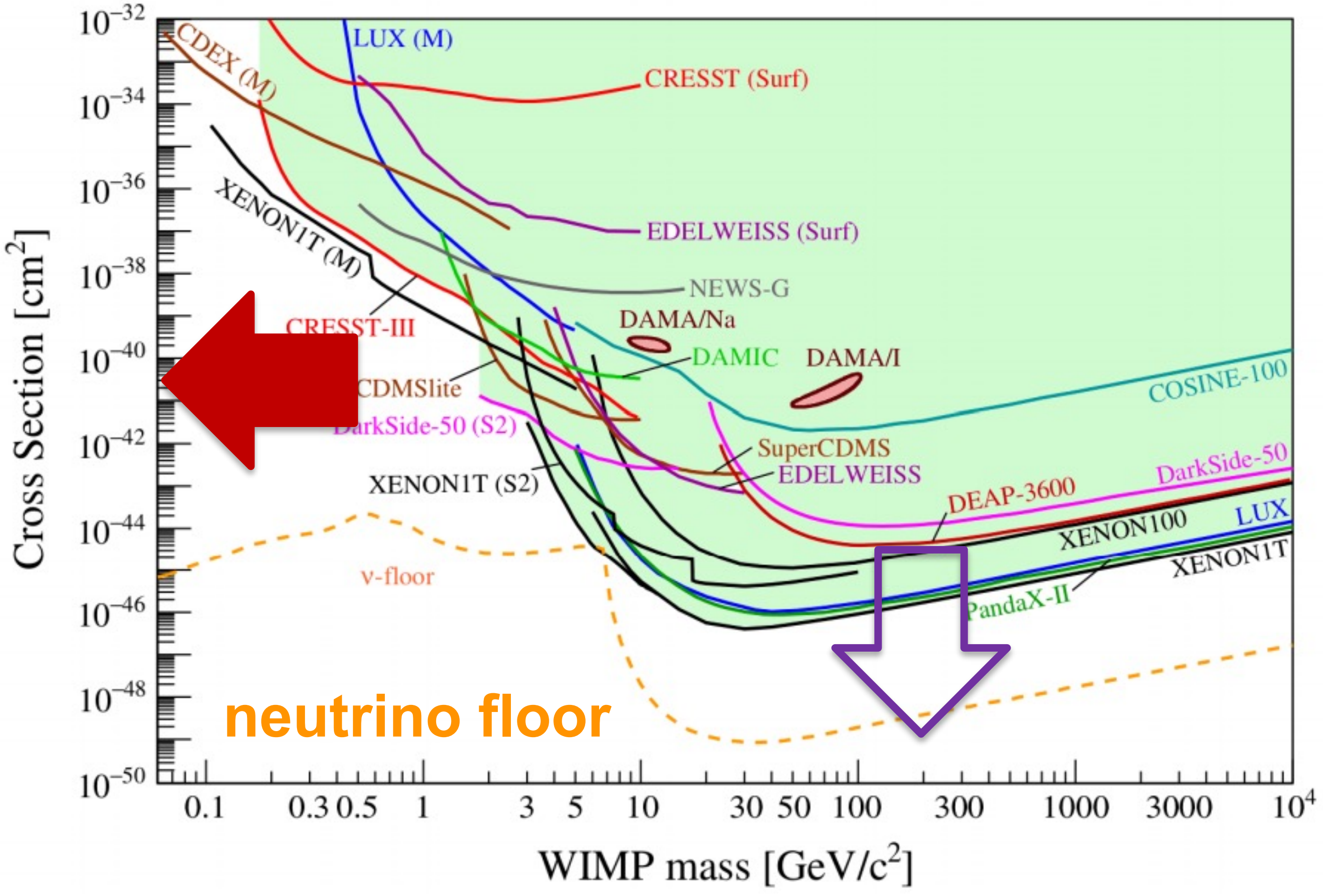
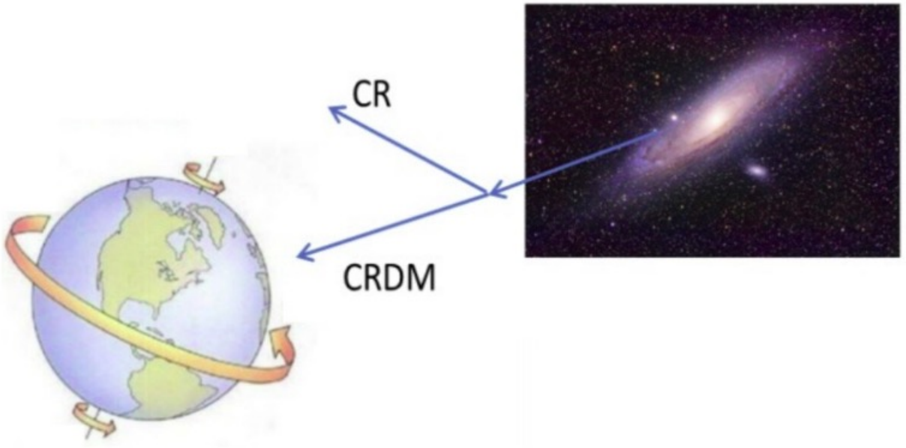
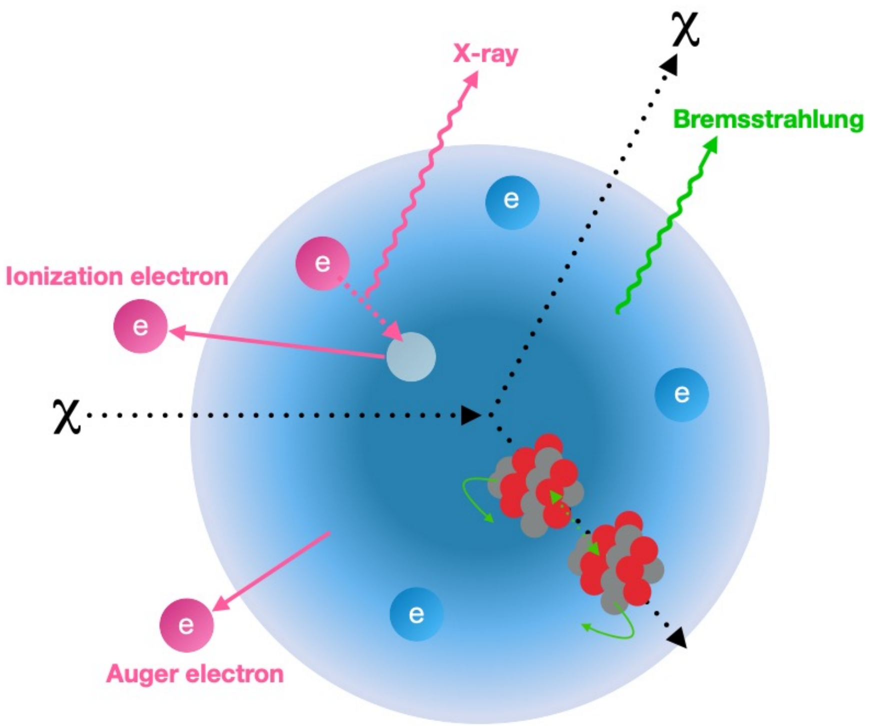
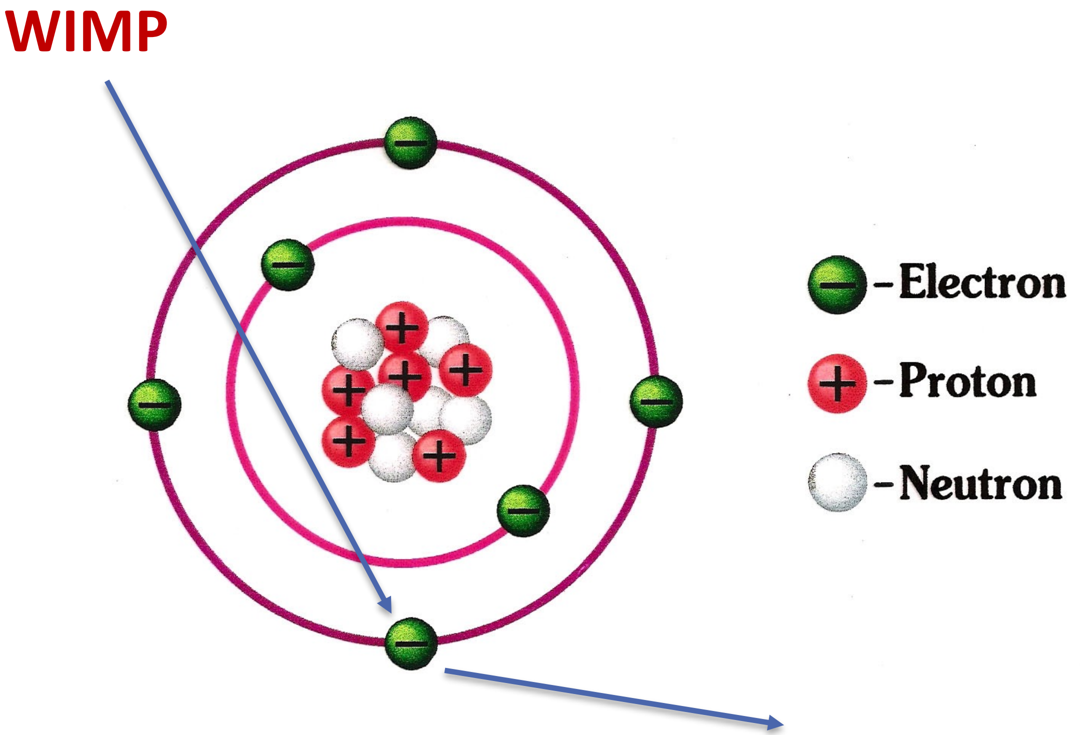


Low Mass Dark Matter

- Axions
- Boosted WIMP
- Migdal effect
- Electron scattering

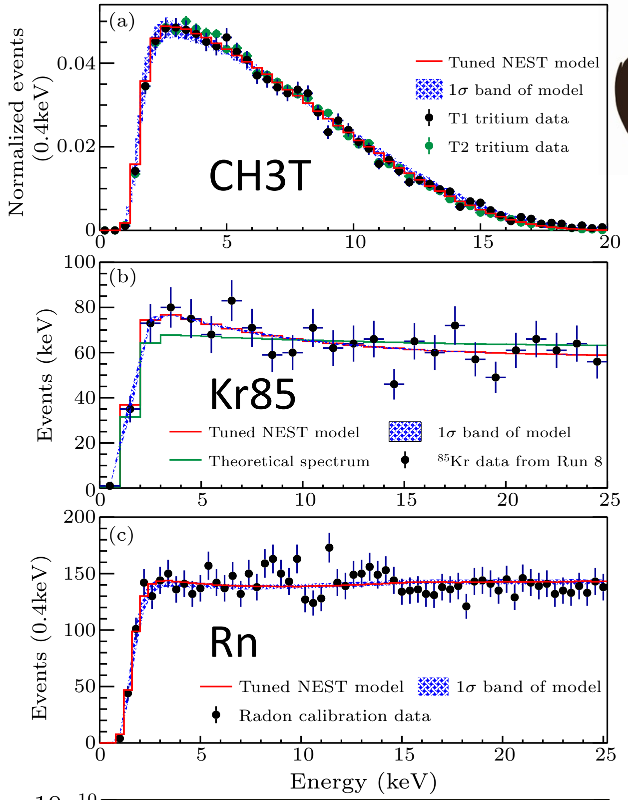




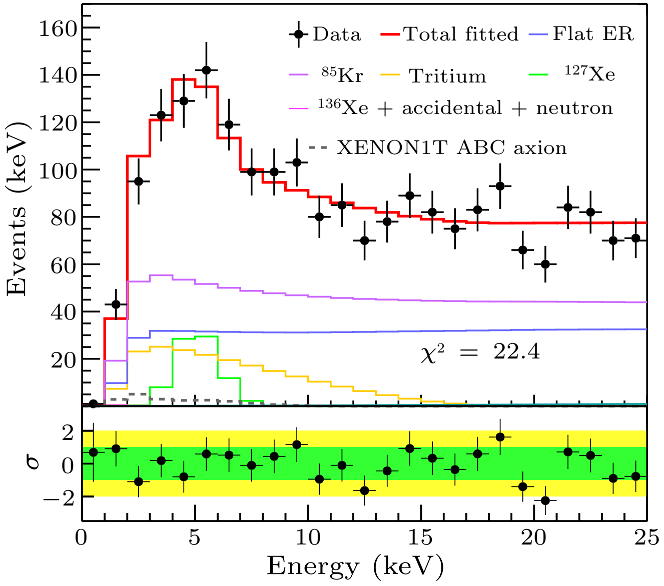


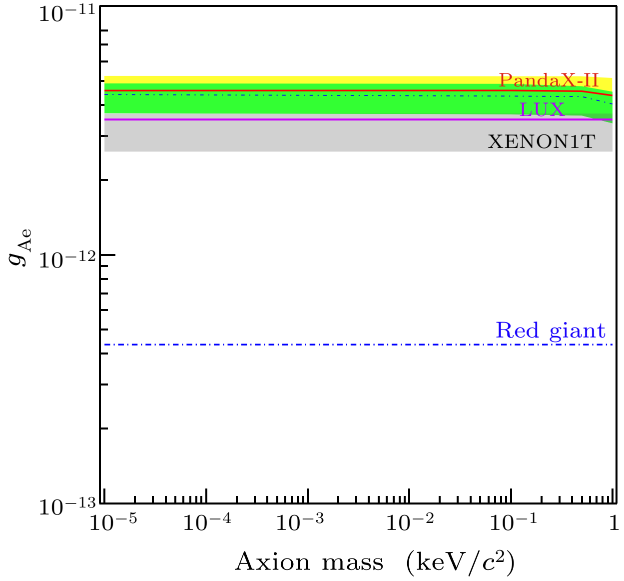
PandaX-II: electron scattering

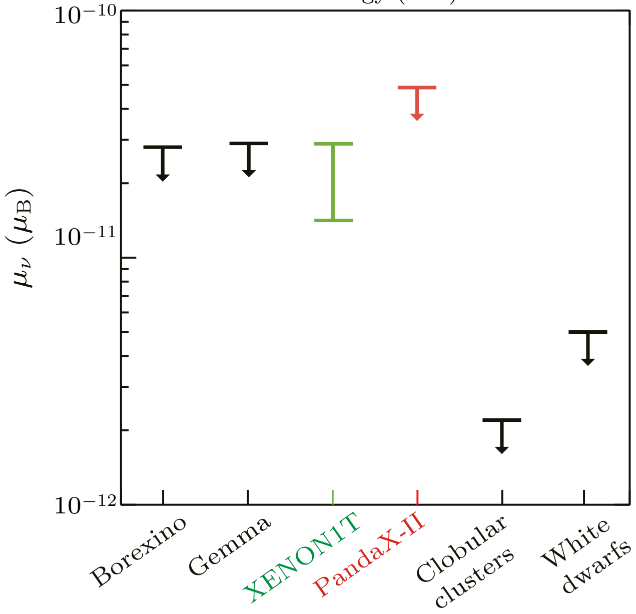
- Signal: axions, neutrino magnetic moment
- Major background spectra obtained from calibration data directly
- Independent check of XENON1T low energy ER excess



CPL Vol 38, No. 1 (2021) 011301

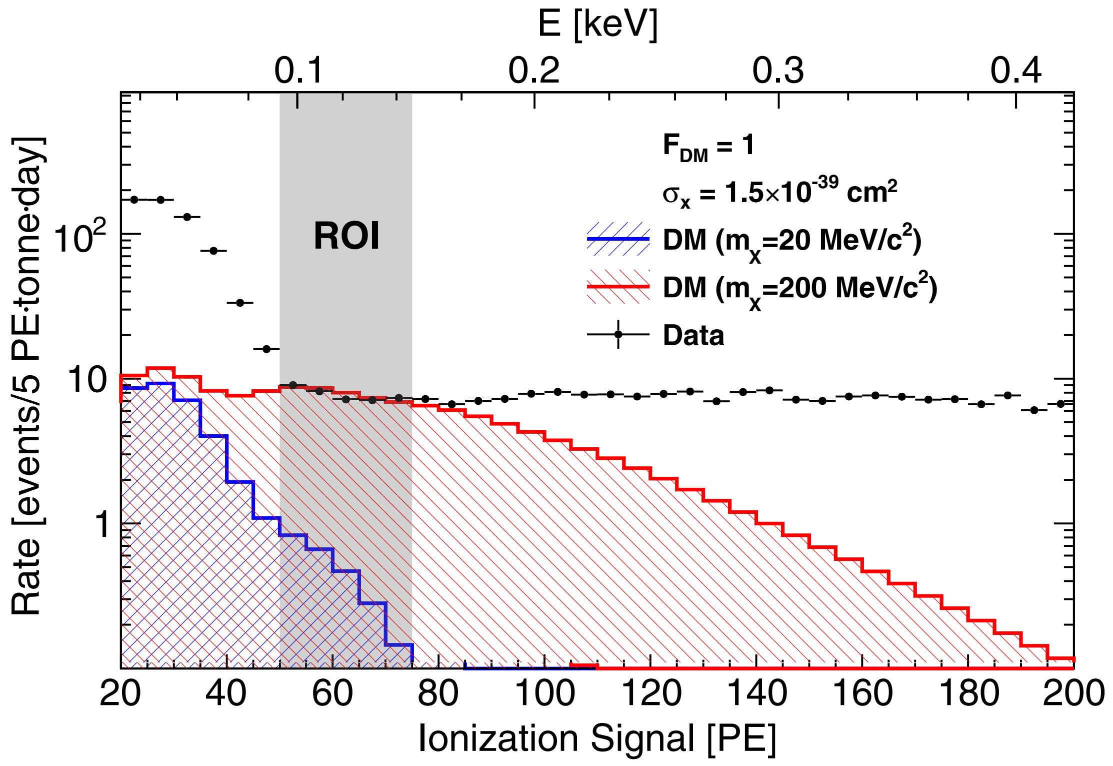




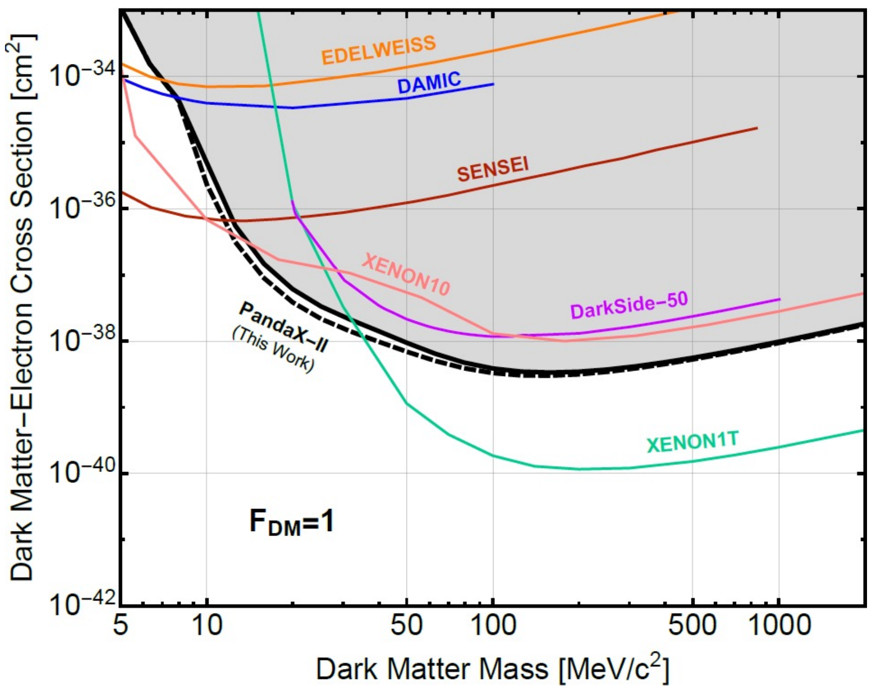


PandaX-II: WIMP-electron scattering

- Light WIMP scattering with electrons
- S2-only analysis：effective threshold 80eV
- 15-30 MeV/c^2 WIMP: strongest constraints

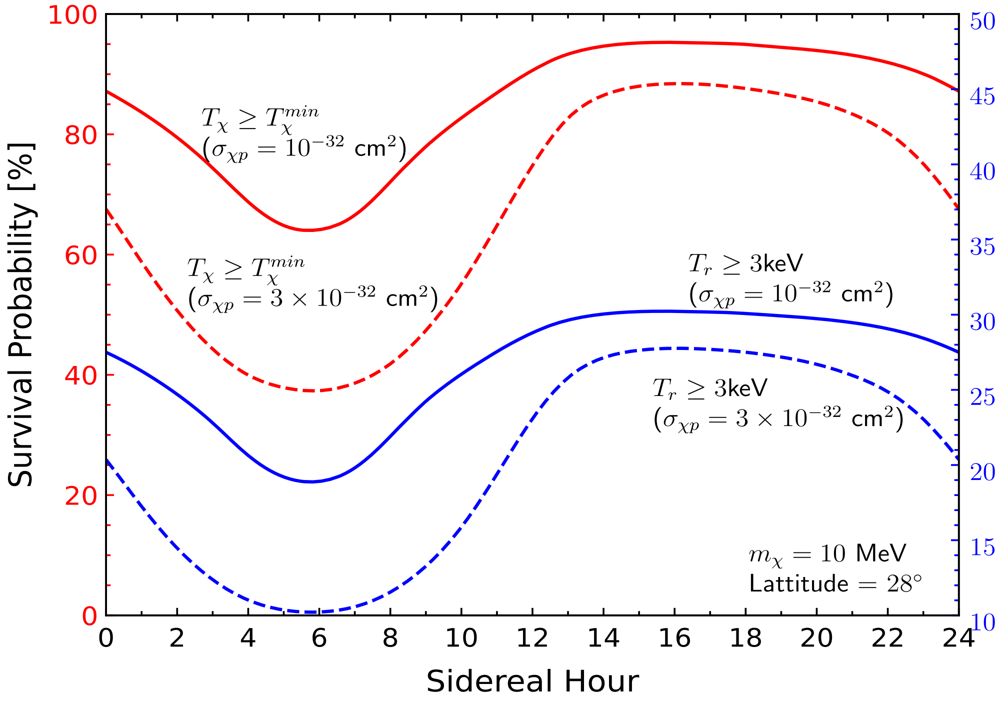


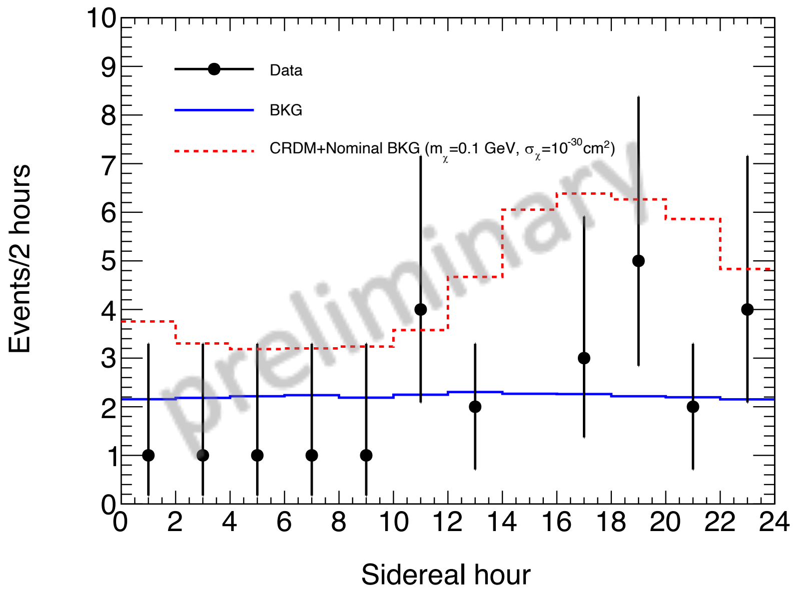
PRL 126, 211803 (2021)

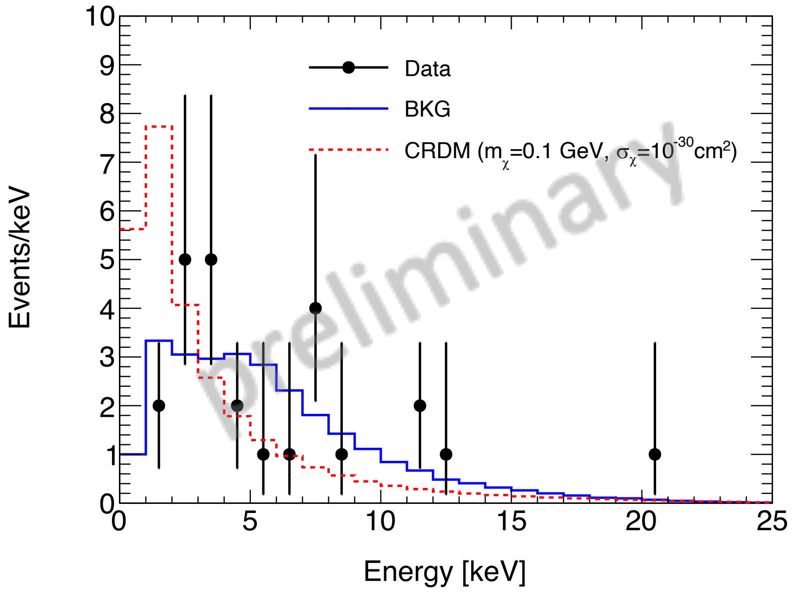


PandaX-II: cosmic ray boosted DM

- Light DM with cosmic ray boosting
- Signature: **diurnal modulation**
- Using events below NR median
  - 25 events (expected 26.6 background)







S. Ge, J. Liu, Q. Y, NZ PRL 126 (2021) 9, 091804

3rd Generation Xenon Experiments

- Darwin experiment
  - 60tonne xenon，100-150M Euros

Home > News > XENON/DARWIN and LZ members have agreed to w...

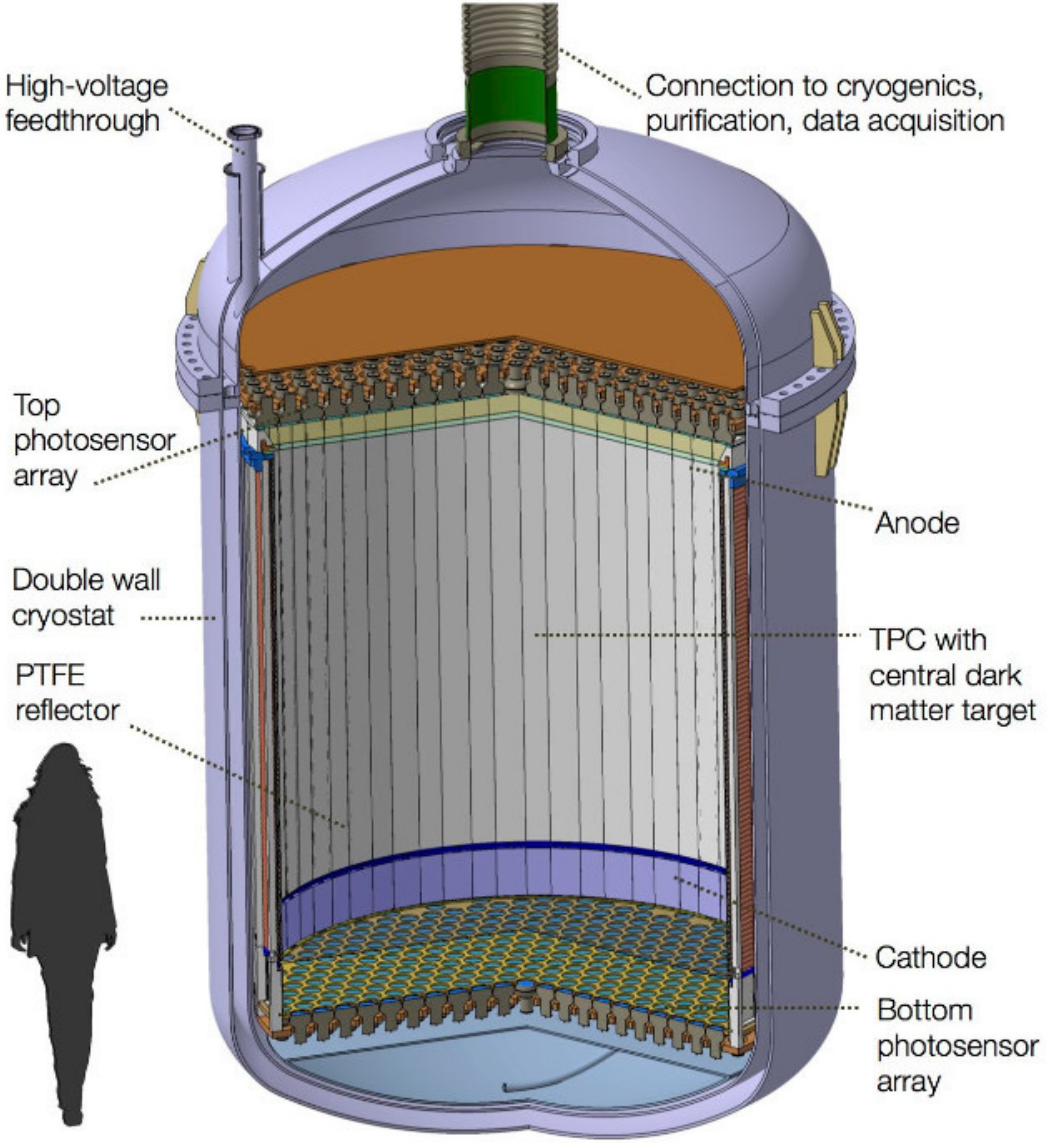
XENON/DARWIN and LZ members have agreed to work together on next generation dark matter search experiment

The XENON/DARWIN and LUX-ZEPLIN (LZ) collaborations have now joined forces to work together on the design, construction, and operation of a new, single, multi-tonne scale xenon observatory to explore dark matter. The detector will be highly sensitive to a wide range of proposed dark matter particles and their interactions with visible matter. Over the last 20+ years, experiments using liquefied xenon targets have delivered world-leading results in the global quest for direct dark matter detection. This next-generation detector aims to continue the pursuit.

Press release: darwin.physik.uzh.ch

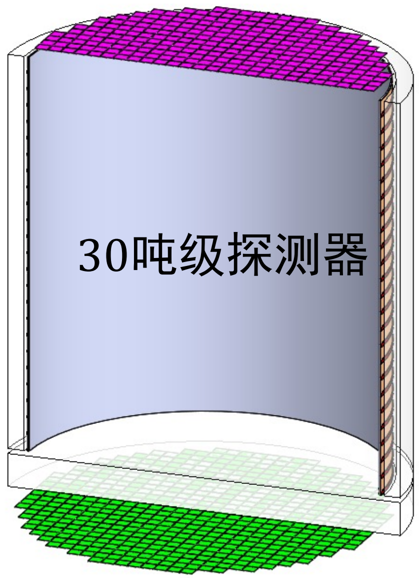
July 29, 2021

Nature **586,** 344-345 (2020)

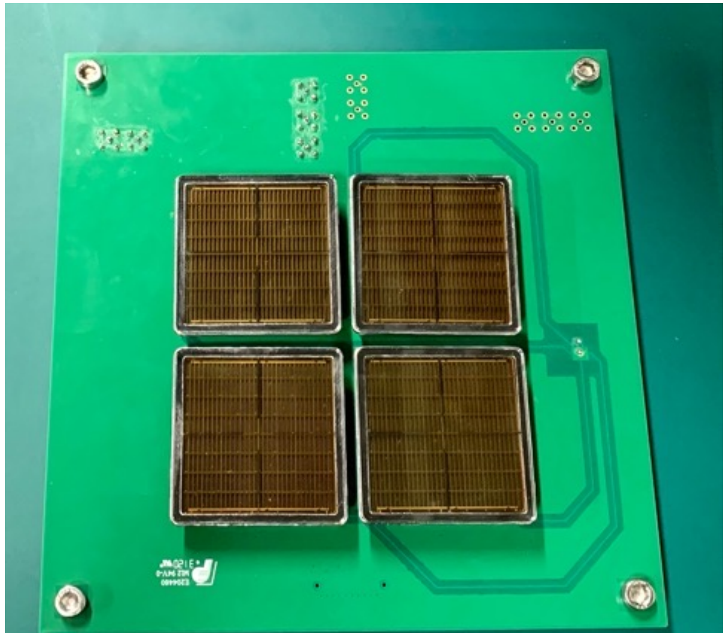


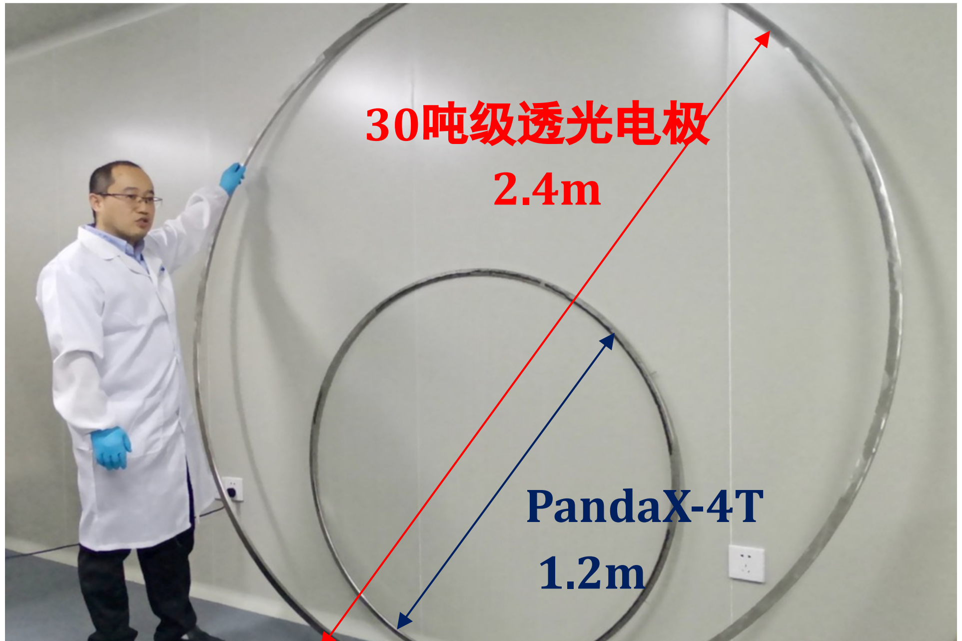
R&D of PandaX-xT

- Low background PMT
- Large size TPC
- Xenon isotope separation



Unit: mBq/pc	R12699 (30T)	R11410 (4T)
Co-60	0.05±0.06 <0.15	1.16±0.72 <2.34
Cs-137	0.12±0.08 <0.25	0.52±0.81 <1.85
K-40	36.91±2.45	8.37±8.47 <22.31
Th-232(early)	0.35±0.35 <0.92	4.33±2.16 <7.88
Th-232(late)	0.80±0.29 <1.28	1.50±0.96 <3.08
U-235	0.00±0.17 <0.28	13.13±8.53 <27.16
U-238(early)	2.26±4.36 <9.44	26.29±16.90 <54.09
U-238(late)	0.63±0.26 <1.07	2.05±1.18 <3.99

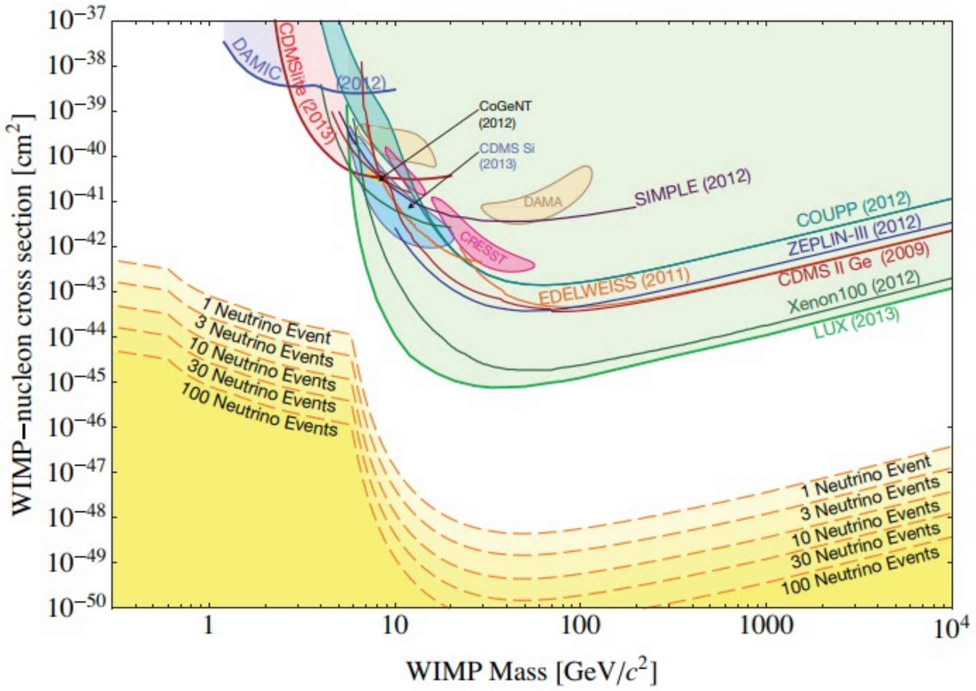

新型低本底光电探测阵列研发

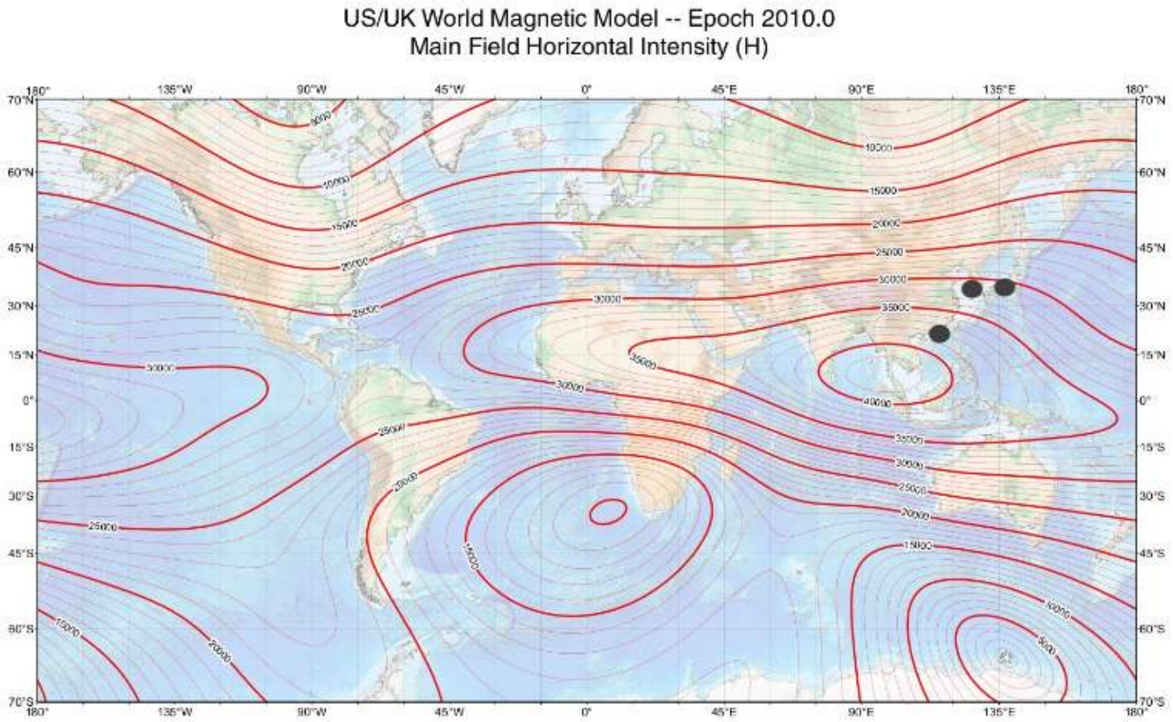


30吨级探测器高透光电极研发

"Neutrino Floor"

- Non-uniform atmosphere neutrinos distribution, due to magnetic field
- CJPL has a unique advantage towards the "neutrino floor"



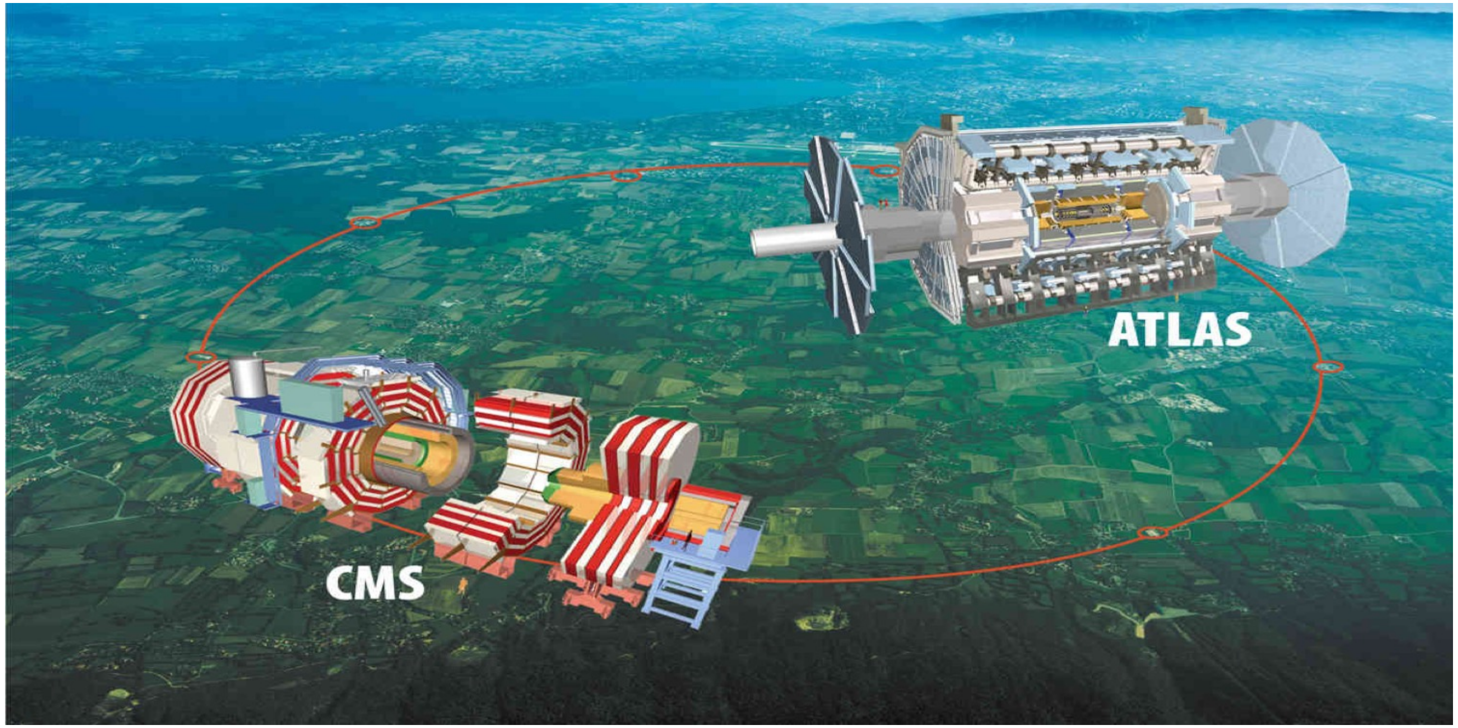


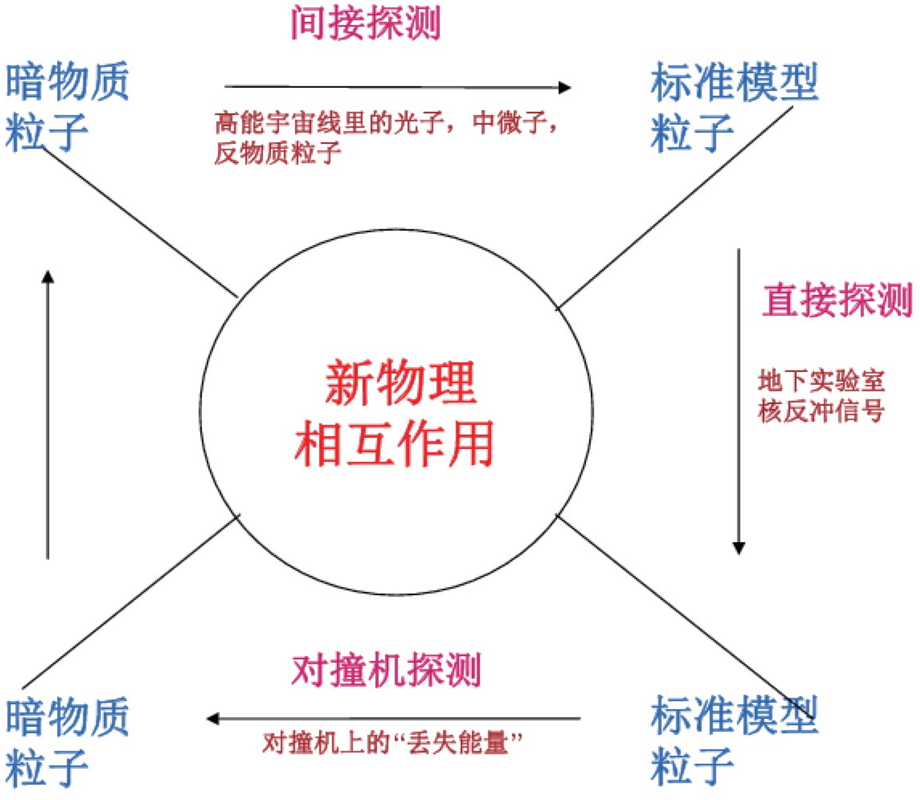
magnetic field

Site	Flux (m^2 sec sr GeV)^-1 [100MeV]
Kamioka	4249
Gran Sasso	7304
Sudbury	11879
Frejus	8215
INO	2554
South Pole	12001
Pythasalmi	12208
Homestake	11774
JUNO	2871

Honda et al. arXiv: 1502.03916 neutrino flux

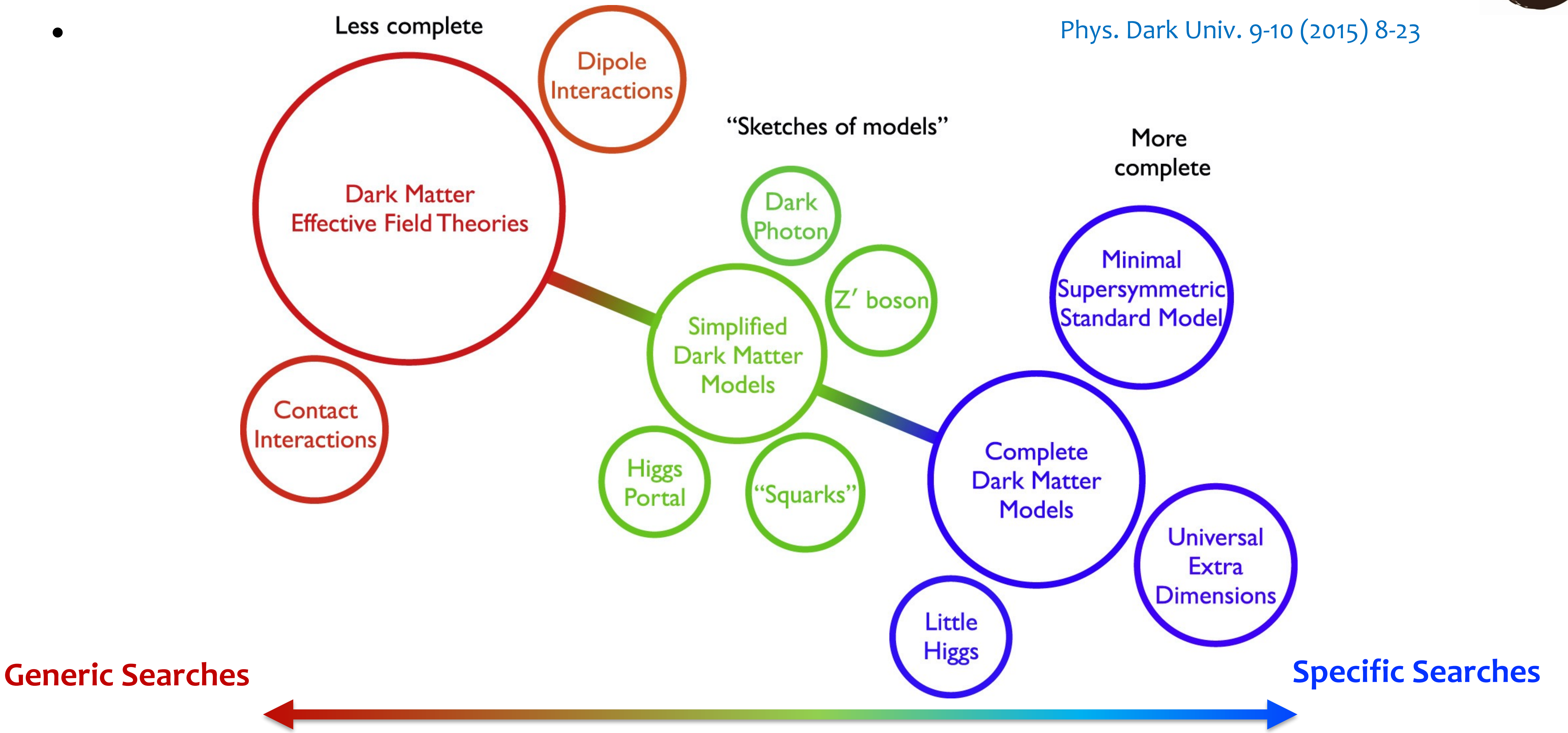
Collider Searches





Dark Matter Models

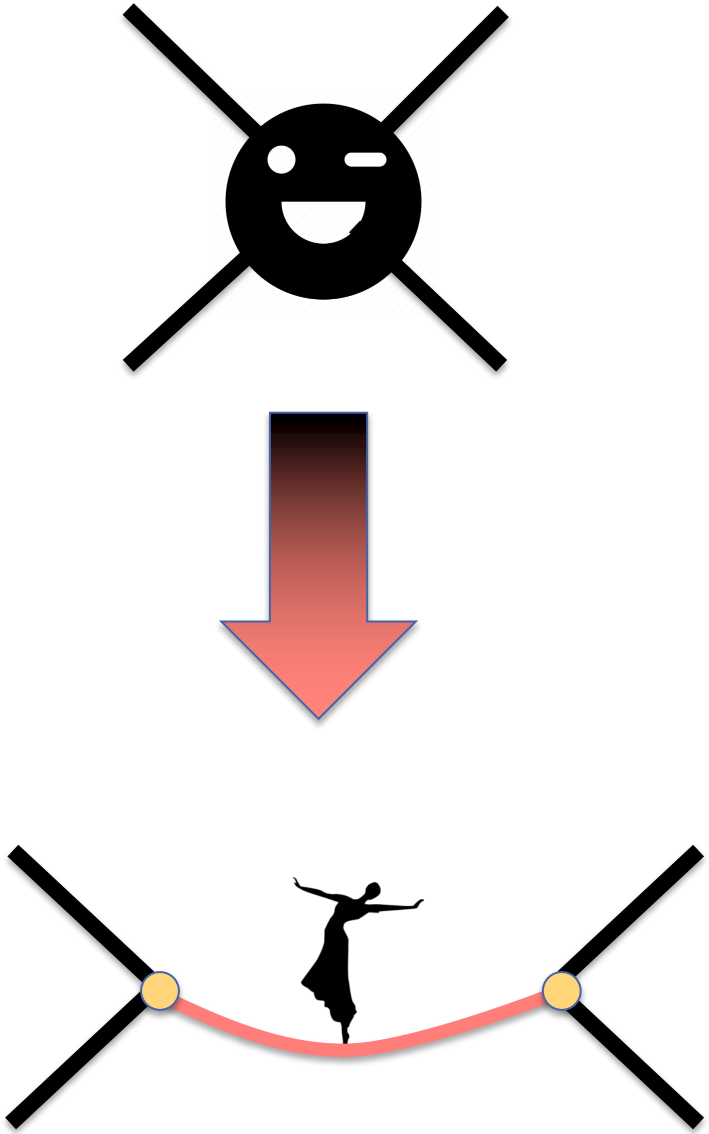
Phys. Dark Univ. 9-10 (2015) 8-23



Simplified Model with Mediator

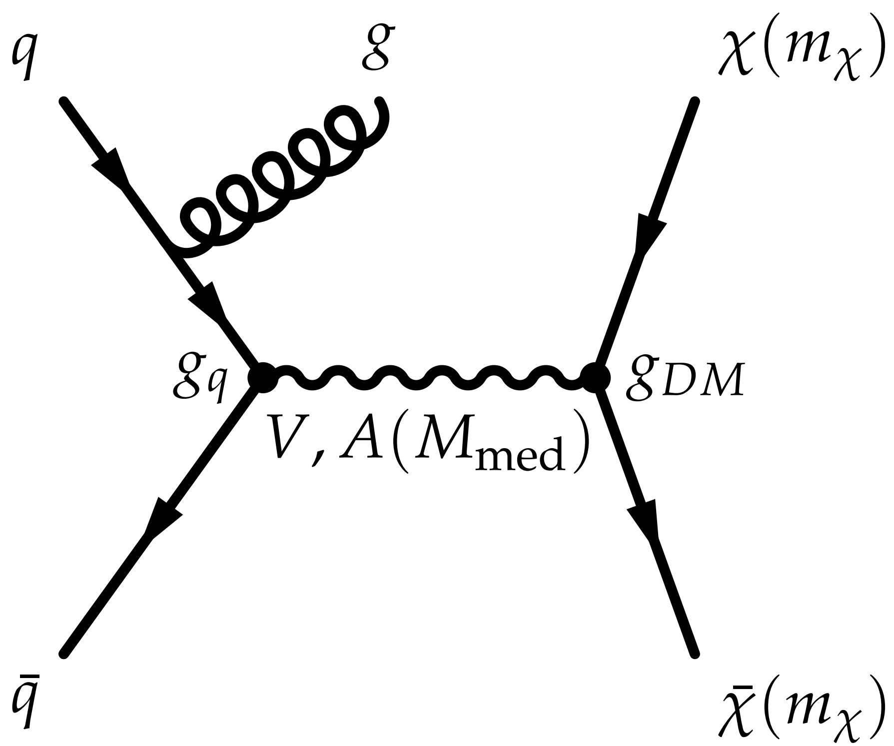
- keep the mediator information
  - mass: $m_{Z'}$
  - spin : vector, axial-vector, etc
  - coupling: g_q g_l g_{DM}

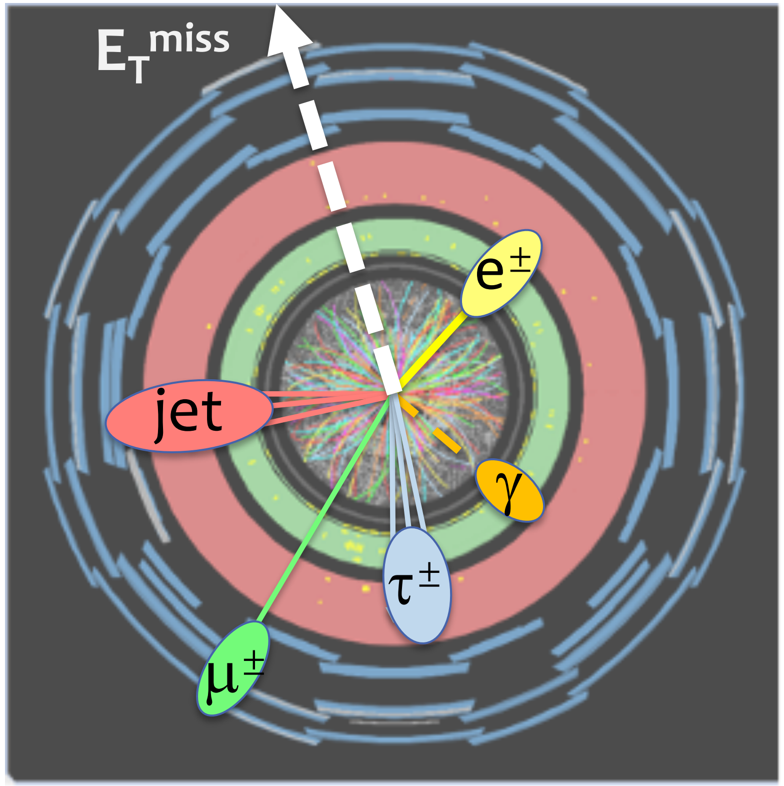
- simplified model:
  - starting point to build complete theories
  - colliders can search for the mediator directly



Mono-X Search

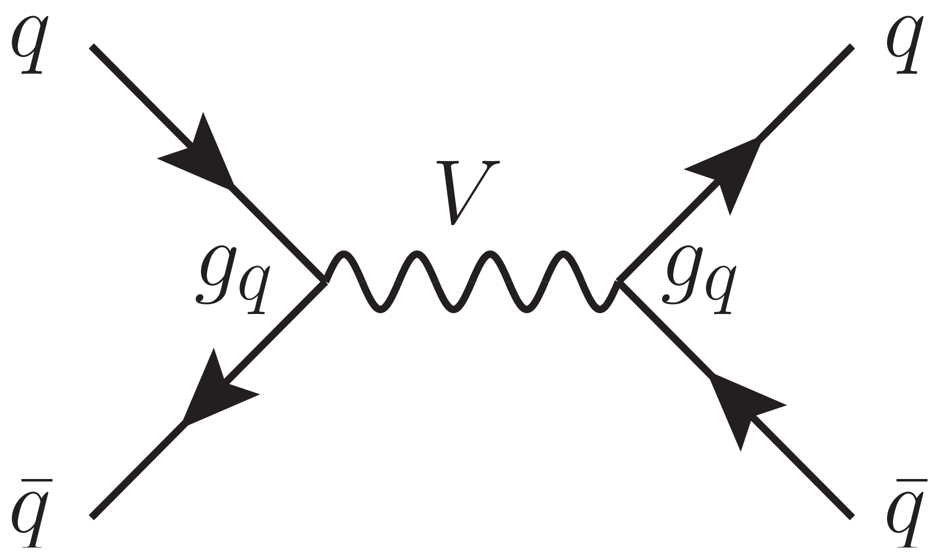
- dark matter production in association with X
  - dark matter escape detection
  - X: visible particles
  - E_T^{miss}: momentum imbalance in transverse plane

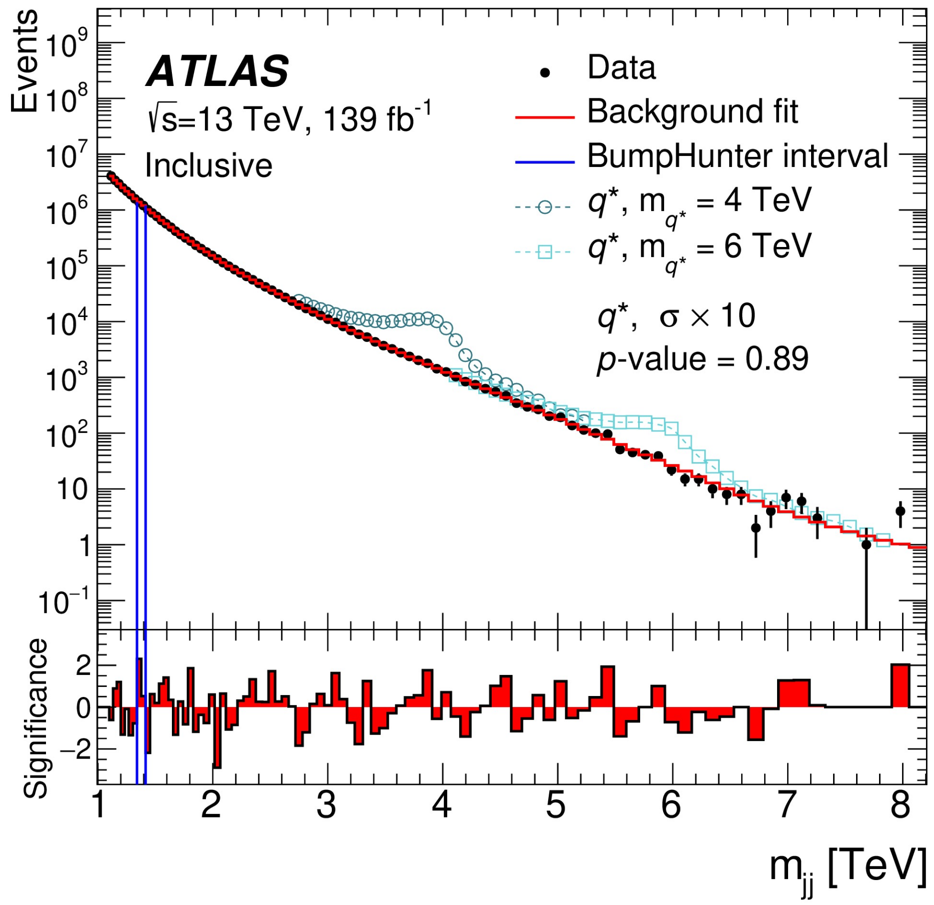




Di-jet Resonance

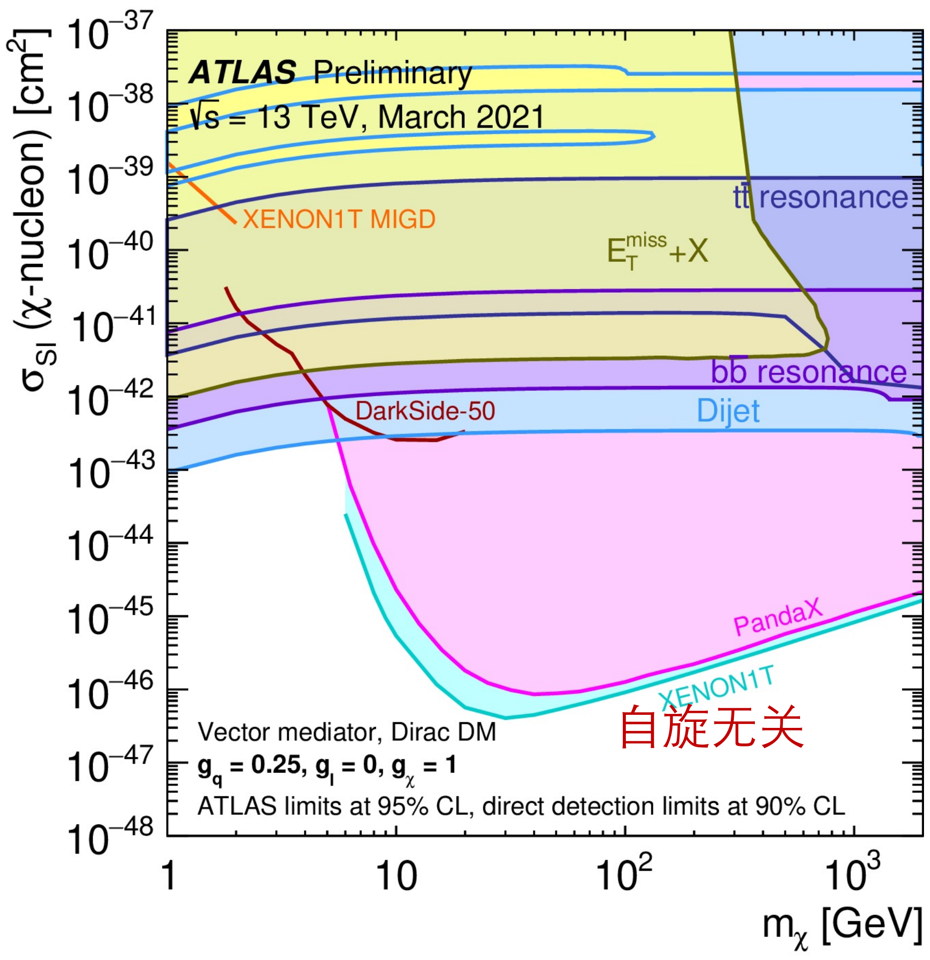
- direct search of the mediator
- dijet resonance: inclusive, 1 or 2 b-jets

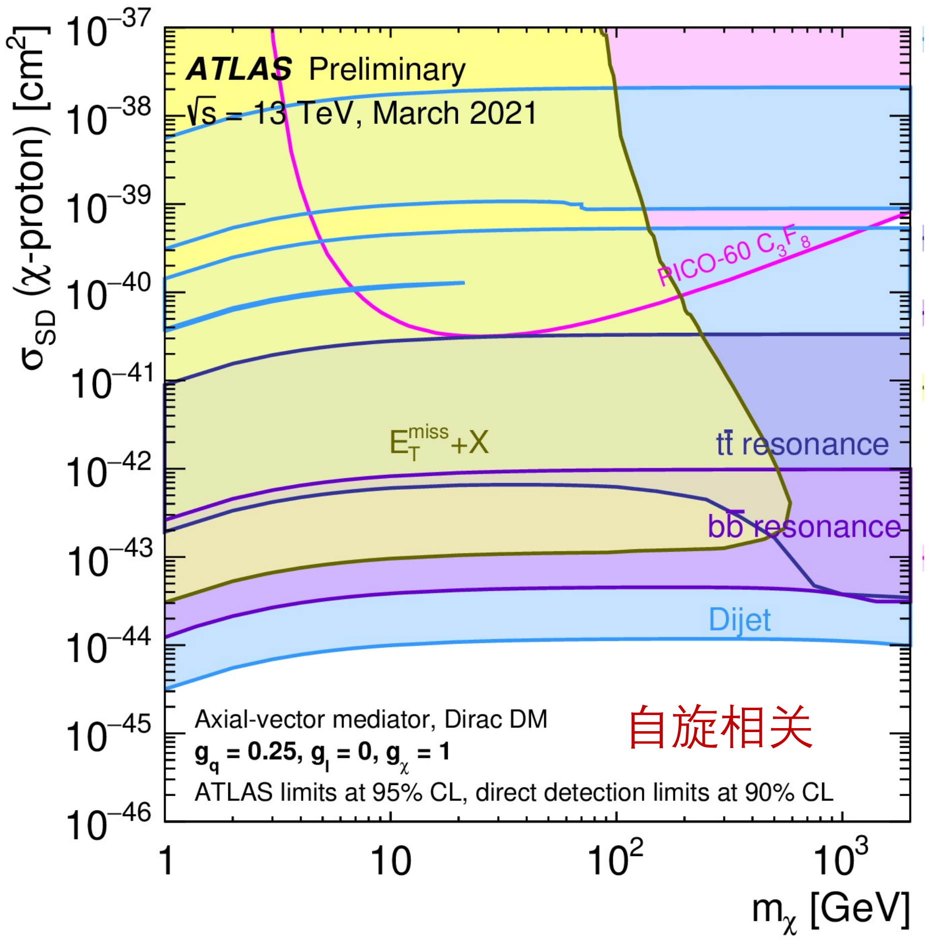




Combined Constraints

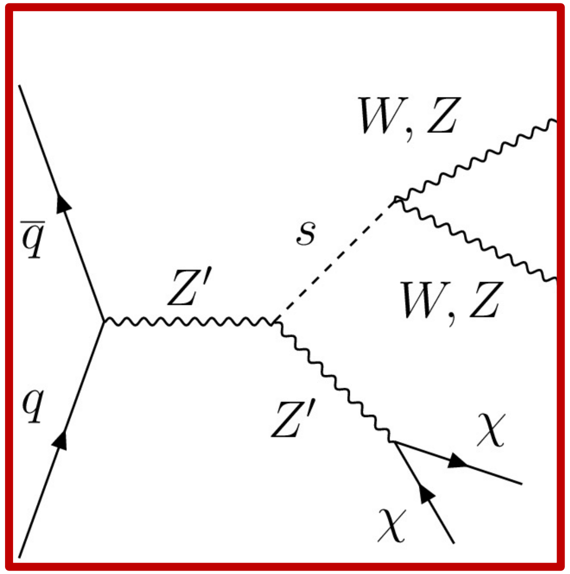
- With direct detection experiments

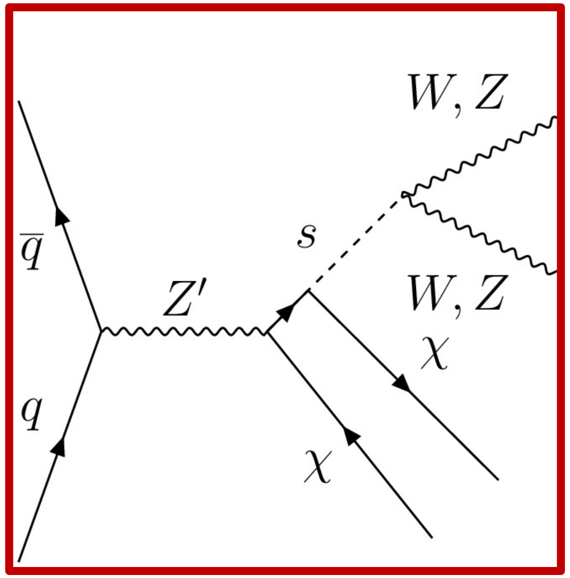




Dark Higgs

- dark matter mass from Higgs mechanism in dark sector
  - dark Higgs boson *s* : can be even lighter than DM
  - simplified model: dark Higgs + Z’ mediator + DM
  - dark Higgs mixing with SM Higgs: decay to vector bosons

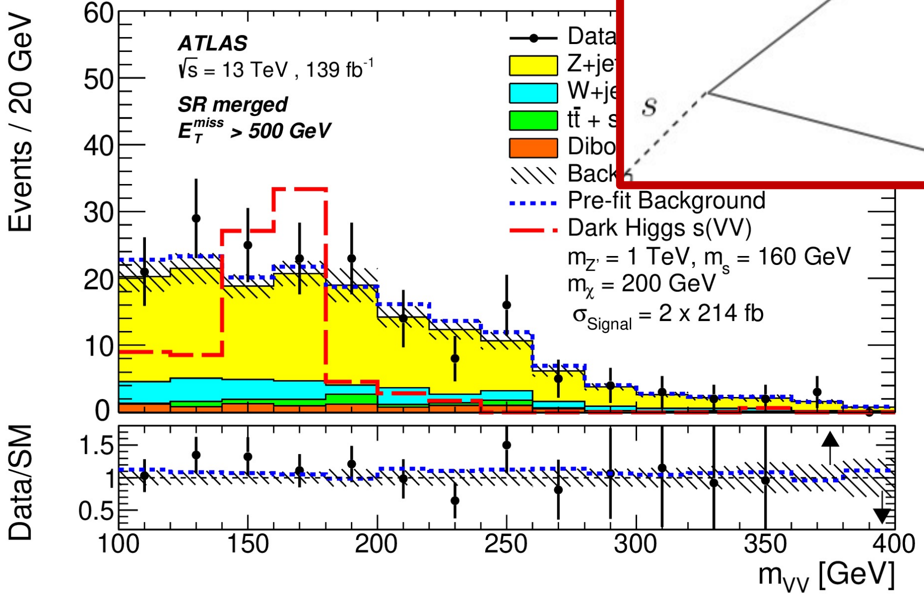


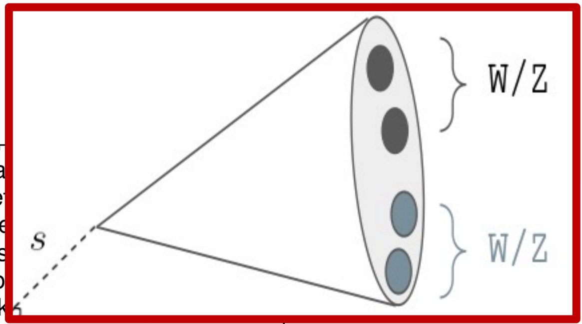


JHEP 1704 (2017) 143

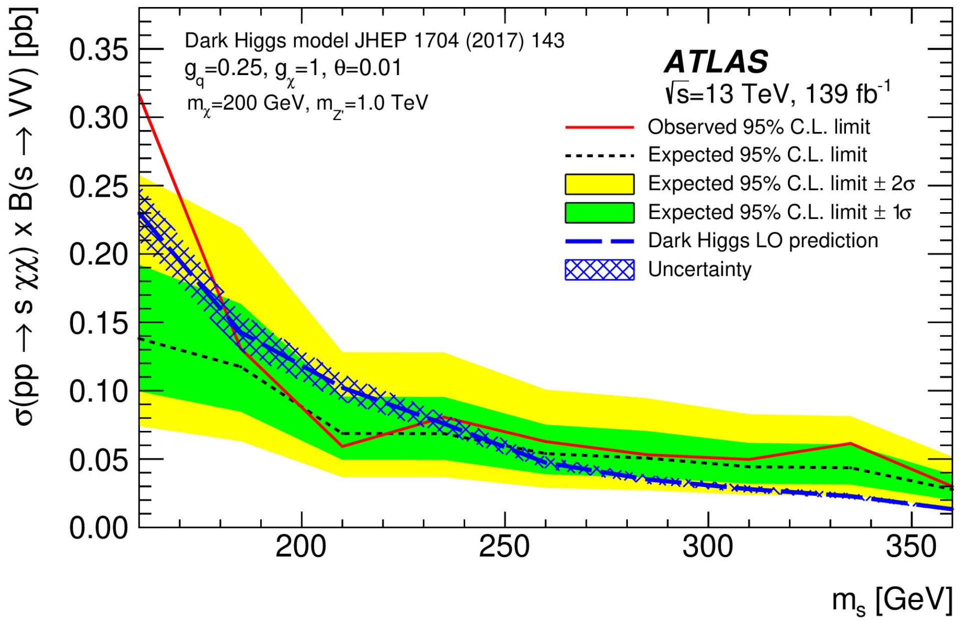
Mono-S(VV)

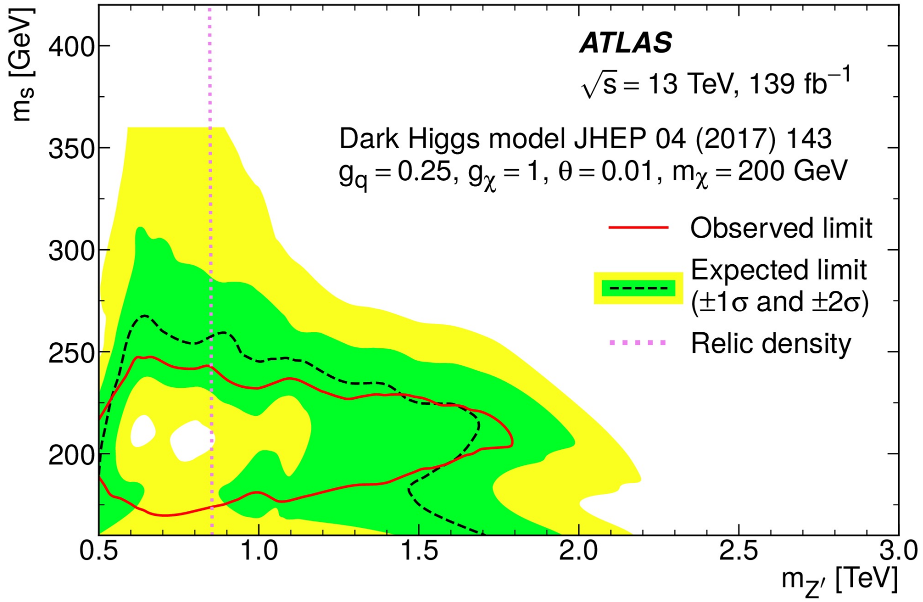
- reconstruct dark Higgs with a fat jet (containing 2 V -> 4 jets)
  - track-assisted reclustering (TAR) algorithm: better jet substructure resolution





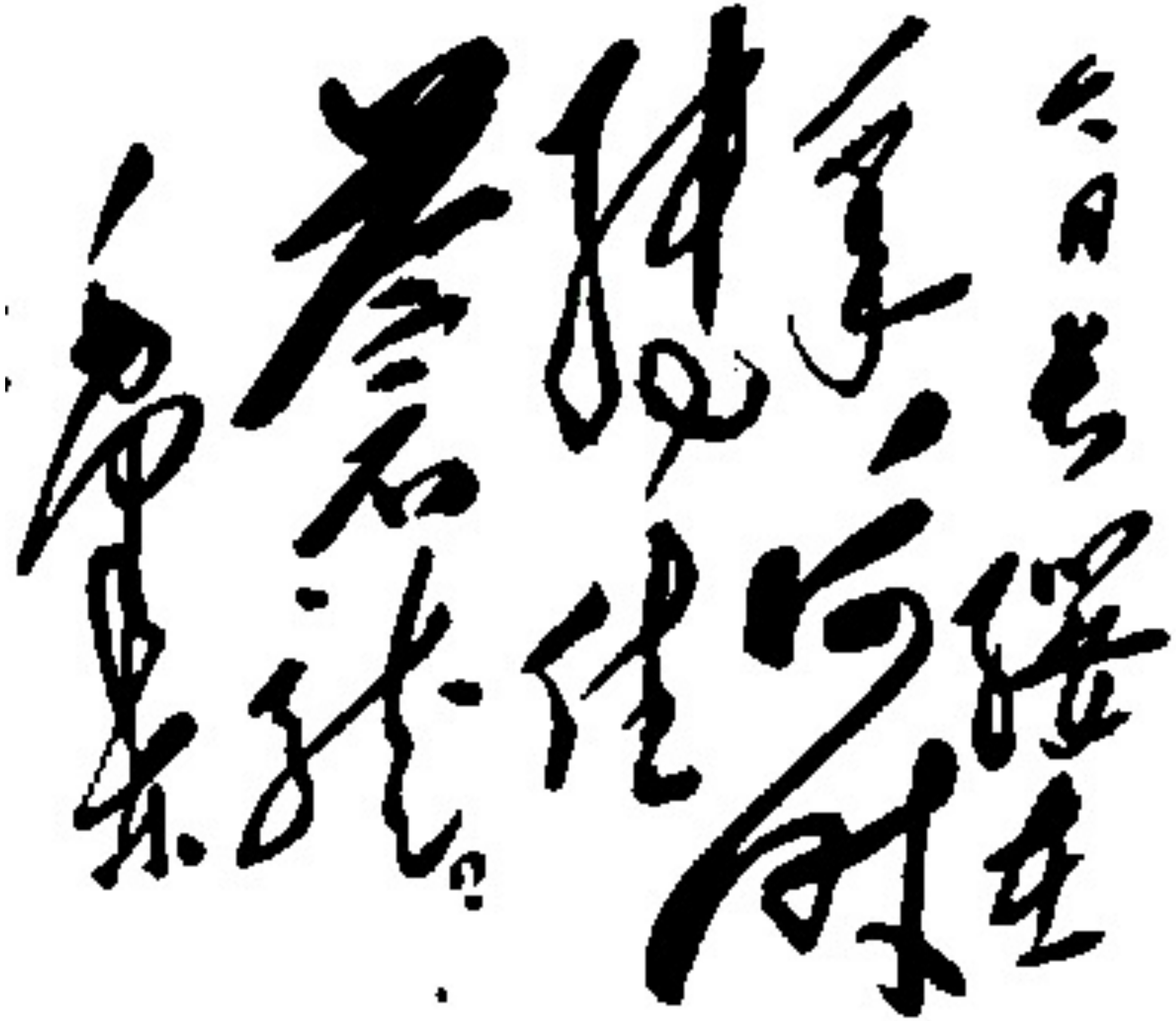
PRL 126 (2021) 121802





Summary

- Dark matter detection plays a key role in new physics search.
- Quick progresses in recent years
- In China, a sizeable team has formed, producing leading results
- Active communication among theorists and experimentalists



谢谢大家！