cherenkov telescope array

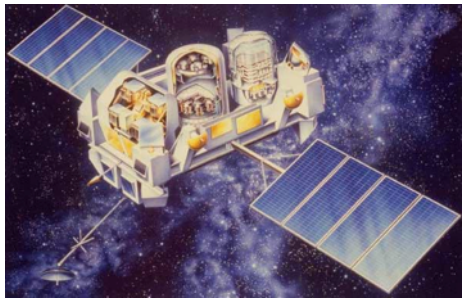
DL3 in GammaLib & ctools

Jürgen Knödlseder

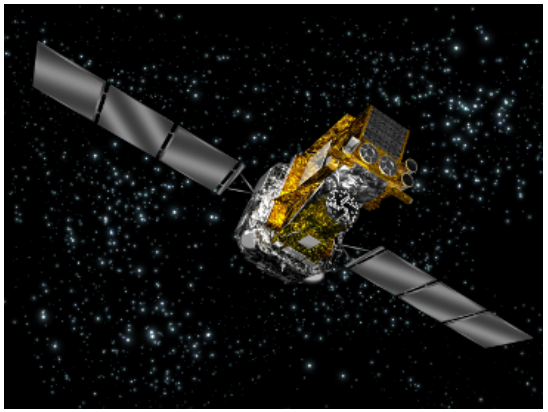
Topics covered

- GammaLib and ctools
- Event lists
- Instrument response functions
- Stacked analysis

The span of gamma-ray astronomy



CGRO

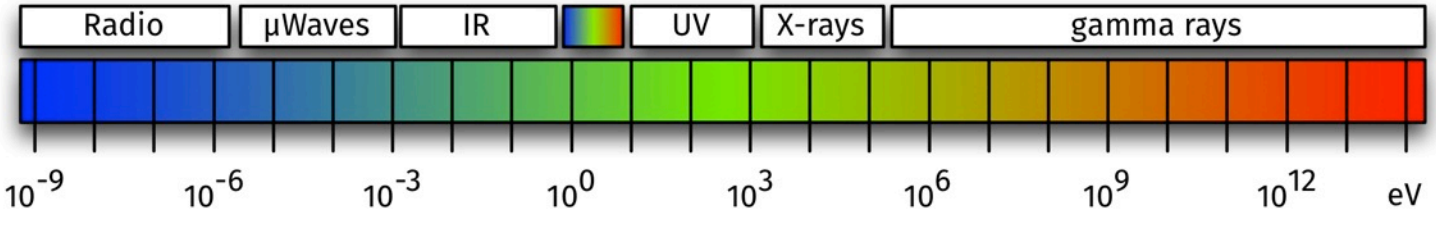


INTEGRAL

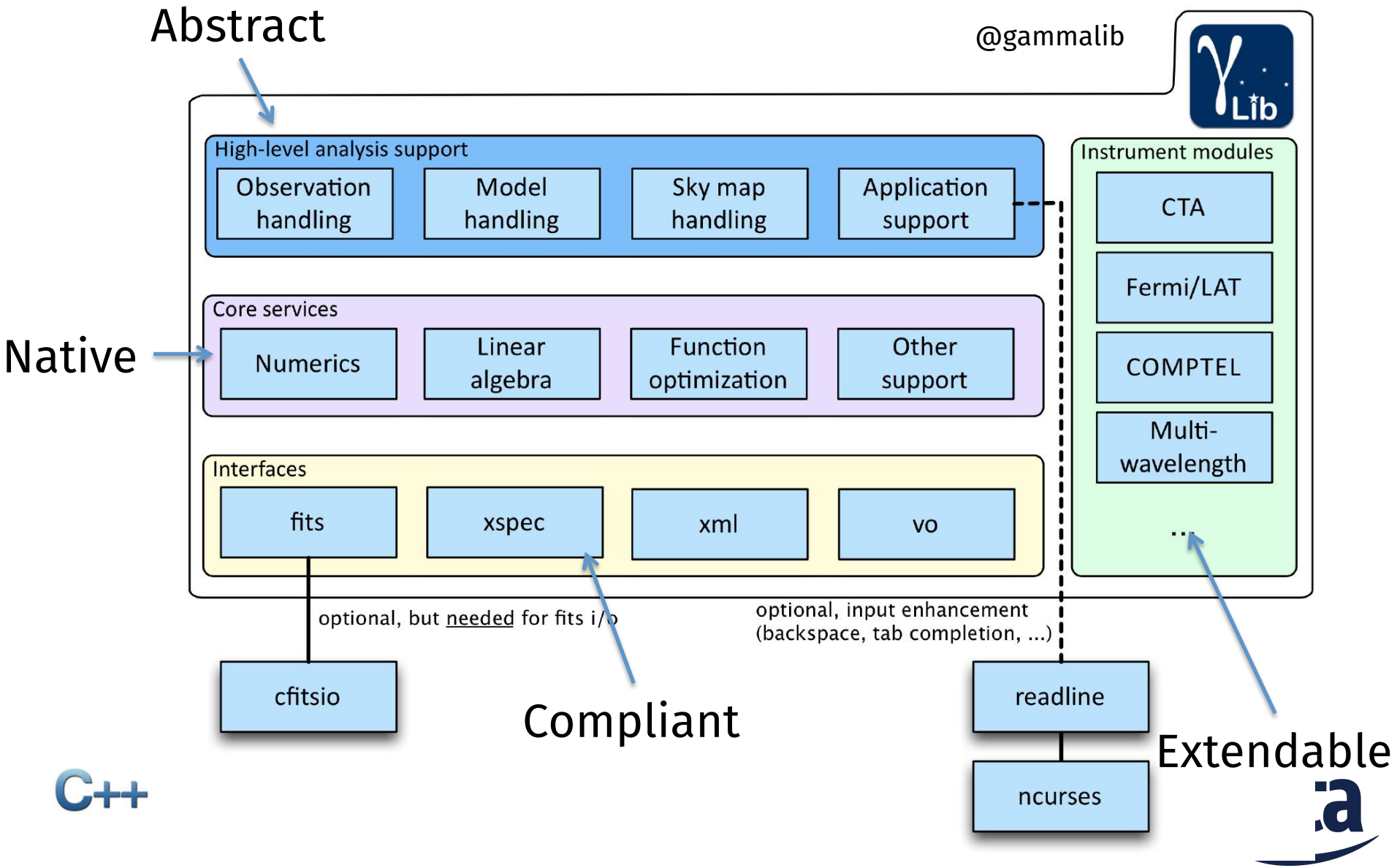
Fermi

HAWC

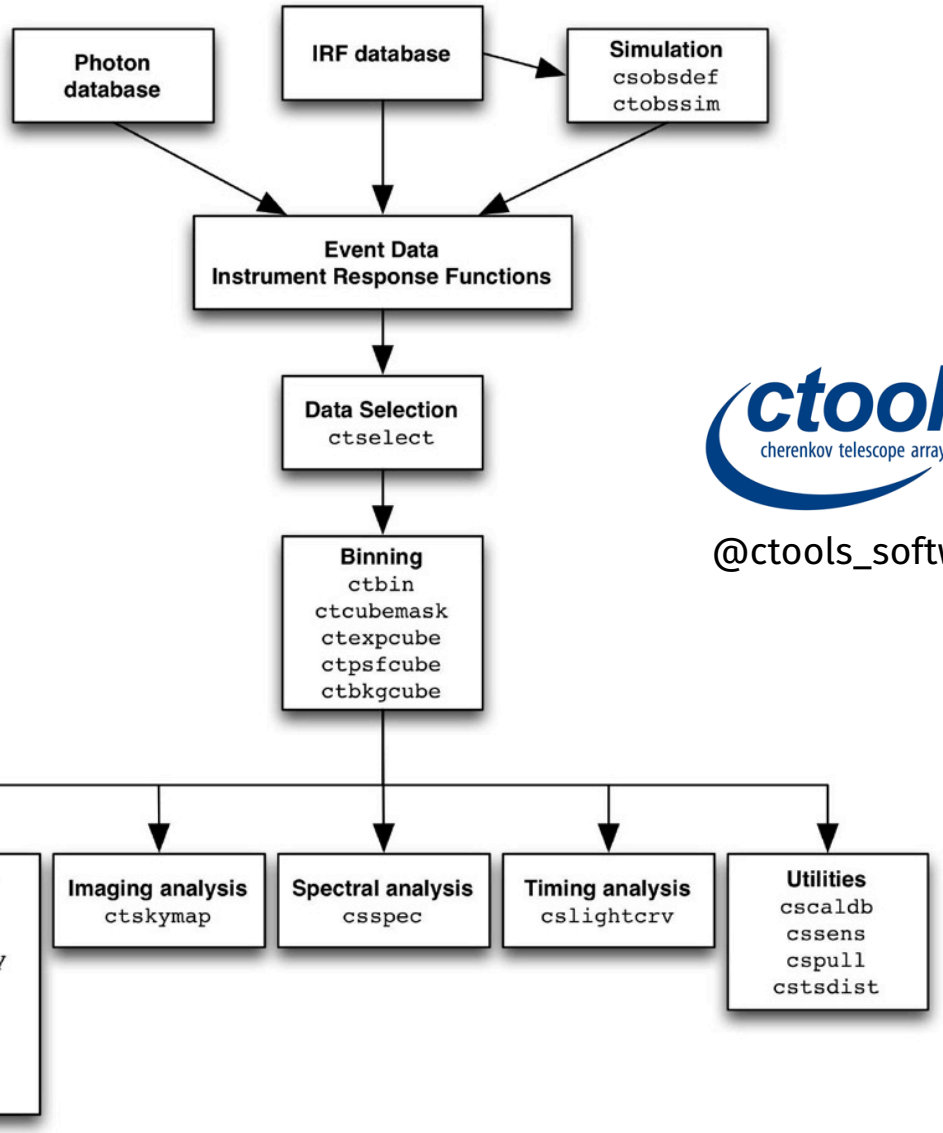
ASTROGAM



GammaLib


Abstract
@gammalib
Lib
High-level analysis support
Observation handling
Model handling
Sky map handling
Application support
Instrument modules
CTA
Fermi/LAT
COMPTEL
Multi-wavelength
...
Core services
Native
Numerics
Linear algebra
Function optimization
Other support
Interfaces
fits
xspec
xml
vo
optional, but needed for fits i/o
optional, input enhancement
(backspace, tab completion, ...)
cfitsio
Compliant
readline
ncurses
Extendable
C++

ctools



ctools
cherenkov telescope array

@ctools_software

python

C++

cta

GammaLib concepts

- Observation `(GObservation)`
  - period in time during which an instrument was taking data, in a stable configuration that can be described by an instrument response function
  - Instrument response can be time dependent
  - Time period does not need to be contiguous (GTI)
- Event `(GEvent)`
  - Elementary constituent of the data, characterised by an instrument direction, measured energy and trigger time
  - Can be unbinned (event atom) or binned (event bin)
- Response `(GResponse)`
  - Transformation from the physical properties of a photon to the measured characteristics of an event

CTA event lists

- Starting point

FITS Data format for ACTs v1.0.0

Karl Kosack, CTA DAFA Working Package

2011-05-18

- (Minimal) implementation

0	Primary	Image	0	Header	Image	Table
1	EVENTS	Binary	7 cols X 4119 rows	Header	Hist	Plot	All	Select
2	GTI	Binary	2 cols X 1 rows	Header	Hist	Plot	All	Select

Select All	EVENT_ID 1J	TIME 1D s	RA 1E deg	DEC 1E deg	ENERGY 1E TeV	DETX 1E deg	DETY 1E deg
Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	1	3.596789240837E-01	8.362013E+01	2.197107E+01	1.570517E-01	-3.893483E-02	-9.149051E-03
2	2	9.667769908905E+00	8.360922E+01	2.195930E+01	1.137184E-01	-5.070112E-02	-1.927271E-02
3	3	1.314883381128E+01	8.365855E+01	2.205752E+01	1.149002E-01	4.752544E-02	2.645994E-02
4	4	1.550700747967E+01	8.362605E+01	2.206566E+01	1.719268E-01	5.566480E-02	-3.665101E-03
5	5	1.589011639357E+01	8.375288E+01	2.202609E+01	1.138880E-01	1.613743E-02	1.139171E-01

CTA event lists - header

Data sub-space keywords to define Region of Interest (Fermi/LAT format)

OGIP standard time reference

Pointing information (only fixed pointing supported, ALT/AZ not used)

```
TUNIT7  = 'deg     '           / physical unit of field
EXTNAME = 'EVENTS  '           / name of this extension
DSTYP1  = 'TIME    '           / Data sub-space type
DSUNI1  = 's       '           / Data sub-space unit
DSVAL1  = 'TABLE   '           / Data sub-space value
DSREF1  = ':GTI    '           / Data sub-space reference
DSTYP2  = 'ENERGY  '           / Data sub-space type
DSUNI2  = 'TeV     '           / Data sub-space unit
DSVAL2  = '0.1:100 '           / Data sub-space value
DSTYP3  = 'POS(RA,DEC)'        / Data sub-space type
DSUNI3  = 'deg     '           / Data sub-space unit
DSVAL3  = 'CIRCLE(83.63,22.01,10)' / Data sub-space value
NDSKEYS =                    3 / Number of data sub-space keys
CREATOR = 'GammaLib'           / Program which created the file
TELESCOP= 'CTA     '           / Telescope
OBS_ID  =                    0 / Observation identifier
DATE_OBS= '2000-01-01'         / Observation start date
TIME_OBS= '11:58:56'           / Observation start time
DATE_END= '2000-01-01'         / Observation end date
TIME_END= '12:28:56'           / Observation end time
TSTART  =     0.0000000000E+00 / [s] Mission time of start of observati
TSTOP   =     1.8000000000E+03 / [s] Mission time of end of observation
MJDREFI =                51544 / [days] Integer part of time reference
MJDREFF =     5.0000000000E-01 / [days] Fractional part of time referen
TIMEUNIT= 's       '           / Time unit
TIMESYS = 'TT      '           / Time system
TIMEREF = 'LOCAL   '           / Time reference
TELAPSE =     1.8000000000E+03 / [s] Mission elapsed time
ONTIME  =     1.8000000000E+03 / [s] Total good time including deadtime
LIVETIME=     1.7100000000E+03 / [s] Total livetime
DEADC   =     9.5000000000E-01 / Deadtime correction factor
TIMEDEL =     1.0000000000E+00 / Time resolution
OBJECT  = '        '           / Observed object
RA_OBJ  =     0.0000000000E+00 / [deg] Target Right Ascension
DEC_OBJ =     0.0000000000E+00 / [deg] Target Declination
RA_PNT  =     8.3630000000E+01 / [deg] Pointing Right Ascension
DEC_PNT =     2.2010000000E+01 / [deg] Pointing Declination
ALT_PNT =     9.0000000000E+01 / [deg] Average altitude of pointing
AZ_PNT  =     0.0000000000E+00 / [deg] Average azimuth of pointing
RADECSYS= 'FK5     '           / Coordinate system
EQUINOX =     2.0000000000E+03 / Epoch
CONV_DEP=     0.0000000000E+00 / Convergence depth of telescopes
CONV_RA =     0.0000000000E+00 / [deg] Convergence Right Ascension
CONV_DEC=     0.0000000000E+00 / [deg] Convergence Declination
OBSERVER= 'string  '           / Observer
N_TELS  =                    0 / Number of telescopes in event list
TELLIST = 'string  '           / Telescope IDs
GEOLAT  =     0.0000000000E+00 / [deg] Geographic latitude of array cen
GEOLON  =     0.0000000000E+00 / [deg] Geographic longitude of array ce
ALTITUDE=     0.0000000000E+00 / [km] Altitude of array centre
EUNIT   = 'TeV     '           / Energy unit
EVTVER  = 'draft1  '           / Event list version number
END
```

Current CTA IRF handling

$$R_\gamma(\alpha', \delta', E'|\alpha, \delta, E, \vec{a}) = A_\gamma(\alpha, \delta, E, \vec{a}) \times PSF(\alpha', \delta'|\alpha, \delta, E, \vec{a}) \times D(E'|\alpha, \delta, E, \vec{a})$$

effective area (cm2)

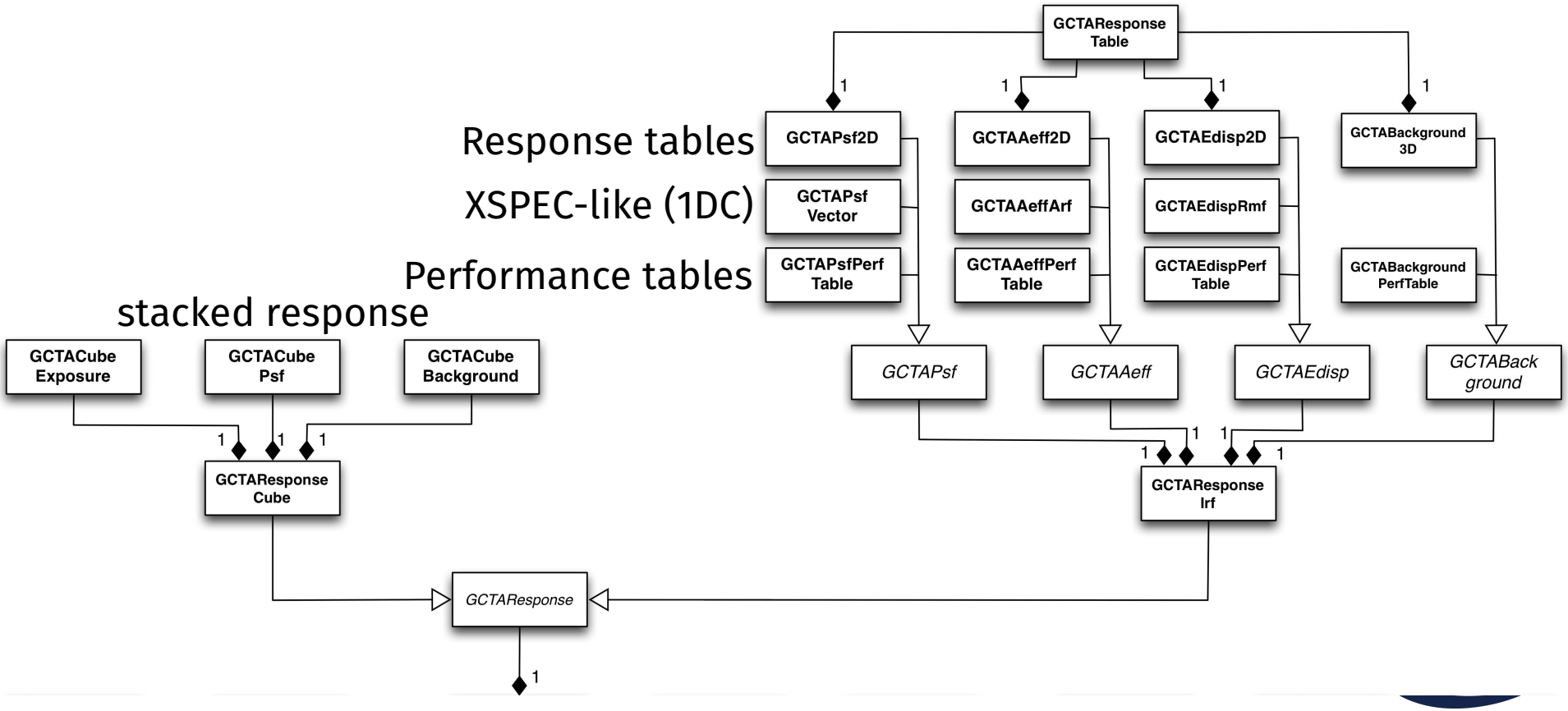
point spread function

energy dispersion

Full area, no angle cuts

$$1 = \int d\alpha'\, d\delta'\, PSF(\alpha', \delta'|\alpha, \delta, E, \vec{a})$$

$$1 = \int dE'\, D(E'|\alpha, \delta, E, \vec{a})$$



Legacy: performance tables

log(E)	Area	r68	r80	ERes.	BG Rate	Diff Sens
-1.7	261.6	0.3621	0.4908	0.5134	1.89924e-02	6.88237e-11
-1.5	5458.2	0.2712	0.3685	0.4129	1.00972e-01	1.72717e-11
-1.3	15590.0	0.1662	0.2103	0.2721	5.75623e-02	6.16963e-12
-1.1	26554.1	0.1253	0.1567	0.2611	2.13008e-02	2.89932e-12
-0.9	52100.5	0.1048	0.1305	0.1987	8.87292e-03	1.39764e-12
-0.7	66132.1	0.0827	0.1024	0.1698	1.09756e-03	6.03531e-13
-0.5	108656.8	0.0703	0.0867	0.1506	4.84287e-04	3.98147e-13
-0.3	129833.0	0.0585	0.0722	0.1338	1.57546e-04	3.23090e-13
-0.1	284604.3	0.0531	0.0656	0.1008	1.36703e-04	2.20178e-13
0.1	263175.3	0.0410	0.0506	0.0831	2.09694e-05	1.87452e-13
0.3	778048.6	0.0470	0.0591	0.0842	6.92374e-05	1.53976e-13
0.5	929818.8	0.0391	0.0492	0.0650	1.45844e-05	1.18947e-13
0.7	1078450.0	0.0335	0.0415	0.0541	1.15959e-05	1.51927e-13
0.9	1448579.1	0.0317	0.0397	0.0516	4.71231e-06	1.42439e-13
1.1	1899905.0	0.0290	0.0372	0.0501	8.14997e-06	1.96670e-13
1.3	2476403.8	0.0285	0.0367	0.0538	5.91940e-06	2.20695e-13
1.5	2832570.6	0.0284	0.0372	0.0636	7.33847e-06	3.22523e-13
1.7	3534065.3	0.0290	0.0386	0.0731	1.34549e-05	4.84153e-13
1.9	3250103.4	0.0238	0.0308	0.0729	4.42228e-06	6.26265e-13
2.1	3916071.6	0.0260	0.0354	0.0908	2.26648e-06	7.69921e-13

Notes
1) log(E) = log10(E/TeV) - bin centre
2) Eff Area - in square metres after background cut (no theta cut)
3) Ang. Res - 68% containment radius of gamma-ray PSF post cuts - in degrees
4) Ang. Res - 80% containment radius of gamma-ray PSF post cuts - in degrees
5) Fractional Energy Resolution (rms)
6) BG Rate - inside point-source selection region - post call cuts - in Hz
7) Diff Sens - differential sensitivity for this bin expressed as E^2 dN/dE - in erg cm^-2 s^-1 - for a 50 hours exposure - 5 sigma significance including systematics and statistics and at least 10 photons.

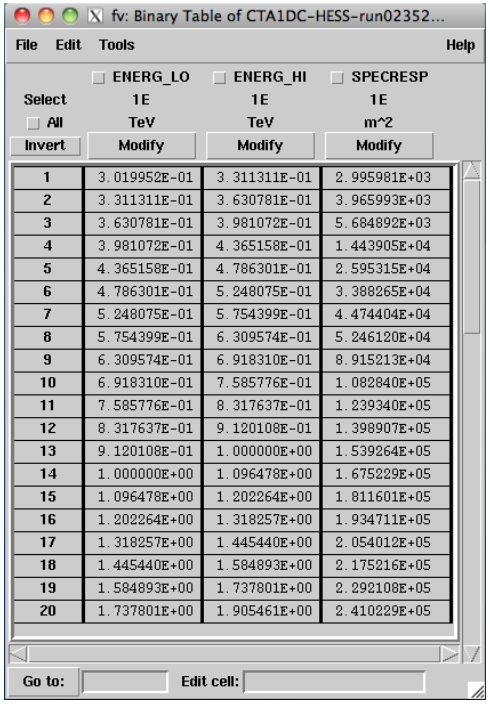
```
GCTAAeffPerfTable
GCTAPsfPerfTable
GCTAEdispPerfTable
GCTABackgroundPerfTable
```

Only on-axis information

A_{eff} and B_{rate} off-axis dependence modelled using $B(\theta) \propto \exp\left(-\frac{1}{2}\frac{\theta^4}{\sigma^2}\right)$

Gaussians assumed for PSF and energy dispersion

Legacy: ARF, RMF, PSF vectors

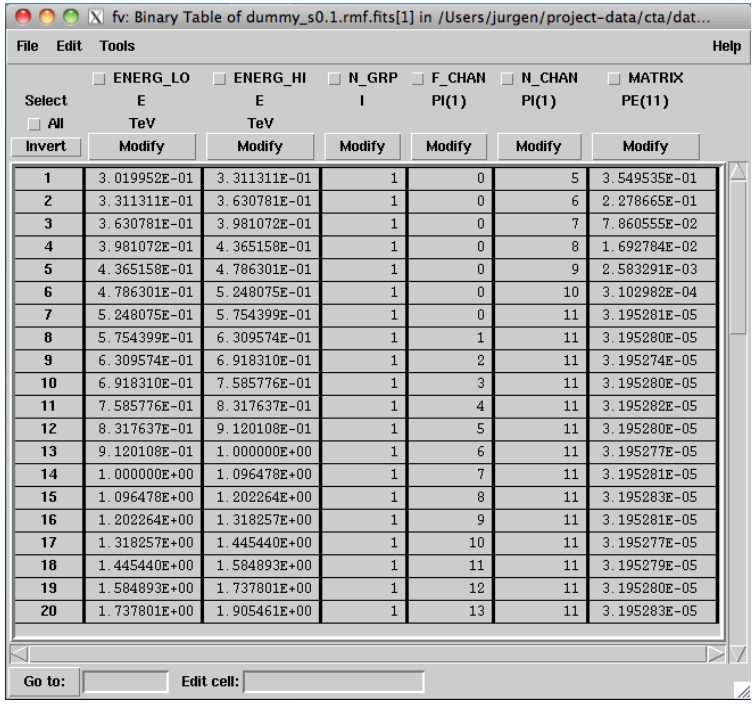

fv: Binary Table of CTA1DC-HESS-run02352...

File Edit Tools Help

Select All Invert

	ENERG_LO 1E TeV Modify	ENERG_HI 1E TeV Modify	SPECRESP 1E m^2 Modify
1	3.019952E-01	3.311311E-01	2.995981E+03
2	3.311311E-01	3.630781E-01	3.965993E+03
3	3.630781E-01	3.981072E-01	5.684892E+03
4	3.981072E-01	4.365158E-01	1.443905E+04
5	4.365158E-01	4.786301E-01	2.595315E+04
6	4.786301E-01	5.248075E-01	3.388265E+04
7	5.248075E-01	5.754399E-01	4.474404E+04
8	5.754399E-01	6.309574E-01	5.246120E+04
9	6.309574E-01	6.918310E-01	8.915213E+04
10	6.918310E-01	7.585776E-01	1.082840E+05
11	7.585776E-01	8.317637E-01	1.239340E+05
12	8.317637E-01	9.120108E-01	1.398907E+05
13	9.120108E-01	1.000000E+00	1.539264E+05
14	1.000000E+00	1.096478E+00	1.675229E+05
15	1.096478E+00	1.202264E+00	1.811601E+05
16	1.202264E+00	1.318257E+00	1.934711E+05
17	1.318257E+00	1.445440E+00	2.054012E+05
18	1.445440E+00	1.584893E+00	2.175216E+05
19	1.584893E+00	1.737801E+00	2.292108E+05
20	1.737801E+00	1.905461E+00	2.410229E+05

Go to: Edit cell: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File Edit Tools Help

Select All Invert

	ENERG_LO E TeV Modify	ENERG_HI E TeV Modify	N_GRP I Modify	F_CHAN PI(1) Modify	N_CHAN PI(1) Modify	MATRIX PE(11) Modify
1	3.019952E-01	3.311311E-01	1	0	5	3.549535E-01
2	3.311311E-01	3.630781E-01	1	0	6	2.278665E-01
3	3.630781E-01	3.981072E-01	1	0	7	7.860555E-02
4	3.981072E-01	4.365158E-01	1	0	8	1.692784E-02
5	4.365158E-01	4.786301E-01	1	0	9	2.583291E-03
6	4.786301E-01	5.248075E-01	1	0	10	3.102982E-04
7	5.248075E-01	5.754399E-01	1	0	11	3.195281E-05
8	5.754399E-01	6.309574E-01	1	1	11	3.195280E-05
9	6.309574E-01	6.918310E-01	1	2	11	3.195274E-05
10	6.918310E-01	7.585776E-01	1	3	11	3.195280E-05
11	7.585776E-01	8.317637E-01	1	4	11	3.195282E-05
12	8.317637E-01	9.120108E-01	1	5	11	3.195280E-05
13	9.120108E-01	1.000000E+00	1	6	11	3.195277E-05
14	1.000000E+00	1.096478E+00	1	7	11	3.195281E-05
15	1.096478E+00	1.202264E+00	1	8	11	3.195283E-05
16	1.202264E+00	1.318257E+00	1	9	11	3.195281E-05
17	1.318257E+00	1.445440E+00	1	10	11	3.195277E-05
18	1.445440E+00	1.584893E+00	1	11	11	3.195279E-05
19	1.584893E+00	1.737801E+00	1	12	11	3.195280E-05
20	1.737801E+00	1.905461E+00	1	13	11	3.195283E-05

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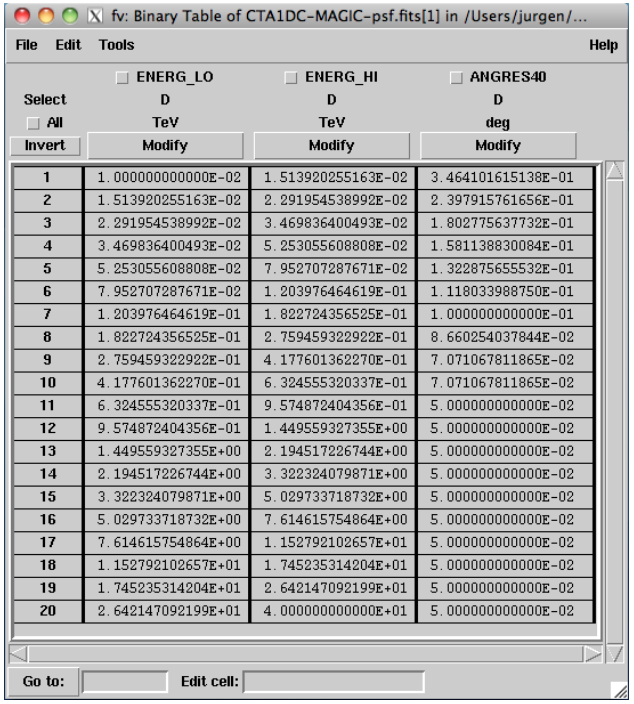

fv: Binary Table of CTA1DC-MAGIC-psf.fits[1] in /Users/jurgen/...

File Edit Tools Help

Select All Invert

	ENERG_LO D TeV Modify	ENERG_HI D TeV Modify	ANGRES40 D deg Modify
1	1.000000000000E-02	1.513920255163E-02	3.464101615138E-01
2	1.513920255163E-02	2.291954538992E-02	2.397915761656E-01
3	2.291954538992E-02	3.469836400493E-02	1.802775637732E-01
4	3.469836400493E-02	5.253055608808E-02	1.581138830084E-01
5	5.253055608808E-02	7.952707287671E-02	1.322875655532E-01
6	7.952707287671E-02	1.203976464619E-01	1.118033988750E-01
7	1.203976464619E-01	1.822724356525E-01	1.000000000000E-01
8	1.822724356525E-01	2.759459322922E-01	8.660254037844E-02
9	2.759459322922E-01	4.177601362270E-01	7.071067811865E-02
10	4.177601362270E-01	6.324555320337E-01	7.071067811865E-02
11	6.324555320337E-01	9.574872404356E-01	5.000000000000E-02
12	9.574872404356E-01	1.449559327355E+00	5.000000000000E-02
13	1.449559327355E+00	2.194517226744E+00	5.000000000000E-02
14	2.194517226744E+00	3.322324079871E+00	5.000000000000E-02
15	3.322324079871E+00	5.029733718732E+00	5.000000000000E-02
16	5.029733718732E+00	7.614615754864E+00	5.000000000000E-02
17	7.614615754864E+00	1.152792102657E+01	5.000000000000E-02
18	1.152792102657E+01	1.745235314204E+01	5.000000000000E-02
19	1.745235314204E+01	2.642147092199E+01	5.000000000000E-02
20	2.642147092199E+01	4.000000000000E+01	5.000000000000E-02

Go to: Edit cell:

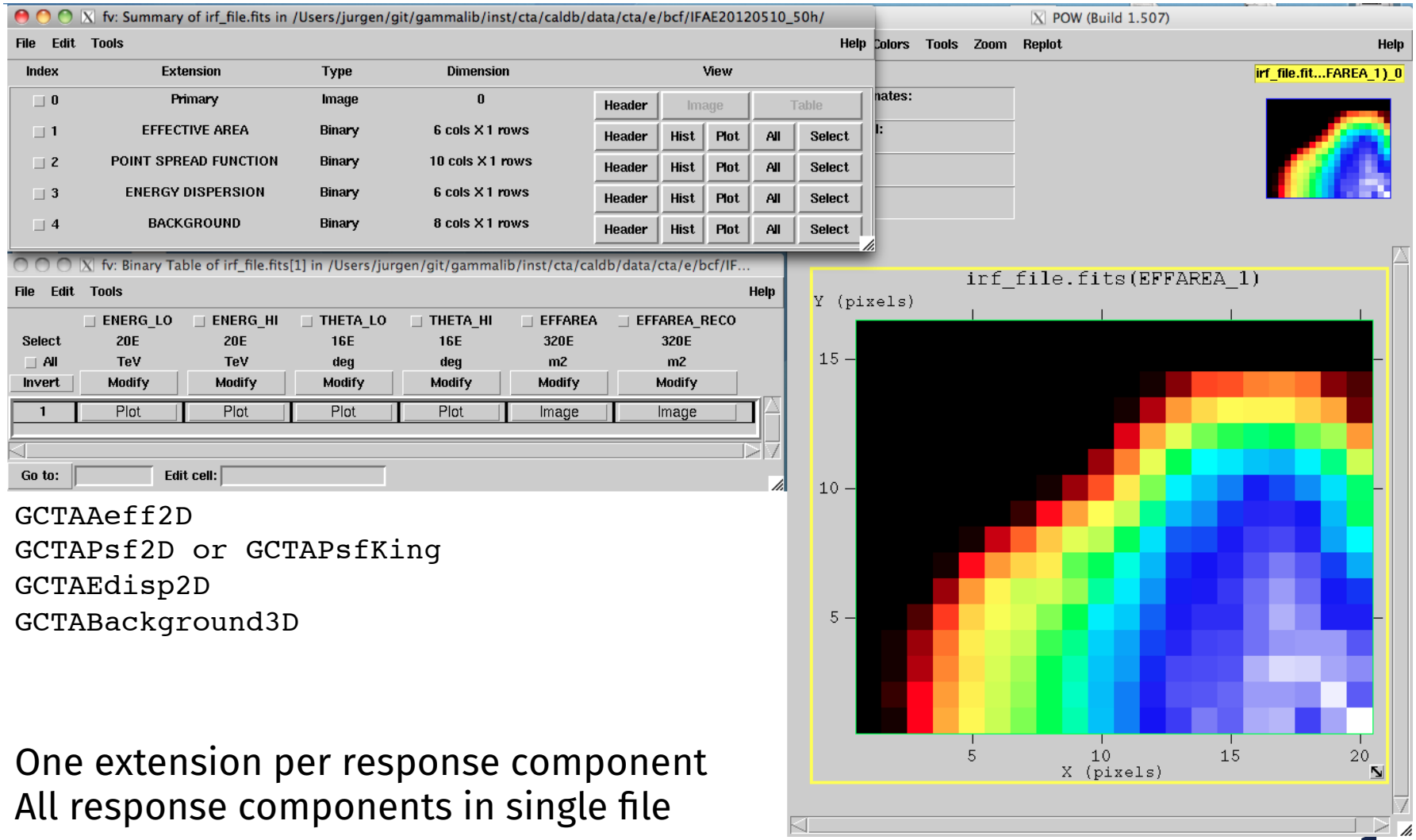
`GCTAAeffArf`
`GCTAPsfVector`
`GCTAEdispRmf`

Only on-axis information

A_{eff} off-axis dependence modelled using $B(\theta) \propto \exp\left(-\frac{1}{2}\frac{\theta^4}{\sigma^2}\right)$

Gaussian assumed for PSF

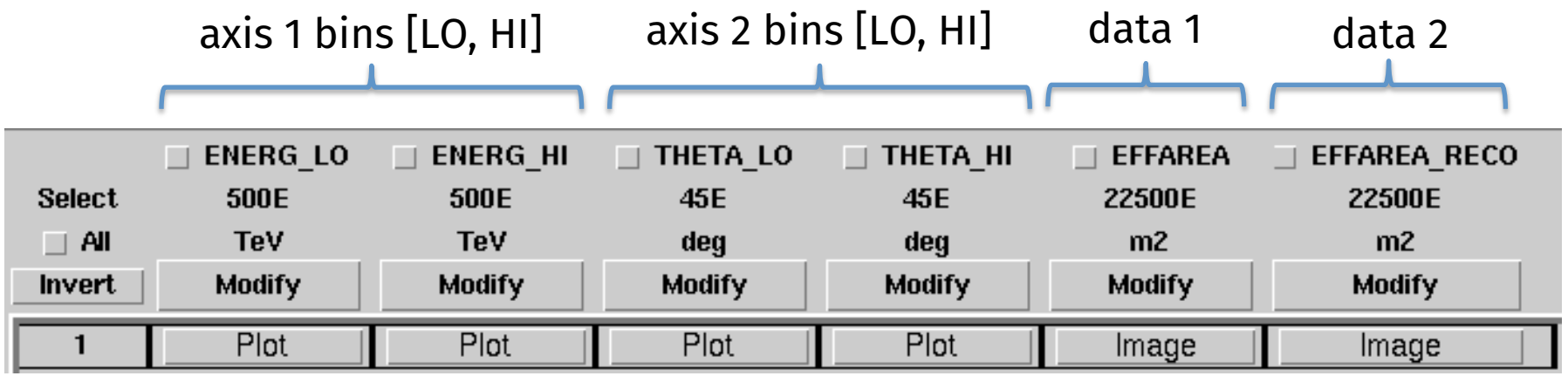
Response tables



GCTAAeff2D
GCTAPsf2D or GCTAPsfKing
GCTAEdisp2D
GCTABackground3D

One extension per response component
All response components in single file

Response tables



Format of Fermi/LAT instrument response files
Handles:

- n-dimensional cubes (don't need to be contiguous)
- arbitrary number of data blocks
- parametric models (each data block is a parameter)

Handling of this format implement by the class GCTAResponseTable

Effective area

Function of energy and off axis angle
Store A_{eff} values as function or true and measured energy

Point Spread Function

	ENERG_LO	ENERG_HI	THETA_LO	THETA_HI	SCALE	SIGMA_1	AMPL_2	SIGMA_2	AMPL_3	SIGMA_3
Select	21E	21E	2E	2E	42E	42E	42E	42E	42E	42E
All	TeV	TeV	deg	deg		deg		deg		deg
Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	Plot	Plot	Plot	Plot	Image	Image	Image	Image	Image	Image

	ENERG_LO	ENERG_HI	THETA_LO	THETA_HI	GAMMA	SIGMA
Select	20E	20E	16E	16E	320E	320E
All	TeV	TeV	deg	deg		deg
Invert	Modify	Modify	Modify	Modify	Modify	Modify
1	Plot	Plot	Plot	Plot	Image	Image

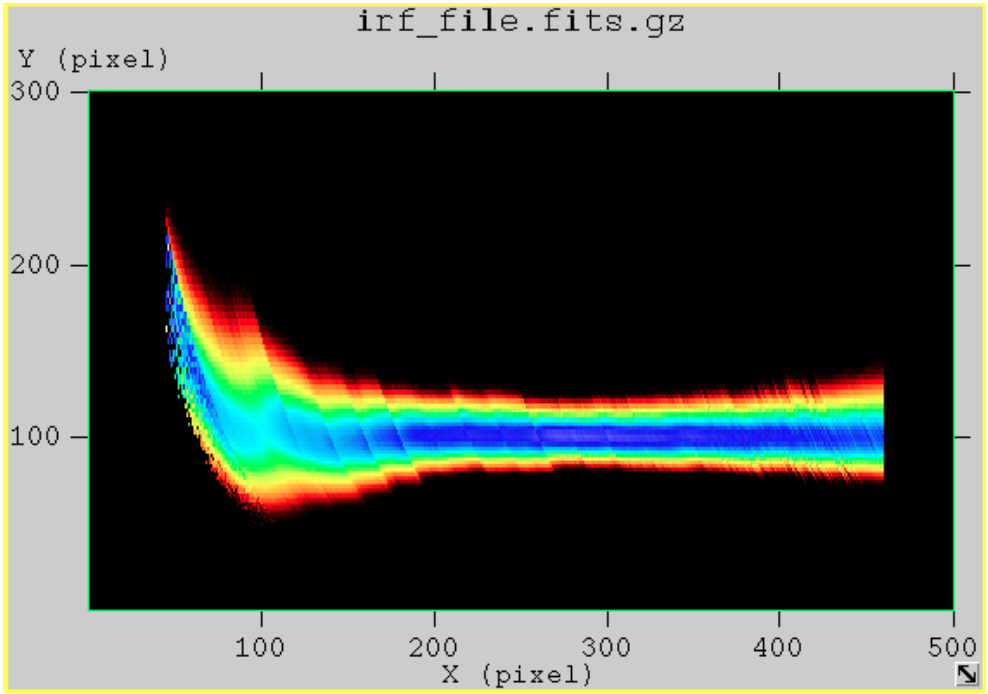
Function of energy and off axis angle
Two parametric variants:

- 3-Gaussians (6 parameters)
- King function (2 parameters)

Energy dispersion

	ETRUE_LO	ETRUE_HI	MIGRA_LO	MIGRA_HI	THETA_LO	THETA_HI	MATRIX
Select	500E	500E	300E	300E	2E	2E	300000E
All	TeV	TeV			deg	deg	
Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	Plot	Plot	Plot	Plot	Plot	Plot	Movie

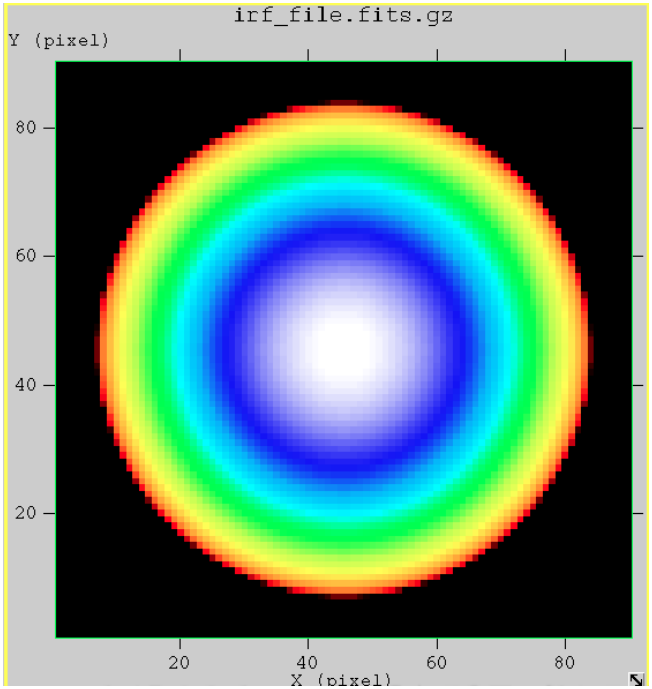
Function of true energy, E_{reco}/E_{true} and off axis angle
Store migration matrix (3D)



Background rate templates

	DETX_LO	DETX_HI	DETY_LO	DETY_HI	ENERG_LO	ENERG_HI	BGD
Select	90E	90E	90E	90E	21E	21E	170100E
All	deg	deg	deg	deg	TeV	TeV	1/s/MeV/sr
Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	Plot	Plot	Plot	Plot	Plot	Plot	Movie

Function of DETX, DETY and measured energy
Store rates per energy and solid angle (3D)



Stacked analysis

- Goal
  - Combine (stack) data for multiple observations into a single events cube
- Requires
  - computation of an effective exposure (Exposure Cube)
  - computation of a (exposure) averaged point spread function (Psf Cube)
  - computation of a (exposure) averaged energy dispersion (Energy Dispersion Cube)
  - computation of a (lifetime) averaged background rate (Background Cube)

Stacked analysis response cubes

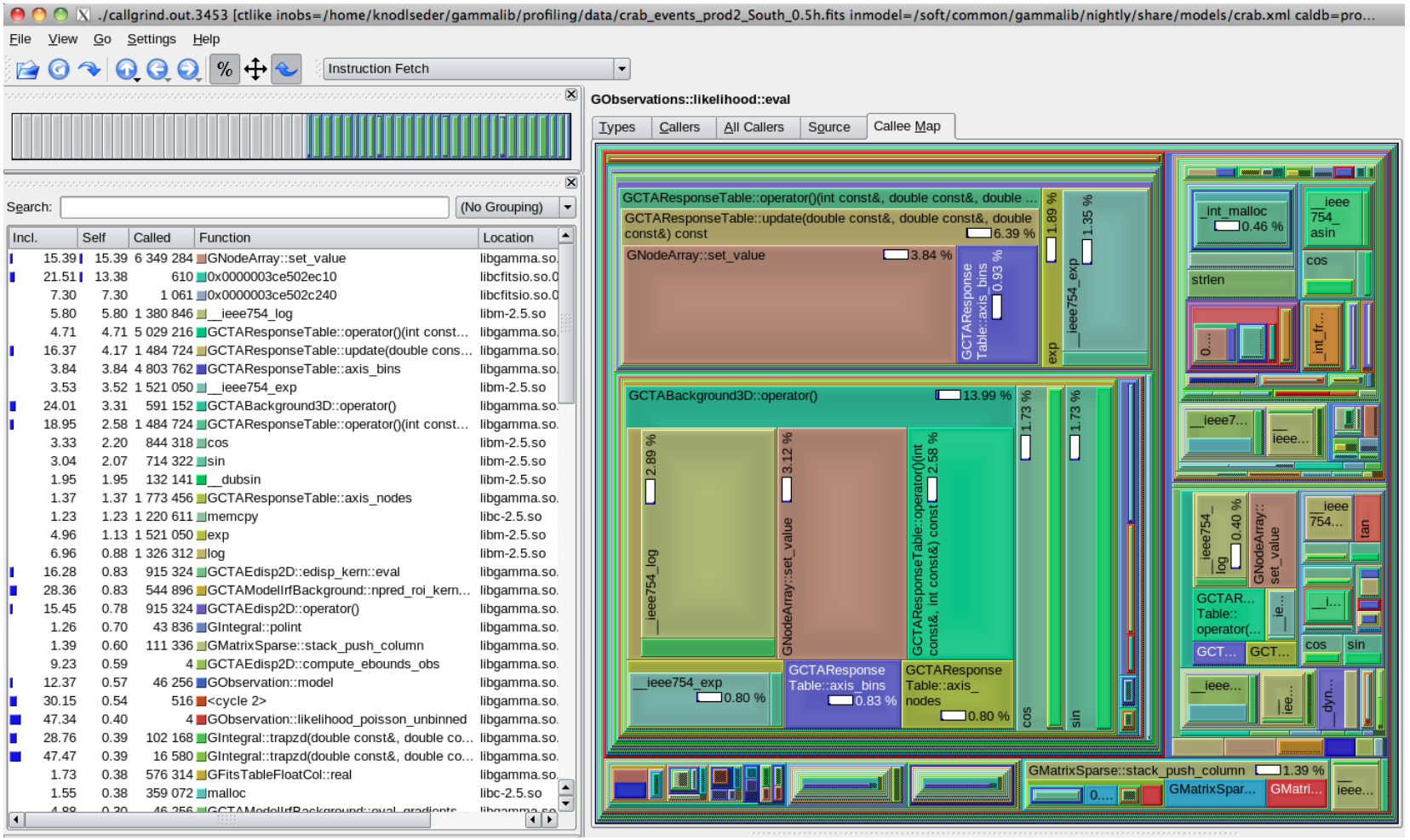
$$X_{\mathrm{cube}}(\boldsymbol{p}, E) = \sum_i A_{\mathrm{eff},i}(\boldsymbol{p}, E, t) \times \tau_i,$$

$$PSF_{\mathrm{cube}}(\boldsymbol{p}, E, \delta) = \frac{\sum_i PSF_i(\boldsymbol{p}'|\boldsymbol{p}, E, t) \times A_{\mathrm{eff},i}(\boldsymbol{p}, E, t) \times \tau_i}{\sum_i A_{\mathrm{eff},i}(\boldsymbol{p}, E, t) \times \tau_i},$$

$$D_{\mathrm{cube}}(E'|\boldsymbol{p}, E) = \frac{\sum_i D_i(E'|\boldsymbol{p}, E, t) \times A_{\mathrm{eff},i}(\boldsymbol{p}, E, t) \times \tau_i}{\sum_i A_{\mathrm{eff},i}(\boldsymbol{p}, E, t) \times \tau_i},$$

$$B_{\mathrm{cube}}(\boldsymbol{p}', E') = \frac{\sum_i B_i(\boldsymbol{p}', E', t') \times \tau_i}{\sum_i \tau_i}.$$

A word about implementation



Response information is heavily accessed and corresponding code needs to be optimised for speed; this explains why specific response classes have been implemented.

Summary

- Minimum event list implement following Karl's proposal
  - EVENT_ID, TIME, ENERGY, RA, DEC, DETX, DETY
- Instrument response function format based on Fermi/LAT format
  - We're using this format since 2012 and have not yet encountered any show stopper
  - It apparently fits also the needs of existing IACTs