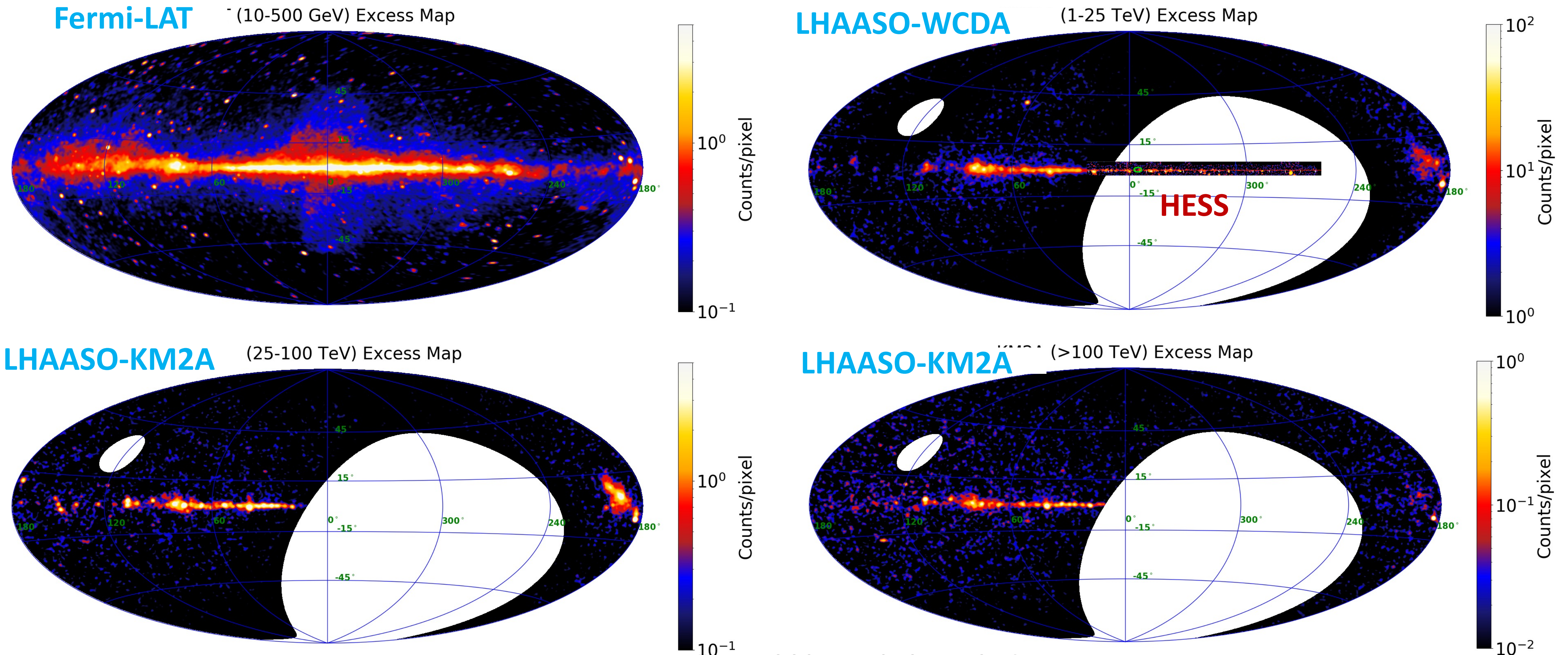
基于KM2A对伽马射线天体源的测量及软件的使用方法

- **Shaoqiang Xi**
- LHAASO Collaboration

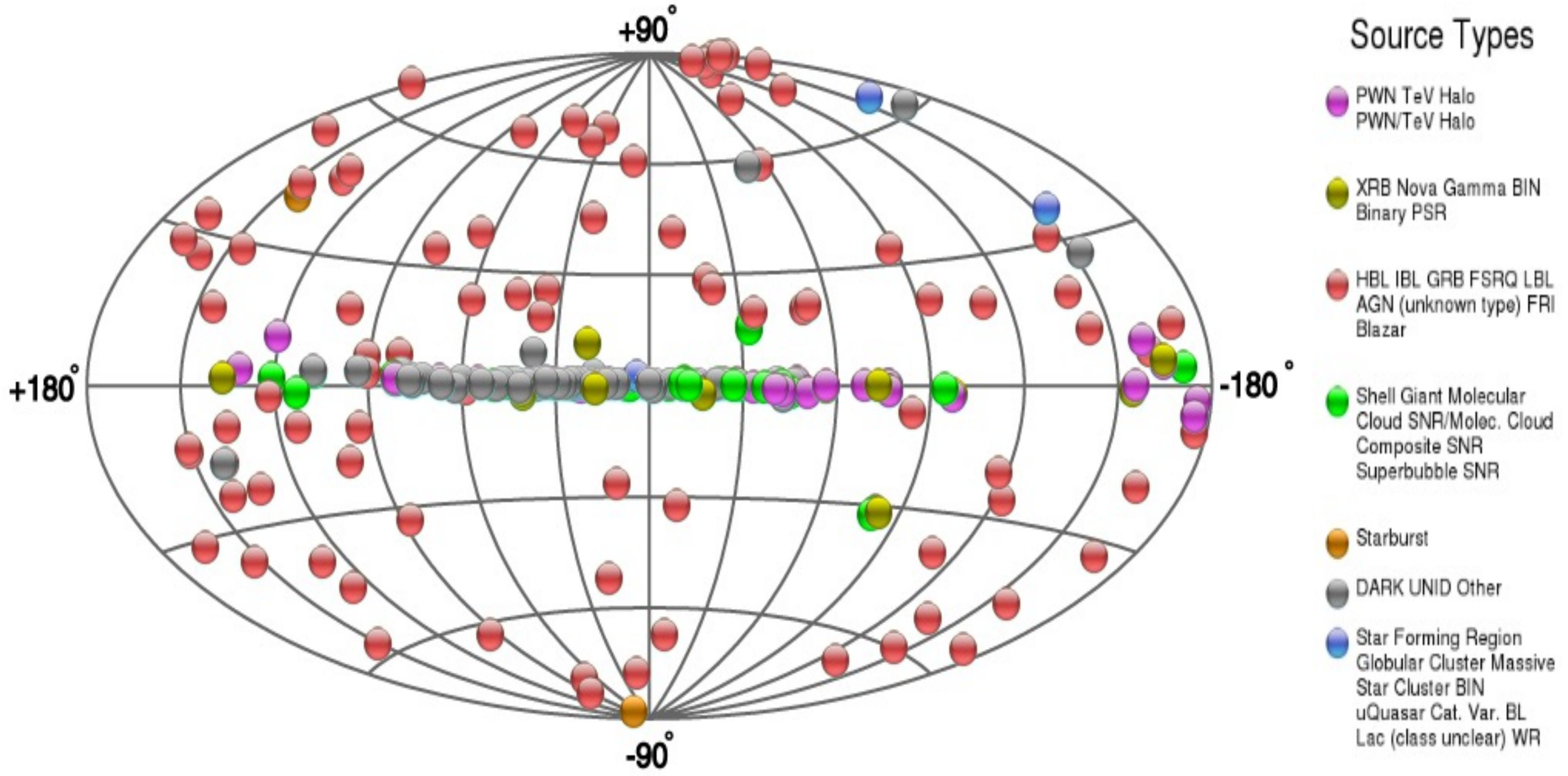
- Part0: Brief review of gamma-ray sources detected by LHAASO

Gamma-ray Sky



2024ApJS..271...25C

TeV Gamma-ray Sources



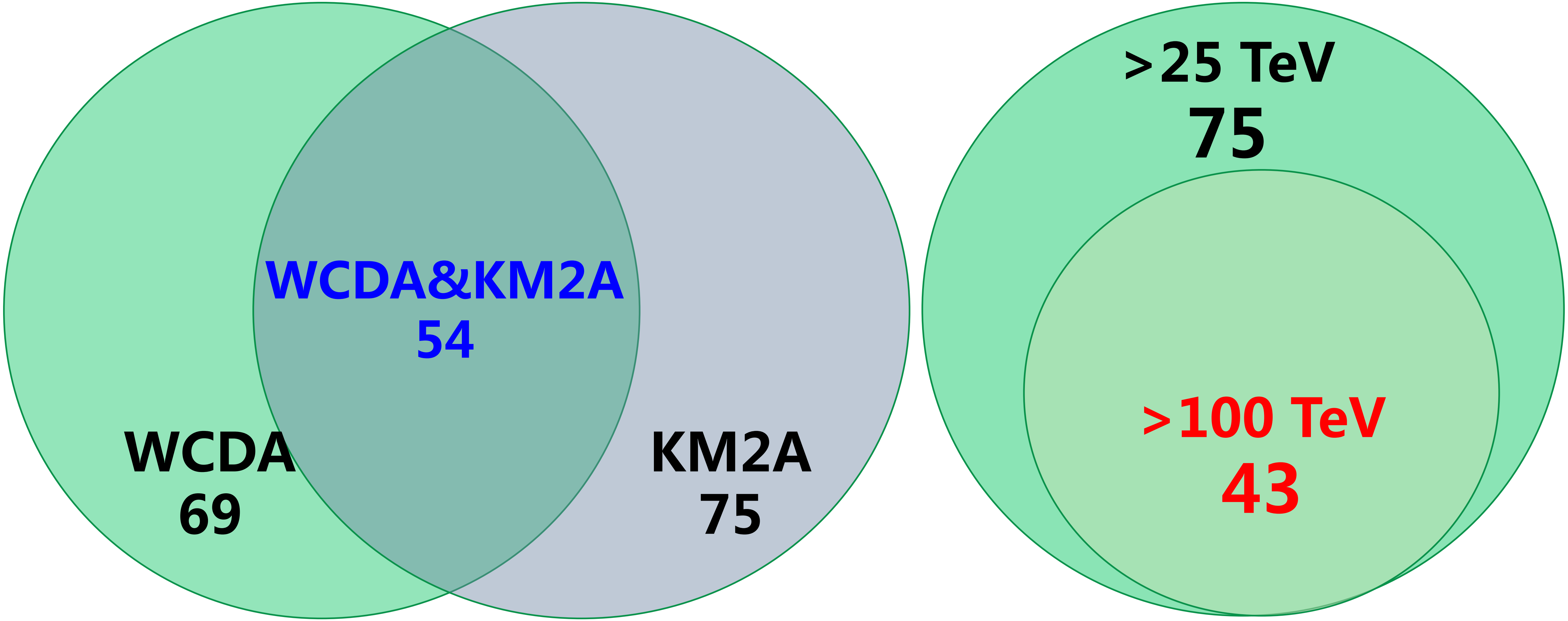
～300 TeVCat sources and its identification

Extragalactic:

1. AGN(Blazars,radio galaxy)
2. Starburst
3. GRB

1. pulsar+SNR+PWN
2. Star Cluster/SFR
3. Binary（HMX）
4. Cloud+CRs？
5. …

90 1st LHAASO sources



69 WCDA sources,75 KM2A sources, 43 UHE sources

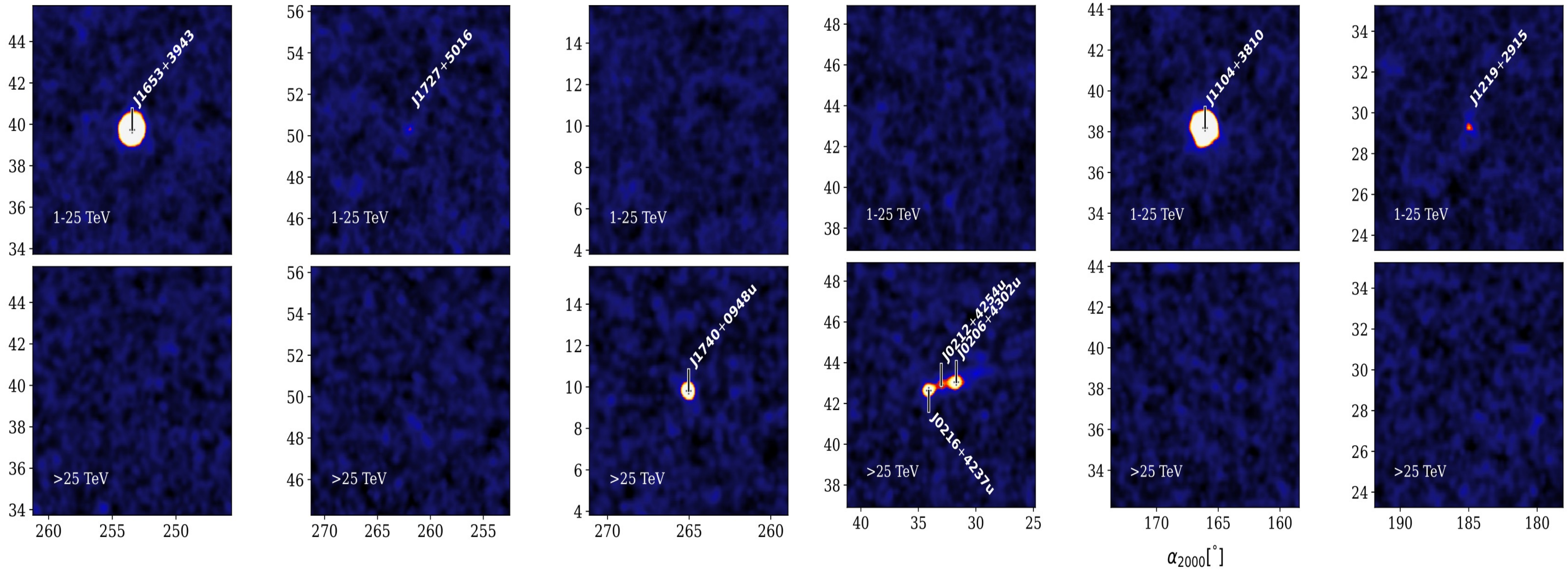
8 Sources

Mrk 421
z=0.031

1ES 1727+502
z=0.055

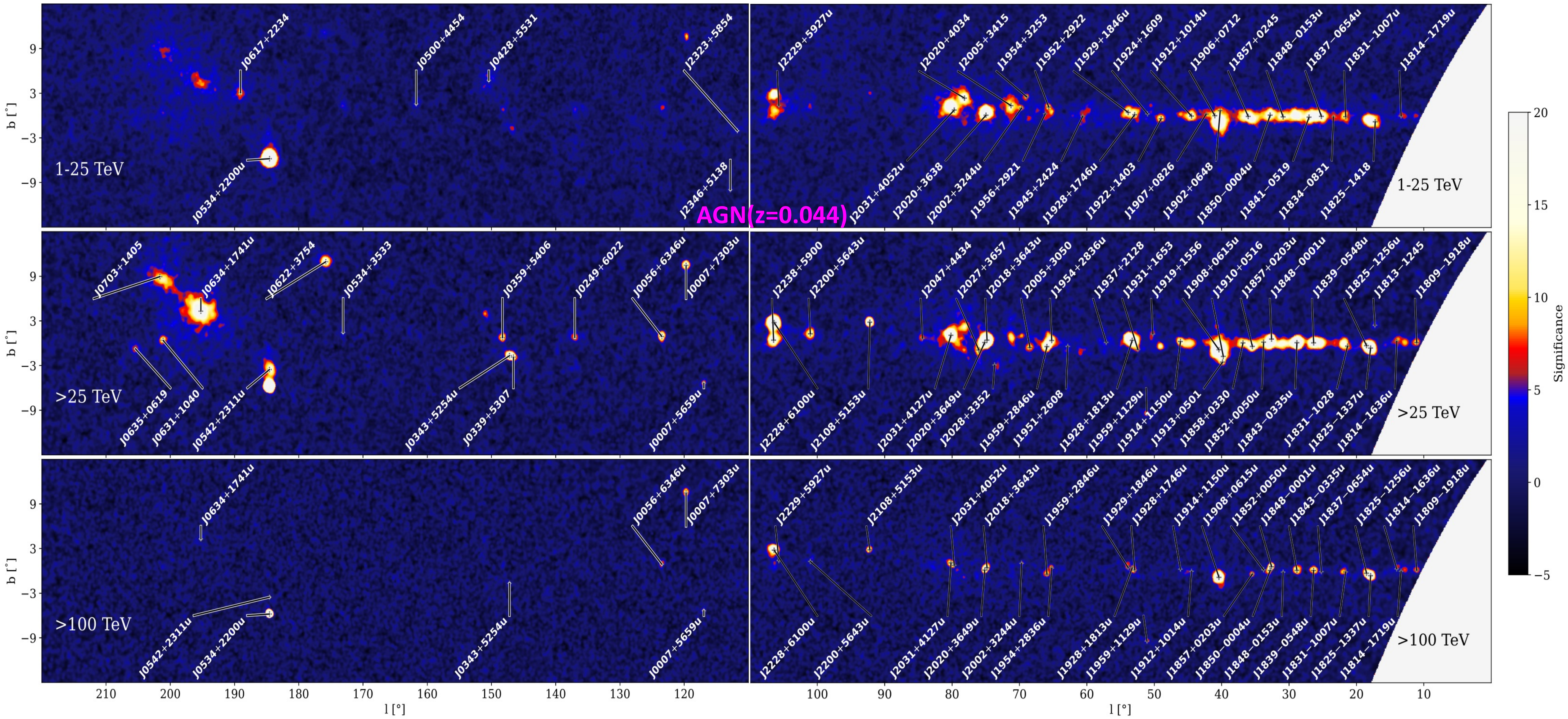
Mrk 501
z=0.034

NGC 4278
z=0.002



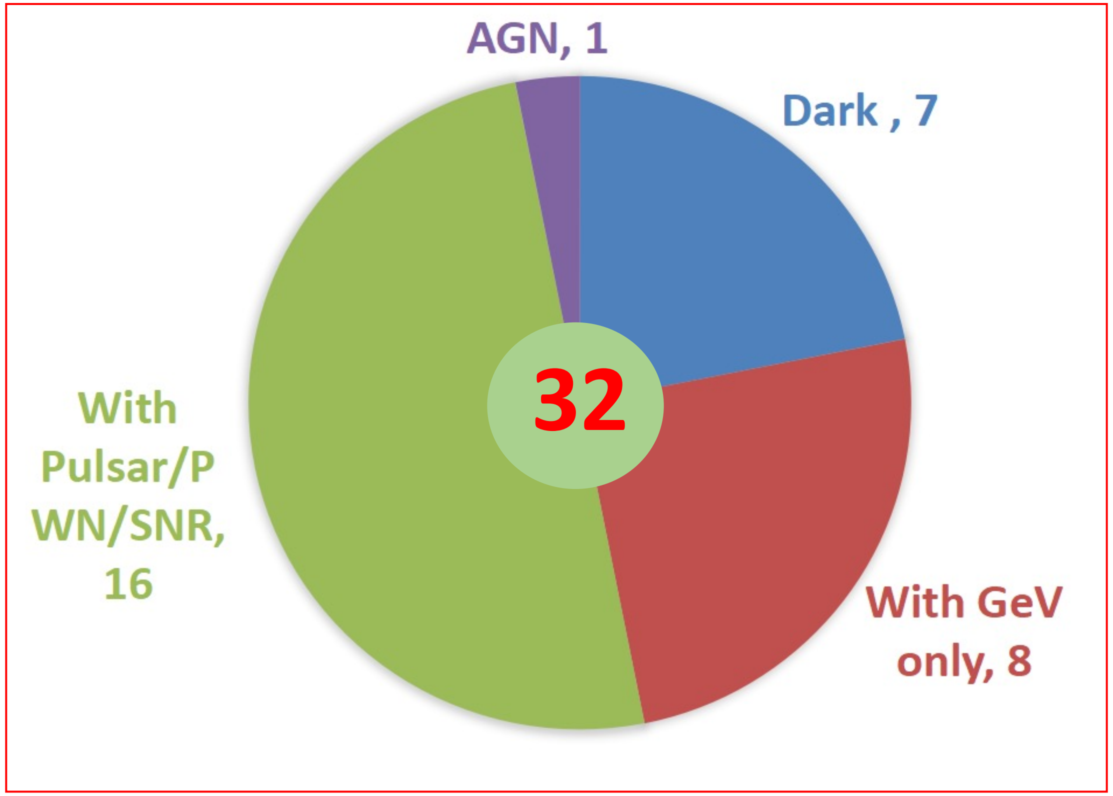
LHAASO 高海拔宇宙线观测站

82 sources

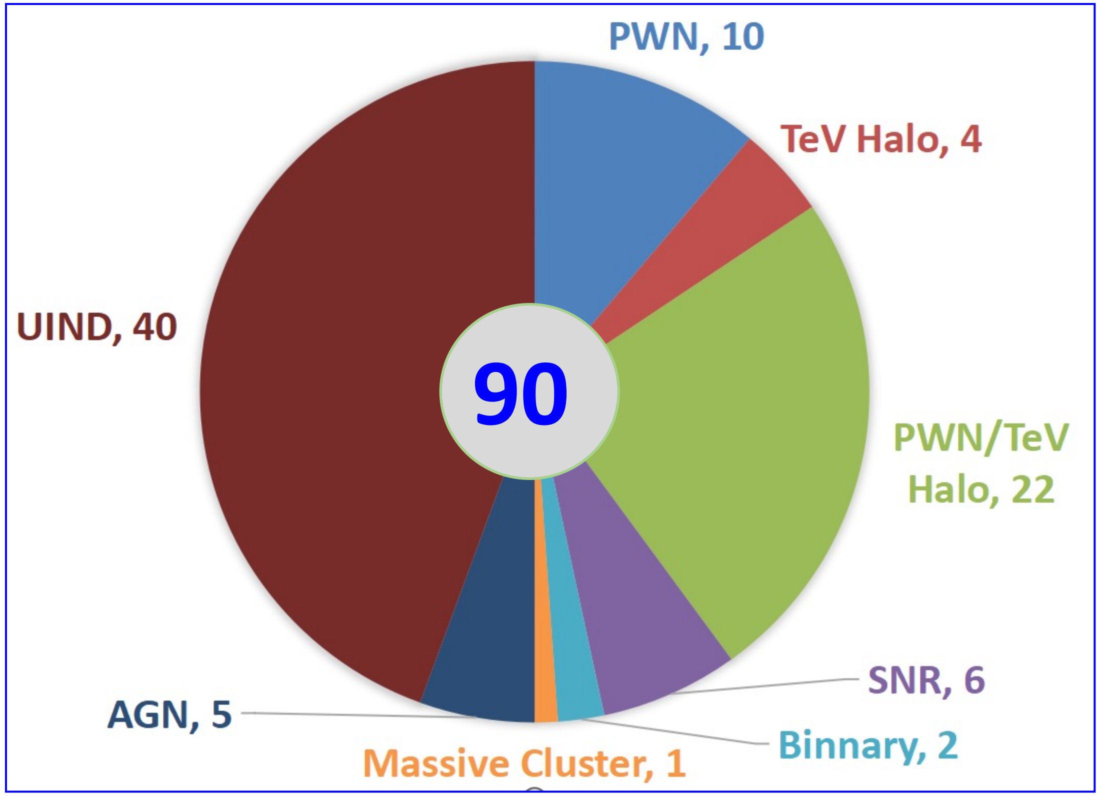


Associations

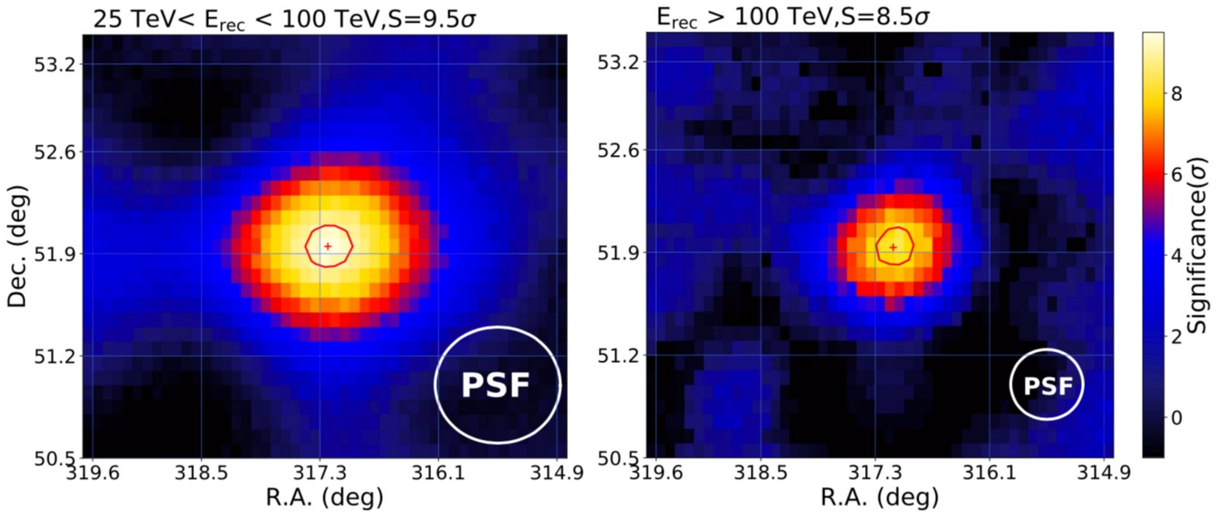
- **58 sources with TeVCat+3HAWC association**
- **32 new sources (25+7)**



Preliminary

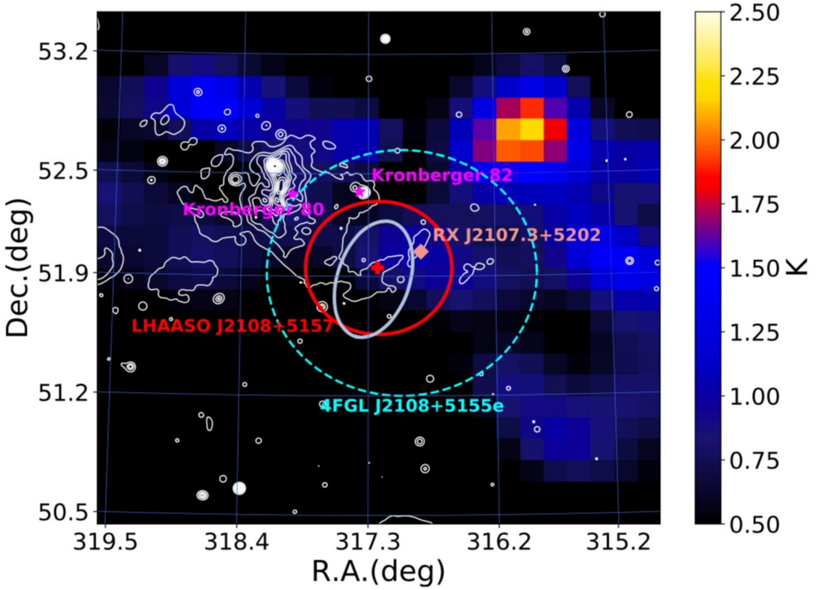


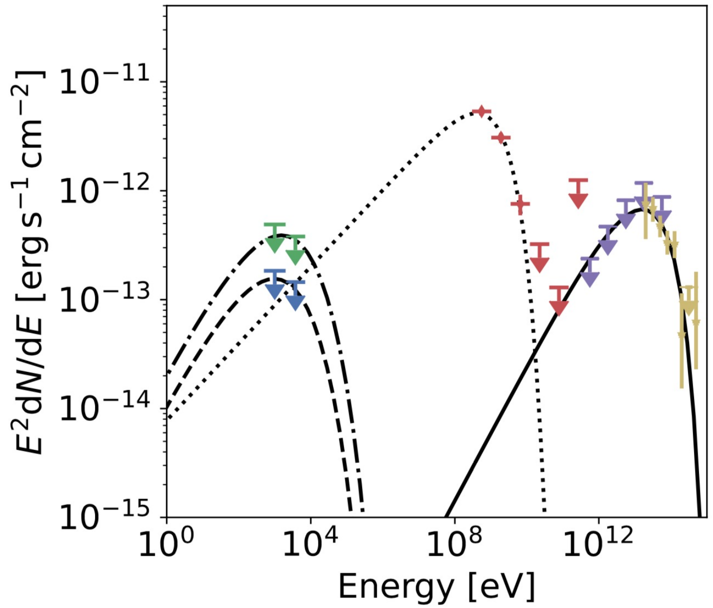
For example: Data analysis for LHAAO J2108+5157



Dedicated Analysis:

1. Sky map (significance map)
2. Spectrum
3. Multi-wavelength association
   (Molecular Cloud? Gas? Radio, X-ray?)



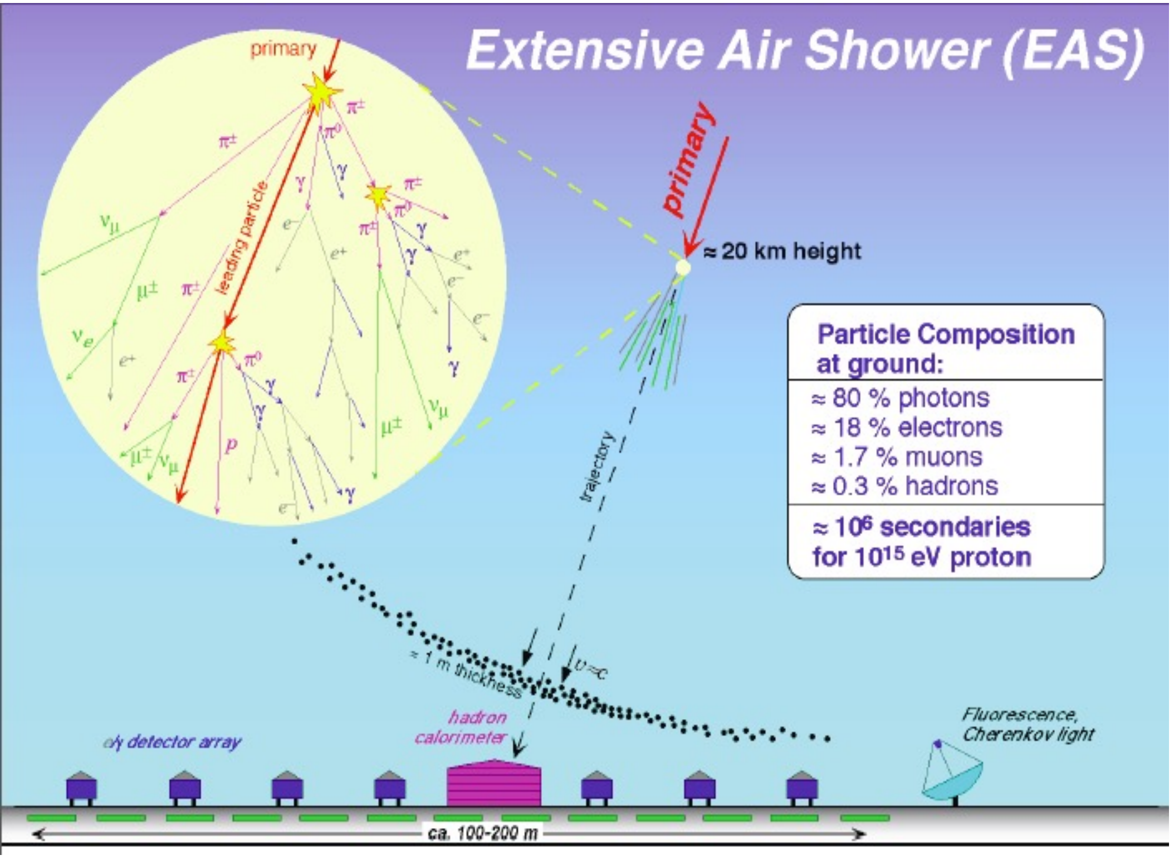


2021ApJ...919L..22C， Pirola et al 2023

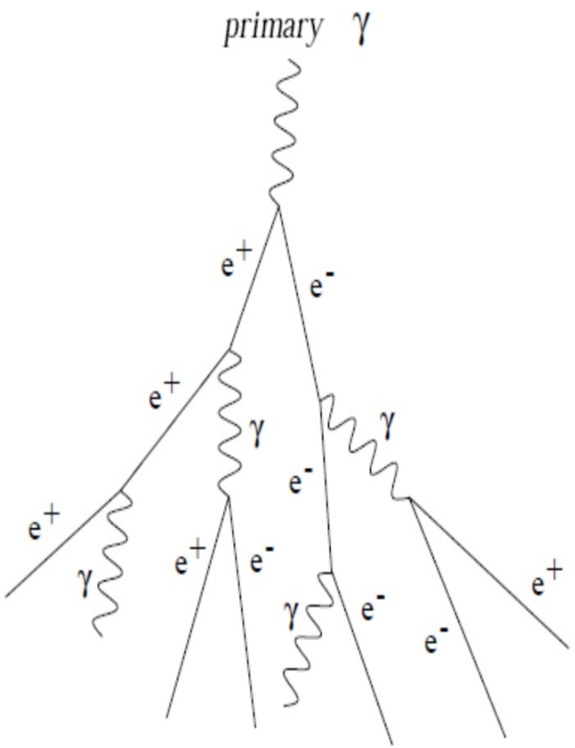
- Part1: basis of LHAASO gamma-ray data analysis

Basis of LHAASO Observation

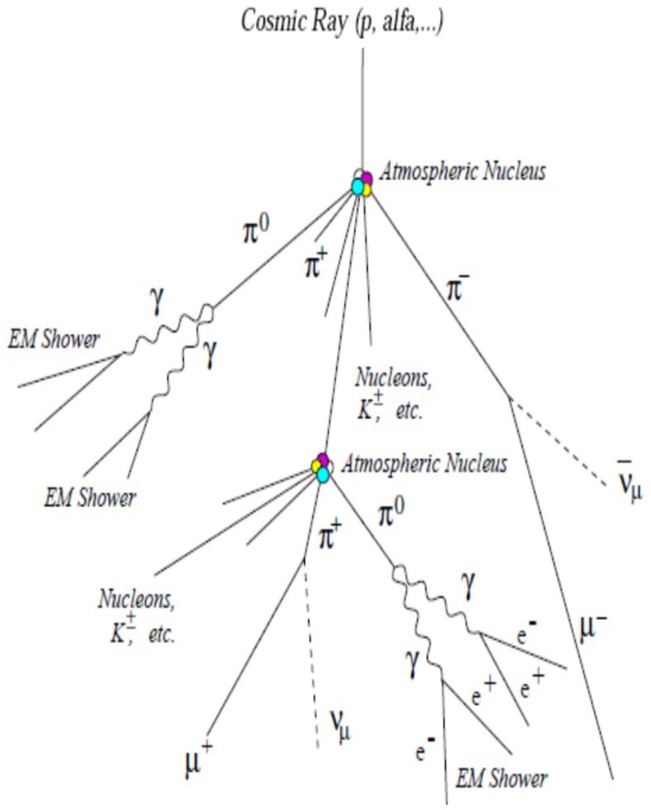
Large High Altitude Air Shower Observatory



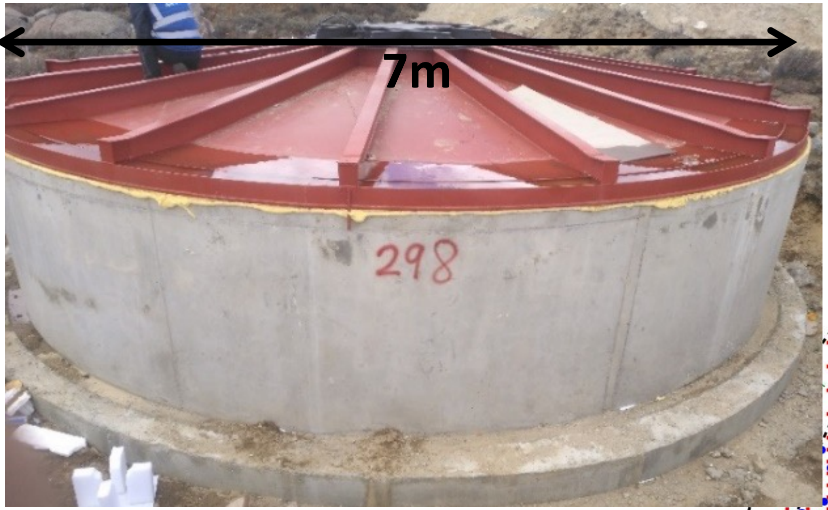
Photon

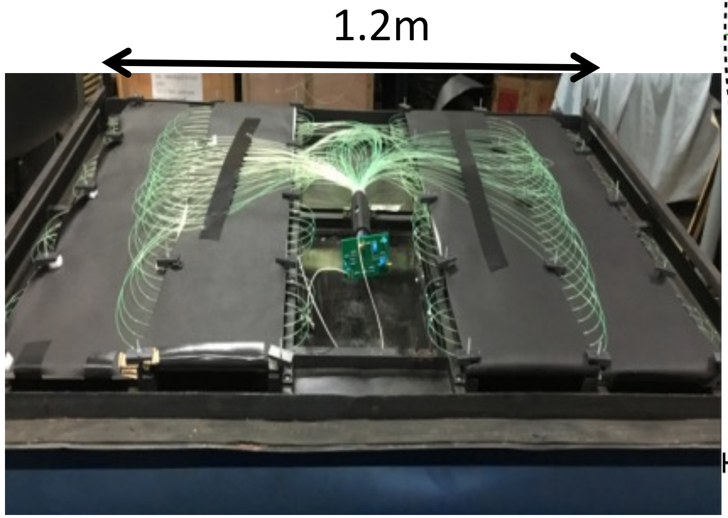


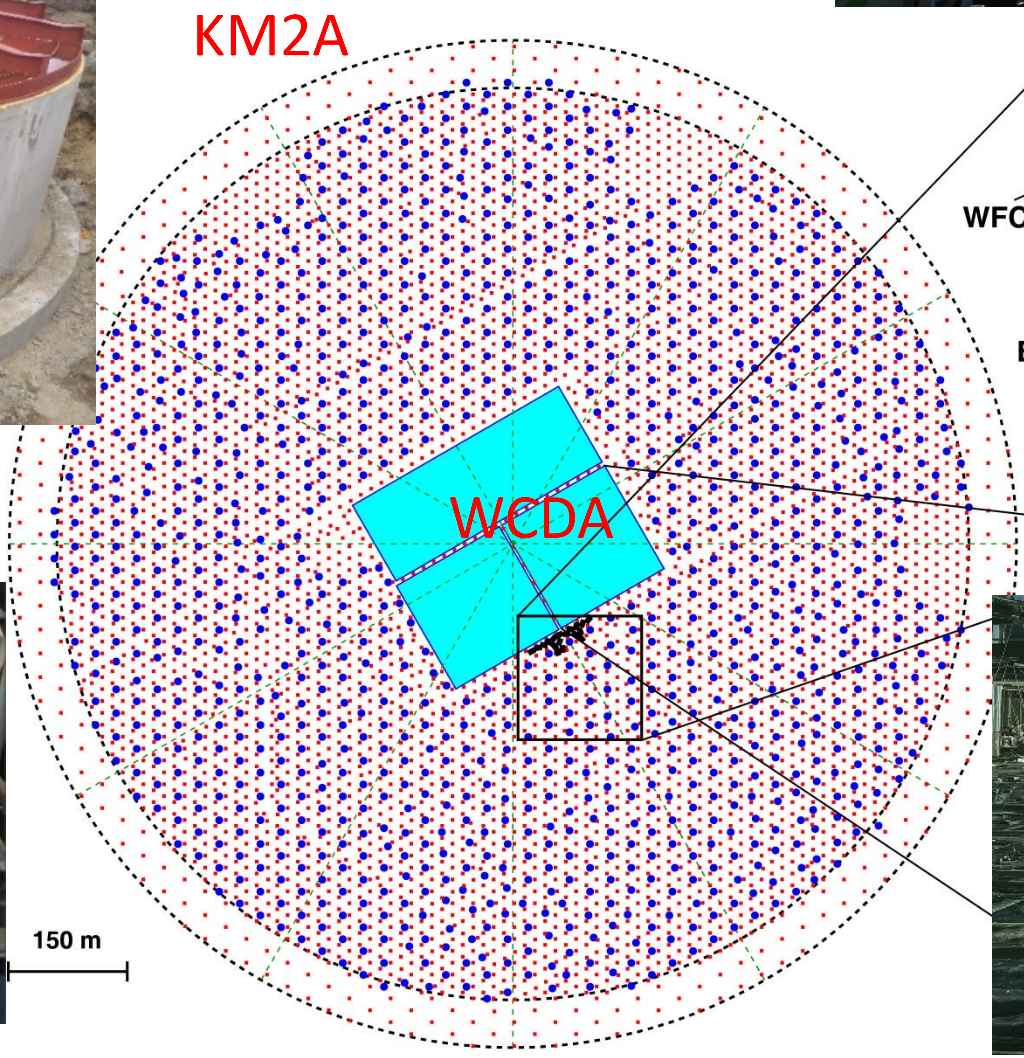
Cosmic Ray

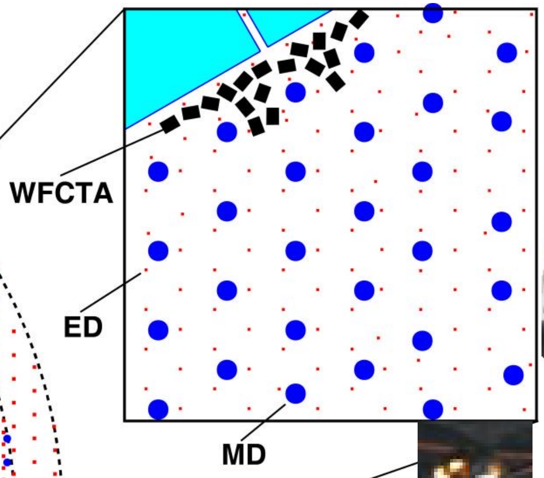


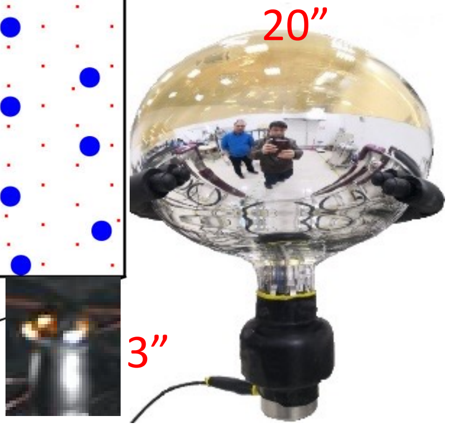
LHAASO Layout

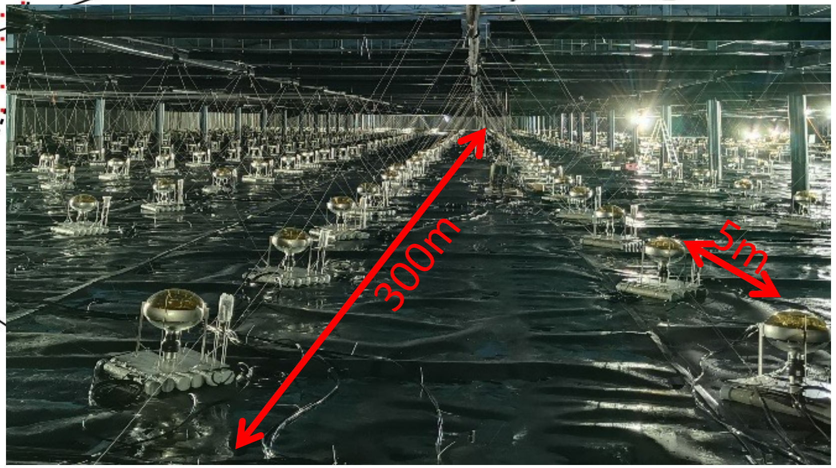






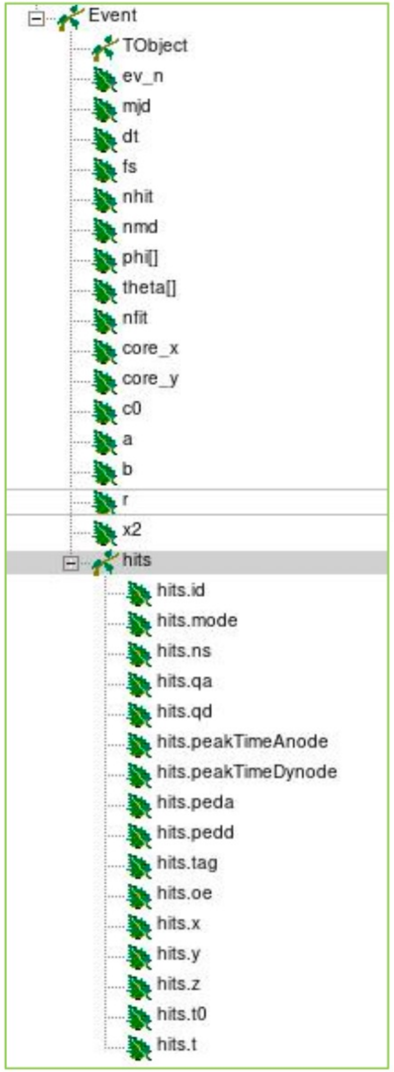




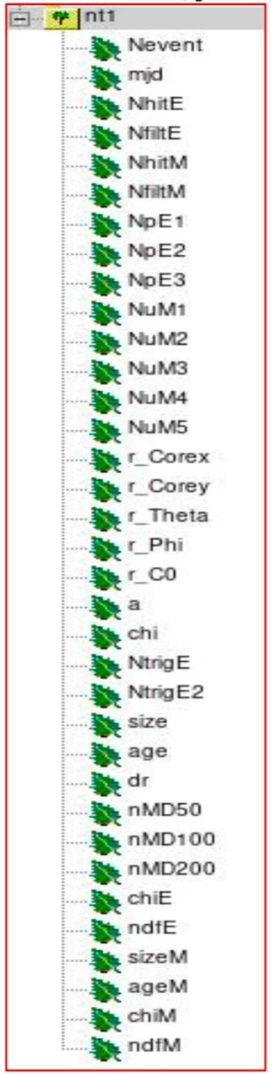


Experiment data

RAW Data



Rec Data (γ+CR)



- 1. Nevent: 累计的事例数个数
- 2. Mjd: 约化儒略日
- 3. NhitE: 读取事例中 ED 阵列 hit 数
- 4. NfiltE：距离 shower 前锋面-50ns 至 100ns、距离芯位 200m 以内的 ED 数
- 5. NhitM：读取事例中 ED 阵列 hit 数 6
- 6. NfiltM：距离 shower 前锋面-30ns 至 50ns、距离芯位 200m 以内的 MD 数
- 7. NpE1：距离 shower 前锋面-30ns 至 50ns、距离芯位 100m 以内的电磁粒子数
- 8. NpE2：距离 shower 前锋面-30ns 至 50ns、距离芯位 40-100m 以内的电磁粒子数
- 9. NpE3：距离 shower 前锋面-30ns 至 50ns、距离芯位 200m 以内的电磁粒子数
- 10. NuM1：距离 shower 前锋面-30ns 至 50ns、距离芯位 15-200m 以内的缪子数
- 11. NuM2：距离 shower 前锋面-30ns 至 50ns、距离芯位 40-100m 以内的缪子数
- 12. NuM3：距离 shower 前锋面-30ns 至 50ns、距离芯位 40-200m 以内的缪子数
- 13. NuM4：距离 shower 前锋面-30ns 至 50ns、距离芯位 15-400m 以内的缪子数
- 14. r_Corex：重建 shower 芯位 x 坐标（北为正, 北偏西 0.61°）
- 15. r_Corey：重建 shower 芯位 y 坐标（西为正）
- 16. r_Theta：重建原初事例的天顶角

path: /eos/lhaaso/rec/km2a/

Gamma-like Rec Data and Sky Cube

```
rec_phi         = 0.393799
rec_theta       = 0.648655
tra             = -0.228925
tdec            = -0.0978232
ra_J2000        = 3.72014
dec_J2000       = -0.0961715
glon            = 5.88105
glat            = 0.906139
r2moon          = 1.24496
r2sun           = 2.94387
rec_E           = 1.33339
pcut            = .80706
mjd             = 58970.7
```

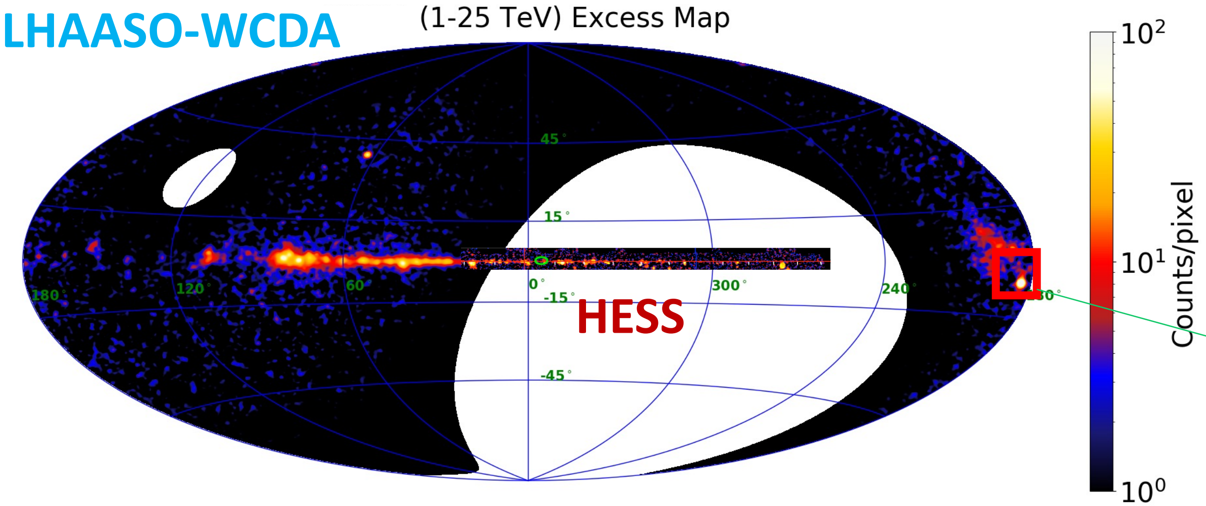
- 重建方位角 (rec_phi)
- 重建的时角 (tra, tdec)
- J2000坐标值 (ra_J2000, dec_J2000)
- 银道坐标值 (glon, glat)
- 光子离月球和太阳的距离 (r2moon, r2sun)
- 重建的能量 (rec_E)
- Gamma/p鉴别参数 (pcut)
- 到达时间 (mjd)

/home/lhaaso/xishaoqiang/lhaaso/data/pass3_full/data.fits

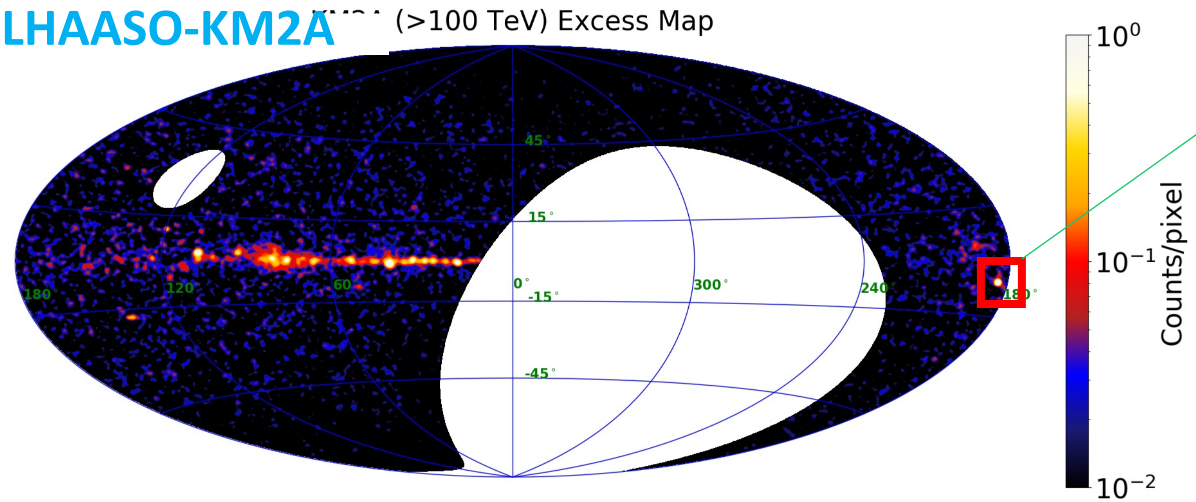
```
[xishaoqiang@lxlogin003 pass3_ful
root [0]
Attaching file data.root as _file
(TFile *) 0x25616b0
root [1] .ls
TFile**         data.root
 TFile*         data.root
  KEY: TH3F     all_sky_cube_on;1
  KEY: TH3F     all_sky_cube_bg;1
  KEY: TH1D     header;1          1
  KEY: TH3F     gll_cube_on;1
  KEY: TH3F     gll_cube_bg;1
```

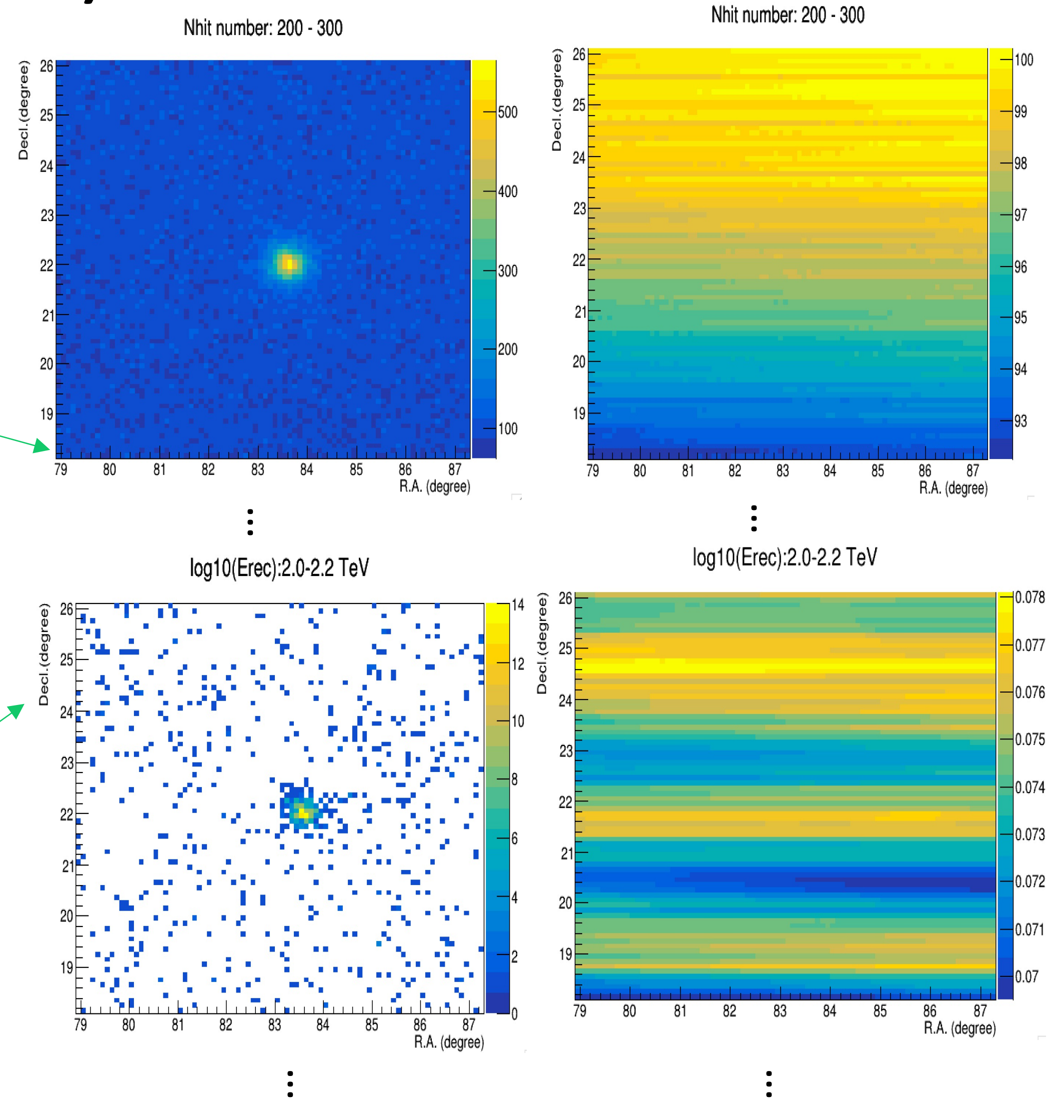
LHAASO Sky Map (Counts Maps)

LHAASO-WCDA



LHAASO-KM2A

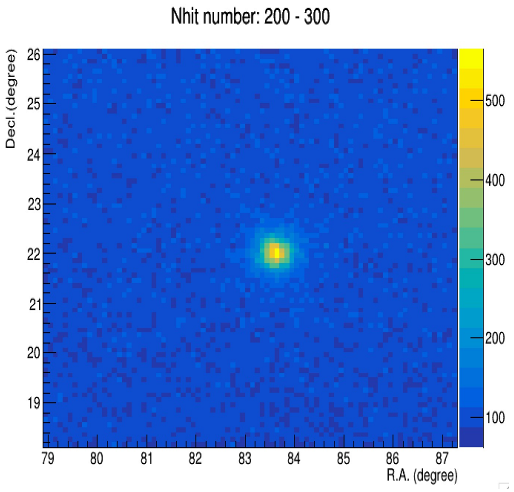




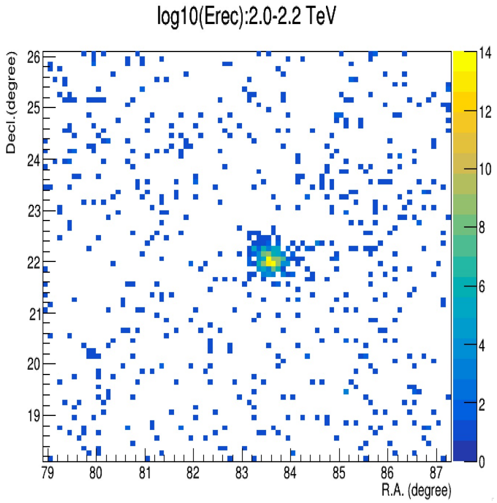
Obs.(on map)

CR bg map

Questions?



⋮



⋮

Obs.(on map)

- Is there a source?
- If there is, what is its location?
- What is its morphology?
- What is its flux?
- What is its spectrum(flux in each bin)?
- …

How can I answer?

Maximum likelihood Analysis and Hypothesis Test

LHAASO 高海拔宇宙线观测站

Maximum likelihood Estimation:

- Experiment: n events;

- Model: $\lambda(\theta)$ = CR+GDE+S(θ)

  $P(n/\lambda)=\frac{\lambda^n e^{-\lambda}}{n!}$

  $\ln\mathcal{L}(\lambda) = n ln\lambda - \lambda - \ln(n!)$

  $\frac{\partial ln\mathcal{L}}{\partial\lambda} = \frac{n}{\lambda} - 1 = 0$

- $$ln\mathcal{L}(N_{obs}|\theta) = \sum_{j=0}^{N_{bins}} lnP(N^j_{obs}|\theta)$$

Hypothesis Testing:

- Source detection:

  H0: λ= CR+GDE

  H1: $\lambda(\theta)$ = CR+GDE+S(θ)

  TS = 2($\ln\mathcal{L}_1(\lambda)$- $\ln\mathcal{L}_0(\lambda)$)

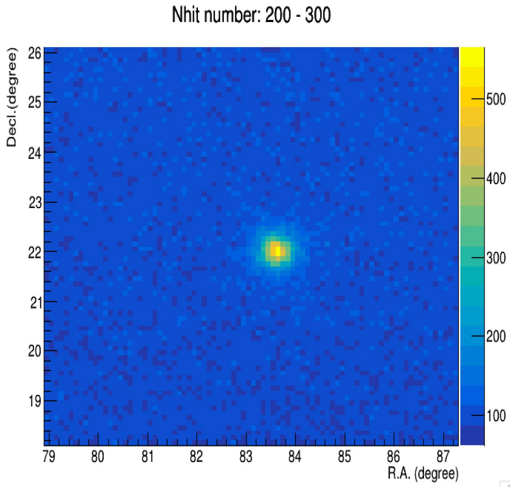
- Extended Test:

  H0: $\lambda(\theta)$ = CR+GDE+$S_p(\theta)$

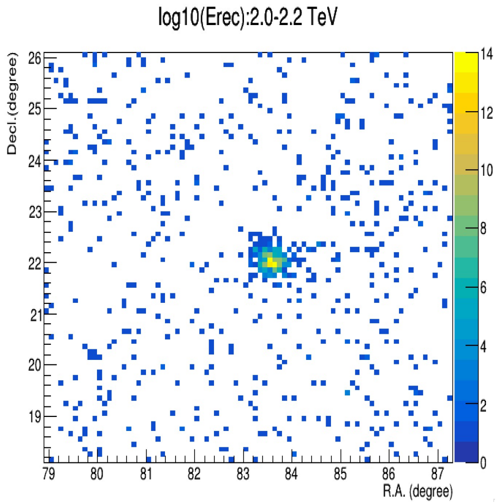
  H1: $\lambda(\theta)$ = CR+GDE+$S_G(\theta)$

  TS_{ext} = 2($\ln\mathcal{L}_1(\lambda)$- $\ln\mathcal{L}_0(\lambda)$)

- ...


Nhit number: 200 - 300
Decl.(degree)
26
25
24
23
22
21
20
19
79
80
81
82
83
84
85
86
87
R.A. (degree)
500
400
300
200
100

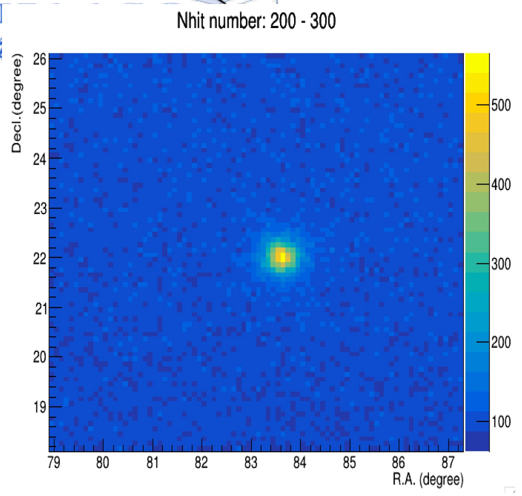
⋮


log10(Erec):2.0-2.2 TeV
Decl.(degree)
26
25
24
23
22
21
20
19
79
80
81
82
83
84
85
86
87
R.A. (degree)
14
12
10
8
6
4
2
0

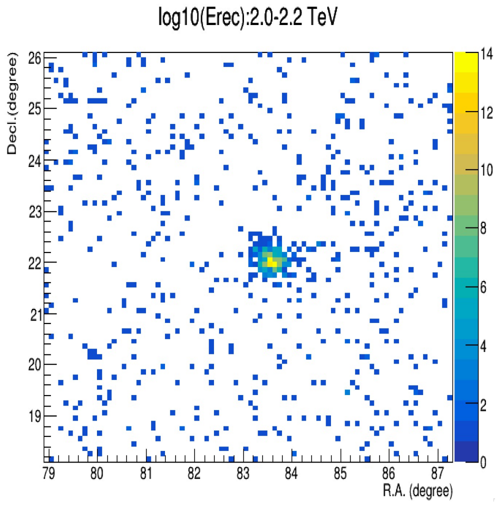
⋮

Obs.(on map)

H0: CR+GDE

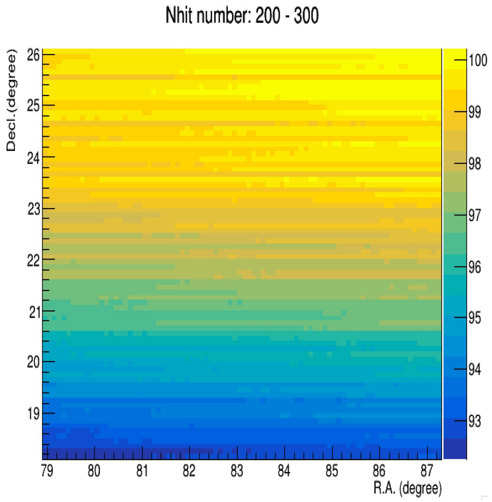


⋮

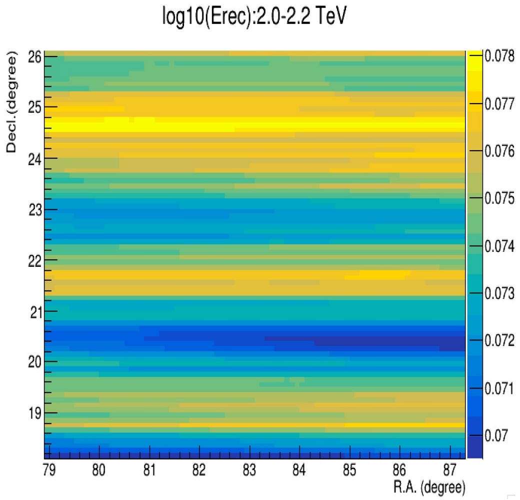


⋮

Obs.(on map)

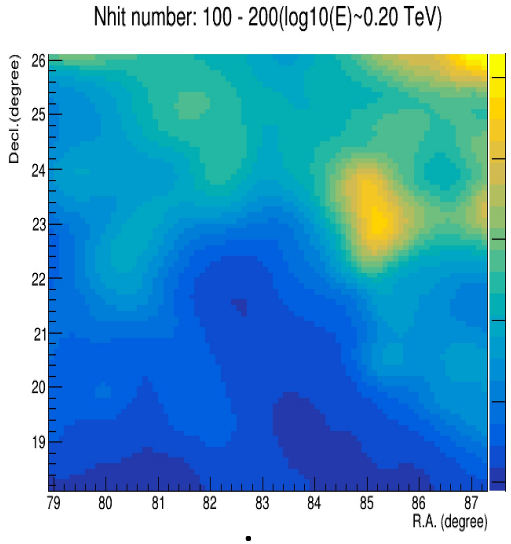


⋮

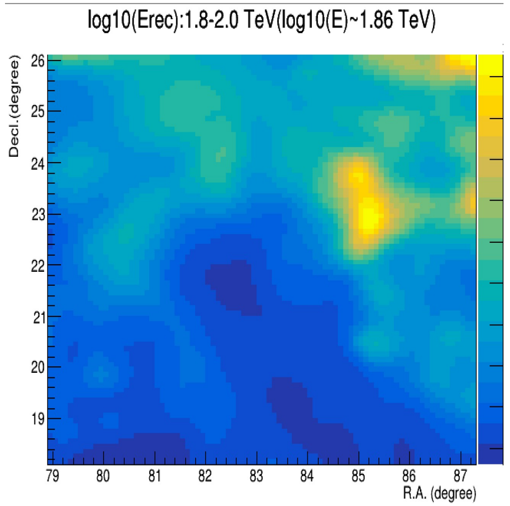


⋮

CR bg map



⋮



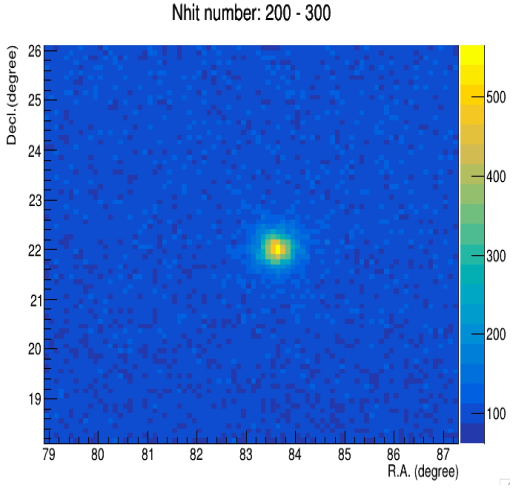
⋮

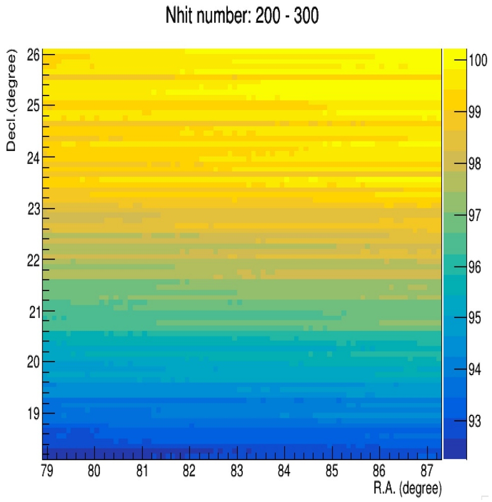
GDE bg map

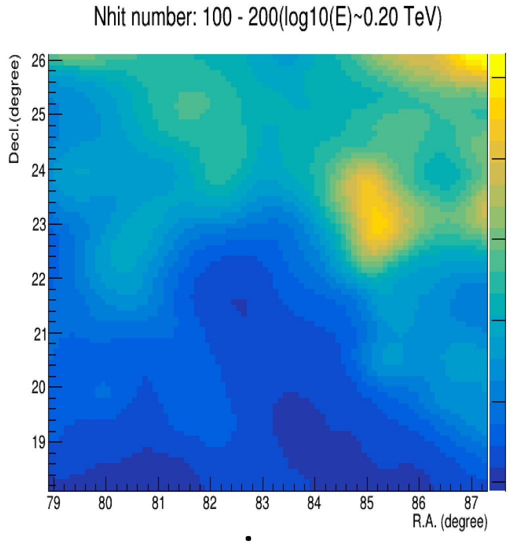
like0=?

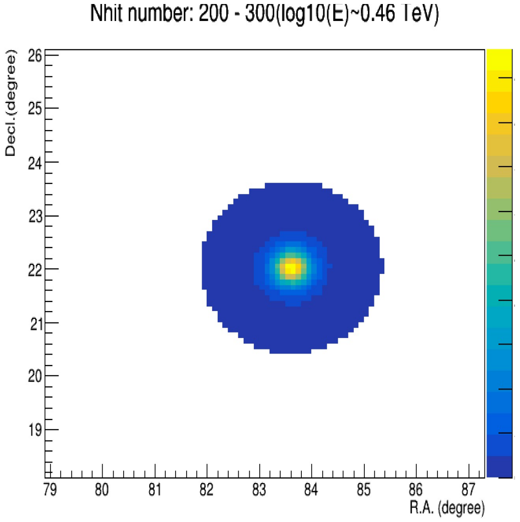
H1:CR+GDE+Src

like1=?

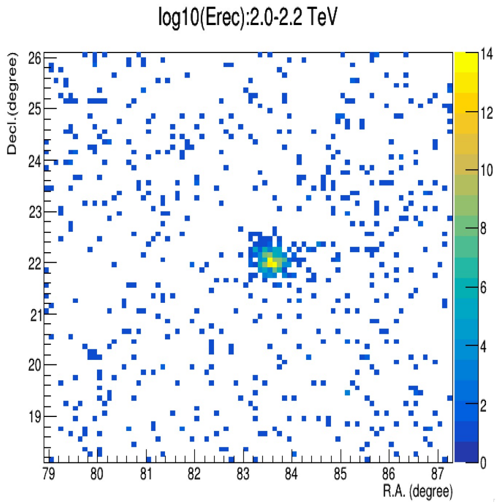


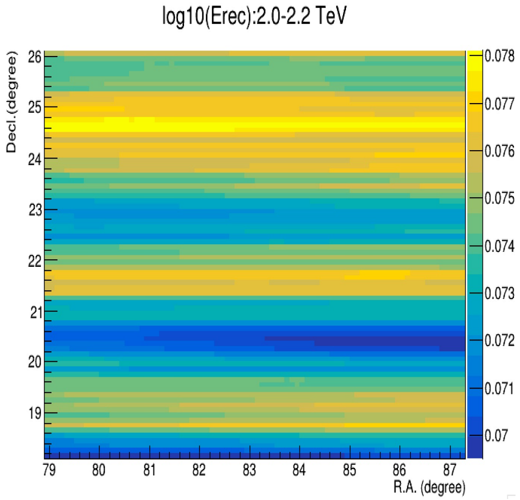


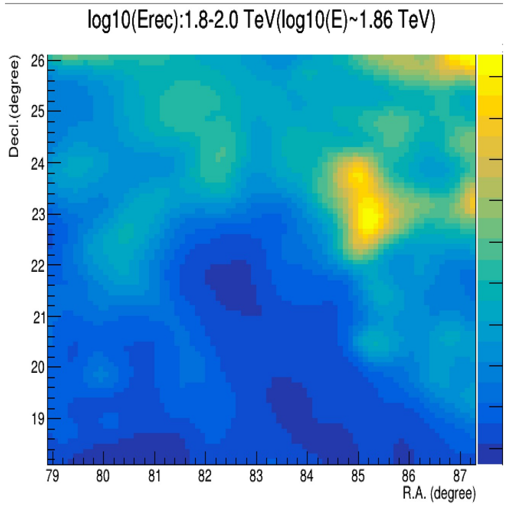


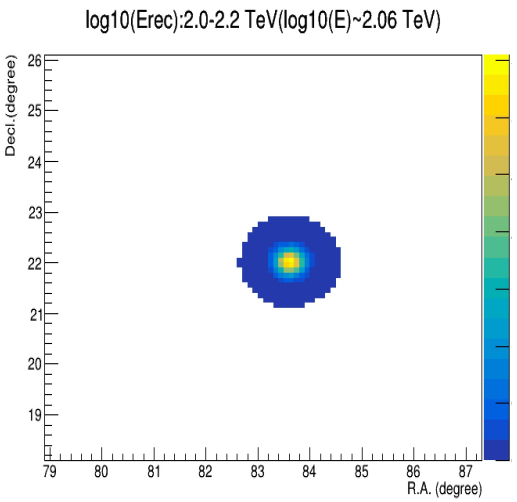


⋮





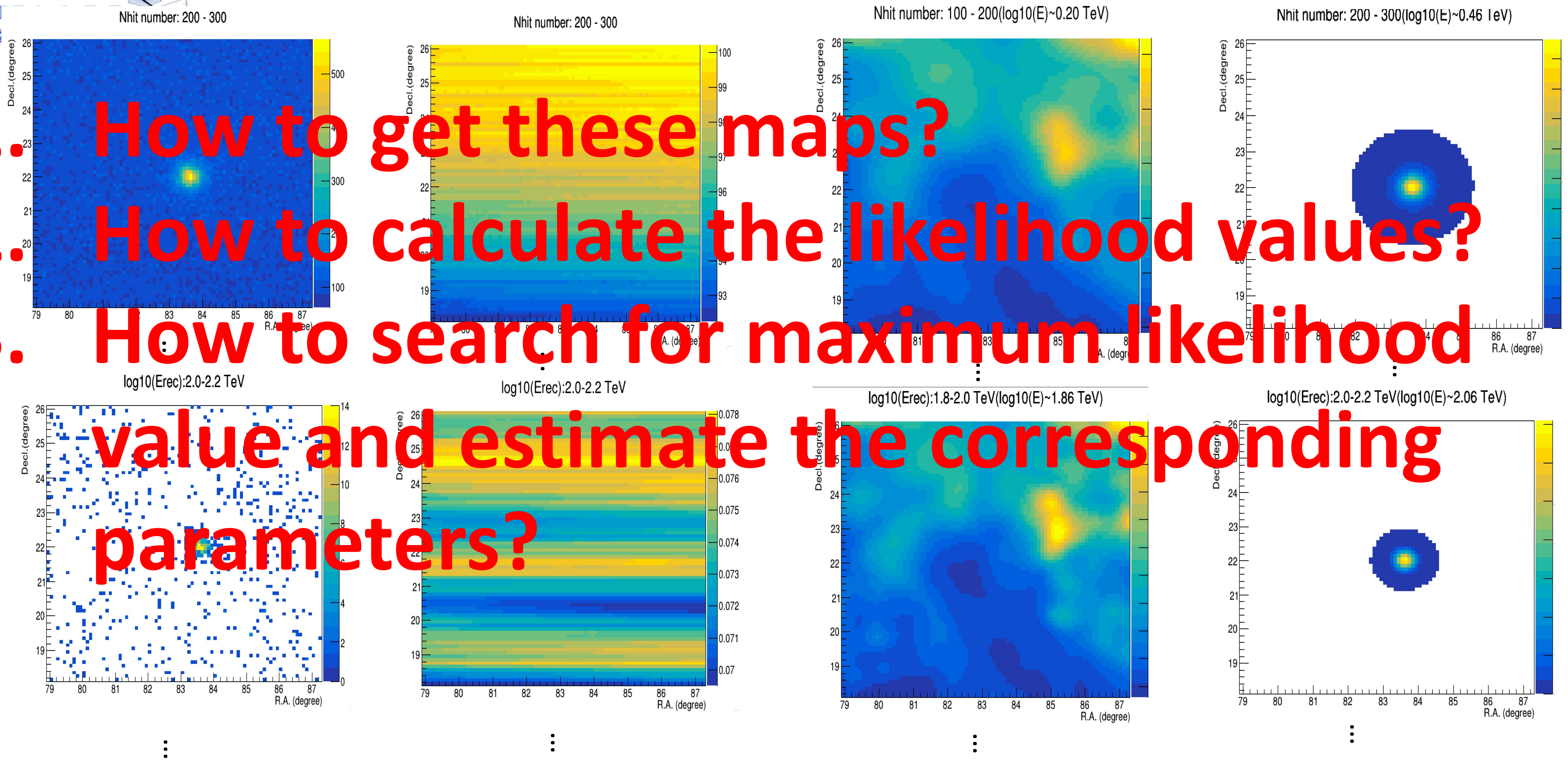




⋮

Obs.(on map) | CR bg map | GDE bg map | (Ra=83.633 Dec=22.015)

1. How to get these maps?
2. How to calculate the likelihood values?
3. How to search for maximum likelihood value and estimate the corresponding parameters?



Obs.(on map)

CR bg map

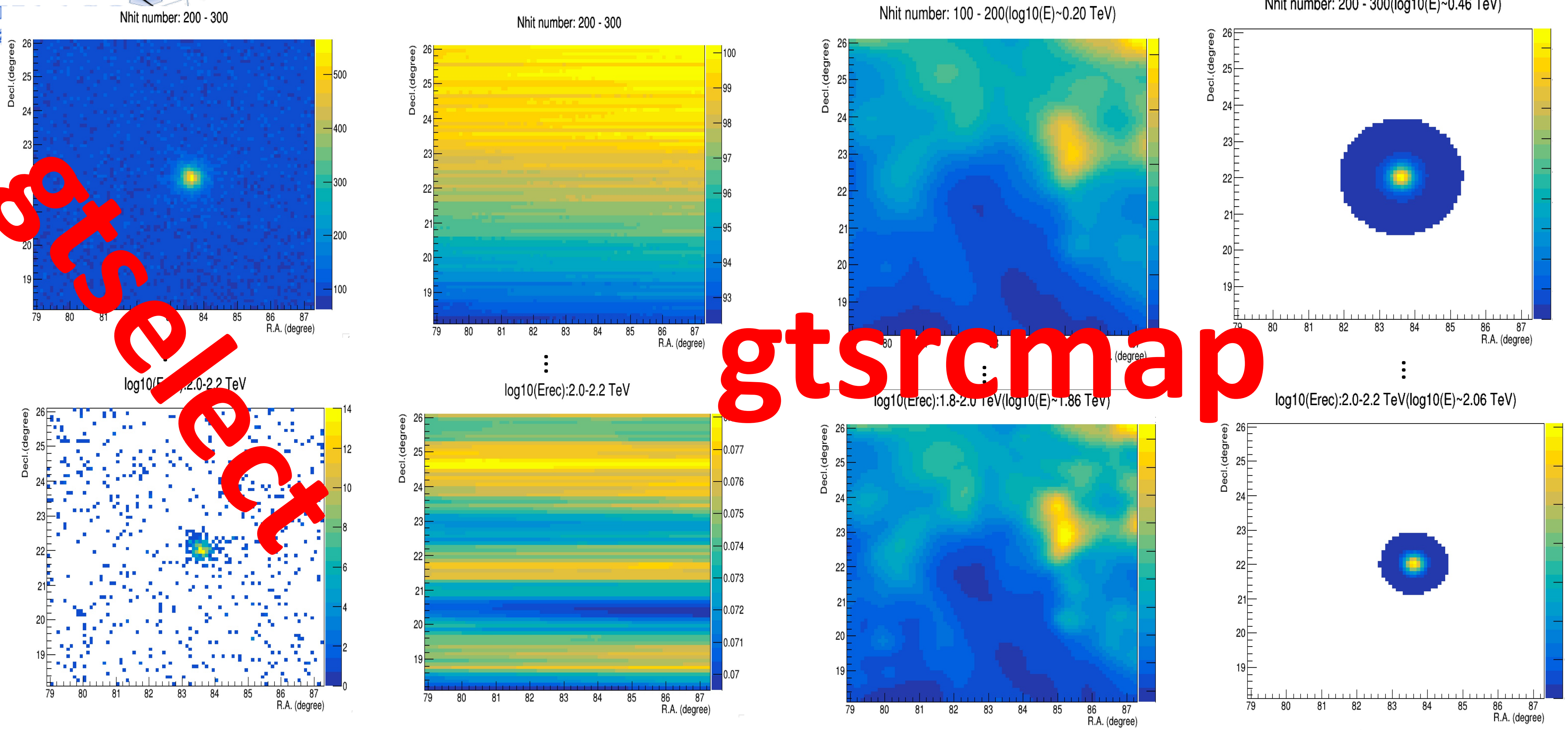
GDE bg map

(Ra=83.633 Dec=22.015)

- Part2: gamma tool (gt) introduction

- **gtselect**
- **gtsrcmap**
- **gtlike**

Illustration of Data Analysis



Obs.(on map)

CR bg map

GDE bg map

(Ra=83.633 Dec=22.015)

gtlike

like0, like1 TS(Ra=83.633,Dec=22.015) = ?

1. gtselect

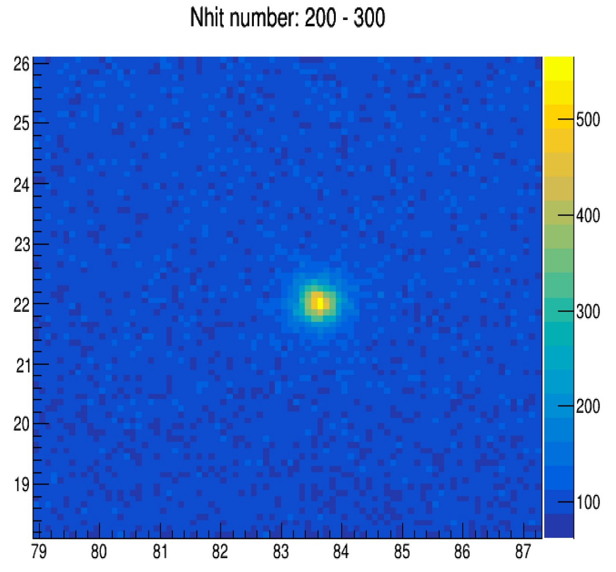
- **Configuration file： bg.yaml**

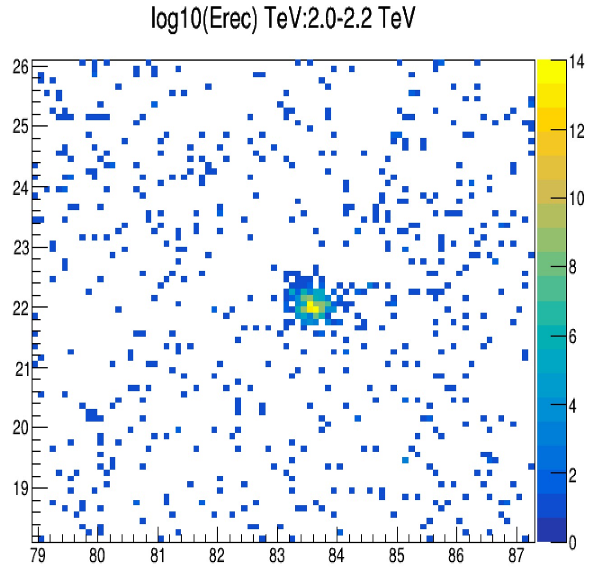
```yaml
selection:
  all_sky_map: /home/lhaaso/xishaoqiang/LHAASO_Analysis/data/data_1LHAASO/data.root
  roi_map: roi_ccube.root
  roi_x_range: [84,78.9,87.3] # ra_bins,ra_min,ra_max; interval must be 0.1 degree
  roi_y_range: [80,18.1,26.1] # dec_bins,dec_min,dec_max; interval must be 0.1 degree
  roi_e_range: [17,0.0,3.4] #bins,log10(e_min),log10(emax); interval must be 0.2
```

0.0-1.0: represent WCDA data； 1.0-3.4 represent KM2A data；

- **Run:** gtselect bg.yaml

```
-bash-4.2$ ls
bg.yaml  roi_ccube.root
```



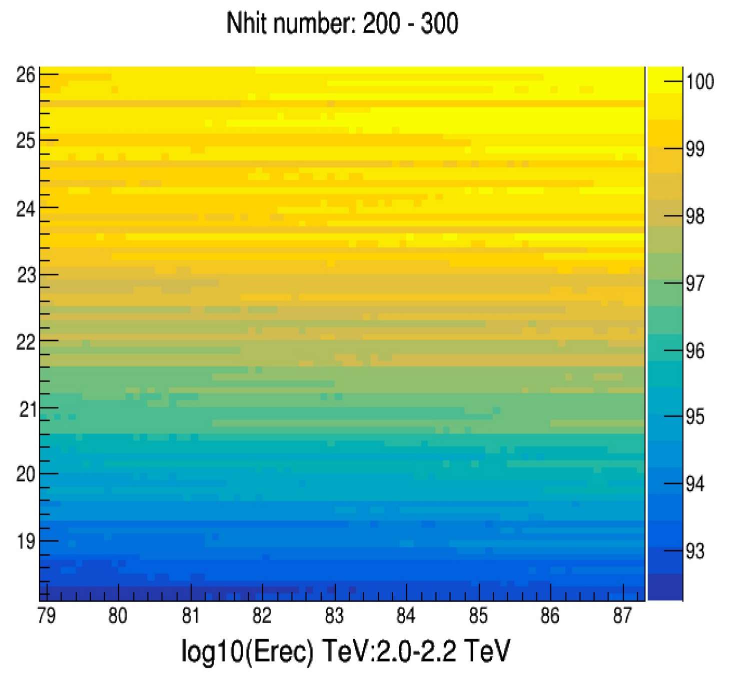


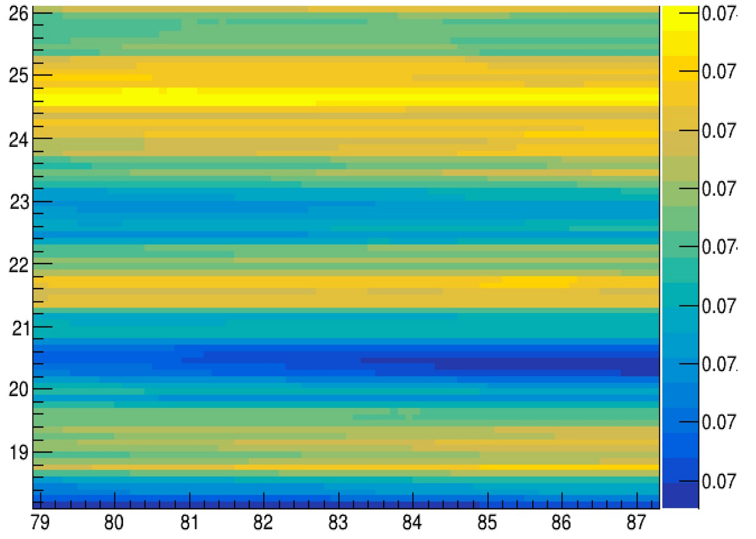
2. gtsrcmap (CR BG)

- **Run :** `gtsrcmap bg.yaml`

```yaml
selection:
  all_sky_map: /home/lhaaso/xishaoqiang/LHAASO_Analysis/data/data_1LHAASO/data.root
  roi_map: roi_ccube.root
  roi_x_range: [84, 78.9, 87.3]
  roi_y_range: [80, 18.1, 26.1]
  roi_e_range: [17, 0.0, 3.4]
source_dict:
  iso_bg: ### Cosmic-ray residual background;
    sed_model:
      sed_type: PL
      norm: [1, 0, 0, 1e-14]
      index: [2.7, 0, 0]
      E_0: 10
    spatial_model:
      src_map: iso_bg_srcmap.root
      spatial_type: iso_bg
```

```
-bash-4.2$ ls
bg.yaml  iso_bg_srcmap.root  roi_ccube.root
```



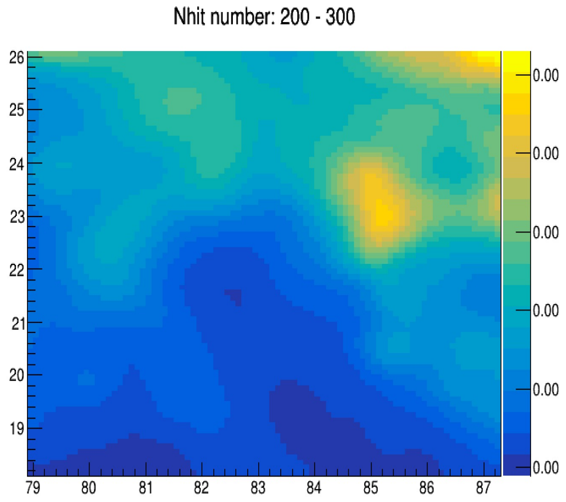


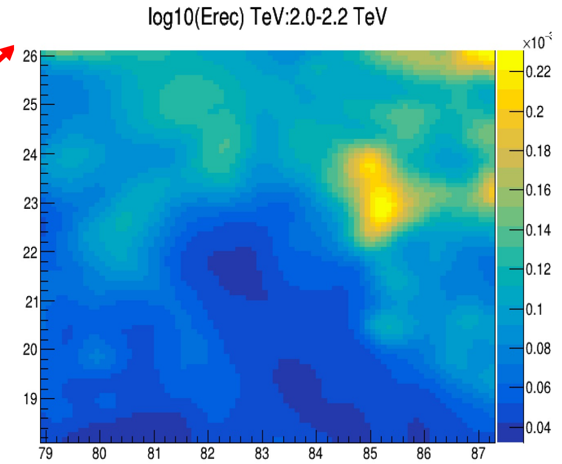
2. gtsrcmap (GDE BG)

- **Run:** `gtsrcmap bg.yaml`

```
source_dict:
  iso_bg:  ### Cosmic-ray residual background;
    sed_model:
      sed_type: PL
      norm: [1, 0, 0, 1e-14]
      index: [2.7, 0, 0]
      E_0: 10
    spatial_model:
      src_map: iso_bg_srcmap.root
      spatial_type: iso_bg
  gll_bg: ### Diffuse Background considering plank dust distribution
    sed_model:
      sed_type: PL
      norm: [5.63, 0.9314, 0.9314, 1e-15]
      index: [2.82, 0.1032, 0.1032]
      E_0: 50
    spatial_model:
      src_map: dust_gll_bg_srcmap.root
      spatial_type: file_map
      template_cutting: /home/lhaaso/xishaoqiang/LHAASO_Analysis/data/data_1LHAASO/gll_dust.root
      template_h2d_name: gll_region
      template_root_path: /home/lhaaso/xishaoqiang/LHAASO_Analysis/data/GDE_Template/gll_dust.root
```

l: 5 to 235 deg;
b: -20 to 20 deg;






```
-bash-4.2$ ls
bg.yaml  dust_gll_bg_srcmap.root  iso_bg_srcmap.root  roi_ccube.root
```

3. Gtlike

```
source_dict:
  iso_bg:
    sed_model:
      sed_type: PL
      norm: [1, 0, 0, 1e-14]
      index: [2.7, 0, 0]
      E_0: 10
    spatial_model:
      src_map: iso_bg_srcmap.root
      spatial_type: iso_bg
    each_bin:
      real_E: [0.10, 0.30, 0.50, 0.70, 0.90, 1.10,
      real_E_error: [0.10, 0.10, 0.10, 0.10, 0.10,
      R_68: [0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0
  gll_bg:
    sed_model:
      sed_type: PL
      norm: [5.63, 0.9314, 0.9314, 1e-15]
      index: [2.82, 0.1032, 0.1032]
      E_0: 50
    spatial_model:
      src_map: dust_gll_bg_srcmap.root
      spatial_type: gll_bg
      template_cutting: /home/lhaaso/xishaoqiang/L
      template_h2d_name: gll_region
      template_root_path: /home/lhaaso/xishaoqiang
    each_bin:
      real_E: [0.20, 0.46, 0.68, 0.96, 1.27, 1.07,
      real_E_error: [0.38, 0.33, 0.30, 0.28, 0.26,
      R_68: [0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0
```

- **Run:** `gtlike bg.yaml bg.yaml`

```
output_option:
  gtlike:
    Error_status: 1
    negative_loglike: -30322215.0
```

H0: CR BG+ GDE BG (bg.yaml)

$$\ln \mathcal{L}_0 : -(-30322215.0)$$

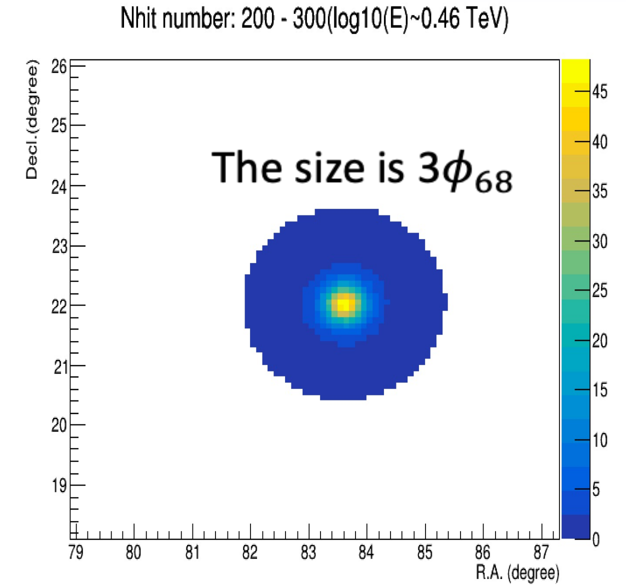
2. gtsrcmap (Crab map)

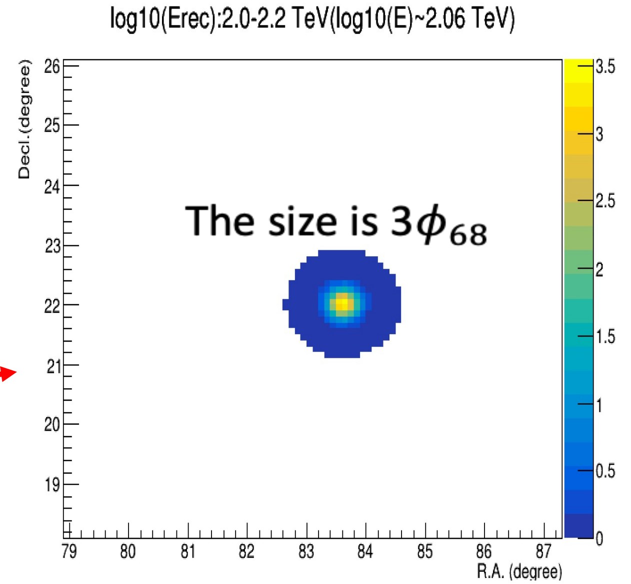
cp bg.yaml src.yaml

- **Run:** gtsrcmap src.yaml

```
gll_bg: ### Diffuse Background considering plank dust distribution
  sed_model:
    sed_type: PL
    norm: [5.63, 0.9314, 0.9314, 1e-15]
    index: [2.82, 0.1032, 0.1032]
    E_0: 50
  spatial_model:
    src_map: dust_gll_bg_srcmap.root
    spatial_type: file_map
    template_cutting: /home/lhaaso/xishaoqiang/LHAASO_Analysis/data/data_1LHAASO/gll_dust.root
    template_h2d_name: gll_region
    template_root_path: /home/lhaaso/xishaoqiang/LHAASO_Analysis/data/GDE_Template/gll_dust.root
J0534+2200: ### crab
  sed_model:
    sed_type: PL
    norm: [1.2621, 0.0000, 0.0000, 1e-14] ## [value, error/range, error/range, scale]
    index: [2.7715, 0, 0]                 ## [value, error/range, error/range]
    E_0: 20.0
  spatial_model:
    src_map: J0534+2200_srcmap.root
    spatial_type: ps
    ra: [83.6215, 0, 0]
    dec: [22.0159, 0, 0]
```

```
iso_bg_srcmap.root   J0534+2200_srcmap.root   roi_ccube.roo
```





3. gtlike

LHAASO 高海拔宇宙线观测站

- **Run:** `gtlike src.yaml src.yaml`

```yaml
source_dict:
  iso_bg:
    sed_model:
      sed_type: PL
      norm: [1, 0, 0, 1e-14]
      index: [2.7, 0, 0]
      E_0: 10
    spatial_model:
      src_map: iso_bg_srcmap.root
      spatial_type: iso_bg
    each_bin:
      real_E: [0.10, 0.30, 0.50, 0.70, 0.90, 1.10,
      real_E_error: [0.10, 0.10, 0.10, 0.10, 0.10,
      R_68: [0.00, 0.00, 0.00, 0.00, 0.00, 0.00,
  gll_bg:
    sed_model:
      sed_type: PL
      norm: [5.63, 0.9314, 0.9314, 1e-15]
      index: [2.82, 0.1032, 0.1032]
      E_0: 50
    spatial_model:
      src_map: dust_gll_bg_srcmap.root
      spatial_type: gll_bg
      template_cutting: /home/lhaaso/xishaoqiang/l
      template_h2d_name: gll_region
      template_root_path: /home/lhaaso/xishaoqiang
    each_bin:
      real_E: [0.20, 0.46, 0.68, 0.96, 1.27, 1.07,
      real_E_error: [0.38, 0.33, 0.30, 0.28, 0.26,
      R_68: [0.00, 0.00, 0.00, 0.00, 0.00, 0.00,
```

$\ln \mathcal{L}_0: -(-30322215.0)$

```yaml
  J0534+2200:
    sed_model:
      sed_type: PL
      norm: [1.2621, 1e-5, 1e5, 1e-14]
      index: [2.7715, 0, 10]
      E_0: 20.0
    spatial_model:
      src_map: J0534+2200_srcmap.root
      spatial_type: ps
      ra: [83.6215, 81.464189, 85.778811]
      dec: [22.0159, 20.015900, 24.015900]
    each_bin:
      real_E: [0.20, 0.46, 0.68, 0.95, 1.27,
      real_E_error: [0.38, 0.33, 0.30, 0.28,
      R_68: [0.73, 0.46, 0.37, 0.30, 0.25,
```

$$\text{PL}: \frac{dN}{dE} = norm * (E/E\_0)^{-index}$$

```yaml
  J0534+2200:
    sed_model:
      sed_type: PL
      norm: [0.9788, 0.0084, 0.0084, 1e-14]
      index: [2.8346, 0.0043, 0.0043]
      E_0: 20.0
    spatial_model:
      src_map: J0534+2200_srcmap.root
      spatial_type: ps
      ra: [83.6228, 0.0015, 0.0015]
      dec: [22.0152, 0.0014, 0.0014]
    each_bin:
      real_E: [0.20, 0.46, 0.68, 0.95, 1.27,
      real_E_error: [0.38, 0.33, 0.30, 0.28,
      R_68: [0.73, 0.46, 0.37, 0.30, 0.25,
    statistics:
      TS: 96544.478
output_option:
  gtlike:
    Error_status: 3
    negative_loglike: -30370487.2
```

- **H1: CR BG+ GDE BG+crab (src.yaml)**

$$\ln \mathcal{L}_1 = -(-30370487.2)$$

$$\text{TS} = 2\,(\ln \mathcal{L}_1 - \ln \mathcal{L}_0) \qquad signficance \sim \sqrt{TS} = 310.7\sigma$$

Summary configuration file

```
selection:
  all_sky_map: /home/lhaaso/xishaoqiang/LHAASO_Analysis/data/data_1LHAASO/data.root
  roi_map: roi_ccube.root
  roi_x_range: [84, 78.9, 87.3]
  roi_y_range: [80, 18.1, 26.1]
  roi_e_range: [17, 0.0, 3.4]
```

Selection data

```
output_option:
  gtlike:
    Error_status: 3
    negative_loglike: -30370487.2
```

Output likelihood

```
source_dict:
  iso_bg:
    sed_model:
      sed_type: PL
      norm: [1, 0, 0, 1e-14]
      index: [2.7, 0, 0]
      E_0: 10
    spatial_model:
      src_map: iso_bg_srcmap.root
      spatial_type: iso_bg
```

CR BG

```
  gll_bg:
    sed_model:
      sed_type: PL
      norm: [5.63, 0.9314, 0.9314, 1e-15]
      index: [2.82, 0.1032, 0.1032]
      E_0: 50
    spatial_model:
      src_map: dust_gll_bg_srcmap.root
      spatial_type: gll_bg
      template_cutting: /home/lhaaso/xishaoqiar
      template_h2d_name: gll_region
      template_root_path: /home/lhaaso/xishaoq
```

GDE BG

```
  J0534+2200:
    sed_model:
      sed_type: PL
      norm: [0.9788, 0.0084, 0.0084, 1e-14]
      index: [2.8346, 0.0043, 0.0043]
      E_0: 20.0
    spatial_model:
      src_map: J0534+2200_srcmap.root
      spatial_type: ps
      ra: [83.6228, 0.0015, 0.0015]
      dec: [22.0152, 0.0014, 0.0014]
```

Point source

Summary tool

- **gtselect:** selection the data.
- **gtsrcmap:** get the map expected by source model (such as: CR BG, GDE, point source,…)
- **gtlike:** estimate the model parameter, calculate the likelihood value.

Tool is easy! Let’s go to design our script.

How to get spectral point?

```
selection:
  all_sky_map: /home/lhaaso/xishaoqiang/
  roi_map: roi_ccube.root
  roi_x_range: [84, 78.9, 87.3]
  roi_y_range: [80, 18.1, 26.1]
  roi_e_range: [17, 0.0, 3.4]
```

```
selection:
  all_sky_map: /home/lhaaso/xishao
  roi_map: roi_ccube.root
  roi_x_range: [84, 78.9, 87.3]
  roi_y_range: [80, 18.1, 26.1]
  roi_e_range: [1, 0.0, 0.2]
```

gtselect

gtsrcmap

gtlike

```
J0534+2200:
  sed_model:
    sed_type: PL
    norm: [0.9788, 0.0084, 0.0084, 1e-14]
    index: [2.8346, 0.0043, 0.0043]
    E_0: 20.0
  spatial_model:
    src_map: J0534+2200_srcmap.root
    spatial_type: ps
    ra: [83.6228, 0.0015, 0.0015]
    dec: [22.0152, 0.0014, 0.0014]
```

```
J0534+2200:
  sed_model:
    sed_type: PL
    norm: [1.3046, 1e-5, 1e5, 1.0e-11]
    index: [2.8346, 0, 0]
    E_0: 1.6
  spatial_model:
    src_map: J0534+2200_srcmap.root
    spatial_type: ps
    ra: [83.6228, 0.0015, 0.0015]
    dec: [22.0152, 0.0014, 0.0014]
```

```
J0534+2200:
  sed_model:
    sed_type: PL
    norm: [1.1722, -0.0097, 0.0098, 1.0e-11]
    index: [2.8346, 0, 0]
    E_0: 1.6
  spatial_model:
    src_map: J0534+2200_srcmap.root
    spatial_type: ps
    ra: [83.6228, 0.0015, 0.0015]
    dec: [22.0152, 0.0014, 0.0014]
```

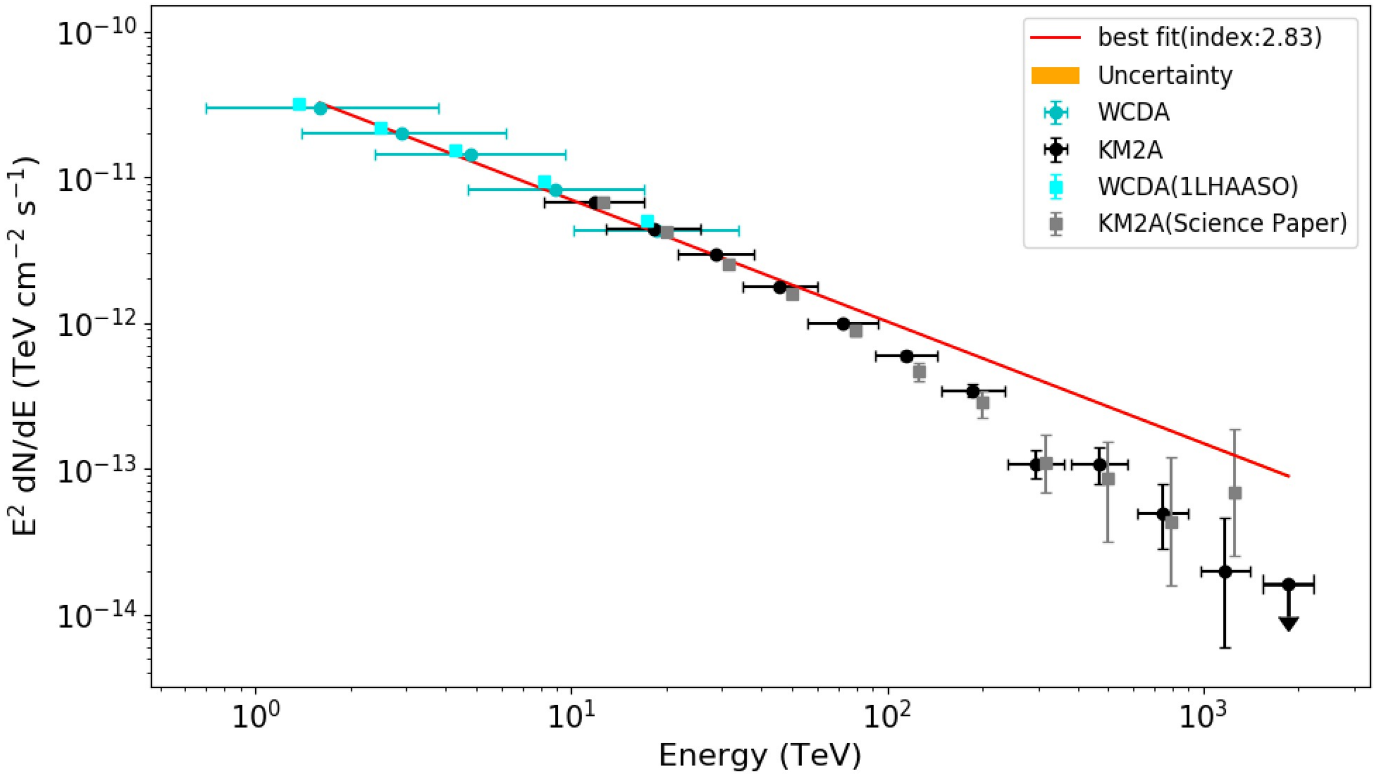
How to get spectral point?(gtsed)

Set src.yaml :

```
56 output_option:
57   gtsed:
58     sed_folder: J0534_sed
59     e_bin_set: [0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4]
```

```
gtsed src.yaml J0534+2200
```

Power-Law spectrum can not describe crab SED well!

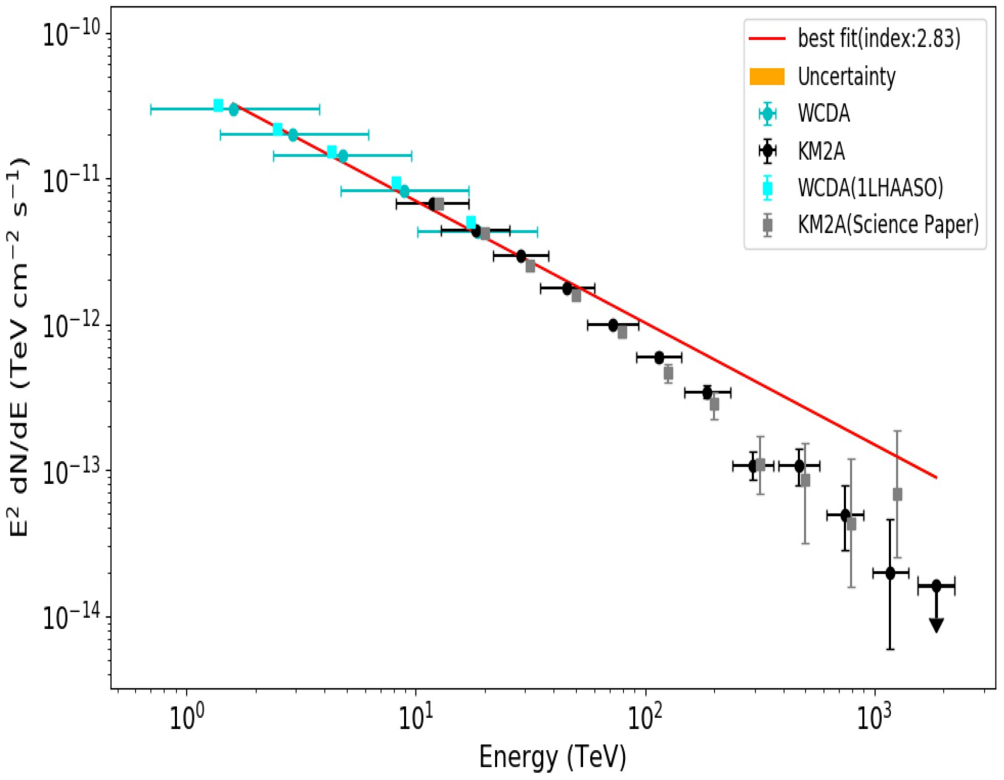


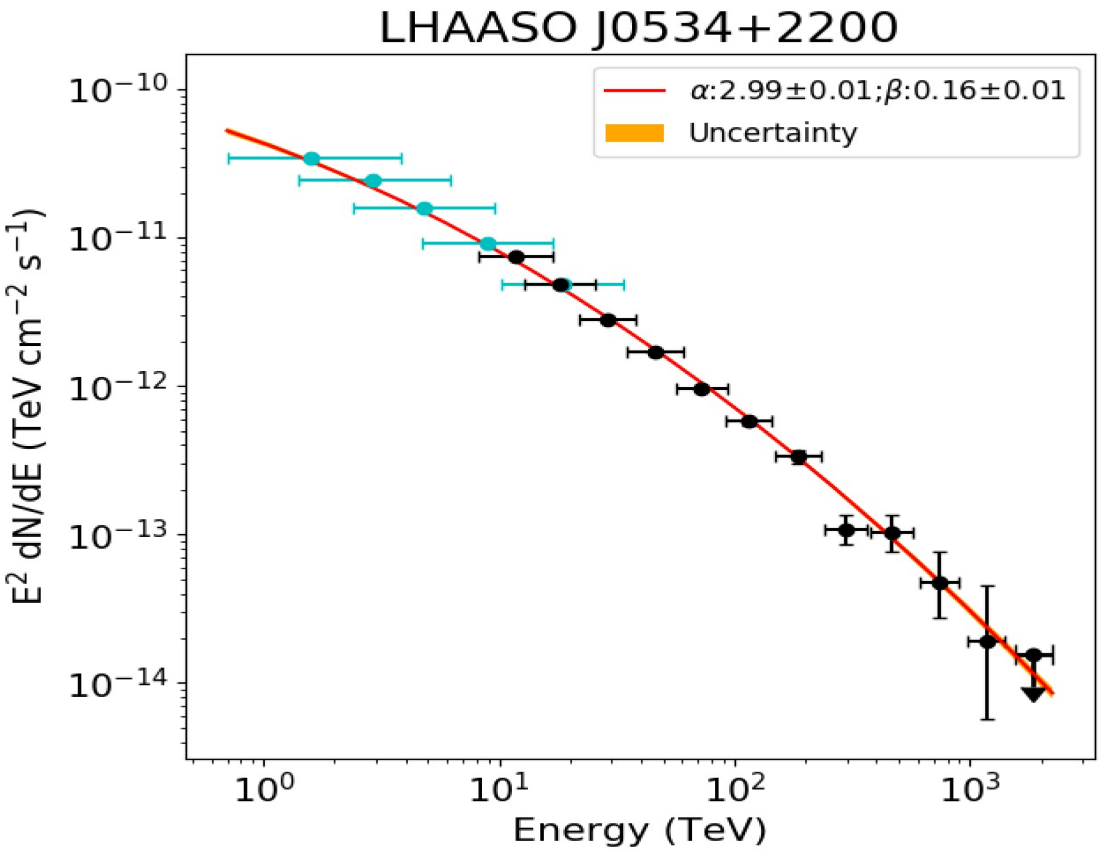
How to Change the SED model?

```
#Power Law SED model
    sed_model:
      sed_type: PL
      norm: [1.1613, 1e-5, 1e5, 1e-14]
      index: [3.0465, 1, 5]
      E_0: 20
#Log-Parabola SED model
    sed_model:
      sed_type: LP
      norm: [5.2373, -0.3041, 0.3030, 1e-15]
      index1: [2.0172, -0.1632, 0.1507]
      index2: [2.0149, -0.2659, 0.2878]
      E_0: 20
#Power Law expcutoff SED model
    sed_model:
      sed_type: PLC
      norm: [1, 0, 0, 1e-14]
      index: [3, 0, 0]
      E_b: [40.3,0,0]
      E_0: 20
```

```
#Broken Power Law SED model:
    sed_model:
      sed_type: BPL
      norm: [0.1707, 0.01937, 0.01937, 1e-17]
      index1: [2.1832, 0.17256, 0.17256]
      index2: [4.1925, 0.17096, 0.17096]
      E_b: [250.4132, 0, 0]
#IC CMB SED model： (Considering a EPLC electron spectrum)
    sed_model:
      sed_type: IC
      norm: [0.9988, 0.4645, 0.4645, 1e45]
      index: [2.8795, 0.0868, 0.0868]
      E_b: [3000, 218.0425, 218.0425]
      E_0: 1.0 ## TeV
      d_pc: 1000 ## pc
      t_ph: 2.7  ## CMB T (K)
      edens_ph: 0.25 ### CMB density (eV)
#Hadronic SED model： (Considering a EPLC proton spectrum)。
    sed_model:
      sed_type: PP
      norm: [3.1678, 2.1211, 2.1211, 1e46]
      index: [1.9932, 0.1157, 0.1157]
      E_b: [2138.3607, 769.6618, 769.6618]
      E_0: 1.0
      d_pc: 1000 ## pc
      n_H: 1  ## target H density (1/cm3)
```

Change Power-Law to Log-parabola model





Power-Law spectrum can not describe crab SED well!

Log-parabola SED model

How to get significance map(TS map)?

```
J0534+2200:
  sed_model:
    sed_type: PL
    norm: [0.9788, 0.0084, 0.0084, 1e-14]
    index: [2.8346, 0.0043, 0.0043]
    E_0: 20.0
  spatial_model:
    src_map: J0534+2200_srcmap.root
    spatial_type: ps
    ra: [83.6228, 0.0015, 0.0015]
    dec: [22.0152, 0.0014, 0.0014]
output_option:
  gtlike:
    Error_status: 3
    negative_loglike: -30370487.2
```

```
J0534+2200:
  sed_model:
    sed_type: PL
    norm: [0.9643, 0.0078, 0.0078, 1e-14]
    index: [2.8333, 0.0040, 0.0040]
    E_0: 20.0
  spatial_model:
    src_map: J0534+2200_srcmap.root
    spatial_type: ps
    ra: [83.7228, 0.0015, 0.0015]
    dec: [22.0152, 0.0014, 0.0014]
output_option:
  gtlike:
    Error_status: 3
    negative_loglike: -30368243.5
```

gtselect
gtsrcmap
gtlike

TS Map :

Create a grid of position, calculate the likelihood for a source in each position

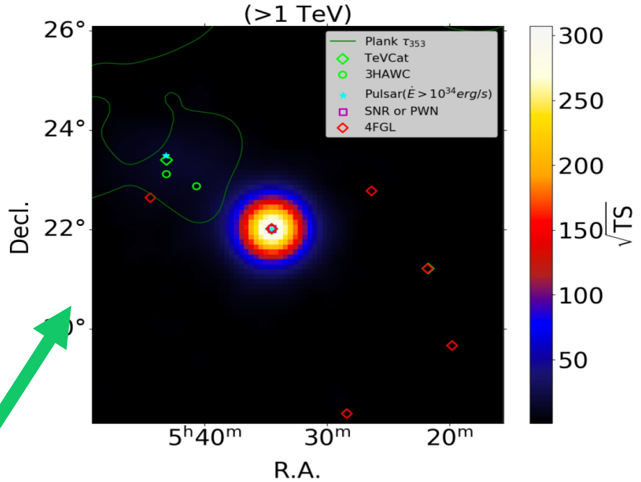
How to get significance map ?(gttsmap)

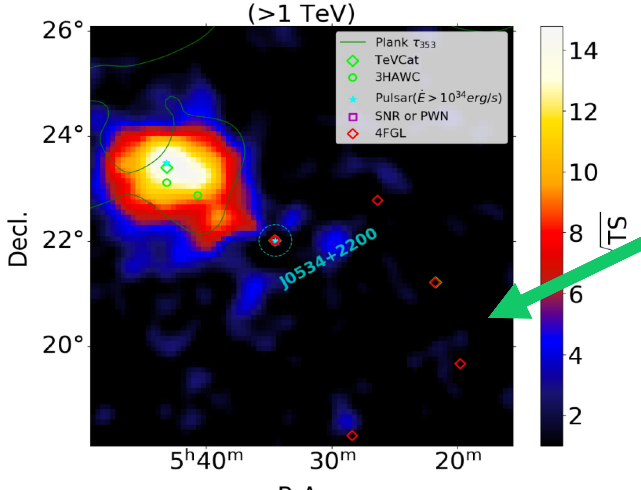
TS Map: in each position, we assume a source and calculated its TS value.

Set bg.yaml :

```
output_option:
  gtlike:
    Error_status: 1
    negative_loglike: -30322215.0
  gttsmap:
    tsmap_folder: bg_tsmap
    tsmap_x_range: [84, 78.9, 87.3]
    tsmap_y_range: [80, 18.1, 26.1]
```

gttsmap bg.yaml





Set src.yaml :

```
output_option:
  gtlike:
    Error_status: 3
    negative_loglike: -30370487.2
  gttsmap:
    tsmap_folder: src_tsmap
    tsmap_x_range: [84, 78.9, 87.3]
    tsmap_y_range: [80, 18.1, 26.1]
```

gttsmap src.yaml

How can I get its morphology?

```
#point-like spatial model
    spatial_model:
      src_map: crab_srcmap.root
      spatial_type: ps
      ra: [83.6205, 82.6, 84.6]
      dec: [22.0356, 21.03, 23.03]
#Gaussian spatial model
    spatial_model:
      src_map: J0542+2311_srcmap.root
      spatial_type: gaussian
      ra: [85.5090, 0.0874, 0.0874]
      dec: [23.0482, 0.0698, 0.0698]
      ext: [1.0699, 0.0612, 0.0612]
#Disk spatial model
    spatial_model:
      src_map: J0542+2311_srcmap.root
      spatial_type: disk
      ra: [85.5090, 0.0874, 0.0874]
      dec: [23.0482, 0.0698, 0.0698]
      ext: [1.0699, 0.0612, 0.0612]
```

```
#Halo-like spatial model
    spatial_model:
      src_map: J0542+2311_srcmap.root
      spatial_type: halo
      ra: [85.5090, 0.0874, 0.0874]
      dec: [23.0482, 0.0698, 0.0698]
      ext: [1.0699, 0.0612, 0.0612]
#Ellipse disk sptial model
    spatial_model:
      src_map: J0542+2311_srcmap.root
      spatial_type: ellipse_disk
      ra: [85.5090, 0.0874, 0.0874]
      dec: [23.0482, 0.0698, 0.0698]
      a_deg: [1.0699, 0.0612, 0.0612]
      b2a: [0.1, 0.0, 0.0]
      alpha: [30, 0.0, 0.0]
#Ellipse gaussian spatial model
    spatial_model:
      src_map: J0542+2311_srcmap.root
      spatial_type: ellipse_gaussian
      ra: [85.5090, 0.0874, 0.0874]
      dec: [23.0482, 0.0698, 0.0698]
      a_deg: [1.0699, 0.0612, 0.0612]
      2a: [0.1, 0.0, 0.0]
      alpha: [30, 0.0, 0.0]
```

```
#Rectangle spatial model
    spatial_model:
      src_map: J0206+4307_rec_srcmap.root
      spatial_type: rectangle
      ra: [31.6266, 0.0853, 0.0853]
      dec: [43.1250, 0.0003, 0.0003]
      a_deg: [2.4172, 0.0147, 0.0147]
      b2a: [0.0742, 0.0007, 0.0007]
      alpha: [14.1273, 0.0588, 0.0588]
#Other shape using a th2d expression
    spatial_model:
      src_map: file_bg_srcmap.root
      spatial_type: file_map
      template_h2d_name: file_th2d_name
      template_root_path: file_th2d.root
```

Eight Spatial Model

How to get the Light curve?(gtlc)

In the future: just change the path of all_sky_map.

```yaml
selection:
  all_sky_map: /home/lhaaso/xishaoqiang/LHAASO_Analysis/data/data_1LHAASO/data.root
  roi_map: roi_ccube.root
  roi_x_range: [84, 78.9, 87.3]
  roi_y_range: [80, 18.1, 26.1]
  roi_e_range: [17, 0.0, 3.4]
```

Sky map for every day is in preparing!

Connect with me or Pro. Chen.

Other tools

工具名	功能
gtselect	实验天图选择工具，实现对不同天区数据天图的选择；
gtsrcmap	模型天图计算工具，实现对不同模型假设预期天图的计算，包括效率估计以及 PSF 卷积等；
gtlike	最大释然估计工具，实现最大释然估计，确定模型参数最佳估计值以及误差等；
gttsmap	显著性天图生成工具，python 脚本；
gtsed	能谱图生成工具，python 脚本；
gtlc	光变曲线生成工具，python 脚本；
gtirfs	响应函数生成工具，实现位置追踪，统计模拟数据，计算响应函数；
fk52gal_sky	天图坐标转换；
root2fits.py	root TH2D 格式图转换到 fits 格式文件；
fits2root.py	Fits 格式文件转换到 root TH2D 格式；
gtobssim	泊松抽样，产生模拟的数据；
gttsmap_one	单线程显著性 map 生成工具，该工具被用于 gttsmap 内部调研；
optimize_eachsrc_sed	源能谱测试优化工具，主要实现对每个源能谱是否弯曲的检测；
optimize_eachsrc	源迭代优化工具，主要实现每个源参数的检测；
gtlikeProf	脚本文件产生某一个参数的 likelihood 轮廓图；
tune_yaml	改写 yaml 文件工具；
plot_map.py	画天图工具；
plot_sed.py	画 SED 工具；
get_new_fits.py	Fits 文件选择与转会工具；

Tool + ***.yaml or (key)

Make available the tools

You don't need to install it, but

1. You need to a IHEP serve account.

2. You just need to
   source /afs/ihep.ac.cn/users/x/xishaoqiang/.bashrc_everyone

3. A guide for analysis：
   https://jupyter.ihep.ac.cn/y_BDDe77RYuEL1jAW5kVBA/publish

Thank You!

Maximum likelihood Estimation (MLE)

- Parameters can be estimated by maximizing likelihood. Easier to work with log-likelihood:

$$\ln \mathcal{L}(\Theta) = \ln \mathcal{L}(\Theta|X) = \sum_i \ln P(x_i|\Theta)$$

- Estimates of $\{\hat{\theta}_k\}$ from solving simultaneous equations:

$$\left.\frac{\partial \ln \mathcal{L}}{\partial \theta_j}\right|_{\{\hat{\theta}_k\}} = 0$$

- For one parameter, if we have: $\mathcal{L}(\theta) \sim e^{-\frac{(\theta-\hat{\theta})^2}{2\sigma_\theta^2}}$

then: $\left.\frac{\partial^2 \ln \mathcal{L}}{\partial \theta^2}\right|_{\hat{\theta}} = -\frac{1}{\sigma_\theta^2}$

Gaussian approximation

so 2nd derivative is related to "errors"

For the Event Counting experiment

- Experiment detects *n* events (e.g. γ rays)
- Model: Poisson process with mean of of λ:

$$P(x|\theta) \to P(n|\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

- Log likelihood: $\ln \mathcal{L}(\lambda) = n \ln \lambda - \lambda - \ln n!$
- ML estimate and error in Gaussian regime:

$$\frac{\partial \ln \mathcal{L}}{\partial \lambda} = \frac{n}{\lambda} - 1 \implies \hat{\lambda} = n$$

$$\frac{1}{\sigma_\lambda^2} = - \left. \frac{\partial^2 \ln \mathcal{L}}{\partial \lambda^2} \right|_{\hat{\lambda}} = \frac{n}{\hat{\lambda}^2} \implies \sigma_\lambda^2 = n$$

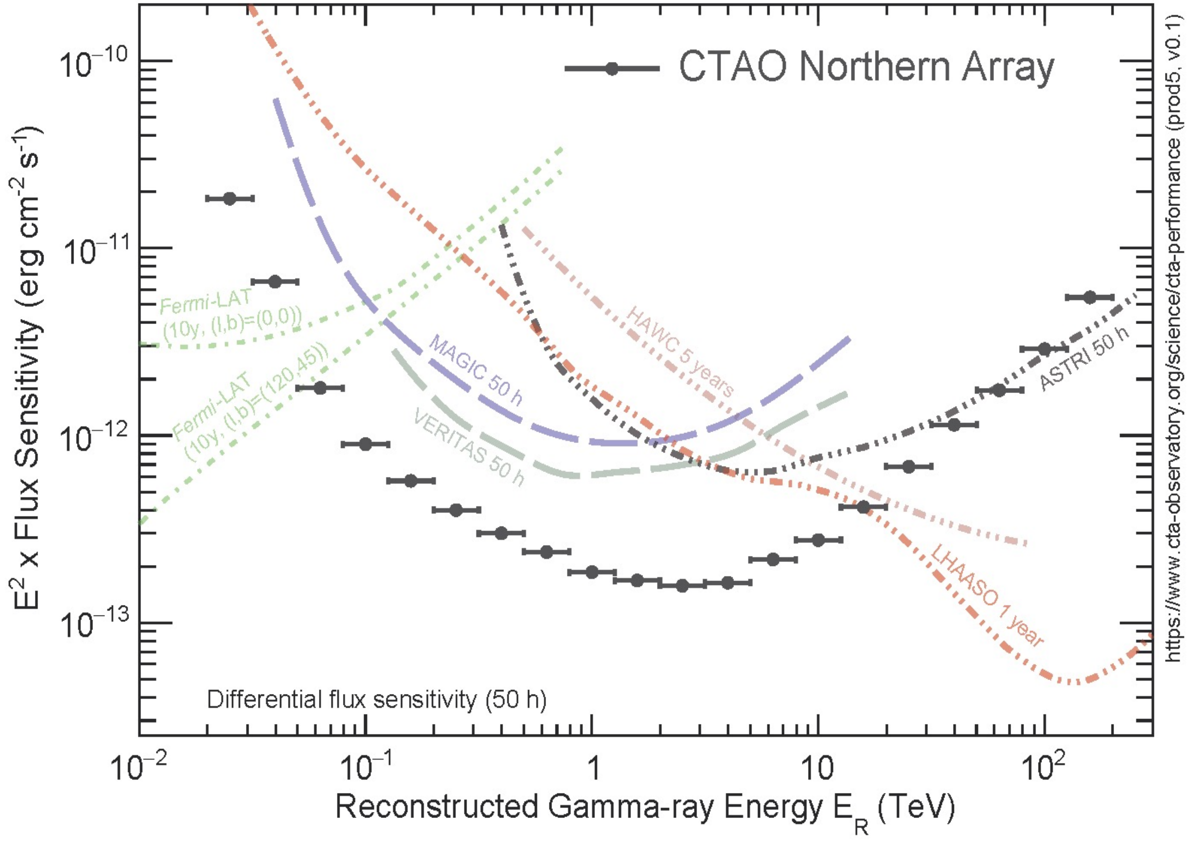
Gaussian approximation

LHAASO Performance

	Range	resolution
Spatial	FoV： 2 Sr Dec.: -20º to 80º	0.2º（100 TeV ，Crab-like）
Time	Data from 2019/12（Duty Cycle：～95%）	ns
Energy	0.5 TeV – a few PeV	14% （100 TeV, Crab-like）

- The Best 100 TeV (UHE) Gamma-ray Observatory !

BG refusion+ Area： sensitivity



LHAASO UHE Era!

LHAASO Highlight For Gamma-ray Source