SWGO
The Southern Wide-field
Gamma-ray Observatory

Dark Matter Searches with Wide-field TeV Observatories

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Next Generation Gamma-ray Searches for Dark Matter
May 30, 2023

LA-UR-23-25629

SWGO
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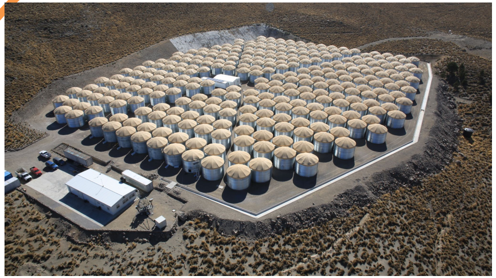
Wide-field Observatories

GeV Gamma-ray
Wide FoV

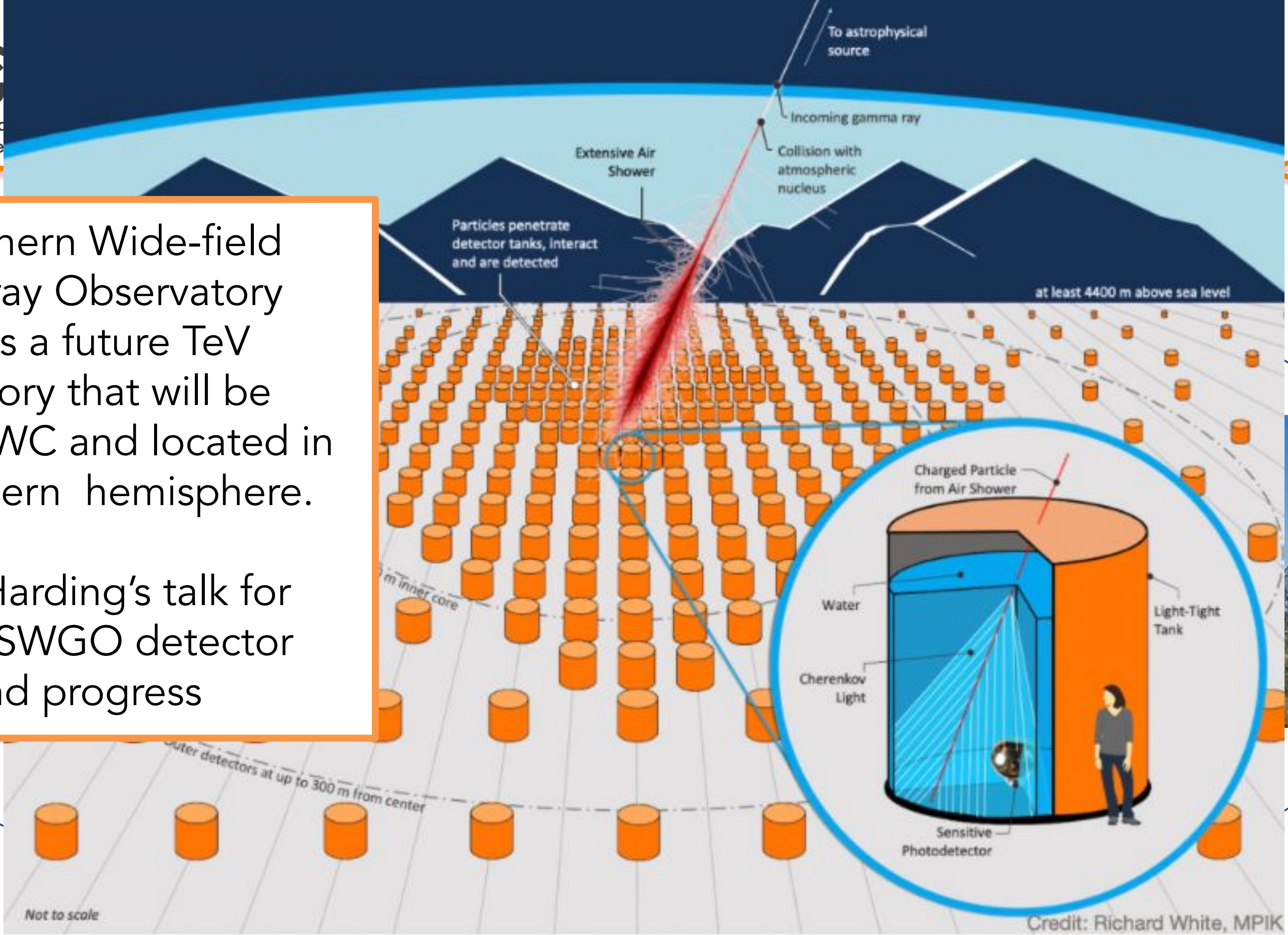


e.g. HAWC, LHAASO, SWGO
TeV Gamma-ray Wide FoV

IACTs (e.g. HESS)
TeV Gamma-ray
Small FoV

The Southern Wide-field Gamma-ray Observatory (SWGO) is a future TeV Observatory that will be ~10x HAWC and located in the southern hemisphere.

See Pat Harding's talk for more on SWGO detector details and progress



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Wide-field Observatories

	IACT Arrays	Ground-particle Arrays
Field of view	$3°$–$10°$	$90°$
Duty cycle	10%–30%	>95%
Energy range	30 GeV – >100 TeV	~500 GeV – > 1 PeV
Angular resolution	$0.05°$–$0.02°$	$0.4°$–$0.1°$
Energy resolution	~7%	60%–20%
Background rejection	>95%	90%–99.8%

SWGO Science Case White Paper
arXiv:1902.08429

Wide-field Observatories

IACTs and Wide FoV Observatories are complementary…

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Wide-field Observatories

The Southern Wide-field Gamma-ray Observatory

AND Wide FoV Observatories are unique!
e.g. 18 TeV photons from GRB 221009A with LHAASO

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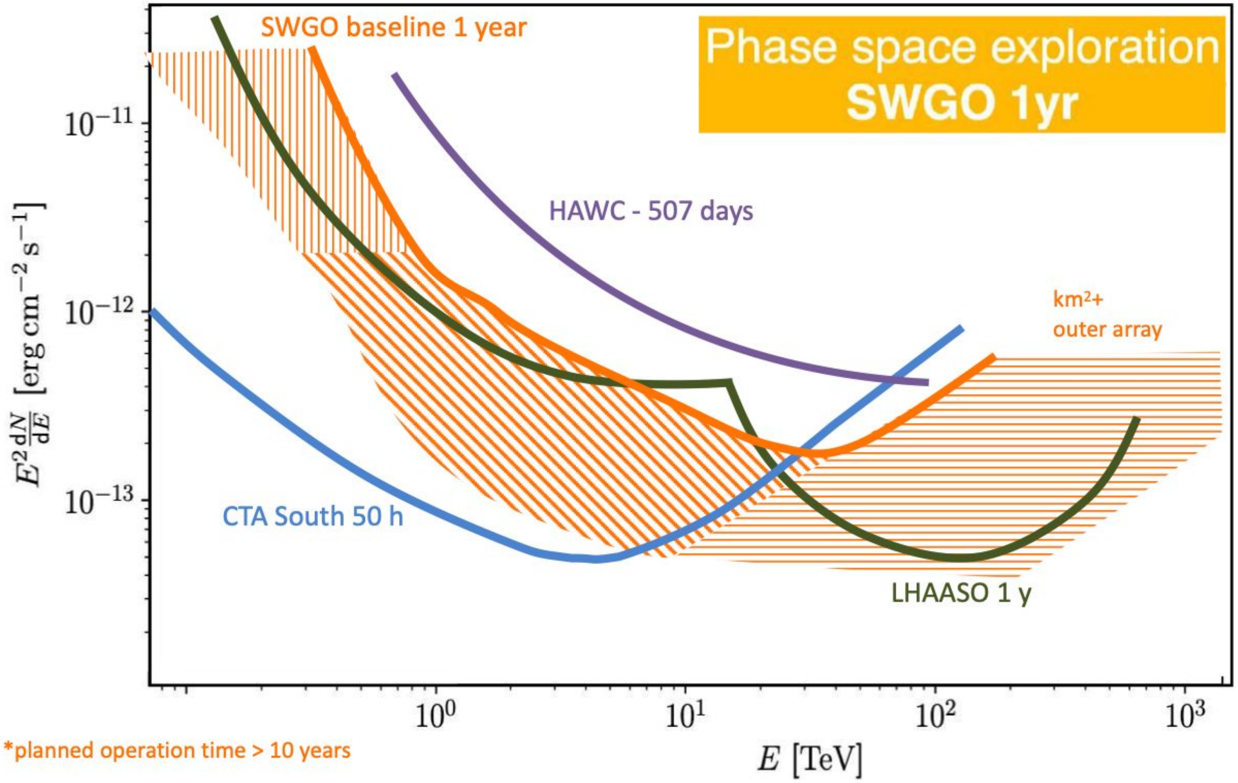
Gamma-ray Sensitivity



*planned operation time > 10 years

23

TeV Observatory Locations

TeV Observatory Locations

Wide FoV Observatories

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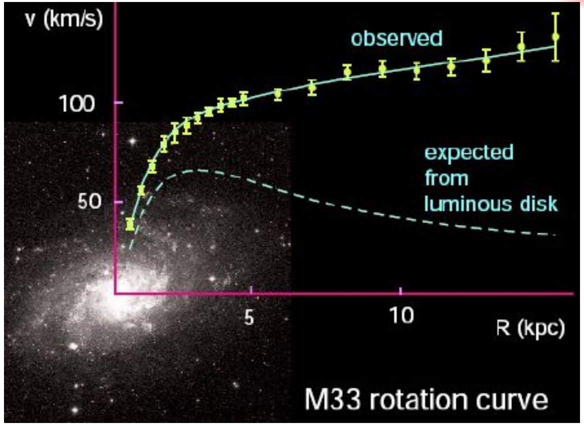
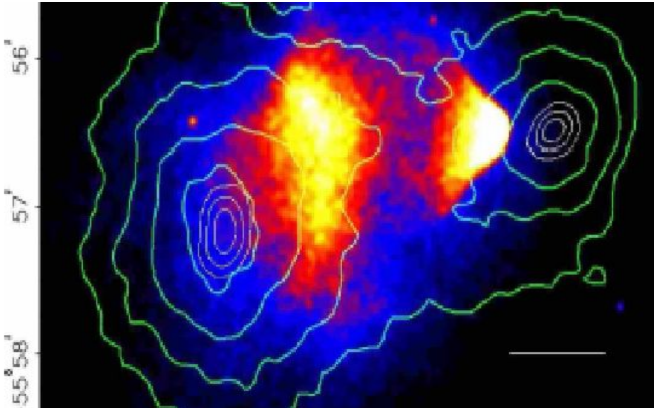
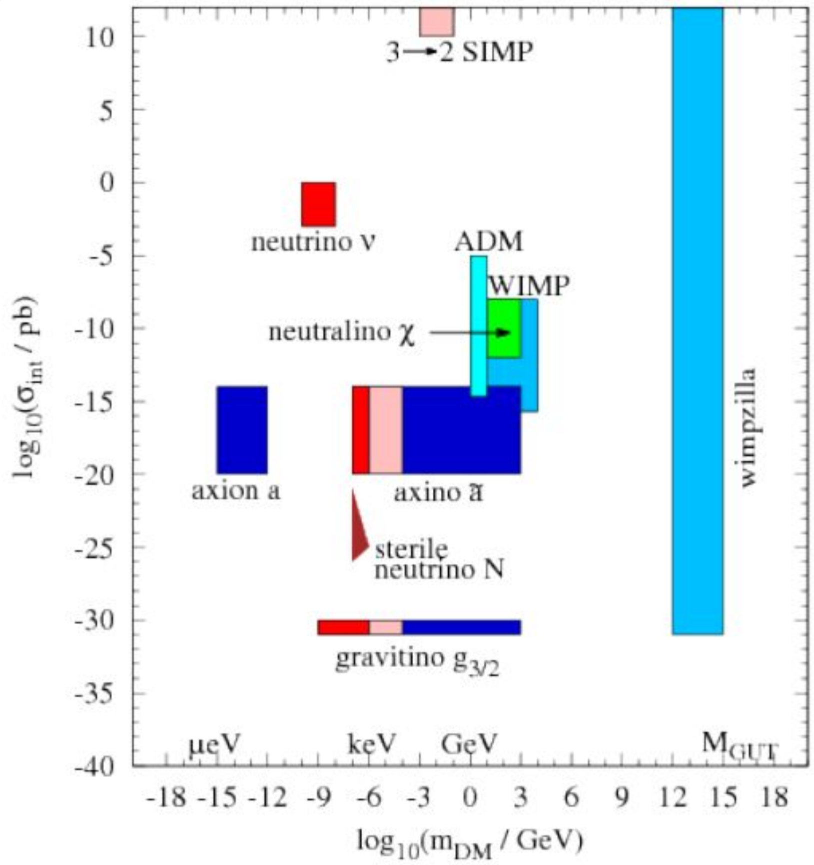
Dark Matter Primer

- Galaxies form in large dark matter halos, which make up most of their mass
  - Coma Cluster + virial, F. Zwicky (1937)
  - Rotation Curves, V. Rubin et al (1980)
- Dark matter is virtually collisionless
  - The Bullet Cluster, D. Clowe et al (2006)
- Dark matter is non-baryonic
  - CMB acoustic oscillations
  - Big Bang nucleosynthesis





Dark Matter Candidates



Baer+ PR 555 (2015)

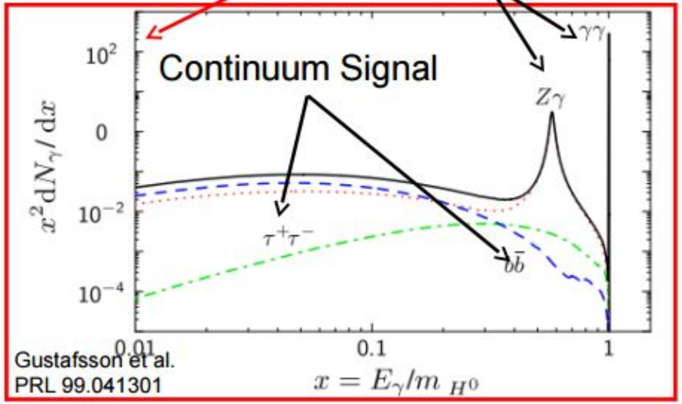
Gamma rays from Dark Matter

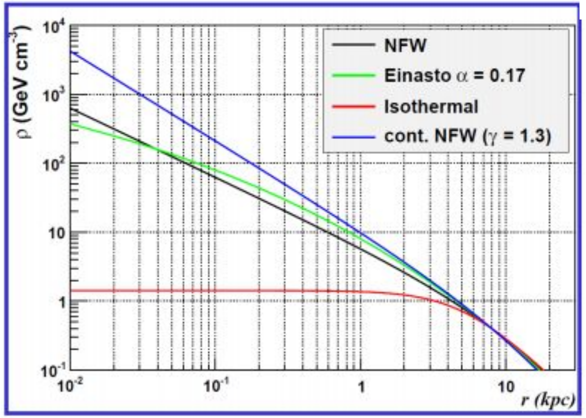
What we observe | **Intrinsic Particle Properties** | **Astrophysics**

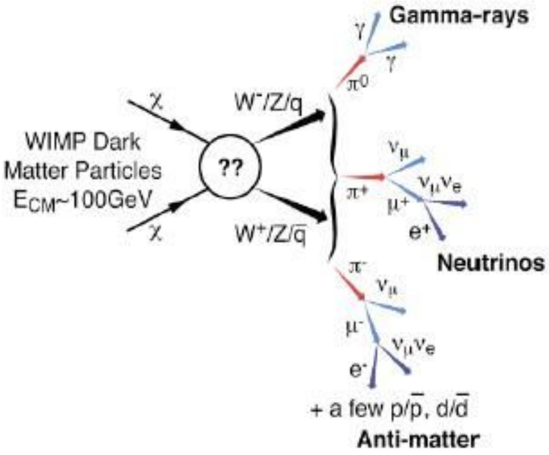
$$\Phi_\chi(E,\Psi)=\frac{\langle\sigma_\chi v\rangle}{2}\sum\frac{dN_f}{dE}B_f\int_{LOS}dl(\Psi)\frac{1}{4\pi}\frac{\rho(l)^2}{m_\chi^2}$$

J-factor – Line of sight integral over a ROI

Monochromatic Signal







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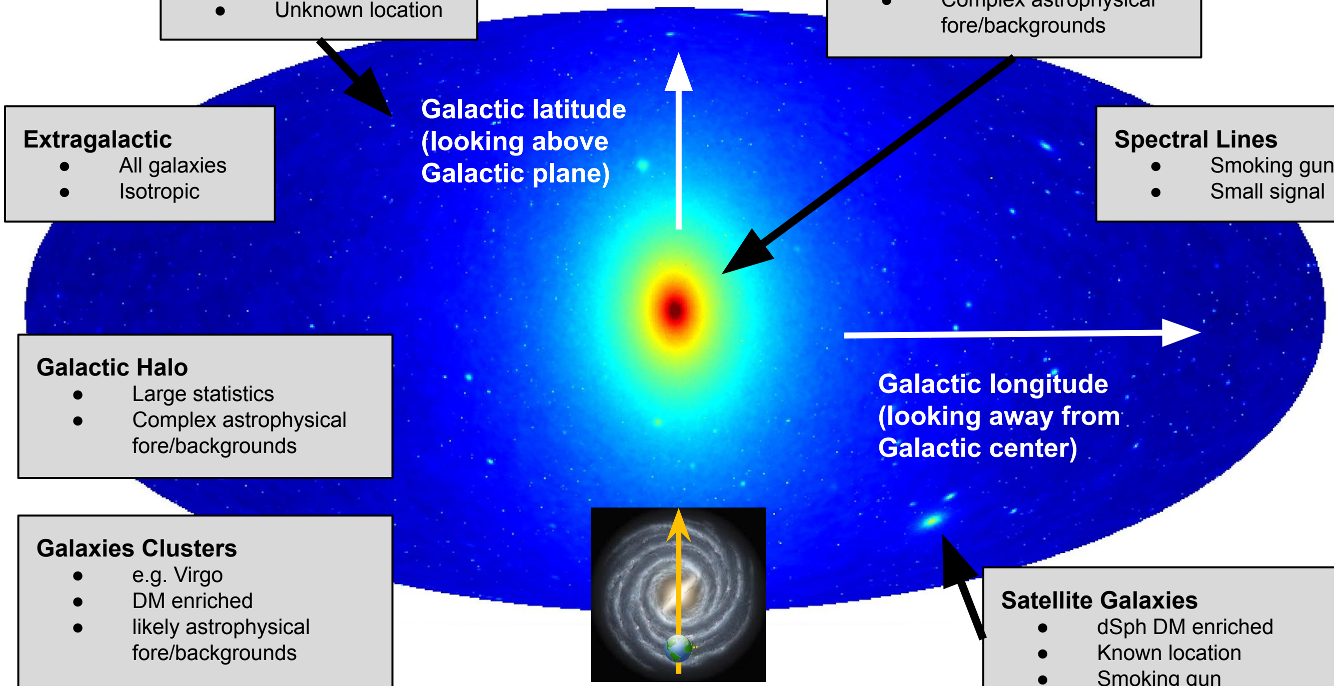
Wide FoV Dark Matter Searches

- Gamma rays maintain directionality so we search for gamma ray sources in dark matter rich regions from dark matter annihilation/decay
- Wide FoV advantage
  - Wide field of view -> daily monitoring of several DM regions
    - Galactic Center, dwarf galaxies, galaxy clusters, undiscovered dwarfs
    - Which sources you are sensitive to depends on your location! (e.g. northern or southern hemisphere)
  - Wide field of view -> good sensitivity to extended sources
    - e.g. TeV halos like the Geminga Pulsar Wind Nebula
  - High energy reach -> uniquely explore for mass above ~20 TeV
    - Better sensitivity at high energies than CTA
    - More overlap with IceCube DM search parameter space
      - Multimessenger studies!

Dark Matter Targets



Gamma ray signal from dark matter only – Aquarius simulation

HAWC Dark Matter Searches

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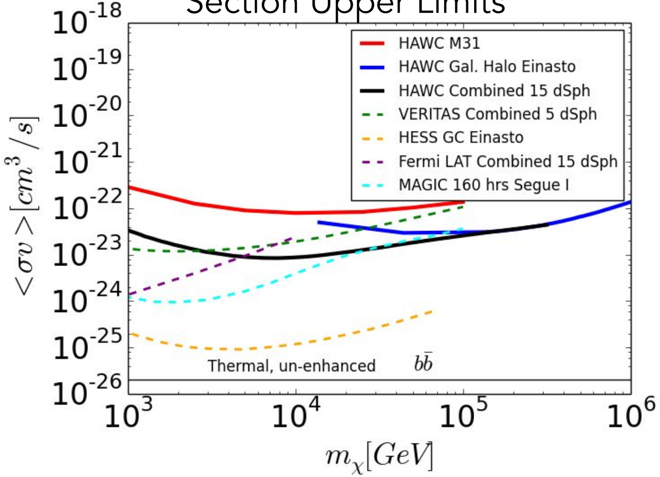
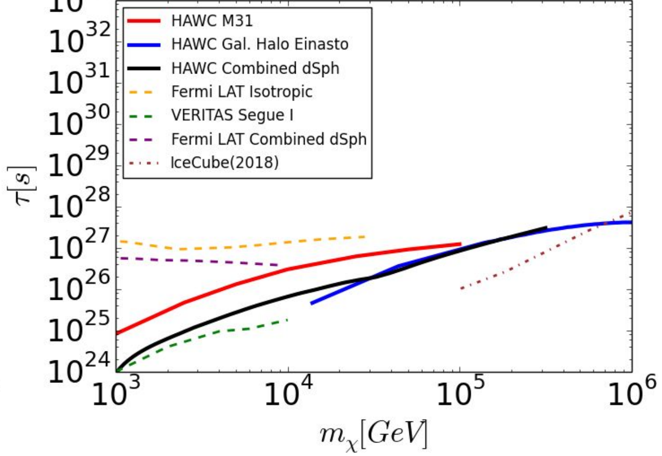
DM Annihilation Cross Section Upper Limits



DM Decay Lifetime Lower Limits



HAWC M31: Albert+ JCAP 1806 (2018) 043
HAWC dSph: Albert+ ApJ 853 (2018) no.2, 154

HAWC Gal Halo: Abeysekara+ JCAP 1802 (2018) 049

- No gamma-ray excess detected in any target
- Limits set on DM annihilation cross section and decay lifetime
  - → Able to see extended objects (e.g. Galactic Halo)

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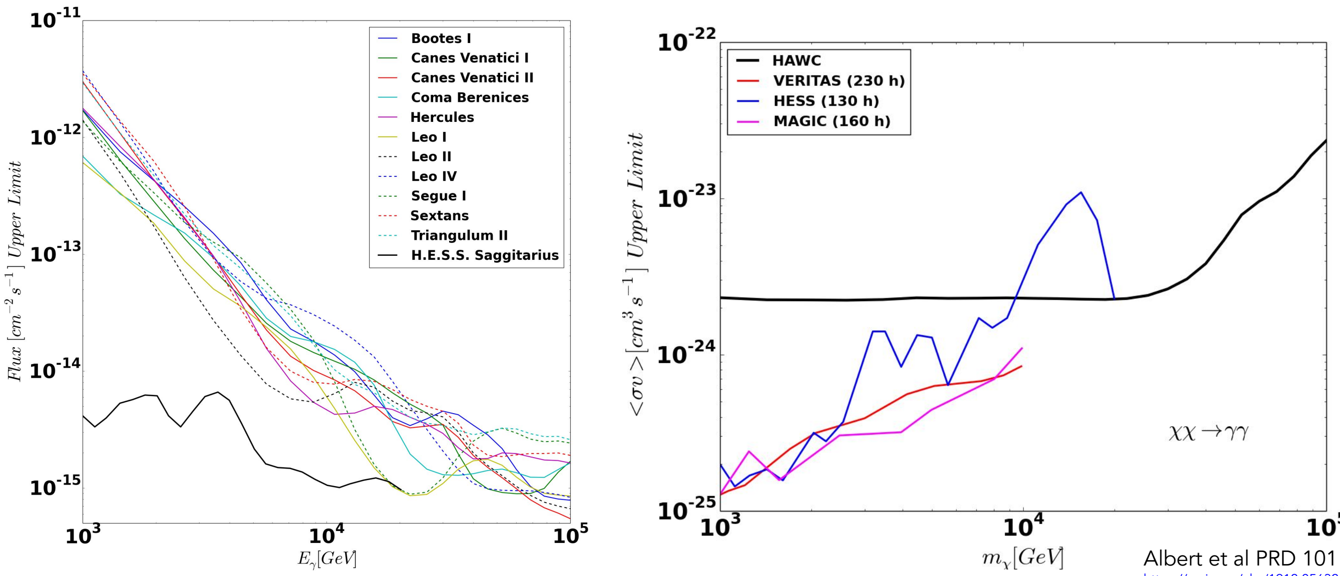
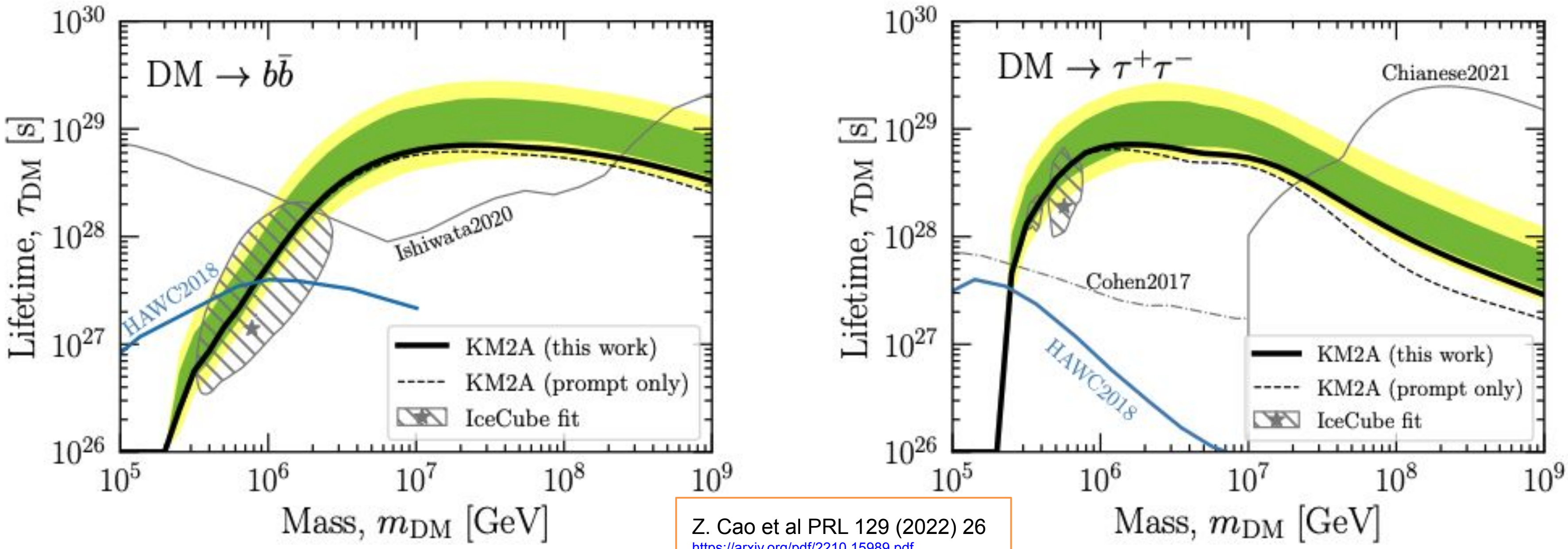
HAWC Spectral Line Limits



Albert et al PRD 101 (2020)10
https://arxiv.org/abs/1912.05632

- DM annihilation directly to gamma rays produces a spectral line at the DM mass
- HAWC line search explores 20 -- 100 TeV for the first time
- HAWC DM line limits are the strongest from 10 – 100 TeV

Recent Results – LHAASO Galactic Halo



Z. Cao et al PRL 129 (2022) 26
https://arxiv.org/pdf/2210.15989.pdf

- Search in the Galactic halo (15° ≤ b ≤ 45° and 30° ≤ l ≤ 60°)
- Set world leading DM decay limits
- 570 days of partial array (KM2A only) data
  - Gamma ray energy > 10 TeV

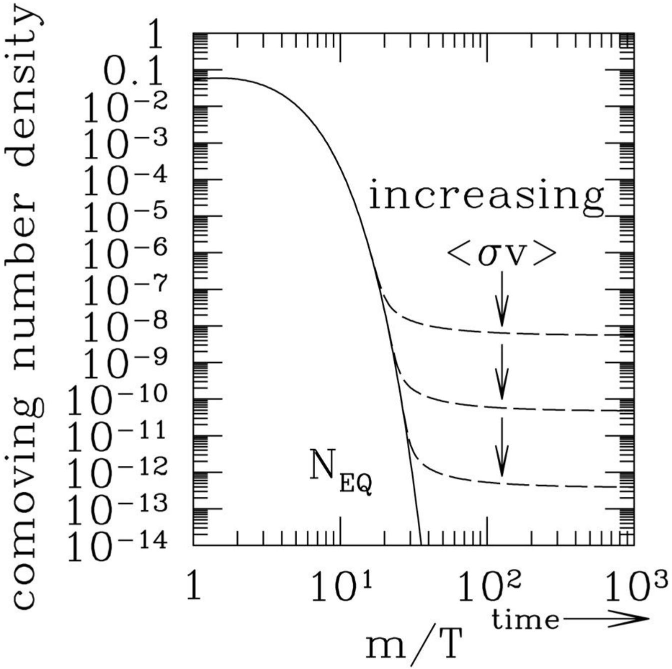
Thermal Relic WIMPs

- Weakly Interacting Massive Particle (WIMP)
  5 GeV - 100 TeV mass scale

- A thermally-coupled ~100 GeV particle in the early Universe with weak scale $\boldsymbol{\sigma}_{ann}$ <u>independently</u> produces the observed dark matter abundance today measured by the CMB

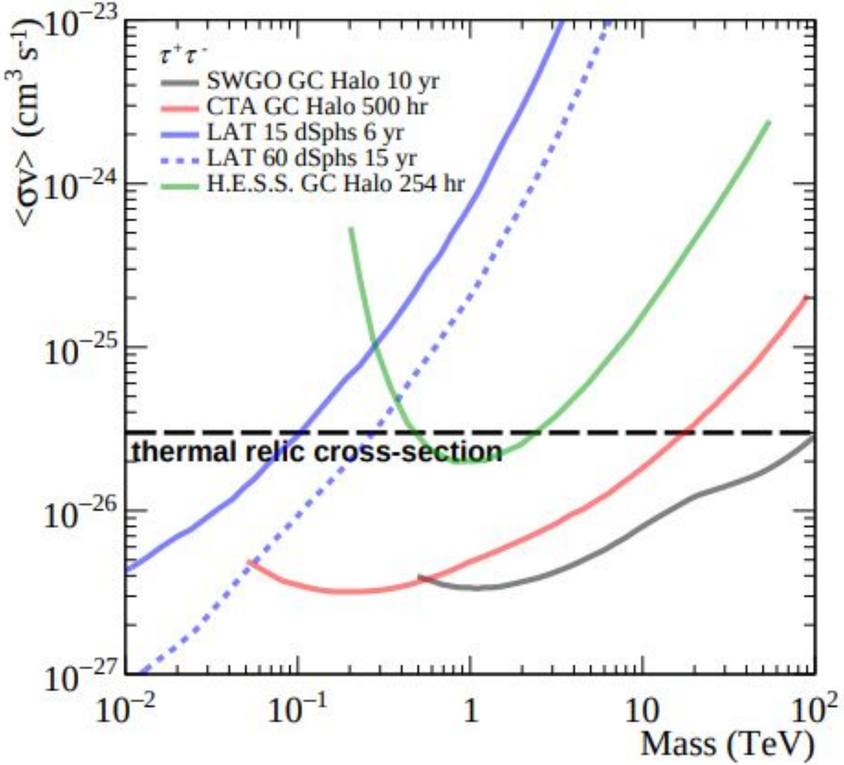
- Several WIMP candidates from <u>independently</u> motivated theories like SUSY

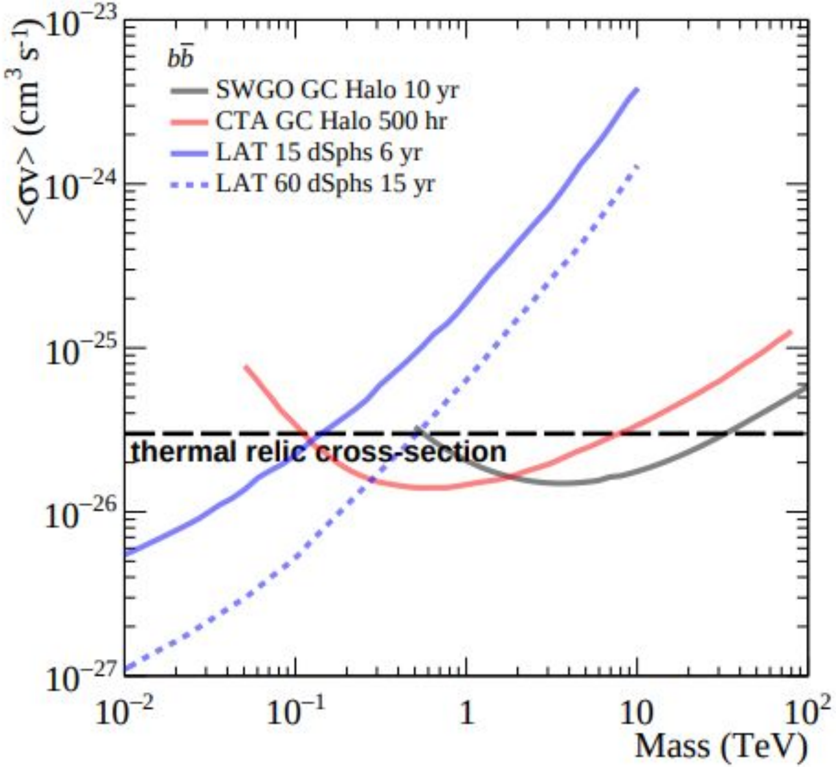
- Thermal WIMPs aren't the only dark matter candidates, but are a well-motivated hypothesis we must test!
  → We have only just begun to probe WIMP phase space. Fermi LAT dwarf spheroidal limits exclude mass < ~100 GeV (in bb and tautau channels)



E. Kolb and M. Turner, *<u>The Early Universe</u>*, Westview Press (1994)

SWGO Expected Limits

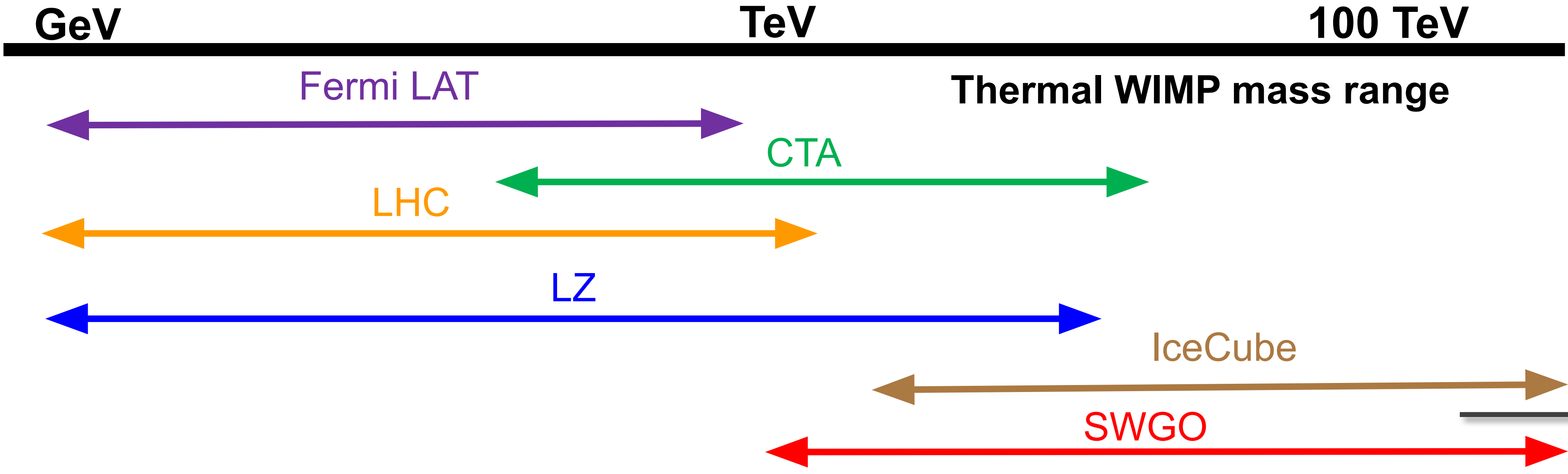




arXiv:1902.08429

Sensitivities to thermal WIMPs

- SWGO is the only future gamma-ray experiment that probe up to 100 TeV in mass
- SWGO is the only future gamma-ray experiment with significant overlap with IceCube
  → Multimessenger!
- Indirect (astrophysical) detection is the only way to probe >20 TeV WIMPs



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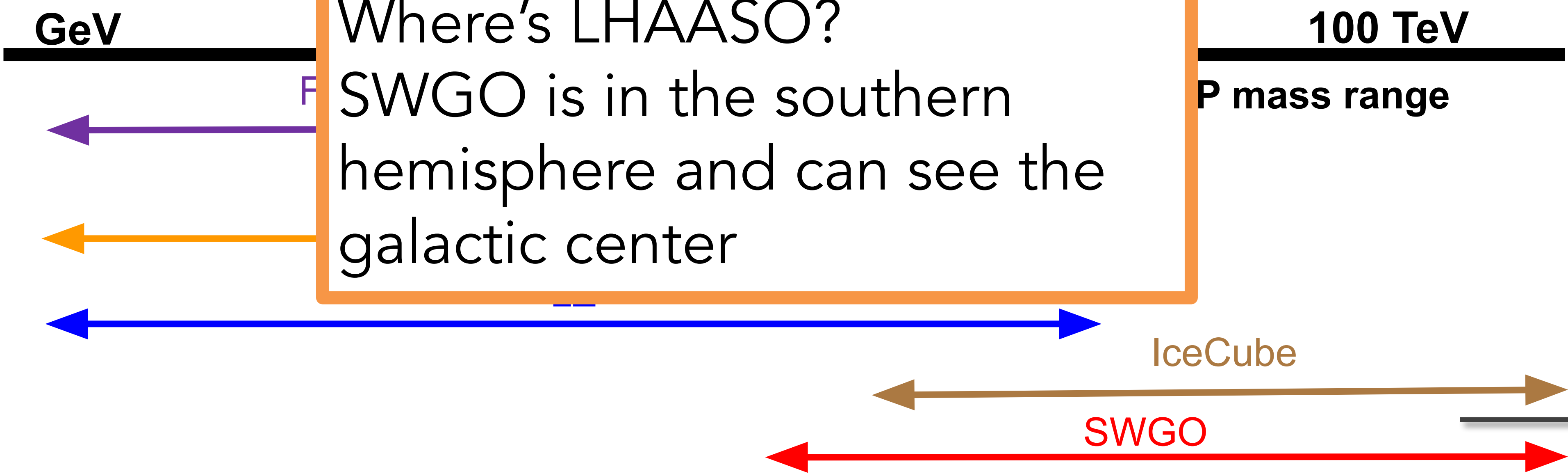
Where's LHAASO?
SWGO is in the southern hemisphere and can see the galactic center



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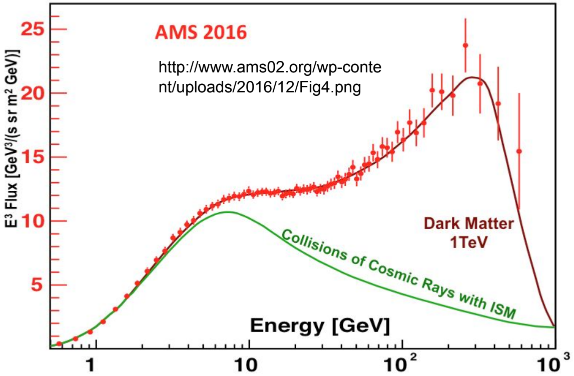
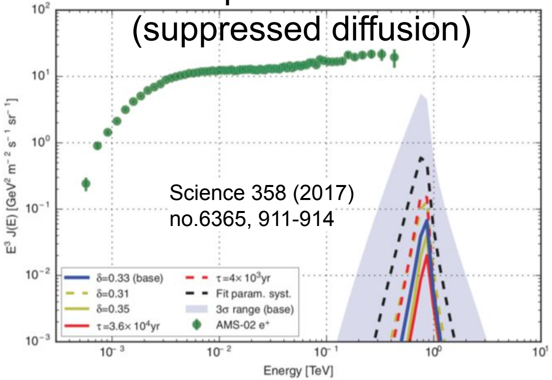
Other Dark Matter Searches

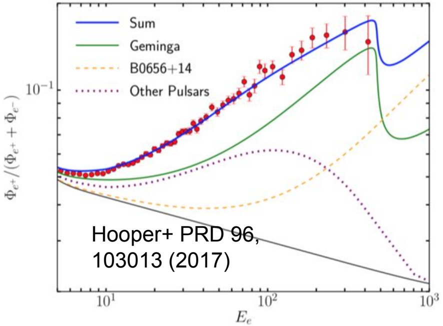
HAWC Geminga Observations and Dark Matter



Local positron flux
(suppressed diffusion)



Local positron flux
(enhanced diffusion)



- AMS-2 sees an excess of local positrons that may be from dark matter annihilations
  - Nearby PWN like Geminga have been proposed as an alternative
- HAWC discovered TeV gamma rays from the Geminga PWN
  - These gamma rays are made by cosmic ray interactions so they indirectly tell you about how many cosmic rays are produced at and escape from Geminga
- Current uncertainties in the diffusion rate between Geminga and Earth make it hard to say if Geminga is producing the AMS-2 positions or not
  - Future detections of other nearby PWN will help

Axion Like Particles (ALPs)

- Axions are hypothetical particles proposed to solve the ‘Strong CP’ problem in QCD
- Axions couple to photons in magnetic fields
- You can generalize the mass and coupling ($g_{a\gamma}$) to get ‘axion like particles’ (ALPs)
- Axions and/or ALPs could constitute all or some of the dark matter

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

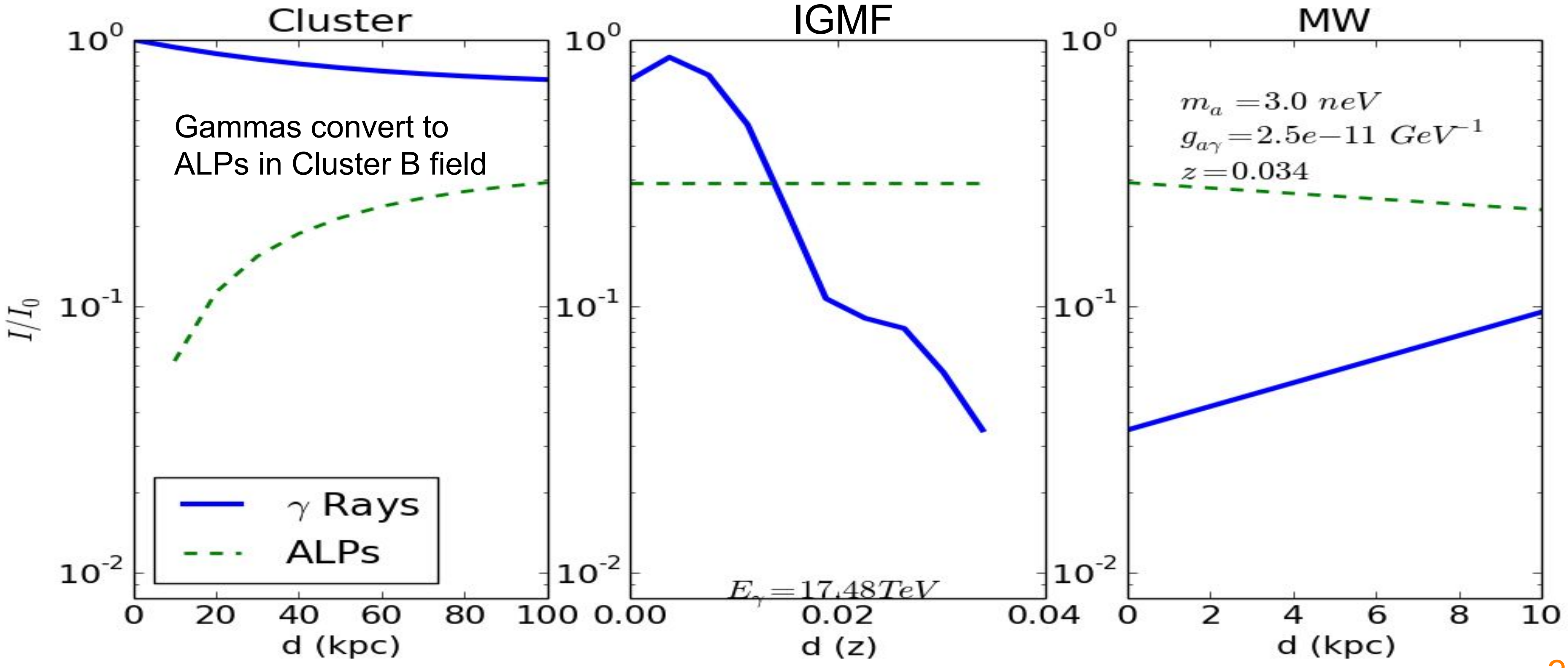
$$m_a \approx 6\ \mu\text{eV} \left(\frac{f_a}{10^{12}\ \text{GeV}} \right)^{-1}$$

$= 6\ \mu\text{eV}\ g_{a\gamma}$

- Axions have standard relation between mass and f_a (Peccei-Quinn scale)

- for ALPs, m_a and $g_{a\gamma}$ are independent
  - → See B. Berenji+ (2016) arXiv:1602.00091

Example ALP Gamma Path (Mrk501)



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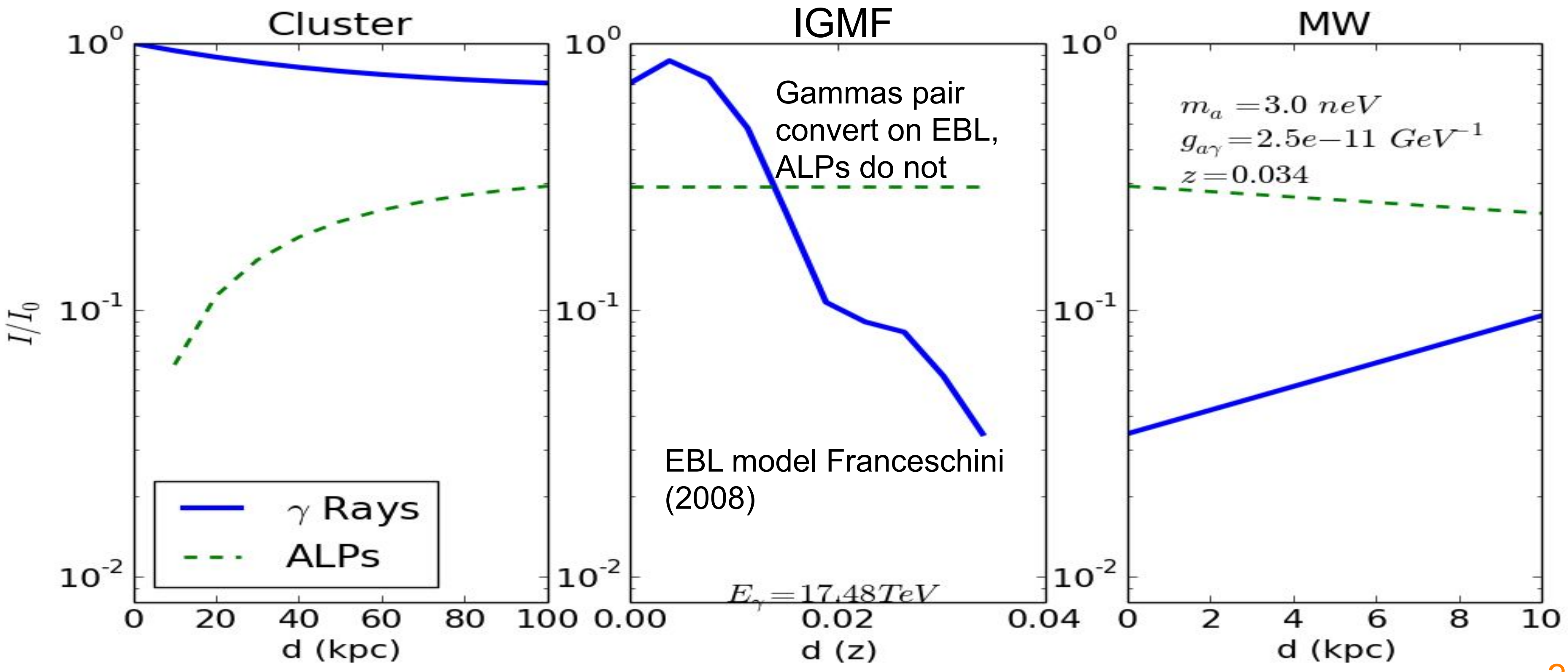

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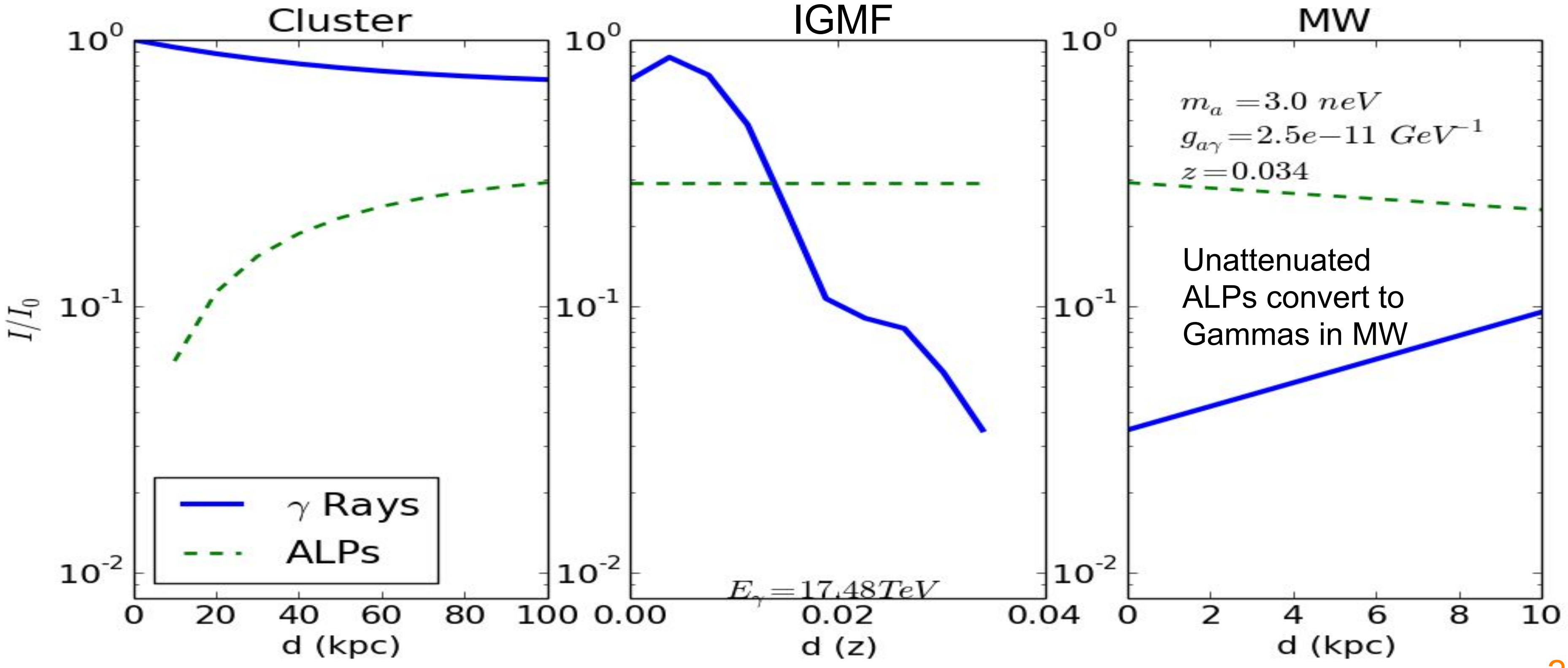

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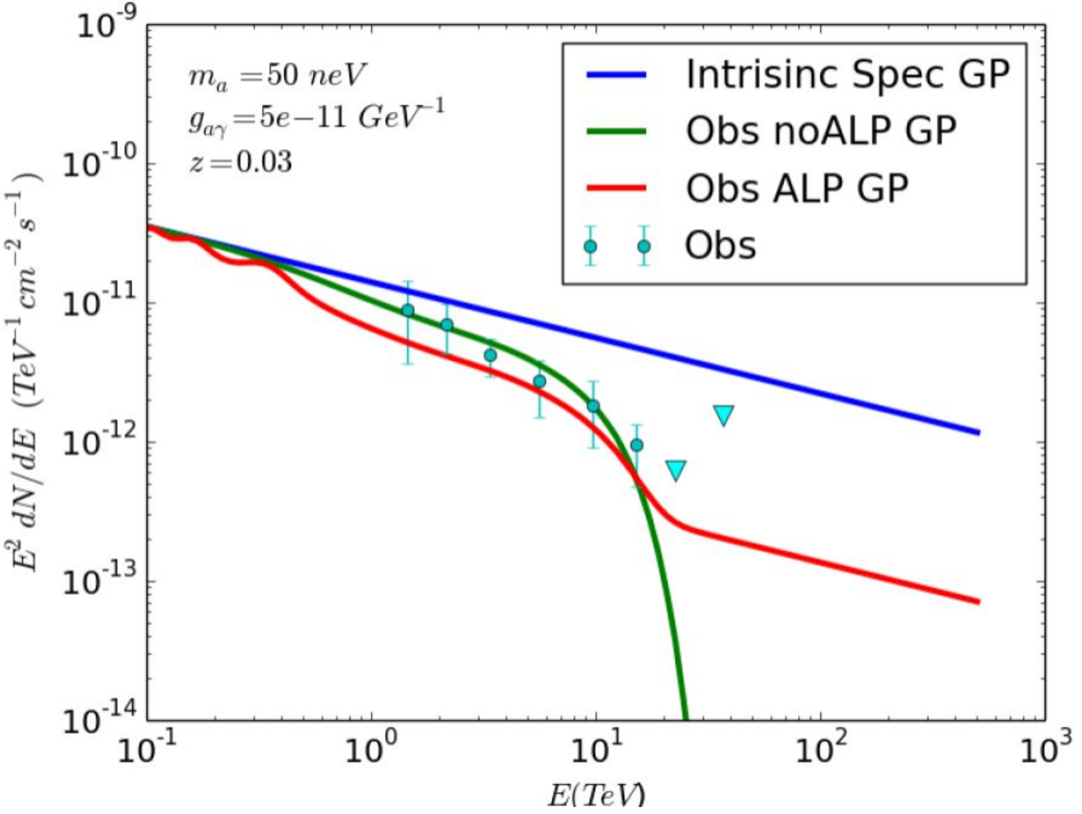
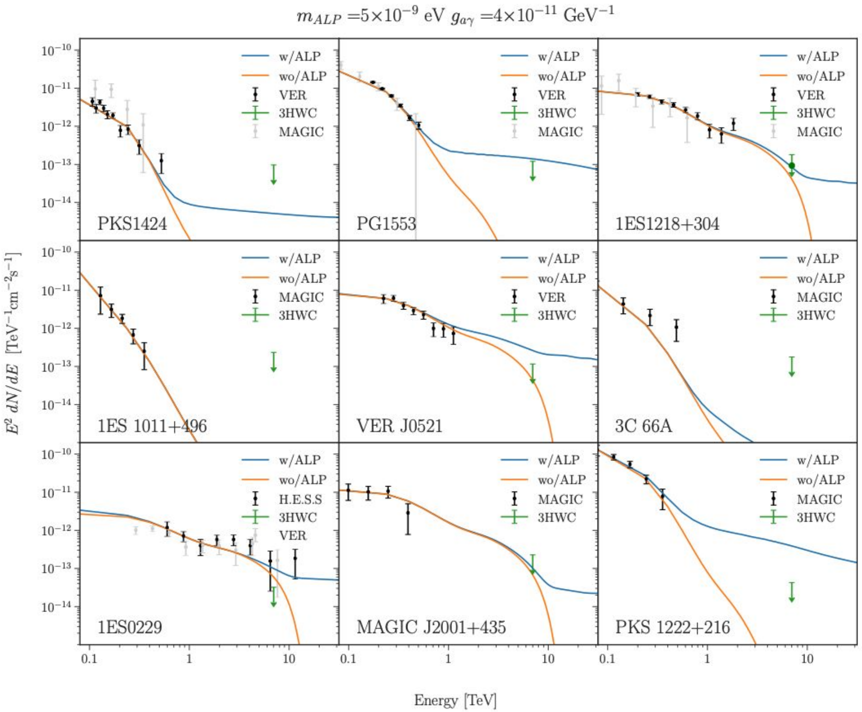


Axion-like Particles (ALPs)

- Search for >20 TeV gamma rays from distant galaxies
  - non-ALP signal cuts off from EBL attenuation, but ALP doesn't
- Wide FoV advantage
  - Wide field of view -> daily monitoring of several hard sources
    - e.g. RX J1713.7-3946
  - High energy reach -> better sensitivity to hard sources
- Can also search for sharp spectral irregularities
  - Need excellent energy resolution that the IACTs have



Jacobsen et al (2022)
https://arxiv.org/pdf/2203.04332.pdf

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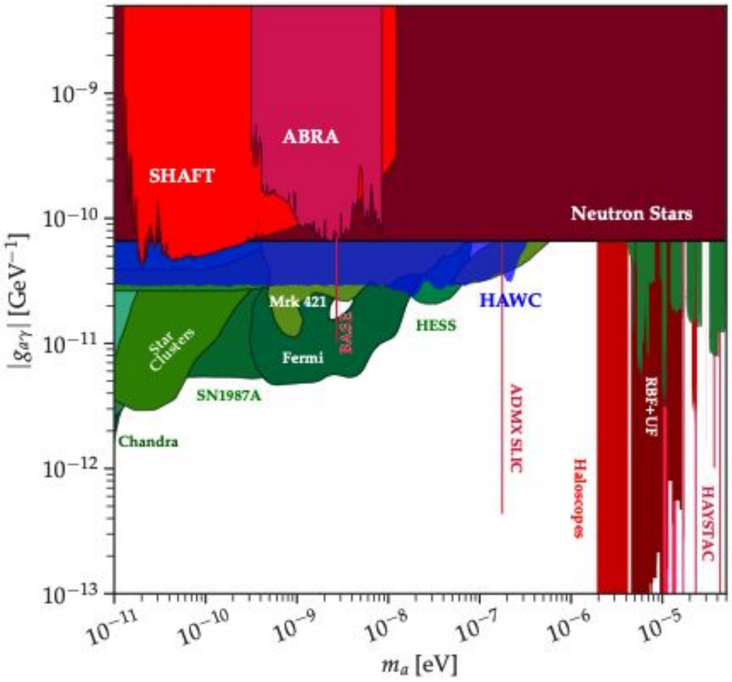


Jacobsen et al (2022)
https://arxiv.org/pdf/2203.04332.pdf

GRB 221009A – the B.O.A.T.

TITLE: GCN CIRCULAR
NUMBER: 32677
SUBJECT: LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV
DATE: 22/10/11 09:21:54 GMT
FROM: Judith Racusin at GSFC <judith.racusin@nasa.gov>

Yong Huang, Shicong Hu, Songzhan Chen, Min Zha, Cheng Liu, Zhiguo Yao and Zhen Cao report on behalf of the LHAASO experiment

We report the observation of GRB 221009A, which was detected by Swift (Kennea et al. GCN #32635), Fermi-GBM (Veres et al. GCN #32636, Lesage et al. GCN #32642), Fermi-LAT (Bissaldi et al. GCN #32637), IPN (Svinkin et al. GCN #32641) and so on.

GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the significance above 100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d., where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRBs.

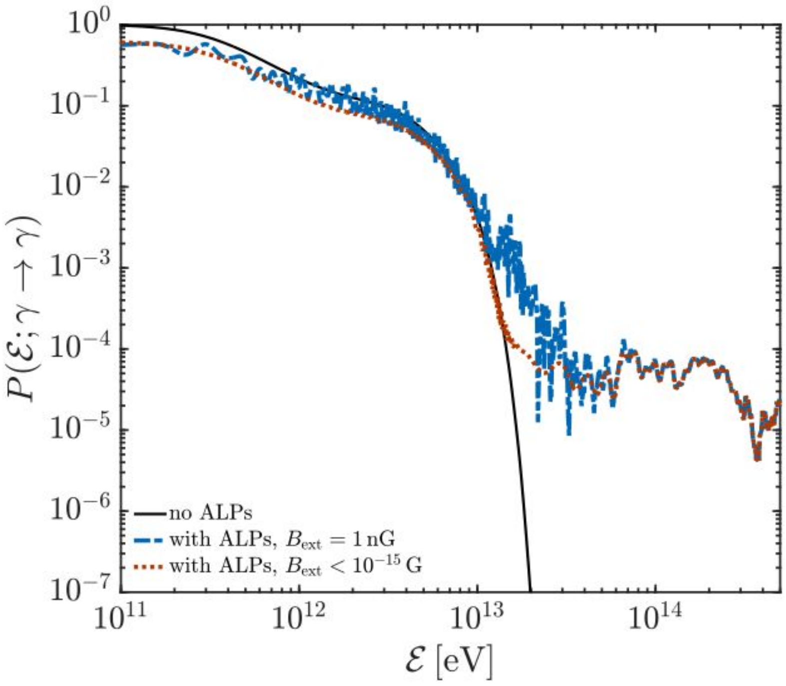
The LHAASO is a multi-purpose experiment for gamma-ray astronomy (in the energy band between 10^11 and 10^15 eV) and cosmic ray measurements.

- LHAASO detected the highest energy gamma rays ever seen from a GRB! (>10 TeV)
  - Brightest of all time (B.O.A.T.)
- Given long distance (z = 0.15) gammas >10 TeV should be attenuated

Particle Physics with GRB 221009A

- LHAASO detected the highest energy gamma rays ever seen from a GRB! (>10 TeV, up to 18 TeV)
  - → Possible 251 TeV event from Carpet-2 at Baksen Neutrino Observatory
- Given long distance (z = 0.15) gammas >10 TeV should be attenuated
  - → Several new particle physics models have been proposed to explain LHAASO detection
    - ✓ 18 TeV is not quite high enough to be a smoking gun for new physics
    - ✓ Need new physics to explain 251 TeV event, but that detection is not firm
- Wide FoV TeV Observatories have great discovery potential to see >20 TeV gamma rays from extragalactic sources in the coming years

Photon Survival Probability



Galanti et al (2023)
https://arxiv.org/pdf/2210.05659.pdf

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Conclusions

- Wide FoV TeV Observatories offer an exciting and unique view of the gamma-ray sky
- They are able to probe heavy mass dark matter models other experiments cannot probe
  - SWGO's Galactic Halo search is expected to reach up to 100 TeV for thermal relic WIMPs
- HAWC and LHAASO have already made exciting discoveries with important dark matter implications
  - TeV Halos like Geminga PWN
  - GRB 221009A
- SWGO will be the first Wide FoV TeV Gamma-ray Observatory in the southern hemisphere, opening up new regions of discovery space