Boosted Dark Matter Searches with Super-Kamiokande

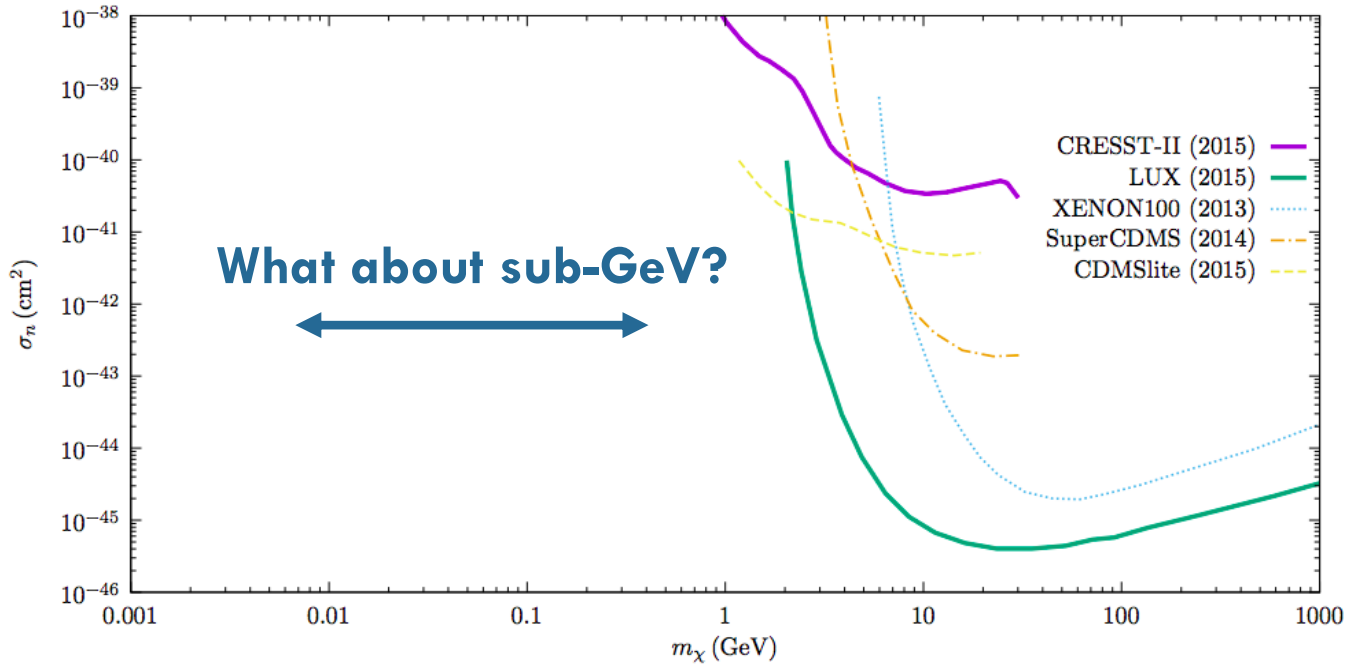
Nadège IOVINE

Motivation

No convincing signal from **dark matter** observed so far

Strong constraints set by various experiments for **WIMP-like dark matter scenarios**

The region **below 1 GeV** remains **largely unexplored**



Most efforts to push limits down

Sub-GeV Dark Matter

Focus on dark matter masses **below GeV-scale**

$$\Omega_{DM} \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_{DM}^2}{g_{DM}^4}$$

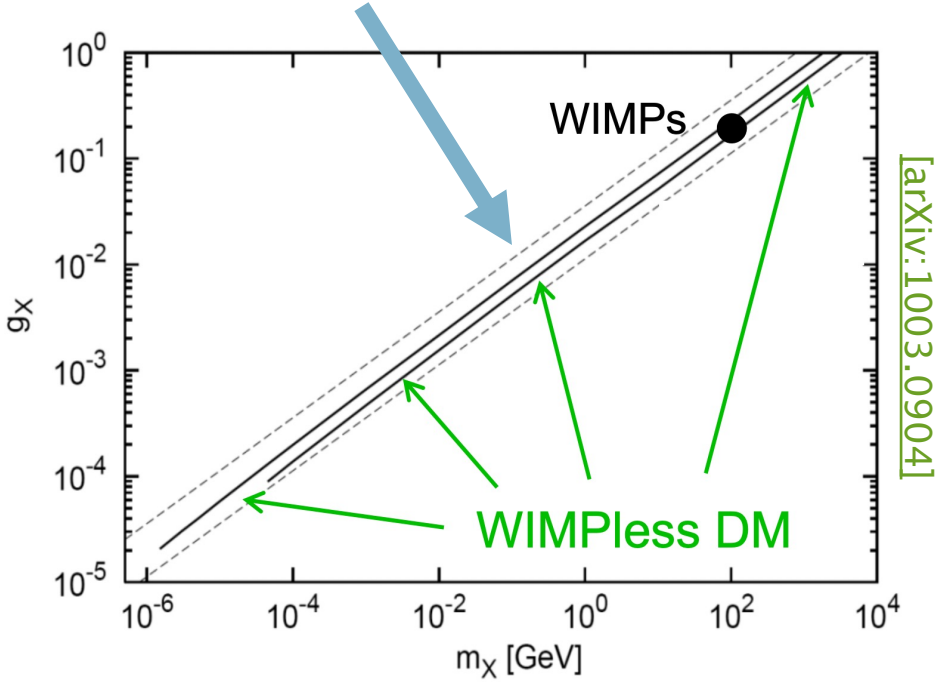
"WIMP-less Miracle"

- Low-mass DM could also be **thermal relic candidates**
- Ω_{DM} only constraints the **mass-coupling ratio**

  → **Wide range** of masses and couplings is **allowed**
- Hard to detect due to **low coupling**

  → Introduction of **boosting mechanism**

  → Sub-GeV DM **detectable by current experiments**



[arXiv:1003.0904]

Boosted Dark Matter

Boosted Dark Matter could **knock nucleons and electrons out** of atoms

Several possible boosting mechanism

- **Two-component dark matter** scenario

  Dominant DM component A not coupled to SM

  → Annihilate or decay into **lighter DM particle B**

  → **Naturally boosted** dark matter

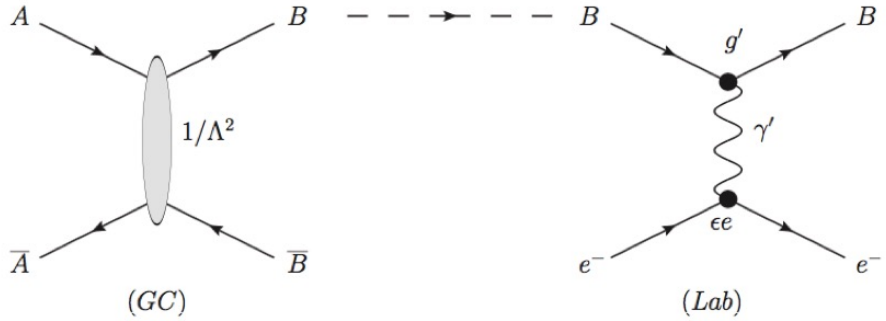
- **Cosmic-ray-boosted** dark matter

  Dark matter **up-scattered by cosmic-rays**

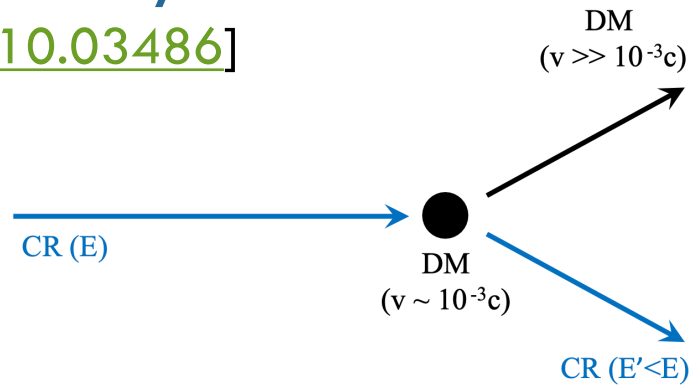
  → Boosted to **relativistic energies**

- …

Two-component boosted DM
[1405.7370]



Cosmic ray boosted DM
[1610.03486]



The Super-Kamiokande Detector

Underground Cherenkov Detector (50 kT)

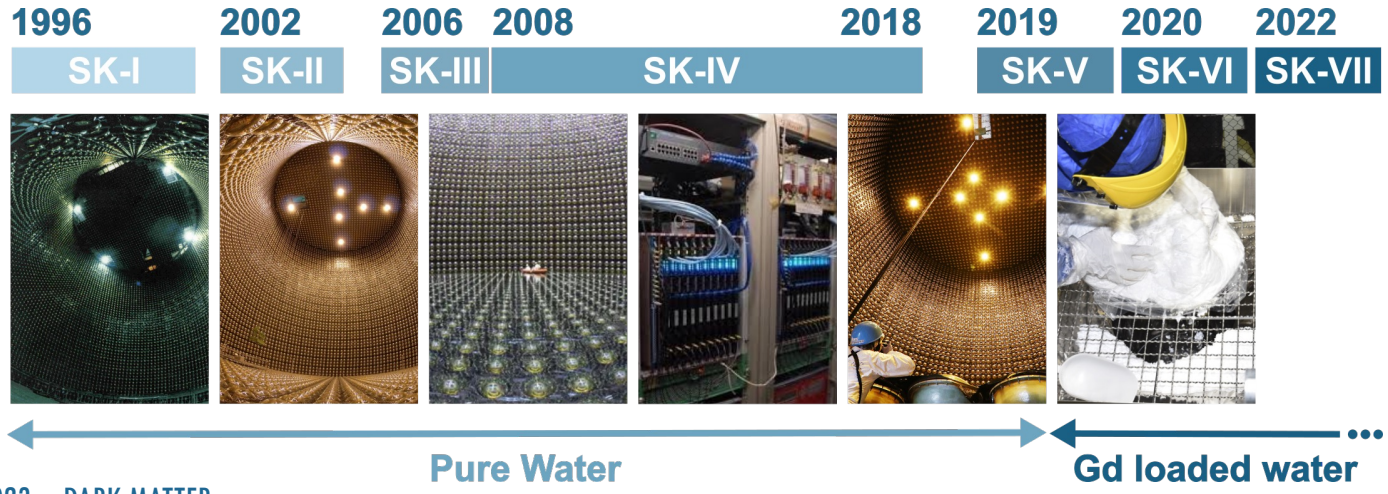
2700 m.w.e overburden shielding it from Cosmic Ray

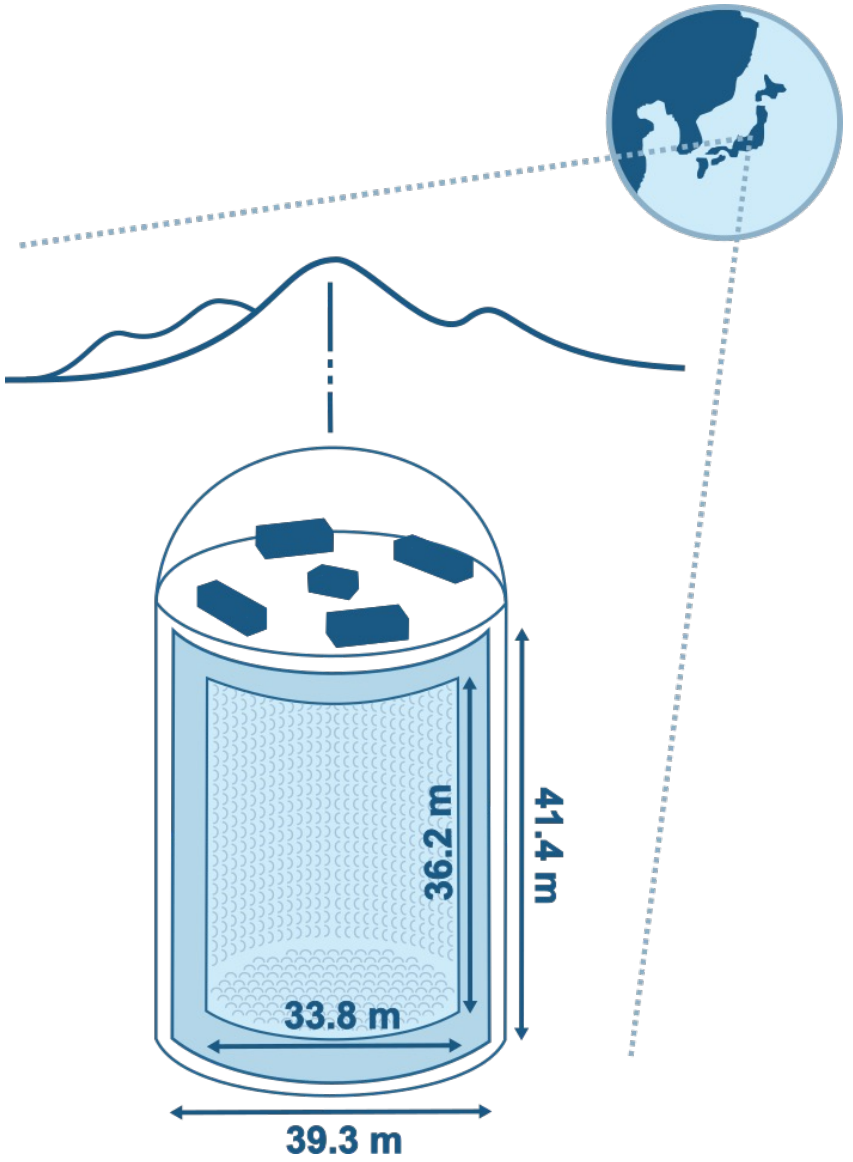
Inner Detector (ID)

22.5 kT fiducial volume with 11,129 PMTs

Outer Detector (OD)

2m thick water layer around ID with 1,885 PMTs





BDM Search Strategy with electrons

Signal signature

Electrons recoiled by **Boosted DM**

→ **Single electron** event

→ **Fuzzy single-ring event**

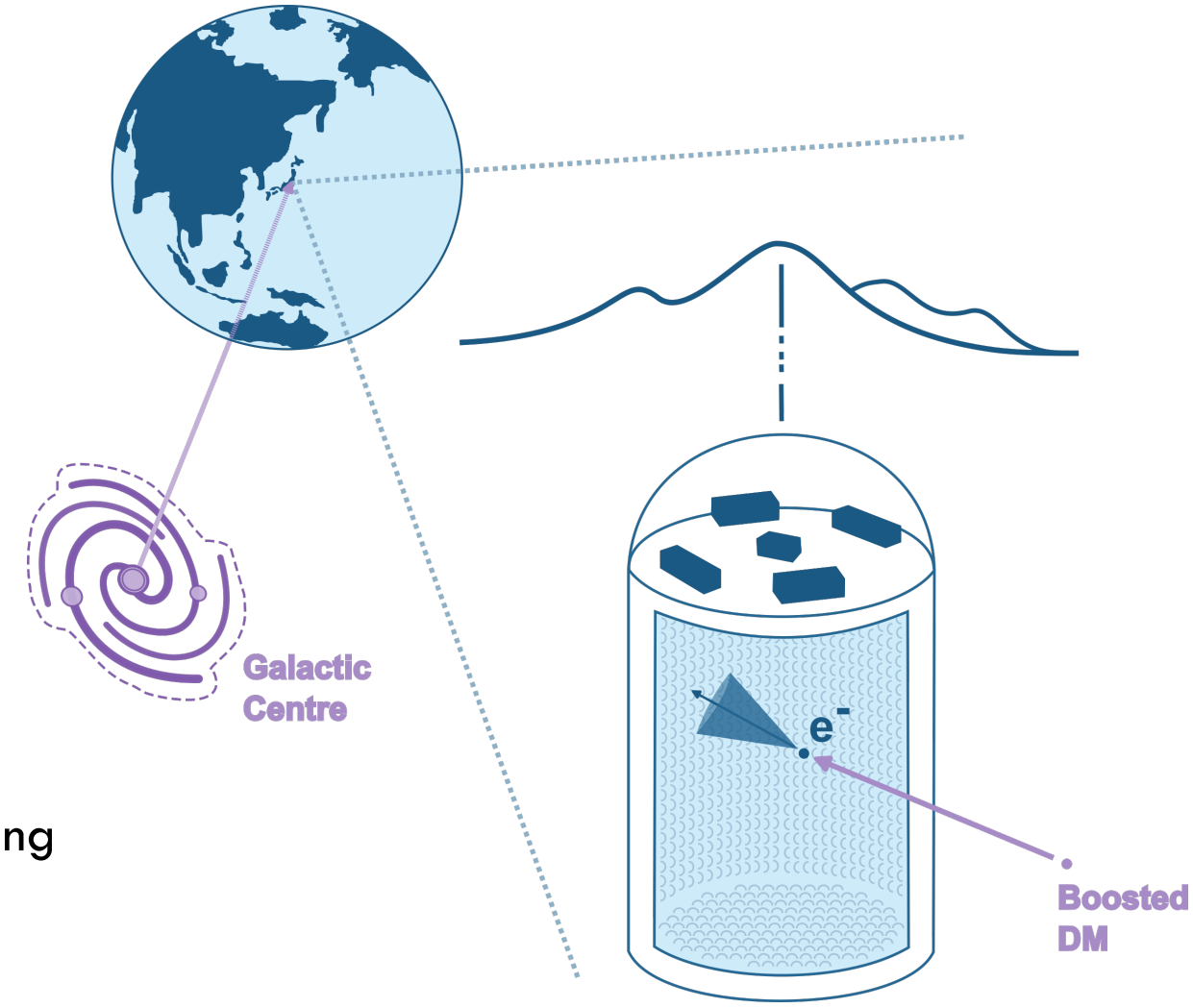
Where to look for Boosted DM?

Regions with **high dark matter concentration**

→ Look towards the **Galactic Centre (GC)**

Search strategy

Look for an **excess of scattered electrons** pointing in the direction of the GC



First BDM Search with e^- in Super-K

Chris Kachulis

Directional model-independent search

→ Applicable to any theory predicting recoiled electrons from GC

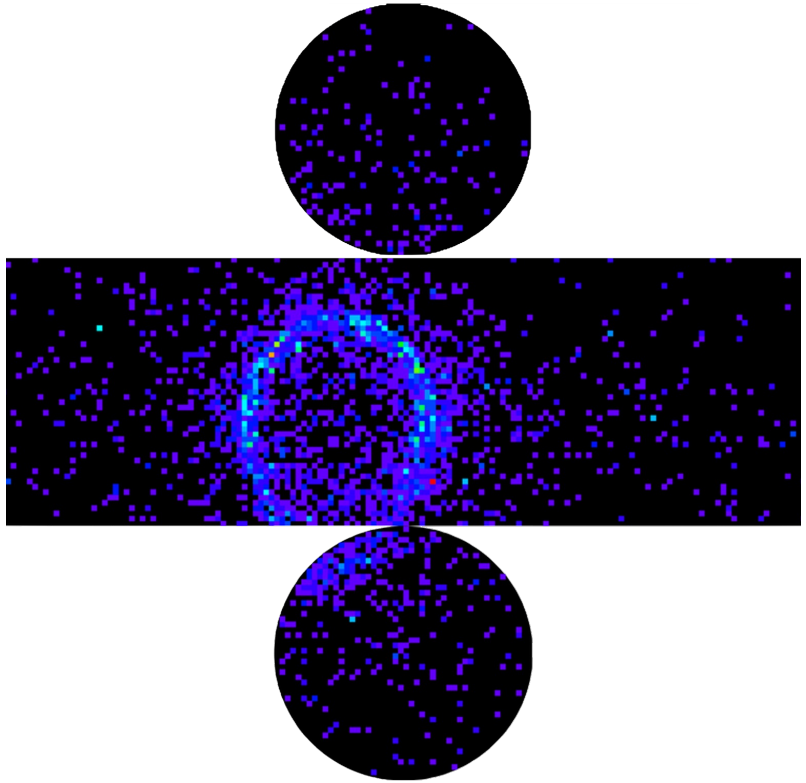
Event selection on SK-IV data

- Select **single-ring** events identified as **electron-like**
- Events with **no tagged neutron** or **decay electrons**

Analysis plan

- Search conducted within **cones around GC**
  8 cones with half-opening angles ranging from **5° to 40°**
- Divided into **three energy ranges**
  $E \in [0.1, 1.33]$ GeV, $E \in [1.33, 20]$ GeV and $E > 20$ GeV

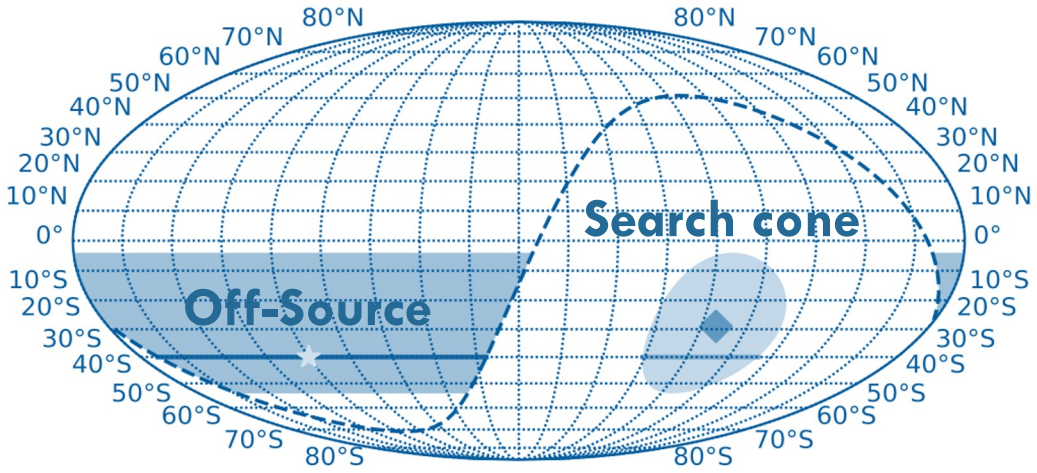
→ Treat **each combination** as an **independent analysis**



Results of the BDM Search with e⁻

On-off source search which **counts events** both in

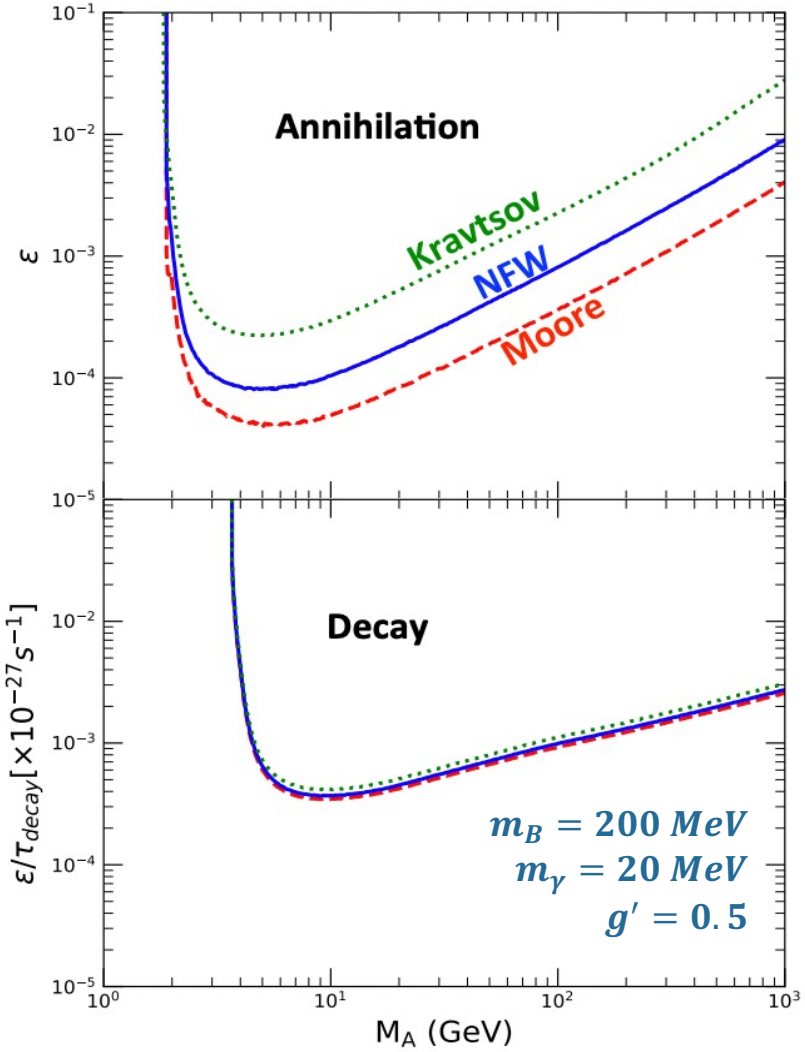
- **On-source** region (cone around GC)
- **Off-source** region (outside 80° cone around GC)



Compare off-source and on-source data

→ Draw confidence intervals on the number of signal events

→ Consistent with the **background-only hypothesis**



Phys. Rev. Lett. 120, 221301 (2018)

BDM Search with Low-Energy Electrons

Nadège Iovine

Search with focus on **low-energy electrons**

→ **Model-dependent** search as want to **use energy distribution of the events**

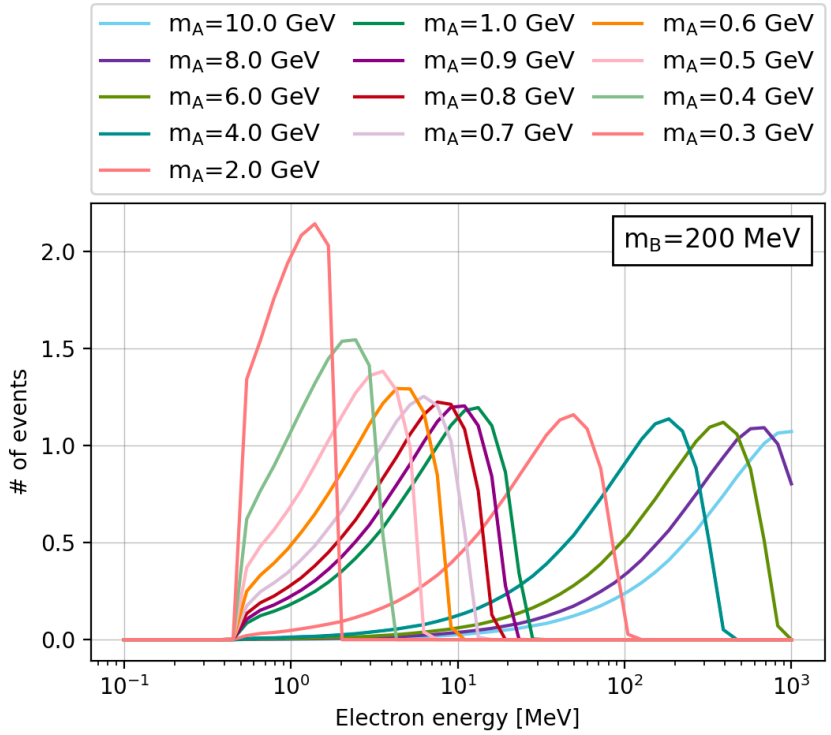
Analysis plan

- Consider events from the **entire sky**

  Search conducted with **3D distributions of events**
  - **Direction** – Right ascension (RA) & Declination (δ)
  - **Energy** – Monochromatic signal with $E_B = m_A$
- Explore **new parameter space** with lower DM masses

Event selection on SK-VI data

- Select **single-ring** events with energies **E ∈ [10, 100] MeV**

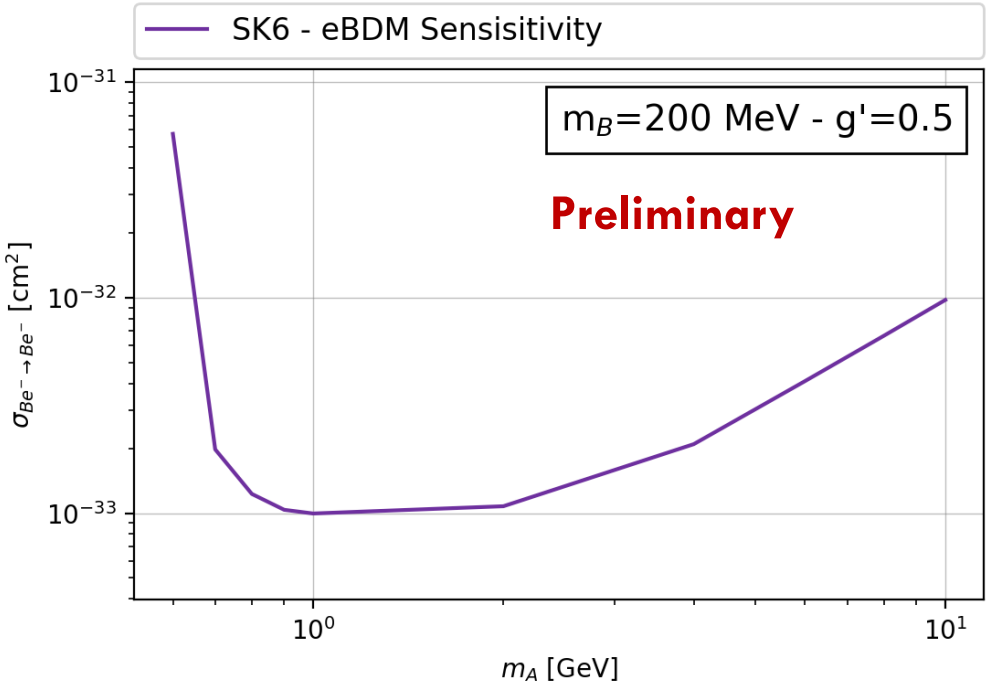


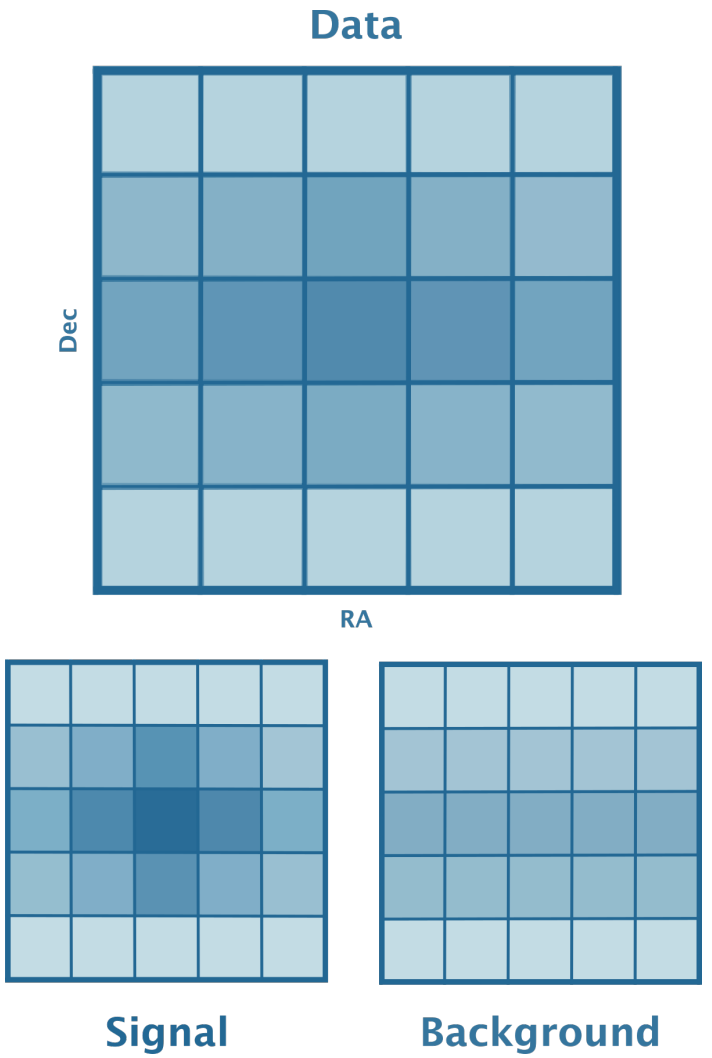
Sensitivities

Binned likelihood method with **Poisson distribution**

Comparison bin per bin with expectations from

- **Background:** MC weighted with **atmospheric neutrino flux**
- **Signal:** MC weighted with **- source morphology**
  - recoiled electron spectrum

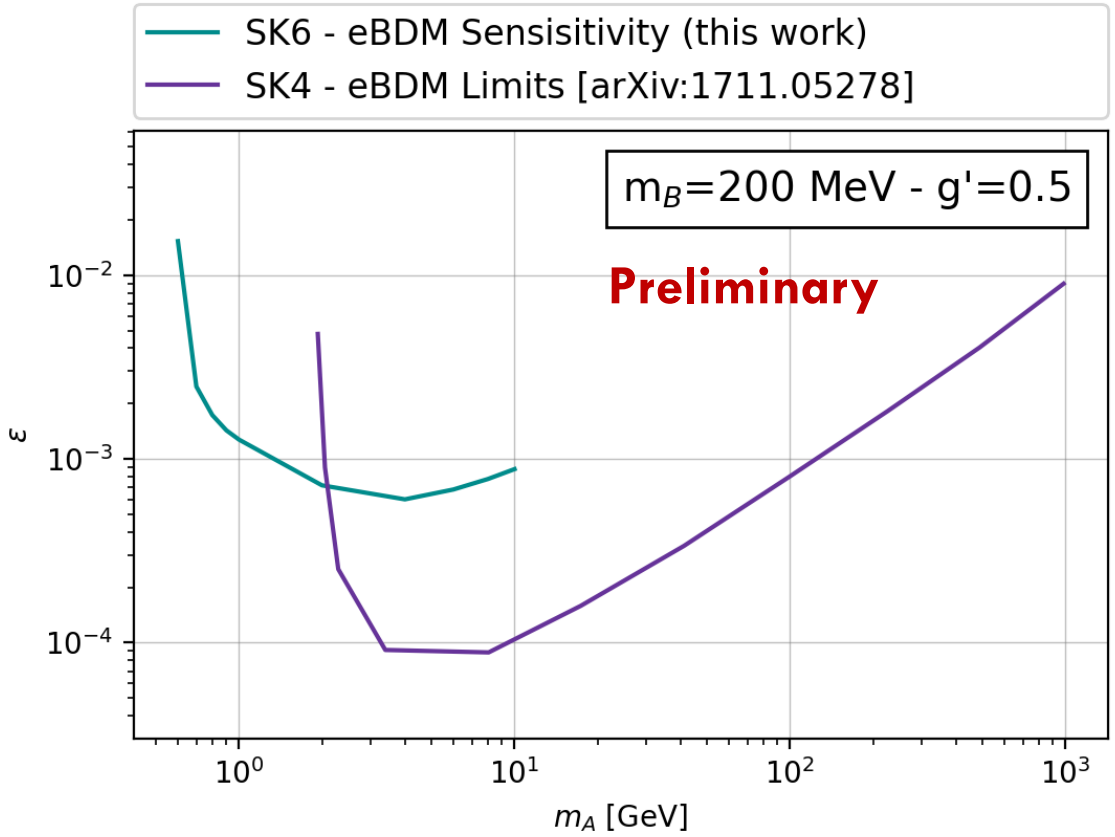




Comparison to SK BDM-e^- search

Search extended towards lower energies compared to the previous Super-K results

→ **Improved sensitivity** for BDM energies **below a few GeV**



BDM Search Strategy in Super-K with Hadrons

Signal Signature

Protons recoiled by **cosmic-ray-boosted DM**

→ **Sharp single-ring** events

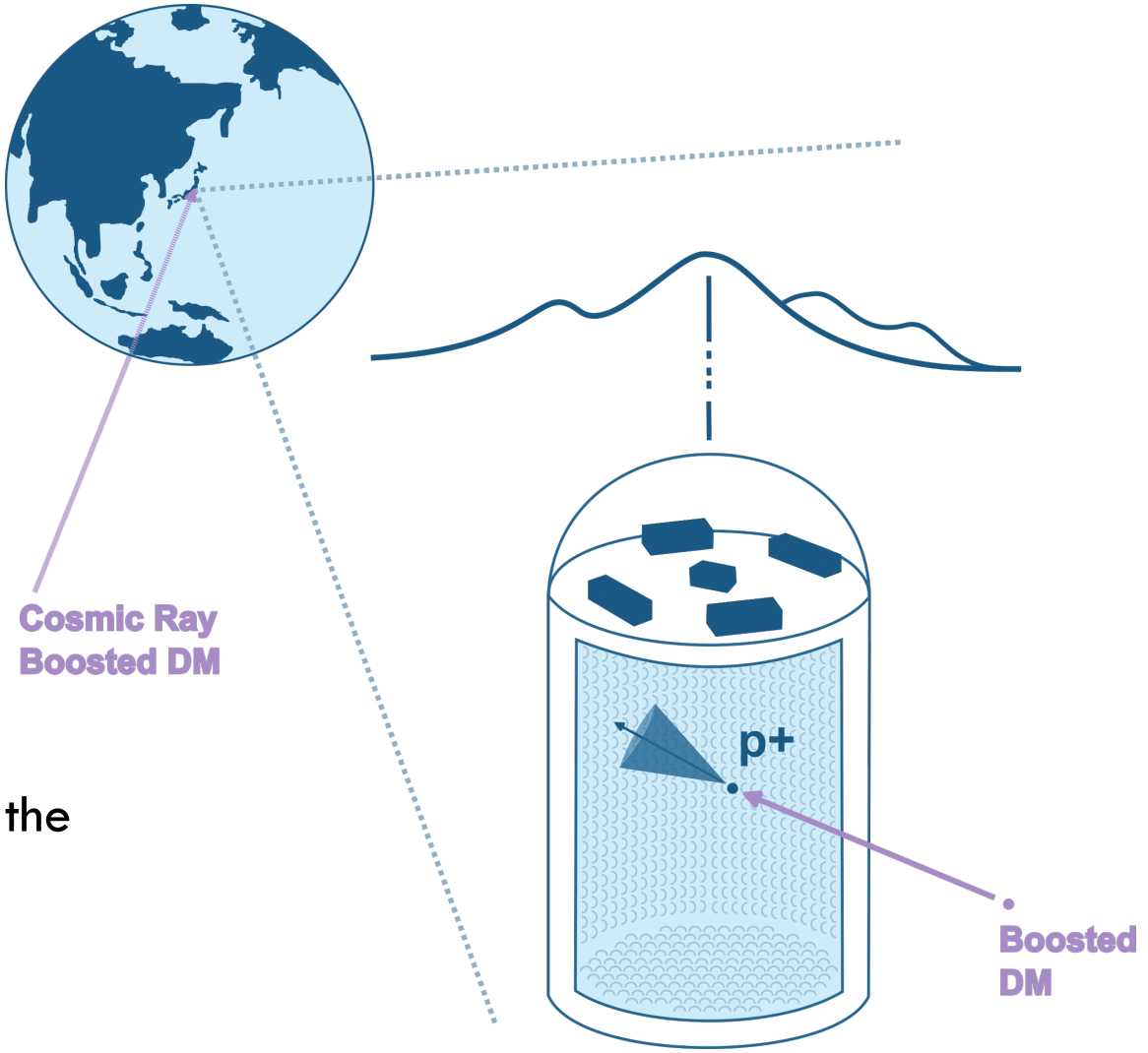
Where to look for Boosted DM?

Regions with **high dark matter concentration**

→ Search in direction of the **Galactic Centre**

Search strategy

Look for an **excess of scattered protons** pointing in the direction of the GC



Cosmic-Ray BDM Search with Hadrons

Linyan Wan

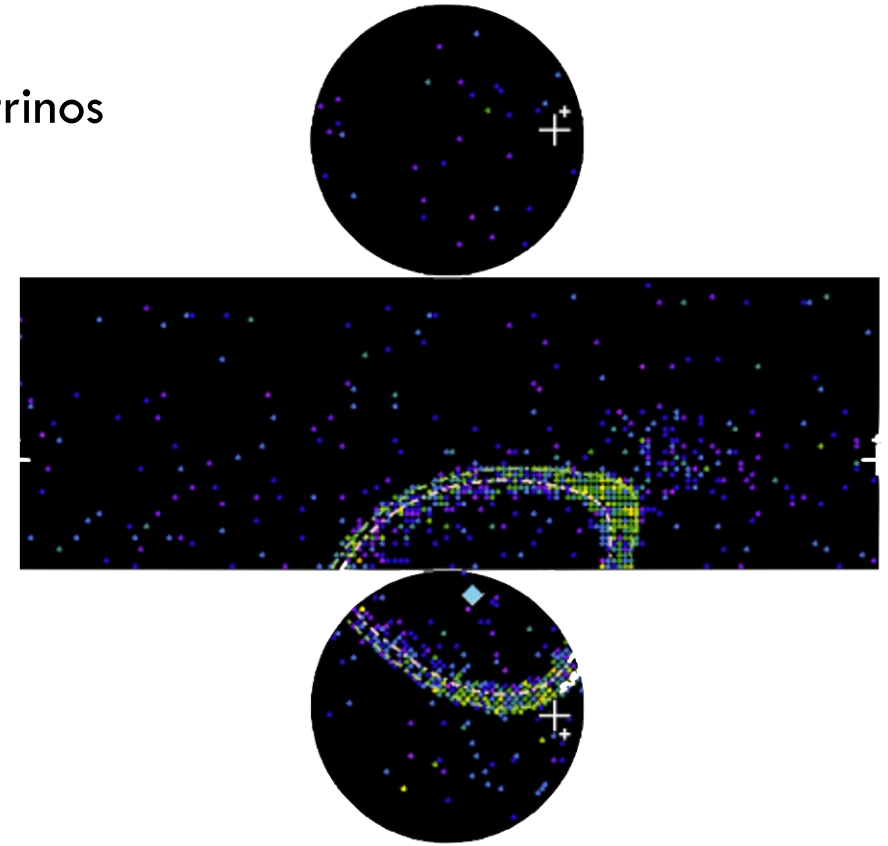
Search focus on **CRDM** with energies between **MeV/c^2 to GeV/c^2**

Event Selection consists of SK I-IV data

Select protons over low-energy muons from atmospheric neutrinos

- **Pattern-fitting** based proton reconstruction
- Cut on the **proton momentum**
  Detection limited within 1.2 GeV/c < p_p < 2.3 GeV/c
- **Multi-variate analysis** (MVA)
  Neural network trained on proton and non-proton rings

→ Final sample with **77% proton purity**

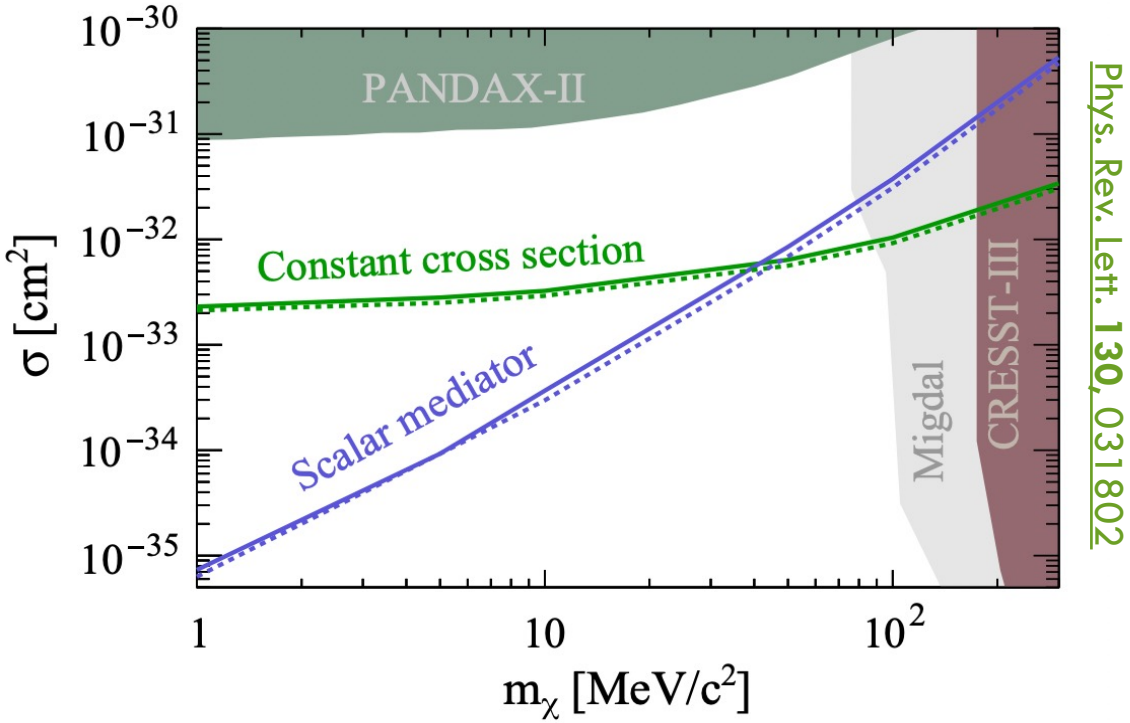


Results of the Cosmic-Ray BDM Search with Hadrons

On-off source search with **off-source shifted by 180° in RA** from the **Galactic Centre**

Compute **confidence intervals** on the number of signal events

→ Consistent with the **background-only hypothesis**



Conclusion & Outlooks

Searches for electrons recoiled by Boosted DM

- First **search for Boosted DM** in Super-K using **high-energy electrons**

  → **No significant excess** in the direction of the GC or the Sun

  → Results presented to be **model-independent**

- Extend the **Boosted DM search** with electrons in Super-K **to low energies**

  → Consider both the **energy and directional information**

  Future steps: Improve **event selection** and **extend analysis** to higher energies

Search for cosmic-ray-boosted DM with hadrons

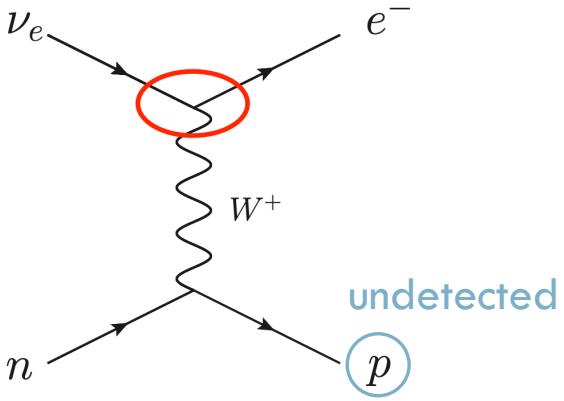
- Derived **most stringent limit on hadronic coupling** of sub-GeV DM

  → Good **motivation for search** for CRDM with **next-generation neutrino detectors**

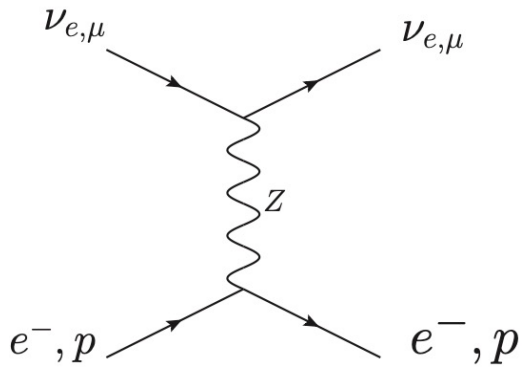
Back-Up Slides

Background of Boosted DM Search

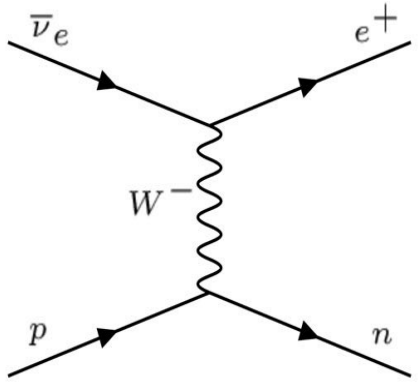
Charged-Current Interaction



Neutrino neutral-current scattering

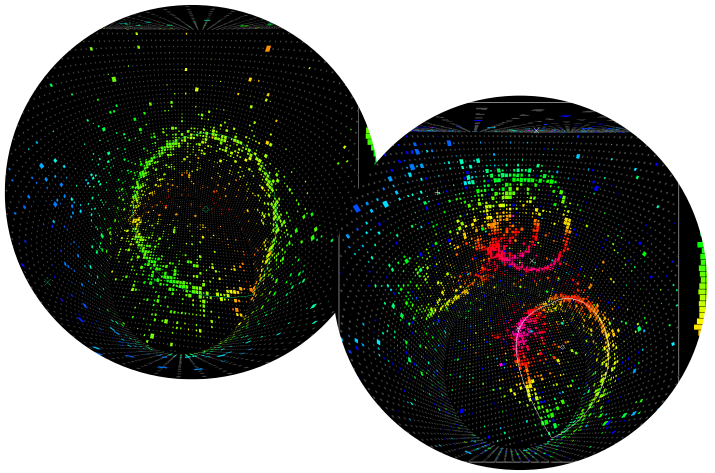


Inverse Beta decay (IBD)



Signal-Background Discrimination

- **Directional information**
  → Boosted DM from the GC vs isotropic ν_{atm} and ν_{sun}
- **Energy information**
  → Mono-energetic flux ($E_B = m_A$)
- **Multi-ring veto and neutron tagging**
  → recoiled e^- vs ν_{atm} scattering ($e^{+/-}$ + other particles)

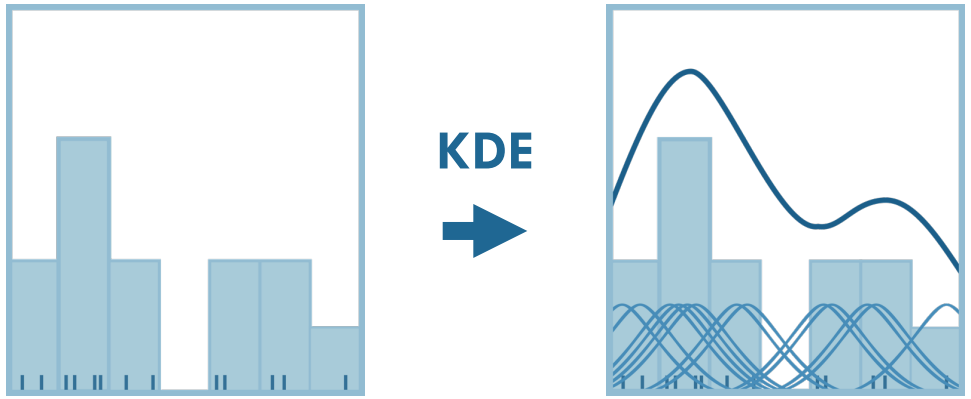


Probability Density Functions (PDFs)

Kernel Density Estimation (KDE)

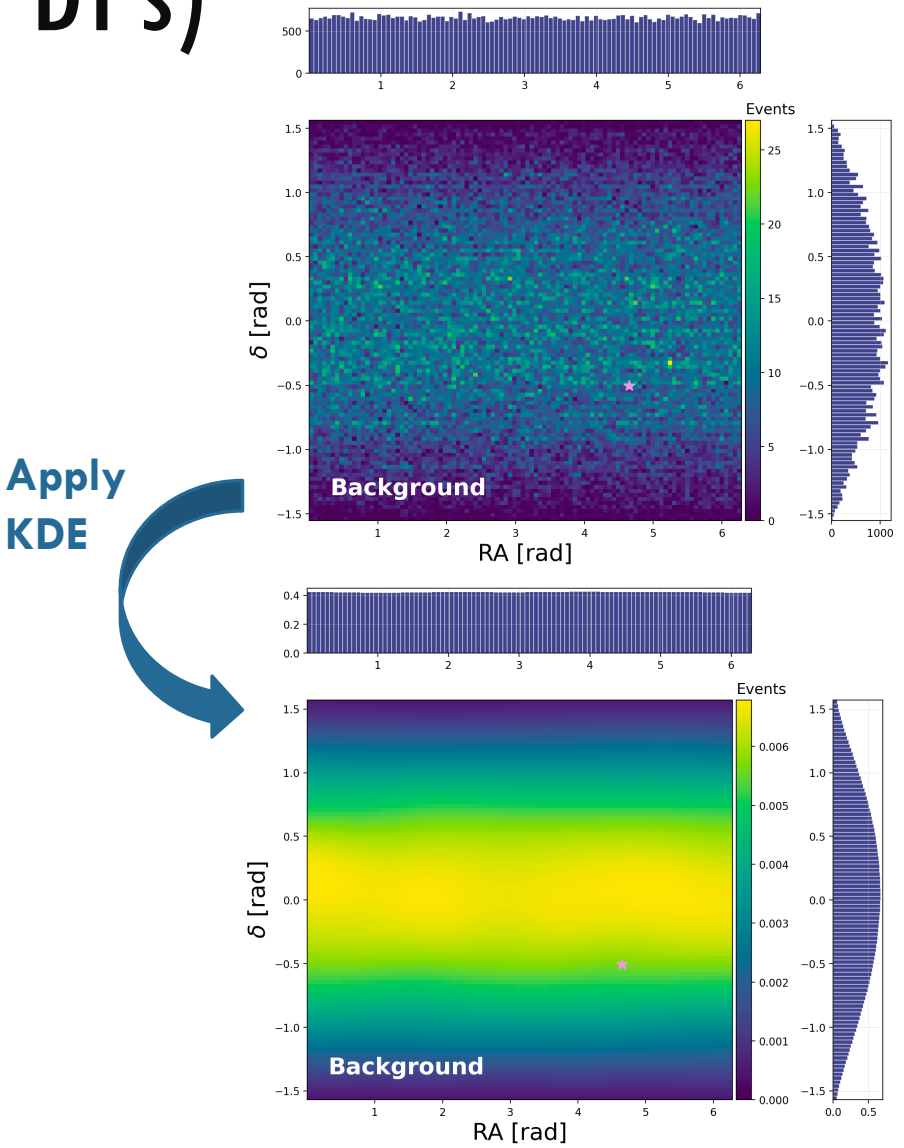
Use KDE method implemented in sklearn python package

- **Gaussian kernel**
- **Bandwidth** selected with **cross-validation** method



KDE method built from **3D distributions of events**

- **Direction** - Right ascension (RA) & Declination (δ)
- **Energy**

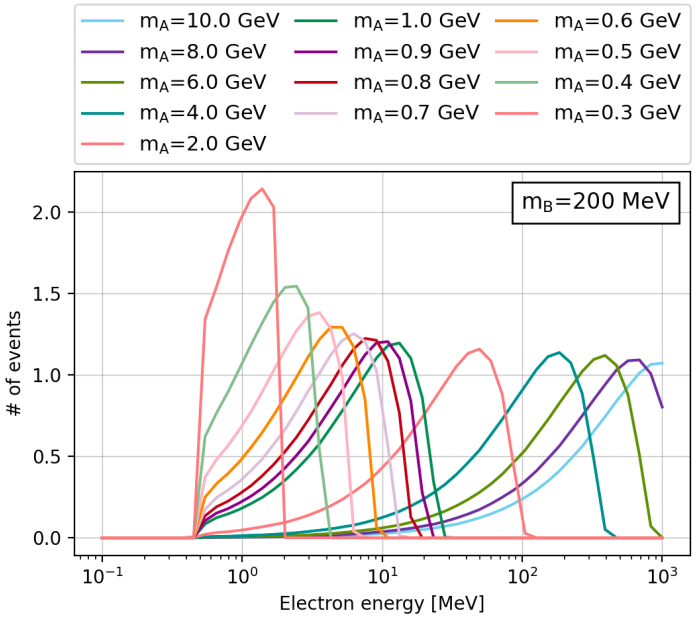


Signal Distributions

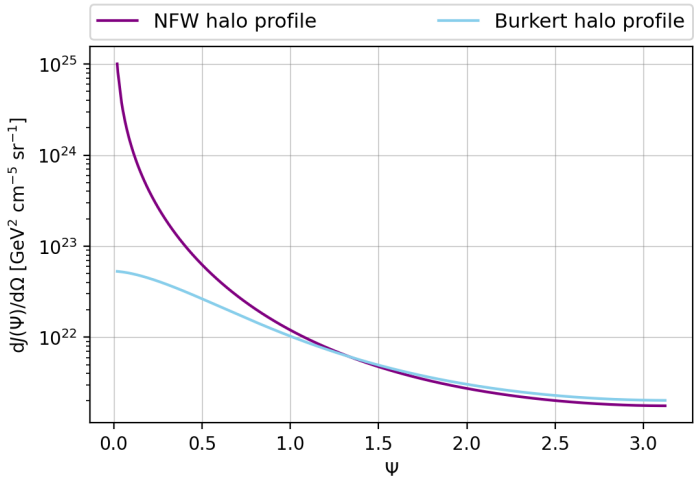
General Monte Carlo electron sample weighted with BDM flux

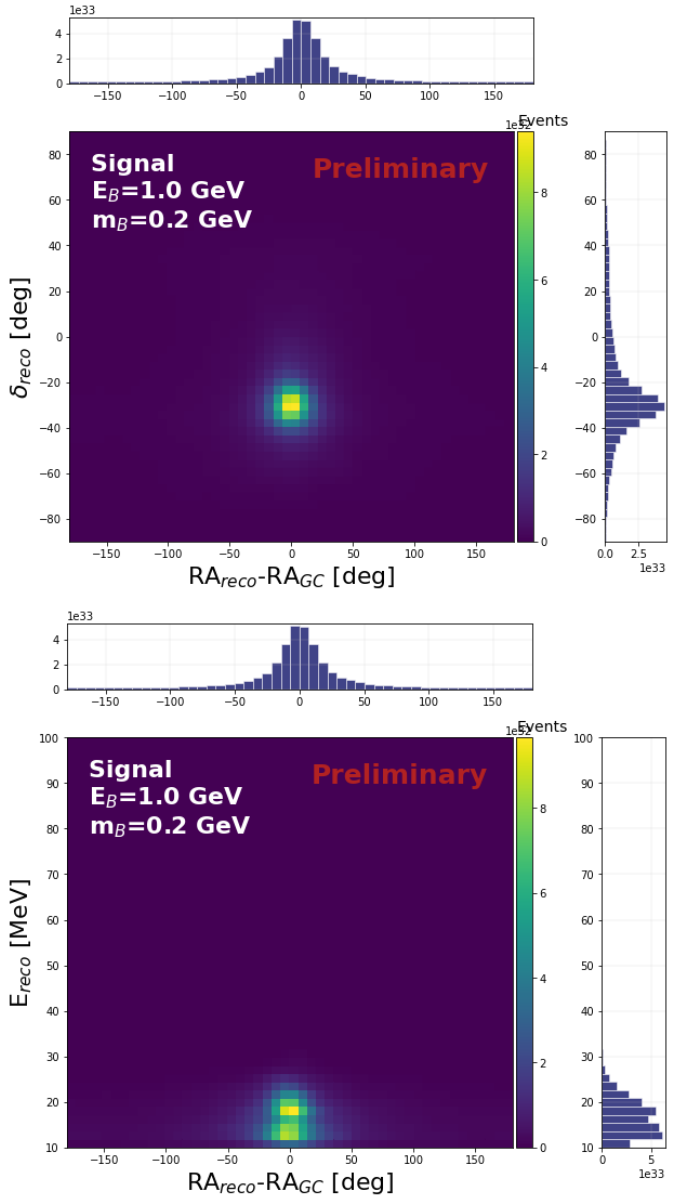
$$\frac{\mathrm{d}\phi_B}{\mathrm{d}\Omega\,\mathrm{d}E_B} = \frac{1}{2}\frac{\langle\sigma_{A\bar{A}\to B\bar{B}}\,v\rangle}{4\pi\,m_B^2}\boxed{\frac{dN_B}{dE_B}}\boxed{\int_{l.o.s}\rho_\chi^2(r(s,\Psi,\theta))\mathrm{d}s}$$

Scattered Electron Spectrum



DM halo shape



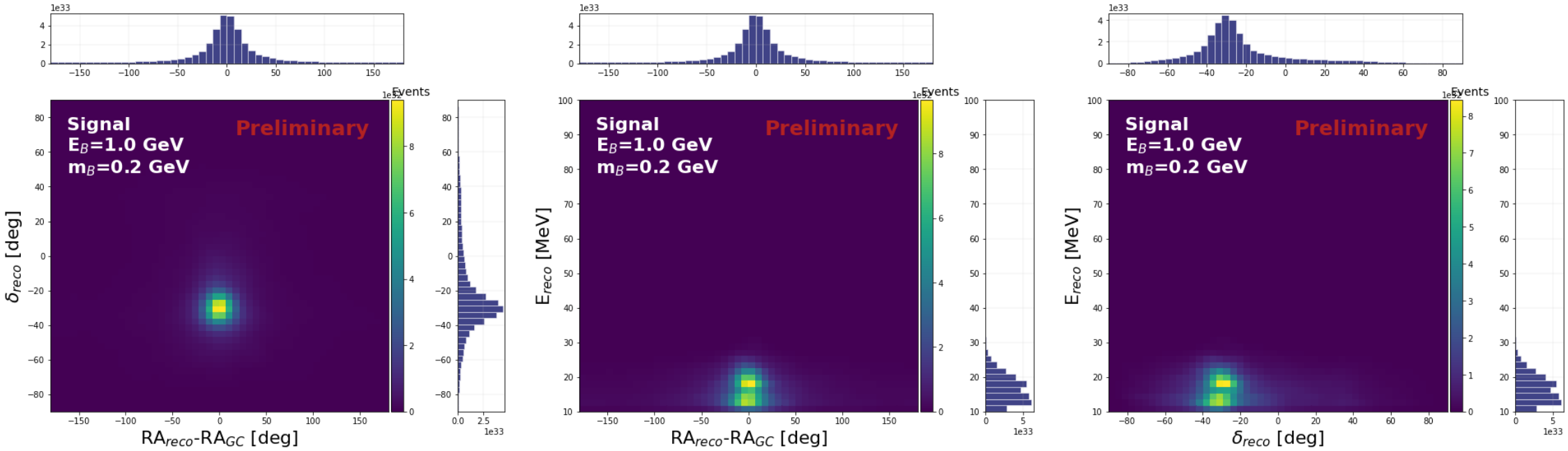


Signal PDFs

General MC electron sample weighted with **source morphology and energy spectrum (ϕ_B)**

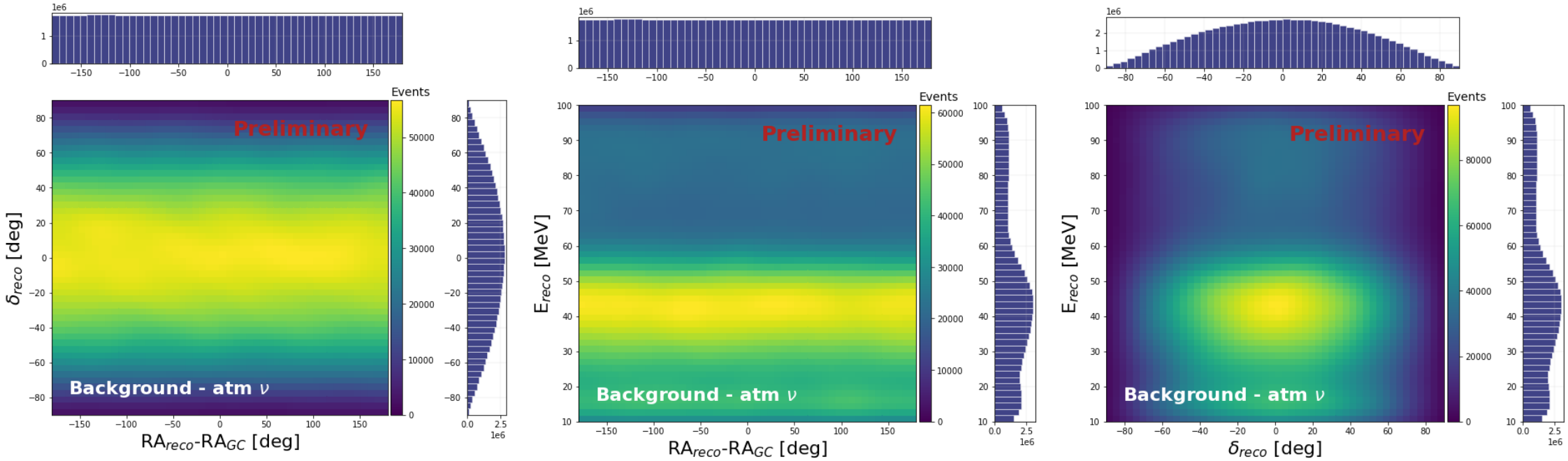
PDFs built with **KDE method** with final weight being:

$$N_{sig} = \Delta T * N_{target} * \phi_B * \sigma_{Be->Be}$$



Background PDFs

PDFs built using **KDE method** from MC events **weighted with atmospheric neutrino flux ->Honda2016**



Sensitivities

BDM – electron cross-section ($\sigma_{Be\to Be}$)

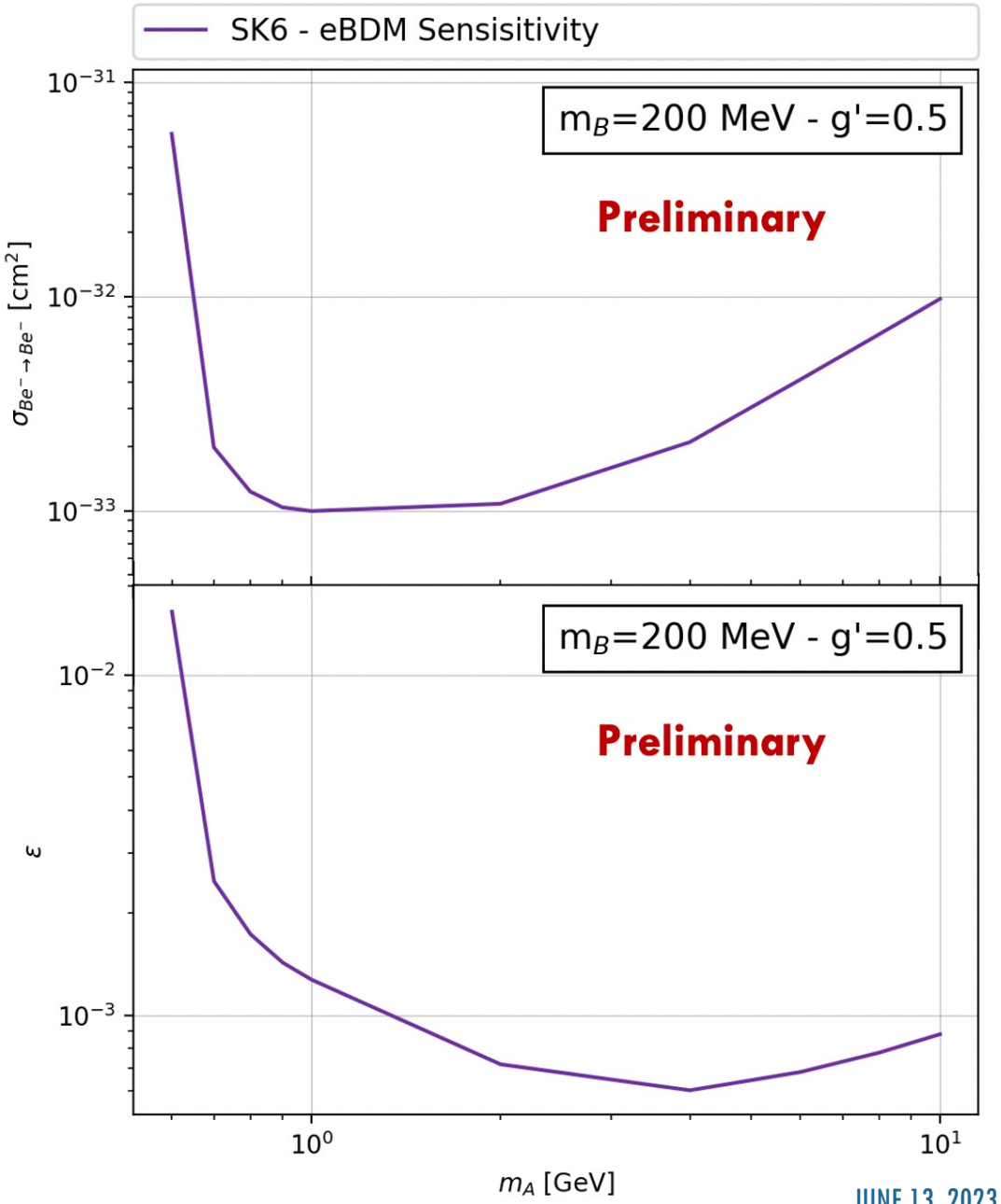
Conversion from μ_{best} using N_{bg}/N_{sig} with

$$N_{sig} = \Delta T * N_{target} * \phi_B * \sigma_{Be->Be}$$

Dark photon - electron coupling (ϵ)

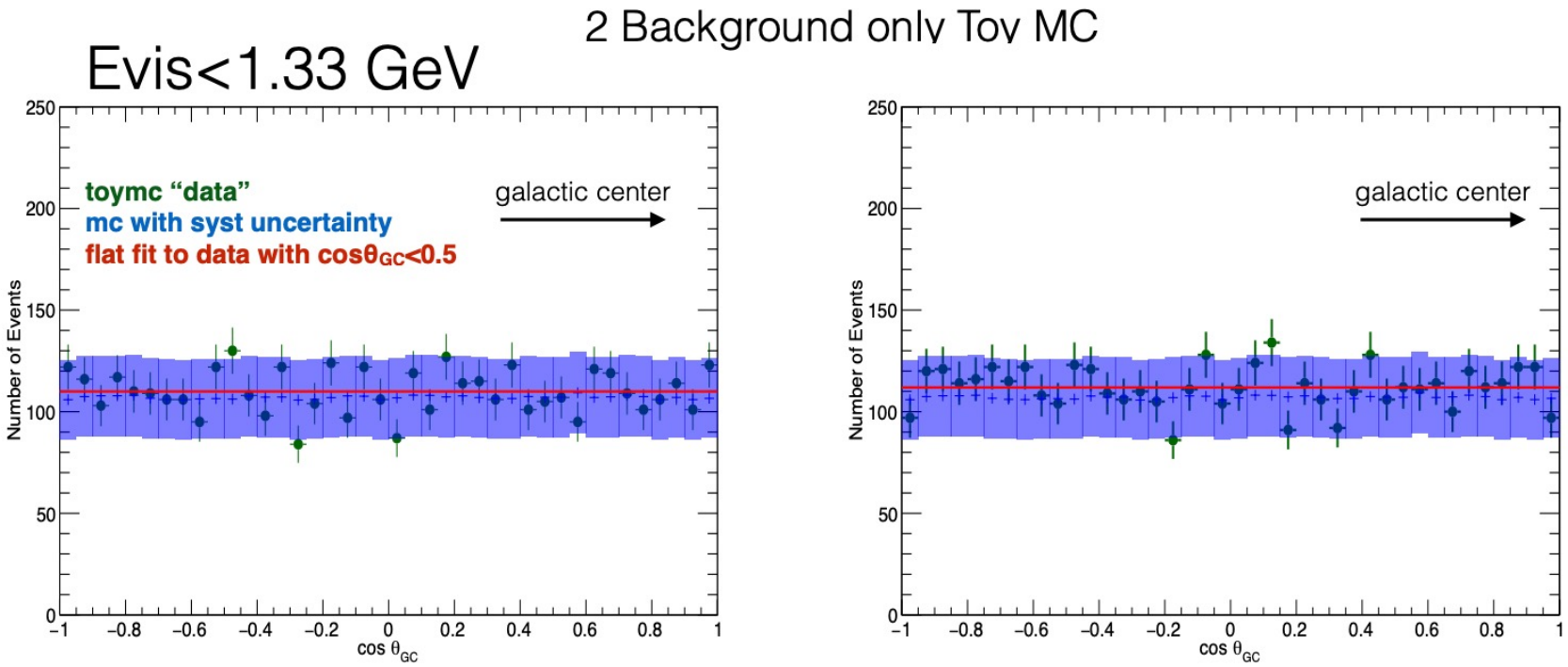
Conversion based on [arXiv:1405.7370]

$$\frac{d\sigma}{dt} = \frac{1}{8\pi}\frac{(\epsilon e g)^2}{(t-m_r^2)^2}\frac{8m_A^2 m_e^2 + t(t+2s)}{\lambda(s,m_e^2,m_B^2)}$$



Background – High E electron Search

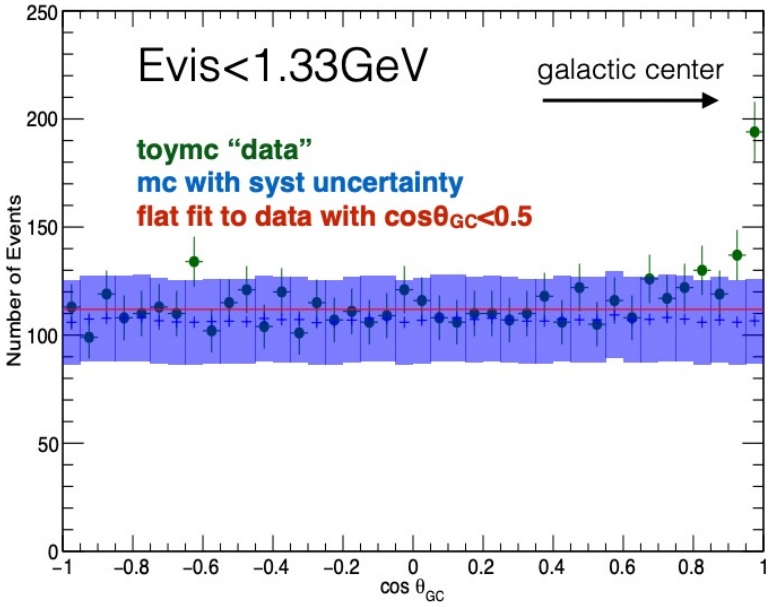
What Background Looks Like



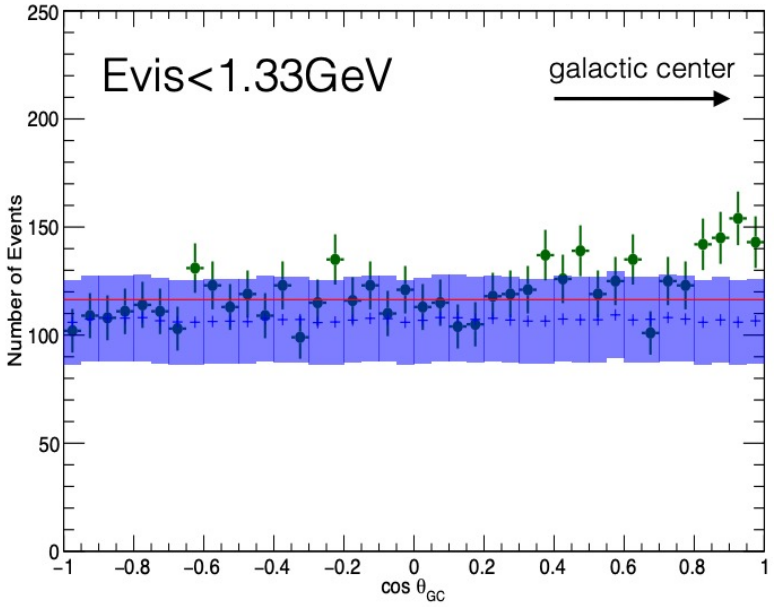
Signal – High E electron Search

What an excess Looks Like

200 injected DM events, NFW annihilation



400 injected DM events, NFW decay



High E electron Search – On-off source method

$$\chi^2 = 2[B(1+\epsilon) - O_{\text{off}} + O_{\text{off}} \ln \frac{O_{\text{off}}}{B(1+\epsilon)}] \quad \text{(off-source bin)}$$

$$+2[B(1+\epsilon) + S - O_{\text{on}} + O_{\text{on}} \ln \frac{O_{\text{on}}}{B(1+\epsilon)+S}] \quad \text{(on-source bin)}$$

$$+(\frac{\epsilon}{\sigma})^2 \quad \text{(systematic term)}$$

This is the same test statistic used in our standard 3-flavor analysis

I use a similar technique to Osc3++ to find the value of ε which minimizes χ^2, though it is much less complex since there is only one systematic term

χ^2 is constructed such that $\Delta\chi^2 = -2\Delta\ln\mathcal{L}$ where $\mathcal{L}$ is the likelihood profiling over systematics

High-E electron BDM – Signal Computation

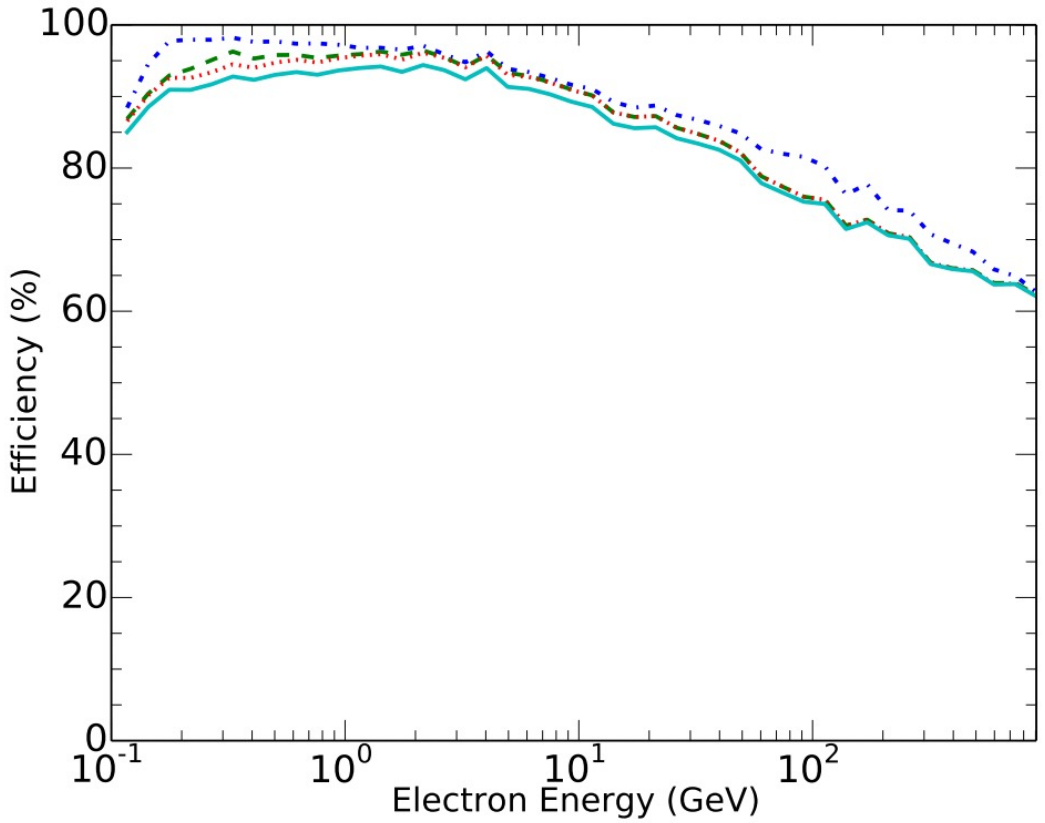


FIG. 1. Signal efficiency of the FCFV selection and analysis cuts as a function of energy. Beginning with the FCFV selection (dashed-dotted blue), the addition of the 1-ring (for E_{vis} <100GeV, dashed green), *e*-like (dotted red) and finally 0 decay electrons and 0 tagged neutrons cuts to arrive at the final efficiency (solid cyan) are shown. The efficiency of the 0 decay electrons cut is $> 99.99\%$, so that the drop from the dotted red line to solid cyan line is due solely to the neutron tagging cut.

CRDM – Signal Computation

Number of events is calculated by

$$N = \Phi \times \sigma \times \epsilon \times N_p \times T$$
$$= \frac{\phi}{g_{Z'}^4} \times \frac{\sigma}{g_{Z'}^4} \times \epsilon \times N_p \times T \times (g_{Z'}^4)^2$$

N_p: number of proton within FV at SK
T: livetime for SK1-4
$g_{Z'}$: dark matter-nucleon coupling
σ: cross-section, $\sigma \propto g_{Z'}^4$
Φ: DM flux, $\Phi \propto g_{Z'}^4$

Mediator mass is fixed at 1 GeV for the moment.

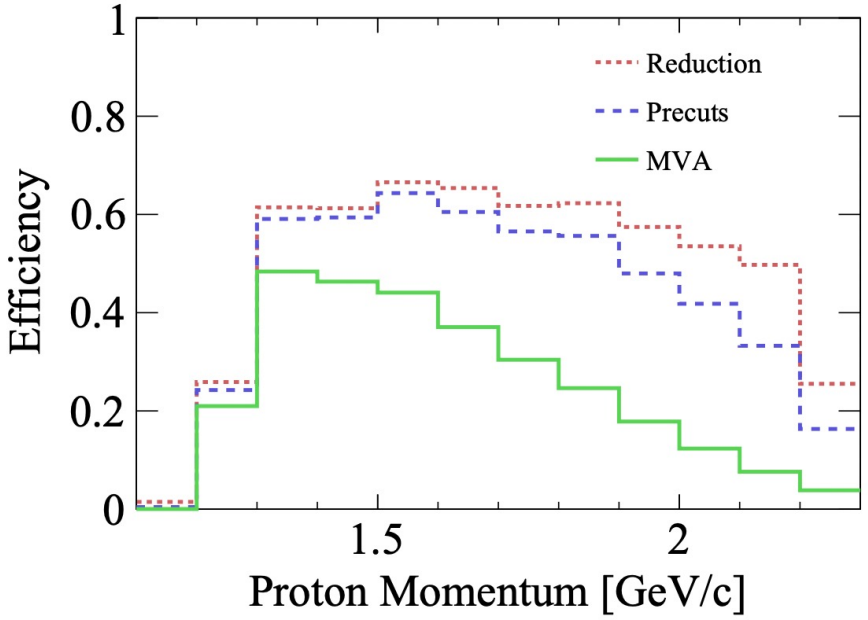


FIG. 1. The selection efficiencies for the proton sample. The red dotted line indicates the reduction efficiency of the FCFV sample above 30 MeV. The blue dashed line represents the efficiency after precuts. The green solid line is the efficiency after the MVA cut.

CRDM – Opening Angle to GC

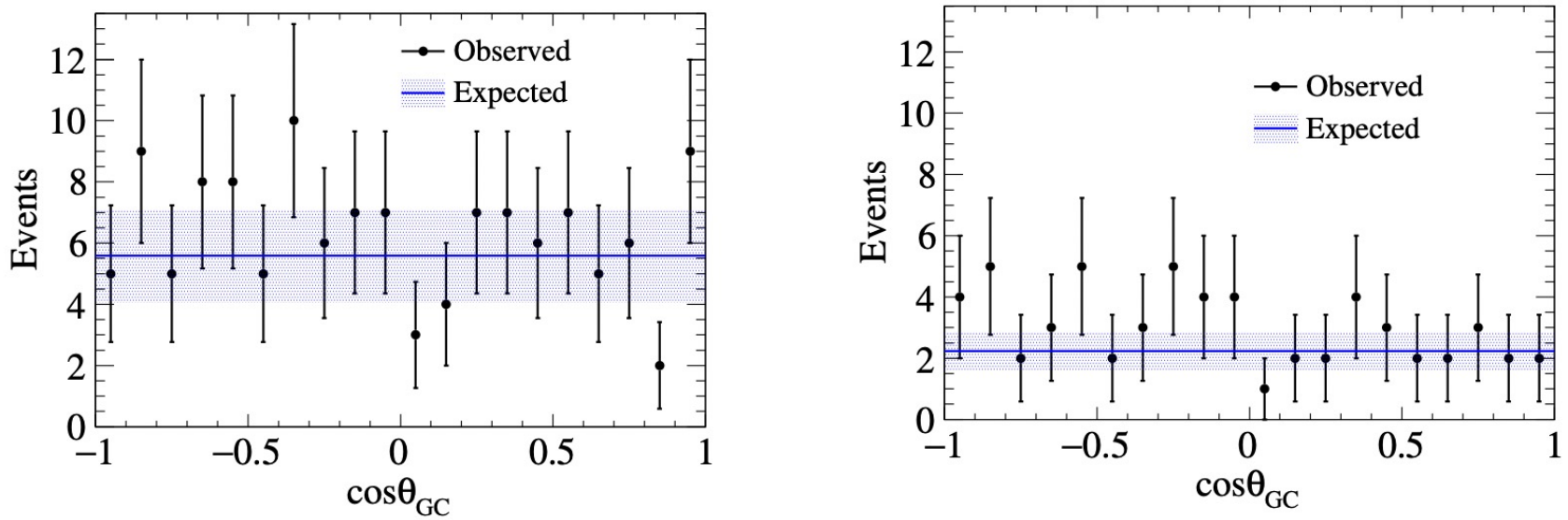


FIG. 2. The angle between proton ring and the GC for events in the proton sample, without (upper) and with (lower) the zenith angle cut. The black points indicate data with statistical uncertainty. The blue bands indicate MC expectation with systematic uncertainty.