

近代物理进展讲座

-非加速器高能物理实验

林箐

中国科学技术大学

2025-12



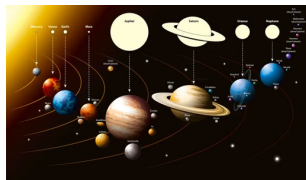


- 非加速器物理简介
- 非加速器物理实验
 - 暗物质
 - 中微子
 - 磁单极子&宇宙线探测

自然界的基本科学问题



星系



行星



热力学

量子力学

核物理

粒子物理

极大

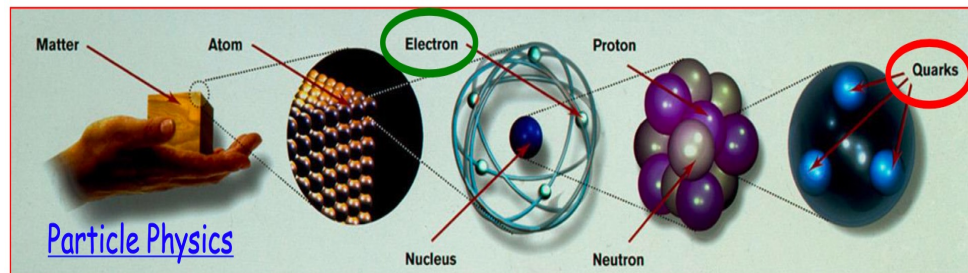
极小

人类宏观尺度

恒星



宇宙大尺度



10^{26}

10^{14}

10^{11}

10^8

1

10^{-6}

10^{-9}

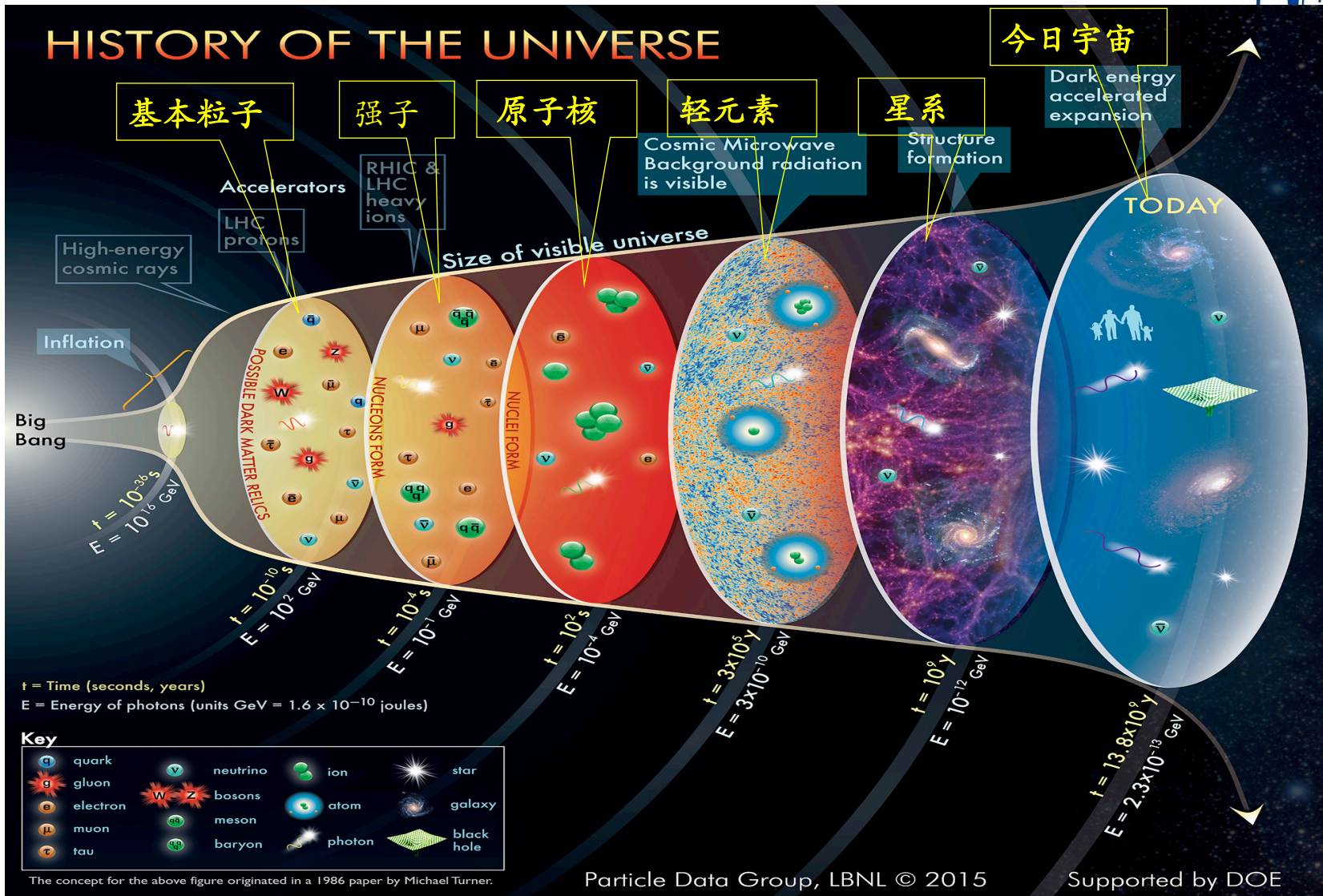
10^{-14}

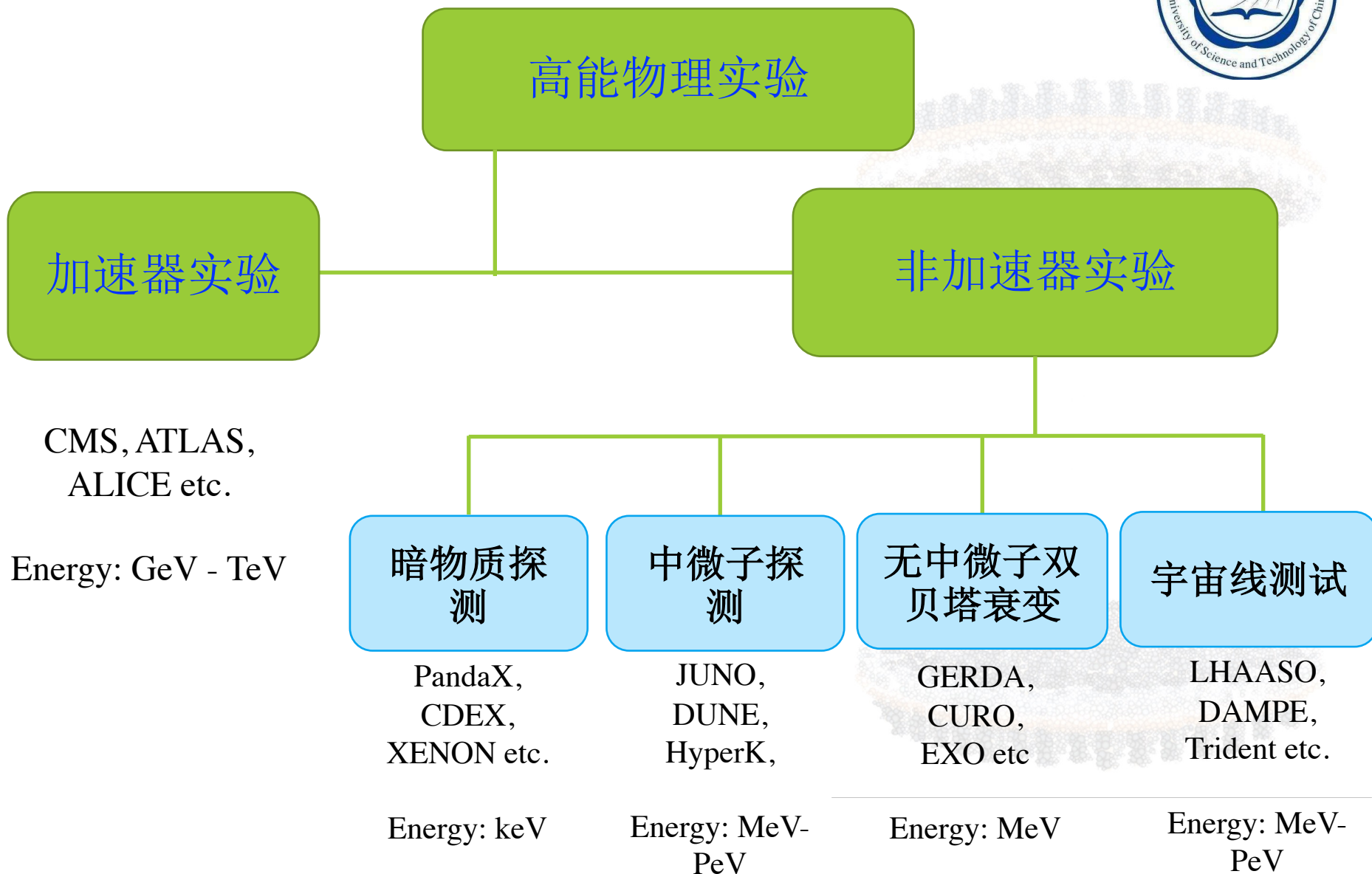
10^{-15}

10^{-18}

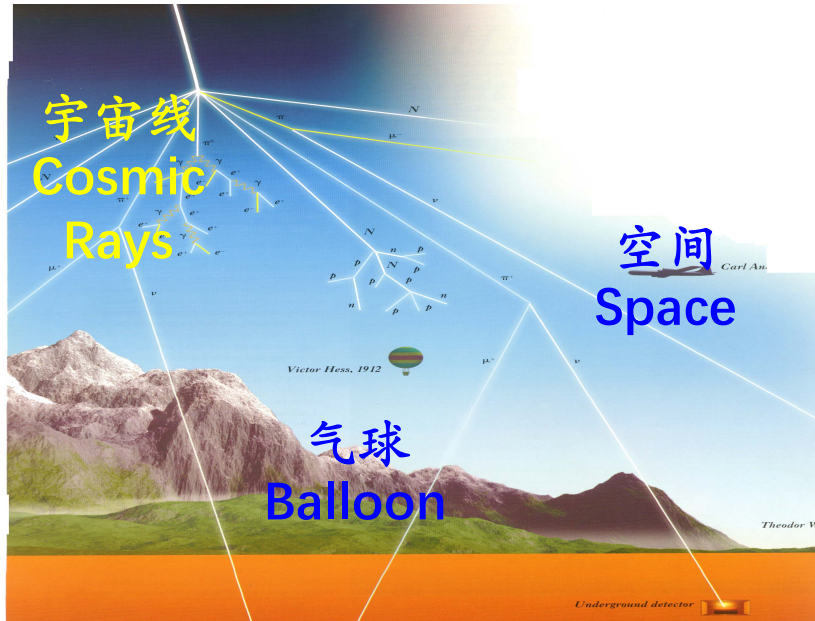
米

最小和最大 (粒子物理和天文学)



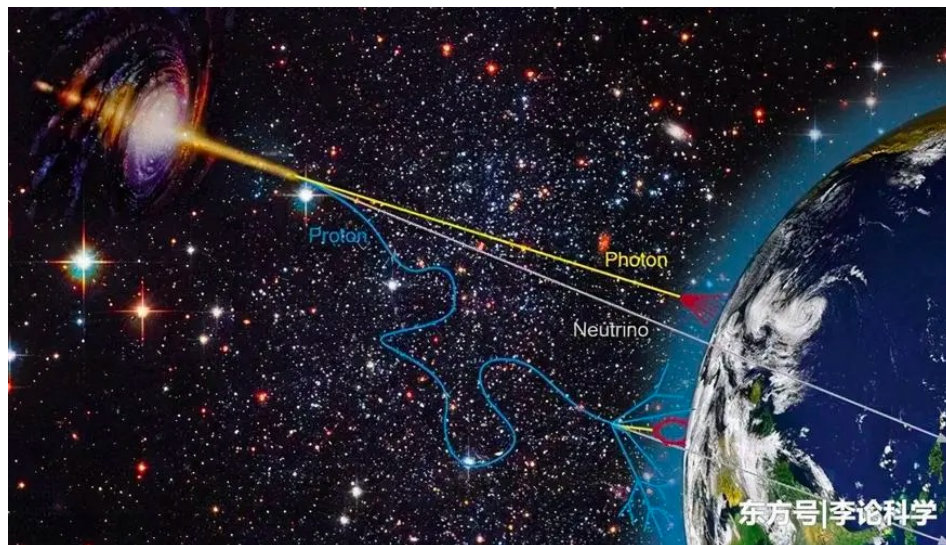


实验手段 - 靠天吃饭



深地 Underground

通过观测**宇宙线**来发现
新粒子, 研究其特性



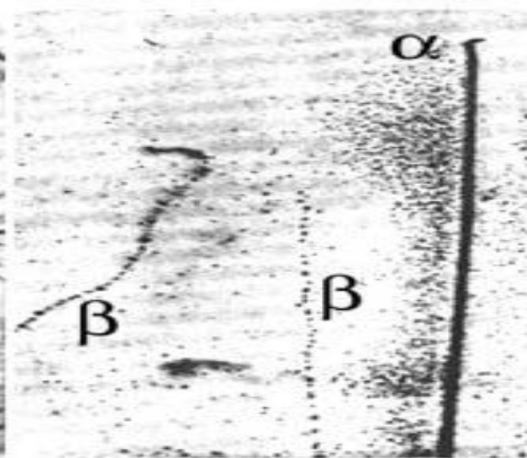
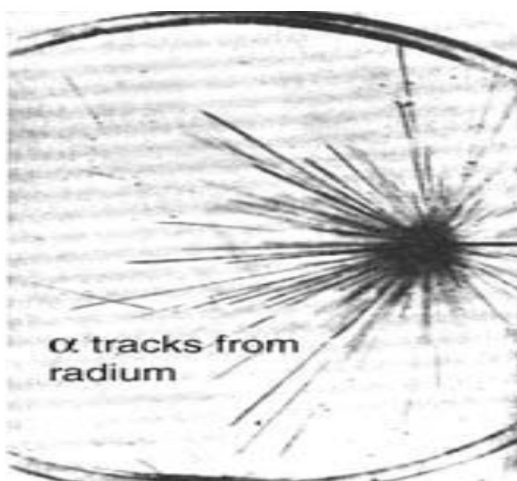
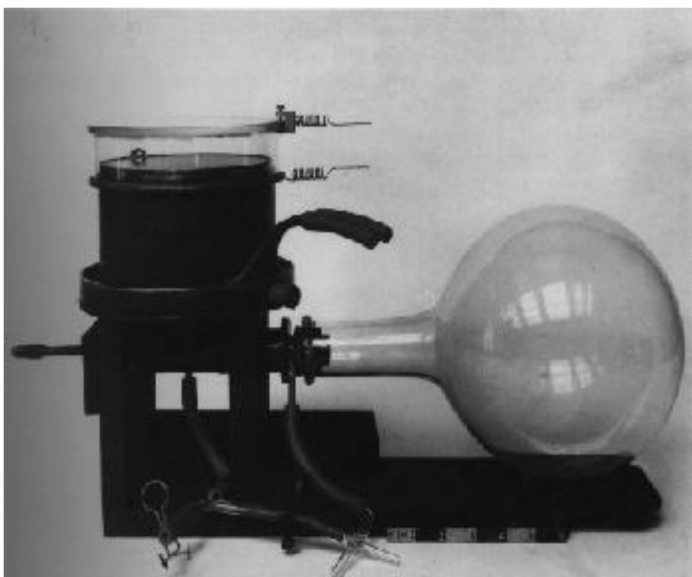
工欲善其事 必先利其器 - 云室



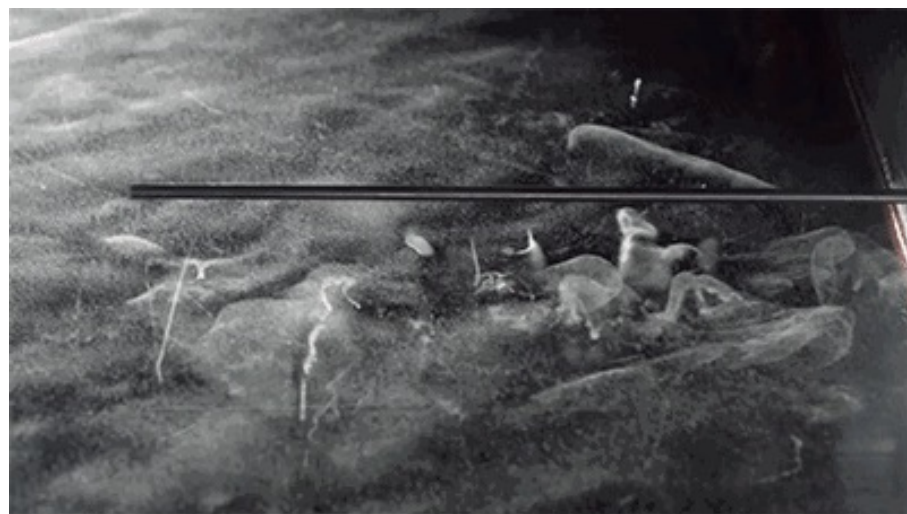
威尔逊 (Charles Thomson Rees Wilson)，1894年起研究云雾中的光学现象。1895年，他设计了一套设备，使水蒸气冷凝来形成云雾。当时普遍认为，要使水蒸气凝结，每颗雾珠必须有一个尘埃为核心。威尔逊发现：潮湿而无尘的空气膨胀时出现水滴。他认为这可能是水蒸气以大气中导电离子为核心而凝聚的结果。用X-Ray 管辐照云室，发现水滴数大量增加，证明离子是‘凝结核’。

威尔逊在云室方面的贡献，获得了1927年诺贝尔物理学奖

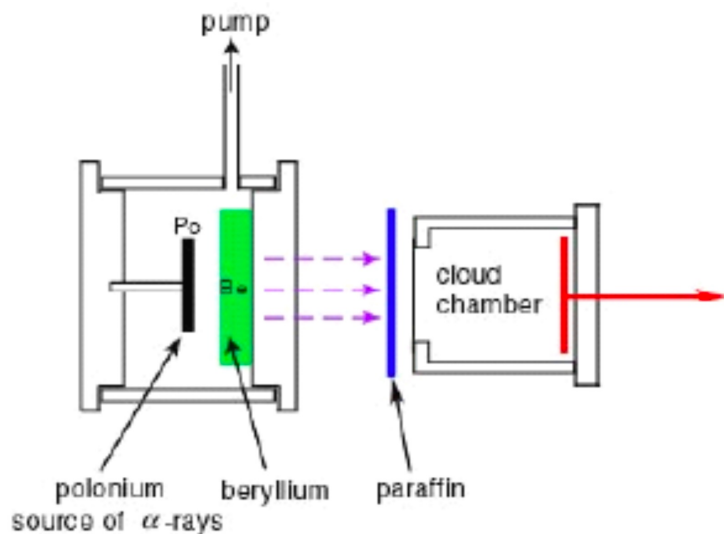
C. T. R. Wilson,
1912, Cloud chamber



云室图像

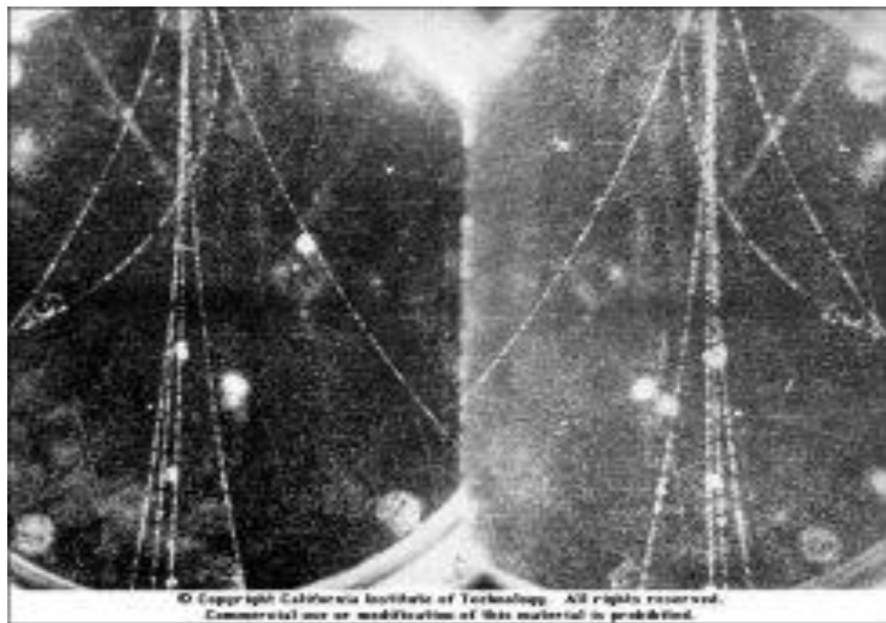


中子的发现



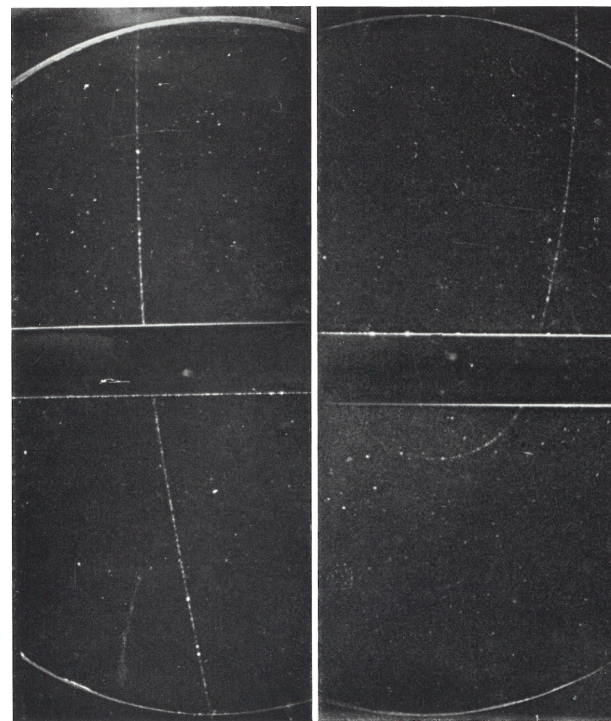
1932年，英国物理学家查德威克（**James Chadwick**）采用计数器和云雾室实验，证实玻特的贯穿辐射不是 γ 射线，而是一种以前尚未发现的、与氢核（质子）的质量差不多的、但不带电的中性粒子。

正电子的发现



实验拍摄的宇宙线的照片
正电子和负电子向相反方向弯曲。

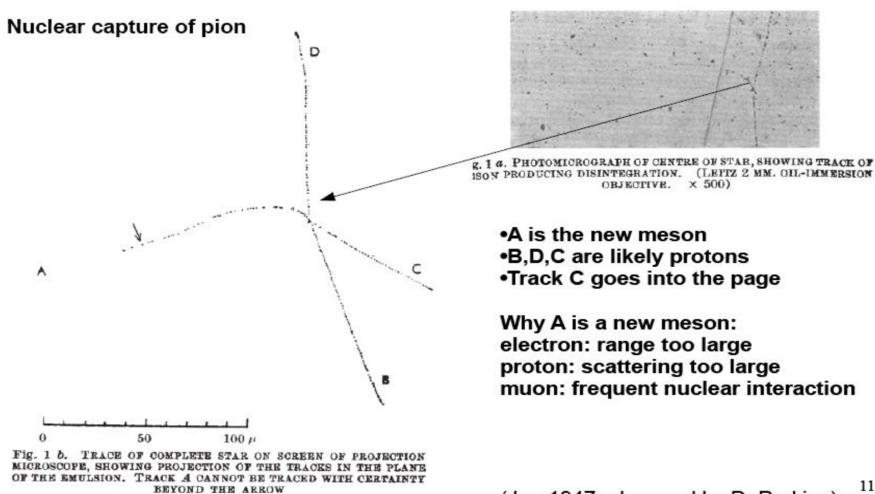
缪子的发现



云室中看到比电子径迹曲率小，
但比质子电离密度大的未知粒子
径迹。

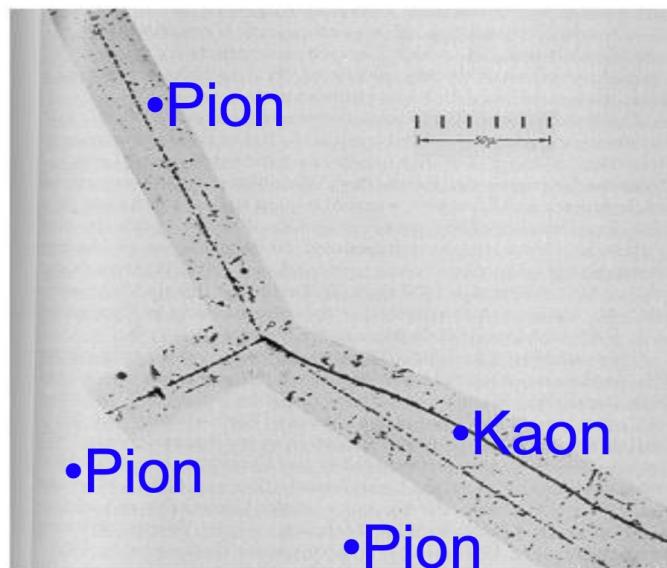
Pi介子的发现

Nuclear capture of pion



1947年Powell, Perkins利用核乳胶在宇宙射线中发现pi介子，获得1950诺贝尔物理学奖。

K介子的发现



1948/49, Kodak and Ilford 研制出更灵敏核乳胶。发现 Kaon 衰变 3 Pions .

粒子物理的重大成果



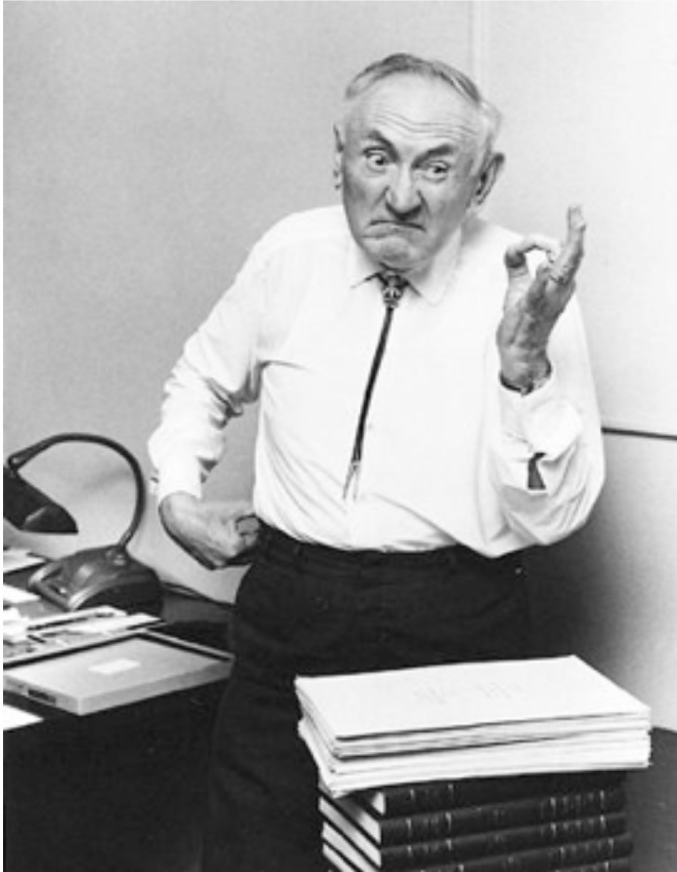
- | | |
|---|-----------|
| • 1895: 发现X-rays, W.C. Röntgen | 1901年诺贝尔奖 |
| • 1896: 发现放射性, H. Becquerel | 1903年诺贝尔奖 |
| • 1897: 电子, J.J. Thomson | 1906年诺贝尔奖 |
| • 1911: 原子核, E. Rutherford | |
| • 1919: F.Hess 气球实验, 1925 年Millikan 称它作宇宙线 | |
| • 1919: 核嬗变, (质子) E. Rutherford $\alpha + {}^{14}\text{N} \rightarrow {}^{17}\text{O} + {}^1\text{H}$ | |
| • 1932: 中子的发现, J. Chadwick | 1935年诺贝尔奖 |
| • 1932: 正电子, C.D. Anderson | 1936年诺贝尔奖 |
| • 1937: 介子, S.H.Neddermeyer, C.D.Anderson 1937
$m = 130 m_e$, J. Street, E. Stevenson 1937 | |
| • 1947: Pion, C. Powell | 1950年诺贝尔奖 |
| • 1947: Kaon, G.Rochester | |
| • 1955: Antiproton, E. Segre, O. Chamberlian | 1959年诺贝尔奖 |
| • 1956: 中微子, F. Rheines | 1959年诺贝尔奖 |
| • 1962: μ 中微子, L. Lederman, M. Schwartz, J. Steinberger | 1988年诺贝尔奖 |
| • 1974: 发现粲素, J/y 粒子, S.C.C.Ting, B.Richter | 1976年诺贝尔奖 |
| • 1975: 发现t 轻子, M.Pertl | 1995年诺贝尔奖 |
| • 1977: 发现底夸克素, L.Lederman | |
| • 1983: 发现 中间玻色子 $W^\pm, Z^0$, C. Rubbia | 1984年诺贝尔奖 |
| • 1995: 发现Top夸克 | |
| • 2012: 发现Higgs F.Englert, P.Higgs | 2013年诺贝尔奖 |

加速器实验



- 非加速器物理简介
- 非加速器物理实验
 - 暗物质
 - 中微子
 - 磁单极子&宇宙线探测

First Evidence of Dark Matter



Fritz Zwicky, 1933



Coma Cluster, 0.3 billion light years away

Virial Theorem to Coma Cluster.
400 times more “unseen” matter
than visually observed!!

More Evidence: Galaxy Rotation Curve



Credit: <https://youtu.be/sI23cwbbNqs>



Vera Rubin, 1976

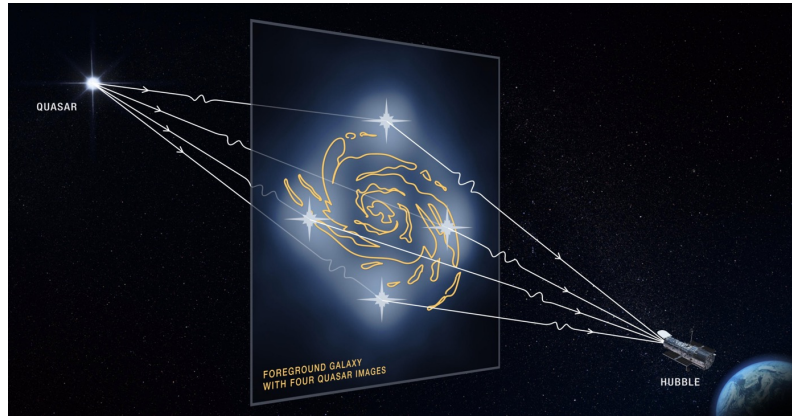


Galactic object velocity (M33, ~ 2.7 million light-years).

Found **6 times** as much dark matter as visible matter.

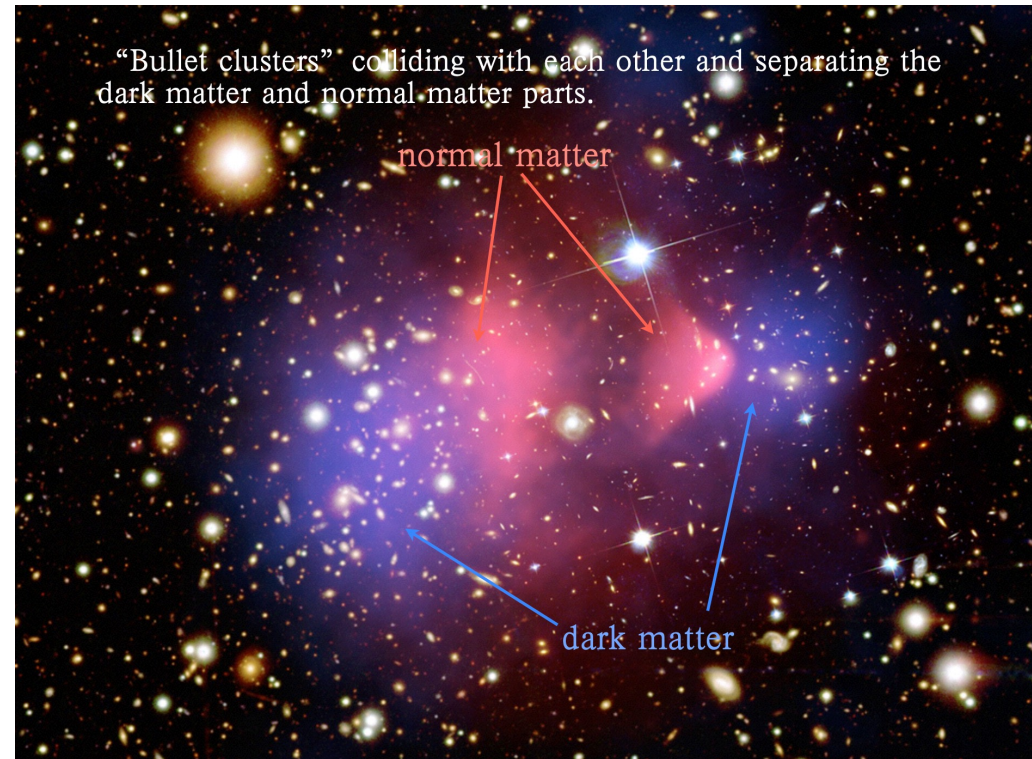
Galaxies are embedded in a dark matter halo!

More Evidence: Bullet Cluster



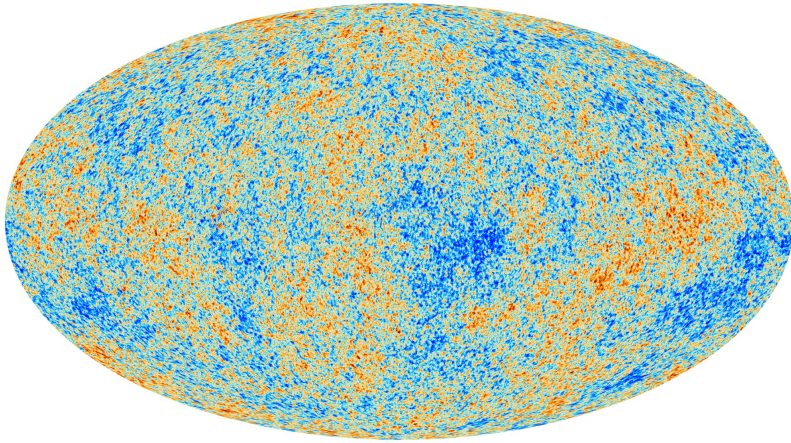
Use **gravitational lensing** to measure spatial distribution of dark matter after cluster collision.

Use **X-ray** to measure the distribution of normal matters.

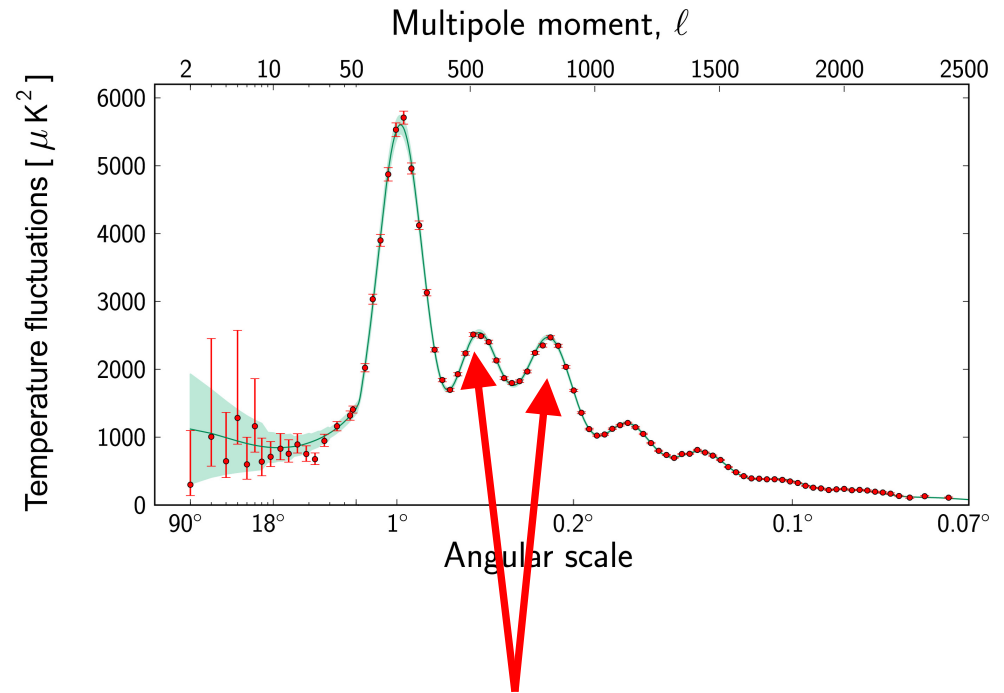


Clear separation between gravitational matters and normal matters!

More Evidence: Cosmic Microwave Background (CMB)



Planck CMB map, 2015

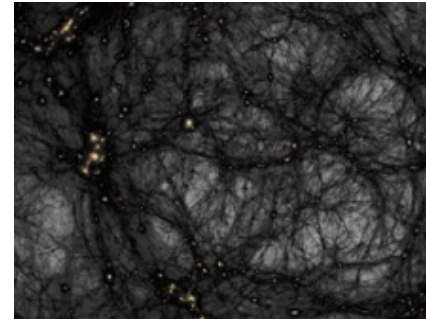


Second and third peaks reveal the ratio of baryonic and dark matter in Universe.

Current View of Dark Matter



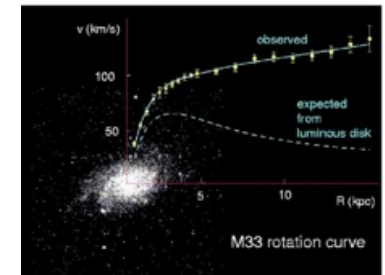
Large Structure



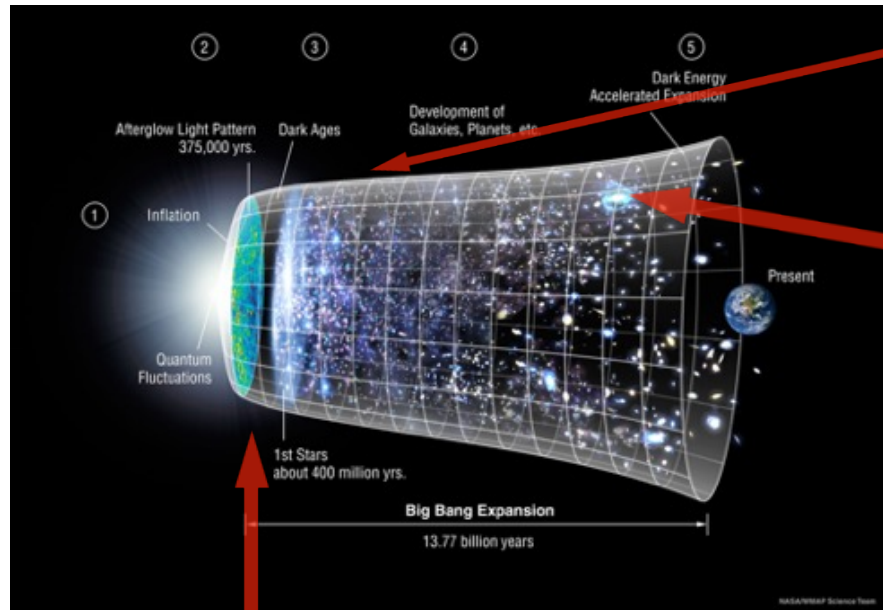
Small Structure



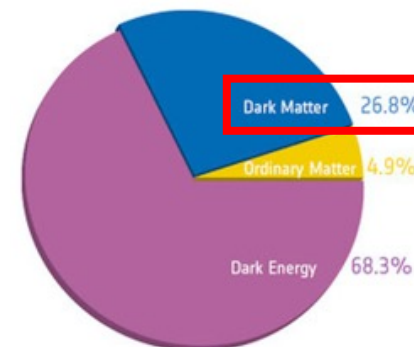
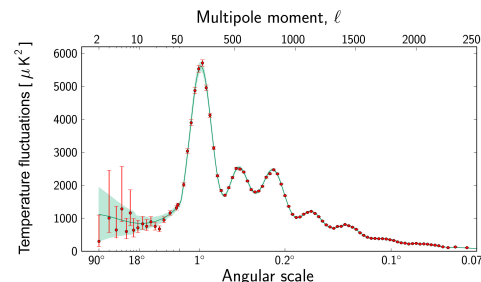
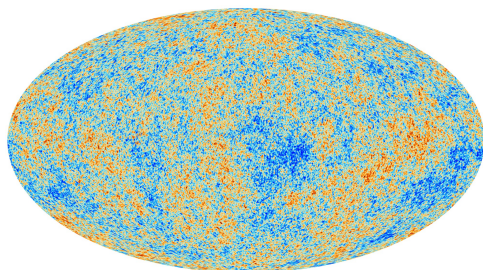
Bullet cluster collision



Galaxy rotation curve

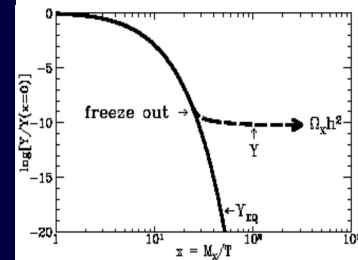
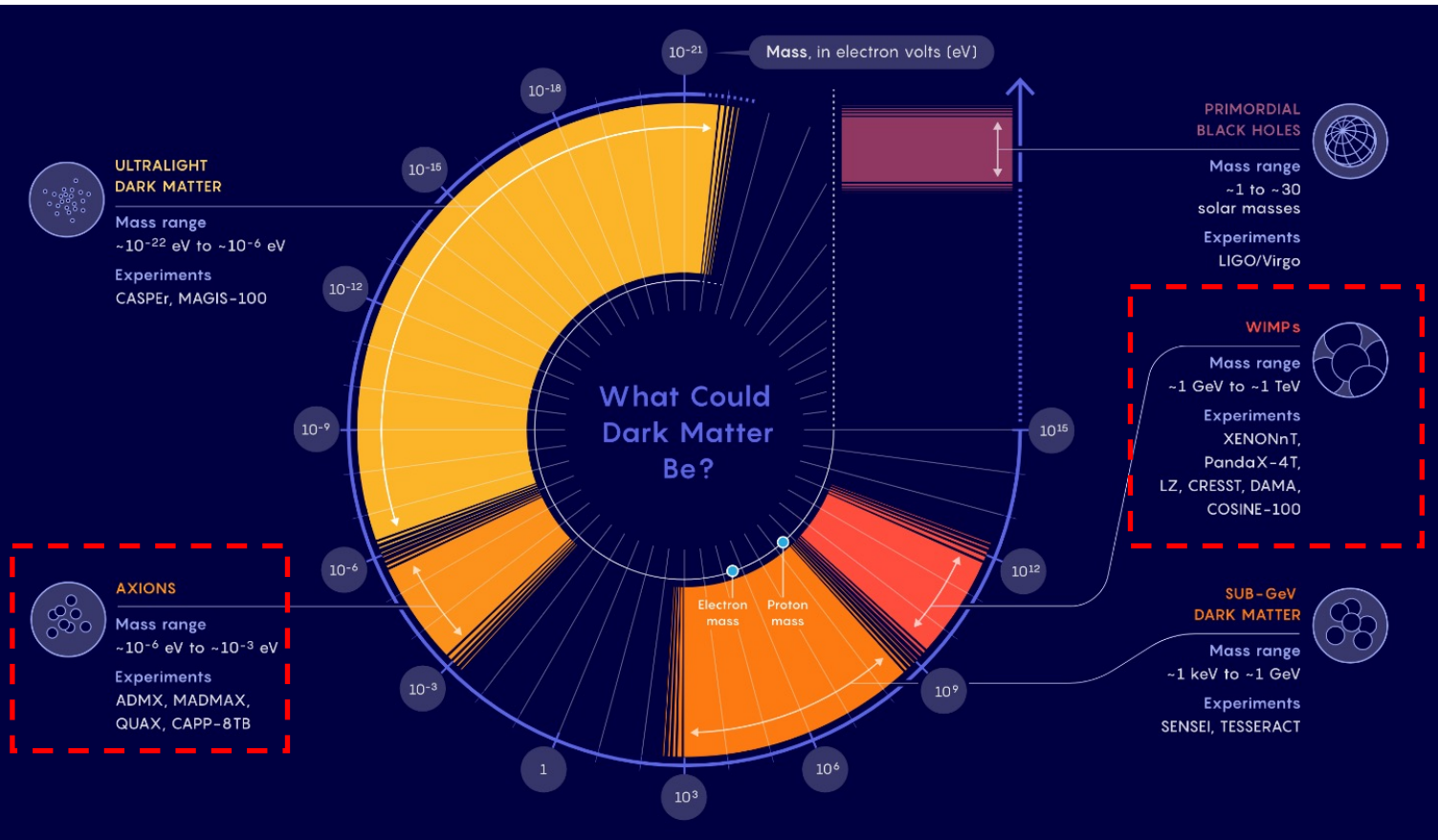


Primordial Universe

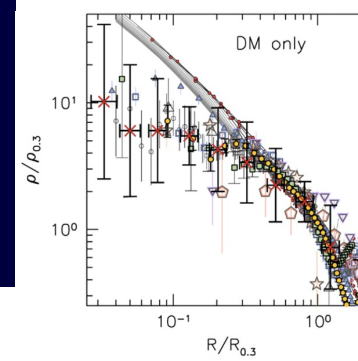


Gravitational evidences suggest **dark matter** is the **dominant form of matter** in Universe!

Dark Matter Candidates



Core-cusp Problem



Samuel Velasco/Quanta Magazine

Detection Scenario



SM particle

SM particle'

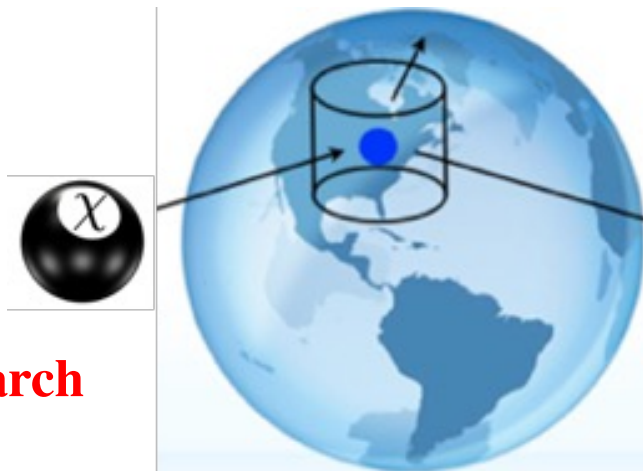
DM particle

DM particle'



Indirect Search

Collider Search

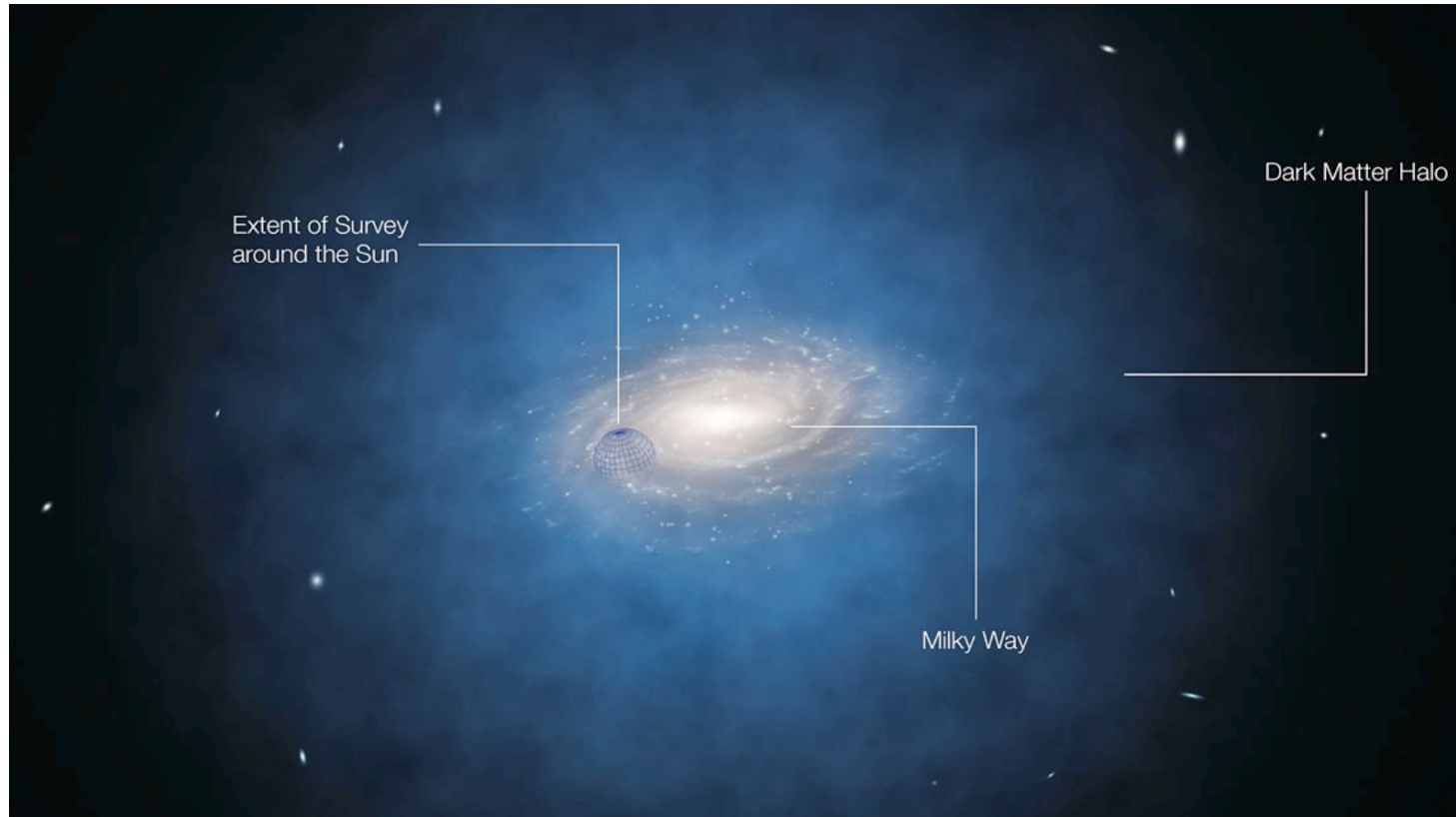


Direct Search

Requirements:

- $\sim \text{keV}$ threshold;
- Low background, better to have PID;

Local Flux of Dark Matter Particles

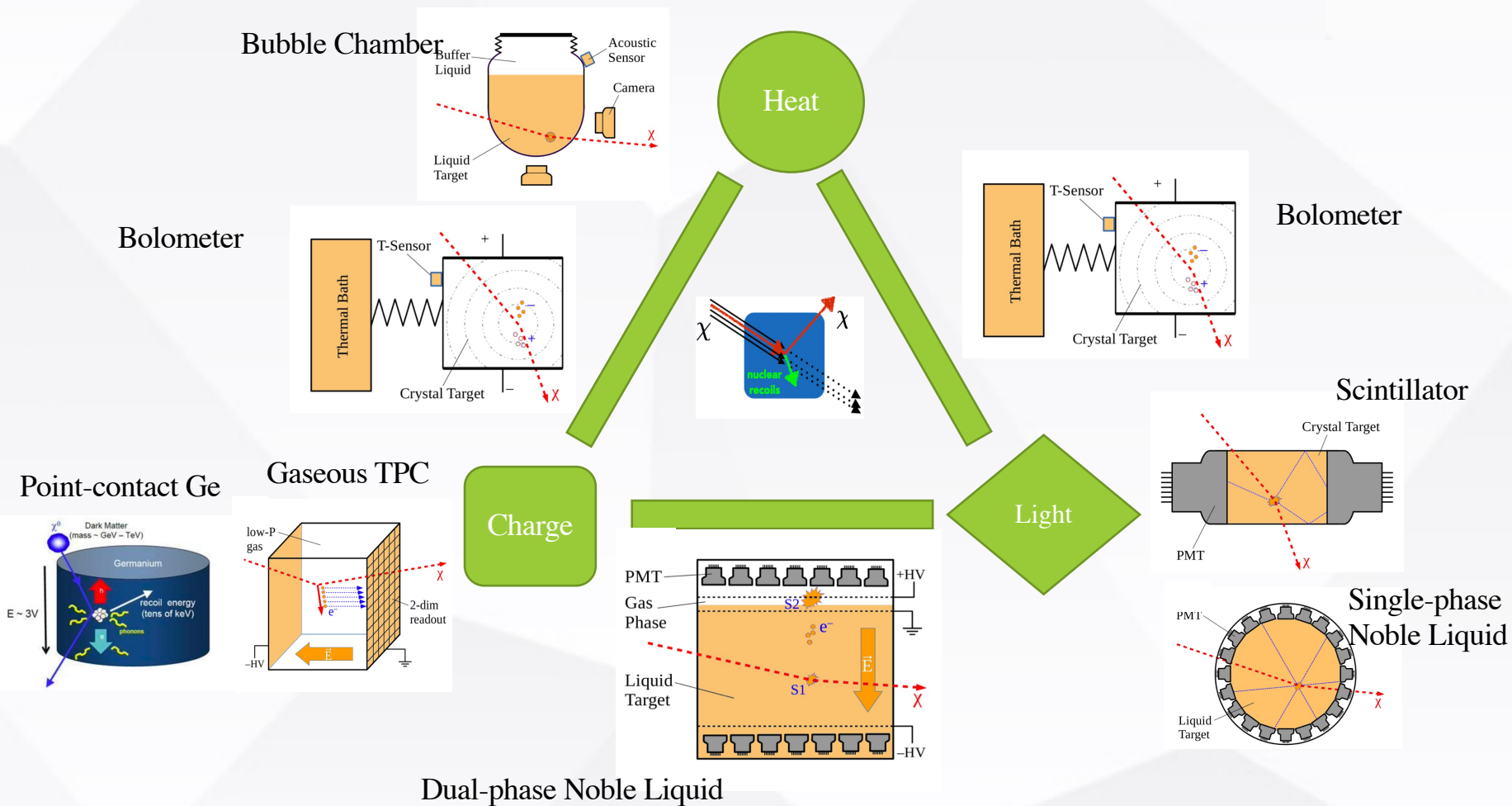


- **100000000** ($1e8$) DM particle crossing single human body ($\sim 1e29$ atoms) **every second!**
- **Every year** DM interacts with human body **less than 1** (current experimental results).
- **Every day**, there are **100000000** ($1e8$) energy depositions in human body caused by **cosmic rays and background gamma radiation**.

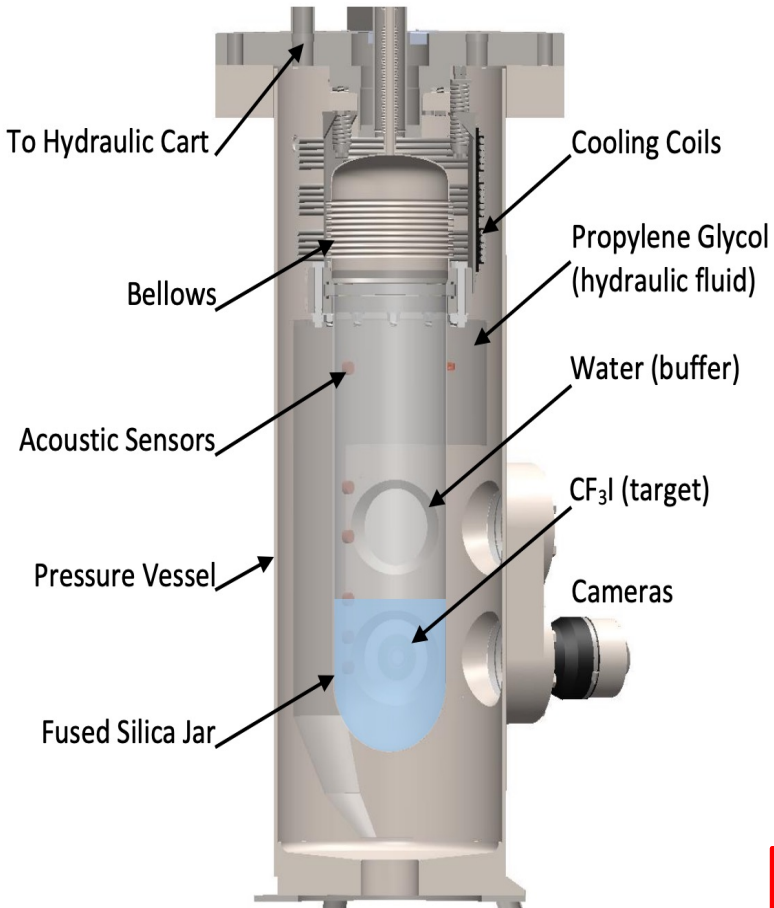
暗物质直接探测技术



Courtesy of APPEC report



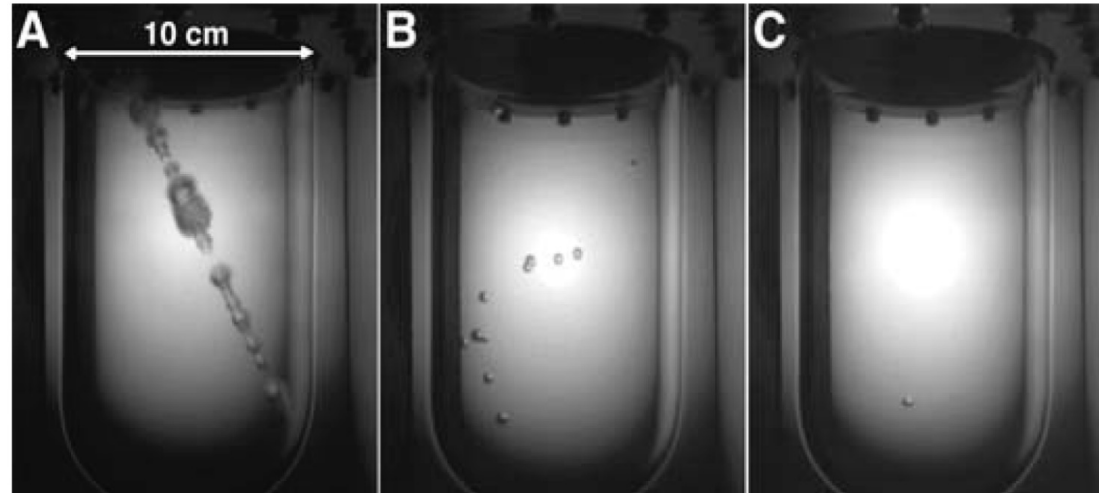
Bubble Chamber: PICO



MIP

Neutron

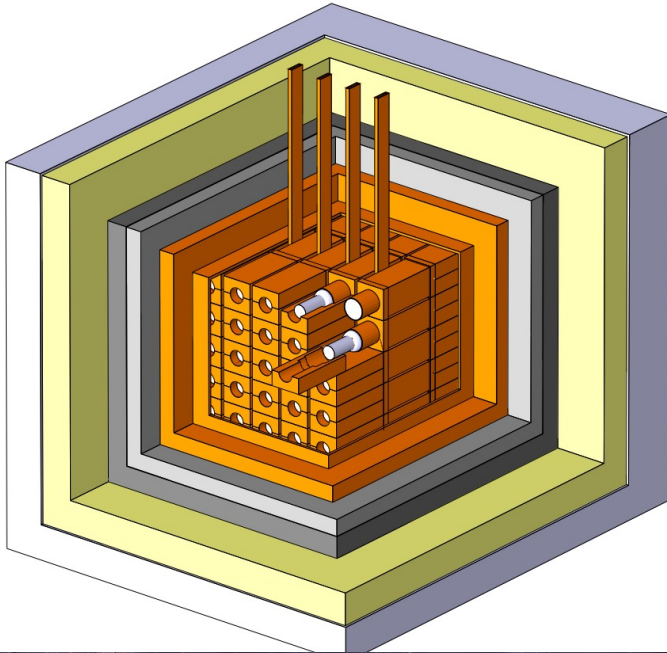
**Dark Matter
like**



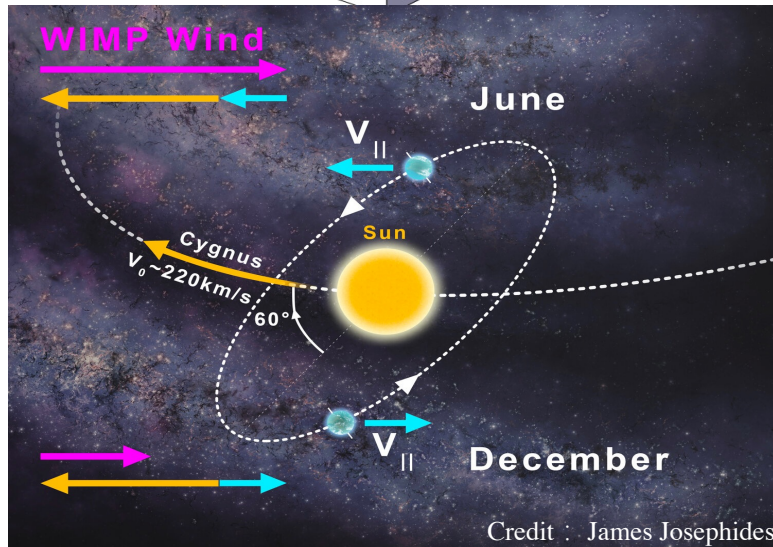
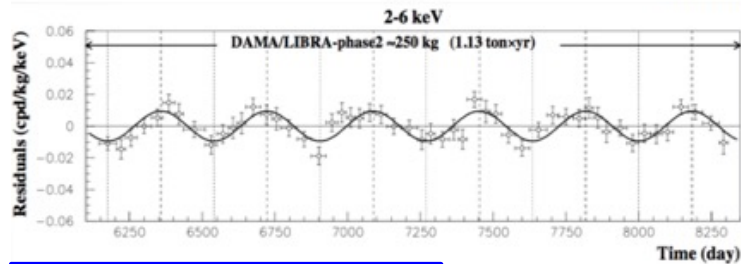
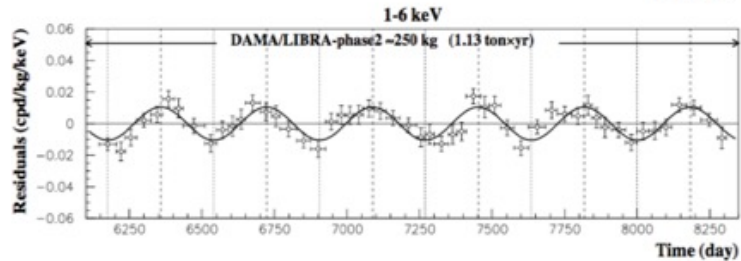
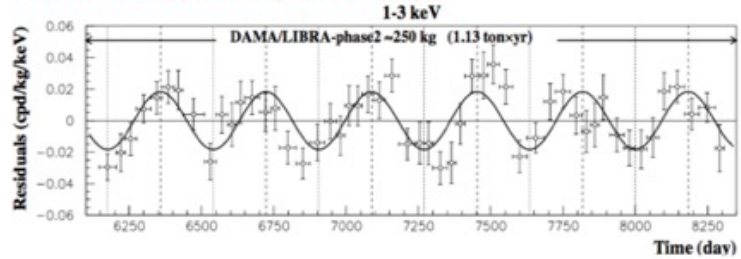
Pros: Almost background free.

Cons: No event-by-event energy info;
Few info for checking anomaly

Scintillating Crystal: DAMA/LIBRA



DAMA/LIBRA-phase2 (1.13 ton $\times$ yr)



Credit : James Josephides

Pros: Simple

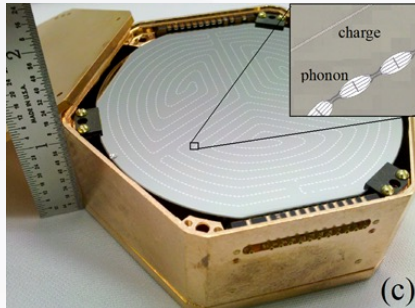
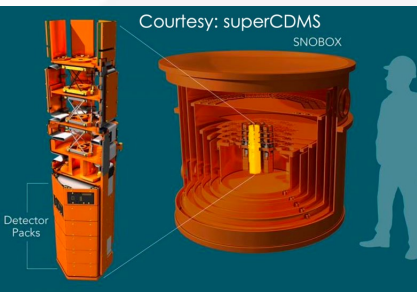
Cons:

- 1) No discrimination
- 2) Background rate still too high.

低温量热器

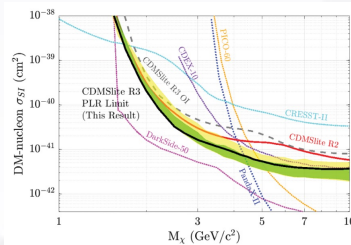
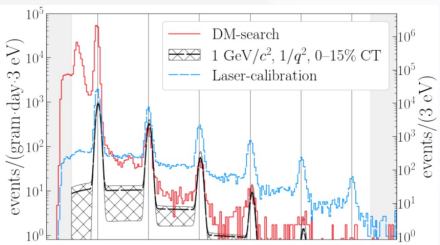


SuperCDMS @ SNOLAB



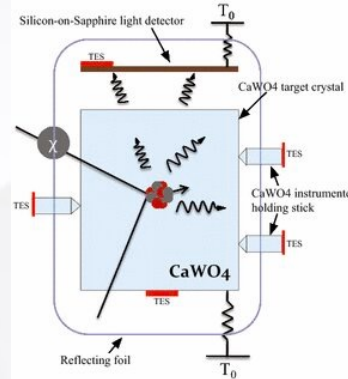
PHYSICAL REVIEW LETTERS 121, 051301 (2018)

Phys. Rev. D 102, 091101 (2020) PHYS. REV. D 99, 062001 (2019)

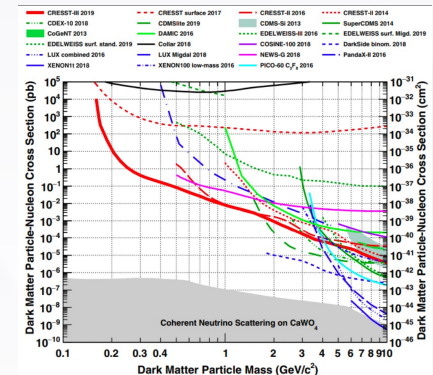
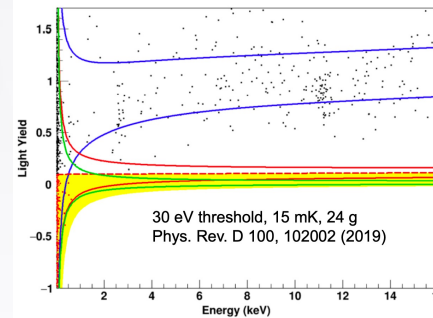
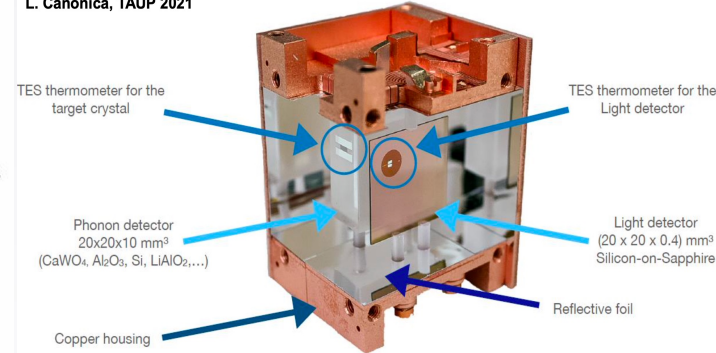


- Super-high resolution, 3% to single e-h pair;
- High sensitivity to GeV WIMP.
- **Current status: Infrastructure under construction**

M. Mancuso, Journal of Low Temperature Physics 199, 547 (2022) CRESST @ LNGS

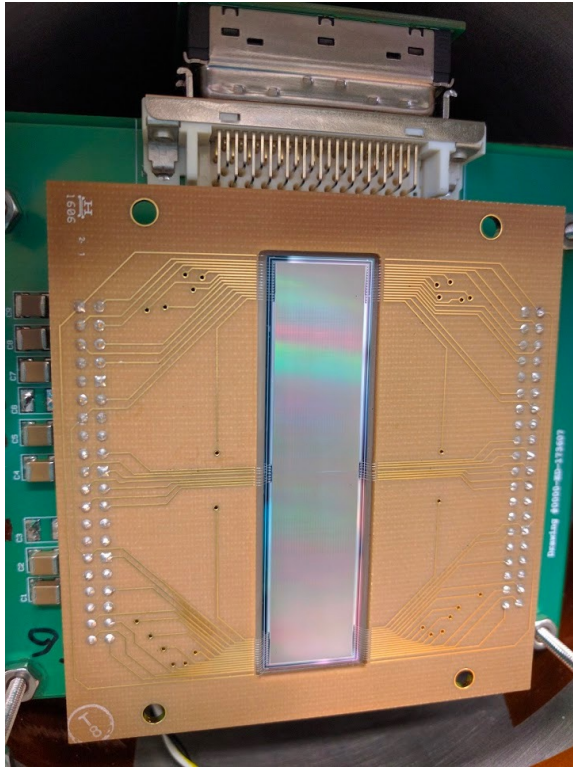


L. Canonica, TAUP 2021



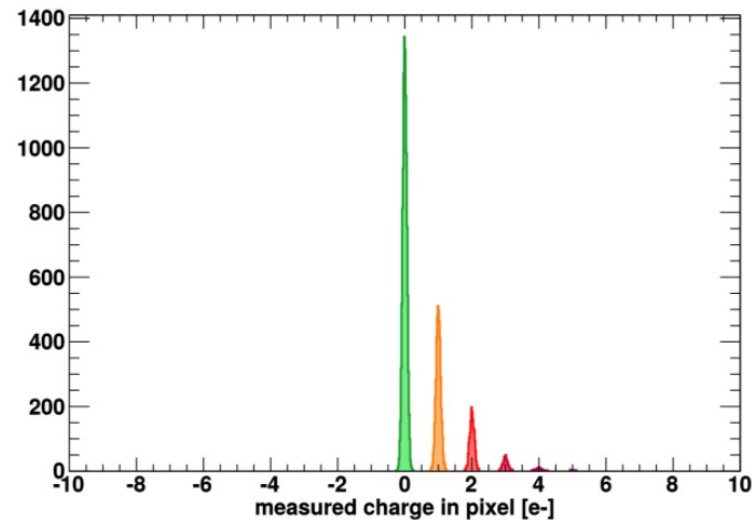
- Great background rejection power.
- **Status: Complementary target material & Infrastructure upgrading**

Super-low Threshold: SENSEI



- $\sim 0.01g$ Si skipper CCD.
- Reduced noise through skipper CCD technique (non-destructively measure charge multiple times)
- Single electron sensitivity.

Readout-noise: 0.067 e RMS

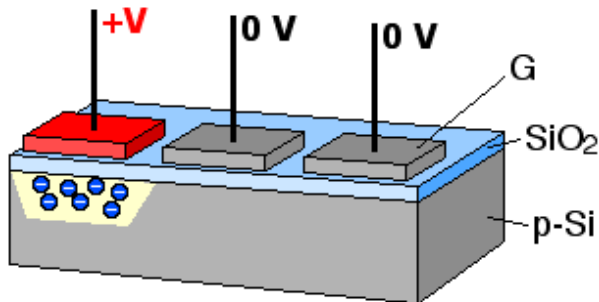


Pros:

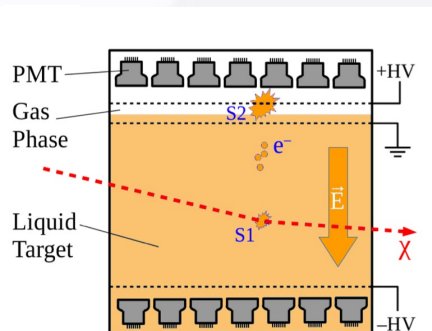
- Ultra-low threshold
- Ultra-low noise

Cons:

- High cost per unit
- Background level high.
- No discrimination.



惰性液体探测器



DarkSide-50
(DarkSide-20k
ARGO)

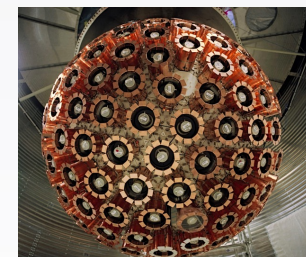
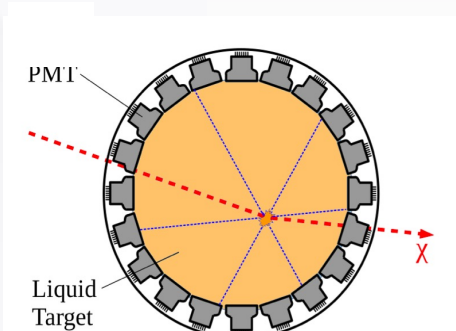


PandaX-4T
XENONnT
LZ
(XLZD
PandaX-xT)

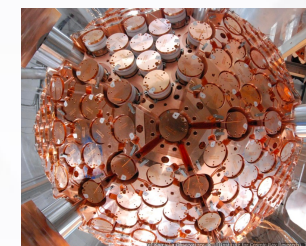


Scalability	Good	Good
Density	3 kg/L	1.4 kg/L
A	133	40
Long-lived bkg	Xe136 Negligible	Ar39 (1 Bq/kg in ^{nat} Ar, T _{half} =269yr)
Bkg rej.	S2/S1, 3D pos.	S2/S1, Pulse shape, 3D pos.
Scintillation light	178 nm	128 nm (need WLS)
Cost	¥15000/kg	¥20/kg for ^{nat} Ar

- ❑ High sensitivity to >10GeV DM due to its good scalability and bkg discrimination;
- ❑ Liquid xenon dual-phase TPC currently has the world-leading sensitivity to >10GeV DM.

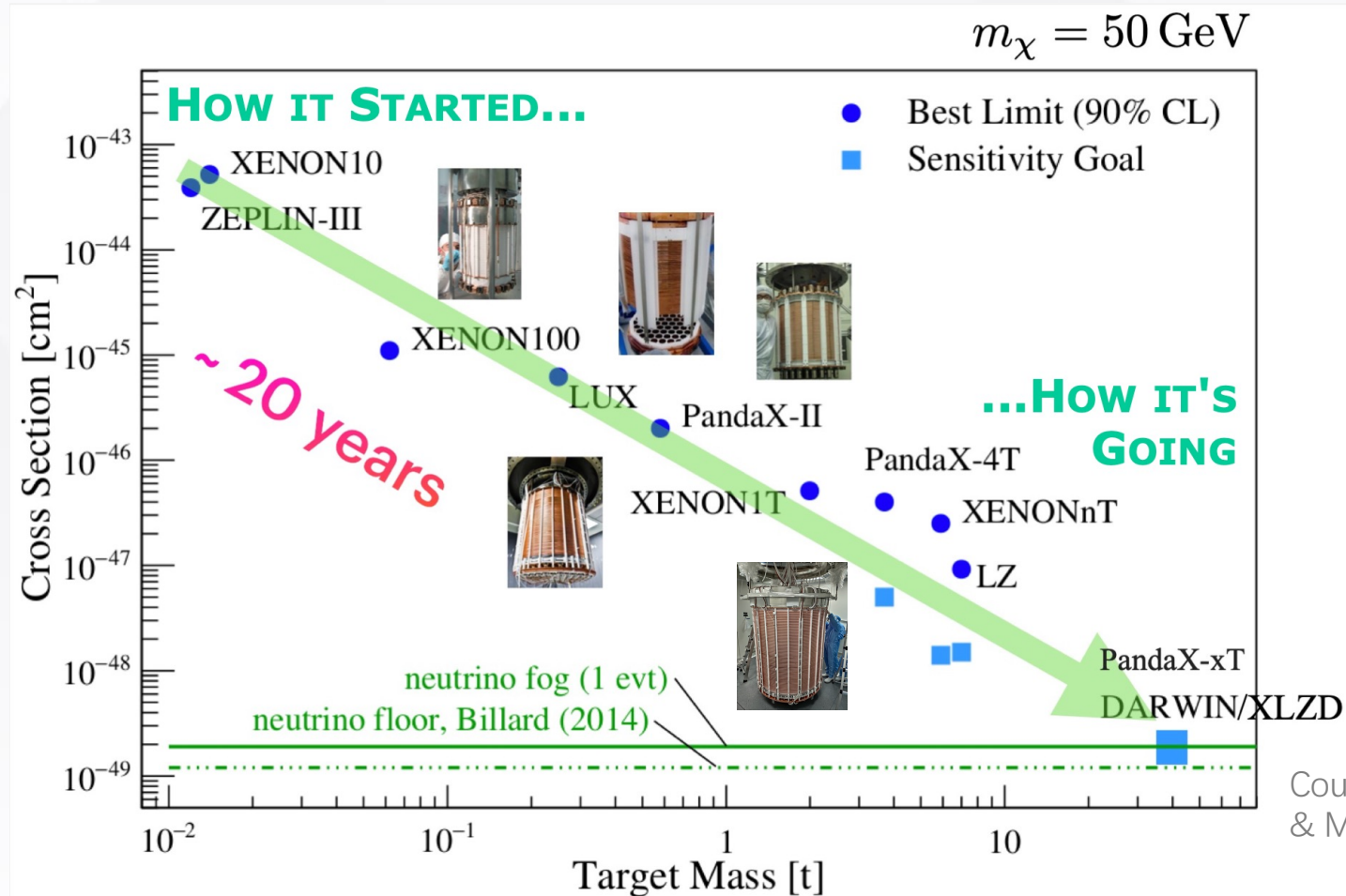


DEAP-3600



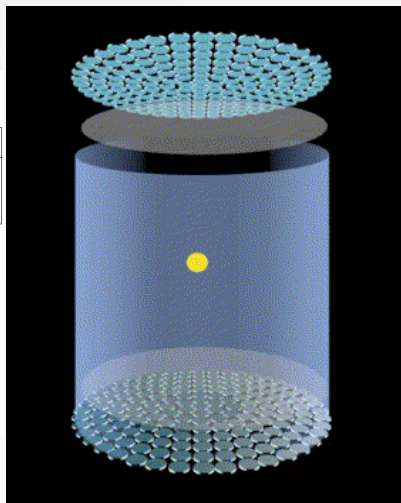
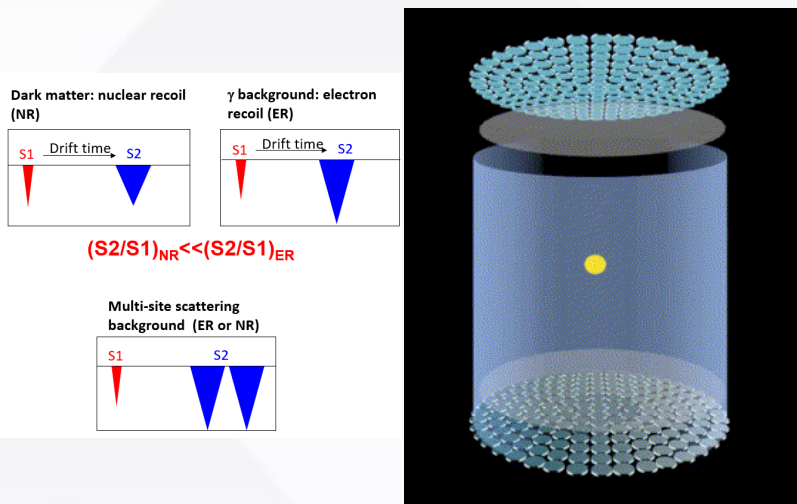
XMASS

惰性液体探测器灵敏度

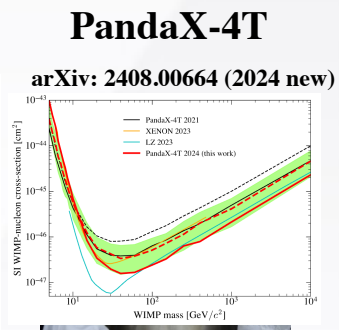
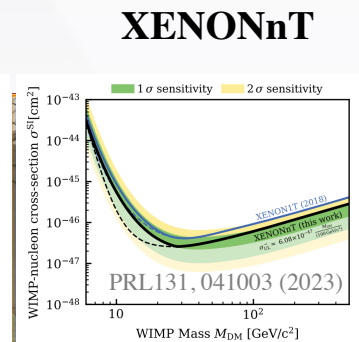
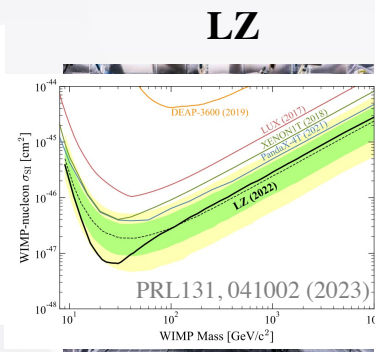
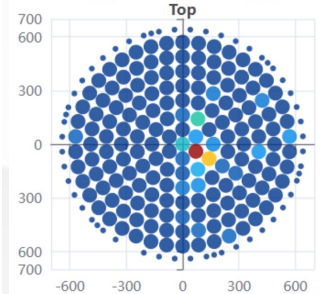
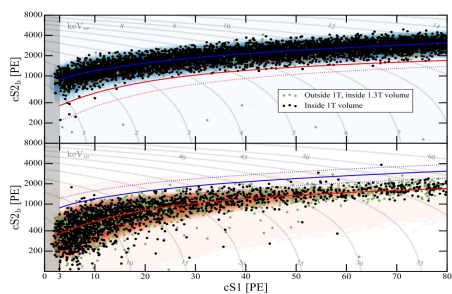
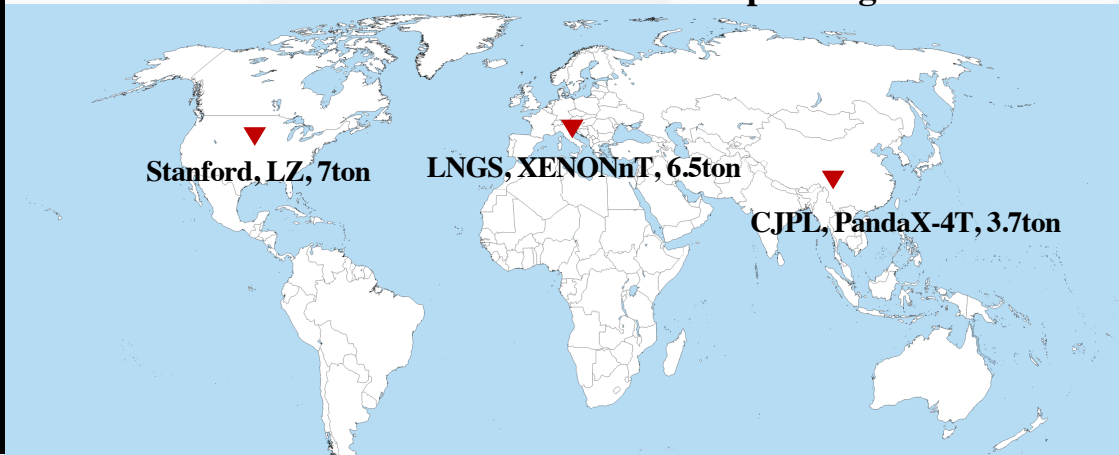


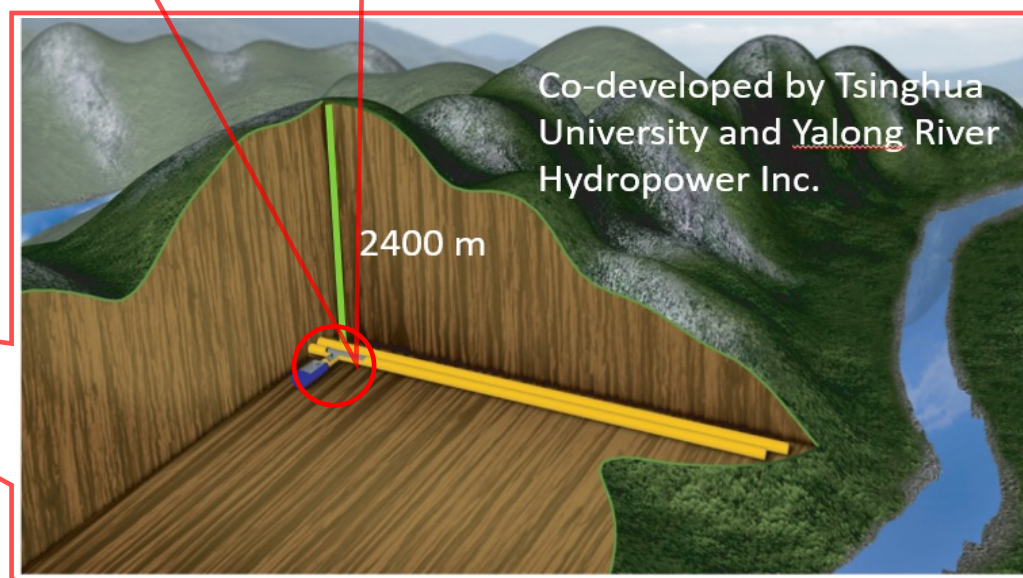
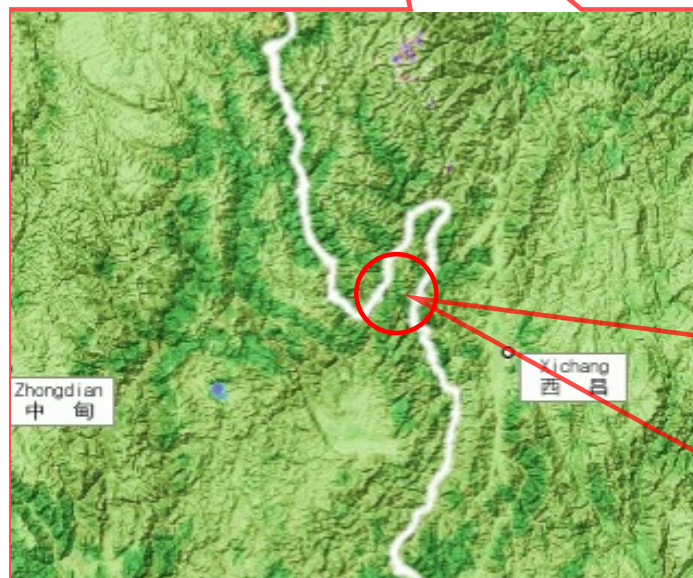
Courtesy to P. Ullio
& M.E. Monzani

二相型氙时间投影室实验

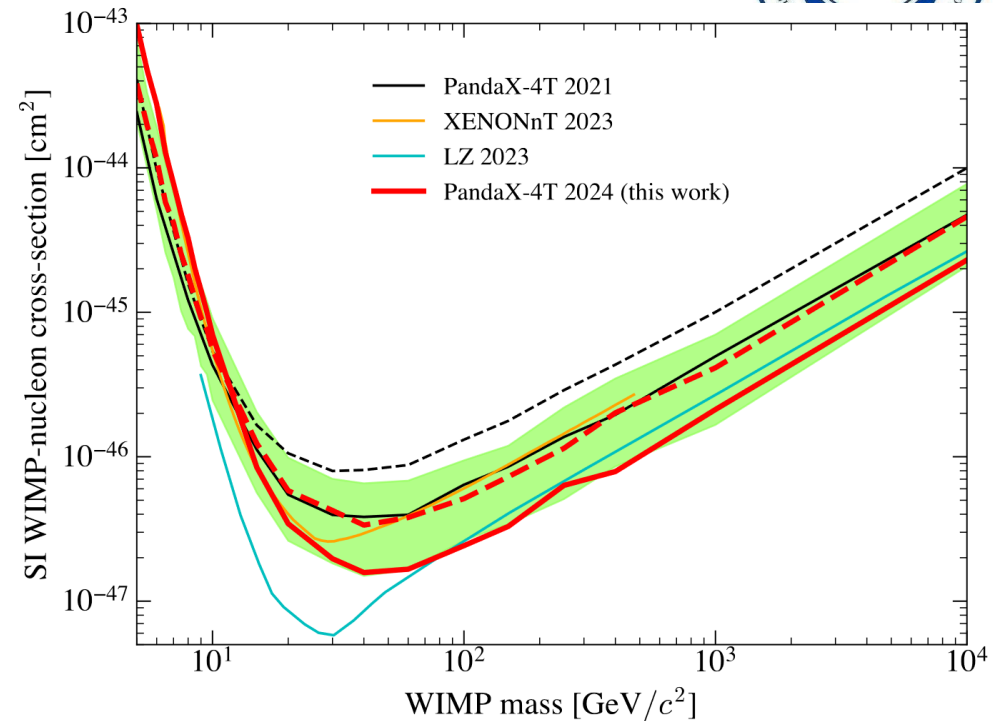
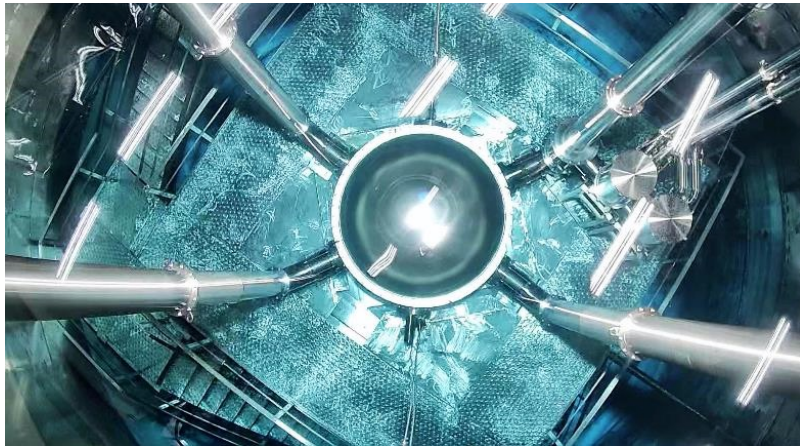


Three multi-tonne detectors operating.





PandaX-4T Dark Matter Search Results

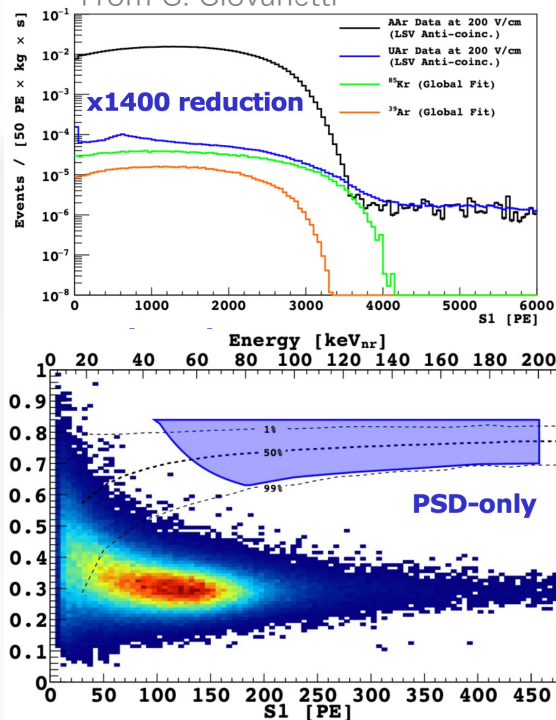


- PandaX-4T detector assembled at May, 2020, and started taking commissioning data at Nov., 2020.
- Total exposure = **1.54** tonne-year;
- **$1.6 \times 10^{-47} \text{ cm}^2$** @ 40GeV;

液氩实验



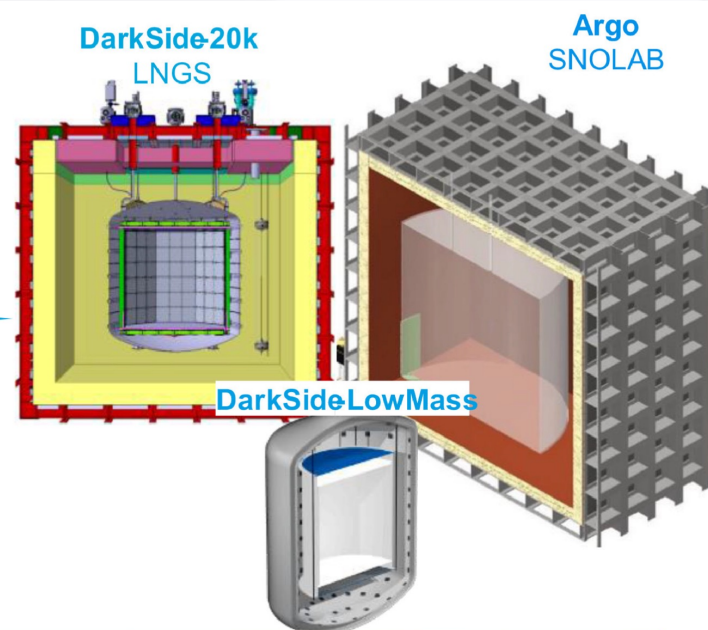
From G. Giovanetti



Global Argon Dark Matter Collaboration



From M. E. Monzani, IDM2024



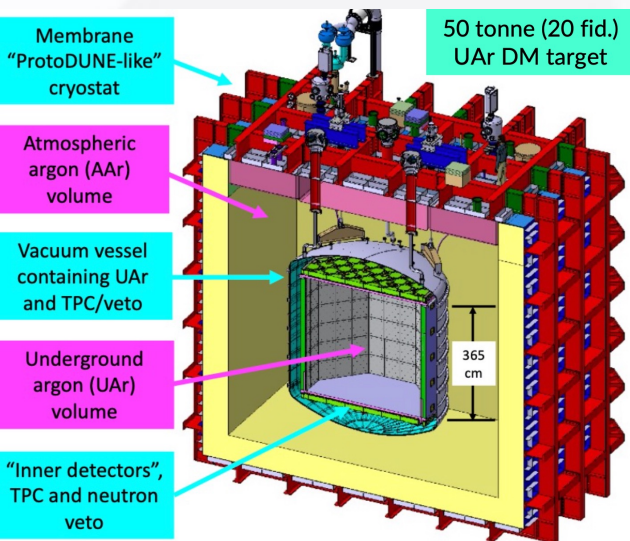
2011 2013 2016 2026 2030+

Higher intrinsic bkg with natural Ar, but with PSD discrimination!

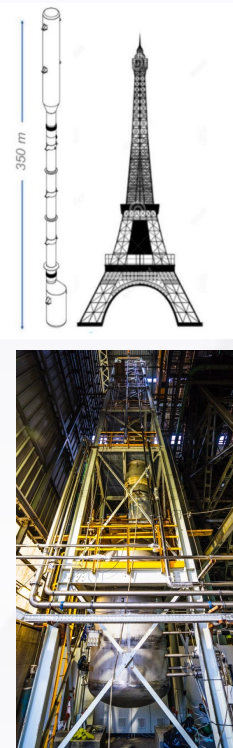
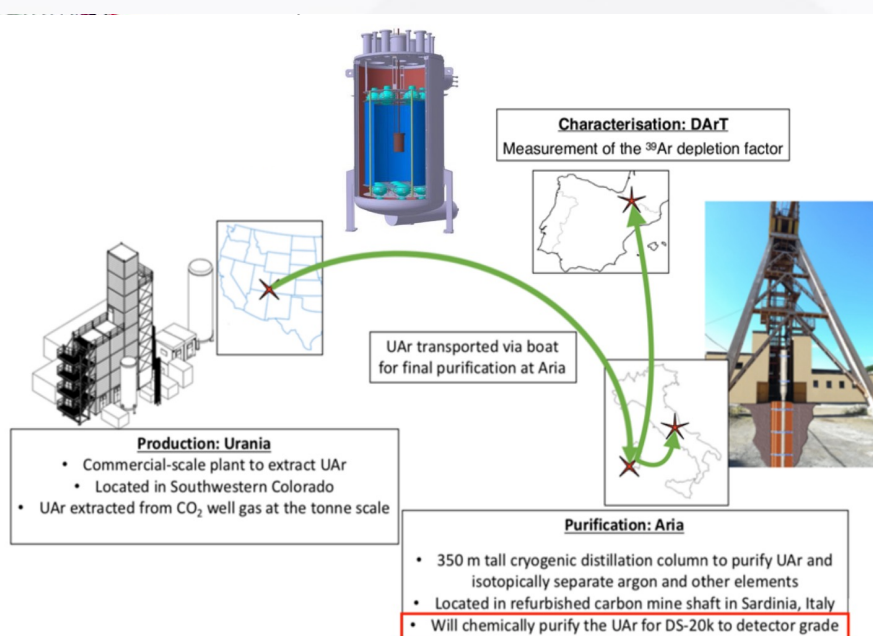
DarkSide-20k



From M.E. Montani, IDM2024



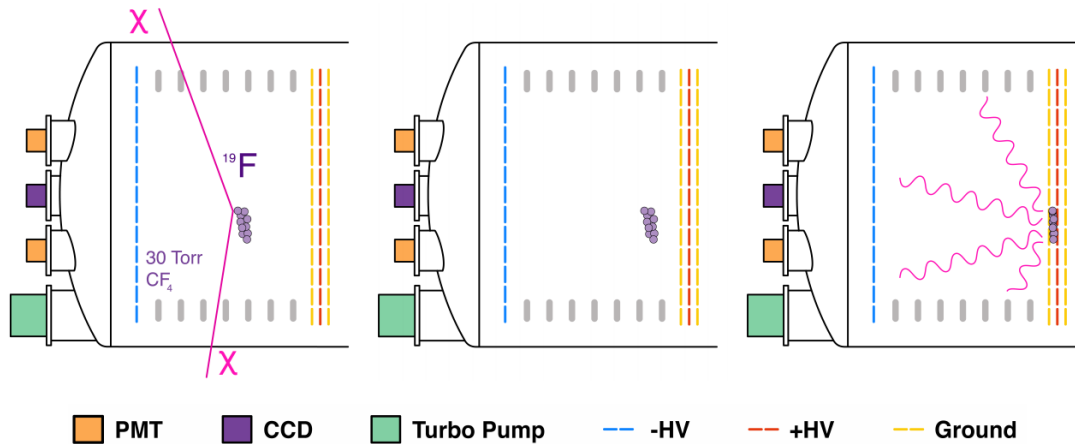
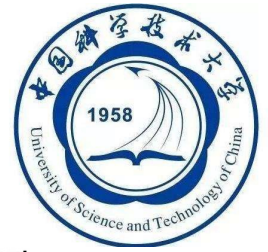
From Roberto Santorelli - La Thuile 2022



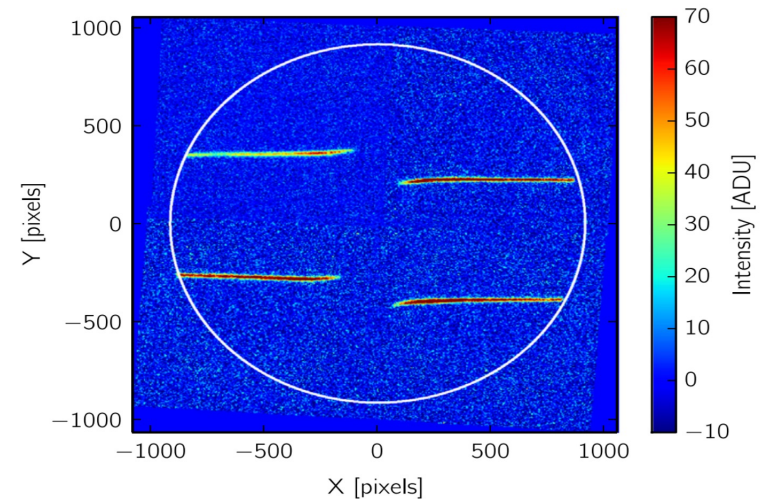
- ☐ Under construction, 2025~2026 data taking;
- ☐ 50-tonne total mass;
- ☐ 20t fiducial mass for 10-year exposure;
- ☐ SiPM 4pi coverage;

- ☐ UAr mined from Urania;
- ☐ Further distilled at Aria facility;

Directional Detector: DMTPC



Alpha tracks



- 30-70 Torr CF₄ gas.
- 1m³ volume
- Particle discrimination through track length and dE/dx.
- Angular sensitivity

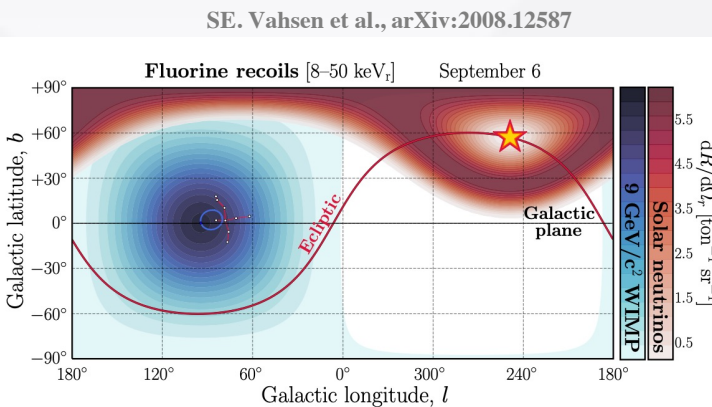
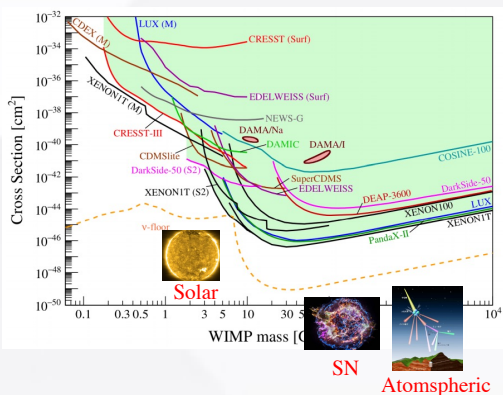
Pros:

- High discrimination power
- Angular resolution
- Spatial resolution.

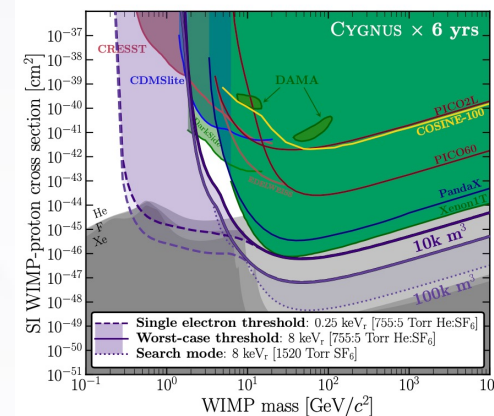
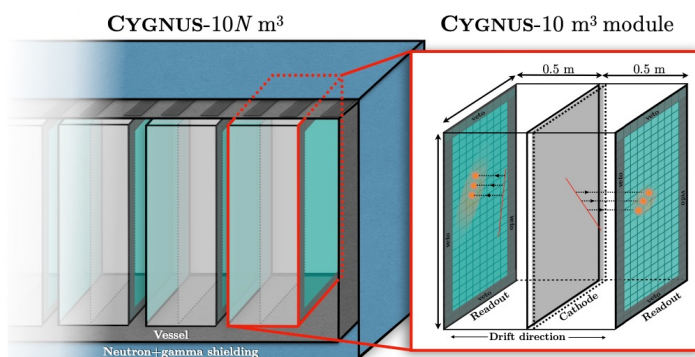
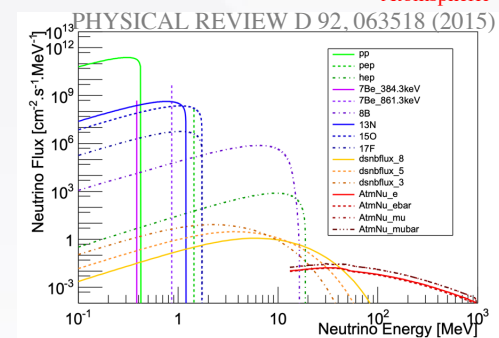
Cons:

- High threshold
- Low energy resolution.
- Exposure too low.

大型气体探测器：方向重建



- Low-pressure gaseous TPC;
- Highly pixelized charge readout for high track resolution;
- Directionality can help go beyond neutrino floor to some extent.

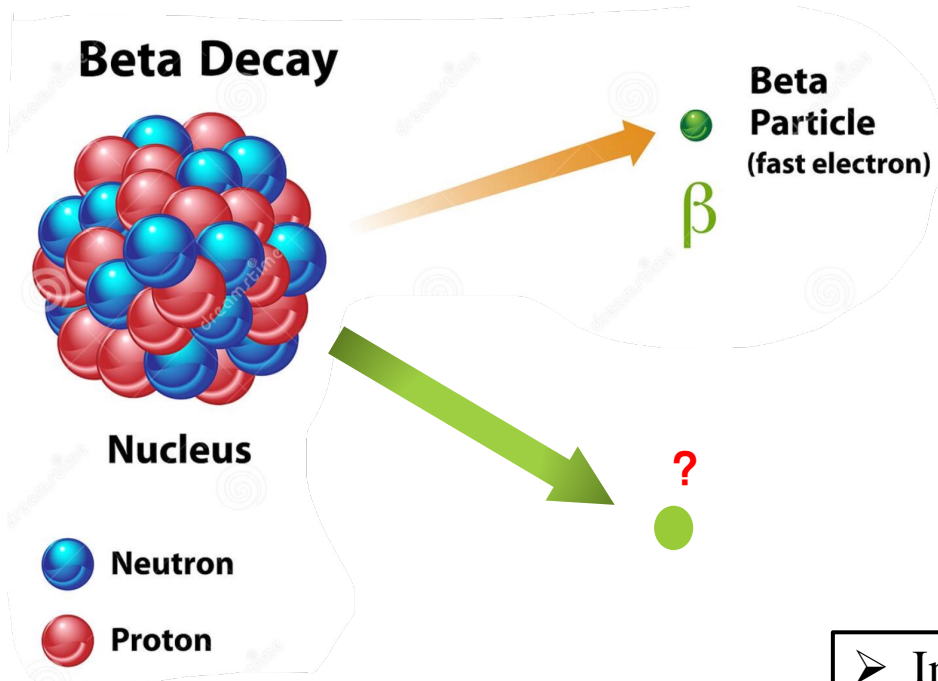


Ultimate background: neutrinos

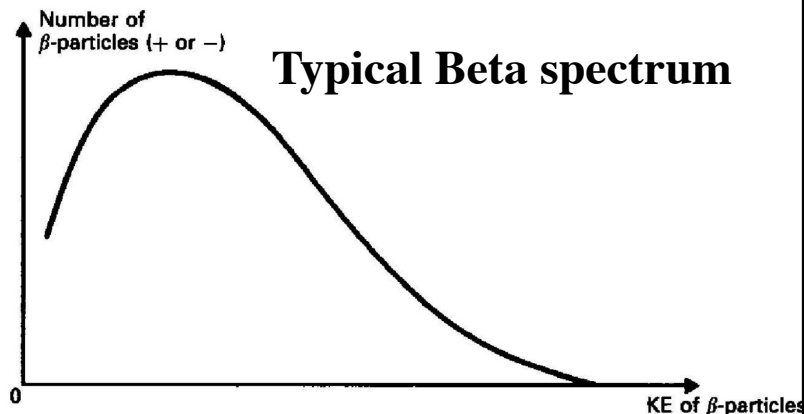


- 非加速器物理简介
- 非加速器物理实验
 - 暗物质
 - 中微子
 - 磁单极子&宇宙线探测

Early History of Neutrino



- In a beta decay, a nucleus decays another by emitting an electron.
- Conservation of energy tells us the energy of electron (beta radiation) shall have fixed energy. Measurements say NO!
- In 1930, Wolfgang Pauli postulates that another invisible particle is also emitted during beta decay. It has very weak interaction so hard to detect.



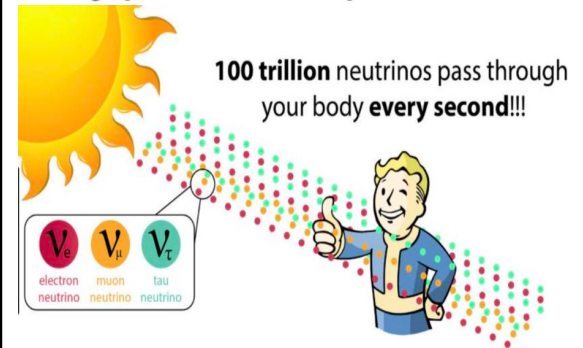
Known Facts of Neutrino

- Neutrinos are **fundamental particles**!
- **Trillions (10^{12})** of neutrinos pass per second through your body for every second of your life! They come from our Sun!
- Neutrinos are **ghostly particles**. They need **a light year of lead ($\sim 10^{13}$ km)** to be stopped with 50% chance.
- There are **a billion neutrinos for each atom** in the Universe. There are $\sim 3e8$ neutrinos per cubic meter: relic neutrinos.
- Neutrinos have a fixed chirality. They **only** interact through **weak interaction**!

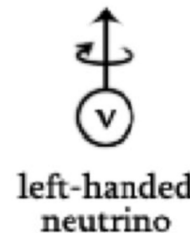
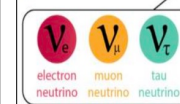


FACT: about 65 million neutrinos pass through your thumbnail every second.

Learn Something
New Every Day
LSNED.com



100 trillion neutrinos pass through your body **every second!!!**

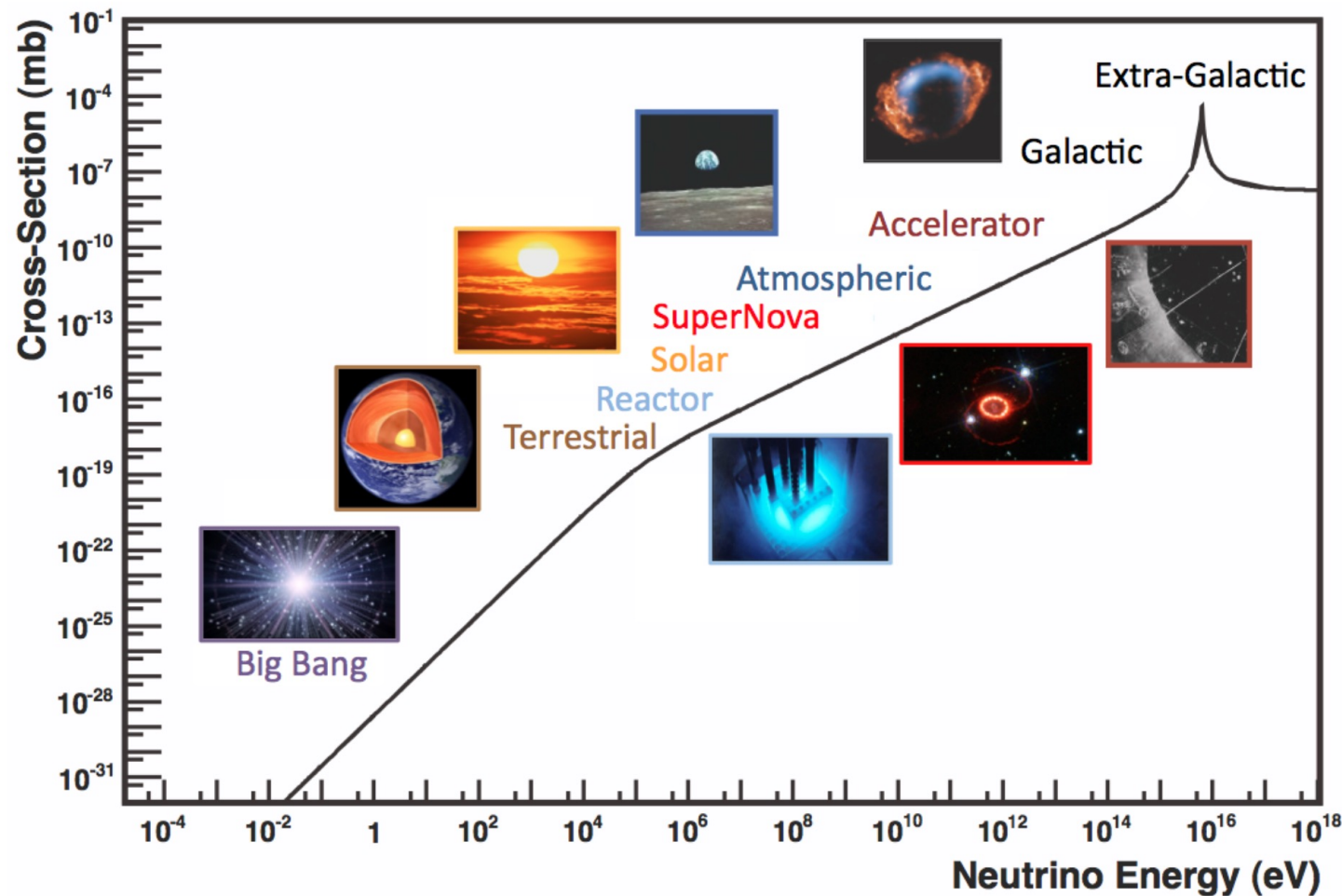


left-handed
neutrino



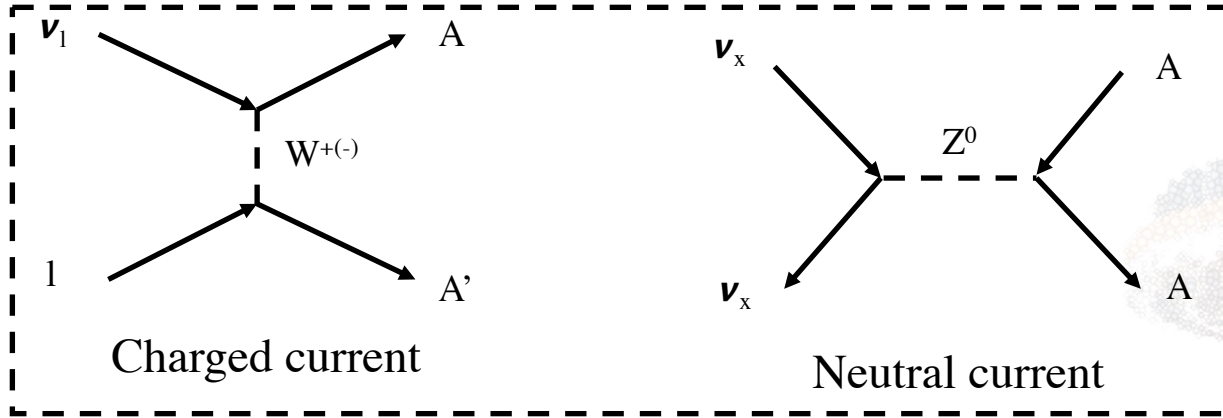
right-handed
neutrino

Neutrinos are Everywhere

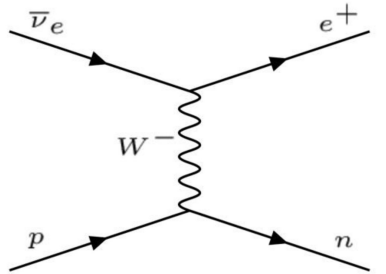


- Neutrinos are everywhere in Universe. Energy ranges from **eV** to **EeV** (10^{18} eV)! Interaction rate increases as energy!
- On earth, we can produce **MeV-GeV** neutrinos.

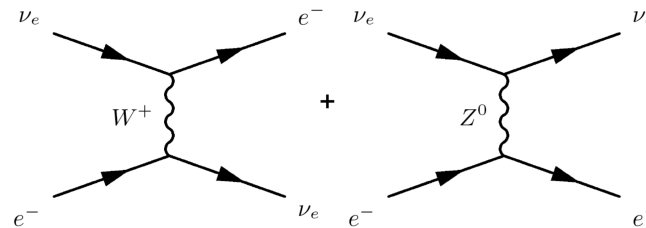
Neutrino Interactions



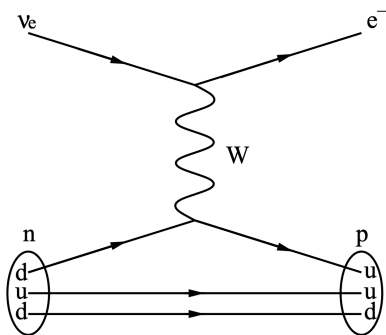
Fundamental Interaction



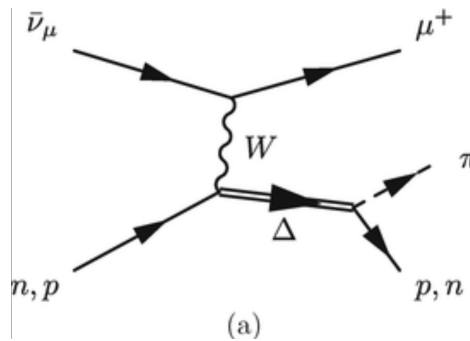
Inverse Beta Decay



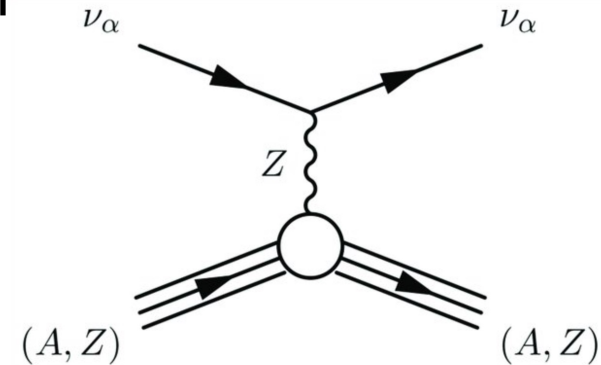
Neutrino-Electron Scattering



Neutrino Capture



Charged Current Quasi-Elastic



Coherent Elastic v-Nuclei Scattering (CEvNS)

- Deposit energy $\sim$ keV;
- Cross section high;

Discovery of Neutrino



Savannah River reactor

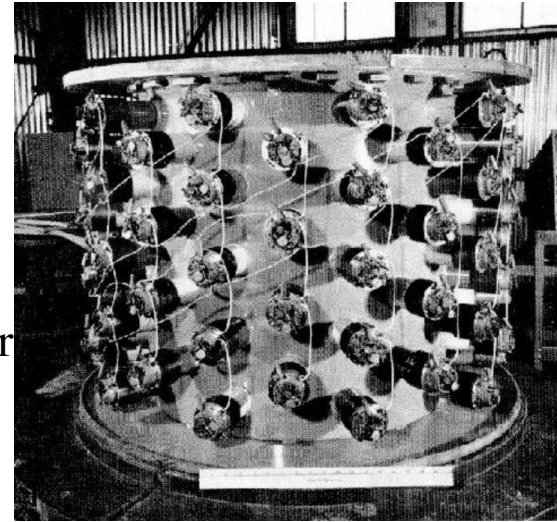


10^{19} neutrinos
per second!



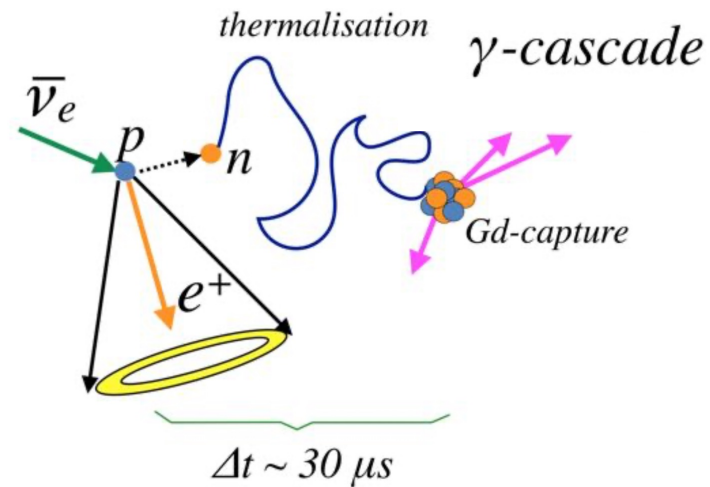
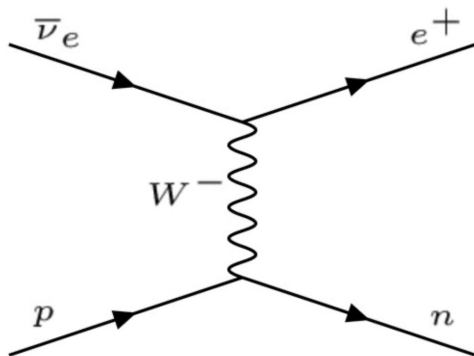
11m from reactor

Savannah River neutrino detector



Filled with 200
liters of water,
dissolved with
40kg of CdCl_2 .
And liquid
scintillator for
gamma
detection.

Inversed Beta Decay (threshold 1.8MeV)



Discovery of Neutrino

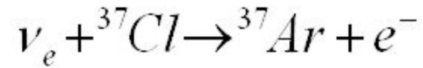


- Interestingly, this was not the first idea of Cowan and Reines.
- They originally had proposed (and got approved!) to put an experiment close to an even more intense neutrino source!
100 meter away from an atomic bomb blast!
- They abandoned that idea when they realized there were certain ‘**practical problems**’ for the detector... (to survive the blast)

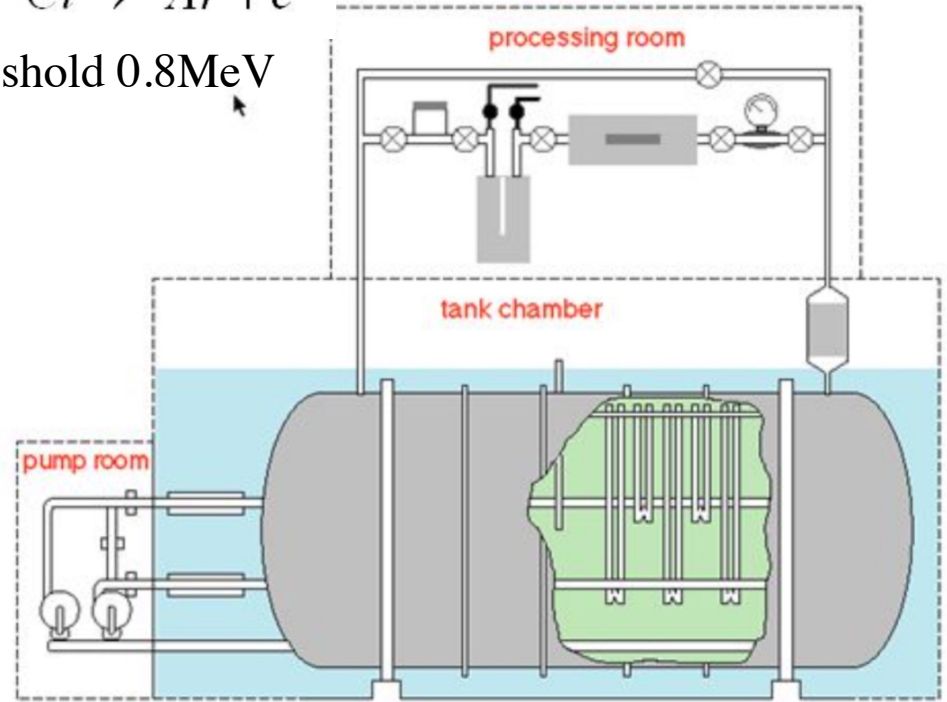
The Mystery of the Missing Neutrino



Homestake Experiment: First to detect solar neutrino

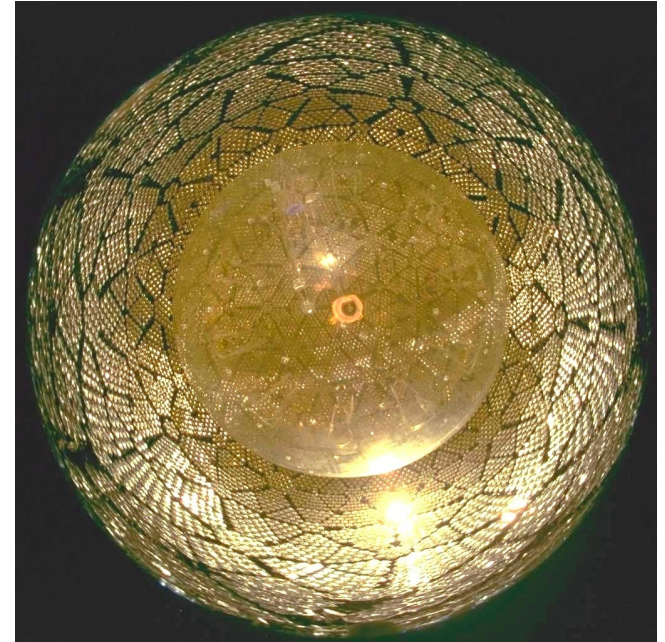
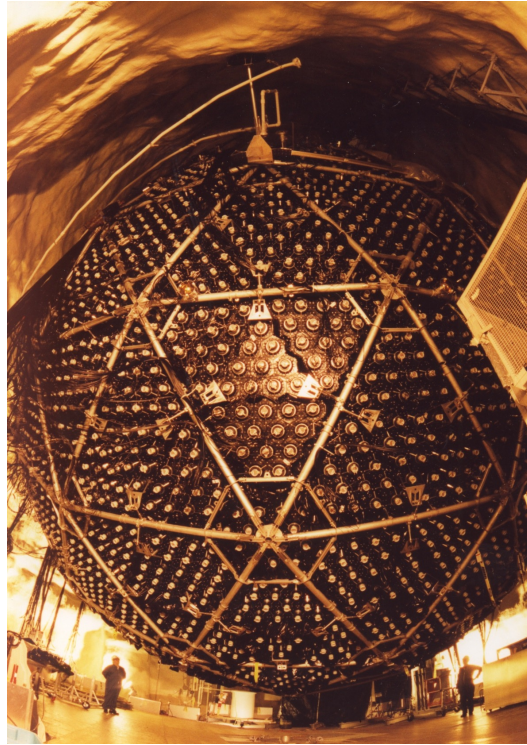
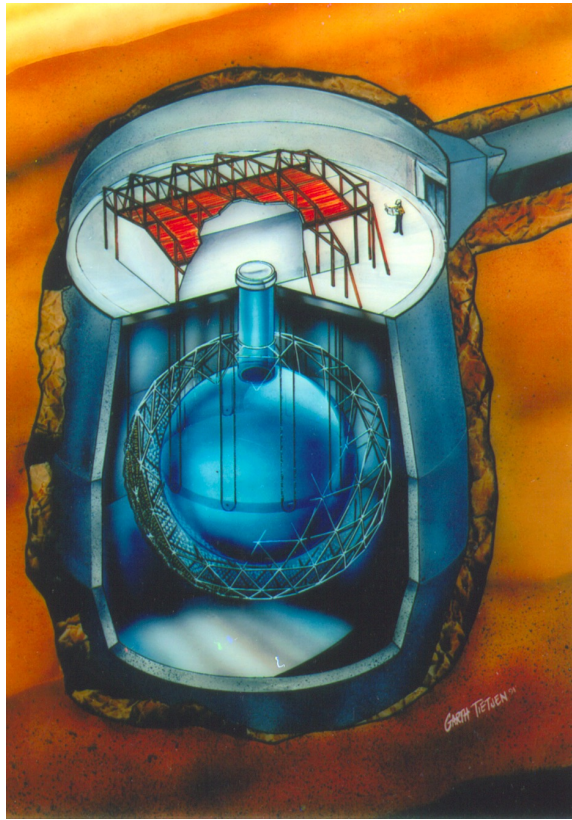


Threshold 0.8 MeV



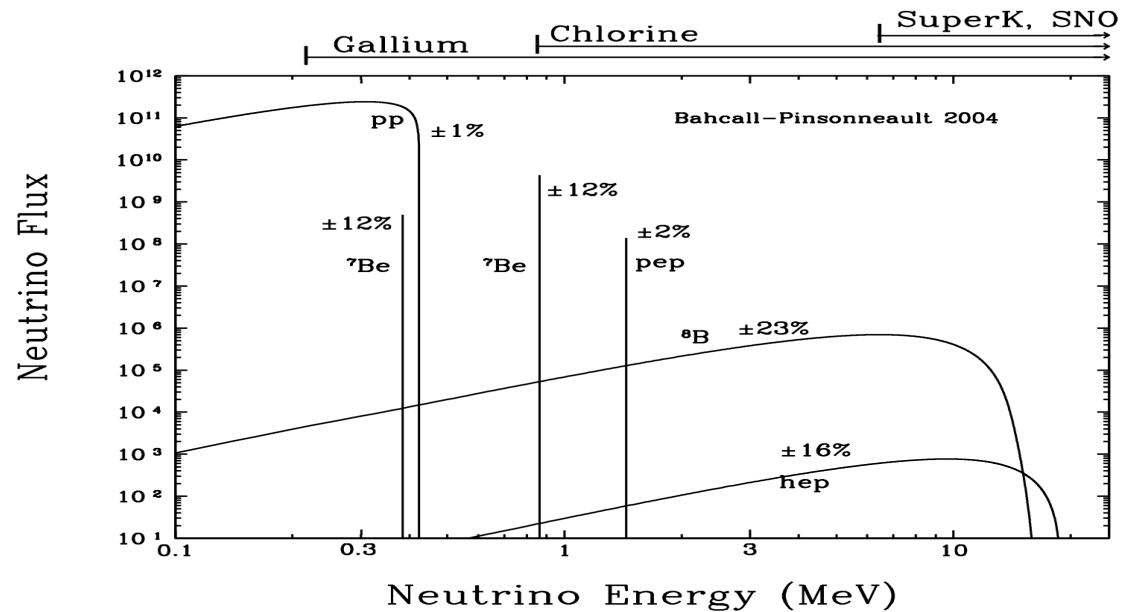
- Argon 37 has a half-life of 36 days.
- Helium bubbled through main chamber to collect Ar into a small gas chamber.
- Expected **1.5 Ar atoms/day** from Solar model, detected only **1/3**.

Sudbury Neutrino Observatory (SNO)



- SNO has a central transparent acrylic spherical vessel filled with **1000 tonnes of heavy water (D_2O)**. Light water (H_2O) fills outer vessel. **9438** photomultipliers views the whole volume.
- Before SNO, other experiments have confirmed the solar neutrino deficit in different energy range, however with different missing ratio. Such as SuperK observes slightly more solar neutrino than Homestake experiment.

Three Detection Channels



Charge Current Quasi-Elastic Scattering:



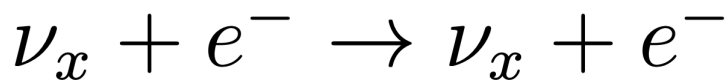
Because of energy is too low, only ν_e can participate such channel.

Neutral Current Scattering:



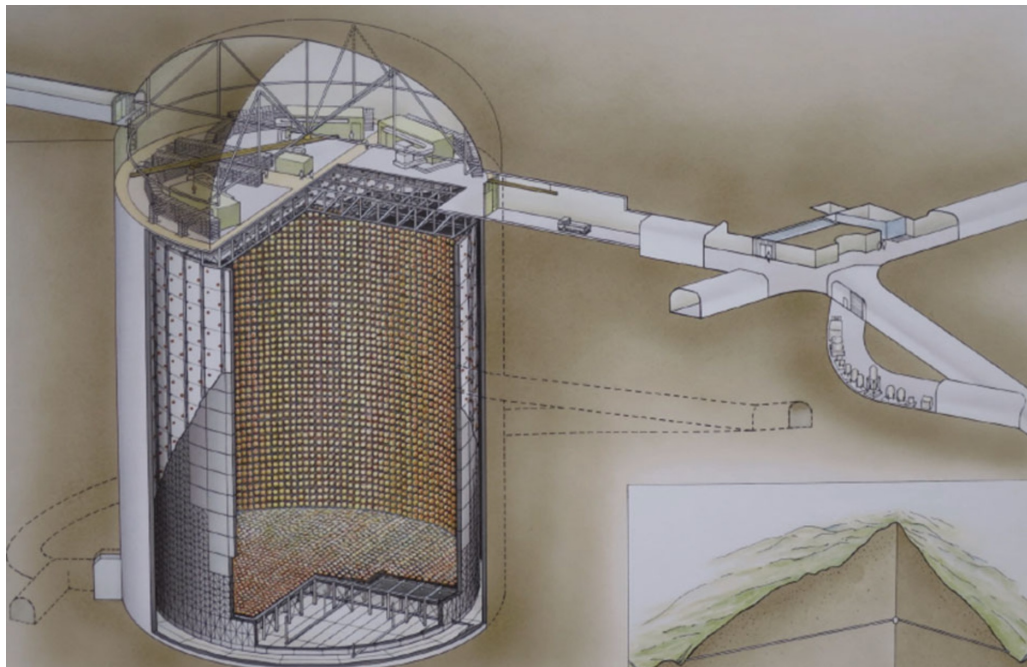
All flavors participate in such channel, with equal odd.

Electron Elastic Scattering:

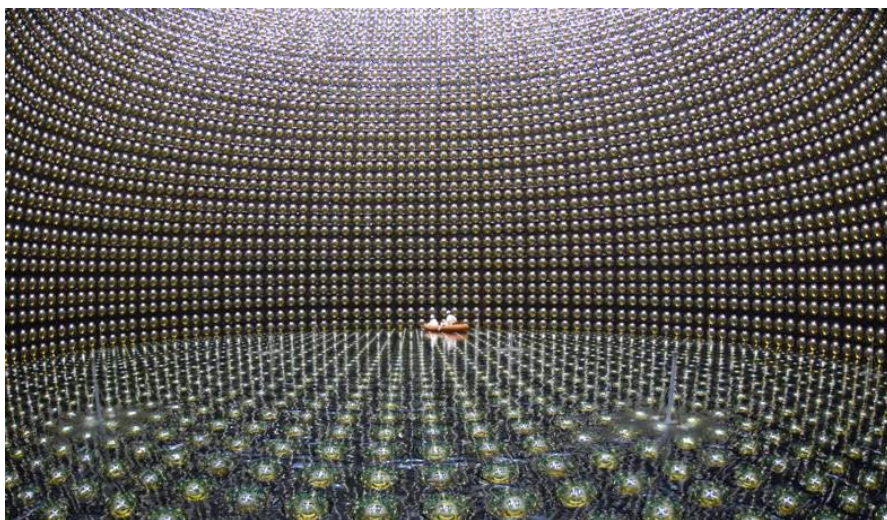


All flavors participate in such channel, with ν_e 6 times more probability than ν_μ and ν_τ

Super Kamiokande



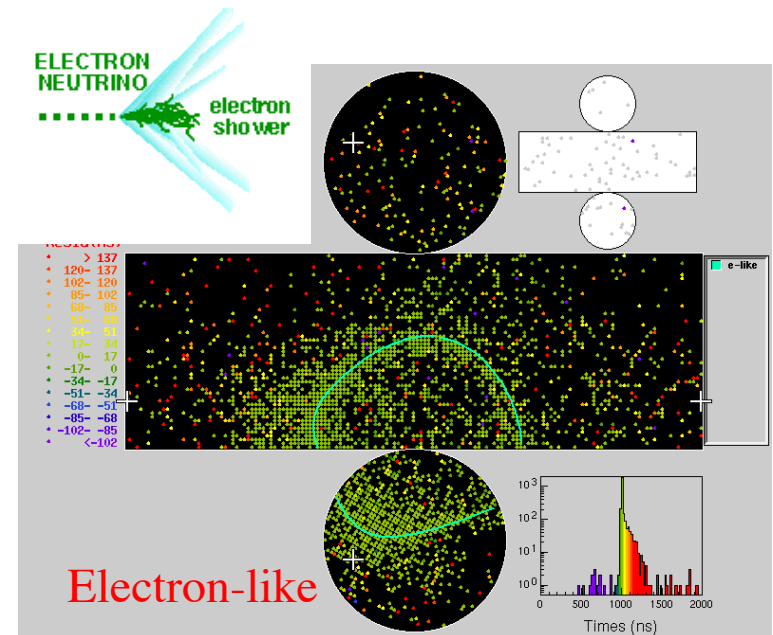
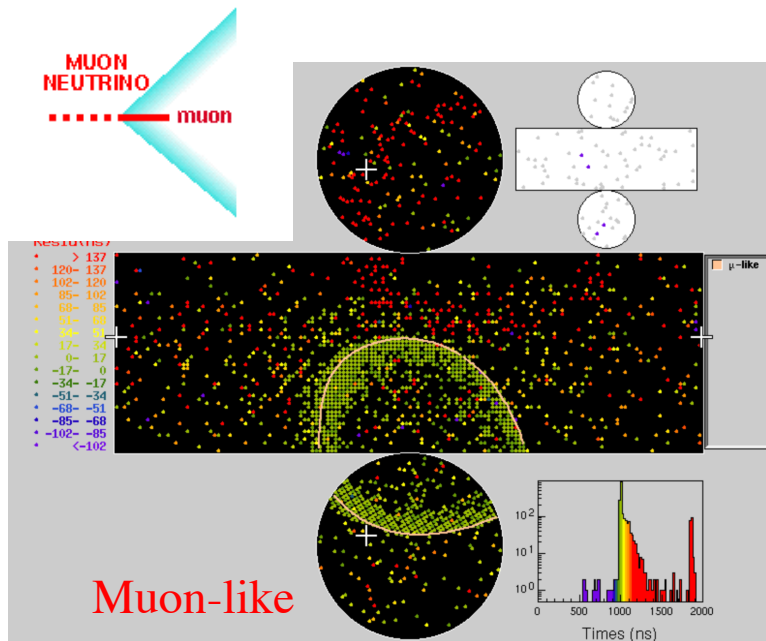
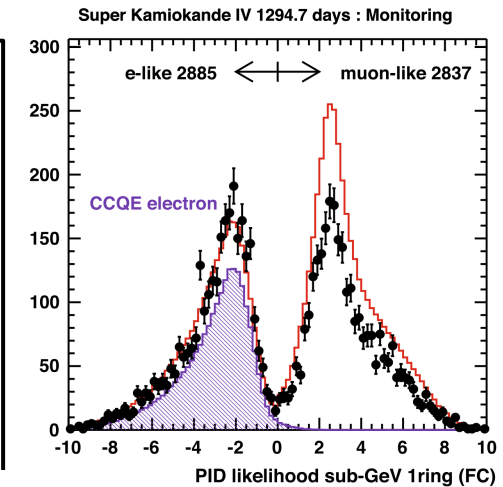
- Detector is filled with **50k tonne** ultra pure water;
- **13,000** Photo-multipliers are instrumented inside.



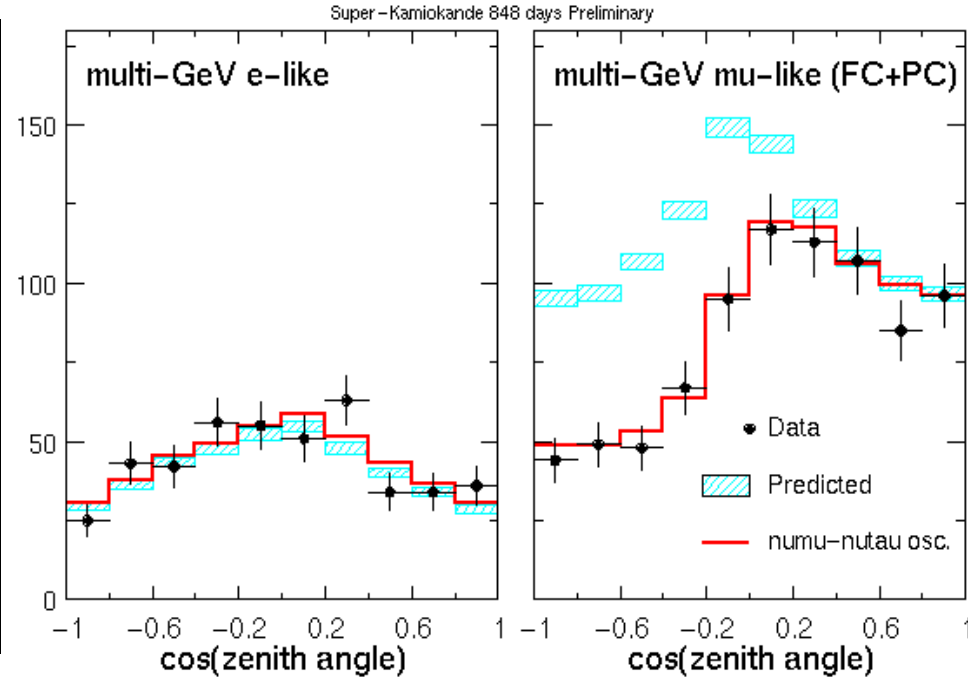
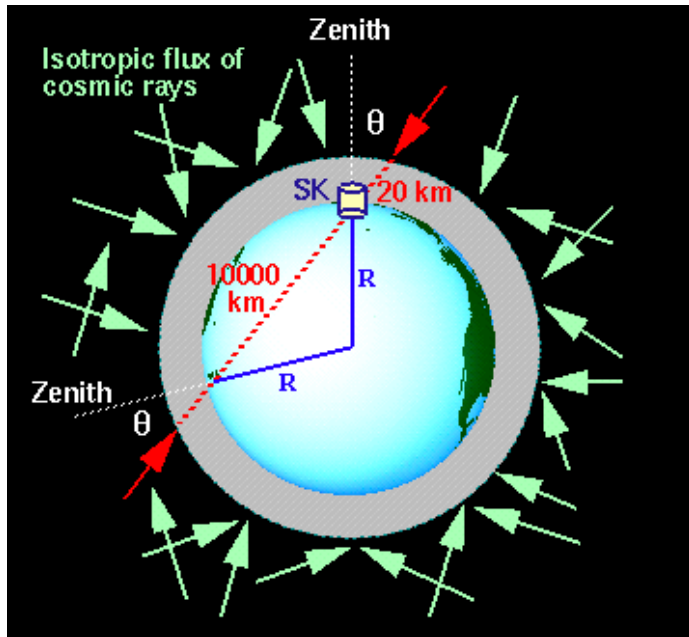
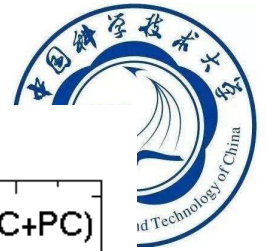
Atmospheric Neutrino in SuperK



- Electron- and muon-neutrinos are produced through **pion and Kaon decays** after high energy cosmic rays collide with atmosphere;
- CCQE channel $\nu_l + N \rightarrow l + N'$ for detecting μ or e neutrino.
- Signature is Cherenkov radiations produced by charge particles moving through material;
- High-energy electrons can produce **electromagnetic shower** (secondary particles), "blurring" the "ring" structure.



Atmospheric Neutrino in SuperK



- Electron- and muon-neutrino ratio measured not to be what was predicted by pion and Kaon decay;
- And the ratio has dependence on the zenith angle, aka the travel length from the production site of atmospheric neutrino;
- It turns out to be the result of muon-neutrino oscillating into tau-neutrino.

Neutrino Oscillation



Two Neutrino case:

$$U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \quad P_{\alpha \rightarrow \beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2 \left(1.27 \frac{\Delta m^2 L [\text{eV}^2] [\text{km}]}{E [\text{GeV}]} \right)$$

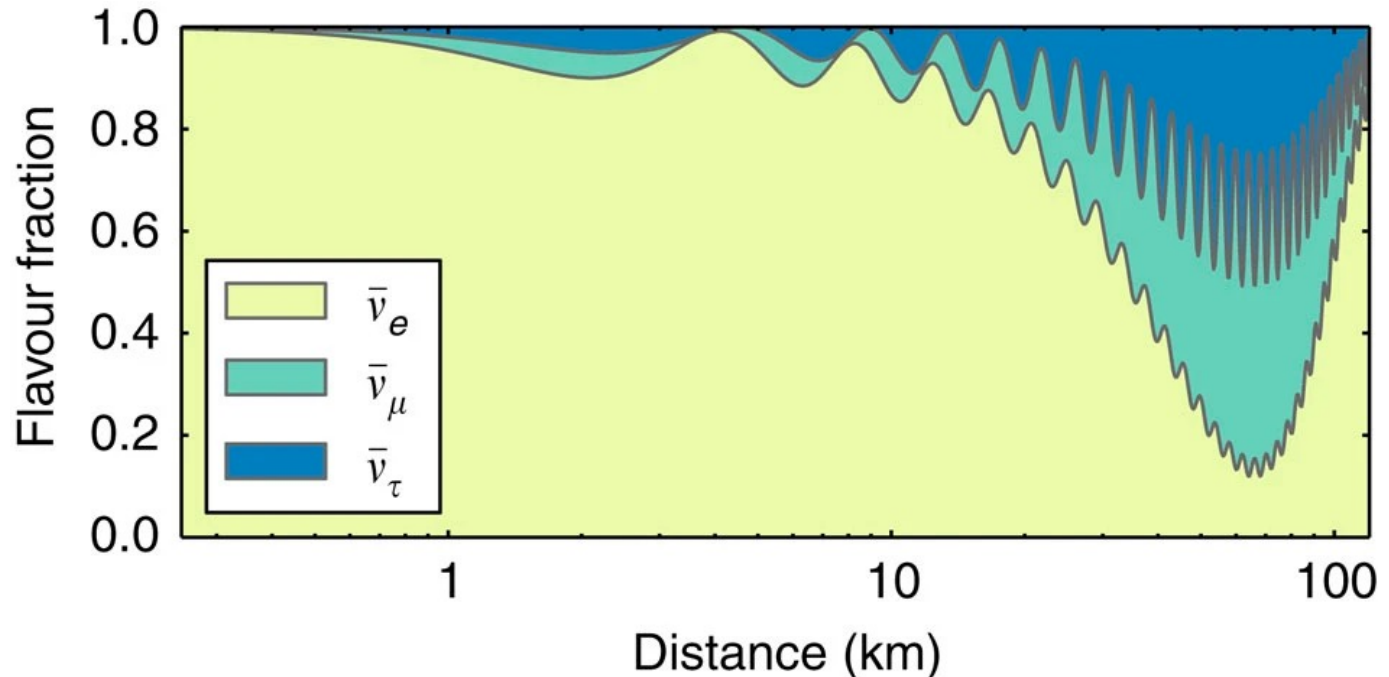
Important Parameters

L - Baseline

Δm^2_{12} - mass difference

Higher the energy is, longer the baseline.

An oscillation example for reactor neutrino (MeV)



Neutrino Oscillation



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

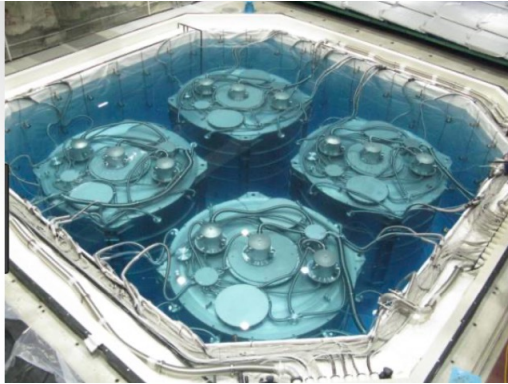
ν_μ disappearance

Solar neutrino oscillation

ν_e appearance in ν_μ beam
Or
reactor neutrino experiments

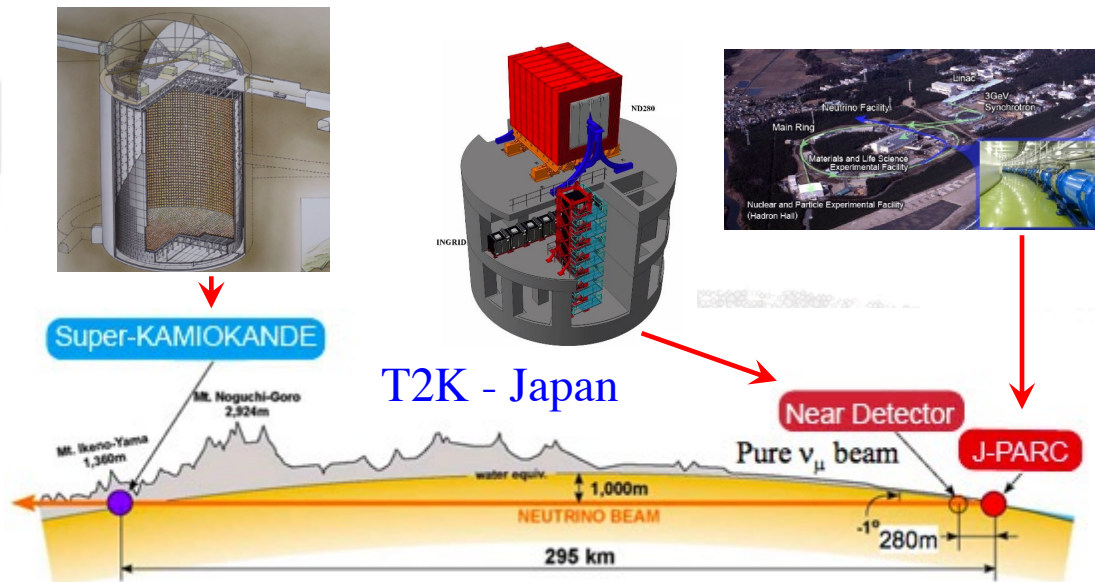
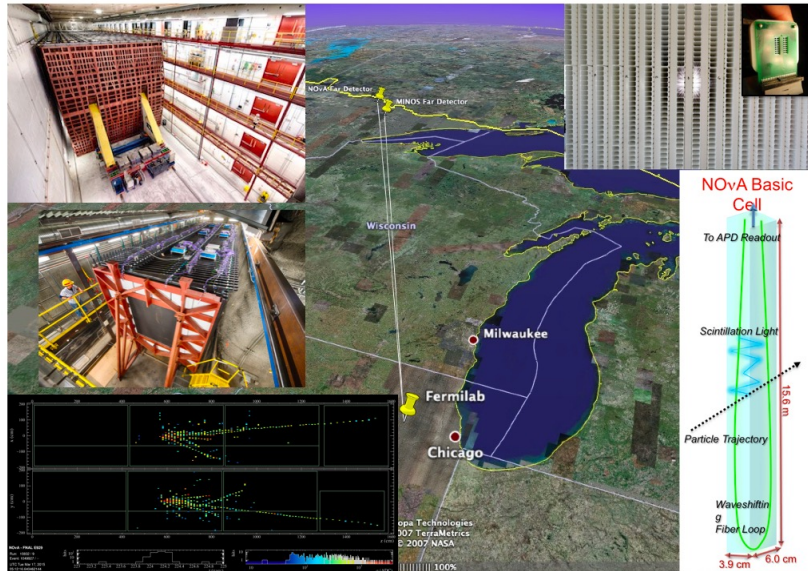
ν -less double beta decay

Daya Bay - China



The main image is an aerial photograph of the Fukushima Daiichi Nuclear Power Plant. The plant is situated on a peninsula surrounded by water. It features several large, white, cylindrical cooling towers and a complex of industrial buildings. Two inset images are overlaid on the main image. The inset on the left is labeled 'CLIMATE DETECTION' and shows a cross-section of a reactor core with a 'CLIMATE DETECTION' label. The inset on the right is labeled 'SWITCHABLE DETECTION' and shows a cross-section of a reactor core with a 'SWITCHABLE DETECTION' label. The background of the main image is a lush green landscape with a river flowing through it.

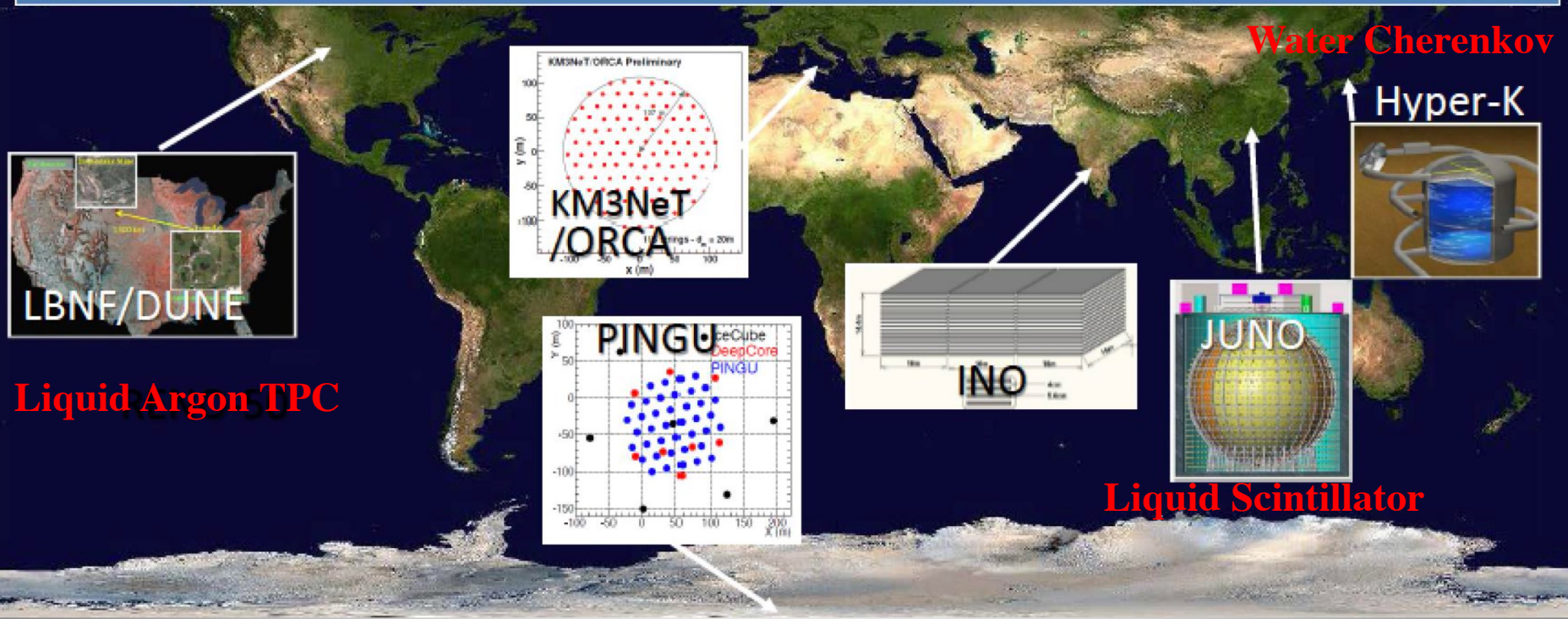
NOvA - USA



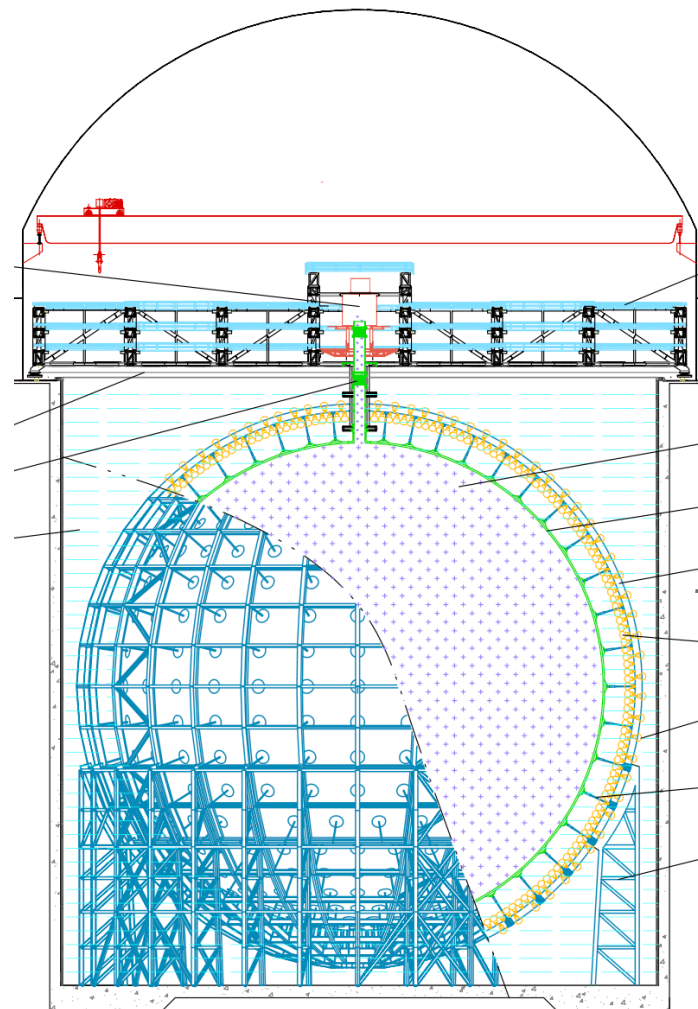
Future Experiments



We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with $> 3 \sigma$ CL from each exp.

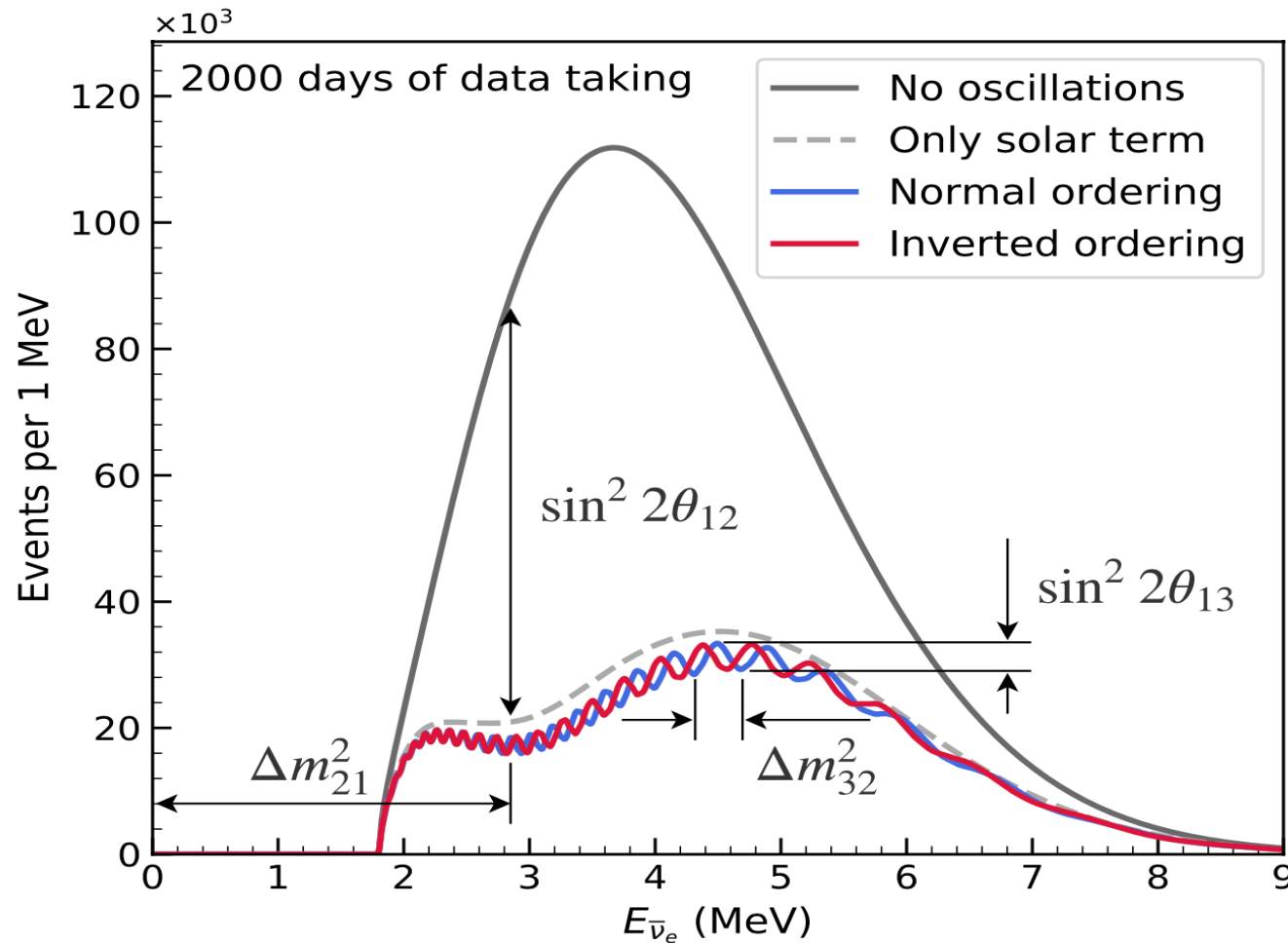


JUNO Experiment



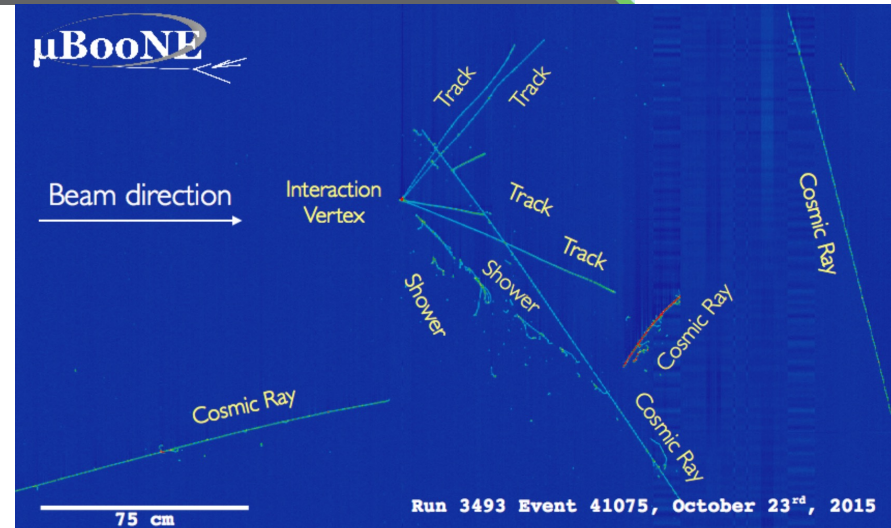
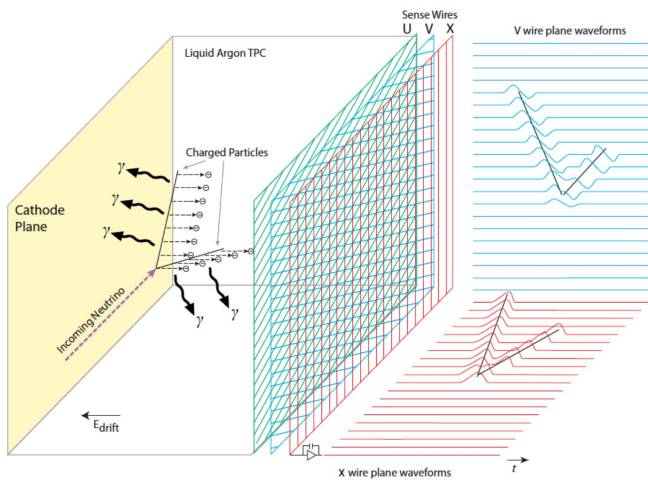
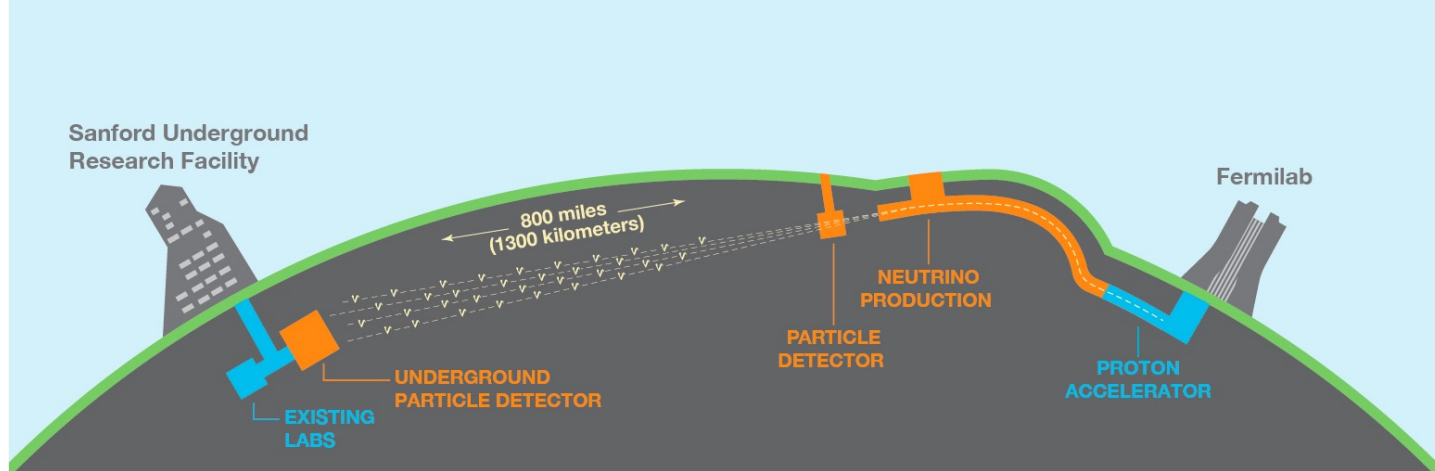
- Central detector is **20k tonne** liquid scintillator.
- Equal Distances (53km) to two reactors.
- Photo detection efficiency is **27%**.
- Main neutrino channel is **inversed beta decay**.

Primary Physics Goal of JUNO



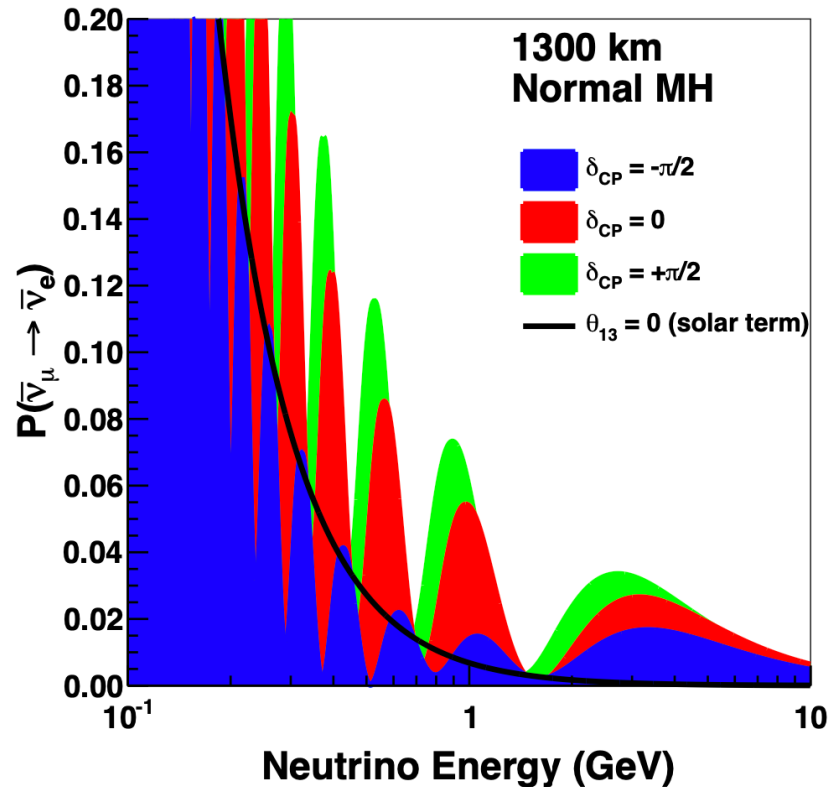
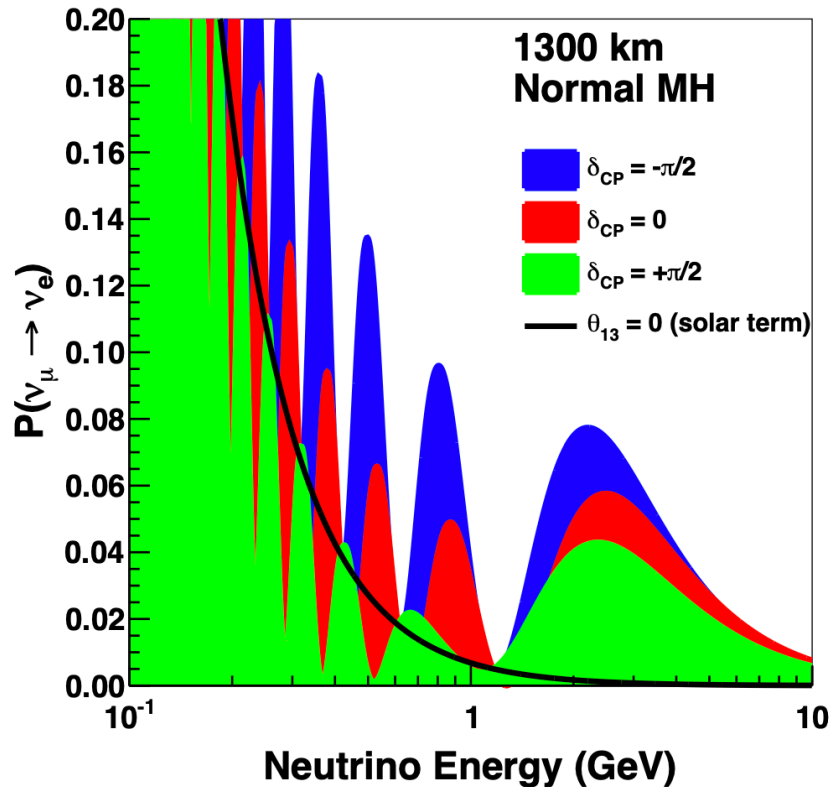
- Main physics target of JUNO is mass hierarchy of neutrinos. It is determined through the “phase” of 1-3 oscillation in energy spectrum;
- It requires very high energy resolution, about **3% at 1MeV**.

DUNE Experiment



- Four **10k tonne** level far detector.
- Accelerator produced muon-neutrino and muon anti-neutrino;
- Main detection channel is CCQE;
- LArTPC can identify the topology (outgoing product particles).

Primary Physics Goal of DUNE



- Besides the mass hierarchy, DUNE can also discover the CP phase by significance of **>5 sigma**.

Hyper-K实验

