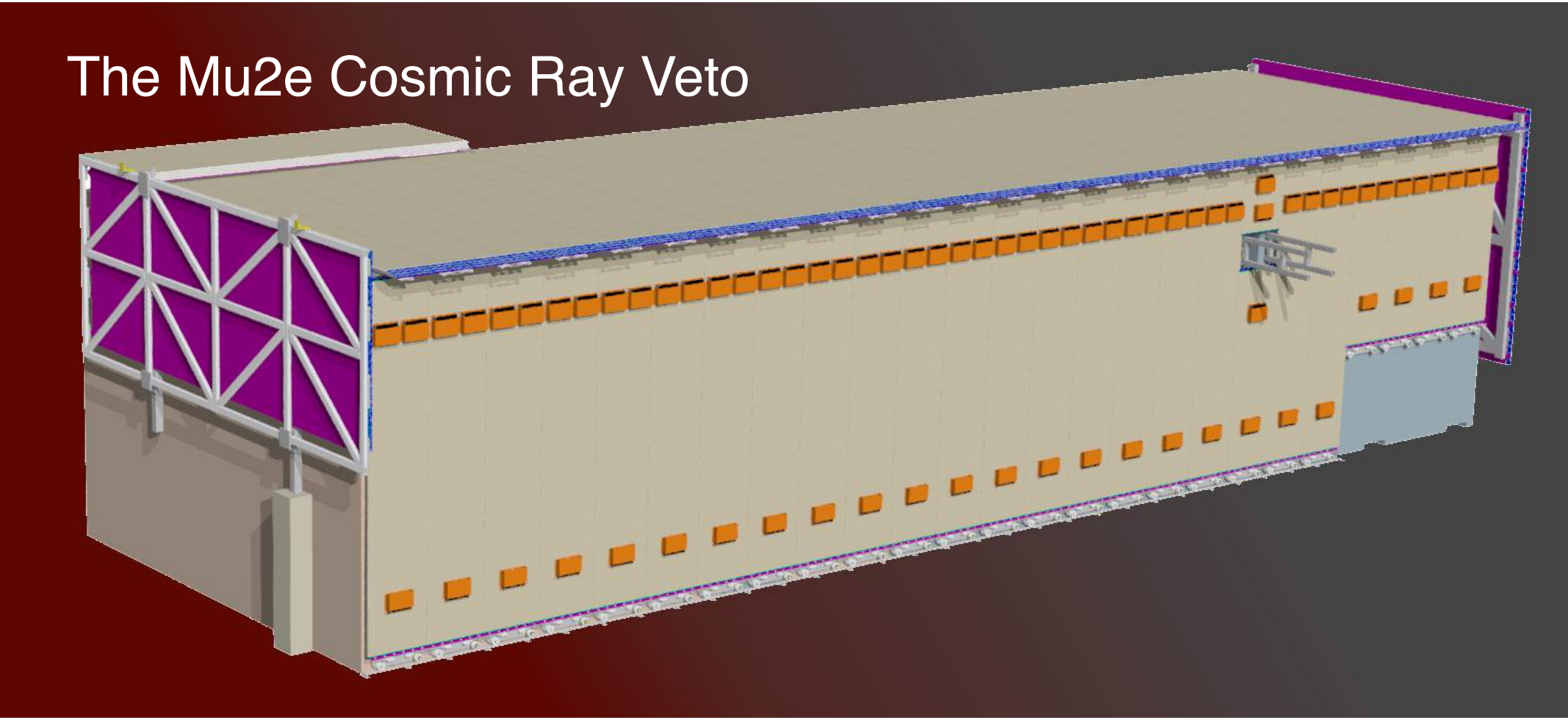
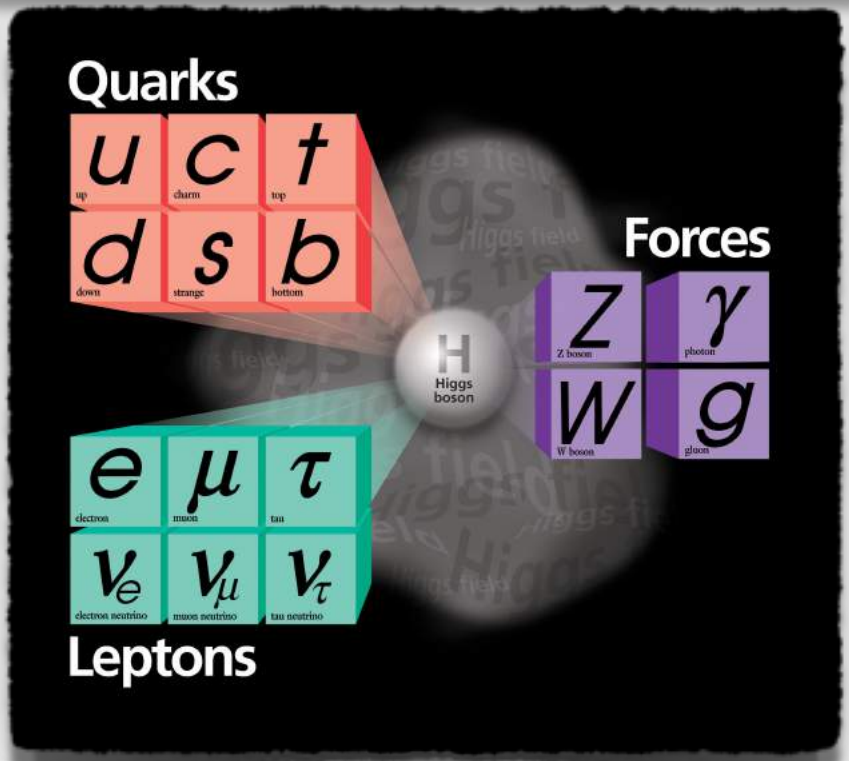
The Mu2e Cosmic Ray Veto

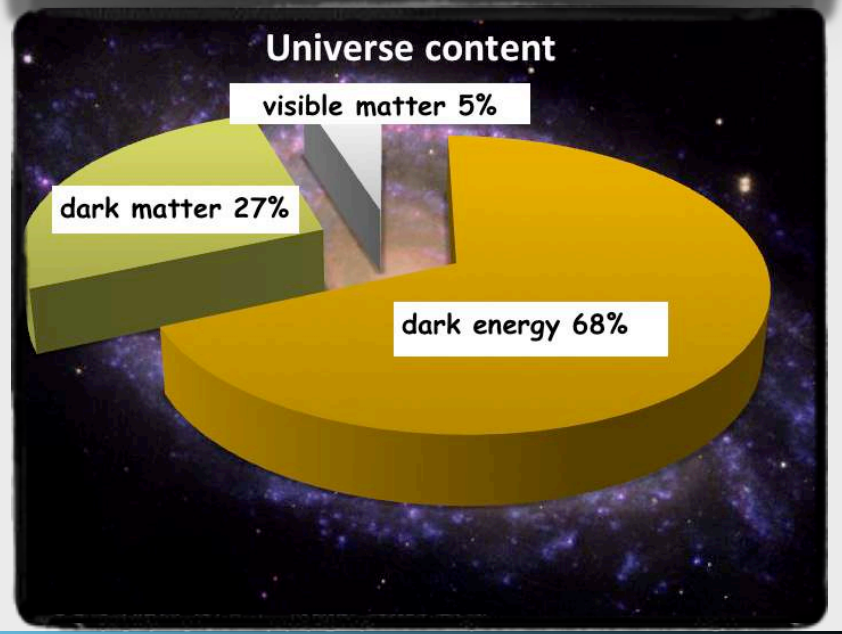


Newcomers lunch

Standard Model

- Standard Modern - successful theory
- Open questions:
  - Dark energy and dark matter
  - Baryon Asymmetry
  - Hierarchy problem
  - Family structures and masses
  - …
- We can look for answers at various frontiers
  - Energy, intensity or cosmic frontiers





Intensity frontier: Muon Campus

- Intensity Frontier with muons - an alternative way to look for answers
- Access New Physics at higher energies through loops
  - **g-2**: Measuring muon's anomalous magnetic moment to 140 ppb
  - **Mu2e:** Looking for ultra-rare decays

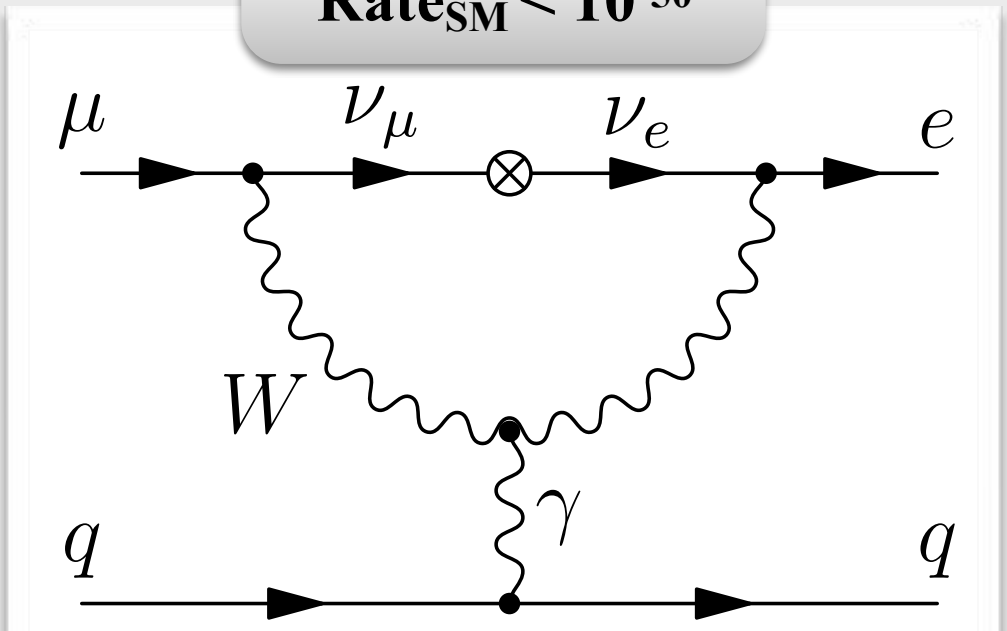
Mu2e (μ → e)

- Mu2e will search for neutrino-less, coherent muon conversion into an electron in the presence of Al nucleus:

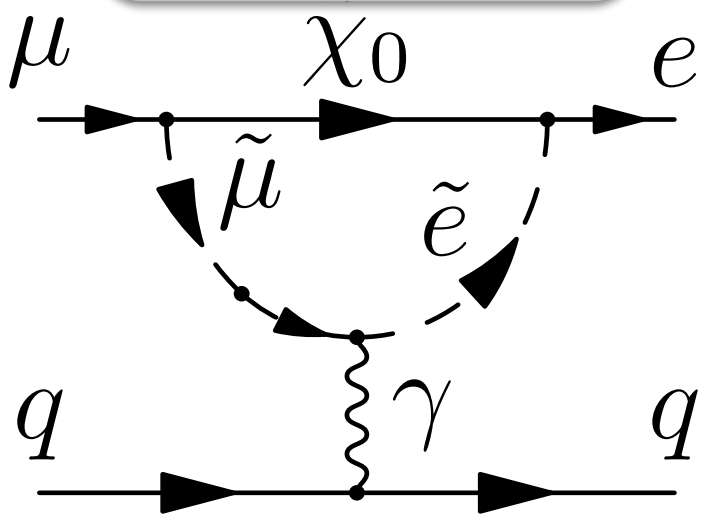
$$\mu^- + Al \rightarrow e^- + Al$$

- In the SM, $\mu \rightarrow e^-$ occurs at the rate of $<10^{-50}$
  - Signal observation at Mu2e is unambiguous sign of new physics

$Rate_{SM} < 10^{-50}$



$Rate_{BSM} \sim 10^{-15}$



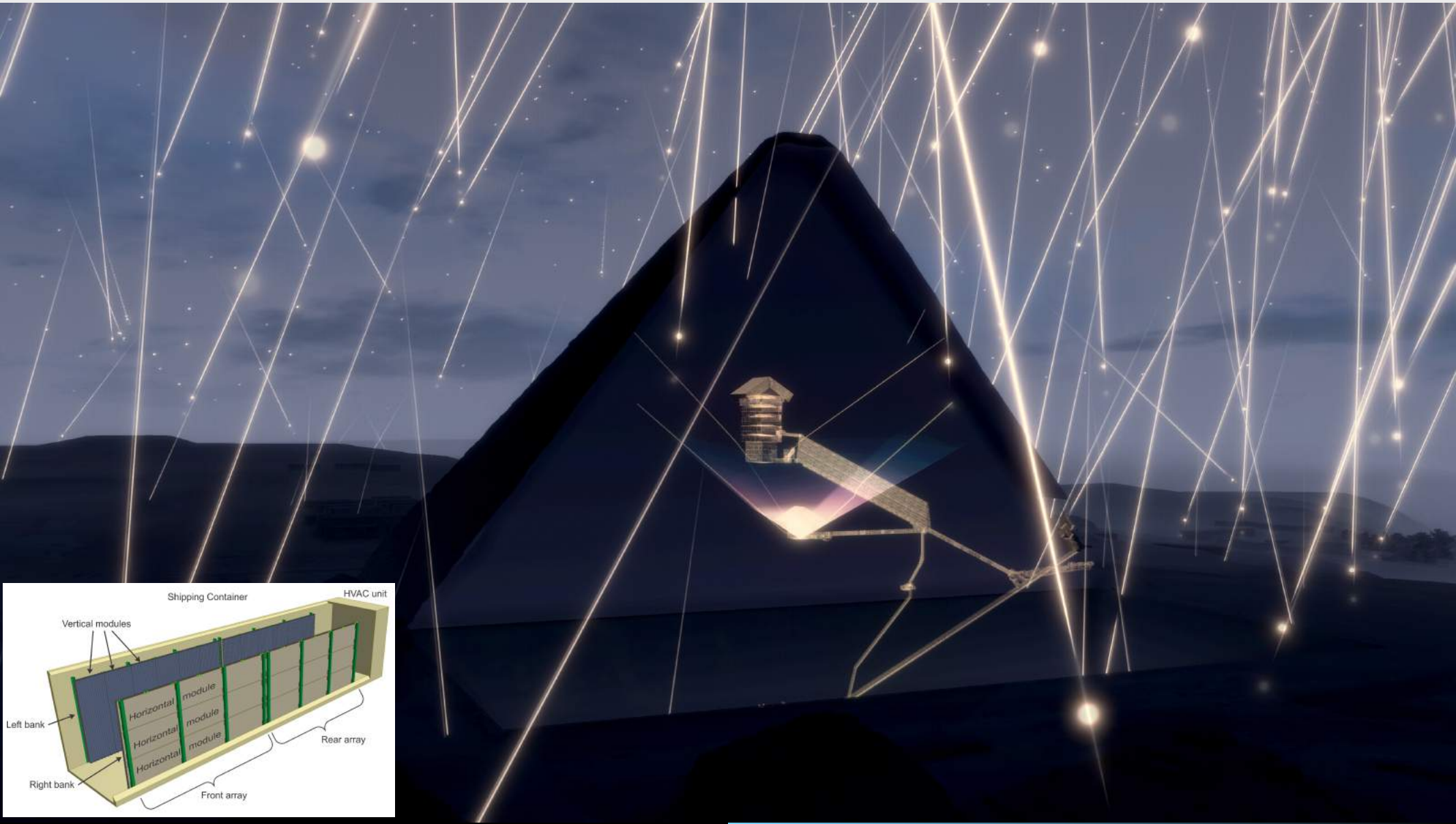
Other CLFV Processes

- Most stringent limits come from muon sector

Process	Current Limit	Next Generation Exp
$\tau \rightarrow \mu\eta$	BR < 6.5E-8	
$\tau \rightarrow \mu\gamma$	BR < 6.8E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2E-8	
$\tau \rightarrow eee$	BR < 3.6E-8	
$K_L \rightarrow e\mu$	BR < 4.7E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3E-11	
$B^0 \rightarrow e\mu$	BR < 7.8E-8	
$B^+ \rightarrow K^+ e\mu$	BR < 9.1E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0E-12	10^{-16} (PSI)
$\mu^- N \rightarrow e^- N$	$R_{\mu e}$ < 7.0E-13	10^{-17} (Mu2e, COMET)

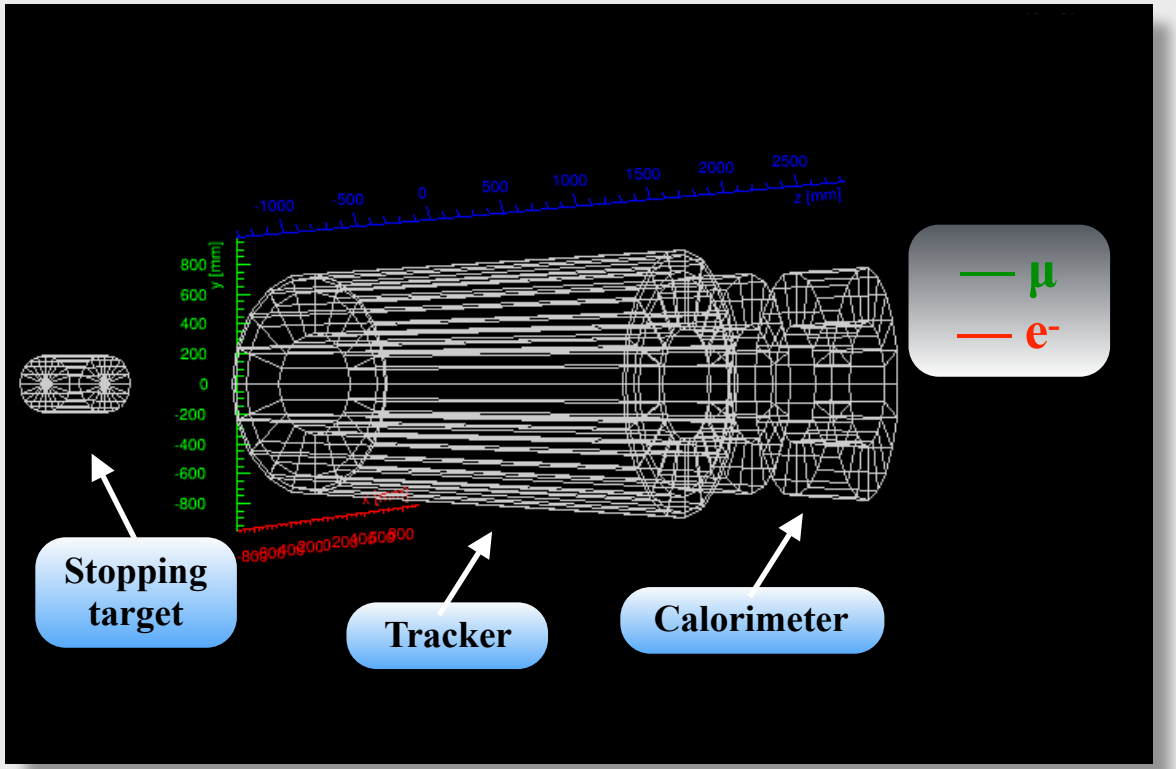
Egypt pyramids tomography

- Use cosmic muons to study internal structures of pyramids



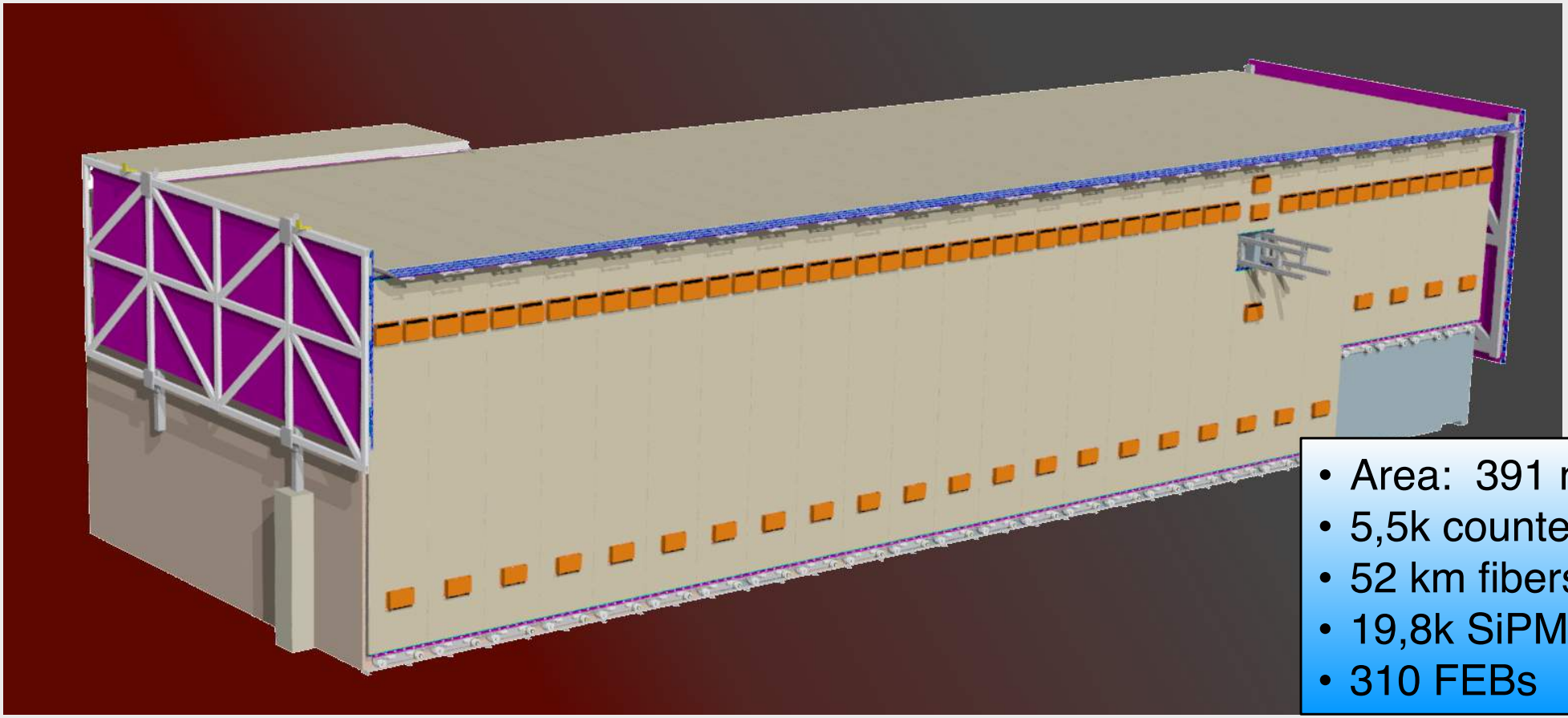
Cosmic Ray Background

- Nasty side of muons: Mu2e is exposed to 1.25E9 cosmic muons per day
- Cosmic ray muons produce a background
  - Interactions with material inside DS, decays and faking electrons
- Mu2e expects 1 signal-like event per day induced by cosmic rays
  - 780 events over Mu2e lifetime
  - Total expected background at Mu2e: 0.41
- CRV needs to suppress cosmic ray background by a factor of 10,000



Cosmic Ray Veto

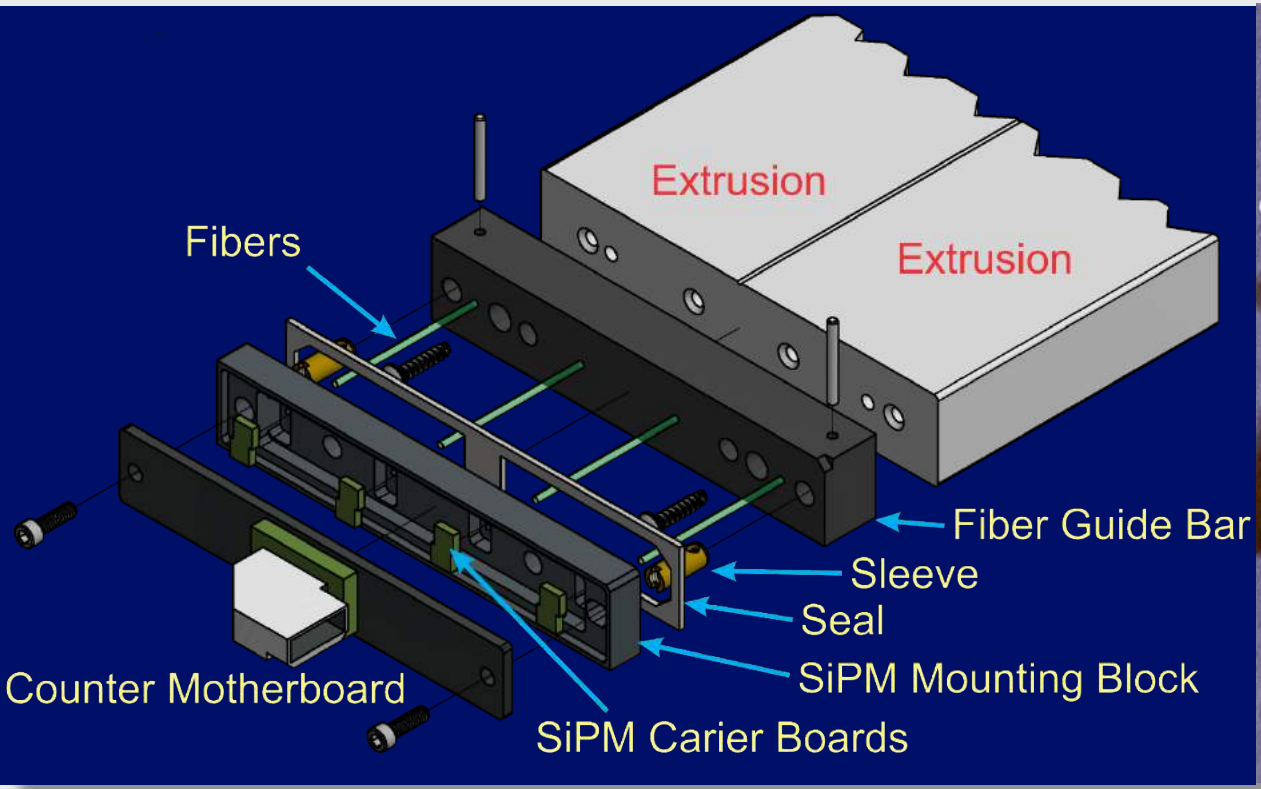
- CRV consists of 4-layer scintillating 5x2 cm^2 counters, read-out through wavelength-shifting fibers by 2x2 mm^2 SiPMs
- Cosmic ray muon detection - hits coincidence in at least 3 layers localized in time and space
- Veto (offline) 125 ns from a signal window after a coincidence in the CRV

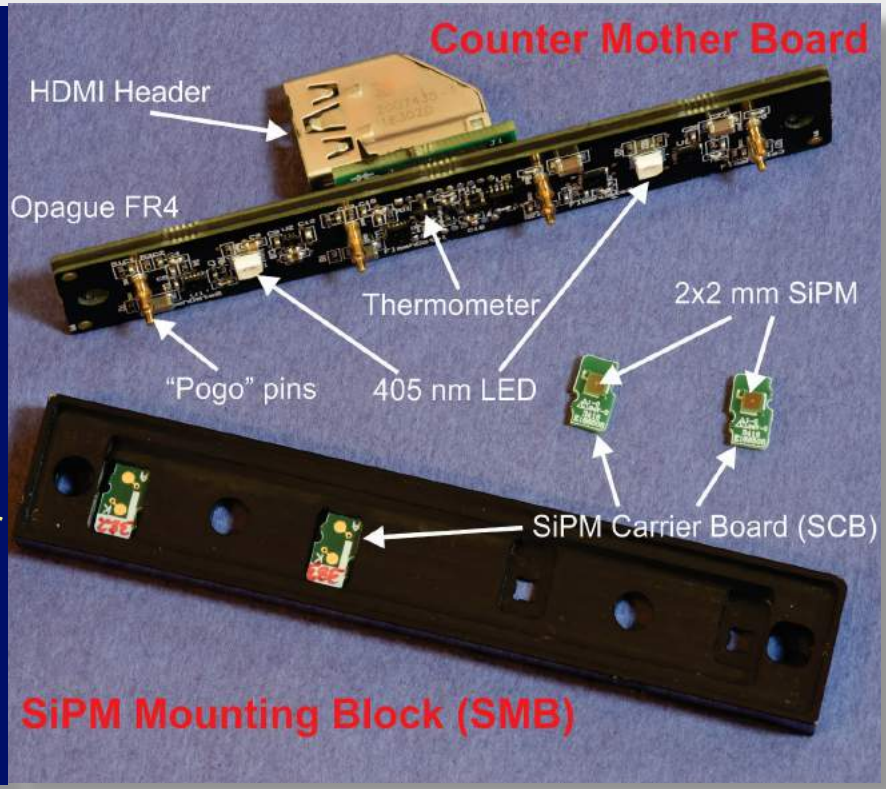


- Area: 391 m^2
- 5,5k counters
- 52 km fibers
- 19,8k SiPMs
- 310 FEBs

CRV building block: di-counter

- Counters: extruded PS doped with 1%PPO+0.05%POPOP, coated with TiO2
  - Glued in pairs to make di-counters
- Each counter has two 1.4 mm wavelength-shifting fibers placed in channels
- Fiber Guide Bar is glued and fly-cut
- Fibers are read out by SiPMs

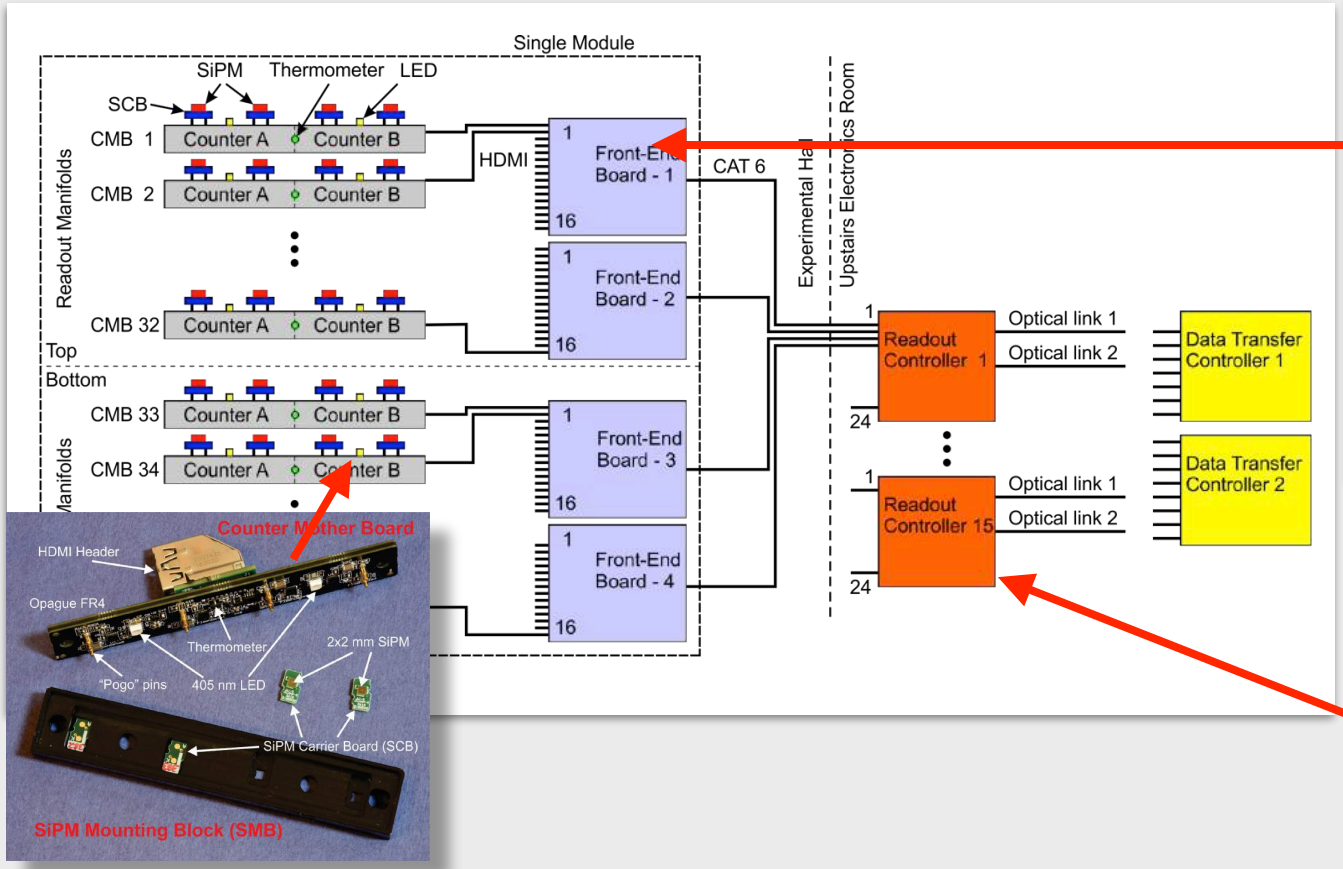


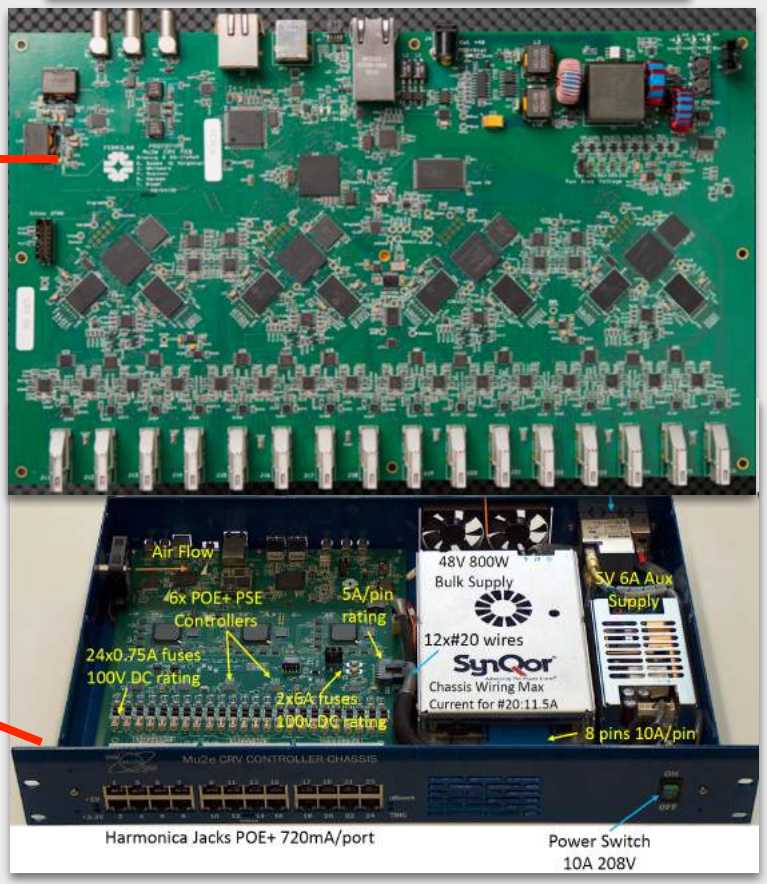


Electronics

- Surface mounted SiPMs -> Carrier Boards (19,840)
- Carried Boards -> Counter Motherboards (4960)
- Counter Motherboards -> Front-end Boards (310)
- Front-end Boards -> Readout Controllers (15)

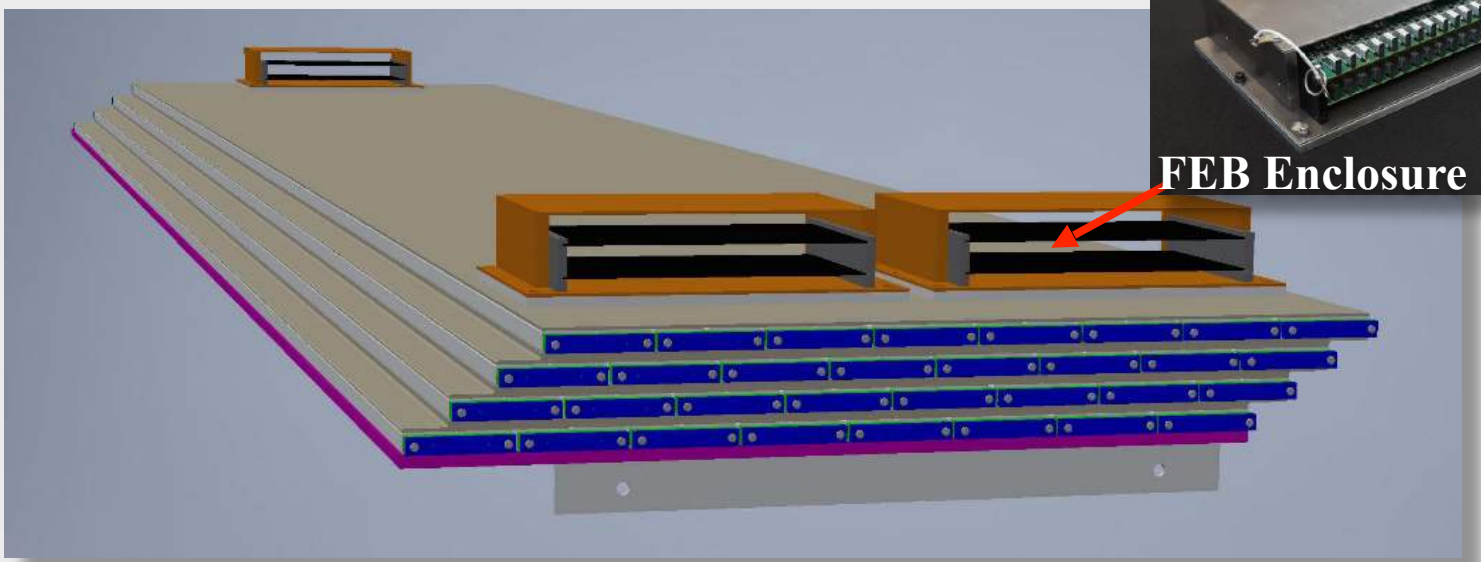
SiPM pixels:	1584
Dynamic range:	2048
Sampling rate:	12.6 ns
Rate to DAQ:	55 MB/s
Data per run:	0.5 PB
Time resolution:	~ 2 ns
Zero suppression:	6 PE
Triggered read-out	

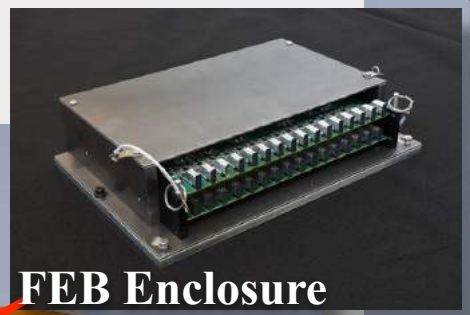




CRV module

- Di-counters are used to build a module
  - 4 layers of 8 di-counters separated by aluminum absorbers
- Entire assembly glued together
- Weight: 149 - 1091 kg
- Length: 0.9 - 6.9 m
- Number of modules: 86





Module fabrication at UVa

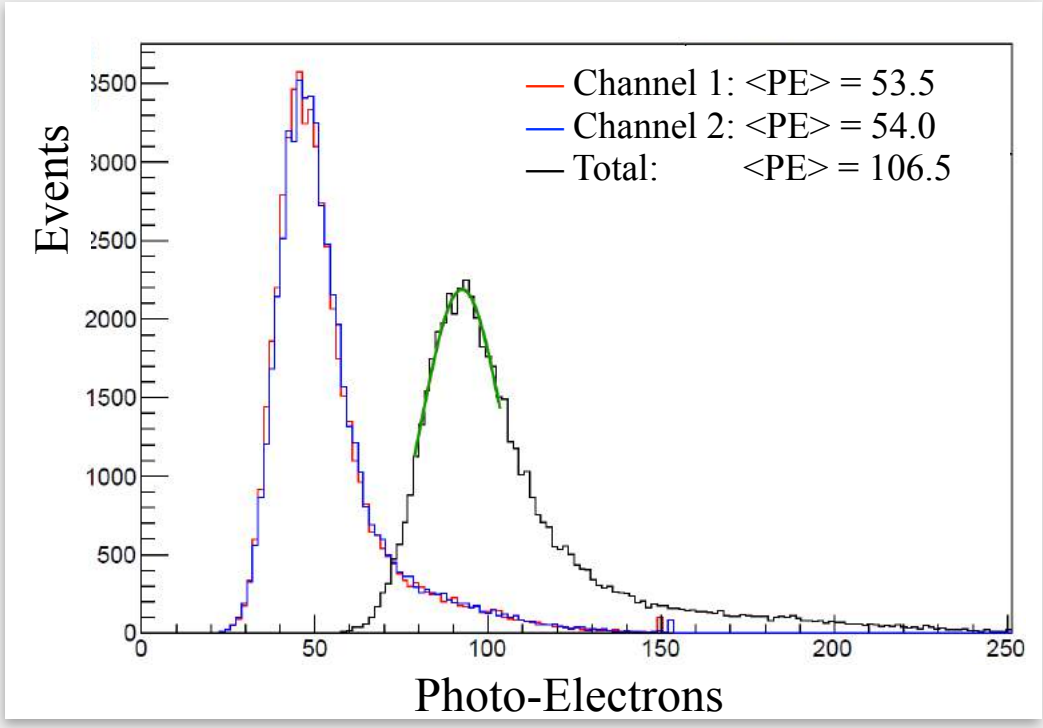
- Module factory has been set up at University of Virginia
- 9 prototype modules have been fabricated
- Manufacturing tolerances very demanding and critical
- Production is underway
  - The factory will be producing a module/week

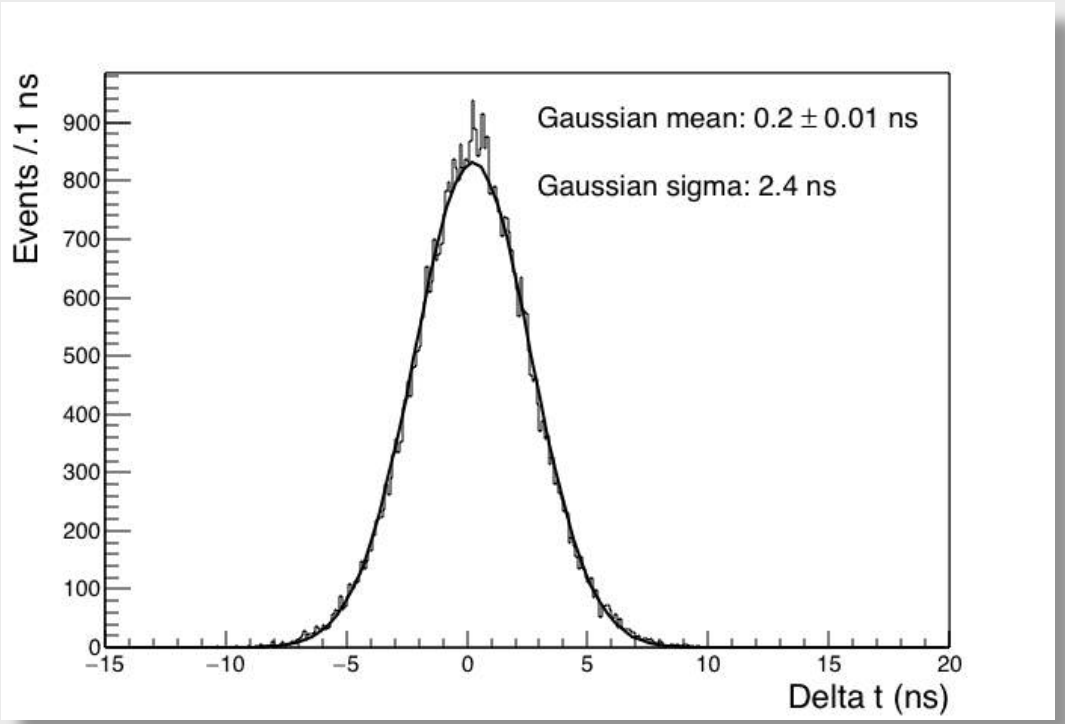
Module fabrication

https://youtu.be/ACJTbAOXOuQ

CRV performance

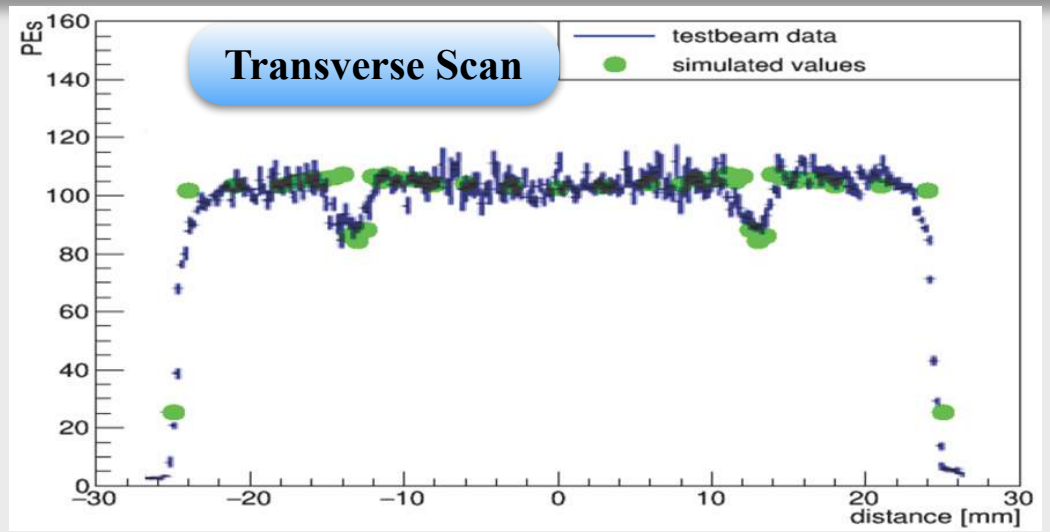
- Test beam results with CRV prototype
- Light yield: 54 PE/SiPM at 1 m
  - Requirement: 25 PE/SiPM
- Timing resolution: 1.7 ns
  - Requirement: 4 ns

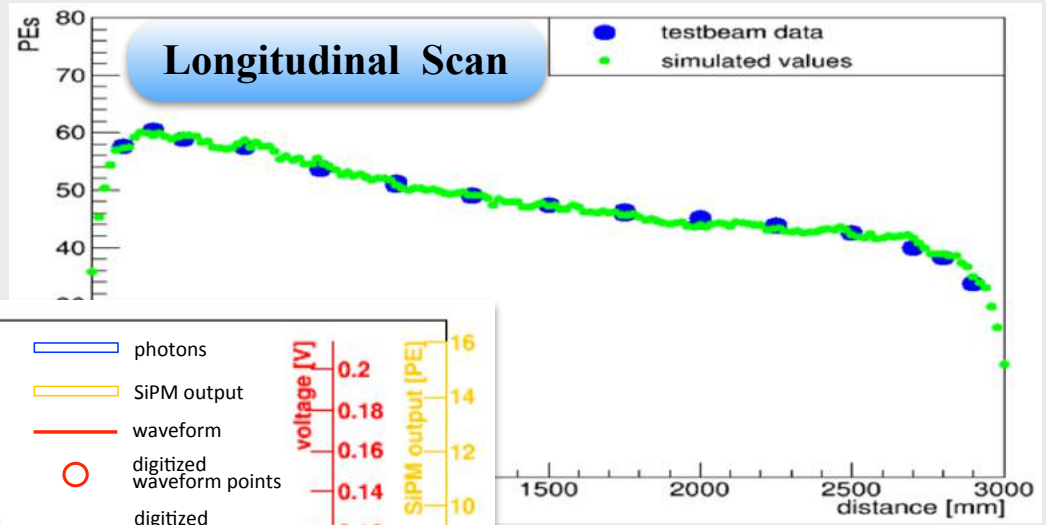


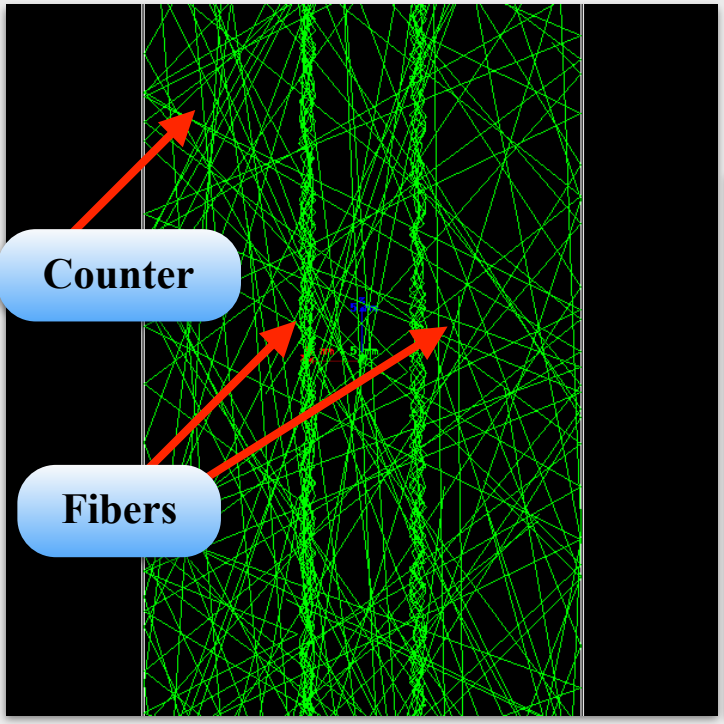


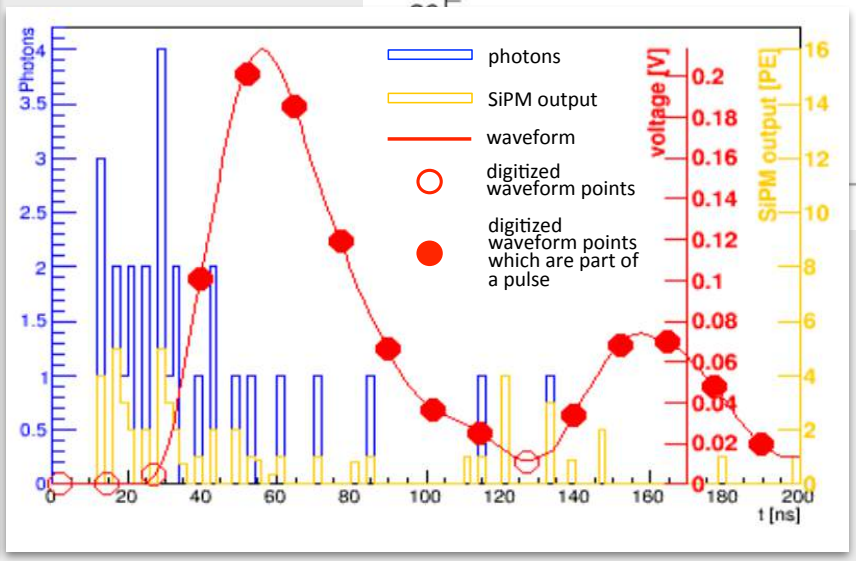
Modeling counter response

- MC has been developed to simulate CRV response to incident particles
- MC is tuned to agree with test-beam data



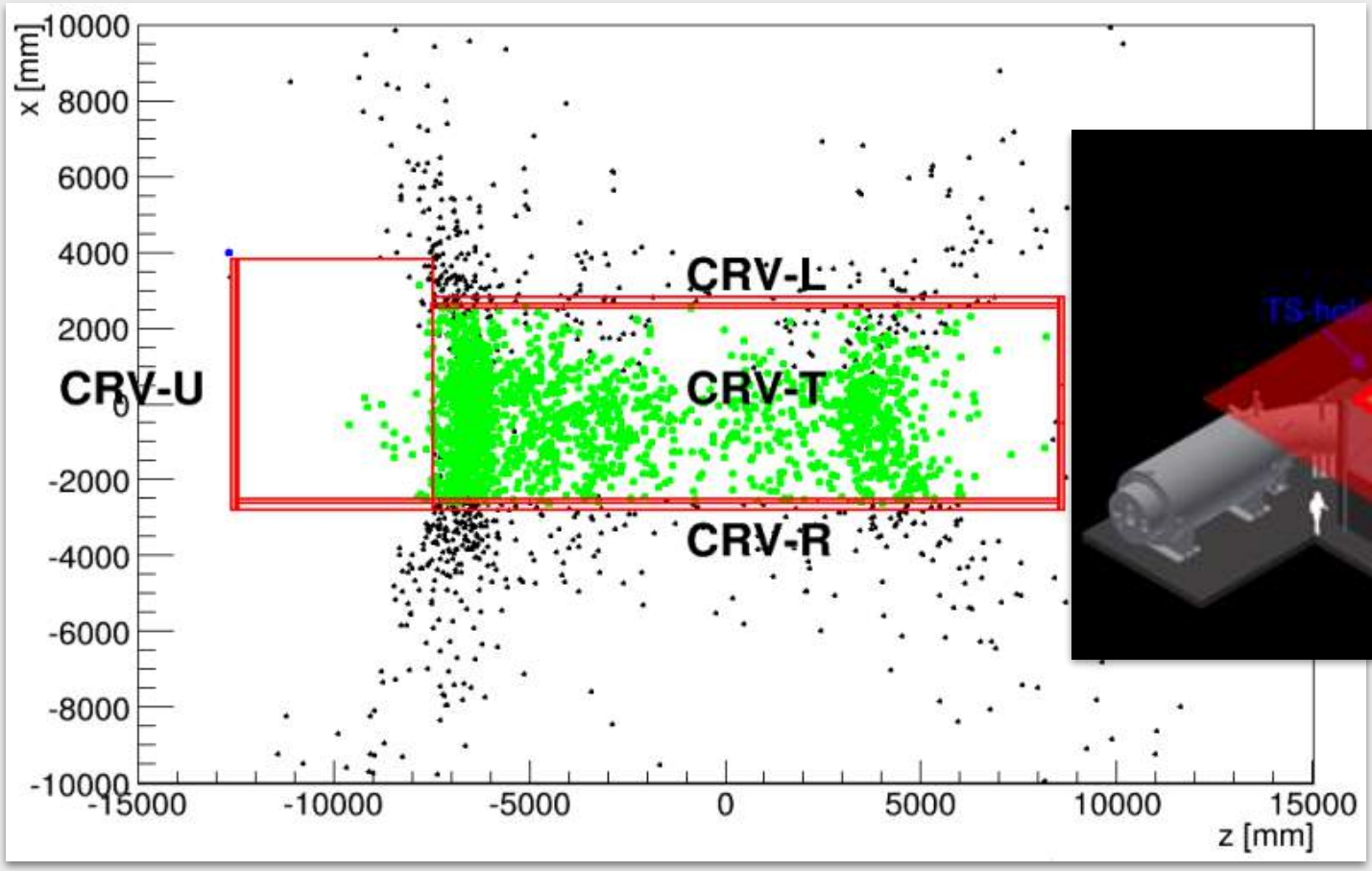


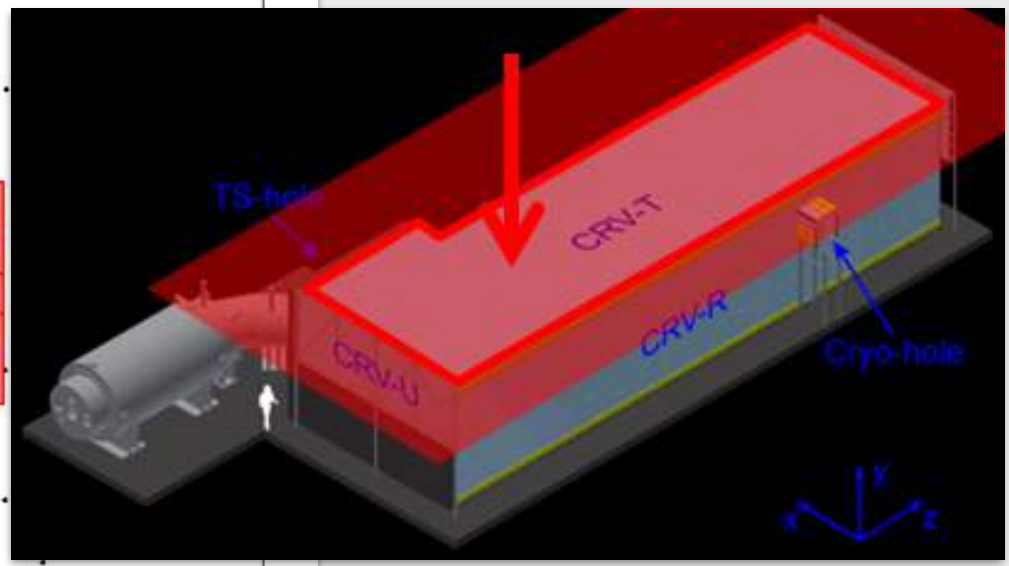




Cosmic ray simulation

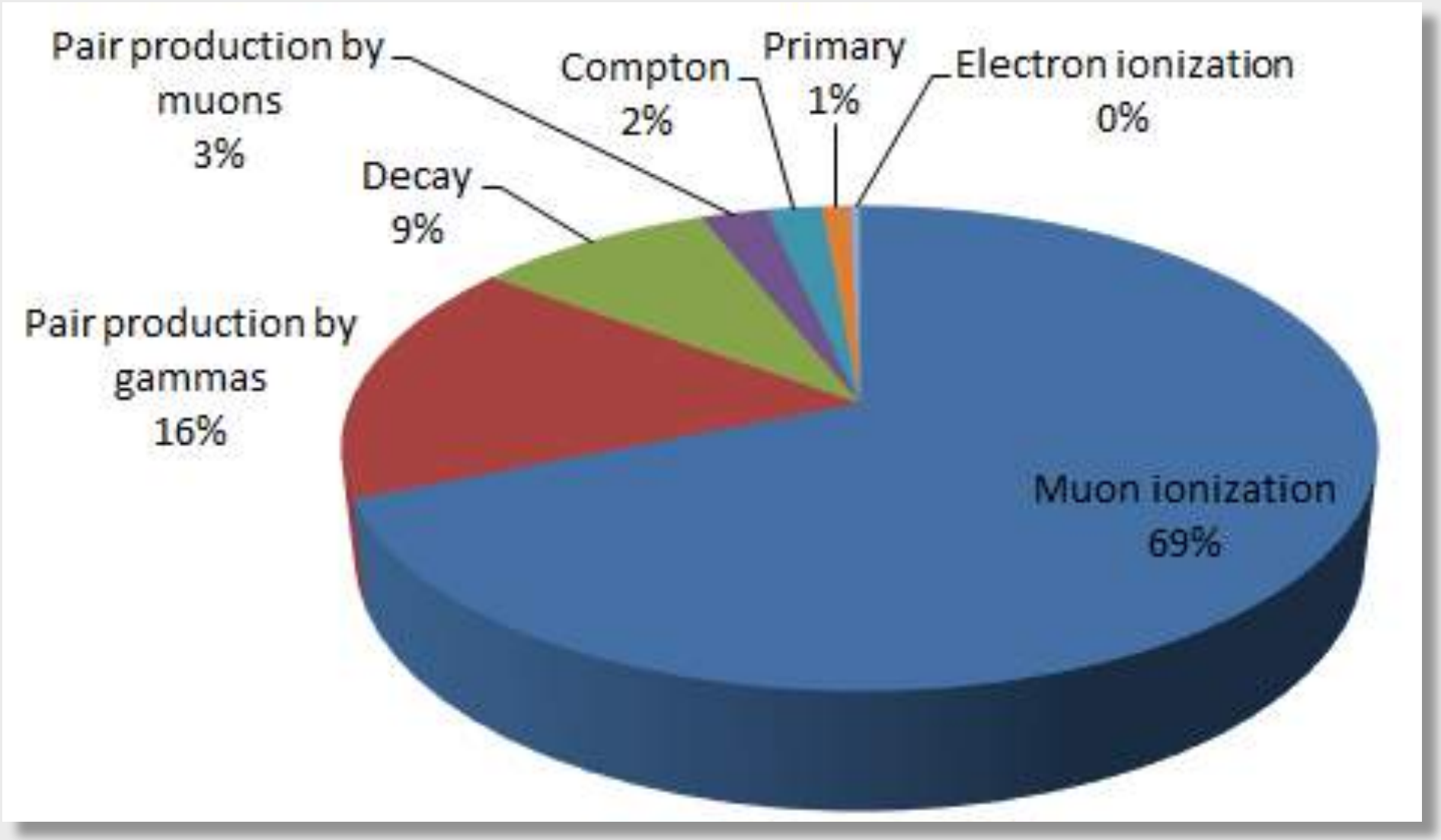
- Probability that a cosmic-ray muon produces a conversion-like event is: $< 1 \times 10^{-9}$
- Simulation campaign: 3.7×10^{12} (12.8M CPU hours) cosmic ray muons generated
- Two types of simulations:
  - Global simulation: covering an area around CRV (4x live-time)
  - Targeted simulations: covering areas with limited coverage (250x live-time)





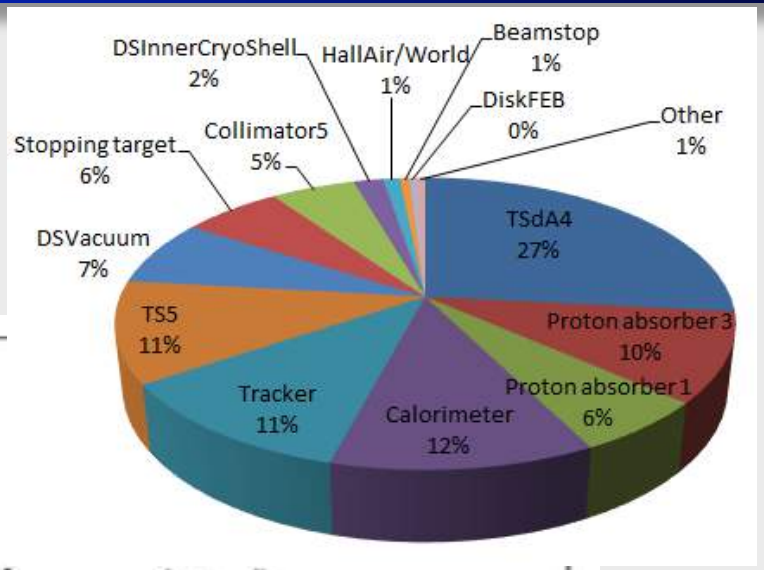
Background: Production mechanism

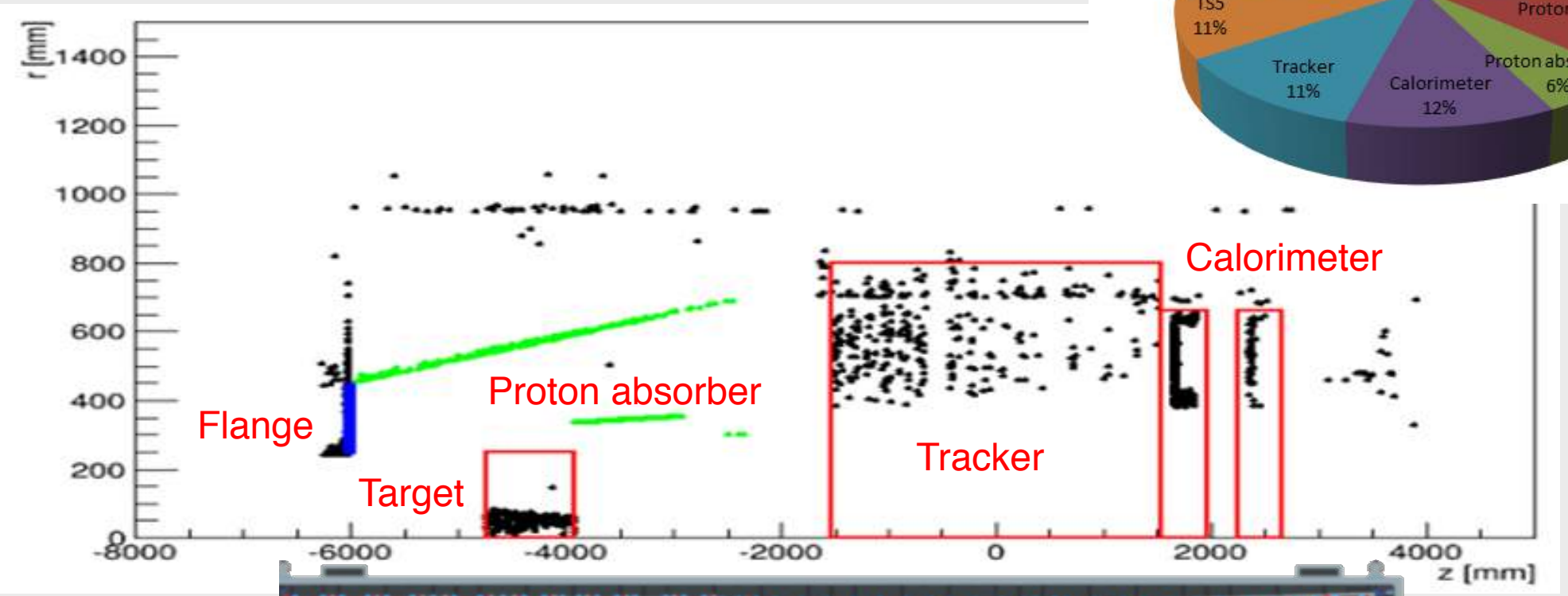
- Largest source of cosmic ray background is delta-ray production

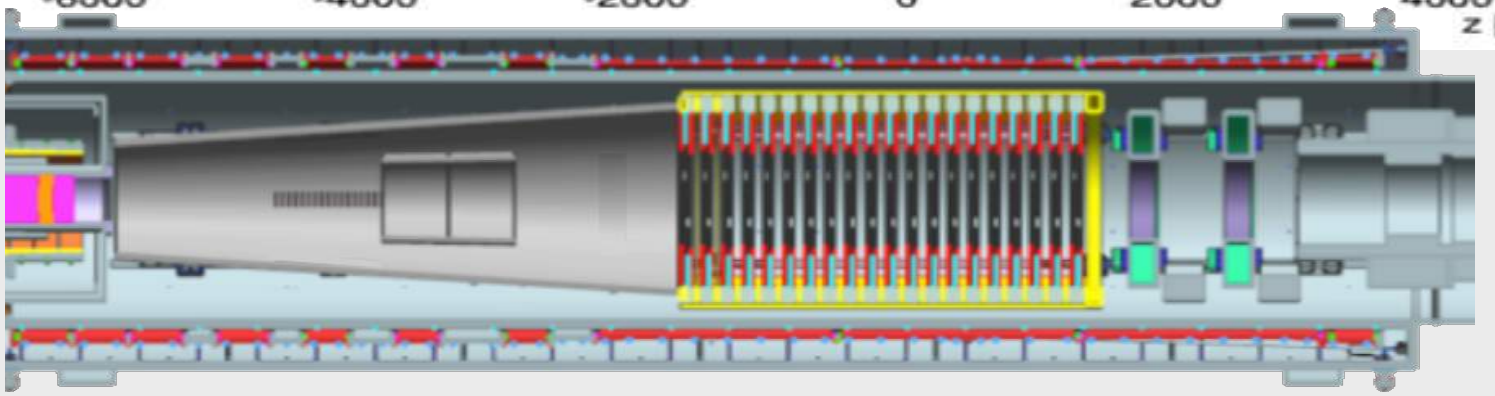


Background: Production sources

- Dominant fraction of cosmic background is produced from materials inside the DS

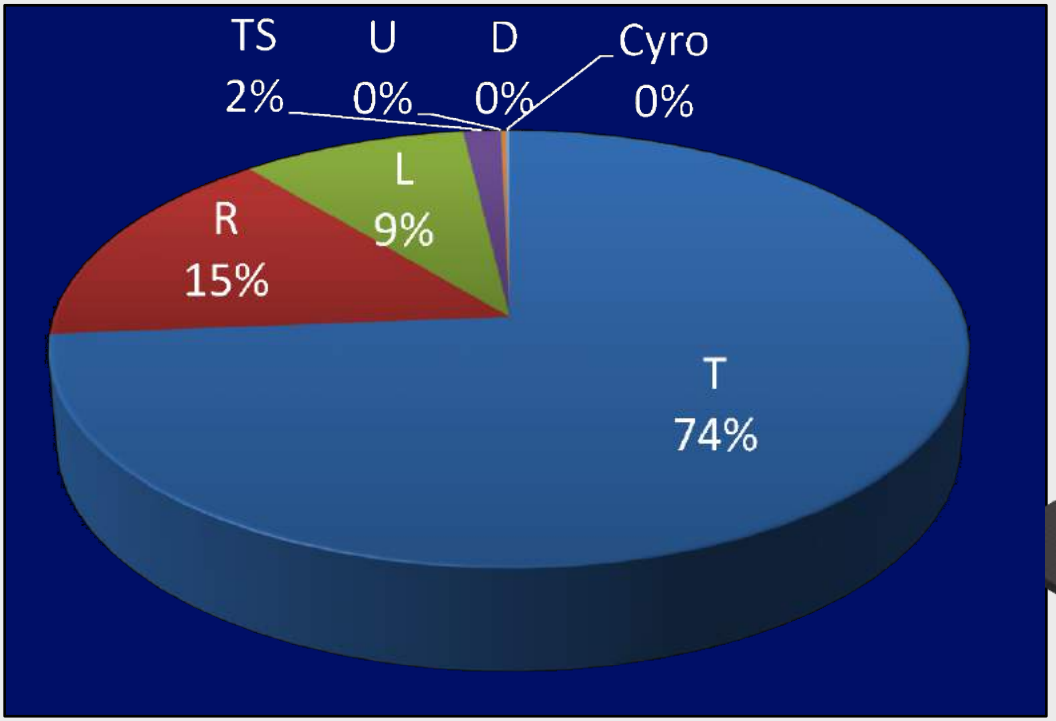


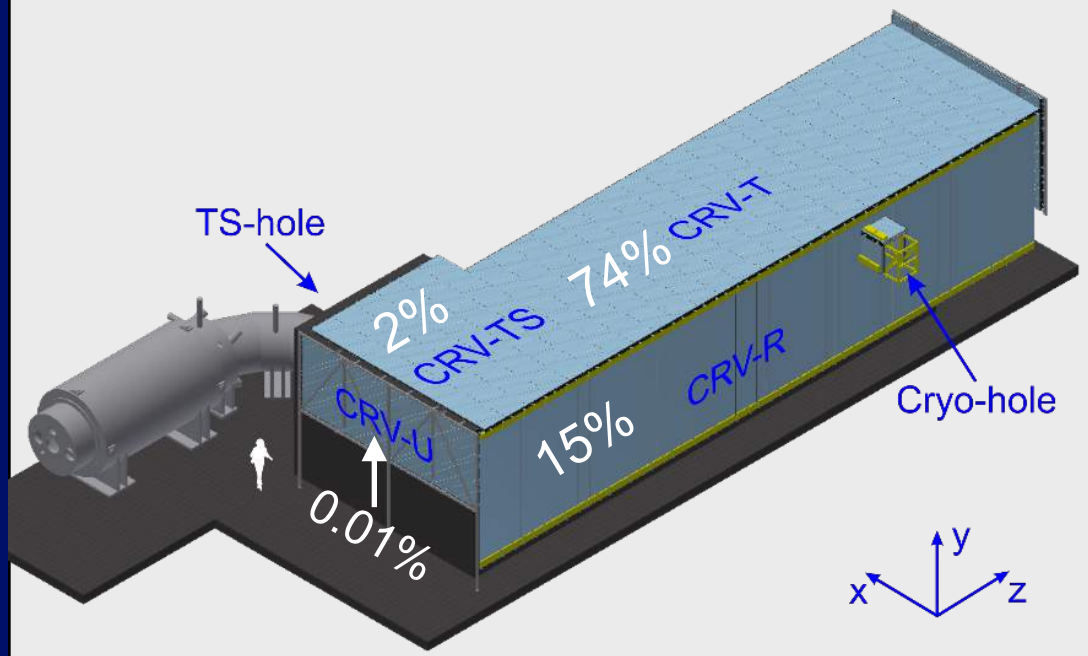




Background: Sectoral efficiencies

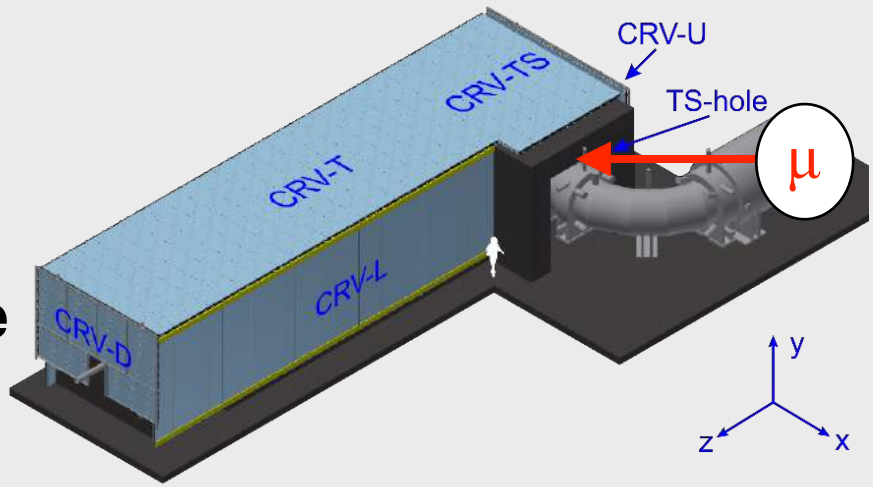
- CRV needs to reject 780 events over its lifetime
- Dominant (74%) fraction of muons enter from from the top
  - Top sector of CRV efficiency is >99.99%
- Other CRV regions reject much smaller fraction of muons, and require much smaller efficiencies
- **Total reducible background: 0.07 events**



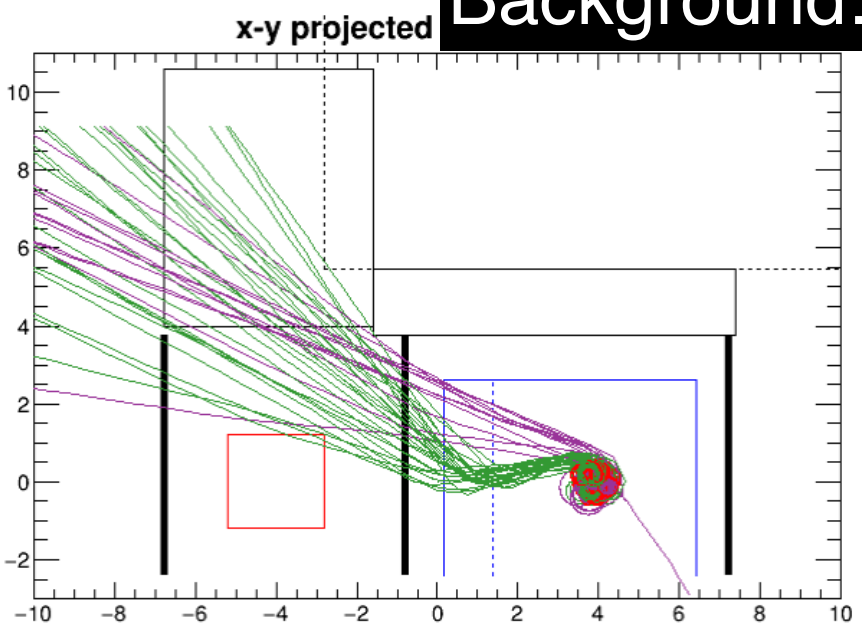


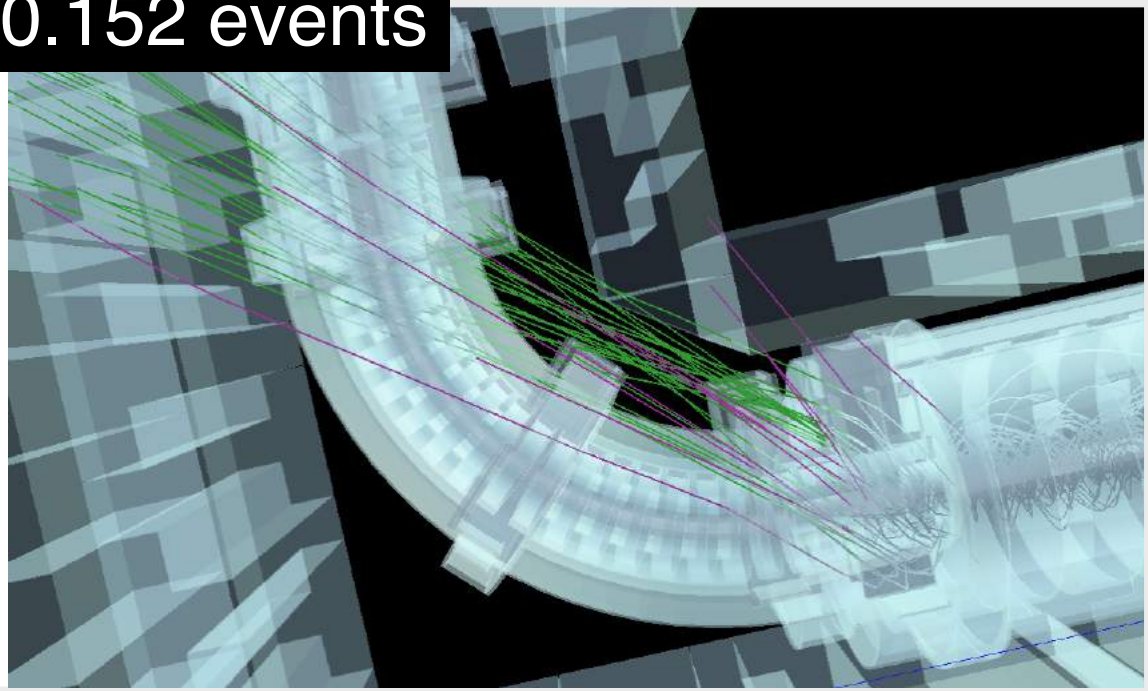
Background: Irreducible background

- A special simulation of events going through the TS hole with 257X the total live time (770 years) we found 39 events that mimic conversion electrons
- **This is the largest background for Mu2e**
- Two-thirds of this component can be reduced by absorbers and CRV-TS extension



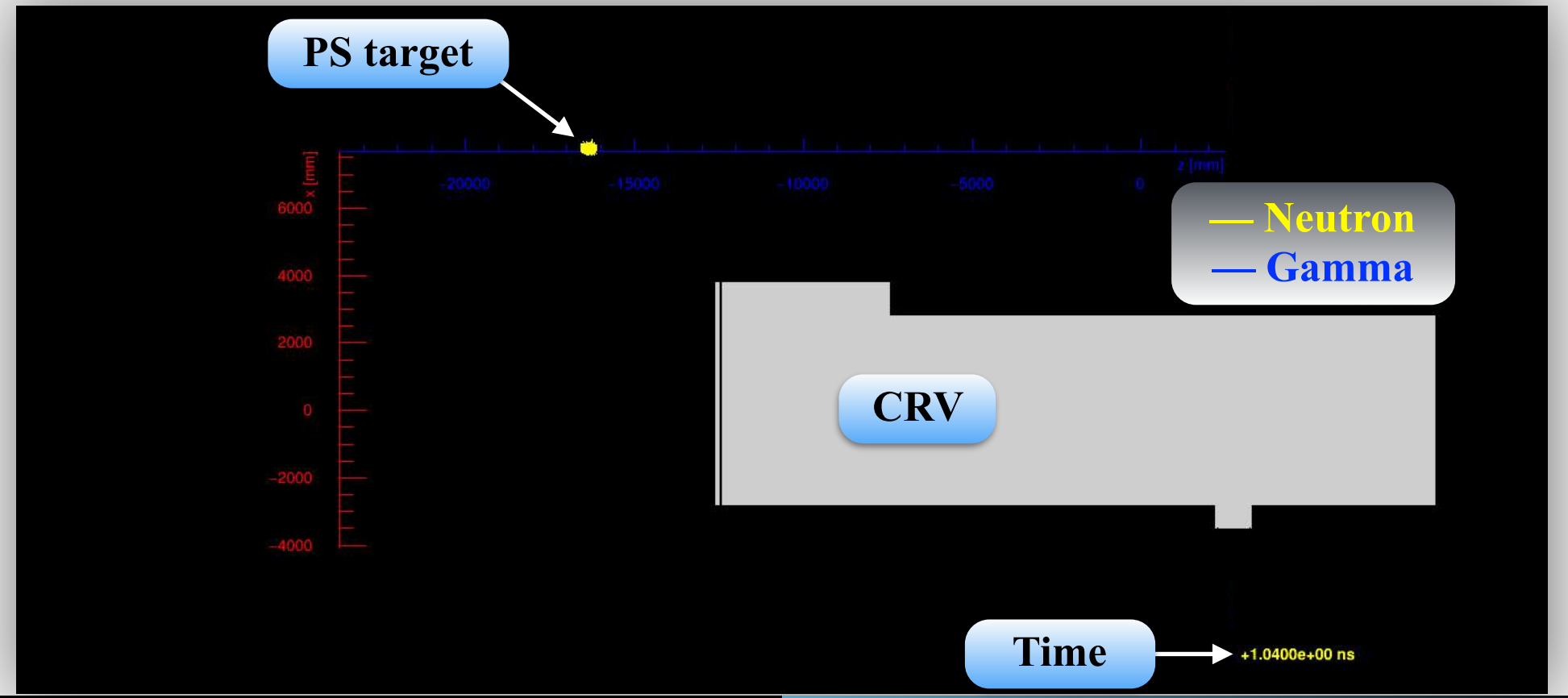
Background: 0.152 events



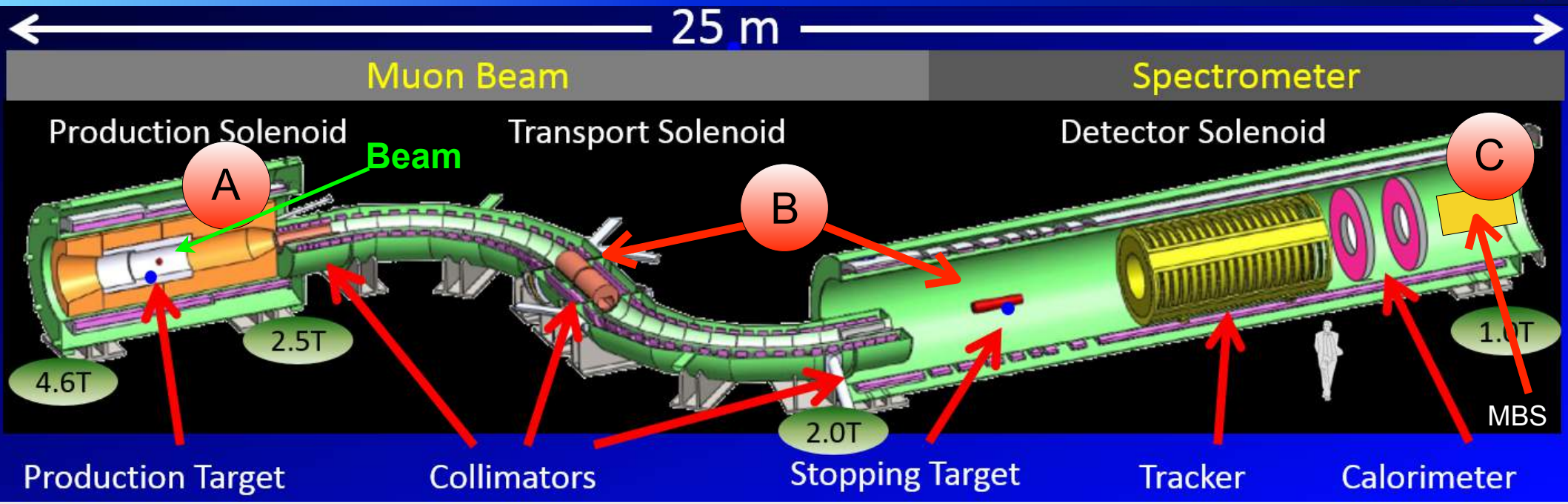


Beam induced radiation

- CRV needs to operate in a sea of neutrons and gammas
- Particle fluxes from beam interactions:
  - **Damage** CRV components
  - **Produce noise** in CRV, increasing DAQ rates. Noise hits in CRV fake CR muons and increase the dead-time
    - CRV ignores hits outside of the signal window



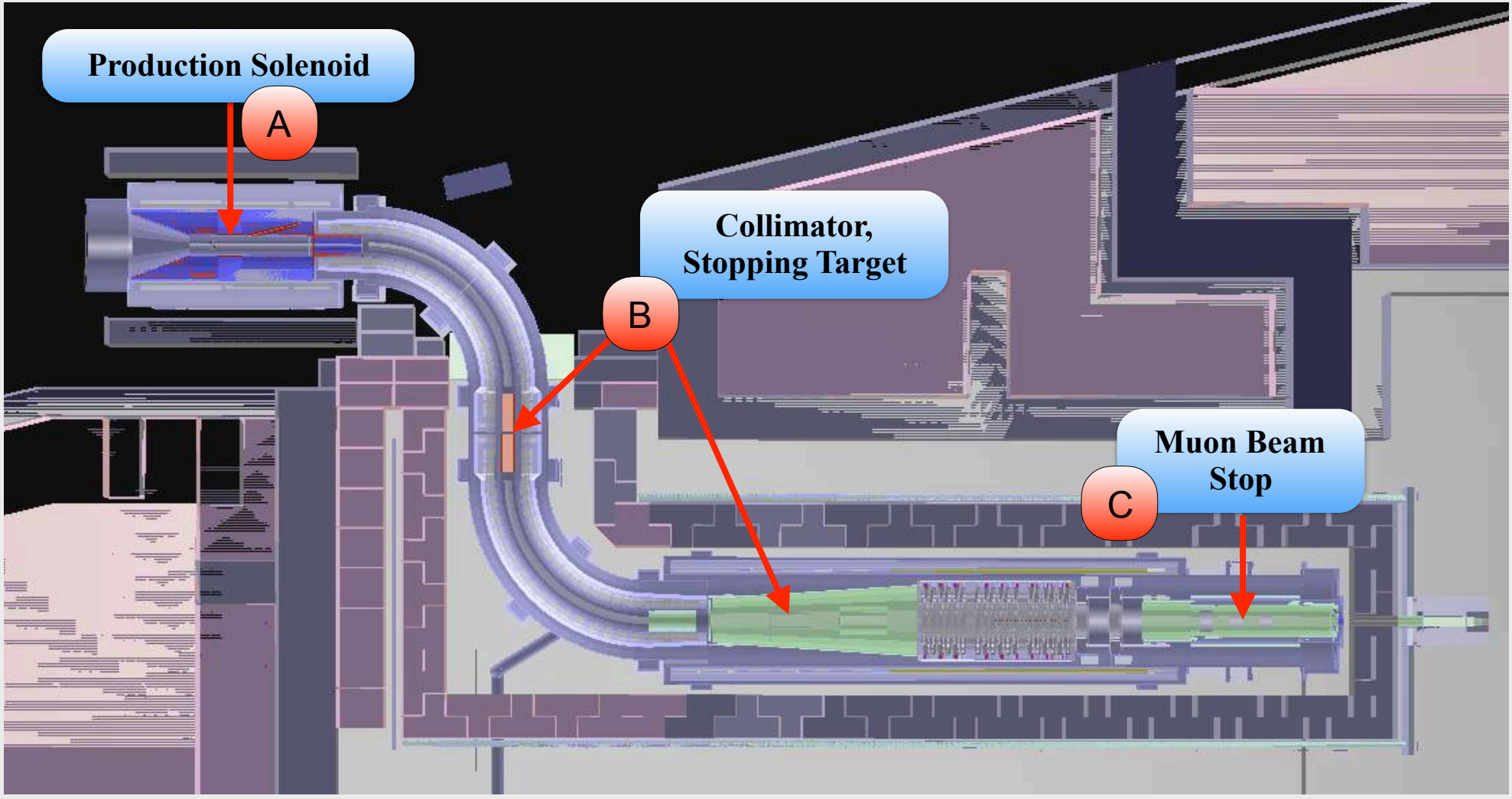
Beam induced noise: Sources



- A PS is the largest source of neutrons. The source is prompt and reduced in the signal window
  - Neutrons get thermalized, captured and produce gammas
- B Fast neutrons, produced in the signal window, are from μ-captures on beam-line and stopping target
  - Fast neutron recoil off a proton depositing energy in CRV
- C High energy gammas in the Muon Beam Stop (MBS): electron brems from μ-decays. Muons escaping MBS decay producing high energy electrons

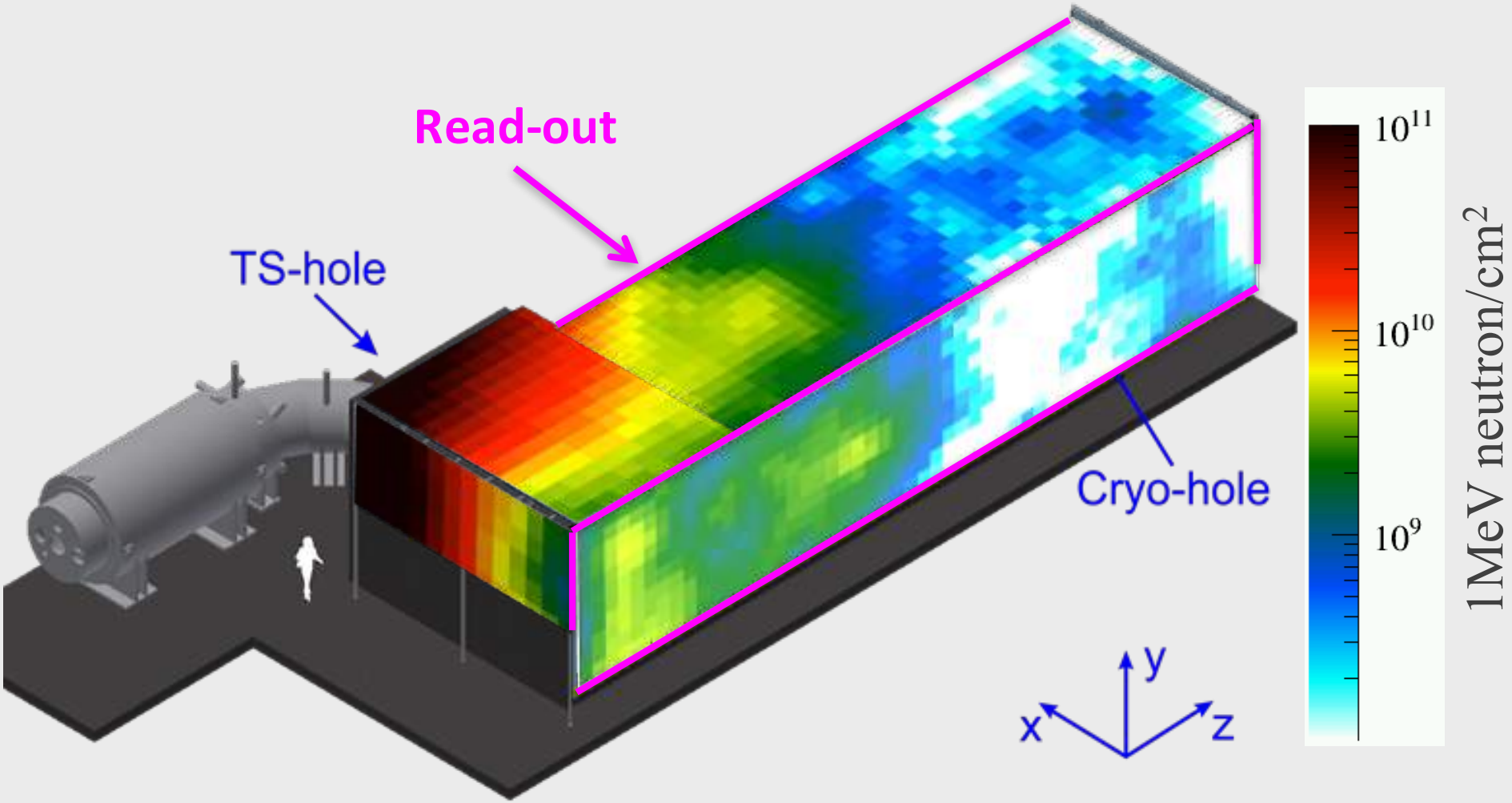
CRV shielding

- CRV is shielded from beam induced backgrounds by 1 yd of T-shaped concrete walls
- Shielding needs to be effective and reasonably priced
  - Big effort to optimize shielding price-performance



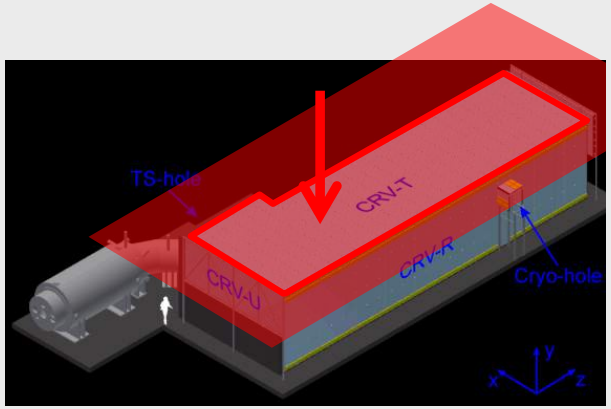
Neutron damage to SiPM

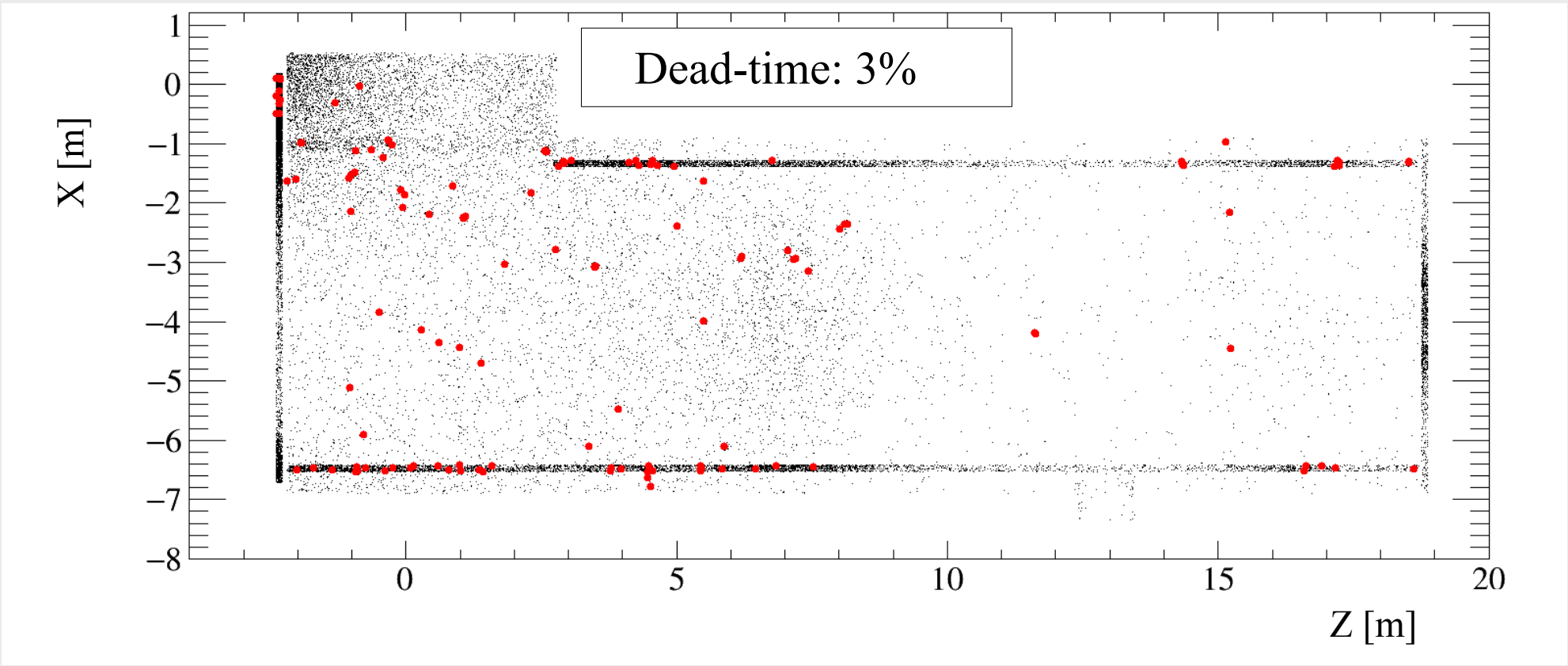
- Fast neutrons produce damage to SiPMs
  - Rad damage is driven by PS and collimators. Requirement is 10^{10} n/cm^2
- Rad damage to scintillator and fibers is negligible



Dead-time

- Background hits in CRV fake CR muons and produce dead-time
- CRV dead-time is 3%
- Dead-time is stable under beam intensity variations and the choices of CRV thresholds





CRV Status

Produced scintillating counters

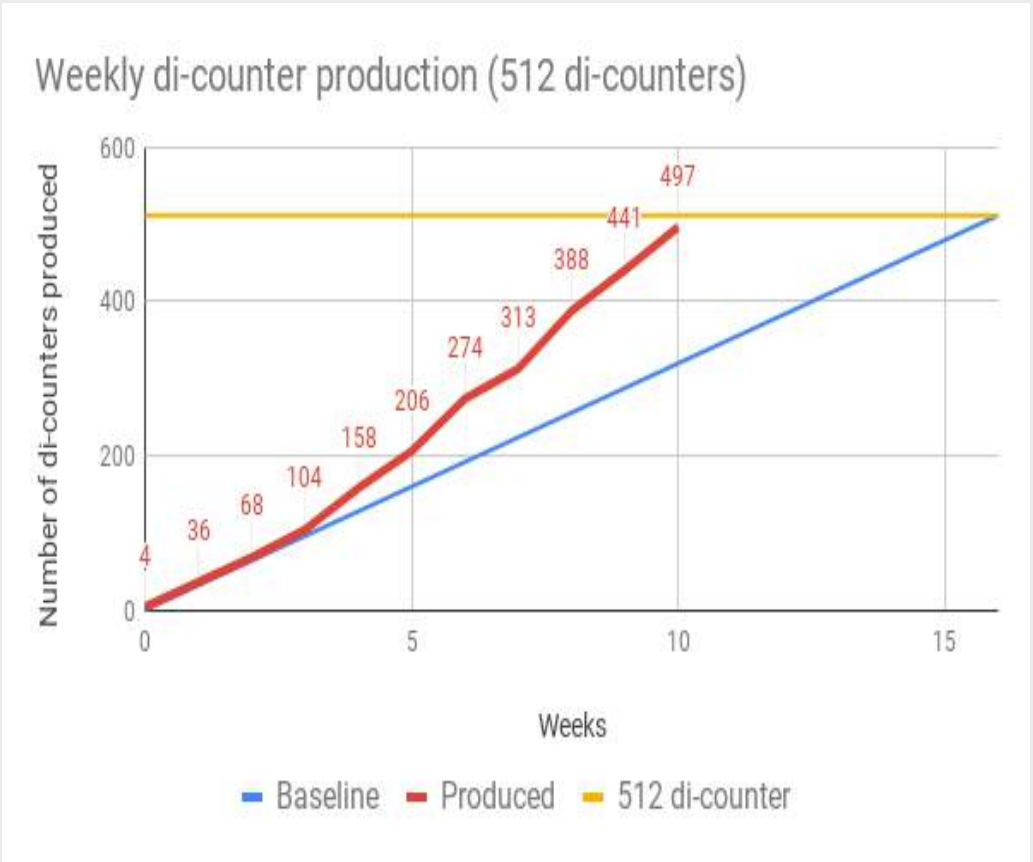
Purchased and tested WLS fibers

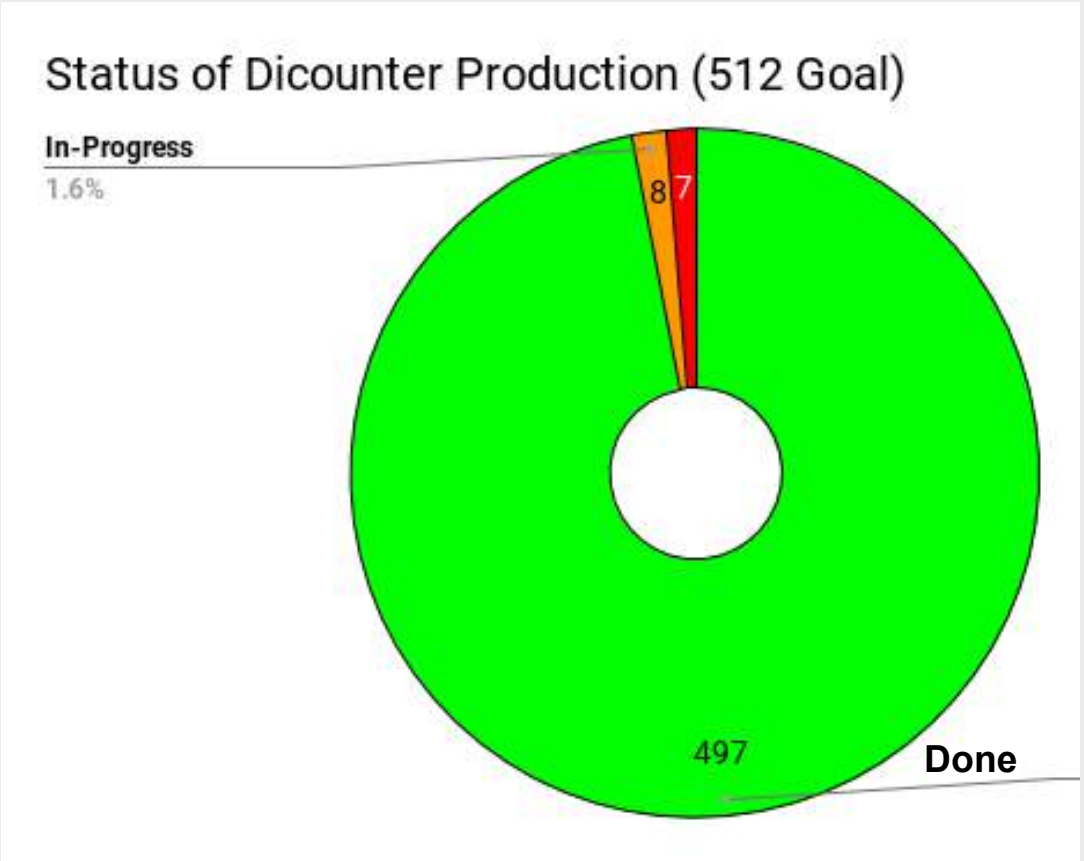
Glueing counter pairs

Fibers are installed

Di-counters production progress

- The goal for the Summer is to produce 512 di-counters
- We're well ahead of the production schedule
- Great effort by the team of undergraduate students





Summary

- Muons are fascinating
  - They're an excellent probe to physics beyond the SM
  - Cosmic ray muons produce a large background for Mu2e
- CRV is an essential component of Mu2e. CRV design is challenging
  - Maintain 99.99% cosmic ray veto efficiency over 3 years
  - Operate in high radiation environment
- We've just started CRV fabrication
  - The production progress is ahead of schedule
  - It will take 2 years to build CRV
- Once CRV is fabricated, it will be installed at Mu2e to shield us against cosmic muons

Backup