

# The Search for Dark Matter in Liquid Argon with Darkside-20k

Ako Jamil *for the GADMC*

Princeton University

September 4, 2023

Lepton Interactions with Nucleons and Nuclei 2023, Marciana Marina, Isola d'Elba



# Evidence for Dark Matter at All Scales

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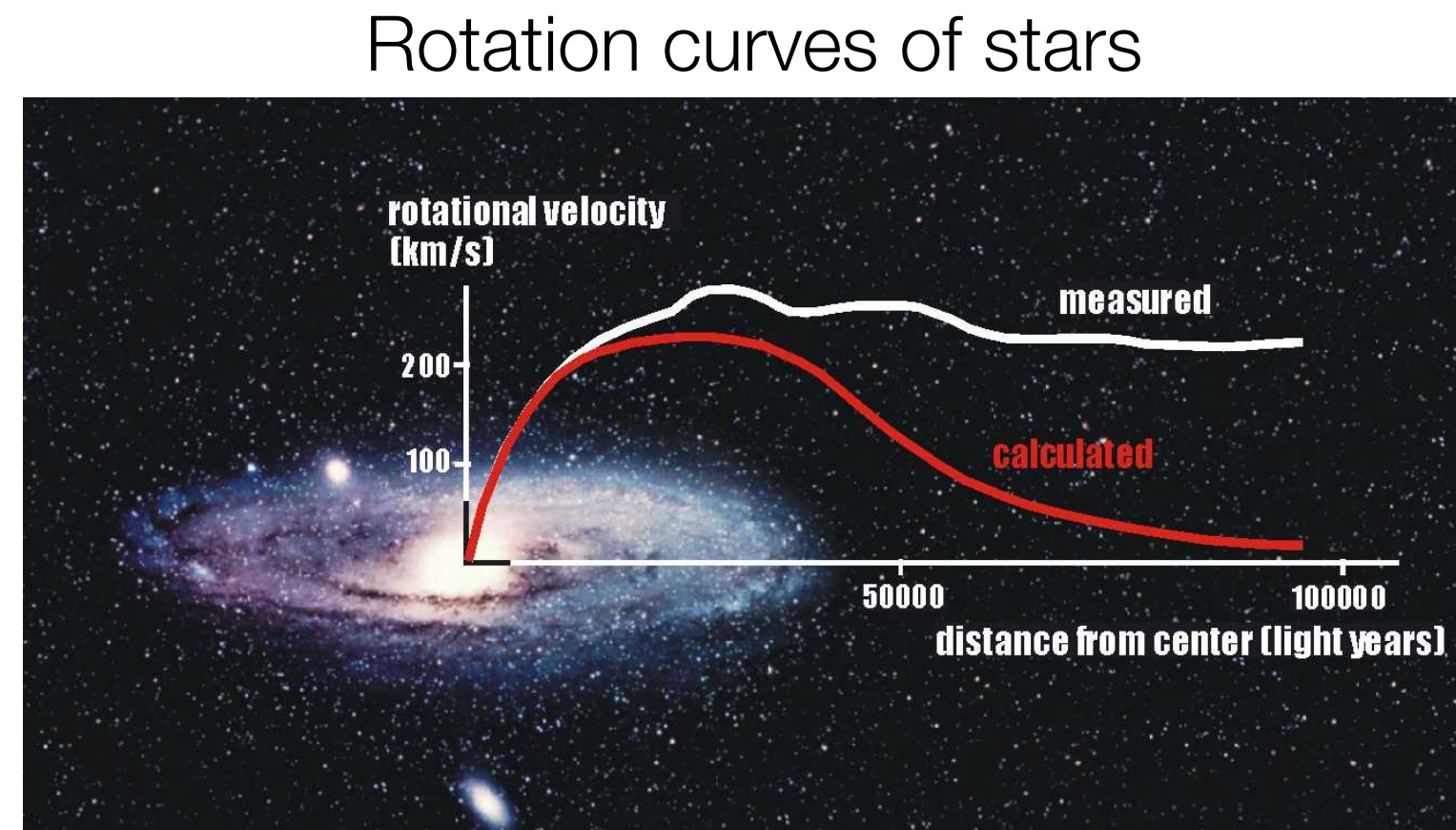
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- Numerous cosmological evidence for the existence of dark matter

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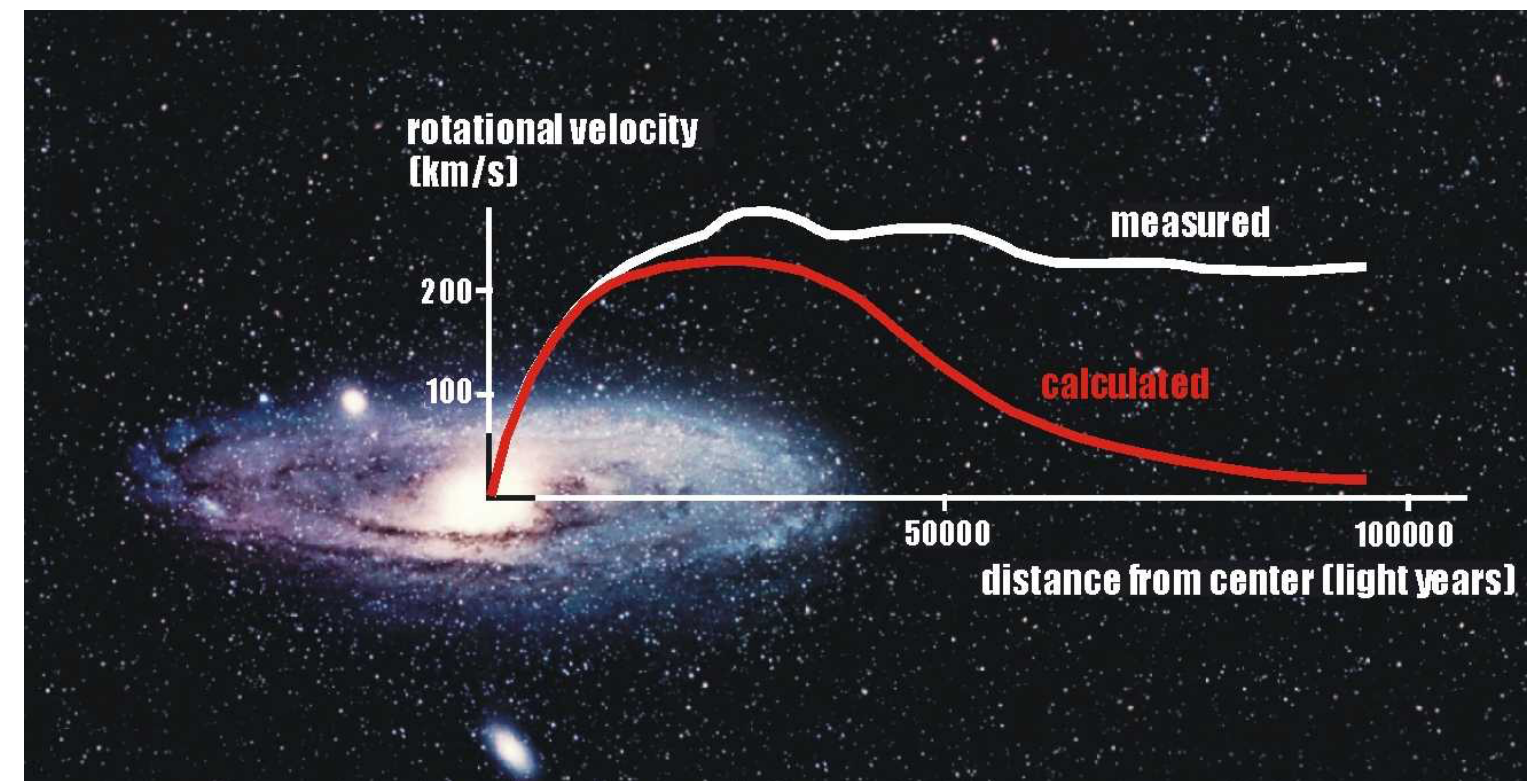
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Rotation curves of stars



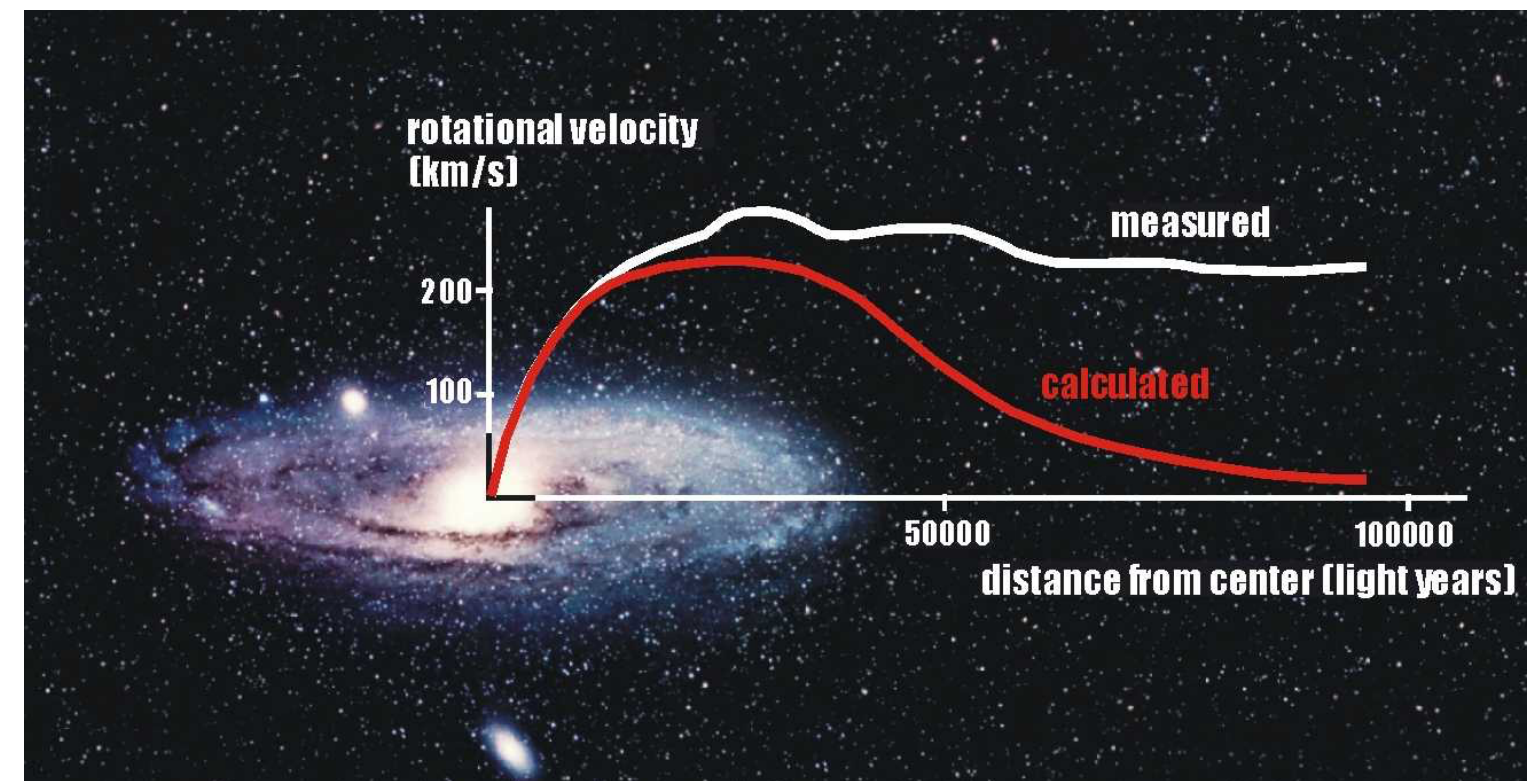
Colliding galaxy clusters



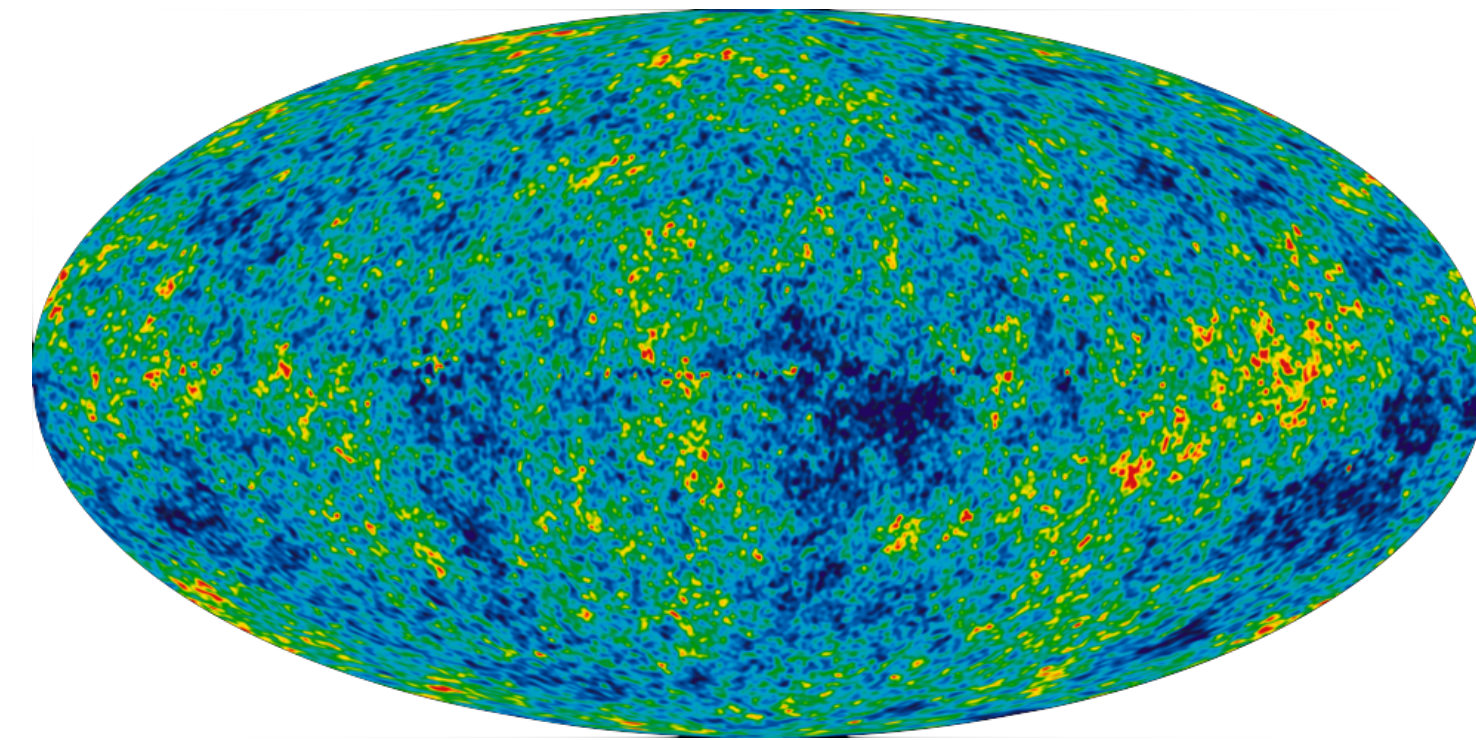
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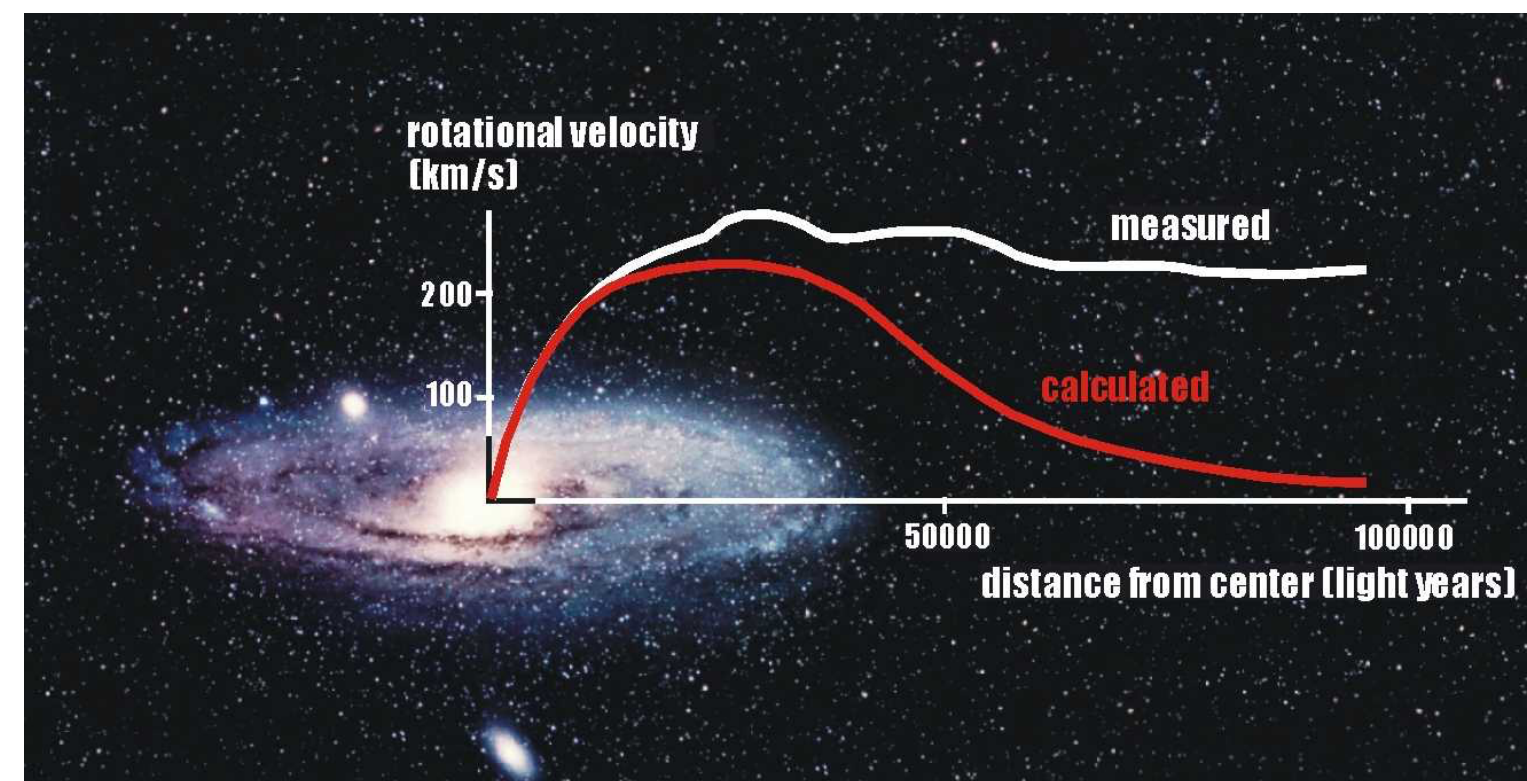


Cosmic Microwave Background

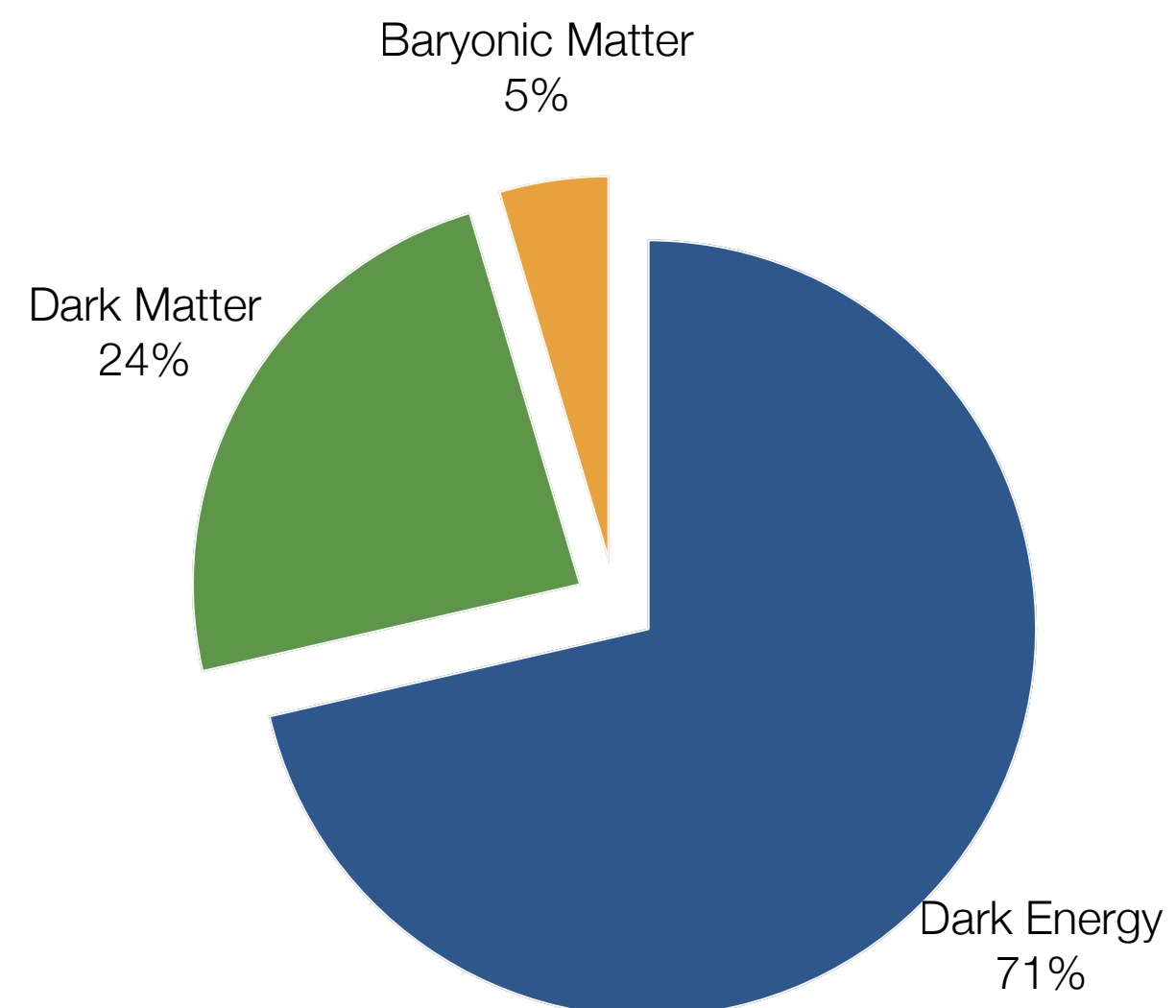
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- Numerous cosmological evidence for the existence of dark matter
- Energy budget of the universe

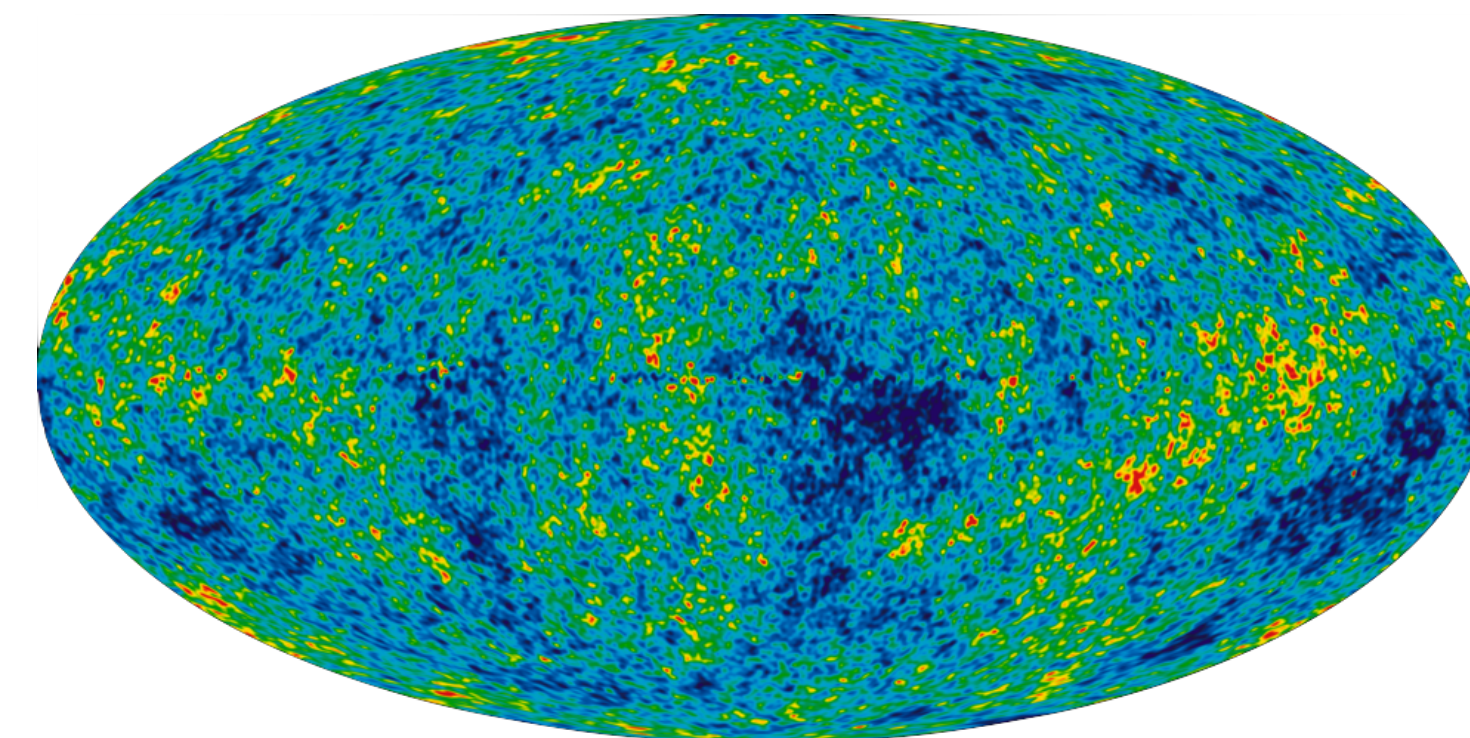
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[https://wmap.gsfc.nasa.gov/universe/uni\\_matter.html](https://wmap.gsfc.nasa.gov/universe/uni_matter.html)



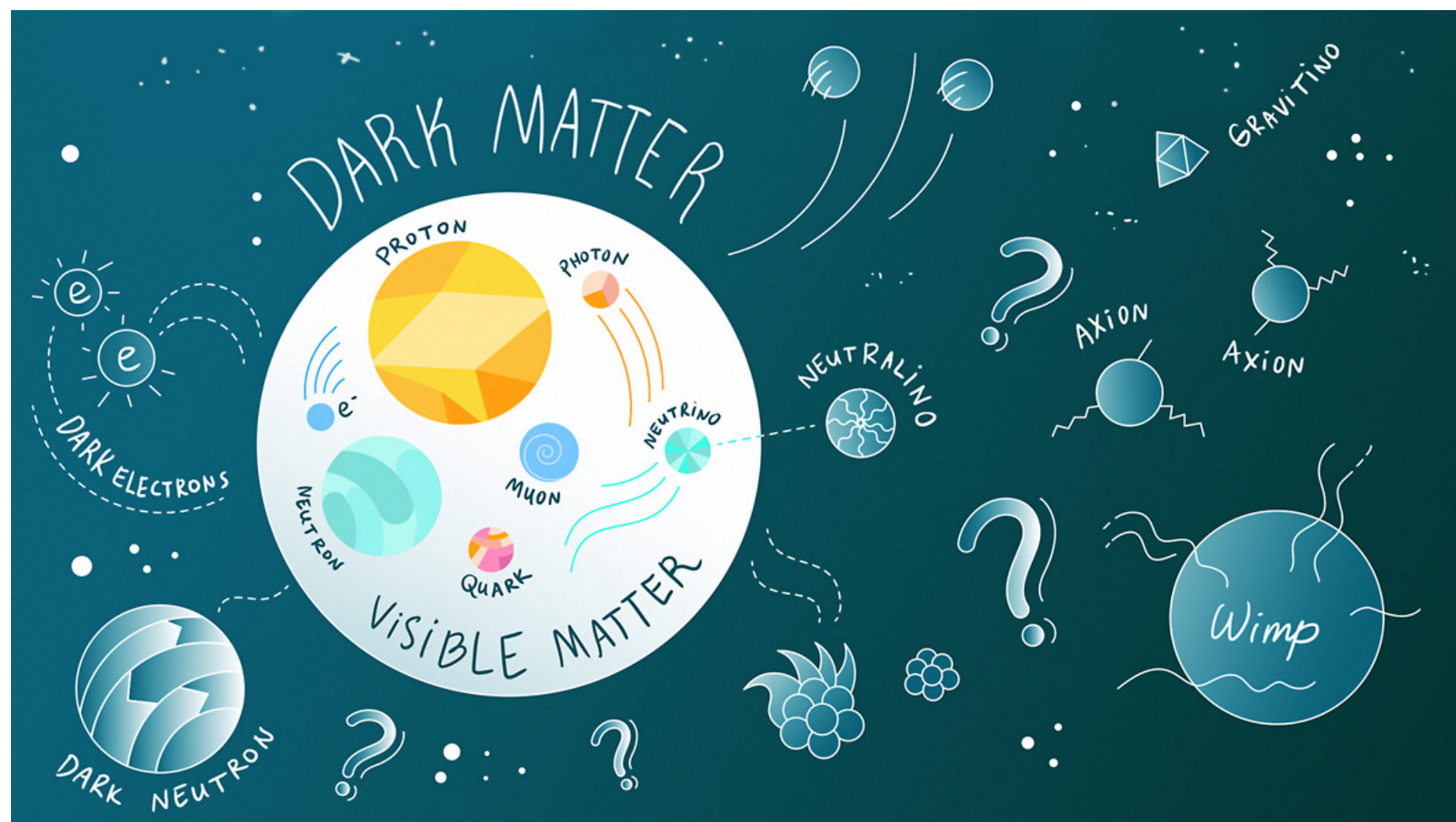
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# Dark Matter Candidates

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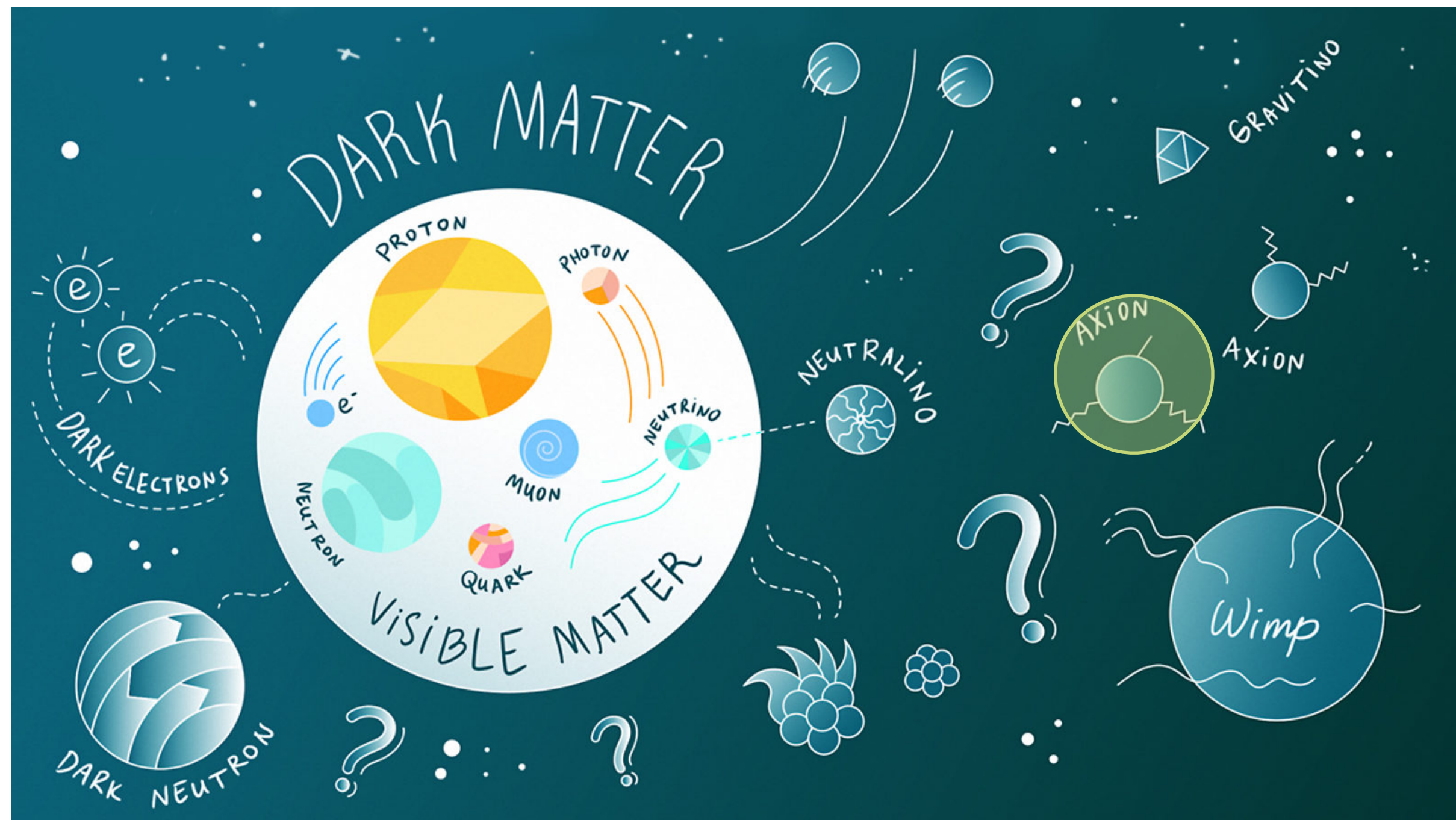
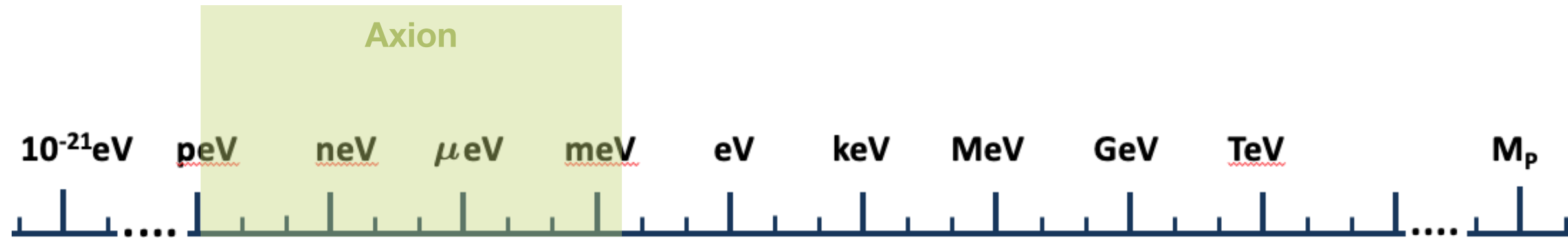


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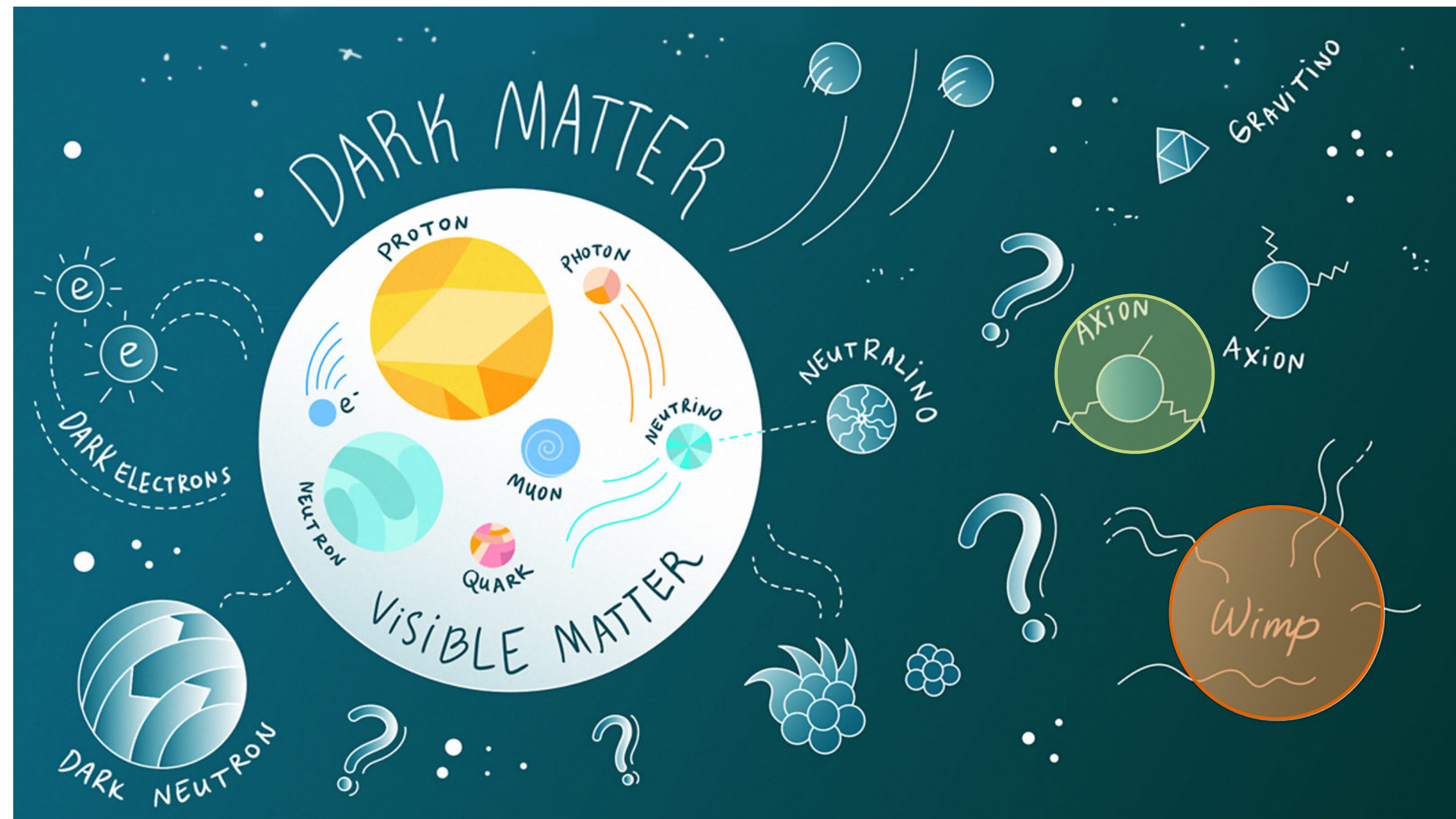
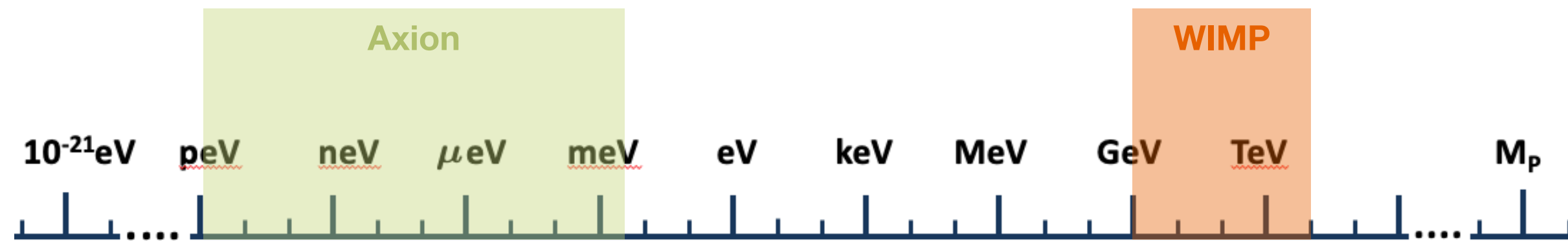
<https://www.symmetrymagazine.org>

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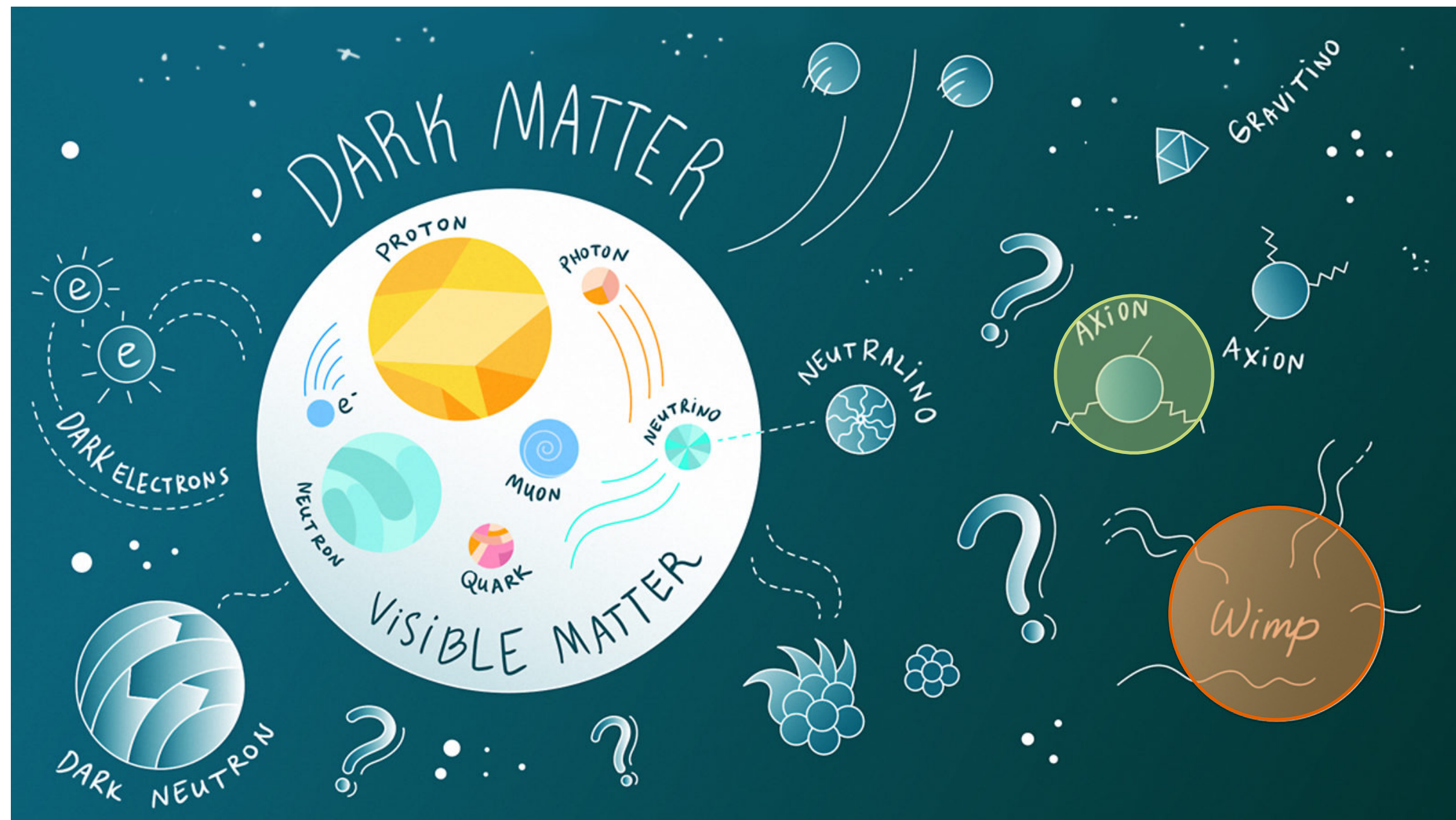
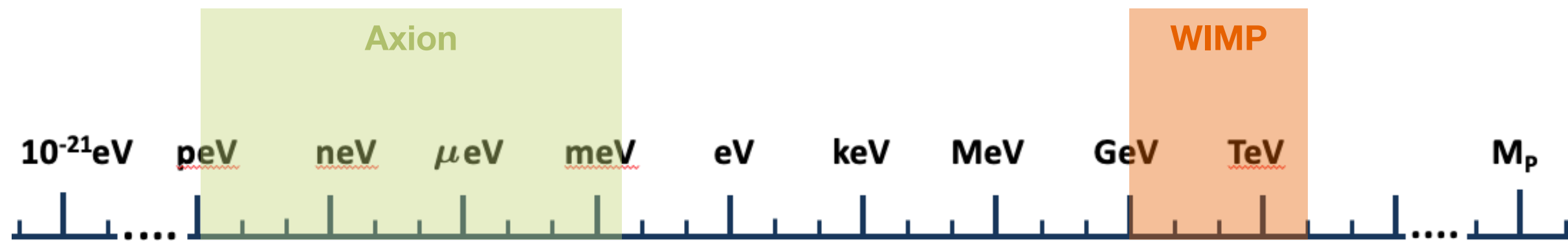
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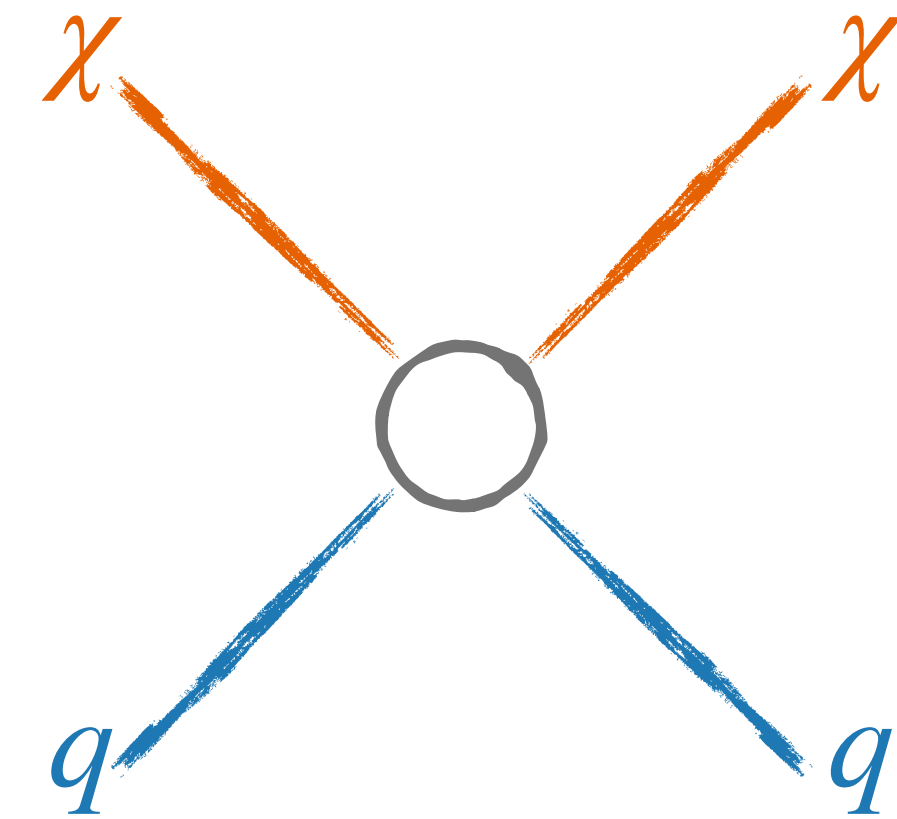


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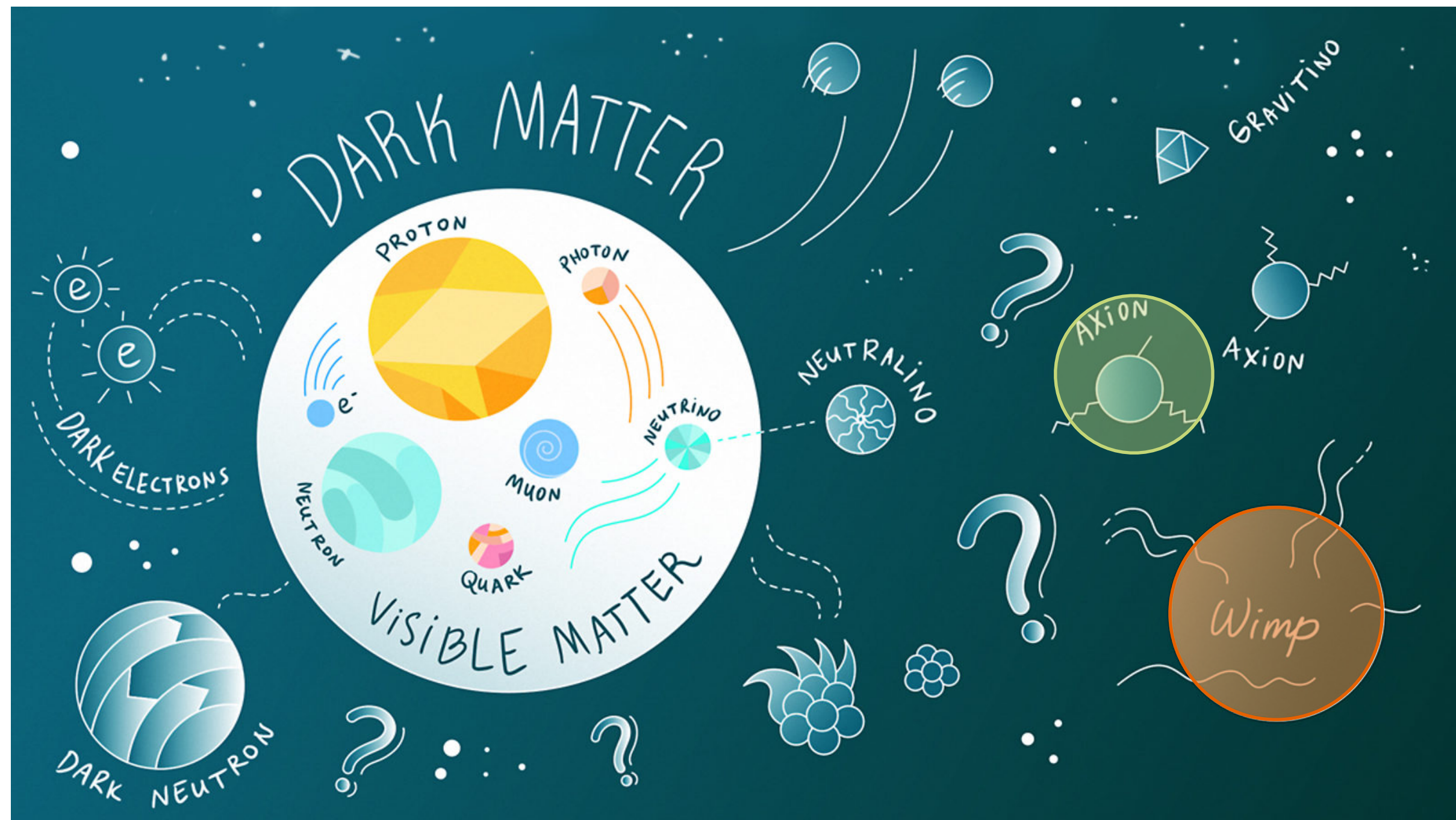
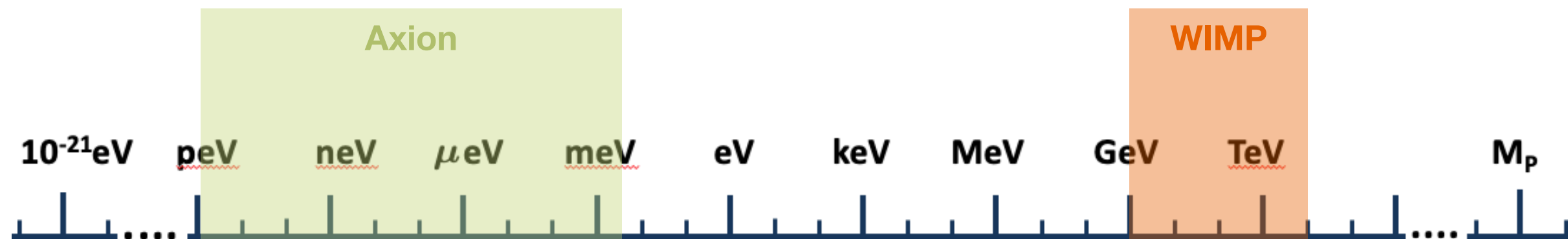
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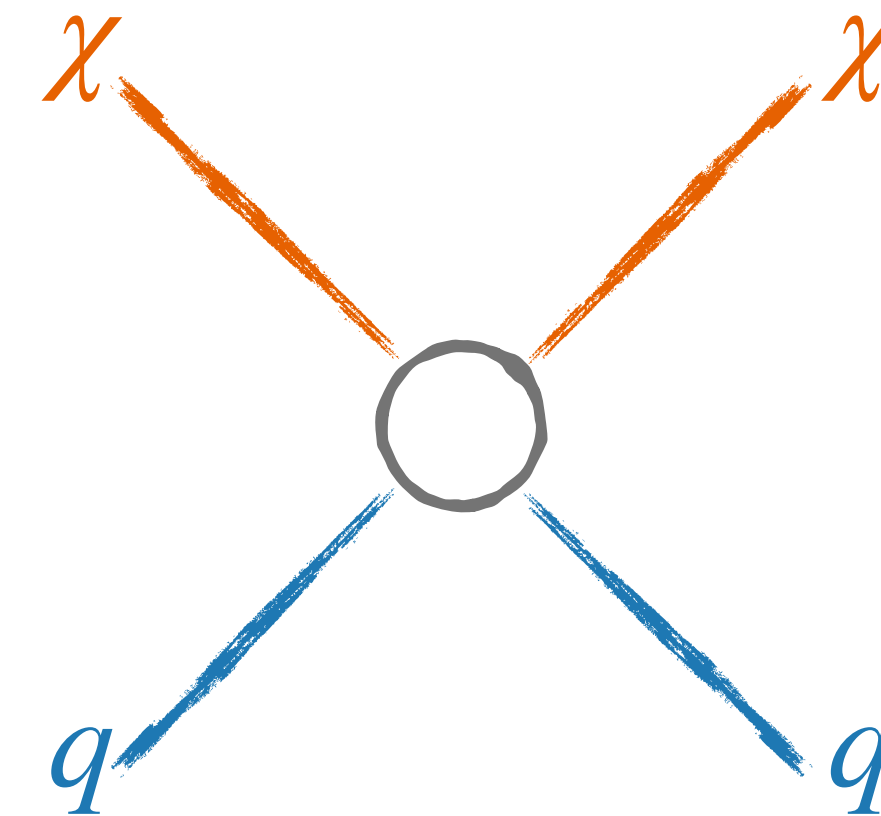


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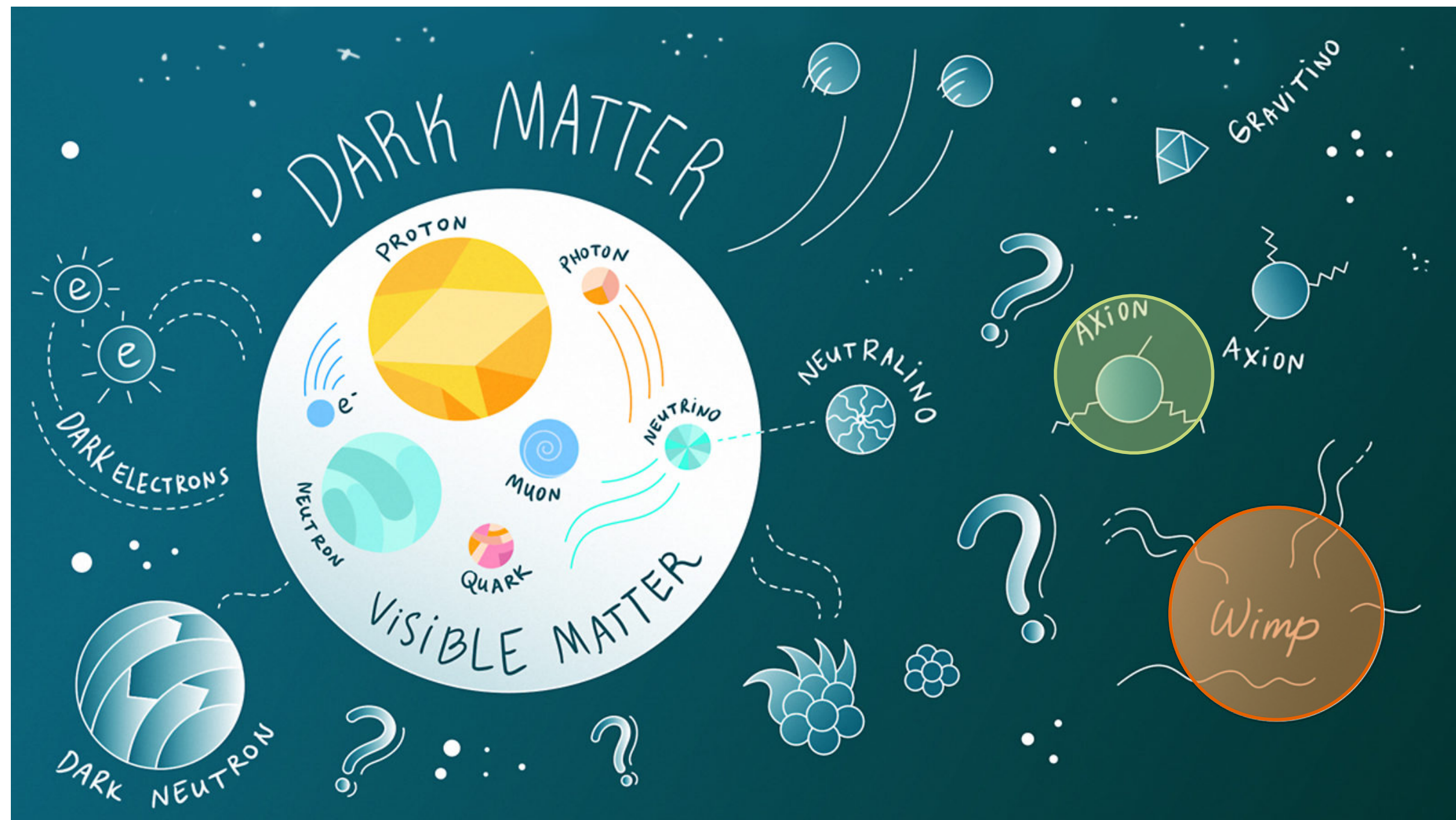
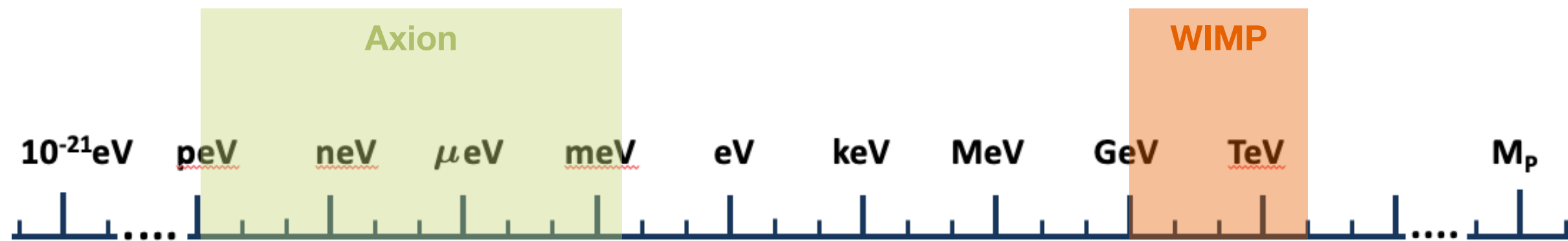


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ANNIHILATION

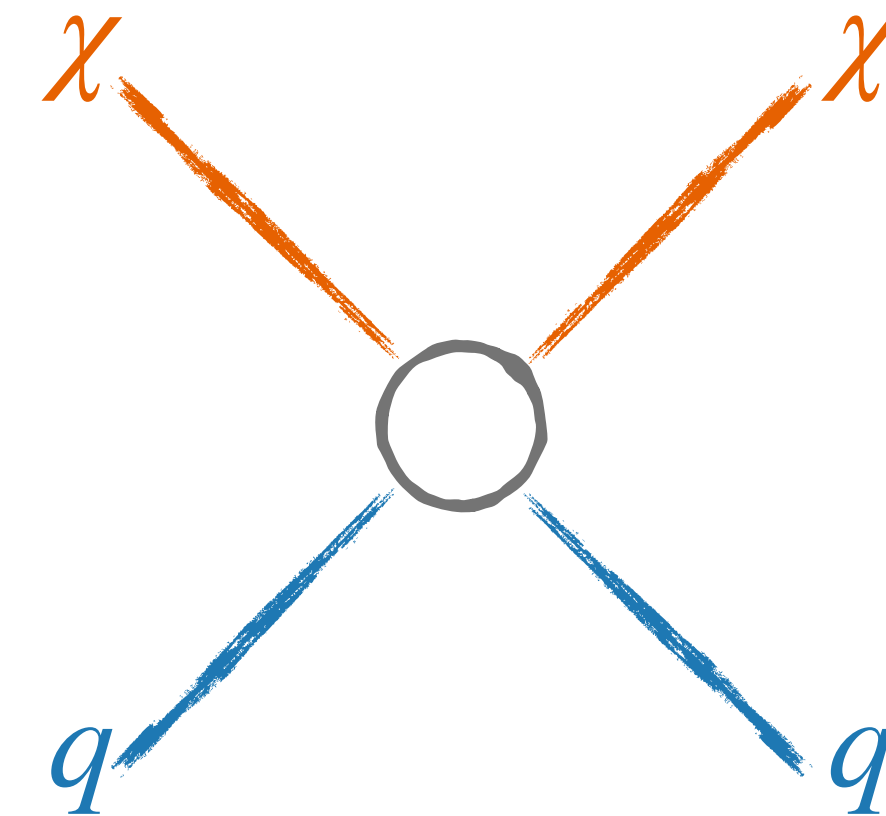


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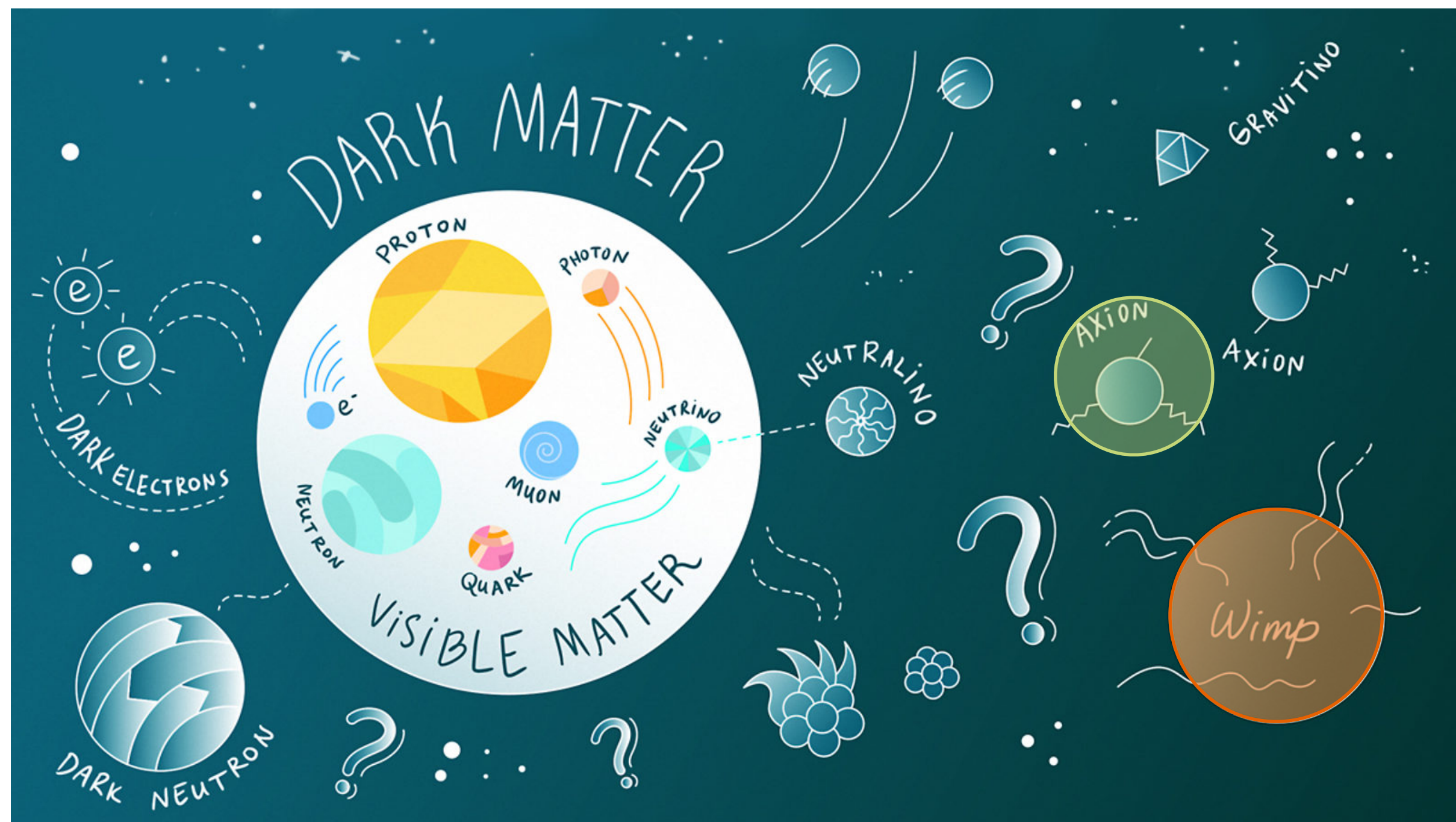
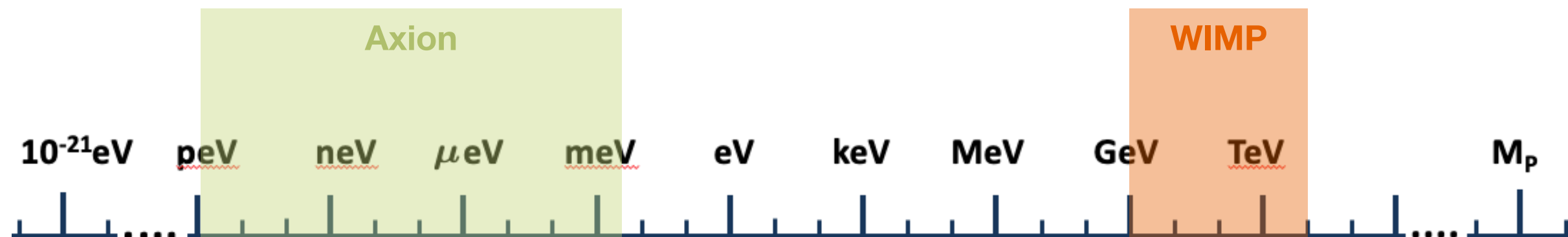
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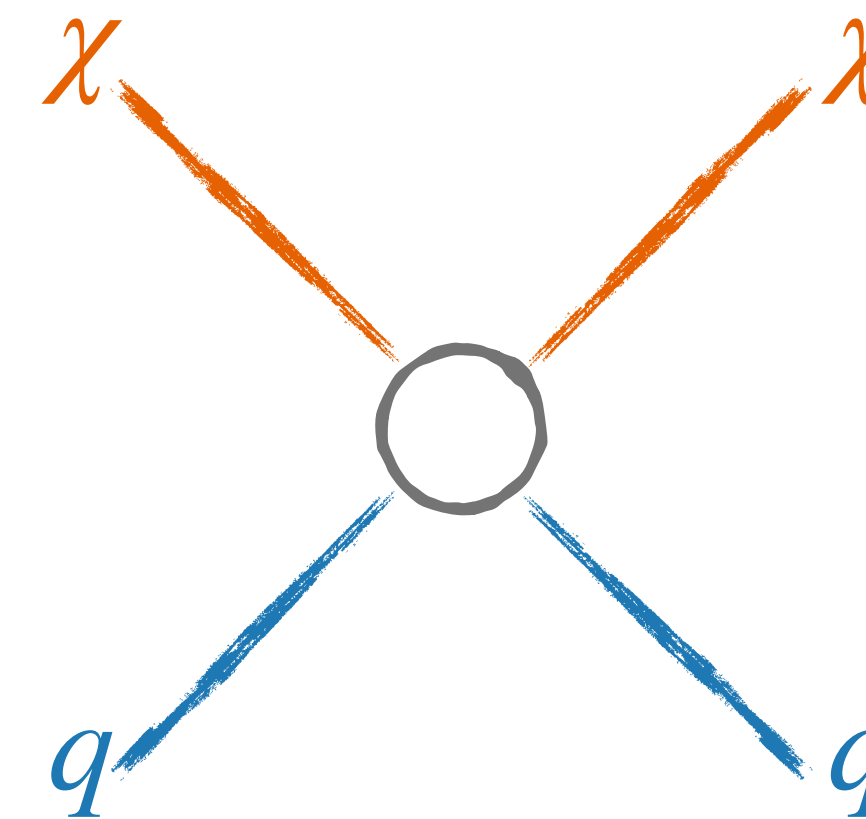
SCATTERING

# Dark Matter Candidates



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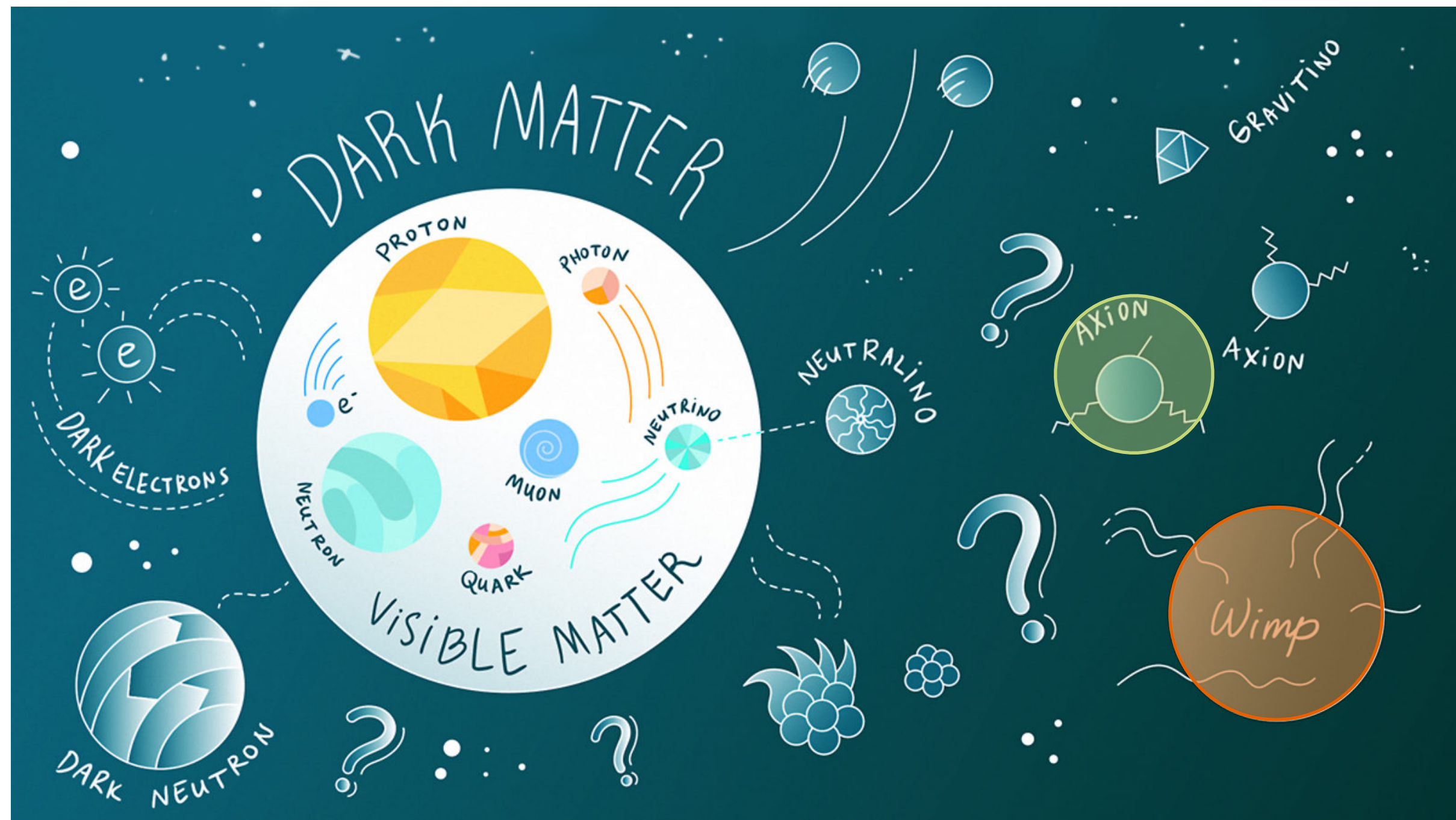
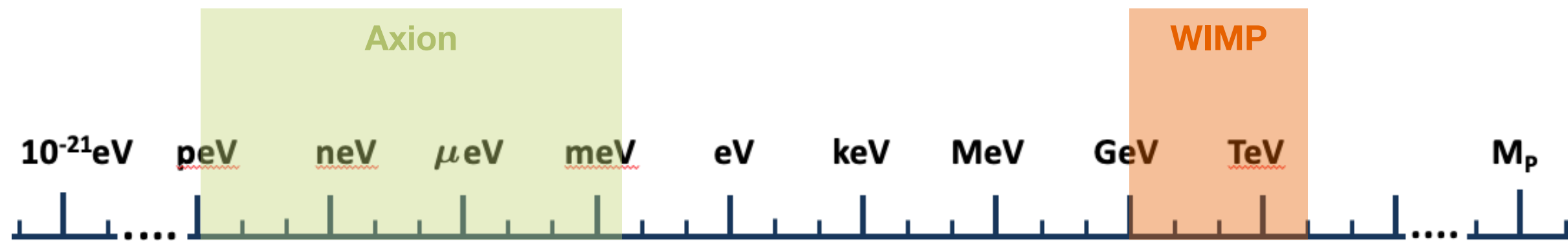


PRODUCTION



SCATTERING

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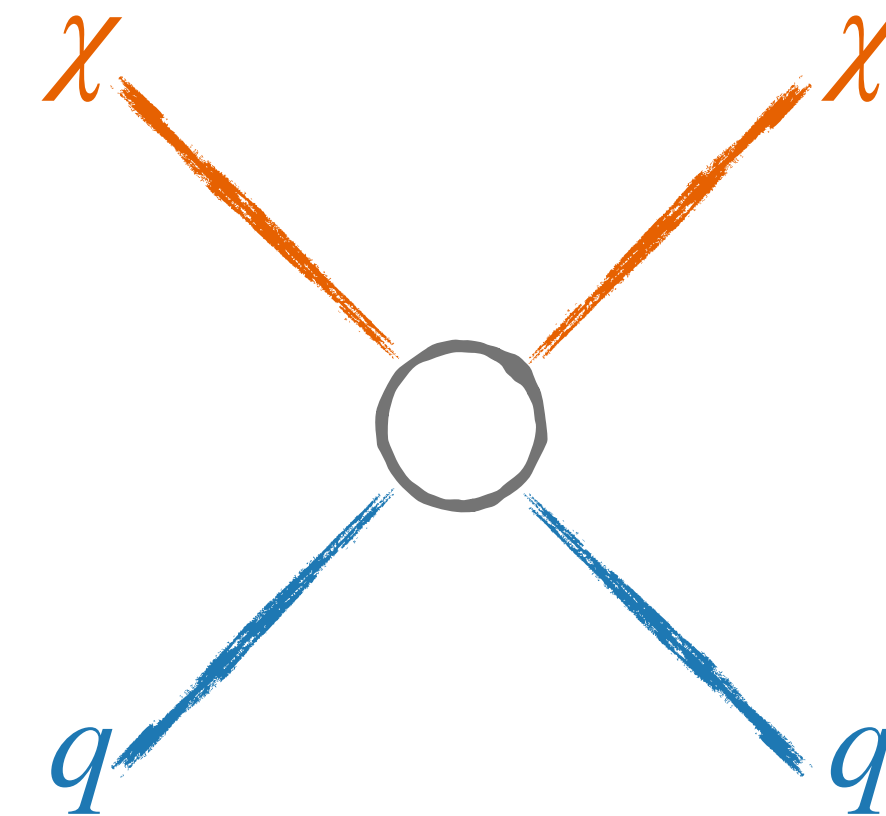


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ANNIHILATION



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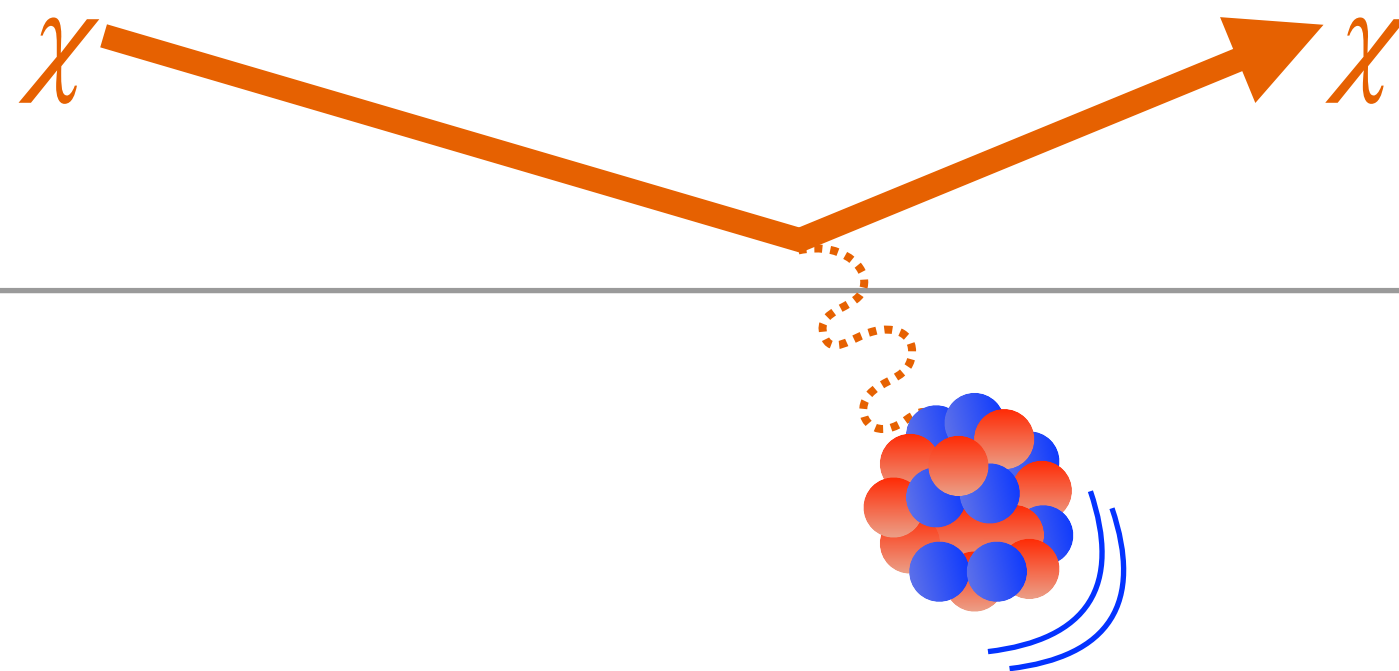


SCATTERING



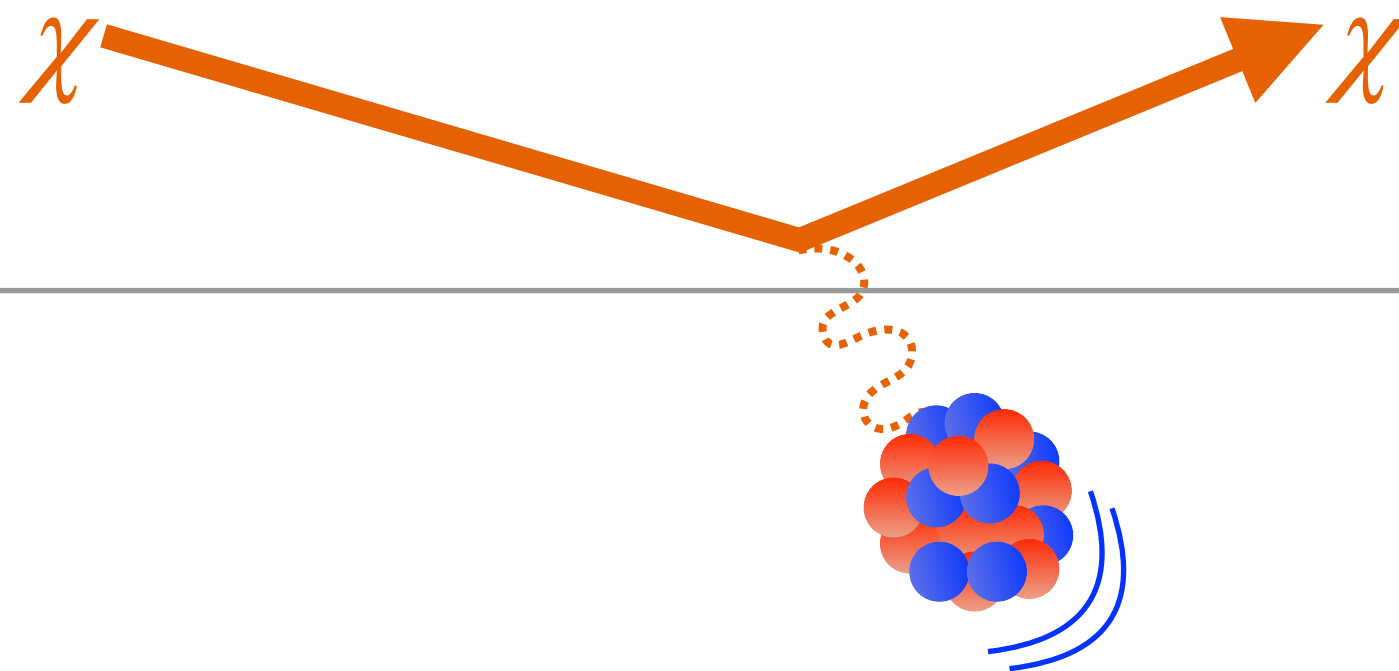
# WIMP Signal

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$$\frac{dR}{dE_r}$$

# WIMP Signal



$$\frac{dR}{dE_r}$$

 $\propto$ 

WIMP-nucleon  
cross section

$$\sigma_{SI}^p$$

$$2\mu_{\chi p}^2 M_\chi$$

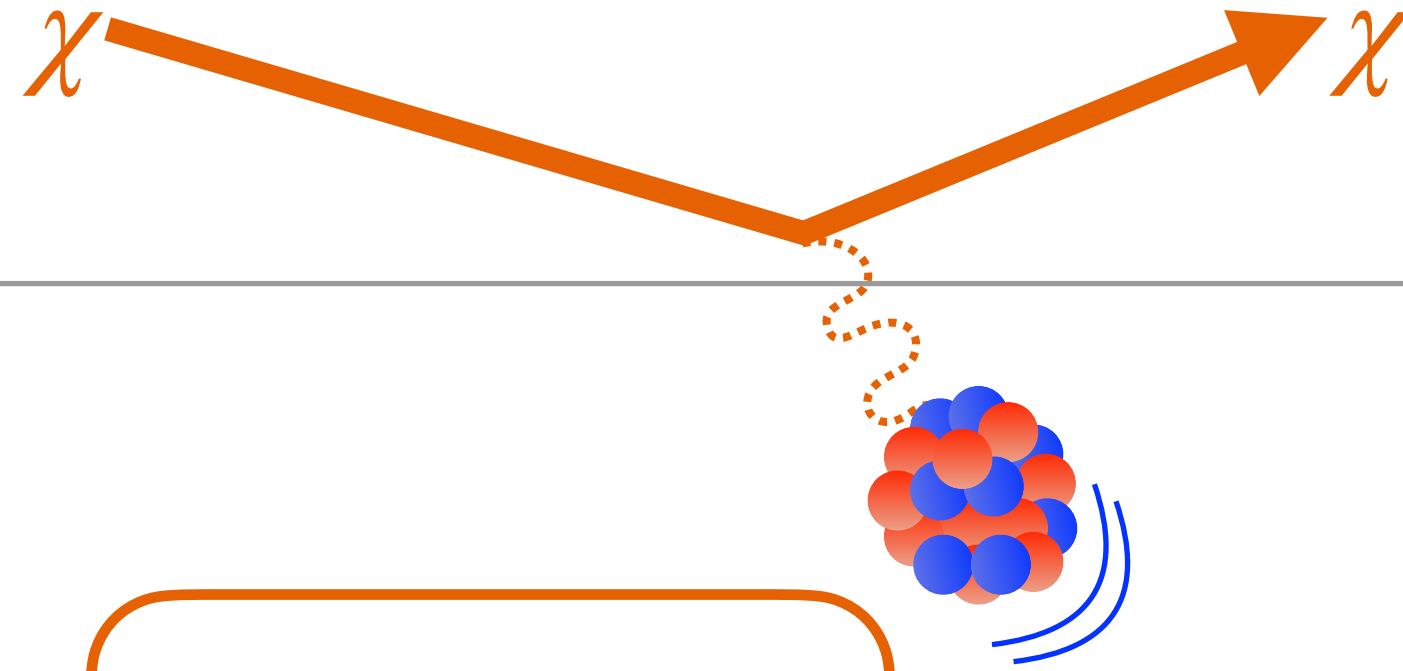
WIMP-nucleon  
reduced mass

WIMP  
mass



PHYSICS

# WIMP Signal



$$\frac{dR}{dE_r}$$

 $\propto$ 

WIMP-nucleon cross section

$$\frac{\sigma_{SI}^p}{2\mu_{\chi p}^2 M_\chi}$$

WIMP-nucleon reduced mass      WIMP mass

↓

PHYSICS

 $\times$ 

Nuclear form factor

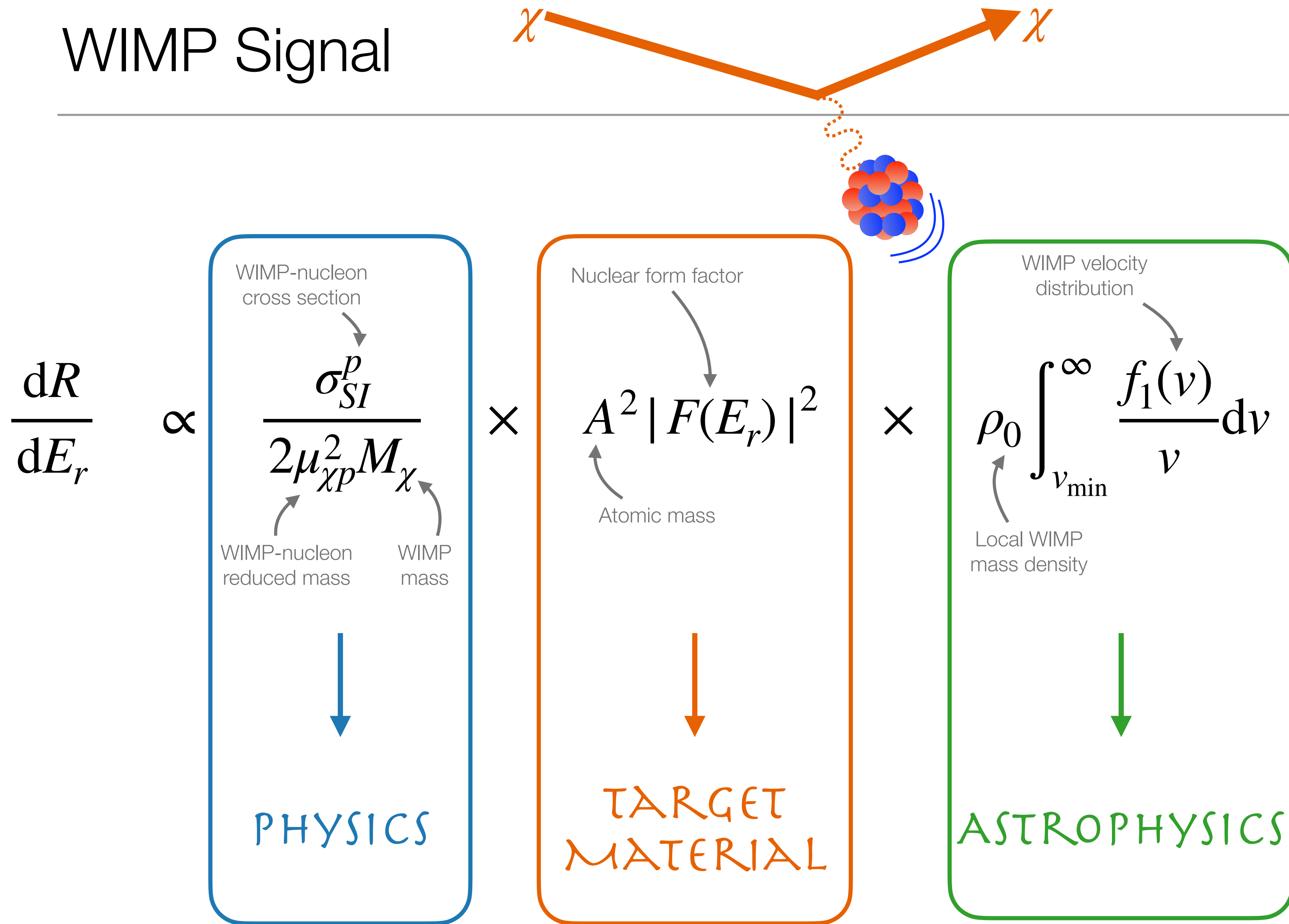
$$A^2 |F(E_r)|^2$$

Atomic mass

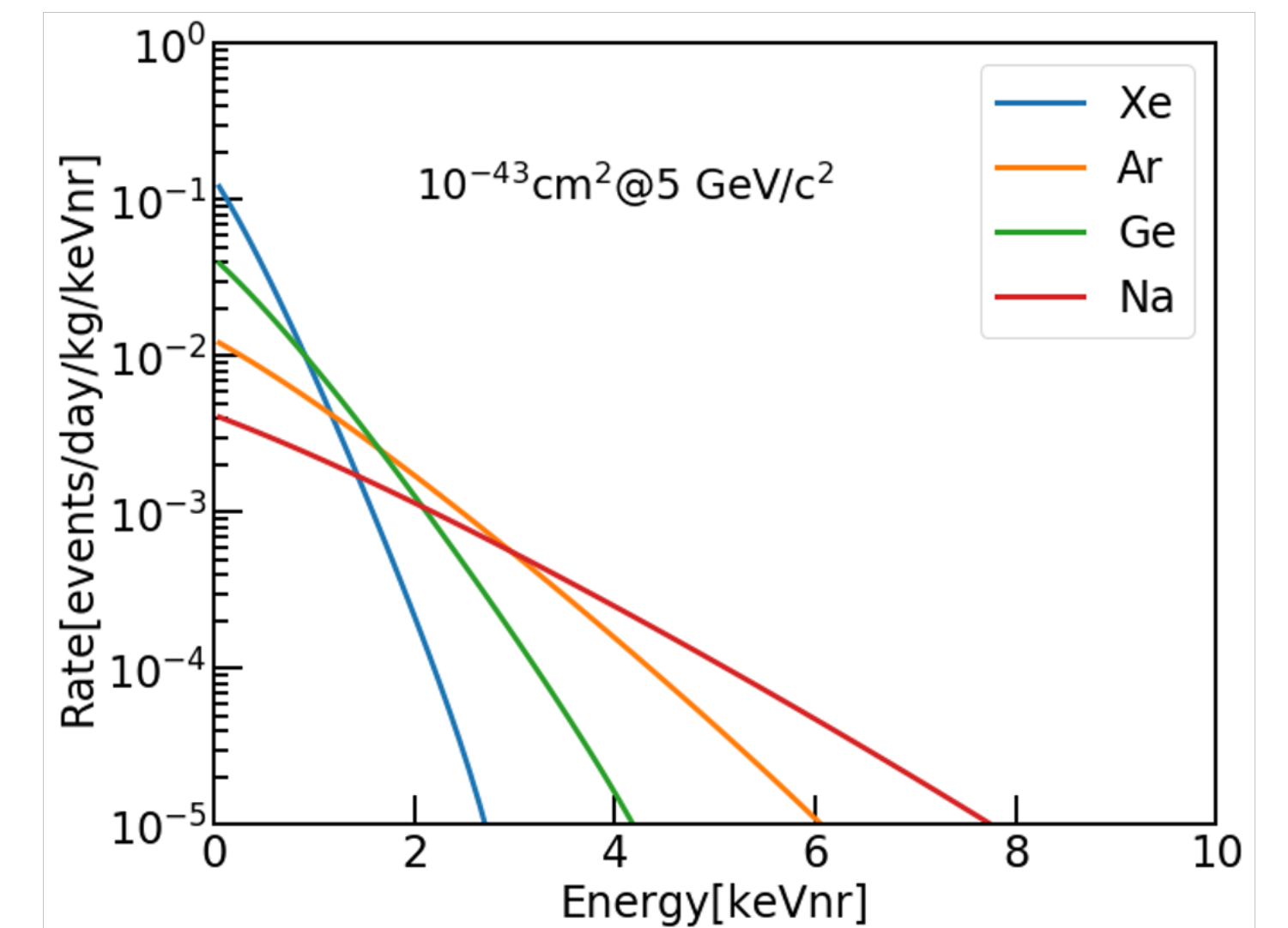
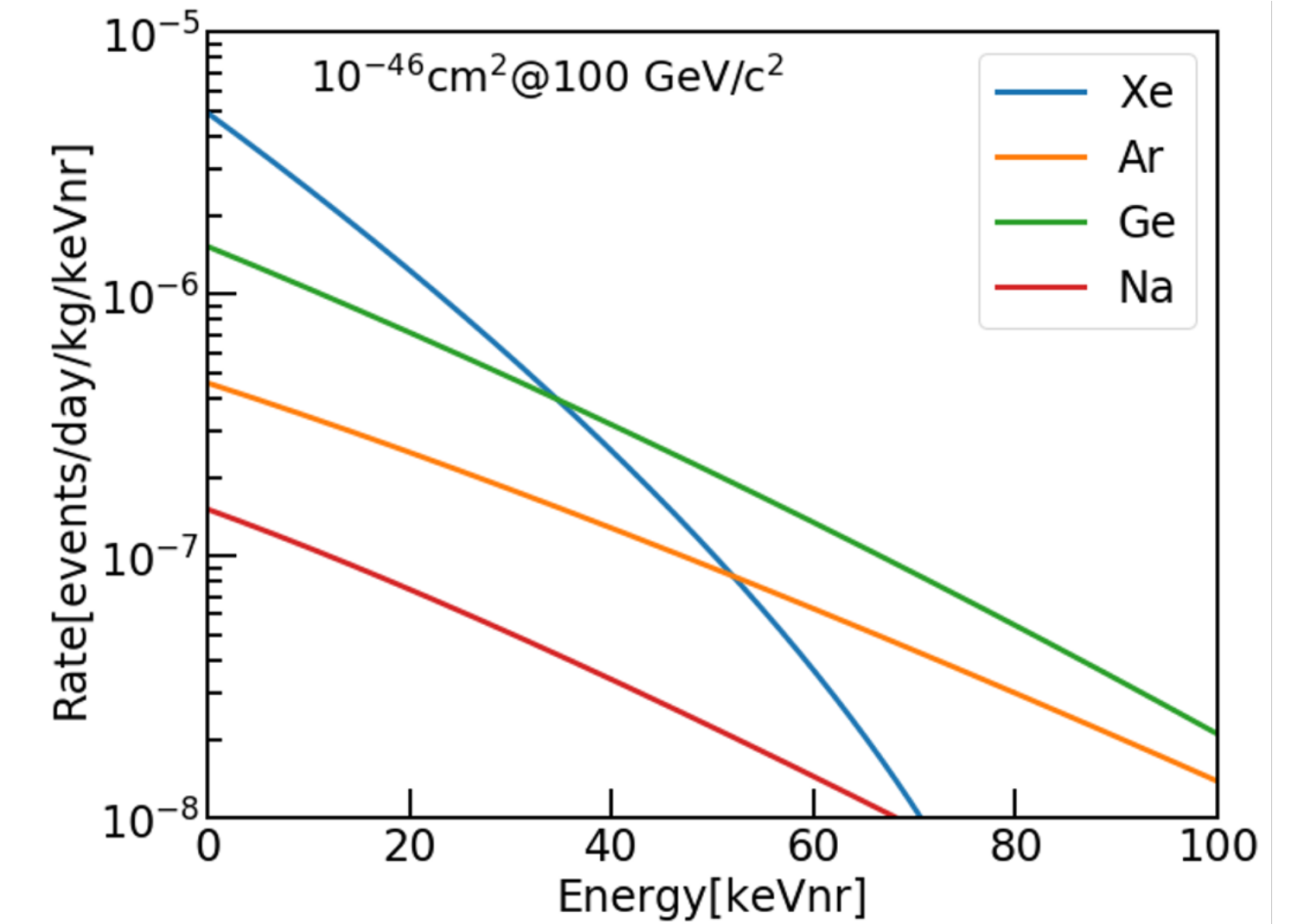
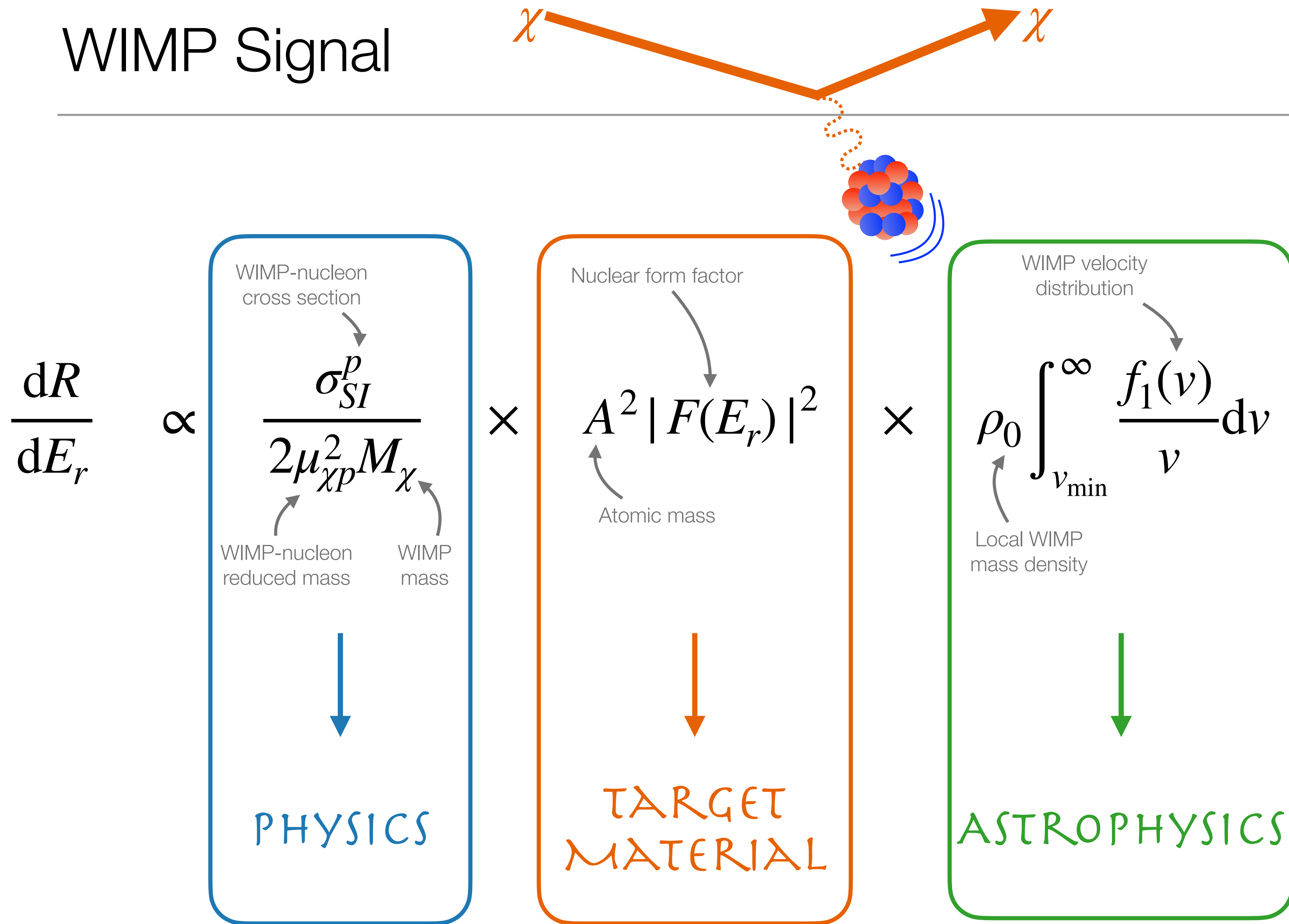
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TARGET MATERIAL

# WIMP Signal



# WIMP Signal



# Noble Liquids

- Argon and xenon are used ubiquitously in dark matter and neutrino experiments
- Scalable to ton-scale or even larger detectors
- Allow easy purification for both electro-negative and radioactivity (even online)
- Powerful background rejection techniques (S2/S1, PSD) through combination of measurable quantities
  - Scintillation (S1)
  - Ionization (S2)
- Provide excellent self-shielding capabilities



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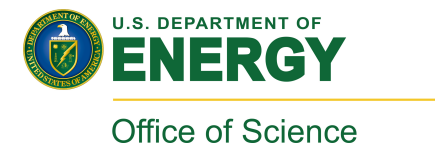
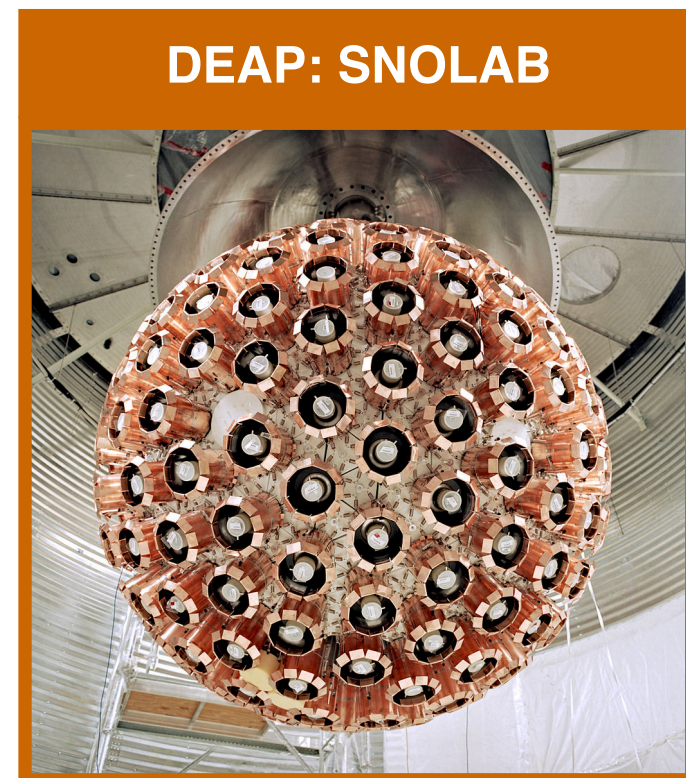
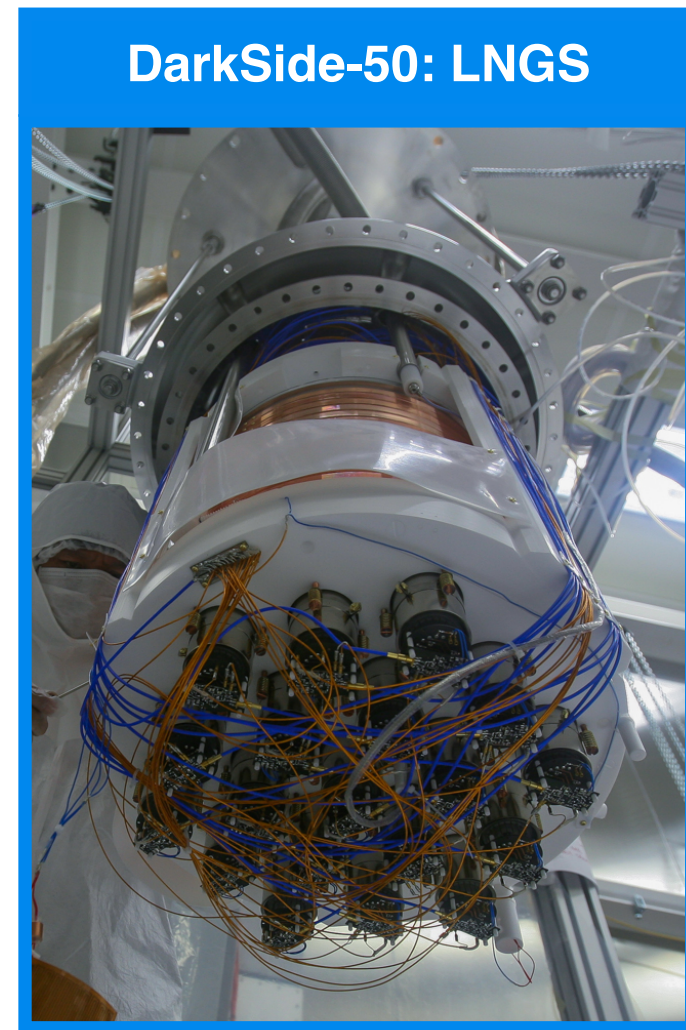
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$^{39}\text{Ar}$  present at  $\sim 1 \text{ Bq/kg}$  in the atmospheric argon  
 $\beta$ -decay with  $565 \text{ keV}$  endpoint,  $t_{1/2} = 269 \text{ yr}$

# The Global Argon Dark Matter Collaboration (GADMC)

**A union of 4 collaborations, with over 400 scientists, spanning over 100 institutions across 13 countries**



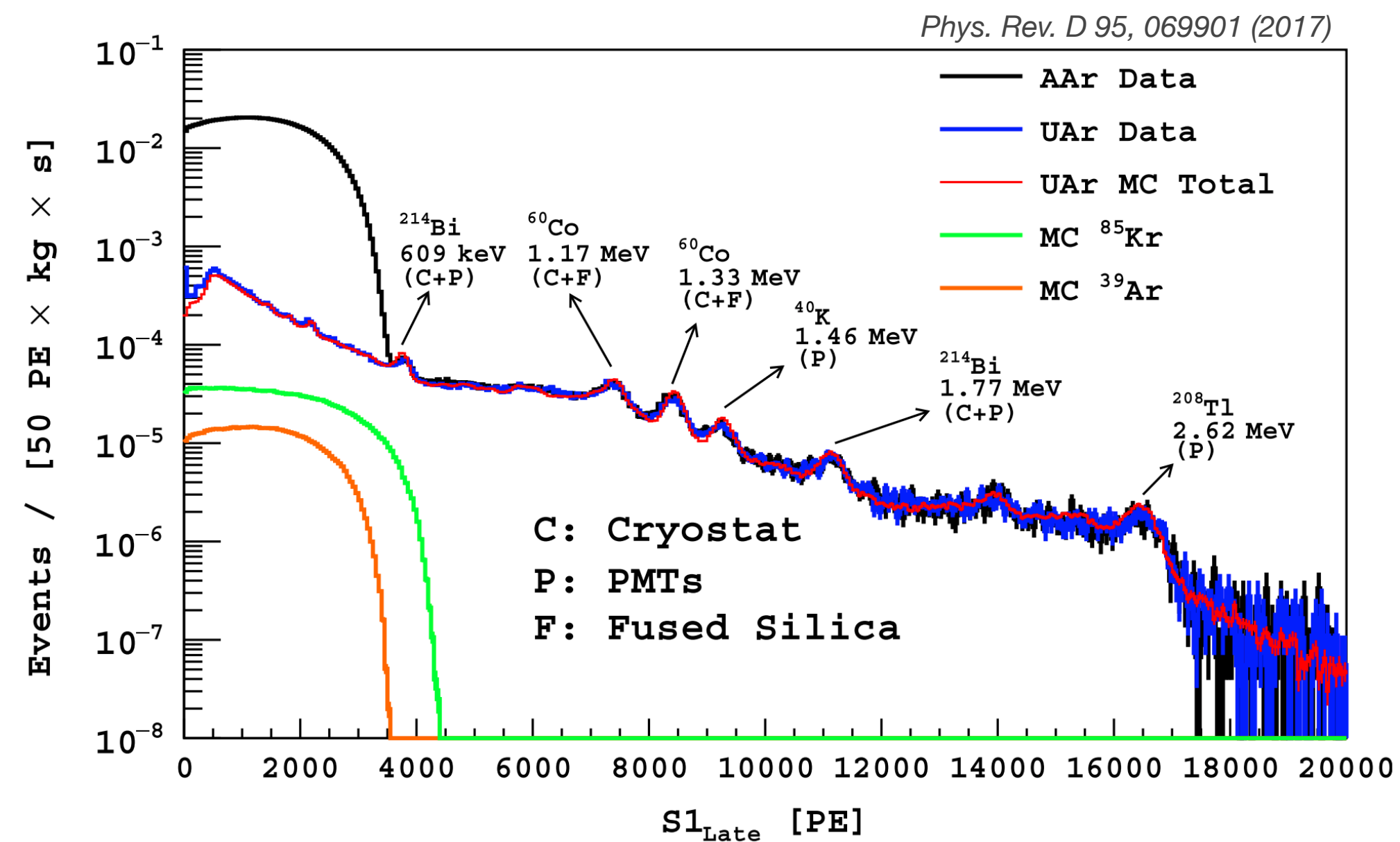
# Key Technologies for DarkSide-20k

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## Underground Argon

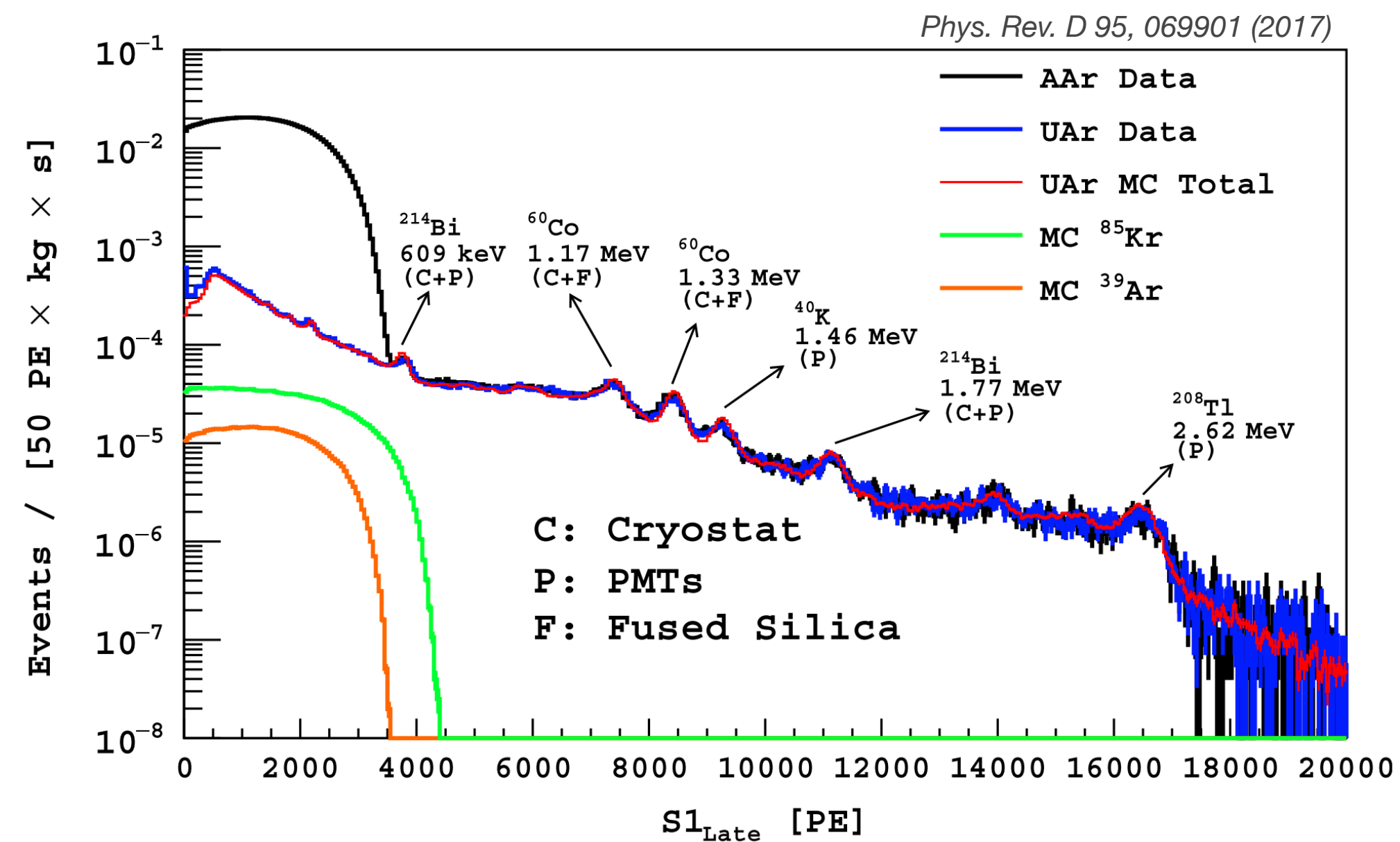
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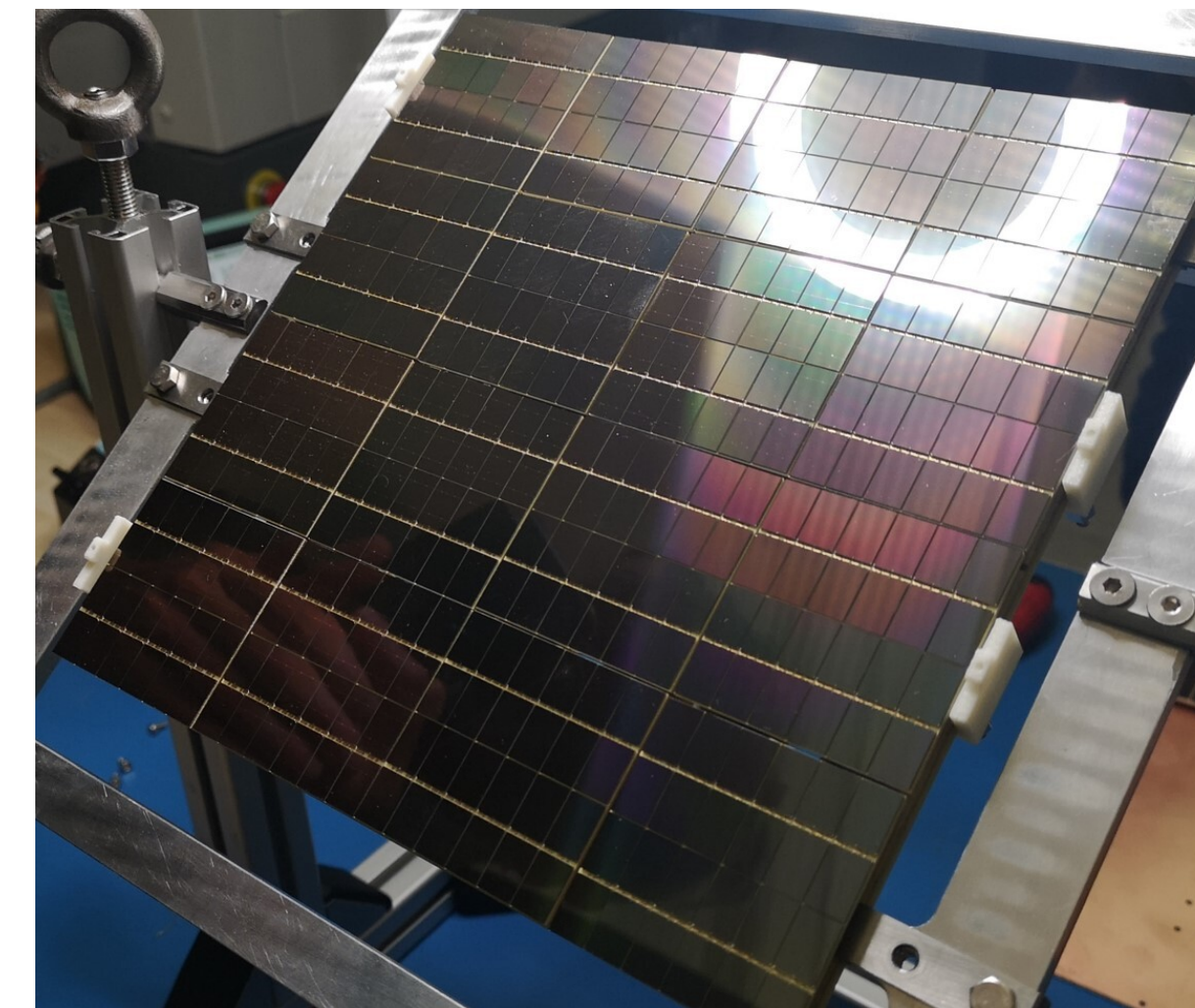
## Underground Argon

Developed UAr as a detector medium with a reduction factor of  $\sim 1400\times$  in  $^{39}\text{Ar}$



## Silicon Photomultiplier

Developed low-radioactivity, low-noise, high-efficiency SiPM arrays that can cover large areas in a cost-effective manner



# Industrial Scale Underground Argon (UAr)

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## Production

URANIA Site  
Cortez, CO, US

- Industrial-scale extraction plant
- Extraction rate of (250 – 330) kg/day
- Production capability of  $\approx 120$  t over two years for Darkside
- UAr purity of 99.99 %





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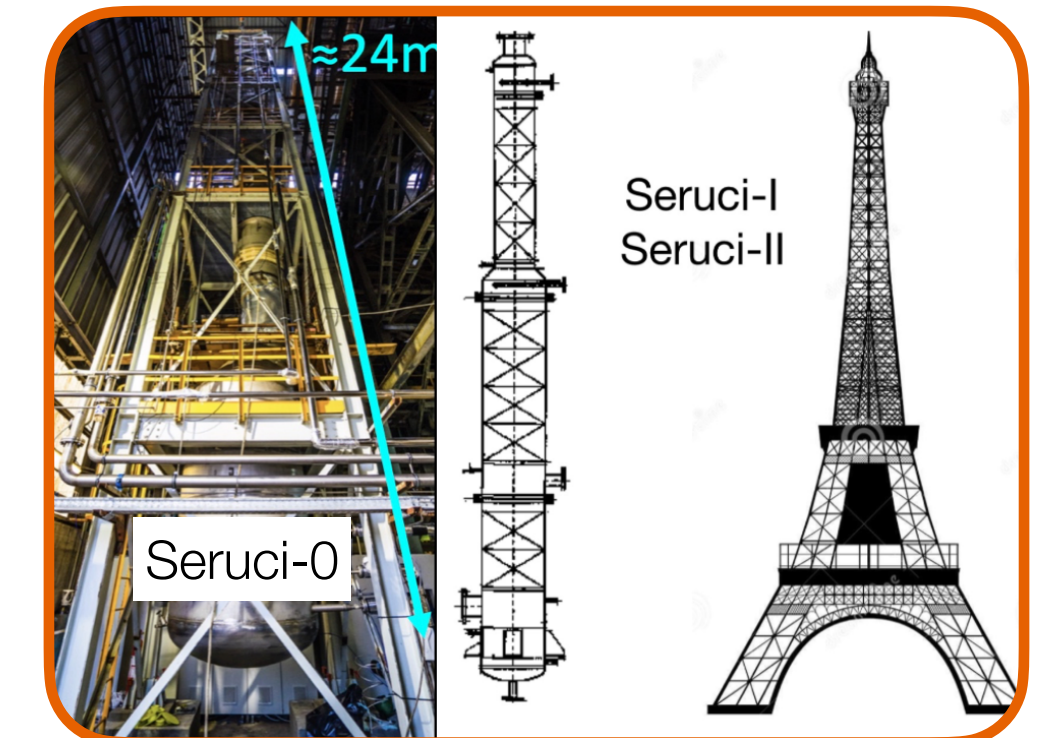


## Purification

ARIA Site  
Sardinia, Italy

- Seruci-0 demonstrator tested
- 350 m long cryogenic distillation column
- $\mathcal{O}(1 \text{ tonne/day})$  purification throughput
- Resulting UAr purity of 99.999 %

<https://doi.org/10.1140/epjc/s10052-021-09121-9>  
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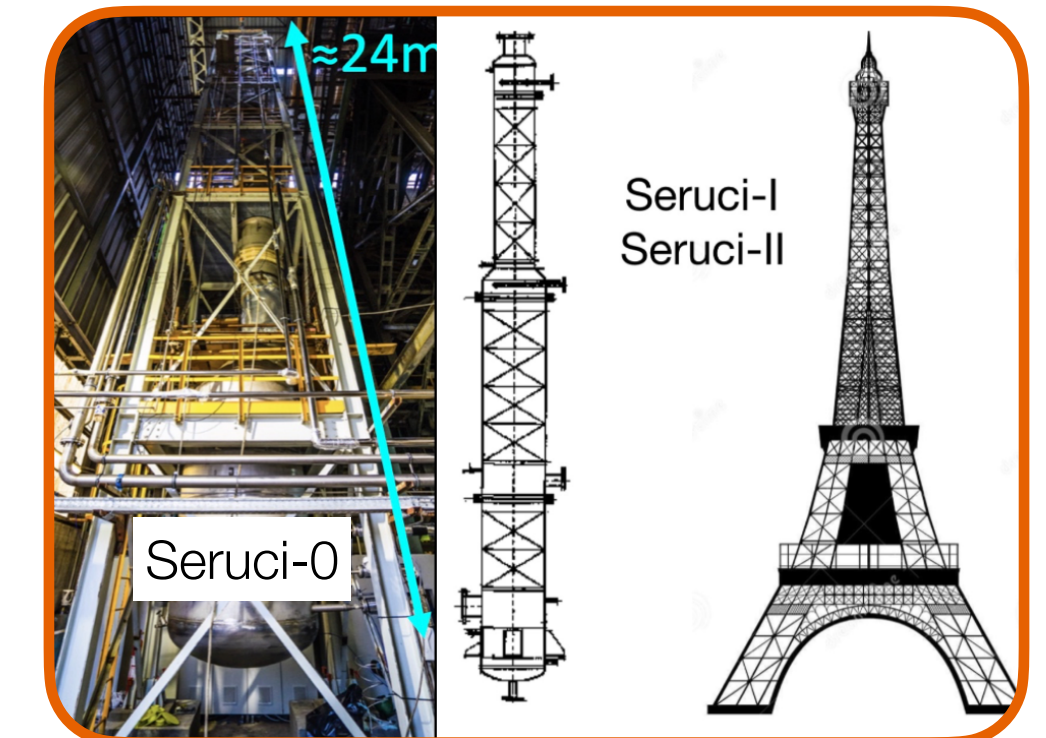


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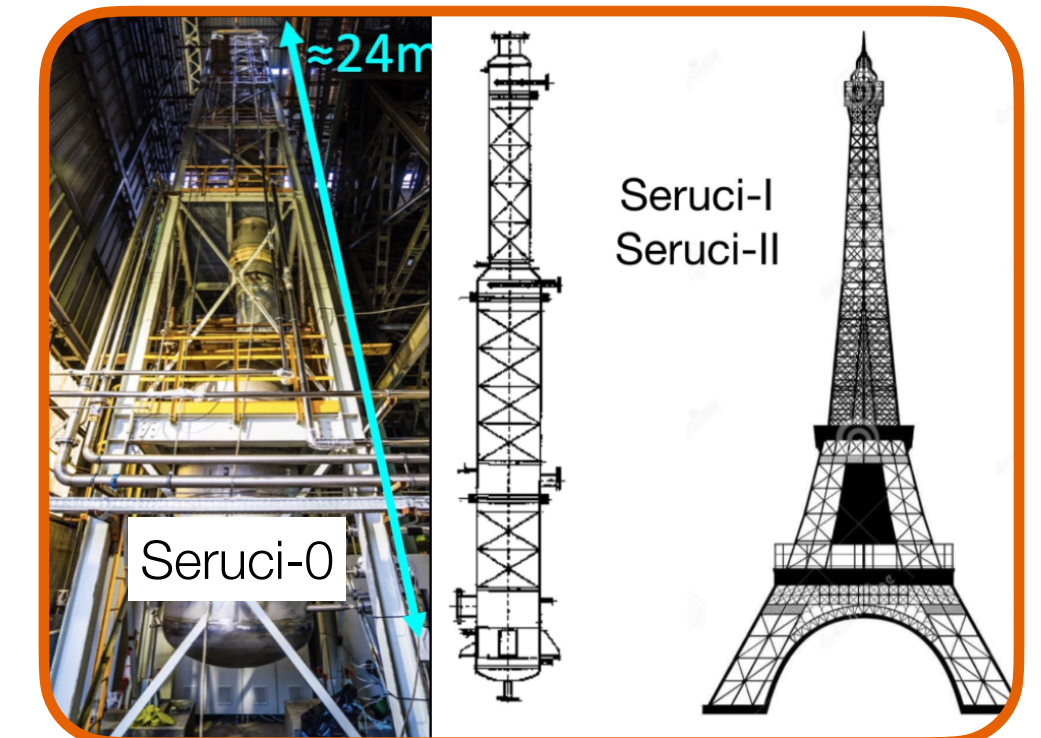


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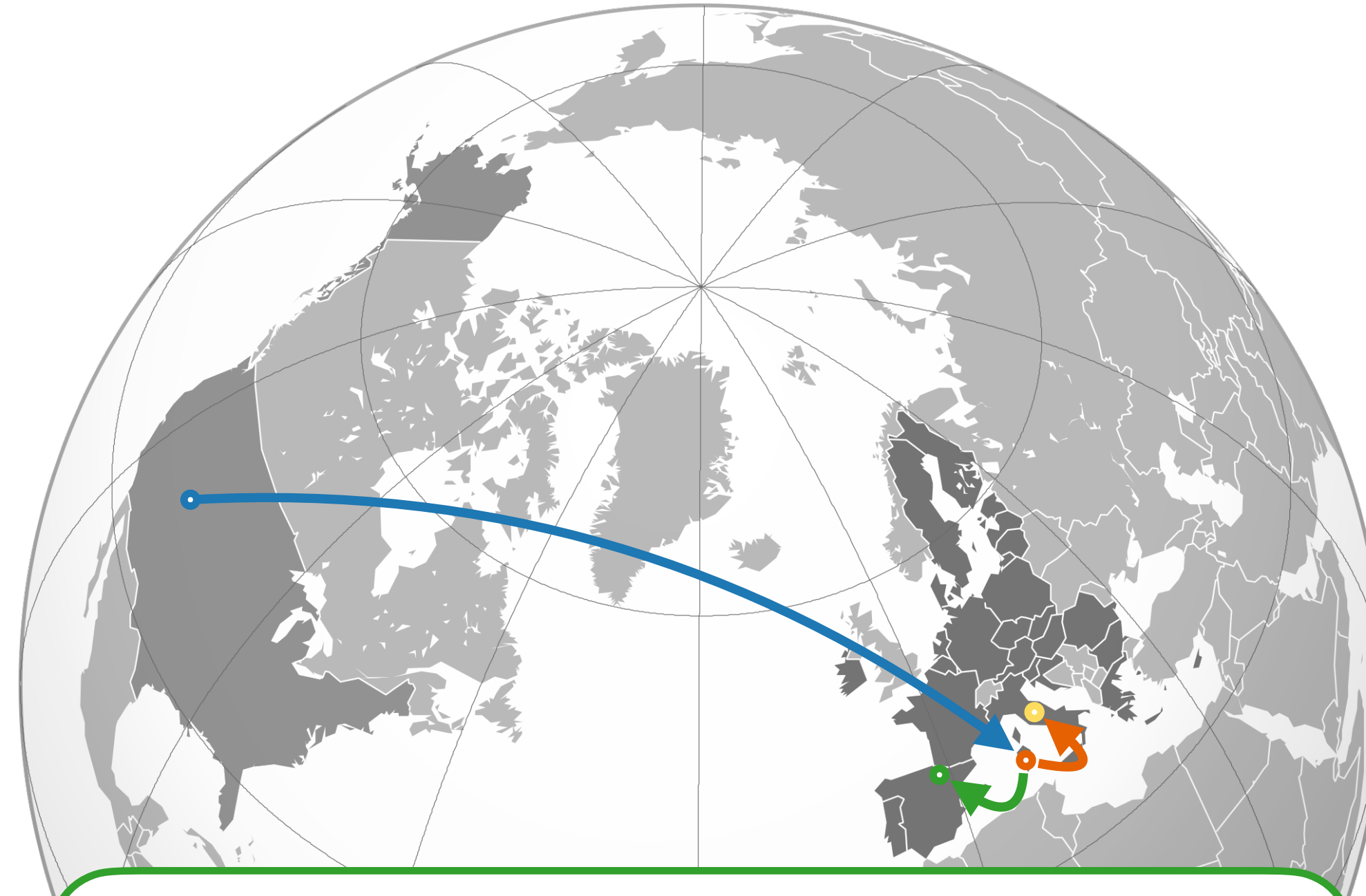


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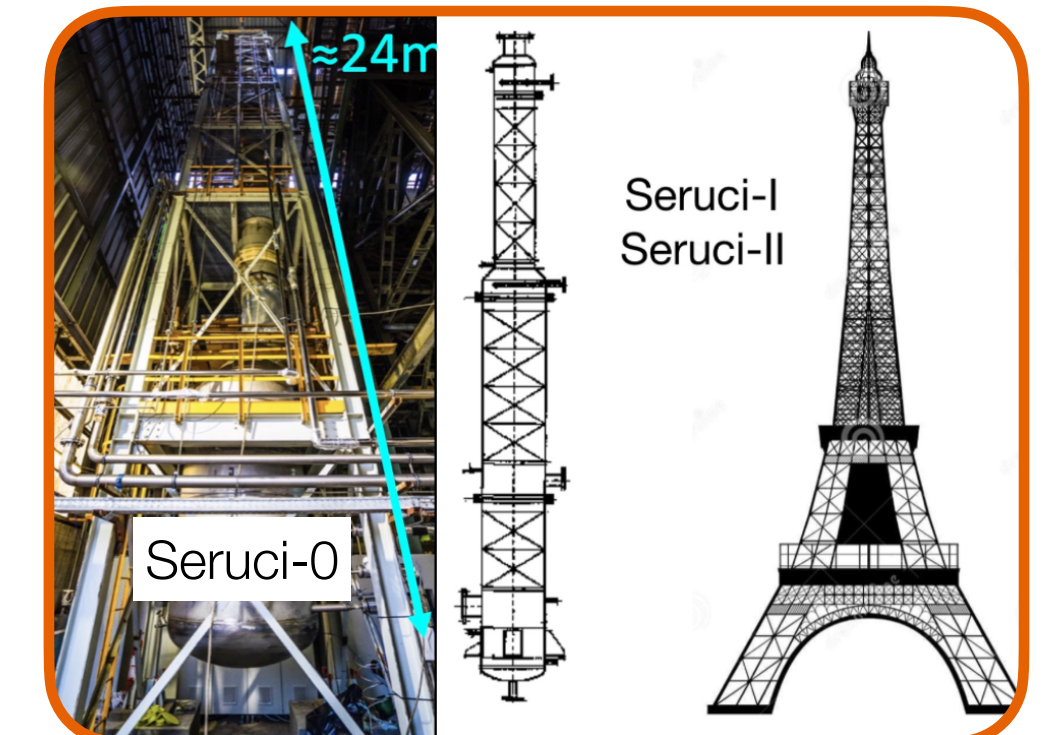


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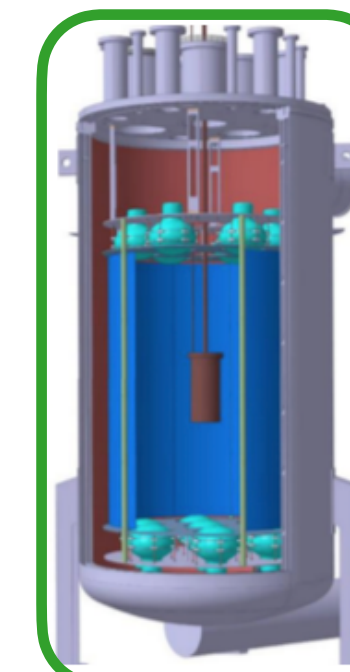
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## Qualification

DArT  
Canfranc, Spain

- Single-phase detector to measure  $^{39}\text{Ar}$  depletion factor
- Sensitive to  $^{39}\text{Ar}$  down to a reduction factor of 1400 with 7% accuracy  
<https://doi.org/10.1088/1748-0221/15/02/P02024>
- DArT soon to be installed inside ArDM



# Low-radioactivity, high-efficiency SiPM Development

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- Developed with Fondazione Bruno Kessler (FBK)
  - Photon detection efficiency:  $> 40\%$  at 77K
  - Dark count rate:  $< 0.01 \text{ Hz/mm}^2$  at 77K (7 VoV)
  - SNR:  $> 8$  (TPC PDU)

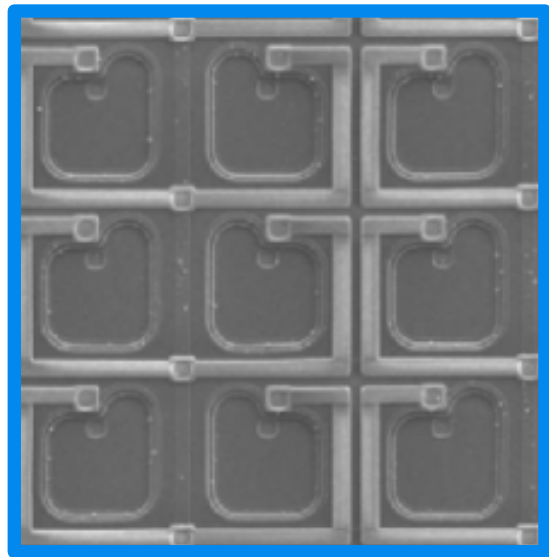


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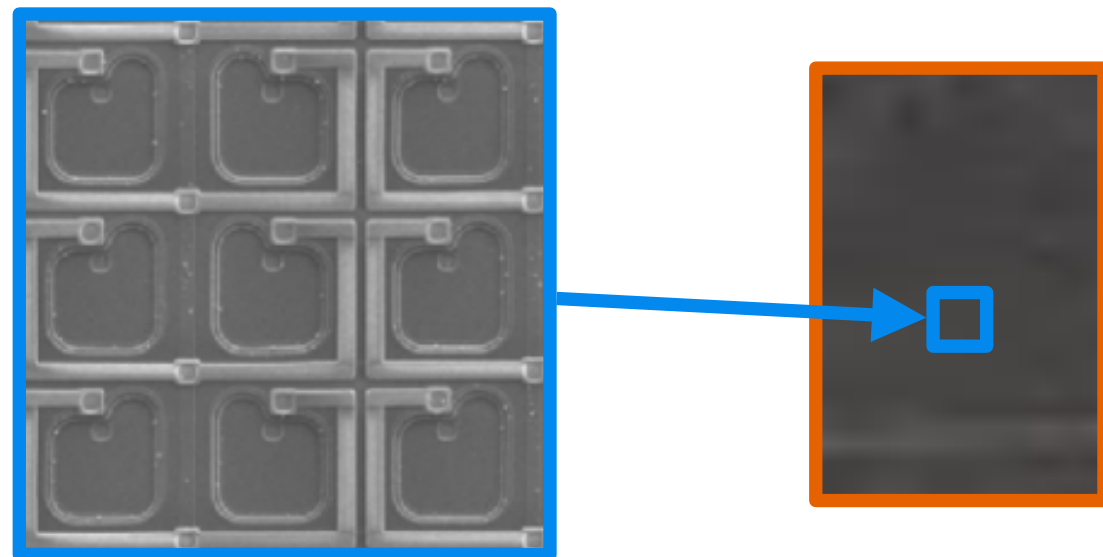


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SiPM  
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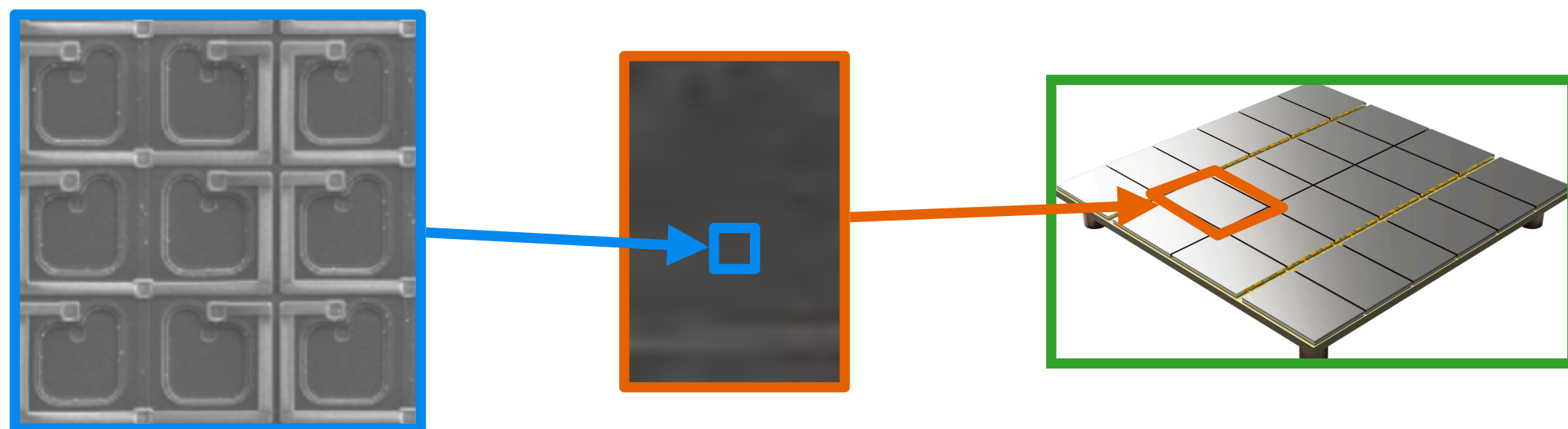
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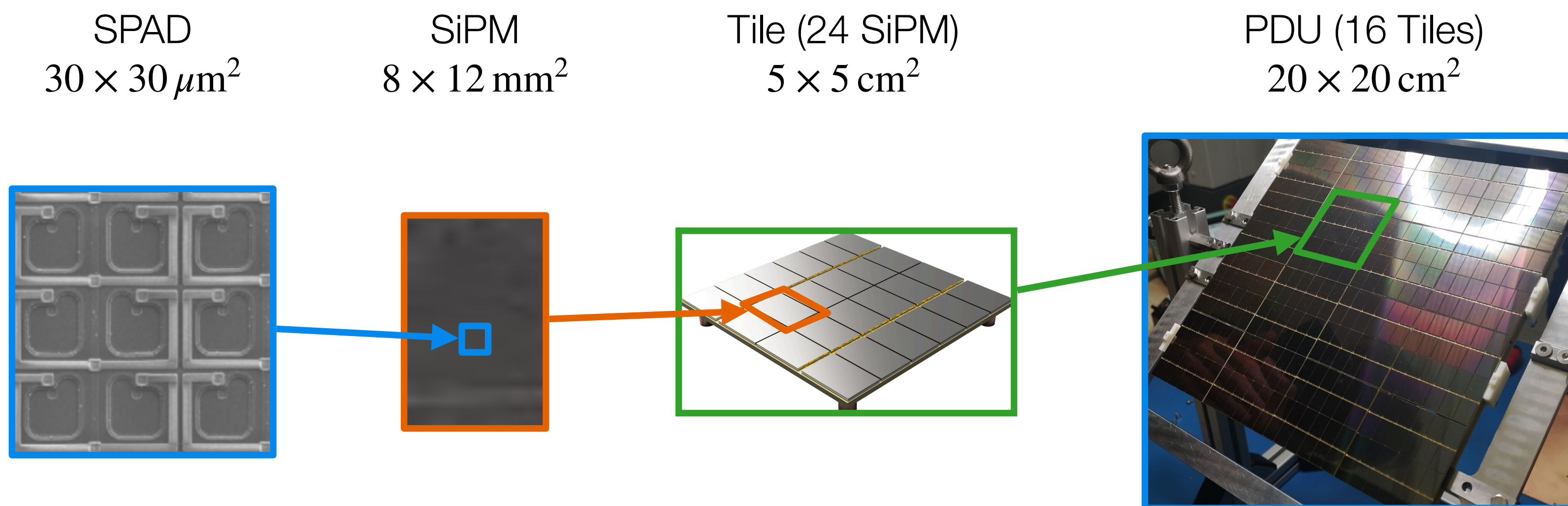
SiPM  
 $8 \times 12 \text{ mm}^2$

Tile (24 SiPM)  
 $5 \times 5 \text{ cm}^2$



# Low-radioactivity, high-efficiency SiPM Development

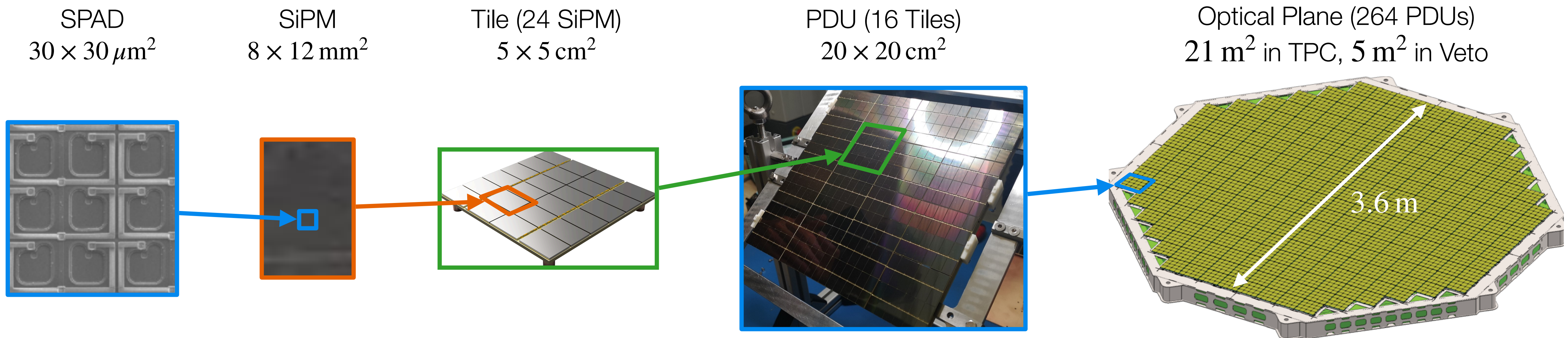
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PDU packaging and assembly at Nuova  
Officina Assergi (NOA) at LNGS



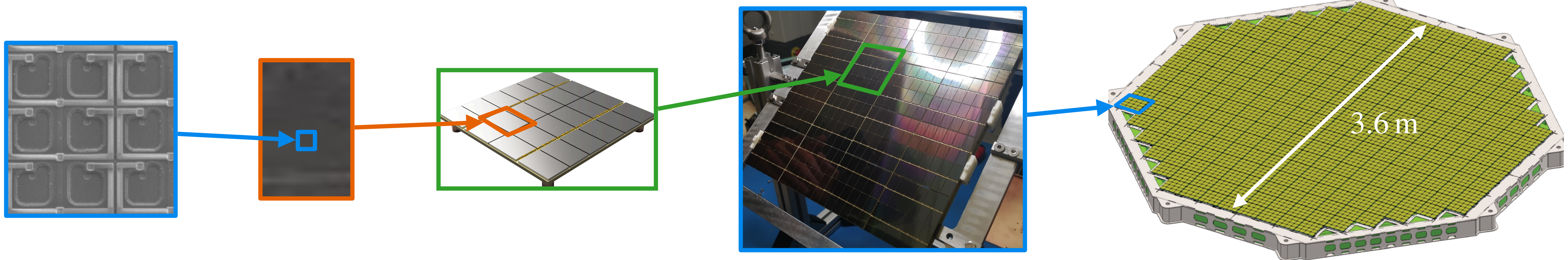
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SiPM  
 $8 \times 12 \text{ mm}^2$

Tile (24 SiPM)  
 $5 \times 5 \text{ cm}^2$

PDU (16 Tiles)  
 $20 \times 20 \text{ cm}^2$

Optical Plane (264 PDUs)  
 $21 \text{ m}^2$  in TPC,  $5 \text{ m}^2$  in Veto



DarkSide Collaboration: "Cryogenic Characterization of FBK RGB-HD SiPMs", JINST 12 P09030 (2017)

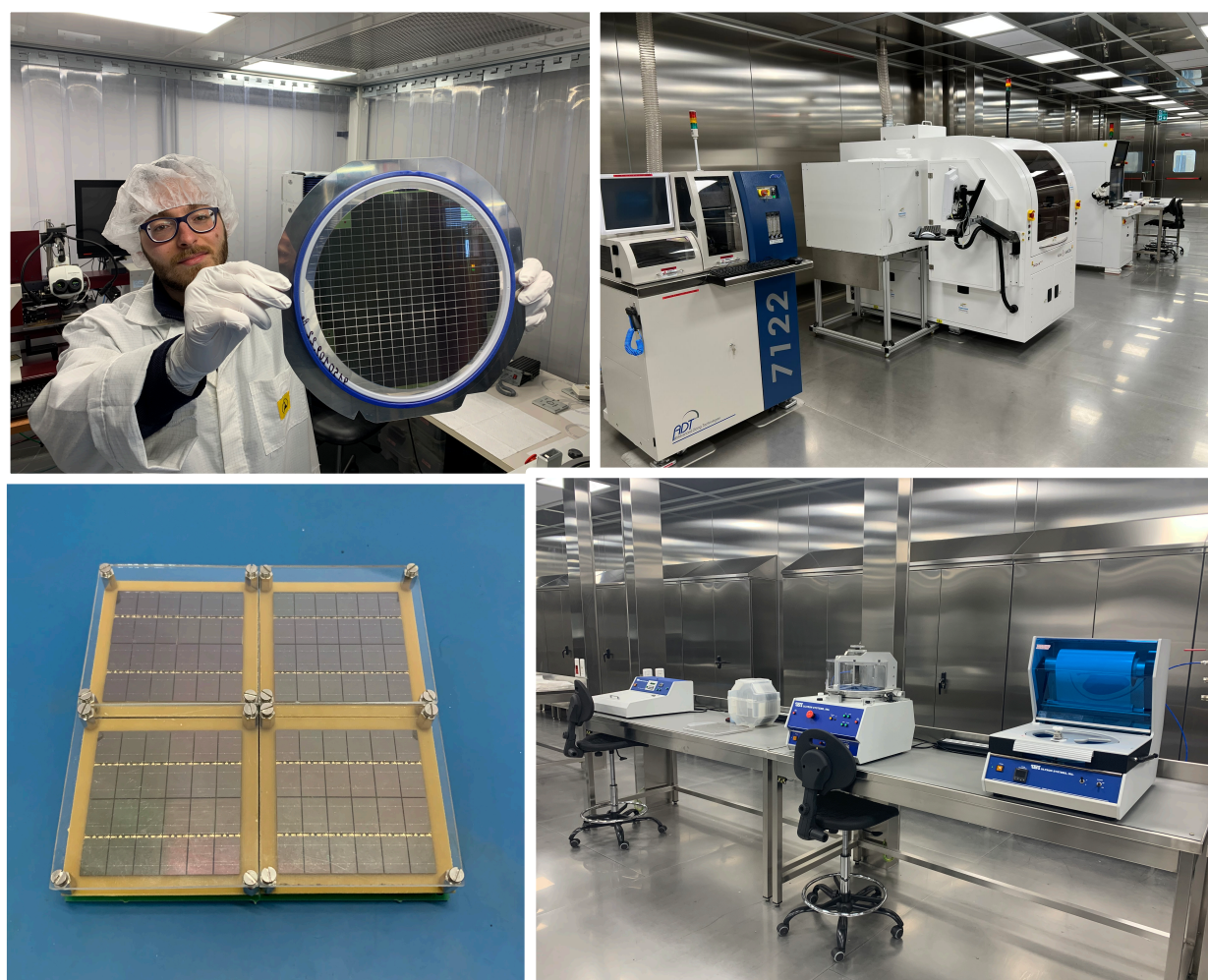
# SiPM Production and Testing

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# SiPM Production and Testing

## Nuova Officina Assergi (NOA) @LNGS

- ISO-6 class with 420 m<sup>2</sup>
- CR3: Production facility for TPC PDUs
- DS-20k production in  $\approx$  70 weeks
- CR2: TPC and optical plane assembly area

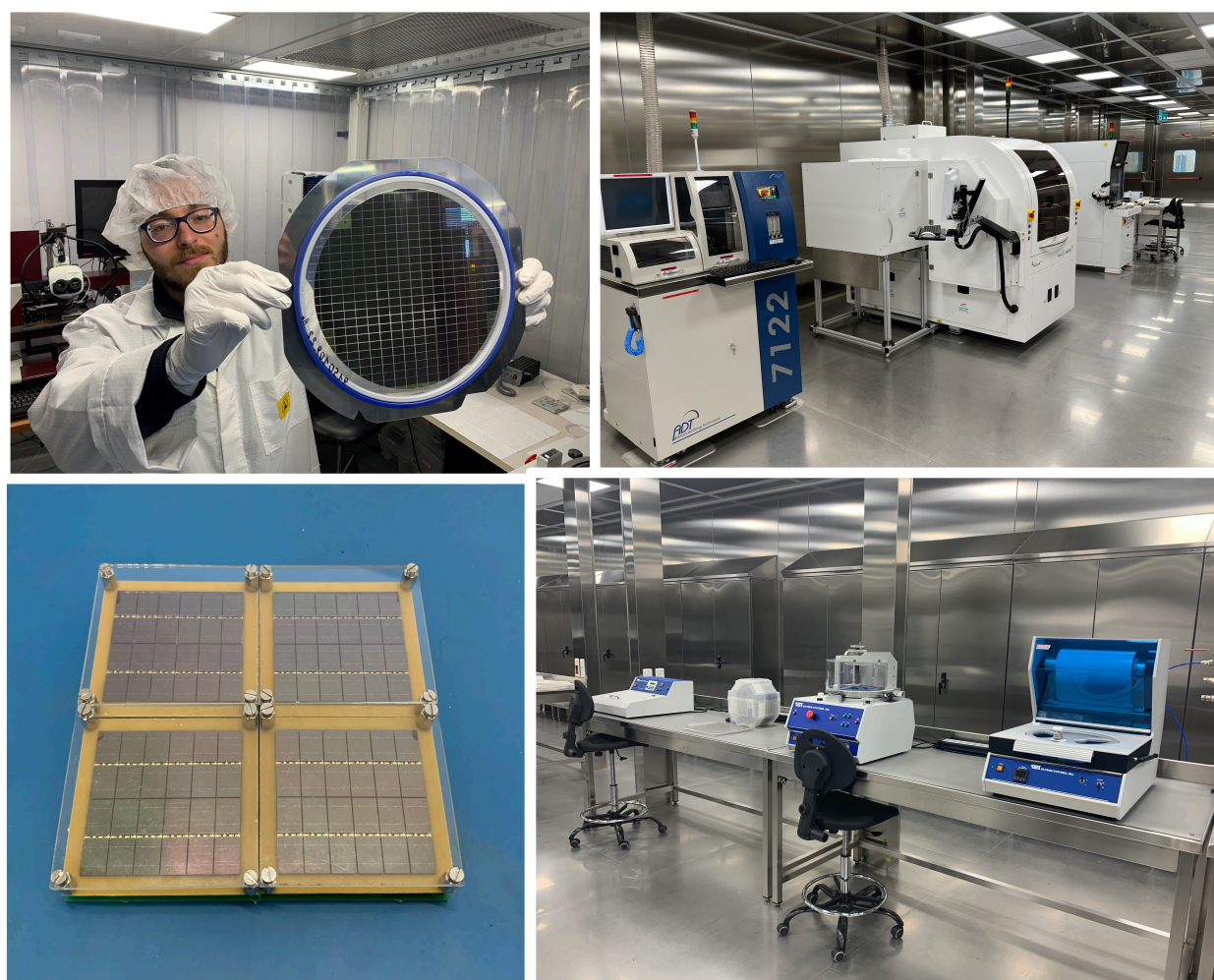




# SiPM Production and Testing

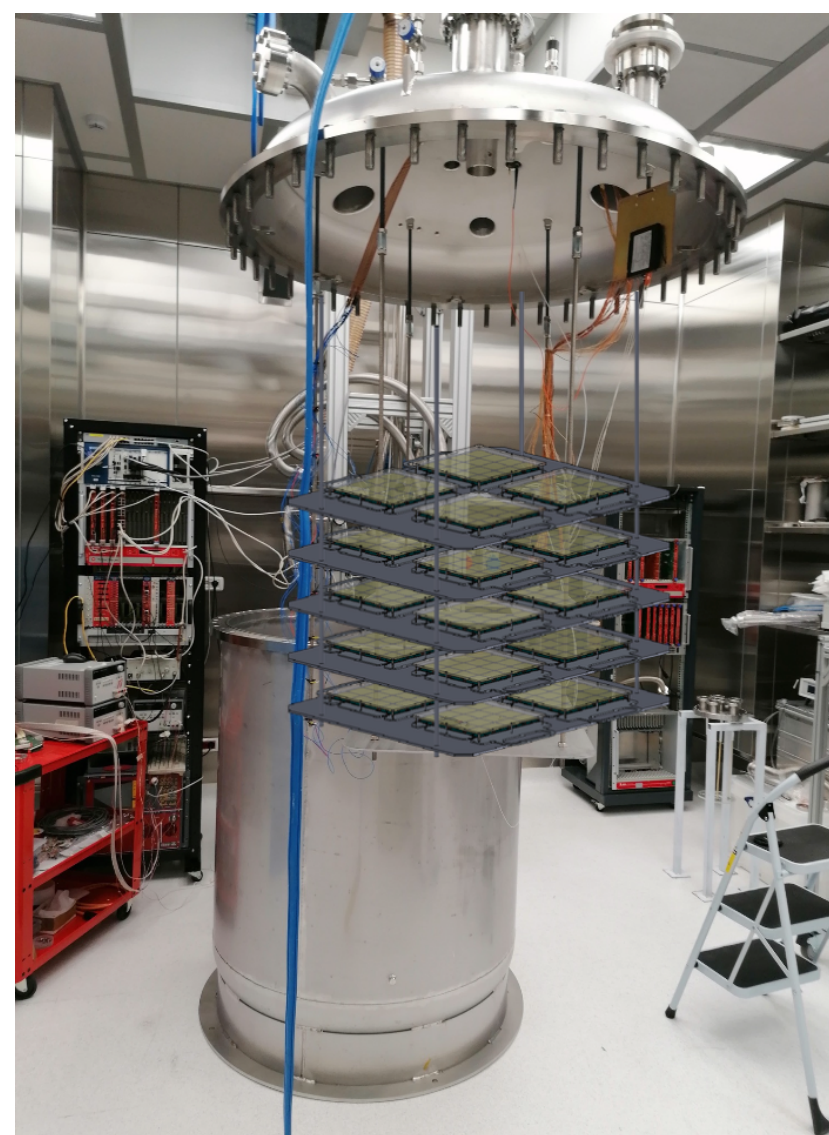
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## PDU Test Facility @Naples

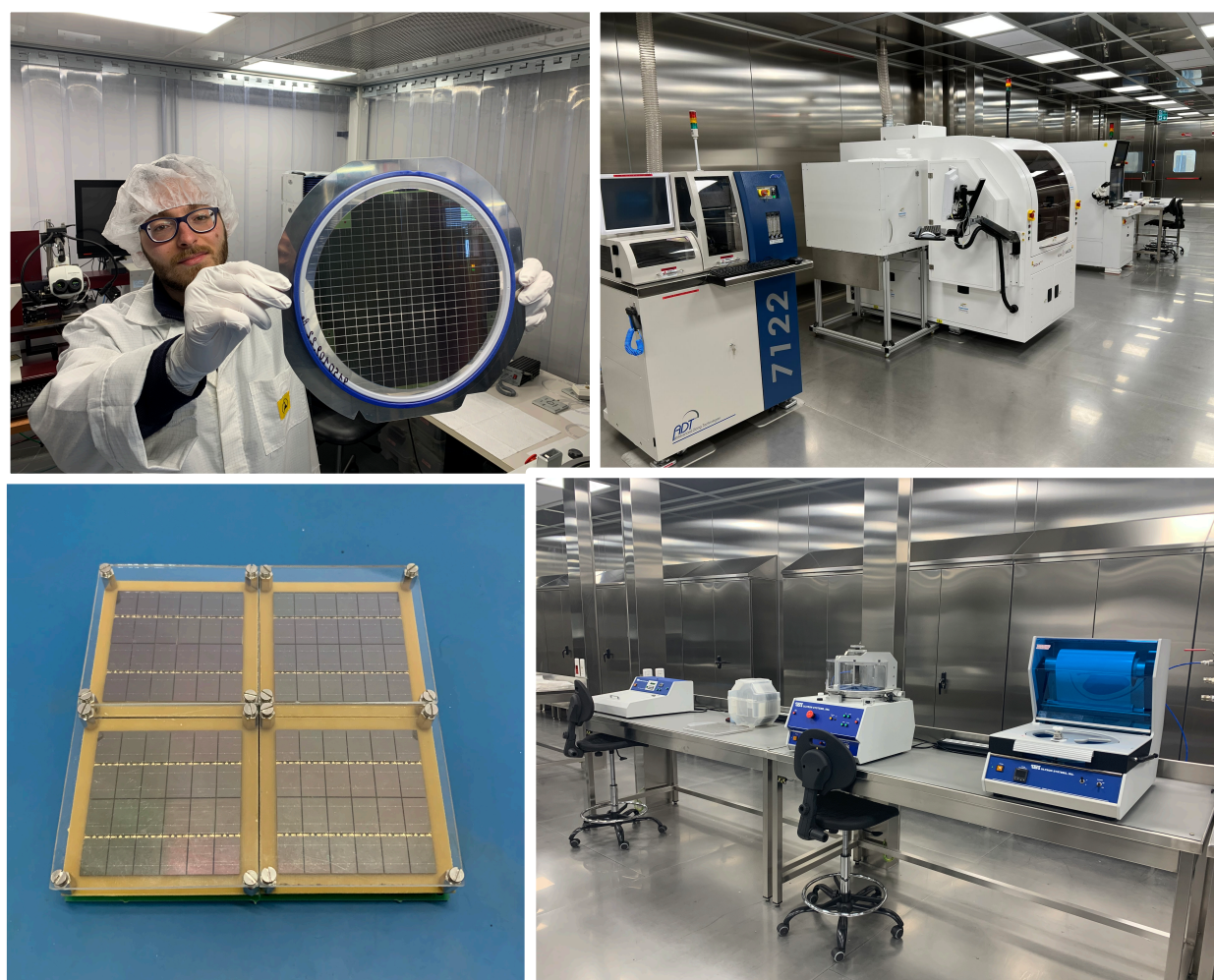
- Testing facility for TPC PDUs
- 800 l cryostat with LN2
- 12 PDU capacity
- TPC prototype setup



# SiPM Production and Testing

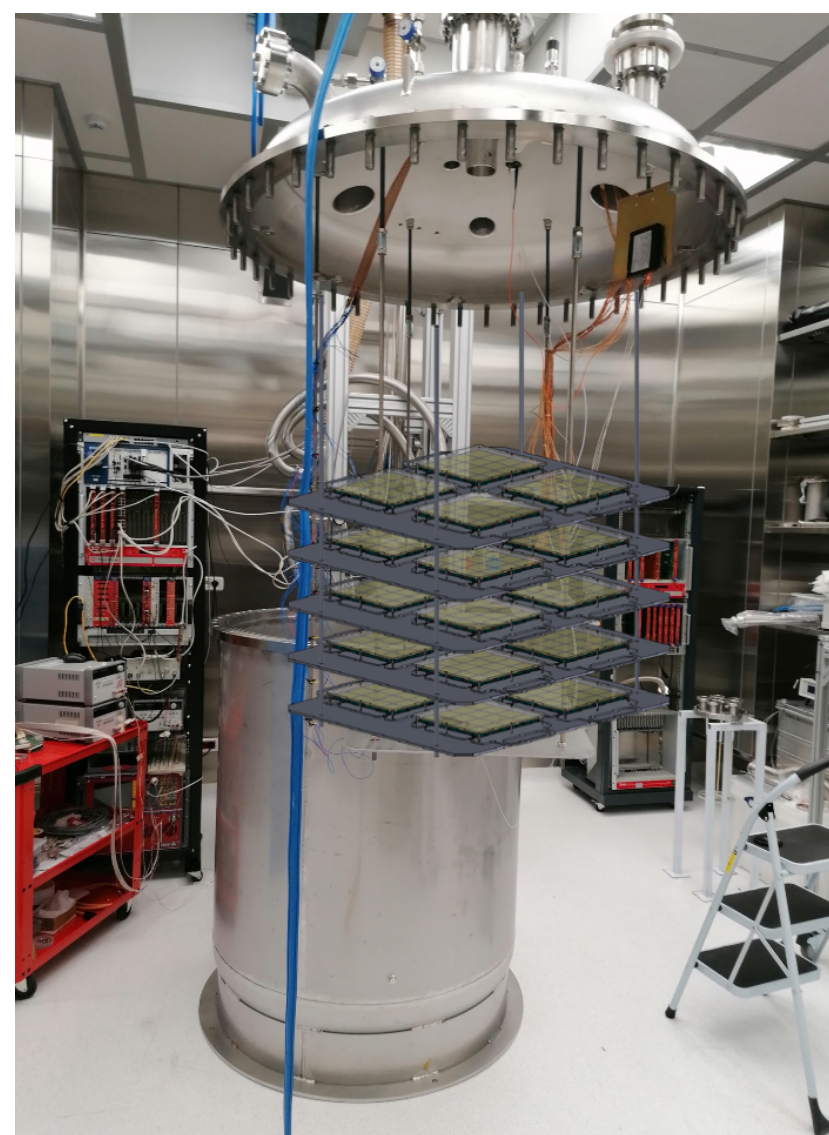
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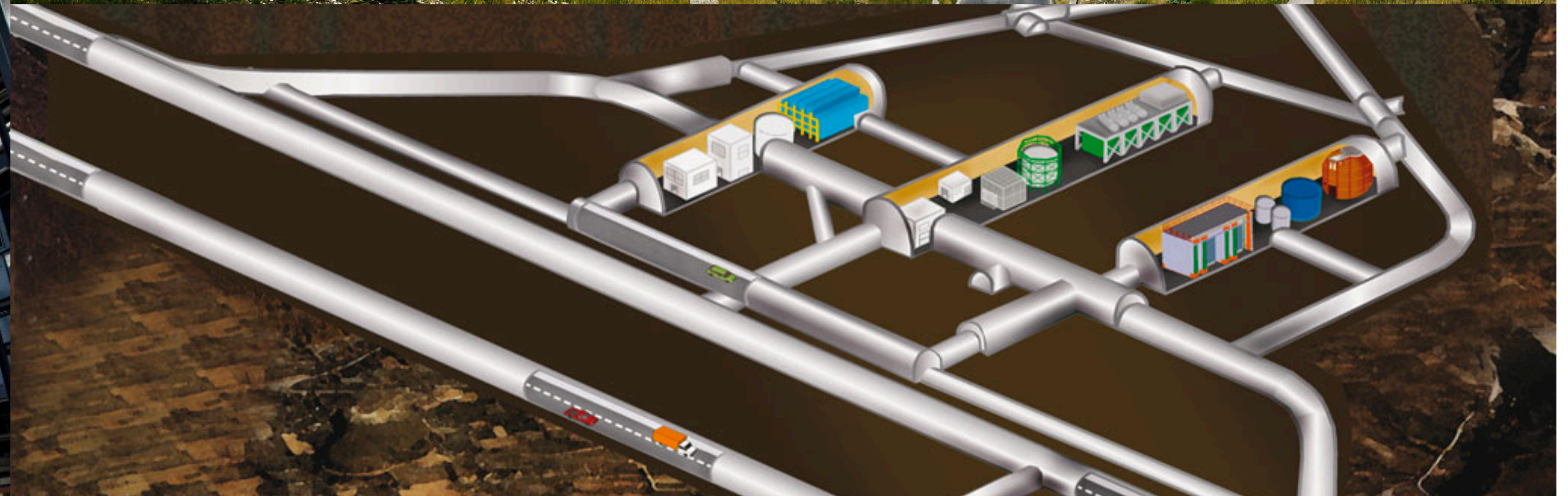
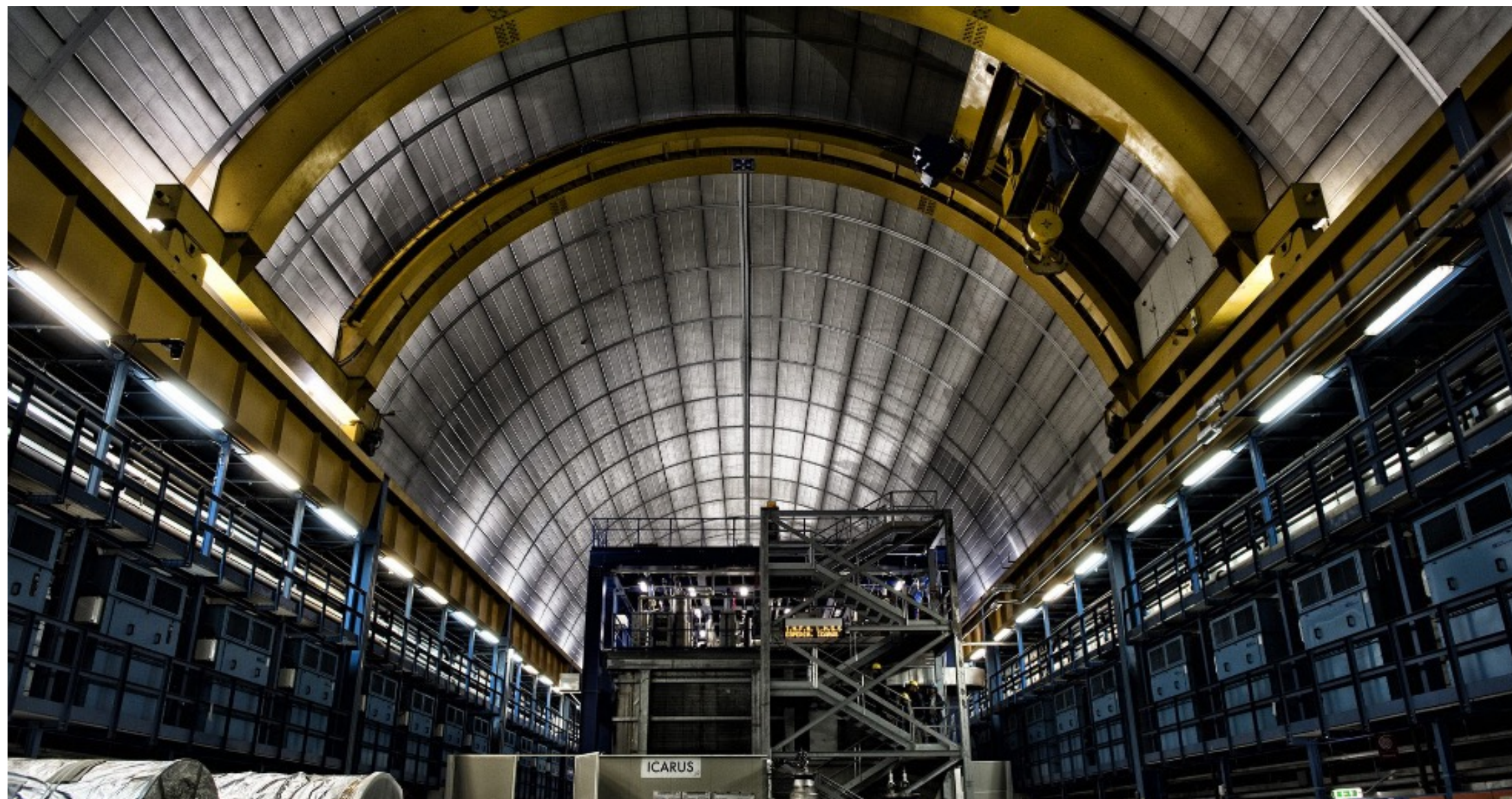
## vPDU Test Facilities @UK

- Facilities for veto PDUs
- Production and testing pipeline across DS-20k institutions in the UK
- Production goal of 65 tiles per week

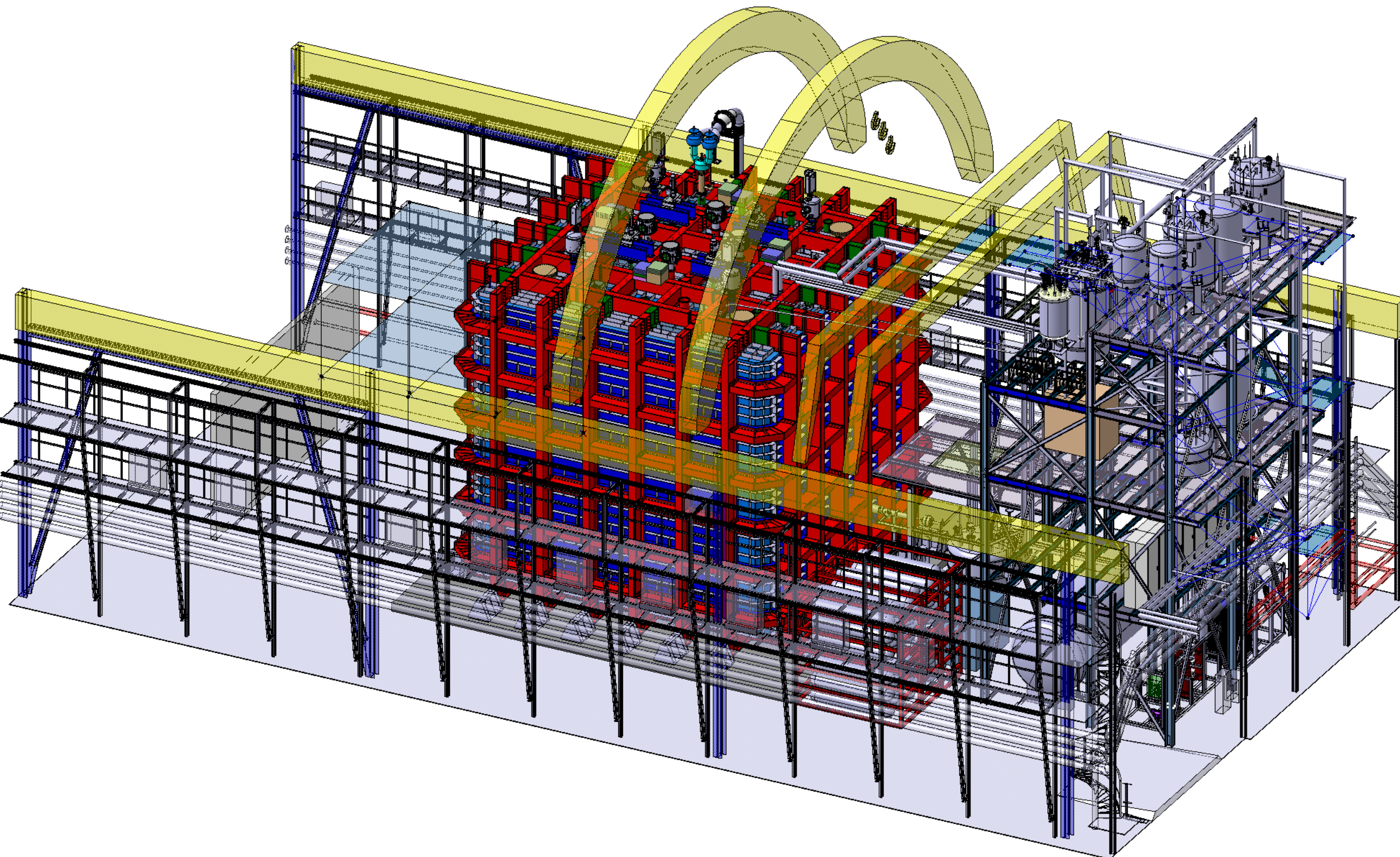


# LNGS as the Host Laboratory

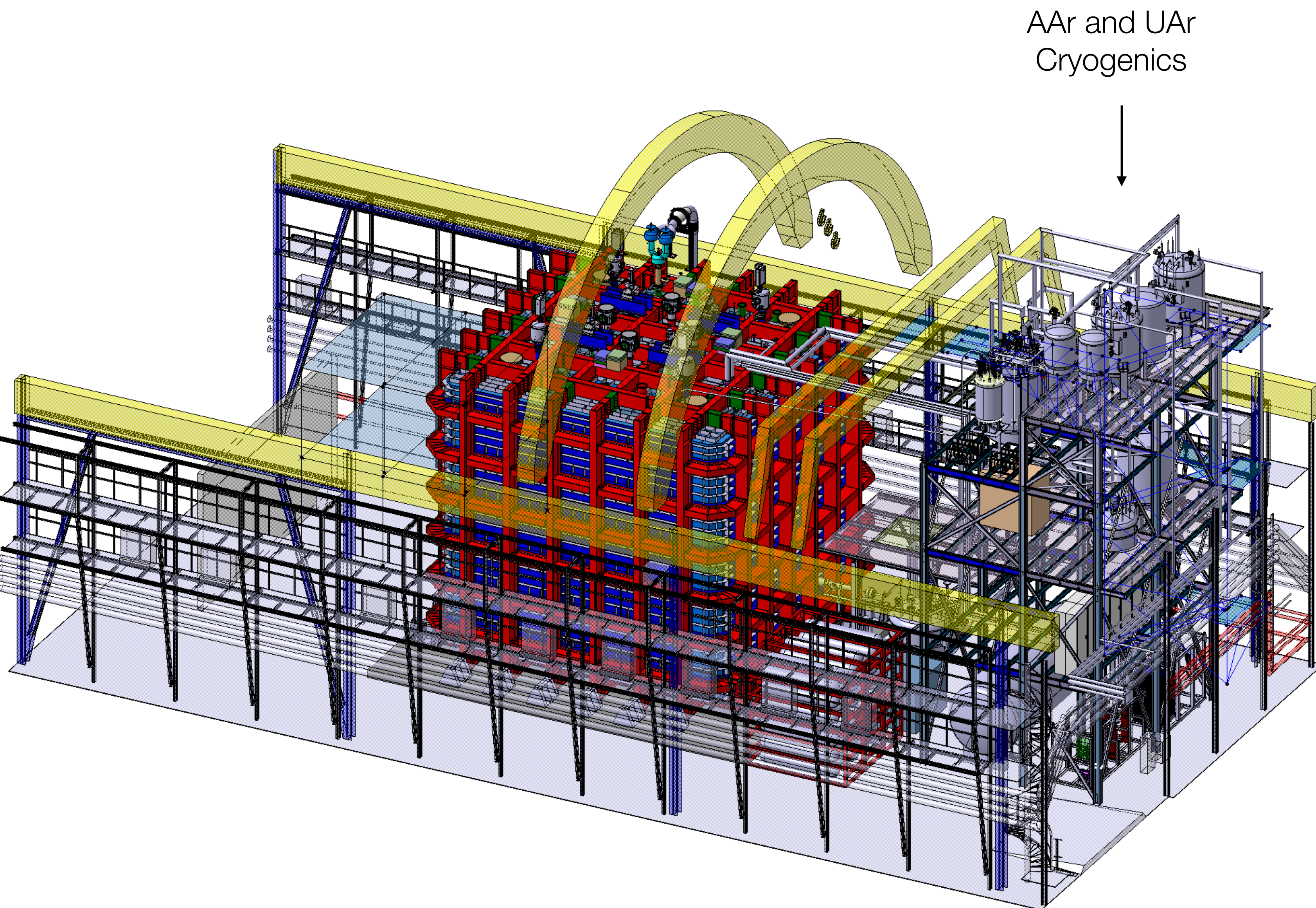
- Overburden of 3400 m.w.e.
- Muon flux reduced by  $\sim 10^6$



# DarkSide-20k in Hall C at LNGS



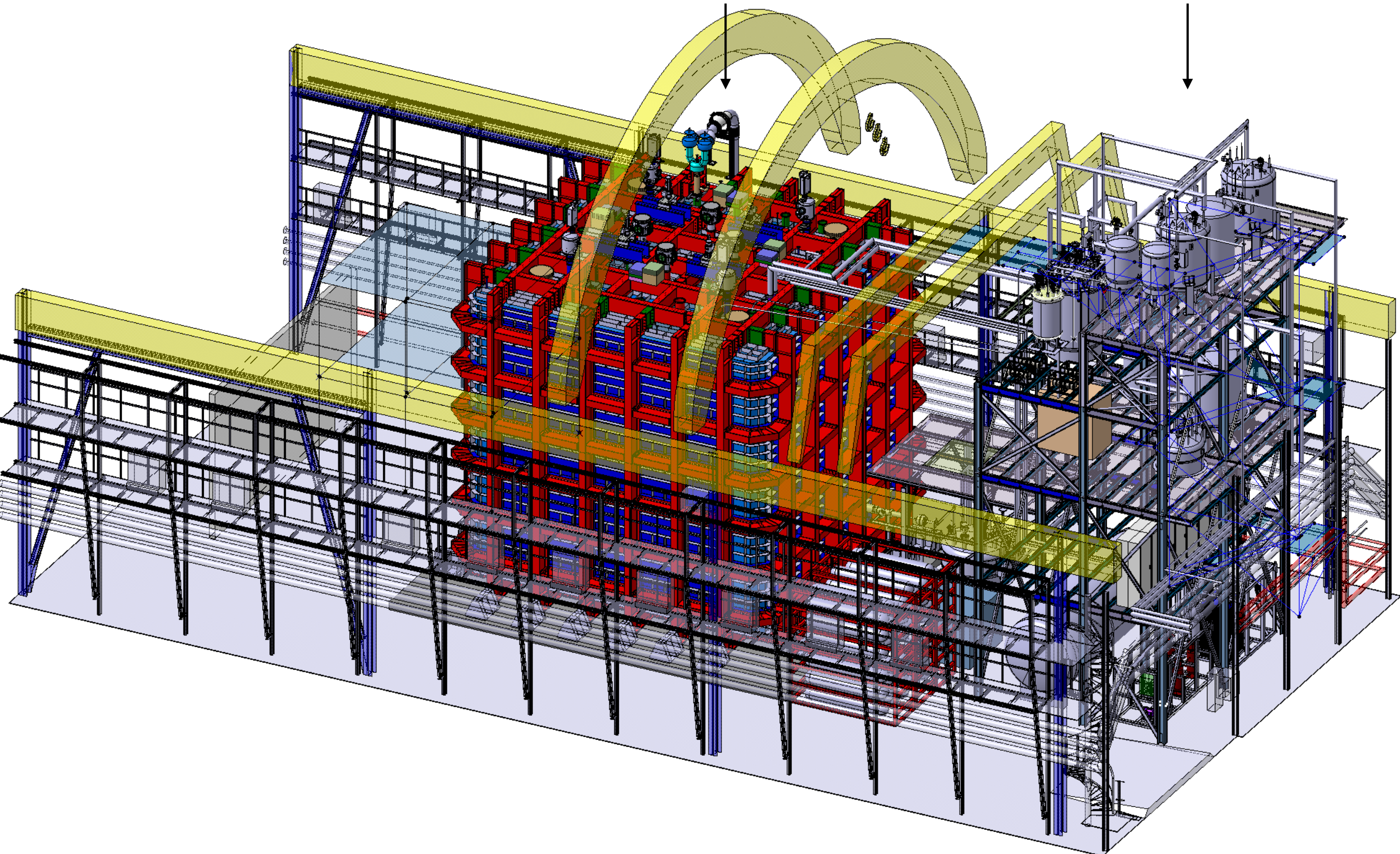
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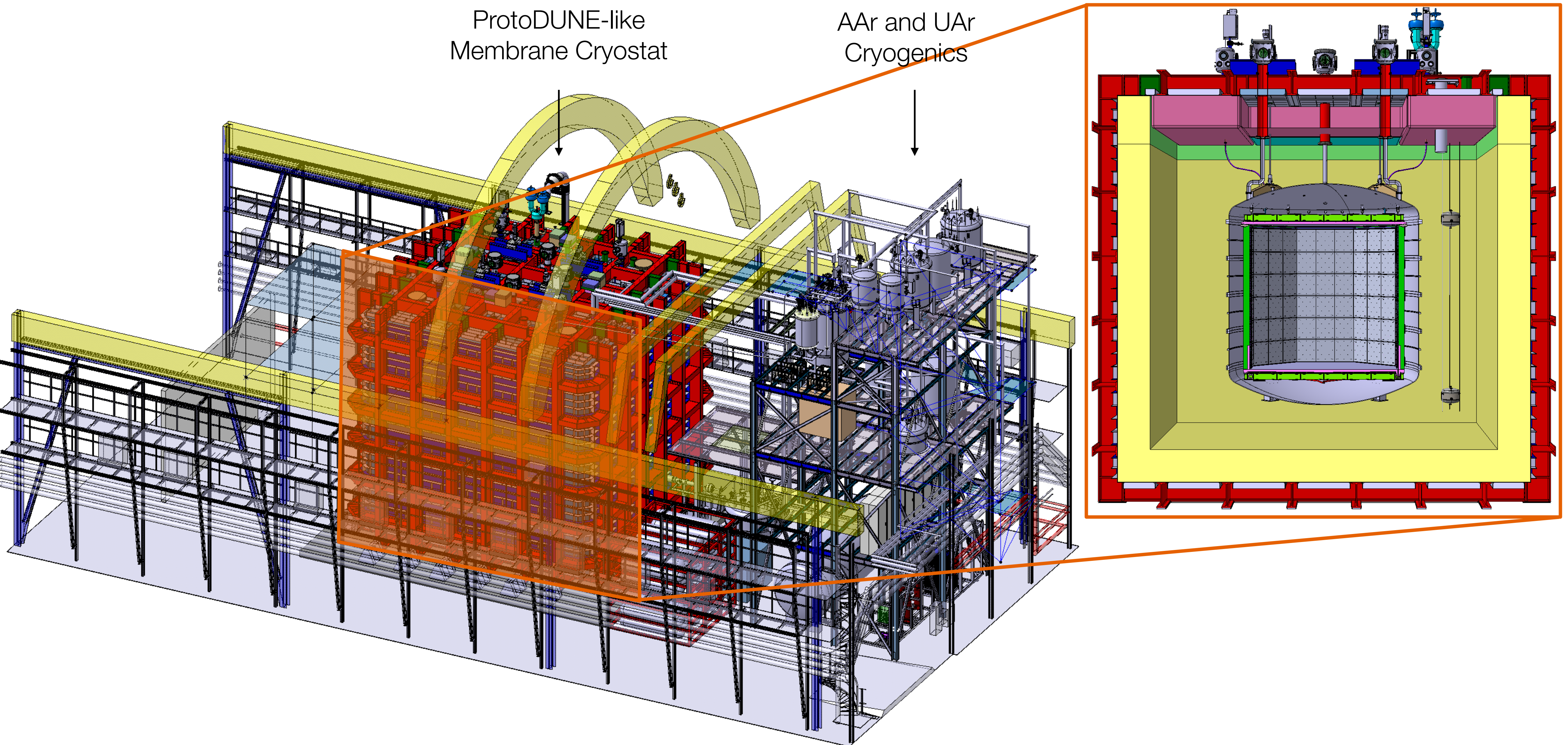
# DarkSide-20k in Hall C at LNGS

ProtoDUNE-like  
Membrane Cryostat

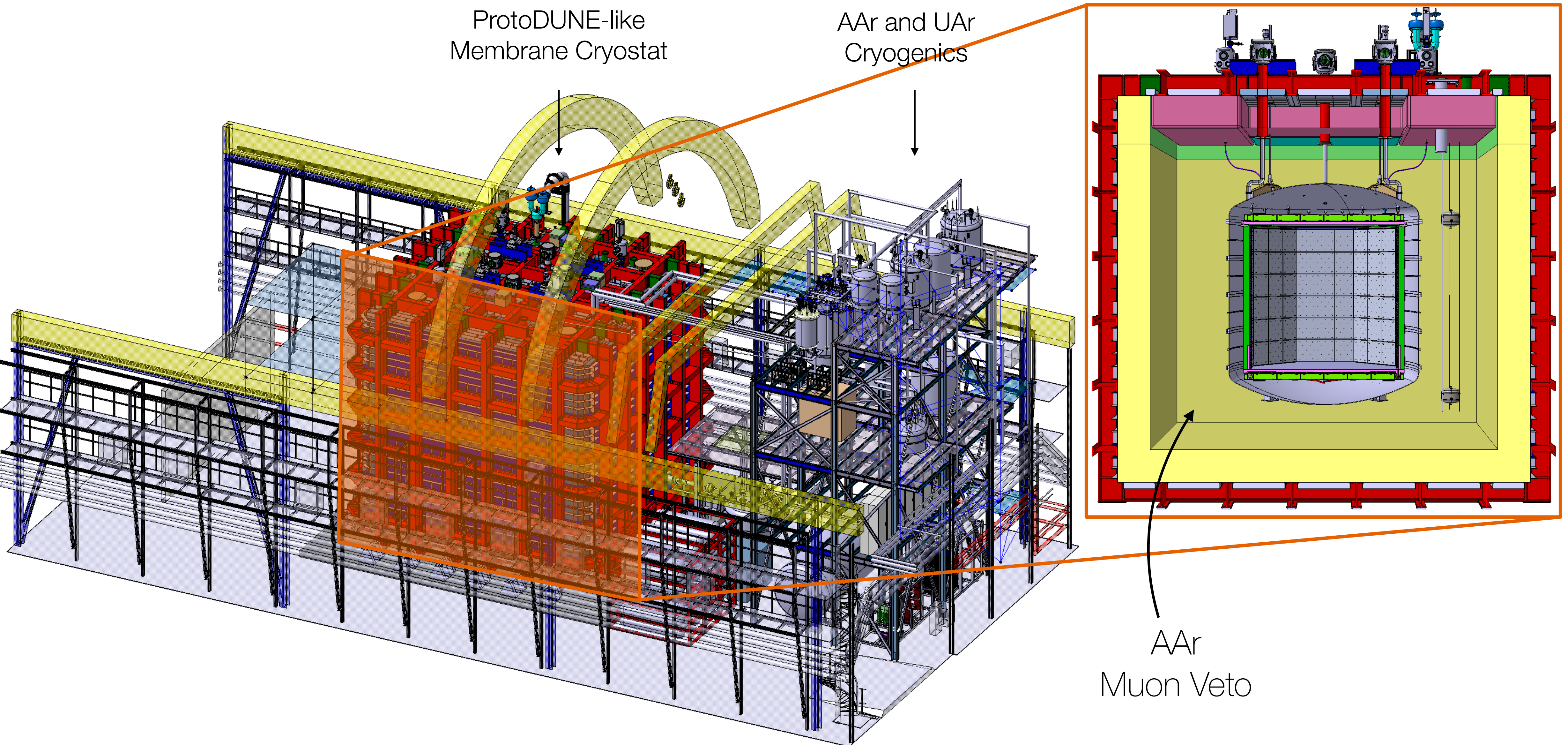
AAr and UAr  
Cryogenics



# DarkSide-20k in Hall C at LNGS



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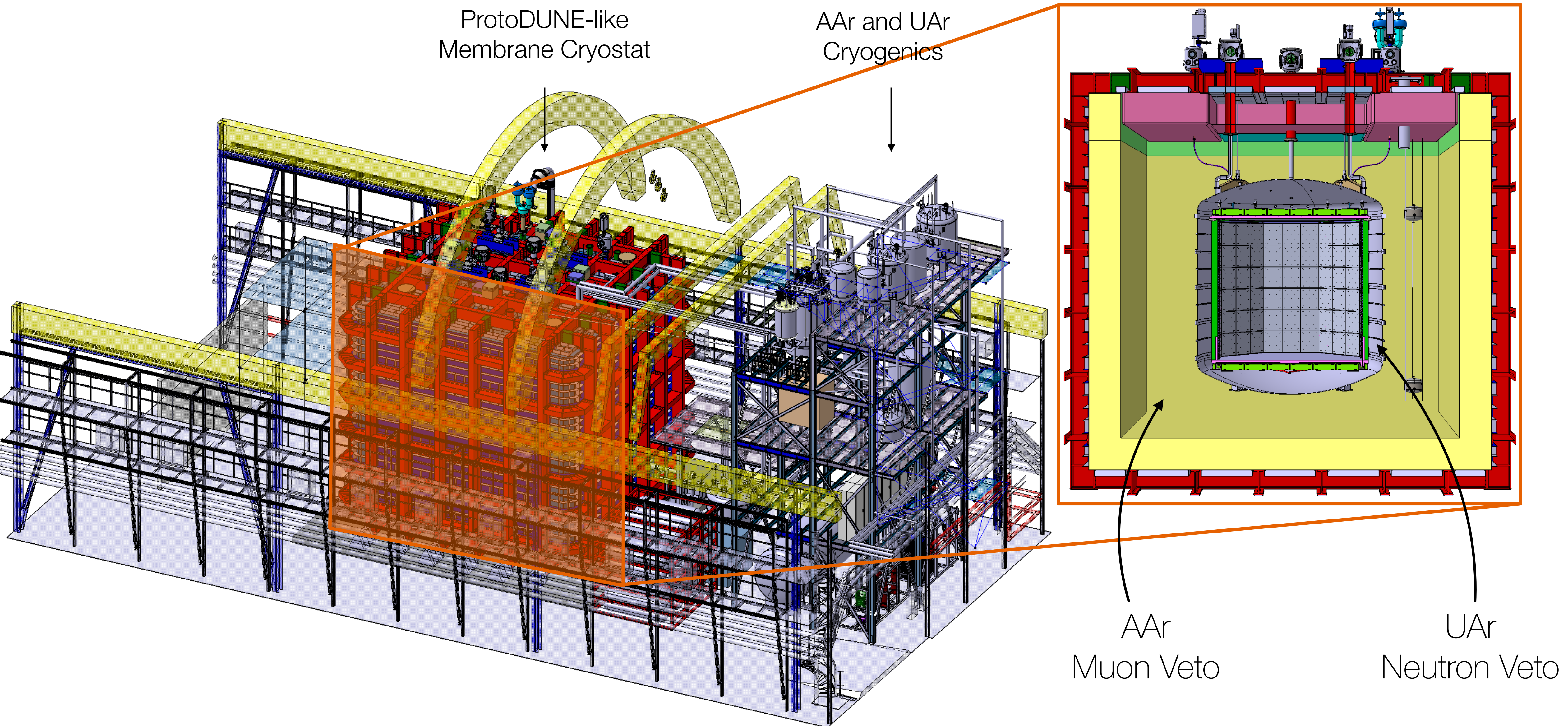
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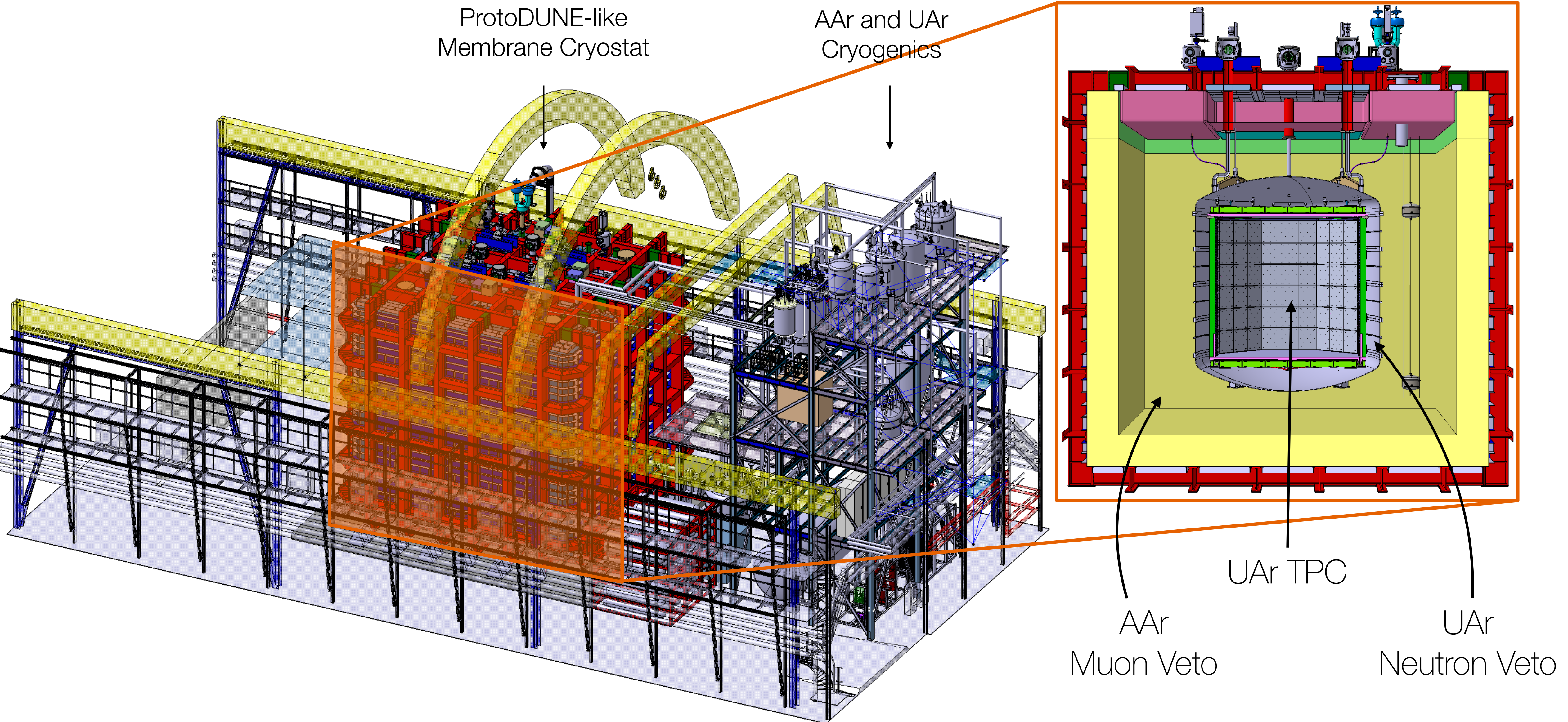
AAr  
Muon Veto



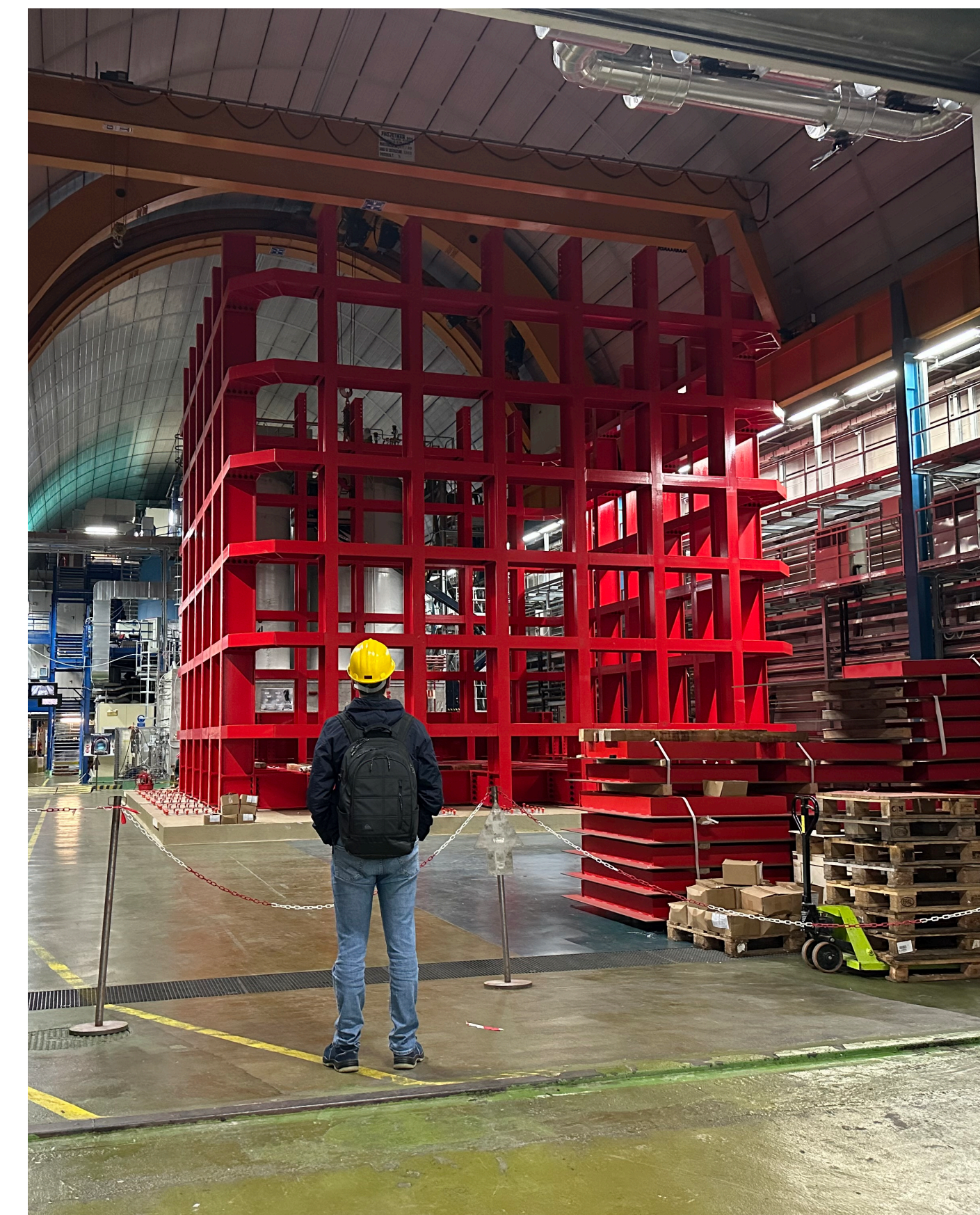
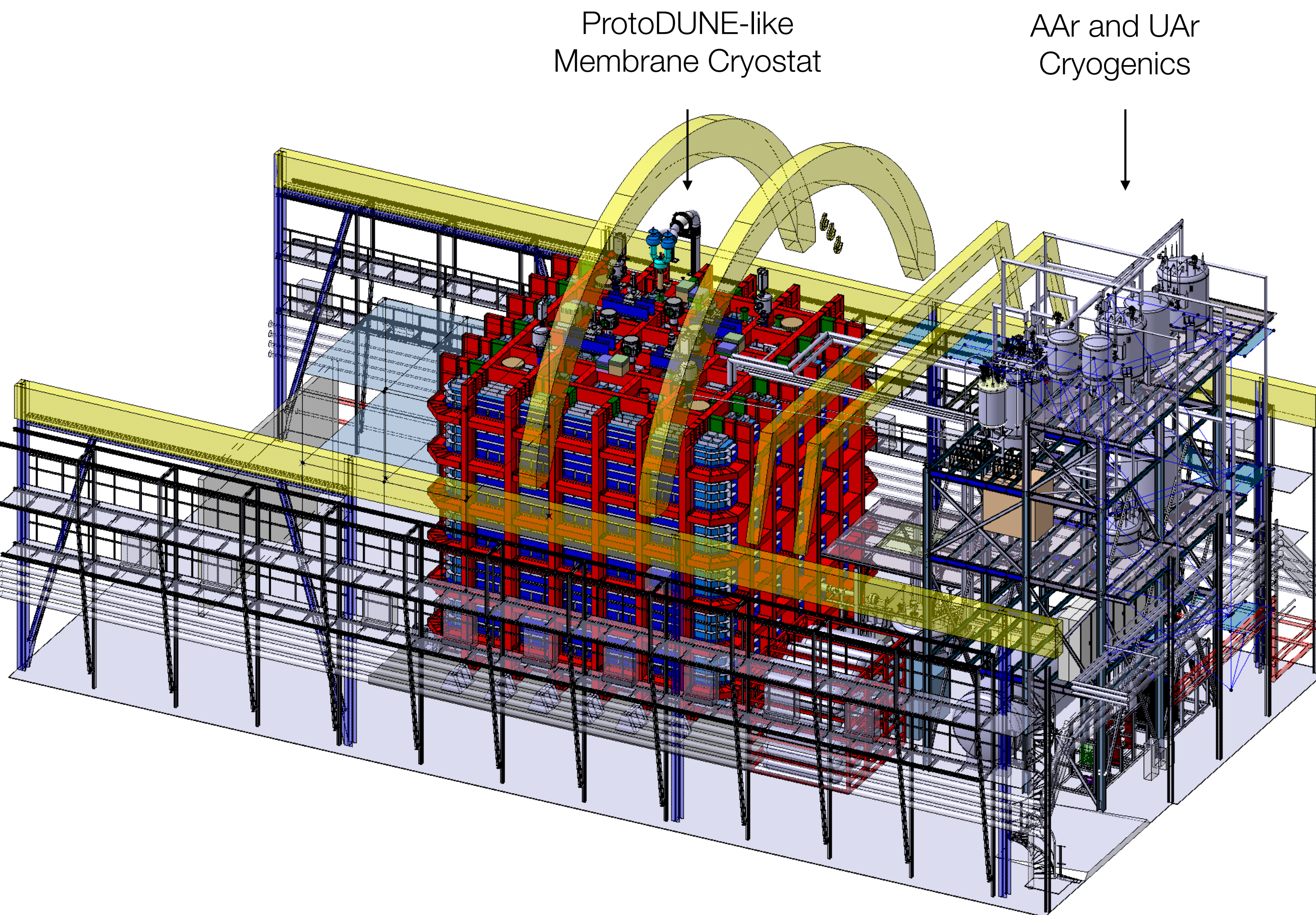
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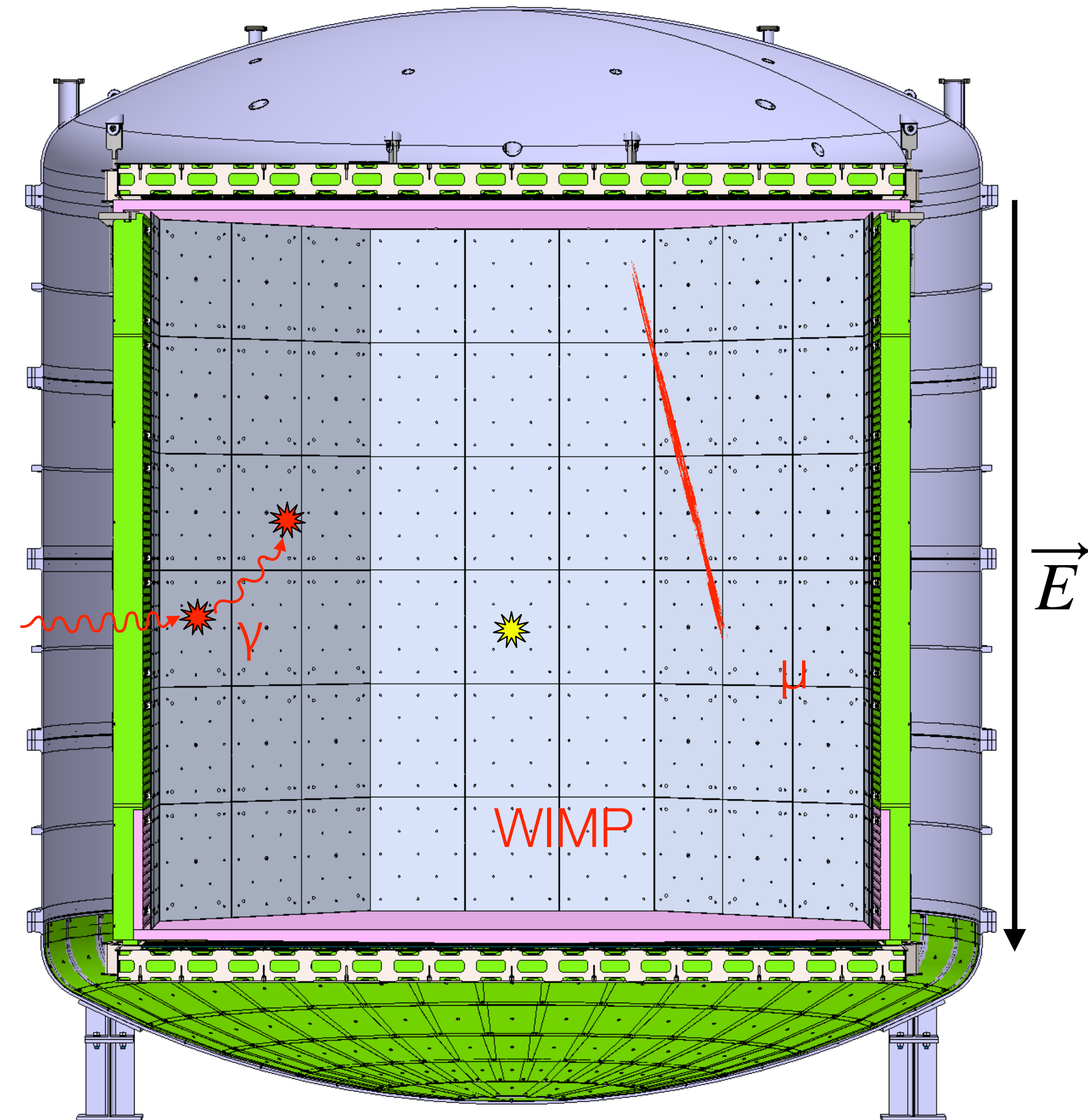


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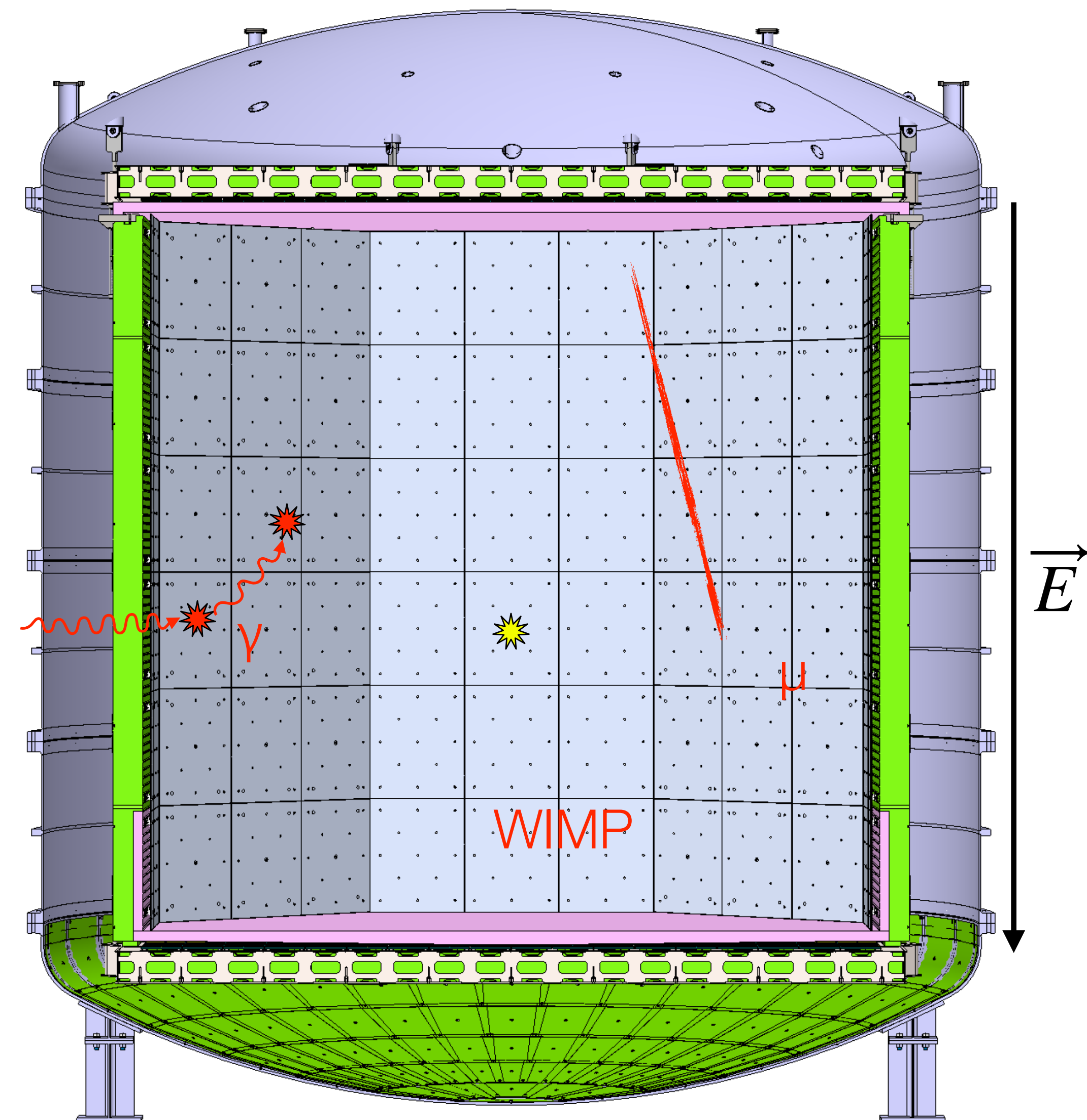
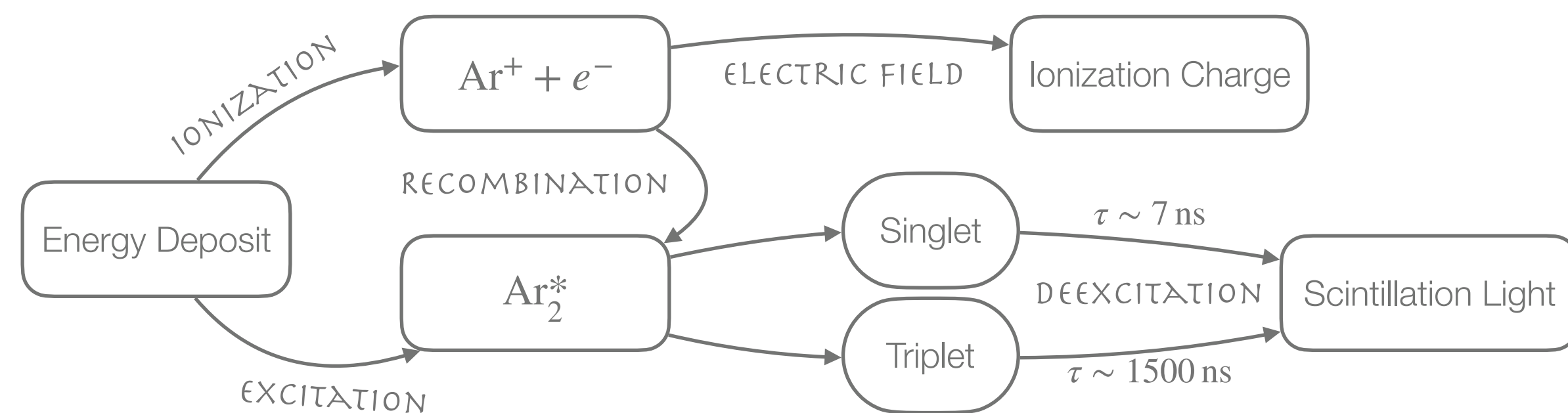
DarkSide-20k construction has begun!

# Liquid Argon Dual-Phase Time Projection Chamber



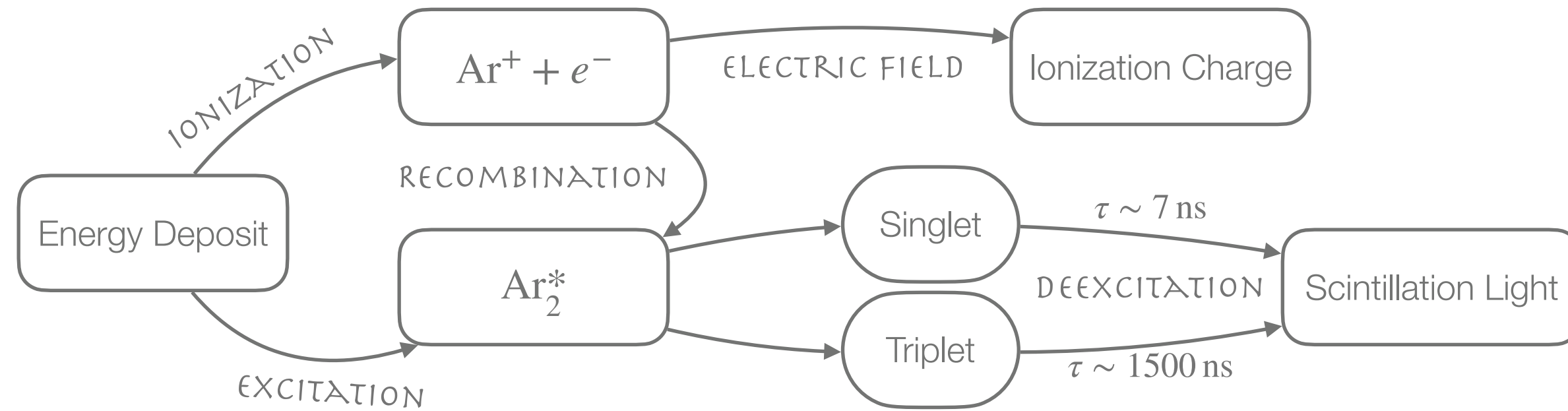
# Liquid Argon Dual-Phase Time Projection Chamber

- Ionizing radiation will either ionize or excite Xe atoms

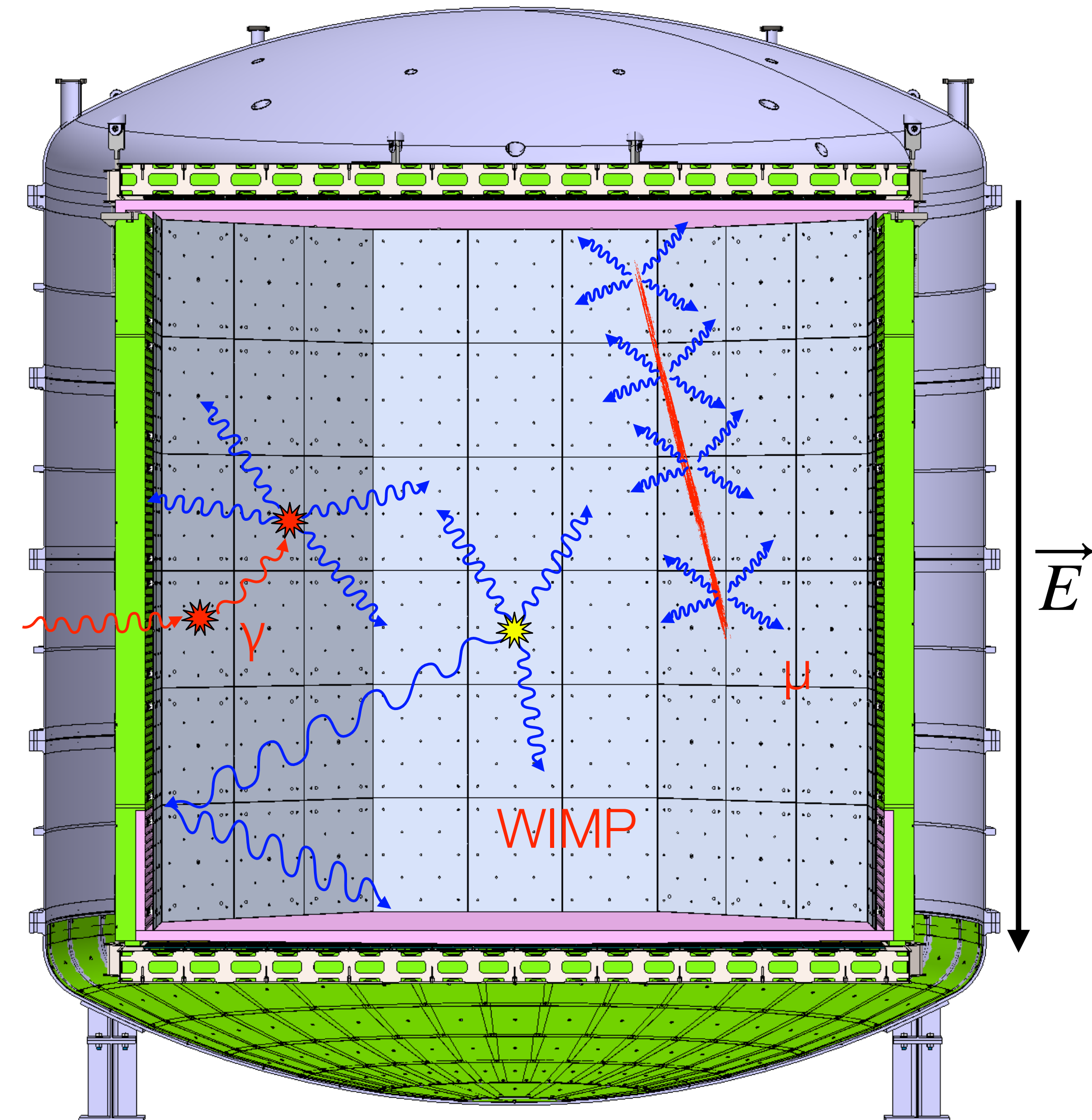
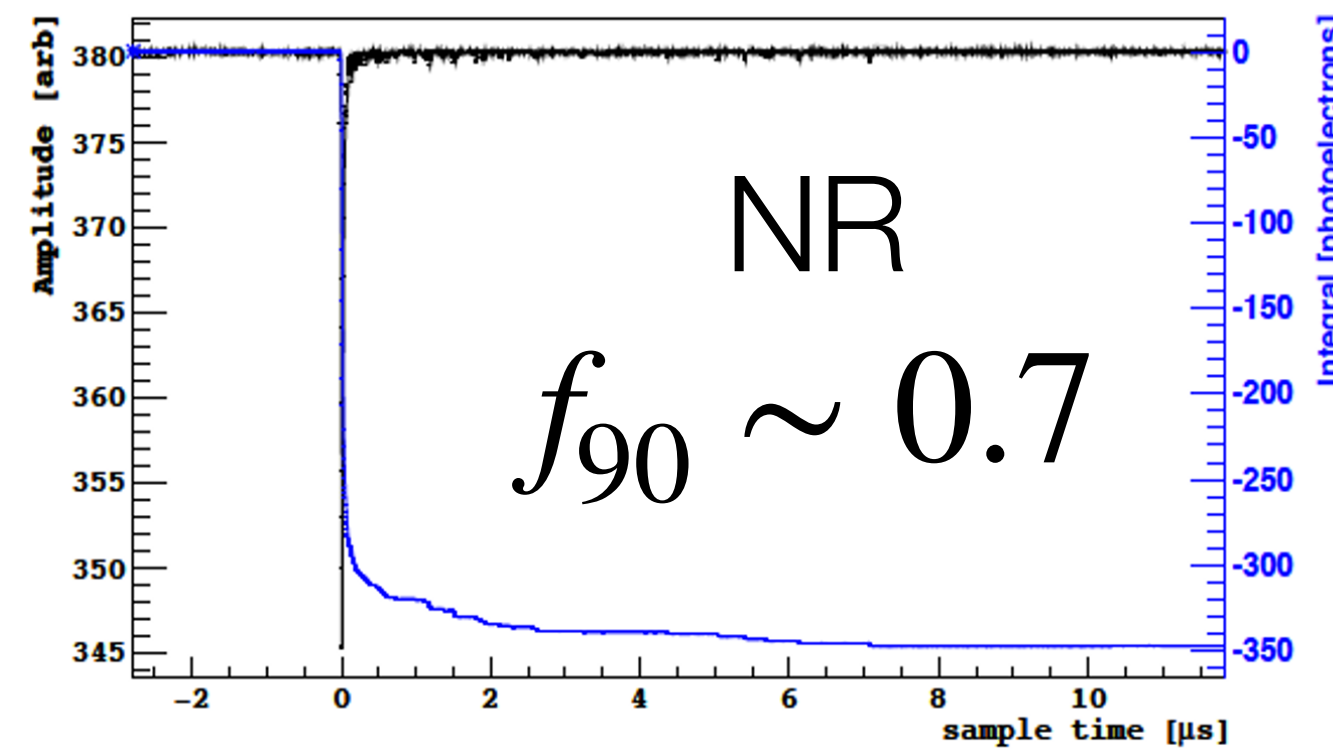
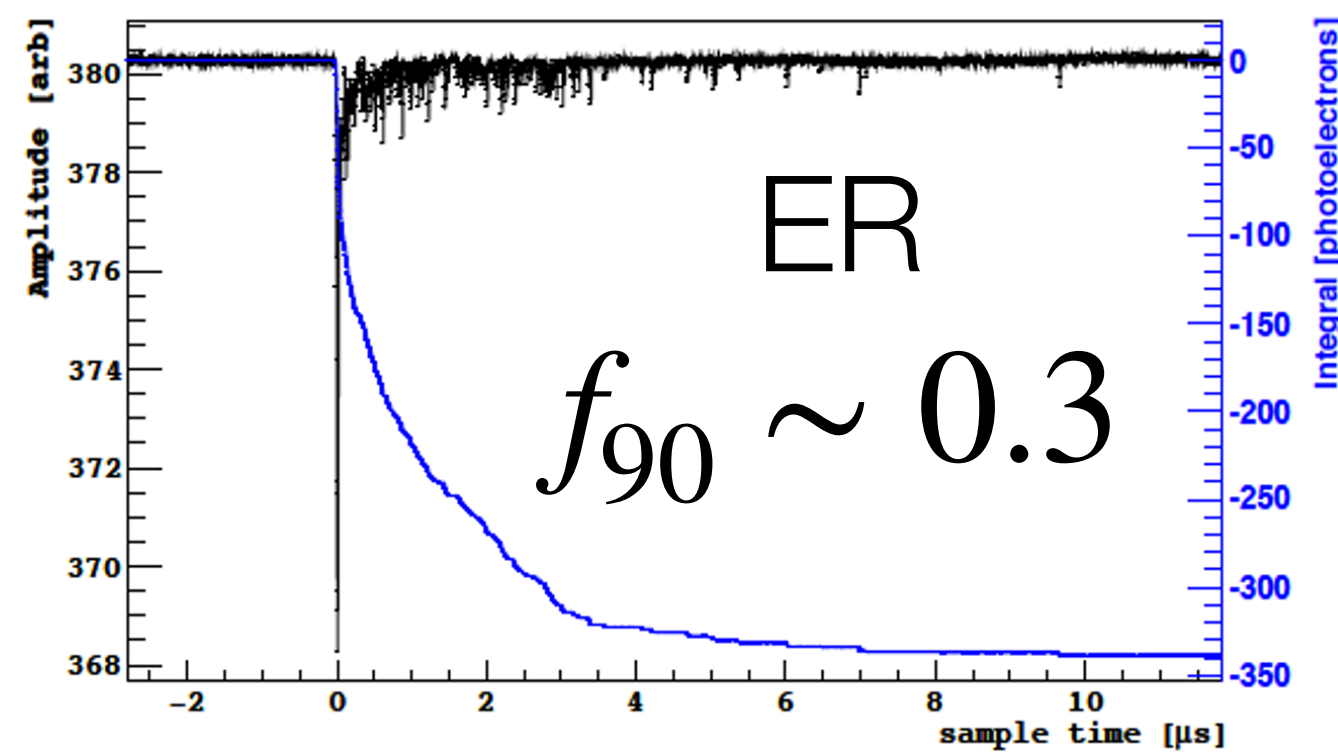


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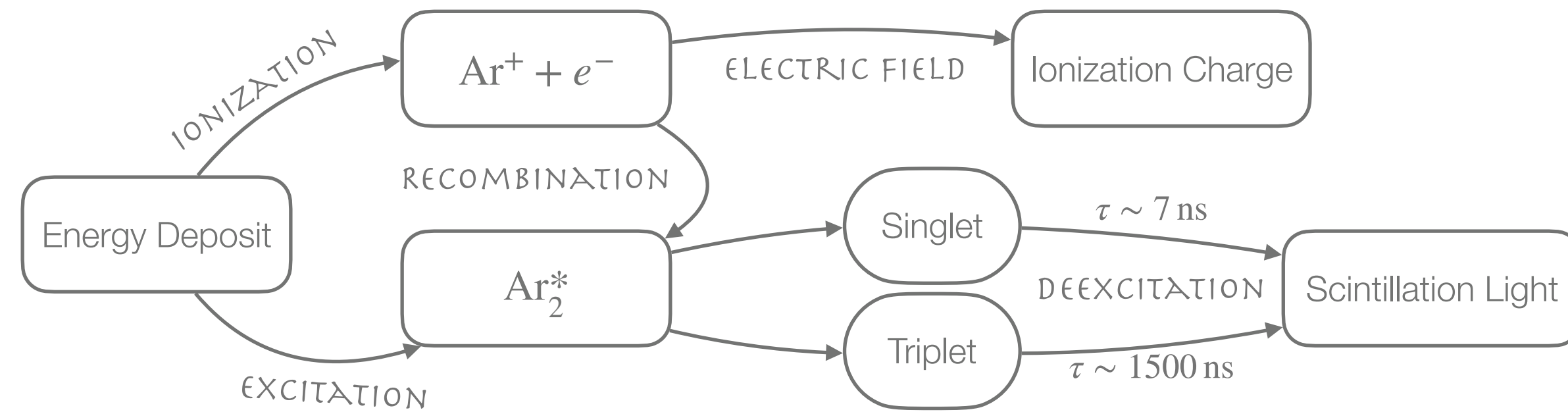


- Prompt scintillation photons (S1) are immediately detected by the optical planes

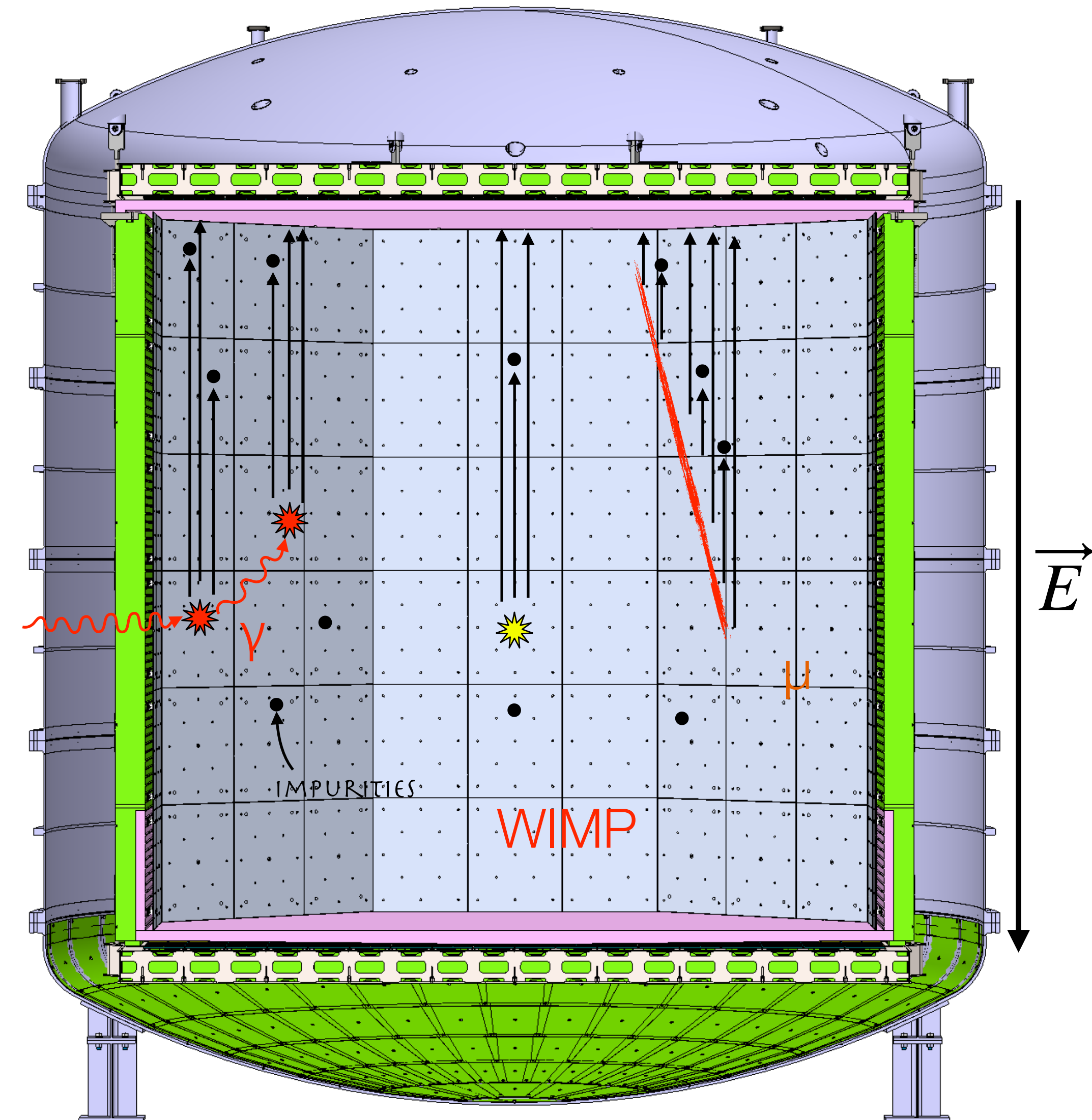


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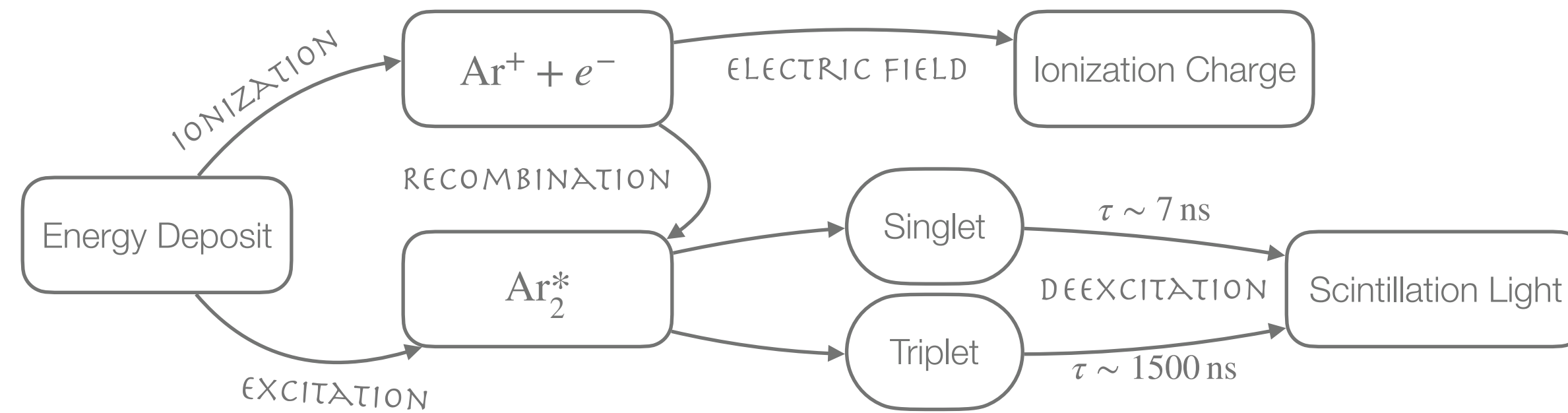


- Prompt scintillation photons (S1) are immediately detected by the optical planes
- Electrons are drifted towards the grid and extracted into the gas phase

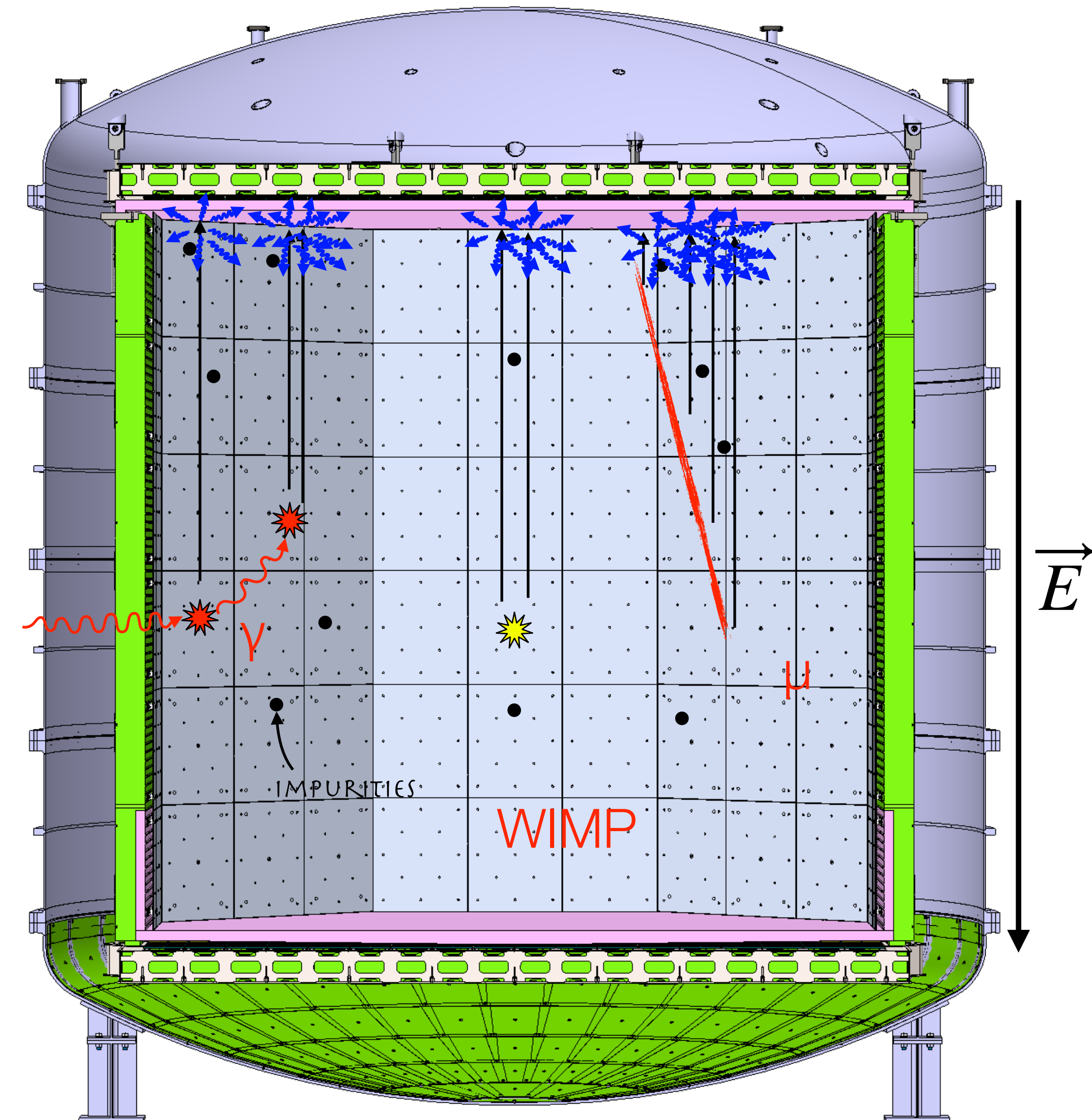


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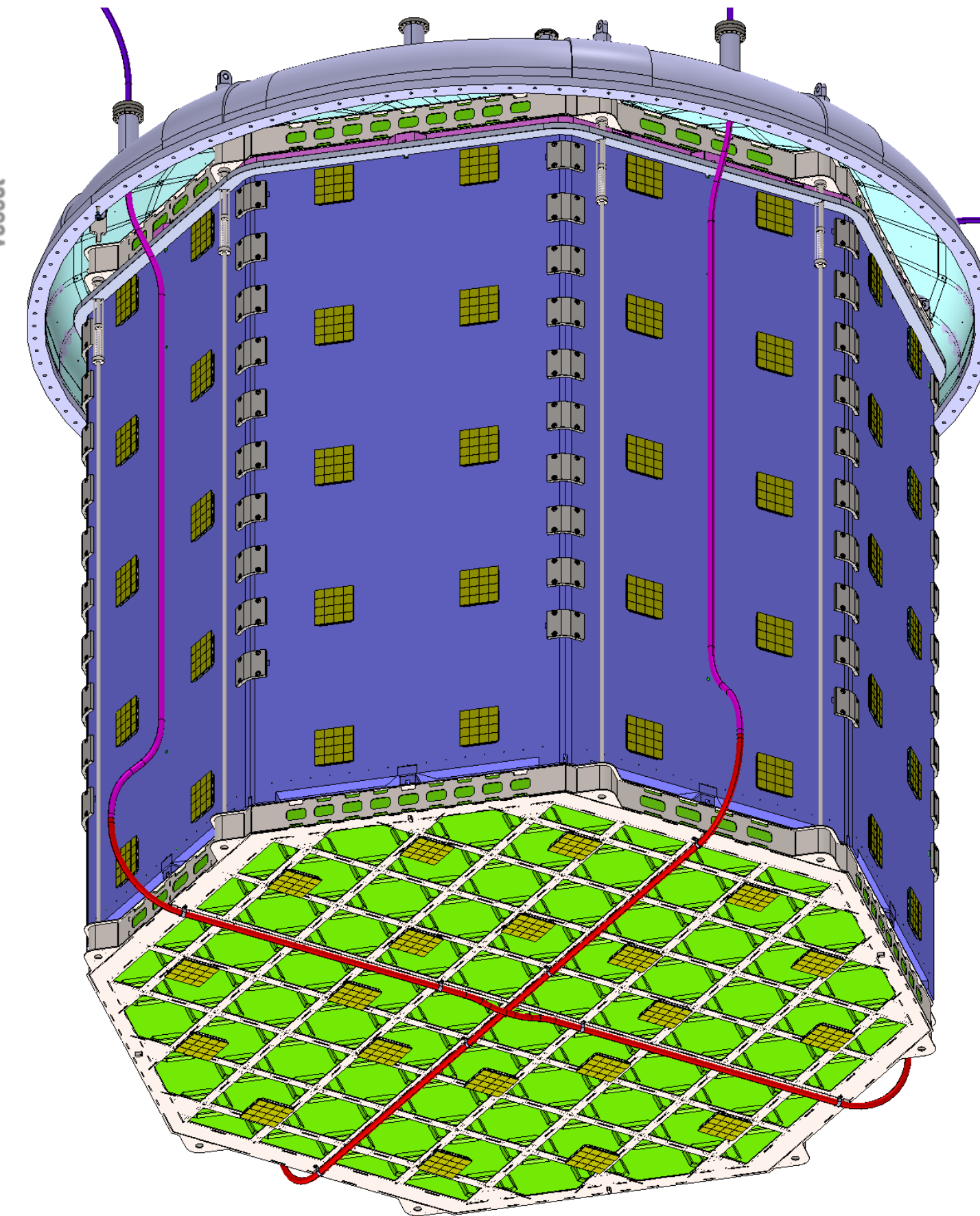
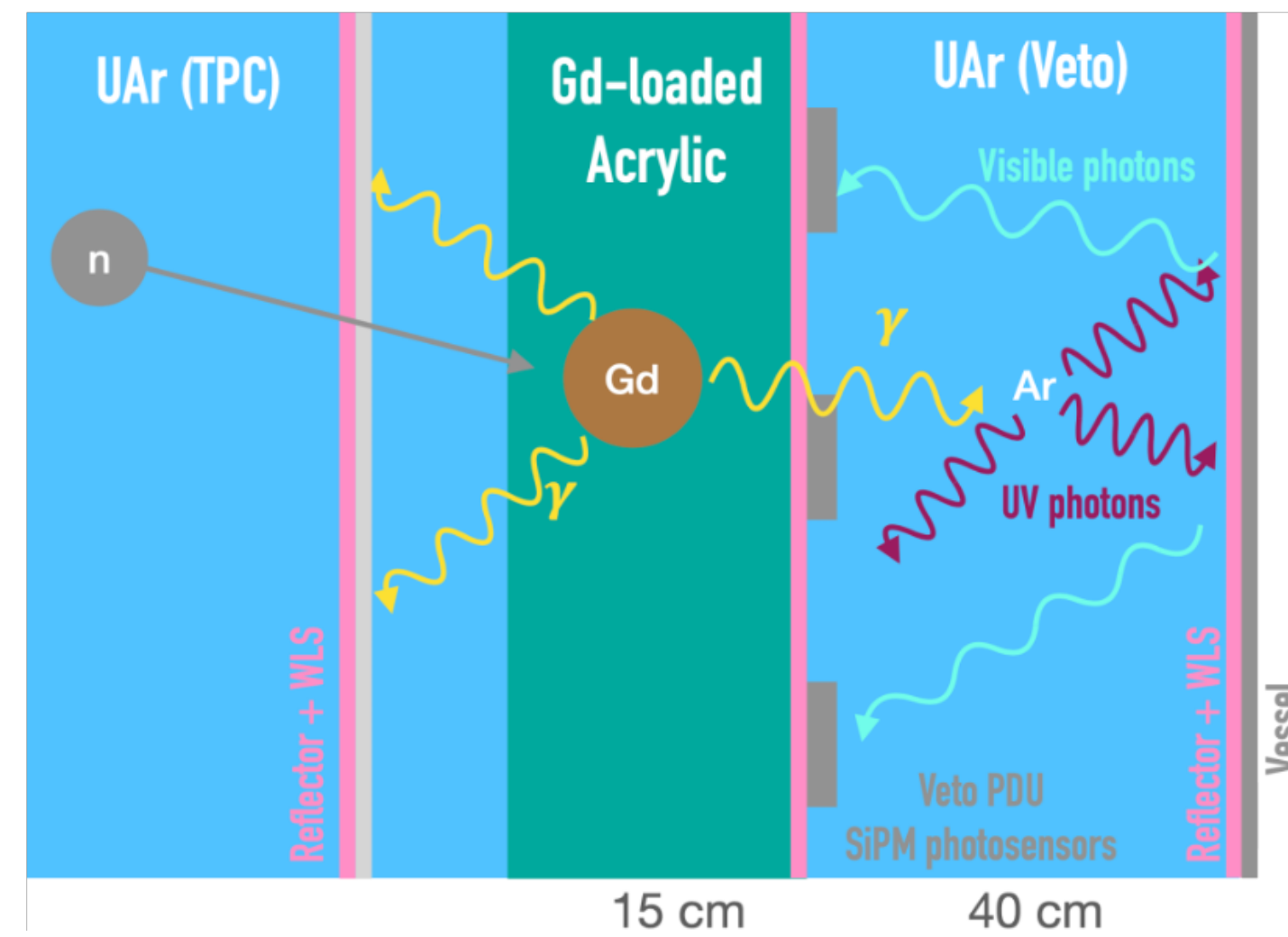
- Prompt scintillation photons (S1) are immediately detected by the optical planes
- Electrons are drifted towards the grid and extracted into the gas phase
- Accelerated electrons produce secondary electroluminescence photons (S2)
- Position resolution of  $\sim 1 \text{ cm}$  in XY and  $\sim 1 \text{ mm}$  in Z





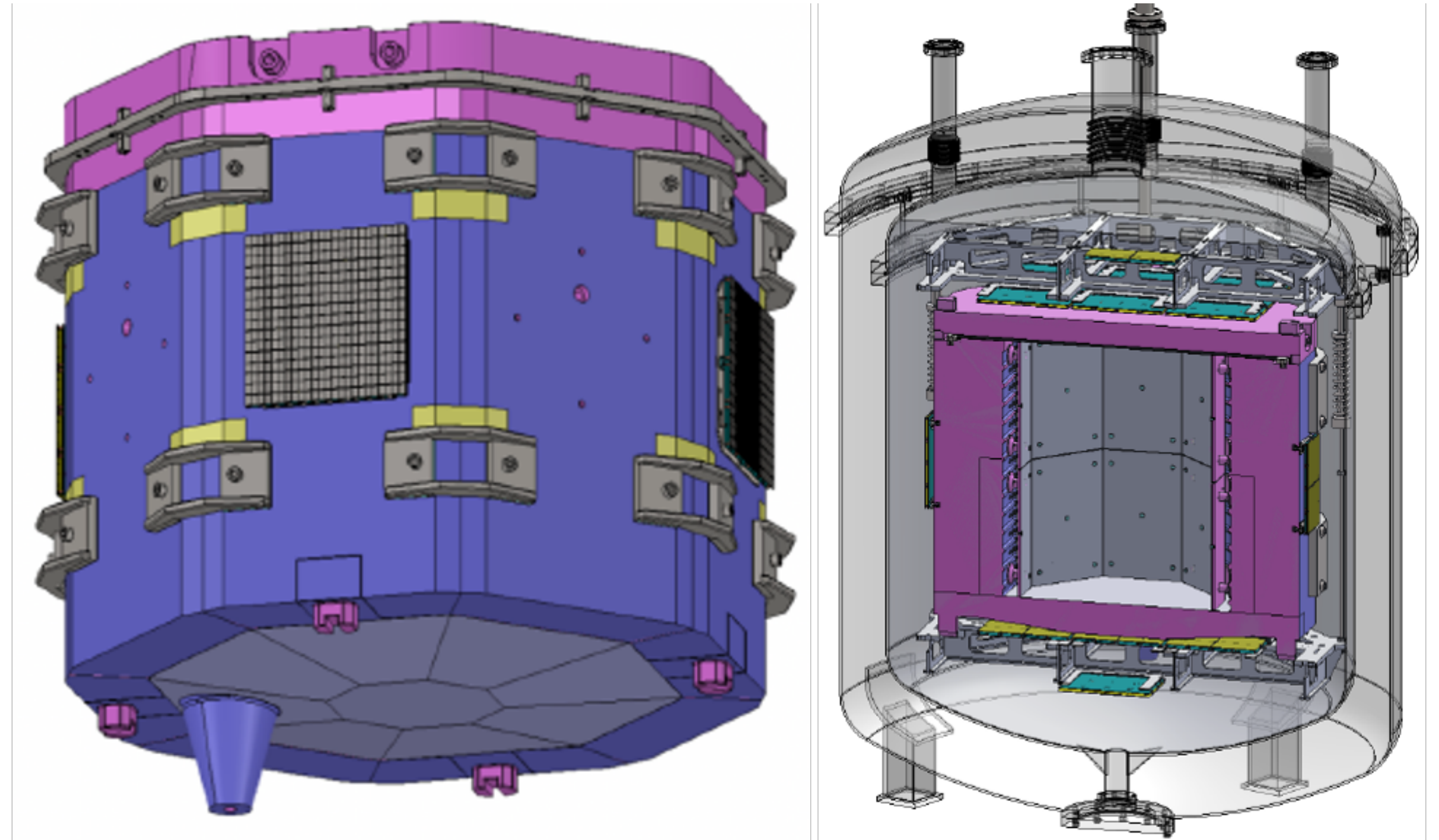
# Underground Argon Neutron Veto

- Neutrons are moderated by the PMMA and capture on gadolinium
- $\gamma$ -rays are emitted (totaling  $\approx 8$  MeV)
- VUV-photons from argon are wavelength shifted (PEN) in the veto region and detected by the veto photodetectors (vPDU)



# DarkSide Mockup

- Tonne-scale mechanical mockup of DS-20k to be installed in Hall-C in 2024
- Tests of collaboration process flow, i.e. PMMA work in Canada
- Tests of detector design, i.e.
  - cold cycling
  - gas pocket control
  - High voltage (HHV)
  - Clevios coating
  - service connections
- UAr cryogenic system assembled at LNGS



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MOCKUP CRYOSTAT








CONDENSER BOX

# Backgrounds and Mitigation Strategies




## Electron Recoils (ER)

- $^{39}\text{Ar}$   $\beta$ -decays 
- $\gamma$ -decays from 
  - $^{238}\text{U}$  and  $^{232}\text{Th}$
  - $^{40}\text{K}$ ,  $^{60}\text{Co}$ ,  $^{137}\text{Cs}$
- $\nu - e$  scattering of solar neutrinos 

## Nuclear Recoils (NR)

- Radiogenic neutrons 
- $(\alpha, n)$ -reactions 
- $^{238}\text{U}$  fission 
- Cosmogenic neutrons 
- CEvNS from atmospheric neutrinos 

## Random Coincidences

- $\alpha$  + S2 coincidence 
- Corr. ER + Cherenkov 
- Uncorr. ER + Cherenkov 

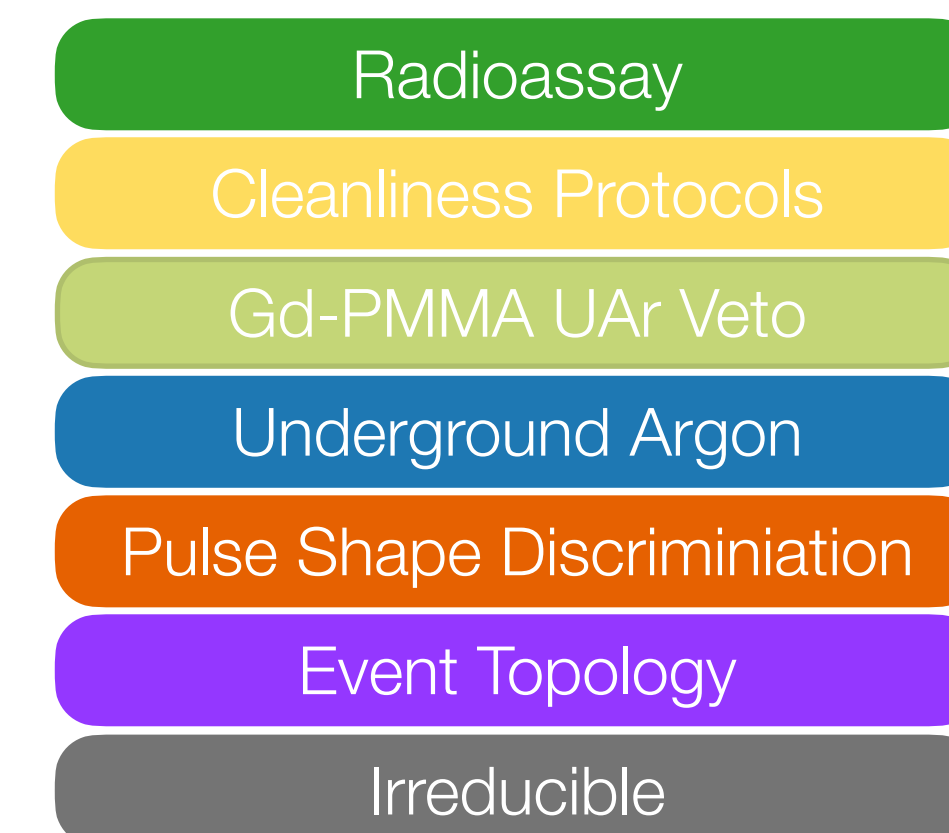
## Radon

- Neutrons from  $^{222}\text{Rn}$  diffusion and surface plate-out 

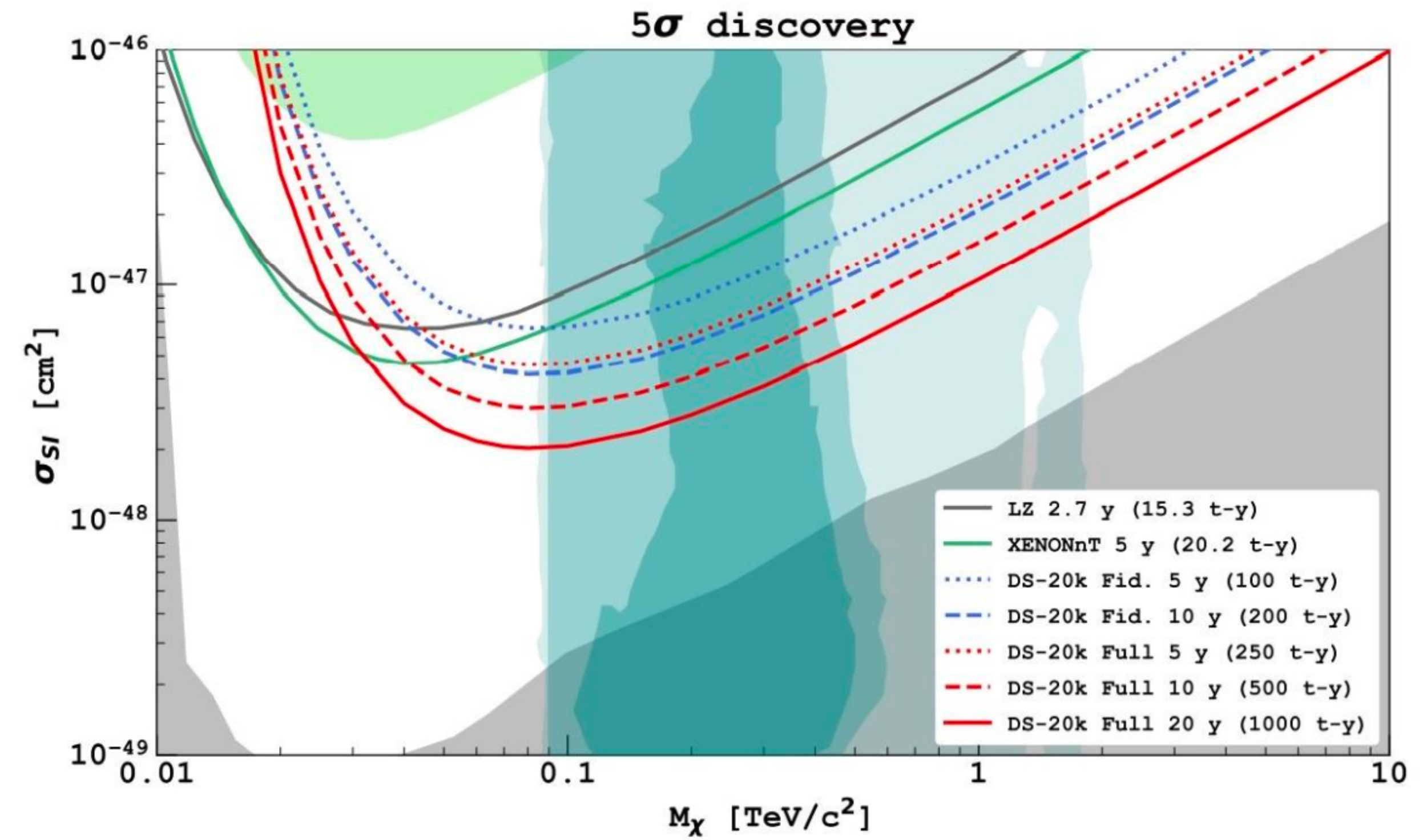
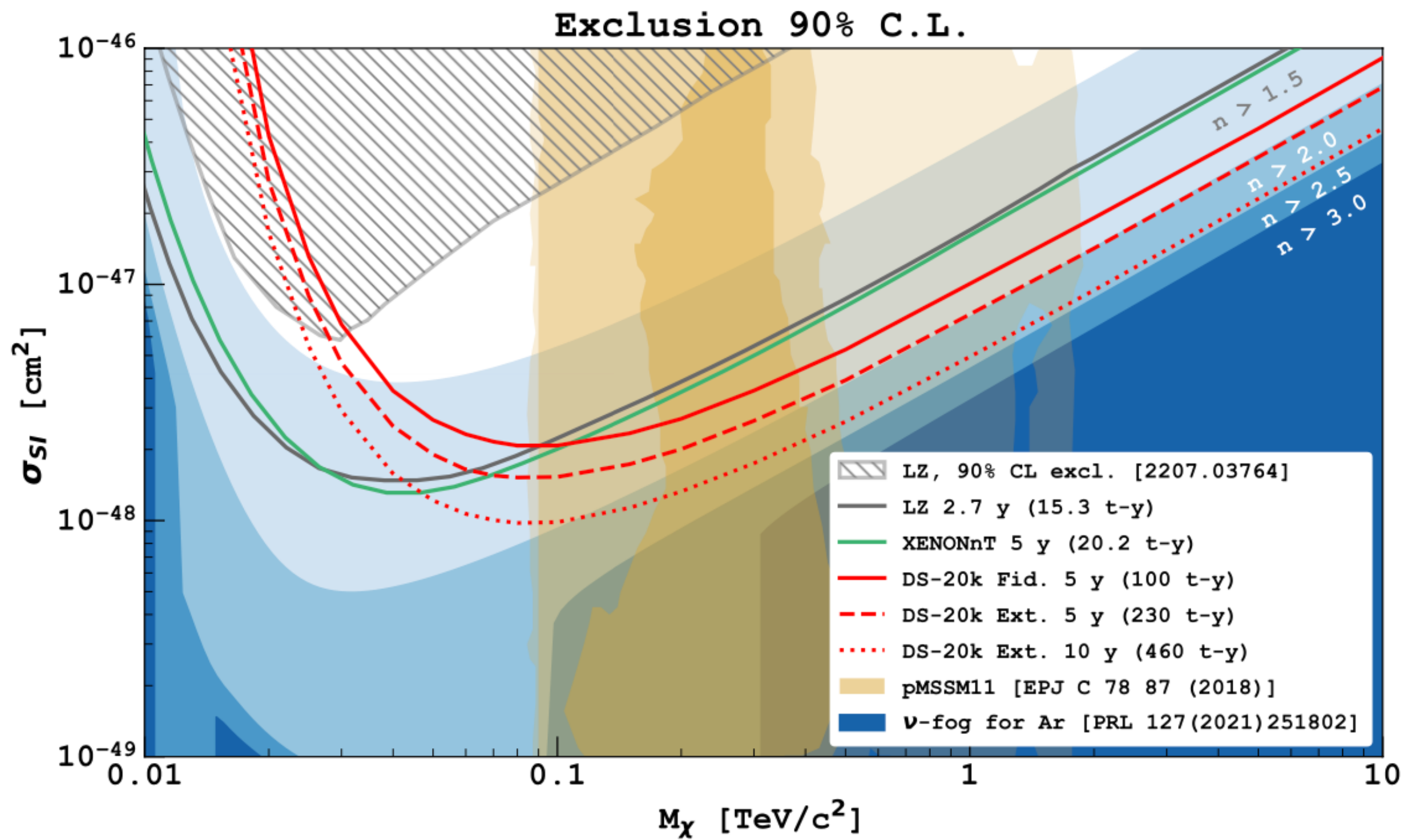
Background type	Bg events in ROI [200 t yr] <sup>-1</sup>
$(\alpha, n)$ neutrons from U and Th	$9.5 \times 10^{-2}$
Fission neutrons from U-238	$< 2.3 \times 10^{-3}$
Neutrons from Rn-222 diffusion and surface plate-out	$< 1.4 \times 10^{-2}$
Cosmogenic neutrons	$< 6.0 \times 10^{-1}$
Neutrons from the lab rock	$1.5 \times 10^{-2}$
Random surface $\alpha$ decay + S2 coincidence	$< 5.0 \times 10^{-2}$
Correlated ER + Cherenkov	$< 1.8 \times 10^{-2}$
Uncorrelated ER + Cherenkov	$< 3.0 \times 10^{-2}$
ER	$< 1.0 \times 10^{-1}$

→ Less than 1 cts of instrumental background over 200 t yr within (30 – 200) keV<sub>nr</sub>

+3.2 cts from CEvNS (irreducible)



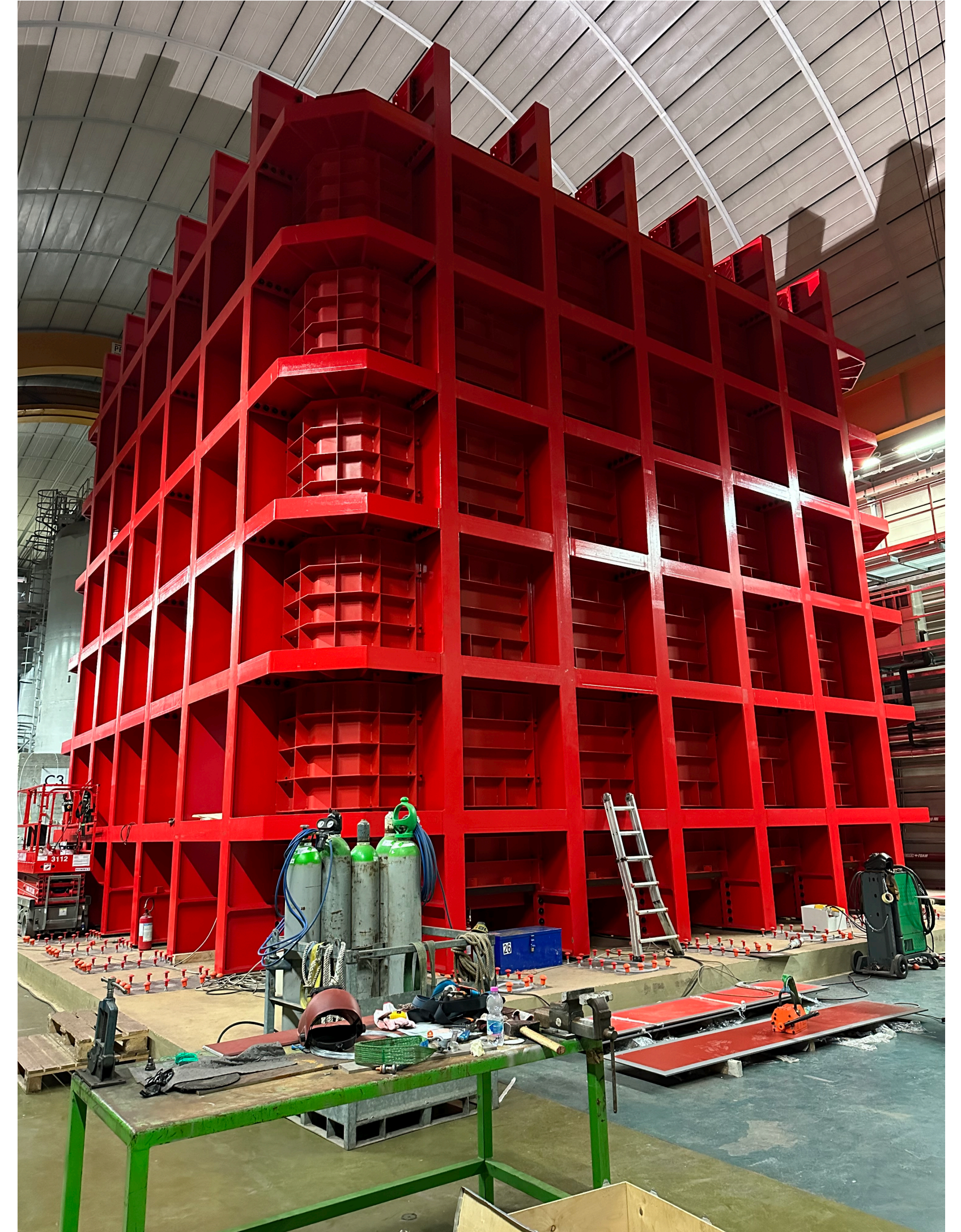
# DS-20k Projected Sensitivity



*Unprecedented sensitivity to high-mass WIMP dark matter!*

# Summary

- DarkSide-20k: dual-phase time projection chamber (TPC) for direct dark matter searches
- Industrial scale extraction of UAr
- Gd-loaded PMMA panels will form the TPC mechanical structure (barrel)
- TPC design is in an advanced stage and the assembly procedure is being finalized
- Mechanical mockup testing scheduled to take place at LNGS mid-next year
- SiPM readout advanced to the final production design
- Aria has shown the first results of isotopic separation in argon
- The construction of the ProtoDUNE-like has begun earlier this year





GADMC COLLABORATION MEETING  
LNCS  
JUNE 2023