Lecture 4: Searching for Dark Matter

Outline

- **Astrophysical evidences for dark matter**
- **Dark matter as WIMPs**
  - Collider
  - Indirect search
  - Direct search
- **Direct search: status report**
- **Nobel-gas liquid detectors + XENON100**
- **Dark matter exp in China (CXO)**

Astrophysical Evidences

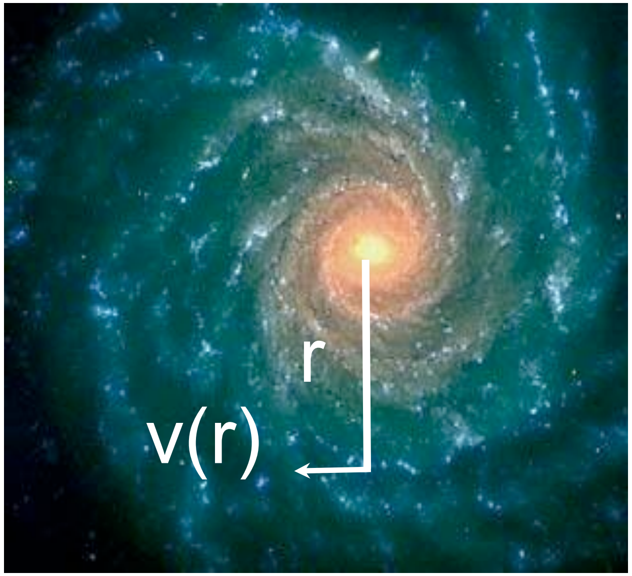
- Galaxy rotational curve
- Gravitational lensing
- CMB
- Galaxy distribution

Sun's rotation around the milky way

- In the milky way, all stars are moving around the center.
- According to Newton's law of gravity, the rotation speed has to do with gravitational mass distribution,

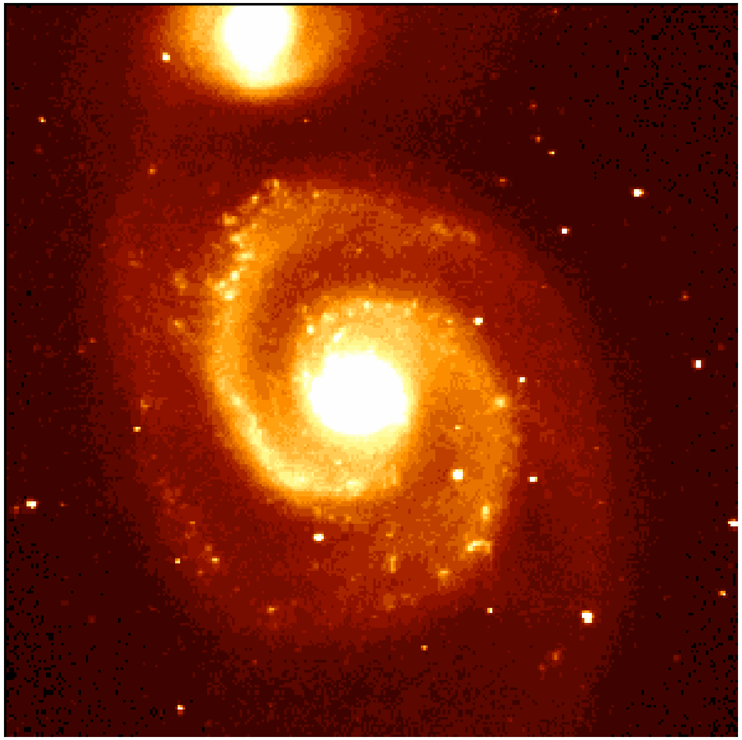
$$v(r) \propto \sqrt{M(r)/r},$$

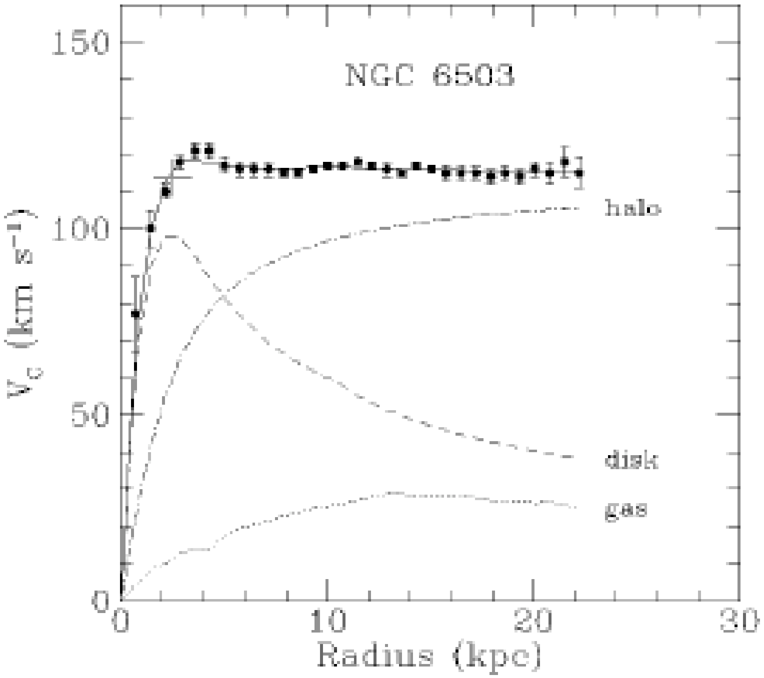
- According to this, the sun's speed shall be around 170km/s , but the actual speed is around 220km/s, or even 250km/s



Rotational Curve (Ford,Rubin, 70')

- In a galaxy, the rotational speed of stars as a function of distance form the rotational curve.

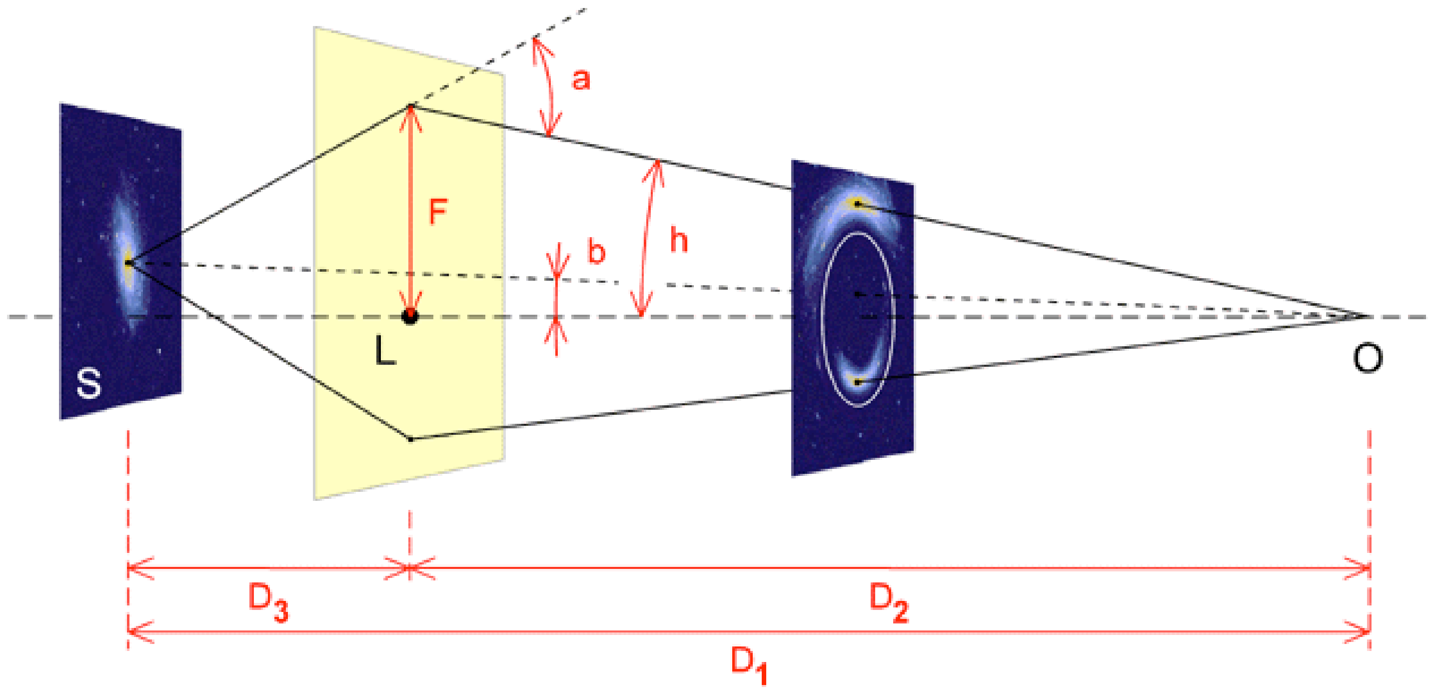




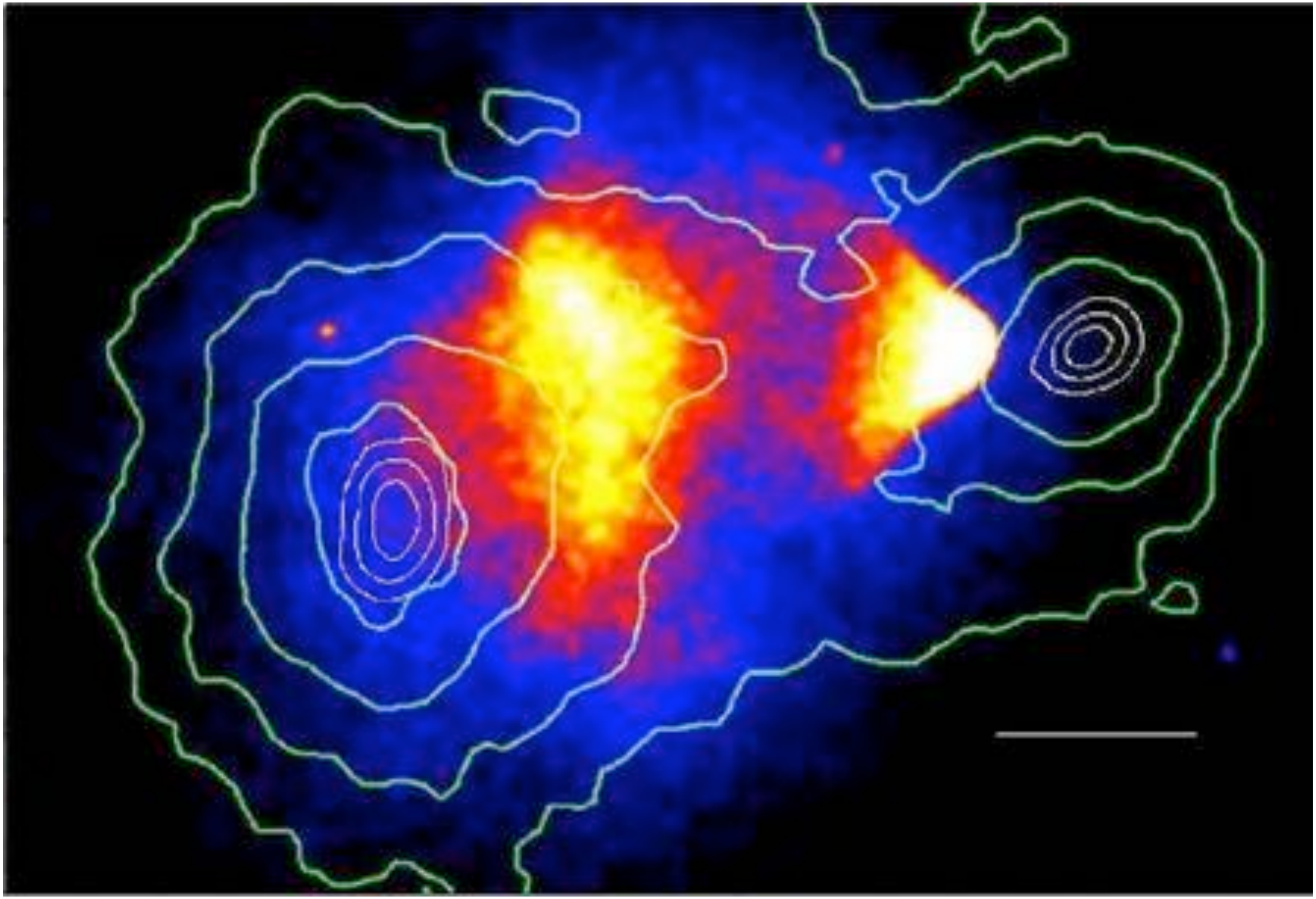
95% mass from dark matter !

Gravitational lensing

- **When light passes through a gravitational field, it deflects. From the size of deflection, we can calculate the gravitational field and distribution of dark matter.**

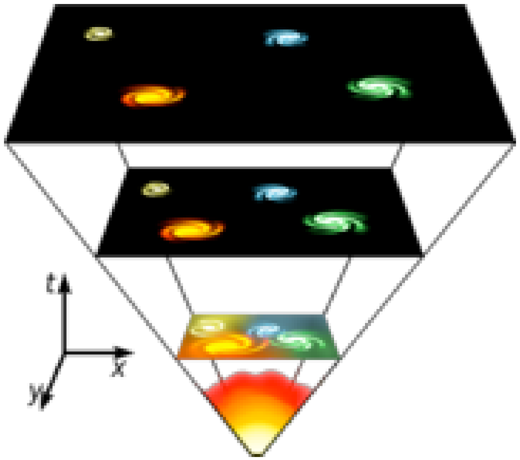


Bullet Cluster



Standard Big-Bag Cosmolgy

- According to the standard model of cosmology, the universe started from a big-bang 13 billion years ago.



- Since then, the universe cools and expands. At about 300,000 yrs, the universe changed from electron-nucleus plasma into neutral atoms, and the universe became transparent.
- Since then, the light propagates quasi-freely and comes to us now as a the 13 byrs old fossil (Dicke, Gamow, 1946)。

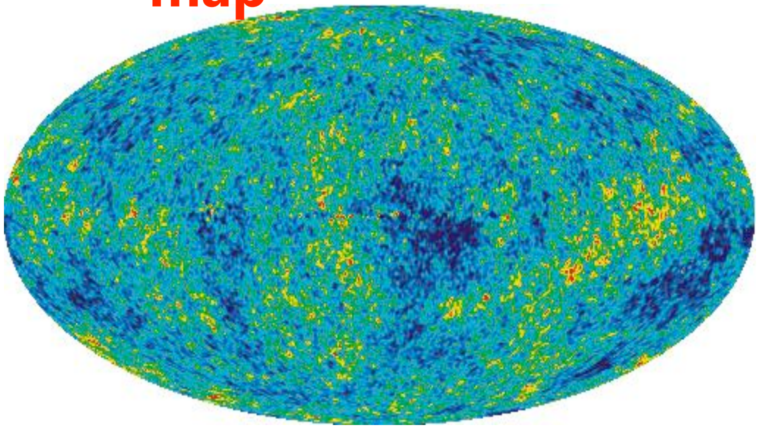
CMB

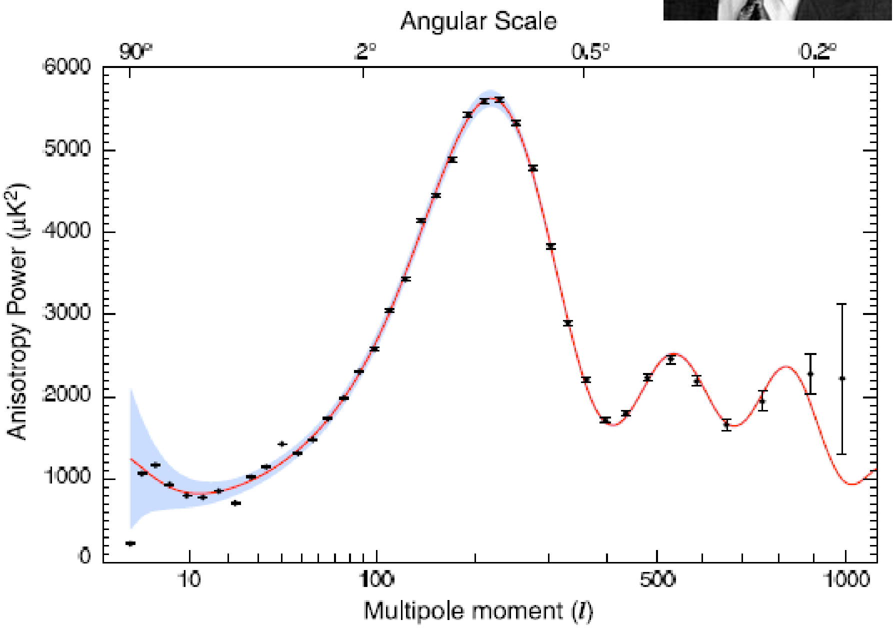
- In 1965 ， Penzias and Wilson (Bell Lab) discovered the CMB accidently. 1978 Noble prize.
- 1990, J. Mather discovered through COBE sattelite ，CMB is a perfect black-body radiation with the temperature also the same in the every direction ！

Fluctuations of CMB

- In 1992 , Smoot discovered 10^{-5} level temperature fluctuation at different directions (COBE)

CMB fluctuation map



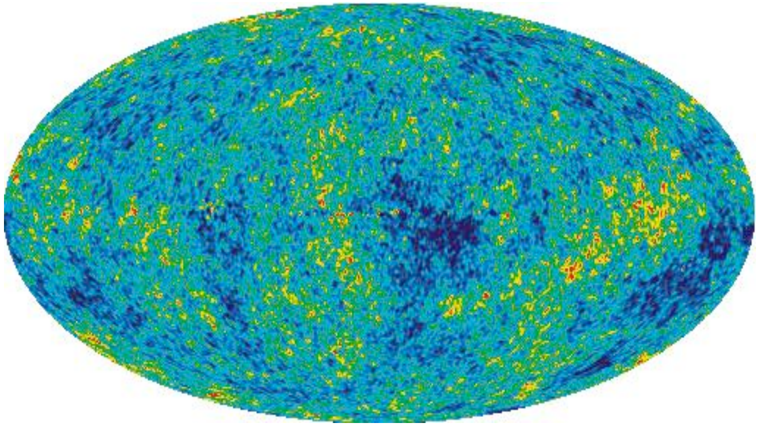


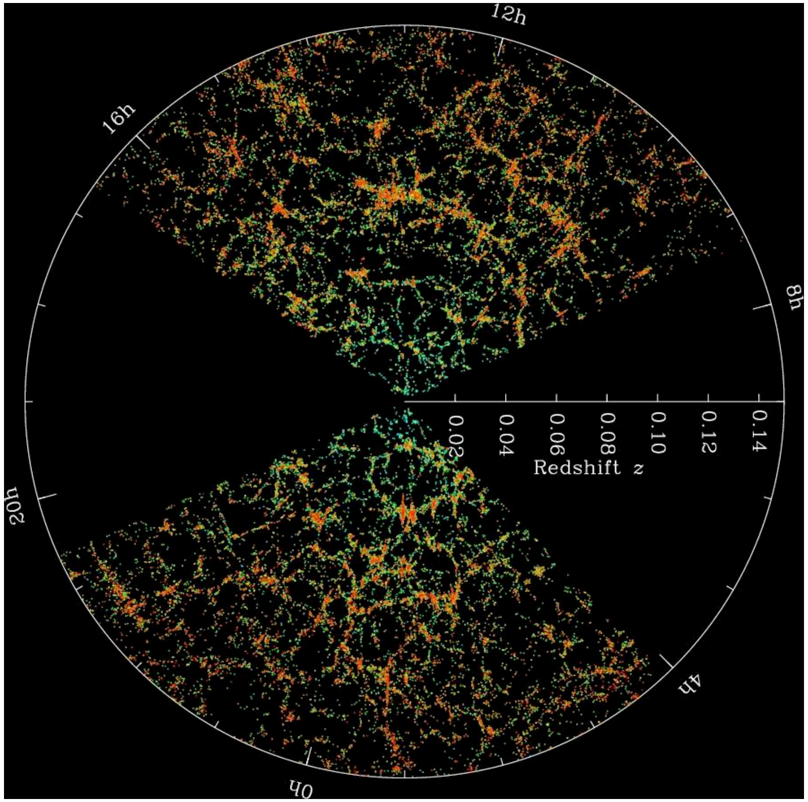
- 2006 Nobel Prize for Mather and Smoot

Large scale structure of the universe

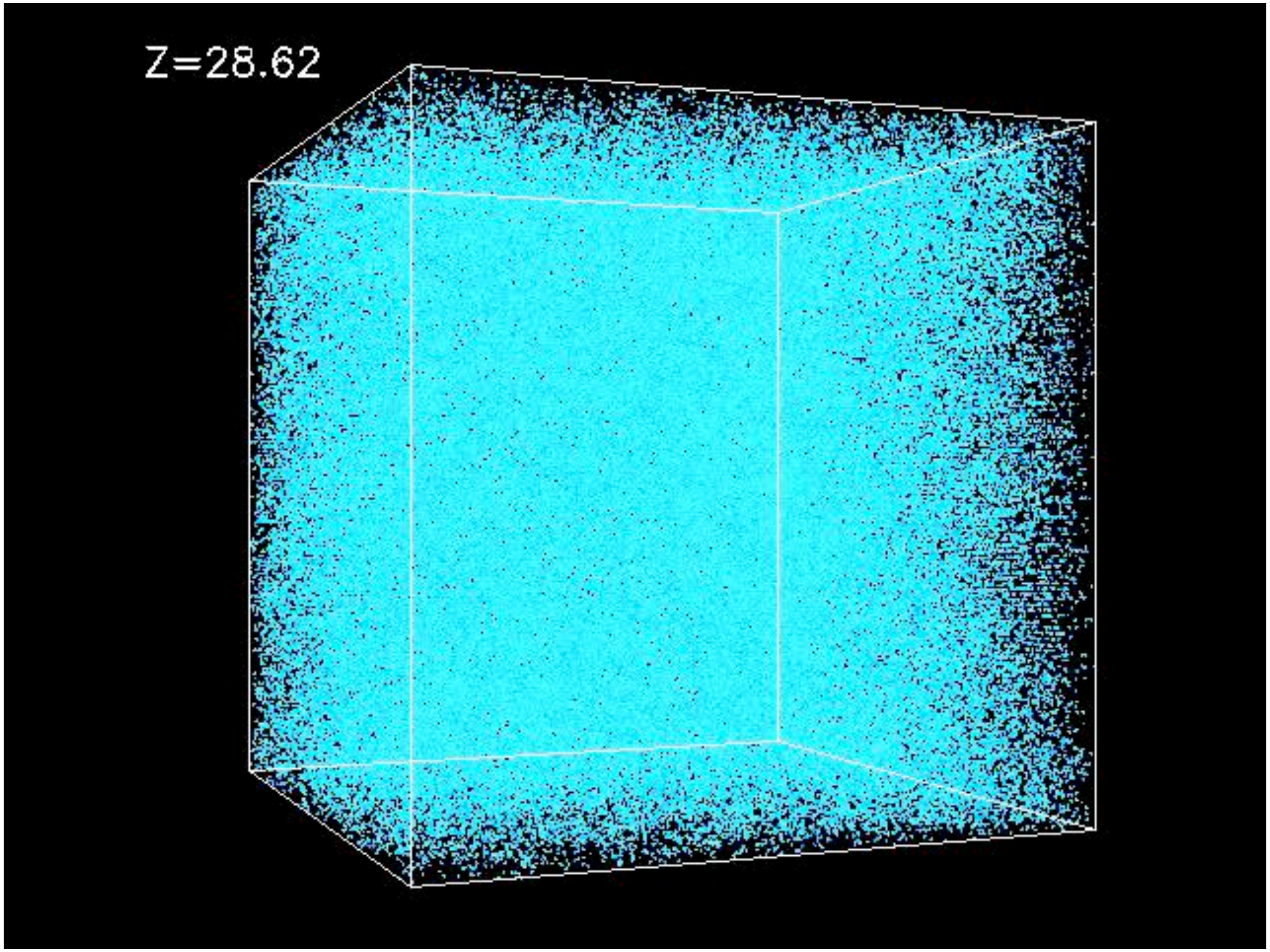
- **Today's universe is quite lumpy and this lumpiness is generated from this 10^{-5} level CMB fluctuation.**

CMB fluctuation





Evolution of the large-scale structure

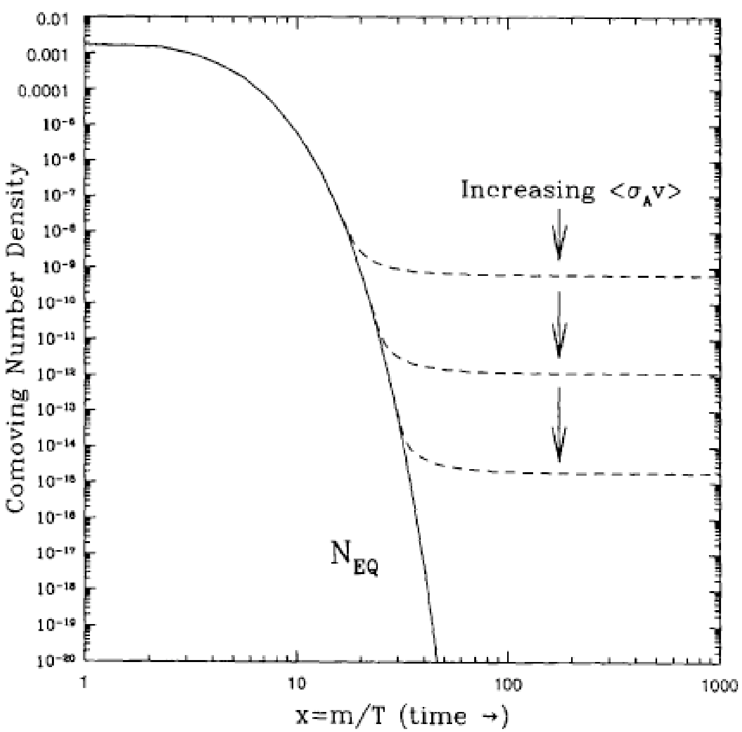


What is Dark Matter?

- Very likely, a kind of particles
  - Electrically neutral
  - Long lived
  - No strong or interactions
- Candidates
  - MACHOS
  - Primodial Black Holes, Mirror Matter
  - Axions
  - WIMPs, WIMPzillas
  - ....

Dark Matter Relics in the Universe

- In the early hot universe, the DM particles are in thermal equilibrium with everyone else.
- As the universe cools and expands, it tries to keep thermal equilibrium through annihilation.
- At certain point, the DM particle density become too small to annihilate each other, they remain as relics of the universe.



$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle} .$$

WIMP Miracle

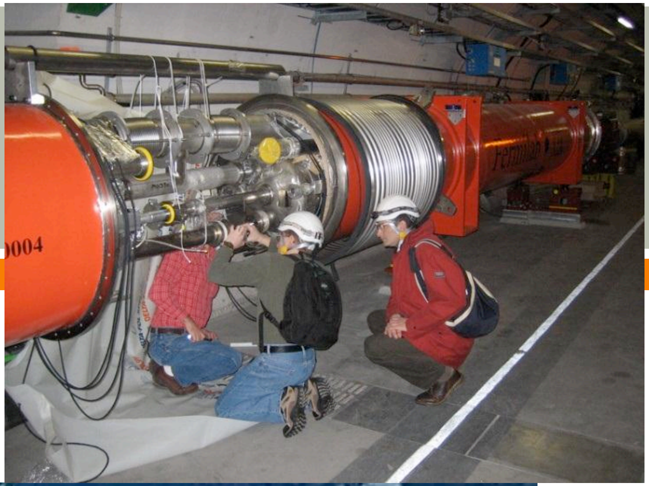
- To understand the percent of DM energy in the universe today, we need the DM particles having annihilation cross sections on the order of

$$\sim 10^{-40}\ cm^2$$

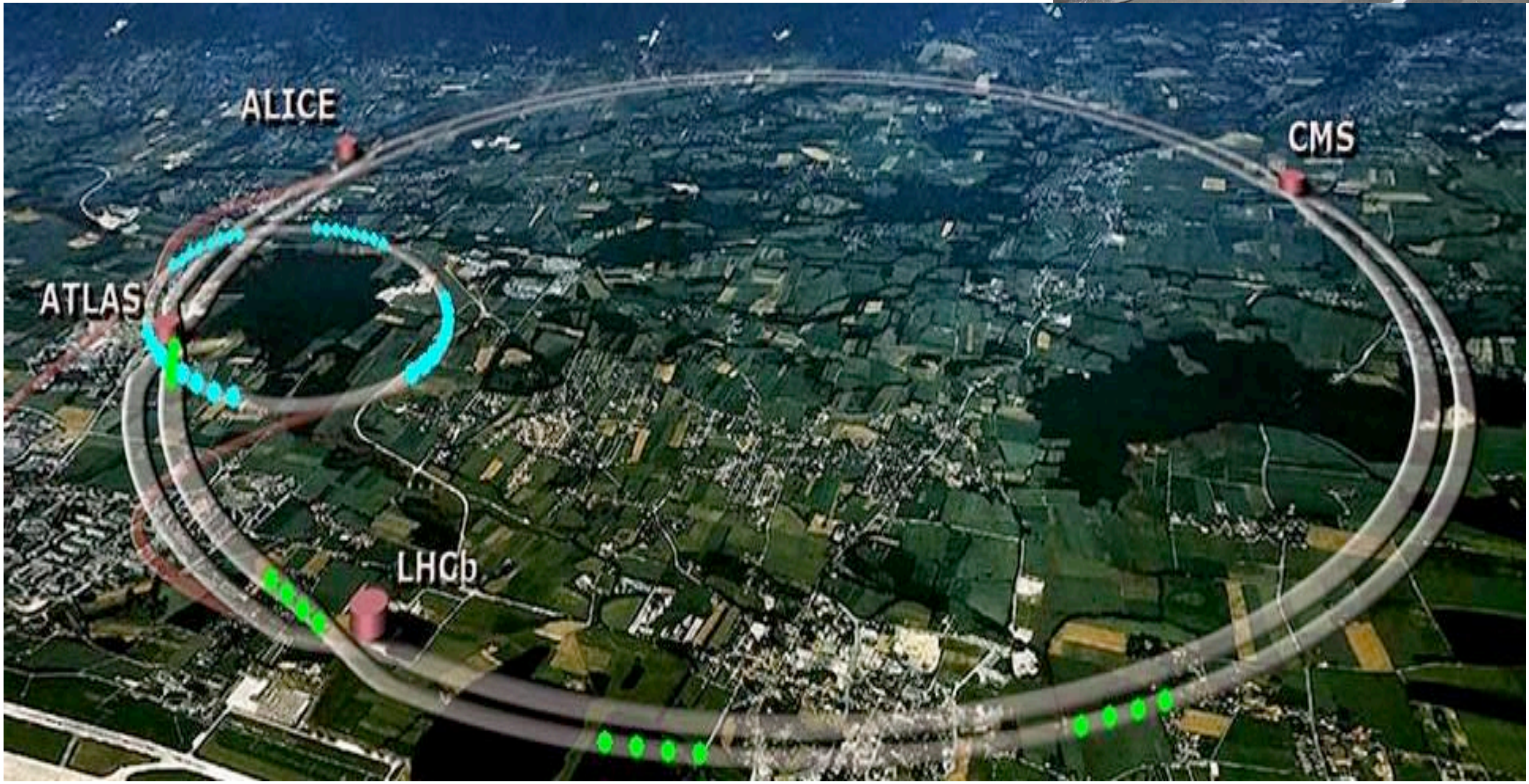
Therefore, apart from the gravitational interactions, the DM particles likely have weak interaction as well!

- WIMPs：Weakly -Interacting Massive Particles!
- If DM particles do have weak interactions, they might play an important role in electroweak symmetry breaking!

Collider Search:LHC

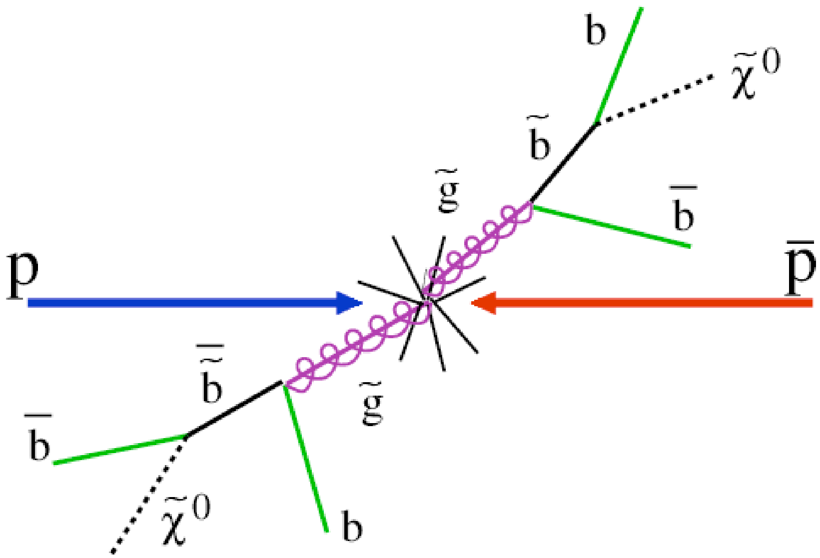


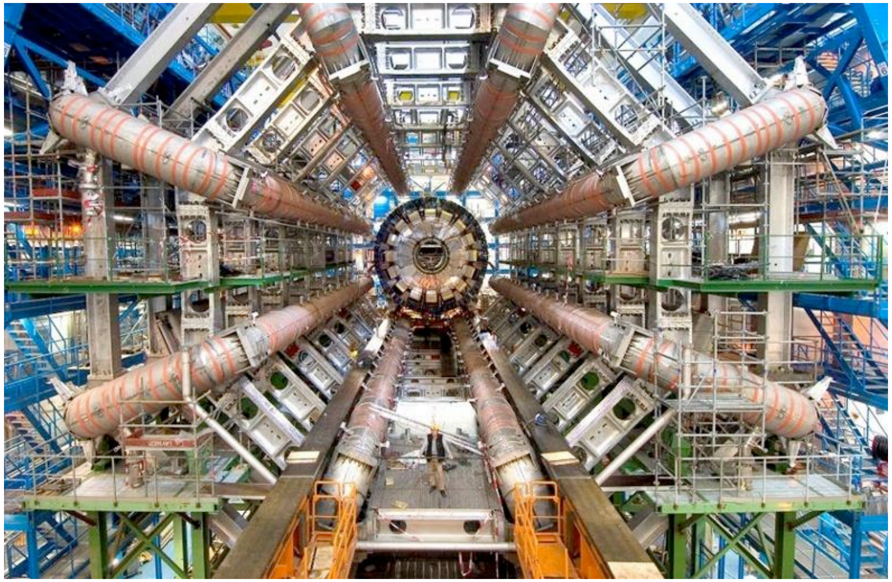
- 7 TeV proton + 7 TeV proton



LHC and Dark Matter

- If DM particle have weak interactions, and their masses are smaller than ~3TeV, they might be produced at LHC!

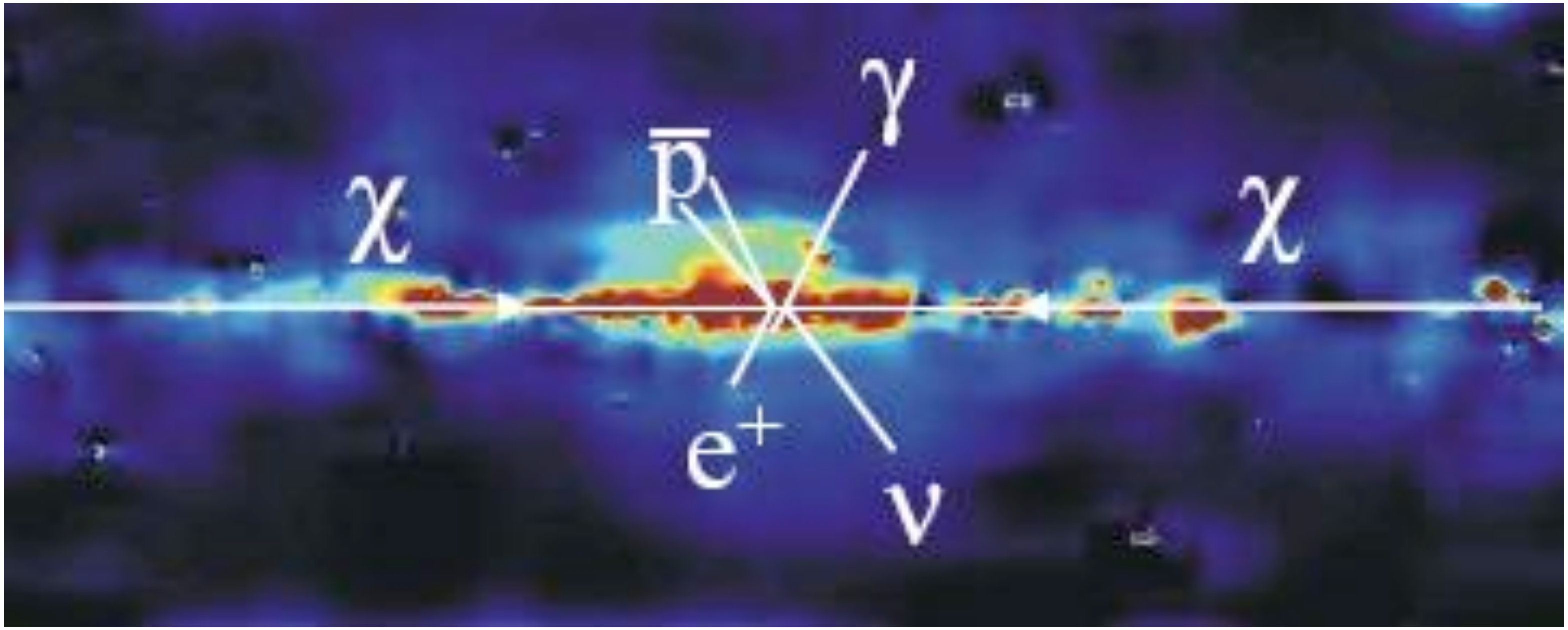




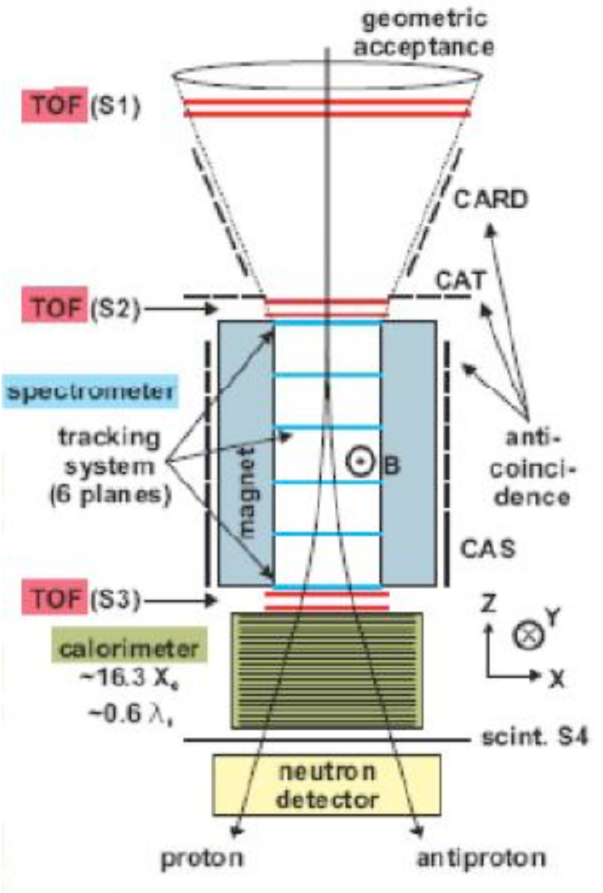
Indirect Search

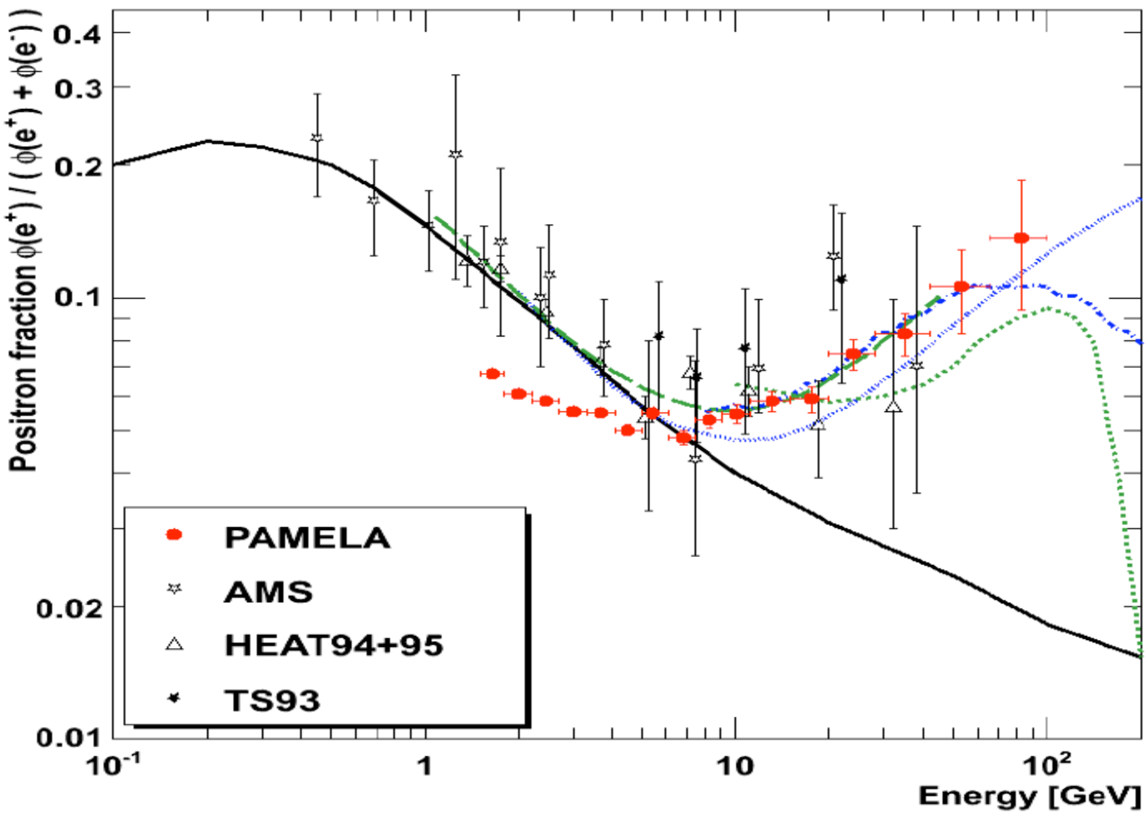
DM particle can be annihilated in the milky way, producing particles of SM

- Electron-positron pairs, quark-antiquark pairs
- High-energy x-ray， gamma ray, neutrinos

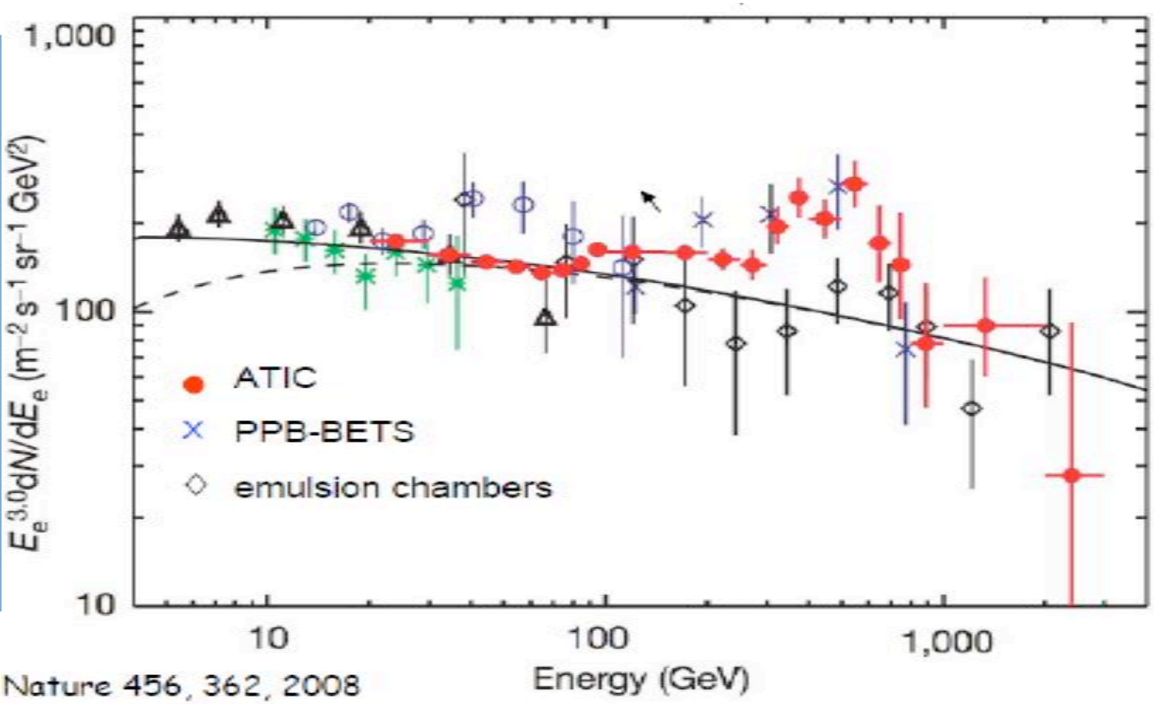


Pemela(satellite)high-energy positron

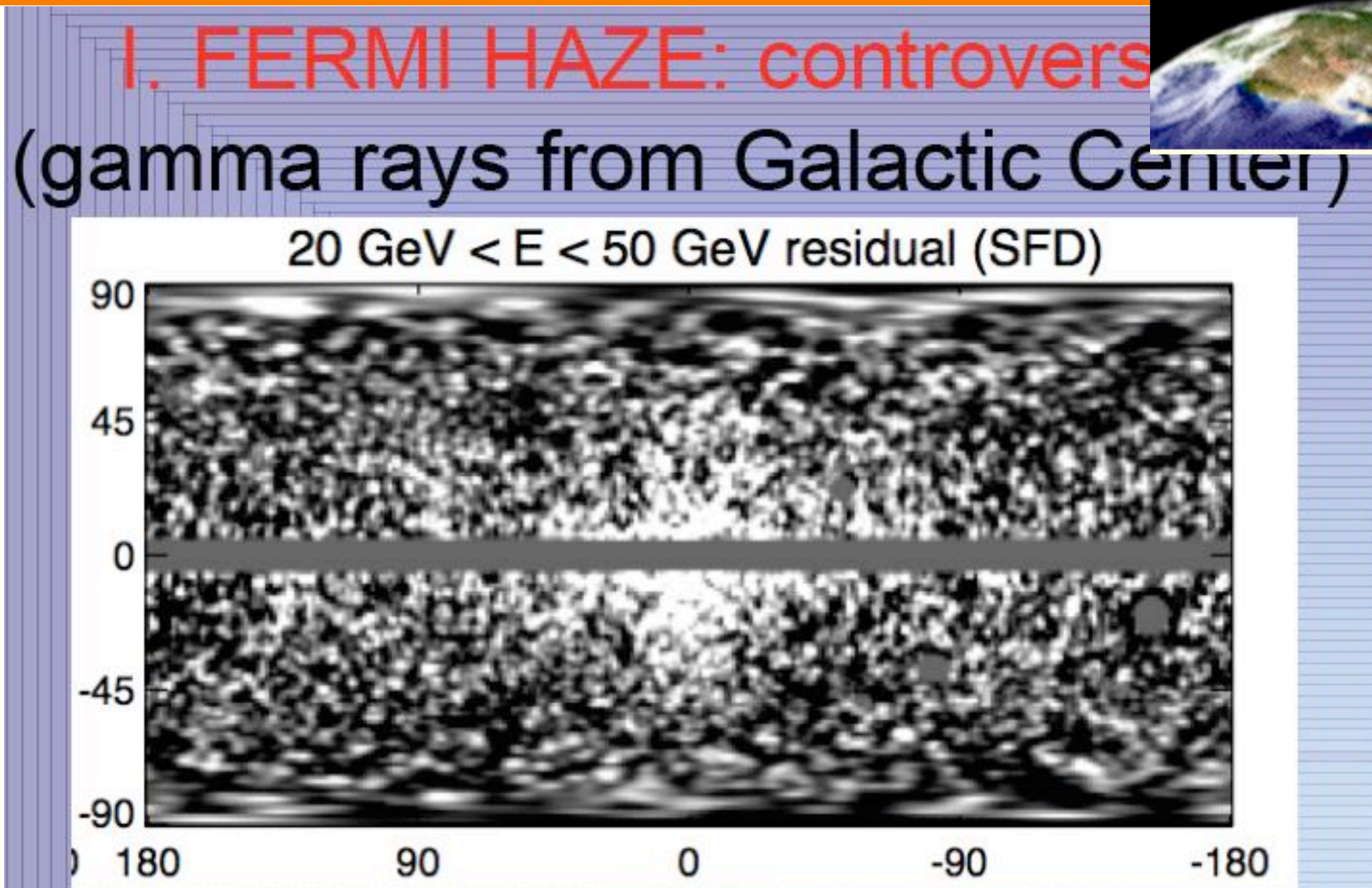




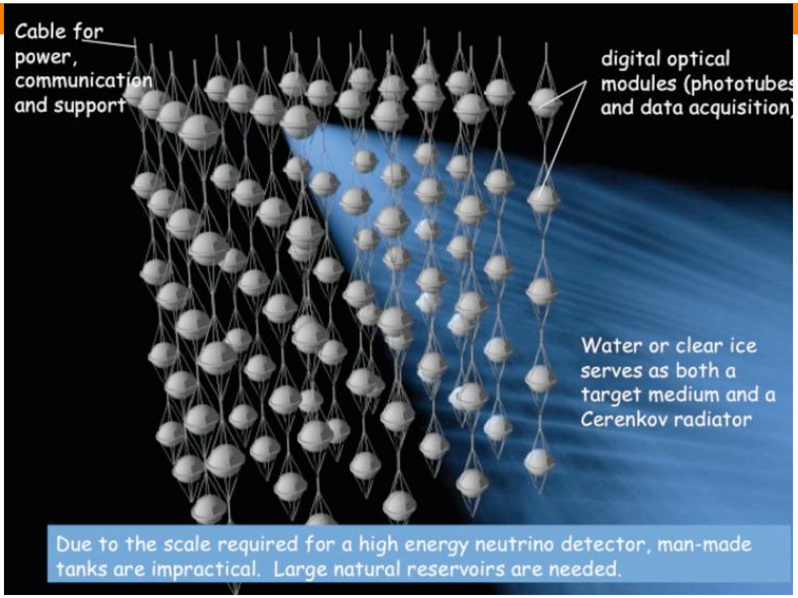
Attic(bloom)： high-energy electron

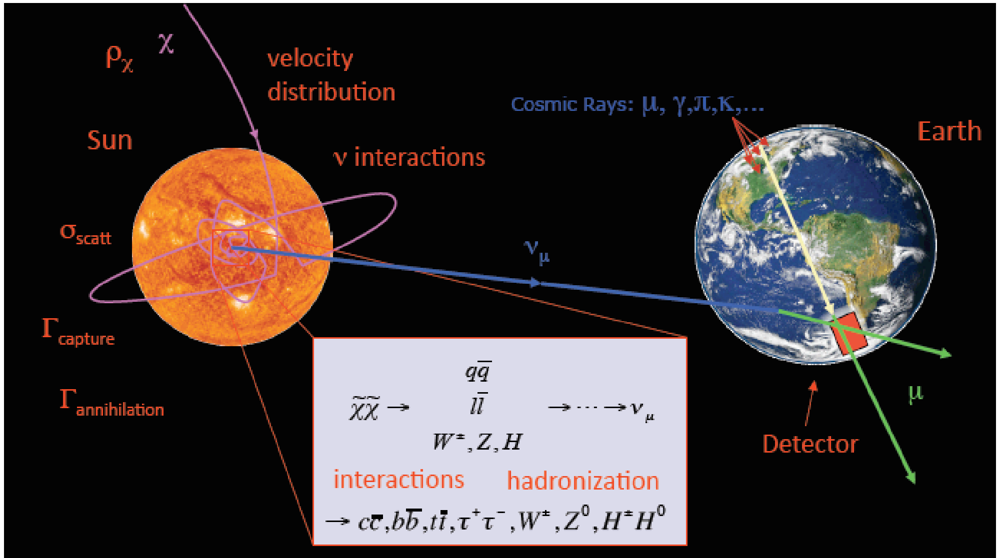


FERMI Haze


I. FERMI HAZE: controvers
(gamma rays from Galactic Center)
20 GeV < E < 50 GeV residual (SFD)
90
45
0
-45
-90
180
90
0
-90
-180

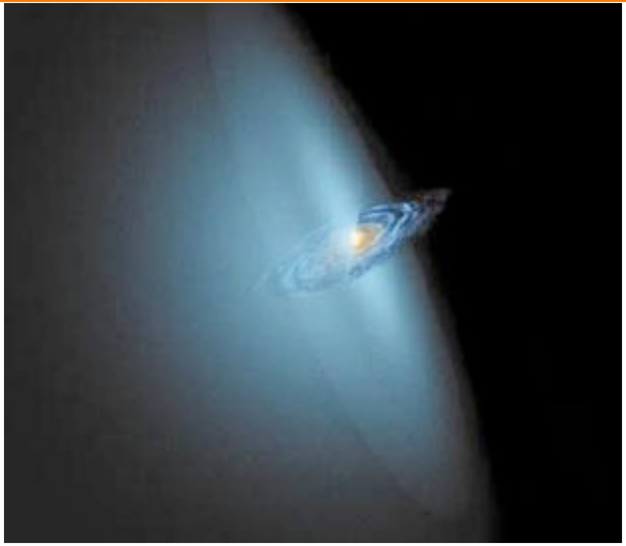
Ice-cube(south-pole): high-E neutrinos



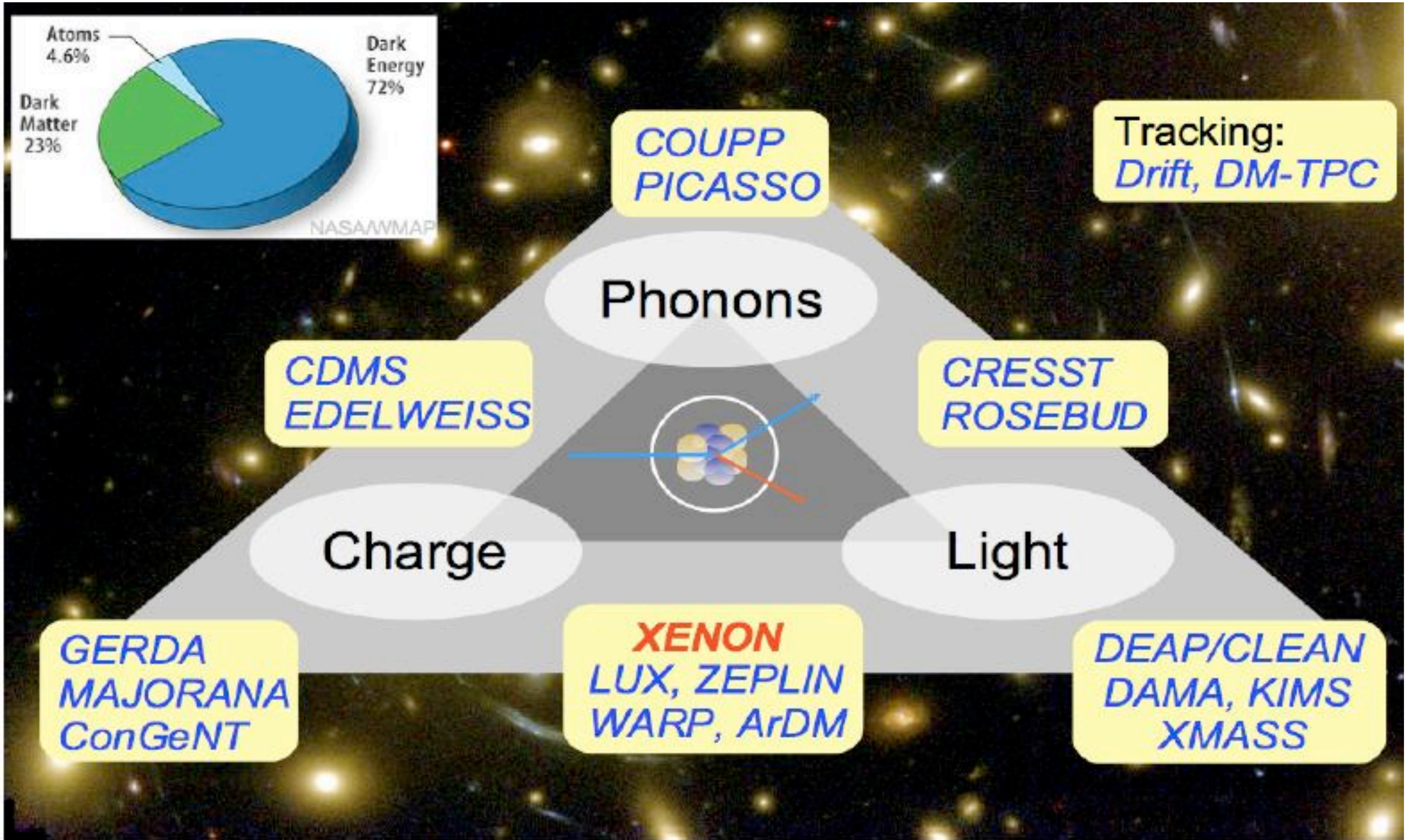


Direct Detection

- DM forms a giant sea, enclosing the milky way. Our Earth is like a little fish traveling through the sea.
- The flow of DM particles has small probability hits the atomic nucleus, less than 1/100 kg/day.
- Direct detection measures the recoil effects from the DM collision.



Three types of signals

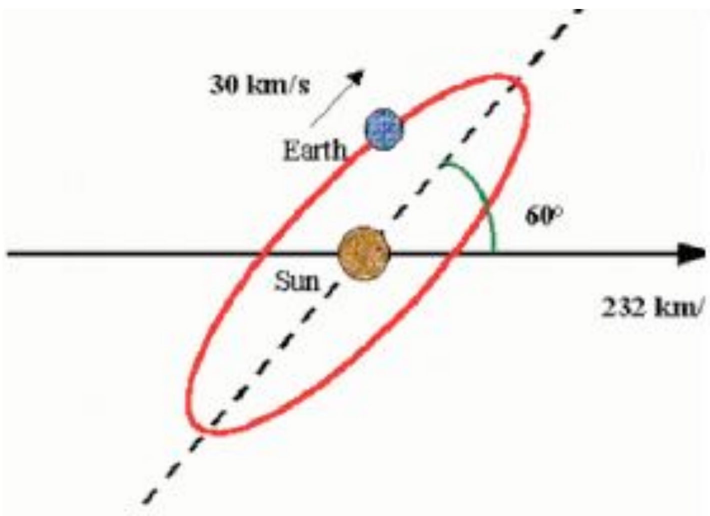


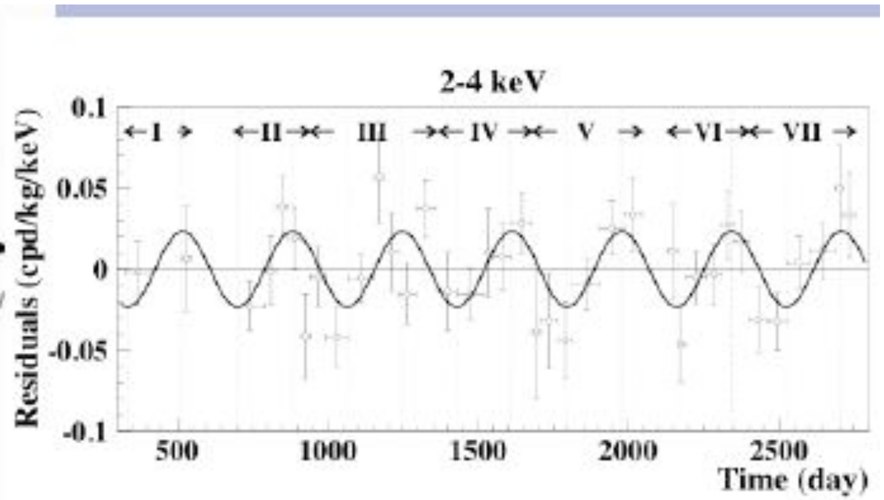
Three main detection technolgies

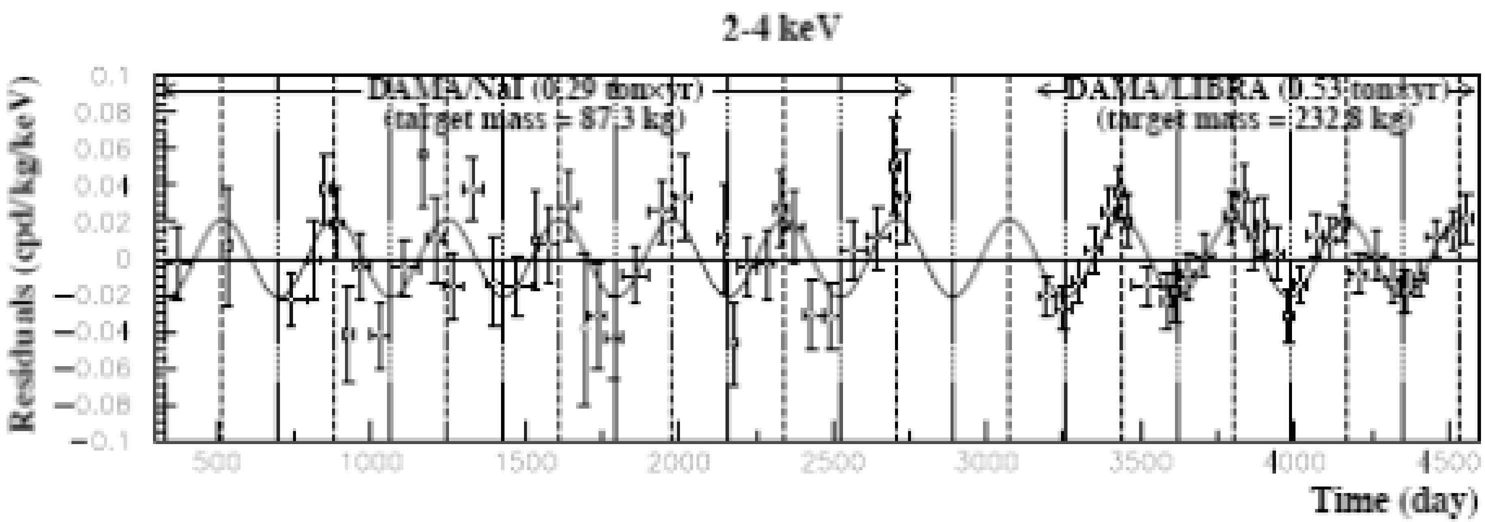
- **Semiconductors（Ge，Si）**
  - Heat and current
  - features：low-temp（0.02K）、high-cost, scalability
- **Crystals（NaI， CsI）**
  - light
  - features：hard to distinguish background from signals
- **Liquid noble（Ar,Xe）**
  - Light and charge
  - Features: high background-separation capability, low cost


世界各国的地下实验室和暗物质直接探测实验
Yangyang
KIMS
Homestake
LUX
SNOLAB
DEAP/CLEAN
PICASSO
Boulby
ZEPLIN
DRIFT
Kamioka
XMASS
Soudan
CDMS
Frejus/
Modane
EDELWEISS
Gran Sasso
CRESST
DAMA/LIBRA
WARP
XENON
We are involved in this

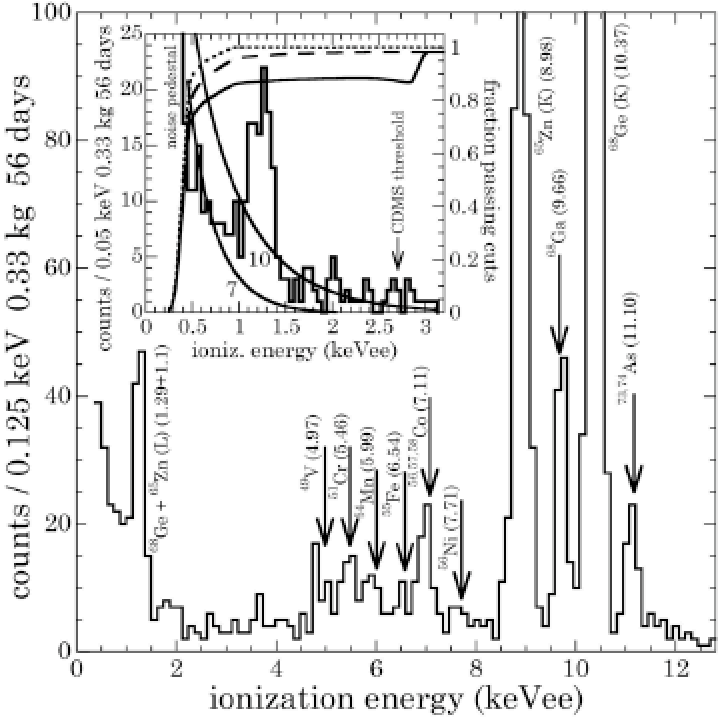
Direct detection: DAMA

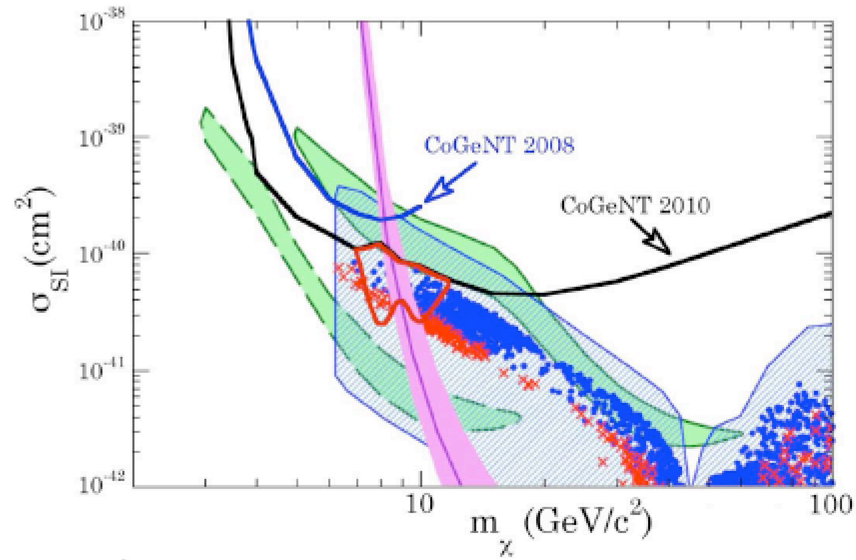






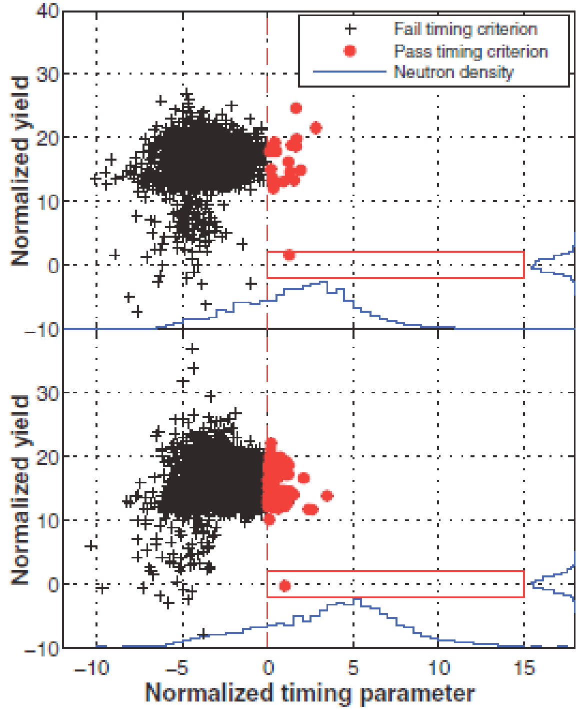
Direct detection status: CoGeNT

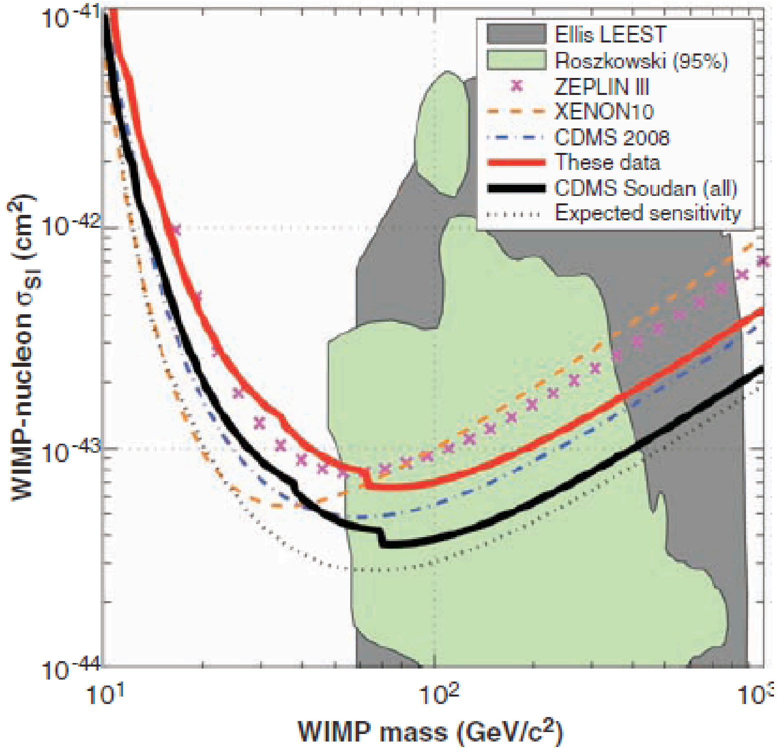




arXiv: 1002.4703

Direct detection status: CDMS





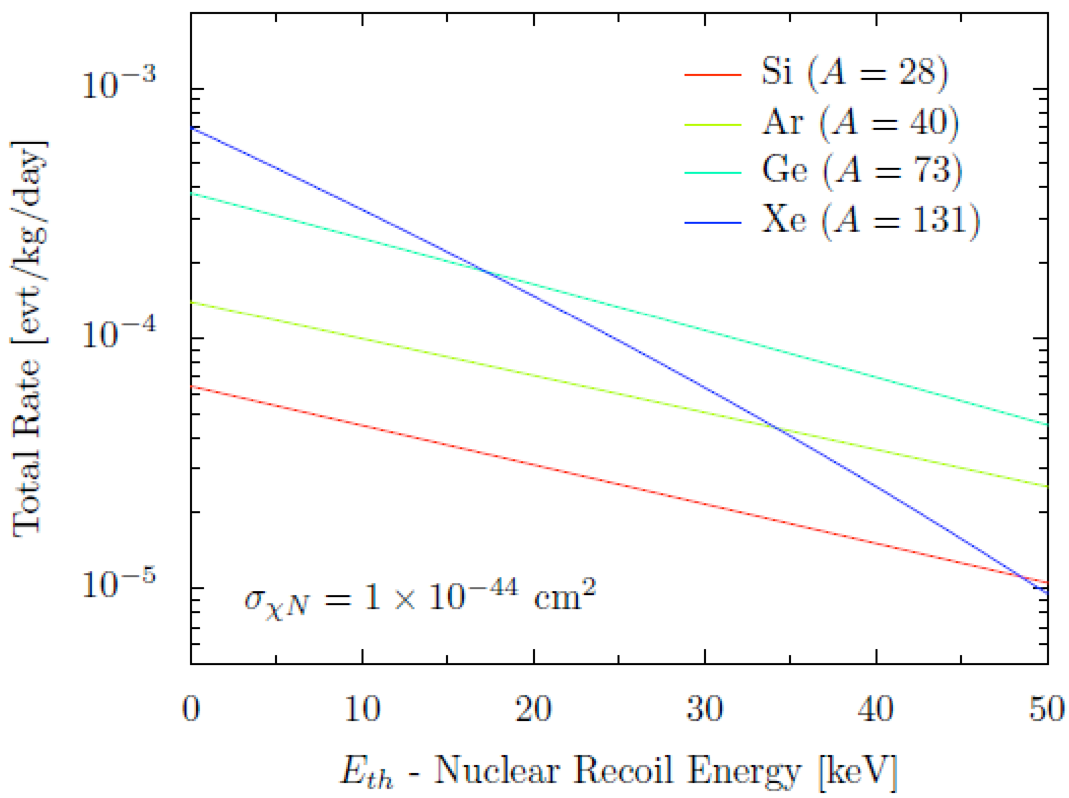
Science 26 March 2010:
Vol. 327. no. 5973, pp. 1619 - 1621

Liquid Noble Detectors

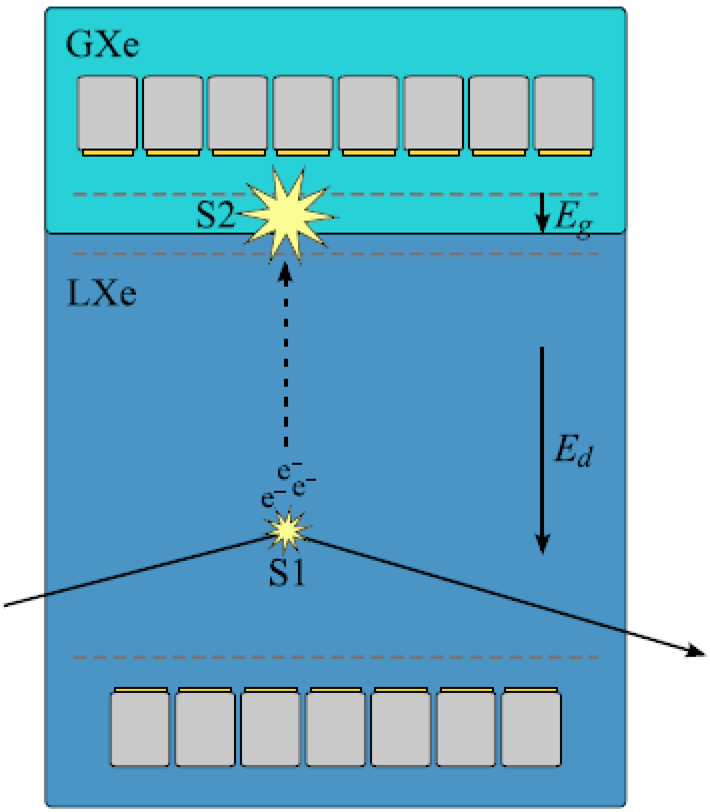
- XMASS - 800 kg (100 kg fiducial). Xe single-phase
  - Kamioka
  - Funded. Under construction.
- WARP - 100 kg dual phase Ar
  - Gran Sasso
  - Funded, commissioning
- XENON100 - 70 kg active + 70 kg veto. Xe two-phase
  - Gran Sasso
  - Funded, commissioning.
- LUX - 300 kg active. Xe two-phase
  - SUSEL (Homestake, South Dakota)
  - Funded. Under construction.
- DEAP/MiniCLEAN - 360 and 3600 kg single phase Ar (+Ne?)
- ArDM - large dual phase Ar - 800 kg Ar dual phase

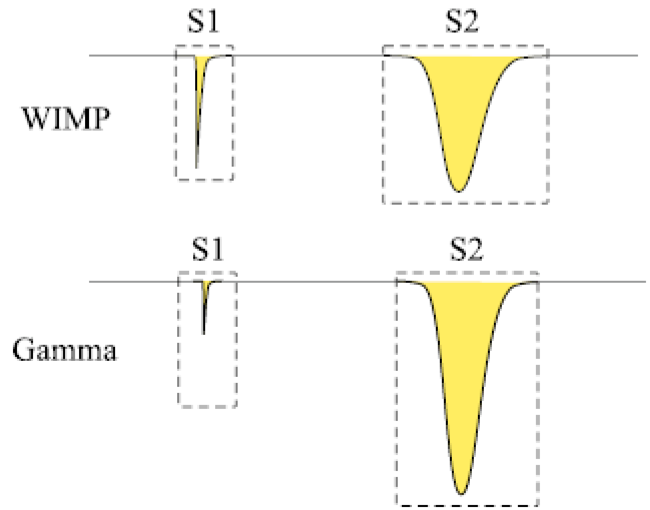
Why Xenon?

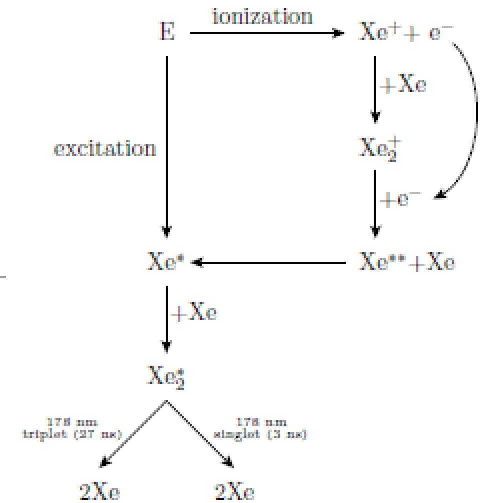
- Large mass number A (~131), expect high rate for SI interactions ($\sigma \sim A^2$) if energy threshold for nuclear recoils is low
- ~50% odd isotopes (^{129}Xe,^{131} Xe) for SD interactions
- No long-lived radioisotopes, Kr can be reduced to ppt levels
- High stopping power ($Z = 54$, $\rho = 3\,\mathrm{g\,cm^{-3}}$), active volume is self shielding
- Efficient scintillator (~80% light yield of NaI), fast response
- Nuclear recoil discrimination with simultaneous measurement of scintillation and ionization



Principle







- Bottom PMT array below cathode, fully immersed in LXe to efficiently detect scintillation signal (S1).
- Top PMTs in GXe to detect the proportional signal (S2).
- Distribution of the S2 signal on top PMTs gives xy coordinates while drift time measurement provides z coordinate of the event.
- Ratio of ionization and scintillation (S2/S1) allows discrimination between electron and nuclear recoils.

XENON100 Collaboration

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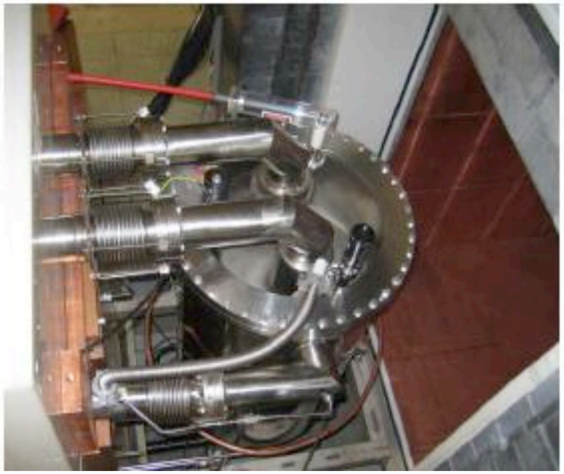
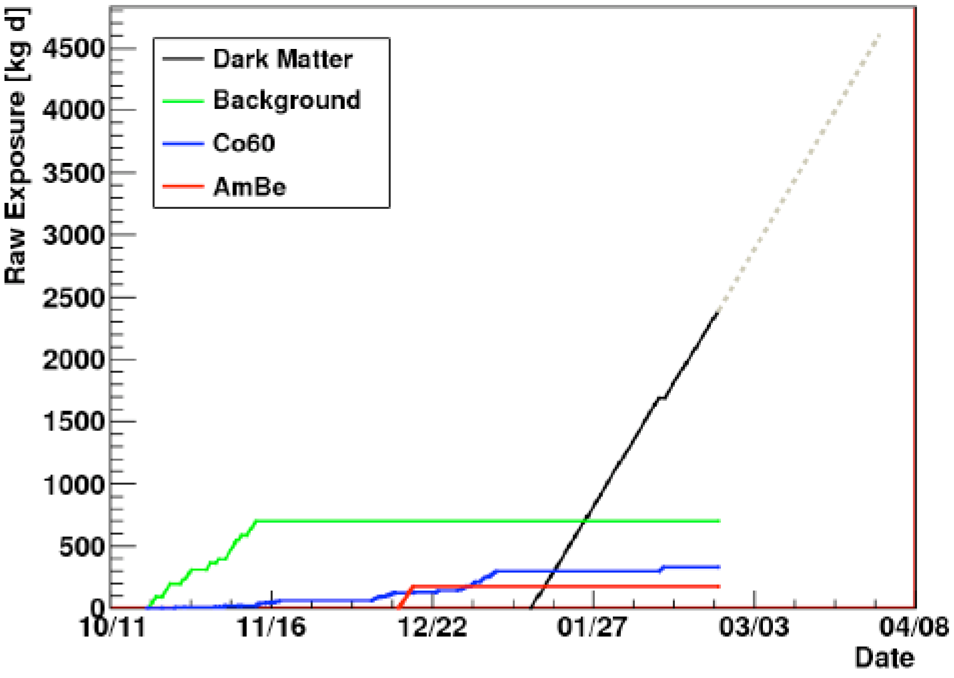
XENON100

- Reuse techniques and technologies developed for the XENON10 prototype to build a detector with a $\times 10$ increase in fiducial mass and a $\times 100$ reduction in background.
- Reduce the background from internal components
  - Pulse tube refrigerator and motor valve outside the shield,
  - All signal and HV feedthroughs also outside the shield,
  - Extensive material screening program to choose materials,
  - Kr distillation column to reduce Kr contamination in Xe.
- Reduce the background contribution from external sources
  - New 5 cm layer of copper to the XENON10 shield to reduce the contribution from the the polyethylene,
  - LXe Active veto surrounding the target.
- 170 kg LXe total mass consisting of a 65 kg target surrounded by a 105 kg active veto. 15 cm radius, 30 cm drift length active volume.

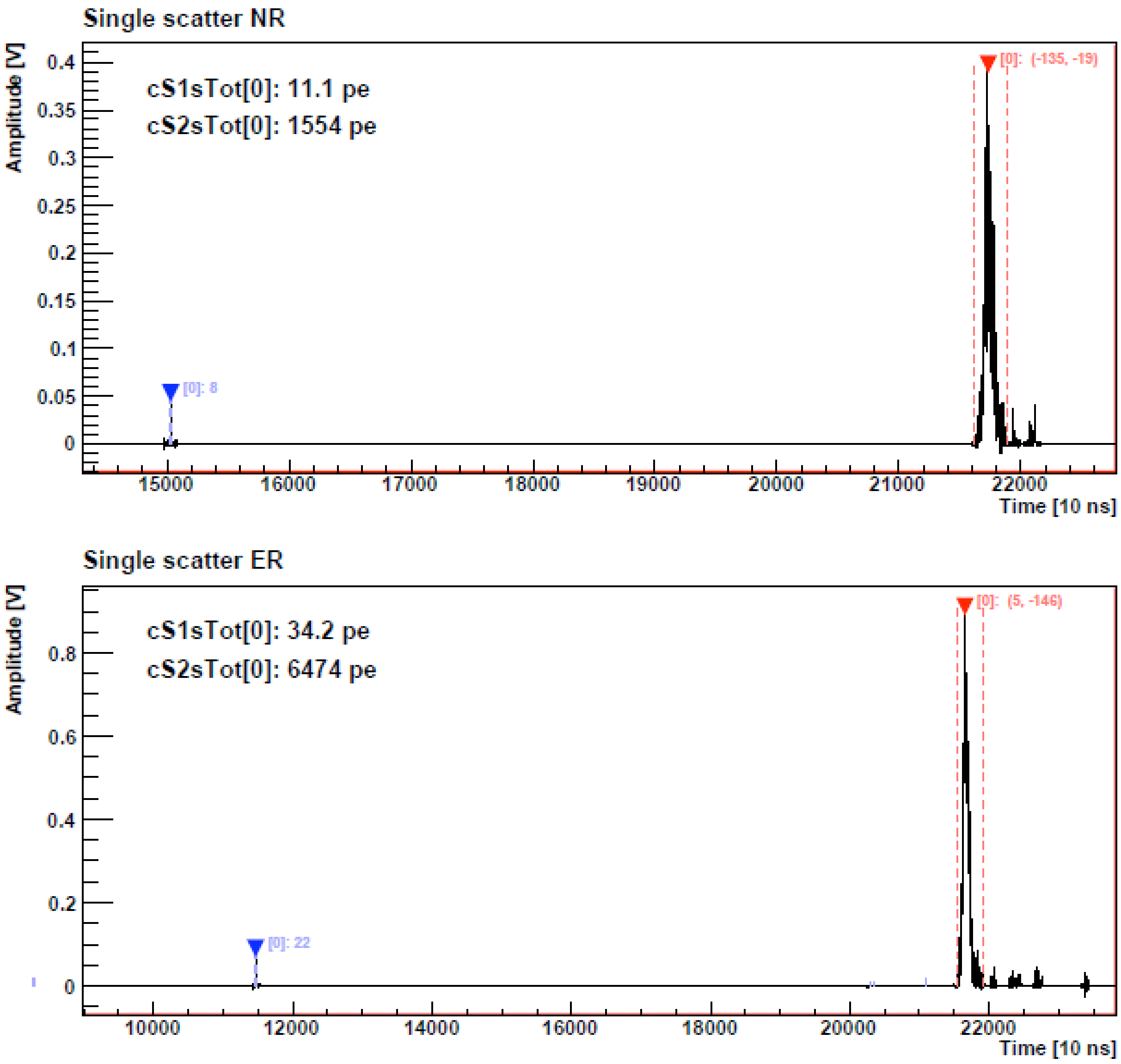


XENON100: Status

- XENON100 is operating reliably and stably underground at LNGS for the last 6 months.
- Neutron calibration was performed in mid-December.
- Gamma calibrations are being taken on a regular basis.
- Background level measured is consistent with a factor 100 reduction compared to XENON10.
- Started first blind Dark Matter Search run on January 13th.



XENON100: Typical Low Energy Events



XENON100: Data Selection

Three levels of cuts are applied to the calibration data:

L0: Basic quality cuts

Designed to remove noisy events, events with unphysical parameters. Very high acceptance.

- S1 coincidence cut
- S2 threshold cut
- S2 saturation cut
- S2 width cut
- Signal/Noise cut

L1: Scatter cuts

Designed to remove events with multiple interactions (multiple S2s), with delayed coincidences (multiple S1s) or with misidentified S1s.

- S1 single peak cut
- S2 single peak cut

L2: Fiducial volume cuts

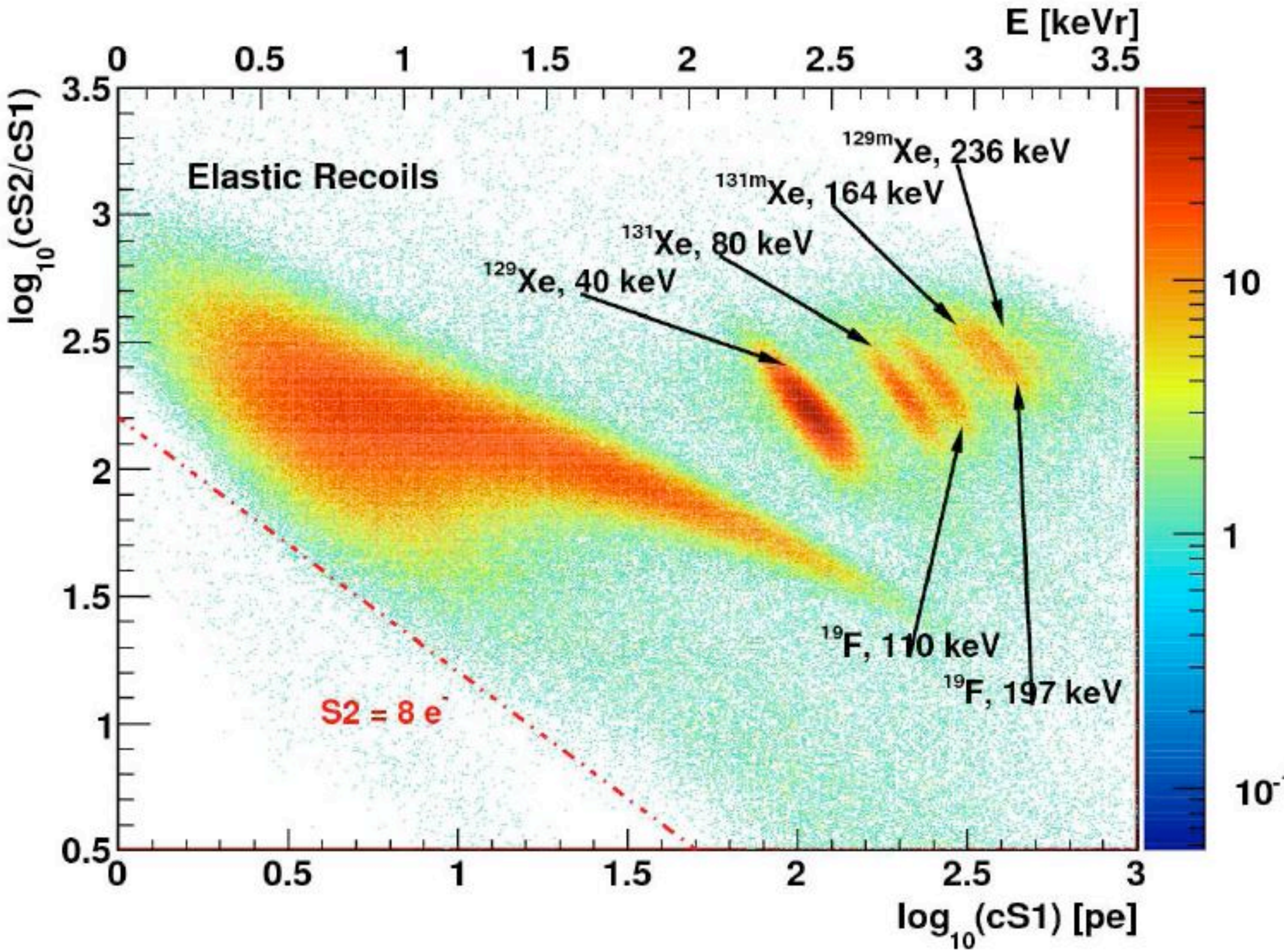
Because of the high stopping power of LXe, fiducialization is an extremely effective way of reducing background. Possible fiducial volumes:

- 50 kg
  - $r < 14$ cm
  - 2 cm $< z < 29$ cm
- 30 kg
  - $r < 13$ cm
  - 4 cm $< z < 27$ cm

XENON100: Neutron Calibration 1

- Calibration performed with a 3.7 MBq (220 n/s) AmBe source from 12/15/09 to 12/18/09.
- Accumulated 3×10^6 events in 3 days, 5×10^4 single scatter nuclear recoils <100 keVr. Much more statistics than for the XENON10 neutron calibration to be able to describe the nuclear recoil band up to higher energies.
- Since WIMPs are expected to elastically scatter off of nuclei understanding the behavior of single elastic nuclear recoils in Xe is essential.
- In addition, the neutron calibration gives gammas from inelastic recoils and activated Xe lines that can be used to infer the spatial dependence of S1 and S2 signals (analysis is ongoing).
- For the data presented here the spatial dependence of the S1 signal is corrected using factors obtained from Cs137 calibrations at uniform positions around the detector. The drift time dependence of the S2 signal is also infered from weekly Cs137 calibrations.

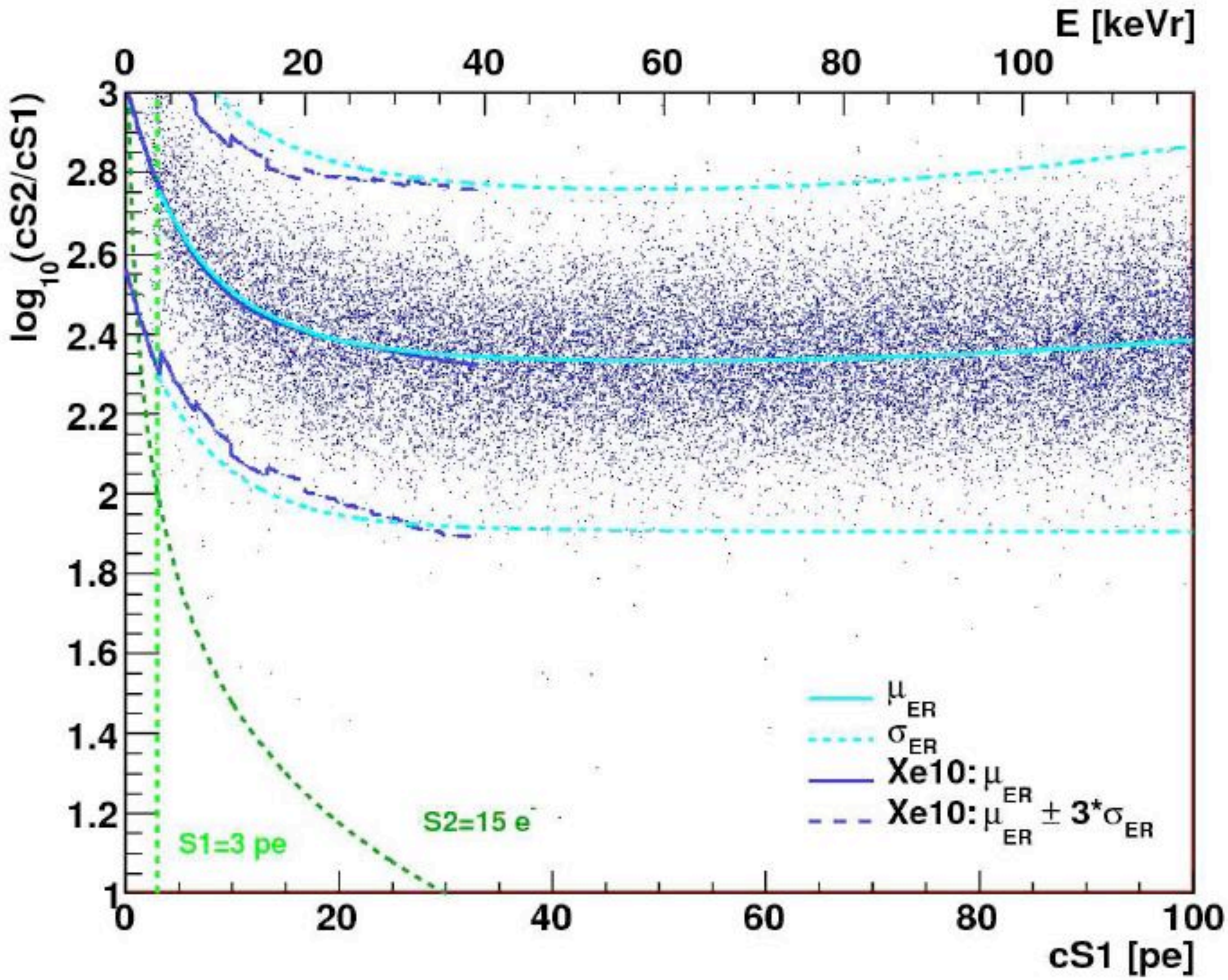
XENON100: Neutron Calibration 2



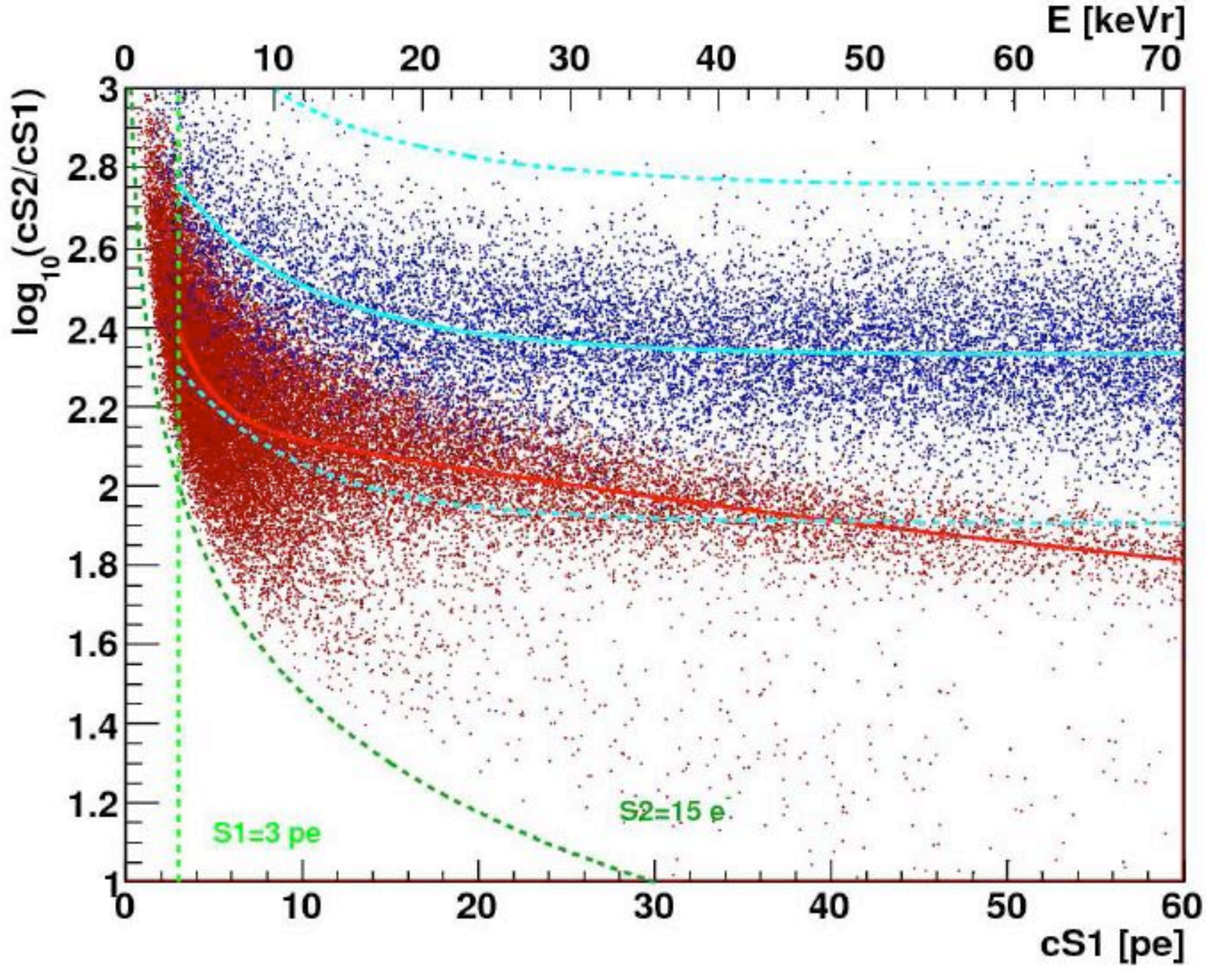
XENON100: Gamma Calibration

- A gamma calibration is performed on a regular basis with a 1 kBq Co60 source at different positions around the detector.
- High energy gammas from Co60 (1.17 Mev, 1.33 MeV) allow for an efficient low energy electron recoil band calibration due to their increased Compton mean free path.
- The data acquisition system (DAQ) was designed to allow calibration at high rate in order to accumulate much larger statistics for the electron recoil band compared to what was accumulated with XENON10.
- The ultimate limit is set by the inherently slow response of a large ionization detector (maximum drift time of 175 μs).
- DAQ/processing/storage system allows data taking at rates of 100 evts/keVee/liveday in a 30 kg fiducial volume with the Co60 source, a factor 1000 higher than the background.

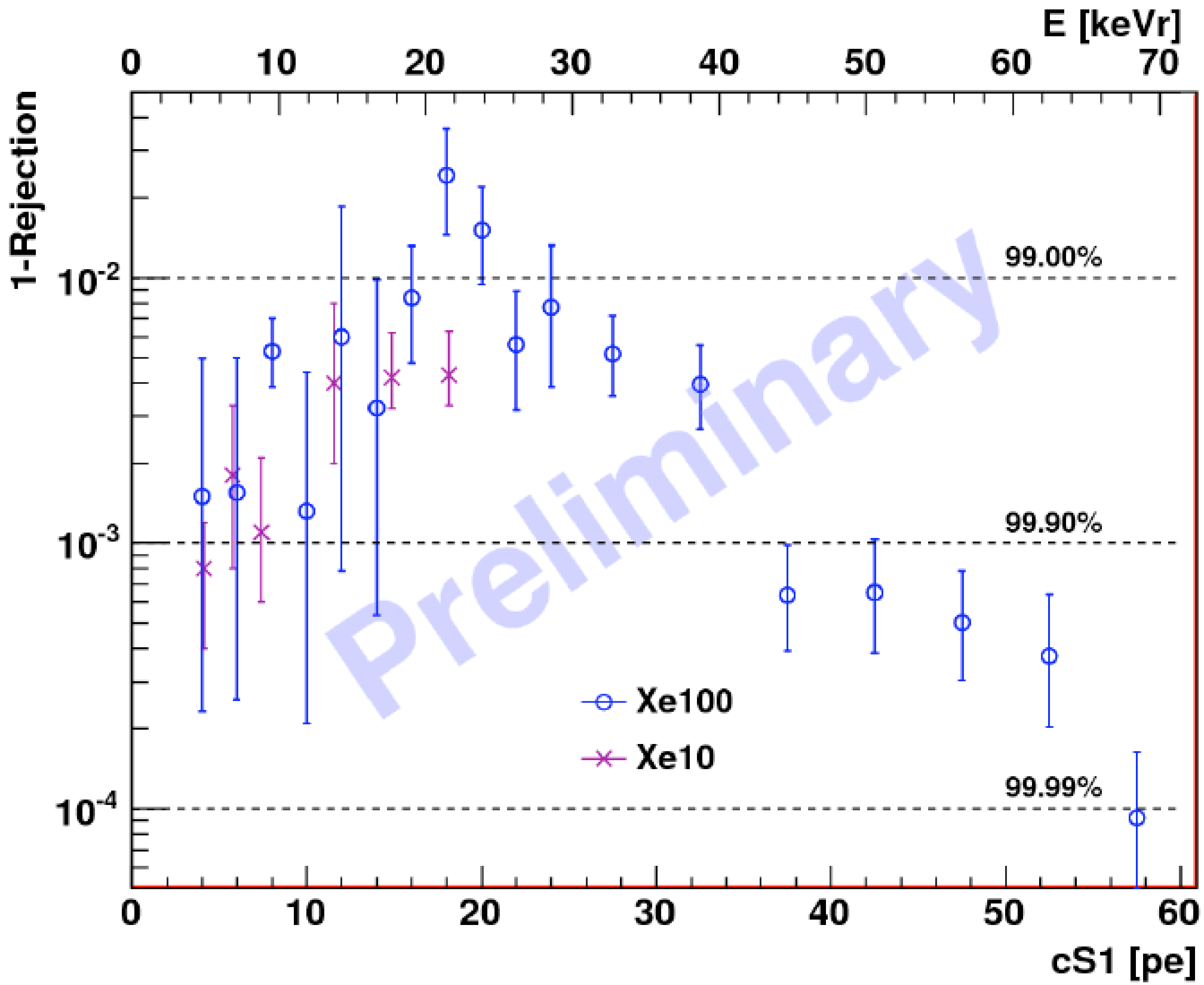
XENON100: Electron Recoil Band



XENON100: Rejection Power 1



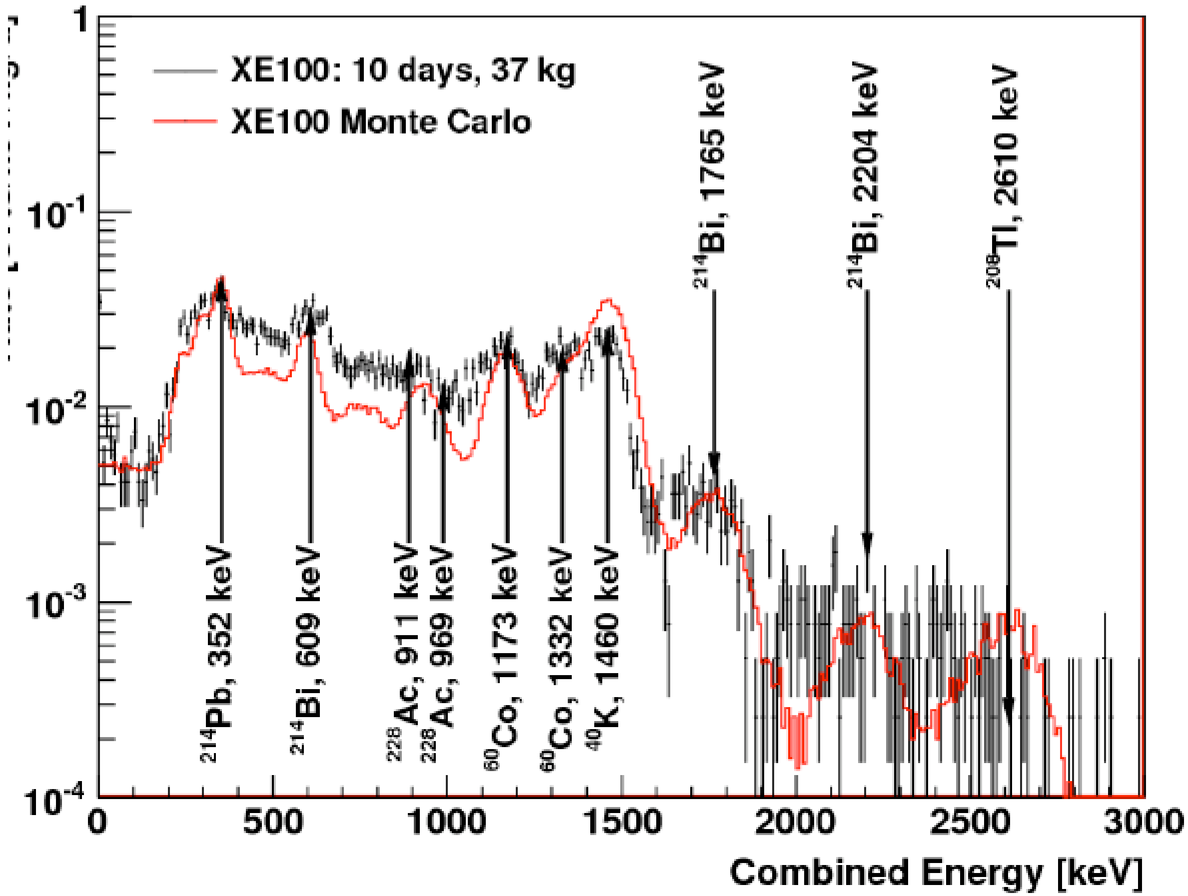
XENON100: Rejection Power 2



XENON100: Background 1

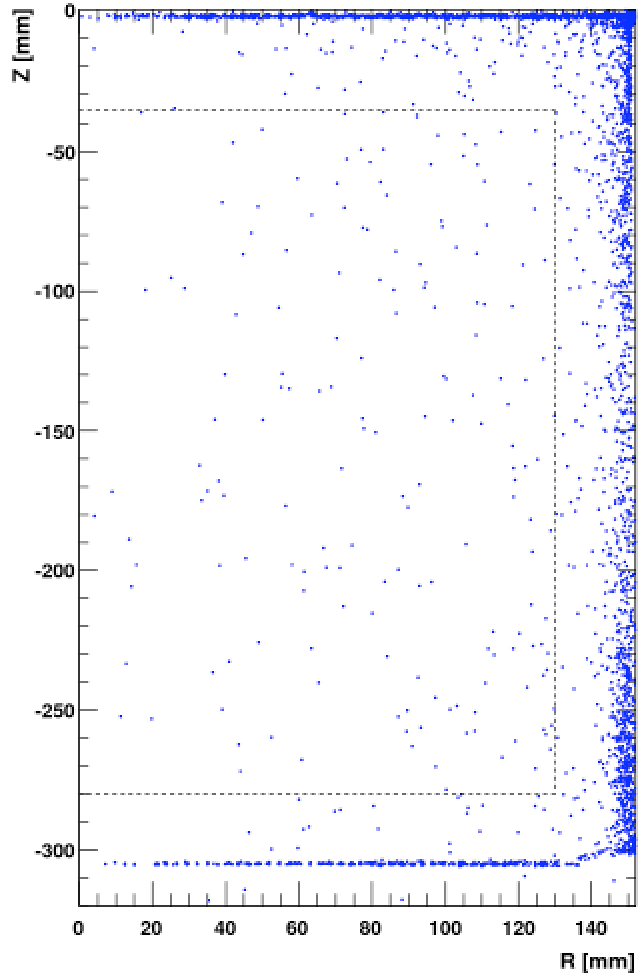
- Measured background is in good agreement with Monte Carlo predictions (no tuning).
- The measured single scatter rate below 100 keVee is

  5×10^{-3} evts/kg/keV/d
- Background level in fiducial volume is a factor 100 lower than XENON10 (0.6 evts/kg/keV/d).

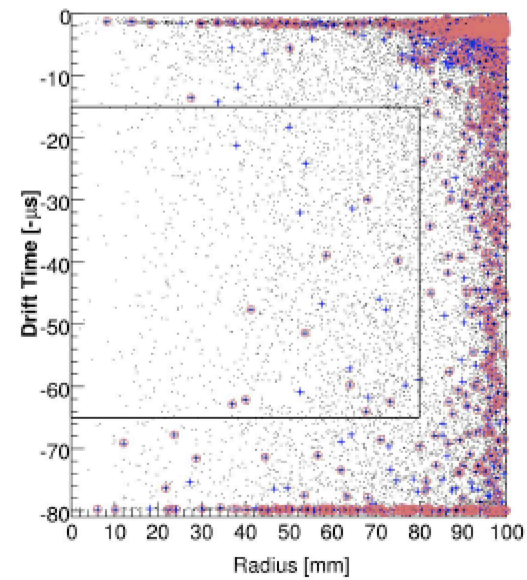


XENON100: Background 2

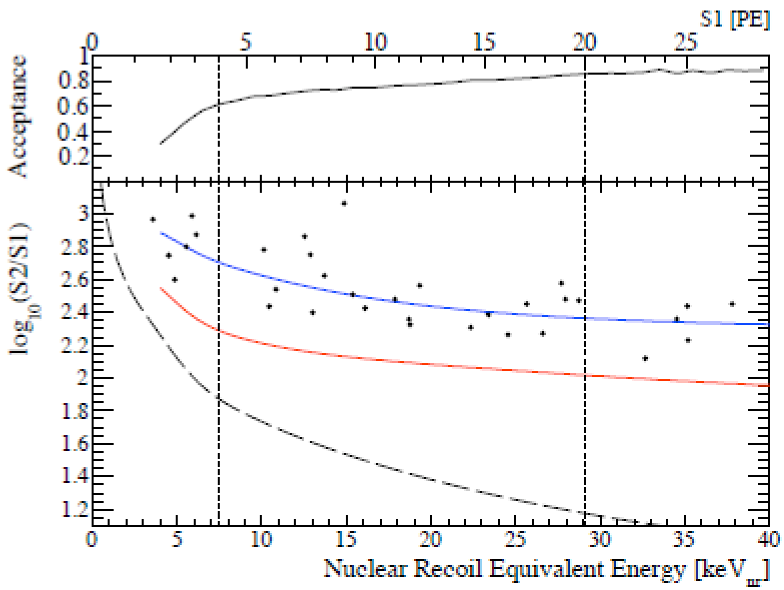
- Dramatic background reduction from XENON10 to XENON100 is evident by comparing the event distributions for similar exposures.
- With an ER/NR rejection power of 99.5% at 50% NR acceptance, XENON100 will be able to run background-free for 40 days with a fiducial volume of 50 kg or 200 days with a fiducial volume of 30 kg.

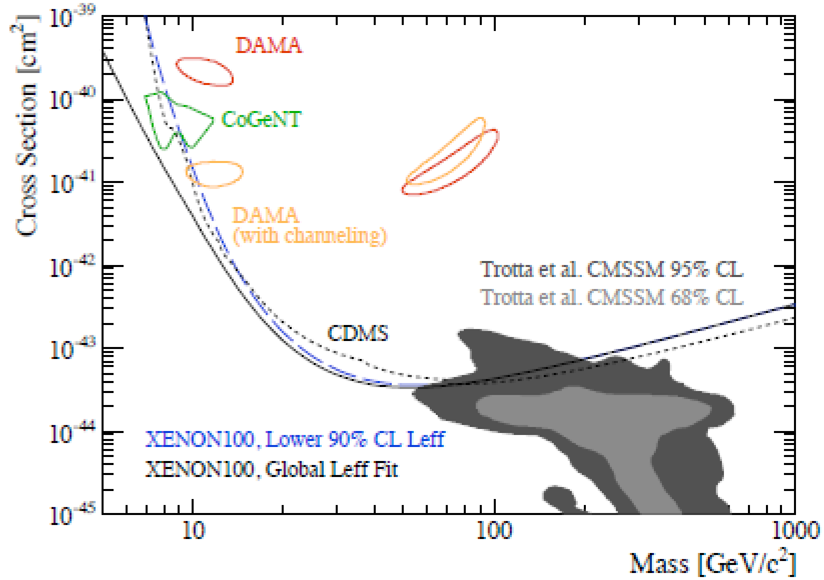


XENON100, 4-60 keVee
37 kg fiducial, 10 d

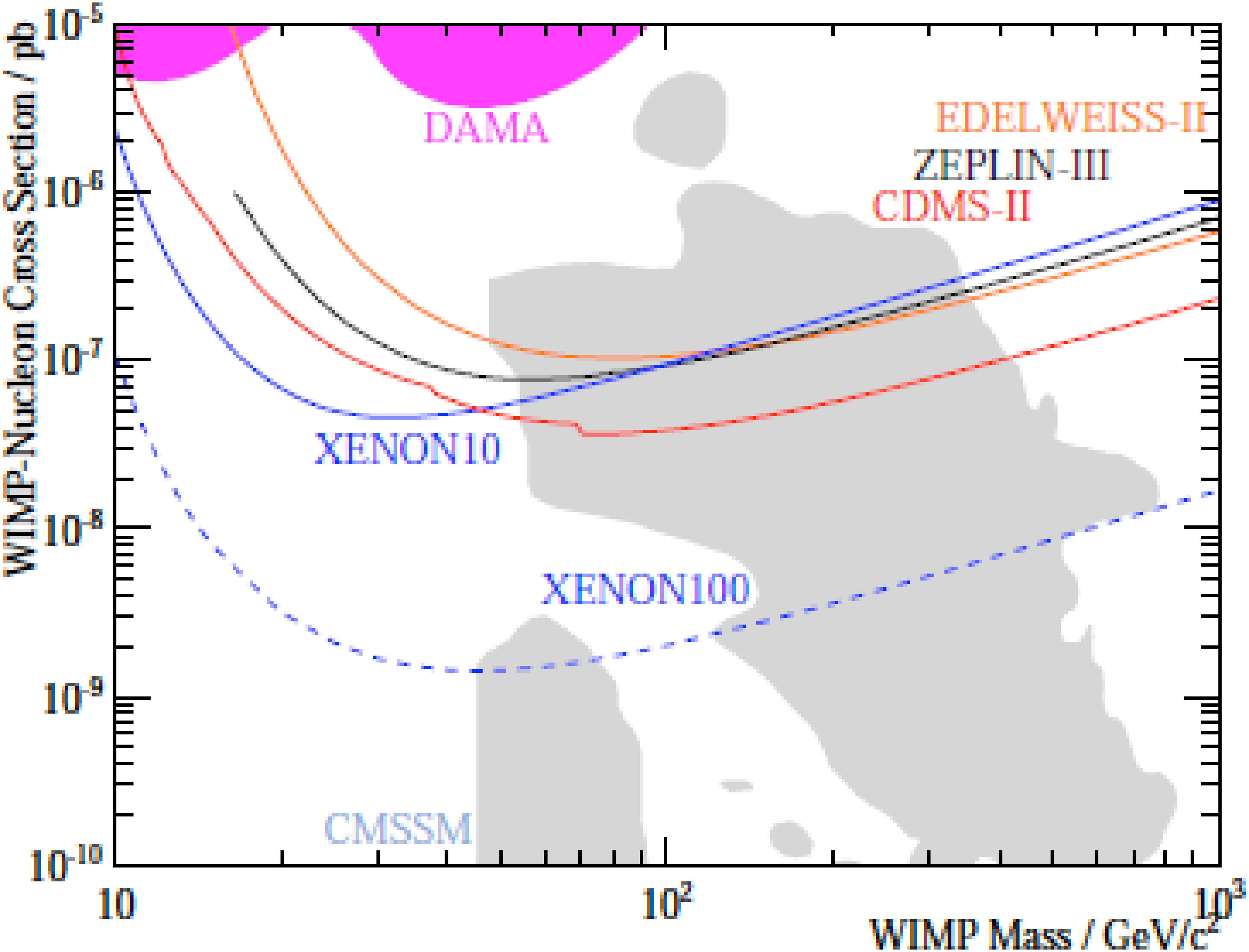


XENON10, 2-12 keVee
5 kg fiducial, 58 d





arXiv:1005.0380, to appear in Phys. Rev. Lett.

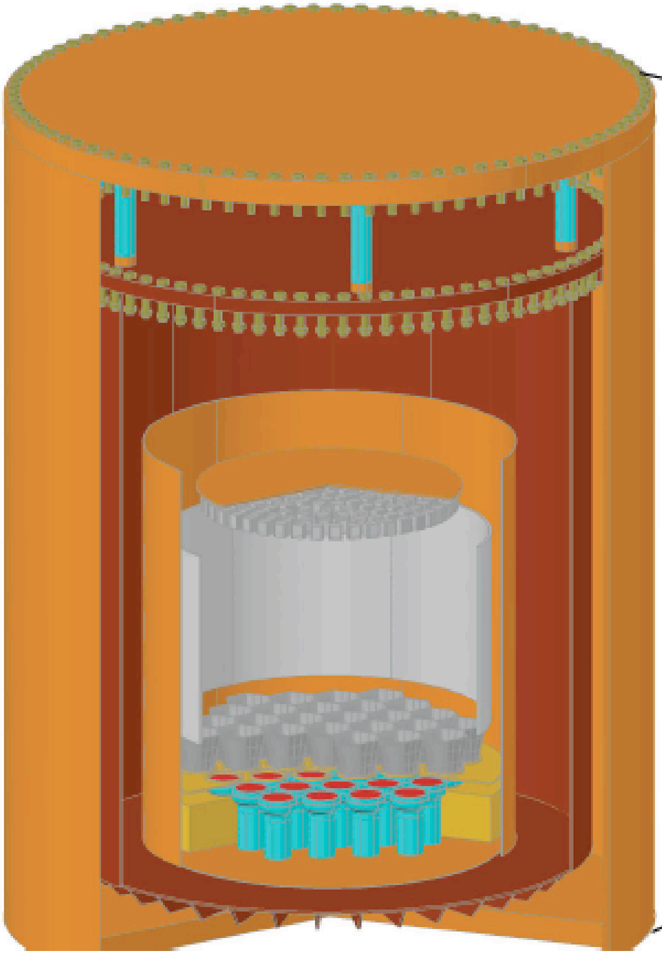


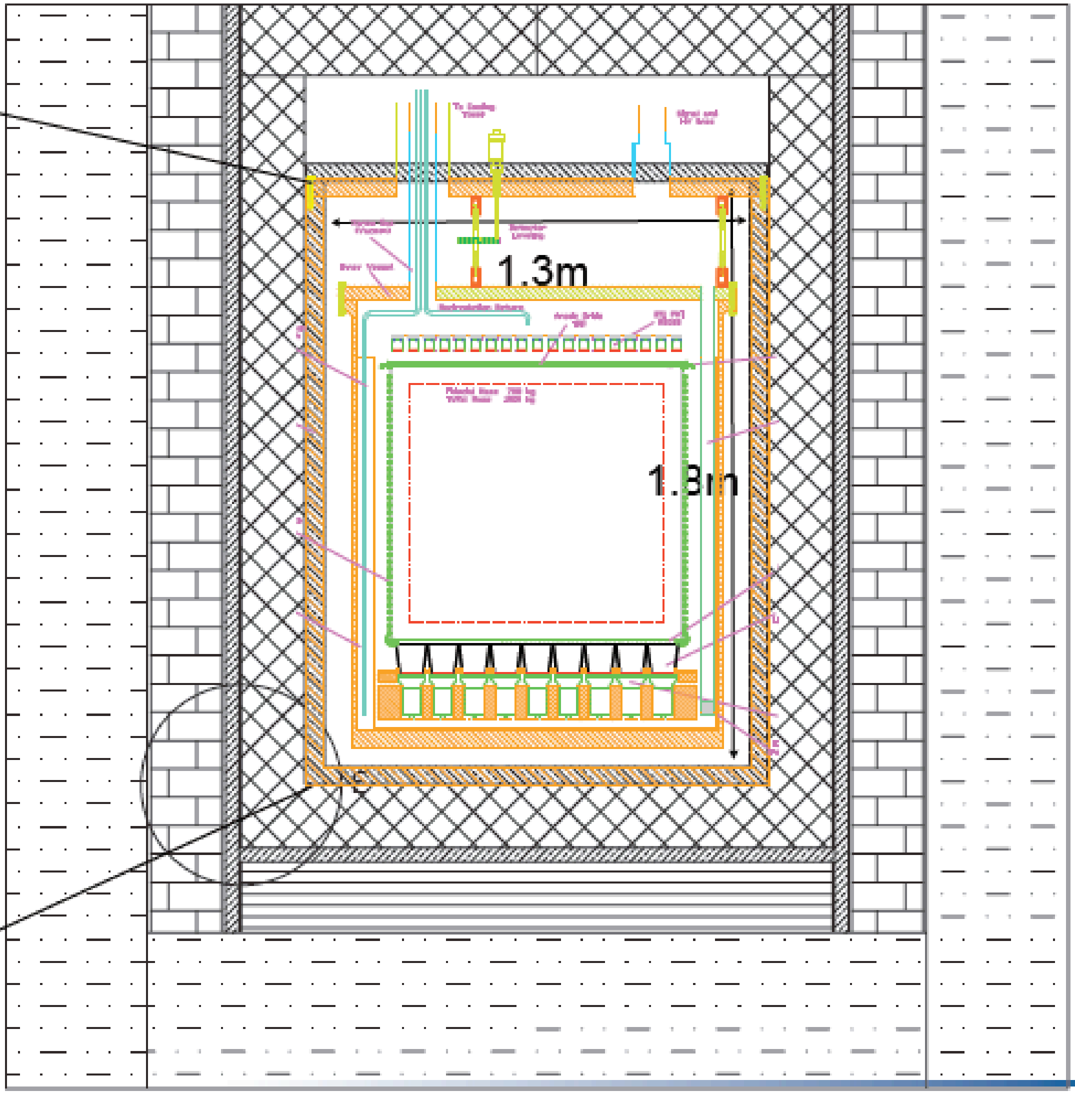
WIMP-Nucleon Cross Section / pb
WIMP Mass / GeV/c²
DAMA
EDELWEISS-II
ZEPLIN-III
CDMS-II
XENON10
XENON100
CMSSM
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10
10²
10³

China Xenon Collaboration

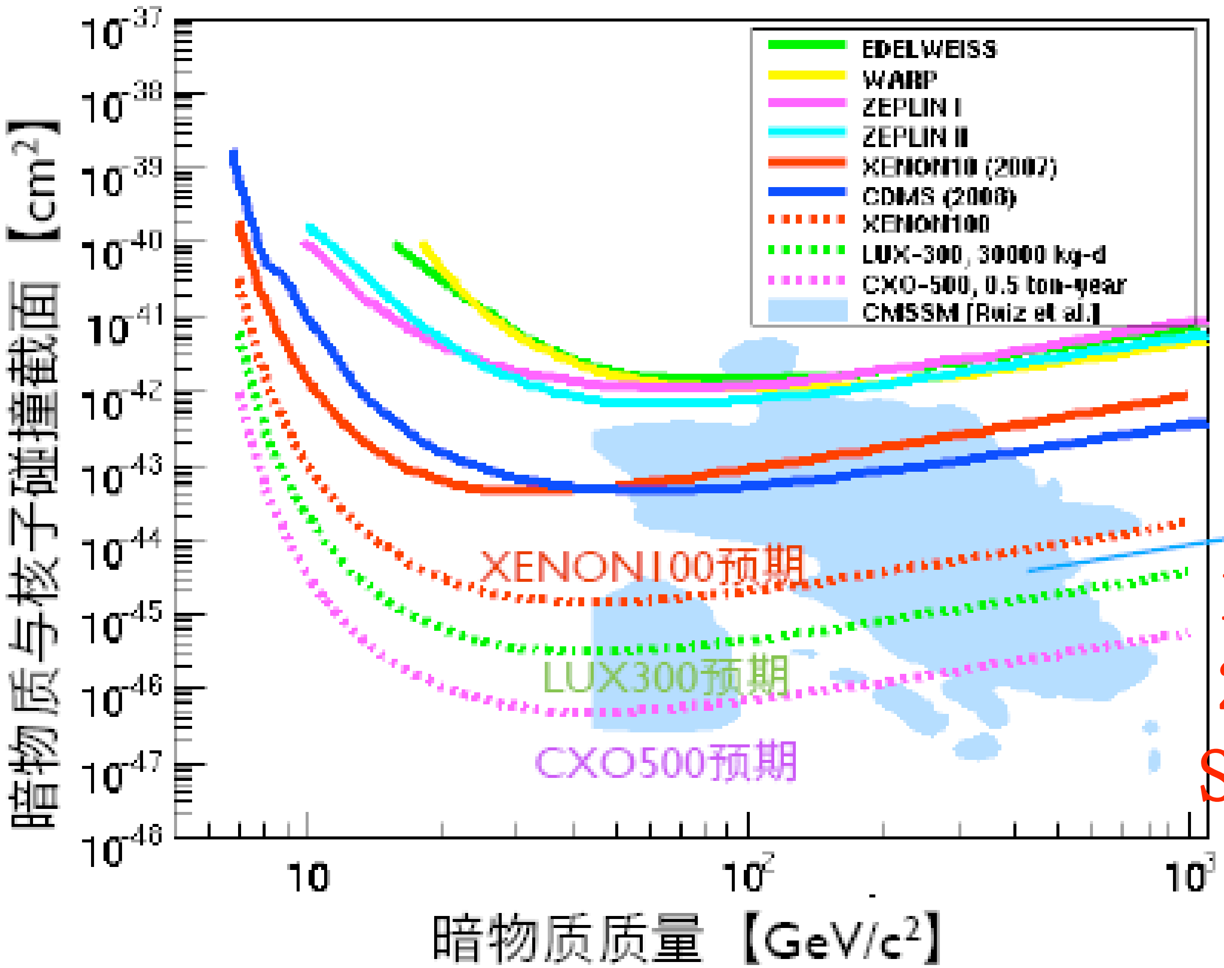
- **Established in 2009**
- **Main Participants**
  - Shanghai Jiao Tong University
  - Shanghai Applied Physics Institute, CAS
  - ShanDong University
  - China Institute of Atomic Energy

CXO探测器





Expectations

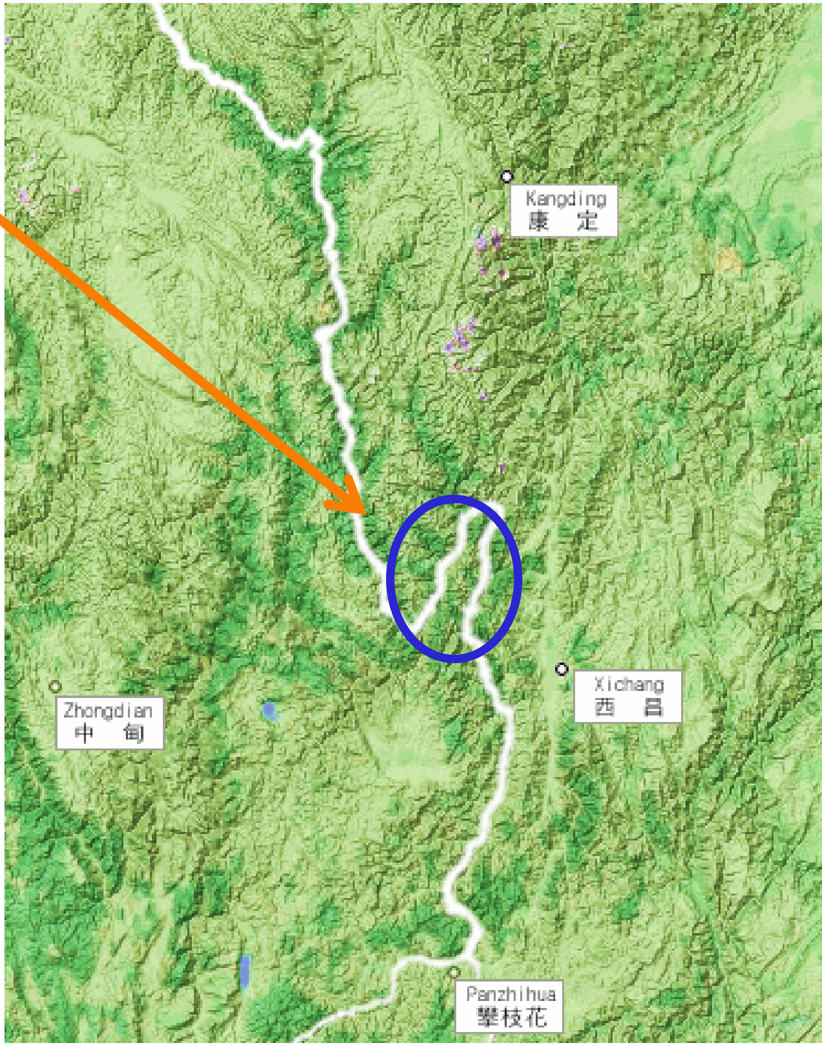


1）Dark Matter!

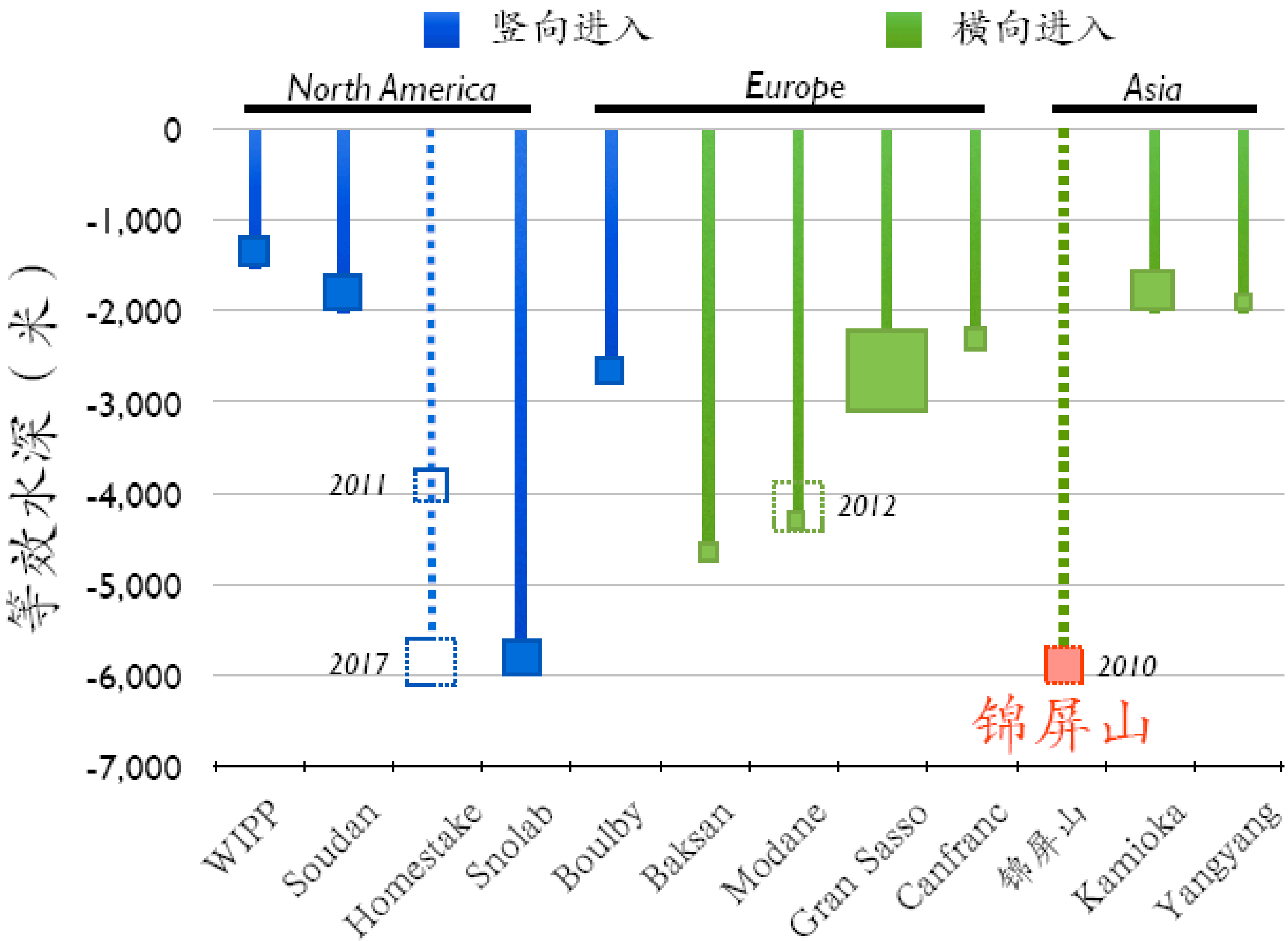
2）Exclude SUSY!

JinPing Lab

- JinPing Lab is located at JinPing Mountain, Sichuan, china, where a hydropower is being built by digging 7 tunnels through the mountain.
- Two of the tunnels are used for traffic with length 17km, width 6m, and largest overburden 2500km (6000wme).



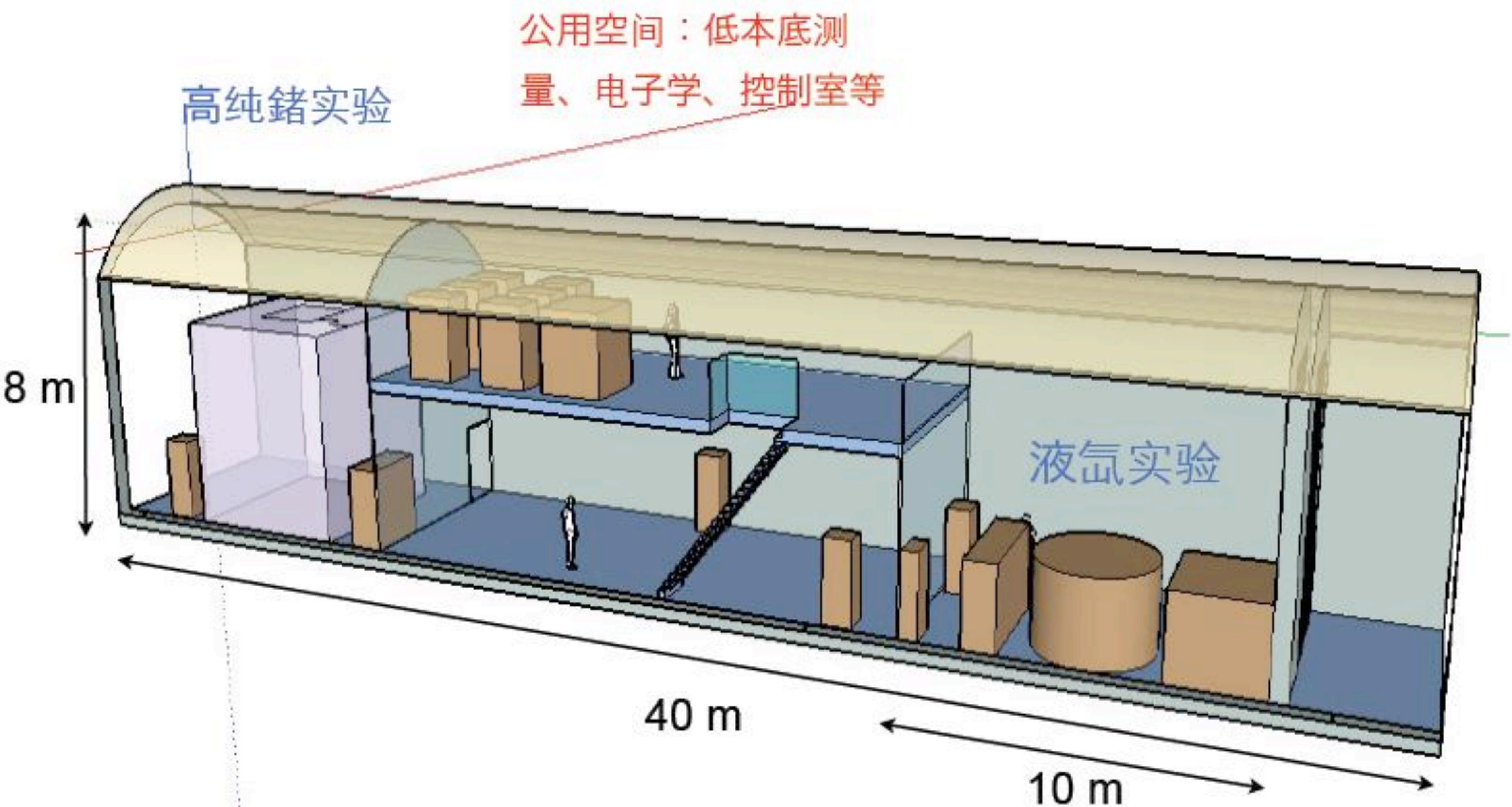
Underground Labs

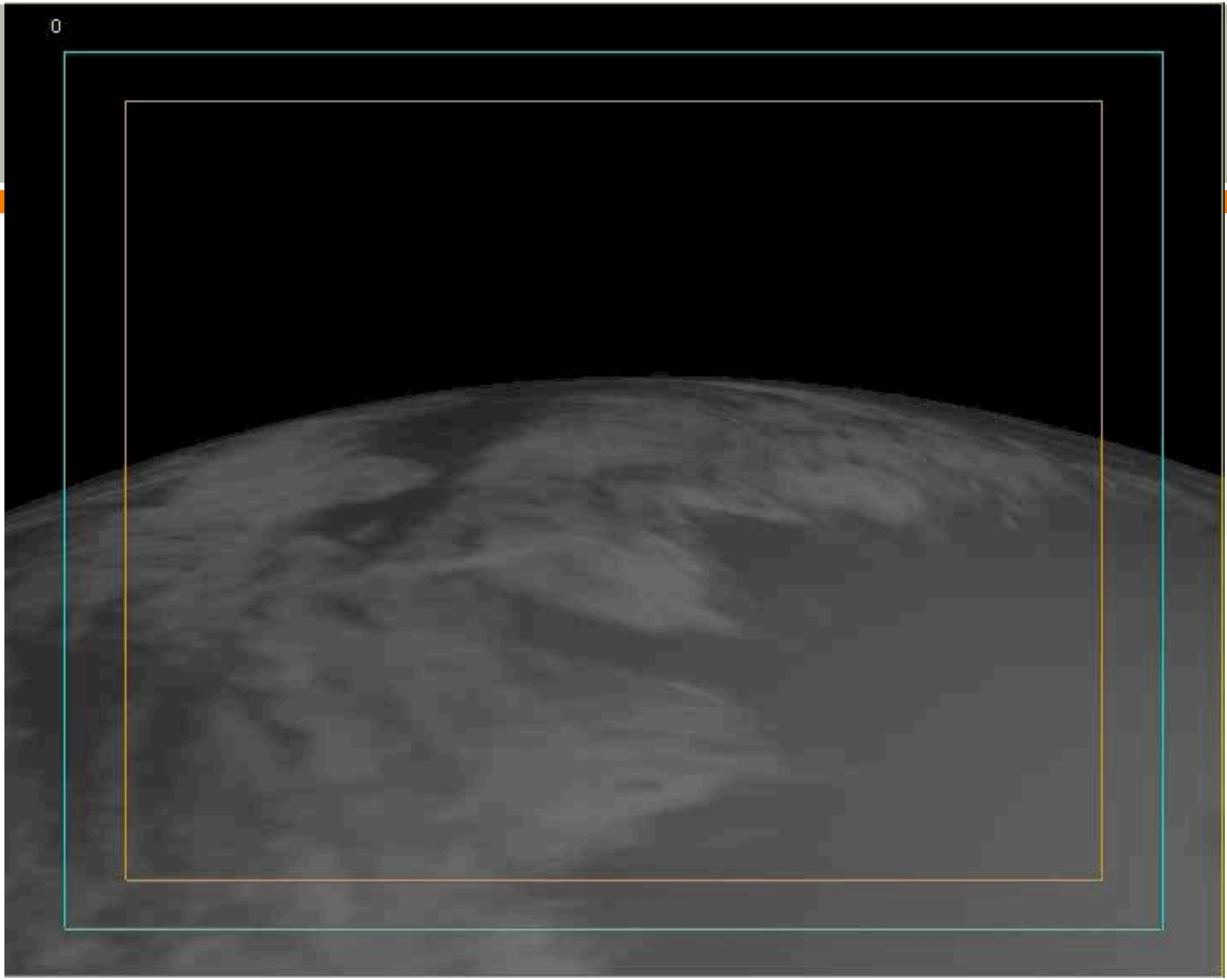



2010/02/08

液氙实验空间

锦屏地下实验室布局




0

Experimental postdoc in Shanghai?

- We are looking for DM enthusiasts to join our group in Shanghai as a postdoc or junior faculty.



- Send me a CV,

Xiangdong Ji (xji@umd.edu, xdji@sjtu.edu.cn)