"ctools" tutorial

Ulisses Barres de Almeida
“ctools" tutorial

Ulisses Barres de Almeida

DISCLAIMER: I am not a developer! This tutorial is based on other lessons from where I learned CTA analysis tools. Specially by J. Knodelseder & F. Longo.
This presentation aims to be a short practical introduction to one set of tools being developed for CTA analysis.

“ctools” is similar to “fermi tools” in concept and after this you should be able to go and play with the tools yourself.

**Prerequisites:** Rodrigo’s “fermi tools” hands-on sessions + Gernot’s ACT analysis introduction
What is ctools?

**ctools** is a project in development for CTA. It consists on a set of fermi tools-like executables for step-wise data analysis by end-users.

**Accessible from:**
check the wiki

**Contact information:**
subscribe to ctools@irap.omp.eu
What is ctools?

Accessible from:
https://cta-redmine.irap.omp.eu/projects/ctools
check the wiki

Contact information:
subscribe to ctools@irap.omp.eu

*ctools are based on GammaLib, a toolbox for high-level analysis of gamma-ray data
What is provided by GammaLib?

High-level analysis functionalities tools — i.e., post-reconstruction events operations

- event I/O
- IRF implementation
- data format
- parameter specifications
- versatile for multi-mission analysis*
- and joint multi-instrument data analysis

http://gammalib.sourceforge.net/
What is provided by GammaLib?

- **High-level analysis support**
  - Observation handling
  - Model handling
  - Sky map handling
  - Application support

- **Core services**
  - Numerics
  - Linear algebra
  - Function optimization
  - Other support

- **Interfaces**
  - fits
  - xspec
  - xml
  - vo
  - cfitsio
  - optional, but needed for fits i/o

- **Instrument modules**
  - CTA
  - Fermi/LAT
  - COMPTEL
  - Multi-wavelength
  - ...
  - readline
  - ncurses
  - optional, input enhancement (backspace, tab completion, ...)
Introduction

**ctools** is a collection of utilities for operating on CTA event data (photon lists) and IRFs in the FITS format, pretty much like the fools you operated at the hands-on yesterday.

Each routine performs specific tasks such as:

- binning
- event selection
- model fitting
- ...

It shares all functionalities and interface capabilities of fermi tools, i.e. FITS files handling (“ftools”), python scripts, IRAF-style parameters files, HEASARC library packages, etc.
in practice...

- background model
- instrument response functions
- simulated (reconstructed) event lists
- skymaps
- spectra
- lightcurve
Across the borders

A common set of tools for high-energy photon-counting instruments

+ HEASARC’s cfitsio library
The Fermi/LAT example from Rodrigo’s hands on yesterday — if you are familiar with Fermi tools you can use ctools directly
Equivalence between Fermi and ctools

Equivalent modular structure for science data analysis
Some definitions

**ctools**

- `ctbin` — Generates counts cube
- `ctbkgcube` — Generates background cube
- `ctbutterfly` — Compute butterfly
- `ctcubemask` — Filter counts cube
- `ctexpcube` — Generates exposure cube
- `ctlike` — Performs maximum likelihood fitting
- `ctmodel` — Computes model counts cube
- `ctobssim` — Simulate CTA observations
- `ctpsfcube` — Generates point spread function cube
- `ctselect` — Selects event data
- `ctskymap` — Generates sky map
- `ctstmap` — Generates Test Statistics map
- `ctulimit` — Calculates upper limit

---

**Equivalence between Fermi and ctools**

Equivalent modular structure for science data analysis
Starting with ctools

download the code from
http://cta.irap.omp.eu/ctools/download.html

Get the source files and binary package for ctools and gammalib:
Installing ctools (you did not do it for Fermi!)

use mac binary package
or build from source

$ ./configure
$ make
$ make install

Building from source!
(first GammaLib, then ctools)

Using the Mac OS X binary package!
(includes GammaLib & ctools)

$ export GAMMALIB=/usr/local/gamma
$ source $GAMMALIB/bin/gammalib-init.sh
$ export CTOOLS=/usr/local/gamma
$ source $CTOOLS/bin/ctools-init.sh

Configuring gammalib and ctools:

Configuring gammalib and ctools:

this goes into your /.bashrc script...
Data structure

Event data

- reconstructed direction;
- reconstructed energy;
- time tag

For a given time interval, events can be binned in a 3 dimensional data space for each time interval...

counts cube

GTI - good time interval
[energy range]
IRF
Simulating CTA data

No real data yet for CTA

simulated CTA data is done with the tool “ctobssim”:

```bash
$ ctobssim
Model ["CTOOLS/share/models/crab.xml"
RA of pointing (degrees) (0-360) [83.63]
Dec of pointing (degrees) (-90-90) [22.01]
Calibration database [dummy]
Instrument response function [cta_dummy_irf]
Radius of FOV (degrees) (0-180) [5.0]
Start time (MET in s) (0) [0.0]
End time (MET in s) (0) [1800.0]
Lower energy limit (TeV) (0) [0.1]
Upper energy limit (TeV) (0) [100.0]
Output event data file or observation definition file [events.fits]
```

...as with Fermi tools, you are queried about each parameter [or leave it as default]

**$CTOOLS** is an alias for the environment variable path

The CTA IRFs (effective area, PSF width, etc.) are taken from a performance table at

$CTOOLS/share/caldb/cta
Simulating CTA data

An example IRAF parameter file

```
# # General parameters
#=====================
inobs, f, h, NONE,,, "Input event list or observation definition XML file"
inmodel, f, a, $CTOOLSH/ share/models/crab.xml,, "Input model definition XML file"
caldb, s, a, prod2,,, "Calibration database"
irf, s, a, South_0.5h,,, "Instrument response function"
edisp, b, h, no,,, "Apply energy dispersion?"
ouevents, f, a, events.fits,,, "Output event data file or observation definition XML file"
prefix, s, h, sim_events,,, "Prefix for event lists in observation definition XML file"
startindex, i, h, 1,,, "Start index for event lists in observation definition XML file"

# # Simulation parameters
#======================
seed, i, h, 1,,, "Random number generator seed"
ra, r, a, 83.63,0,360, "RA of pointing (degrees)"
dec, r, a, 22.01,-90,90, "Dec of pointing (degrees)"
rad, r, a, 5.0,0,180, "Radius of FOV (degrees)"
tmin, r, a, 0.0, "Start time (MET in s)"
tmax, r, a, 1800.0, "End time (MET in s)"
emin, r, a, 0.1, "Lower energy limit (TeV)"
emax, r, a, 100.0, "Upper energy limit (TeV)"
deadc, r, h, 0.95,0,1, "Average deadtime correction factor"
maxrate, r, h, 1.0e6, "Maximum photon rate"
eslices, i, h, 10,1,100, "Number of energy slices"

# # Standard parameters
#=====================
publish, b, h, no,,, "Publish event list on VO Hub?"
chatter, i, h, 2,0,4, "Chattiness of output"
clobber, b, h, yes,,, "Overwrite existing output files with new output files?"
debug, b, h, no,,, "Debugging mode activated"
mode, s, h, q1,,, "Mode of automatic parameters"
logfile, f, h, ctobssim.log,,, "Log filename"
```
Simulating CTA data

No real data yet for CTA

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Model [CTOOLS/share/models/crab.xml]
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Start time (MET in s) (0) [0.0]
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Lower energy limit (TeV) (0) [0.1]
Upper energy limit (TeV) (0) [100.0]
Output event data file or observation definition file [events.fits]
```

CTA events are simulated based on certain dummy instrument properties (the IRFs), plus a source and background model.
Simulating CTA data

No real data yet for CTA

CTA events are simulated based on certain dummy instrument properties (the IRFs), plus a source and background model.

CTA model data

The output events .fits file will contain all relevant event data within the specified circular ROI (region of interest).

The duration of a run (observation) is 30 min, and typical energy range is from 0.1 to 100 TeV.
What is a data model?

The source model is specified in a XML file

\[ M(x, y, E) = M_{\text{spectral}}(E) \times M_{\text{spatial}}(x, y) \]

Comprising of a spectral (Energy) and a spatial (map) model distribution
Containing both source and background.

In the previous example, we have a Crab model (PWL point source)
+ offset Gaussian background
What is a data model?

The source model is specified in a XML file

In the previous example, we have a Crab model (PWL point source) + offset Gaussian background

```xml
<?xml version="1.0" standalone="no"?>
<source_library title="source library">
  <source name="Crab" type="PointSource">
    <spectrum type="PowerLaw">
      <parameter name="Prefactor" scale="1e-16" value="5.7" min="1e-07" max="1000.0" free="1"/>
      <parameter name="Index" scale="-1" value="2.48" min="0.0" max="+5.0" free="1"/>
      <parameter name="Scale" scale="1e6" value="0.3" min="0.01" max="1000.0" free="0"/>
    </spectrum>
    <spatialModel type="SkyDirFunction">
      <parameter name="RA" scale="1.0" value="83.6331" min="-360" max="360" free="1"/>
      <parameter name="DEC" scale="1.0" value="22.0145" min="-90" max="90" free="1"/>
    </spatialModel>
  </source>
  <source name="Background" type="RadialAcceptance" instrument="CTA">
    <spectrum type="FileFunction" file="$CTOOLS/share/models/bkg_dummy.txt">
      <parameter name="Normalization" scale="1.0" value="1.0" min="0.0" max="1000.0" free="1"/>
    </spectrum>
    <radialModel type="Gaussian">
      <parameter name="Sigma" scale="1.0" value="3.0" min="0.01" max="10.0" free="1"/>
    </radialModel>
  </source>
</source_library>
```
What is a data model?

The source model

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    </radialModel>
  </source>
</source_library>
```

[PWL] : Prefactor + Index + Scale

\[
\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^\gamma
\]

(parameter value = value*scale)

[min, max] range + free = 1/0

(ph/cm²/s/MeV)
What is a data model?

The background model

Spectrum = on axis background counting rate, per energy bin
(ph/s/sr/TeV)

RadialModel = describe radial variation of the count rate
Gaussian (width ~ deg2)
The data model library (J. Knodelseder)

- **Spatial**
  - Point source
  - Radial symmetric models
    - Gaussian
    - Disk
    - Shell
  - Elliptical models
    - Gaussian
    - Disk
  - “Diffuse” models
    - Map
    - Map cubes (energy dependent maps)
    - Isotropic
  - Composite

- **Spectral**
  - Power law
  - Broken power law
  - Exponentially cut off power law
  - Super exponentially cut off power law
  - Log parabola
  - Gaussian (line)
  - File function (arbitrary spectrum)
  - Node function (arbitrary fit)
  - Constant
  - Composite
  - Multiplicative (useful for EBL)

- **Temporal**
  - Constant
  - Light curve
  - Phase curve

And more to come (e.g. Dark Matter Halo)
The data model library (J. Knodelseder)

- **Spectral**
  - Power law
  - Broken power law
  - Exponentially cut off power law
  - Super exponentially cut off power law
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- **Spectral**
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  - File function (arbitrary spectrum)
  - Node function (arbitrary fit)
  - Constant
  - Composite
  - Multiplicative (useful for EBL)

On you can provide your own function file with (Energy, diff. Flux)
The simulated events.fits file

To read the events.fits file
simply use fv (as you probably did with the fermi data!) or ds9

structure info for the fits:
  metadata;
tabulated events;
binary table for GTI.
The simulated events.fits file

The metadata (or header)

- **EXTNAME** = 'EVENTS'
- **DSYP1** = 'TIME'
- **DSYN1** = 's'
- **DVAL1** = 'Data sub-space type'
- **DSYP2** = 'TABLE'
- **DSYR1** = '0.014'
- **DVAL2** = 'Data sub-space reference'
- **DSYP3** = 'POS(RA, DEC)'
- **DSYR2** = 'Data sub-space type'
- **DVAL3** = 'CIRCLE(266.5963,-29.6233.5)'
- **DSYN3** = 'deg'
- **DVAL3** = 'Data sub-space value'
- **NDKEYS** = 3
- **NNAM** = 'GammaLib'
- **TELESCOP** = 'CTA'
- **OBS_ID** = 1
- **DATE_OBS** = '2021-01-01'
- **TIME_OBS** = '11:59:51'
- **DATE_END** = '2021-01-01'
- **TIME_END** = '12:28:51'
- **TSTART** = 6.6277440000E+08
- **TSTOP** = 6.6277619200E+08
- **MJDREFI** = 51544
- **MJDREFF** = 5.0000000000E+00
- **TIMEUNIT** = 's'
- **TIMESYS** = 'TT'
- **TIMEREF** = 'LOCAL'
- **TELAPSE** = 1.8000000000E+03
- **ONTIME** = 1.8000000000E+03
- **LIVE TIME** = 1.7100000000E+03
- **DEADC** = 9.4999998808E-01
- **TIMEDEL** = 1
- **OBJECT** = 'Galactic Centre'
- **RA_OBJ** = 0
- **DEC_OBJ** = 0
- **RA_PNT** = 2.6659631348E-02
- **DEC_PNT** = -2.9623300000E+01
- **ALT_PNT** = 9.0000000000E+01
- **AZ_PNT** = 0
- **RADEC1S** = 'FK5'
- **EQUINOX** = 2.0000000000E+03
- **CONV_DPS** = 0
- **CONV_RA** = 0
- **CONV_DEC** = 0
- **OBSERVER** = 'CTA Consortium'
- **N_TELS** = 0
- **TELLIST** = 'Baseline'
- **GEOLAT** = -2.4627400000E+01
- **GEOLON** = 7.9404100000E+01

Data space

- **Date and time interval covered**
- **Reference (zero) time**
- **Exposure and livetime**
- **Pointing**
# The simulated events.fits file

## The events table

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<thead>
<tr>
<th>Select</th>
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<th>TIME 1D</th>
<th>RA 1E deg</th>
<th>DEC 1E deg</th>
<th>ENERGY 1E TeV</th>
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The simulated events.fits file

The events table

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<tr>
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<td>5.366057E-02</td>
</tr>
<tr>
<td></td>
<td>66</td>
<td>6.627744059111E+08</td>
<td>-9.296028E+01</td>
<td>-2.870448E+01</td>
<td>3.335994E-02</td>
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<td>-9.349898E+01</td>
<td>-2.983537E+01</td>
<td>4.598151E-02</td>
</tr>
</tbody>
</table>

+ GTIs
The simulated log file...

There is also a log file...

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>+---------------------+</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td>`</td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>+---------------------+</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>=== Observation ===</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>Simulation area ..........: 1.9635e+11 cm²</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>Simulation cone ..........: RA=83.63 deg, Dec=22.01 deg, r=5.5 deg</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>Time interval ............: 0 - 1800 s</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>Photon energy range .......: 100 GeV - 100 TeV</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>Event energy range ........: 100 GeV - 100 TeV</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>MC source photons ..........: 207547 [Crab]</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>MC source events ..........: 995 [Crab]</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>MC source events ..........: 995 (all source models)</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>MC background events ......: 5146</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>MC events ................: 6141 (all models)</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>+---------------------+</code></td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td>`</td>
</tr>
<tr>
<td>2014-10-30T22:35:06:</td>
<td><code>+---------------------+</code></td>
</tr>
</tbody>
</table>

current UTC time

- sim detector area
- duration of sim
- # sim source events

Application "ctobssim" terminated after 10 wall clock seconds, consuming 0.3604 seconds
There is also a log file...

The simulated log file...

```
2014-10-30T22:35:06: +---------------------------------+
2014-10-30T22:35:06: | Simulate observation |               
2014-10-30T22:35:06: +---------------------------------+
2014-10-30T22:35:06: === Observation ===
2014-10-30T22:35:06: Simulation area ..........: 1.9635e+11 cm2
2014-10-30T22:35:06: Simulation cone ............: RA=83.63 deg, Dec=22.01 deg, r=5.5 deg
2014-10-30T22:35:06: Time interval .............: 0 - 1800 s
2014-10-30T22:35:06: Photon energy range ......: 100 GeV - 100 TeV
2014-10-30T22:35:06: Event energy range ......: 100 GeV - 100 TeV
2014-10-30T22:35:06: MC source photons ........: 207547 [Crab]
2014-10-30T22:35:06: MC source events ..........: 995 [Crab]
2014-10-30T22:35:06: MC source events ..........: 995 (all source models)
2014-10-30T22:35:06: MC background events .....: 5146
2014-10-30T22:35:06: MC events ................: 6141 (all models)
2014-10-30T22:35:06: +---------------------------------+
2014-10-30T22:35:06: | Save observation |                     
2014-10-30T22:35:06: +---------------------------------+
2014-10-30T22:35:06: Application "ctobssim" terminated after 10 wall clock seconds, consuming 0.3604 seconds
```
Instrument Response Functions

How does the analysis work?
- `ctools` fits the 3D data space to extract spatial and spectral information about the gamma-ray sources.
  - Parametrised model components
  - Simultaneous fitting of spatial and spectral parameters

- Classical VHE analysis techniques (on/off fitting, aperture photometry, etc.) are under development.

- CTA data live in a 4-dimensional world:
  - Reconstructed arrival direction (2D)
  - Reconstructed energy (1D)
  - Time (1D)
- For a given time interval, events can be binned in a 3-dimensional data space or better…?

Instrument Response Functions

- Only South 20° zenith angle available so far
- 50 hr baseline IRF used to simulate 1dc.pre
- Energy dispersion information ignored so far (will be used for final simulations)

or better…?
Instrument Response Functions

\[ I(\vec{p}) \times \int d\vec{p} \ R(\vec{d}|\vec{p}, \vec{a}) = e(\vec{d}) \]

**I** = gamma-ray intensity at Earth as function of true properties (E, t, ra, dec)

**e** = gamma-ray (expected) event rate as function of reconstructed properties (E’, t’, ra’, dec’)

**R** = instrument response to parameters “p”, where “a” are specific telescope parameters
**Instrument Response Functions**

\[ I(\vec{p}) \times \int d\vec{p} \ R(\vec{d}|\vec{p}, \vec{a}) = e(\vec{d}) \]

\[ R(p', E', t'|d, p, E, t) = A_{\text{eff}}(d, p, E, t) \times \text{PSF}(p'|d, p, E, t) \times E_{\text{disp}}(E'|d, p, E, t) \]
Instrument Response Functions

\[ I(\vec{p}) \times \int d\vec{p} \cdot R(\vec{d} | \vec{p}, \vec{a}) = e(\vec{d}) \]

<table>
<thead>
<tr>
<th>Index</th>
<th>Extension</th>
<th>Type</th>
<th>Dimension</th>
<th>View</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Primary</td>
<td>Image</td>
<td>0</td>
<td>Header</td>
</tr>
<tr>
<td>1</td>
<td>EFFECTIVE AREA</td>
<td>Binary</td>
<td>6 cols x 1 rows</td>
<td>Header, Hist, Plot, All, Select</td>
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<td>3</td>
<td>ENERGY DISPERSION</td>
<td>Binary</td>
<td>7 cols x 1 rows</td>
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</tr>
<tr>
<td>4</td>
<td>BACKGROUND</td>
<td>Binary</td>
<td>7 cols x 1 rows</td>
<td>Header, Hist, Plot, All, Select</td>
</tr>
</tbody>
</table>

N, S, 50 hrs, 5 hrs…
Instrument Response Functions

EFFECTIVE AREA

<table>
<thead>
<tr>
<th>Select</th>
<th>ENERG_LO</th>
<th>ENERG_HI</th>
<th>THETA_LO</th>
<th>THETA_HI</th>
<th>EFFAREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>21E TeV</td>
<td>21E TeV</td>
<td>6E deg</td>
<td>6E deg</td>
<td>126E m²</td>
</tr>
<tr>
<td>Invert</td>
<td>Modify</td>
<td>Modify</td>
<td>Modify</td>
<td>Modify</td>
<td>Modify</td>
</tr>
</tbody>
</table>

PSF

<table>
<thead>
<tr>
<th>Select</th>
<th>ENERG_LO</th>
<th>ENERG_HI</th>
<th>THETA_LO</th>
<th>THETA_HI</th>
<th>SCALE</th>
<th>SIGMA_1</th>
<th>AMPL_2</th>
<th>SIGMA_2</th>
<th>AMPL_3</th>
<th>SIGMA_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>21E TeV</td>
<td>21E TeV</td>
<td>6E deg</td>
<td>6E deg</td>
<td>126E</td>
<td>126E</td>
<td>126E</td>
<td>126E</td>
<td>126E</td>
<td>126E</td>
</tr>
<tr>
<td>Invert</td>
<td>Modify</td>
<td>Modify</td>
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<td>Modify</td>
<td>Modify</td>
<td>Modify</td>
<td>Modify</td>
<td>Modify</td>
</tr>
</tbody>
</table>

1 Plot Plot Plot Plot Image Image Image Image Image
# Instrument Response Functions

## PSF

<table>
<thead>
<tr>
<th>Select</th>
<th>ENERG_LO</th>
<th>ENERG_HI</th>
<th>THETA_LO</th>
<th>THETA_HI</th>
<th>SCALE</th>
<th>SIGMA_1</th>
<th>AMPL_2</th>
<th>SIGMA_2</th>
<th>AMPL_3</th>
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<td>126E</td>
<td>126E</td>
<td>126E</td>
<td>126E</td>
<td>126E</td>
<td>126E</td>
</tr>
</tbody>
</table>

- **Plot**
- **Image**

---

**Plot**

```
irt_file.fits(SIGMA_1,1)
```

- **(pixels)**
  - 6
  - 4
  - 2

- **(pixels)**
  - 5
  - 10
  - 15
  - 20

---

**E**
shown is counts versus position for two different energy ranges....
Instrument Response Functions

ENERGY RECONSTRUCTION

From which you derive $E_{\text{recv}}/E_t$:

- Energy dispersion

True energy $[\text{LO}, \text{HI}]$
- Offset angle $[\text{LO}, \text{HI}]$
- Migration ($E_{\text{recv}}/E_{\text{true}}$) $[\text{LO}, \text{HI}]$
- $[0°, 1°]$ $[1°, 2°]$ $[2°, 3°]$ $[3°, 4°]$ $[4°, 5°]$ $[5°, 6°]$

…with a lot of dispersion

Migration matrix
How to for a few tools...

**ctbin**: binning CTA data

A data cube with RA, DEC and E.

---

$ctbin$

Input event list or observation definition file [events.fits]
First coordinate of image center in degrees (RA or galactic l) [83.63]
Second coordinate of image center in degrees (DEC or galactic b) [22.01]
Projection method e.g. AIT|AZP|CAR|MER|STG|TAN (AIT|AZP|CAR|MER|STG|TAN) [CAR]
Coordinate system (CEL - celestial, GAL - galactic) (CEL|GAL) [CEL]
Image scale (in degrees/pixel) [0.02]
Size of the X axis in pixels [200]
Size of the Y axis in pixels [200]
Algorithm for defining energy bins (FILE|LIN|LOG) [LOG]
Start value for first energy bin in TeV [0.1]
Stop value for last energy bin in TeV [100.0]
Number of energy bins [20]
Output counts cube [cntmap.fits]

---

![File, Edit, Tools table](image)
How to for a few tools...

**ctbin**: binning CTA data

A data cube with RA, DEC and E.

multiple maps for different energy ranges
How to for a few tools...

**ctlike**: fitting CTA data

Log-likelihood model-fitting over binned data

```bash
$ ctlike
Event list, counts cube or observation definition file [events.fits] cntmap.fits
Calibration database [dummy]
Instrument response function [cta_dummy_irf]
Source model [$CTOOLS/share/models/crab.xml]
Source model output file [crab_results.xml]
```
How to for a few tools...

**ctlike**: fitting CTA data

---

Log-likelihood model-fitting over binned data

---

**ctselect**: the first step to work directly on the events file

---

**Un-binned** analysis can also be performed and is more powerful

---

- first define the ROI (circular acceptance cone)
- plus time and energy span
- then run **ctlike**...
How to for a few tools...

**ctlike**: TS calculation

\[ L(\theta; X) = \prod_{i=1}^{N} f_i(x_i; \theta) \]

\[ = f_1(x_1; \theta) f_2(x_2; \theta) \ldots f_N(x_N; \theta) \]

\[ TS = 2 \times (\log L - \log L_{null}) \]

or...

\[ \sqrt{TS} \sim \text{sigma(Gauss)} \]

**ctlike**: use “tscal = 1”
How to for a few tools...

**ctbutterfly** : for spectra estimation - a complex procedure...

```bash
$ ctbutterfly
Input event list, cube or observation definition file [events.fits]
Calibration database [dummy]
Instrument response function [cta_dummy_irf]
Source model [$CTOOLS/share/models/crab.xml] crab_results.xml
Source of interest [Crab]
Start value for first energy bin in TeV [0.1]
Stop value for last energy bin in TeV [100.0]
Output ascii file [butterfly.txt]
```

plot using e.g. python from your butterfly.txt
Combining observations: maps

ctttsmap: to produce a test statistics map (TS map)

\[ TS = 2 \times (\log L - \log L_{null}) \]
**Script tools : SEDs**

**csspec** : produces a broad-band spectrum by running ctlike over several energy bins

```
$ csspec
Parfile csspec.par not found. Create default parfile.
Event list, counts cube, or observation definition file [events.fits] obs.xml
Source model [$CTOOLS/share/models/crab.xml]
Source name [Crab]
Number of spectral points [20]
Use binned analysis in each energy bin (yes|no) [no]
Output file name [spectrum.fits]
```
Script tools: light-curves...

cslightcrv:

```bash
$ cslightcrv
Input event list or observation definition XML file [events.fits] obs_selected.xml
Input model definition XML file [$CTOOLS/share/models/crab.xml] models.xml
Source name [Crab] Src001
Algorithm for defining time bins (FILE|LIN|GTI) [GTI] LIN
Lightcurve start time (MJD) [51544.5] 59236.810
Lightcurve stop time (MJD) [51544.6] 59245.742
Number of time bins (1-10000) [5] 100
Number of energy bins for binned (Θ=unbinned)
```
Script tools: SEDs

**csresmap**: to inspect the residuals of the fitted skymaps...

```
$ csresmap
Input event list, counts cube, or observation definition XML file [events.fits] obs_selected.xml
Input model definition XML file [$CTOOLS/share/models/crab.xml] results.xml
First coordinate of image center in degrees (RA or galactic l) (0-360) [83.63] 0.0
Second coordinate of image center in degrees (DEC or galactic b) (-90-90) [22.01] 0.0
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Coordinate System (CEL|GAL) [CEL] GAL
Projection method (AIT|AZP|CAR|MER|MOL|STG|TAN) [CAR]
Size of the X axis in pixels [200] 400
Size of the Y axis in pixels [200] 400
Pixel size (deg/pixel) [0.02] 0.02
Residual map computation algorithm (SUB|SUBDIV|SUBDIVSQRT) [SUBDIV] SUB
Output residual map file [resmap.fits]
```
Script tools : SEDs

csresmap : to inspect the residuals of the fitted skymaps...

```
$ csresmap
Input event list, counts cube, or observation definition XML file [events.fits] obs_selected.xml
Input model definition XML file [$CTOOLS/share/models/crab.xml] results.xml
First coordinate of image center in degrees (RA or galactic l) (0-360) [83.63] 0.0
Second coordinate of image center in degrees (DEC or galactic b) (-90-90) [22.01] 0.0
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Coordinate System (CEL|GAL) [CEL] GAL
Projection method (AIT|AZP|CAR|MER|MOL|STG|TAN) [CAR]
Size of the X axis in pixels [200] 400
Size of the Y axis in pixels [200] 400
Pixel size (deg/pixel) [0.02] 0.02
Residual map computation algorithm (SUB|SUBDIV|SUBDIVSQRT) [SUBDIV] SUB
Output residual map file [resmap.fits]
```

clearly a residual is remaining...
Diffuse emission model!

```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<source_library title="source library">
  <source name="Src001" type="PointSource">
    <spectrum type="PowerLaw">
      <parameter name="Prefactor" value="1" error="0" scale="5.7e-18" min="0" free="1" />
      <parameter name="Index" value="1" error="-2.48" scale="-4.03225806451613" max="4.03225806451613" />
      <parameter name="PivotEnergy" value="1" scale="300000" free="0" />
    </spectrum>
    <spatialModel type="PointSource">
      <parameter name="RA" value="266.424004498437" error="0" scale="1" free="1" />
      <parameter name="DEC" value="-29.004010253548" error="0" scale="1" free="1" />
    </spatialModel>
  </source>
  <source name="Src002" type="PointSource">
    <spectrum type="PowerLaw">
      <parameter name="Prefactor" value="1" error="0" scale="5.7e-18" min="0" free="1" />
      <parameter name="Index" value="1" error="-2.48" scale="-4.03225806451613" max="4.03225806451613" />
      <parameter name="PivotEnergy" value="1" scale="300000" free="0" />
    </spectrum>
    <spatialModel type="PointSource">
      <parameter name="RA" value="266.831945177213" error="0" scale="1" free="1" />
      <parameter name="DEC" value="-28.1460284439951" error="0" scale="1" free="1" />
    </spatialModel>
  </source>
  <source name="IEM" type="DiffuseSource">
    <spectrum type="ConstantValue">
      <parameter name="Value" value="1" error="0" scale="1" min="1e-05" max="100000" free="1" />
    </spectrum>
    <spatialModel type="MapCubeFunction" file="$CTADATA/models/cube_iem.fits.gz">
      <parameter name="Normalization" value="1" scale="1" min="0.001" max="1000" free="0" />
    </spatialModel>
  </source>
  <source name="Background" type="CTAInfBackground">
    <spectrum type="PowerLaw">
      <parameter name="Prefactor" value="1" error="0" scale="1" min="0" free="1" />
      <parameter name="Index" value="0" error="0" scale="1" min="-10" max="10" free="1" />
      <parameter name="PivotEnergy" value="1" scale="1000000" free="0" />
    </spectrum>
  </source>
</source_library>
```
Script tools: SEDs

**csresmap**: to inspect the residuals of the fitted skymaps...

```bash
$ csresmap
Input event list, counts cube, or observation definition XML file [events.fits] obs_selected.xml
Input model definition XML file [SCTOOLS/share/models/crab.xml] results.xml
First coordinate of image center in degrees (RA or galactic l) (0-360) [83.63] 0.0
Second coordinate of image center in degrees (DEC or galactic b) (-90-90) [22.01] 0.0
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Coordinate System (CEL|GAL) [CEL] GAL
Projection method (AIT|AZP|CAR|MER|MOL|STG|TAN) [CAR]
Size of the X axis in pixels [200] 400
Size of the Y axis in pixels [200] 400
Pixel size (deg/pixel) [0.02] 0.02
Residual map computation algorithm (SUB|SUBDIV|SUBDIVSQR) [SUBDIV] SUB
Output residual map file [resmap.fits]
```

with diffuse model...
Script tools: SEDs

csspec: produces a broad-band spectrum by running ctlike over several energy bins

```
$ csspec
Parfile csspec.par not found. Create default parfile.
Event list, counts cube, or observation definition file [events.fits] obs.xml
Source model [$CTOOLS/share/models/crab.xml]
Source name [Crab]
Number of spectral points [20]
Use binned analysis in each energy bin (yes|no) [no]
Output file name [spectrum.fits]
```

plus...:

- cscaldb — Lists available instrument response functions
- csobsdef — Generates observation definition file
- cslightcry — Computes lightcurve
- cspull — Generates pull distribution
- cssens — Computes CTA sensitivity
- csspec — Computes spectral points
- csresmap — Generates residual map
- cstsdist — Generates TS distribution
VO tools: Important!

```
$ ctskymap publish=yes
Input event list or observation definition XML file [events.fits] obs_selected.xml
First coordinate of image center in degrees (RA or galactic l) (0-360) [83.63] 0.0
Second coordinate of image center in degrees (DEC or galactic b) (-90-90) [22.01] 0.0
Projection method (AIT|AZP|CAR|MER|MOL|STG|TAN) [CAR]
Coordinate system (CEL - celestial, GAL - galactic) (CEL|GAL) [CEL] GAL
Image scale (in degrees/pixel) [0.02]
Size of the X axis in pixels [200] 400
Size of the Y axis in pixels [200] 400
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Background subtraction method (NONE|IRF) [NONE]
Output skymap file [skymap.fits]
```

play with other tools like CDS’s Aladin, etc…
If you have a simulated sky already...

csobselect: selected from simulated observations all pointing with 0.1 deg of GC, for example

```bash
$ csobsselect
Input event list or observation definition XML file [obs.xml] $CTADATA/obs/obs_gc_baseline.xml
Pointing selection region shape (CIRCLE|BOX) [CIRCLE]
Coordinate system (CEL - celestial, GAL - galactic) (CEL|GAL) [CEL] GAL
Galactic longitude of selection centre (deg) (0-360) [184.56] 0.0
Galactic latitude of selection centre (deg) (-90-90) [-5.79] 0.0
Radius of selection circle (deg) (0-180) [5.0] 0.1
Output observation definition XML file [outobs.xml] obs.xml
```

cctselect: selected from these only events between 100 GeV and 100 Tev, e.g.

```bash
$ ctselect
Input event list or observation definition XML file [events.fits] obs.xml
RA for ROI centre (degrees) (0-360) [83.63] UNDEFINED
Start time (CTA MET in seconds) [0.0] UNDEFINED
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Output event list or observation definition XML file [selected_events.fits] obs_selected.xml
```
If you have a simulated sky already...

ctskymap: create a sky map from your selected event files

```
$ ctskymap
Input event list or observation definition XML file [events.fits] obs_selected.xml
First coordinate of image center in degrees (RA or galactic l) (0-360) [83.63] 0.0
Second coordinate of image center in degrees (DEC or galactic b) (-90-90) [22.01] 0.0
Projection method (AIT|AZP|CAR|MER|MOL|STG|TAN) [CAR]
Coordinate system (CEL - celestial, GAL - galactic) (CEL|GAL) [CEL] GAL
Image scale (in degrees/pixel) [0.02]
Size of the X axis in pixels [200] 400
Size of the Y axis in pixels [200] 400
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Background subtraction method (NONE|IRF) [NONE]
Output skymap file [skymap.fits]
```

© Jürgen Knödlseder
If you have a simulated sky already...

cskymap: ...or a background subtracted skymap

```
$ cskymap
Input event list or observation definition XML file [events.fits] obs_selected.xml
First coordinate of image center in degrees (RA or galactic l) (0-360) [83.63] 0.0
Second coordinate of image center in degrees (DEC or galactic b) (-90-90) [22.01] 0.0
Projection method (AIT|AZP|CAR|MER|MOL|STG|TAN) [CAR]
Coordinate system (CEL - celestial, GAL - galactic) (CEL|GAL) [CEL] GAL
Image scale (in degrees/pixel) [0.02]
Size of the X axis in pixels [400]
Size of the Y axis in pixels [400]
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Background subtraction method (NONE|IRF) [NONE] IRF
Output skymap file [skymap.fits] skymap_bkgsubtract.fits
```

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If you have a simulated sky already...

ctskymap: ...or a background subtracted skymap

```
$ ctskymap
Input event list or observation definition XML file [events.fits] obs_selected.xml
First coordinate of image center in degrees (RA or galactic l) (0-360) [83.63] 0.0
Second coordinate of image center in degrees (DEC or galactic b) (-90-90) [22.01] 0.0
Projection method (AIT|AZP|CAR|MER|MOL|STG|TAN) [CAR]
Coordinate system (CEL - celestial, GAL - galactic) (CEL|GAL) [CEL] GAL
Image scale (in degrees/pixel) [0.02]
Size of the X axis in pixels [400]
Size of the Y axis in pixels [400]
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Background subtraction method (NONE|IRF) [NONE] IRF
Output skymap file [skymap.fits] skymap_bkgsubtract.fits
```

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cssrdetect: detecting source candidates within sky map selected events

> detection threshold?
If you have a simulated sky already...

ctskymap: ...the significance of a source

```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<source_library title="source library">
  <source name="Src001" type="PointSource" tcalc="1">
    <spectrum type="PowerLaw">
      <parameter name="Prefactor" value="1" error="0" scale="5.7e-18" min="0" free="1" />
      <parameter name="Index" value="1" error="-0" scale="-2.48" min="-4.03225806451613" max="4.03225806451613" />
      <parameter name="PivotEnergy" value="1" scale="300000" free="0" />
    </spectrum>
    <spatialModel type="PointSource">
      <parameter name="RA" value="266.424004498437" error="0" scale="1" free="1" />
      <parameter name="DEC" value="-29.0049010253548" error="0" scale="1" free="1" />
    </spatialModel>
  </source>
  ...
</source_library>
```

Will be given in terms of a TS (see below!)