LHAASO伽马源分析

Shicong Hu (胡世聪), IHEP

Yunnan university, Kunming

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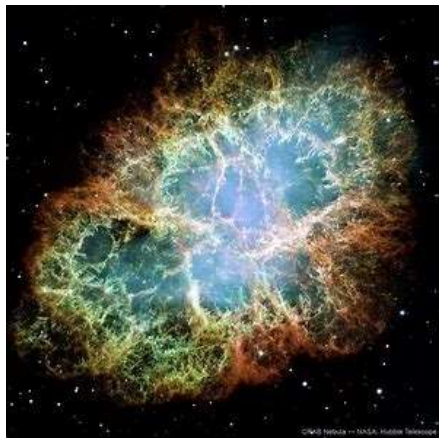
The observation process

Reality | **Observation** | **Data**



\+

Noise/background

$Flux(E, \vec{r}, t \mid \Theta)$
or
Photons

Convolution →
Instrument response
← **De-convolution**
+/-
background

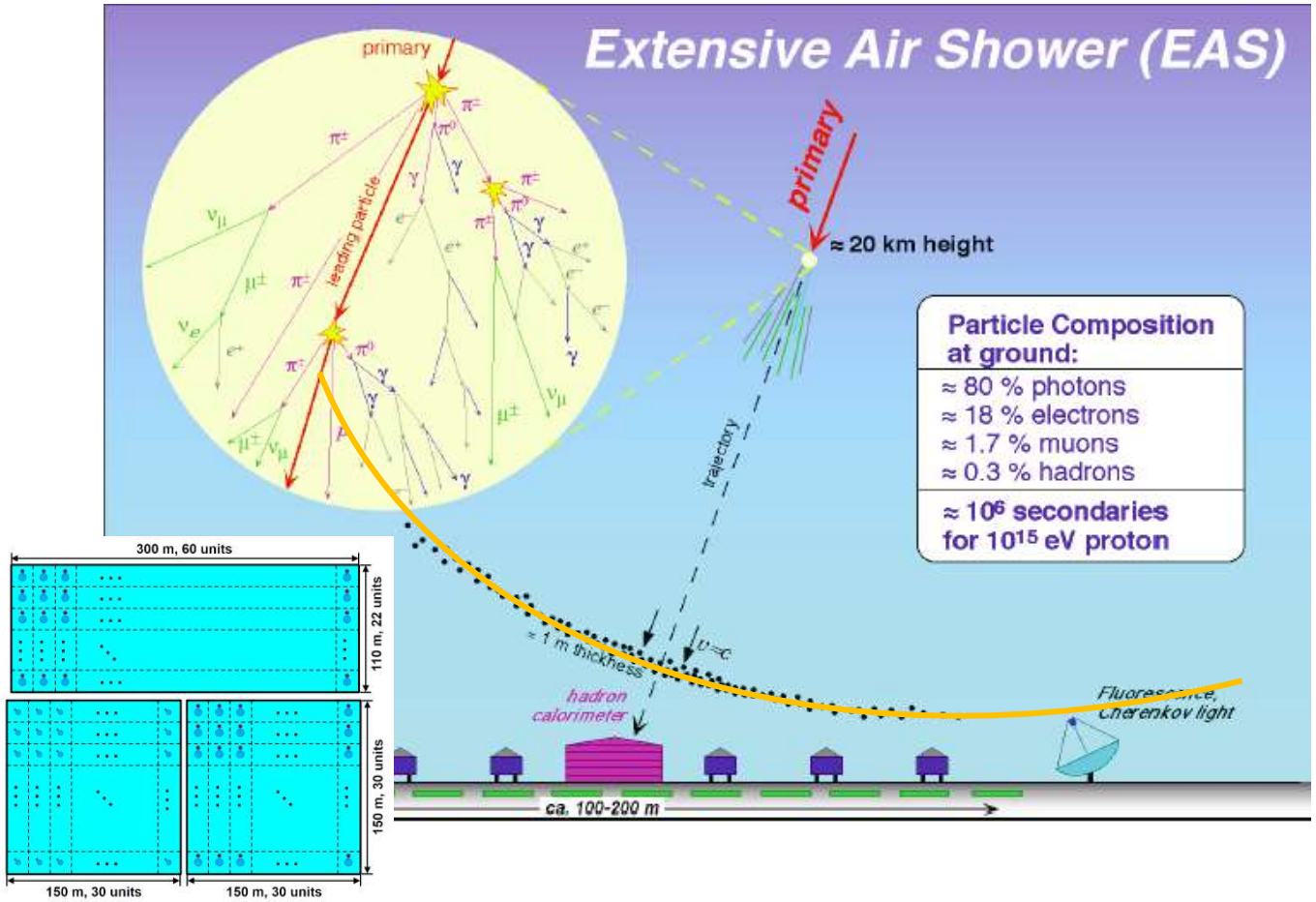
Images ...
or
Events

- **Data**
- **Response**
- **Method**
  - Analysis
  - Background estimation
  - Gamma/Proton
  - Reconstruction
  - Calibration
  - ...

- **Data and detector response**
- **Analysis Method**
- **Software: LA-Gamma**
  - Core function
  - Available models
  - Software frame
- **User guide**
  - User-defined config files

Data and detector response

➢ Event information



- Incident direction: (α, δ)
- Time: t / MJD
- Primary energy

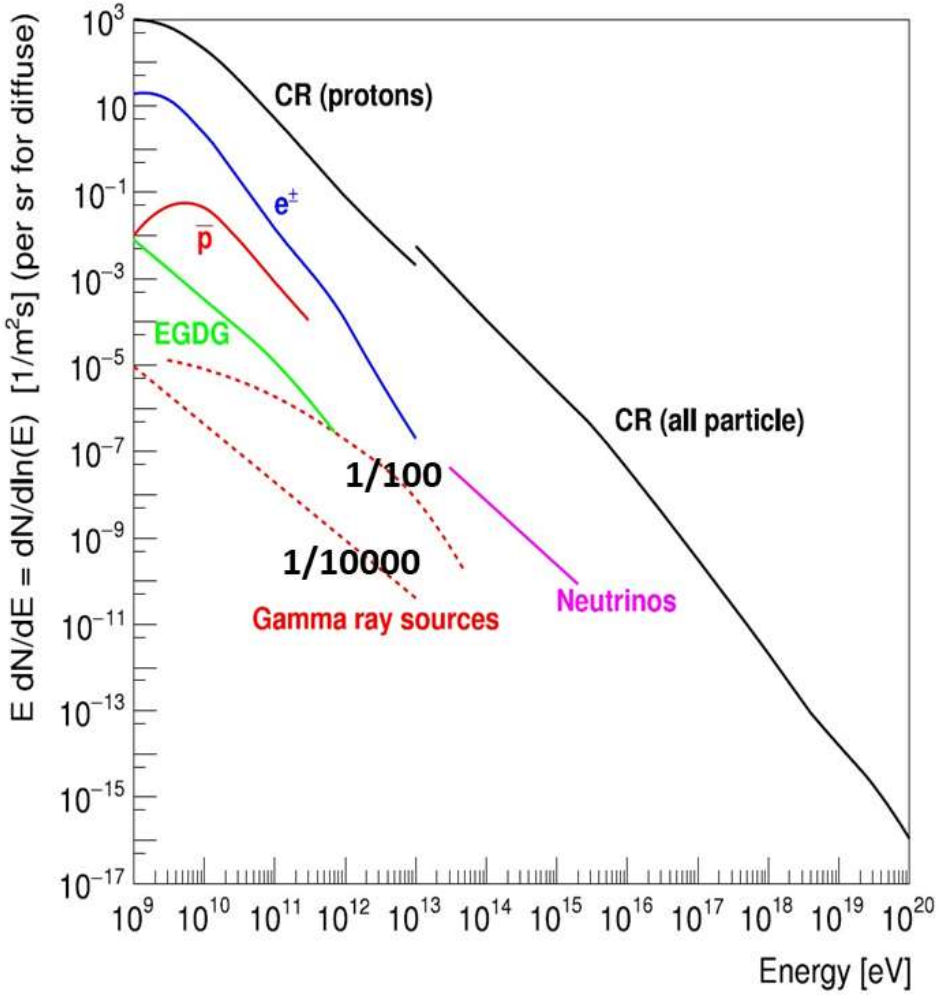
```
Double_t        mjd;            -->standard Modified Julian Day
Double_t        tlive;          -->live-time of this event rela
Float_t         theta;          -->zenith angle in rad in WCDA
Float_t         phi;            -->azimuth angle in rad in WCDA
                                   and ( phi=0 is east directon
                                       ( phi=180 is west direct
Float_t         ang0;           -->openning angle between fits
Float_t         edir;           -->error of fitting direction;
Float_t         ra;             -->RA in rad;
Float_t         dec;            -->DEC in rad;
Float_t         ccindex;        -->shower curvature index if us
Float_t         chi2;           -->Chi2 after curvature correct
Float_t         xc;                                position in m;
Float_t         yc;                                position in m;
Float_t         rmds;           -->Shower core radius with loop
Float_t         pincness;
Float_t         istationcore;
Float_t         dcedge;                            ance to the edg
Float_t         qall;
Float_t         qfit0;          -->Sum. of  Pes after noise fil
Float_t         qfit;           -->Sum. of Pes used in curvatur
Float_t         qmaxt30;        -->Max. PEs. within |DeltaT|<30
Float_t         xqmaxt30;       -->X position of qmaxt30;
Float_t         yqmaxt30;       -->Y position of qmaxt30;
Float_t         qcr15t30;       -->Q. Pes with distanance to c
```

Core position

Gamma/Proton

Core position

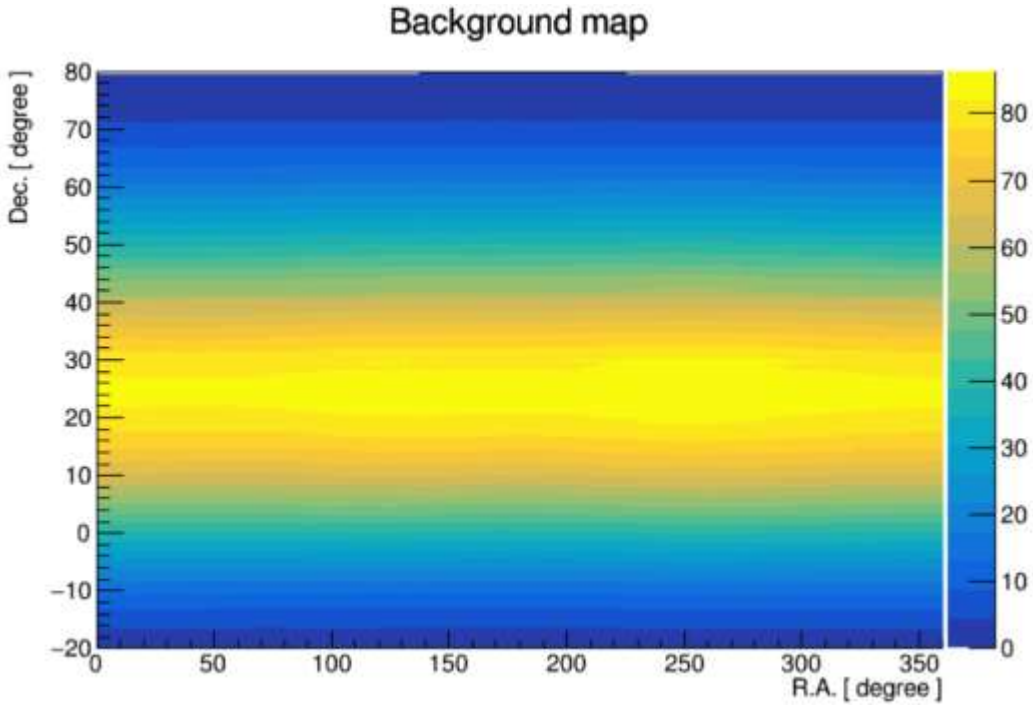
➢ Gamma/Proton



- S/B ratio for Crab-like sources
  - 1/100 -> ~1 @ <1TeV to >10@10TeV
  - Sensitivity: 1% Crab

↓

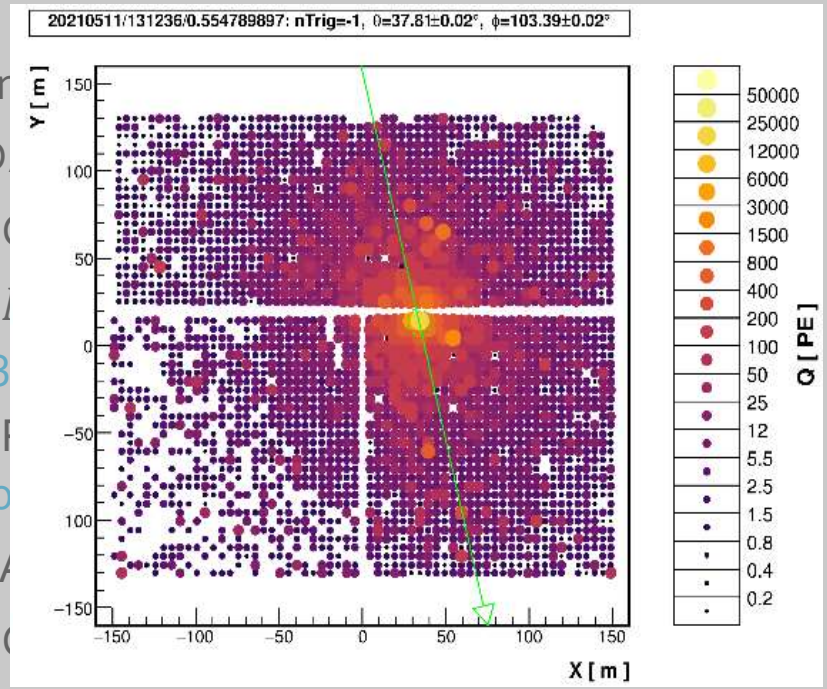
- Background estimation
  - Direct integral method



➢ Data binning

- ➢ Event information
  - -> **Primary energy**
  - Time: t / MJD
  - Incident direction: (α, δ)

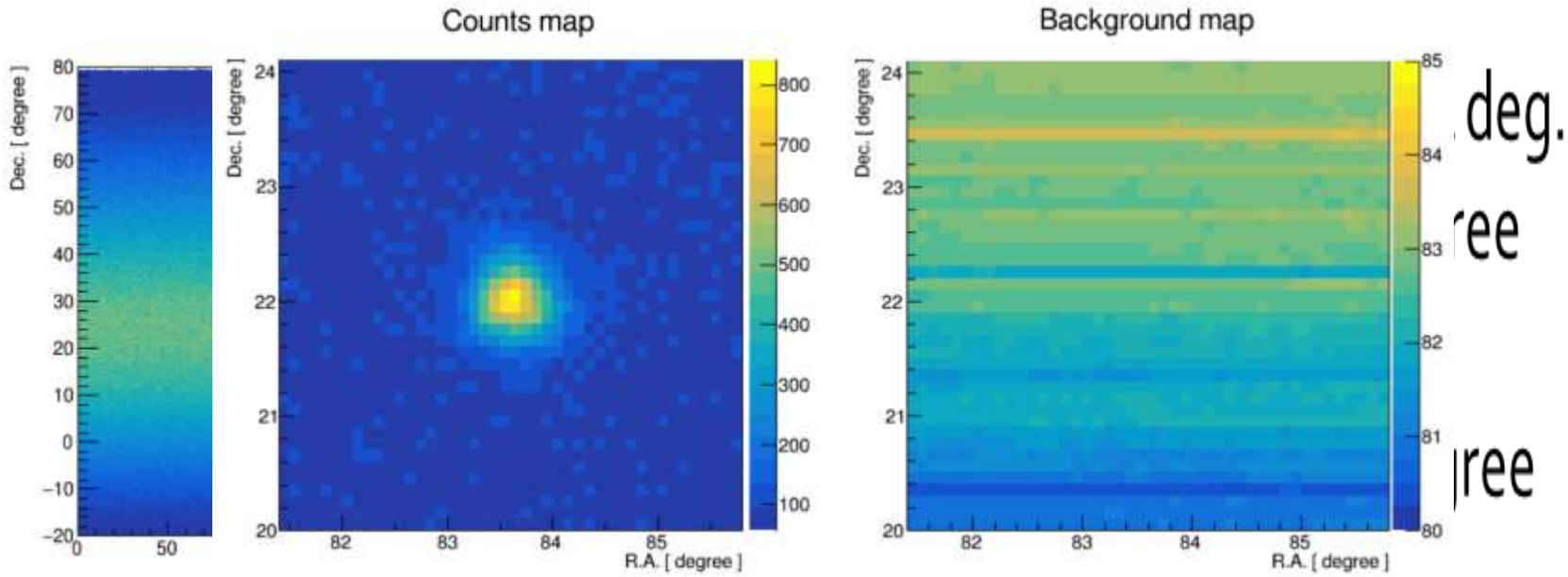
- Energy bin
  - WCD
    - (
    - E
      3
    - F
      0
  - KM2A
    - (
    - log10(E_{rec}/TeV) intervals
      0.6-3.4, step 0.2
    - Primary energy/TeV (Crab-like)
      5 - 2000



➢ Data binning

- ➢ Event selection
  - Zenith angle < 50°
  - Pincness
  - N_{hit} segments
- ➢ Event information
  - Primary energy
  - -> **Incident direction: (α, δ)**
  - Time: t / MJD

◘ Space binning → Counts map and background map



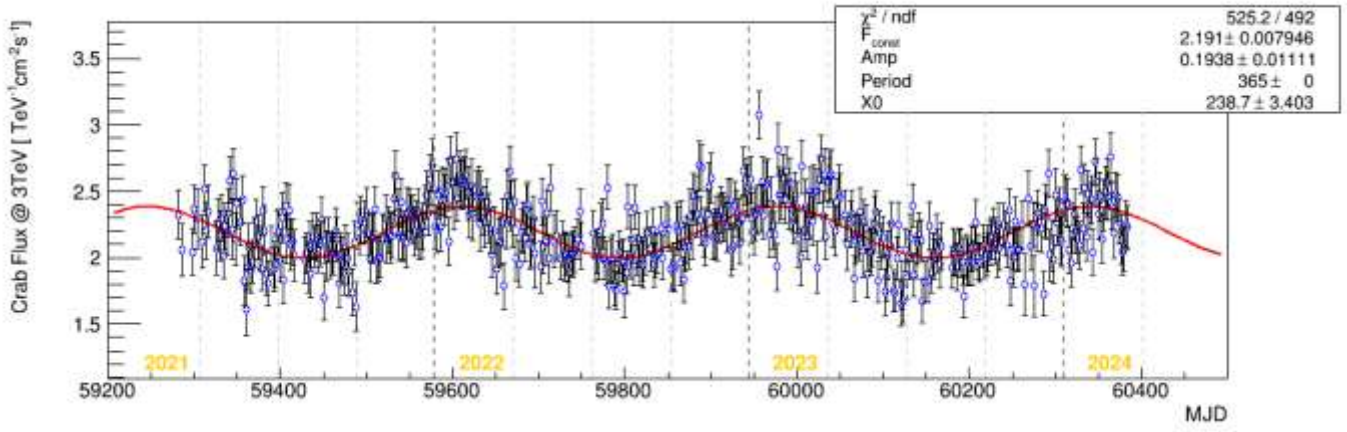
- Pixel size: 0.1 deg. × 0.1 deg.
- R.A. range: 0 – 360 degree
- Zenith angle < 50 deg.
- Dec. range: -20 – 80 degree

➢ Data binning

- Event information
  - Primary energy
  - Incident direction: (α, δ)

  -> **Time: t / MJD**

- Time interval
  - WCDA
    - 202103-202209 (1LHAASO catalog)
    - 202103-202307
    - 202103-202401
  - KM2A
    - 202107-202209 (1LHAASO catalog)
    - 202107-202307
    - 202107-202401



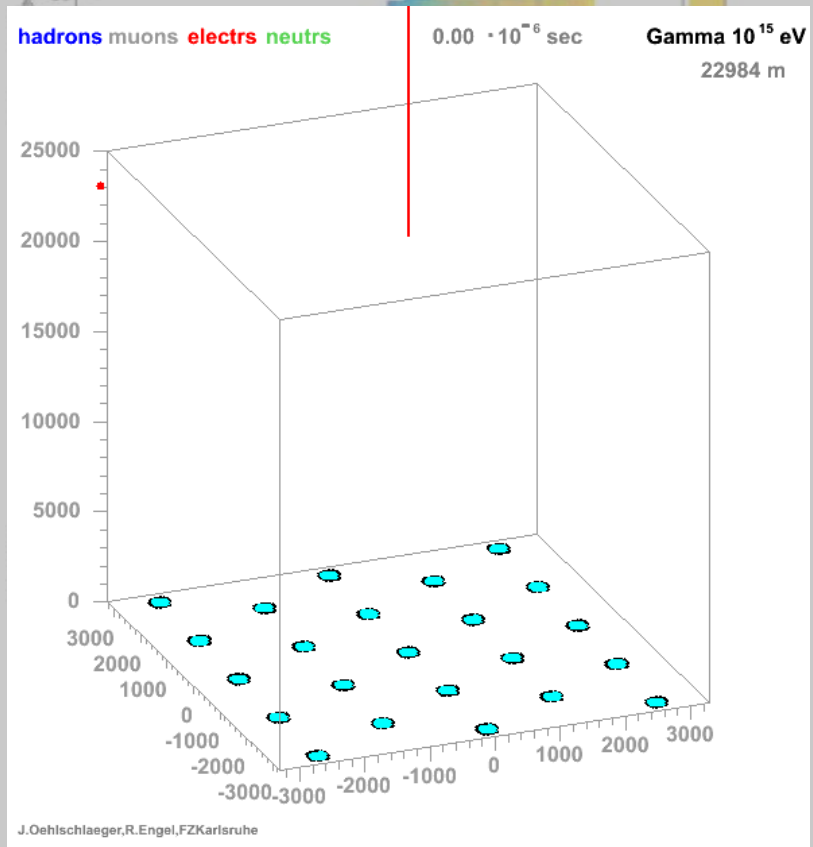
➢ Detector response

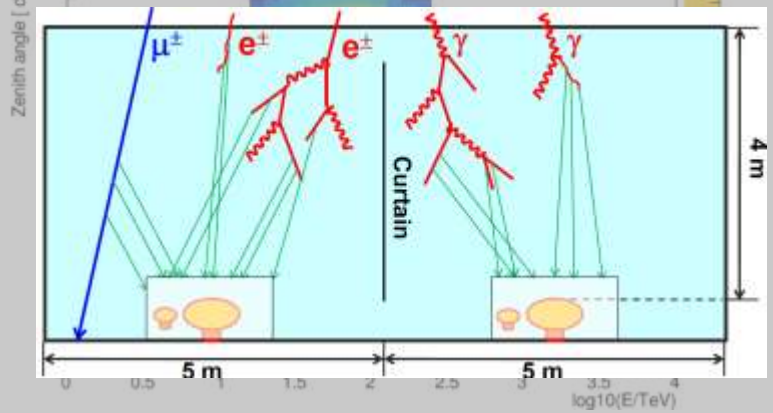
- Detection efficiency: $\eta(E_i, \theta_j)$
  - Energy and zenith angle
  - $\eta(E_i, \theta_j) = \frac{N_{\text{left}}(E_i,\theta_j)}{N_{\text{all}}(E_i,\theta_j)}$
- Point spread function (PSF)
  - WCDA
    - PSF(N^i_{hit})
  - KM2A
    - PSF(E^i_{rec}, δ_j)

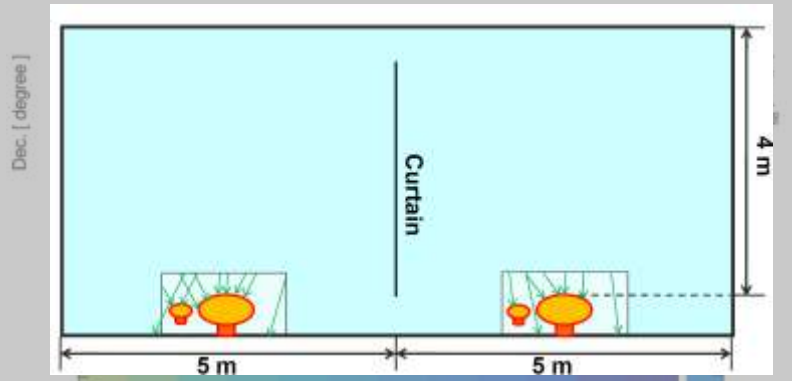
WCDA

KM2A

- Simulation: Corsika+Geant4







Analysis method

☐ Binned maximum likelihood

For *j*th pixel in regions of interest (ROI)

$$P(\boldsymbol{N_j};\lambda_j)=\frac{\lambda_j^{N_j}e^{-\lambda_j}}{N_j!},\lambda_j=\boldsymbol{b_j}+\sum_k\gamma_{jk}$$

in which b_j is the background events, γ_{jk} is the expected gamma ray events from the *k*th sources, the log likelihood is

$$\ln\mathcal{L}(\Theta|N)=\sum_j\left(N_j ln\lambda_j-\lambda_j\right),\Theta=(\Theta_{\mathrm{M}},\Theta_{\mathrm{S}})$$

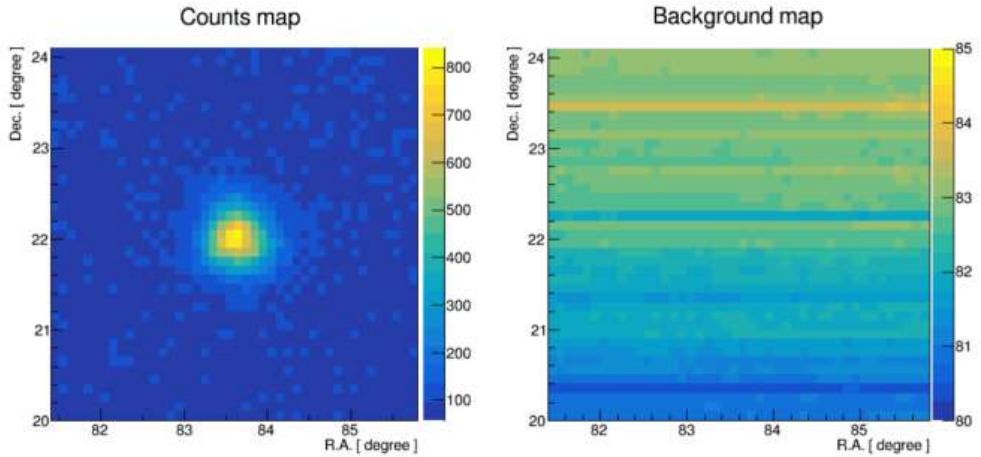
☐ Forward-folding

Assuming spectrum model of source $I_k(E)$, expected excess is

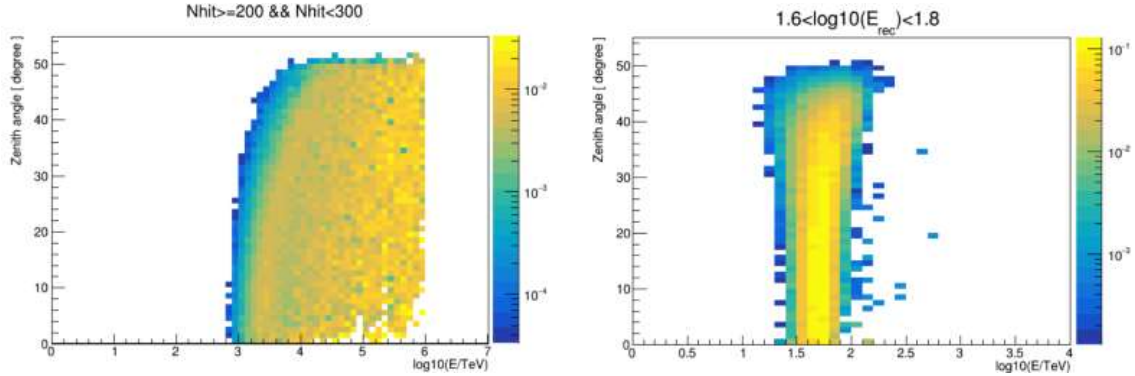
$$\gamma_k=\sum_n\sum_m\int_{\Delta E_j}I_k(E)\mathrm{d}E\times\boldsymbol{\eta(E_m,\theta_n)}\mathrm{S}_0\cos(\theta_n)\mathrm{T}_{\mathrm{obs}}f(\theta_n)$$

$$\gamma_{jk}=\gamma_k\otimes\boldsymbol{PSF}$$

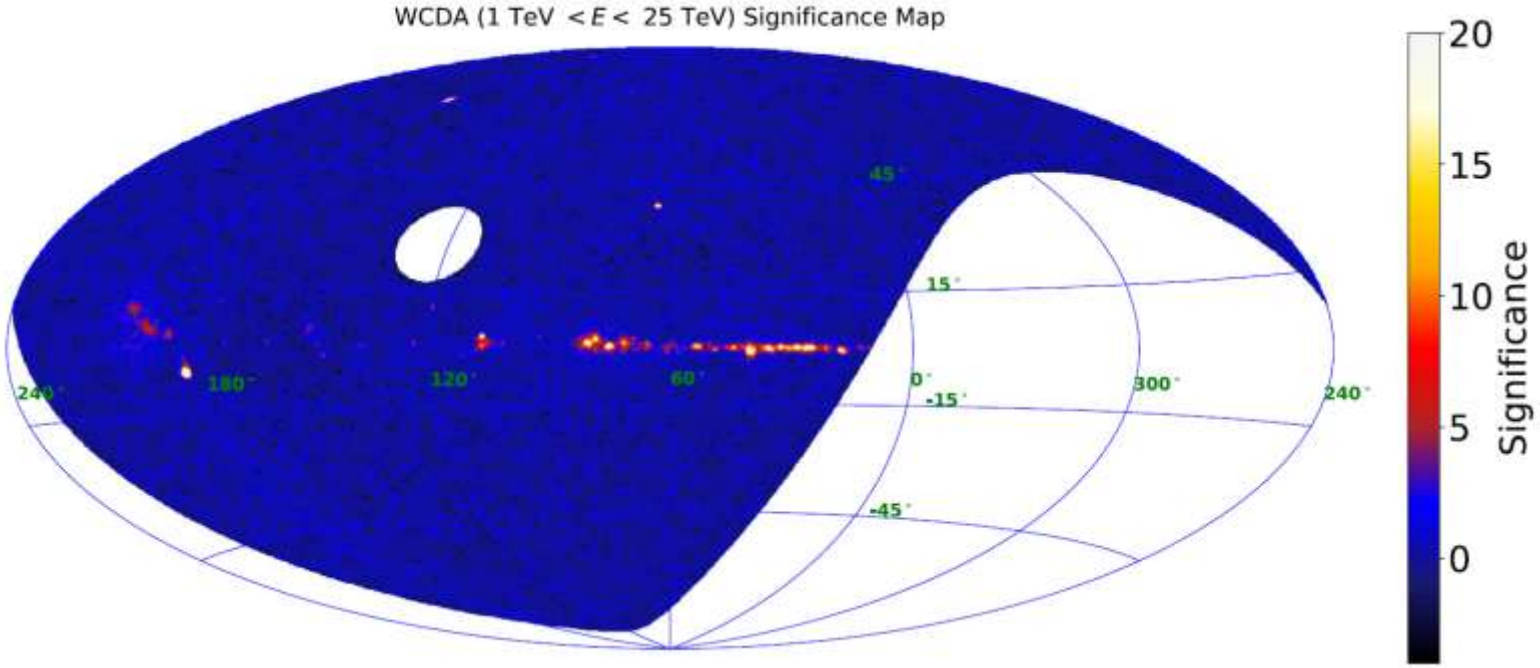
- **Data**: N_j & b_j



- **Response**: $\eta(E_m,\theta_n)$ & *PSF*



➢ Significance



$$S = \sqrt{2}\left\{N_{\text{on}}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\text{on}}}{N_{\text{on}}+N_{\text{off}}}\right)\right] + N_{\text{off}}\ln\left[(1+\alpha)\left(\frac{N_{\text{off}}}{N_{\text{on}}+N_{\text{off}}}\right)\right]\right\}^{1/2} \qquad S = \frac{N_{\text{s}}}{\sqrt{N_{\text{b}}}}$$

- S follows standard normal distribution
  - $S \geq 5\sigma, p < 2.86 \times 10^{-7}$ **Discovery**
  - $S \geq 3\sigma, p < 1.35 \times 10^{-3}$ Indication

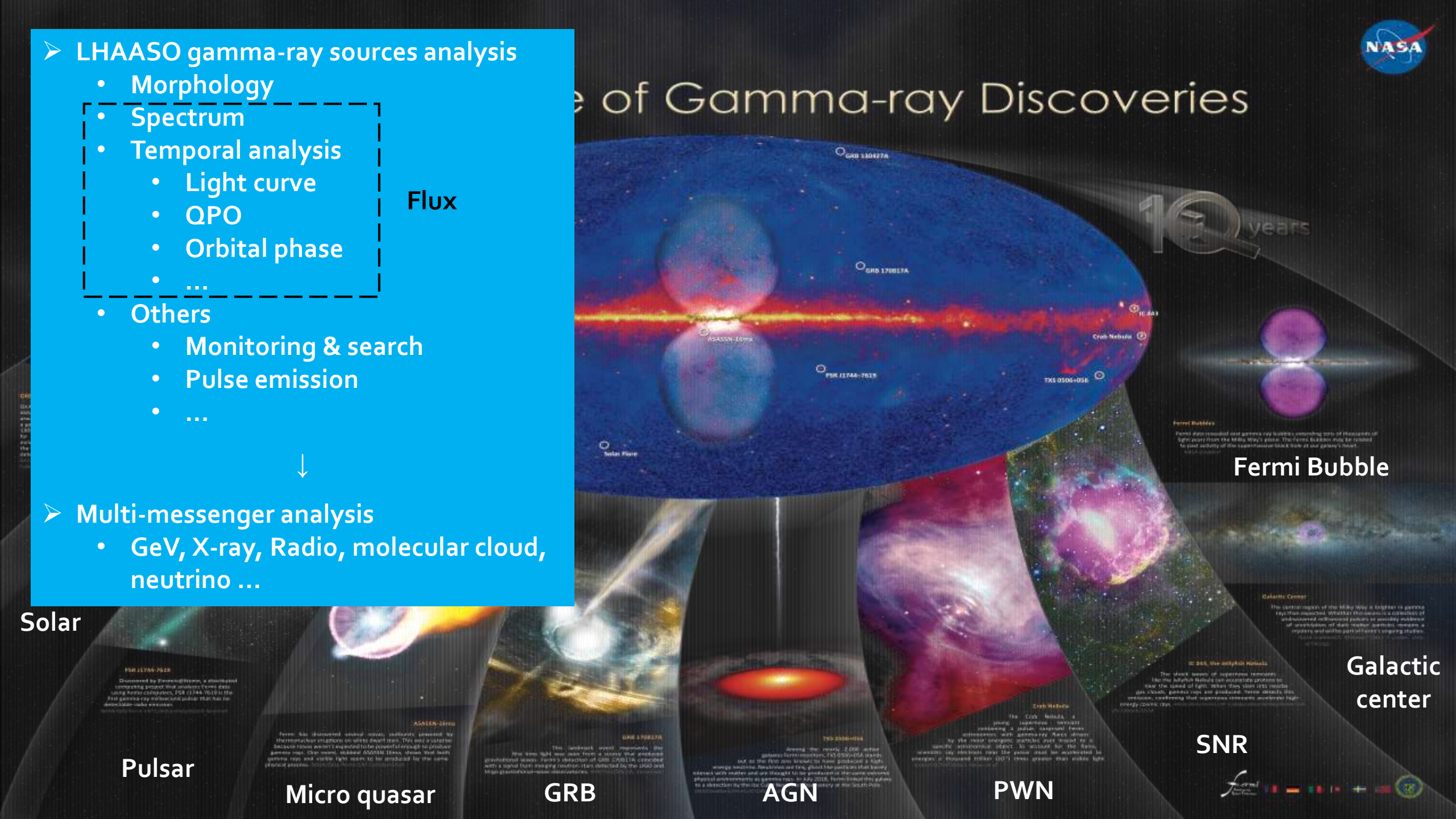
Q & A

- LHAASO gamma-ray sources analysis
  - Morphology
  - Spectrum
  - Temporal analysis
    - Light curve
    - QPO
    - Orbital phase
    - …

  Flux
  - Others
    - Monitoring & search
    - Pulse emission
    - …

↓

- Multi-messenger analysis
  - GeV, X-ray, Radio, molecular cloud, neutrino …

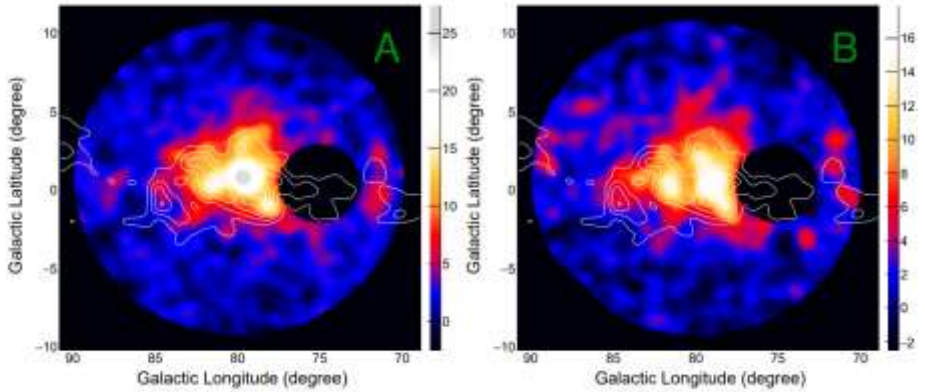


Software: LA-Gamma

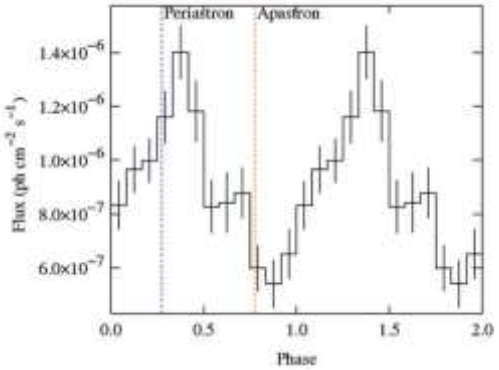
➢ Core function

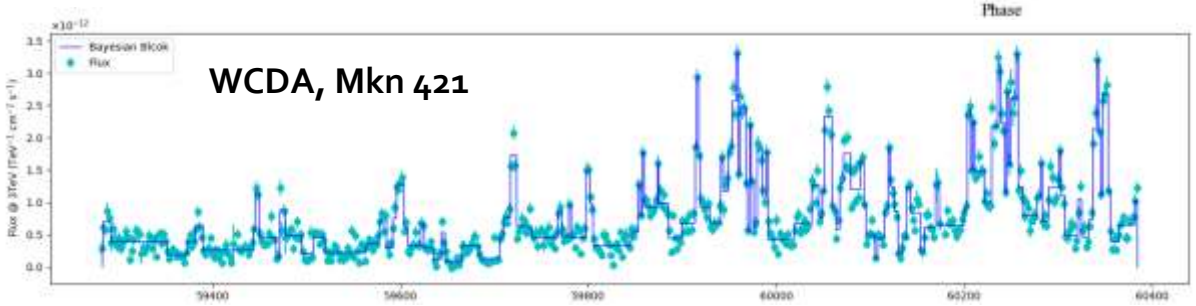
- Joint analysis: WCDA+KM2A
- Multiple sources or DGE components
- Results
  - ✓ Optimum values of SED and spatial parameters
  - ✓ Flux points or Flux upper limits
  - ✓ Morphology map
  - ✓ ……

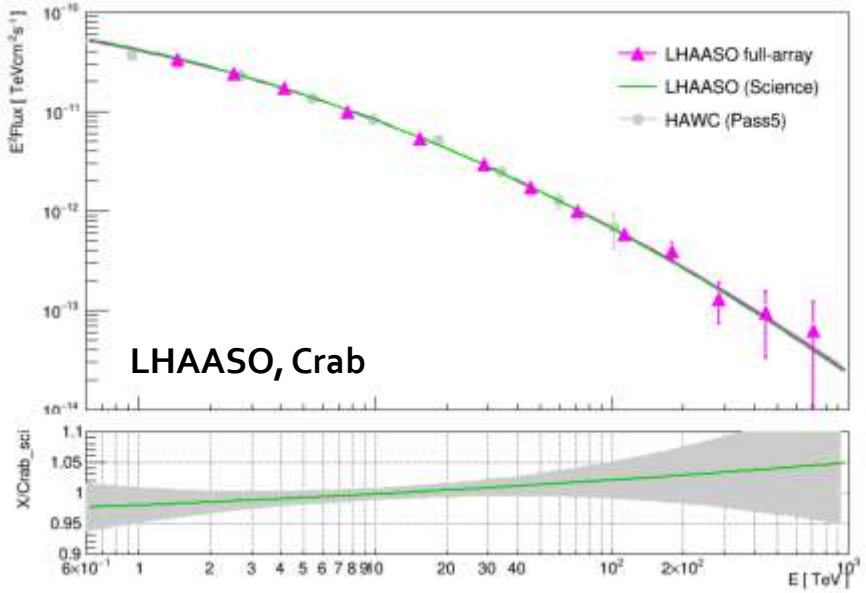
LHAASO, cygnus bubble



Fermi, LS I +61303







➢ Available models

- Spectrum
  - ✓ Log-parabola
  - ✓ Smoothly broken power-law
  - ✓ ……
  - ✓ 6 models in total available **currently**
- Spatial
  - ✓ Disk extension
  - ✓ Diffuse model
  - ✓ ……
  - ✓ 10 models in total available **currently**

✓ **Users can add their own models**

– add models in the format in the config file

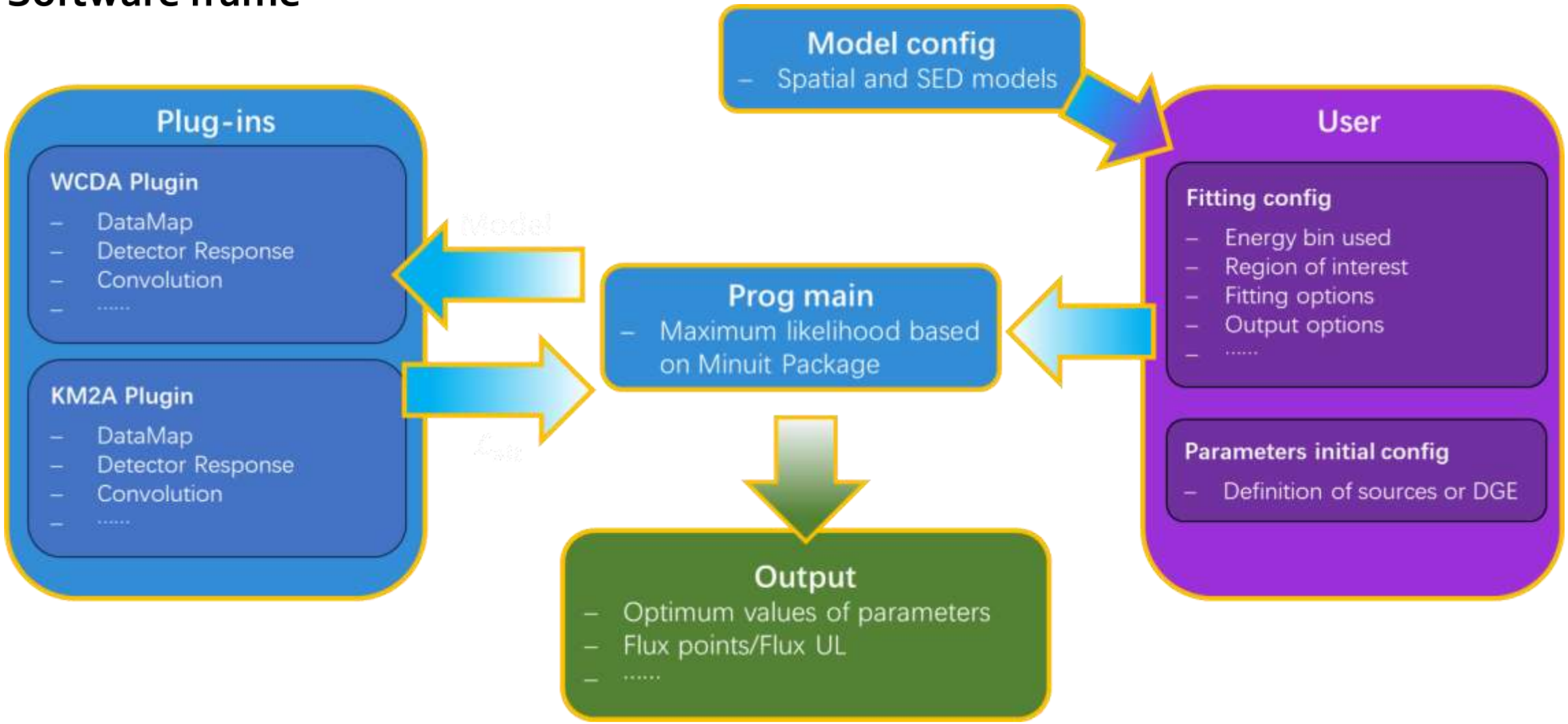
Morphology model

模型描述	程序中的tag	说明
点源	Point	
对称高斯（解析卷积）	Ext_gaus	
对称高斯（数值卷积）	Ext_Gaus	
椭高斯	Ext_EGaus	参数Theta为长轴与ra正向的夹角
均匀盘	Ext_Disk	
扩散模型	Ext_Diff	取自arXiv:2106.09396
任意固定模板	Ext_Temp	
均匀环	Ext_Ring	
壳模型	Ext_Shell	
均匀扇形	Ext_HDisk	

Spectrum model

模型描述	程序中的tag	公式
幂律谱	PL	$F = F_0\left(\frac{E}{E_{piv}}\right)^{-\alpha}$
对数抛物线	LP	$F = F_0\left(\frac{E}{E_{piv}}\right)^{-\alpha-\beta\log\frac{E}{E_{piv}}}$
带指数截断的幂律谱	PEC	$F = F_0\left(\frac{E}{E_{piv}}\right)^{-\alpha}\exp^{-\frac{E}{E_{cut}}}$
慢指数截断的幂律谱	PSEC	$F = F_0\left(\frac{E}{E_{piv}}\right)^{-\alpha}\exp^{-\sqrt{\frac{E}{E_{cut}}}}$
尖锐拐折的双幂律谱	BPL	$F = F_0\left(\frac{E}{E_b}\right)^{-\alpha_1}(E \le E_b)$ $= \left(\frac{E}{E_b}\right)^{-\alpha_2}(E > E_b)$
平滑拐折的双幂律谱	SBPL	$F = F_0\left(\frac{E}{E_b}\right)^{-\alpha_1}\left\{\frac{1}{2}\left[1+\left(\frac{E}{E_b}\right)^{\frac{1}{\beta}}\right]\right\}^{(\alpha_1-\alpha_2)\beta}$

➢ Software frame



➢ Fit.yaml

```
WorkDir: /home/lhaaso/hushicong/Standard_prog_lib/Source
DataConfig:
  WCDA: config/Data/WCDA/Mk/Data_20210305_20230731.yaml
  KM2A: config/Data/KM2A/Data_20210720_20230731.yaml
CorOpt: 0
DataUsed:
  SmoothBkg: 1
  WCDA:
    Active: 1
    NbinUsed: [1, 5]
    ReBin:
      Active: 0
      Rebin: [2, 2, 1]
  KM2A:
    Active: 1
    NbinUsed: [1.4, 3.0]
ROI:
  ROIfile: none
  Inlcude: [0, 0, 83.63, 22.02, 4, 6]
  Exclude:
    Active: 0
    Region: [0, 80.63, 22.02, 1, 1]

Fit:
  Fitting: 1
  FluxPoint: 1
  TS_Src: 0
  TS_Bin: 1
  FluxUL: 1

TSmap:
  Active: 0
  WCDA: [0, 1, 5]
  KM2A: [0, 1.4, 3.0]
  SrcID: 0
  JOBScript: JOB_TS_Crab_Src0.sh

Output:
  DrawOpt: 1
  Outdir: Results/Crab
  fParResu: ParRes.yaml
  fConExcess: ConExcess.root
```

- Change the name of Data config to select DataMap of a period
- Available data sample
  - WCDA
    - 20210305-20220930 (1LHAASO catalog)
    - 20210305-20230731
    - 20210305-20240131
  - KM2A
    - 20210720-20220930 (1LHAASO catalog)
    - 20210720-20230731
    - 20210720-20240131

➢ Fit.yaml

```yaml
WorkDir: /home/lhaaso/hushicong/Standard_prog_lib/Source_
DataConfig:
  WCDA: config/Data/WCDA/Mk/Data_20210305_20230731.yaml
  KM2A: config/Data/KM2A/Data_20210720_20230731.yaml
CorOpt: 0
DataUsed:
  SmoothBkg: 1
  WCDA:
    Active: 1
    NbinUsed: [1, 5]
    ReBin:
      Active: 0
      Rebin: [2, 2, 1]
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Fit:
  Fitting: 1
  FluxPoint: 1
  TS_Src: 0
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TSmap:
  Active: 0
  WCDA: [0, 1, 5]
  KM2A: [0, 1.4, 3.0]
  SrcID: 0
  JOBScript: JOB_TS_Crab_Src0.sh

Output:
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  fParResu: ParRes.yaml
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```

- Selection of energy range
  - WCDA
    - Active: use or not use WCDA data
    - NbinUsed: select N_{hit} intervals to use
    - id of N_{hit} segments: 0 - 6
  - KM2A
    - $\log_{10}(E_{\mathrm{rec}})$: 0.6 - 3.2

➢ Fit.yaml

```yaml
WorkDir: /home/lhaaso/hushicong/Standard_prog_lib/Source_
DataConfig:
  WCDA: config/Data/WCDA/Mk/Data_20210305_20230731.yaml
  KM2A: config/Data/KM2A/Data_20210720_20230731.yaml
CorOpt: 0
DataUsed:
  SmoothBkg: 1
  WCDA:
    Active: 1
    NbinUsed: [1, 5]
    ReBin:
      Active: 0
      Rebin: [2, 2, 1]
  KM2A:
    Active: 1
    NbinUsed: [1.4, 3.0]
ROI:
  ROIfile: none
  Inlcude: [0, 0, 83.63, 22.02, 4, 6]
  Exclude:
    Active: 0
    Region: [0, 80.63, 22.02, 1, 1]

Fit:
  Fitting: 1
  FluxPoint: 1
  TS_Src: 0
  TS_Bin: 1
  FluxUL: 1

TSmap:
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  KM2A: [0, 1.4, 3.0]
  SrcID: 0
  JOBScript: JOB_TS_Crab_Src0.sh

Output:
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```

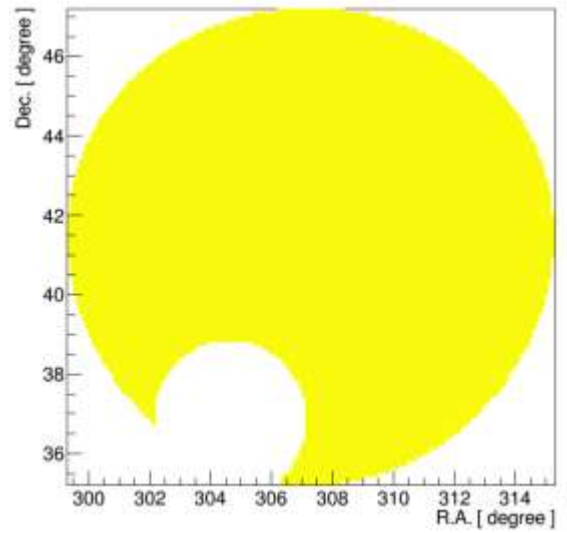

- Region of interest
  - Include
    - 1 Coordinate option
    - 2 Shape option: round or square
    - 3,4 Center of round region
    - 5 Radius of round region
  - Exclude
    - 1 Shape option: round or square
    - 2,3 Center of round region
    - 4 Radius of round region

➢ Fit.yaml

```
WorkDir: /home/lhaaso/hushicong/Standard_prog_lib/Source_
DataConfig:
  WCDA: config/Data/WCDA/Mk/Data_20210305_20230731.yaml
  KM2A: config/Data/KM2A/Data_20210720_20230731.yaml
CorOpt: 0
DataUsed:
  SmoothBkg: 1
  WCDA:
    Active: 1
    NbinUsed: [1, 5]
    ReBin:
      Active: 0
      Rebin: [2, 2, 1]
  KM2A:
    Active: 1
    NbinUsed: [1.4, 3.0]
ROI:
  ROIfile: none
  Inlcude: [0, 0, 83.63, 22.02, 4, 6]
  Exclude:
    Active: 0
    Region: [0, 80.63, 22.02, 1, 1]

Fit:
  Fitting: 1
  FluxPoint: 1
  TS_Src: 0
  TS_Bin: 1
  FluxUL: 1

TSmap:
  Active: 0
  WCDA: [0, 1, 5]
  KM2A: [0, 1.4, 3.0]
  SrcID: 0
  JOBScript: JOB_TS_Crab_Src0.sh

Output:
  DrawOpt: 1
  Outdir: Results/Crab
  fParResu: ParRes.yaml
  fConExcess: ConExcess.root
```

- Fitting options
  - Fitting: fit optimum values of SED and morphology parameters
  - FluxPoint
  - TS_Src: fit TS of each component
  - TS_Bin: fit TS of each bin for each source
  - FluxUL: fit upper limits of flux

➢ Fit.yaml

```yaml
WorkDir: /home/lhaaso/hushicong/Standard_prog_lib/Source_
DataConfig:
  WCDA: config/Data/WCDA/Mk/Data_20210305_20230731.yaml
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CorOpt: 0
DataUsed:
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Fit:
  Fitting: 1
  FluxPoint: 1
  TS_Src: 0
  TS_Bin: 1
  FluxUL: 1

TSmap:
  Active: 0
  WCDA: [0, 1, 5]
  KM2A: [0, 1.4, 3.0]
  SrcID: 0
  JOBScript: JOB_TS_Crab_Src0.sh

Output:
  DrawOpt: 1
  Outdir: Results/Crab
  fParResu: ParRes.yaml
  fConExcess: ConExcess.root
```

- Output options
  - Draw morphology map of each source
  - fParResu: output the optimum values of the parameters to the specified file
  - fConExcess: output expected excess map to the specified file

➢ ParInit.yaml

```
DGE:
    Active: 0
    ConvoPSF: 1
    Template0:
        Name: dust
        Tempfile: /home/lhaaso/hushicong/Standard_prog_li
        TempHist: [hTemp_ana]
        Epiv: 10
        SEDModel:
            type: LP
            F0: [5, 0, 500, 0, 1.e-14]
            alpha: [2.6, 2.0, 3.0, 0]
            beta: [0.1, 0, 1.0, 0]
SRC:
    UseCatalog: 0
    Active: 1
    Epiv: 3
    ParStatus:
        Position: 0
        F0: 0
        Index: 0
        MorPar: 0
    Src0:
        Name: Crab
        Epiv: 3
        SEDModel:
            type: LP
            F0: [2.3, 0, 50, 0, 1.e-12]
            alpha: [2.9, 2.0, 4.0, 0]
            beta: [0.08237, 0.0, 0.3, 0]
        MorModel:
            type: Ext_gaus
            ra: [83.62180, 79.63, 87.63, 0]
            dec: [22.01300, 18.02, 26.02, 0]
            sigma: [0.00858, 0, 0.2, 0]
    Src1:
        Name: Halo
        Epiv: 3
        SEDModel:
            type: PL
            F0: [0.26, 0, 50, 0, 1.e-12]
            alpha: [2.13, 1.0, 4.0, 0]
            #Ecut: [28.78537, 5, 200, 0]
        MorModel:
            type: Ext_gaus
            ra: [85.63468, 81.85, 89.85, 0]
            dec: [23.14186, 19.21, 27.21, 0]
            sigma: [1.25290, 0.5, 6.0, 0]
```

- Definition of DGE component
  - Active: add or not add DGE component
  - Template0: the first DGE component
    - Epiv: pivot energy, Eo in spectrum formula
    - SEDModel
      - Type: tag of SED model in model config file
      - Fo: initial value, limit range, fix option and order
  - Template1
  - …

➢ ParInit.yaml

```
DGE:
    Active: 0
    ConvoPSF: 1
    Template0:
        Name: dust
        Tempfile: /home/lhaaso/hushicong/Standard_prog_li
        TempHist: [hTemp_ana]
        Epiv: 10
        SEDModel:
            type: LP
            F0: [5, 0, 500, 0, 1.e-14]
            alpha: [2.6, 2.0, 3.0, 0]
            beta: [0.1, 0, 1.0, 0]

SRC:
    UseCatalog: 0
    Epiv: 3
    ParStatus:
        Position: 0
        F0: 0
        Index: 0
        MorPar: 0
    Src0:
        Name: Crab
        Epiv: 3
        SEDModel:
            type: LP
            F0: [2.3, 0, 50, 0, 1.e-12]
            alpha: [2.9, 2.0, 4.0, 0]
            beta: [0.08237, 0.0, 0.3, 0]
        MorModel:
            type: Ext_gaus
            ra: [83.62180, 79.63, 87.63, 0]
            dec: [22.01300, 18.02, 26.02, 0]
            sigma: [0.00858, 0, 0.2, 0]
    Src1:
        Name: Halo
        Epiv: 3
        SEDModel:
            type: PL
            F0: [0.26, 0, 50, 0, 1.e-12]
            alpha: [2.13, 1.0, 4.0, 0]
            #Ecut: [28.78537, 5, 200, 0]
        MorModel:
            type: Ext_gaus
            ra: [85.63468, 81.85, 89.85, 0]
            dec: [23.14186, 19.21, 27.21, 0]
            sigma: [1.25290, 0.5, 6.0, 0]
```

- Global definition of sources
  - Epiv: if >o, then Epiv of all sources will be set to this value
  - ParStatus
    - Fix corresponding parameters of all sources

➢ ParInit.yaml

```
DGE:
    Active: 0
    ConvoPSF: 1
    Template0:
        Name: dust
        Tempfile: /home/lhaaso/hushicong/Standard_prog_li
        TempHist: [hTemp_ana]
        Epiv: 10
        SEDModel:
            type: LP
            F0: [5, 0, 500, 0, 1.e-14]
            alpha: [2.6, 2.0, 3.0, 0]
            beta: [0.1, 0, 1.0, 0]

SRC:
    UseCatalog: 0
    Active: 1
    Epiv: 3
    ParStatus:
        Position: 0
        F0: 0
        Index: 0
    Src0:
        Name: Crab
        Epiv: 3
        SEDModel:
            type: LP
            F0: [2.3, 0, 50, 0, 1.e-12]
            alpha: [2.9, 2.0, 4.0, 0]
            beta: [0.08237, 0.0, 0.3, 0]
        MorModel:
            type: Ext_gaus
            ra: [83.62180, 79.63, 87.63, 0]
            dec: [22.01300, 18.02, 26.02, 0]
            sigma: [0.00858, 0, 0.2, 0]
    Src1:
        Name: Halo
        Epiv: 3
        SEDModel:
            type: PL
            F0: [0.26, 0, 50, 0, 1.e-12]
            alpha: [2.13, 1.0, 4.0, 0]
            #Ecut: [28.78537, 5, 200, 0]
        MorModel:
            type: Ext_gaus
            ra: [85.63468, 81.85, 89.85, 0]
            dec: [23.14186, 19.21, 27.21, 0]
            sigma: [1.25290, 0.5, 6.0, 0]
```

- Definition of sources
  - Srco: the first source component
    - Epiv: used if global Epiv<o
    - MorModel
      - Type: tag of morphology model in model config file
      - Fo: initial value, limit range, fix option and order
  - Src1
  - …

Analysis method: Part2

➢ Analysis of diffuse galactic emission (DGE)

- ➢ Different Origins of Gamma-Ray
  - Point Sources
  - Large-scale extended sources
  - Isotropic Background
  - DGE

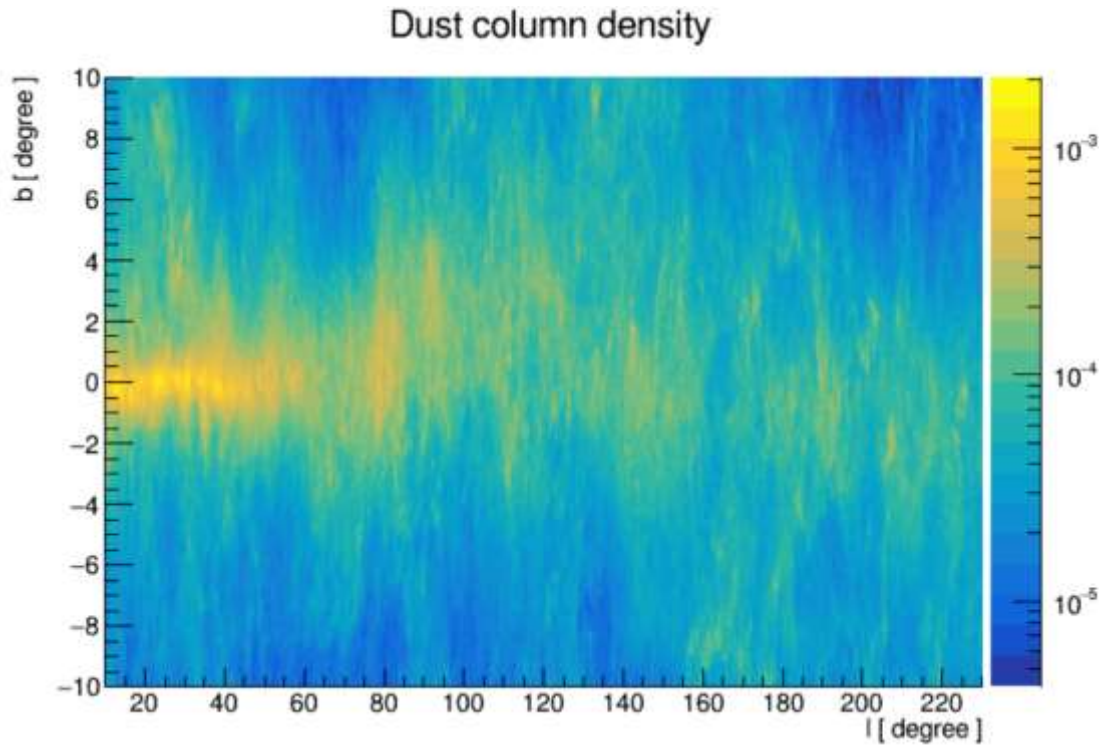
$$p, \alpha + ISM \rightarrow \pi^0 \rightarrow 2\gamma$$

$$e + ISM \rightarrow \gamma \quad \text{bremsstrahlung}$$

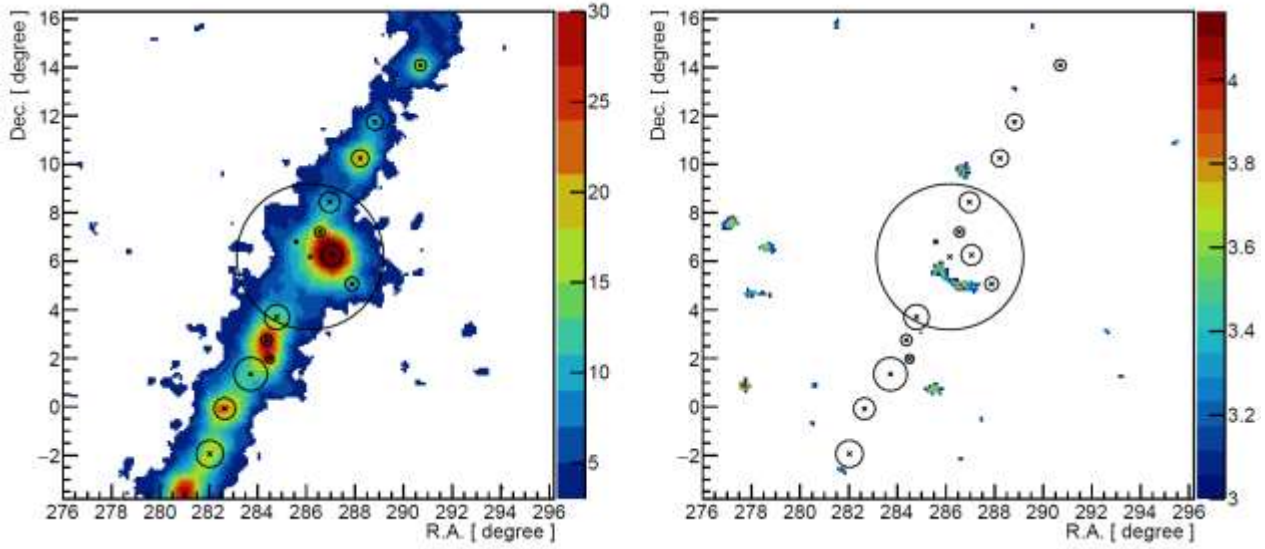
$$e + ISRF \rightarrow \gamma \quad \text{Inverse Compton scattering}$$

- ➢ Free DGE
- ➢ Using published LHAASO results
  - KM2A DGE
  - 1LHAASO catalog

} Uncertainty from DGE



Analysis method: Part2



➢ Test

- Number of sources
- Spectrum model
- Morphology model

➢ Nested model

- a regression model that contains a subset of the predictor variables in another regression model
- TS asymptotically follows Chi2 distribution

➢ AIC $= -2\ln\mathcal{L}_{s+b} + 2k$

- ΔAIC

➢ Test

- Number of sources
  - 1LHAASO catalog
  - Iteration process
  - ΔTS>25
- Spectrum model & Morphology model
  - ΔTS or ΔAIC

➢ Online user guide document

https://jupyter.ihep.ac.cn/8FA_ioKoQ5qqHcidpEA19A

➢ Contact

- Email: hushicong@ihep.ac.cn
- WeChat

Q & A