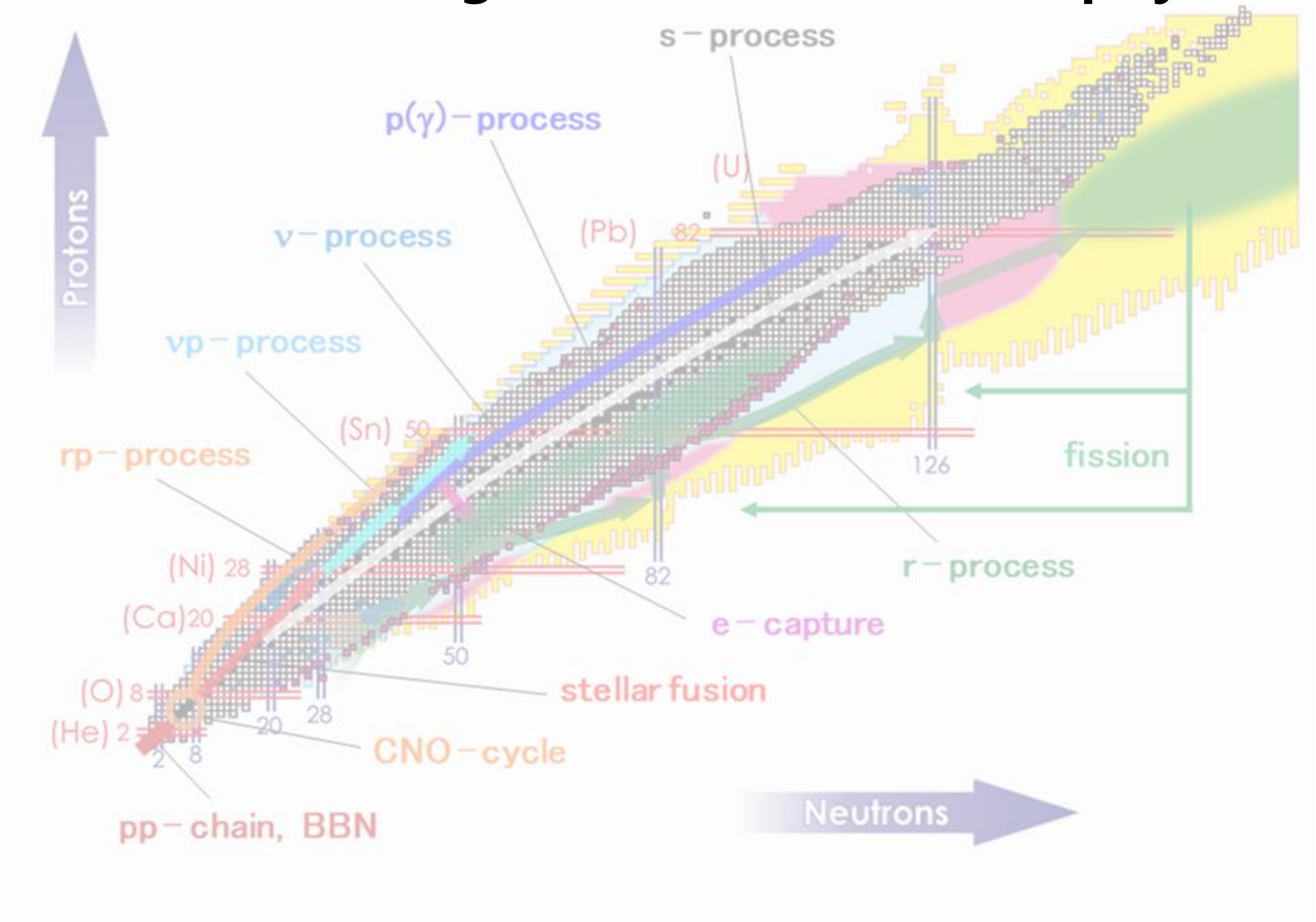
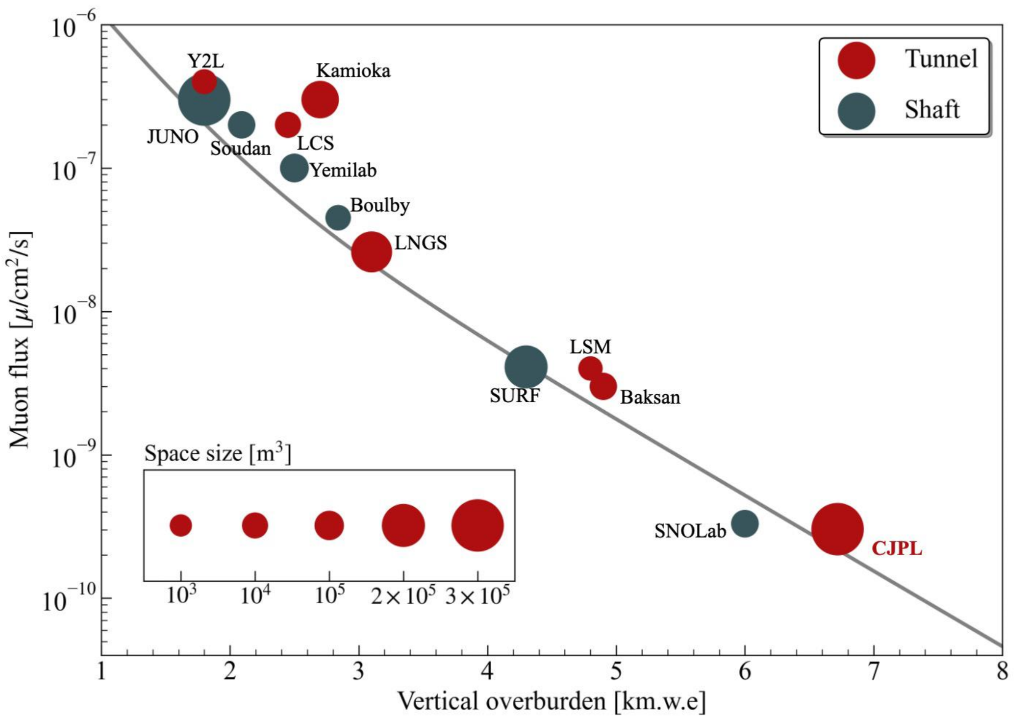
핵 합성 연구를 위한 고심도 지하 이온 빔 가속기
Yemi Underground Nuclear Astrophysics @ Korea (YUNA@K)

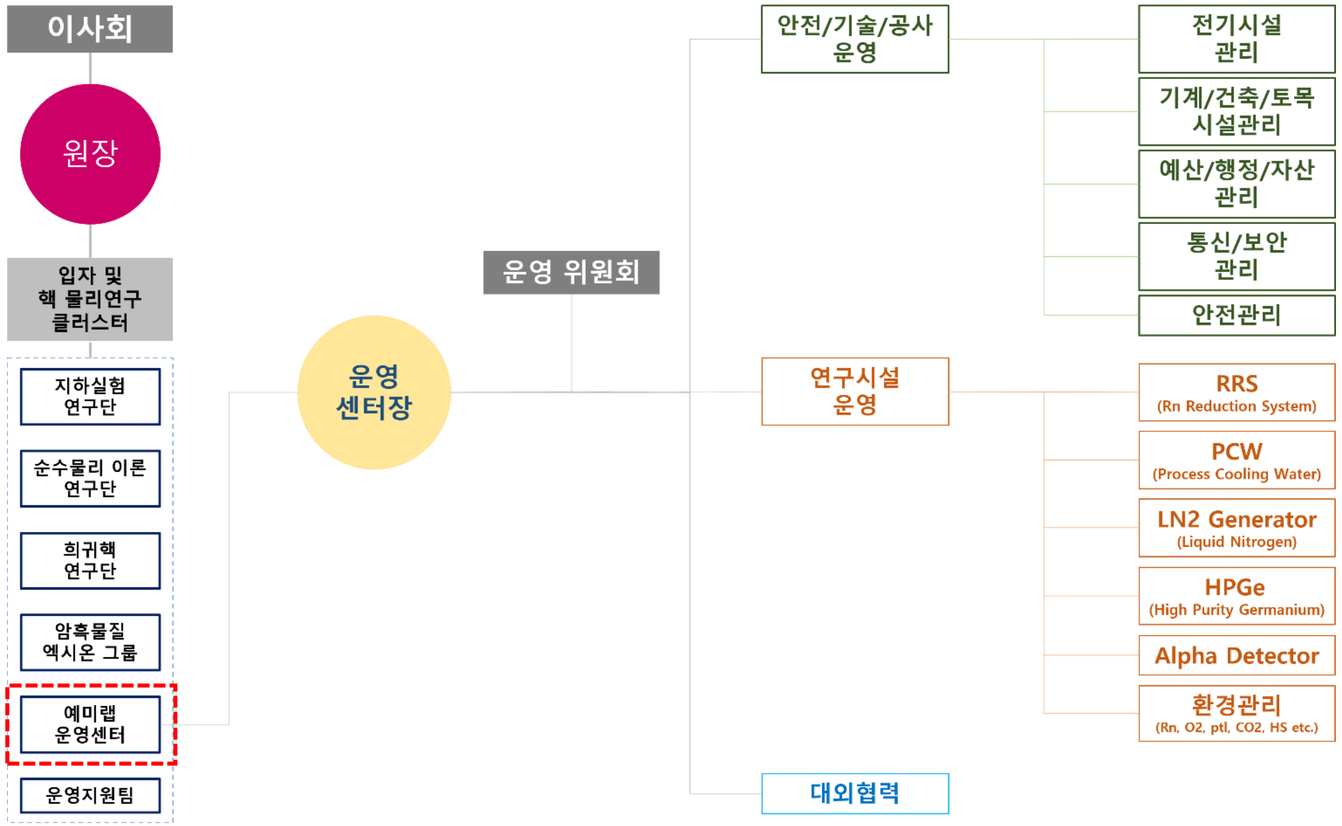


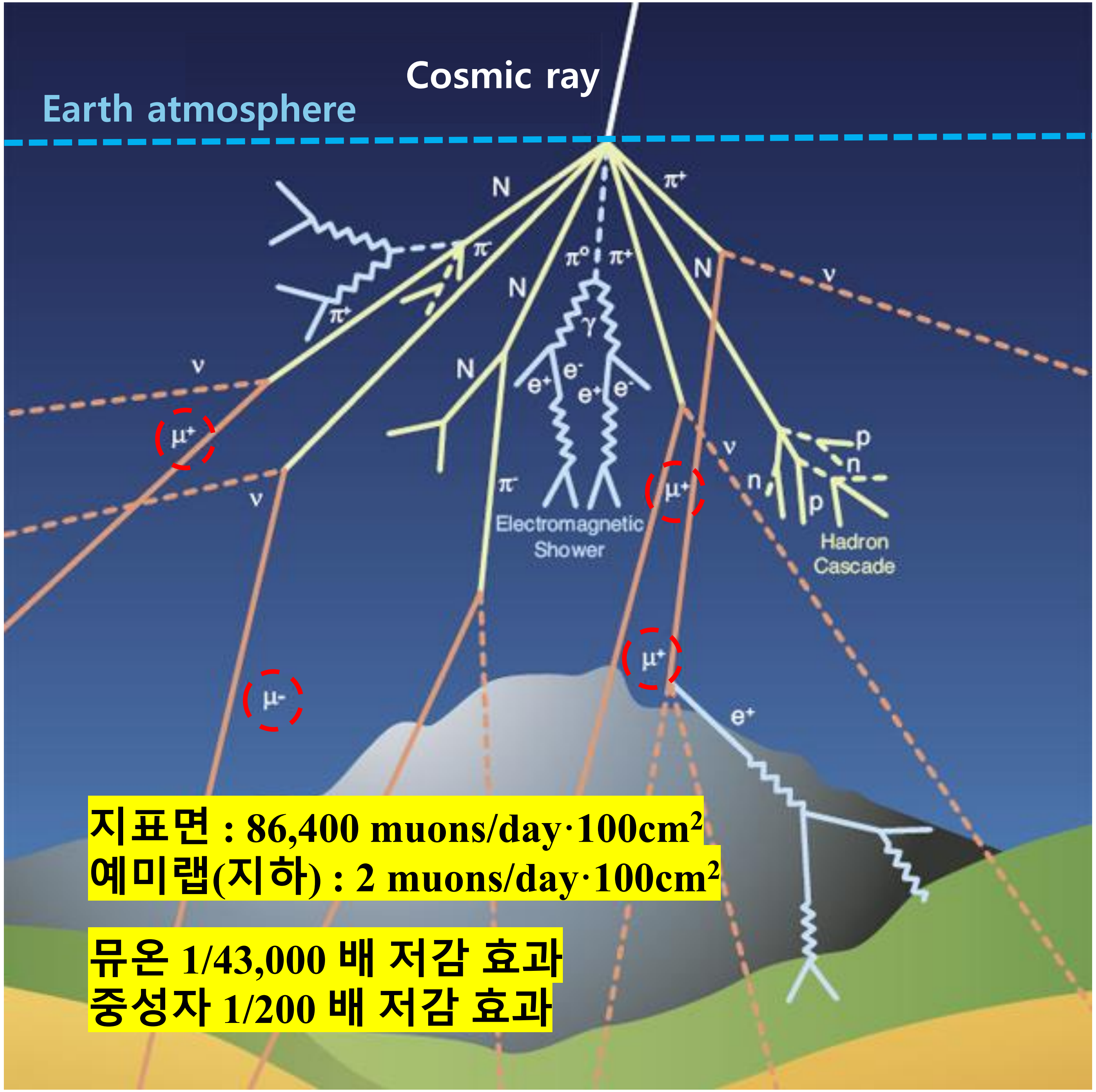
Yemilab Operation Center
Jungho So

예미랩

- 예미산 정상에서 지하 1,009 m (해수면 이하 120m)
- 구축비 : 300억원
- 실험 가용 면적 3,000m² (총면적 10,000m², 세계 6위)
- 2022. 10. 지하실험연구단의 실험 목적으로 준공
- 2025. 03. 예미랩 운영 센터로 독립 운영





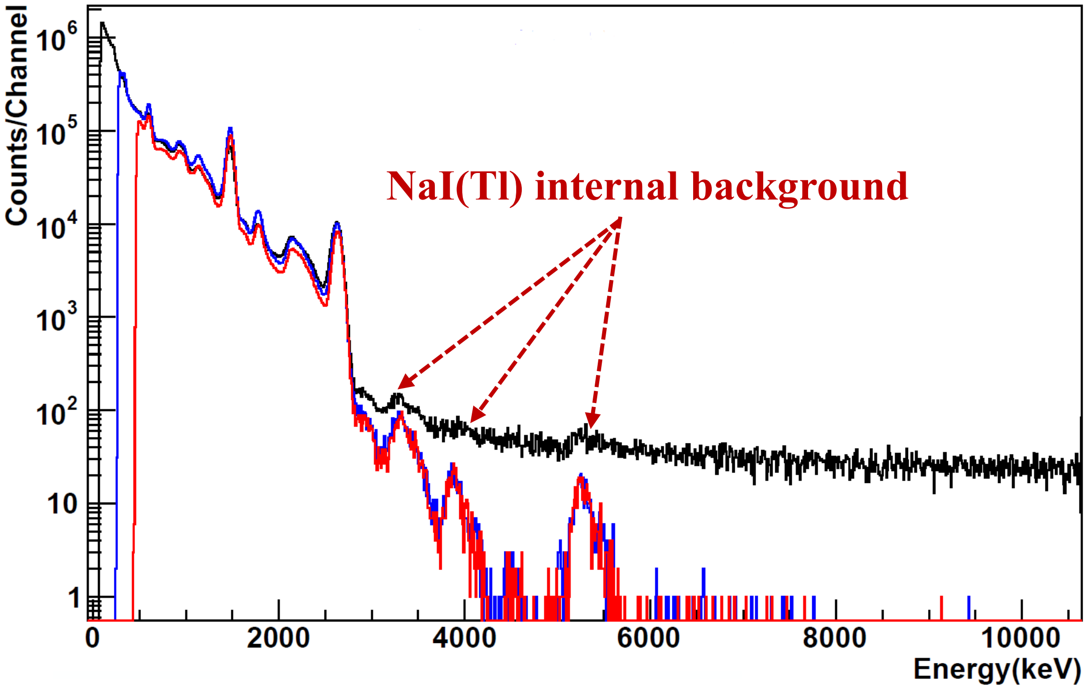


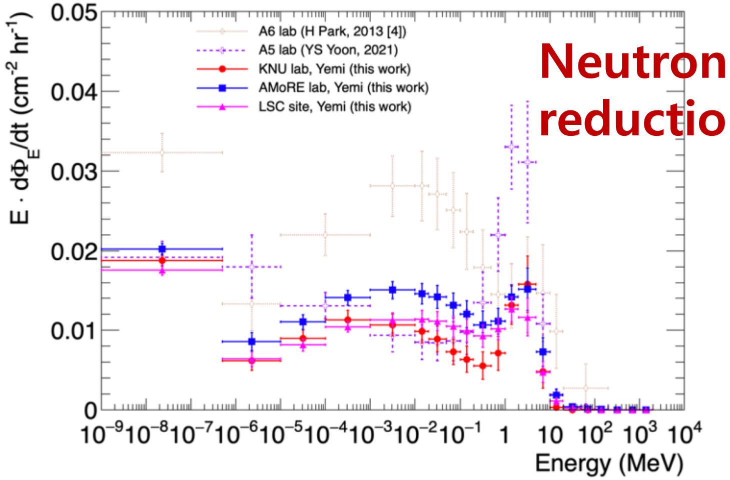
지표면 : 86,400 muons/day·100cm²
예미랩(지하) : 2 muons/day·100cm²

뮤온 1/43,000 배 저감 효과
중성자 1/200 배 저감 효과

NaI(Tl) background spectrum

- Black line : 지상
- Red and Blue line : 예미랩 (지하 1,000m)

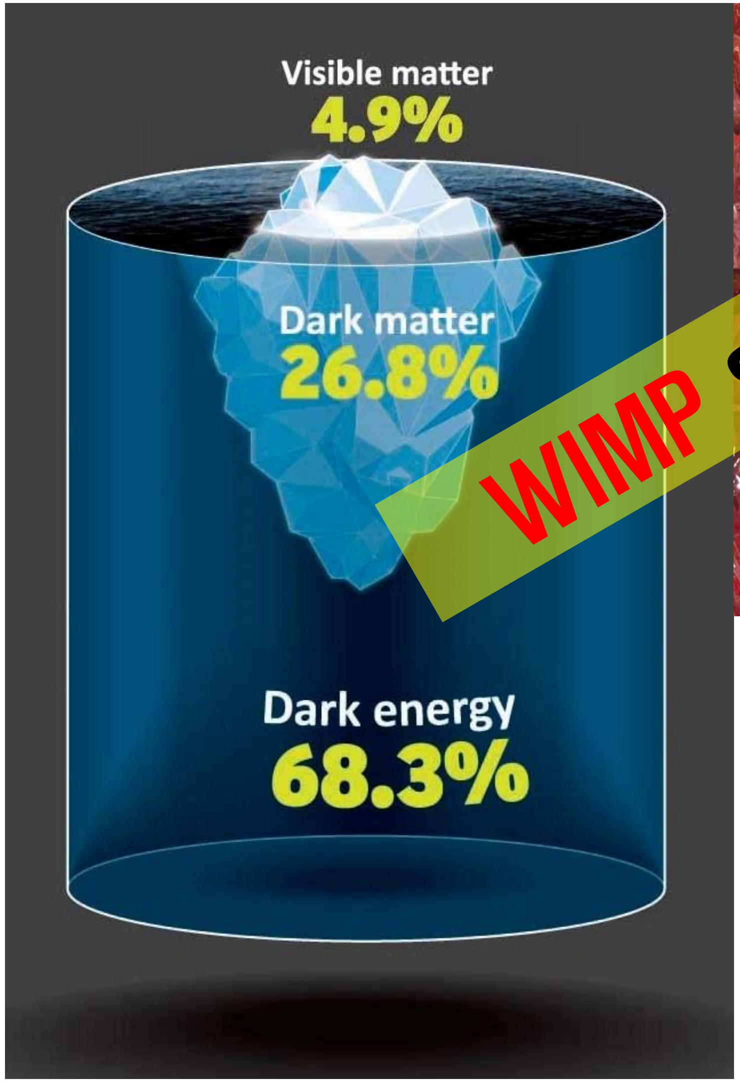




Neutron 1/200 times reduction

CENTER FOR UNDERGROUND PHYSICS

Major Physics topics at Yemilab



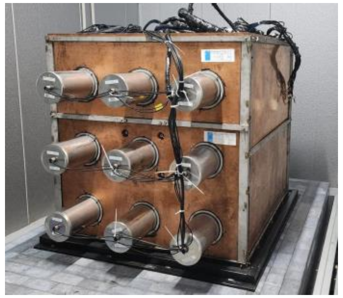
WIMP search

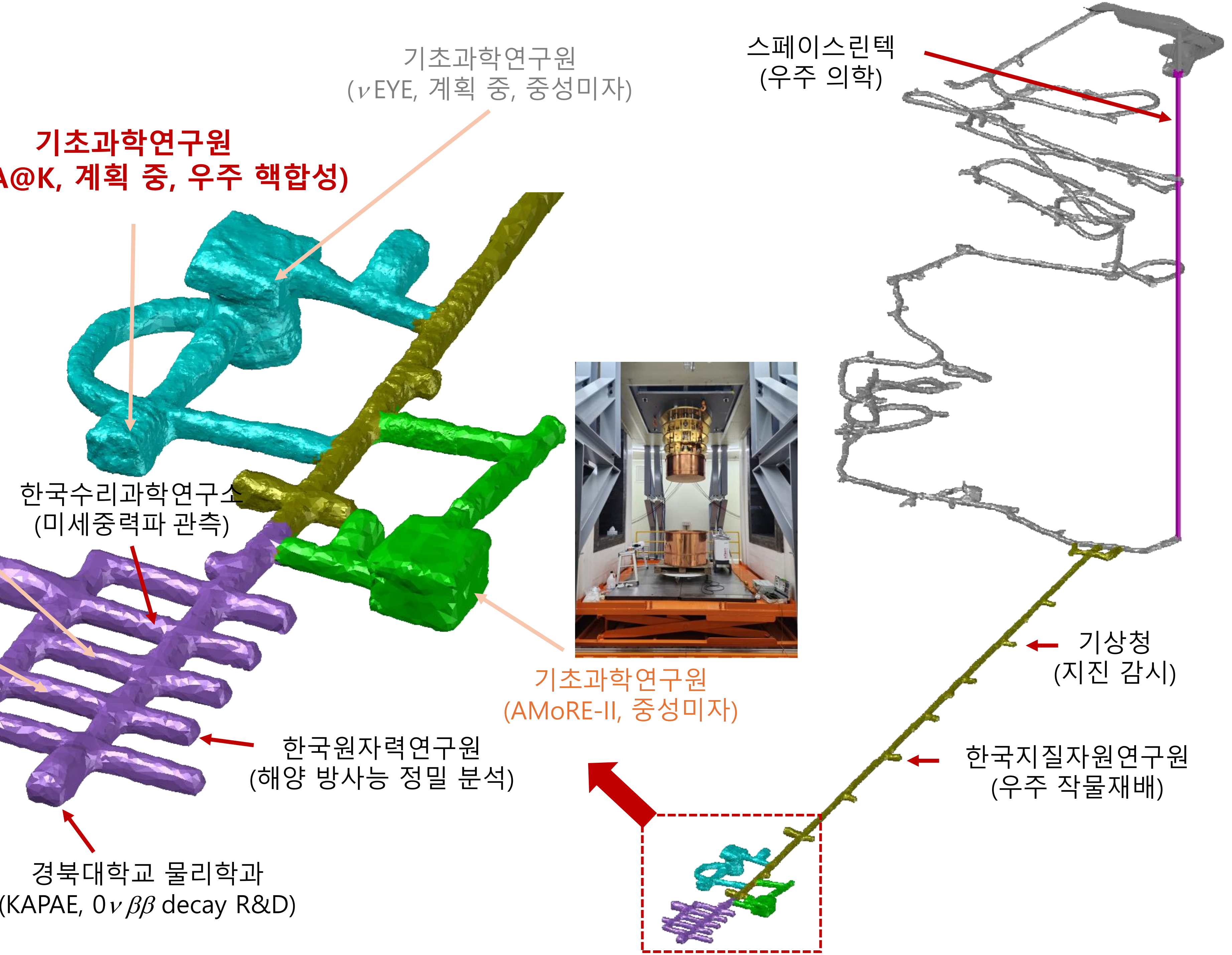
$0\nu\beta\beta$ decay search

다목적 연구시설

5 국립연구기관
1 국립대학
1 스타트업 회사

→ 11개의 연구주제





Nuclear Astrophysics

- **Big Bang nucleosynthesis (Physics of the early universe)**
- **Stellar nucleosynthesis (*pp* chain, CNO cycle, triple α process, EC on ^{7}Be, β^+ decay of ^{8}B, solar ν)**
- **Nucleosynthesis in Massive stars (Carbon, Neon, Oxygen, and Silicon burning)**
- **Slow and rapid neutron capture processes (s-process, r-process)**
- **Explosive nucleosynthesis (Supernovae, X-ray bursters, rp-process, p-process)**
- **Electron screening and pycnonuclear reactions**
- **Nuclei and nuclear matter in compact stars (Neutron stars)**
- **Cosmic ray induced spallation**

→ Measure cross-sections of nuclear reactions of interest in astrophysics

Underground Nuclear Astrophysics

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- **Stellar nucleosynthesis (*pp* chain, CNO cycle, triple α process, EC on ^{7}Be, β^{+} decay of ^{8}B, solar ν)**
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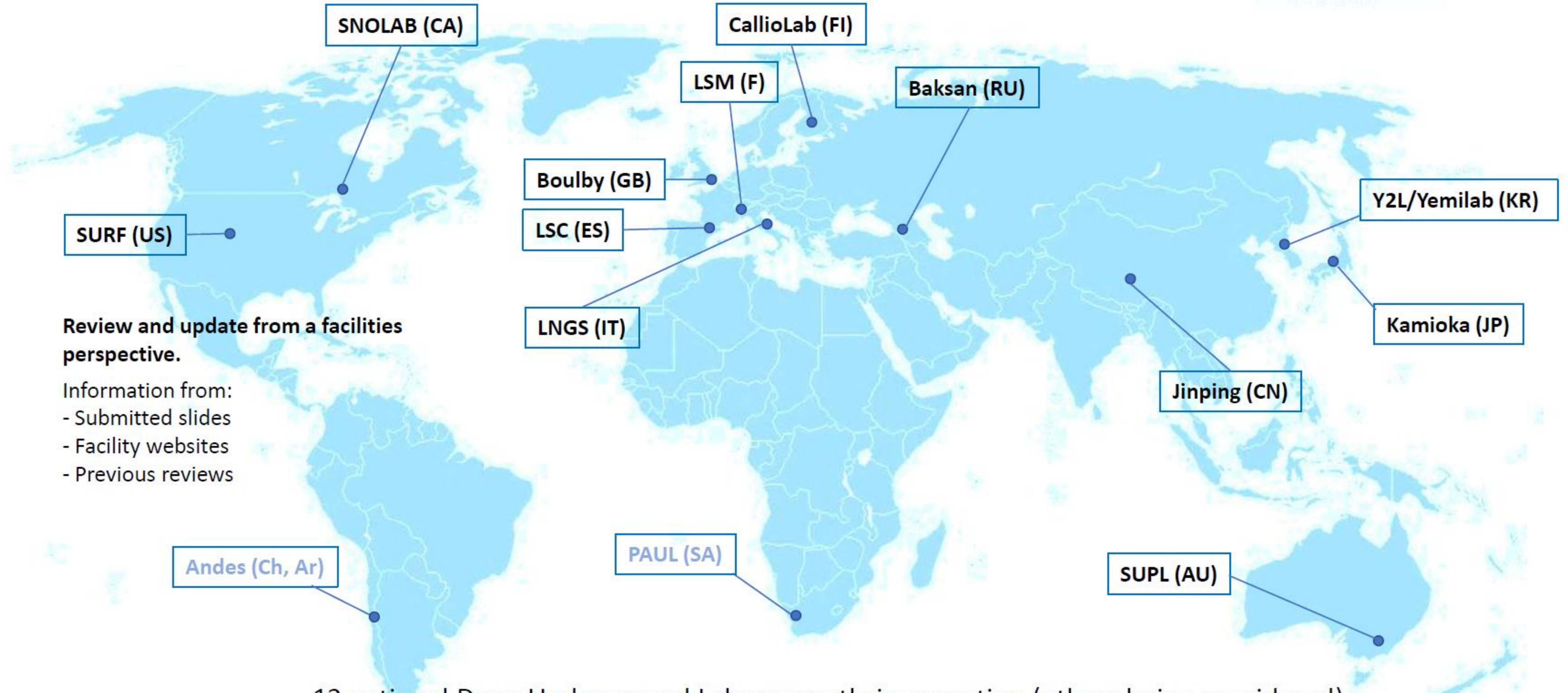
→ Measure cross-sections of nuclear reactions of interest in astrophysics

→ Low background (*n* and μ) environment for precision measurements

World Deep Underground Science Labs

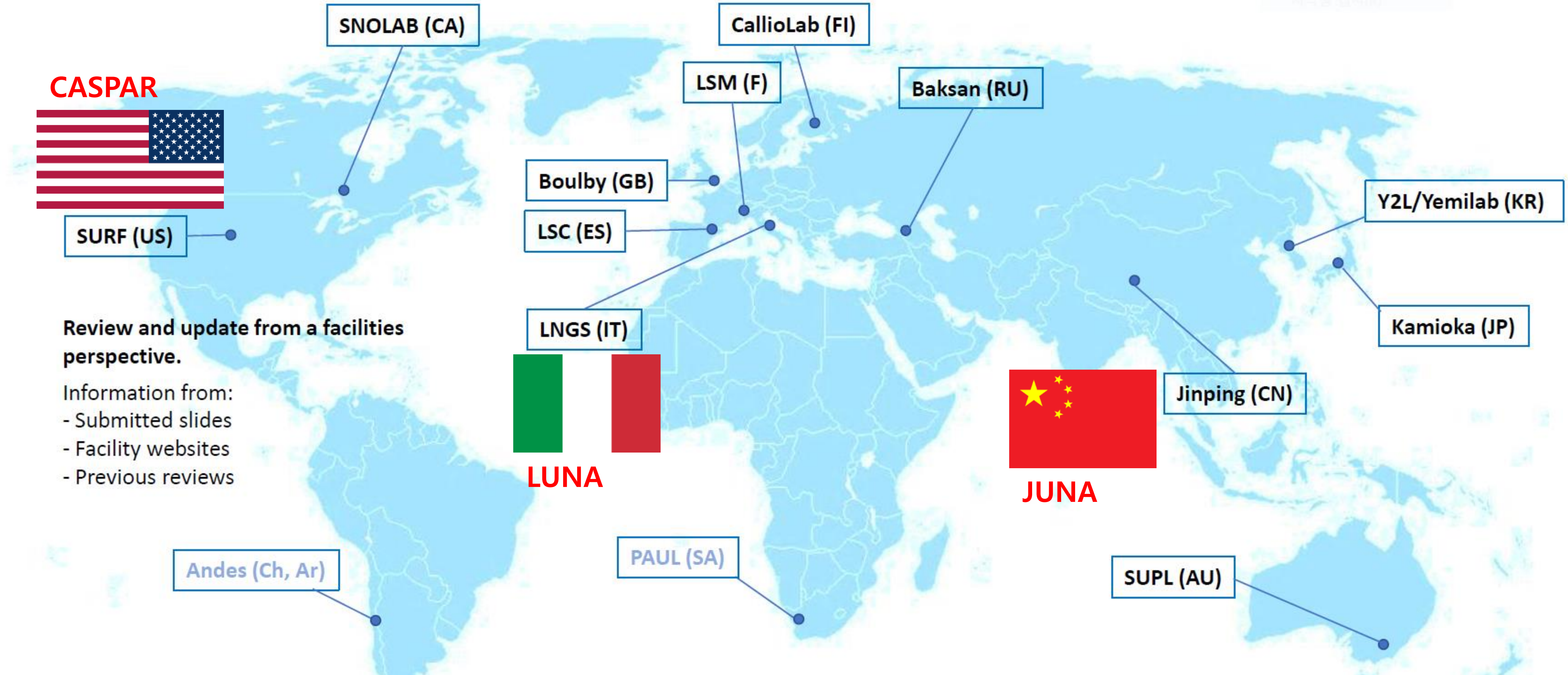


Review and update from a facilities perspective.

Information from:
- Submitted slides
- Facility websites
- Previous reviews

12 national Deep Underground Labs currently in operation (others being considered)
A large almost worldwide distributed infrastructure

World Deep Underground Science Labs



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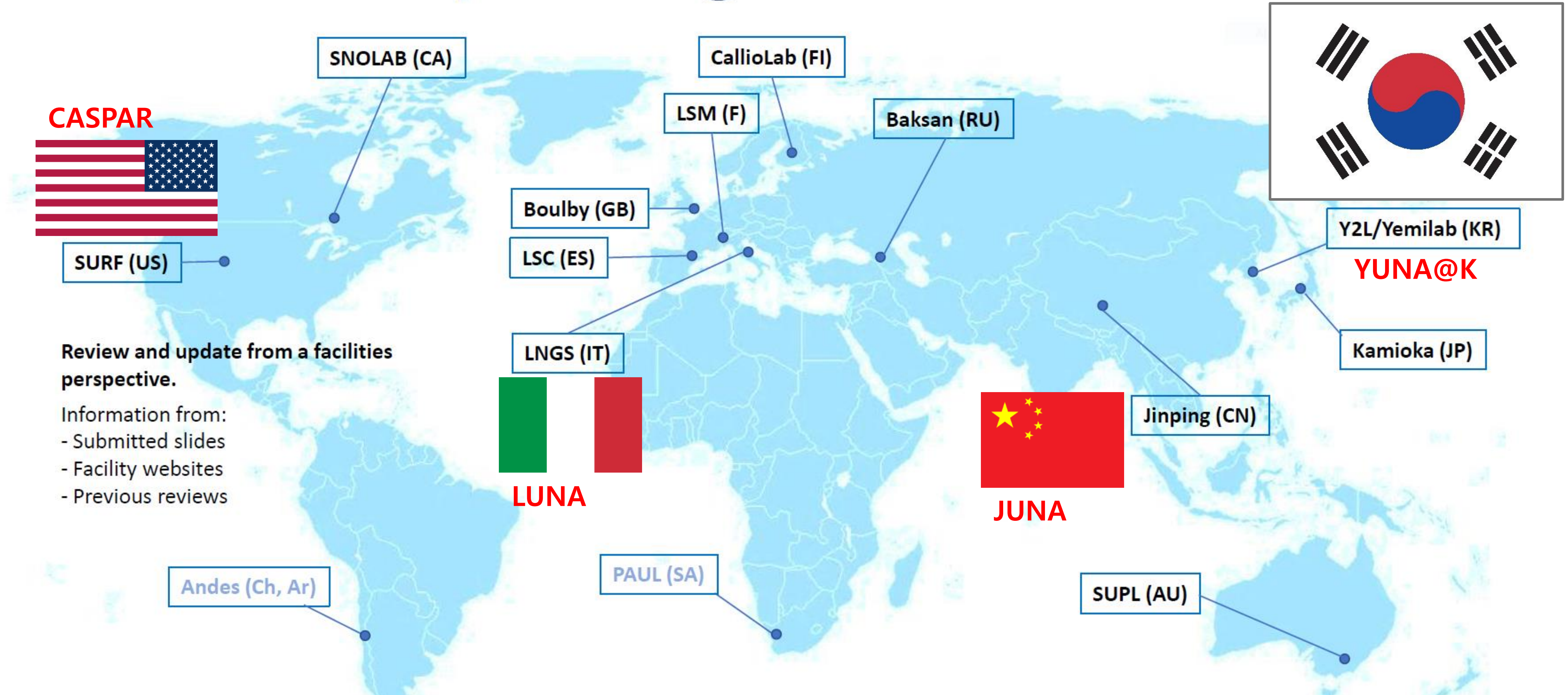

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LUNA @ LNGS

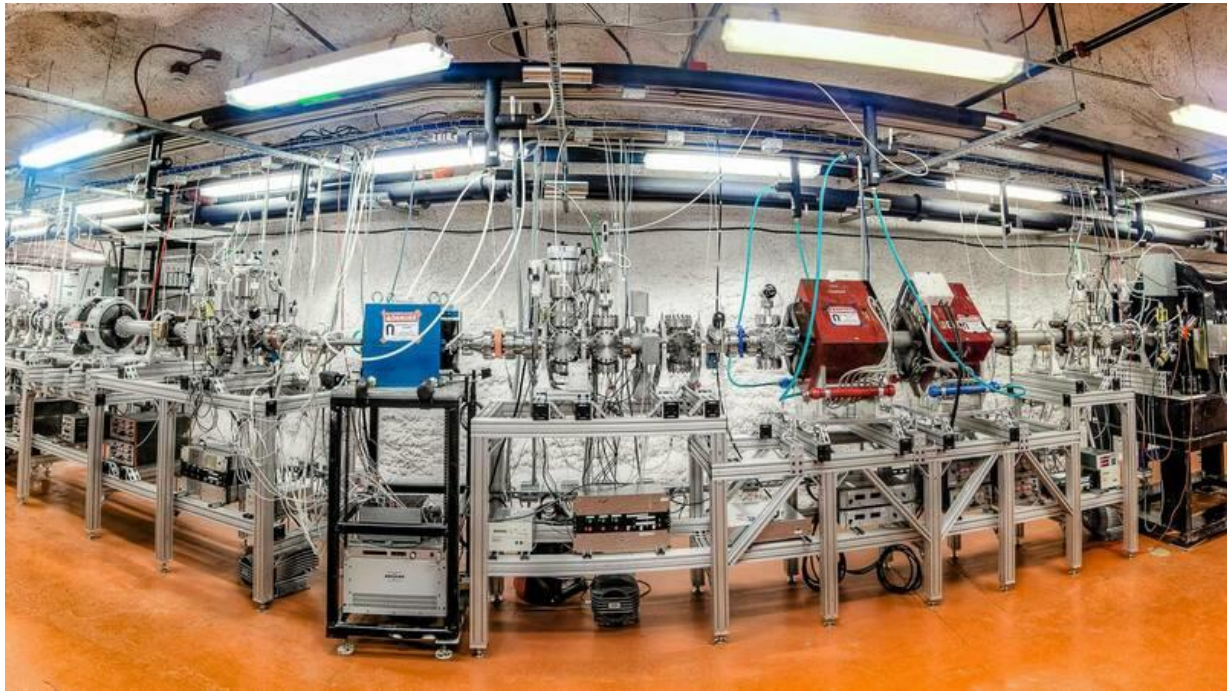
Bellotti Ion beam facility
3.5 MV Singletron

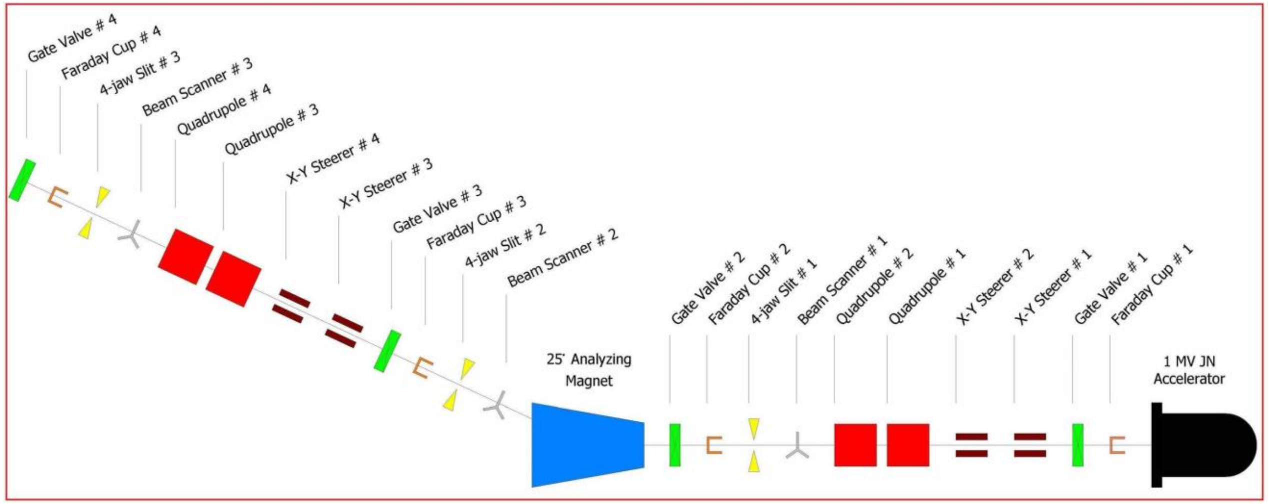
Beam	Energy	Intensity
H^+	0.35 ~ 3.5 MeV	≤ 1000 μA
$^4He^+$		≤ 500 μA
$^{12}C^+$		≤ 150 μA
$^{12}C^{2+}$	1 ~ 7 MeV	≤ 100 μA

Past experiments

- **At the LUNA-50kV**
  - ^{3}He(^{3}He, 2p)^{4}He, D(^{3}He, p)^{4}He, D(d, p)t, D(p, γ)^{3}He
- **At the LUNA-400kV**
  - ^{3}He(α, γ)^{7}Be, ^{14}N(p, γ)^{15}O, ^{15}N(p, γ)^{16}O, ^{25}Mg(p, γ)^{26}Al, ^{2}H(α, γ)^{6}Li
  - ^{17}O(p, γ)^{18}F, ^{17}O(p, α)^{14}N, ^{22}Ne(p, γ)^{23}Na, ^{18}O(p, γ)^{19}F, **D(p, γ)^{3}He**
  - ^{6}Li(p, γ)^{7}Be, ^{13}C(α, n)^{16}O, ^{22}Ne(α, γ)^{26}Mg, ^{12}C(p, γ)^{13}N, ^{20}Ne(p, γ)^{21}Na
  - ^{17}O(p, γ)^{18}F, ^{16}O(p, γ)^{17}F, ^{21}Ne(p, γ)^{22}Na, ^{14}N(p, γ)^{15}O
- **At the Bellotti**
  - ^{14}N(p, γ)^{15}O

CASPAR @ SURF





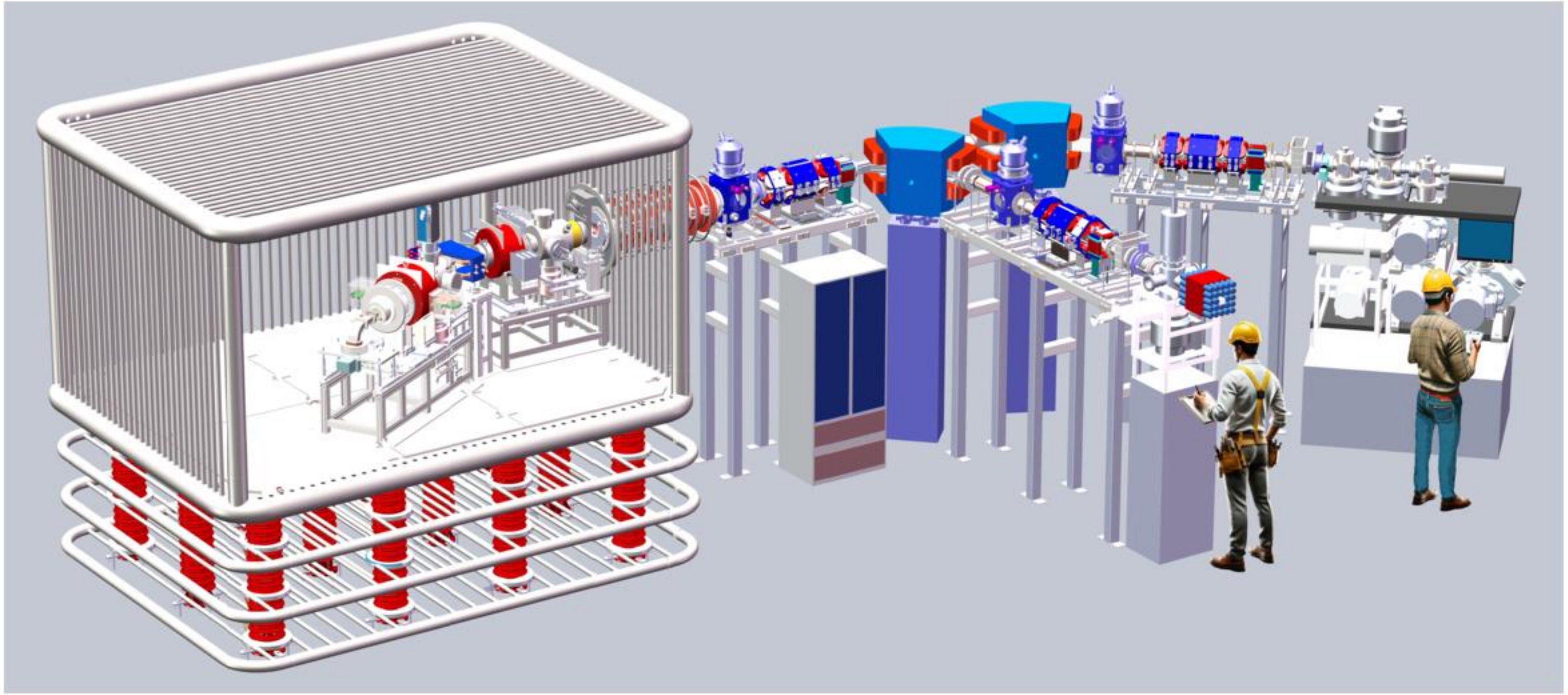
Component	Description
JN Accelerator	Electrostatic accelerator, voltage range 150 kV-1.1 MV
RF Ion Source	Proton Beam ~250 μA, Alpha Beam ~220 μA
Analyzing Magnet	25-degree dipole, 0-degree and "mass 2" lines
Target Stations	Extended, recirculating, windowless gas target
	0-degree and 55-degree solid target system
Vacuum System	Turbomolecular pumping, conflat system beamlines

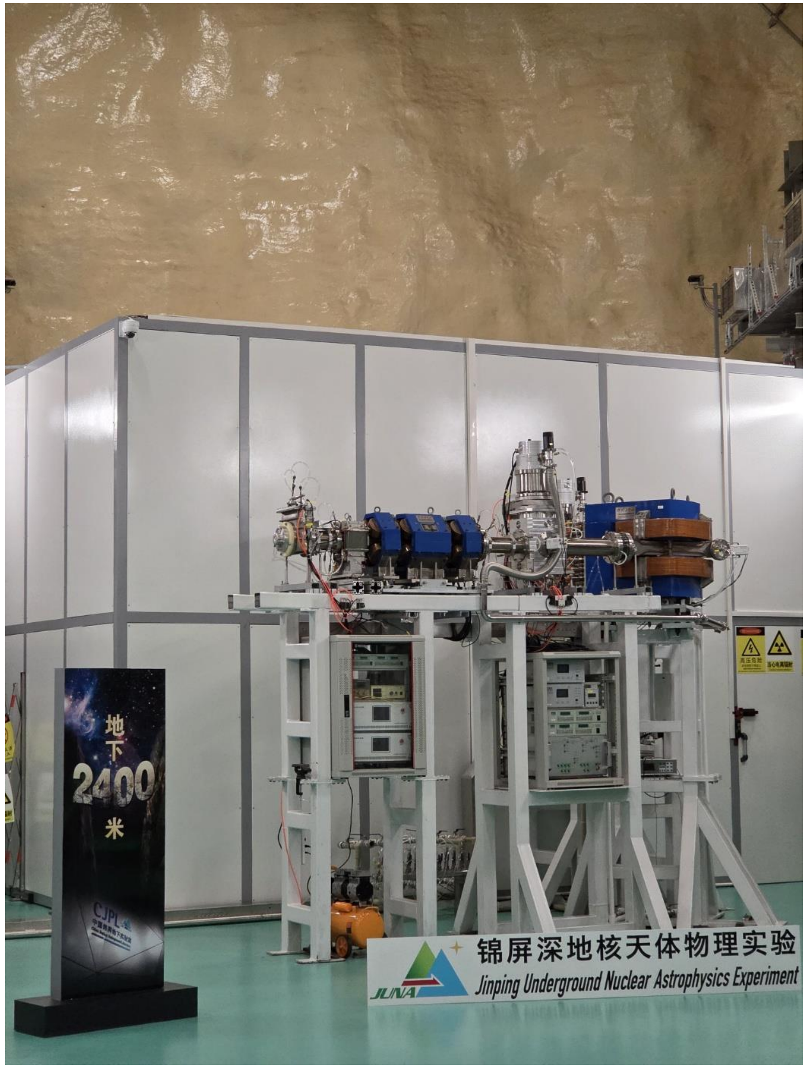
Past experiments

- **$^{18}O(\alpha, \gamma)^{22}Ne$**, $^{22}Ne(\alpha, \gamma)^{26}Mg$, $^{14}N(p, \gamma)^{15}O$, $^{11}B(\alpha, n)^{14}N$

Ref. Nucl. Phys. A 1060 (2025) 123112

JUNA @ CJPL



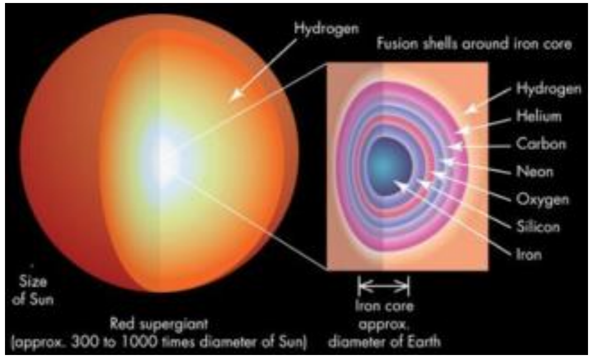


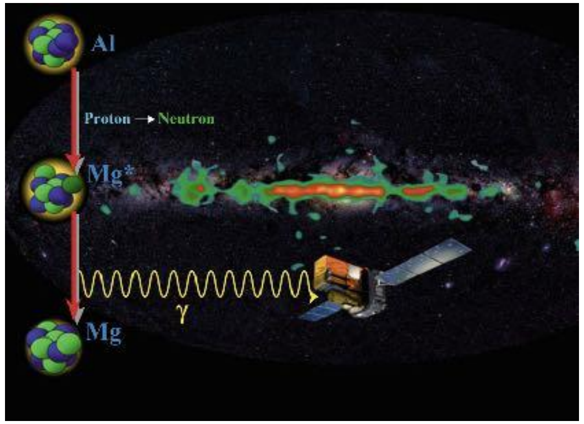
Beam	Energy	Intensity
H^+	50~400 keV	≤ 10 mA
$^4He^+$		
$^4He^{2+}$	100~800 keV	≤ 2 mA

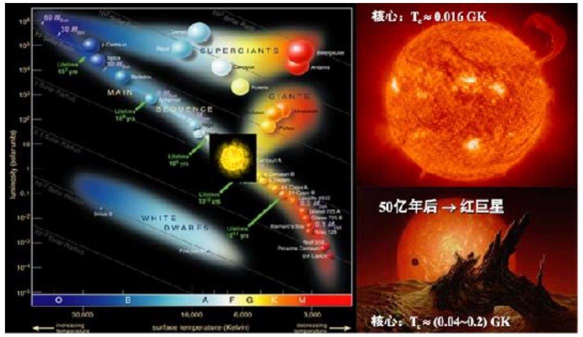
Planned experiments

- $^{13}C(\alpha, n)^{16}O$, $^{25}Mg(p, \gamma)^{26}Al$, $^{19}F(p, \alpha)^{16}O$, $^{19}F(p, \gamma)^{20}Ne$
- **$^{18}O(\alpha, \gamma)^{22}Ne$**, $^{12}C(\alpha, \gamma)^{16}O$, $^{3}He(\alpha, \gamma)^{7}Be$
- $^{22}Ne(\alpha, n)^{25}Mg$, $^{10}B(\alpha, n)^{13}N$, $^{17}O(\alpha, n)^{20}Ne$

Further reactions (Uncertainty)







Physics	Reaction	Current	Desired
Massive star	$^{12}C(\alpha, \gamma)^{16}O$	60% 890 keV	20% 220-380 keV
s-process neutron source	$^{13}C(\alpha, n)^{16}O$	60% 230 keV	10% 140-230 keV
Galaxy ^{26}Al source	$^{25}Mg(p, \gamma)^{26}Al$	20% 92 keV	5% 50-300 keV
F, Ca abundance	$^{19}F(p, \alpha)^{16}O$ $^{19}F(p, \gamma)^{20}Ne$	80 % 189 keV upper limit 240 keV	5 % 50-250 keV 5 % 200 keV

Accelerator (Under discussion)

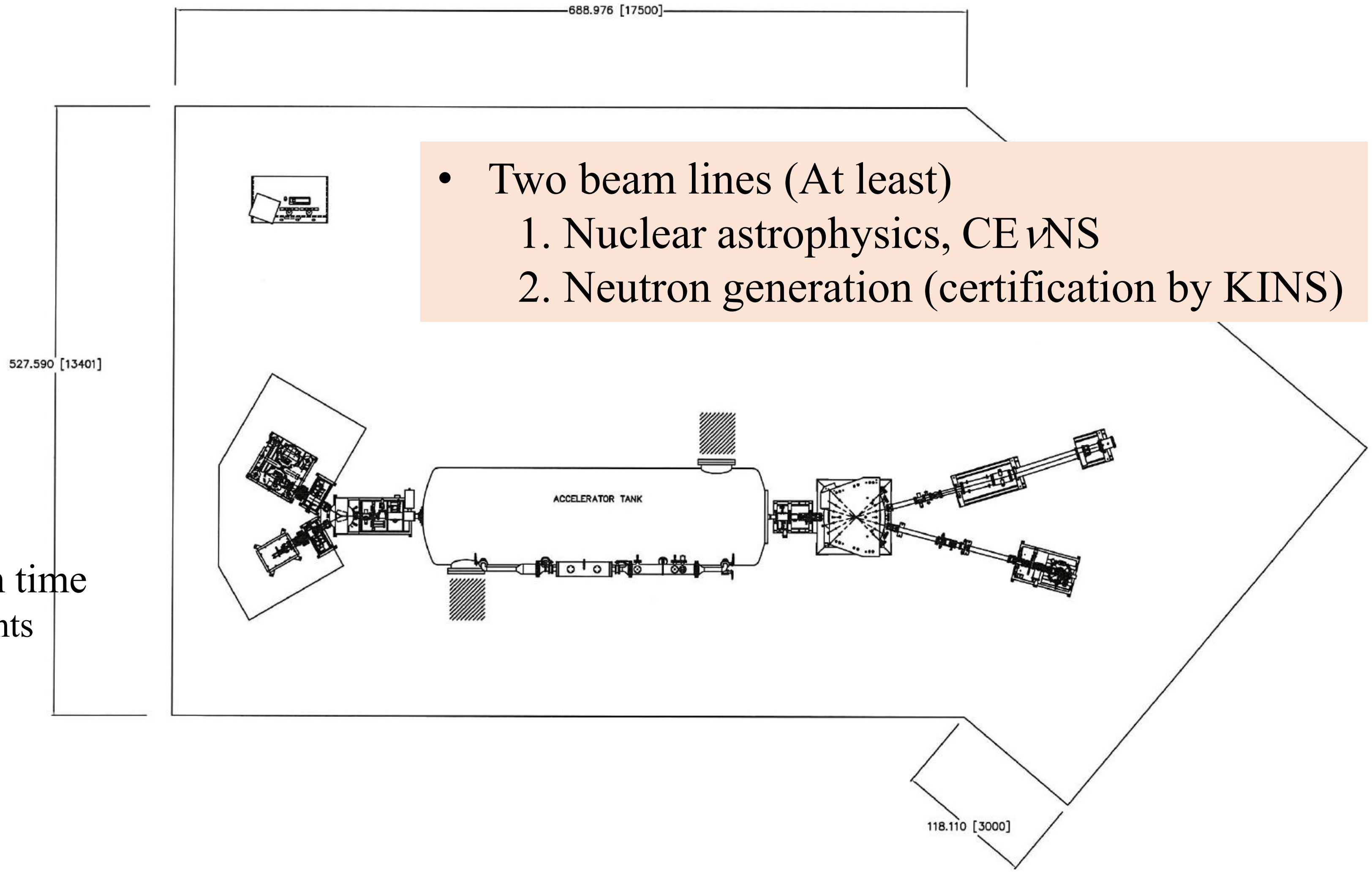
- 4 MV Tandem Pelletron (NEC)

Beam	E(MeV)	C(μA)	Charge
^{1}H	6	50	+1
^{4}He	9	10	+2
^{10}B	15	1.6	+4
^{12}C	12	15	+3
^{16}O	16		+4
^{16}O	20		+5
^{28}Si	12	27	+3

- Low beam current → Longer beam time
  - 24/7 operation during the experiments

- *n* generation : 5 MeV proton

^{7}Li(p, n)reaction ~ 10^{10} n/cm^2·sec



- Two beam lines (At least)
  1. Nuclear astrophysics, CEνNS
  2. Neutron generation (certification by KINS)

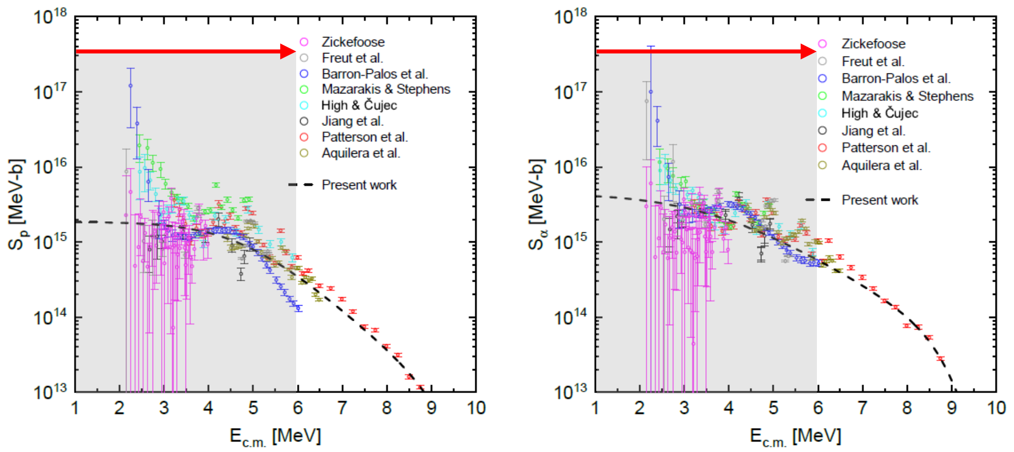
Ref. A&A 702, 86 (2025)

Proposed by Dr. Sunji Kim (IBS CENS)

Evolution of massive stars

- $^{12}C(\alpha, \gamma)^{16}O$: Primarily react during He-burning phase, $^{12}C/^{16}O$ ratio
- ^{12}C $(E_{c.m.} = 6\ MeV)$ + $^{12}C \rightarrow {}^{24}Mg^*$
  - $\rightarrow {}^{20}Ne + \alpha$ (Q = 4.62 MeV)
  - $\rightarrow {}^{23}Na + p$ (Q = 2.24 MeV)
  - $\rightarrow {}^{23}Mg + n$ (Q = -2.62 MeV)

Ref. JKAS (2024), 57, 2, 115–122



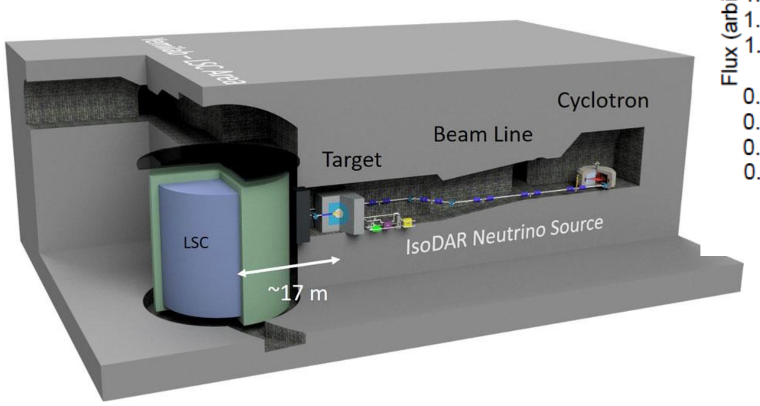
- $^{12}C + {}^{16}O \rightarrow {}^{28}Si^*$
  - $\rightarrow {}^{24}Mg + \alpha$ (Q = 6.77 MeV)
  - $\rightarrow {}^{27}Al + p$ (Q = 5.17 MeV)
  - $\rightarrow {}^{27}Si + n$ (Q = -0.42 MeV)
- $^{16}O + {}^{16}O \rightarrow {}^{32}S^*$
  - $\rightarrow {}^{28}Si + \alpha$ (Q = 9.59 MeV)
  - $\rightarrow {}^{31}P + p$ (Q = 7.68 MeV)
  - $\rightarrow {}^{31}Si + n$ (Q = 1.45 MeV)

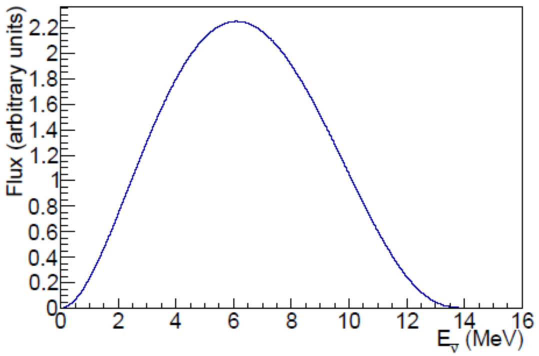
Unique opportunity for low-energy $^{16}O + {}^{16}O$ fusion reaction at the underground laboratory (less neutron BG environment)

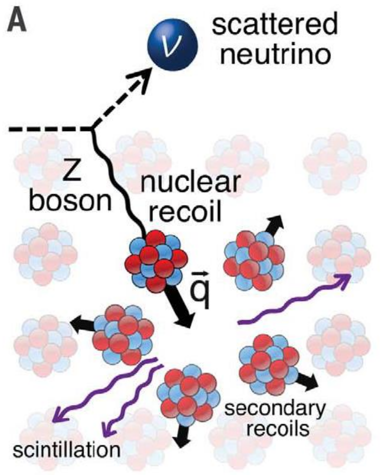
Ref. PRD 105, 052009 (2022)

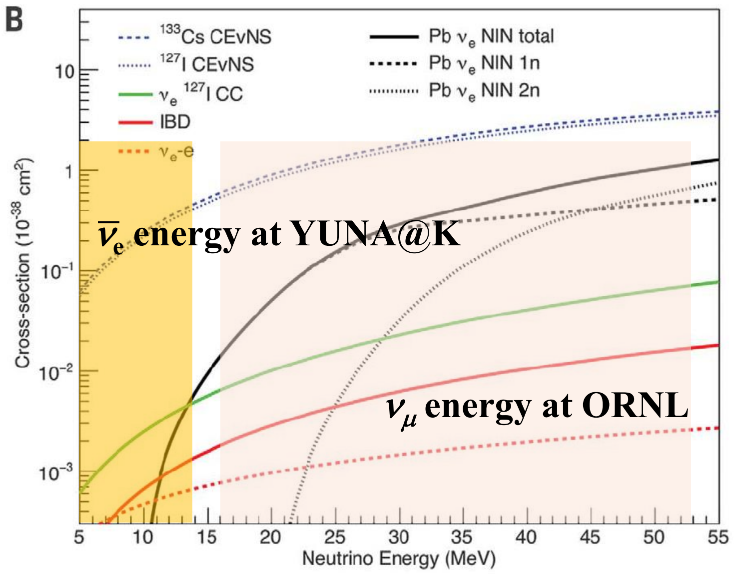
Ref. Science 357, 1123-1126 (2017)

CEνNS (ν generation)

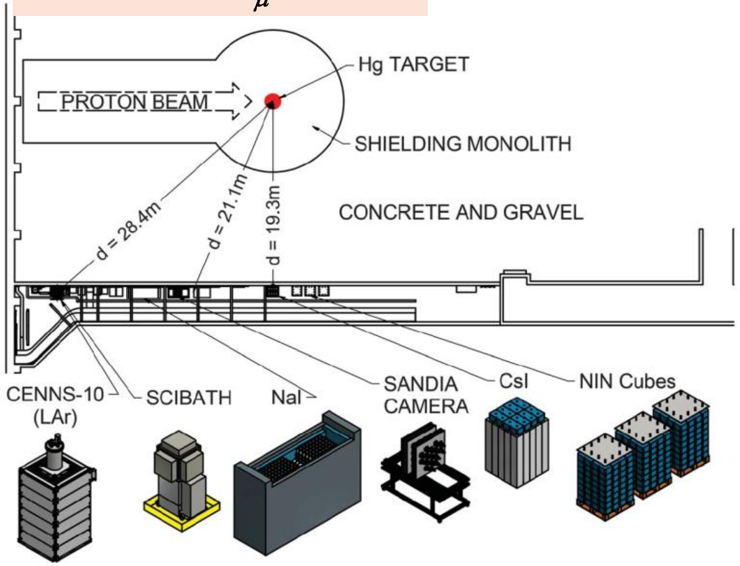




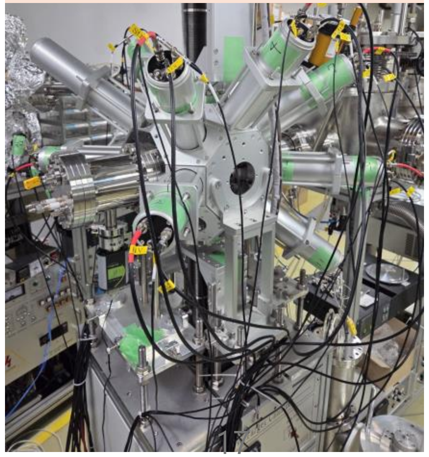




Detectors at ORNL
~ 1.7 x 10^{11} ν_μ/cm^2·sec



Detectors at YUNA@K (Conceptual)



How to generate ν? (from IsoDAR)

60 MeV proton to ^{9}Be target → n generation
^{7}Li + n → ^{8}Li* → ^{8}Li + γ reaction
^{8}Li → ^{8}Be + e^- + $\bar{\nu}_e$ (Half life : 839 ms)

Must need high energy & flux for CEνNS?
Need to study a proper target for CEνNS

Genesis Mission

A National Mission to Accelerate Science Through Artificial Intelligence

Genesis Mission 미국 DOE 최대 프로젝트

A.I.를 활용, 10년 내 미국의 총 생산량을 2배로 향상

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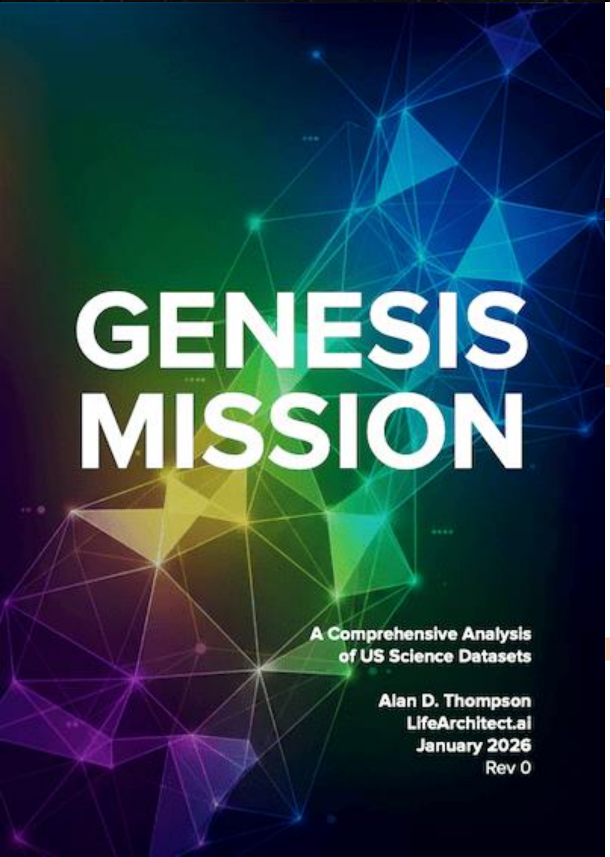
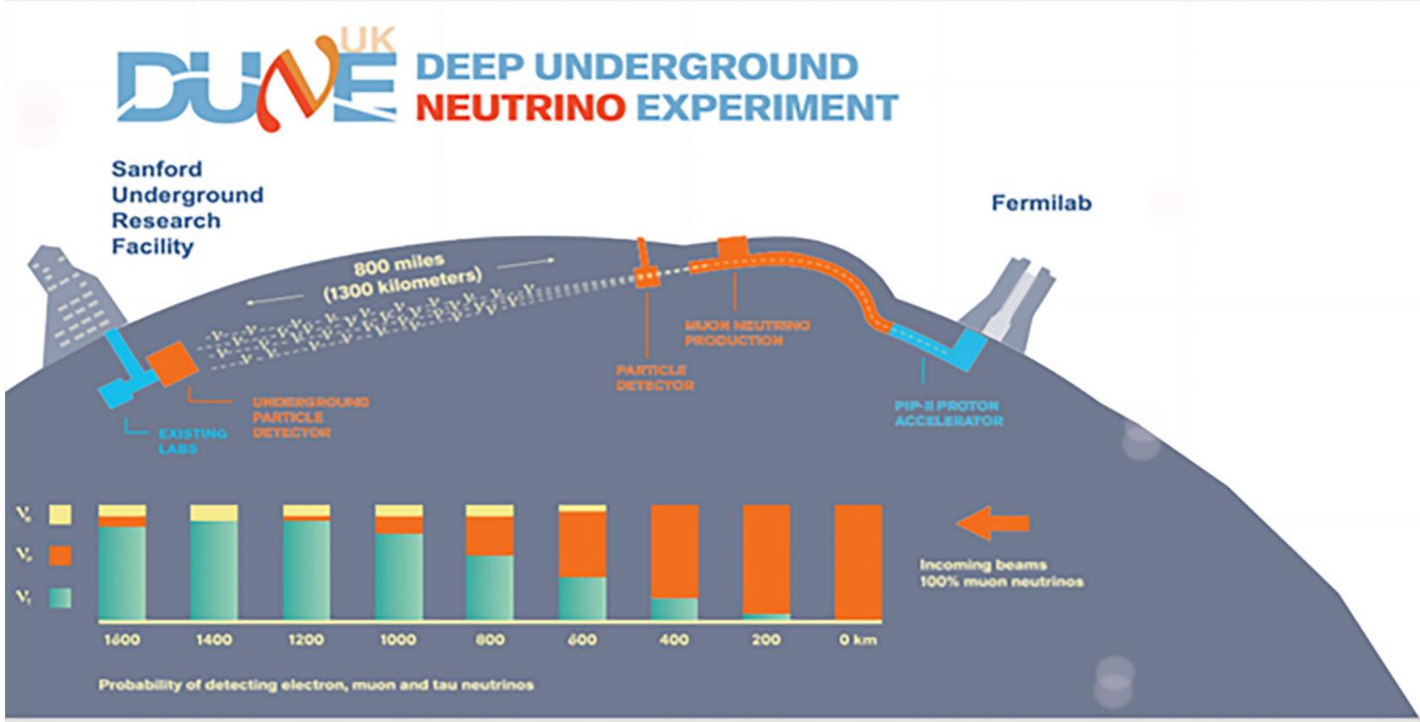


5. Likely DOE 'Tier 1' datasets

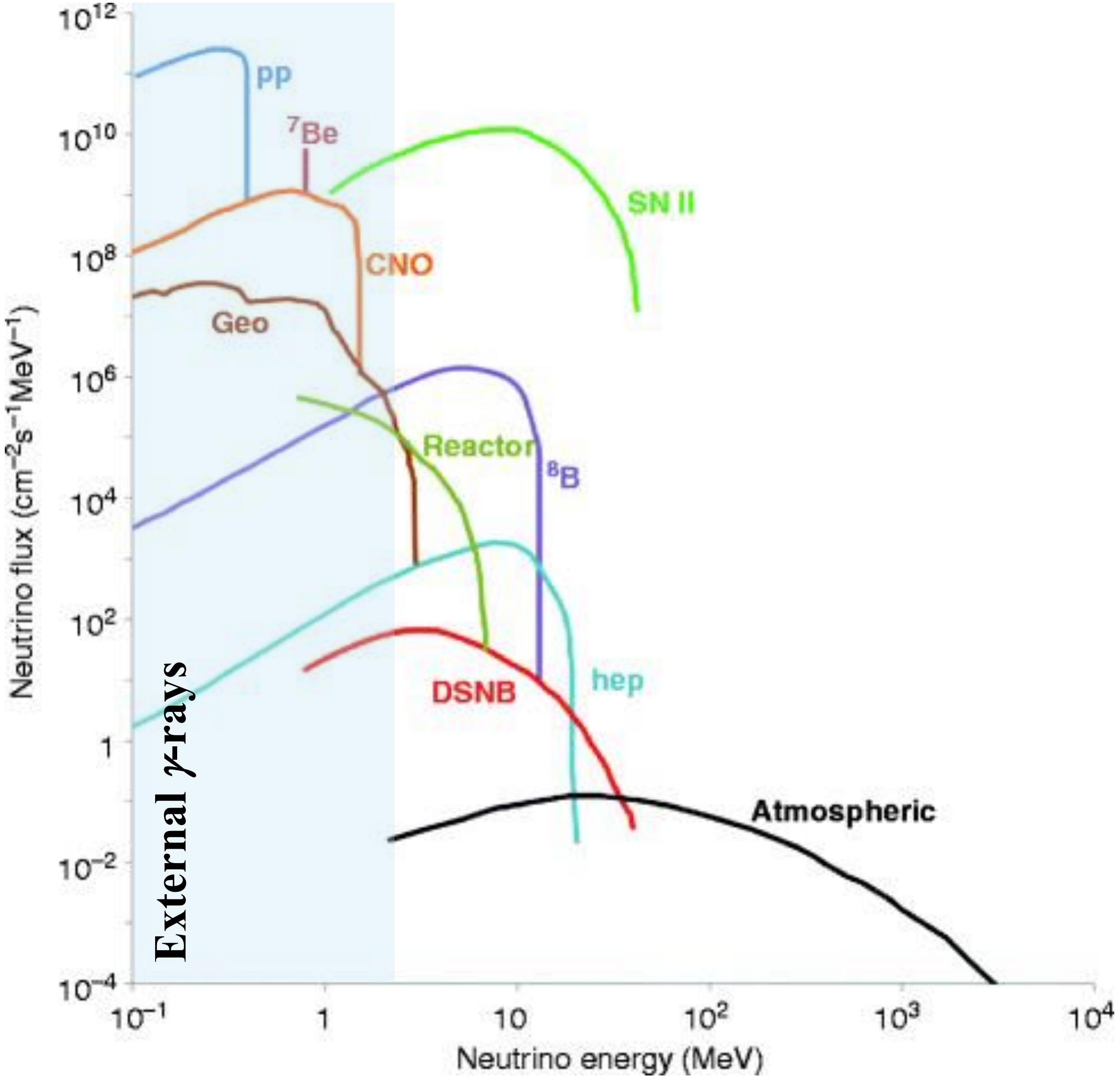
5.1. Accelerating Therapeutics for Medicine
5.2. Advanced Photon Source Upgrade X-ray
5.3. Atmospheric Radiation Measurement
5.4. Community Ice CodE / Energy Exascale Earth System Model
5.5. Continuous Electron Beam Accelerator
5.6. Critical Materials Innovation
5.7. Deep Underground Neutrino Experiment
5.8. Earth System Grid Federation
5.9. Energy Data eXchange
5.10. Environmental Molecular Sciences Laboratory
5.11. Joint Genome Institute
5.12. Hardware/Hybrid Accelerated Cosmology Code
5.13. Large Hadron Collider Compact Muon Solenoid Tier-1
5.14. Legacy Survey of Space and Time
5.15. Linac Coherent Light Source II
5.16. Materials Data Facility
5.17. Materials Project
5.18. Million Veteran Program
5.19. National Ignition Facility Shot Data
5.20. National Solar Radiation Database
5.21. National Spherical Torus Experiment
5.22. National Synchrotron Light Source II
5.23. Relativistic Heavy Ion Collider
5.24. Savannah River Site Environmental Monitoring and Surveillance Data
5.25. Stealth/non-public/top secret dataset
5.26. Stockpile Stewardship
5.27. Summit/Frontier I/O Logs
5.28. Viral Genomics
5.29. Wind Integration National Dataset
5.30. Z Pulsed Power Facility

YUNA@K



Ref. CoSSUF24, Shawn Westerdale (UC Riverside)

Contribution to LAr based Exps. (DUNE)



External radioactivity

$^{238}U/^{235}U$, ^{232}Th, ^{40}K, etc. in detector materials + Rock

$E_\gamma \sim 2.6$ MeV

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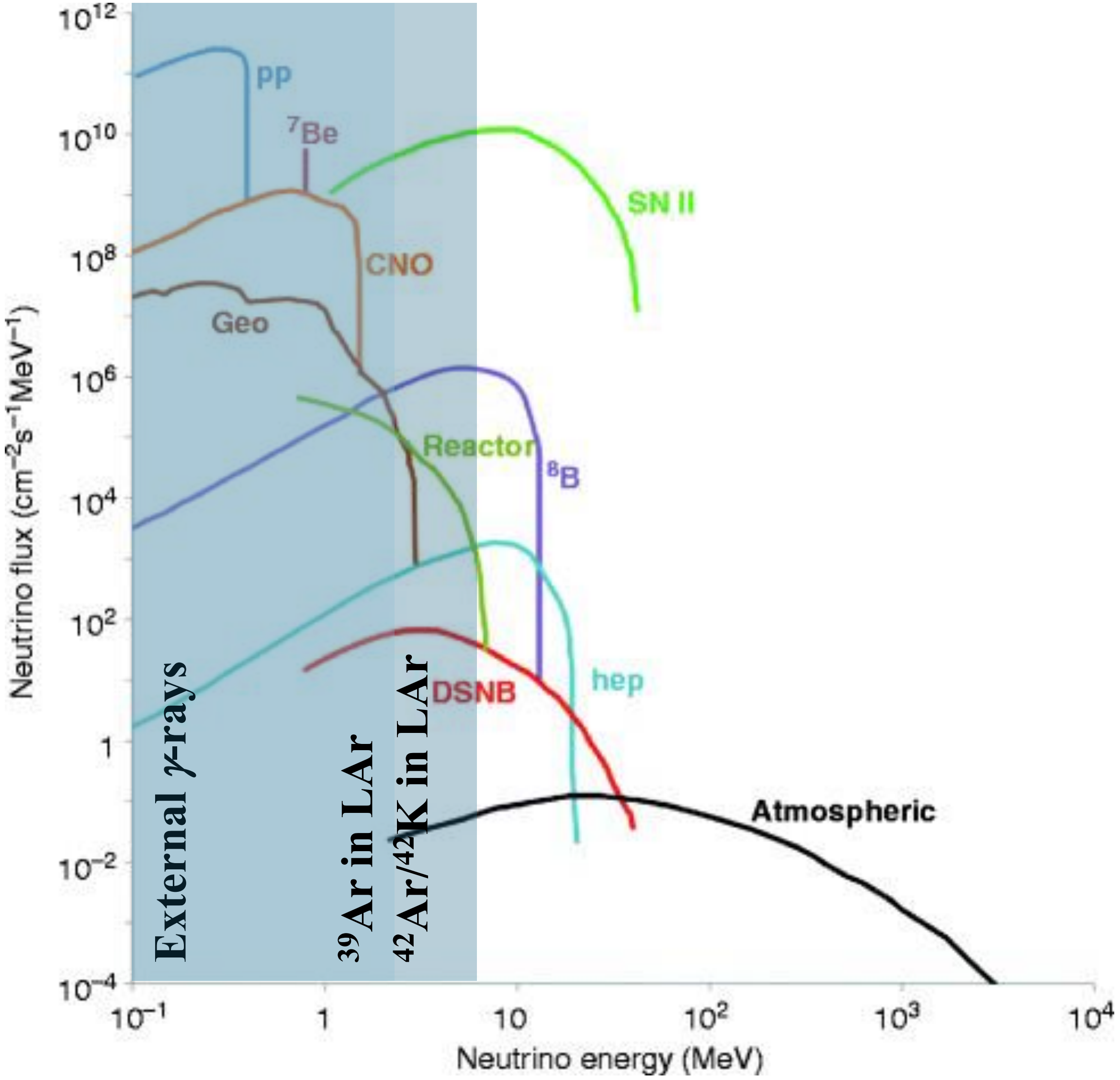

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Dominant : ^{39}Ar ($Q_{\beta} = 565$ keV)

2.6~3.5 MeV dominated by $^{42}Ar/^{42}K$ in LAr

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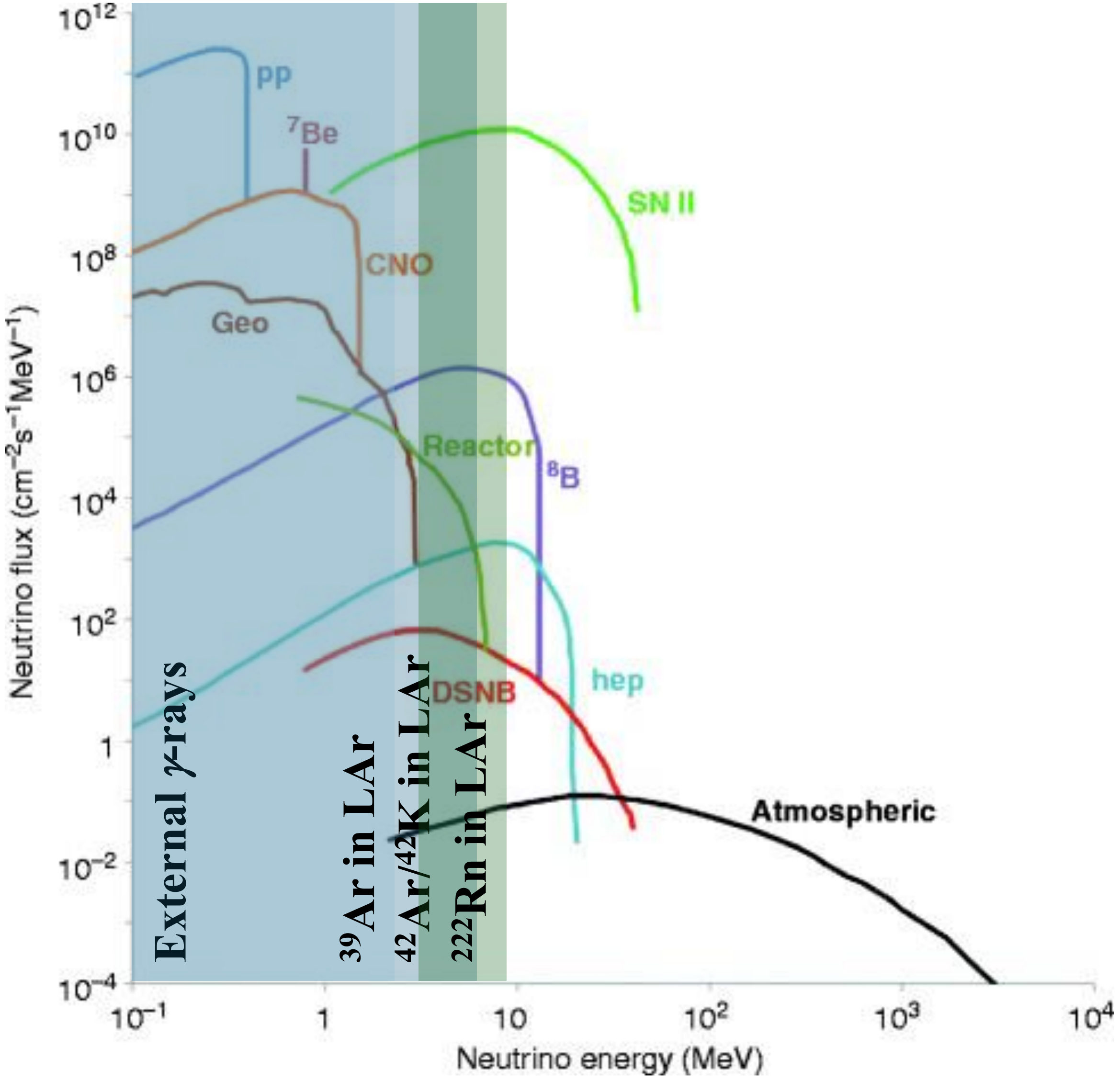

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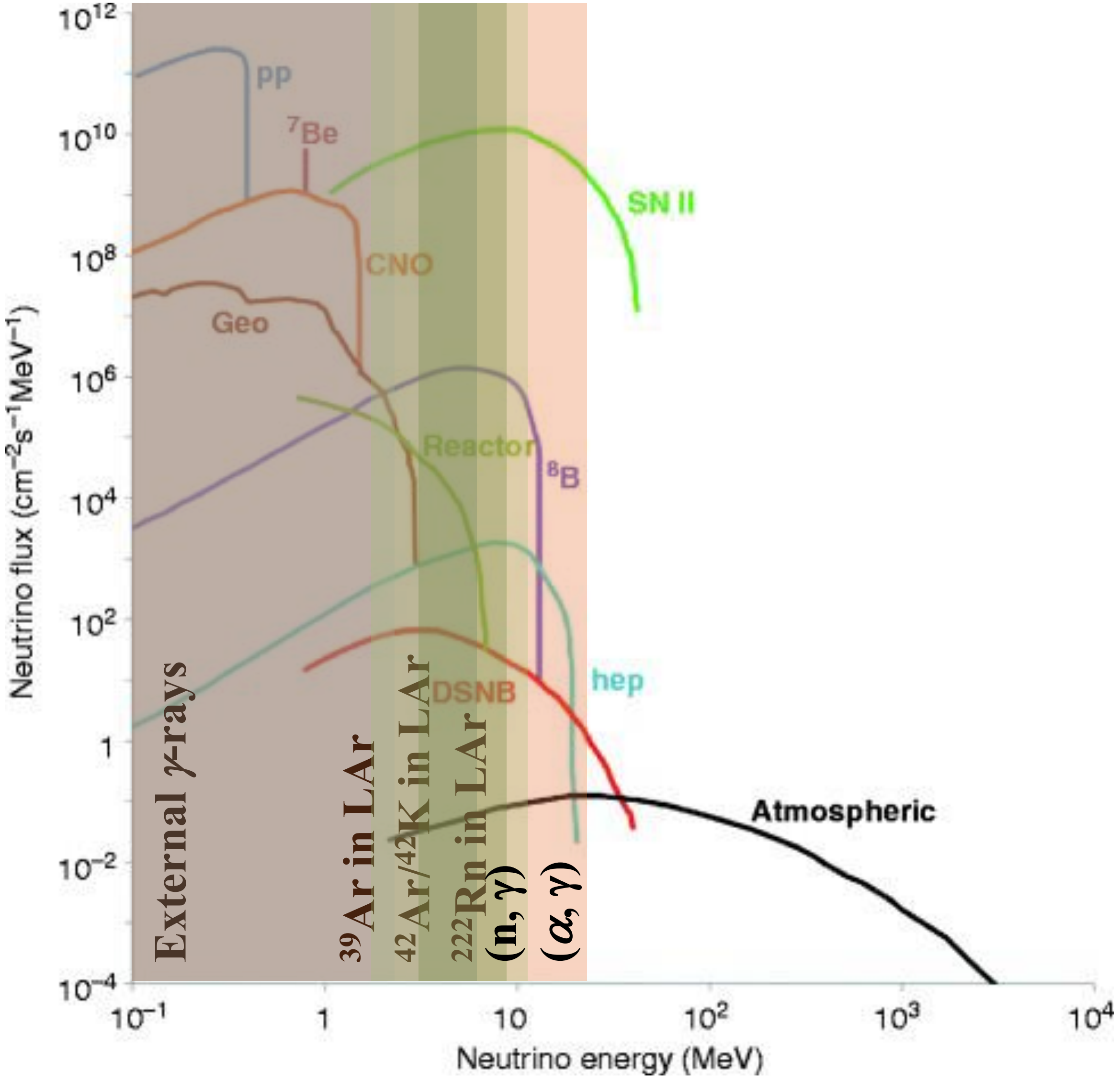

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Radiative *n*/α captures

(n, γ) reaction from radiogenic neutrons 2.2 ~ 10.5 MeV

(α, γ) reaction in LAr up to ~ 17 MeV

Ref. CoSSUF24, Shawn Westerdale (UC Riverside)

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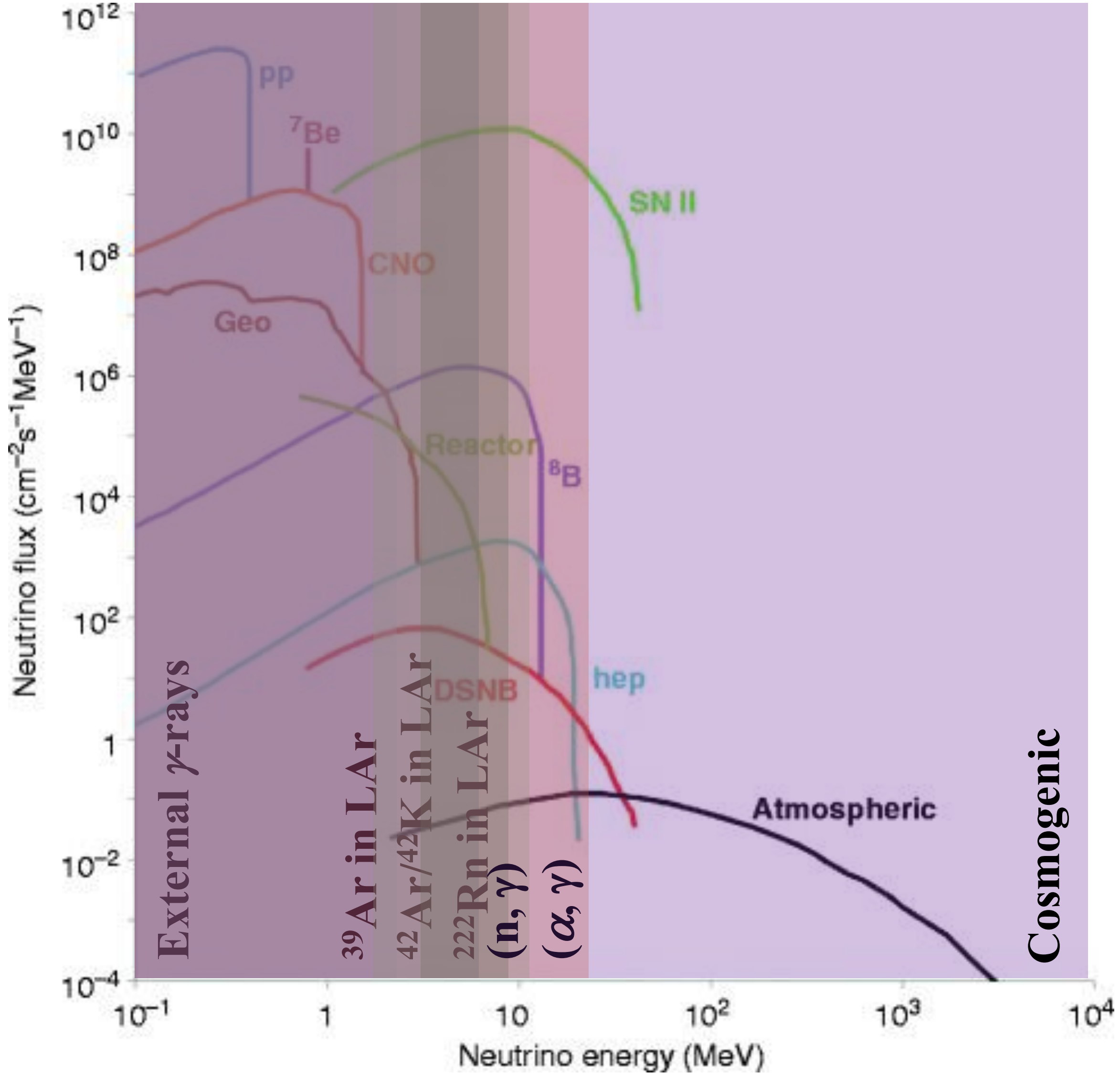

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Cosmogenics
Muon shower up to ~ 1 TeV

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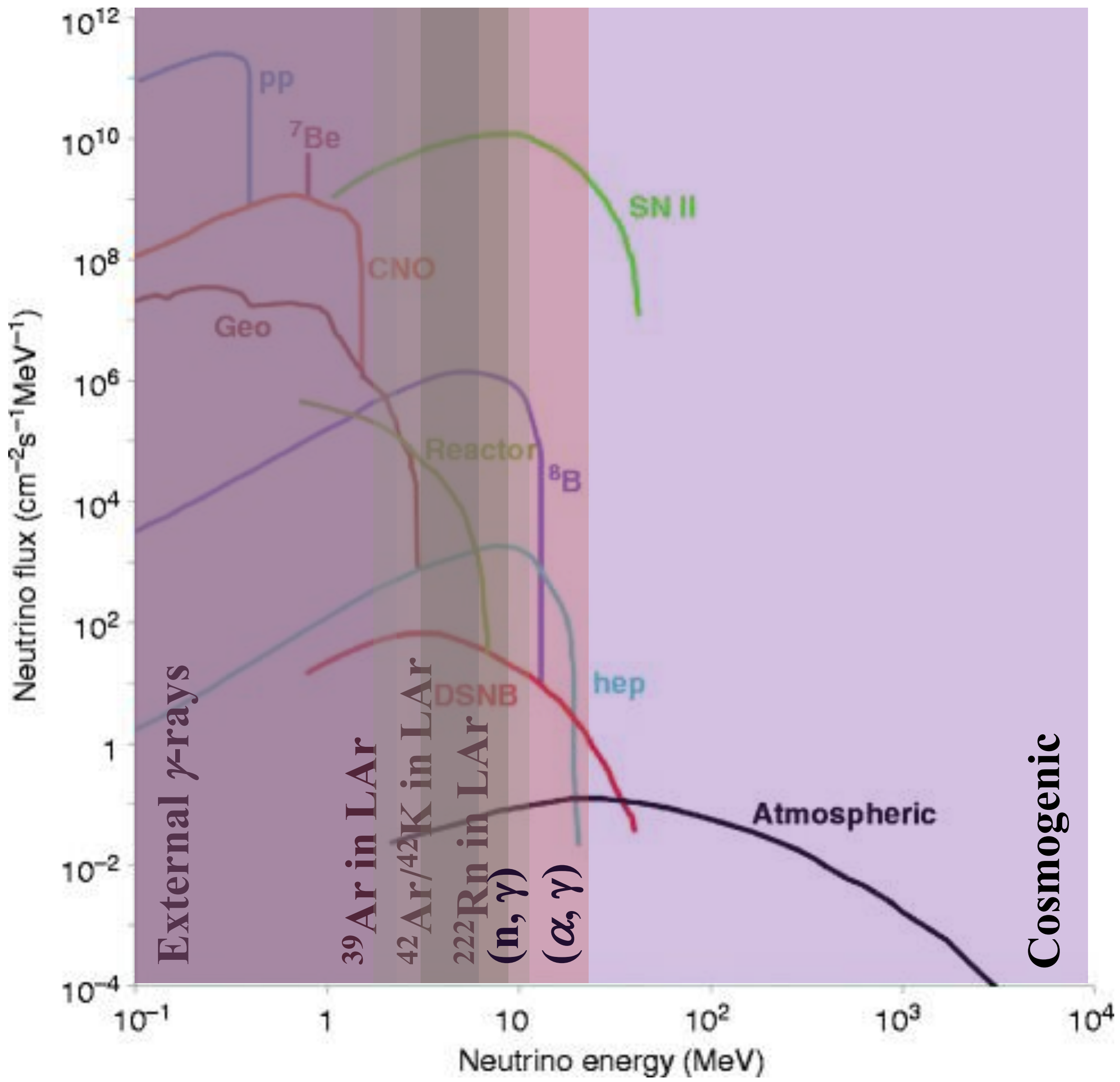

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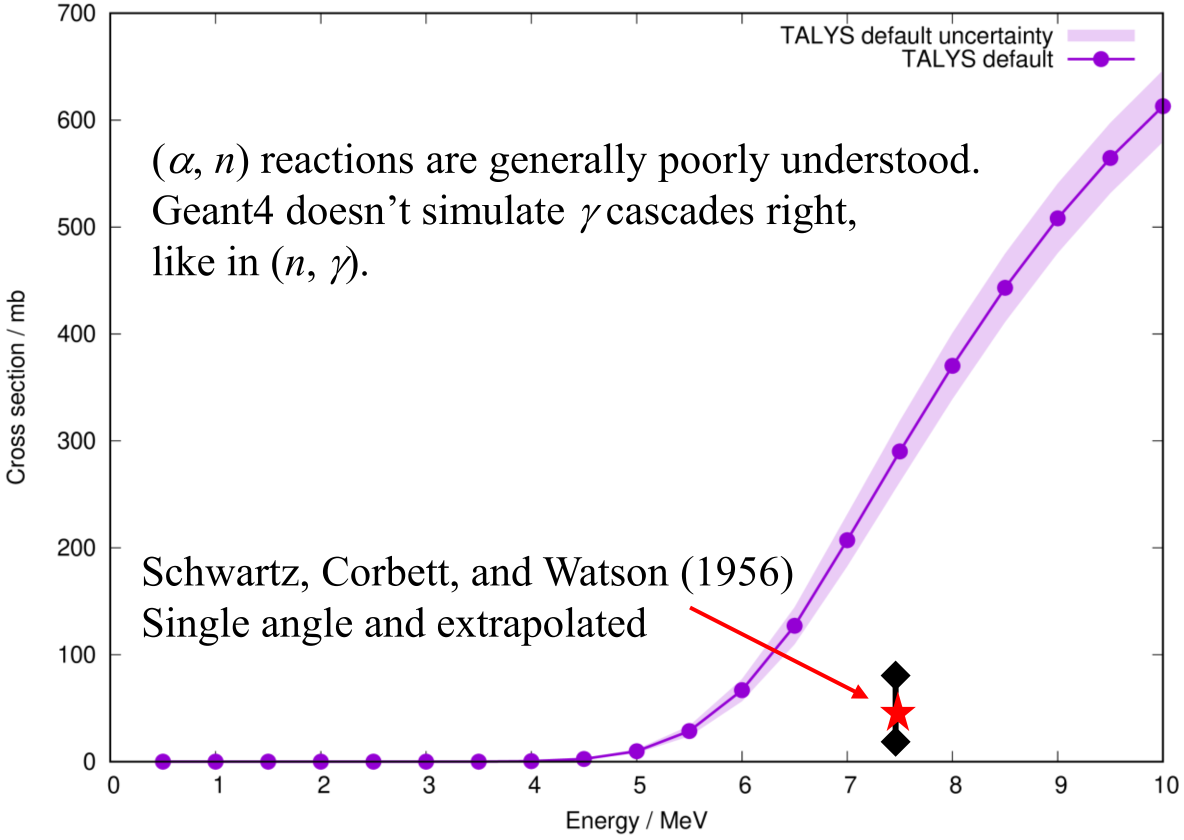
Cosmogenics
Muon shower up to ~ 1 TeV

Ref. CoSSUF24, Shawn Westerdale (UC Riverside)

BG generation in the LAr (can not be fiducialized away)



- Rn in LAr → Ar (α, n), Ar (α, γ) uniformly in fiducial volume
- Neutrons can be penetrating in the center of the LAr (n, γ)

Plot by Holger Kluck using TASMAS to vary TALYS "default" uncertainties, defined so that on average, bands cover data/model uncertainties over all reactions

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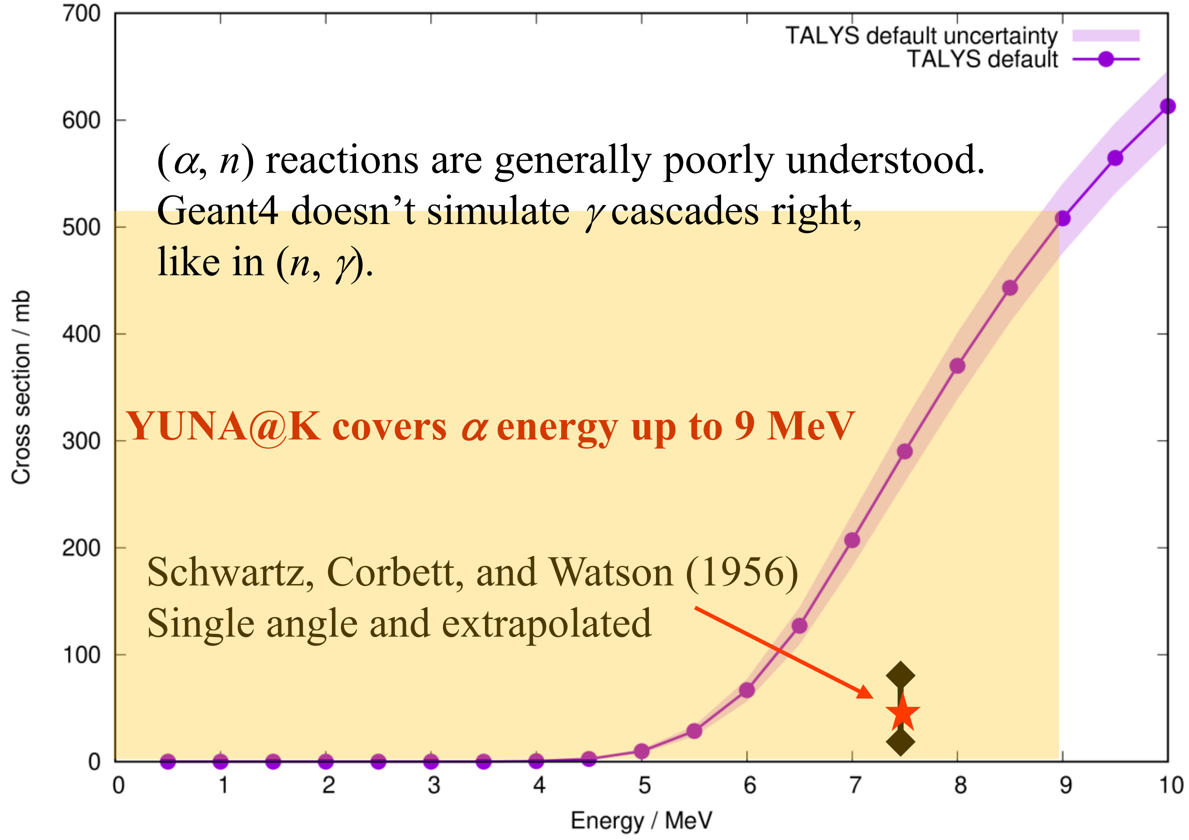

(α, n) reactions are generally poorly understood.
Geant4 doesn't simulate γ cascades right,
like in (n, γ).

YUNA@K covers α energy up to 9 MeV

Schwartz, Corbett, and Watson (1956)
Single angle and extrapolated

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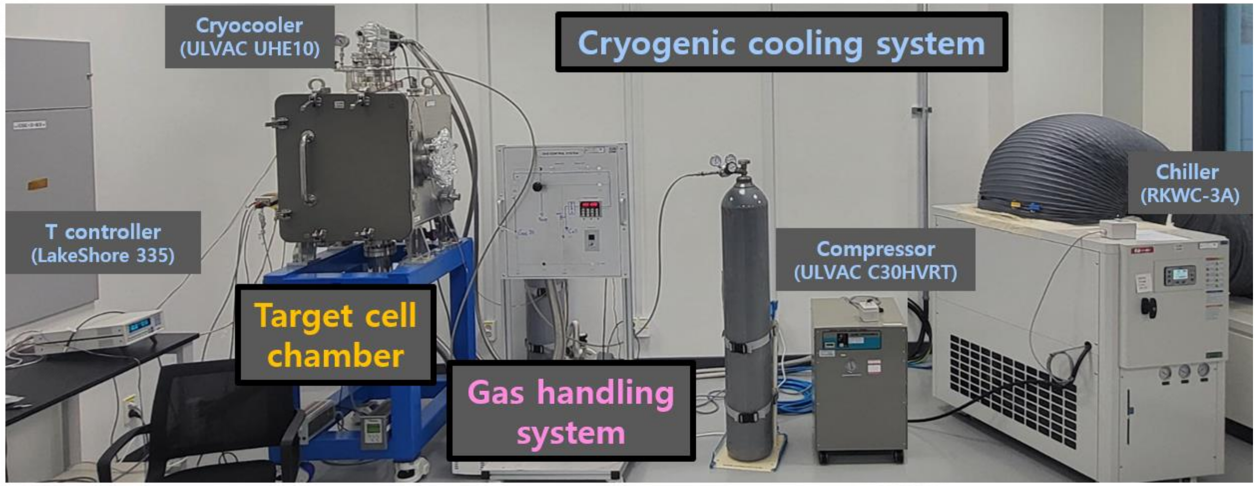
Cryogenic Stable TARget (CryoSTAR by CENS)

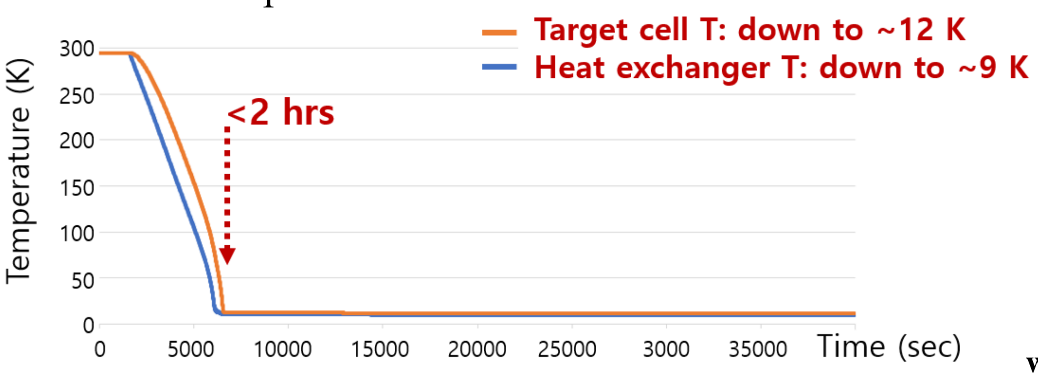
- Aim: Cryogenic gas or liquid reaction target at <40 K for in-beam experiments
- CryoSTAR system and Target cell (experiment dependent spec.)

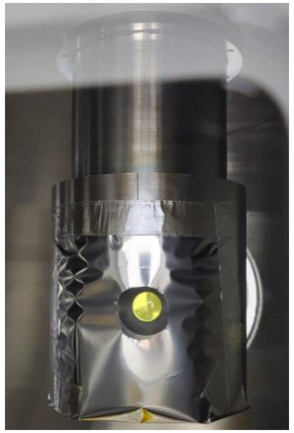


General specifications
- Gas: H_2, D_2, ^4He, Ne, **Ar**, etc.
- Windows: Havar, Mo, etc.
- Pressure: 100-800 torr

- Laboratory phase performance test

- Lowest temperature ~10 K within 2 hours



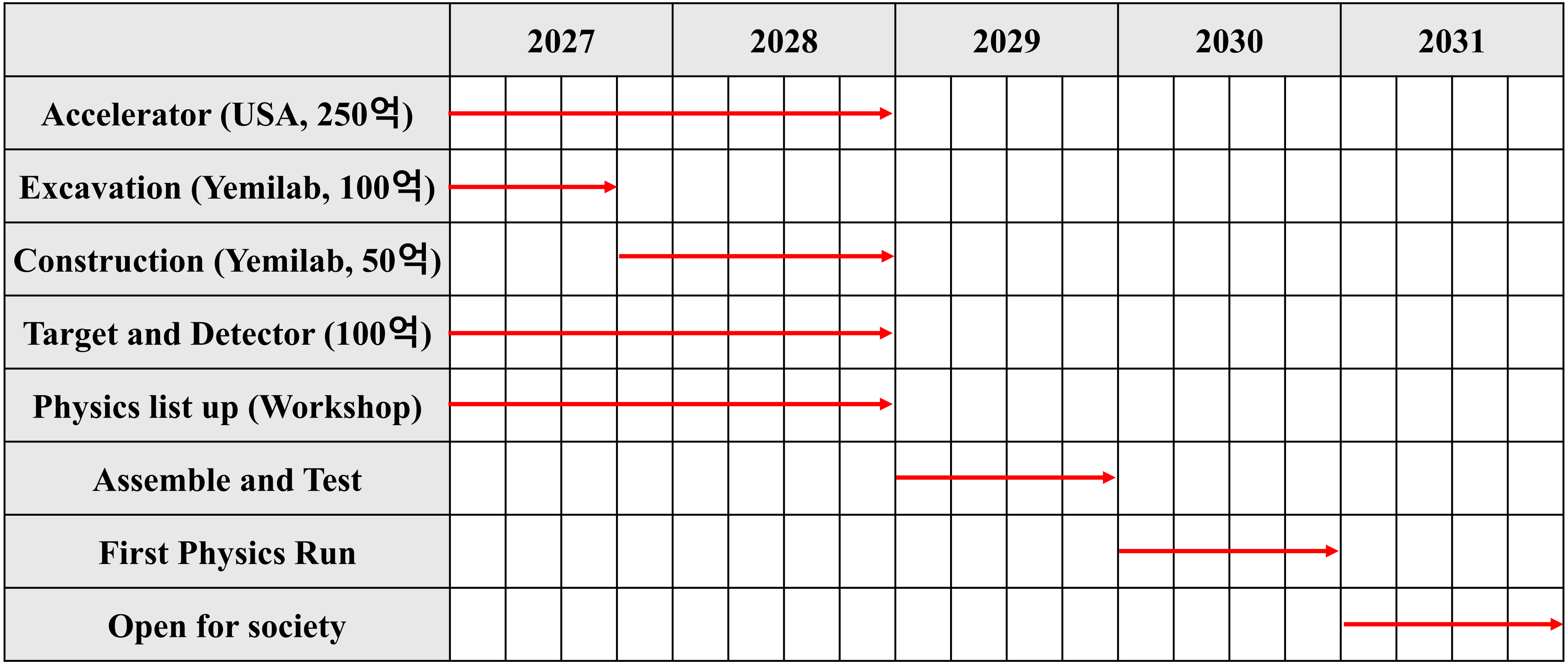


with a radiation shield

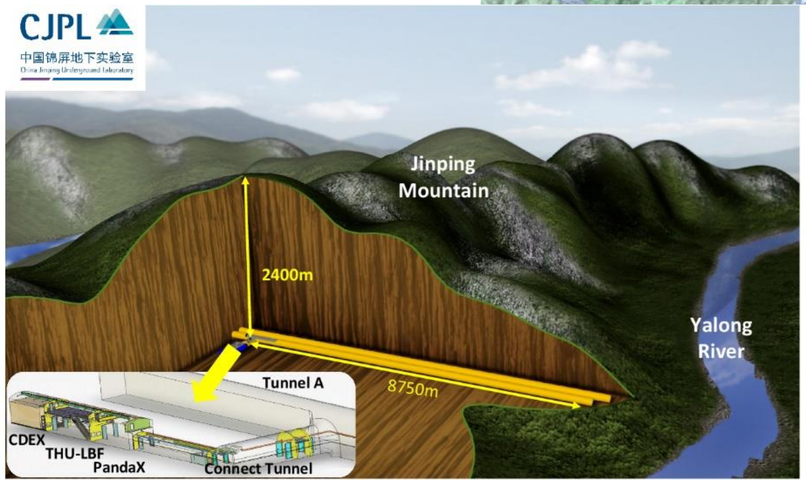
- In-beam experiment plan

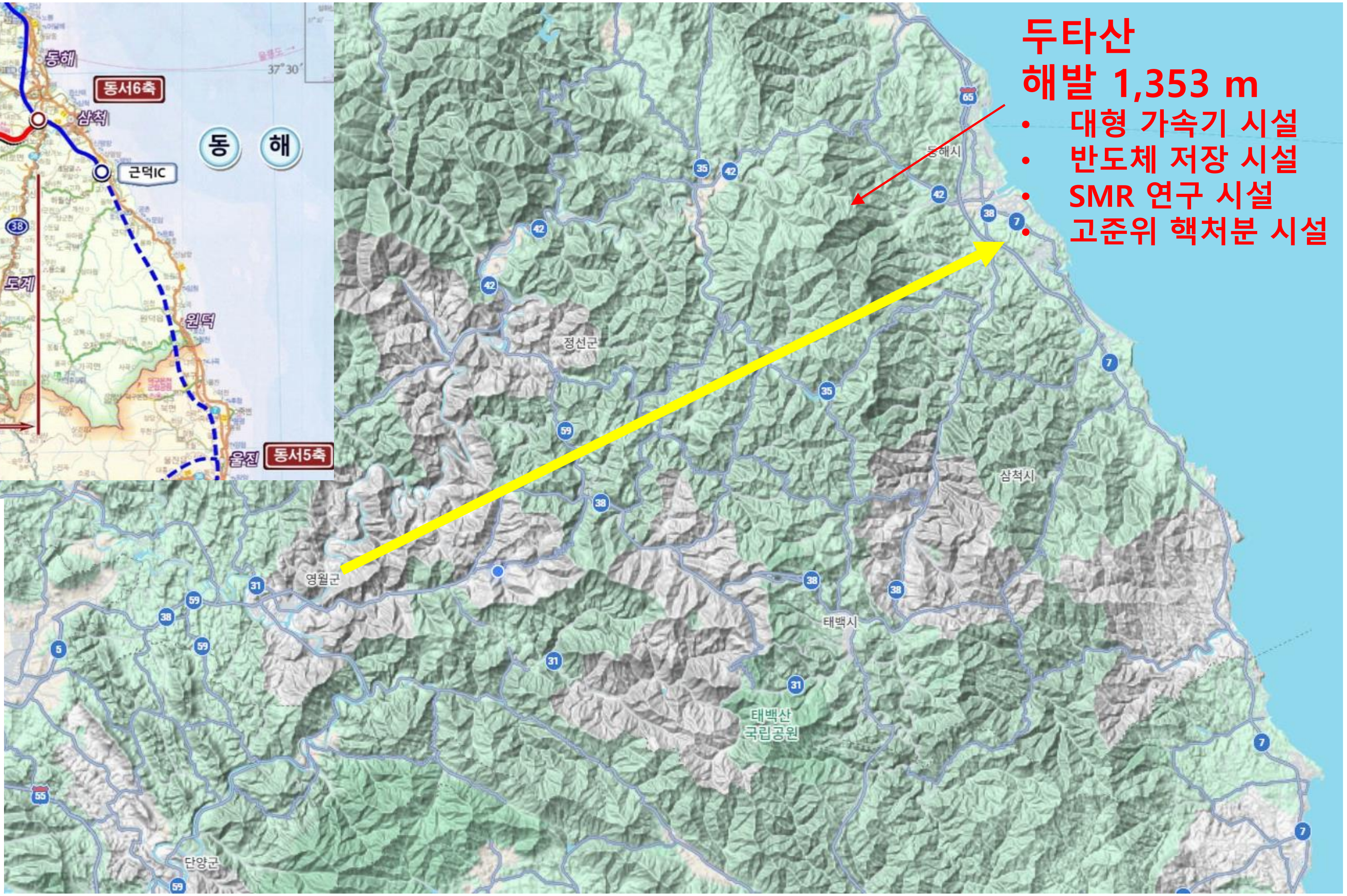
- Three proposals, including a technical beam time request, accepted to IRIS
- In-beam experiments using the CryoSTAR planned for 2027

Budget and Timetable for YUNA@K



미래 초대형 지하연구시설 (태백산맥)





두타산

해발 1,353 m

- 대형 가속기 시설
- 반도체 저장 시설
- SMR 연구 시설
- 고준위 핵처분 시설

Summary

- Korean Underground Nuclear Astrophysics (4MV Tandem accelerator)
  - Evolution of Massive Stars ($^{12}C + ^{12}C$, $^{12}C + ^{16}O$, $^{16}O + ^{16}O$)

- Contribution to world class experiments
  - DUNE, Darkside, LEGEND, and any of LAr TPC experiments

- R&D for future large accelerator facility in new underground laboratory

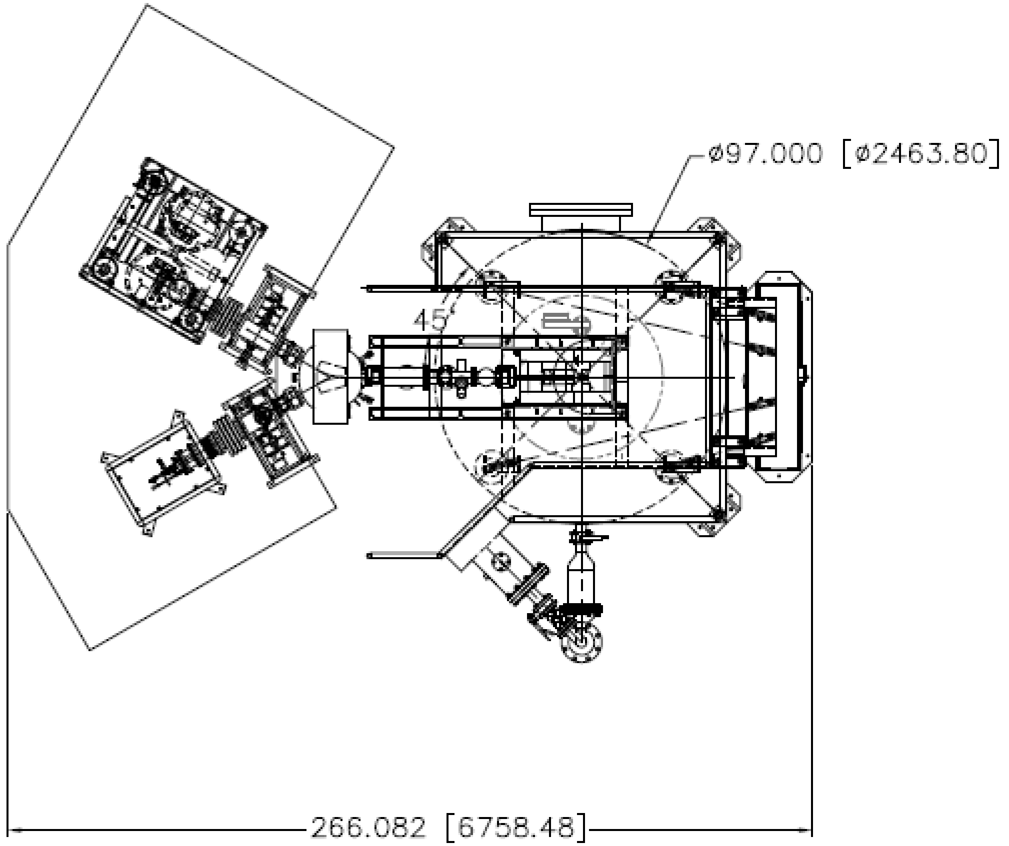
Summary

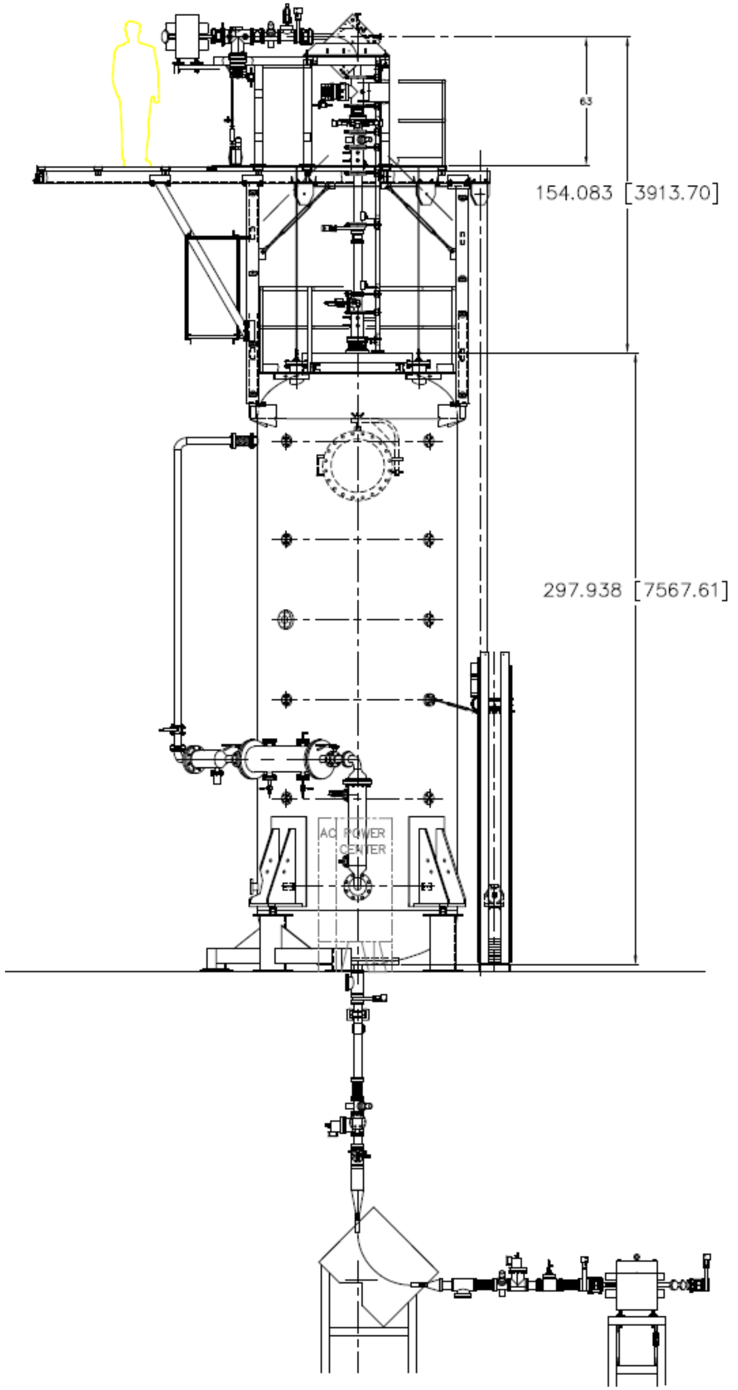
A baby steps

Summary

A baby steps to giant strides

Vertical type (4MV)

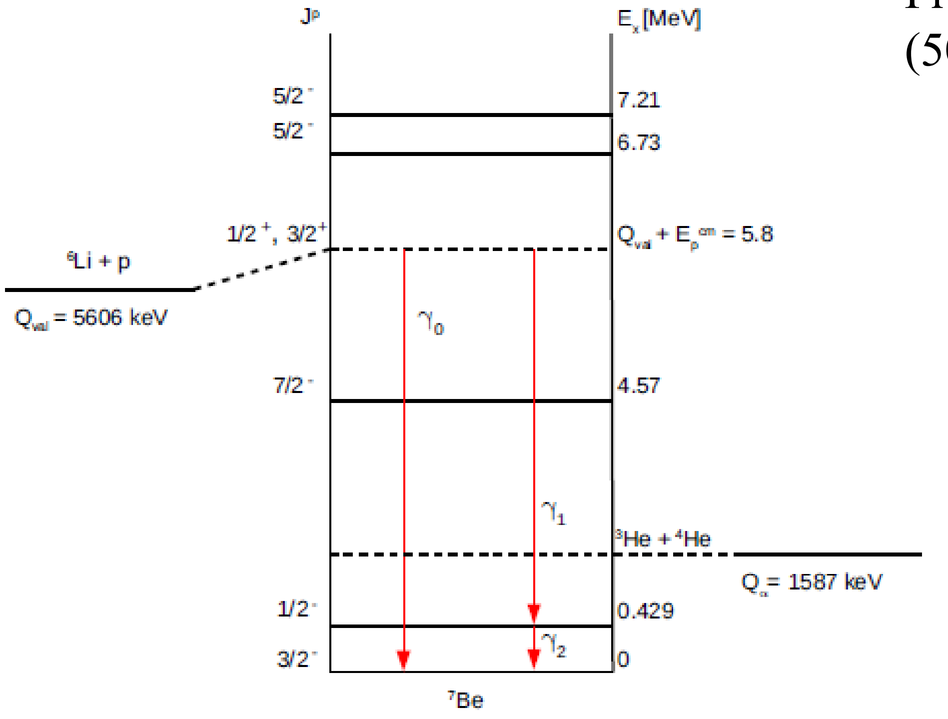


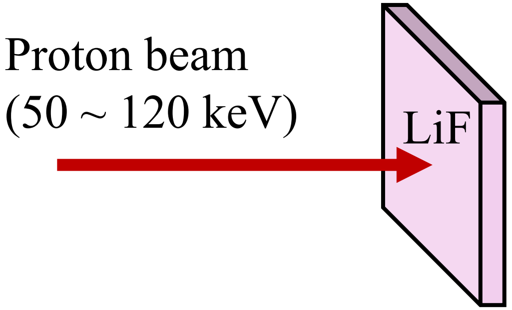


Cluster co-work (with CENS)

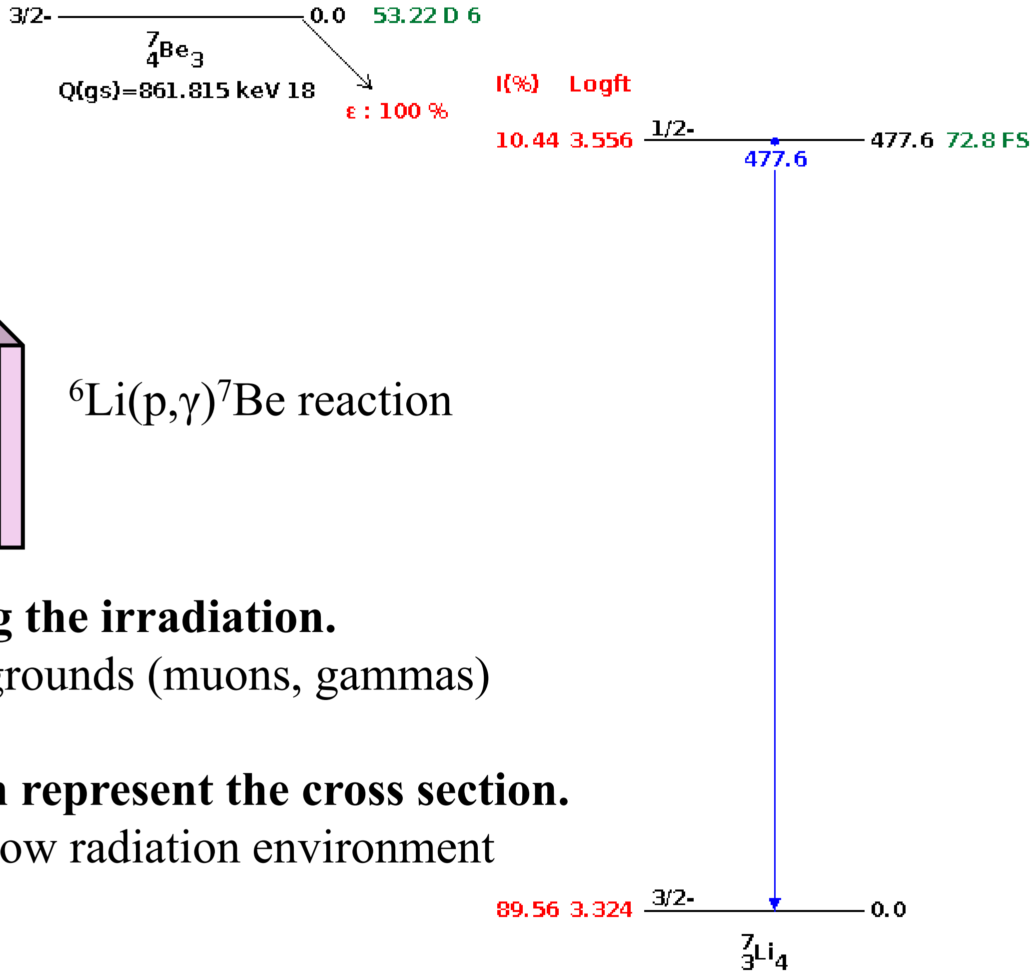
LiF scintillation crystal

- Density : 2.64 g/cm^3
- Non-scintillation at room temperature
- Molecular ratio of Lithium : 27% (Natural abundance ^{6}Li 7.5%)
- Threshold ^{7}Li(p, n)^{7}Be at E_p = 1.88 MeV (Below 1 MeV required)
- ^{19}F(p, $\alpha\gamma_{2\text{-}0}$)^{16}O, stable, no effect by ^{19}F





^{6}Li(p,γ)^{7}Be reaction

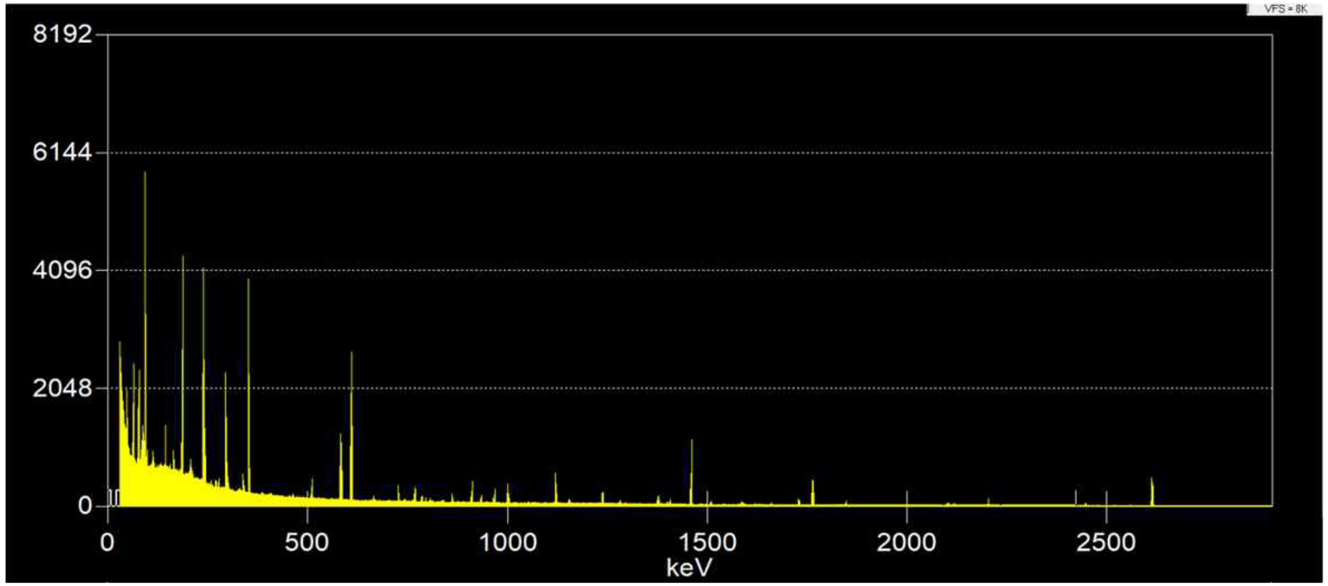


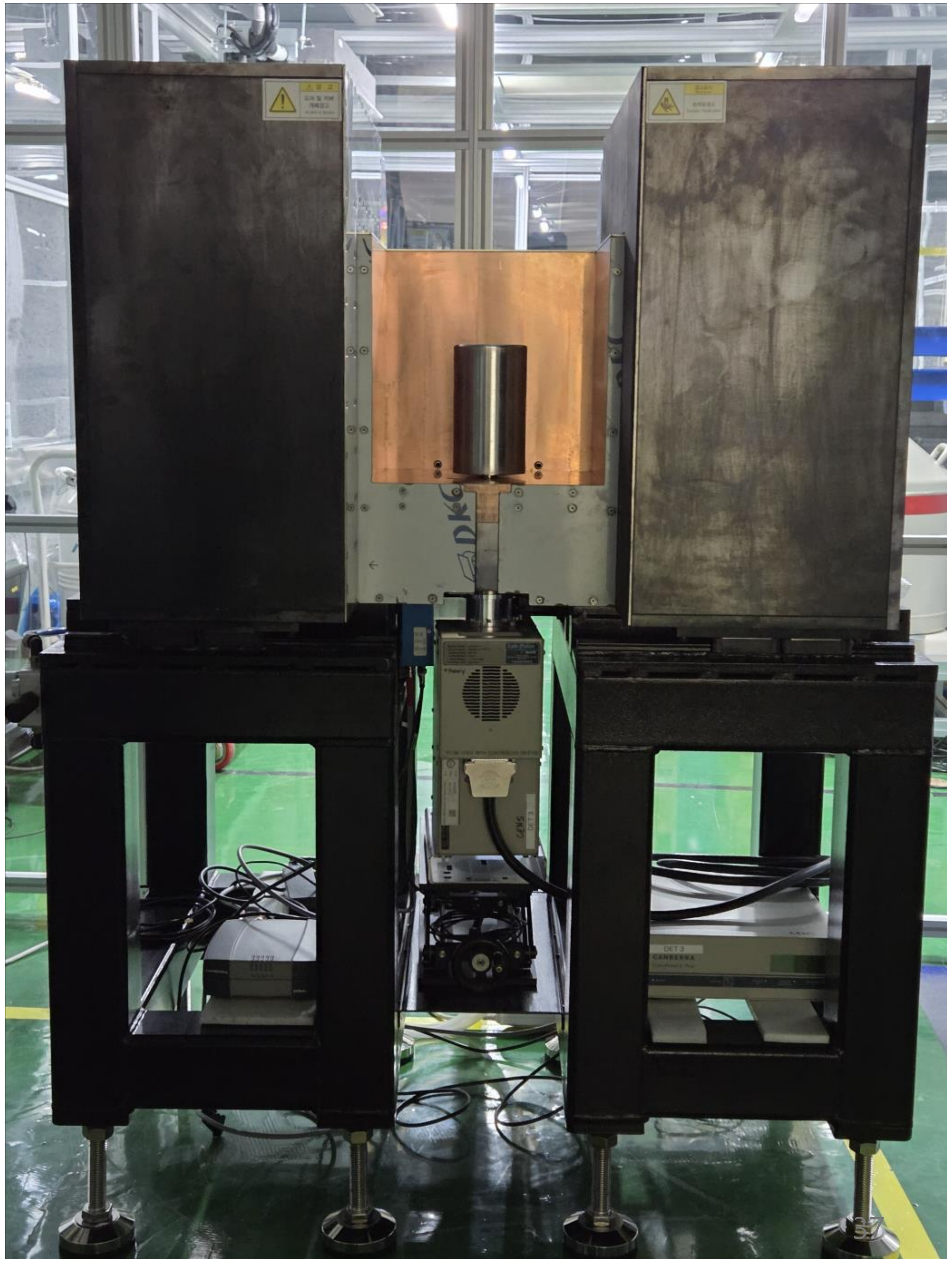
- **Difficult during the irradiation.**
  → External backgrounds (muons, gammas)

- **^{7}Be activity can represent the cross section.**
  → Need an ultra low radiation environment
  → **Yemilab**

Detector at Yemilab

- 100% Cryogen Free HPGe by CENS at HPGe tunnel
- Background run under different Rn levels
- Roughly 10 counts/day at 477.6 keV (±50 keV)
- The activation level can be much lower than the safety limits
    - Easy to transport to the outside of the accelerator facility





How LUNA did? Ref. PRC 102, 052802(R) (2020)

^{6}Li / ^{7}Li = 7.5% / 92.5%

^{6}Li(p, α)^{3}He,
known to be 5% precision
at the energy of astrophysical interest

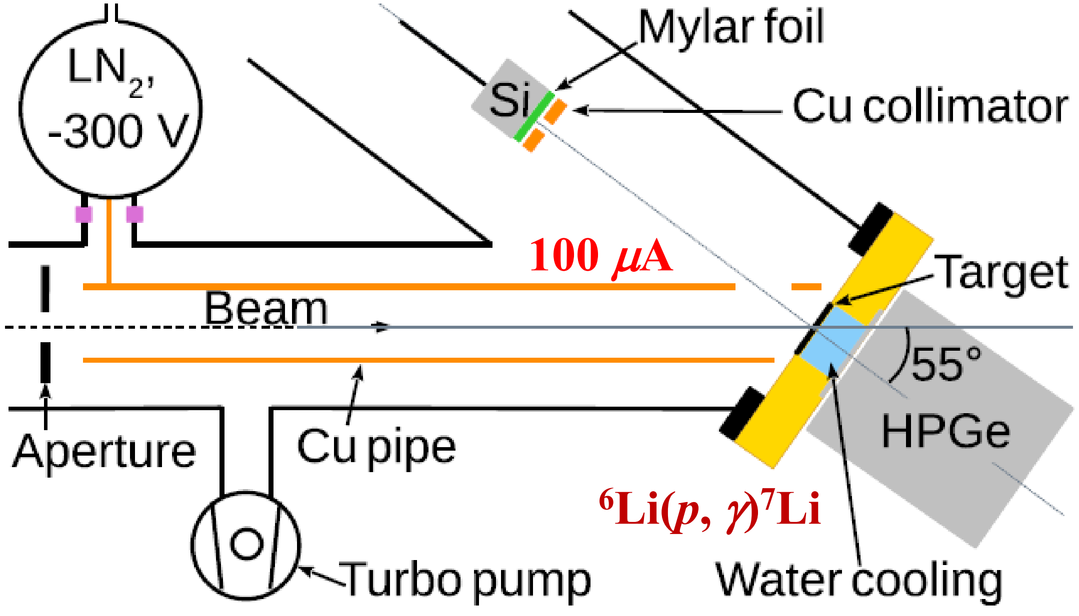


FIG. 1. Sketch of the experimental setup used for the measurement of the ^{6}Li(p, γ)^{7}Be cross section at LUNA.

- BBN lithium production is dominated by ^{2}H(α, γ)^{6}Li and ^{3}He(α, γ)^{7}Be reaction.
  → Predicted BBN ^{6}Li/^{7}Li ~10^{-5} << 0.08 by solar system
- Astrophysical S-factor at low energy can provide the evidence.

- ^{6}Li enriched(95%) targets ($^6Li_2WO_4$ and $^6Li_2O$) as powder form