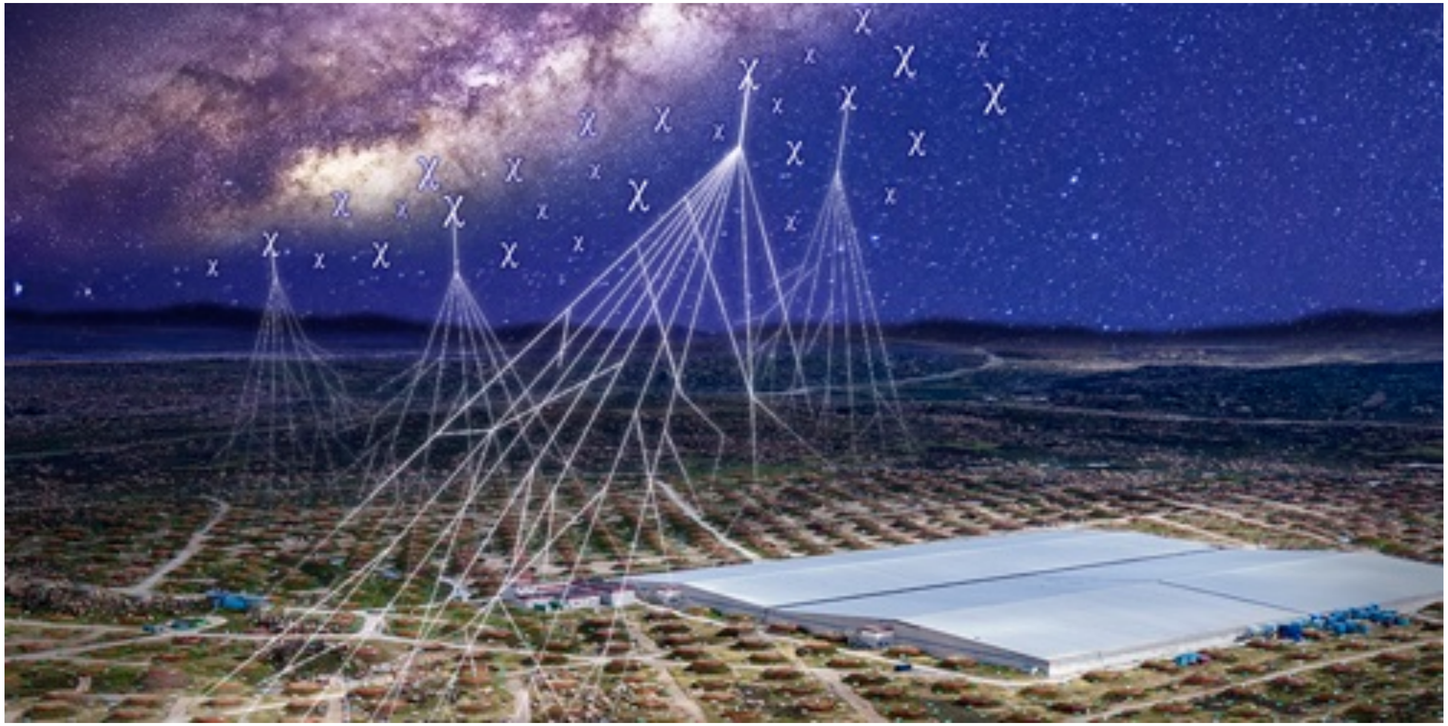
# Searching for Dark Matter with LHAASO



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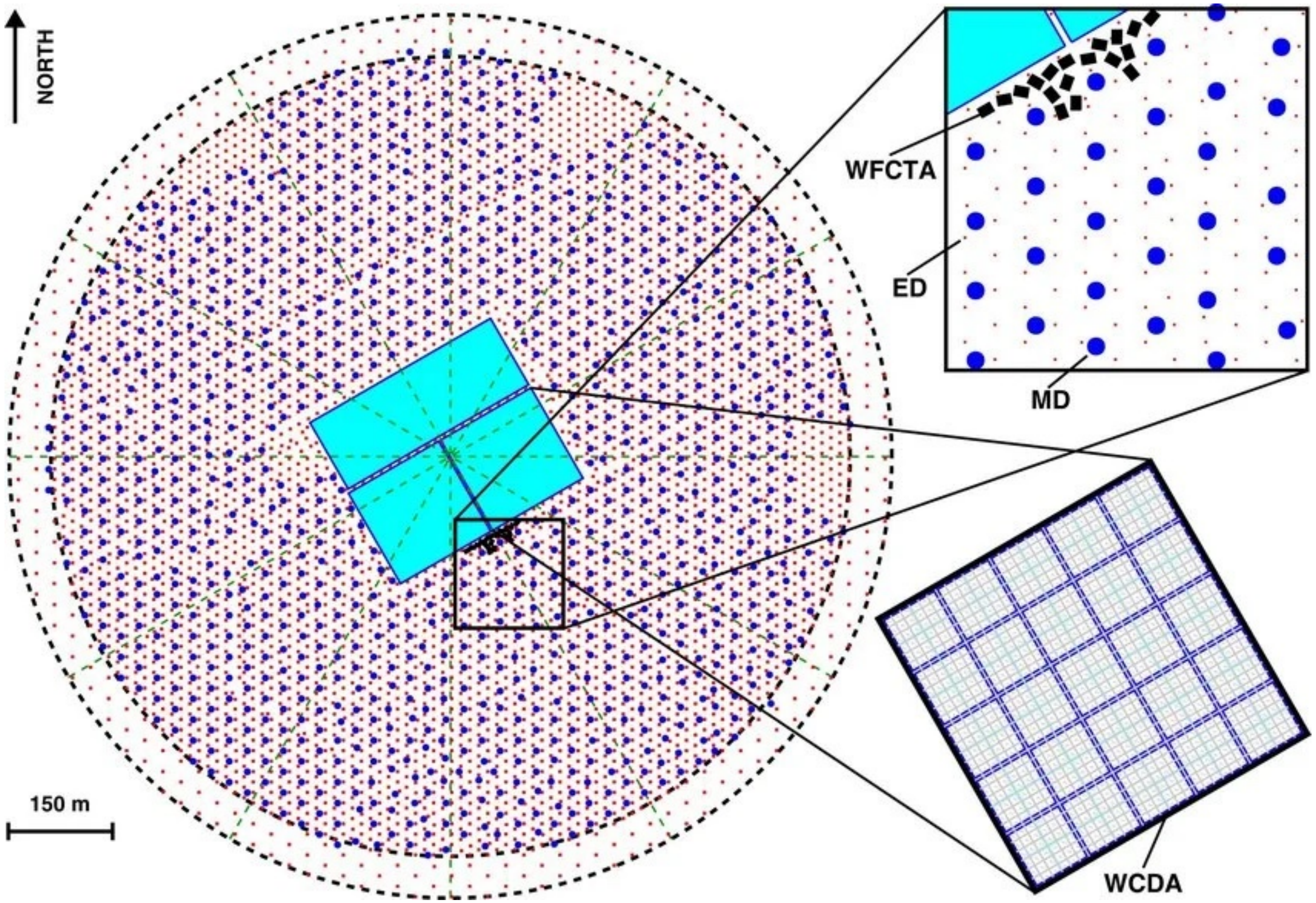
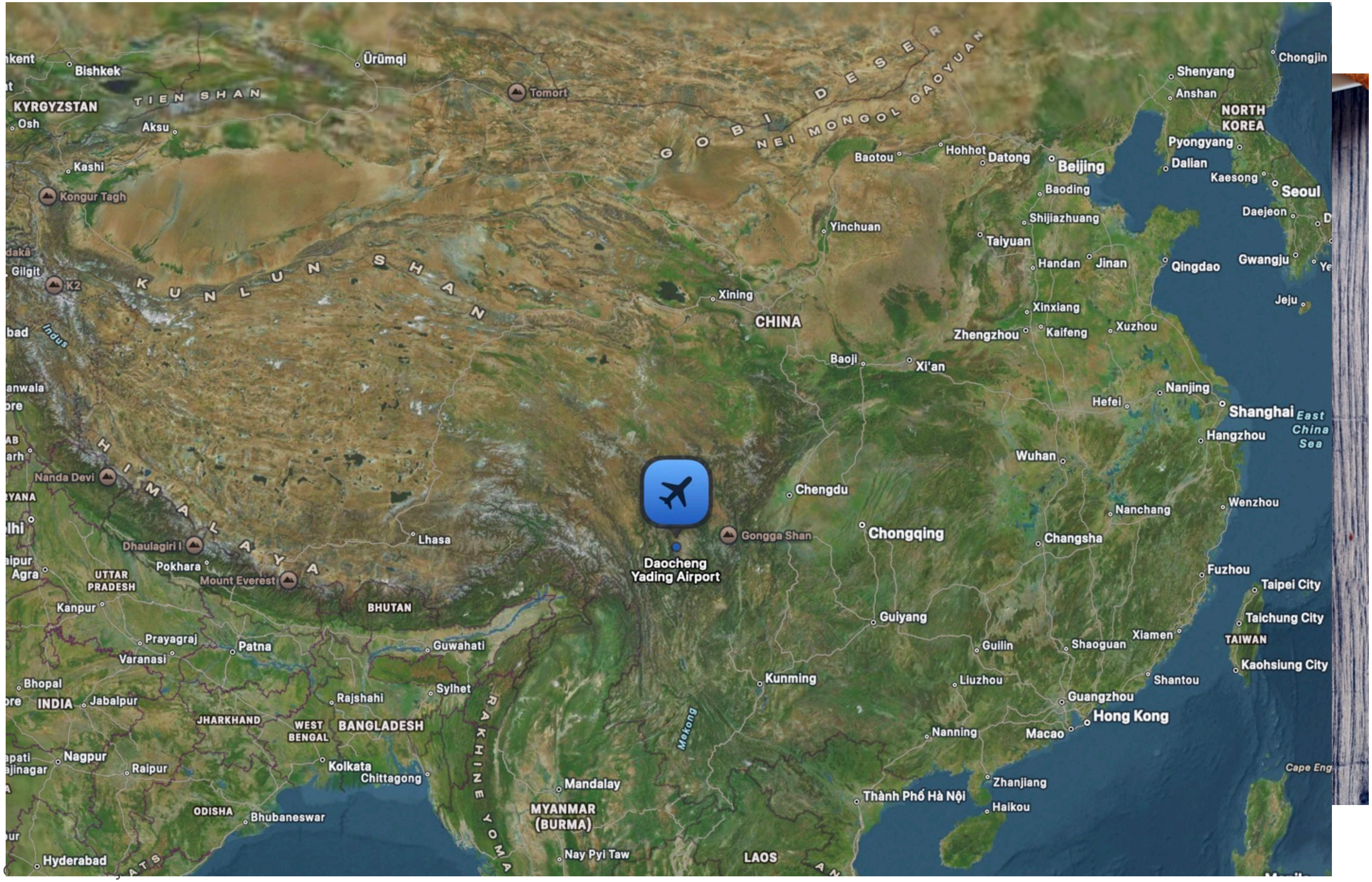
**The Chinese University of Hong Kong (CUHK)**
**香港中文大學**

# What is LHAASO?

- Large High Altitude Air Shower Observatory

- kilometer square array (KM2A)
- Water Cherenkov detector array (WCDA)
- Wide field of view Cherenkov telescope array (WFCTA)

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Yading Airport
Gongga Shan
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CHINA
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Tomort
TIEN SHAN
Aksu
Kashi
Kongur Tagh
Gilgit
K2
KUNLUN SHAN
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Baotou
Hohhot
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Jinan
Qingdao
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Baoji
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TAIWAN
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Xiamen
Shantou
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Nanning
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LAOS
Chongjin
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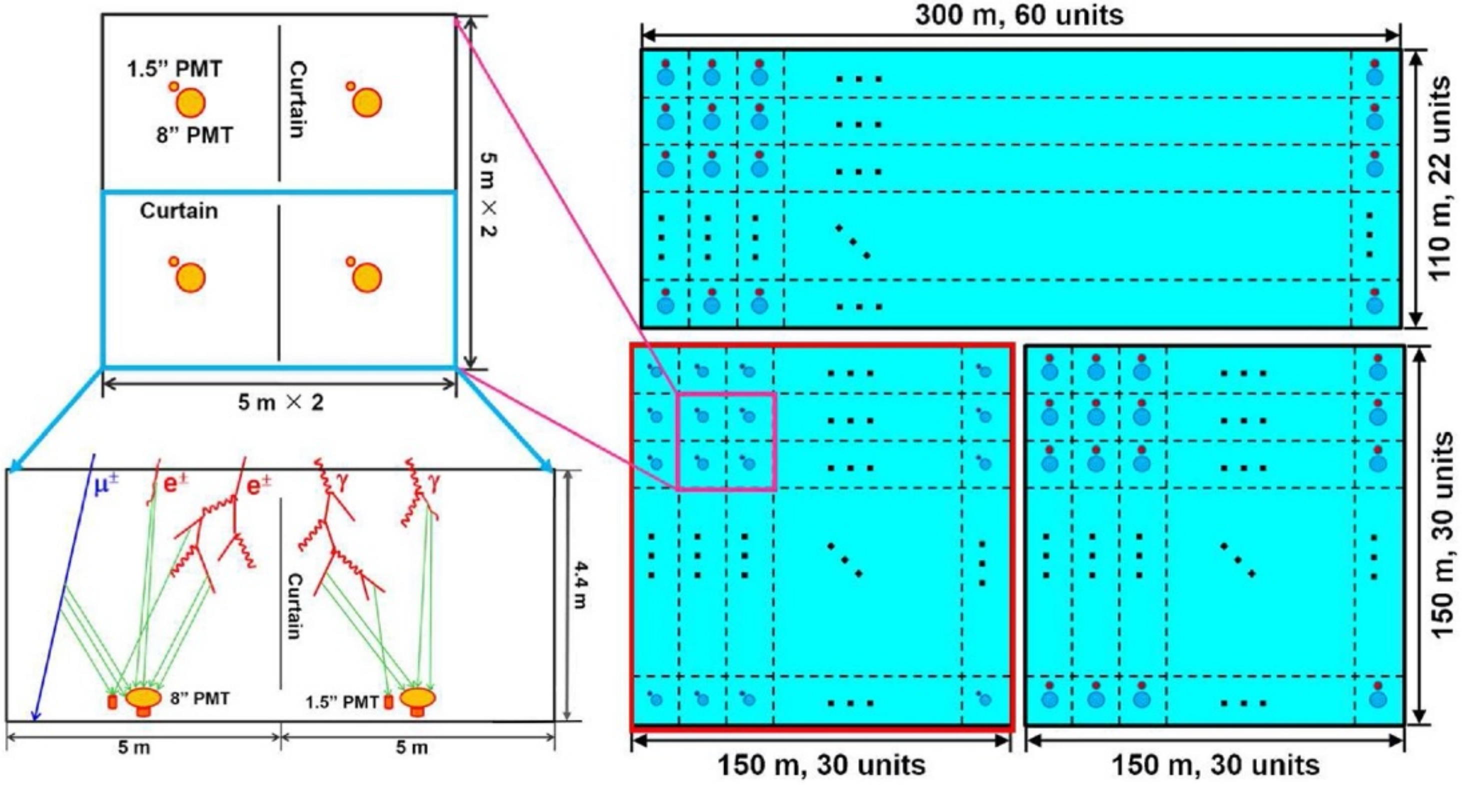
Chittagong
Nagpur
Raipur
ODISHA
Bhubaneswar
Hyderabad
RAKHINE YOMA
Mandalay
MYANMAR (BURMA)
Nay Pyi Taw


Xingyi Lake
LHAASO
Airport
Daocheng Airport

- A nearby hiking site
- Yading

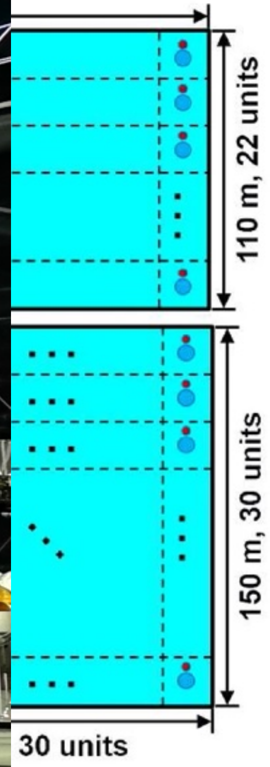
# Water Cherenkov Detector Array (WCDA)

- About 3000 cells
- 78,000$m^2$ surface area
- ~ 4 x HAWC



# Water C

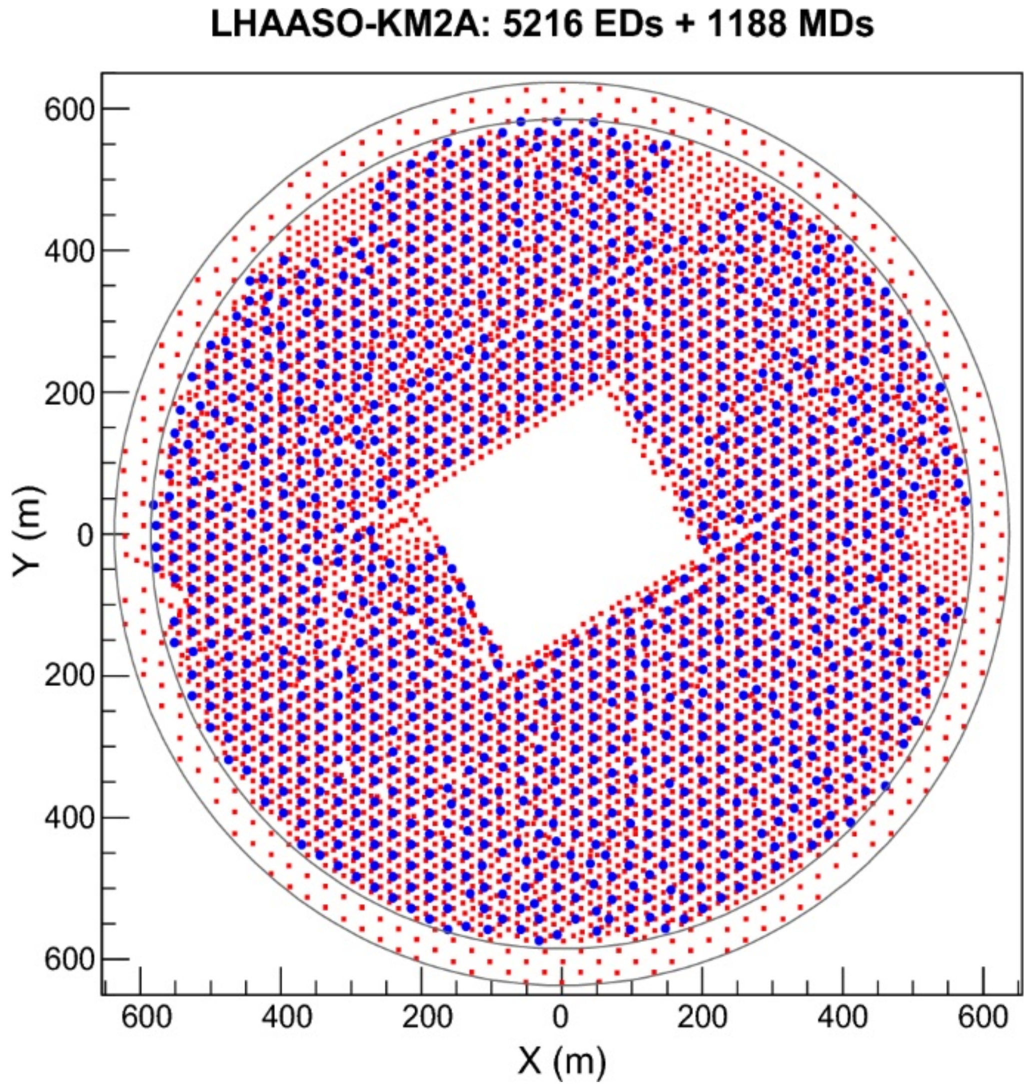
- About 3
- 78,000m
- ~ 4 x HA



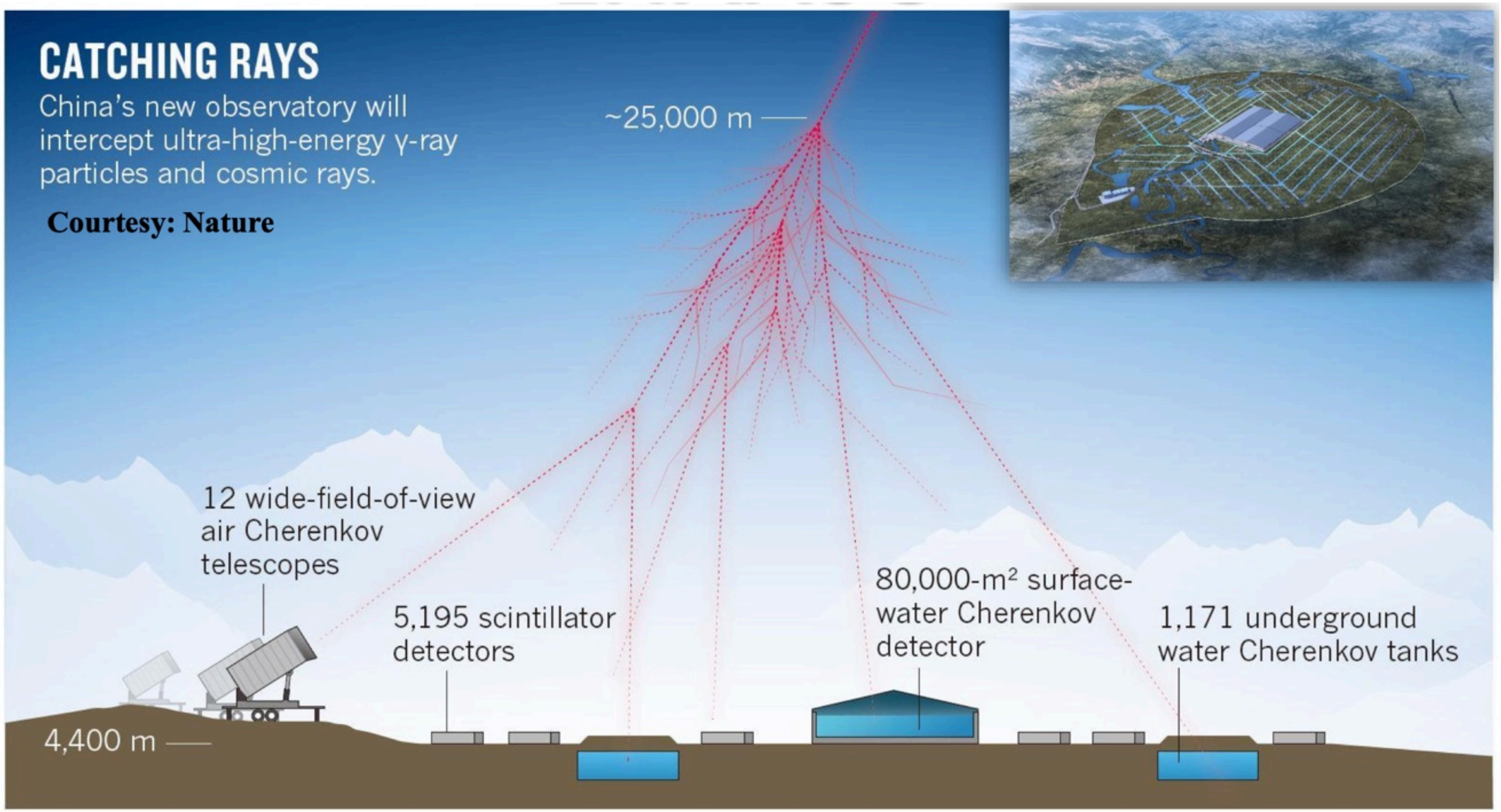
# Kilometer square array (KM2A)

- Kilometer square array (KM2A)
  - ~ 5000 ED: Electromagnetic detector
  - ~ 1000 MD: muon detectors

- Muon rich => Hadronic showers
- Electron rich => EM showers



# LHAASO observation




Prof. Zhang Yi
https://indico-tdli.sjtu.edu.cn/event/43/contributions/400/attachments/179/300/20191129LHAASOmultimsg.pdf

# LHAASO Science Highlight

arXiv > astro-ph > arXiv:2305.17030

Search... Help | Ac

Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 26 May 2023 (v1), last revised 27 Nov 2023 (this version, v2)]

**The First LHAASO Catalog of Gamma-Ray Sources**

Zhen Cao, F. Aharonian, Q. An, Axikegu, Y.X. Bai, Y.W. Bao, D. Bastieri, X.J. Bi, Y.J. Bi, J.T. Cai, Q. Cao, W.Y. Cao, Zhe Cao, J. Chang, J.F. Chang, A.M. Chen, E.S. Chen, Liang Chen, Lin Chen, Long

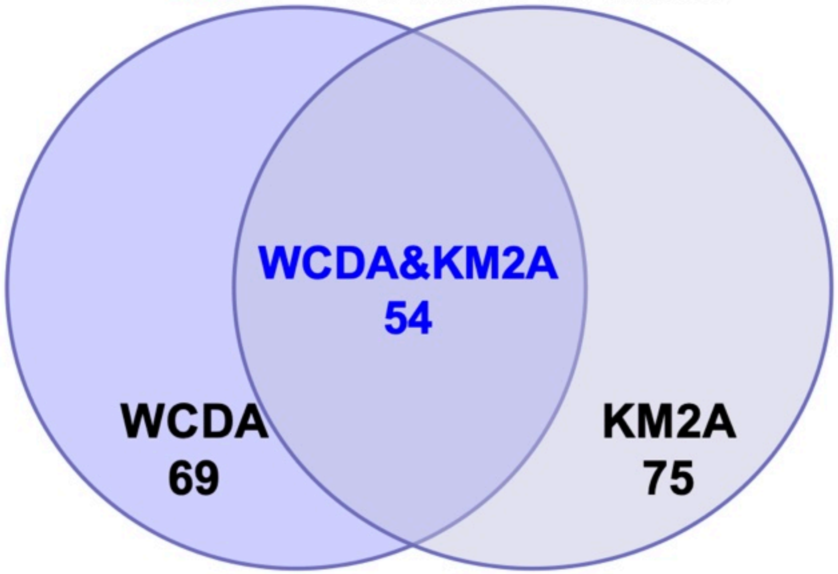
ATPEM 2025: Highlights from LHAASO D.Semikoz

## Construction of the 1st LHAASO sources

**90** 1st LHAASO sources

**WCDA&KM2A**

- Space Angle
- Position error
- Source extension




- Supernova remnants
- Pulsar wind nebulae and pulsar halos
- Gamma-ray binaries
- Young massive star clusters
- Diffuse emission
- Extragalactic sources

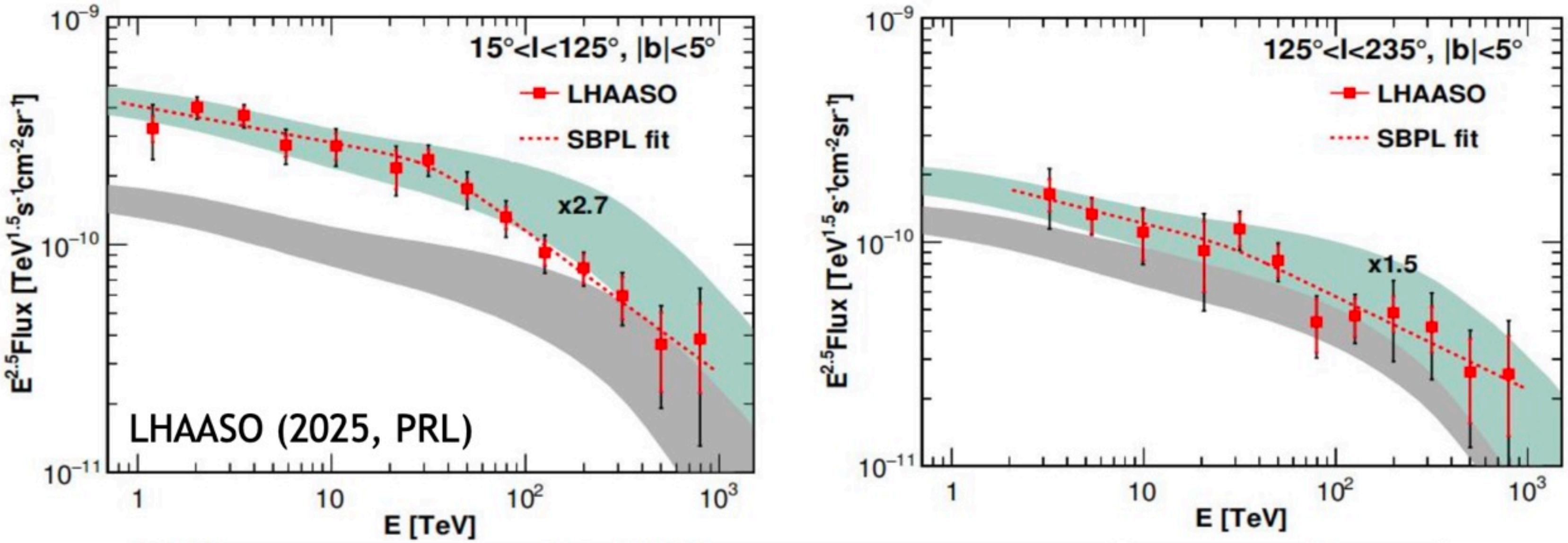
- Sources with significance >4σ at >100 TeV are labeled as UHE sources
- LHAASO: 4 -> 43

- Semikoz ATMEM 2025

# LHAASO Science Highlight

- Quan Qiang ICRC 2025

## LHAASO diffuse results



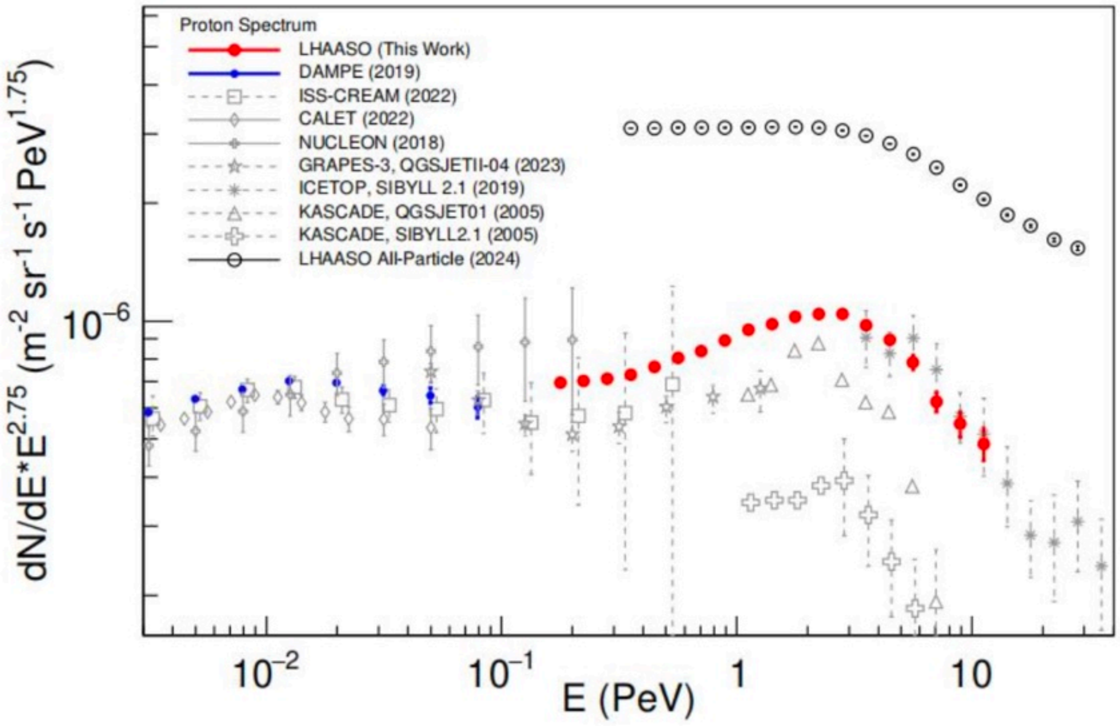

| Region | $\phi_0$ at 10 TeV ($10^{-13}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$) | $\alpha$ | $\beta$ | $E_{br}$ (TeV) |
|---|---|---|---|---|
| $15^\circ < l < 125^\circ$ (inner) | $8.88 \pm 0.53_{stat}$ | $-2.66 \pm 0.05_{stat}$ | $-3.13 \pm 0.08_{stat}$ | $32.84 \pm 11.16_{stat}$ |
| $125^\circ < l < 235^\circ$ (outer) | $3.84 \pm 0.37_{stat}$ | $-2.72 \pm 0.10_{stat}$ | $-2.92 \pm 0.10_{stat}$ | $27.86 \pm 22.49_{stat}$ |

- LHAASO gives the first detection from the outer Galactic plane (125°<l<235°)
- A spectral break around 30 TeV is revealed in the inner Galactic plane
- Measured fluxes are higher than predictions (local CR × gas column × cross section)

# LHAASO Science Highlight

- Quan Qiang ICRC 2025

## Spectrum of the proton component




- ➢ Hardening ~340 TeV, with index change ~ 0.2
- ➢ Softening (knee) ~3.3 PeV, with index change ~ -1.0
- ➢ Slightly earlier break and steeper spectrum above the break than the all-particle one

LHAASO (2505.14447)

# LHAASO New Physics search

Constraints on Heavy Decaying Dark Matter from 570 Days of LHAASO Observations

Phys. Rev. Lett. **129**, 261103 – Published 21 December 2022

LHAASO Collaboration

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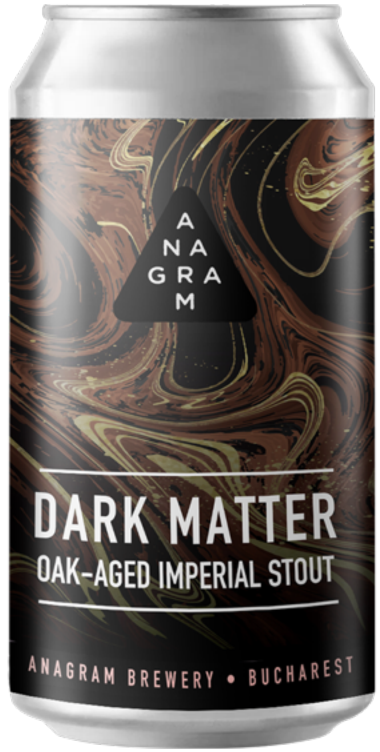
Gennaro Miele (INFN, Napoli)

Shinichiro Ando (GRAPPA, University of Amsterdam)

Damiano Fiorillo (PhD student in INFN, Napoli)



Constraints on Ultra Heavy Dark Matter Properties from Dwarf Spheroidal Galaxies with LHAASO Observations

Phys. Rev. Lett. 133, 061001 – Published 6 August, 2024

LHAASO collaboration

- Other works from the new physics group:

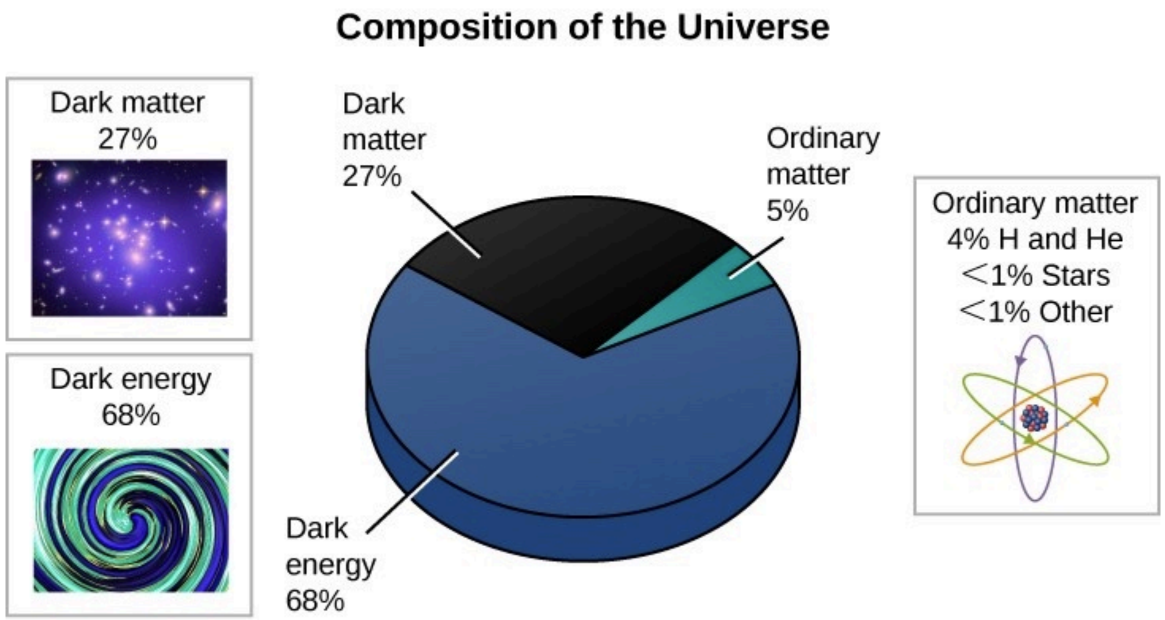
**Stringent Tests of Lorentz Invariance Violation from LHAASO Observations of GRB 221009A**

LHAASO Collaboration • Zhen Cao (Beijing, Inst. High Energy Phys. and Beijing, GUCAS and TIANFU CRRC, Chengdu) et al. (Feb 8, 2024)

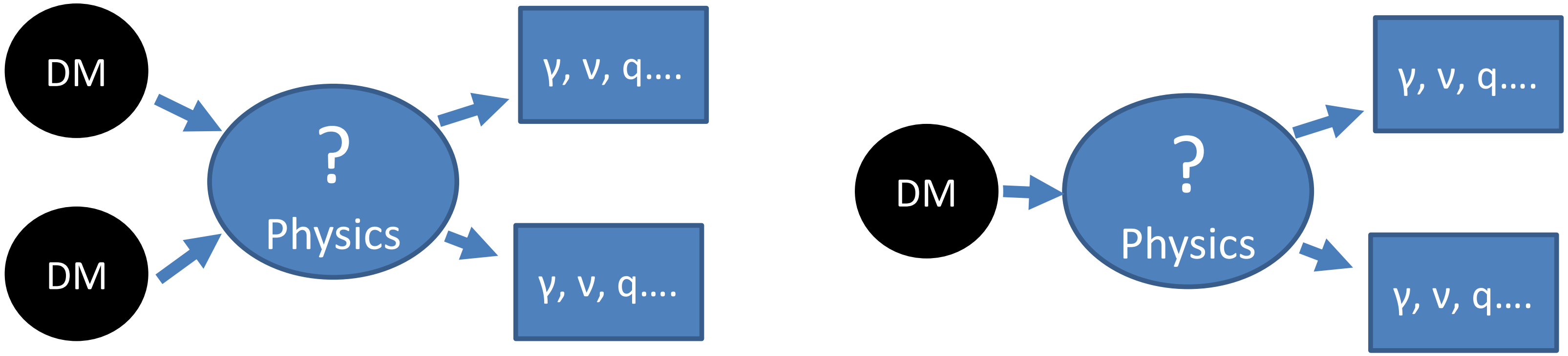
Published in: *Phys.Rev.Lett.* 133 (2024) 7, 071501 • e-Print: 2402.06009 [astro-ph.HE]

# The $\Lambda CDM$ model

- ~70% dark energy/cosmological constant
- ~30% Matter
  - ~25% Dark Matter
  - No particles in the Standard Model of particle physics can explain DM
  - New (Particle) Physics!
-



# Indirect Detection




- Dark Matter could annihilate or decay into standard model particles
- Final products include
  - gamma rays
  - neutrinos
  - electrons/positrons, etc

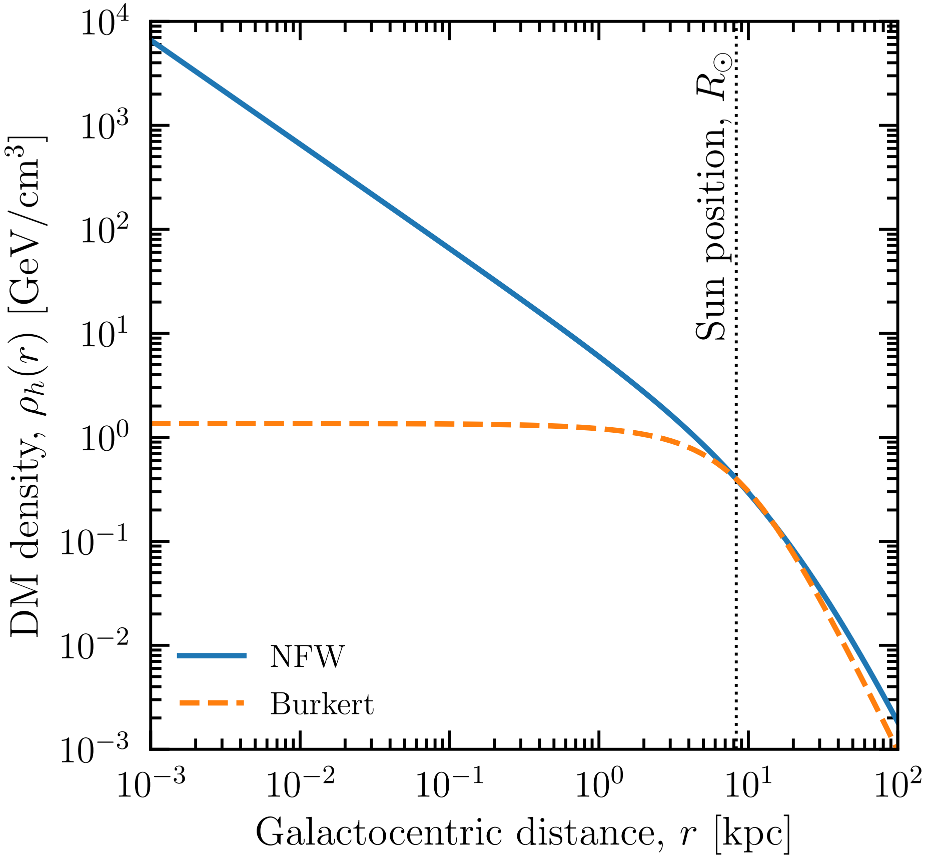
# Prompt component

$$\frac{\mathrm{d}I_\gamma^{\mathrm{prompt}}}{\mathrm{d}E_\gamma} = \frac{1}{4\pi\, m_{\mathrm{DM}}\tau_{\mathrm{DM}}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} D(E_\gamma, b, \ell)$$

***D-factor***

$$D(E_\gamma, b, \ell) = \int_0^\infty \mathrm{d}s\, \rho_h\,[r(s,b,\ell)]\, e^{-\tau_{\gamma\gamma}(E_\gamma, s, b, \ell)}$$

*Photon attenuation*
*(CMB and SL+IR from **GALPROPv54**)*




**Different halo profiles**

- Navarro-Frenk-White (NFW)
- Burkert

**In our ROI, only small dependence on it**

$$\int D\,\mathrm{d}\Omega \simeq 6.26\,(5.85) \times 10^{21}\ \mathrm{GeV/cm^2}$$

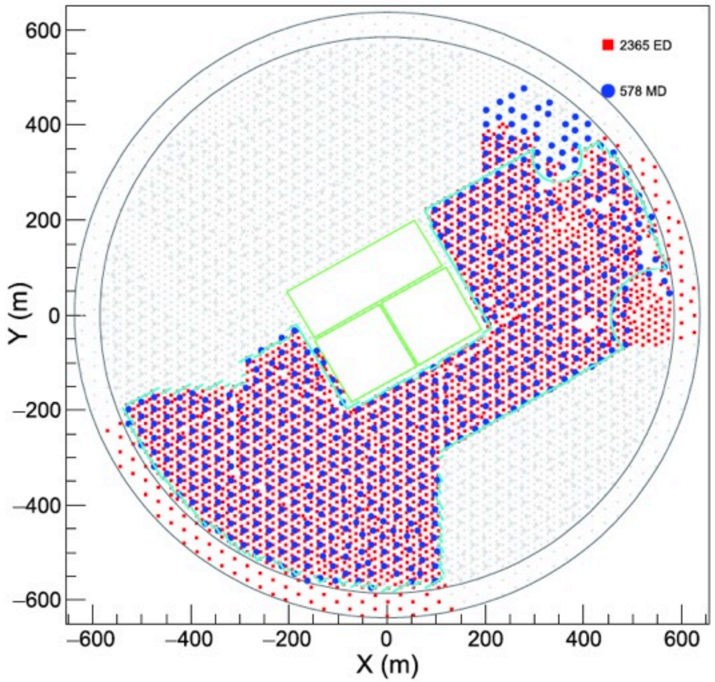
*at $10^5$ GeV for NFW (Burkert) profile*

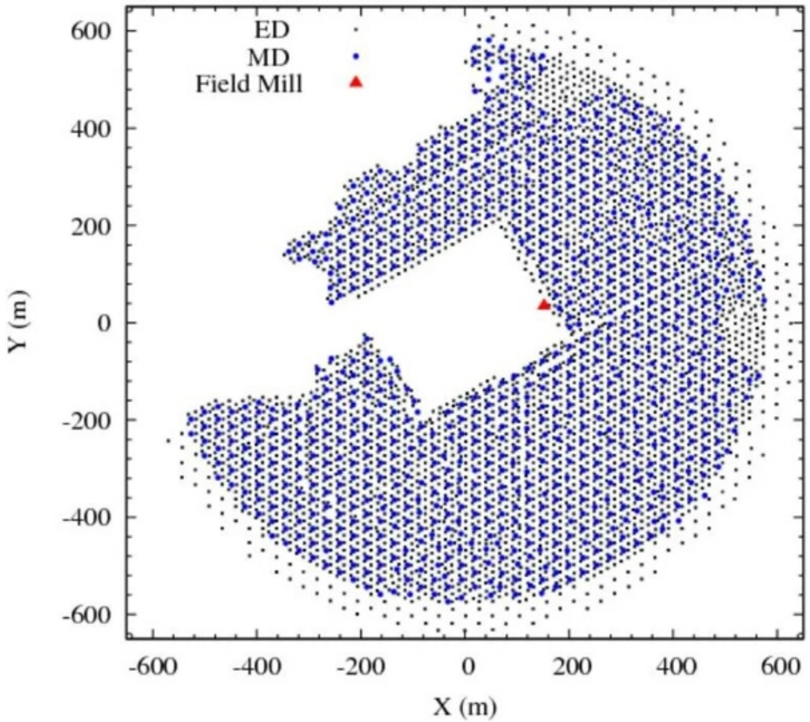
# This work: (1/2 + 3/4) KM2A

- 1/2 KM2A: 340 days
- 3/4 KM2A: 230 days
- Full array completed in July 2021

Constraints on Heavy Decaying Dark Matter from 570 Days of LHAASO Observations

Phys. Rev. Lett. **129**, 261103

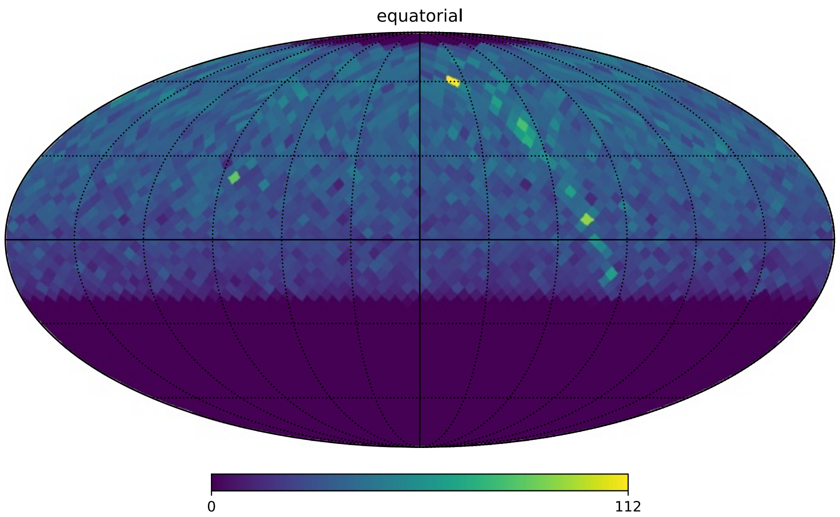


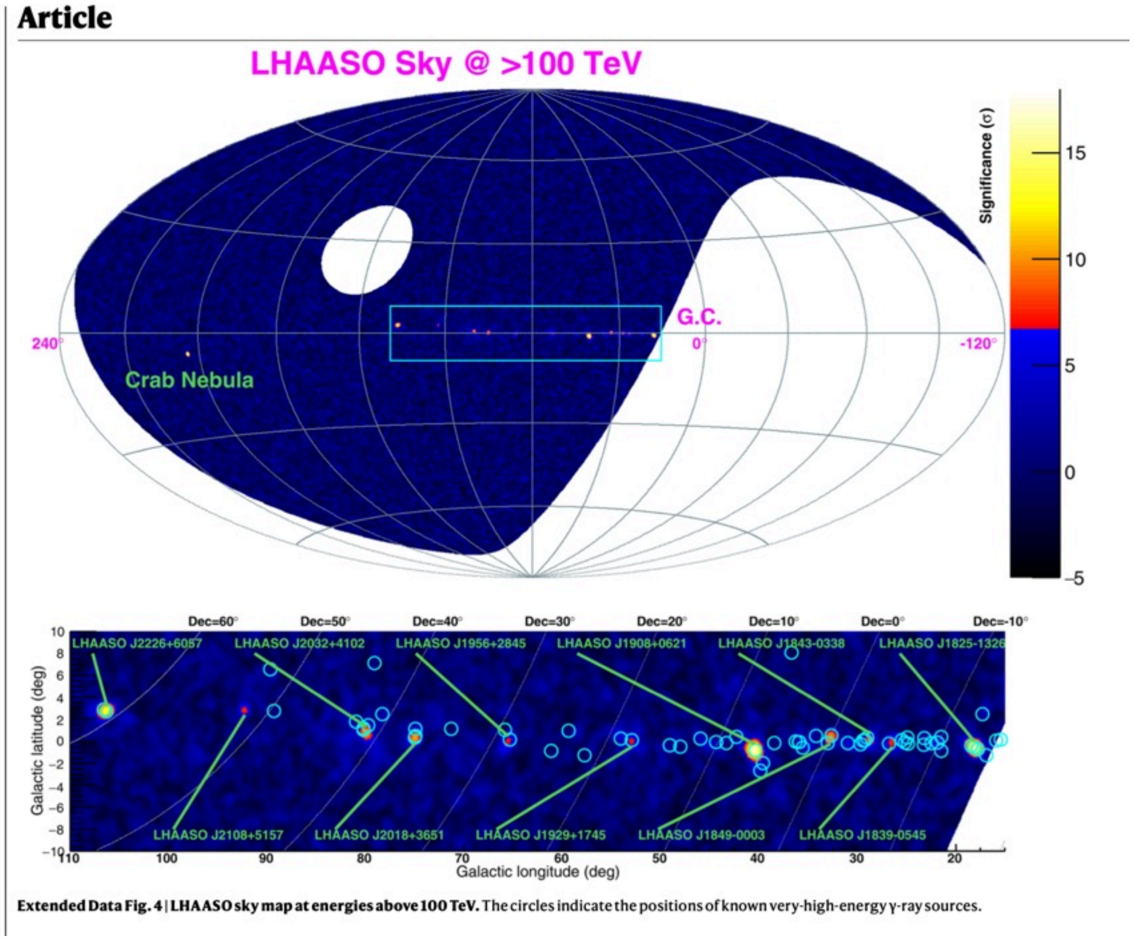
# LHAASO data

- LHAASO sky map

Equatorial coordinate




Galactic Coordinate

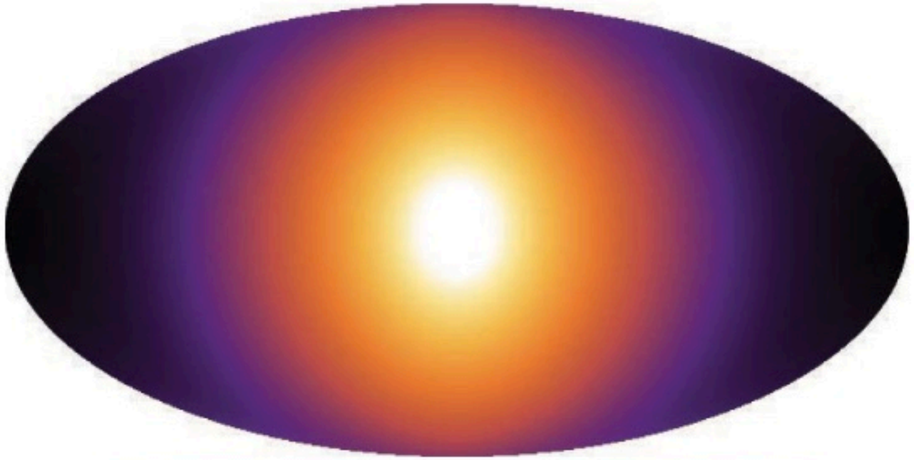



**Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV.** The circles indicate the positions of known very-high-energy γ-ray sources.

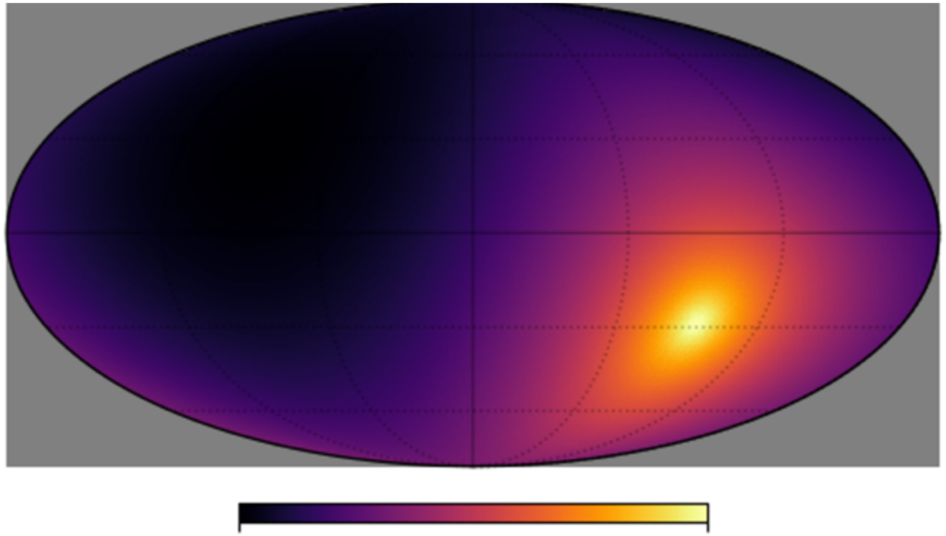
Cao et al
Nature 2021

# Dark Matter signal map

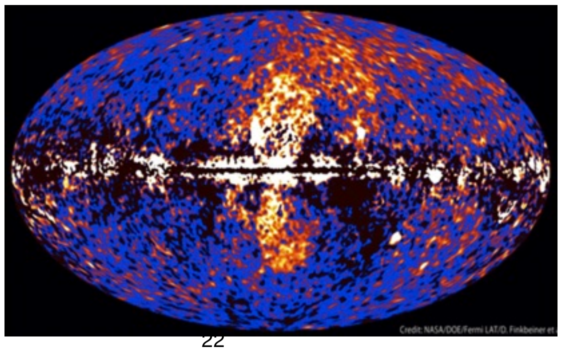
Galactic Coordinate

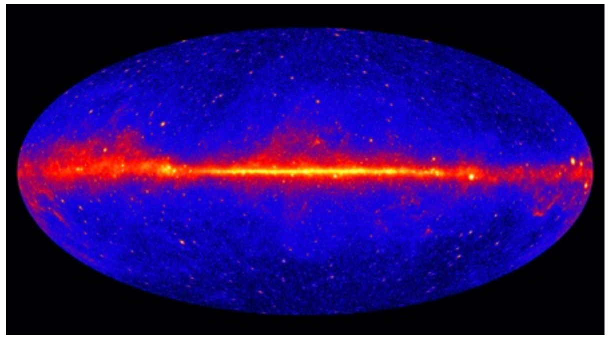


Equitorial Coordinate



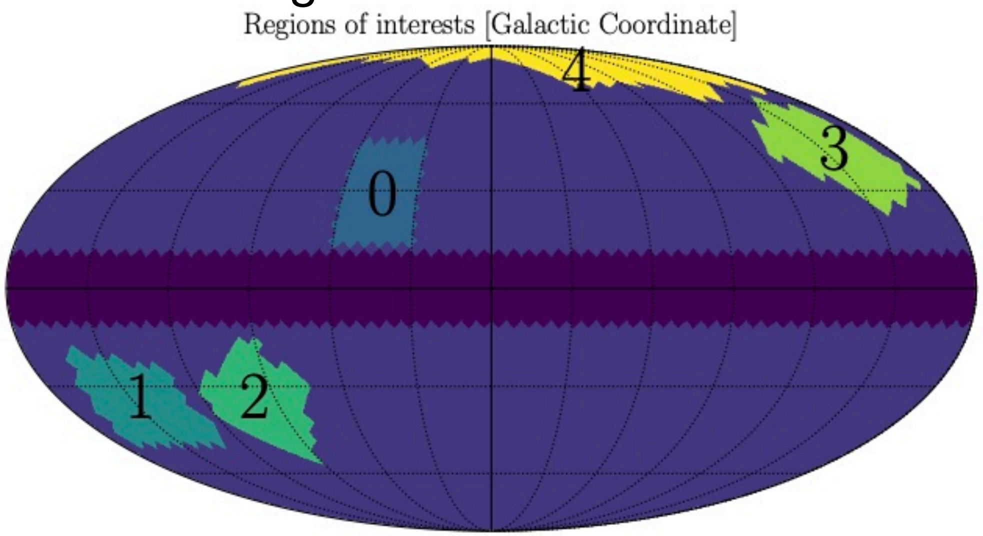
- Potential backgrounds from
  - galactic plane
  - Fermi bubble



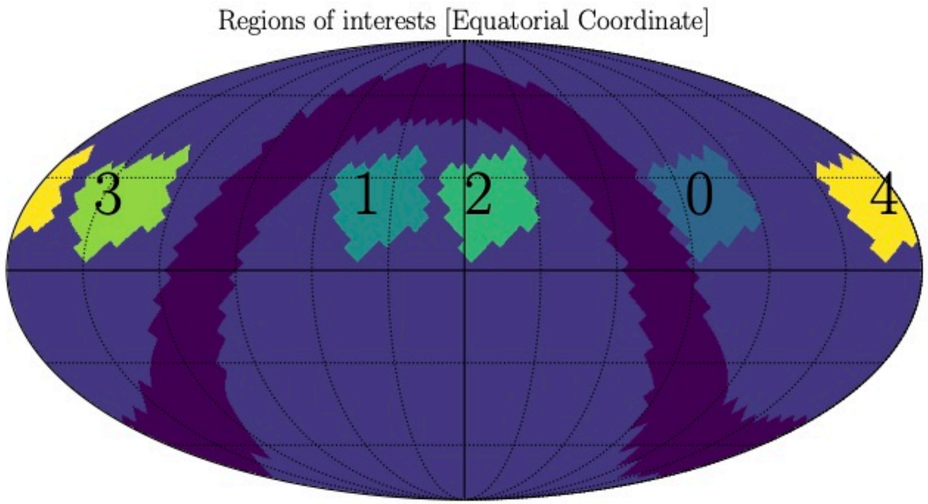


# Dark Matter signal map

- 5 regions of interests
  - exclude Fermi bubble and the plane
- 0:  closest to galactic center (signal)
- 1-4: away from galactic center
  - control regions

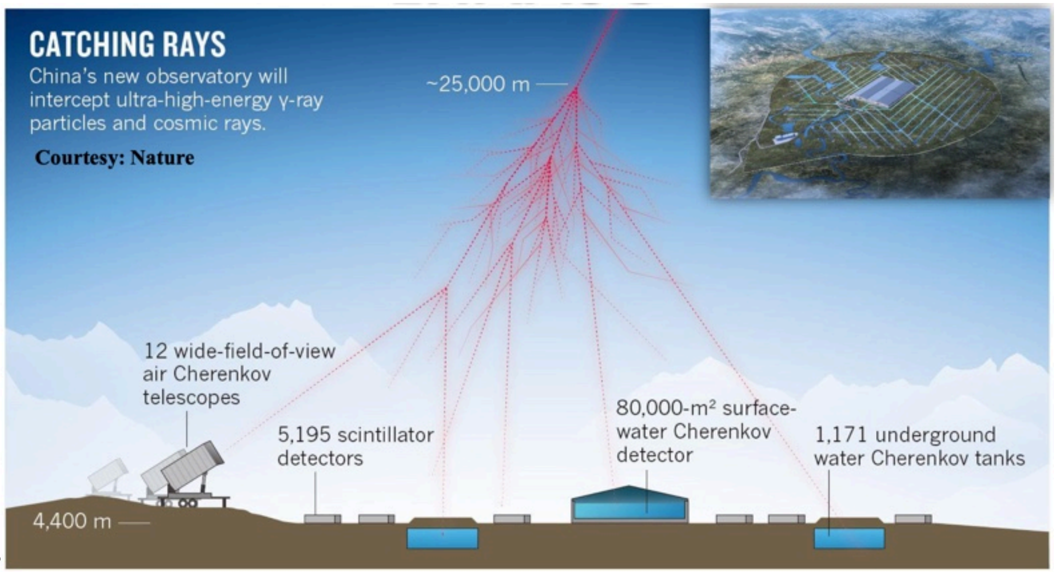


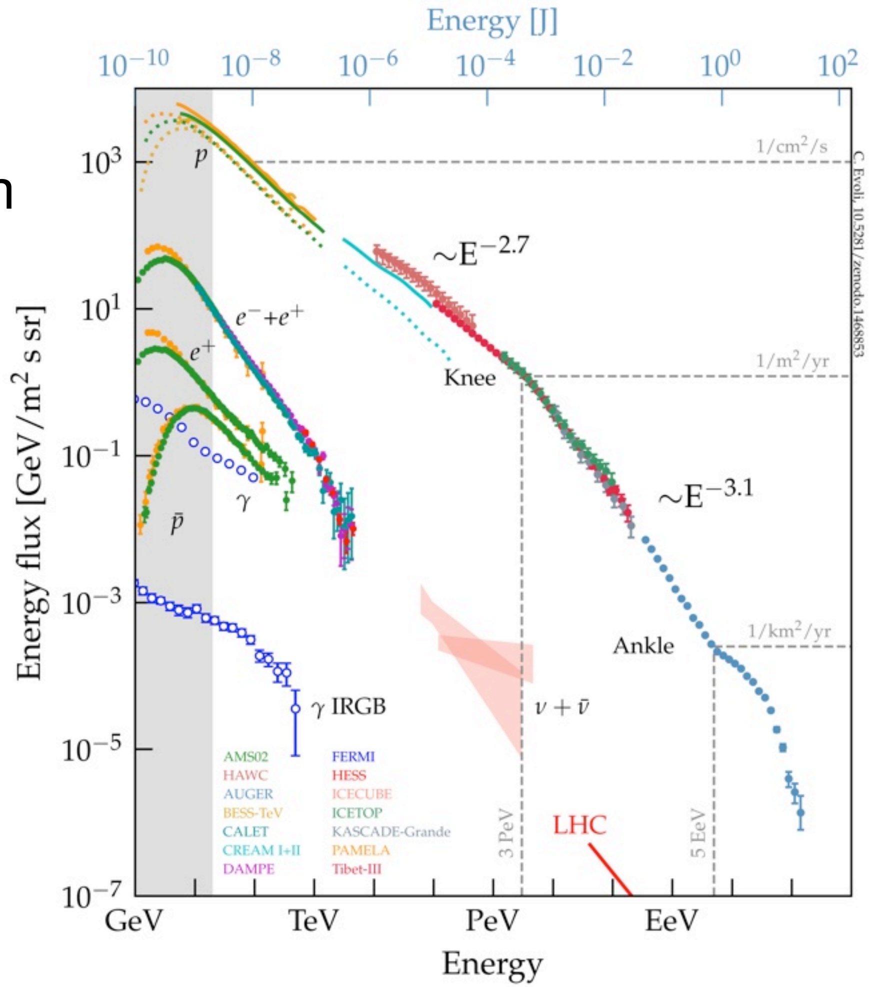

- Control regions:
  - same declination
  - same detector performance
  - for accurate background estimate
- Difference DM signal expectation



# data reduction

- Most of the air showers are hadronic showers from protons etc
- Dominant background to remove

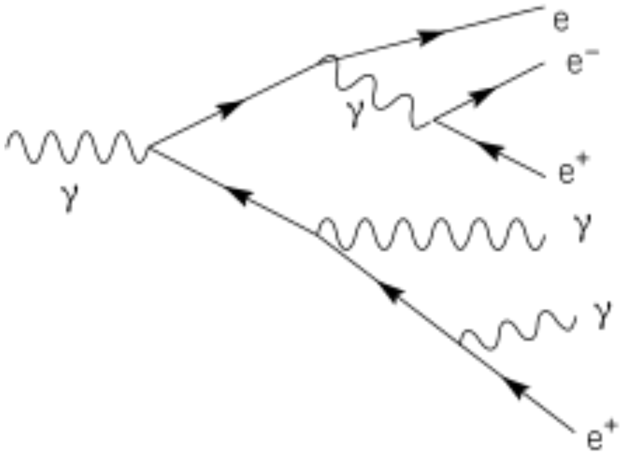


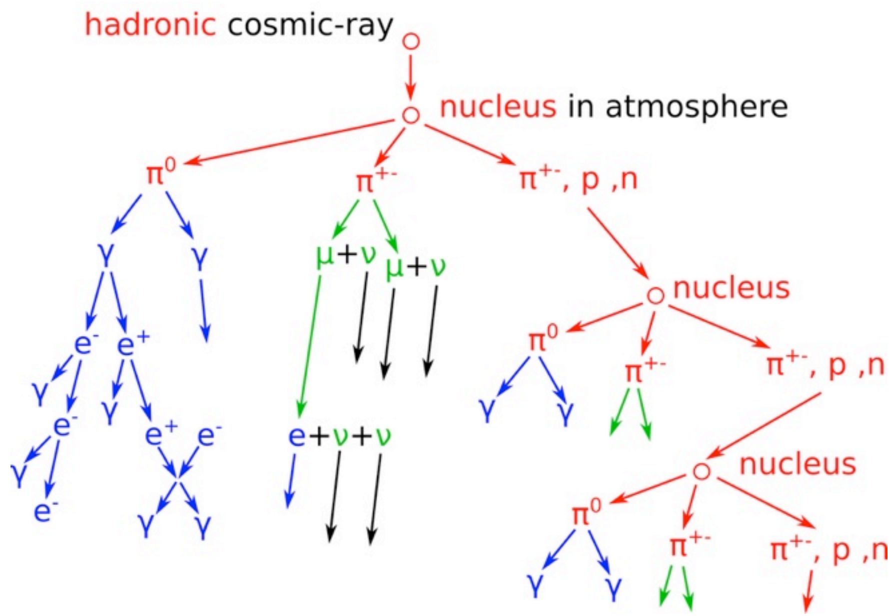



# data reduction

- gamma rays: EM shower (muon poor)
- protons/nuclei: hadronic showers (muon rich)
- The ED and MD are efficient gamma/hadron seperators

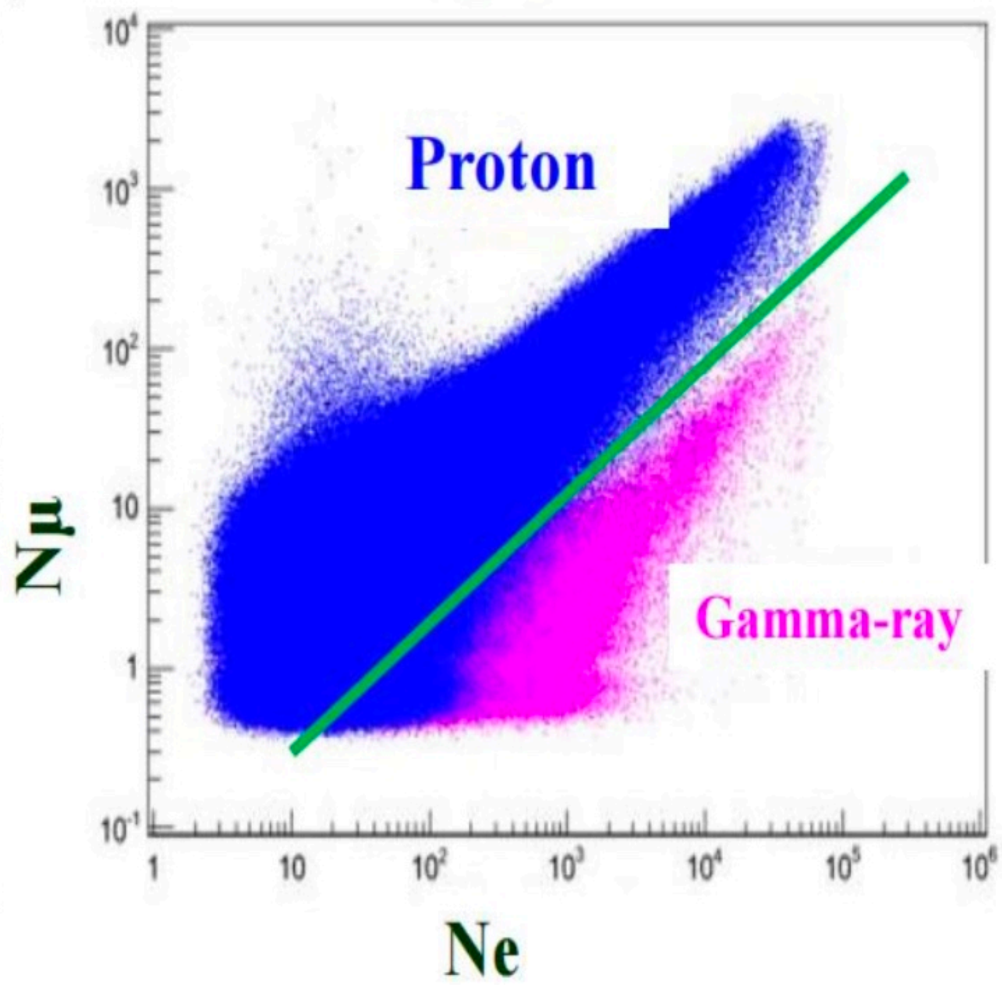
$$R = \log \frac{N_\mu + 0.0001}{N_e}$$



# gamma/hadron seperation

- LHAASO performance study paper
- https://arxiv.org/pdf/2010.06205.pdf
- After the gamma-hadron cut
  - some hadrons survive
  - some gamma would be cut




- KM2A is “background free” at high energy

https://arxiv.org/pdf/2010.06205.pdf

# Dark Matter signal search

- Hypothesis

- Total observed event for each ROI (k)
- = dark matter + background (b)

$$n_k^i(\tau_{\rm DM}, b) = (b^i + s_k^i(\tau_{\rm DM}))\mathcal{E}_k^i \Delta\Omega,$$

$$s_k^i(\tau_{\rm DM}) = \frac{1}{\Delta\Omega}\int d\Omega dE_\gamma \left(\frac{dI_\gamma^{\rm prompt}}{dE_\gamma} + \frac{dI_\gamma^{\rm IC}}{dE_\gamma}\right)$$

TABLE I. Residual events after $\gamma$/hadron separation in the search ($\mathrm{ROI}_0$) and control ($\mathrm{ROI}_1 - \mathrm{ROI}_4$) regions with an observations of 340 days with 1/2-KM2A and 230 days with 3/4-KM2A.

| Energy bin [$\log_{10}(E/\mathrm{GeV})$] | $N_{\mathrm{ROI}_0}$ | $N_{\mathrm{ROI}_1}$ | $N_{\mathrm{ROI}_2}$ | $N_{\mathrm{ROI}_3}$ | $N_{\mathrm{ROI}_4}$ |
|---|---|---|---|---|---|
| 5.0–5.2 | 1209 | 1210 | 1112 | 1160 | 1157 |
| 5.2–5.4 | 150 | 147 | 148 | 150 | 153 |
| 5.4–5.6 | 51 | 58 | 51 | 41 | 43 |
| 5.6–5.8 | 15 | 13 | 14 | 6 | 9 |
| 5.8–6.0 | 7 | 7 | 2 | 1 | 7 |
| 6.0–6.2 | 1 | 0 | 3 | 1 | 2 |

- $\mathcal{E}_k^i$: detector exposure, by tracking the ROI across the sky, compared with MC

# Dark Matter signal search

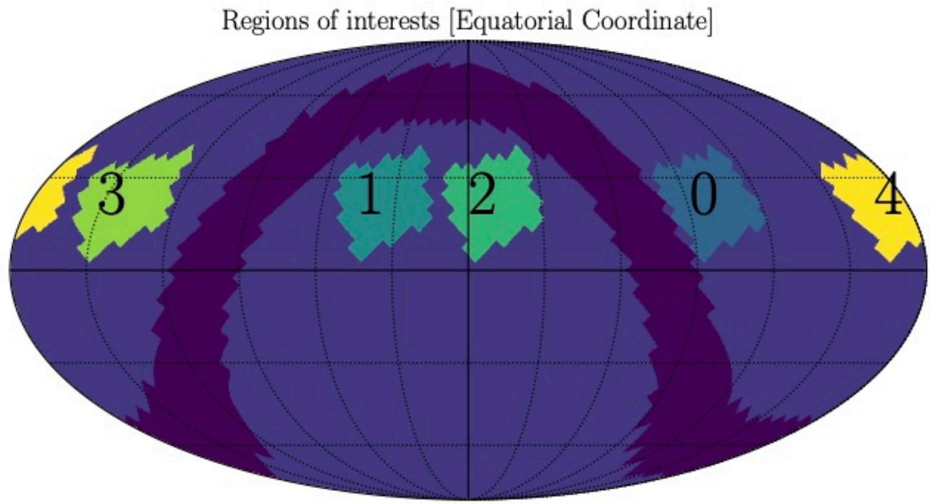
- Important features of this analysis

$$n_k^i(\tau_{\mathrm{DM}}, b) = (b^i + s_k^i(\tau_{\mathrm{DM}}))\mathcal{E}_k^i \Delta\Omega,$$

- The background model $b^i$, is independent of ROI

- Signal $s_k^i$ , is different for each ROI, due to difference in D-factor

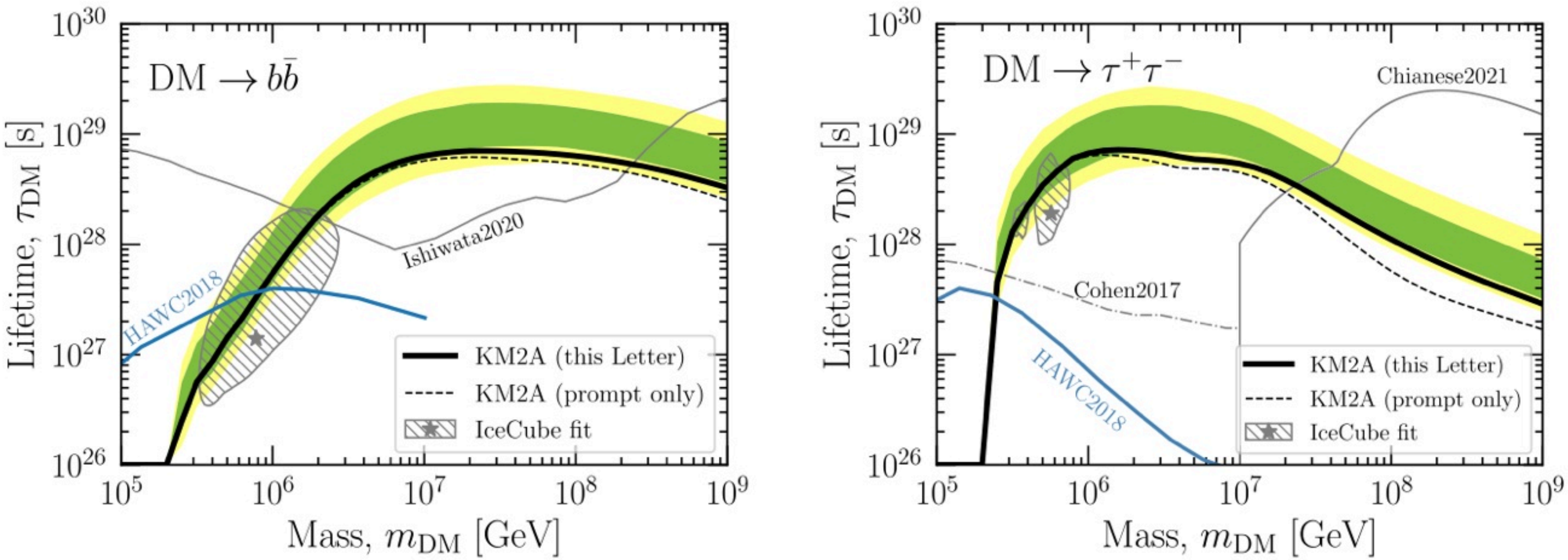
- We assume that we don't know $b^i$
    - allow it to be a free parameter (6 degrees of freedom)




| $\log_{10}(E_\gamma/\mathrm{GeV})$ | $D$-factor $[10^{22}\ \mathrm{GeV/cm^2}]$ | | | | | $N_{\mathrm{DM}}(\mathrm{ROI}_0)$ |
|---|---|---|---|---|---|---|
| | $\mathrm{ROI}_0$ | $\mathrm{ROI}_1$ | $\mathrm{ROI}_2$ | $\mathrm{ROI}_3$ | $\mathrm{ROI}_4$ | $\mathrm{DM} \to b\bar{b}$, $\tau_{\mathrm{DM}} = 6.3 \times 10^{28}$ s |
| 5.0 – 5.2 | 2.68 | 1.18 | 1.55 | 1.20 | 1.60 | 83.6 |
| 5.2 – 5.4 | 2.59 | 1.13 | 1.49 | 1.15 | 1.54 | 41.9 |
| 5.4 – 5.6 | 2.22 | 0.96 | 1.26 | 0.97 | 1.31 | 20.8 |
| 5.6 – 5.8 | 1.66 | 0.73 | 0.95 | 0.74 | 0.98 | 6.6 |
| 5.8 – 6.0 | 1.24 | 0.57 | 0.73 | 0.58 | 0.76 | 1.7 |
| 6.0 – 6.2 | 1.02 | 0.49 | 0.62 | 0.50 | 0.64 | 0.4 |

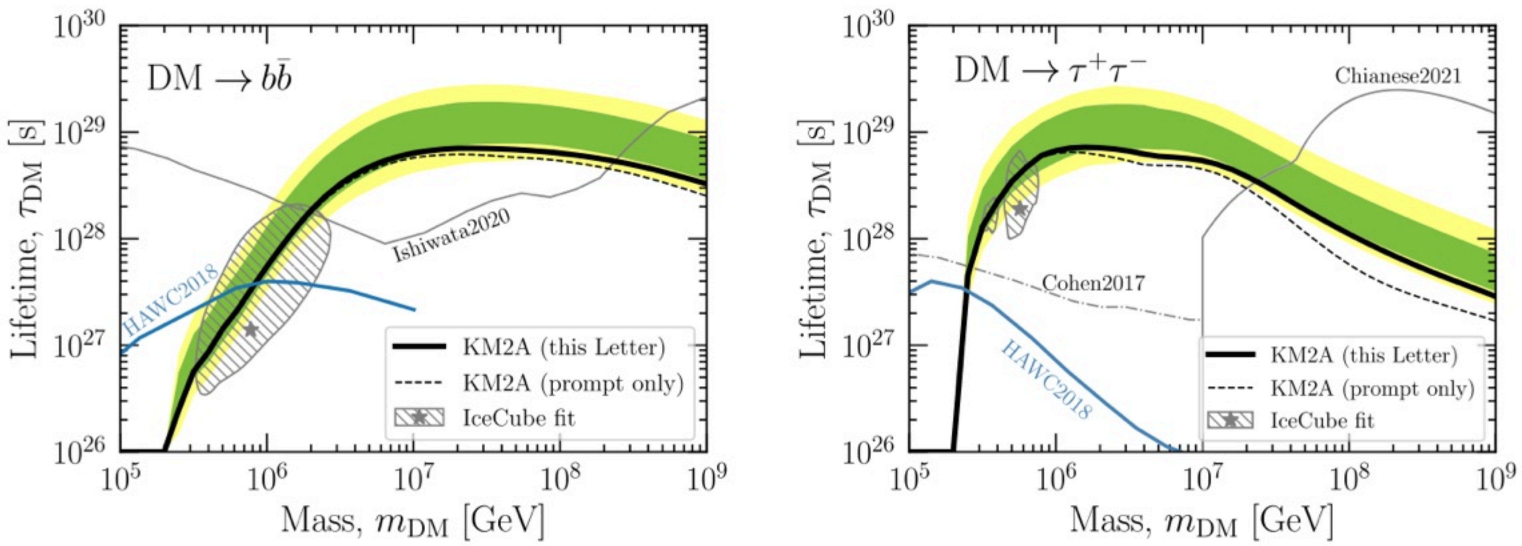
# Results

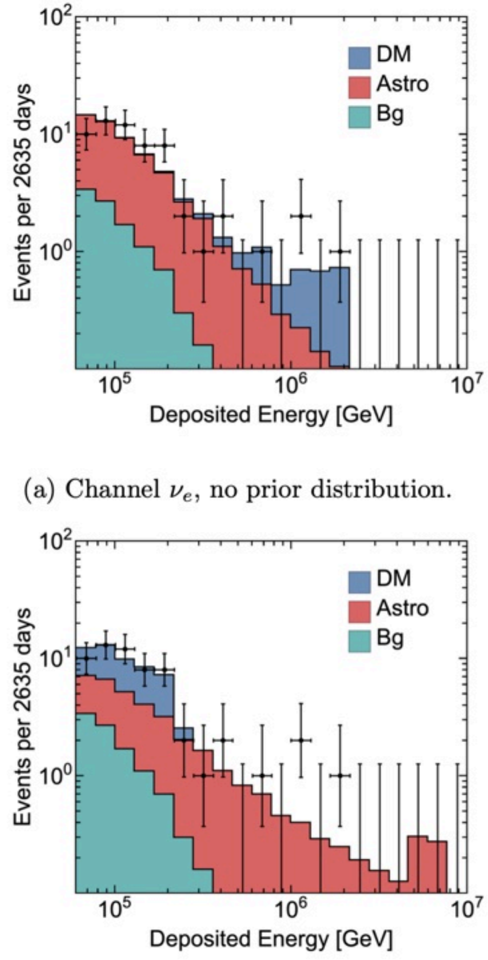
- Lifetime limit plot vs DM mass
- Our results: black solid line
- green (68%) and yellow (95%) band obtained from monte carlo simulation for expected limit



# Implication for IceCube Signal interpretation

- DM has been proposed as an explanation for IceCube events




(a) Channel $\nu_e$, no prior distribution.

(c) Channel $W$, no prior distribution.

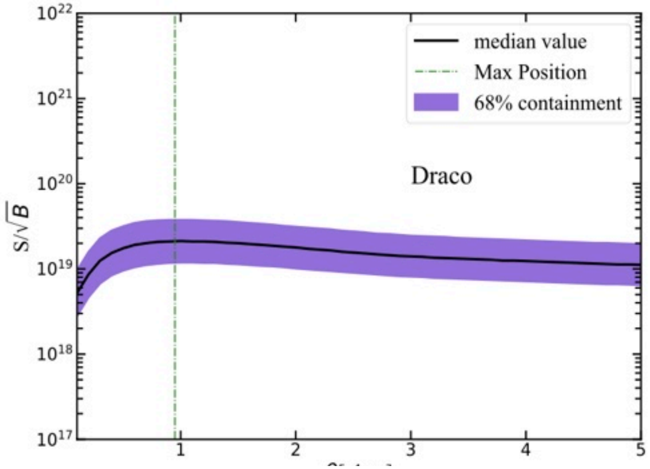
https://arxiv.org/abs/1907.11222

- LHAASO strongly constrain some IceCube DM interpretation

# WCDA + KM2A dSphs analysis

Phys. Rev. Lett. 133, 061001

- A stacked, optimised point source analysis



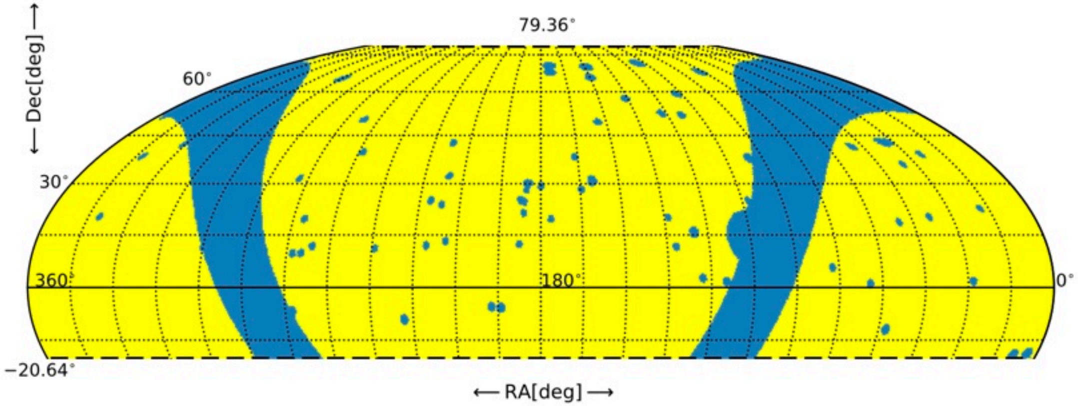




TABLE I. The ROI half width and J- (D-) factor for 16 dSphs considered in this analysis.

| Name | $\log_{10}(J_\theta/\mathrm{GeV}^2\mathrm{cm}^{-5})$ | $\theta_{\mathrm{anni}}$[deg] | $\log_{10}(D_\theta/\mathrm{GeVcm}^{-2})$ | $\theta_{\mathrm{decay}}$[deg] |
|---|---|---|---|---|
| Draco | $18.96^{+0.16}_{-0.15}$ | 1.0 | $19.38^{+0.24}_{-0.32}$ | 2.3 |
| Ursa Minor | $18.79^{+0.12}_{-0.11}$ | 1.0 | $18.68^{+0.33}_{-0.15}$ | 2.1 |
| Ursa Major I | $18.40^{+0.28}_{-0.27}$ | 0.9 | $18.64^{+0.50}_{-0.48}$ | 1.8 |
| Ursa Major II | $19.70^{+0.43}_{-0.43}$ | 1.0 | $19.41^{+0.43}_{-0.57}$ | 2.0 |
| Bootes 1 | $18.39^{+0.36}_{-0.37}$ | 0.9 | $18.77^{+0.40}_{-0.54}$ | 1.8 |
| Canes Venatici I | $17.43^{+0.16}_{-0.15}$ | 0.8 | $18.19^{+0.40}_{-0.39}$ | 1.3 |
| Coma Berenices | $19.26^{+0.35}_{-0.43}$ | 0.9 | $19.12^{+0.46}_{-0.73}$ | 1.8 |
| Leo I | $17.58^{+0.10}_{-0.10}$ | 0.8 | $18.44^{+0.33}_{-0.42}$ | 1.4 |
| Segue 1 | $19.25^{+0.60}_{-0.69}$ | 0.8 | $18.33^{+0.69}_{-0.63}$ | 0.8 |
| Sextans | $17.80^{+0.10}_{-0.10}$ | 1.0 | $18.49^{+0.28}_{-0.21}$ | 1.8 |
| Canes Venatici II | $17.82^{+0.38}_{-0.37}$ | 0.8 | $18.45^{+0.50}_{-0.74}$ | 1.4 |
| Hercules | $17.60^{+0.53}_{-0.69}$ | 0.8 | $17.79^{+0.62}_{-0.61}$ | 1.0 |
| Leo II | $17.72^{+0.18}_{-0.17}$ | 0.8 | $17.85^{+0.62}_{-0.40}$ | 1.0 |
| Willman I | $19.80^{+0.50}_{-0.52}$ | 0.9 | $19.00^{+0.71}_{-0.93}$ | 1.5 |
| Aquarius 2 | $18.57^{+0.50}_{-0.57}$ | 1.1 | $18.53^{+0.61}_{-0.68}$ | 1.3 |
| Leo T | $17.66^{+0.55}_{-0.52}$ | 0.8 | $17.88^{+0.65}_{-0.69}$ | 1.0 |

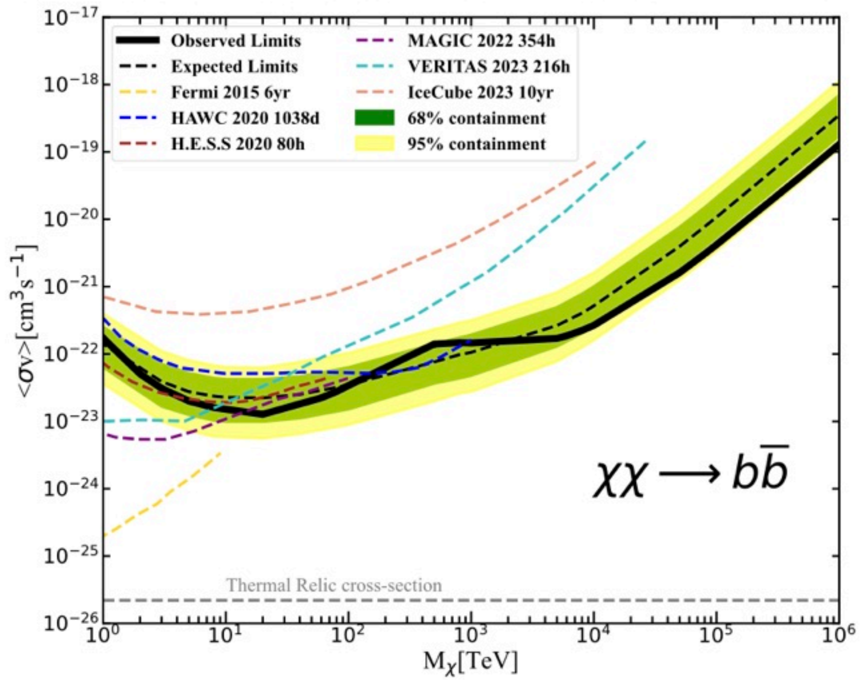
dSphs Modeling
Pace, Strigari
https://arxiv.org/abs/1802.06811

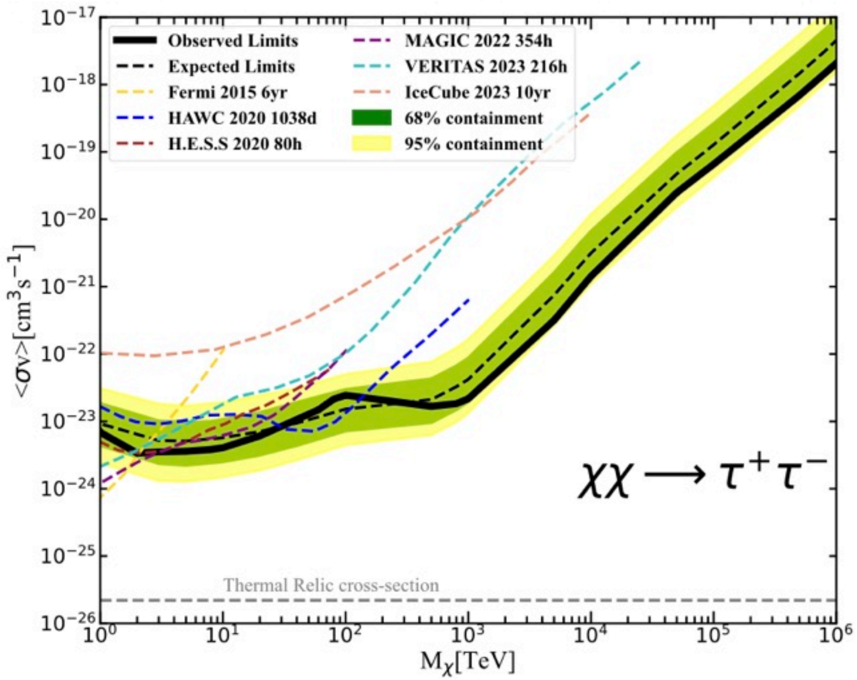
# WCDA + KM2A dSphs analysis

Phys. Rev. Lett. 133, 061001

- Standard cuts for both WCDA and KM2A
- Background estimation from "Direct Integration" method
- First LHAASO annihilation result.

- WCDA 756 days
  - March 5 2021 to March 31 2023
- KM2A 795 days
  - 1/2 + 3/4 + full array up to Feb 28 2022

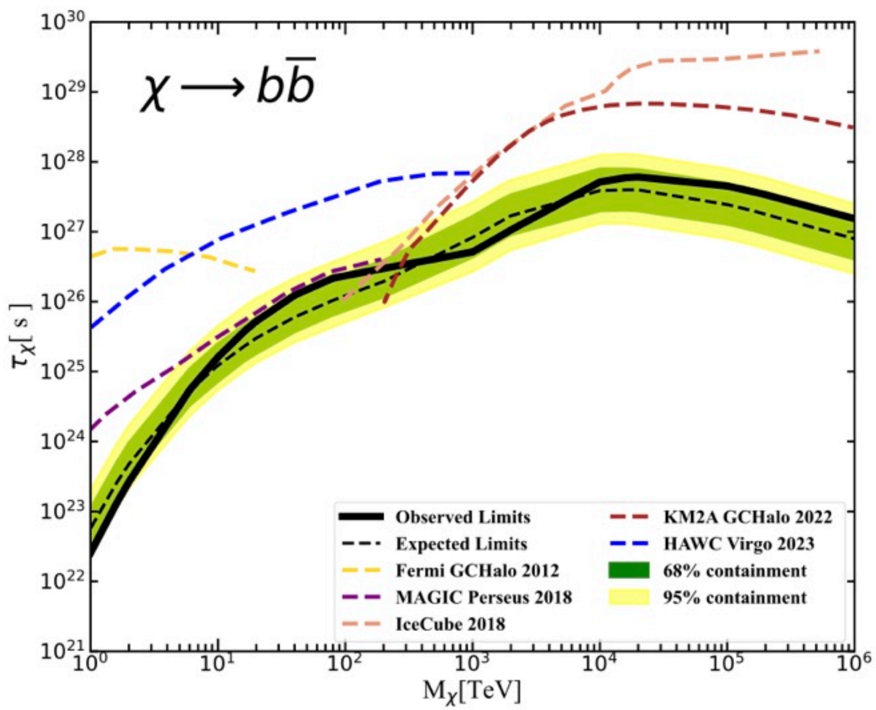


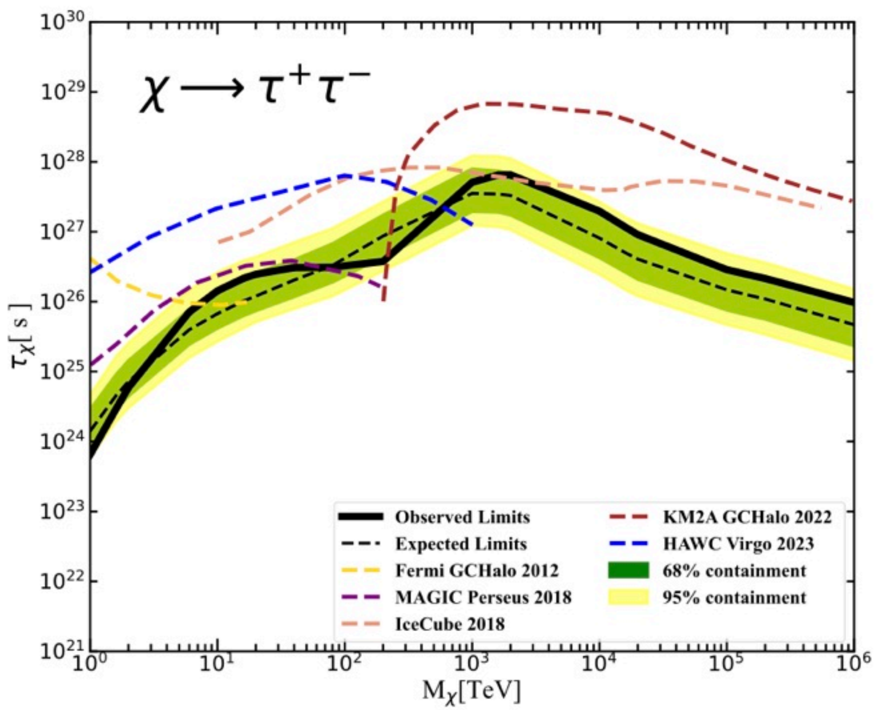



# WCDA + KM2A dSphs analysis

Phys. Rev. Lett. 133, 061001

- Decay analysis not competitive, not surprising



# Full sky analysis (on-going)

WCDA :

20210331-20250731

1484.363 Effective days

7 Nhit bins

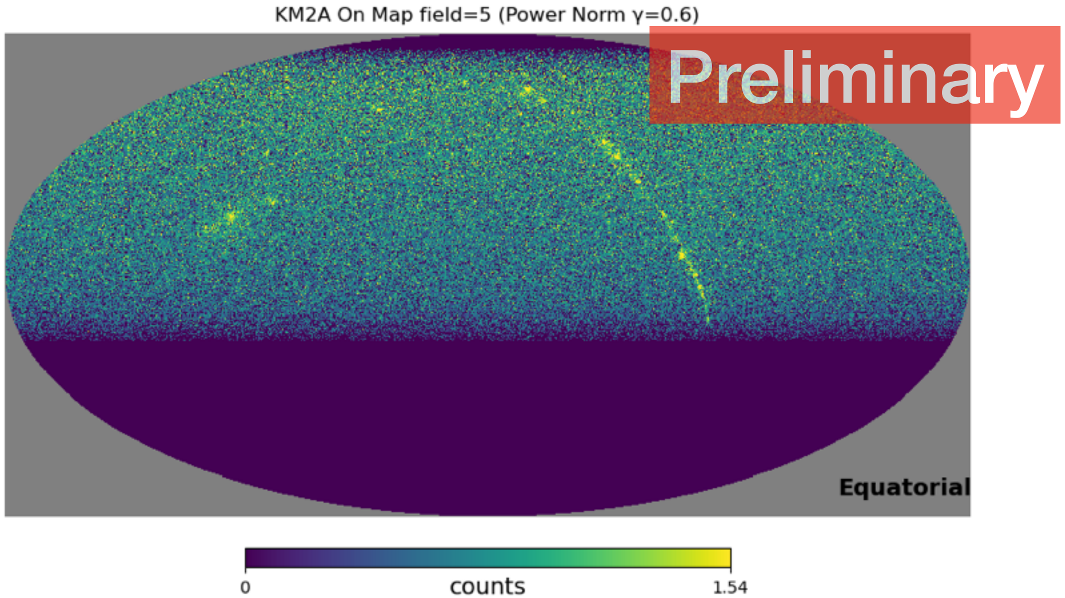
KM2A full array:

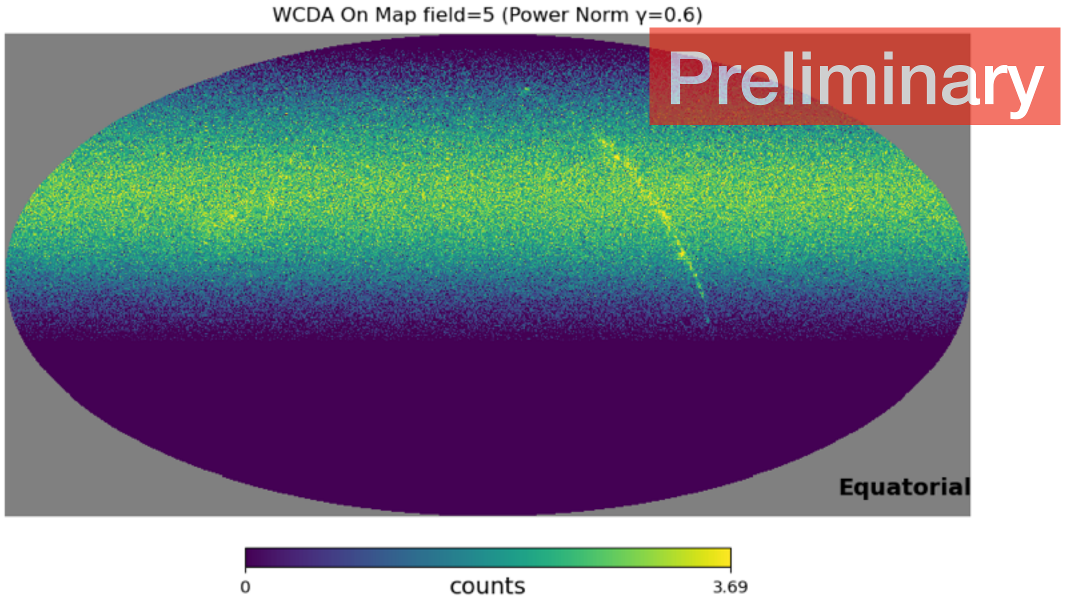
20210720-20250731

1438.810 Effective days

> 10TeV , 11 Energy bins

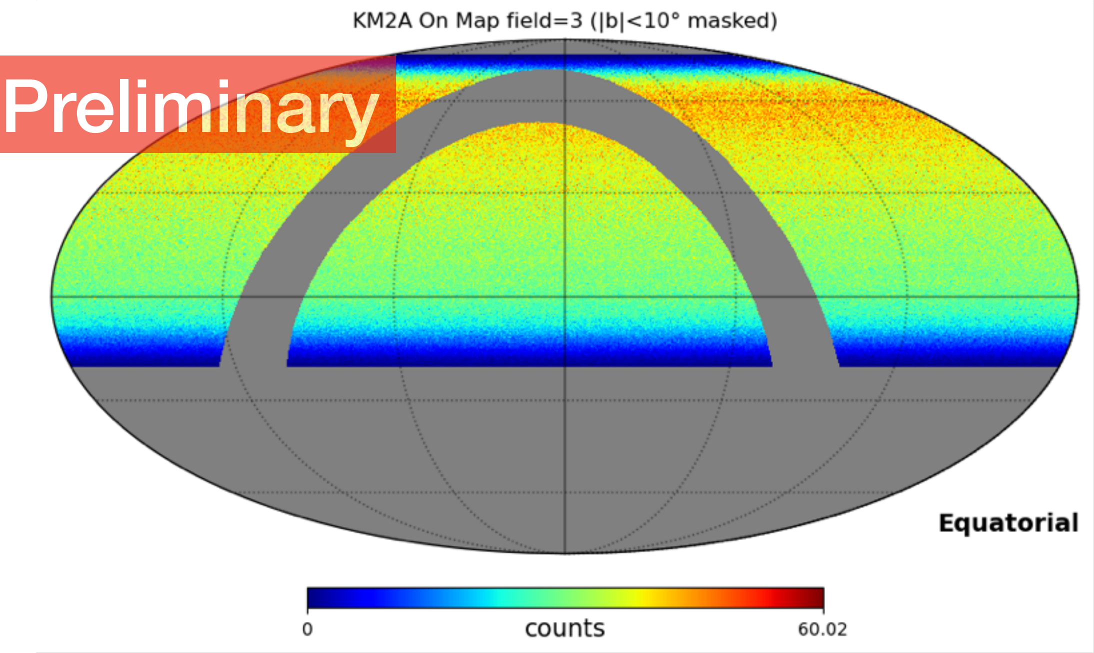
Official released sky map data with standard gamma/hadron cut

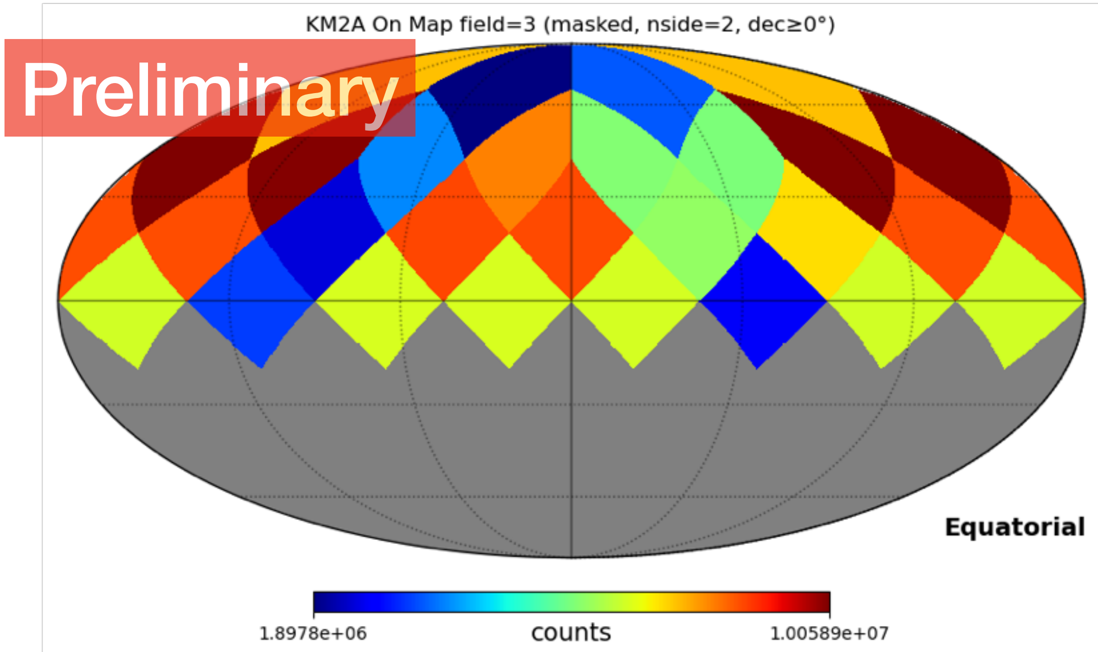


# Down-sizing after source removal

- Galactic planes plus known sources (To do)



# Direct Integration method

THE ASTROPHYSICAL JOURNAL, 750:63 (9pp), 2012 May 1

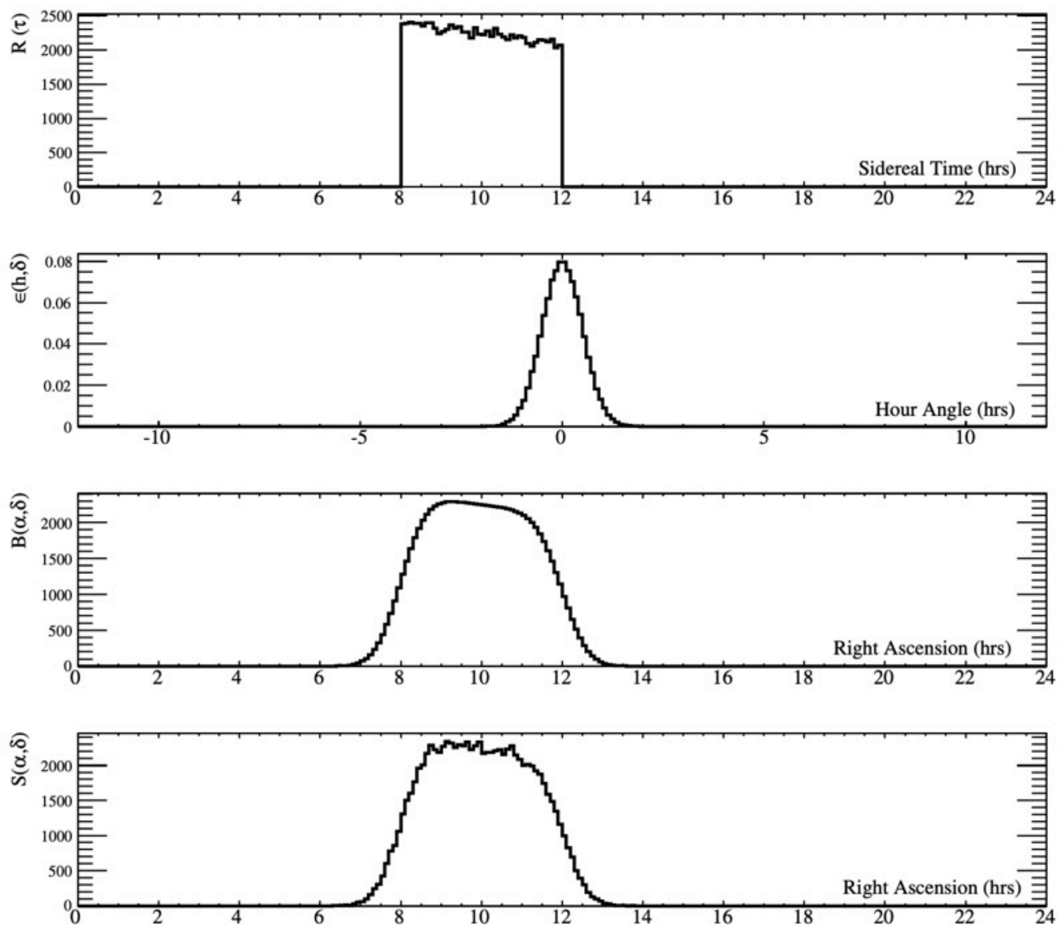
- Example from MILARGO
- Fixed declination
  - 1D sky distribution in RA
- Integration within a time window, 2 - 24 hour
- Assumes stable background contribution within the time window
- Small time window filters ours slow varying background
- Large time window hard to find
- Time consuming

**(1) Event rate (time)**

**(2) Detector efficiency from real events**

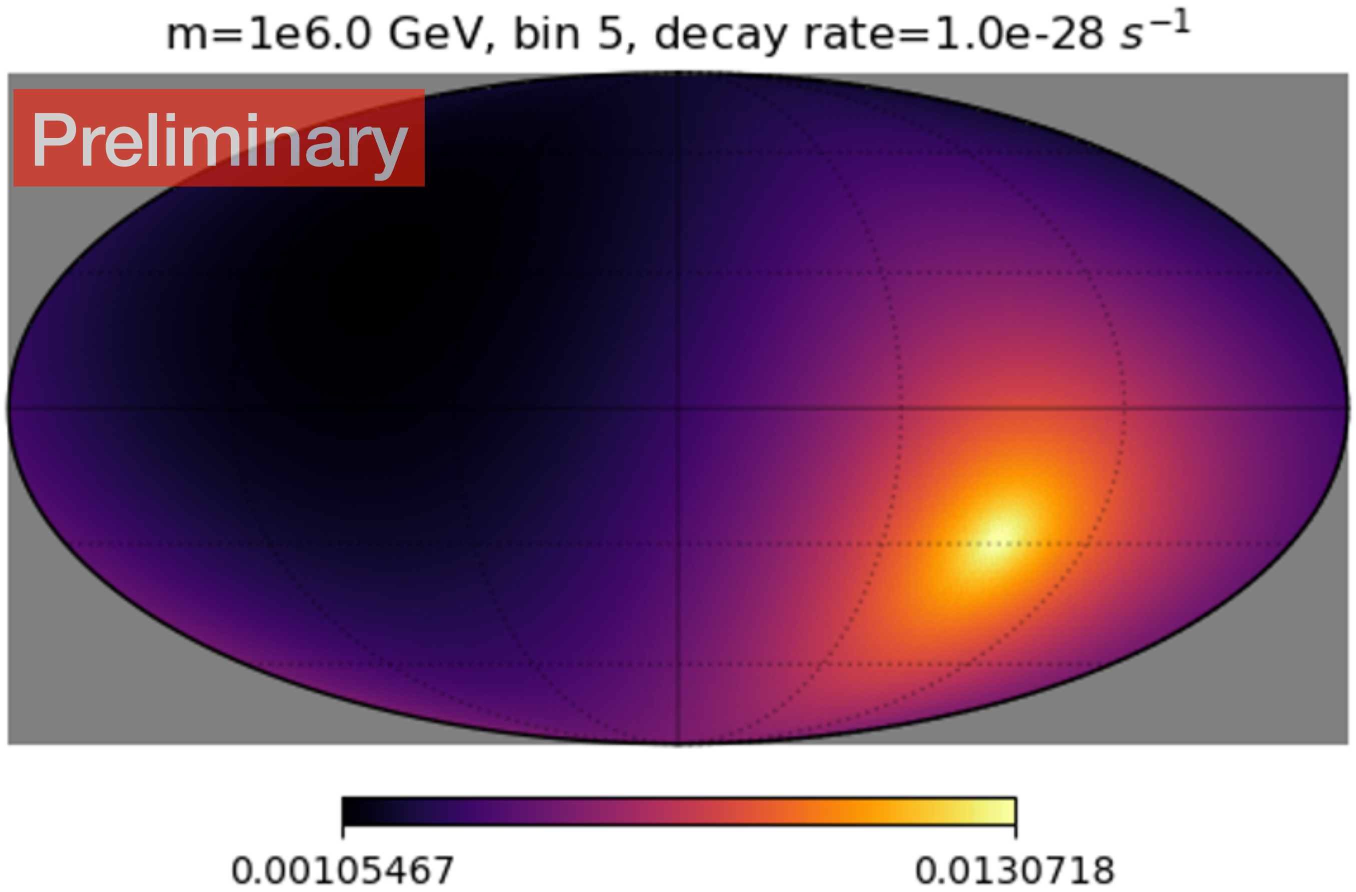
**(1) convolved with (2) -> Background estimation**

**Actual signal distribution**



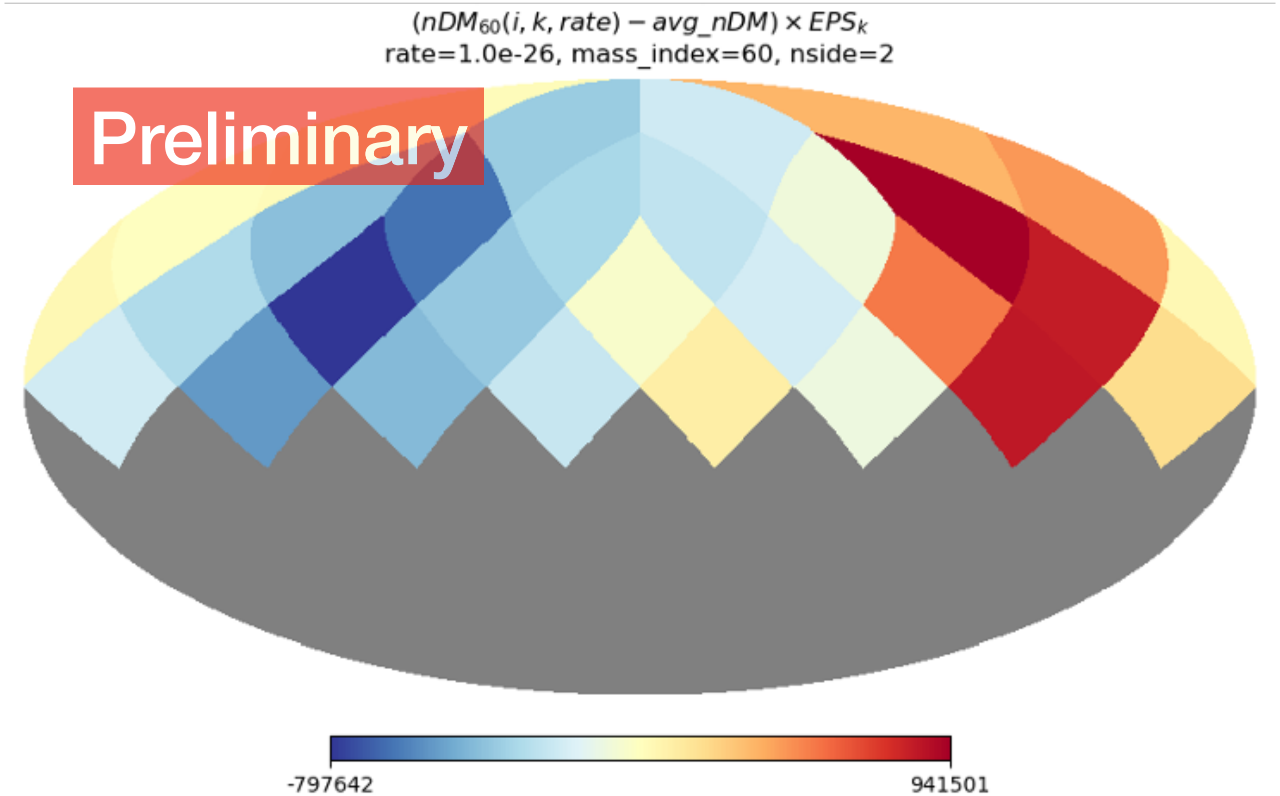
# Dark Matter Map

- Using DI means there will be signal contamination in the background estimate
- 24 hr window ~ integration along RA
- Apply the same source removal, decontaminate, then down size



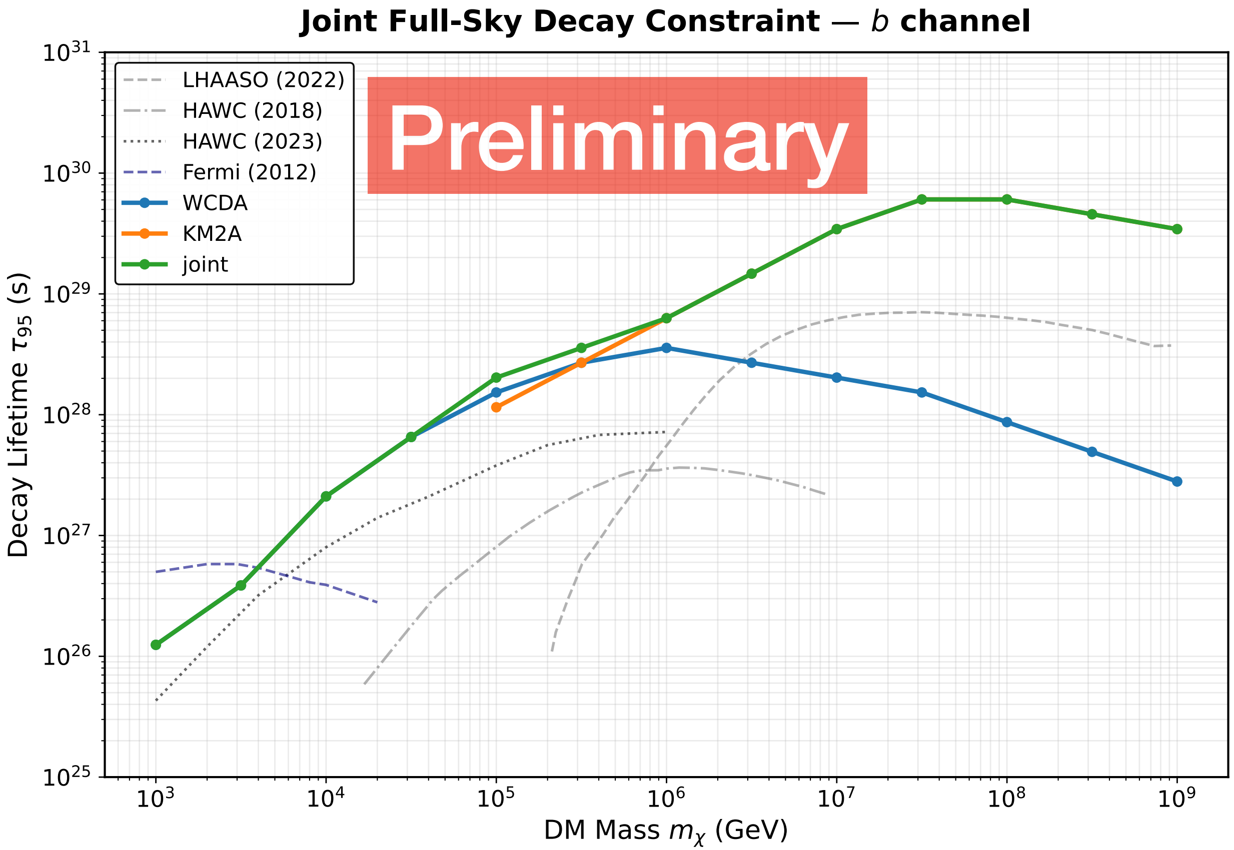
# Dark Matter Map

- Due to decontamination, there are now positive and negative pixels.



# All sky limits

- First all-sky dark matter decay limit with WCDA
- Extended the KM2A analysis from 100 TeV down to 10 TeV
- Strongest constraints on dark matter decay limit above a few TeV.

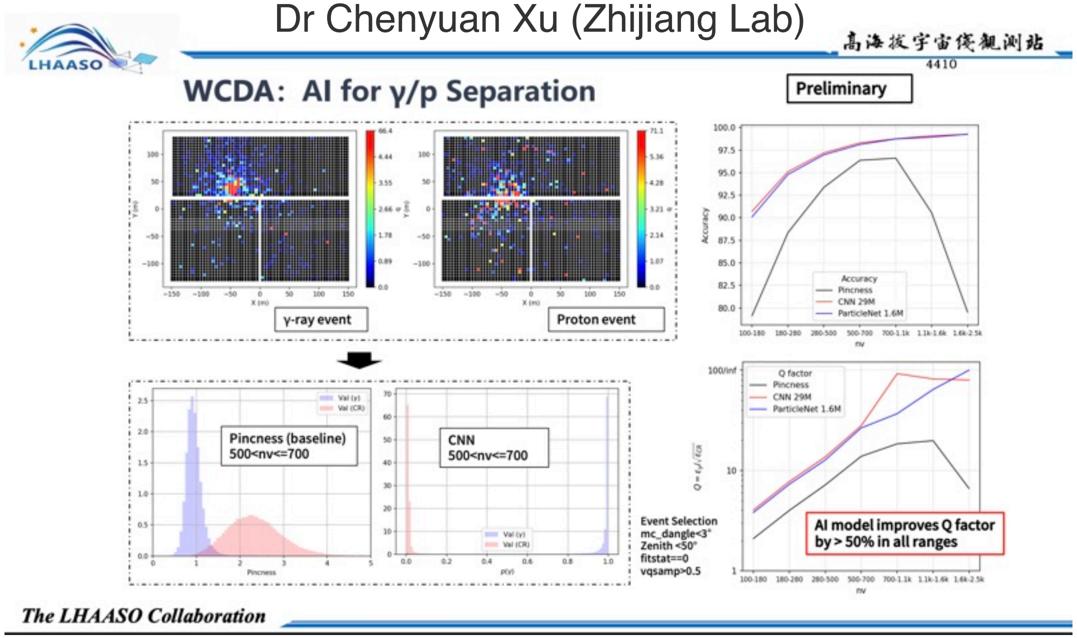


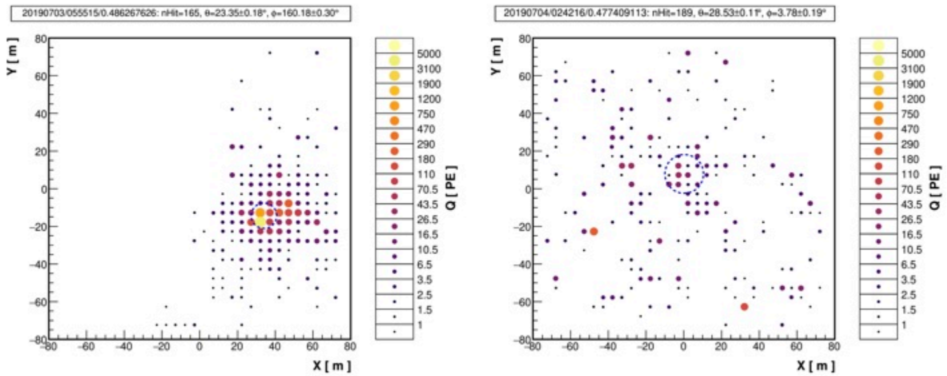
# Dark Matter search from LHAASO

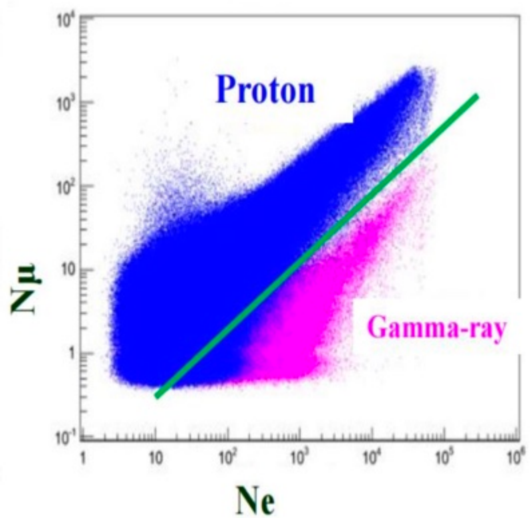
Dr Chenyuan Xu (Zhijiang Lab)

- Currently the most sensitivity dark matter telescope at the VHE

- How to make it better?
  - Background estimate (seems difficult)
  - Gamma/hadron separation (more hopeful, more things can be done)




https://arxiv.org/abs/2101.03508

# Thanks!