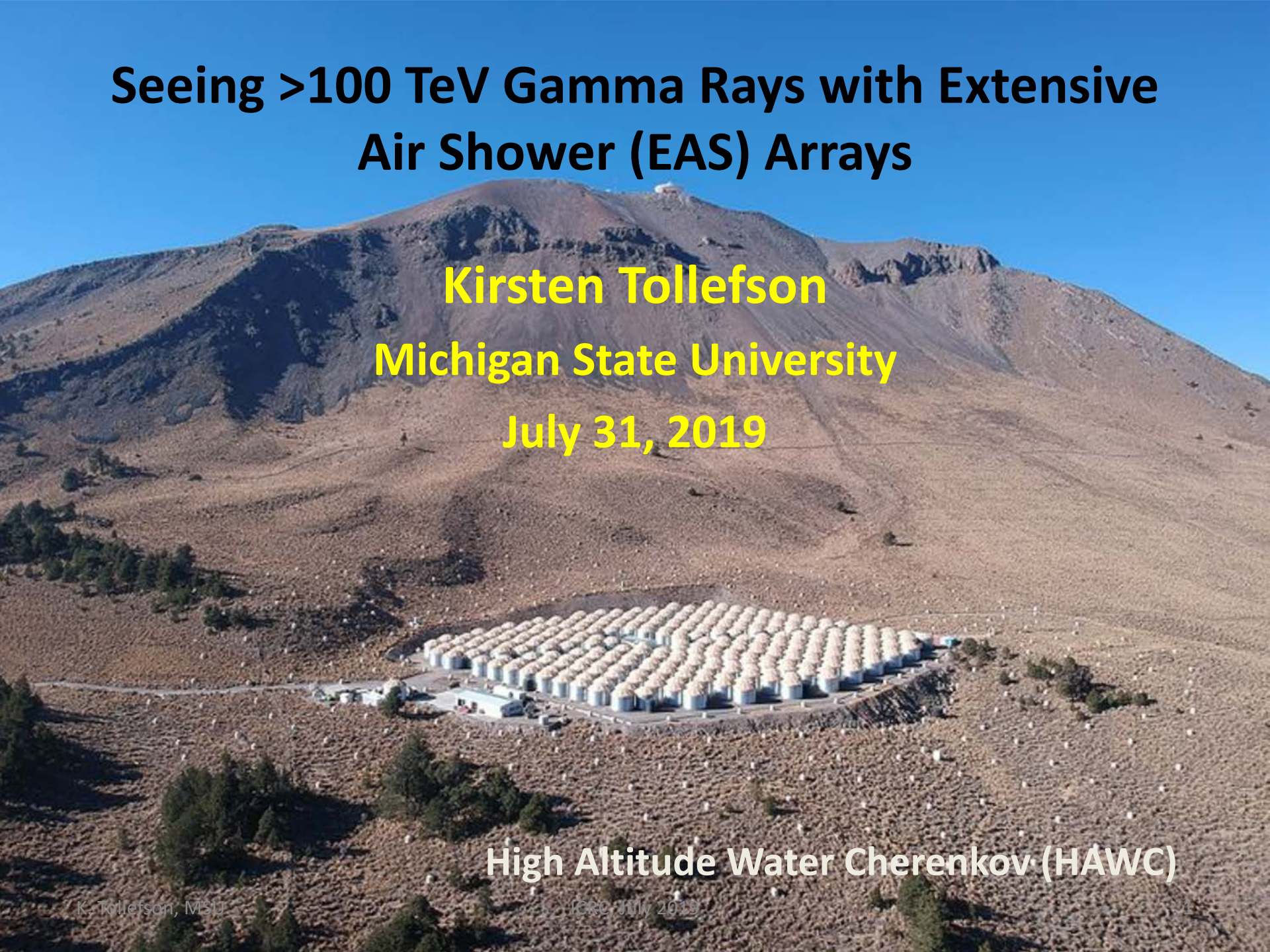
Seeing >100 TeV Gamma Rays with Extensive Air Shower (EAS) Arrays

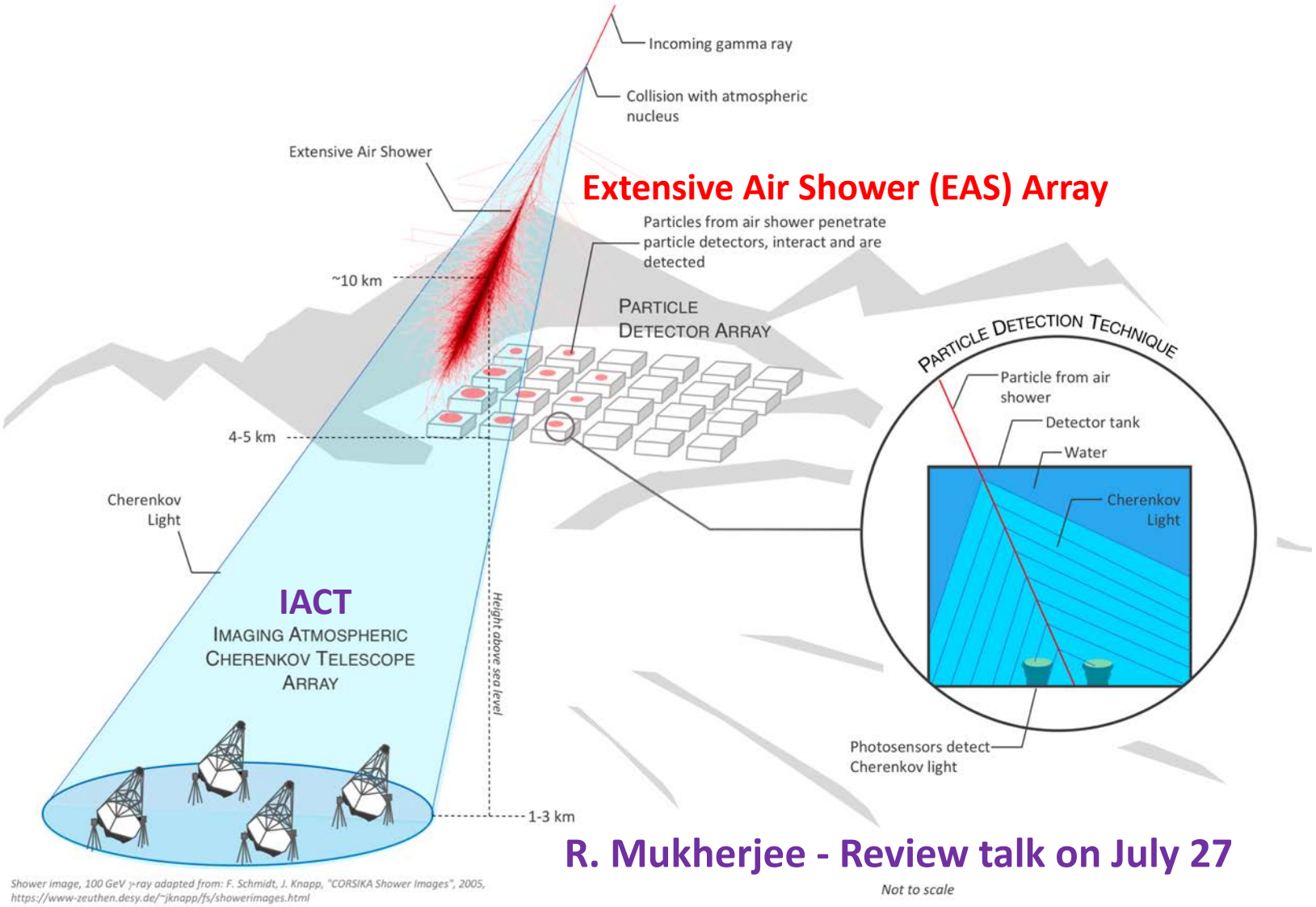
Kirsten Tollefson
Michigan State University

July 31, 2019



High Altitude Water Cherenkov (HAWC)

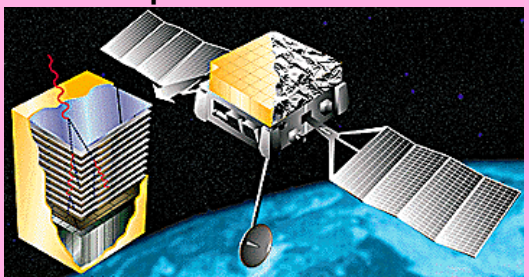
Indirect Gamma-Ray Detector Techniques



Comparison of Detector Techniques

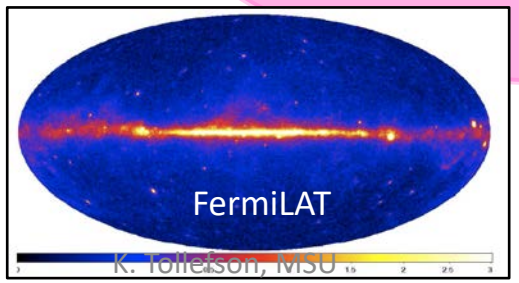
Wide Field of View, Continuous Operations

Space Based

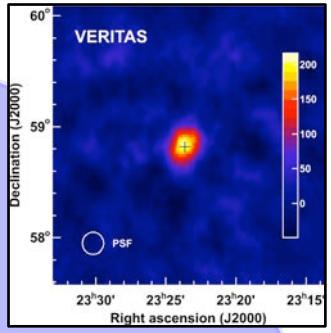


Fermi
AGILE
EGRET

30 MeV – 300 GeV



TeV Sensitivity



Extensive Air Shower (EAS) Arrays

HAWC
ARGO
Milagro
Tibet ASγ
LHAASO

500 GeV – 100 TeV

Imaging Atmospheric Cherenkov Telescopes (IACTs)

VERITAS
HESS
MAGIC
CTA

50 GeV – 20 TeV

Transient Alert Follow-ups

GCN Circular #25225 and ATel #12967 from IceCube yesterday

IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106

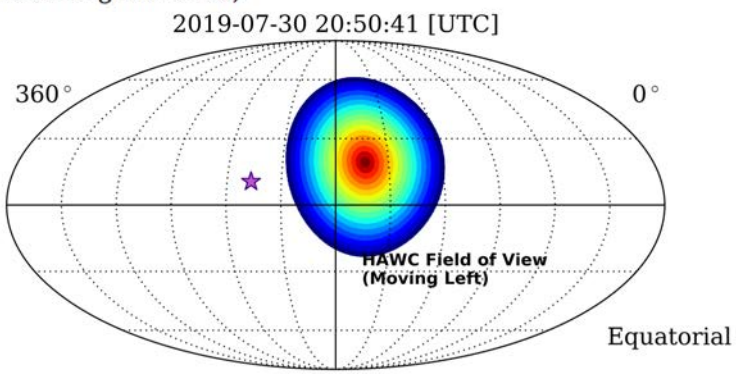
ATel #12967; *Ignacio Taboada (Georgia Institute of Technology), Robert Stein (DESY Zeuthen)*
on 30 Jul 2019; 23:58 UT
Credential Certification: Ignacio Taboada (itaboada@gatech.edu)

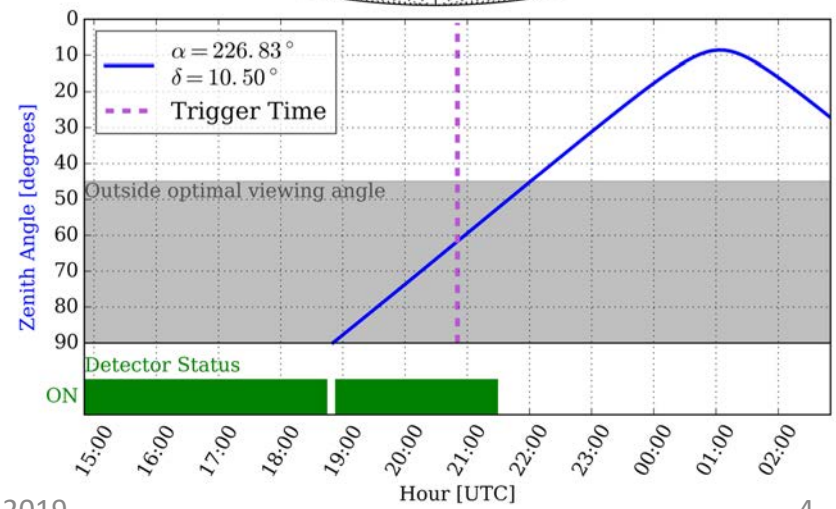
Date/Time: 2019/07/30.86853 UT
RA: 225.79 (+1.28 -1.43 deg 90% containment) J2000
Dec: +10.47 (+1.14 -0.89 deg 90% containment) J2000

Gold Alert – 50% purity threshold for astrophysical neutrino

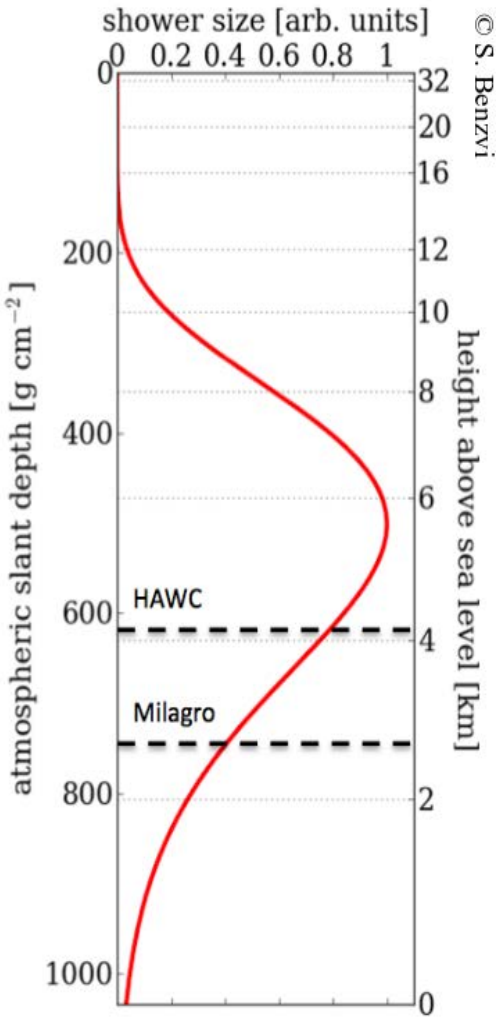
Flat-Spectrum Radio Quasar (FSRQ) PKS 1502+106 is located within 50% uncertainty region of event with an offset of 0.31°

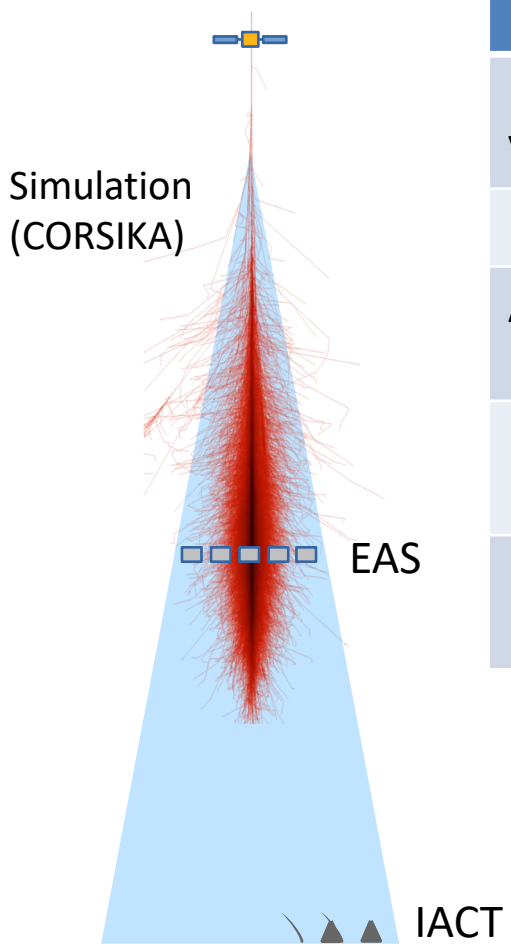
HAWC is following up!





EAS v. IACT



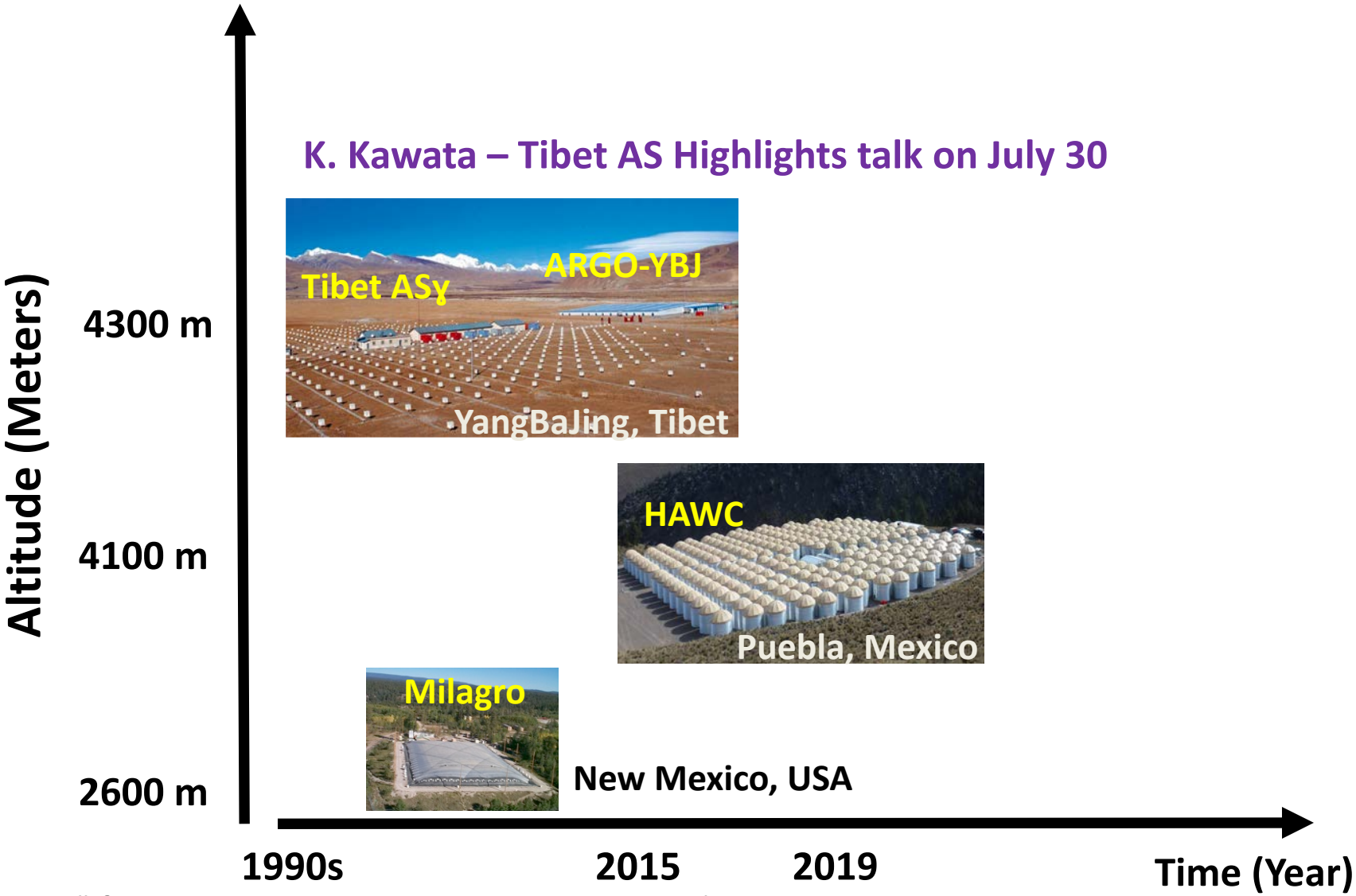


	EAS Array	IACT
Field of View (FOV)	~90° (~2 sr)	~5° (~4 msr)
Duty Factor	~100%	~10%
Angular Resolution	1° - 0.2°	0.1° - 0.06°
Energy Range	**500 GeV - 100 TeV**	50 GeV – 50 TeV
Energy Resolution	50% - 30%	20% - 8%

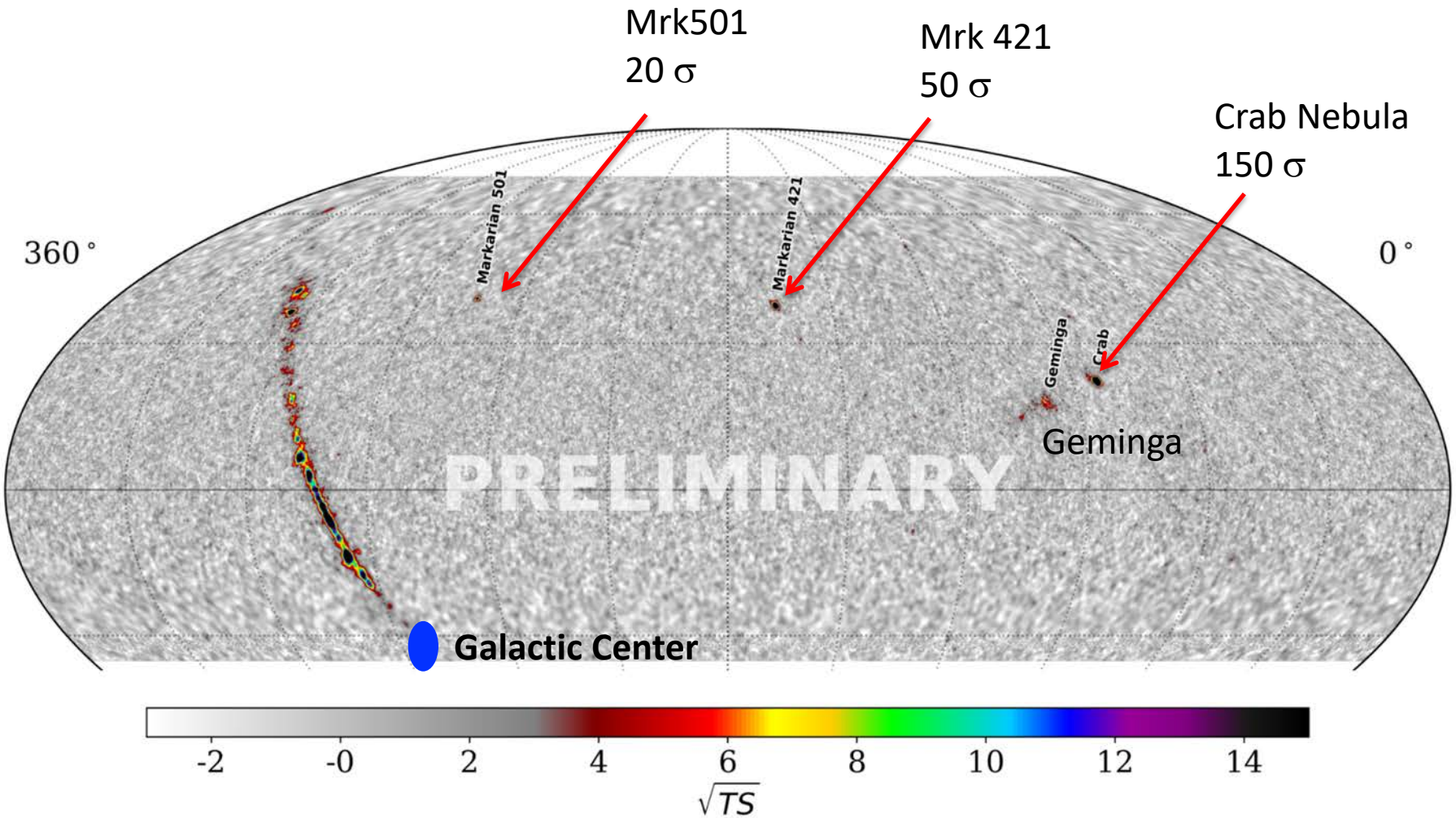
EAS – Altitude Matters

Higher = Lower Energy

EAS Detectors



HAWC Sky Map with 1128 days (~50 sources)

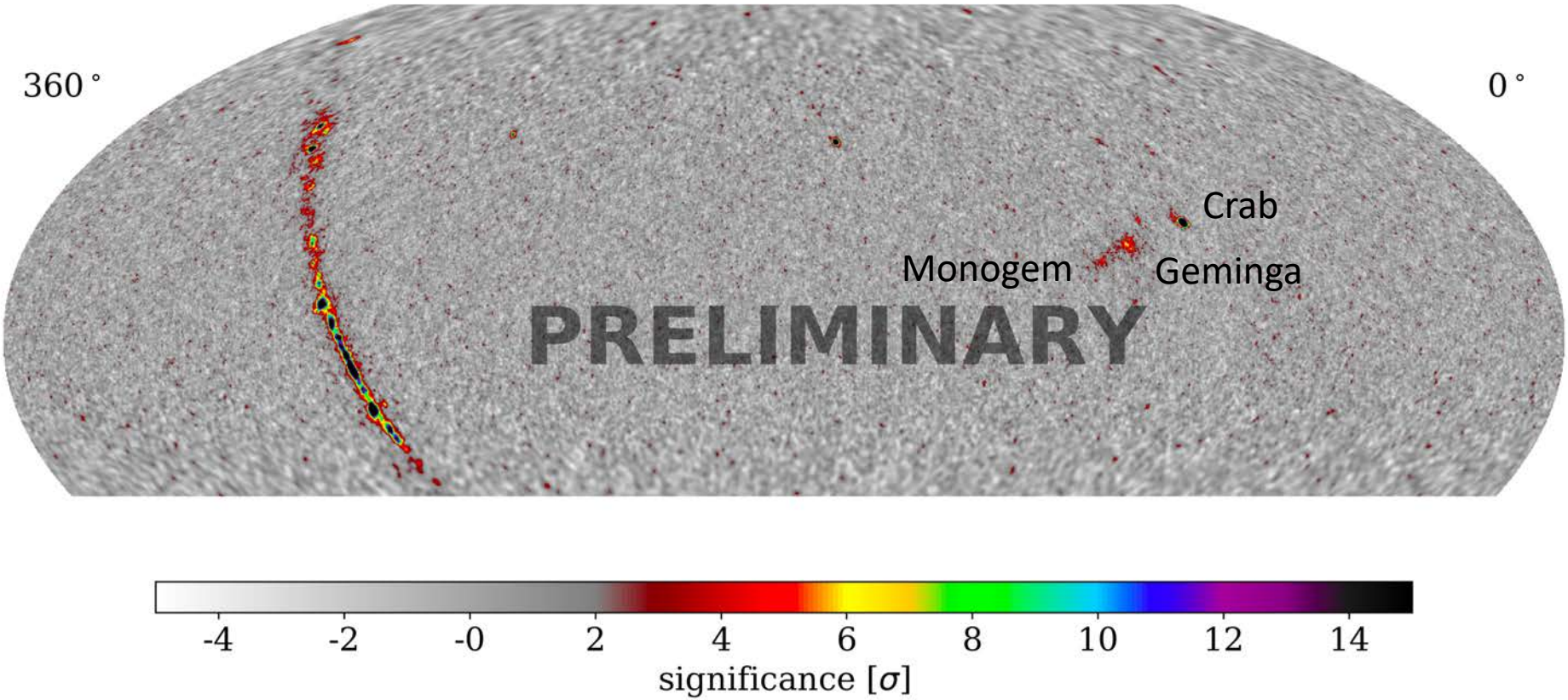


2HWC catalog ApJ 2017 was 507 days and contained 39 sources of which 10 were new

HAWC Sky Map with 1346 Days

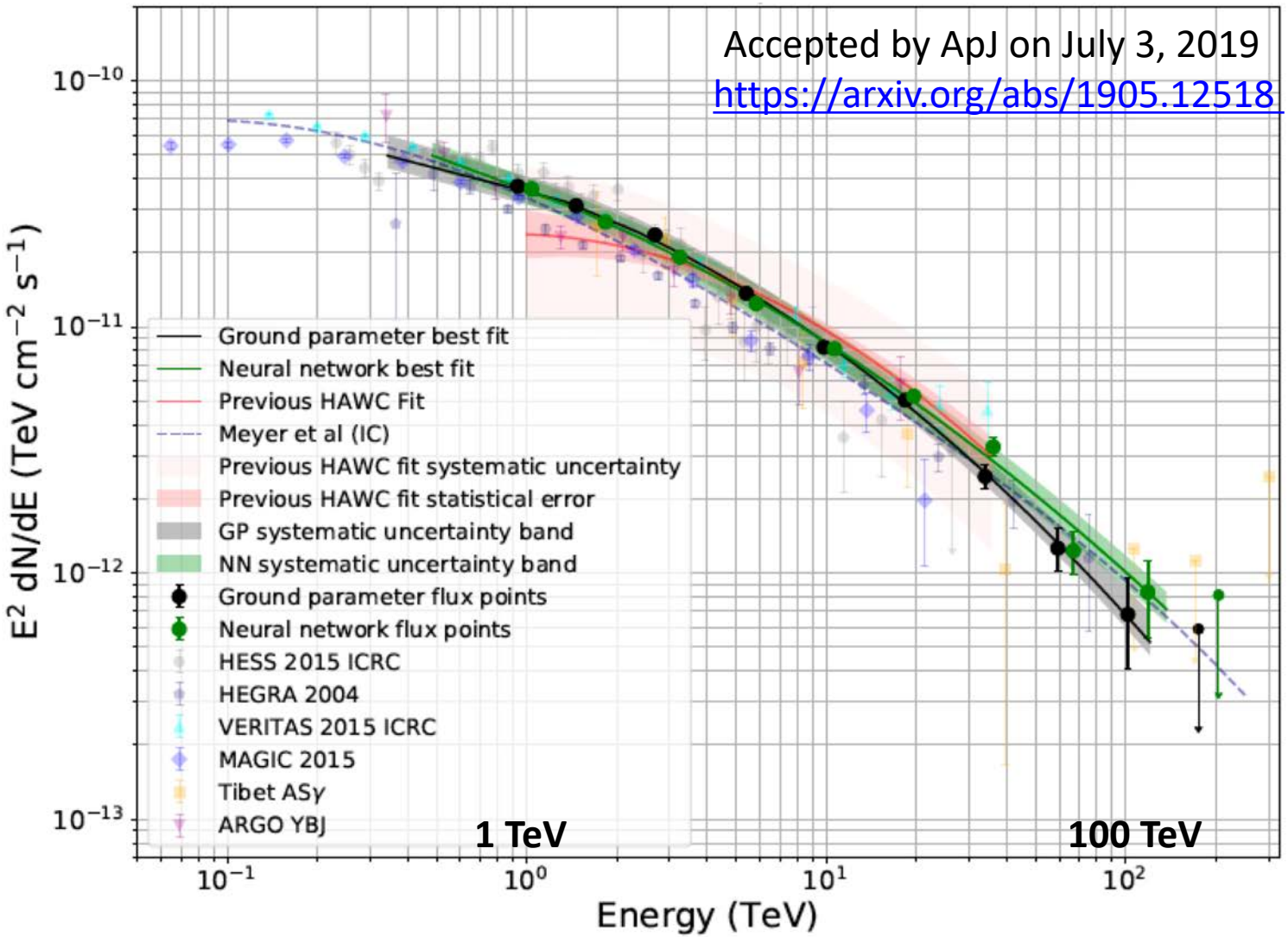
BRAND NEW

New reconstruction improvements coming soon

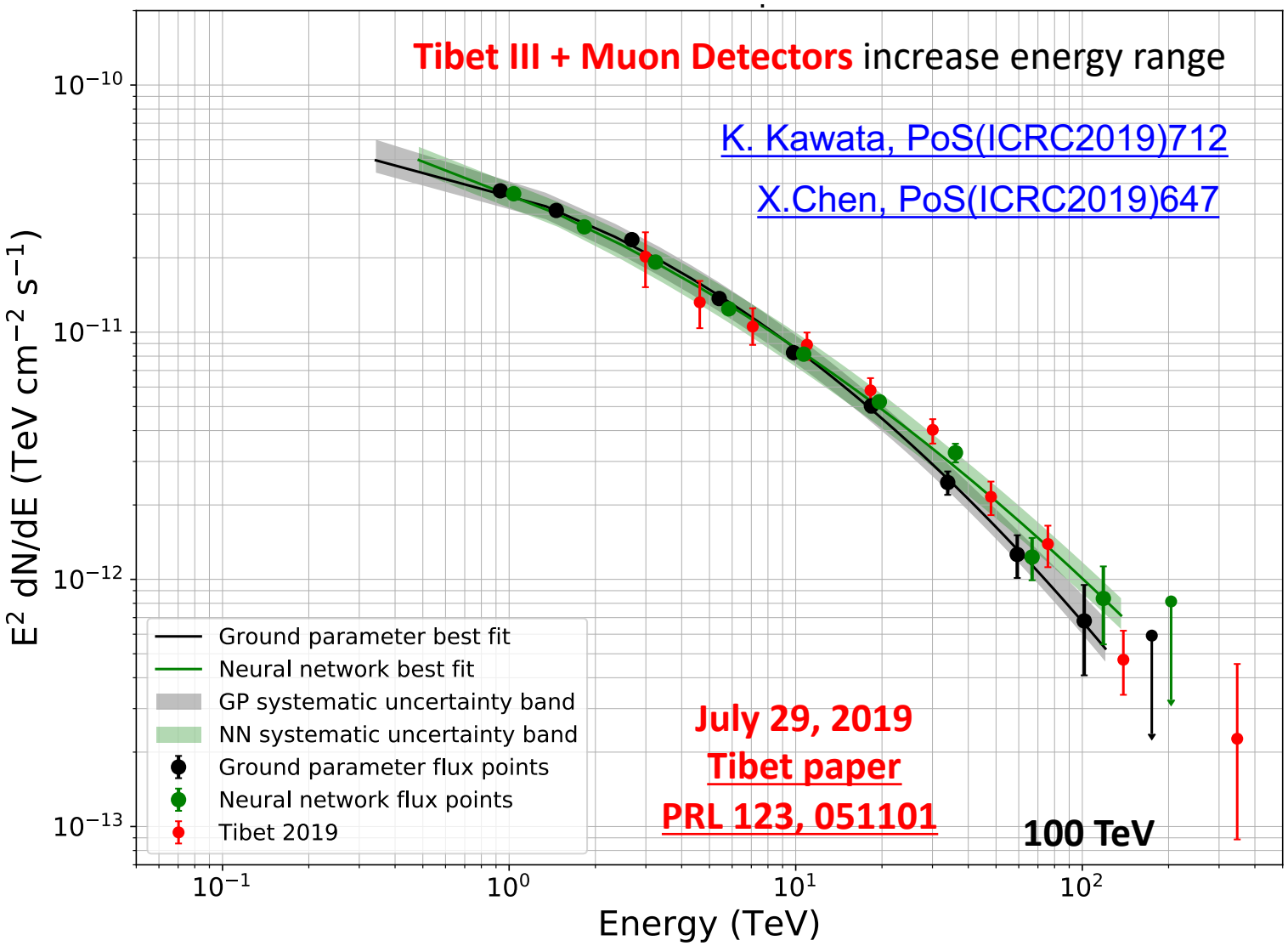


Crab Nebula Spectrum

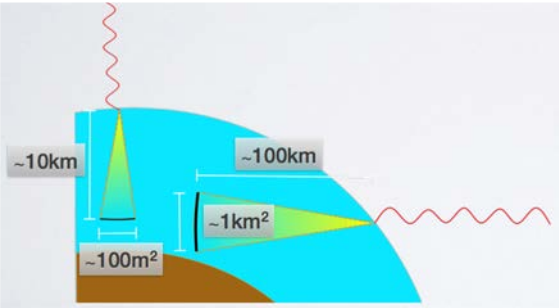
New energy estimators (**NN** and **GP**) vs. **fhit** give better energy resolution



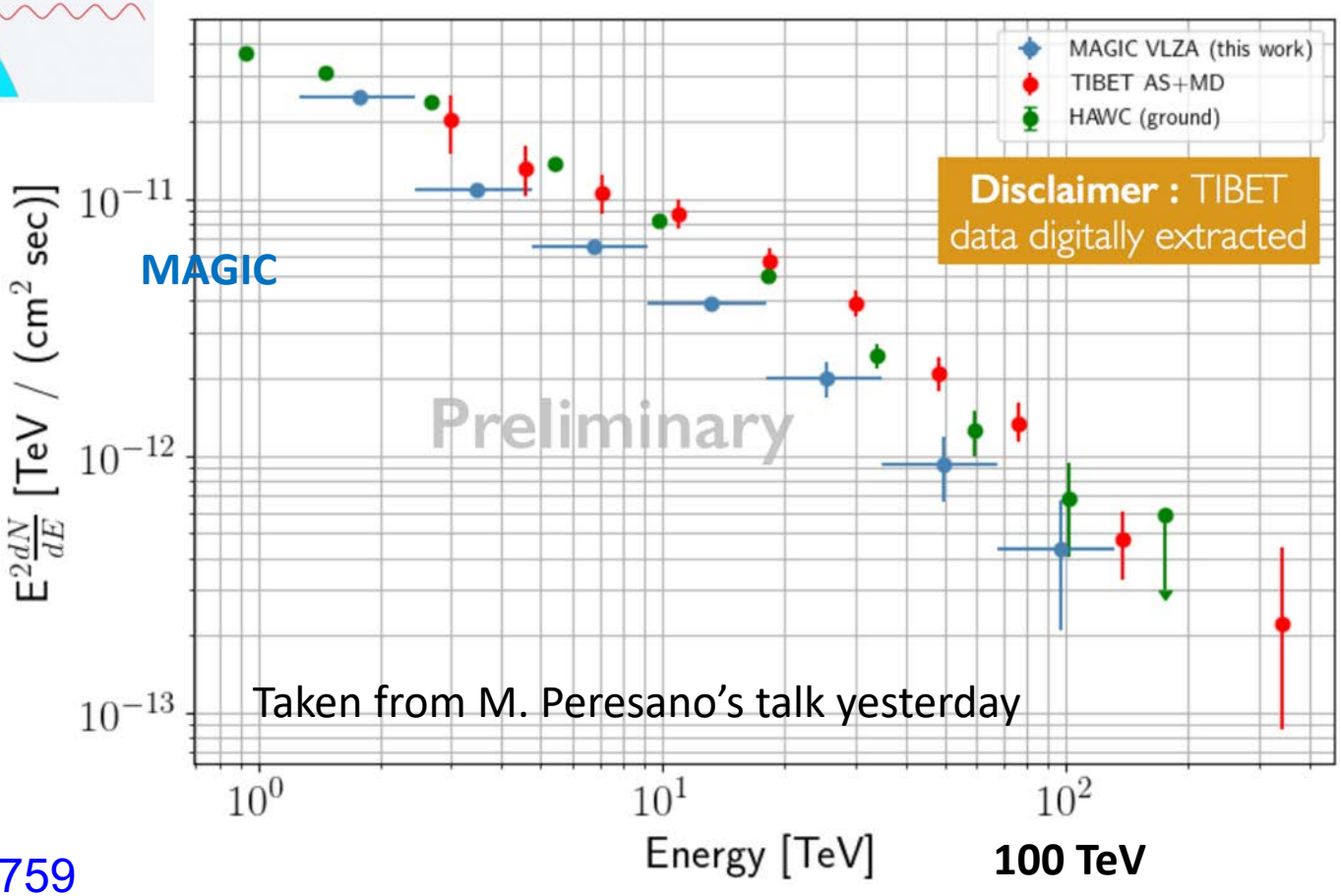
HAWC and Tibet Crab Spectrum



IACTs Getting to Higher Energies



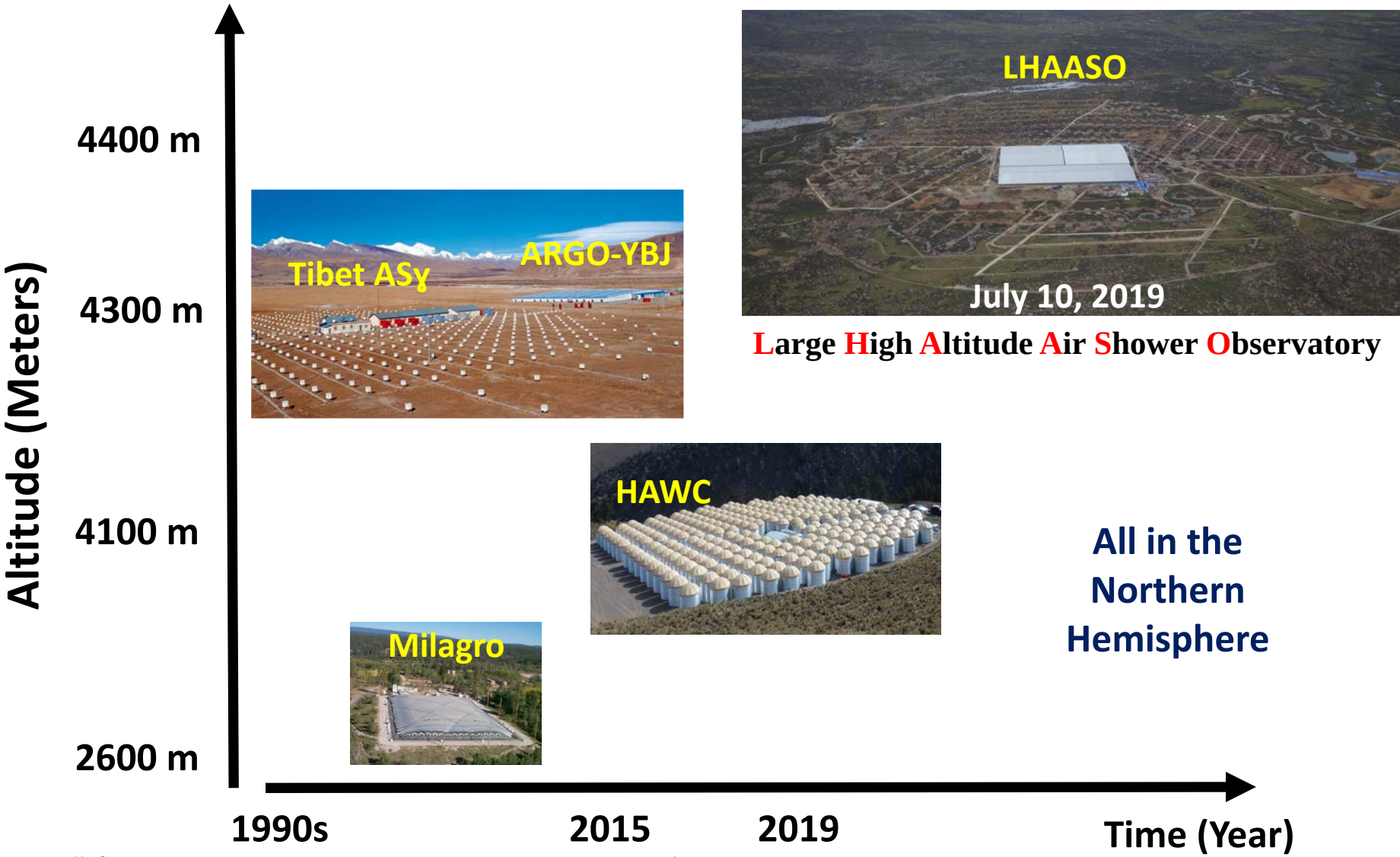
IACTs can observe at very high zenith angles to get to higher energies



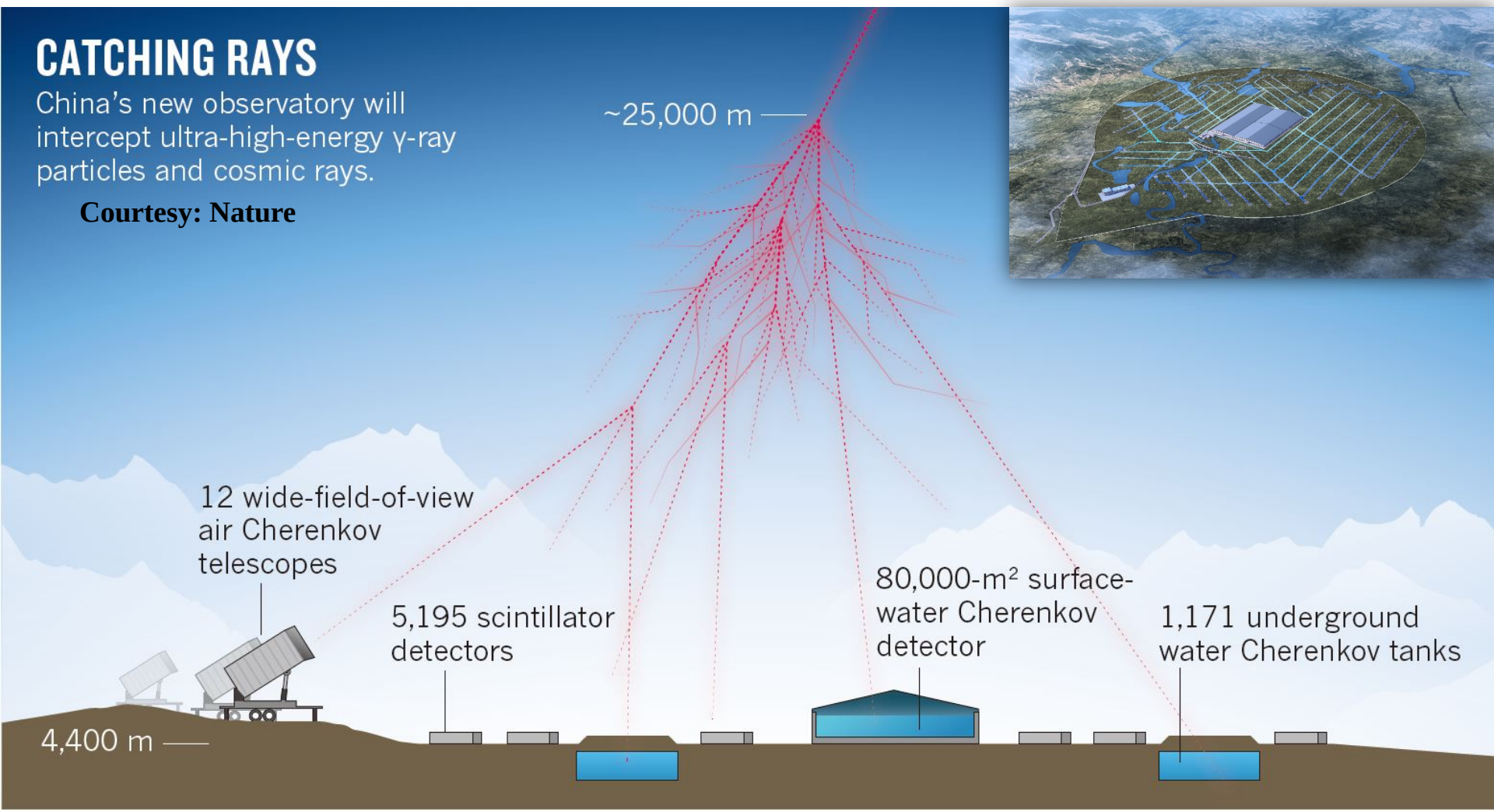
Taken from M. Peresano's talk yesterday

PoS(ICRC2019)759

Altitude and Size of EAS Detectors



Hybrid Detection of EASs by LHAASO

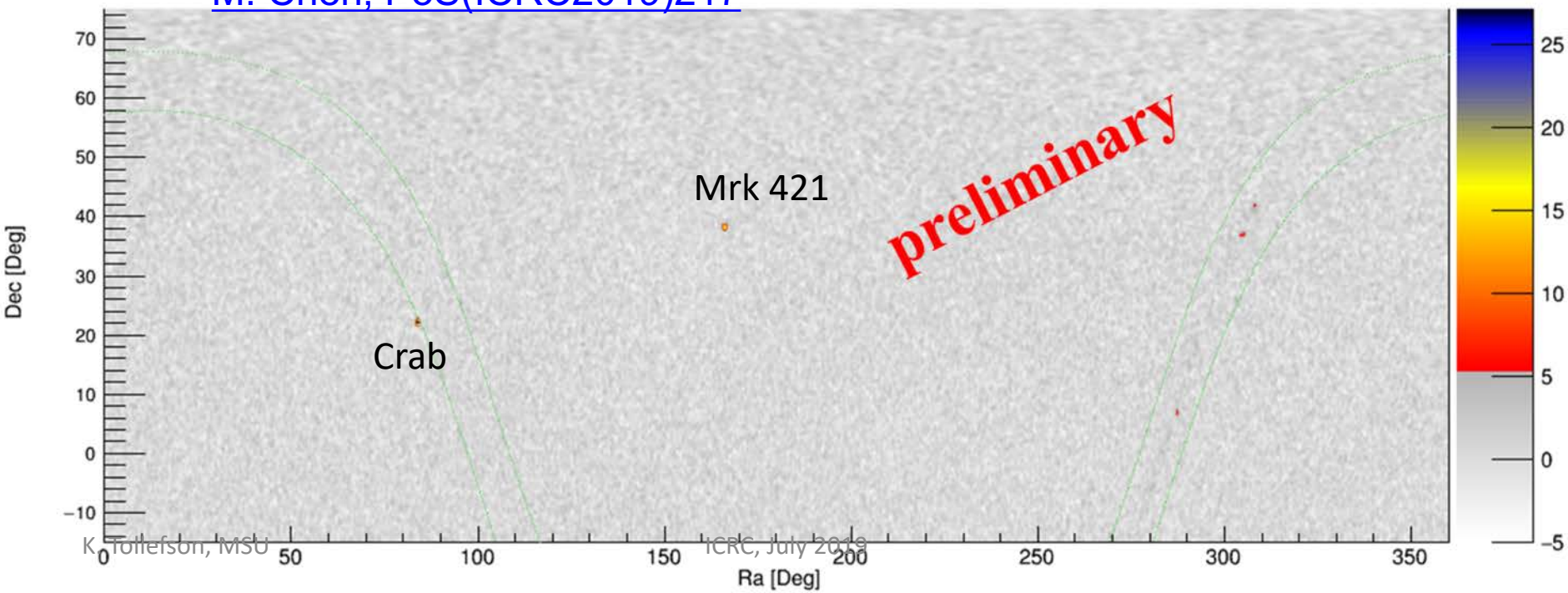


LHAASO WCDA #1 Sky Map

- First water pool (WCDA #1) taking data since April 2019
- ½ LHAASO ready for operation by end of 2019
- Construction complete 2020

- Data up to 2019-06-30
- Live time: 57 days
- Crab: 27σ
- 5 sources > 5 σ

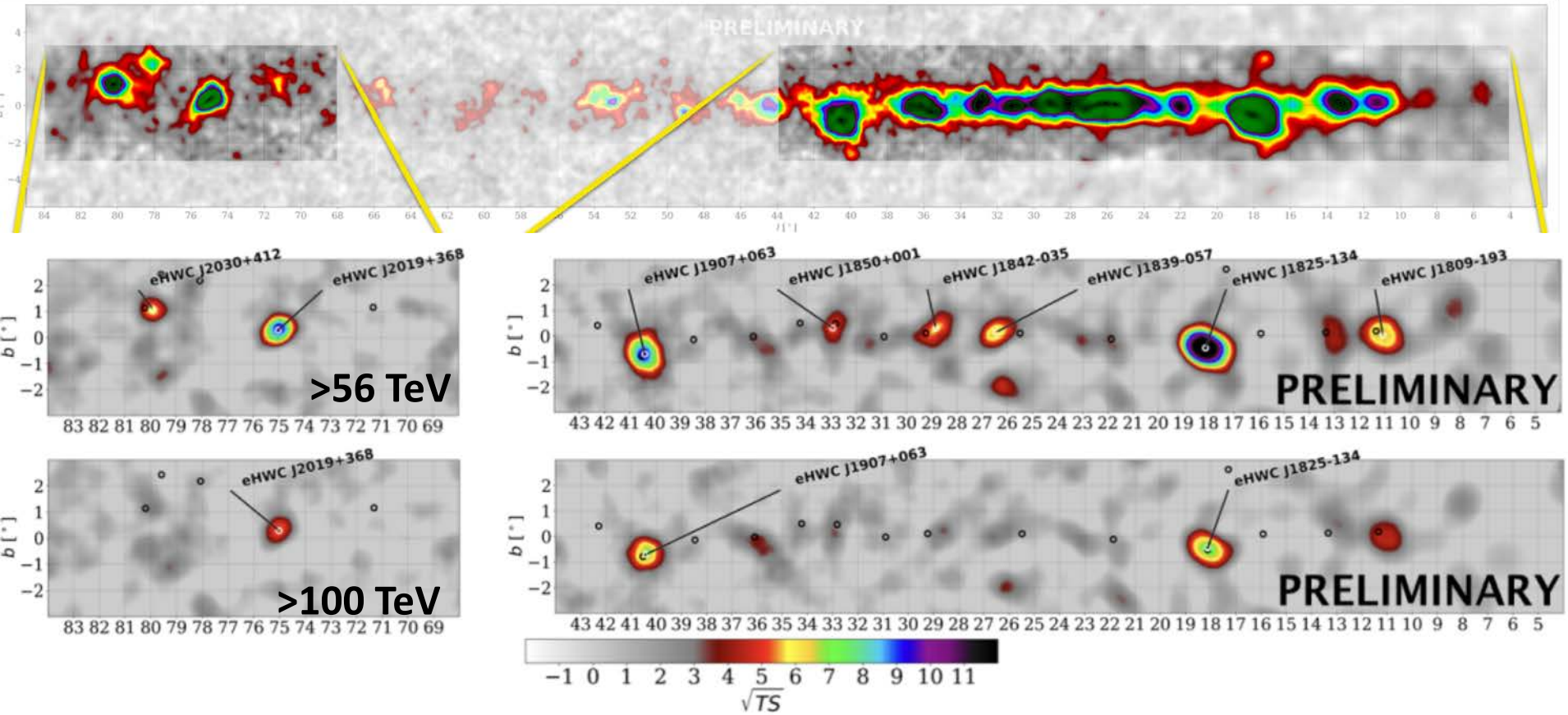
M. Chen, PoS(ICRC2019)217



Highest Energy Source Catalog

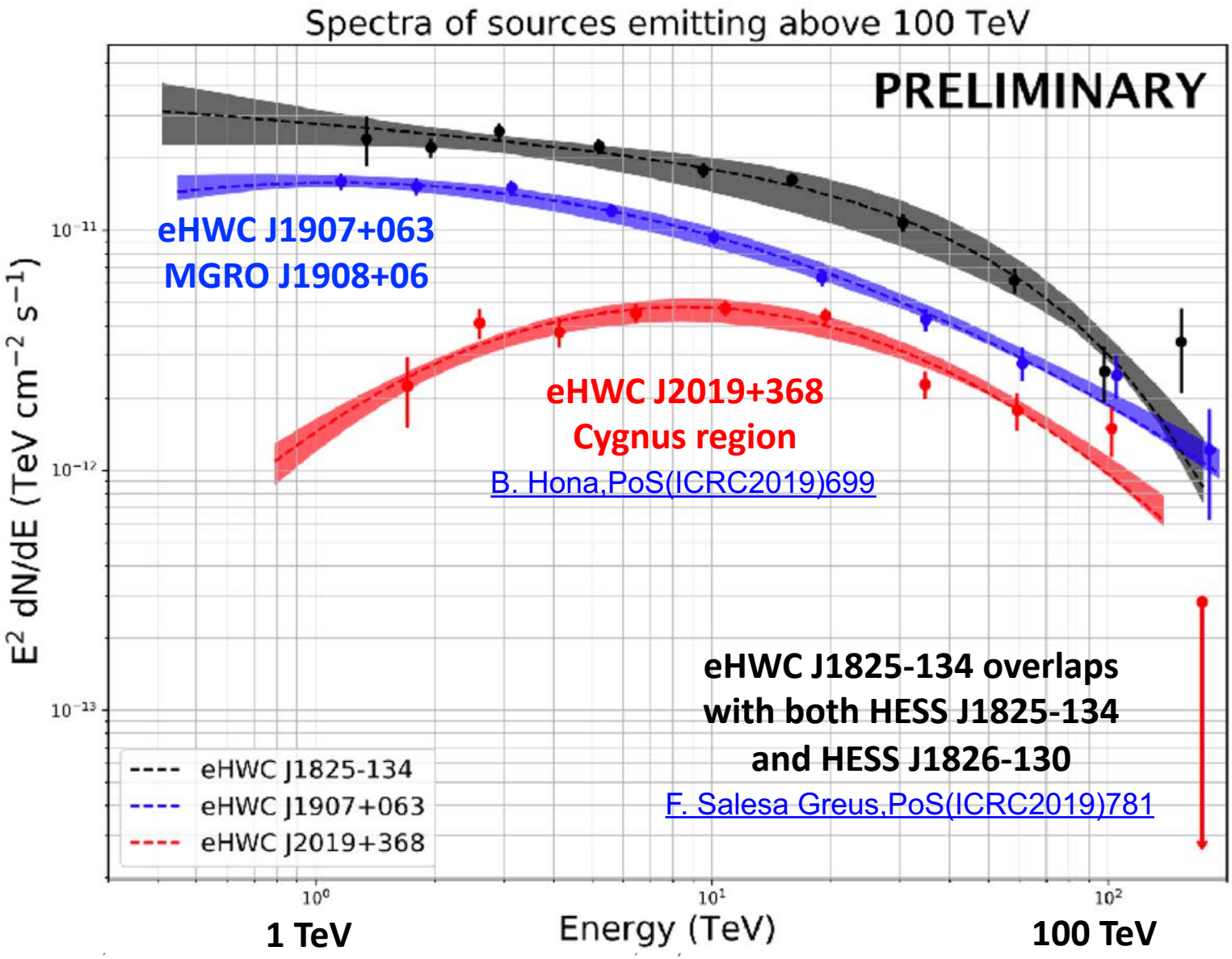
Paper in Preparation

K. Malone, PoS(ICRC2019)781



See 8 extended sources in Inner Galactic Plane > 56 TeV, of which 3 seen > 100 TeV.

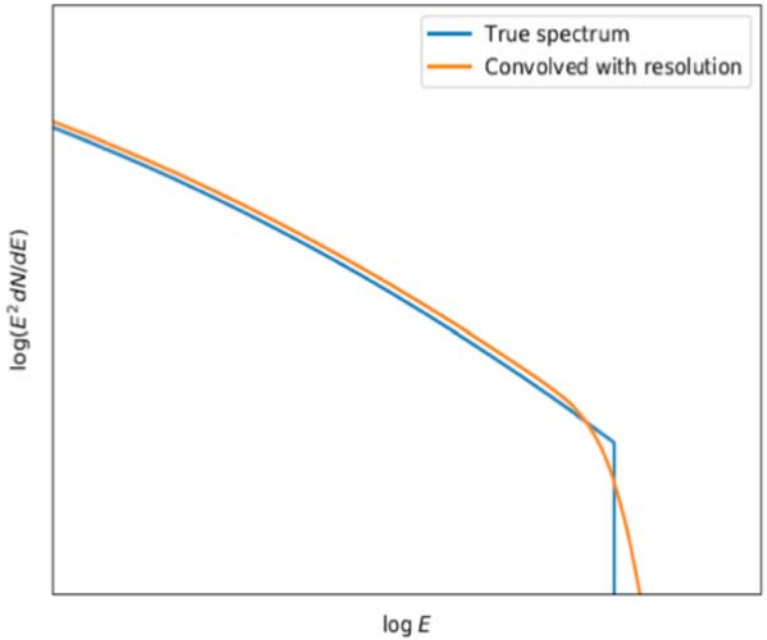
Spectra of 100 TeV Sources



Evidence for >100 TeV Photons with HAWC

- Find cut-off energy (E_c) above which spectrum is inconsistent with background + mis-reconstructed events
- Likelihood fit of chosen spectrum model compared to spectrum with hard cut-off at E_c
  - Galactic sources modeled by power law with exponential cut-off
  - Crab modeled by a power law

$$\Phi_{\mathrm{obs}} = \Phi_{\mathrm{emit}}(\mathrm{E})\Theta(\mathrm{E}_{\mathrm{cut}} - \mathrm{E})$$



J. Linnemann, PoS(ICRC2019)723

Source	Ec(95%) TeV	Ec(3σ) TeV
2HWC J1825-134	253	168
2HWC J1908+063	213	156
Crab (HAWC)	152	96
2HWC J2031+415	144	78
2HWC J2019+367	121	86
J1839-057	79	66
2HWC J1844-032	77	63
Crab (HEGRA)		56 (2.7σ)

Lorentz Invariance Violation (LIV)

LIV can modify dispersion relation:

A general modification to the dispersion relation would rather involve a general function of energy and momentum

$$A = \{E, p\}$$

LIV parameter

$$E_a^2 - p_a^2 = m_a^2 \pm |\alpha_{a,n}| A_a^{n+2} \; ; \; |\alpha_n| = |\epsilon_0^{(n)}| / M^n = 1/(E_{\mathrm{LIV}}^{(n)})^n$$

LIV coefficients

$E_{Pl}, \; E_{QG}$

n = 0, 1, 2, ...

Leading order of correction

Energy scale of new physics

H. Martinez-Huerta and A. Perez-Lorenzana
Phys. Rev., D95(6):063001, 2017

Highest Energy Photons set LIV Limits

Superluminal phenomena, such as photon decay, possible:

$$\alpha_{\gamma,n} < E_\gamma^{-n}\left[\frac{4m_e^2}{E_\gamma^2 - 4m_e^2}\right]$$

m_e = mass of electron

$$E_{LIV}^{(n)} > E_\gamma\left[\frac{E_\gamma^2 - 4m_{e^-}^2}{4m_{e^-}^2}\right]^{1/n}$$

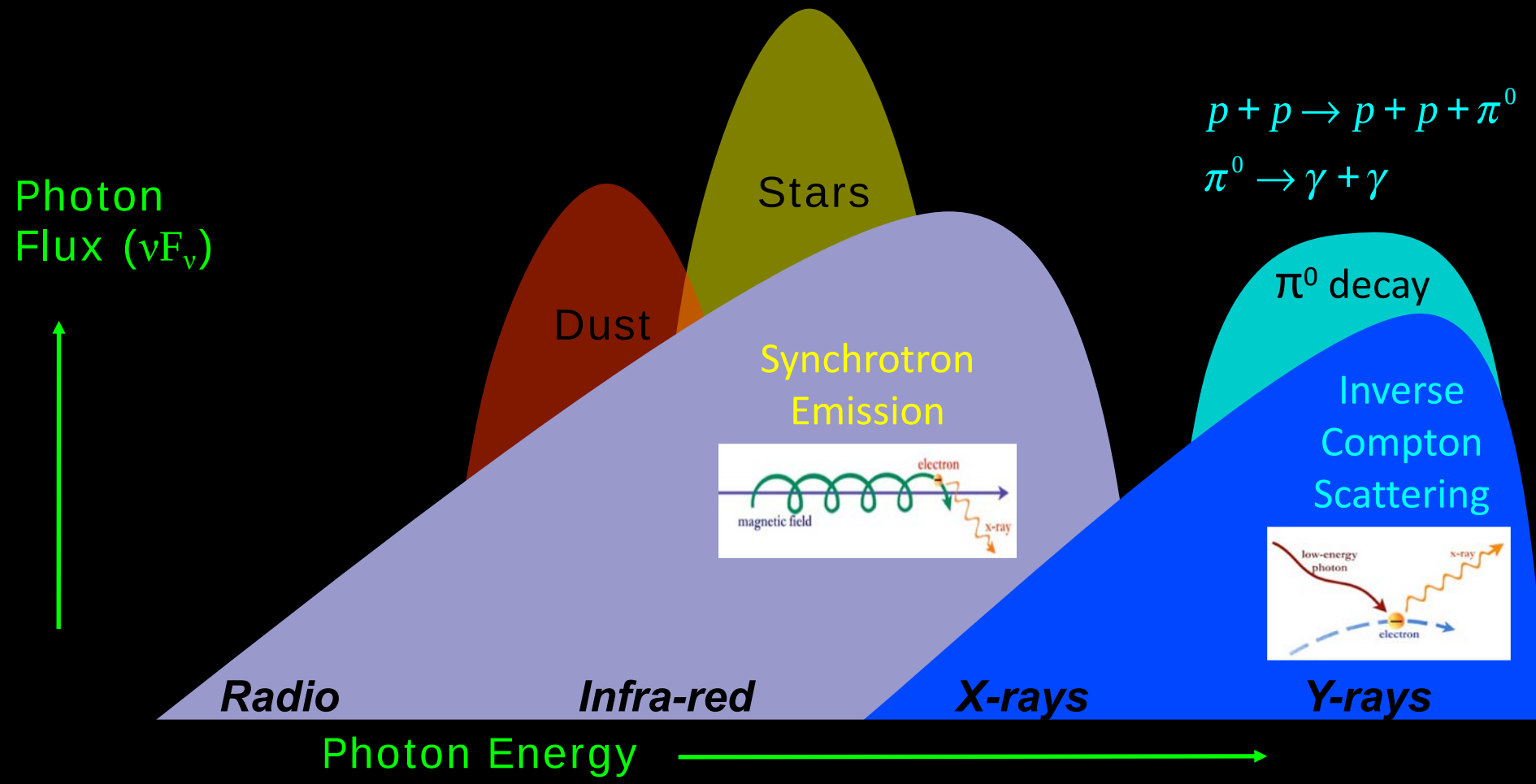
Above this energy threshold, the decay rate is quite efficient that photons should not arrive at Earth from astrophysical distances

- Creates a cut-off in energy spectra
- Existence of HAWC high-energy photons limit $E_{LIV} > 10^{31}$ eV
- Most constraining limit on n=1 of E_{LIV}

See Martinez-Huerta's talk GAI11c at 17:00 TODAY in Shannon Hall

H. Martinez-Huerta, PoS(ICRC2019)328

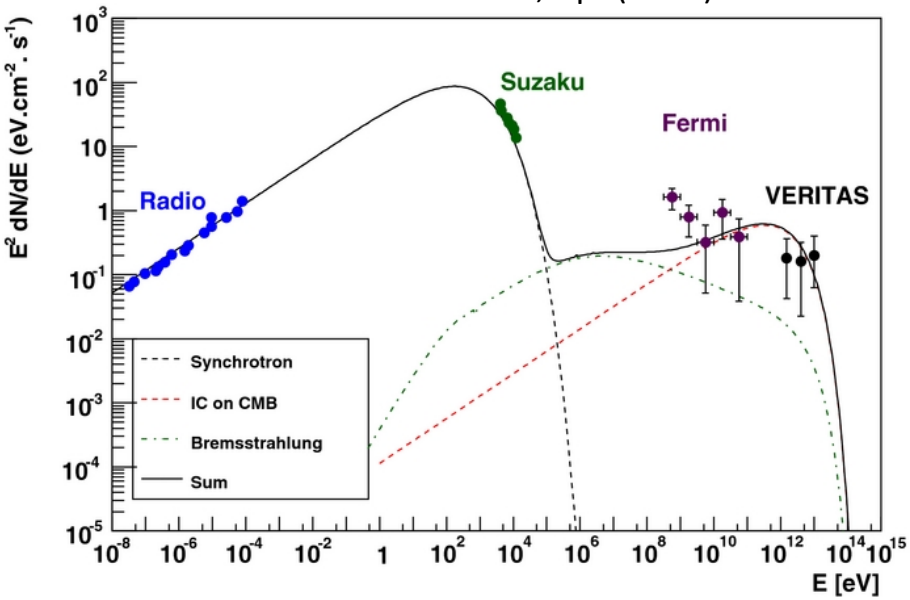
- **High energy** gamma rays are only produced by ***non-thermal*** processes.
  - Inverse Compton Scattering (for electrons) – **Leptonic** Model
  - Neutral pion decay (for protons) – **Hadronic** Model



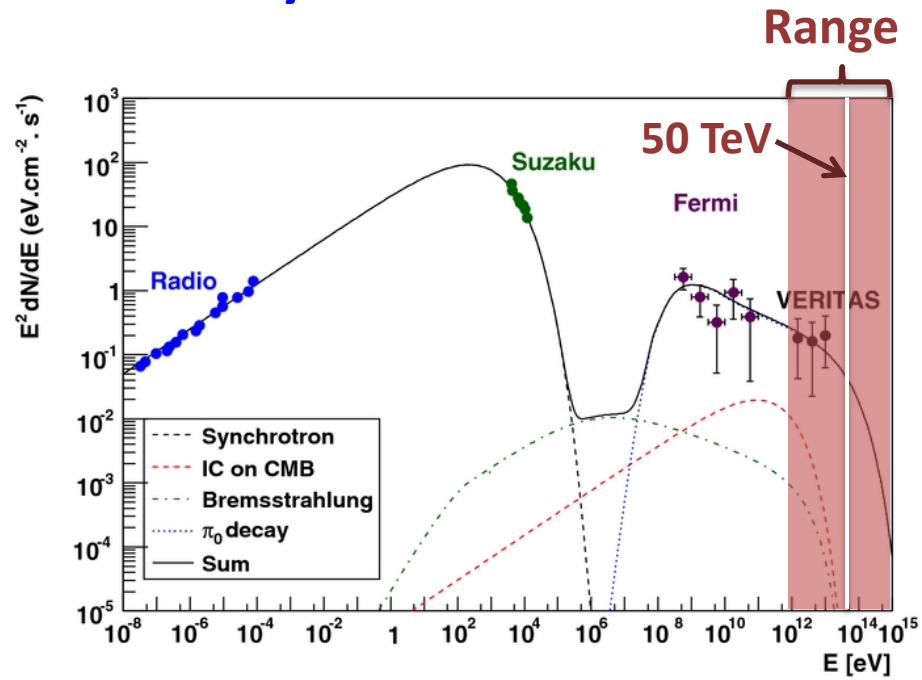
An Example of Particle Acceleration Models for Tycho

Photon Energy Spectrum for Tycho SNR

Giordano *et. al.*, ApJ (2012)



Leptonic Model



Hadronic Model

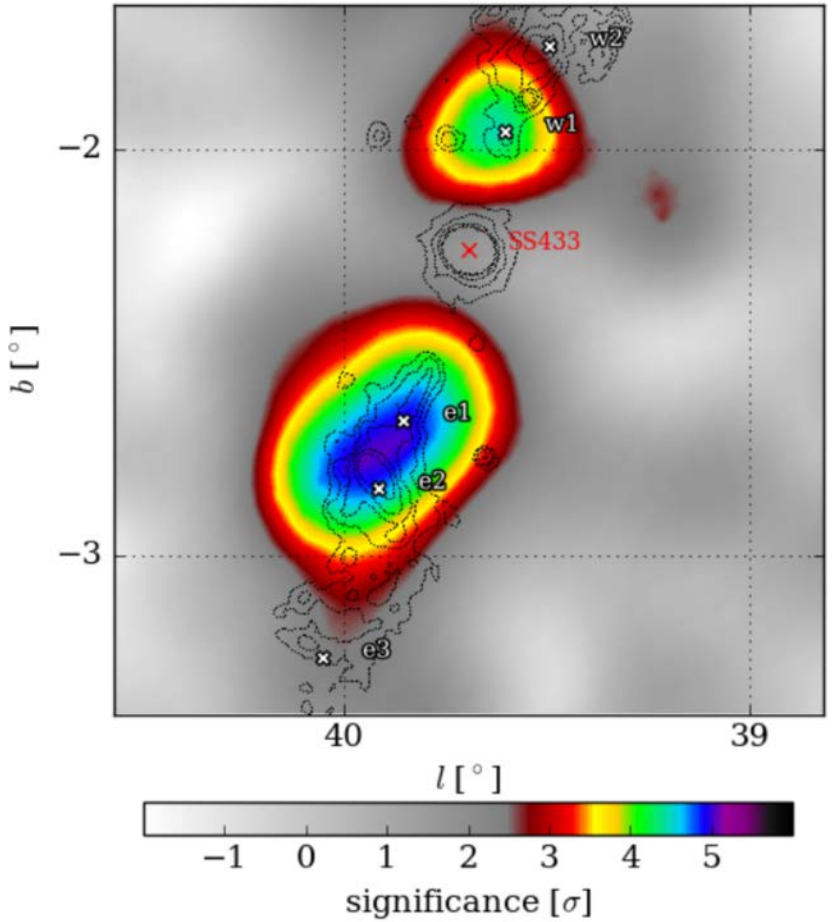
Cutoff energies are higher in hadronic models as the electrons in leptonic models suffer from synchrotron losses

Microquasar SS 433 and its Jets

nature International journal of science **Nature, 562:82-85 (2018)**

First direct proof of particle acceleration to E >100 TeV in jets

- Jets are observed edge-on so the gamma rays are not Doppler boosted to higher energies or higher luminosities
- Cooling time of such high energy electrons requires acceleration in the jet lobes far from central black hole

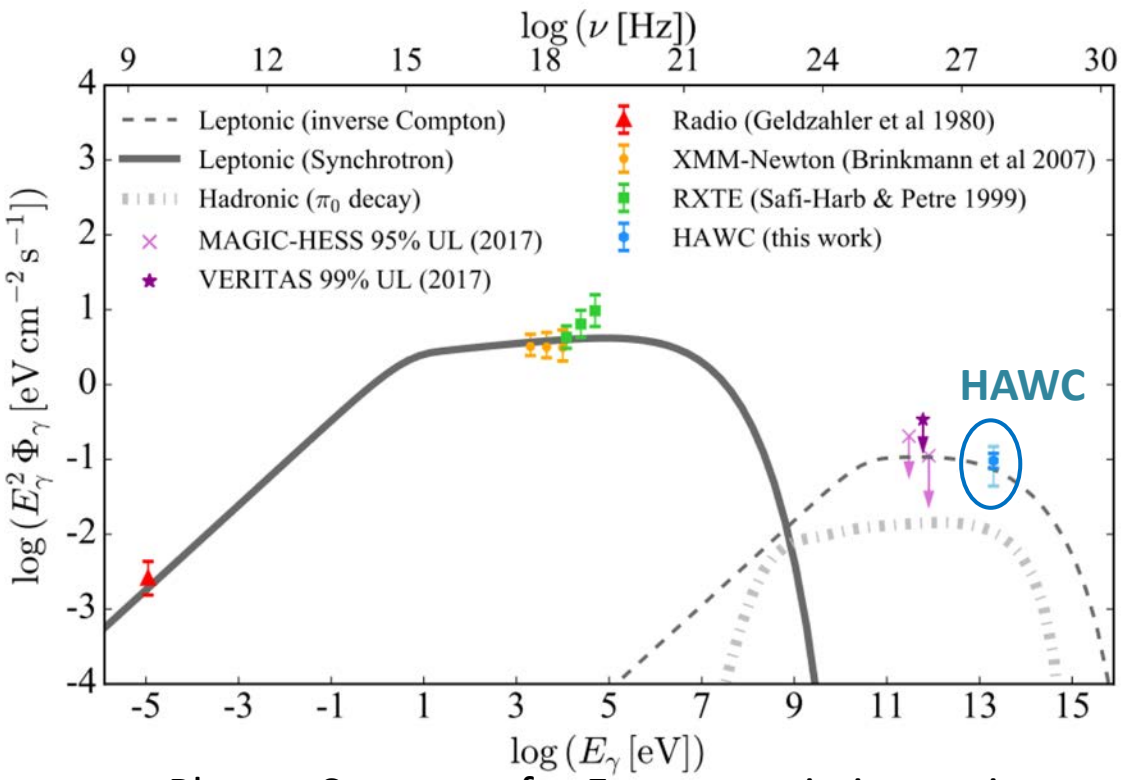


HAWC significance with the overlay of x-ray contours. The HAWC detection is correlated with the jet lobes and not the black hole.

SS 433 Multiwavelength Spectrum

High energy electrons accelerated in low B field from slow jets are difficult to explain

- Hadronic model requires too much energy
- PeV electron model in 16 mGauss field fits data



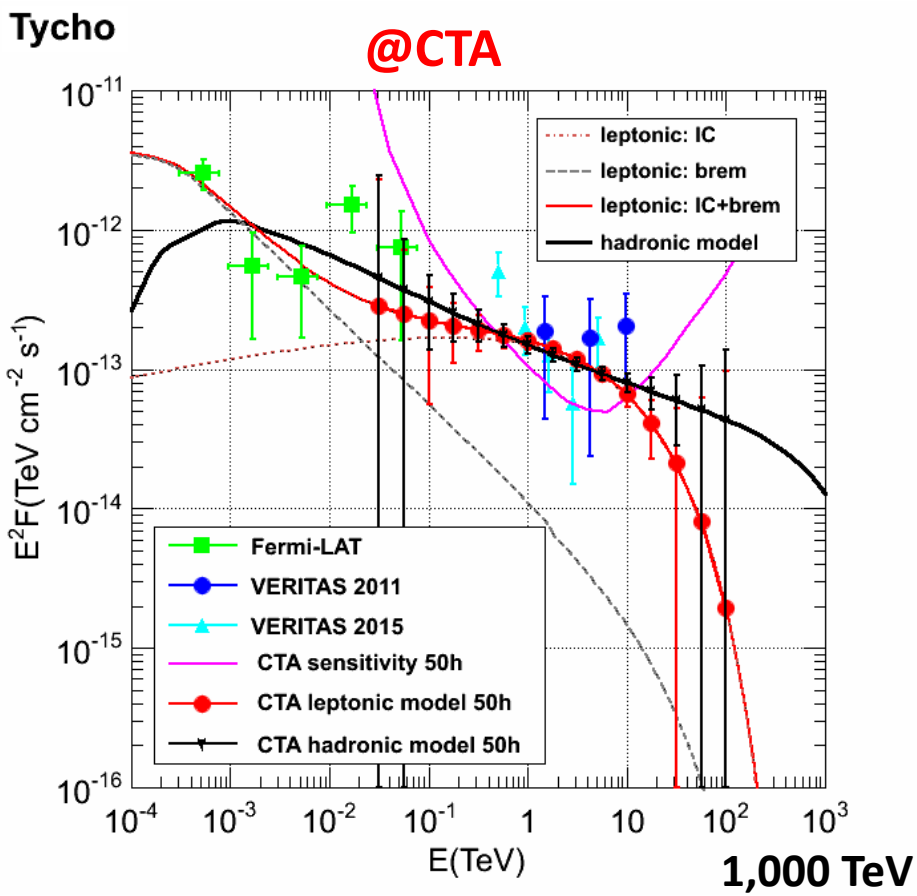
Photon Spectrum for Eastern emission region

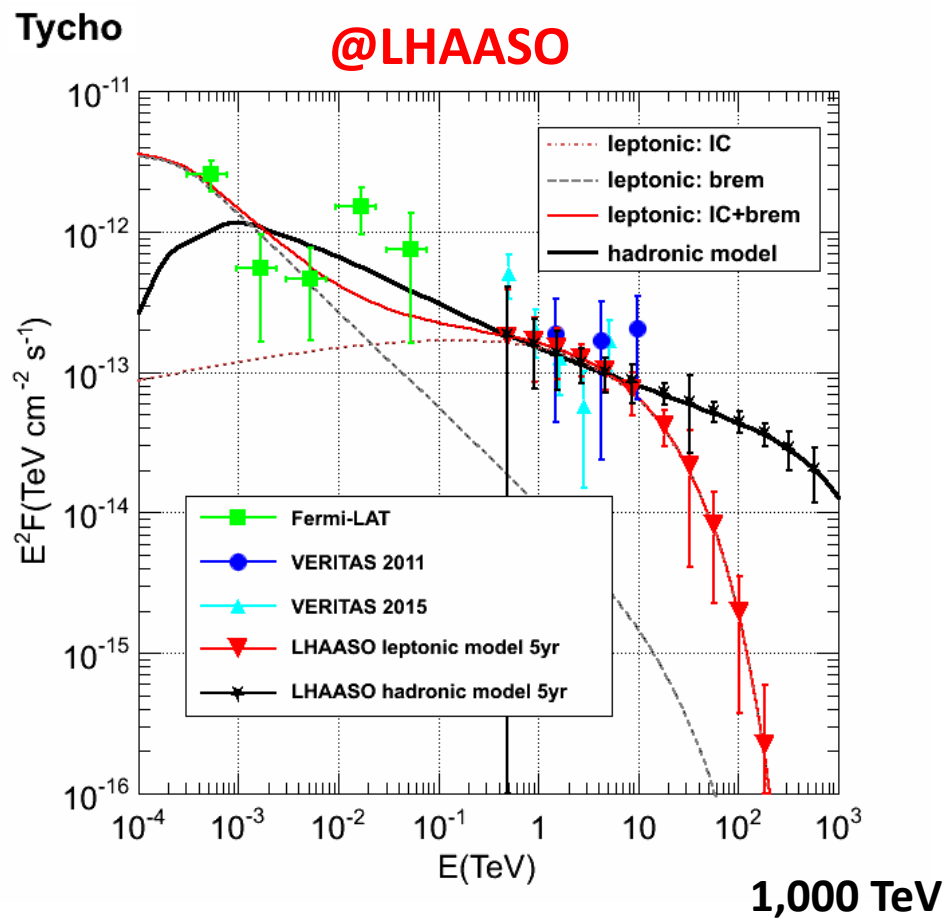
Updating analysis with new Energy Estimators

C.D. Rho, PoS(ICRC2019)772

Future Sensitivity to Acceleration Models for Tycho

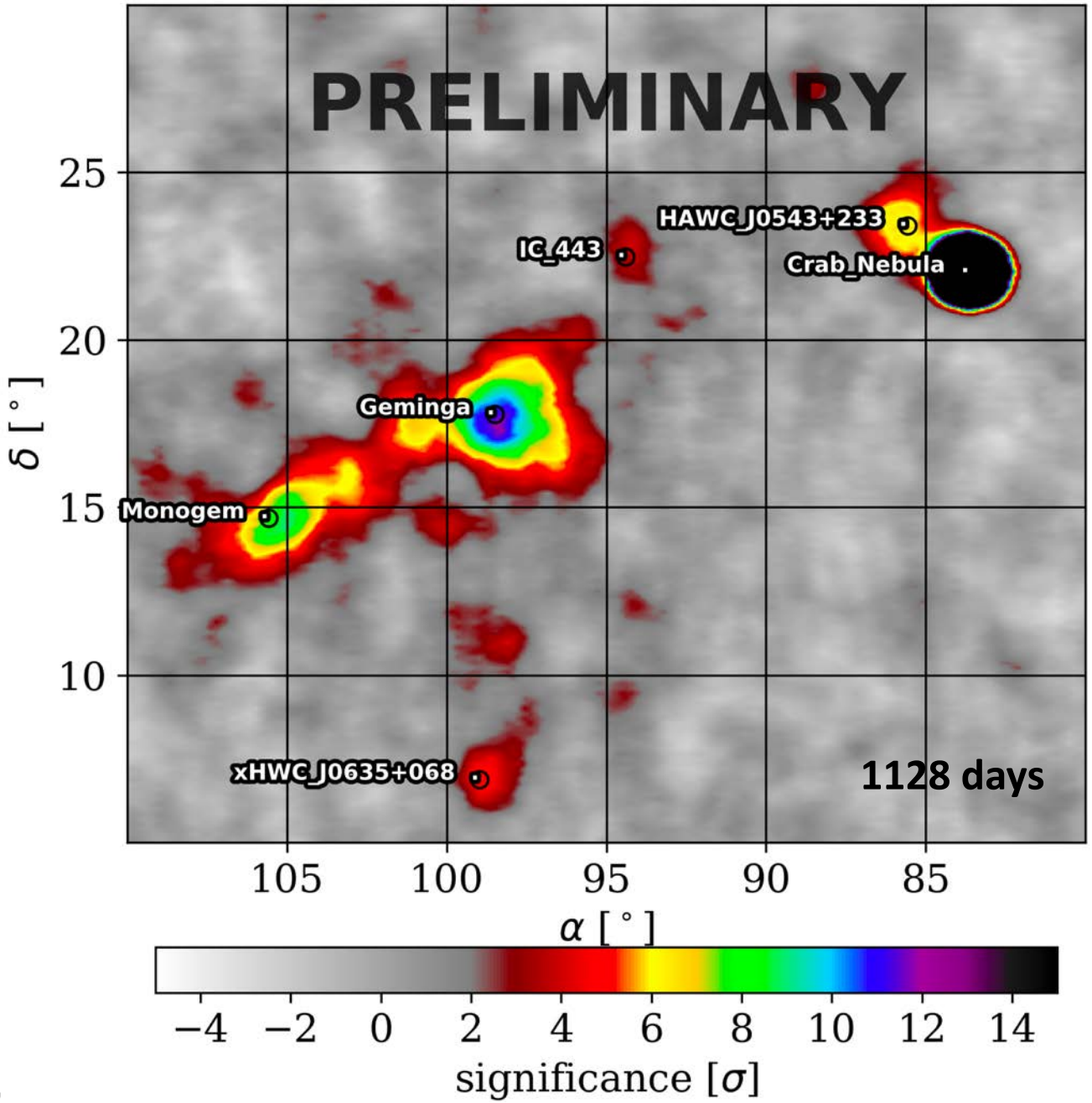
Photon Energy Spectrum for Tycho SNR





Slide courtesy of LHAASO

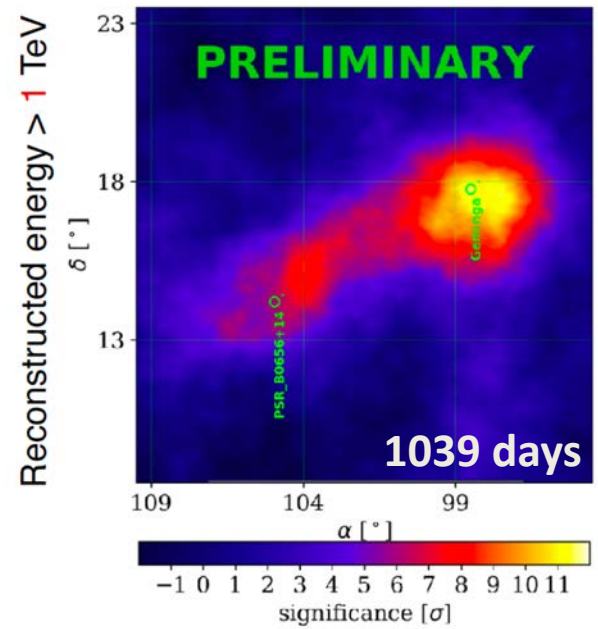
Tycho is not in HAWC's FOV

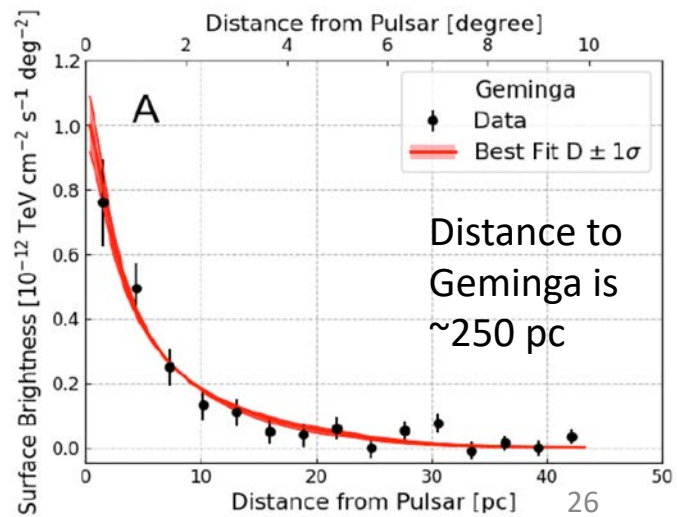

PRELIMINARY
HAWC_J0543+233
IC_443
Crab_Nebula
Geminga
Monogem
xHWC_J0635+068
1128 days
25
20
15
10
δ [°]
105
100
95
90
85
α [°]
−4
−2
0
2
4
6
8
10
12
14
significance [σ]

Geminga, an old pulsar

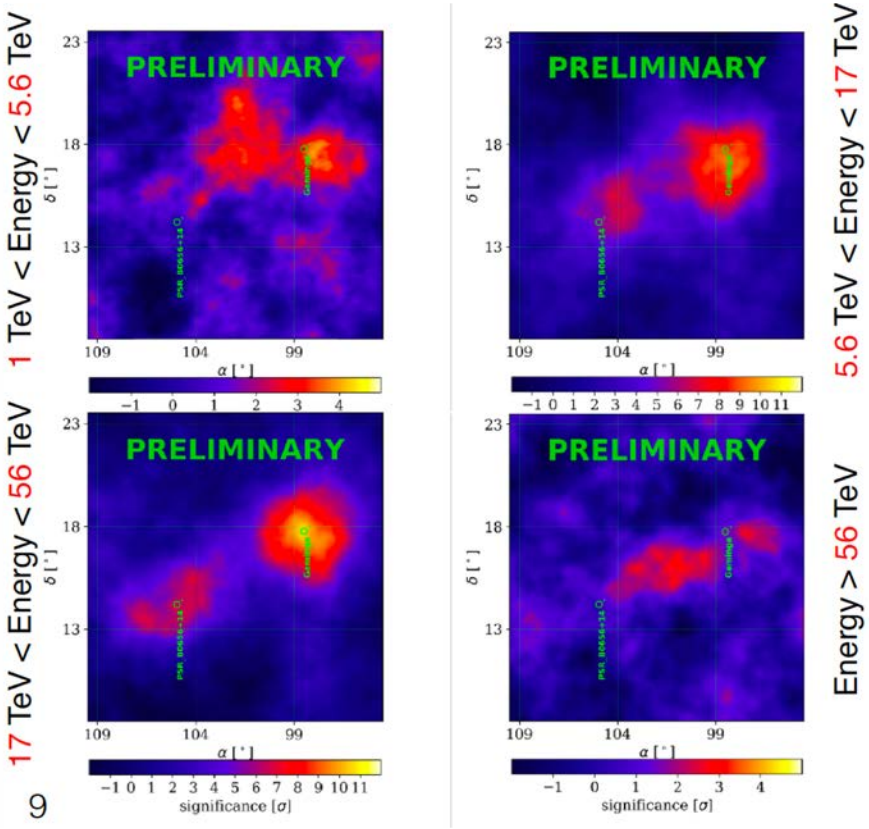
Science 358:911-914 (2017)

- Use angular extent of TeV nebula to measure the diffusion coefficient
- HAWC's measured diffusion coefficient around Geminga is much lower than values derived from CR secondaries
- See **G. Giacinti's Review talk** on July 30 for review of CR transport models



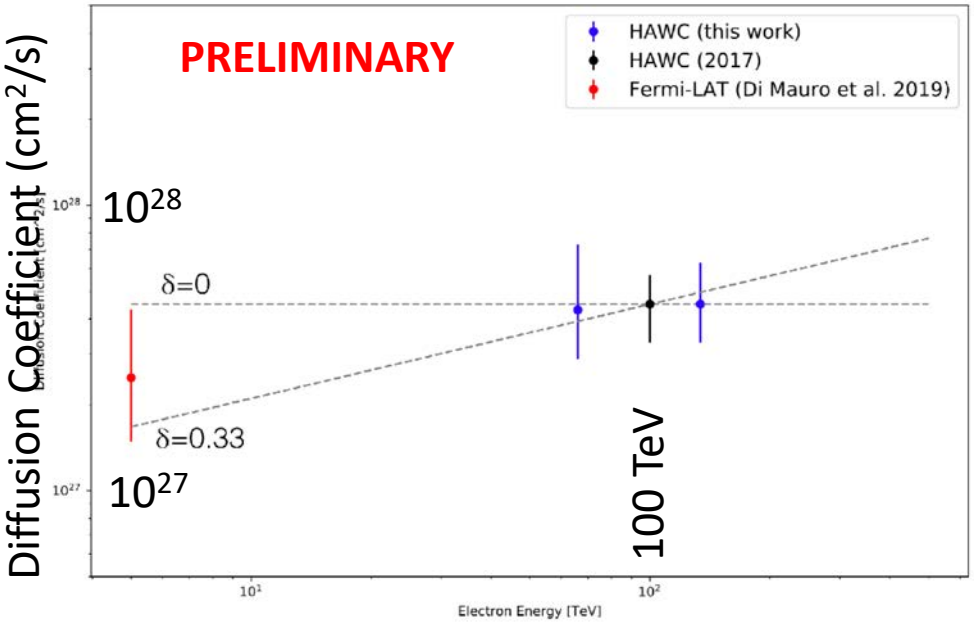


Geminga Update



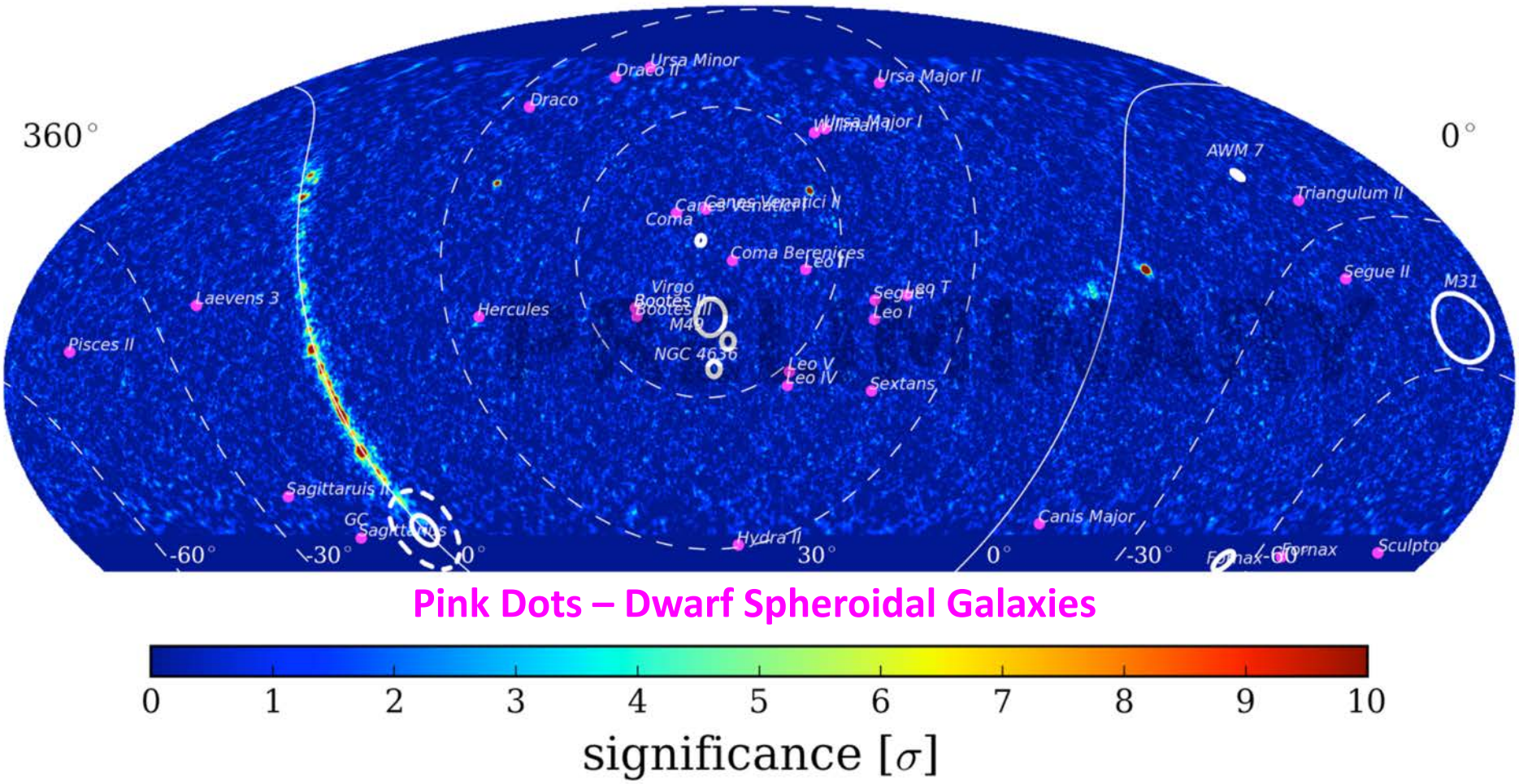
H. Zhou, PoS(ICRC2019)832

Using HAWC's new Energy Estimators observe Geminga from 5 - 56 TeV and make energy dependent measurement of diffusion coefficient



Dark Matter Sources in HAWC's FOV

Newly discovered sources (e.g. dwarf galaxies) can easily be added to searches.

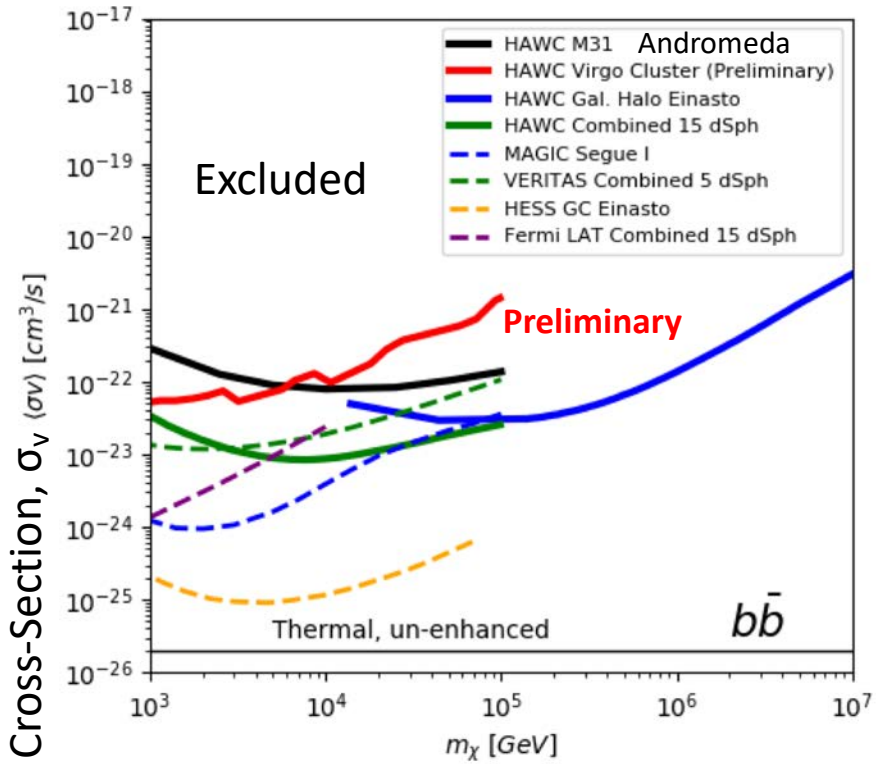


Pink Dots – Dwarf Spheroidal Galaxies

Dark Matter Limits for Various Sources

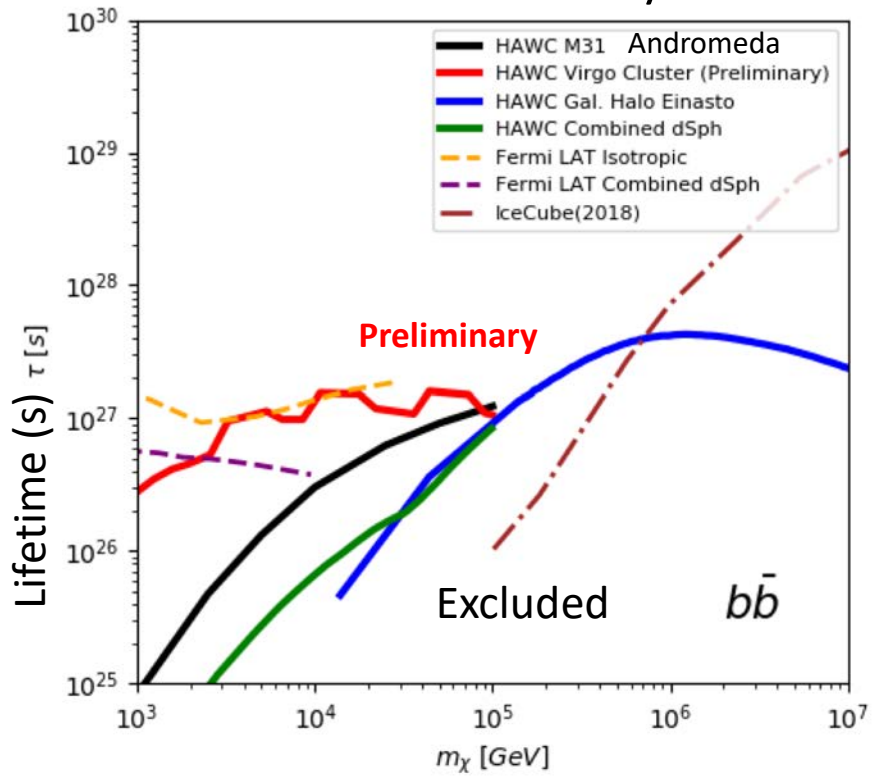
HAWC will extend to higher masses with new energy estimators

WIMP Annhiliation



100 TeV

WIMP Decay

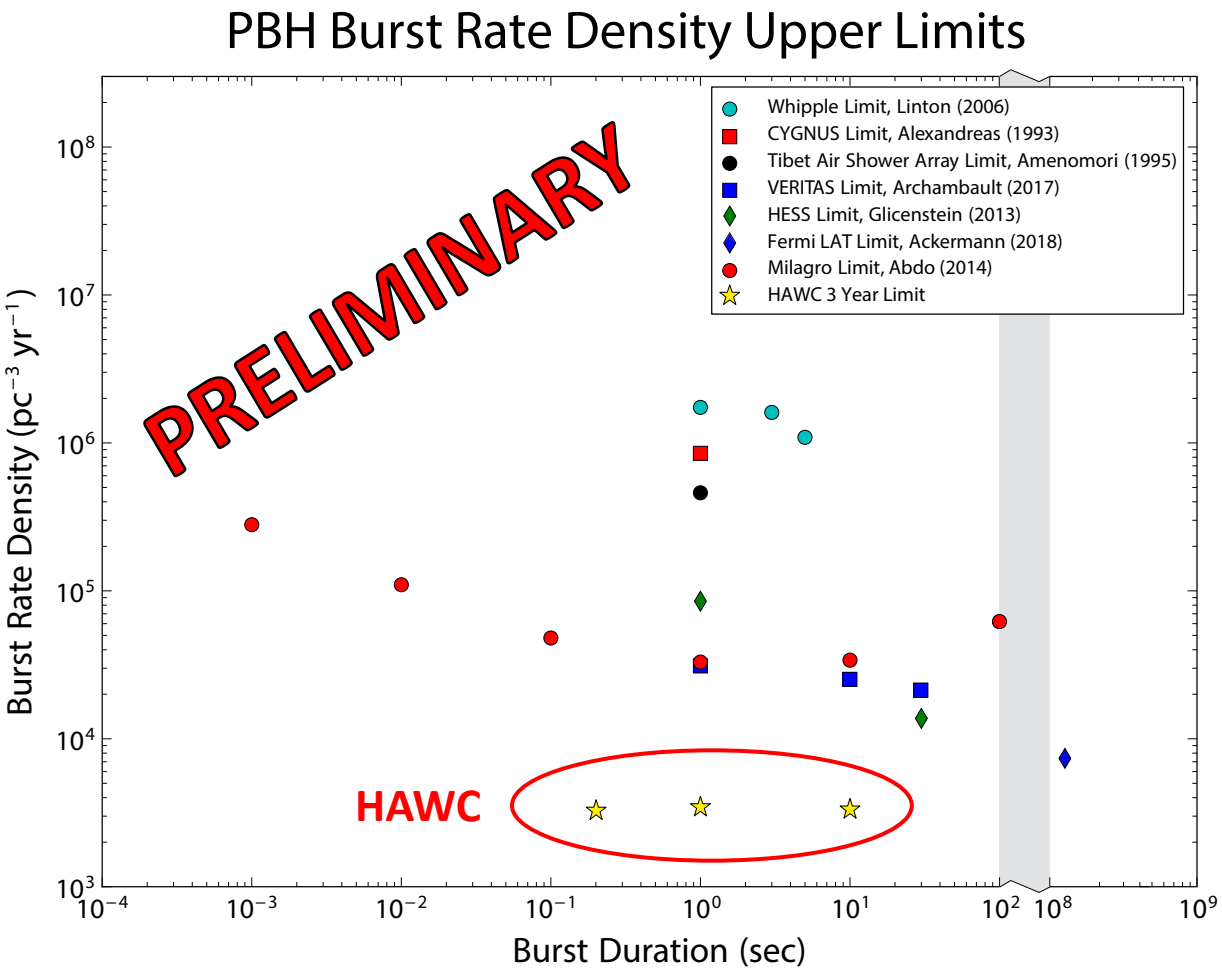


100 TeV

Several talks in Dark Matter Session at 16:30 TODAY Festival Room

S. Hernabdez Cadena, PoS(ICRC2019)520
J. Lundeen, PoS(ICRC2019)528
J. Lundeen, PoS(ICRC2019)529
T. Yapici, PoS(ICRC2019)551
L. Oakes,PoS(ICRC2019)012

Evaporating Primordial Black Holes (PBHs)



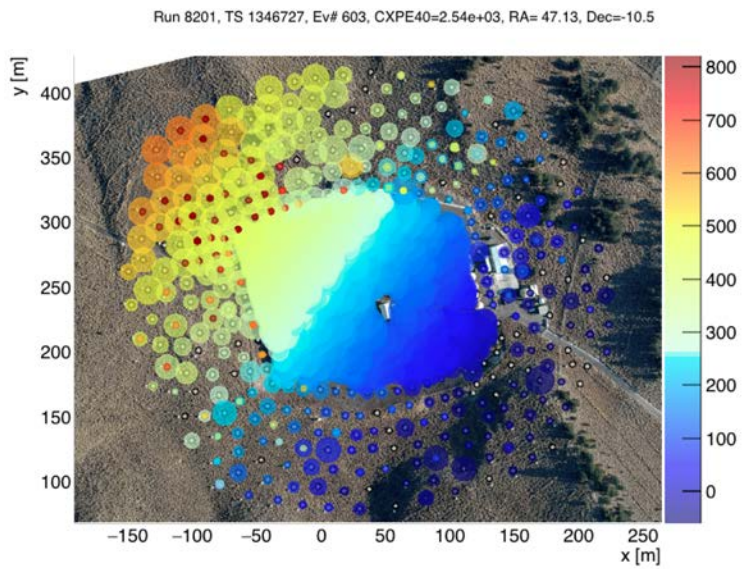
PBHs with an initial mass of ~5×10^{14} g would be expiring now emitting a burst of gamma rays.

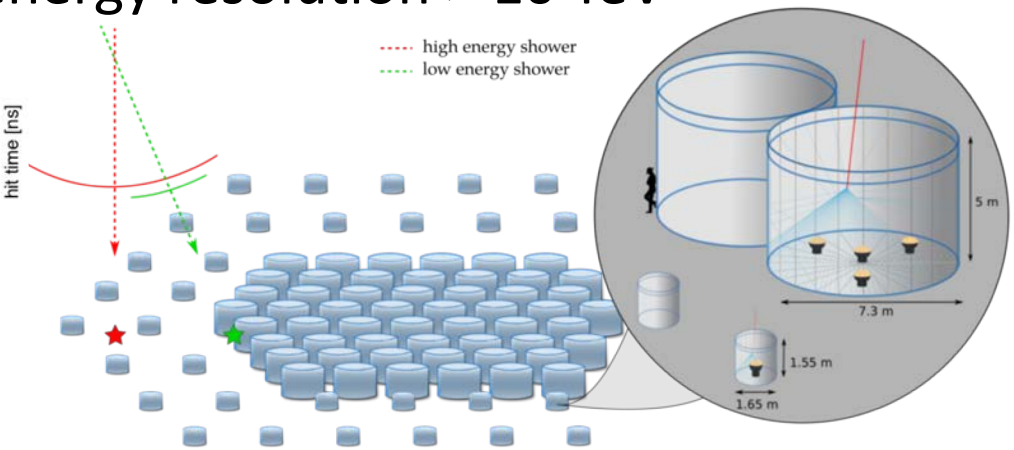
See K. Engel's talk TODAY at 17:00 in Festival Room

K. Engel, PoS(ICRC2019)516

Outriggers Added to HAWC

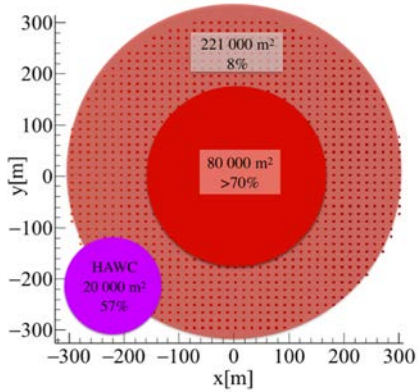
350 Outriggers taking data since August 2018
Will improve energy resolution > 10 TeV

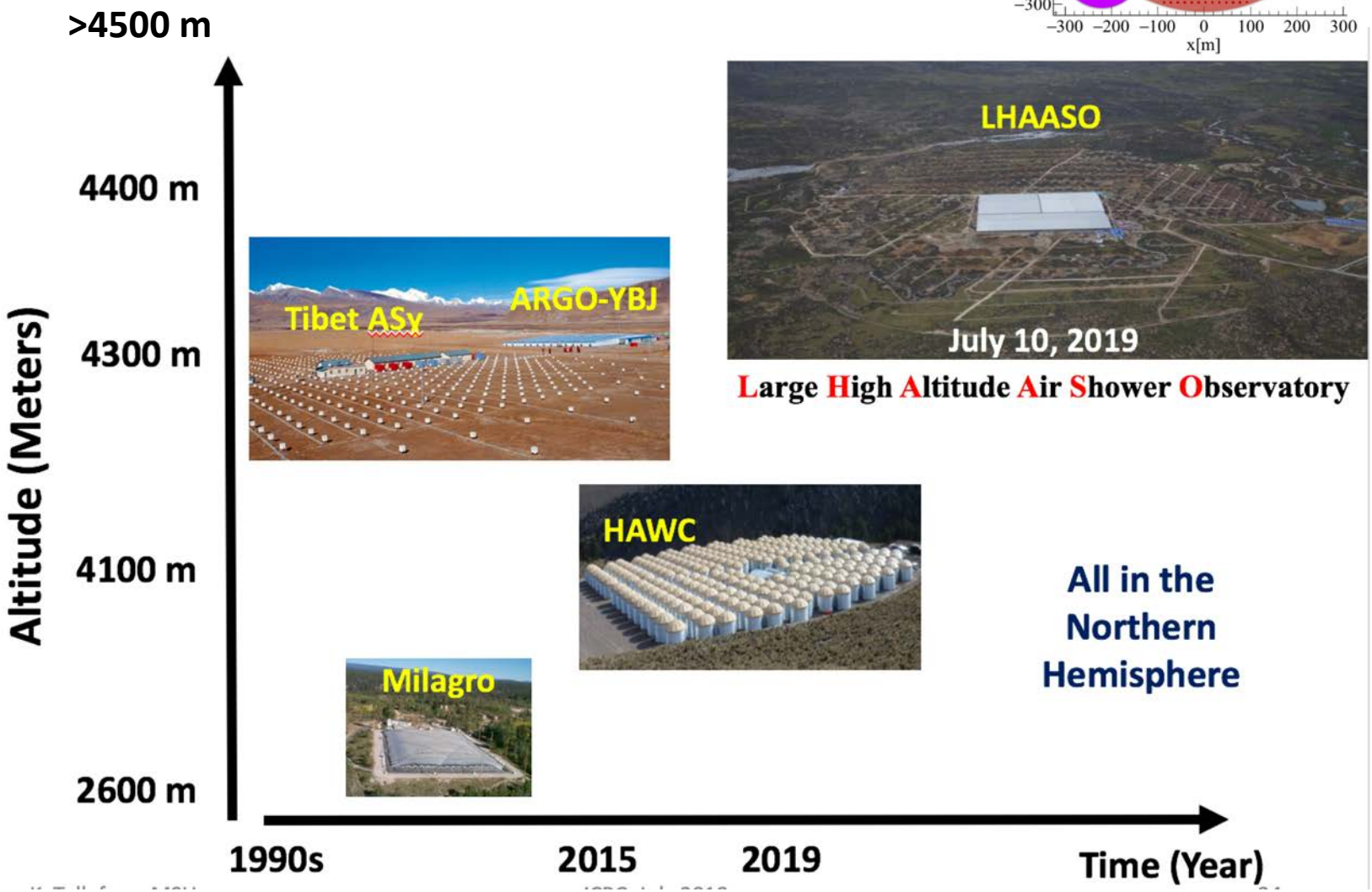




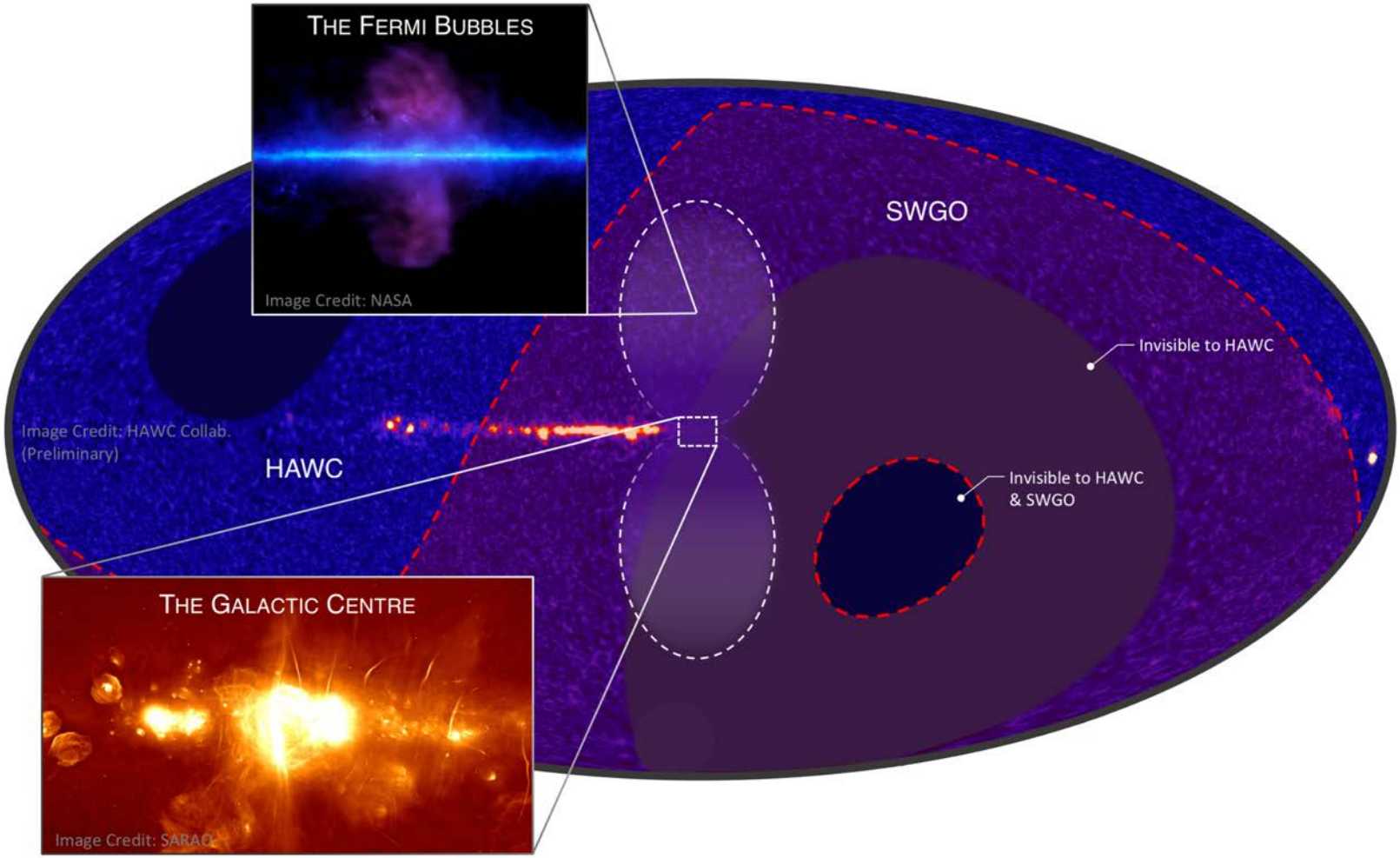
D. Huang, PoS(ICRC2019)700,
V. Joshi, PoS(ICRC2019)707,
V. Marandon, PoS(ICRC2019)736

Southern Wide FOV Gamma-ray Observatory (SWGO)





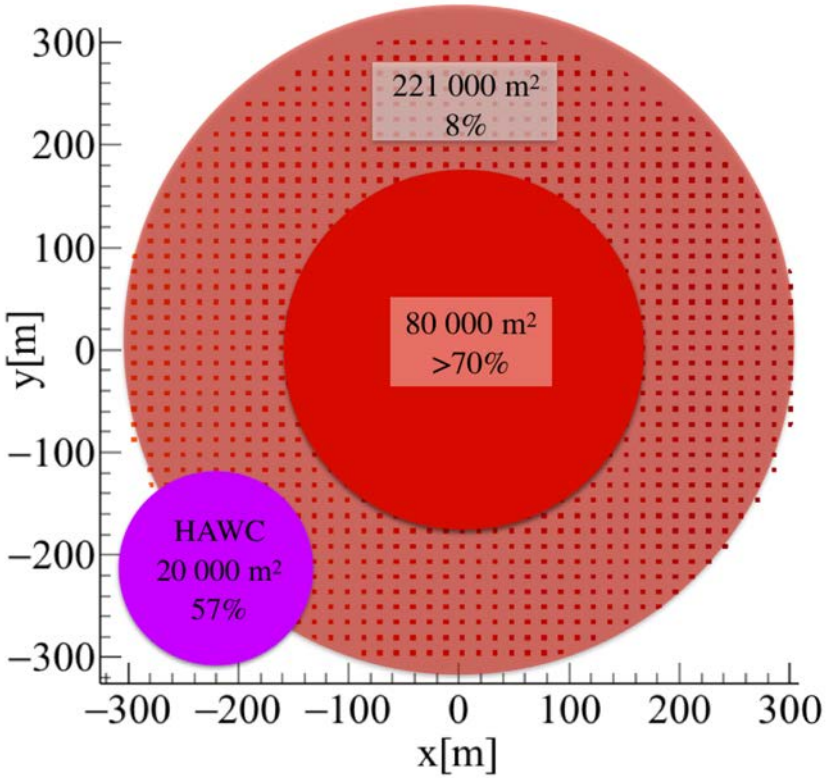
Field of View Comparison for a Northern and a Southern EAS



Southern Wide FOV Gamma-ray Observatory (SWGO)

H. Schoorlemmer, PoS(ICRC2019)785

- Formed new collaboration on July 1, 2019 to pursue R&D for SWGO
- Based on water Cherenkov technique
- Looking at 5 South American sites all >4.5 km up to 5km
- See www.SWGO.org for more info.



Join Us!

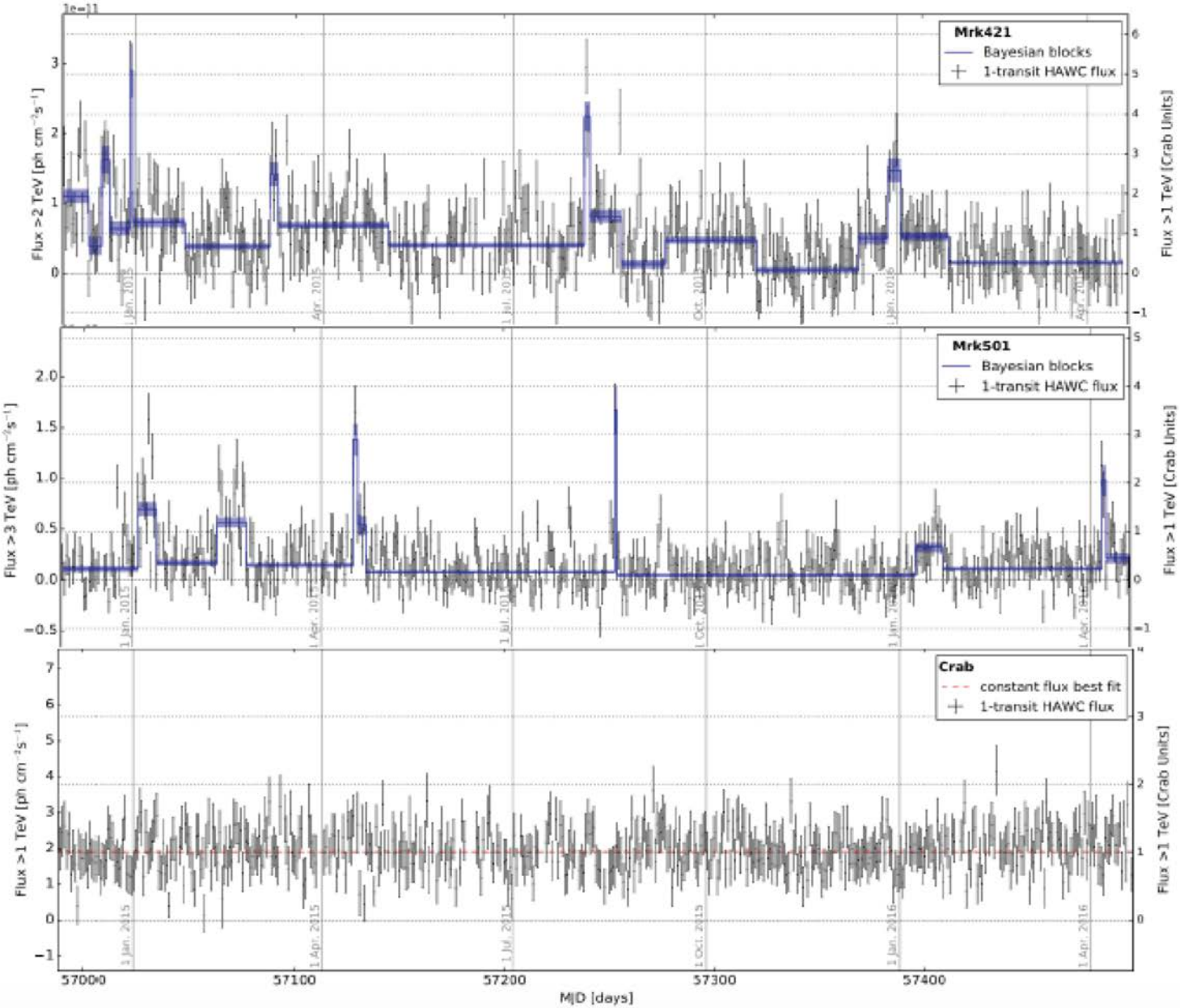
The Future of EAS Arrays is Bright

- Current EAS arrays are continuously surveying the northern hemisphere sky with their wide FOVs and are complementary to IACTs
- HAWC and Tibet ASɣ+MD observe photons with Energies >100 TeV from astrophysical sources!
- LHAASO will be the largest and highest EAS detector when it is fully operational by 2021
- EAS detectors will help illuminate how astrophysical sources accelerate particles to the most extreme energies and constrain fundamental particle physics
- A new collaboration SWGO has been formed to propose an EAS array for the southern hemisphere – Join us!


THANK YOU

Daily Monitoring of Mrk421, Mrk501, Crab

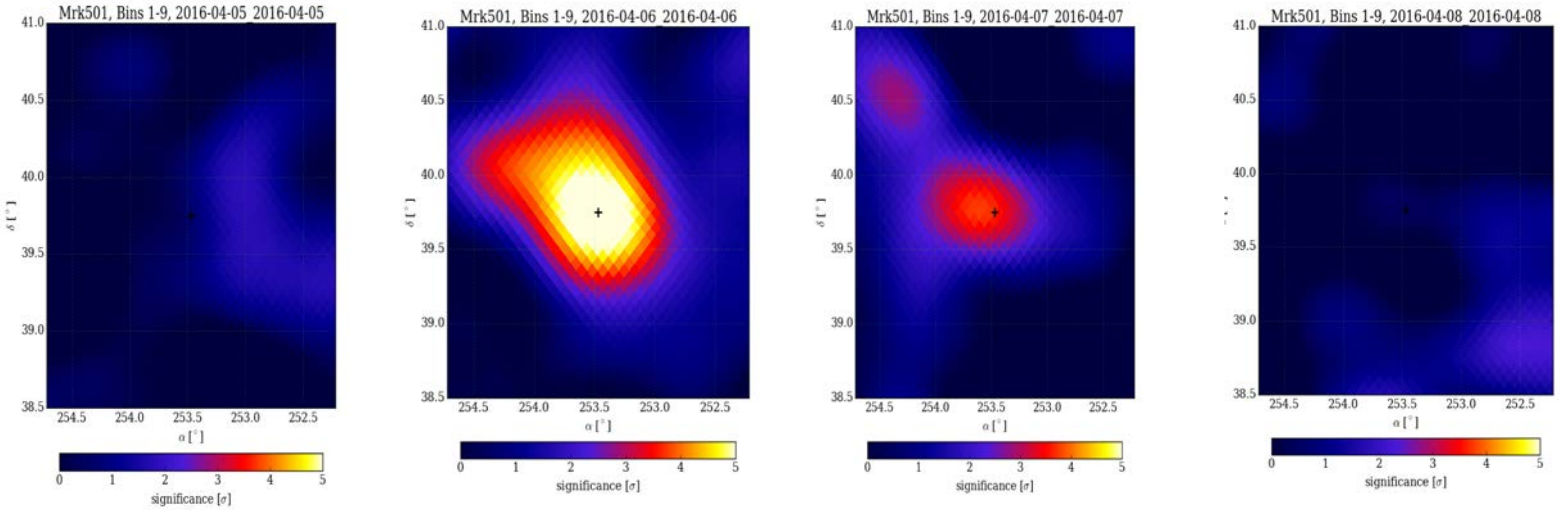
ApJ 2017



HAWC Sends Alerts

HAWC monitors all gamma-ray sources visible to it every day.

Sends alerts such as Astronomer's Telegram (ATeL) to immediately alert community of activity.



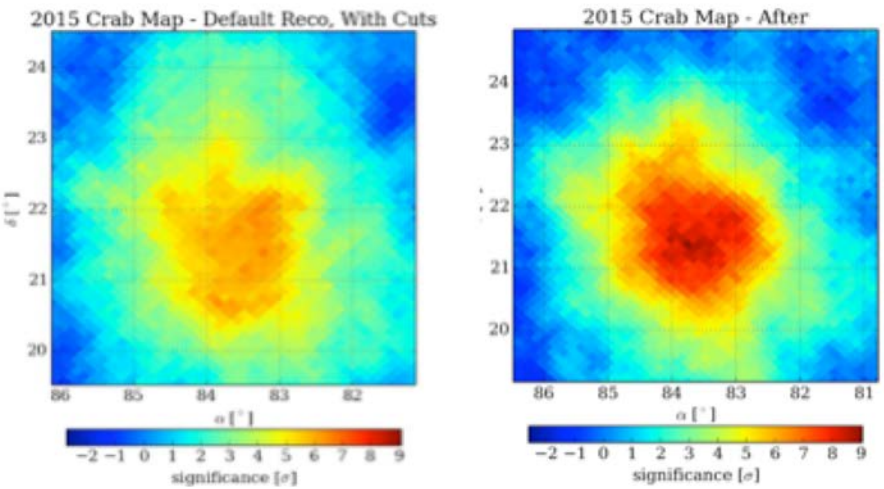
April 5, 2016 April 6, 2016 April 7, 2016 April 8, 2016

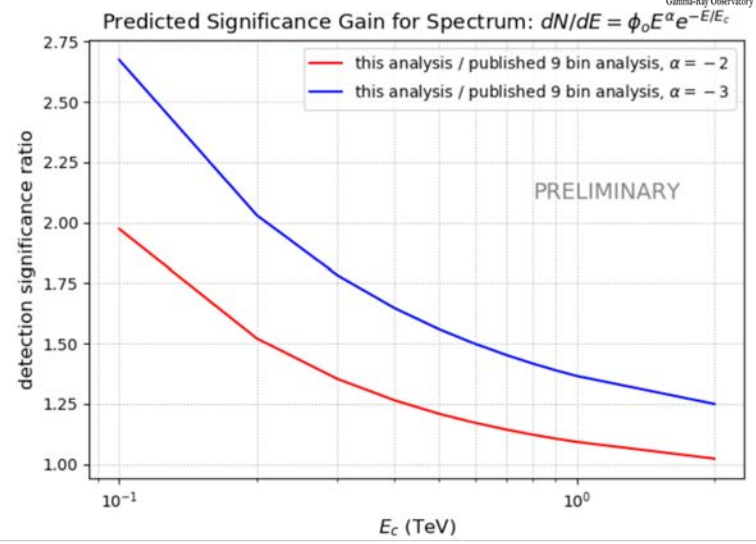
HAWC detection of increased TeV flux state for Markarian 501

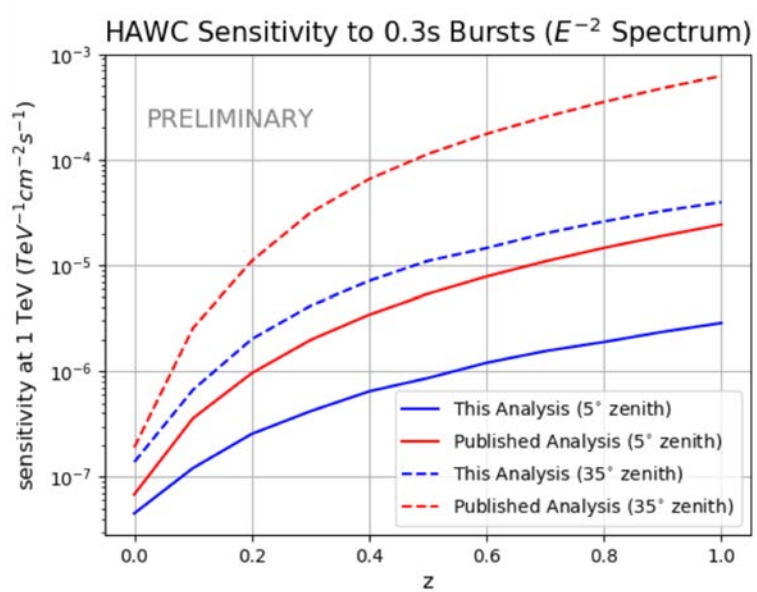
ATel #8922; *Andrés Sandoval (IF-UNAM), Robert Lauer (UNM), Joshua Wood (UMD) on behalf of the HAWC collaboration*
on 7 Apr 2016; 23:38 UT
Credential Certification: C. Michelle Hui (c.m.hui@nasa.gov)

What's Next: Improving HAWC's low E response

Smaller showers overlap in time. New multiplane angle fitter improves HAWC sensitivity at lowest energies. Tests on Crab confirm. Pass 5 reconstruction of past data will occur soon.

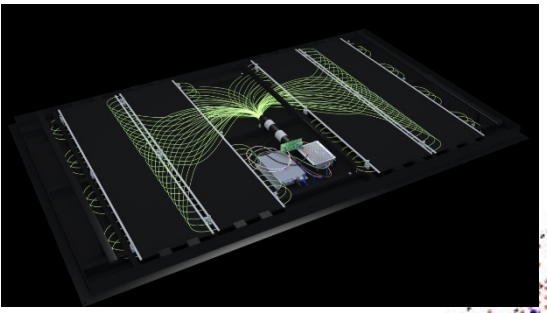


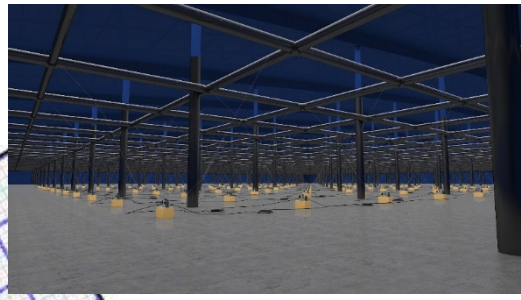




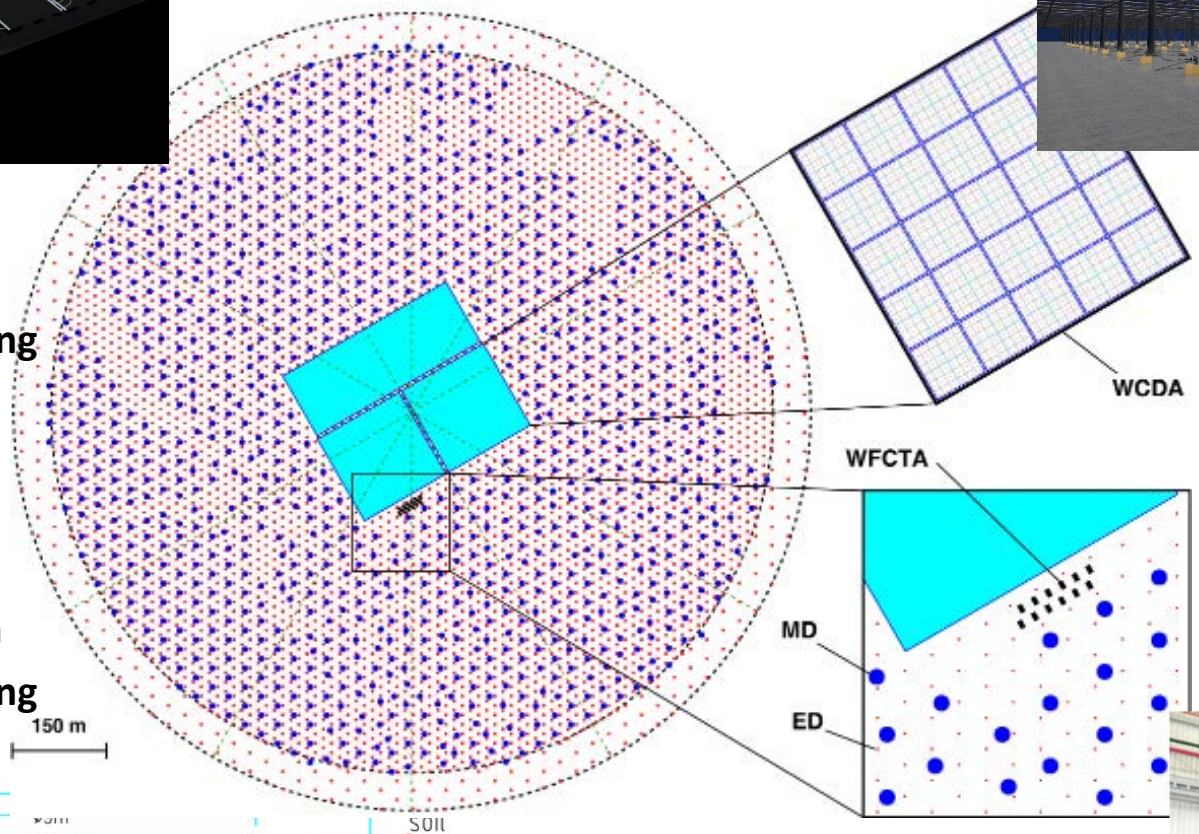
LHAASO - A Large area EAS array

covering 1.3 km^2





- **5195 EDs**
  - **1 m^2 each**
  - **15 m spacing**

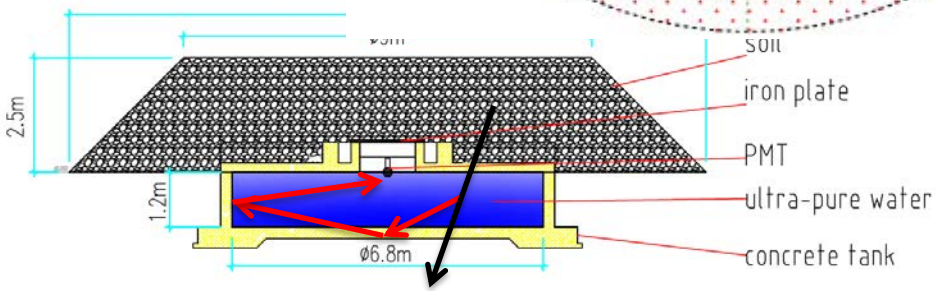


3120 WCDs

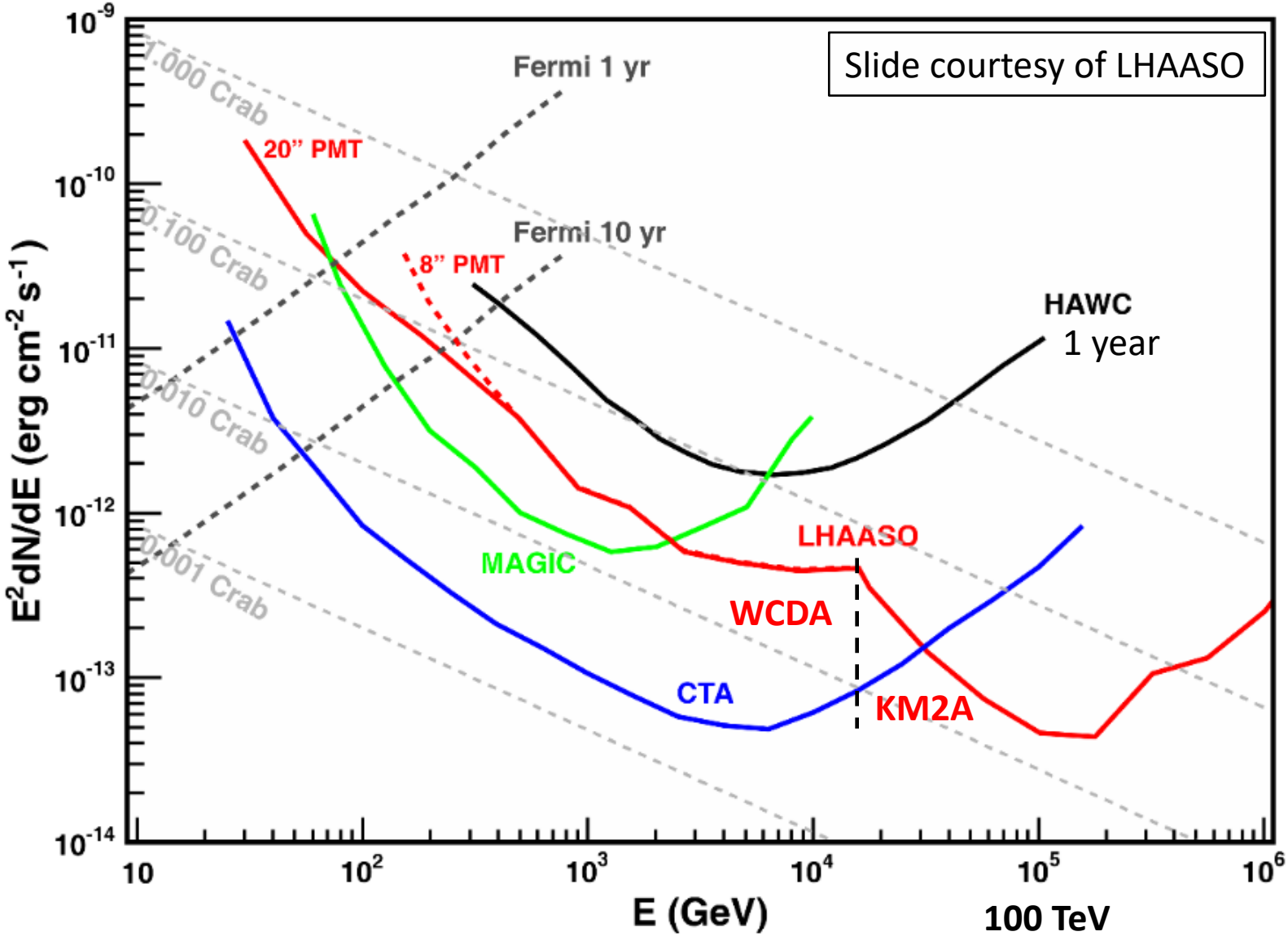
- **25 m^2 each**

- **1171 MDs**
  - **36 m^2 each**
  - **30 m spacing**

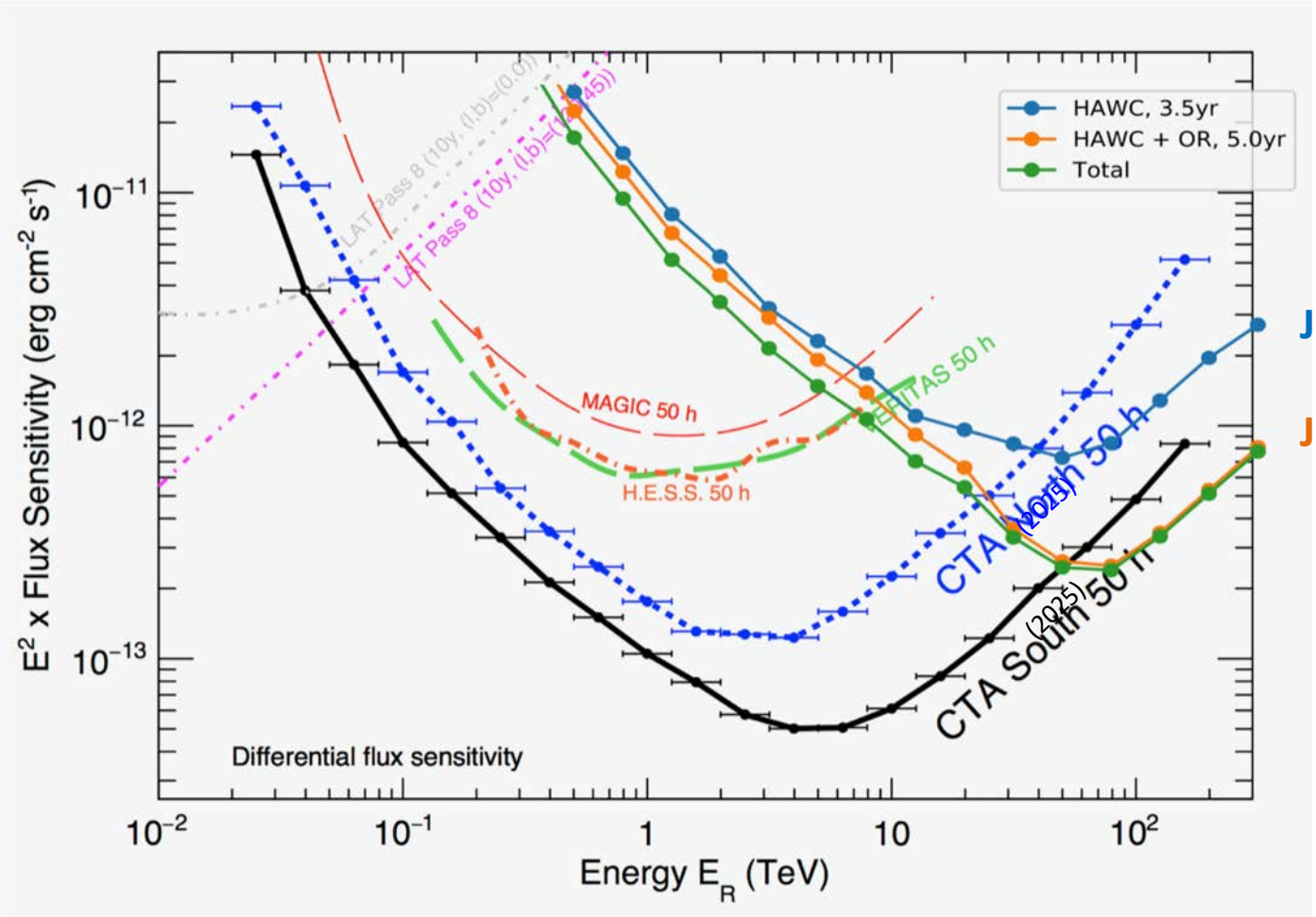
18 WFCTs



LHAASO **1 Year** sensitivity



HAWC's Sensitivity with Outriggers

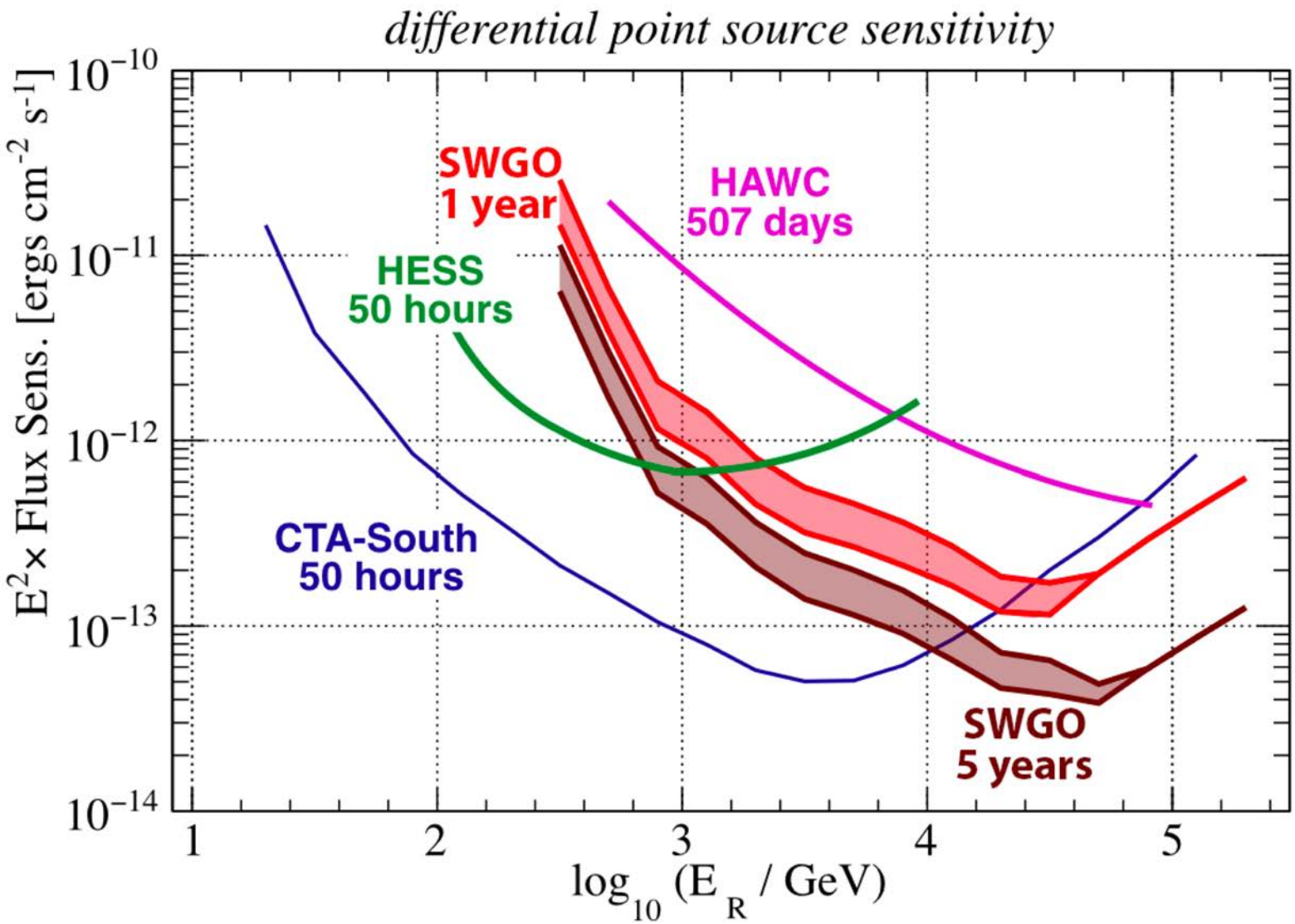


July 2018

July 2023

This sensitivity does not include improvements in HAWC reconstruction and analysis algorithms that will be implemented soon in new reconstruction pass.

Future Detector Sensitivities



Dark Matter Limits with SWGO