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The *Fermi* bubble study with future gamma-ray experiments

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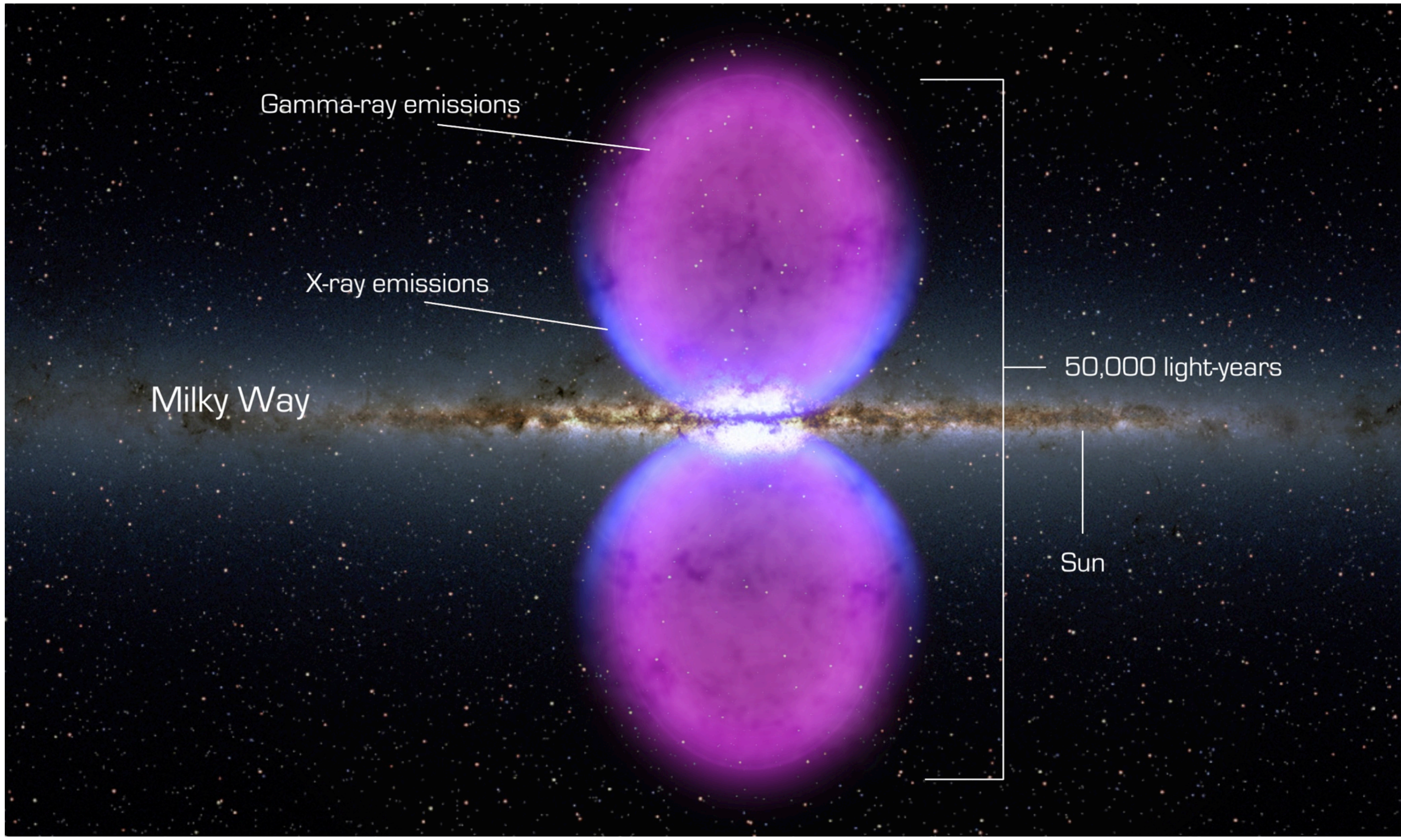
Fermi Bubbles

- Huge gamma-ray emitting globular-shaped objects, D≃9kpc
- 0.5 — 500 GeV γ rays
- uniform injected intensity
- coincident emission at multi-wavelength, X-ray, Microwave, radio
- Total gamma-ray

  luminosity ~ 4.4 x 10^{37} ergs/s



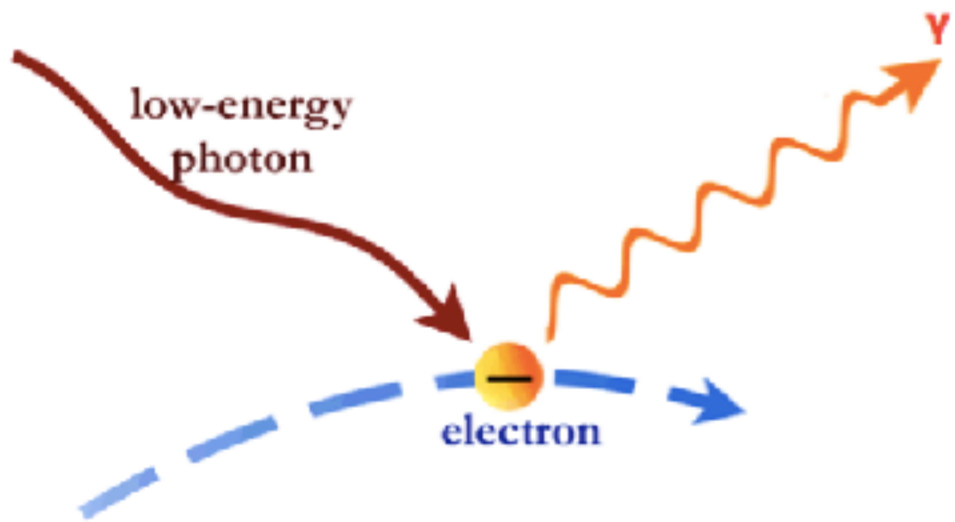
Credit: NASA Goddard Space Flight Center

Su, Slatyer & Finkbeiner, ApJ. 724, 1044 (2010)

Leptonic or Hadronic origin?

Both mechanisms can explain the measured spectrum

- Leptonic model: Compton scattering of relativistic electrons from shocks in the outflow of the GC on photons



- Hadronic model: collision of accelerated protons on background protons in the bubble gas

$$pp \rightarrow \pi^0, \pi^{+/-}$$

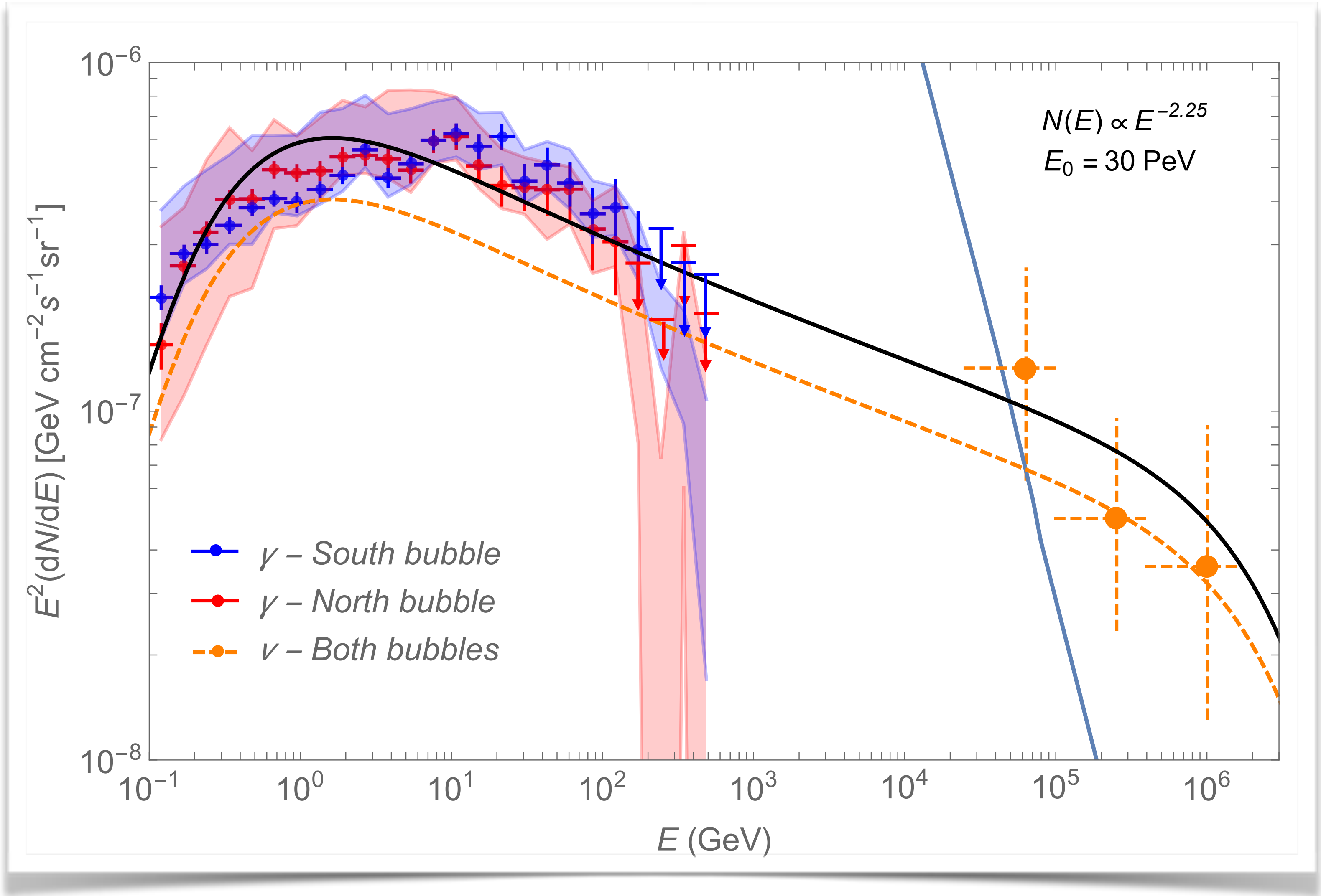
Hadronic Model

- Primary proton spectrum

  $dN_p/dE \propto N_0 E^{-k} \, Exp(-E/E_0)$

  - Motivated by cosmic-ray acceleration in SNRs, E_0 ~0.03- 30 PeV, k~ 2.1 - 2.3

- The average density of bubble interiors ~ 10^{-2} cm^{-3}

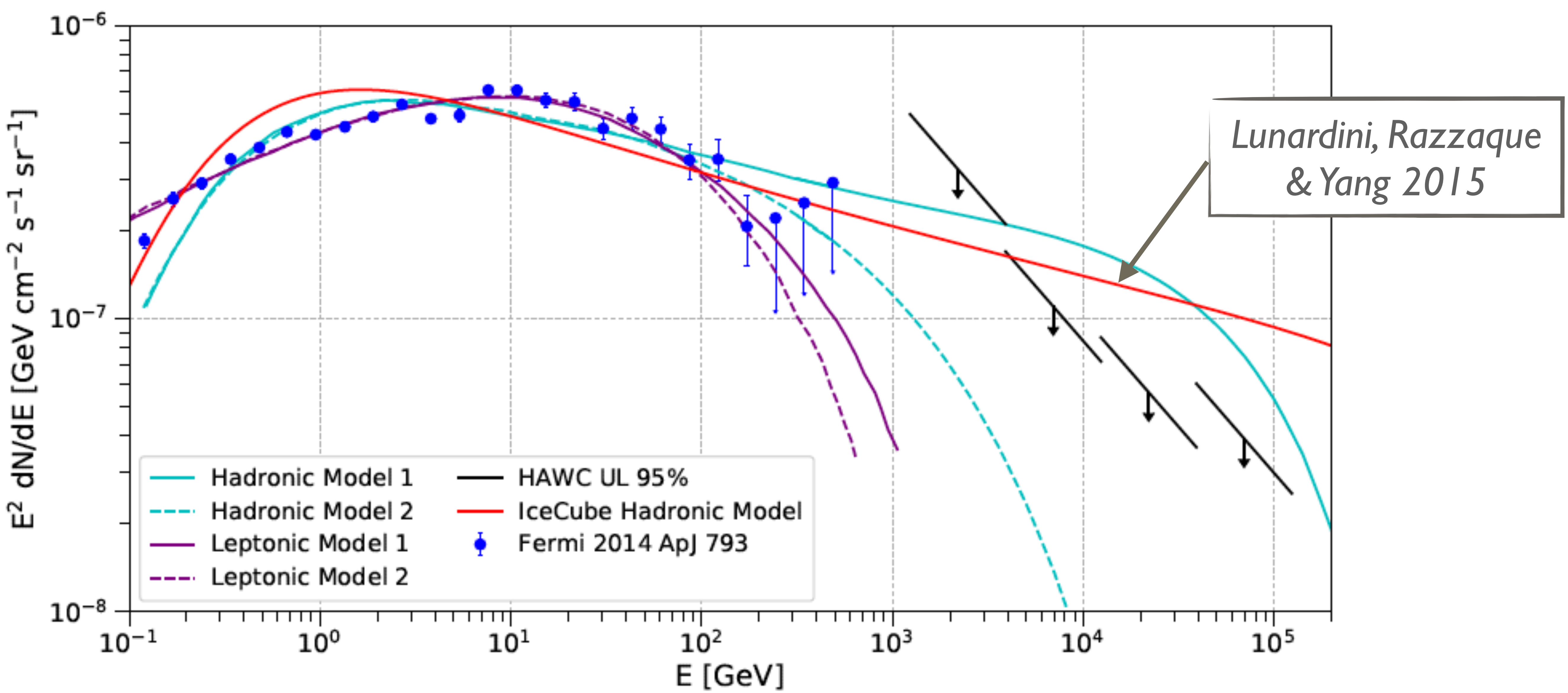


Lunardini, Razzaque & Yang 2015

Crocker and Aharonian,

PRL 106, 2011

Recent HAWC constraints

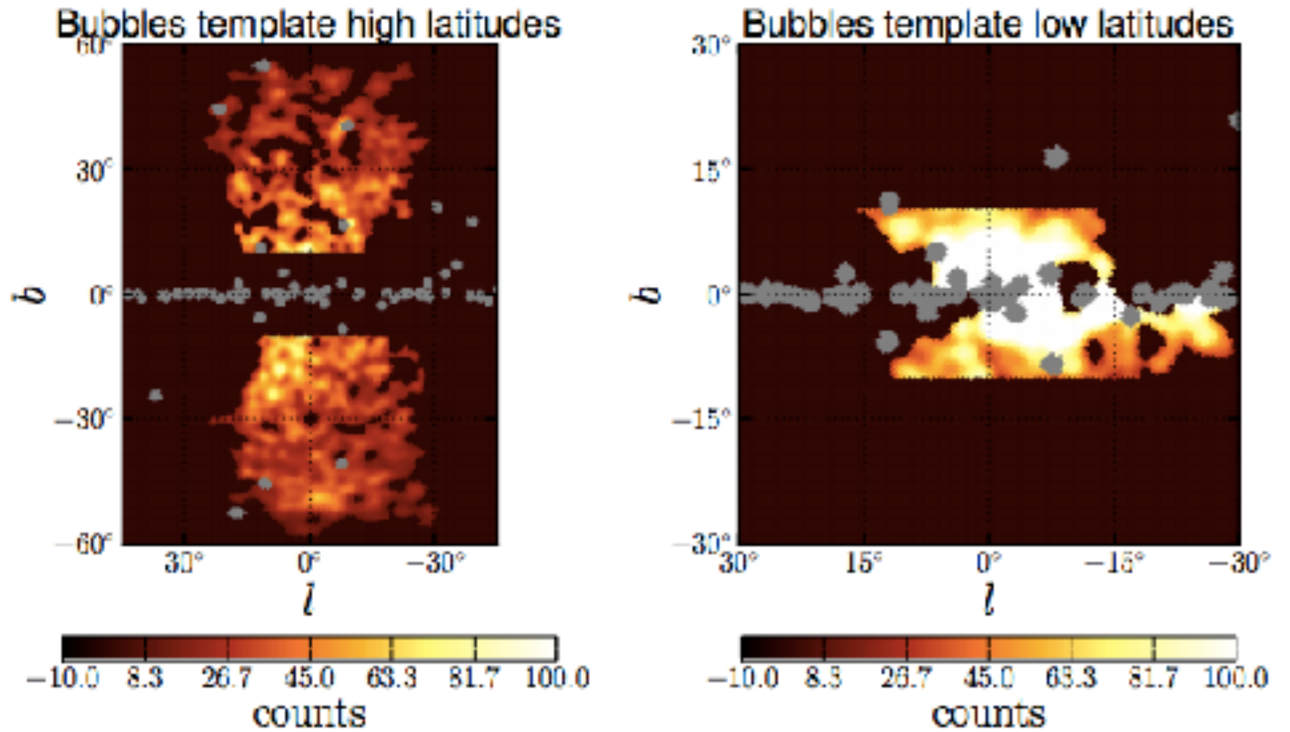


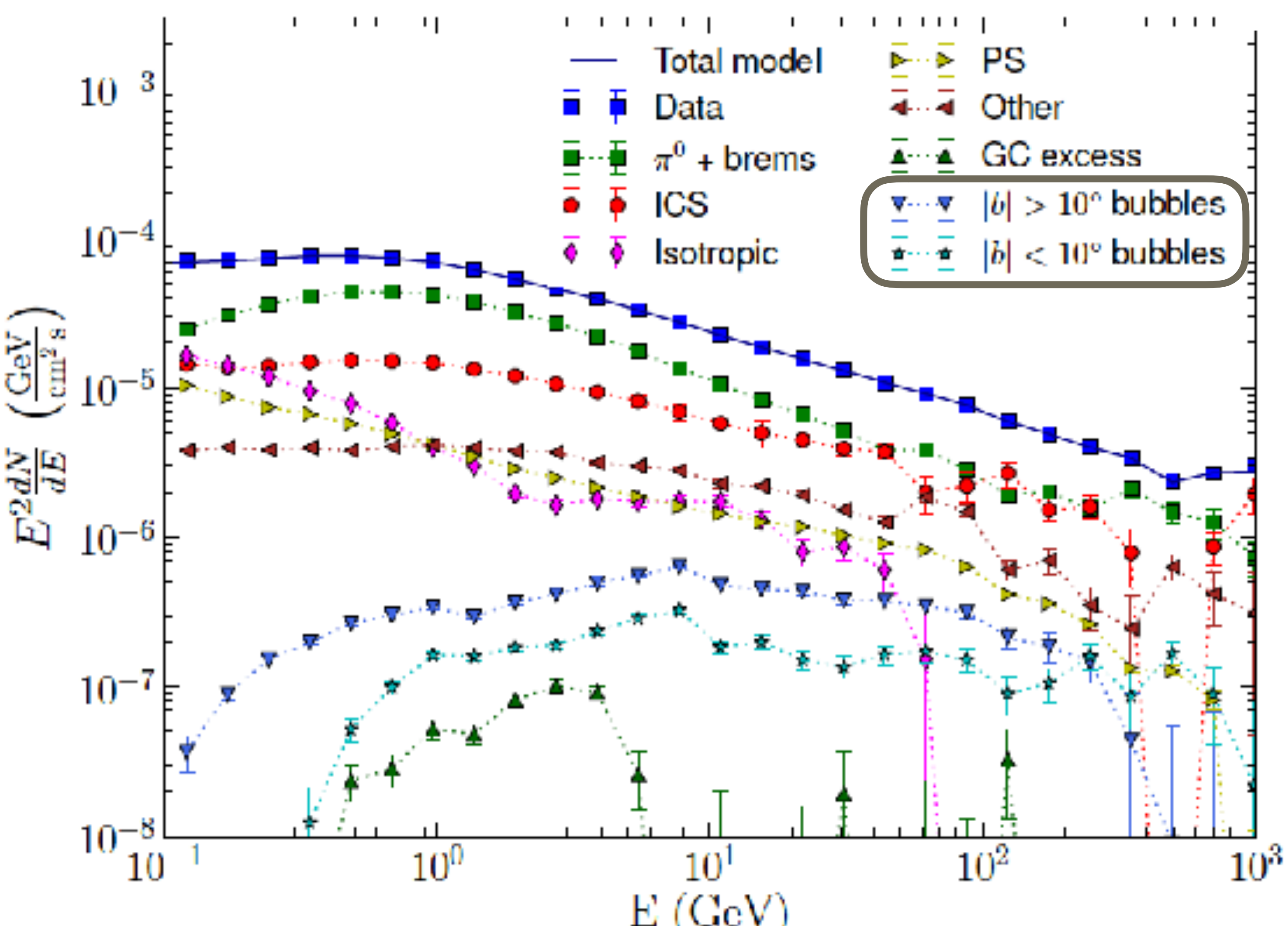
- 290 days data, E>1.2 TeV
- Northern Fermi bubble, b>6°
- Obtained upper limits constrain hadronic models

HAWC Collab. Abeysekara+2017

Updated *Fermi*-LAT analysis

- The spectrum is uniform above |b|=10°
- Low-latitude region, non-uniform intensity, and become increasingly brighter near the Galactic plane

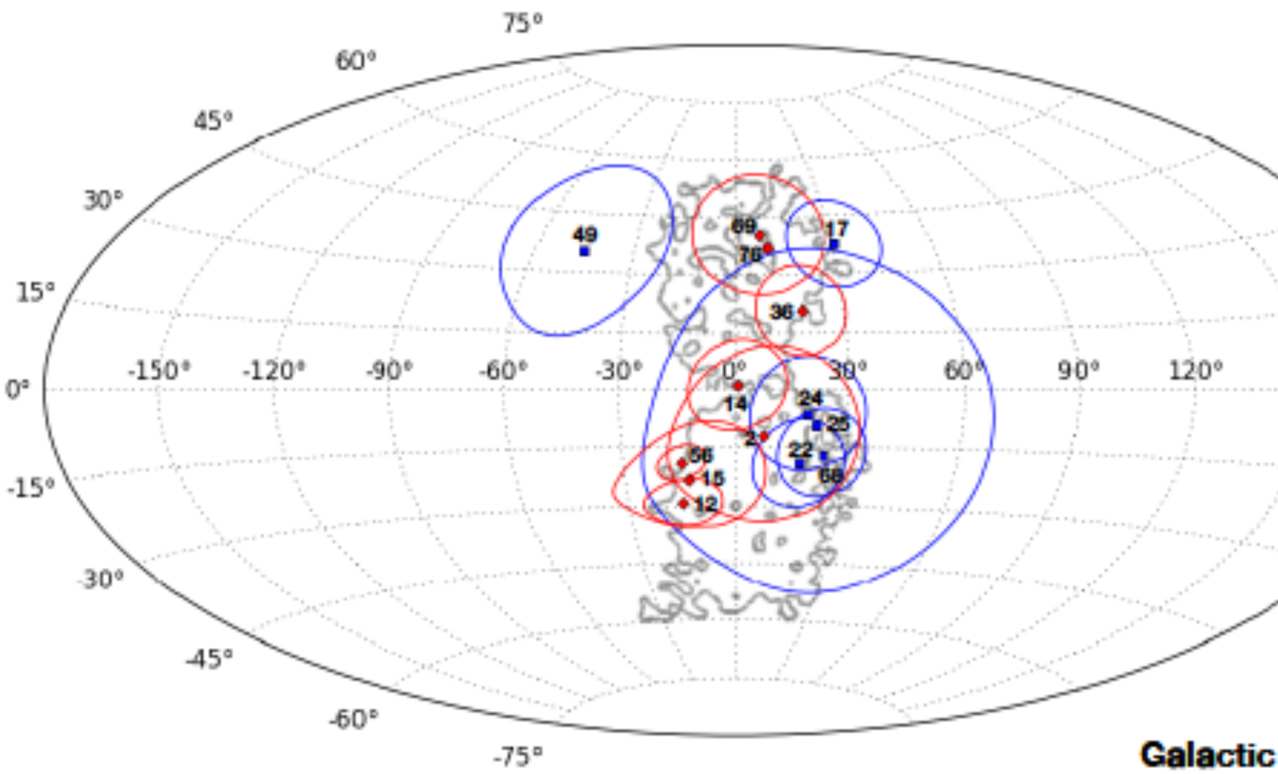




- Between 100 MeV and 100 GeV, low- and high- |b| FB spectra are similar
- Above 100 GeV, low |b| spectrum remain hard, high-|b| with a cutoff

Fermi-LAT Collab. Ackermann+2017

Updated IceCube ν

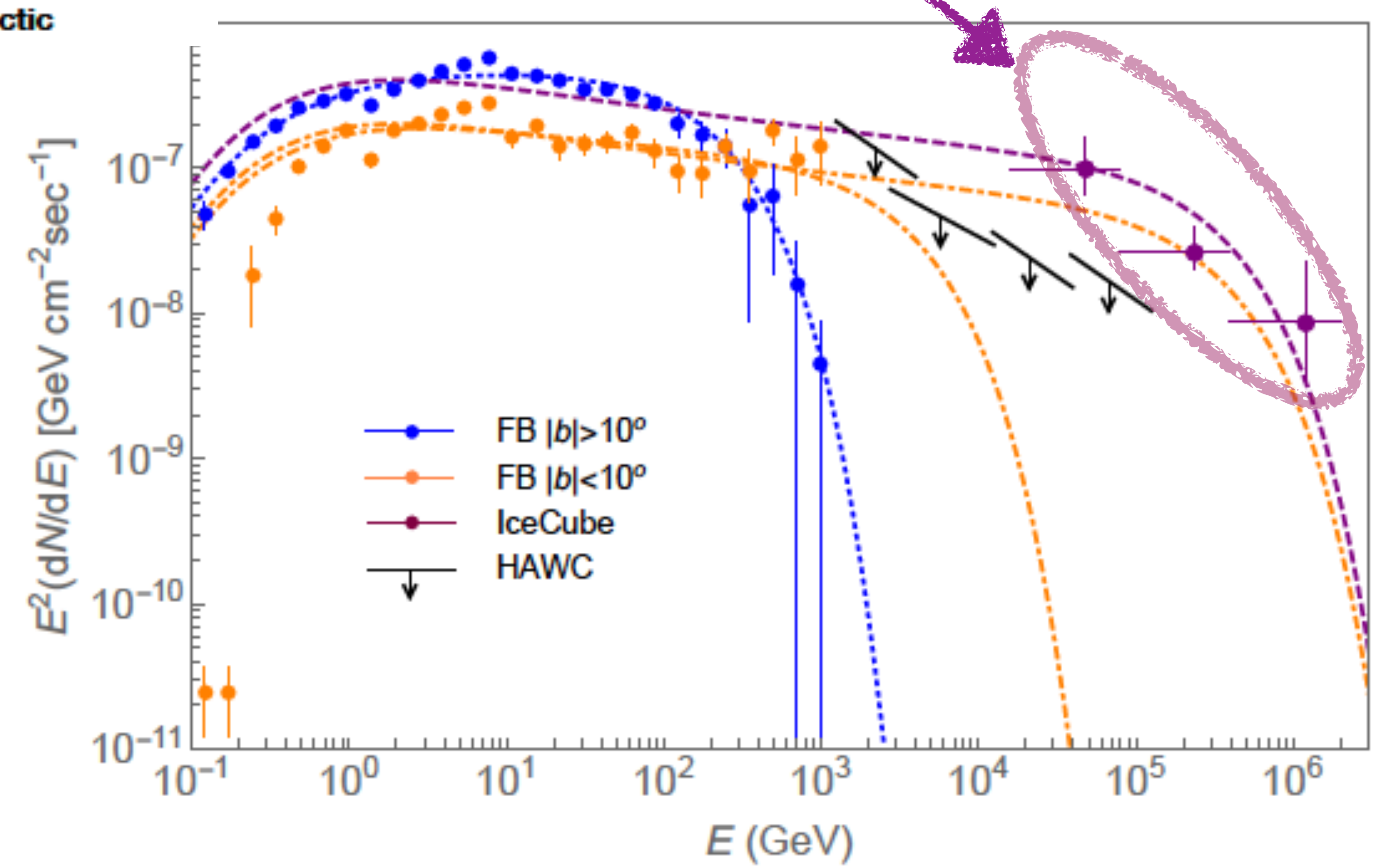


Updated IceCube 6-year HESE dataset above 60 TeV

IC neutrino events: 8 strongly- and 6 weakly-correlated with the FB

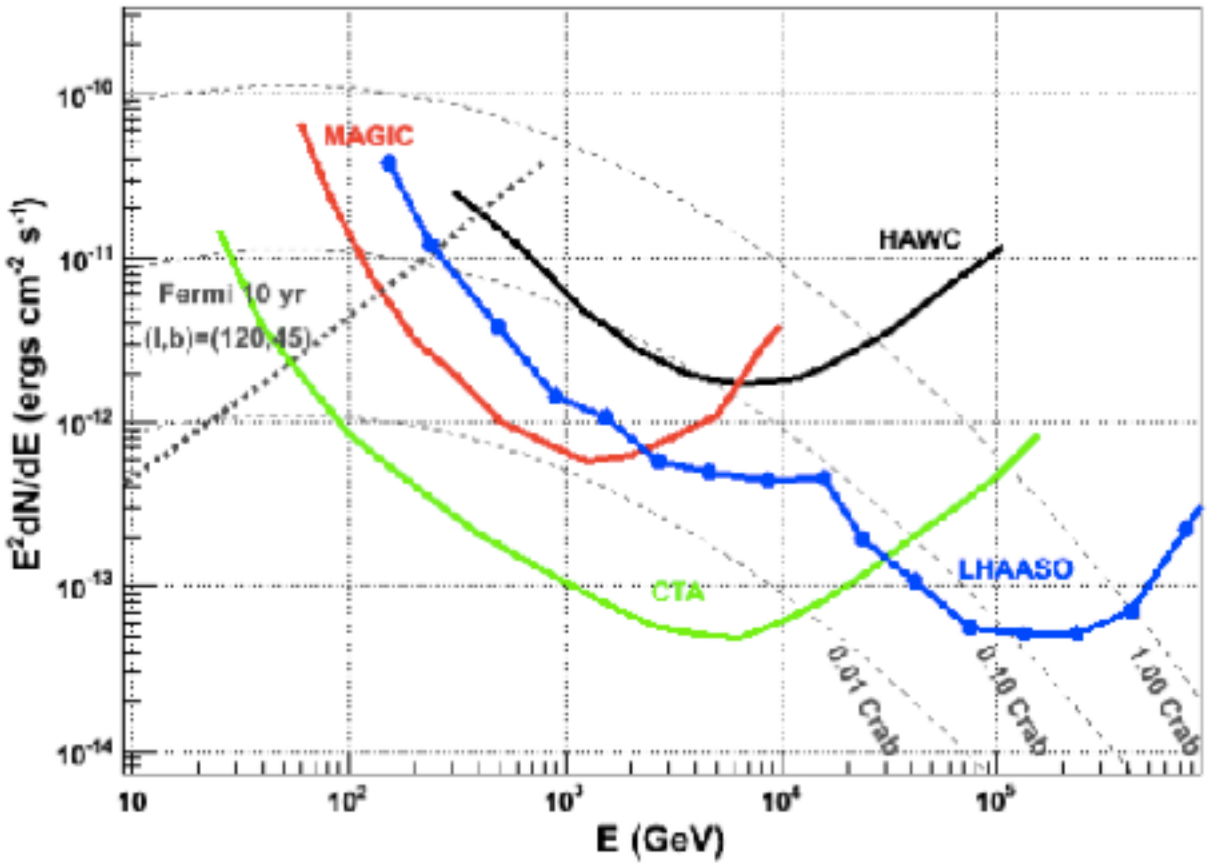
1. $k=2.0$, $E_0=1.6$ TeV
2. $k=2.15$, $E_0=30$ TeV
3. $k=2.2$, $E_0=3$ PeV

HAWC upper limits agree with Fermi-LAT observation high-latitude region

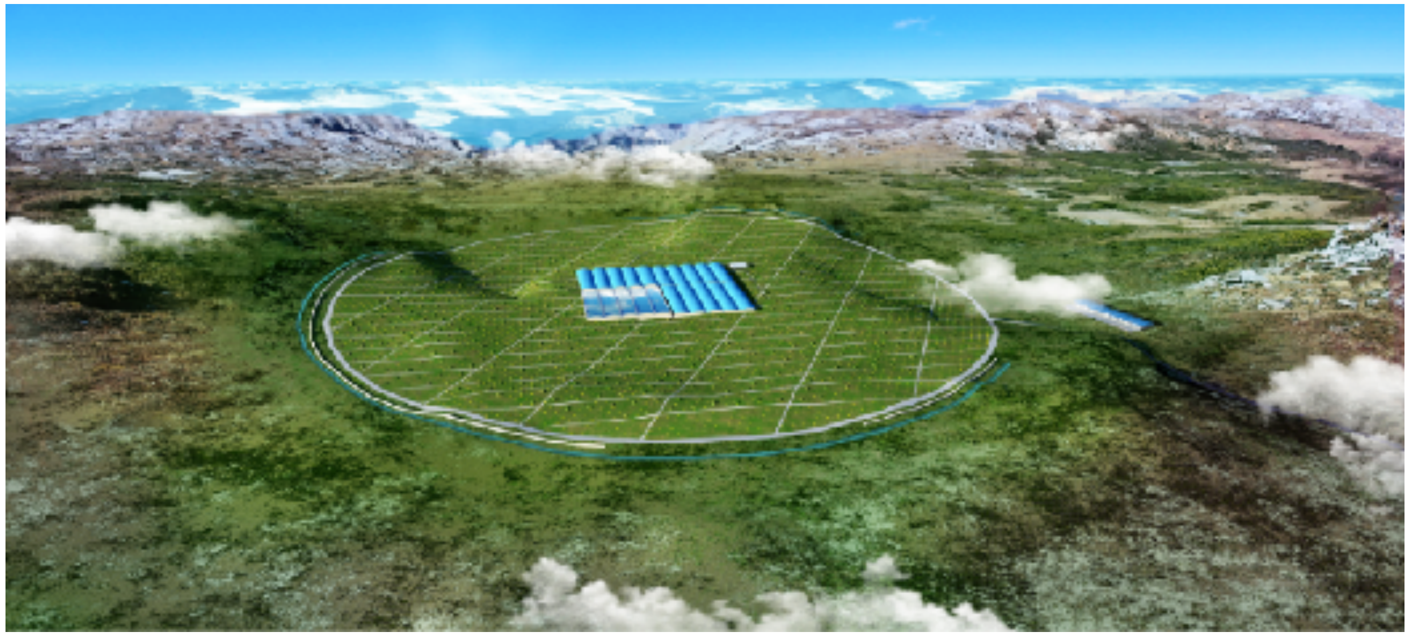


Razzaque & Yang 2018

Constrains with future gamma ray observatory

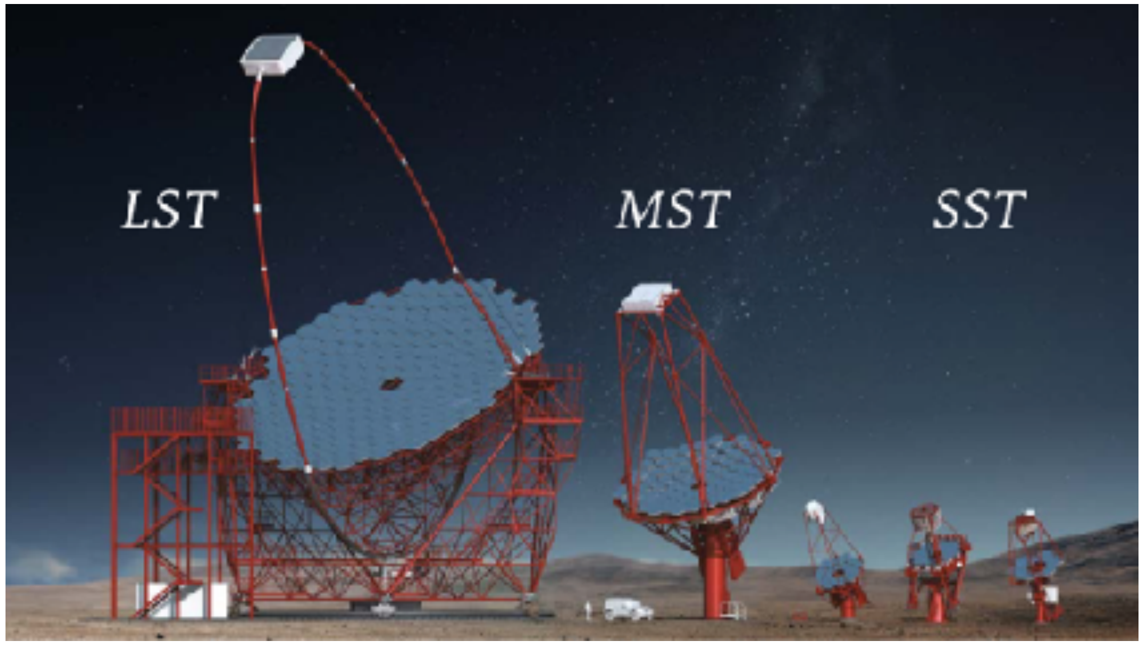


Large High Altitude Air Shower Observatory



LHAASO Collab.

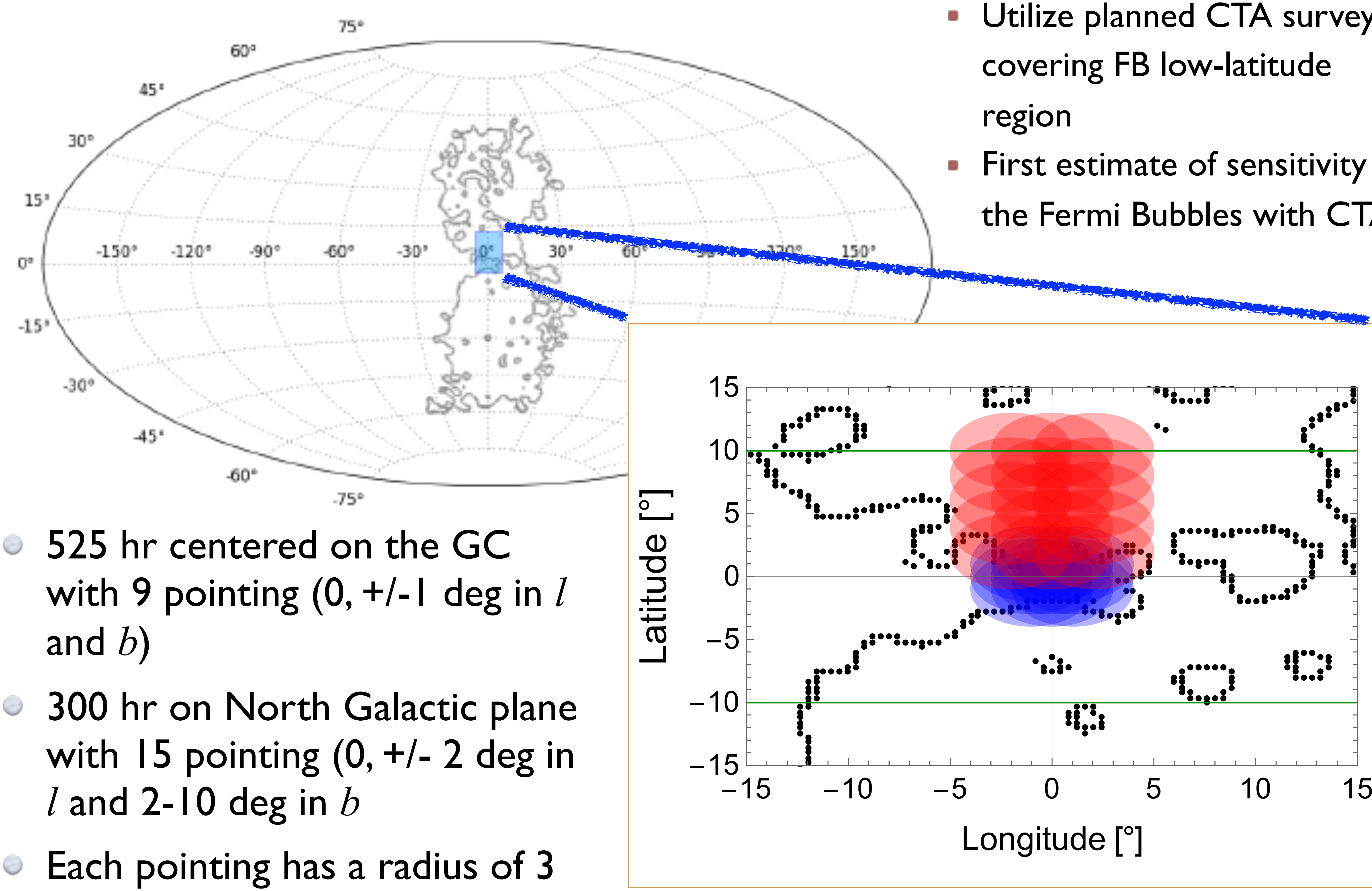
Cherenkov Telescope Array (CTA)



CTA Collab. Acharya+2017

CTA survey strategy

- Utilize planned CTA surveys covering FB low-latitude region
- First estimate of sensitivity to the Fermi Bubbles with CTA



- 525 hr centered on the GC with 9 pointing (0, +/-1 deg in l and b)
- 300 hr on North Galactic plane with 15 pointing (0, +/- 2 deg in l and 2-10 deg in b)
- Each pointing has a radius of 3 degree

CTA Collaboration 2017

CTA sensitivity estimation

One dataset for the Southern Array

- ctools (v1.5.0) - prod 2, South_50h
- Selected region of interest: +/- 2.5 deg in l and +/- 2.5 deg in b
- 0.5 deg pixel (10 x 10 pixels) and 20 energy bins in 30 GeV - 100 TeV

Binned Poisson likelihood function

$$\mathcal{L}_i = \prod_j \frac{m_{ij}^{n_{ij}} e^{-m_{ij}}}{n_{ij}!}$$

n_{ij} — mock data

m_{ij} — model data

(both) generated with ctmodel

Construct Asimov data sets from FB flux models - no statistical fluctuations

$$m_{ij} = \beta_{i,1} b_{ij,\mathrm{CR}} + \beta_{i,2} b_{ij,\mathrm{GDE}} + \mu_i s_{ij,\mathrm{FB}}$$

Model data including signal (FB) and backgrounds (CR and GDE)

CTA sensitivity estimation

Profile likelihood ratio

$$\lambda_i = \frac{\mathcal{L}_i(n|m(\mu, \hat{\hat{\beta}}_{i,1}, \hat{\hat{\beta}}_{i,2}))}{\mathcal{L}_i(n|m_0(\widehat{\mu}, \widehat{\beta_{i,1}}, \widehat{\beta_{i,2}}))}$$

Conditional likelihood - fixed mu

Unconditional likelihood - all free

$$-2ln\lambda_i = 2.71 \longrightarrow$$ μ_i for each energy bin at 95% CL

Sensitivity for each energy bin at 95% CL

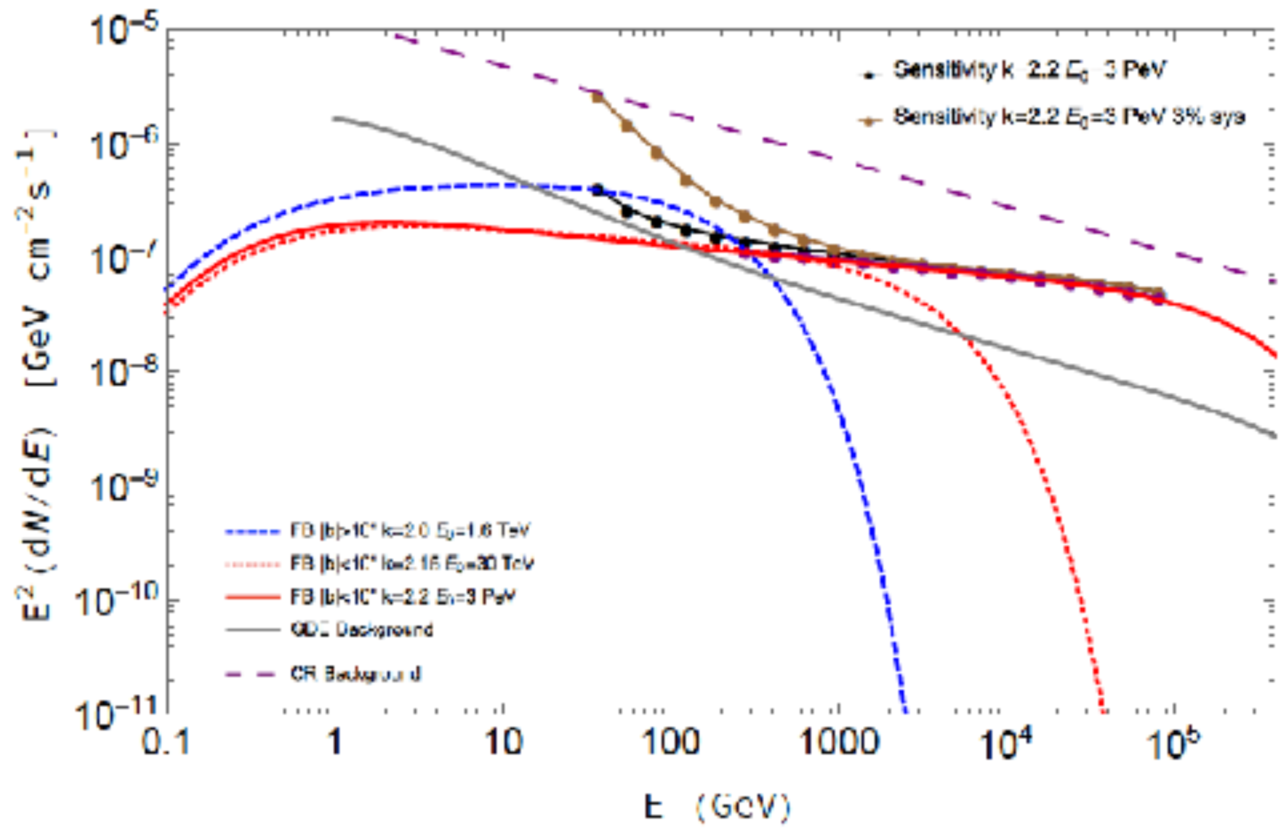
$$\mu_i \times E_{0,i}^2 \times \phi(E_{0,i})$$

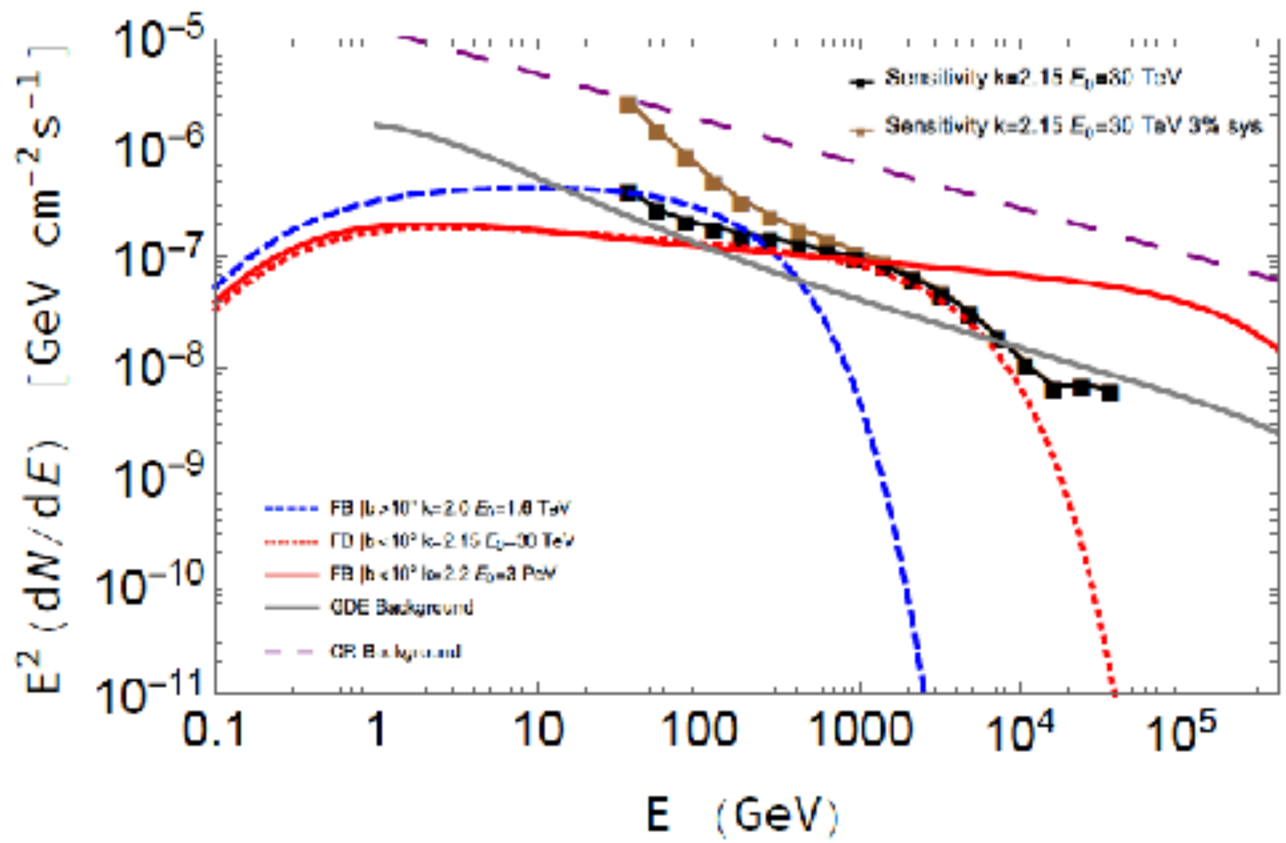
$E_{0,i}$ is the logarithmic mean energy of *i*th energy bin

ϕ is the FB flux

Cowan, Cranmer, Gross & Vitells 2011

Morphological analysis results

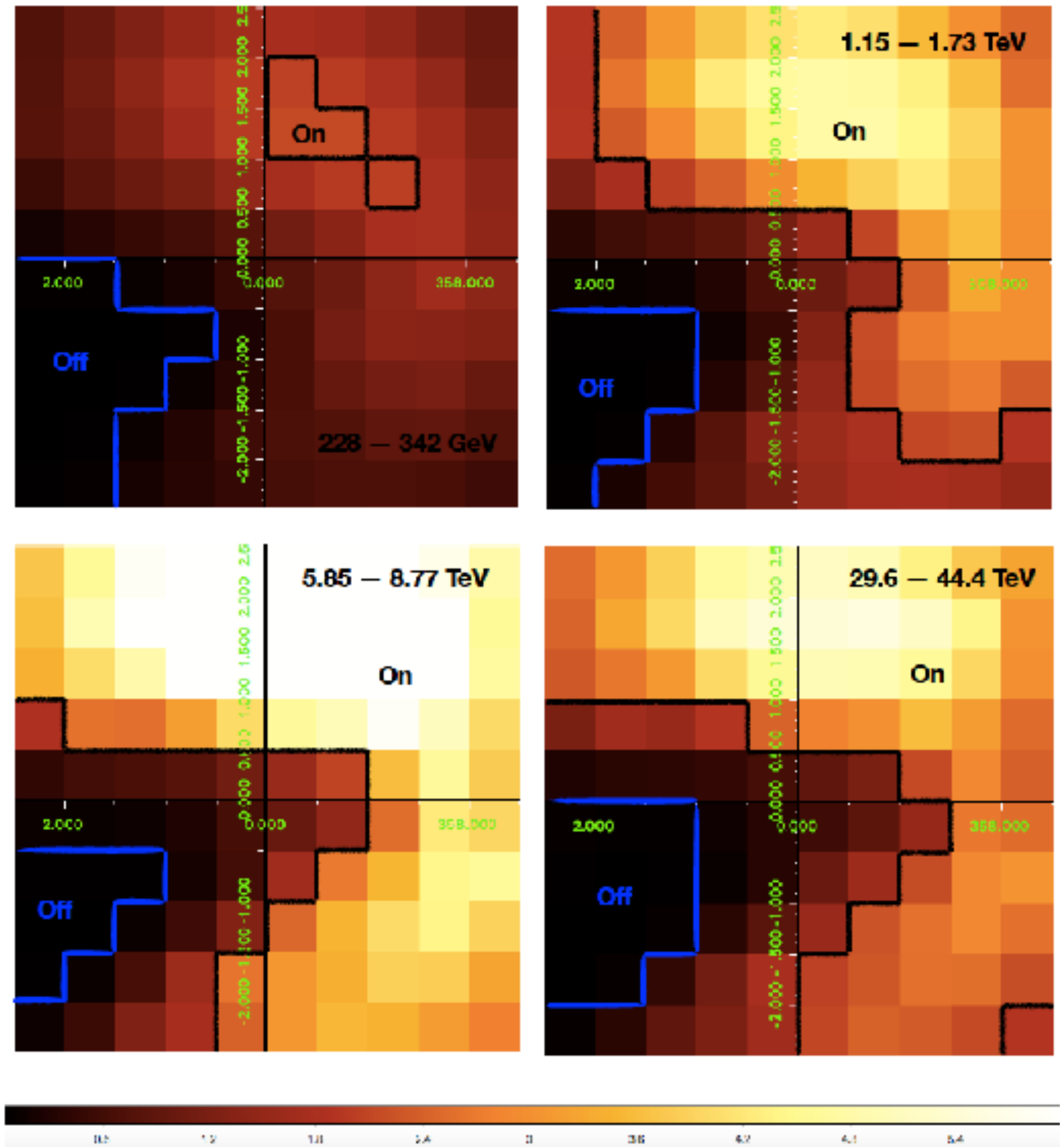




- CTA will have good sensitivity to both the high- and low-cutoff models of the FB flux at low $|b|$ above 1 TeV
- 3% systematic error assumes the nuisance parameters are Gaussian distributed with standard deviation = 0.03

Berge, Funk & Hinton 2007

ON/OFF analysis



on: σ>2 off:σ<0.1

Calculate significance in each pixel to select ON/OFF regions (high-cutoff model for low |*b*|)

$\sigma = \text{sqrt}(2*(n_{ij}*\ln(1+s_{ij}/b_{ij})-s_{ij}))$

- 15 energy bins consisting on regions for the high-cutoff models
- 8 energy bins consisting on regions for the low-cutoff models

$$m_{\rm on} = \beta_1 b_{\rm CR} + \beta_2 b_{\rm GDE} + \mu s_{\rm FB}$$

$$m_{\rm off} = \tau(\beta_1 b_{\rm CR} + \beta_2 b_{\rm GDE})$$

$$\tau = b_{\rm off}/b_{\rm on}$$

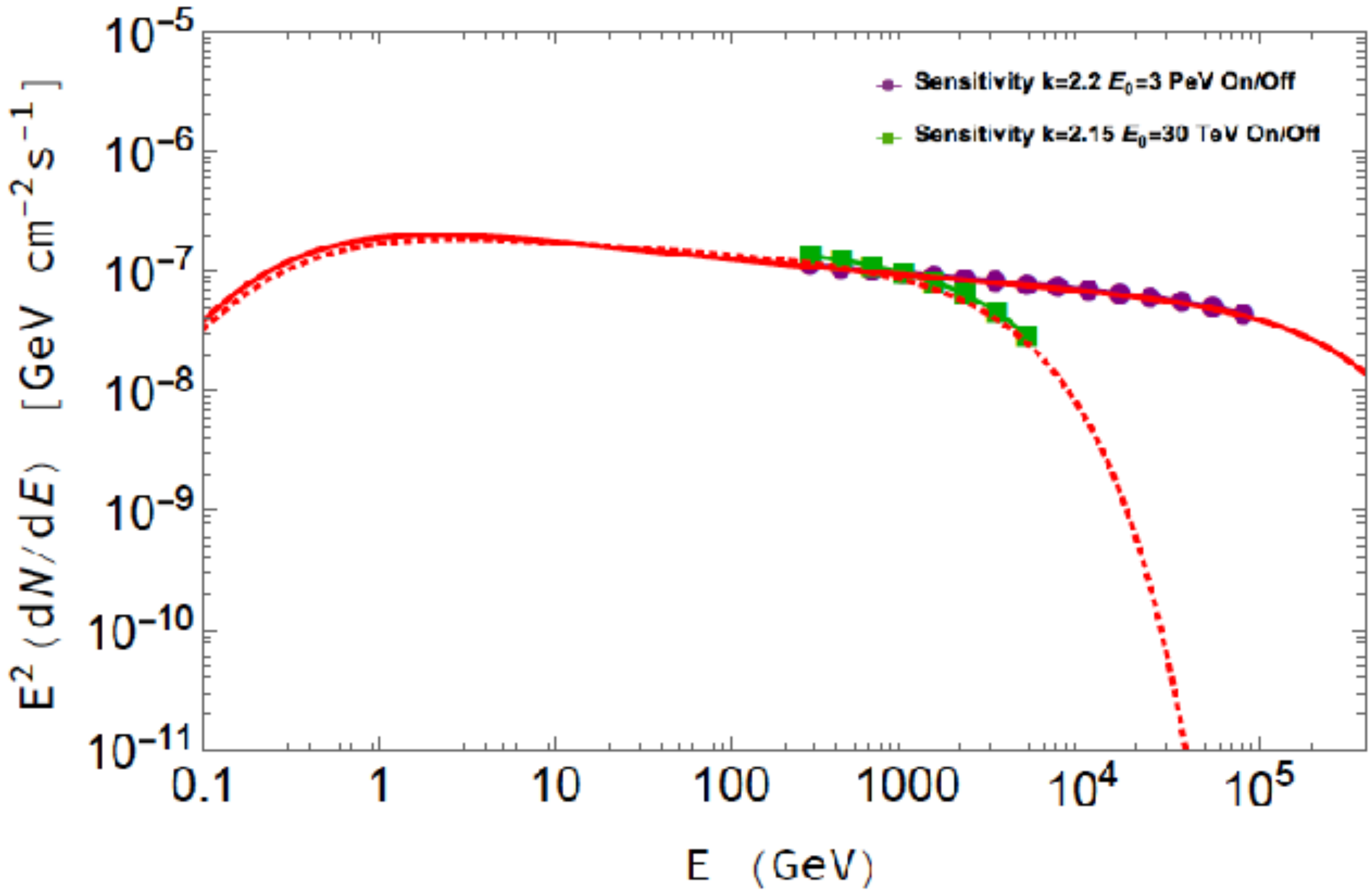
Ratio of the background in on and off region

ON/OFF analysis

Likelihood function

$$\mathcal{L} = \frac{m_{\rm on}(\mu,\beta_1,\beta_2)^{n_{\rm on}}}{n_{\rm on}!} e^{-m_{\rm on}(\mu,\beta_1,\beta_2)} \frac{m_{\rm off}(\beta_1,\beta_2,\tau)^{n_{\rm off}}}{n_{\rm off}!} e^{-m_{\rm off}(\beta_1,\beta_2,\tau)}$$

Cousins, Linnemann & Tucker 2008

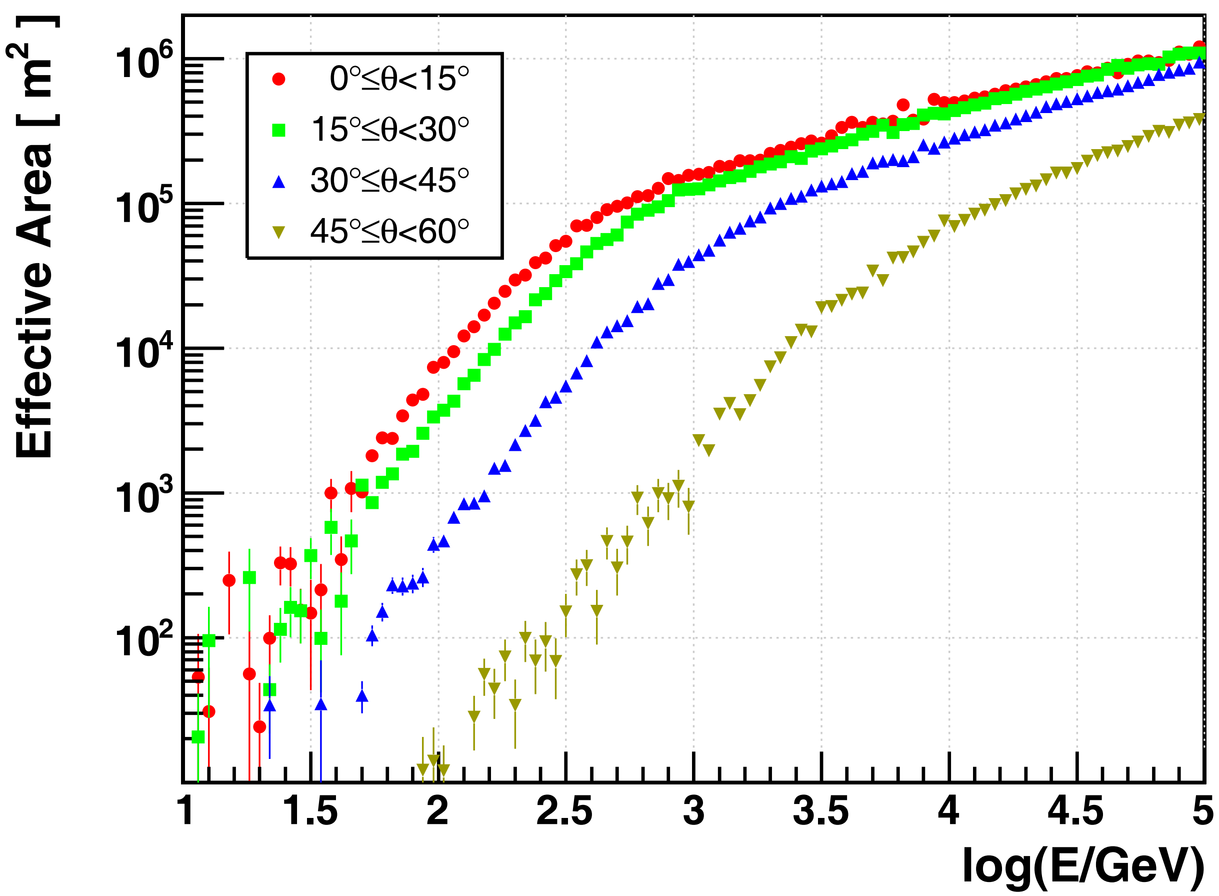


CTA sensitivity (95% CL) to the FB from ON/OFF analysis (high- and low-cutoff models for low $|b|$)

LHAASO project

Large High Altitude Air Shower Observatory

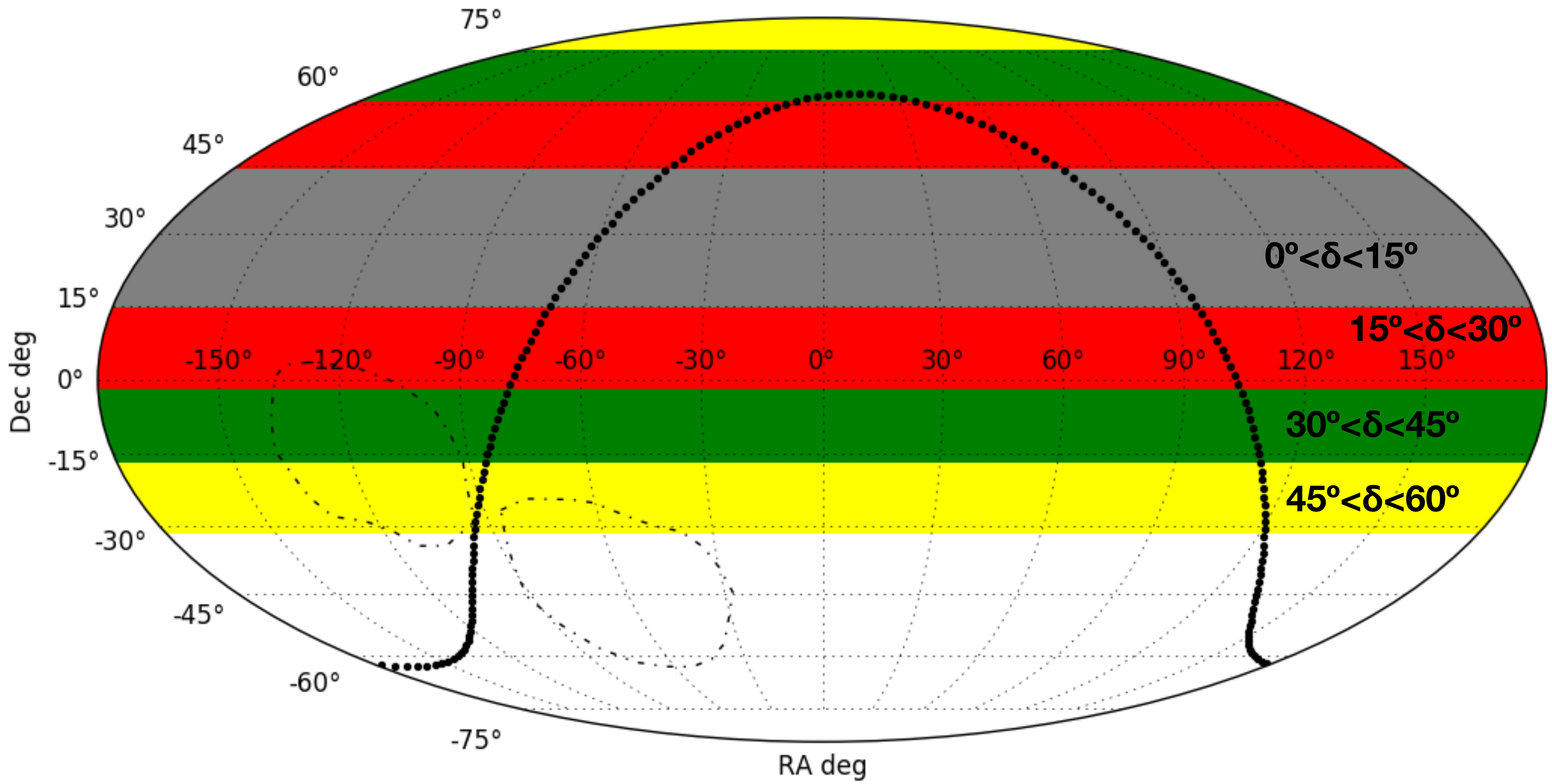
- Haizi Mountain in Sichuan at altitude of 4410 meter
- Hybrid detector -
  - Water Cherenkov
  - Air fluorescence
  - Plastic scintillators



Water Cherenkov Detector Array(WCDA)

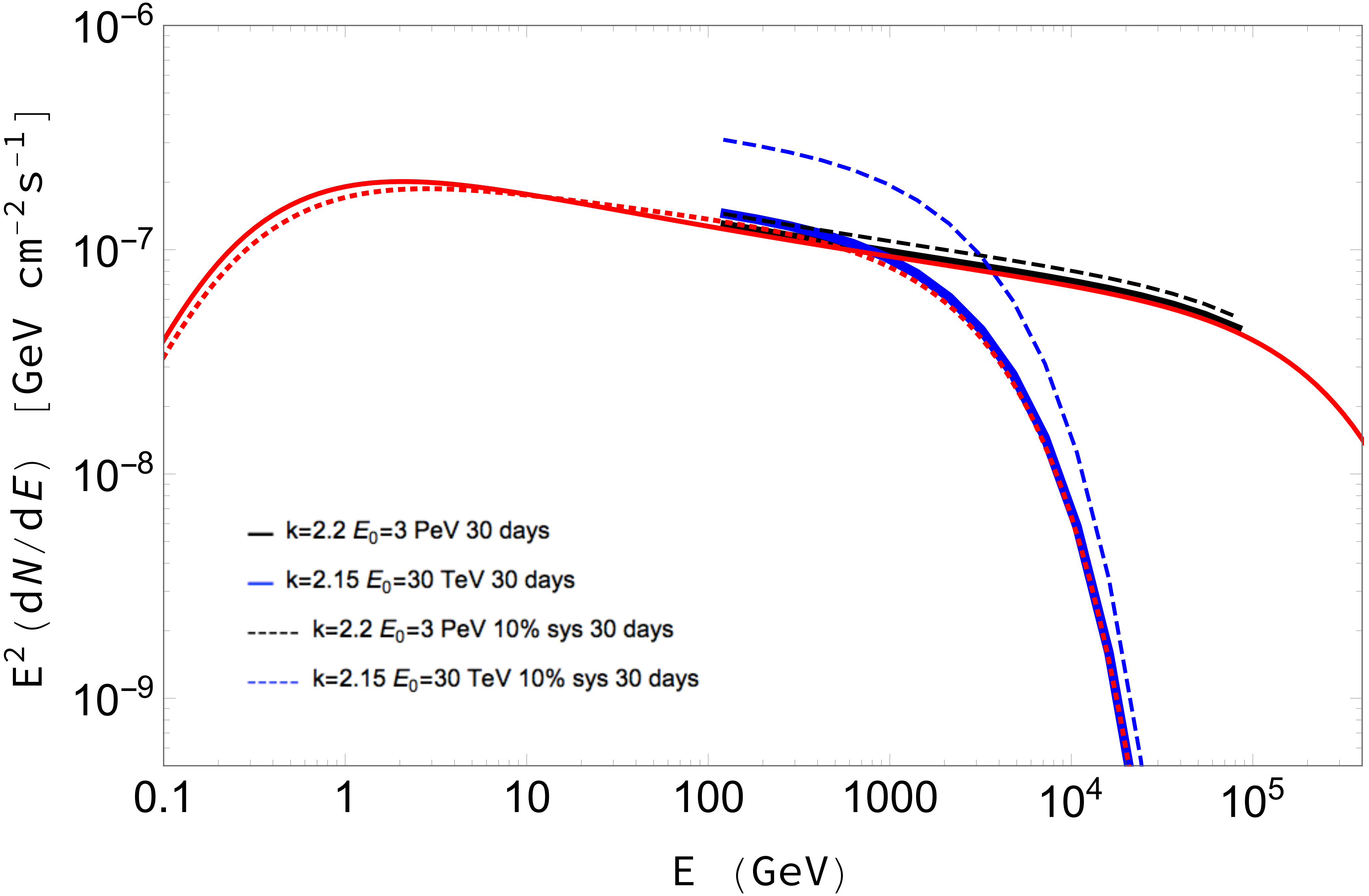
- Energy range of (100 GeV, 100 TeV)
- Gamma effective area — up to 10^6 m^2
- Four zenith bands
- Overall systematic uncertainty, 10%—50%

LHAASO field of view of bubble



Northern bubble can be seen in the zenith angle of (15,30), (30,45) and (45,60)degree with a daily average solid angle of 0.0003, 0.026 and 0.07 sr

LHAASO sensitivity estimation



Sensitivity at 95% CL for 30-day exposure (high- and low-cutoff model for low $|b|$) without and with 10% systematic uncertainty

Summary

- The origin of the *Fermi* bubbles and emission mechanism of gamma rays are still unknown

- With the latest observation of gamma ray and neutrino data from Fermi-LAT, HAWC and IceCube, the hadronic models have been updated

  - HAWC upper limits disfavor hadronic high-energy cutoff model for high-latitude region, in agree with *Fermi*-LAT detection

- Future gamma-ray observatories will constrain both hadronic and leptonic models and provide profound information of bubbles and Galactic center