Introduction to ctools

Luigi Tibaldo, IRAP, Toulouse
luigi.tibaldo@irap.omp.eu
http://userpages.irap.omp.eu/~ltibaldo

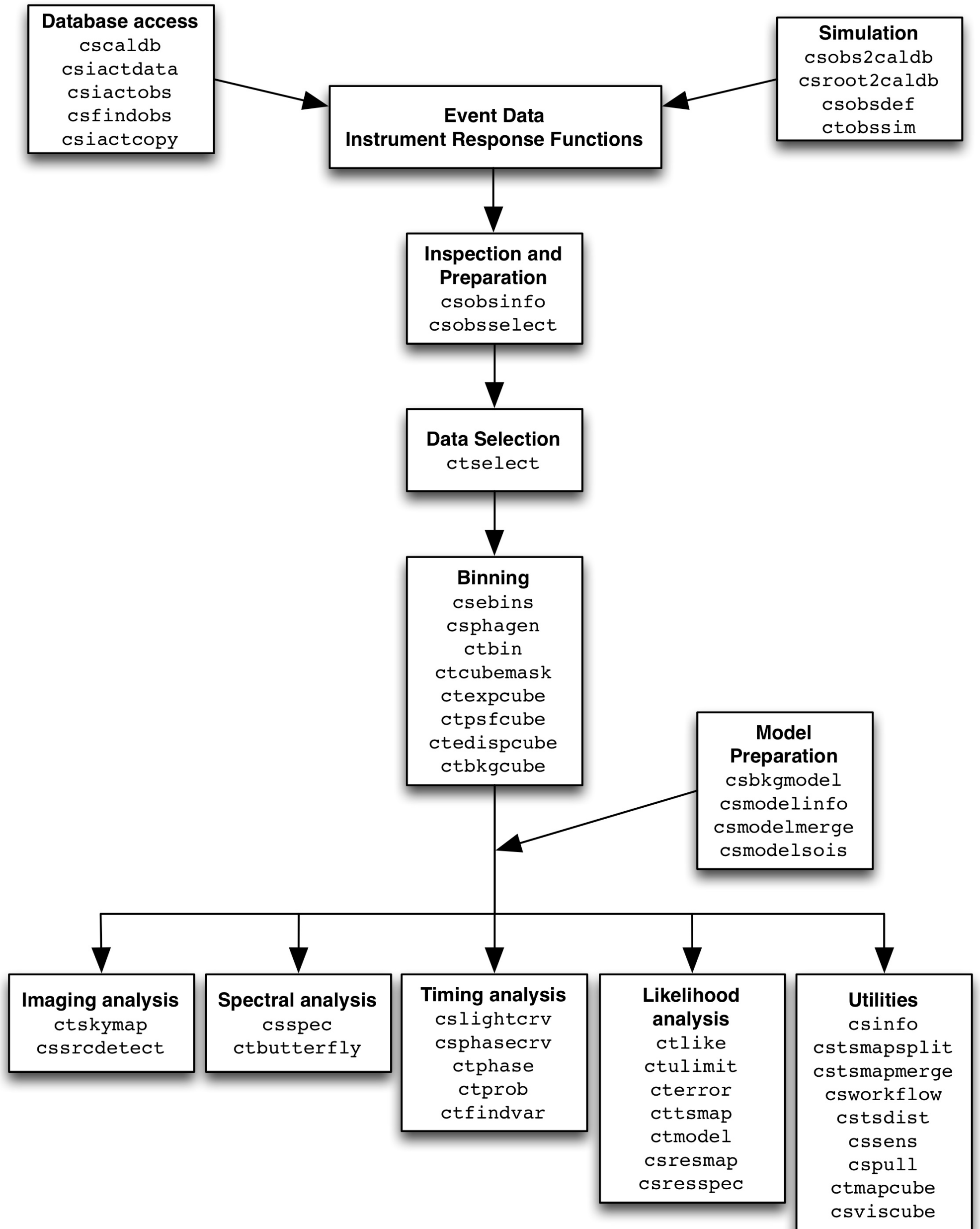
ctools in a nutshell

- Open-source community-developed software package for the scientific analysis of data from imaging atmospheric Cherenkov telescopes (IACTs), developed in the framework of CTA
- Based on GammaLib, a toolbox for scientific analysis of astronomical gamma-ray data (support for IACTs/CTA, *Fermi* LAT, COMPTEL)
- Find all the information on the website

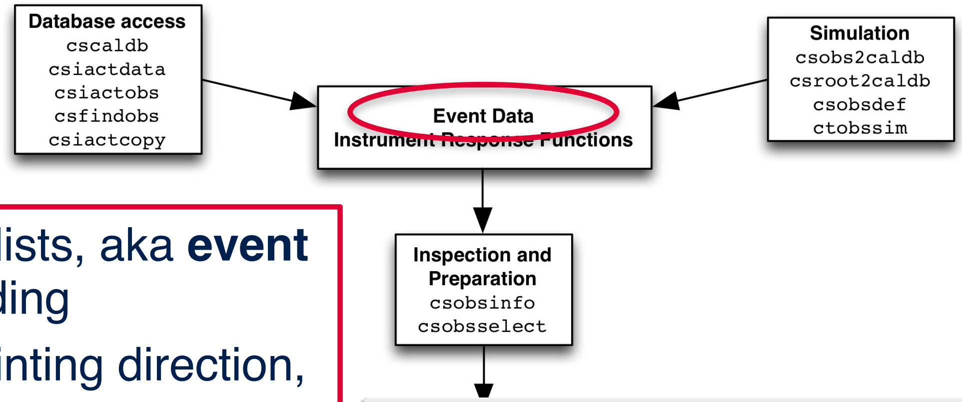
  http://cta.irap.omp.eu/ctools/

  - how to get them
  - how to use them (manual, tutorials, description of tools)
  - how to contribute to development
- Latest release 1.6.1

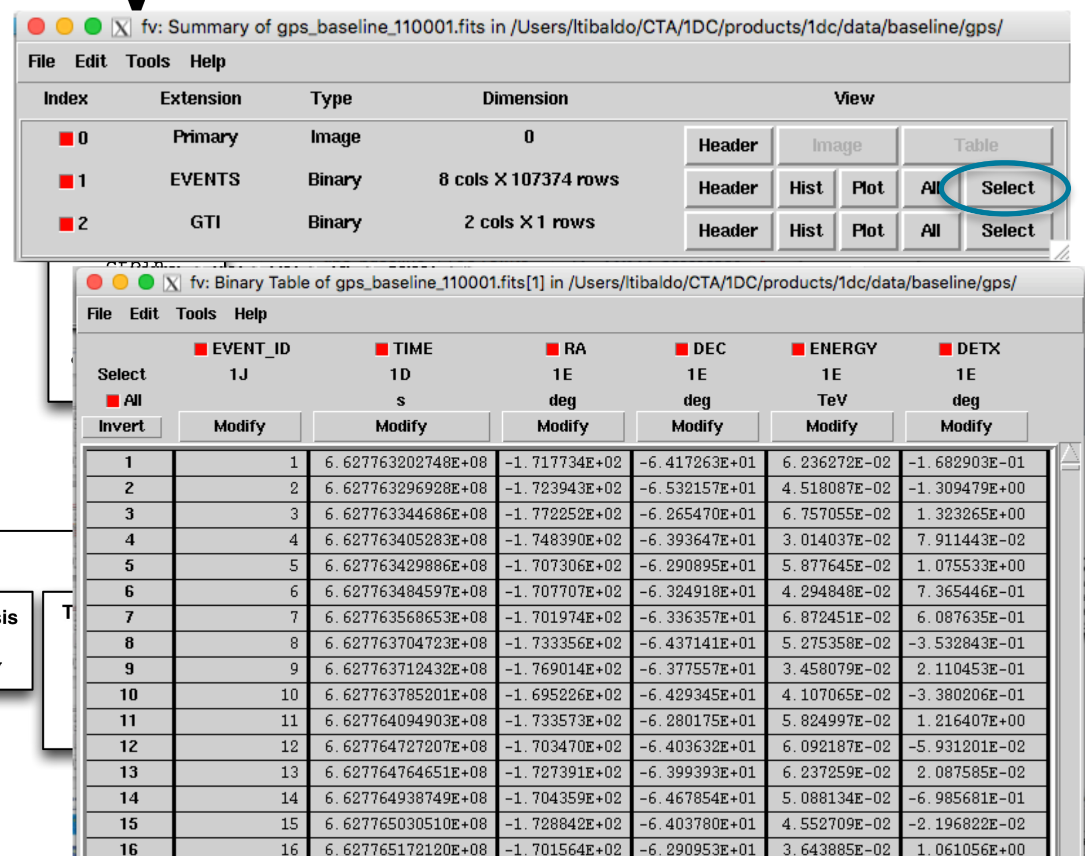
Tools overview



Data



- candidate photon lists, aka **event lists** (FITS), including
  - metadata (pointing direction, livetime …)
  - good time intervals (GTIs): continuous intervals of data taking with stable instrument response
- event lists from different observations combined in observation lists (XML)


fv: Summary of gps_baseline_110001.fits in /Users/ltibaldo/CTA/1DC/products/1dc/data/baseline/gps/

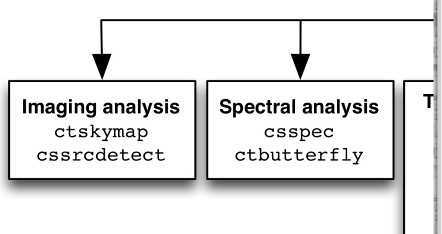
File Edit Tools Help

Index	Extension	Type	Dimension	View				
0	Primary	Image	0	Header	Image	Table		
1	EVENTS	Binary	8 cols X 107374 rows	Header	Hist	Plot	All	Select
2	GTI	Binary	2 cols X 1 rows	Header	Hist	Plot	All	Select

fv: Binary Table of gps_baseline_110001.fits[1] in /Users/ltibaldo/CTA/1DC/products/1dc/data/baseline/gps/

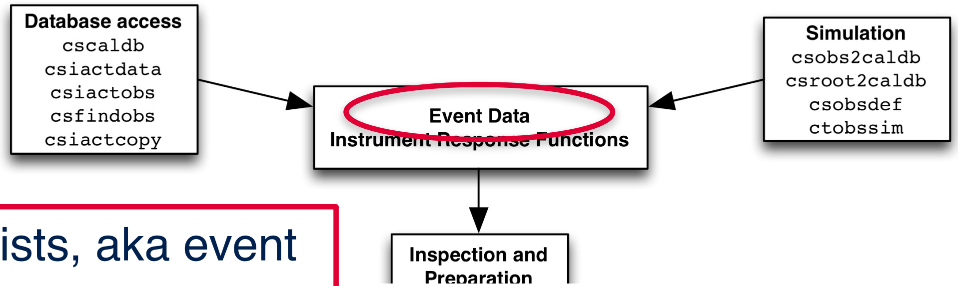
File Edit Tools Help

Select	EVENT_ID	TIME	RA	DEC	ENERGY	DETX
	1J	1D	1E	1E	1E	1E
All		s	deg	deg	TeV	deg
Invert	Modify	Modify	Modify	Modify	Modify	Modify
1	1	6.627763202748E+08	-1.717734E+02	-6.417263E+01	6.236272E-02	-1.682903E-01
2	2	6.627763296928E+08	-1.723943E+02	-6.532157E+01	4.518087E-02	-1.309479E+00
3	3	6.627763344686E+08	-1.772252E+02	-6.265470E+01	6.757055E-02	1.323265E+00
4	4	6.627763405283E+08	-1.748390E+02	-6.393647E+01	3.014037E-02	7.911443E-02
5	5	6.627763429886E+08	-1.707306E+02	-6.290895E+01	5.877645E-02	1.075533E+00
6	6	6.627763484597E+08	-1.707707E+02	-6.324918E+01	4.294848E-02	7.365446E-01
7	7	6.627763568653E+08	-1.701974E+02	-6.336357E+01	6.872451E-02	6.087635E-01
8	8	6.627763704723E+08	-1.733356E+02	-6.437141E+01	5.275358E-02	-3.532843E-01
9	9	6.627763712432E+08	-1.769014E+02	-6.377557E+01	3.458079E-02	2.110453E-01
10	10	6.627763785201E+08	-1.695226E+02	-6.429345E+01	4.107065E-02	-3.380206E-01
11	11	6.627764094903E+08	-1.733573E+02	-6.280175E+01	5.824997E-02	1.216407E+00
12	12	6.627764727207E+08	-1.703470E+02	-6.403632E+01	6.092187E-02	-5.931201E-02
13	13	6.627764764651E+08	-1.727391E+02	-6.399393E+01	6.237259E-02	2.087585E-02
14	14	6.627764938749E+08	-1.704359E+02	-6.467854E+01	5.088134E-02	-6.985681E-01
15	15	6.627765030510E+08	-1.728842E+02	-6.403780E+01	4.552709E-02	-2.196822E-02
16	16	6.627765172120E+08	-1.701564E+02	-6.290953E+01	3.643885E-02	1.061056E+00



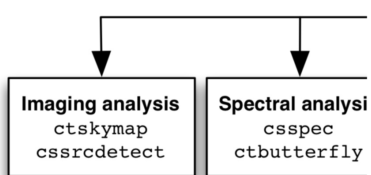
https://gamma-astro-data-formats.readthedocs.io

Data



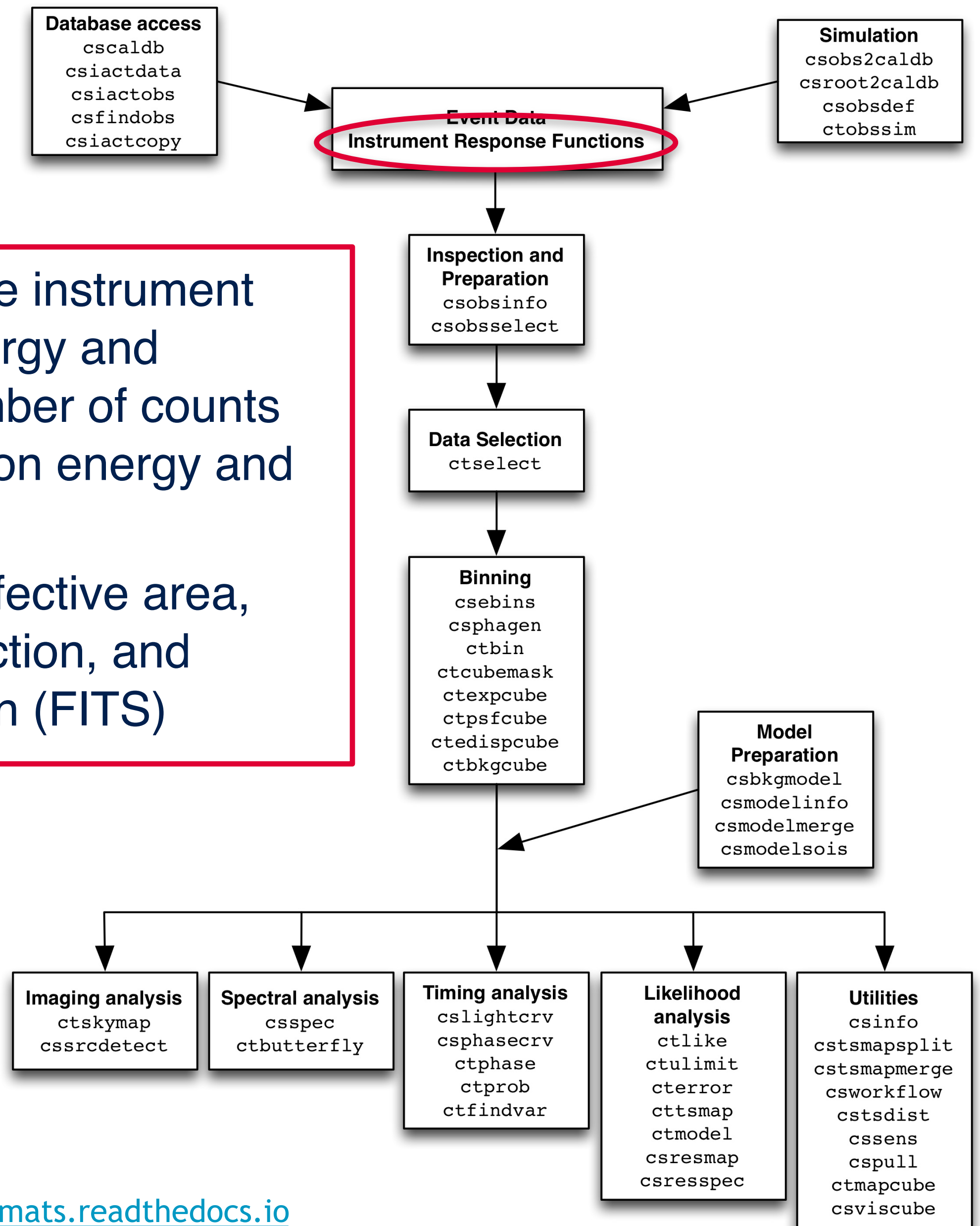
- candidate photon lists, aka event lists (FITS), including
  - metadata (pointing direction, livetime …)
  - good time intervals (GTIs): continuous intervals of data taking with stable instrument response
- event lists from different observations combined in **observation lists** (XML)


```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<observation_list title="observation list">
 <observation name="GPS" id="110000" instrument="CTA">
  <parameter name="Pointing" ra="186.1561" dec="-64.019" />
  <parameter name="EnergyBoundaries" emin="30000" emax="160000000" />
  <parameter name="GoodTimeIntervals" tmin="662774400" tmax="662776200" />
  <parameter name="TimeReference" mjdrefi="51544" mjdreff="0.5" timeunit="s" timesys="TT" timeref="LOCAL" />
  <parameter name="RegionOfInterest" ra="186.1561" dec="-64.019" rad="5" />
  <parameter name="Deadtime" deadc="0.98" />
  <parameter name="Calibration" database="1dc" response="South_z40_50h" />
  <parameter name="EventList" file="$CTADATA/data/baseline/gps/gps_baseline_110000.fits" />
 </observation>
 <observation name="GPS" id="110001" instrument="CTA">
  <parameter name="Pointing" ra="186.1561" dec="-64.019" />
  <parameter name="EnergyBoundaries" emin="30000" emax="160000000" />
  <parameter name="GoodTimeIntervals" tmin="662776320" tmax="662778120" />
  <parameter name="TimeReference" mjdrefi="51544" mjdreff="0.5" timeunit="s" timesys="TT" timeref="LOCAL" />
  <parameter name="RegionOfInterest" ra="186.1561" dec="-64.019" rad="5" />
  <parameter name="Deadtime" deadc="0.98" />
  <parameter name="Calibration" database="1dc" response="South_z40_50h" />
  <parameter name="EventList" file="$CTADATA/data/baseline/gps/gps_baseline_110001.fits" />
 </observation>
 <observation name="GPS" id="110002" instrument="CTA">
  <parameter name="Pointing" ra="186.1561" dec="-64.019" />
  <parameter name="EnergyBoundaries" emin="30000" emax="160000000" />
  <parameter name="GoodTimeIntervals" tmin="662778240" tmax="662780040" />
  <parameter name="TimeReference" mjdrefi="51544" mjdreff="0.5" timeunit="s" timesys="TT" timeref="LOCAL" />
  <parameter name="RegionOfInterest" ra="186.1561" dec="-64.019" rad="5" />
  <parameter name="Deadtime" deadc="0.98" />
  <parameter name="Calibration" database="1dc" response="South_z40_50h" />
  <parameter name="EventList" file="$CTADATA/data/baseline/gps/gps_baseline_110002.fits" />
 </observation>
 <observation name="GPS" id="110003" instrument="CTA">
  <parameter name="Pointing" ra="186.1561" dec="-64.019" />
  <parameter name="EnergyBoundaries" emin="30000" emax="160000000" />
  <parameter name="GoodTimeIntervals" tmin="662780160" tmax="662781960" />
  <parameter name="TimeReference" mjdrefi="51544" mjdreff="0.5" timeunit="s" timesys="TT" timeref="LOCAL" />
  <parameter name="RegionOfInterest" ra="186.1561" dec="-64.019" rad="5" />
  <parameter name="Deadtime" deadc="0.98" />
  <parameter name="Calibration" database="1dc" response="South_z40_50h" />
  <parameter name="EventList" file="$CTADATA/data/baseline/gps/gps_baseline_110003.fits" />
 </observation>
```

https://gamma-astro-data-formats.readthedocs.io

IRFs

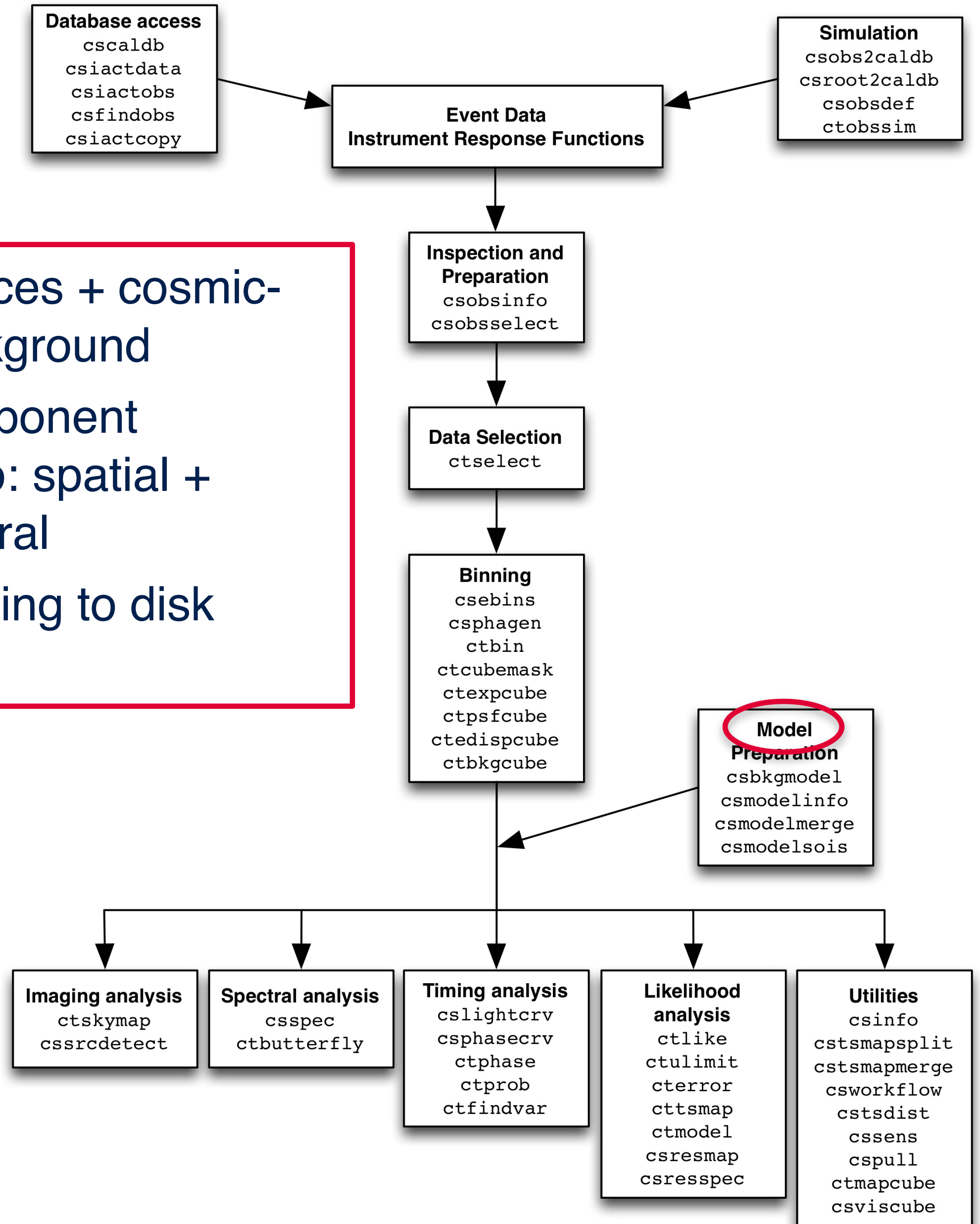


- flux arriving at the instrument (**true** photon energy and direction) → number of counts (**measured** photon energy and direction)
- factorised into effective area, point spread function, and energy dispersion (FITS)

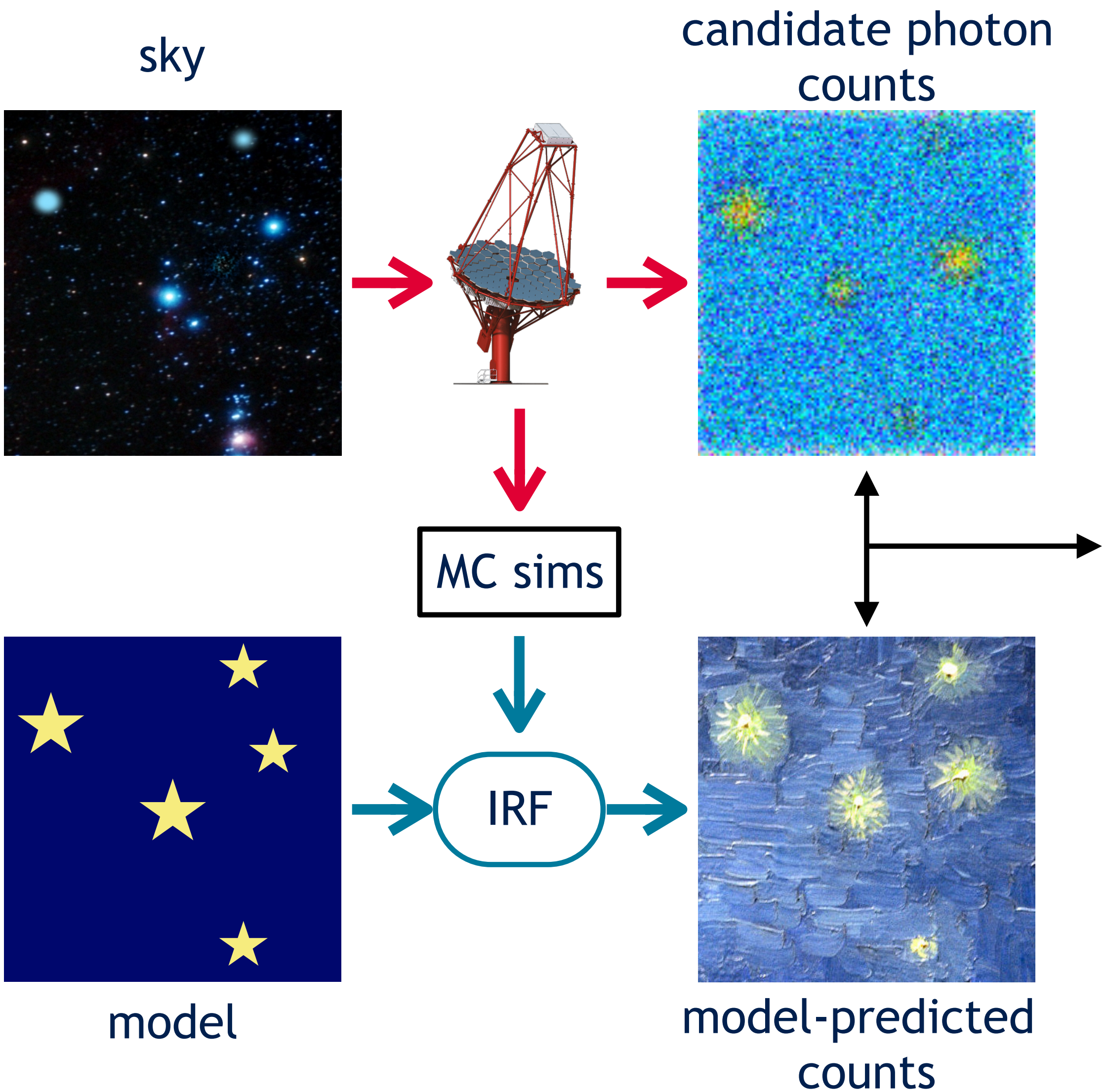
https://gamma-astro-data-formats.readthedocs.io

Models

- gamma-ray sources + cosmic-ray residual background
- each model component decomposed into: spatial + spectral + temporal
- serialised for writing to disk using XML



The likelihood method ...

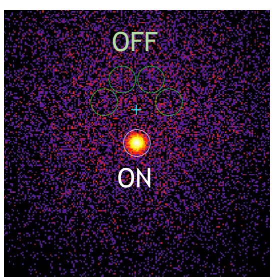


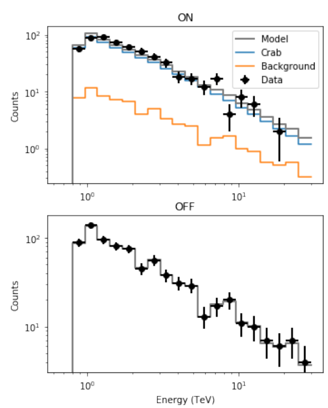
- compute likelihood of given model
- determine best-fit values and uncertainties of model parameters (e.g., source fluxes) via maximum likelihood

… and its different incarnations

On/Off, aka classical

- similar to X-rays
- 2D for imaging and 1D for spectral analysis
- On (source) and Off (background) regions
- fewer assumptions on background, but sacrifices information



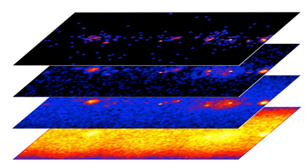


3D

- similar to *Fermi* LAT
- model background and sources together in 3D sky direction + energy space
- full data information exploited but requires adequate background model

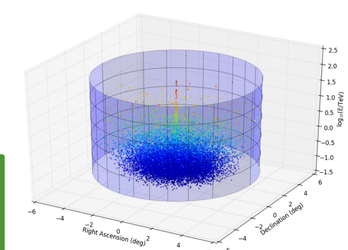
binned

- bin events in sky direction and energy



unbinned

- full information exploited for each event



Multiple observations: for On/Off and binned analysis
- joint analysis → each observation treated independently
- stacked analysis

Using ctools

executables (command line, shell scripts …)

```
$ ctobssim edisp=yes
RA of pointing (degrees) (0-360) [83.63] 83.5
Dec of pointing (degrees) (-90-90) [22.51] 22.8
Radius of FOV (degrees) (0-180) [5.0]
Start time (UTC string, JD, MJD or MET in seconds) [2020-01-01T00:00:00]
Stop time (UTC string, JD, MJD or MET in seconds) [2020-01-01T00:30:00] 2020-01-01T01:00:00
Lower energy limit (TeV) [0.1] 0.03
Upper energy limit (TeV) [100.0] 150.
Calibration database [prod2] prod3b-v2
Instrument response function [South_0.5h] South_z40_0.5h
Input model definition XML file [$CTOOLS/share/models/crab.xml]
Output event data file or observation definition XML file [events.fits]
$
```

Python API (terminal, scripts, Jupyter notebooks)

```
sim = ctools.ctobssim()
sim['inmodel'] = '${CTOOLS}/share/models/crab.xml'
sim['outevents'] = 'events.fits'
sim['caldb'] = 'prod3b-v2'
sim['irf'] = 'South_z40_0.5h'
sim['ra'] = 83.5
sim['dec'] = 22.8
sim['rad'] = 5.0
sim['tmin'] = '2020-01-01T00:00:00'
sim['tmax'] = '2020-01-01T01:00:00'
sim['emin'] = 0.03 # energies as user parameters are always in TeV
sim['emax'] = 150.0
sim['edisp'] = True
sim.execute()
```

Using ctools

executables (command line, shell scripts …)

```
$ ctobssim edisp=yes
RA of pointing (degrees) (0-360) [83.63] 83.5
Dec of pointing (degrees) (-90-90) [22.51] 22.8
Radius of FOV (degrees) (0-180) [5.0]
Start time (UTC string, JD, MJD or MET in seconds) [2020-01-01T00:00:00]
Stop time (UTC string, JD, MJD or MET in seconds) [2020-01-01T00:30:00] 2020-01-01T01:00:00
Lower energy limit (TeV) [0.1] 0.03
Upper energy limit (TeV) [100.0] 150.
Calibration database [prod2] prod3b-v2
Instrument response function [South_0.5h] South_z40_0.5h
Input model definition XML file [$CTOOLS/share/models/crab.xml]
Output event data file or observation definition XML file [events.fits]
$
```

→ edisp=yes: hidden parameter, not inquired automatically
automatic parameter
→ [22.51]: default/latest used value
→ 0.03: user-specified value

Python API (terminal, scripts, Jupyter notebooks)

```
sim = ctools.ctobssim()
sim['inmodel'] = '${CTOOLS}/share/models/crab.xml'
sim['outevents'] = 'events.fits'
sim['caldb'] = 'prod3b-v2'
sim['irf'] = 'South_z40_0.5h'
sim['ra'] = 83.5
sim['dec'] = 22.8
sim['rad'] = 5.0
sim['tmin'] = '2020-01-01T00:00:00'
sim['tmax'] = '2020-01-01T01:00:00'
sim['emin'] = 0.03 # energies as user parameters are always in TeV
sim['emax'] = 150.0
sim['edisp'] = True
sim.execute()
```

Planning for the rest of the sessions

- Now: first step with ctools (demonstration) → simulation/ analysis of CTA observations of the Crab Nebula
- This afternoon/Wednesday: hands-on tutorials♀

1. revisit the Crab Nebula tutorial by playing with different analysis configuration/parameters
2. background modelling*
3. analysis of a variable source*
4. analysis of an extended source*
5. advanced model manipulation and fitting
6. explore your own Science case!

♀ provided as Jupyter notebooks, if you prefer scripts or running from the command line just use the notebooks as guide

* makes use of H.E.S.S. public data

Practical info

You have two options to practise the tools

1. Use the virtual machine provided by the school
2. Install on your machine
   - install ctools: http://cta.irap.omp.eu/ctools/admin/index.html (recommended option: Installing via Anaconda)
   - get Jupyter: https://jupyter.org/install
   - get public H.E.S.S. data: http://cta.irap.omp.eu/ctools/users/tutorials/hess_dr1/data.html
   - get the latest CTA IRFs: http://cta.irap.omp.eu/ctools/users/user_manual/irf_cta.html#getting-cta-irfs (you can get prod3b-v2 IRFs from: https://www.cta-observatory.org/wp-content/uploads/2019/04/CTA-Performance-prod3b-v2-FITS.tar.gz)

You can find these slide and all the notebooks on my webpage.