# The Geant4-based simulation program for PandaX experiments


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04/26/2024

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# Outline

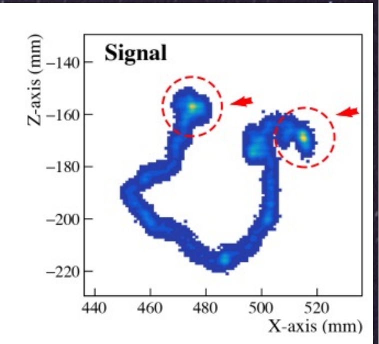
1. PandaX experiments
2. Simulation framework - BambooMC
3. Background estimation
4. Biasing technology for acceleration
5. Summary

# PandaX - Particle and Astrophysical Xenon

- **Increasing the detector-sensitive target volume.**
- **Lowering radioactive background.**

Dark matter WIMP Searches

$2\nu\beta\beta$ and $0\nu\beta\beta$ Research

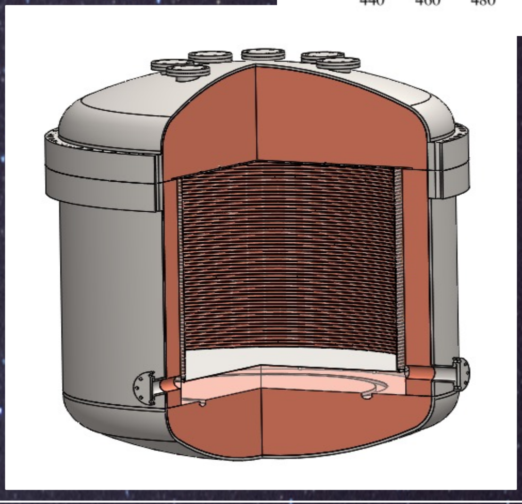



PandaX-I: 120 kg LXe (2009 – 2014)

PandaX-II: 580 kg LXe (2014 – 2019)

PandaX-4T: 3.7 t LXe

PandaX-xT (future)



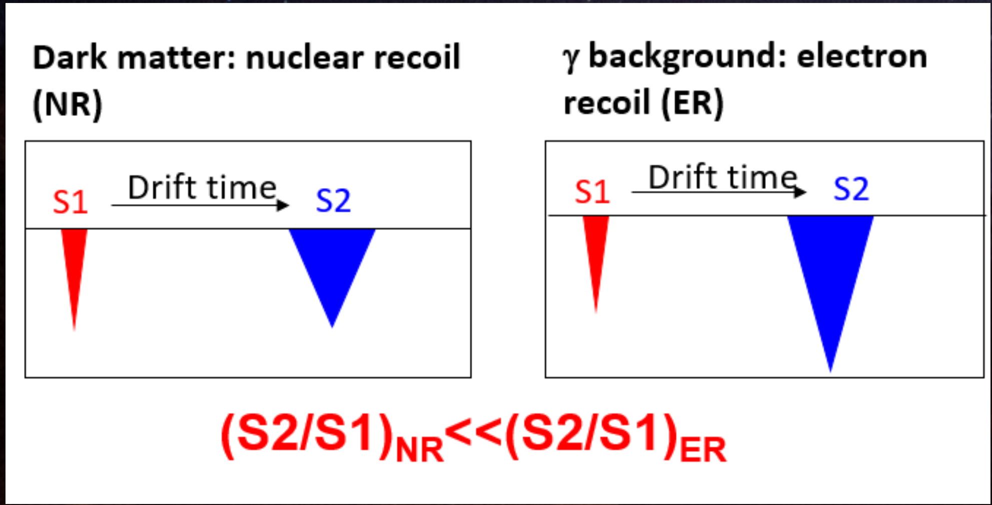
PandaX-III: HPXe 100 kg scale (R&D for the future)

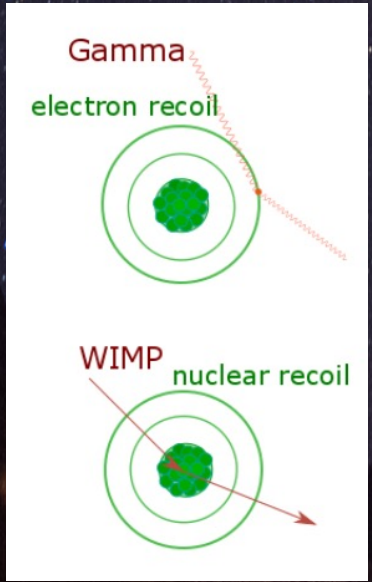
Liquide natural Xe (8.9% $^{136}Xe$)

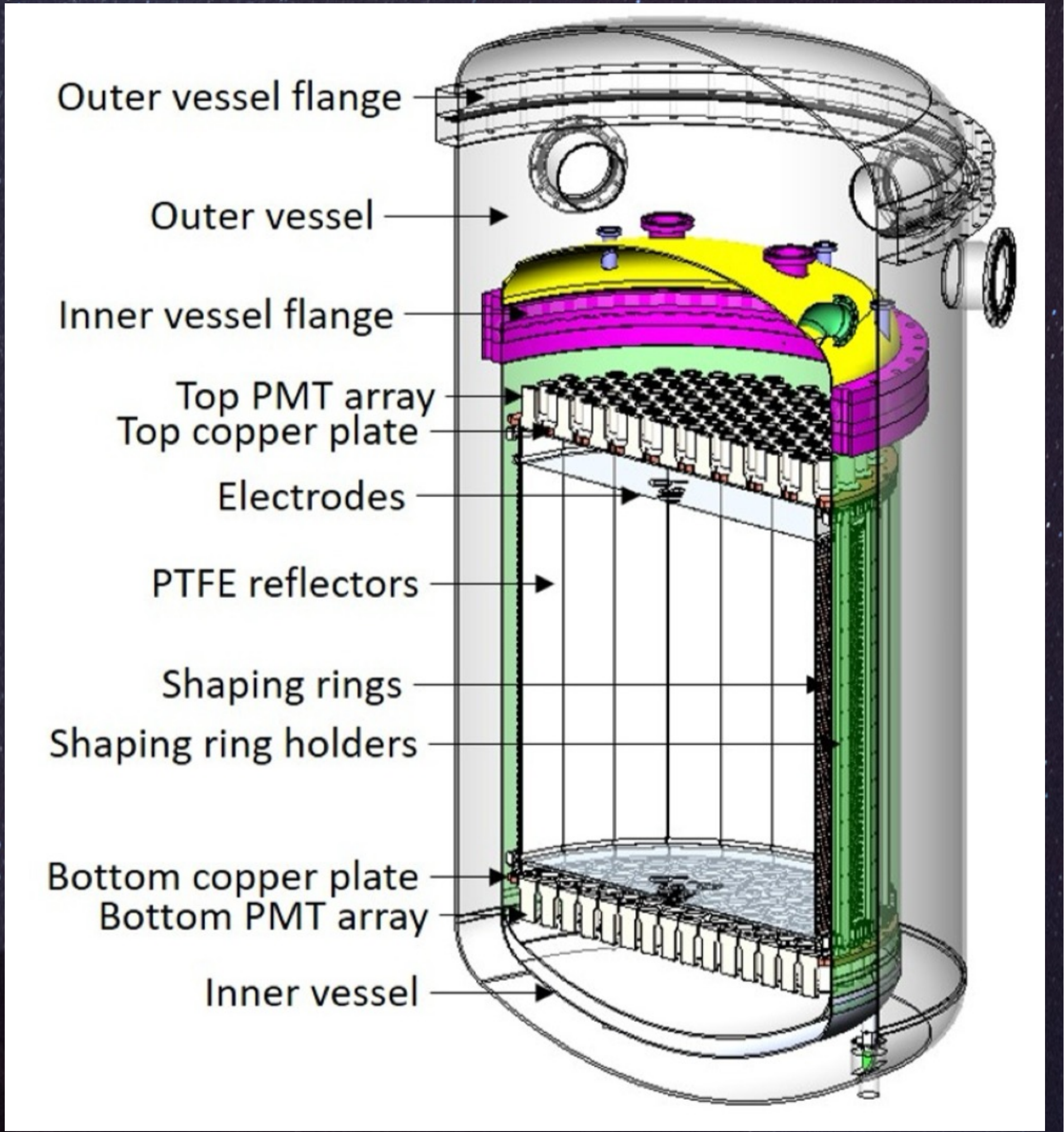
High pressure Xe (90% $^{136}Xe$)

# Dual Phase Xenon TPC in PandaX-4T

- Located at China Jinping Underground Laboratory
- Water shielding: 10 m (D) ×13 m (H)
- Dual-phase Xe TPC: 1.2 m (D) ×1.2 m (H)
- Sensitive volume: 3.7-ton LXe
- Total volume: 5.6 ton LXe
- 3-inch PMTs: 169 top / 199 bottom

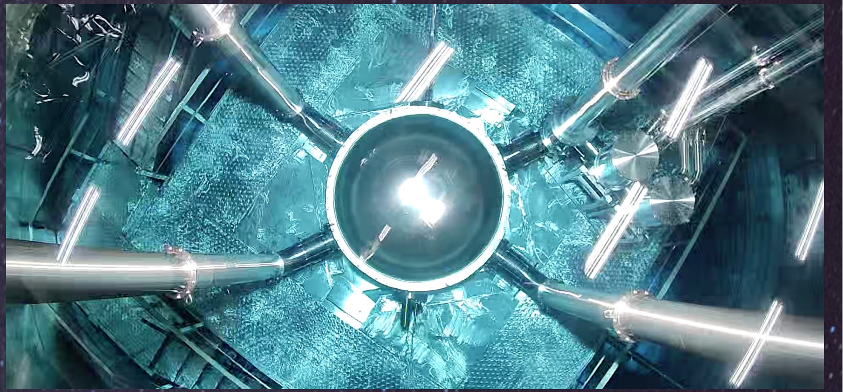


# Status and prospect

| | |
|---|---|
| 2020/11 – 2021/04 | **Commissioning (Run 0)**<br>95 days: ~0.6 tonne-year |
| 2021/07 – 2021/10 | **Tritium removal**<br>xenon distillation, gas flushing, etc |
| 2021/11 – 2022/05 | **Physics run (Run 1)**<br>164 days: ~1.0 tonne-year |
| 2022/09 – 2023/12 | **CJPL B2 hall construction**<br>xenon recuperation, detector upgrade |
| **Resume physics data-taking.** | |



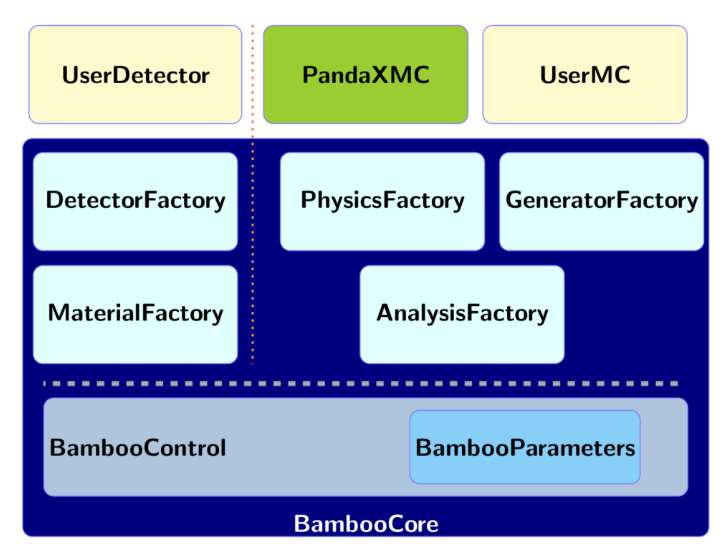

| | Sub-keV | 1 keV | 10 keV | 100 keV | 1 MeV | 10 MeV |
|---|---|---|---|---|---|---|
| Xe-136 (~9%) | | | | | $2\nu\beta\beta$ / $0\nu\beta\beta$ | |
| Xe-134 (~10%) | | | | $2\nu\beta\beta$ / $0\nu\beta\beta$ | | |
| Xe-124 (~0.1%) | | | $2\nu$ECEC | | | Alphas, muons and other physics |
| Xe all isotopes | $^{8}$B solar ν and light DM | WIMP and other DM models | solar pp ν | | | |

# Simulation framework - BambooMC

1. **Calculation of the detection efficiency of the counting stations**
2. **Estimation of the background contribution from the detector materials**
3. **Study of event distributions of different calibration sources**
4. **The correlated production of high energy gammas and neutrons in detector materials.**
5. **…**

BambooMC is a Geant4-based framework:

- C++;
- an input configuration file;
- export the detector geometry to a GDML;
- Designed to be used as a simple framework for different experiments. (PandaX, RELICS, …)
- Modular - It is possible to combine different geometry, physics, generator, and analysis in one program.




***JINST 2021, 16(09): T09004.***

# Simulation framework - BambooMC

- **The BambooCore module provides general functionalities, which can be used in different experiments.**
  1. **Generic parameterization system**
  2. **Dynamic geometry construction**

     shares the same structure, so the geometrical construction codes can be used in different simulations directly.
  3. **Dynamical loading of modular physics list**

**Open source:** [https://github.com/pandax-experiments/BambooMC](https://github.com/pandax-experiments/BambooMC)

```
git clone git@github.com:pandax-experiments/BambooMC.git
cd BambooMC
mkdir build
cd build
cmake -DCMAKE_BUILD_TYPE=Release \
 -DENABLE_DETECTOR_SETS=example,optical_example \
 -DENABLE_USER_MC=pandax ..
make
```

```yaml
run: 2312
geometry:
  material:
    name: SampleMaterial
  detectors:
  - type: SampleWorld
    name: World
    parameters:
      half_x: 2*m
      half_y: 2*m
      half_z: 2*m
  - type: BoxBlock
    name: VacuumBox
    parent: World
    parameters:
      half_x: 1*m
      half_y: 1*m
      half_z: 1*m
      material: vacuum
      sensitive: 2
      filter: neutron,gamma
  - type: BoxBlock
    name: PTFEBlock
    parent: VacuumBox
    parameters:
      half_x: 0.15*mm
      half_y: 0.15*mm
      half_z: 0.15*mm
      material: ptfe
      sensitive: 0
physics:
  name: PandaXPhysicsMod
  parameters:
    cutlength: 0.1*mm
generator:
  name: SimpleGPSGenerator
analysis:
  name: PandaXAnalysis
```

# Background estimation

- **Radioactive Origins**
  1. **Radioactive isotopes in materials**

     $^{40}$K, $^{232}$Th, $^{238}$U; $^{60}$Co and $^{137}$Cs for **ER**; $^{232}$Th, $^{235}$U, and $^{238}$U for **NR**.
  2. **Xenon targets impurities**

     $^{85}$Kr, $^{133}$Xe, $^{222}$Rn, $^{220}$Rn ($^{125}$Xe, $^{127}$Xe, $^{129m}$Xe , and $^{131m}$Xe).
  3. **neutrino-related background.**

     $^{136}$Xe, solar neutrinos
  4. ***The muon-induced background is negligible.**

     **cosmic ray flux is $3.53\times10^{-10}$ cm$^{-2}$s$^{-1}$**


- **ultra-low background platform**
  1. **two high-purity germanium (HPGe) counting stations**
  2. **inductively coupled plasma mass spectrometry (ICP-MS)**
  3. **neutron activation analysis (NAA)**
  4. **radon emanation measurement systems**
  5. **krypton assay station**
  6. **alpha detection system**

***JHEP06(2022)14***

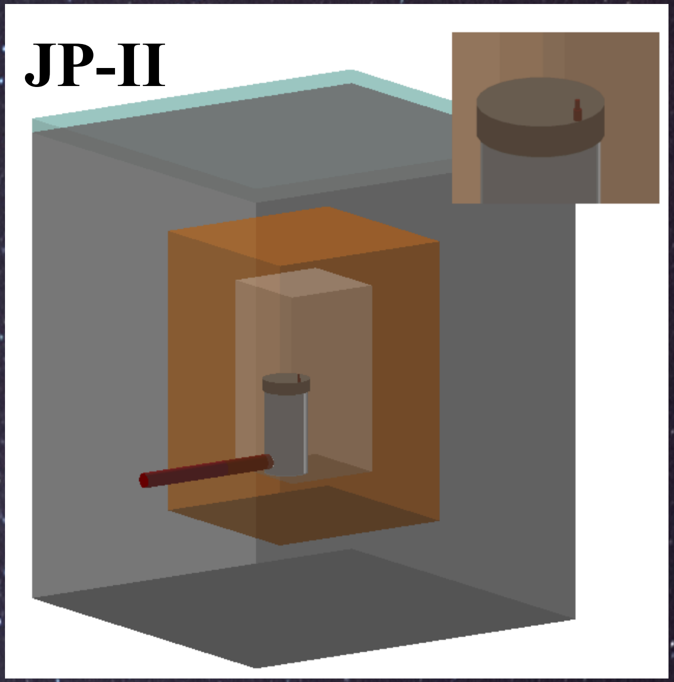
| Detector | JP-I | JP-II |
|---|---|---|
| Manufacturer | ORTEC | Canberra |
| Type | P-type coaxial | Broad energy |
| Mass [kg] | 3.69 | 0.63 |
| Relative efficiency | 175% | 34% |
| Integral [200, 3000] keV [counts/min] | 1.0 | 0.3 |
| FWHM@ 662 keV [keV] | 2.4 | 2.7 |
| FWHM@ 1332 keV [keV] | 3.0 | 2.8 |

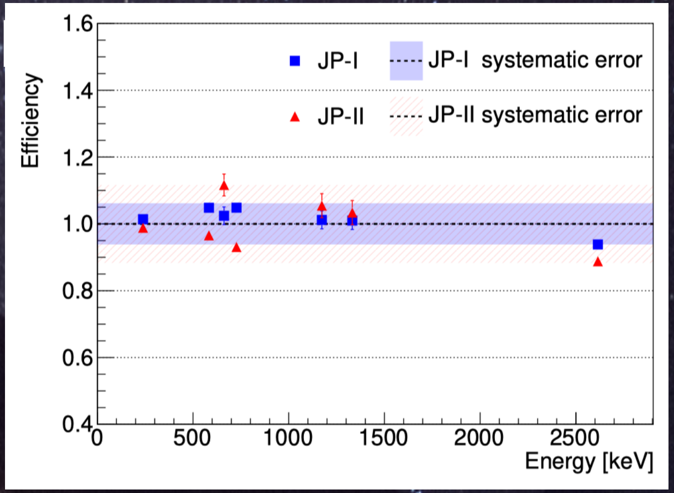
# Detection efficiency of the counting station

- For the samples with material names and geometric parameters dynamically loaded from the configuration files.
- Difference between simulation and measurement is smaller than 5% validated by $^{60}Co$ and $^{137}Cs$.

**BambooMC**

- PandaXPhysics
- SimpleGPSGenerator
- PandaXAnalysis
- CSGEMMXDetector and CSBEDetector
- regular shapes For samples

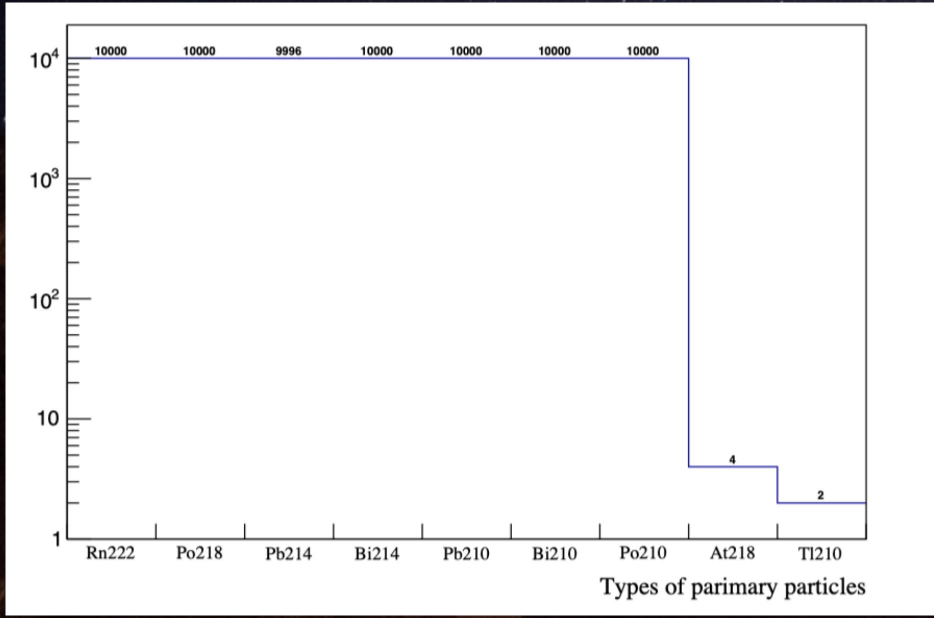


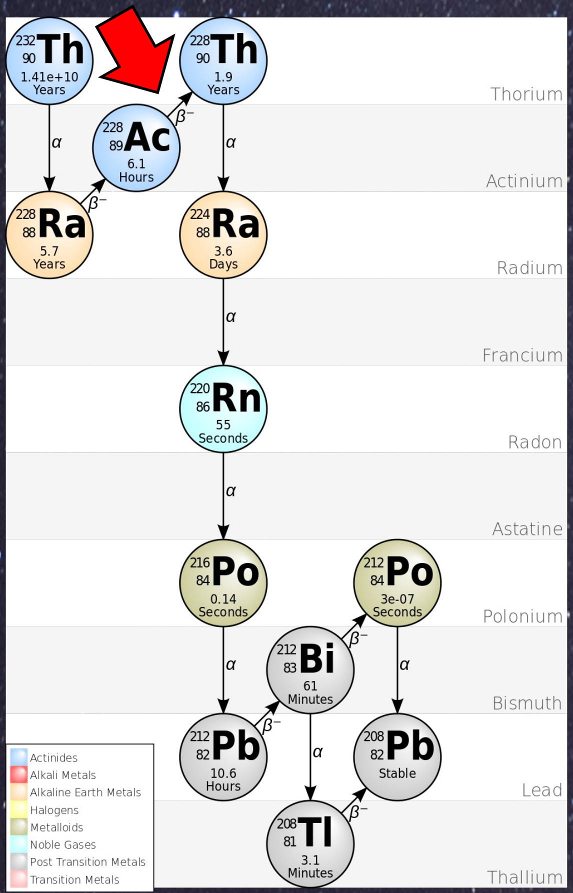



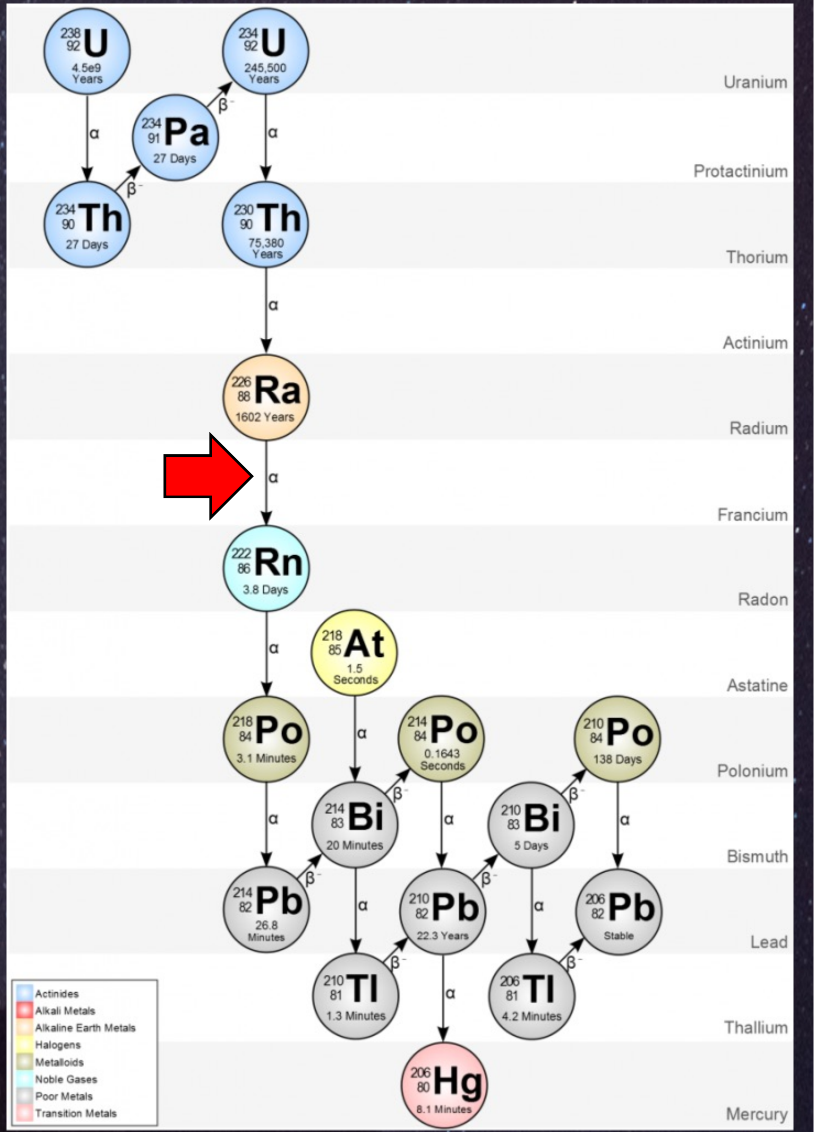

**The dynamic geometry construction of BambooMC simplified the simulation works!**

# Breaking up of long decay chain

- Geant4 will not stop the simulation of an event until the "stop" states.
- PandaXMC module:
  1. EnableDecayChainSplitting
  2. ChainSplittingLifeTime

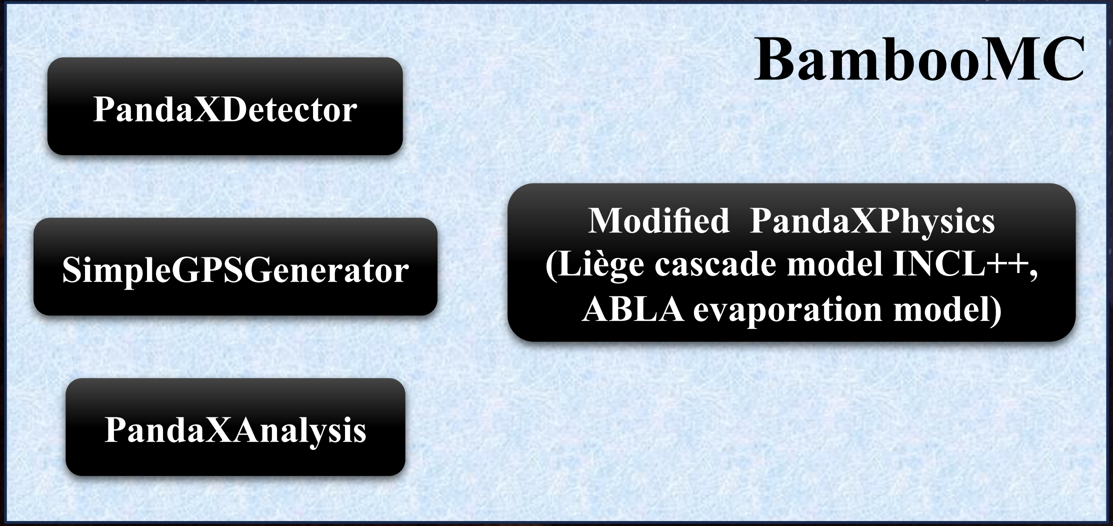


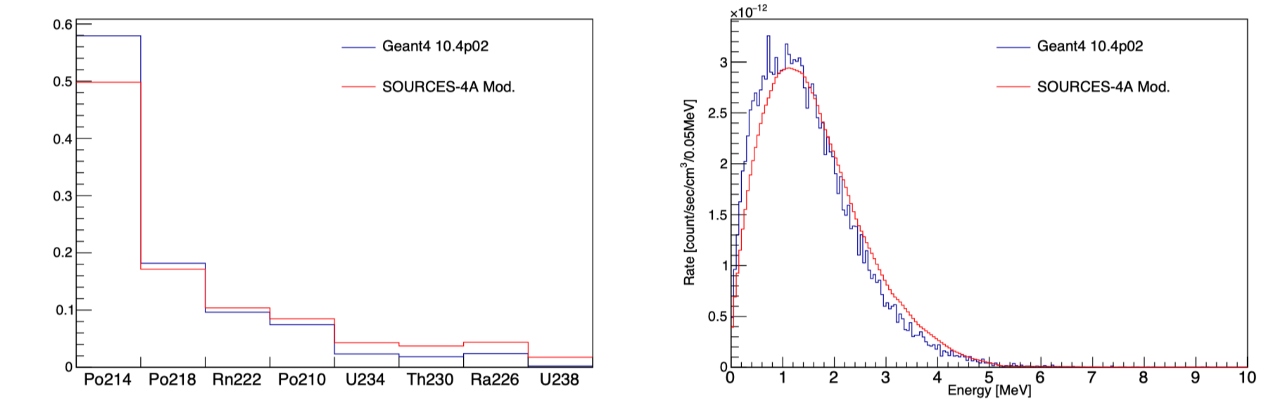



# Improved neutron generator for dark matter search

- **The neutron background should be estimated carefully.**
  1. the $(\alpha,n)$ reactions;
  2. spontaneous fission of radioactive nuclei.
- **<u>SOURCES-4A</u> without correlated production of neutrons and gammas, leading to the over-estimation of neutron background.**



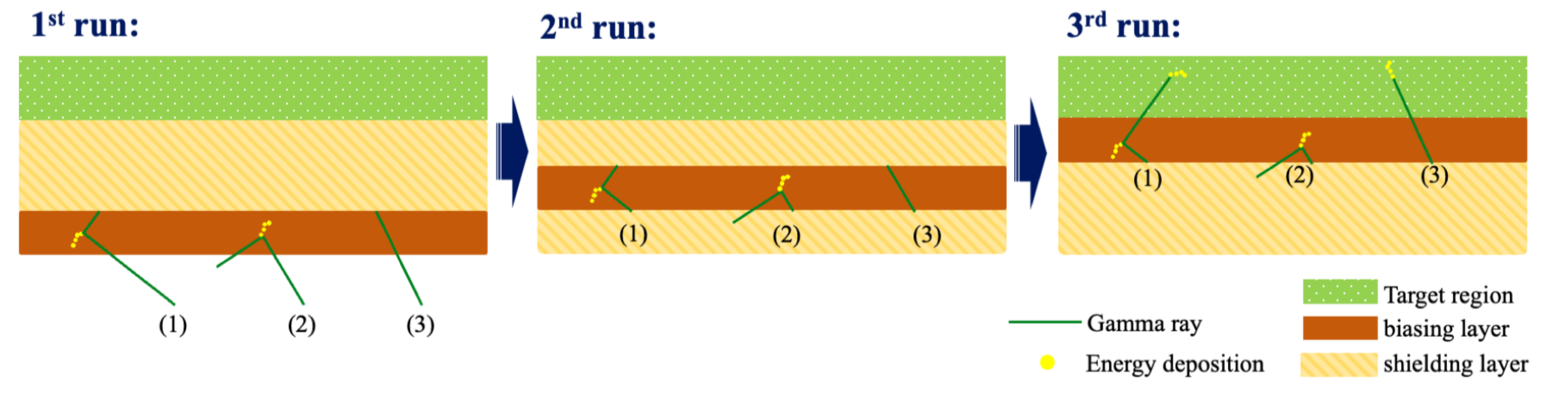




(a) Fraction of neutron contribution nuclei in the $(\alpha, n)$ process.

(b) Energy spectrum of neutrons.

# Biasing technology for simulation acceleration

- biasing techniques can enhance the efficiency and accuracy of simulations.
- The key processes are layering and multiplication.




"bias_hit": Energy deposition

"bias_source": The information of particles that touch the inner boundary, including particle type, energy, momentum, and position.

Type (1): The γ-ray loses some energy and continues to fly until reaching the boundary of the biasing layer;

Type (2): The γ-ray undergoes deflection and exits the shield without touching the surface of the biasing layer;

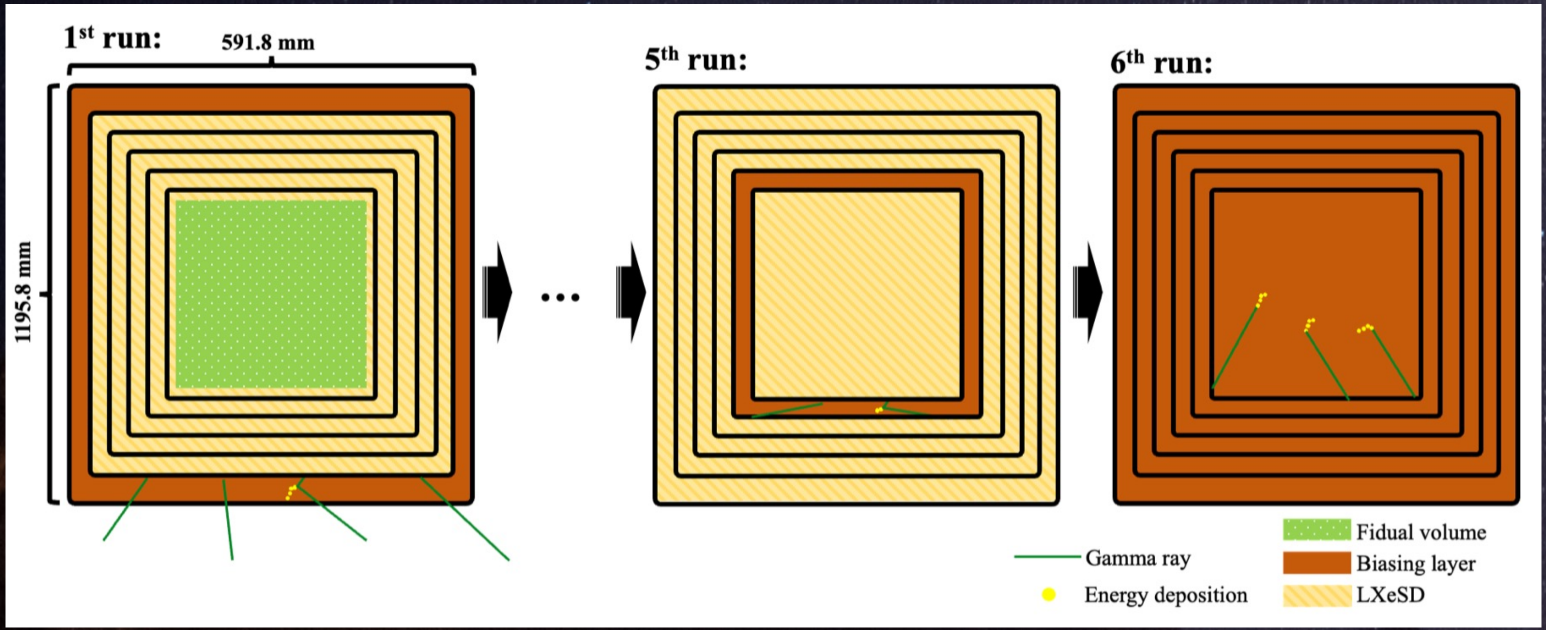
Type (3): The γ-ray does not interact and directly reaches the surface of the biasing layer.

# Biasing for ER background spectrum

- Background model of Analysis of $^{134}$Xe DBD for example.

PRL, 2024, 132(15): 152502.

- The <u>5-layer biasing structure</u> where all layers except the central biasing layer are hollow cylindrical shells.



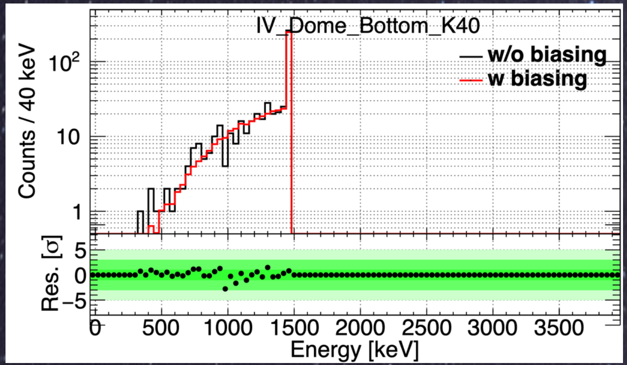

1. Re-entering the FV can be considered negligible.
2. Events with complete energy deposition in a biasing layer cannot enter the FV.

| Location | | Isotope |
|---|---|---|
| Location 1 | Location 2 | |
| Inner vessel | Barrel<br>Dome Bottom<br>Dome Top<br>FlangeB<br>FlangeF | $^{60}$Co<br>$^{40}$K<br>$^{232}$Th<br>$^{238}$U<br>$^{137}$Cs |
| Outer vessel | Barrel<br>Dome Bottom<br>Dome Top<br>FlangeB<br>FlangeF | $^{60}$Co<br>$^{40}$K<br>$^{232}$Th<br>$^{238}$U<br>$^{137}$Cs |
| PMT | Body Bottom<br>Body Top<br>Base Bottom<br>Base Top | $^{60}$Co<br>$^{40}$K<br>$^{232}$Th<br>$^{238}$U<br>$^{137}$Cs |

# Biasing for ER background spectrum

```
<parameter name="EnableBiasing" value="1"/>
<parameter name="CurrentBias" value="IRIS_CURRENT"/> valid when using biasing
<parameter name="NBiasing" value="6"/> valid when using biasing
<parameter name="BiasHeights" value="1050,950,850,750,650"/> mm; valid when using biasing
<parameter name="BiasRadiuses" value="570,550,530,510,490"/> mm; valid when using biasing
<parameter name="BiasFactor" value="1,1,2,2,4,4,10"/> valid when using biasing
<parameter name="FilePrefix" value="IRIS_DIR"/> valid when using biasing
<parameter name="SourceFileName" value="IRIS_SOURCE_FILE"/> valid when using biasing
<parameter name="TargetFileName" value="IRIS_TARGET_FILE"/> valid when using biasing
```

- **$^{40}$K in IV_Dome_Bottom for example**
  - With FV cut.
  - The performance gain is about 7000.




IV_Dome_Bottom_K40

-------- Ratio -------

wBias Entries: 1.51037e+07 : 4.9937e-06

woBias Entries: 523 : 5.23e-06

ratio Difference[(w-wo)/wo]: 4.51818%

ratio sigma: **1.03327**

**multiplier: 28879**

-------- Time -------

woBias time: 0.890 day

wBias time: 3.764 day

**multiplier: 4.231**

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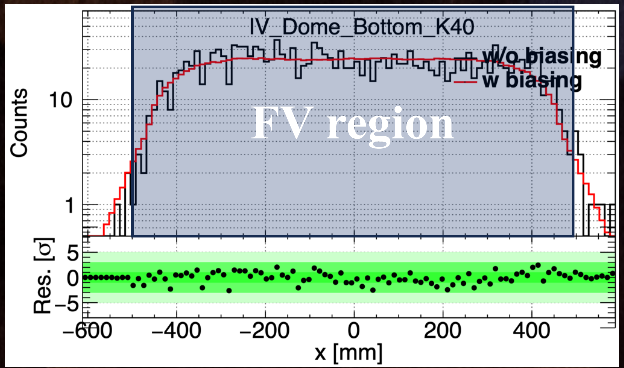
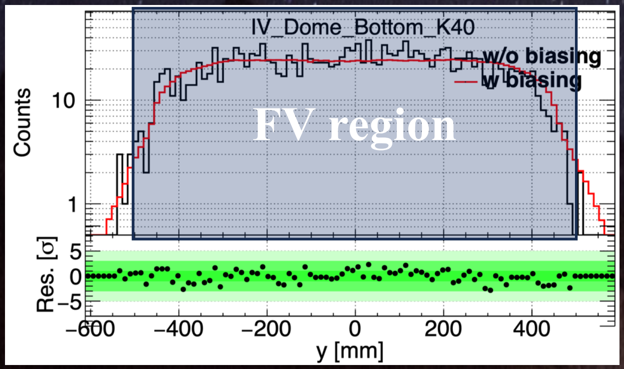
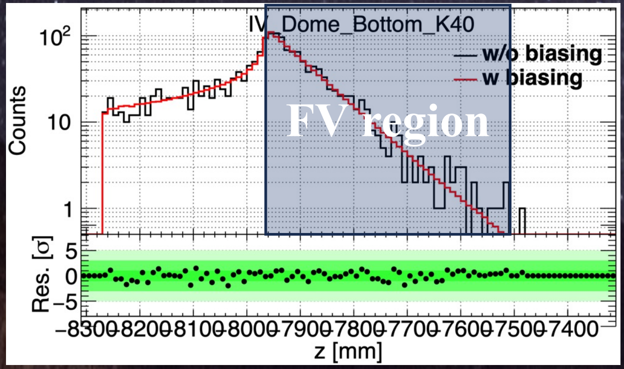
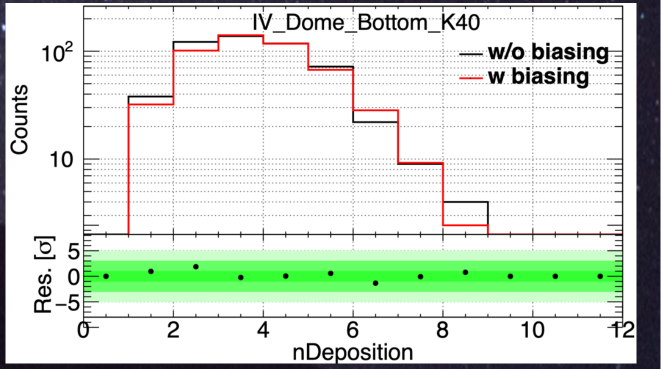
===> **Gain: 6824.986**

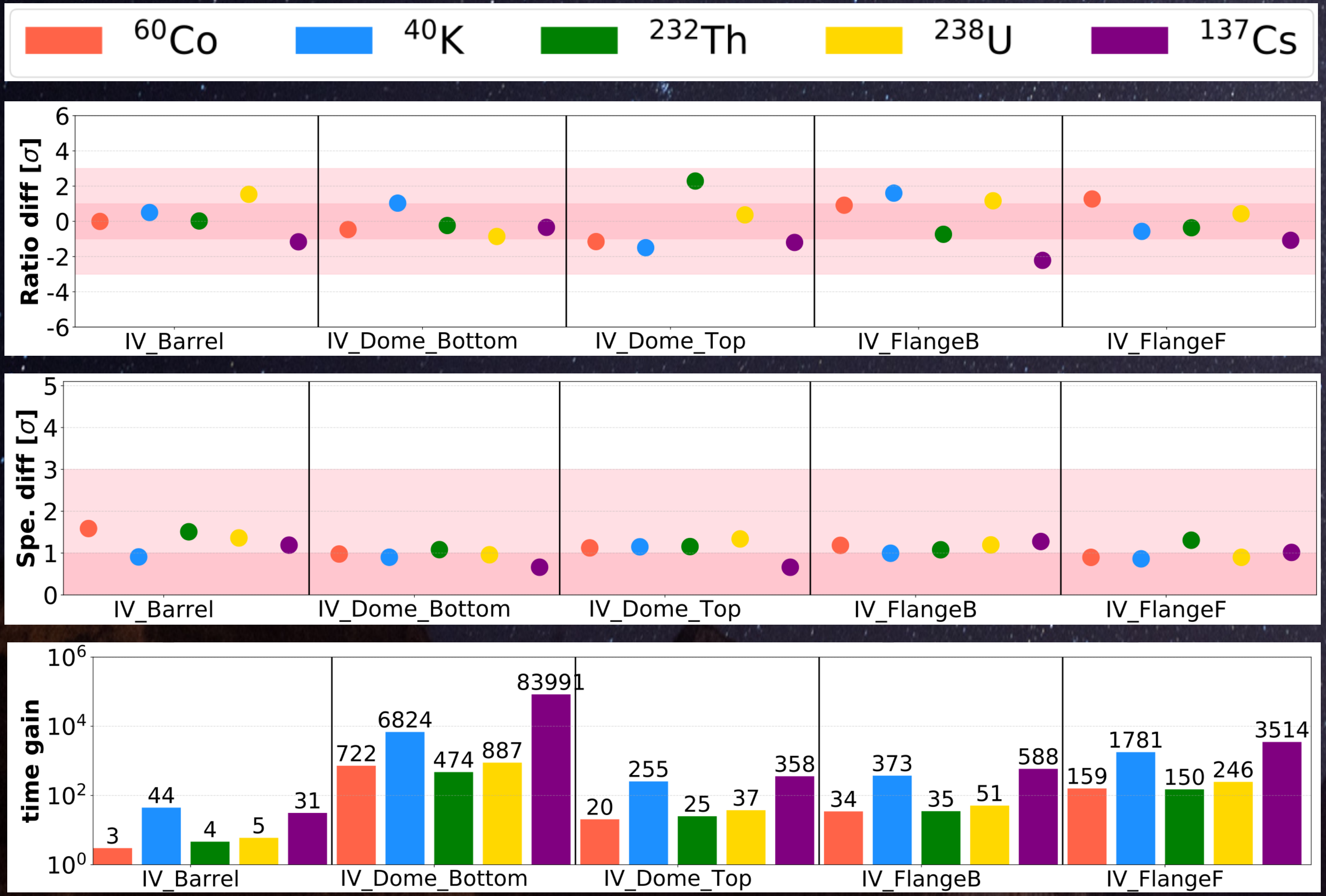


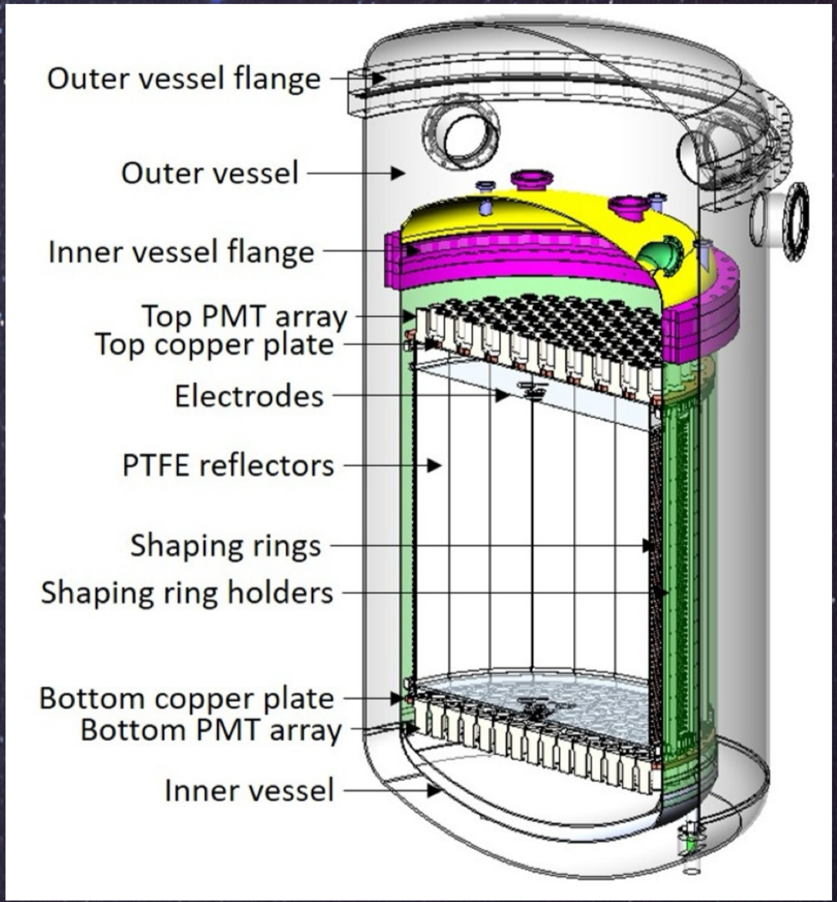



# Biasing for ER background spectrum



# Summary

1. **PandaX experiments have multiple physical goals to search for rare signals.**
2. **A Geant4-based simulation framework, BambooMC, has been widely used for background estimation, including several features:**
    1. Detection efficiency of the counting station;
    2. Breaking up for long decay chain;
    3. Improving neutron generator;
    4. Biasing technology for simulation acceleration.

# PandaX - Particle and Astrophysical Xenon

**Collaboration meeting at April 19-22, 2024**

# Back up

**Tao Li**

Sun Yat-sen University (SYSU)

04/20/2024

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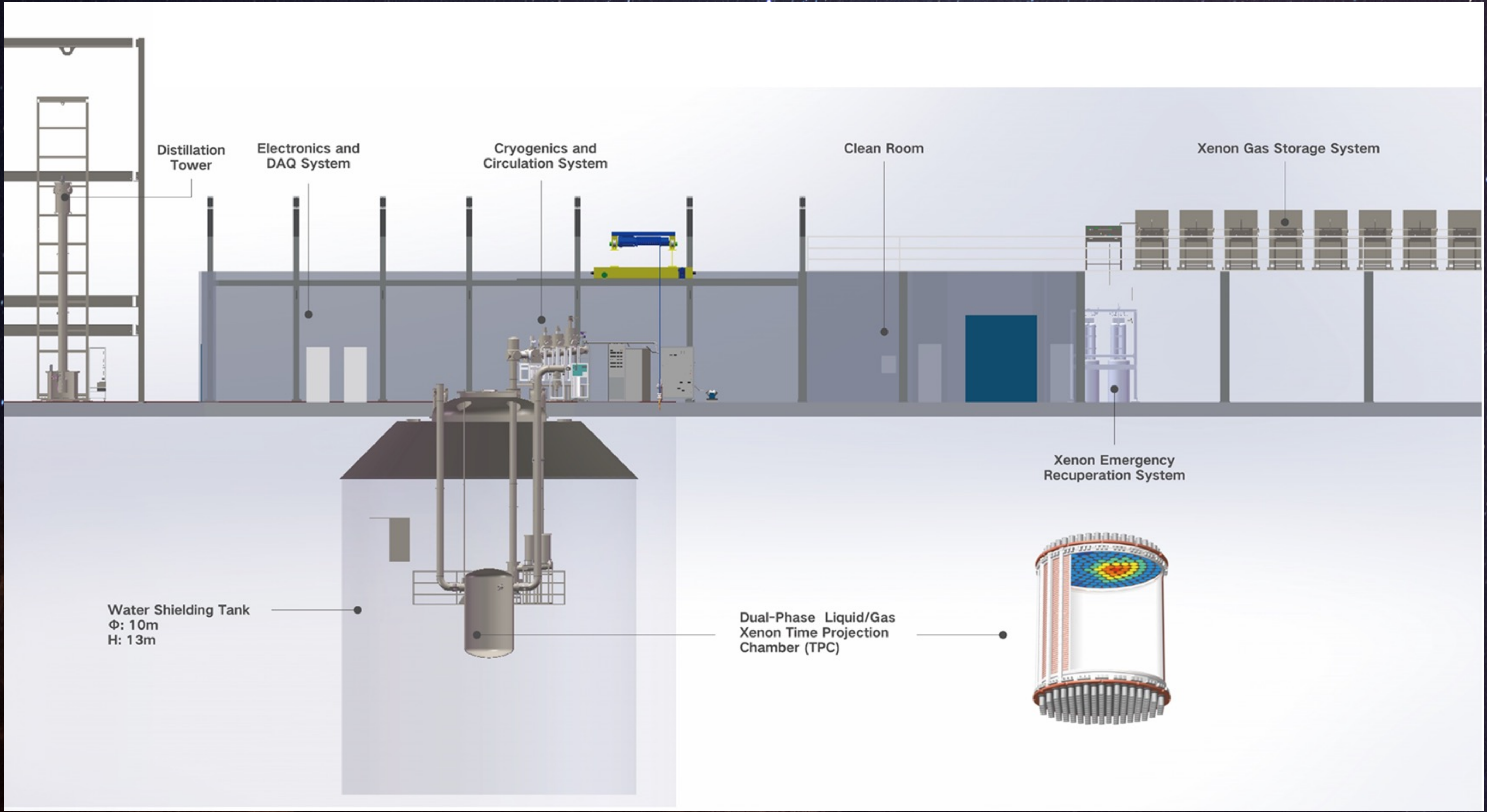
# Layout in CJPL-II hall



# Input configuration file

```xml
<physics name="PandaXPhysics">
  <parameter name="cutlength" value="0.1*mm"/>
</physics>
<generator name="SimpleGPSGenerator"/>
<analysis name="PandaXAnalysis">
  <parameter name="EnableEnergyDeposition" value="1"/>
  <parameter name="EnableSurfaceFlux" value="1"/>
  <parameter name="EnablePrimaryParticle" value="1"/>
  <parameter name="SaveNullEvents" value="0"/>
  <parameter name="UserSeed" value="0"/>
  <parameter name="EnableDecayChainSplitting" value="1"/>
  <parameter name="ChainSplittingLifeTime" value="0.1"/>
</analysis>
```

```cpp
// EM Physics
RegisterPhysics(new G4EmLivermorePhysics(verbose));

// Synchroton Radiation & GN Physics
RegisterPhysics(new G4EmExtraPhysics(verbose));

// Decays
RegisterPhysics(new G4DecayPhysics(verbose));

RegisterPhysics(new G4RadioactiveDecayPhysics(verbose));

// hadron physics
RegisterPhysics(new G4HadronElasticPhysicsHP(verbose));

// shielding, changed api for different version of geant4.
RegisterPhysics(new G4HadronPhysicsShielding(verbose));

// stopping physics
RegisterPhysics(new G4StoppingPhysics(verbose));

// ion physics
RegisterPhysics(new G4IonQMDPhysics(verbose));
```