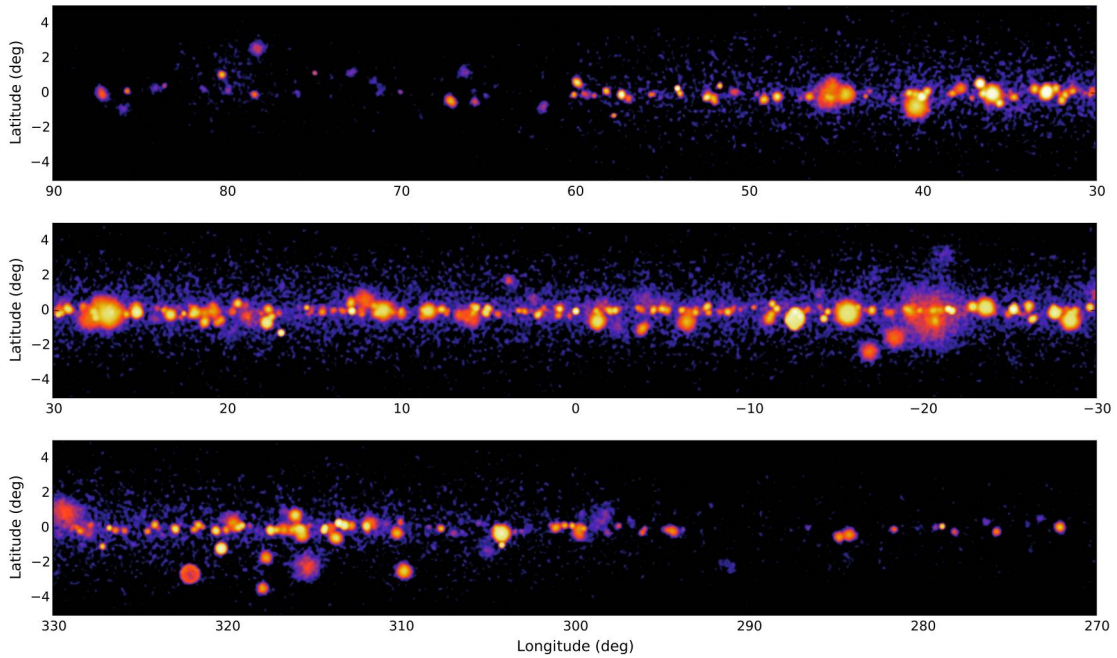
cherenkov telescope array

ctools
cherenkov telescope array

CTA data hands-on workshop

2-3 October 2017

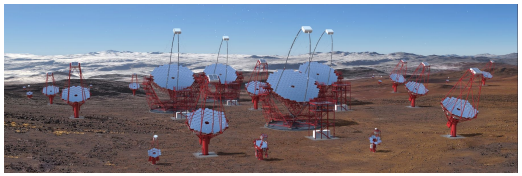
Jürgen Knödlseder



Topics covered

- A few ctools basics
- Using ctools
- How to get help

The CTA data model

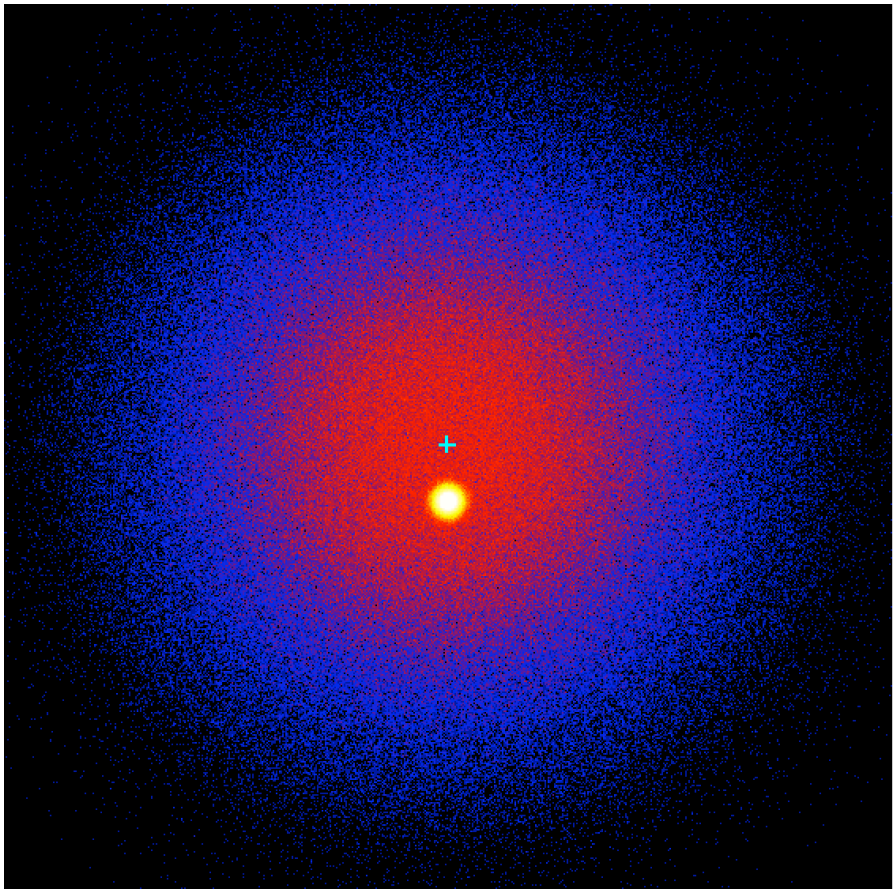


- The Science Community will get from CTAO a **predefined*** data product
  - Science Community can **not** run own calibration, reconstruction or reduction
  - A **number of different data cuts** will be provided to the science community
  - Science Community will get from CTAO the **software for data analysis**
  - CTAO will provide User Support to Science Community
- Data processing runs on CTAO infrastructure
- Data analysis runs on scientist's infrastructure (laptop, institute cluster, etc.)

*by CTAO

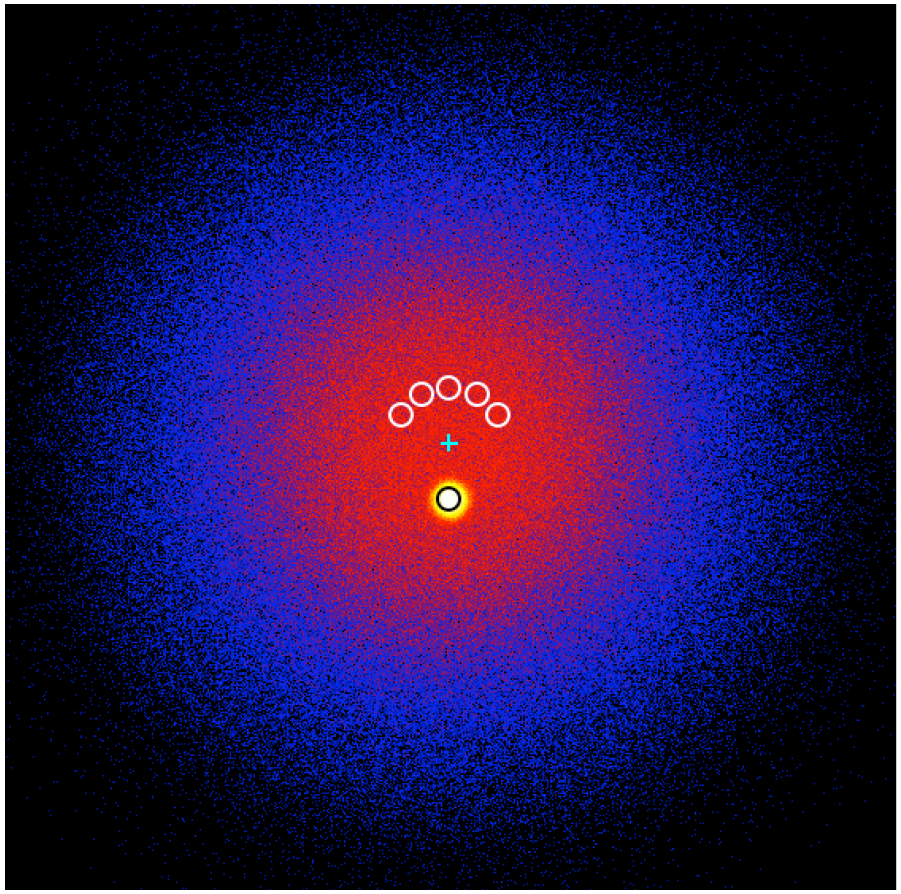
The ctools analysis model

50 h Crab simulation (0.5° off-axis)



The ctools analysis model

50 h Crab simulation (0.5° off-axis)

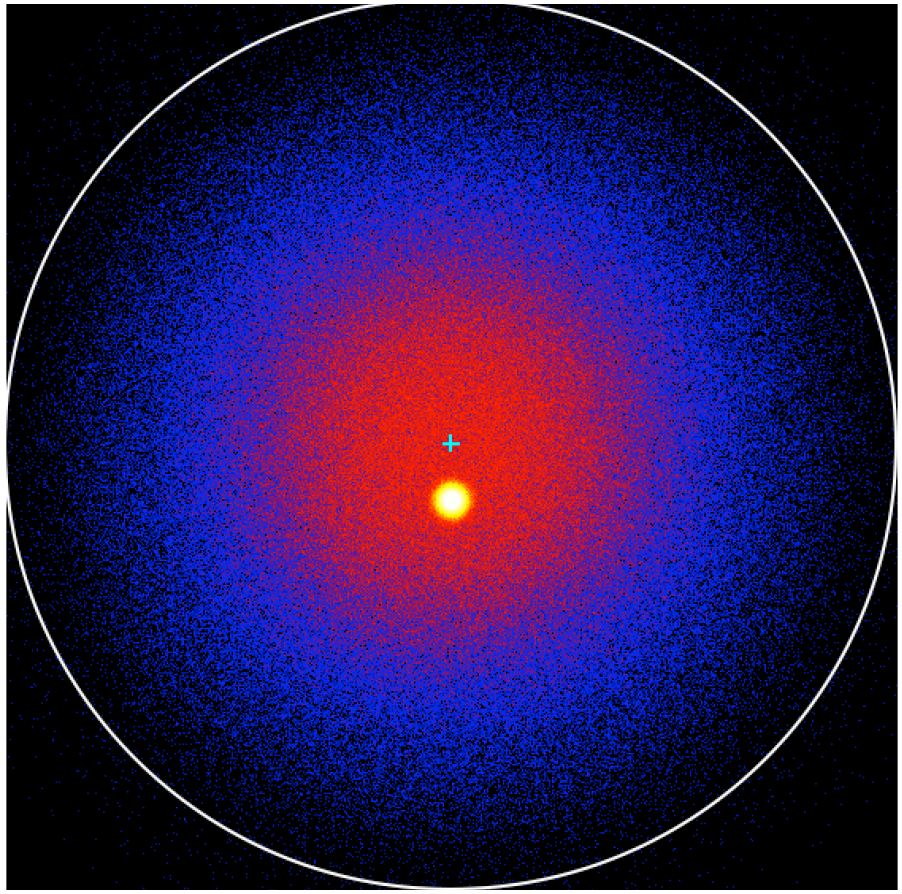


Classical VHE analysis

- Define reflected regions for background determination (white circles, 5 is standard for CTA)
- Assume that the background in these regions is the same as in the source region (axisymmetric background acceptance model)
- Determine source significance by maximum likelihood fitting in on and off regions (i.e. Li & Ma)

The ctools analysis model

50 h Crab simulation (0.5° off-axis)



ctools analysis

- ~~Define reflected regions for background determination (white circles, 5 is standard for CTA)~~
- Assume that the background shape over a Region of Interest (RoI) is known (template fitting) ~~in these regions is the same as in the source region (flat background acceptance model)~~
- Determine source significance by maximum likelihood fitting ~~in on and off regions~~ over the entire RoI ~~(i.e. Li & Ma)~~

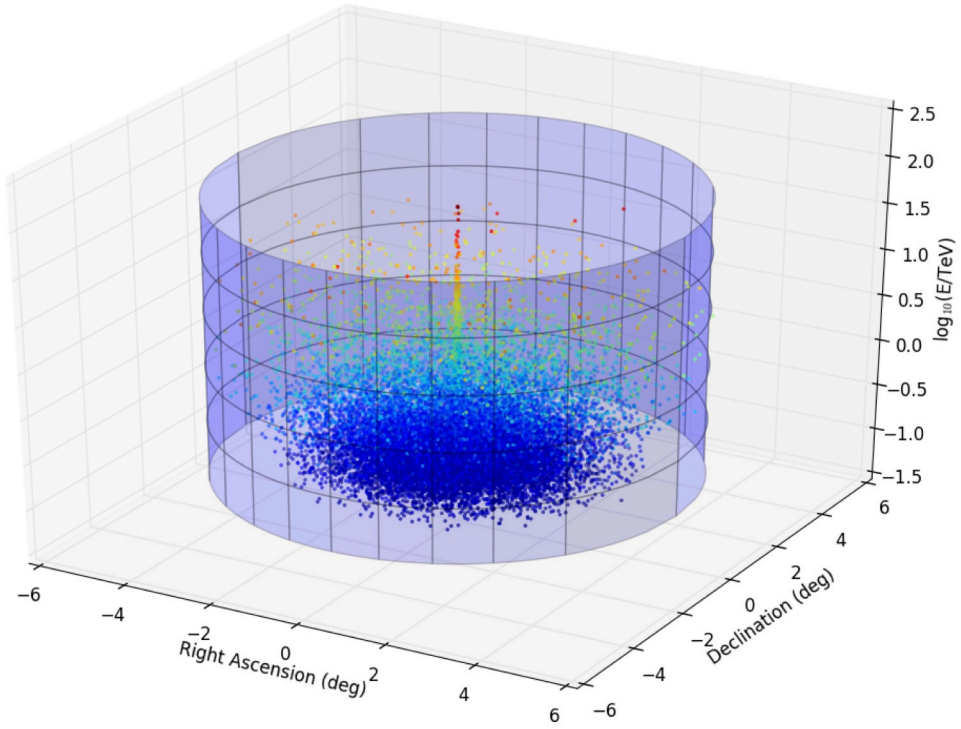
=>

- Main difference expected from different handling of background fitting
- Difference of PSF fitting expected to be small

How does the ctools analysis work?

- CTA event data live in a 4 dimensional world
  - Reconstructed arrival direction (2d)
  - Reconstructed energy (1d)
  - Time (1d)
- **Event lists** can be fitted with a **parametric model** using an **unbinned maximum likelihood algorithm**

fixed pointing



$$-\ln L_i(M) = e_i(M) - \sum_k \ln P_i(\boldsymbol{p}'_k, E'_k, t'_k|M)$$

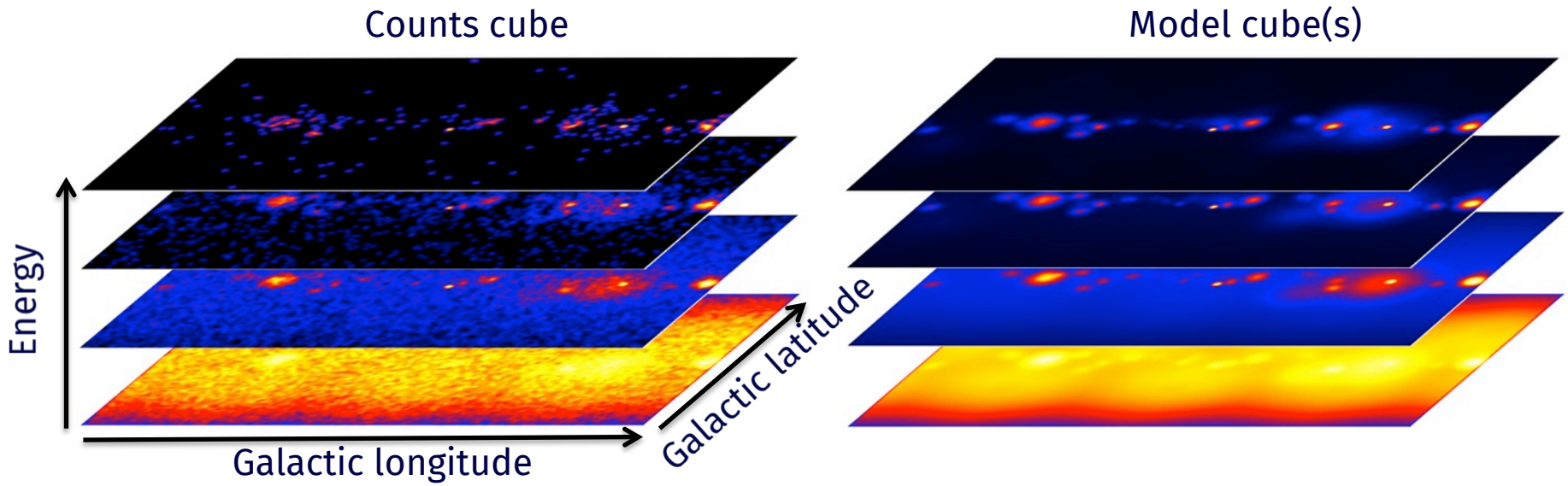
$$e_i(M) = \int_{GTI}\int_{Ebounds}\int_{ROI} P_i(\boldsymbol{p}', E', t'|M)\,\mathrm{d}\boldsymbol{p}'\,\mathrm{d}E'\,\mathrm{d}t'$$

Probability density that given the model *M* an event with reconstructed arrival direction ***p'***, reconstructed energy *E'* and trigger time *t'* occurs.

How does the ctools analysis work?

- For a given time interval, events can be binned in a 3d data space
- **Counts cubes** can be fitted with a **parametric model** using a **binned maximum likelihood algorithm**

fixed pointing



$$-\ln L_i(M) = \sum_k e_{k,i}(M) - n_{k,i} \ln e_{k,i}(M)$$

Sky model factorisation

$$M^S(\boldsymbol{p}, E, t) = \underbrace{M_{\mathrm{S}}(\boldsymbol{p}|E,t)}_{\text{spatial}} \times \underbrace{M_{\mathrm{E}}(E|t)}_{\text{spectral}} \times \underbrace{M_{\mathrm{T}}(t)}_{\text{temporal}}$$

- Point source
- Radial symmetric models
  - Gaussian
  - Disk
  - Shell
  - Profiles (including DM halos)
- Elliptical models
  - Gaussian
  - Disk
- “Diffuse” models
  - Map
  - Map cubes (energy dependent maps)
  - Isotropic
- Composite

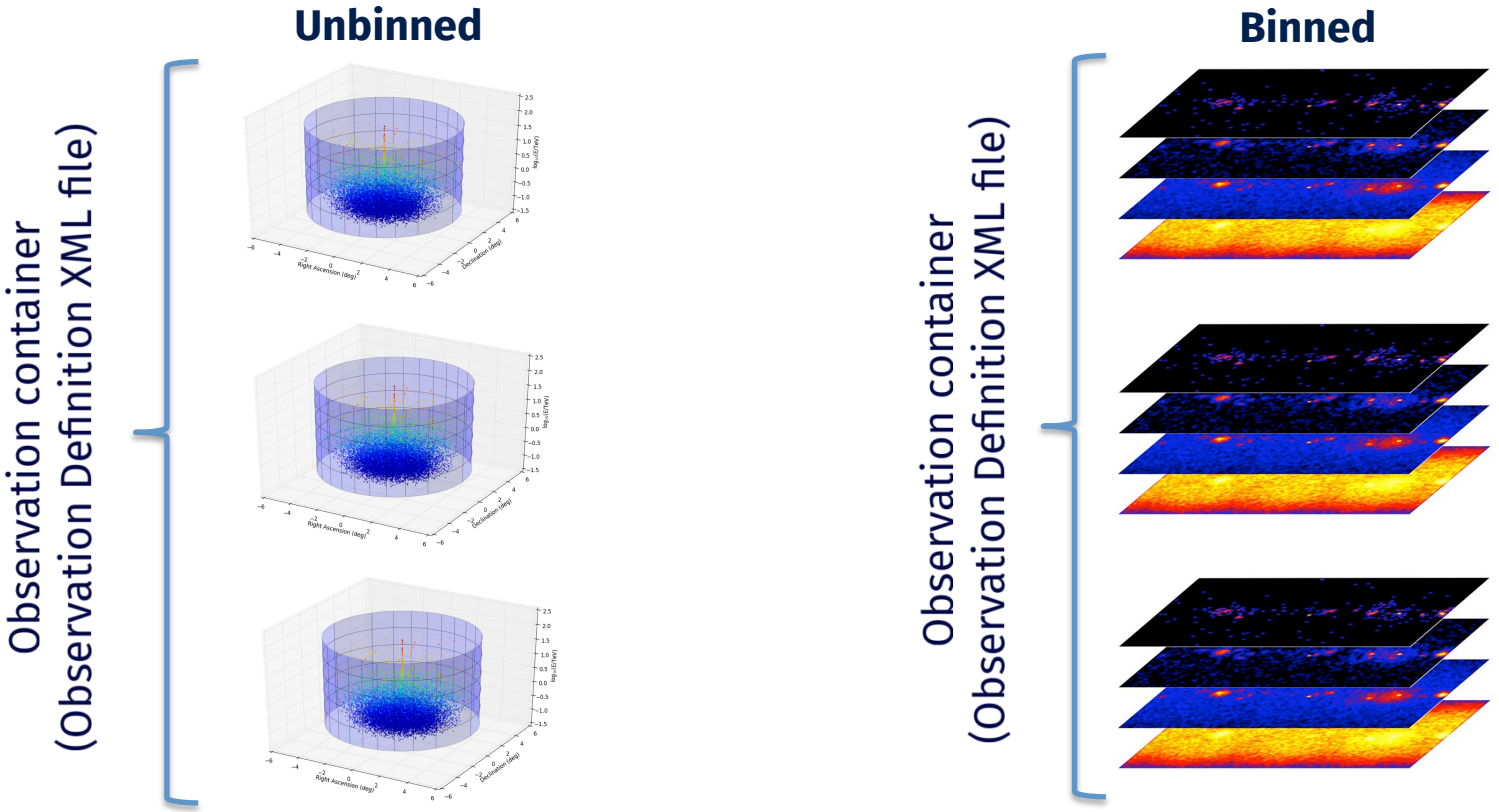
- Power law
- Broken power law
- Smoothly broken power law
- Exponentially cut off power law
- Super exponentially cut off power law
- Log parabola
- Gaussian (line)
- File function (arbitrary spectrum)
- Node function (arbitrary fit)
- Constant
- Composite
- Multiplicative (useful for EBL)

- Constant
- Light curve
- Phase curve

Model definition XML file

```
<?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="PivotEnergy" scale="1e6"   value="0.3"  min="0.01"  max="1000.0" free="0"/>
    </spectrum>
    <spatialModel type="PointSource">
      <parameter name="RA"  scale="1" value="83.6331" min="-360" max="360" free="0"/>
      <parameter name="DEC" scale="1" value="22.0145" min="-90"  max="90"  free="0"/>
    </spatialModel>
    <temporal type="LightCurve" file="model_temporal_lightcurve.fits">
      <parameter name="Normalization" scale="1" value="1.0" min="0.0" max="1000.0" free="0"/>
    </temporal>
  </source>
  <source name="Background" type="CTAIrfBackground" instrument="CTA">
    <spectrum type="PowerLaw">
      <parameter name="Prefactor"   scale="1.0" value="1.0" min="1e-3" max="1e3"    free="1"/>
      <parameter name="Index"       scale="1.0" value="0.0" min="-5.0" max="+5.0"   free="1"/>
      <parameter name="PivotEnergy" scale="1e6" value="1.0" min="0.01" max="1000.0" free="0"/>
    </spectrum>
  </source>
</source_library>
```

Combination of pointings



$$-\ln L(M) = -\sum_i \ln L_i(M)$$

Observation definition XML files

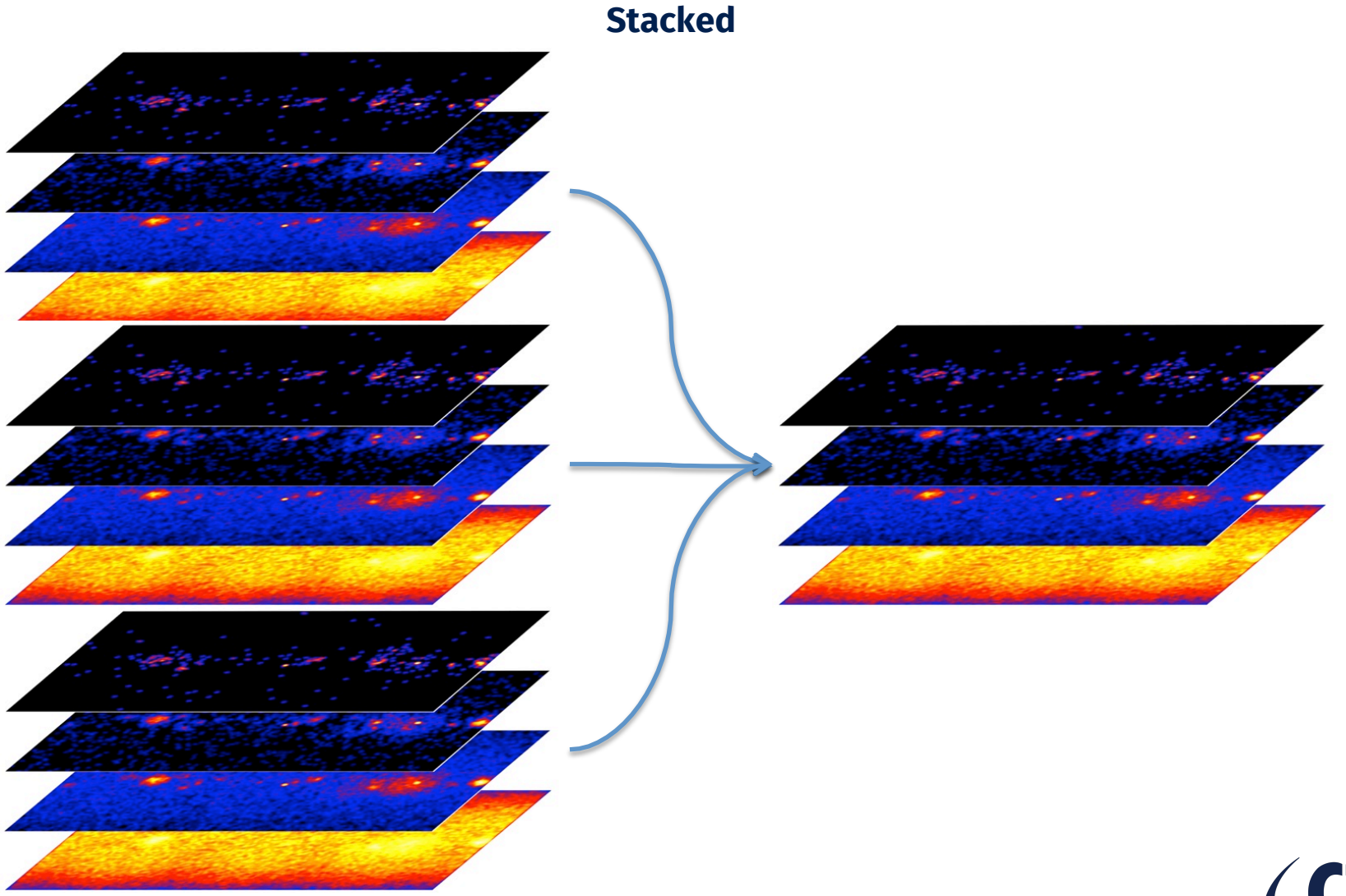
Unbinned

```
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<observation_list title="observation list">
  <observation name="GPS" id="110000" instrument="CTA">
    <parameter name="Calibration" database="1dc" response="South_z40_50h" />
    <parameter name="EventList" file="$CTADATA/data/baseline/gps/gps_baseline_110000.fits" />
  </observation>
  <observation name="GPS" id="110001" instrument="CTA">
    <parameter name="Calibration" database="1dc" response="South_z40_50h" />
    <parameter name="EventList" file="$CTADATA/data/baseline/gps/gps_baseline_110001.fits" />
  </observation>
  <observation name="GPS" id="110002" instrument="CTA">
    <parameter name="Calibration" database="1dc" response="South_z40_50h" />
    <parameter name="EventList" file="$CTADATA/data/baseline/gps/gps_baseline_110002.fits" />
  </observation>
  <observation name="GPS" id="110003" instrument="CTA">
    <parameter name="Calibration" database="1dc" response="South_z40_50h" />
    <parameter name="EventList" file="$CTADATA/data/baseline/gps/gps_baseline_110003.fits" />
  </observation>
</observation_list>
```

Binned

```
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<observation_list title="observation list">
  <observation name="GPS" id="110000" instrument="CTA">
    <parameter name="Calibration" database="1dc" response="South_z40_50h" />
    <parameter name="CountsCube" file="gps_cntcube_110000.fits" />
  </observation>
  <observation name="GPS" id="110001" instrument="CTA">
    <parameter name="Calibration" database="1dc" response="South_z40_50h" />
    <parameter name="CountsCube" file="gps_cntcube_110001.fits" />
  </observation>
  <observation name="GPS" id="110002" instrument="CTA">
    <parameter name="Calibration" database="1dc" response="South_z40_50h" />
    <parameter name="CountsCube" file="gps_cntcube_110002.fits" />
  </observation>
  <observation name="GPS" id="110003" instrument="CTA">
    <parameter name="Calibration" database="1dc" response="South_z40_50h" />
    <parameter name="CountsCube" file="gps_cntcube_110003.fits" />
  </observation>
</observation_list>
```

Combination of counts cubes



Observation definition XML files

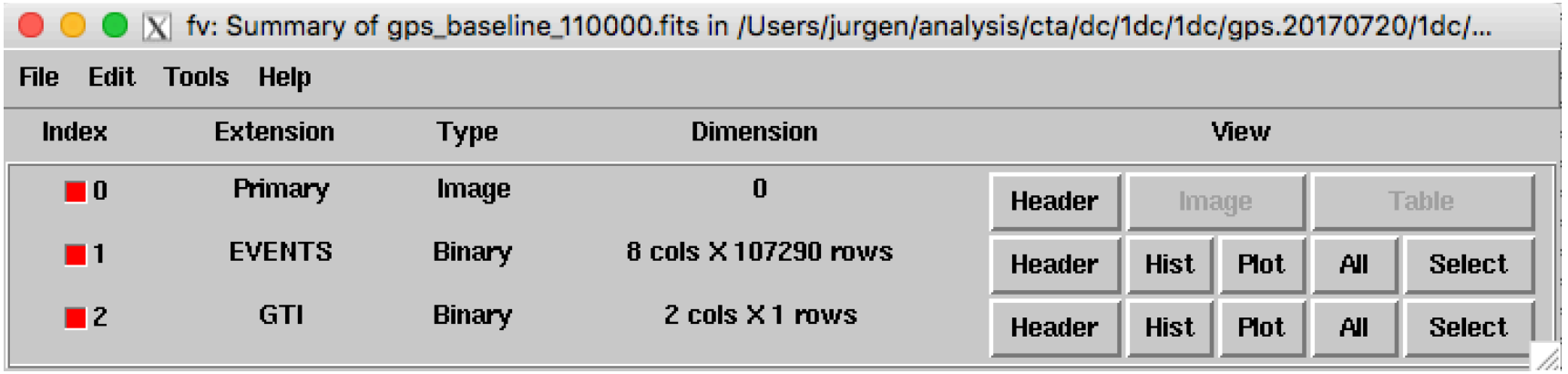
```
<?xml version="1.0" standalone="no"?>
<observation_list title="observation library">
  <observation name="Crab" id="00001" instrument="CTA">
    <parameter name="CountsCube"    file="cntcube.fits"/>
    <parameter name="ExposureCube" file="expcube.fits"/>
    <parameter name="PsfCube"       file="psfcube.fits"/>
    <parameter name="BkgCube"       file="bkgcube.fits"/>
  </observation>
</observation_list>
```

Stacked

Stacked analysis is the recommended standard ctools analysis method

- Events of multiple observations are binned in a single counts cube
- Computation of livetime weighted exposure cube, PSF cube and background cube

Event file format



Event file characteristics

- One event file per (fixed) pointing
- Covers period of 30 min
- Covers energies from 30 GeV to 160 TeV
- Include energy dispersion
- EVENTS extension contains event list (one event per row)
- GTI extension contains Good Time Intervals (single interval)

Event file format

Event list table

fv: Binary Table of gps_baseline_110000.fits[1] in /Users/jurgen/analysis/cta/dc/1dc/1dc/gps.20170720/1dc/data/baseline/gps/

File Edit Tools Help

	EVENT_ID	TIME	RA	DEC	ENERGY	DETX	DETY	MC_ID
Select	1J	1D	1E	1E	1E	1E	1E	1J
All		s	deg	deg	TeV	deg	deg	
Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	1	6.627744032550E+08	-1.732869E+02	-6.240993E+01	4.861494E-02	1.607946E+00	2.580158E-01	2
2	2	6.627744591838E+08	-1.726196E+02	-6.303463E+01	6.110354E-02	9.790584E-01	5.551662E-01	2
3	3	6.627744793092E+08	-1.705929E+02	-6.347148E+01	4.614199E-02	5.105490E-01	1.451438E+00	2
4	4	6.627744907238E+08	-1.756367E+02	-6.364094E+01	4.935673E-02	3.668797E-01	-7.959080E-01	2
5	5	6.627745068648E+08	-1.721235E+02	-6.340126E+01	5.054006E-02	6.073638E-01	7.701997E-01	2
6	6	6.627745188484E+08	-1.719797E+02	-6.314213E+01	6.685498E-02	8.645879E-01	8.421167E-01	2
7	7	6.627745253335E+08	-1.748123E+02	-6.409695E+01	5.897600E-02	-8.116303E-02	-4.230072E-01	2
8	8	6.627745305569E+08	-1.746414E+02	-6.304284E+01	5.658822E-02	9.739035E-01	-3.615367E-01	2
9	9	6.627745571515E+08	-1.715107E+02	-6.220671E+01	5.724507E-02	1.792477E+00	1.087869E+00	2
10	10	6.627745692051E+08	-1.710337E+02	-6.171667E+01	5.577112E-02	2.273161E+00	1.331486E+00	2
11	11	6.627745874472E+08	-1.730401E+02	-6.253468E+01	7.003513E-02	1.481997E+00	3.707363E-01	2
12	12	6.627746088038E+08	-1.742967E+02	-6.370272E+01	3.768072E-02	3.155670E-01	-2.005937E-01	2
13	13	6.627746315176E+08	-1.752712E+02	-6.583829E+01	4.306062E-02	-1.825866E+00	-5.842795E-01	2
14	14	6.627746368873E+08	-1.688460E+02	-6.380654E+01	5.558641E-02	1.260536E-01	2.203822E+00	2
15	15	6.627746500328E+08	-1.735892E+02	-6.547857E+01	6.137832E-02	-1.459779E+00	1.056988E-01	2
16	16	6.627746642211E+08	-1.767322E+02	-6.260846E+01	5.654409E-02	1.380554E+00	-1.328510E+00	2
17	17	6.627746702556E+08	-1.742908E+02	-6.426160E+01	5.121857E-02	-2.432814E-01	-1.940633E-01	2
18	18	6.627746789837E+08	-1.712142E+02	-6.232095E+01	6.666495E-02	1.672971E+00	1.221390E+00	2
19	19	6.627747002520E+08	-1.746416E+02	-6.311734E+01	3.215407E-02	8.994074E-01	-3.607161E-01	2
20	20	6.627747280266E+08	-1.722550E+02	-6.524733E+01	4.411121E-02	-1.236651E+00	6.652415E-01	2

Go to: Edit cell:

Event file format

Event list header

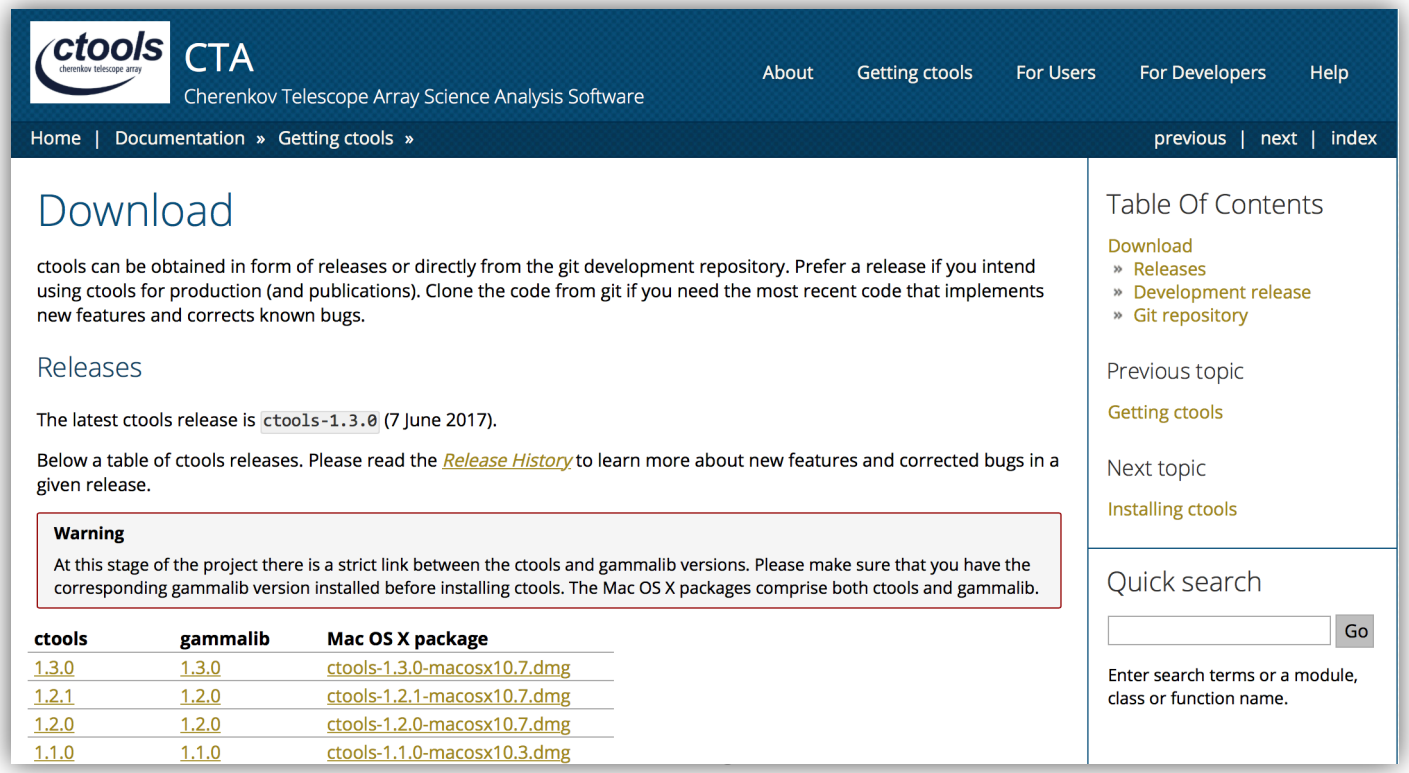
```
EXTNAME = 'EVENTS  '           / name of this extension
DSTYP1  = 'TIME    '           / Data sub-space type
DSUNI1  = 's       '           / Data sub-space unit
DSVAL1  = 'TABLE   '           / Data sub-space value
DSREF1  = ':GTI    '           / Data sub-space reference
DSTYP2  = 'ENERGY  '           / Data sub-space type
DSUNI2  = 'TeV     '           / Data sub-space unit
DSVAL2  = '0.03:160'           / Data sub-space value
DSTYP3  = 'POS(RA,DEC)'        / Data sub-space type
DSUNI3  = 'deg     '           / Data sub-space unit
DSVAL3  = 'CIRCLE(186.1561,-64.019,5)' / Data sub-space value
NDSKEYS =                    3 / Number of data sub-space keys
NMCIDS  =                   43 / Number of Monte Carlo identifiers
MID00001=                    2 / Monte Carlo identifier for model 1
MMN00001= 'IEM     '           / Name of model 1
MID00002=                  213 / Monte Carlo identifier for model 2
MMN00002= 'pwn_128 '           / Name of model 2
MID00003=                  686 / Monte Carlo identifier for model 3
MMN00003= 'composite_90'       / Name of model 3
MID00004=                 1071 / Monte Carlo identifier for model 4

MID00040=                  610 / Monte Carlo identifier for model 40
MMN00040= 'composite_14'       / Name of model 40
MID00041=                  620 / Monte Carlo identifier for model 41
MMN00041= 'composite_24'       / Name of model 41
MID00042=                  704 / Monte Carlo identifier for model 42
MMN00042= 'composite_109'      / Name of model 42
MID00043=                    1 / Monte Carlo identifier for model 43
MMN00043= 'Background model'   / Name of model 43
CREATOR = 'ctobssim (1.4.0)'   / Program which created the file
TELESCOP= 'CTA     '           / Telescope
```

```
OBS_ID  =                110000 / Observation identifier
DATE_OBS= '2021-01-01'          / Observation start date
TIME_OBS= '11:58:51'            / Observation start time
DATE_END= '2021-01-01'          / Observation end date
TIME_END= '12:28:51'            / Observation end time
TSTART  =     6.6277440000E+08 / [s] Mission time of start of observation
TSTOP   =     6.6277619200E+08 / [s] Mission time of end of observation
MJDREFI =                51544 / [days] Integer part of time reference MJD
MJDREFF =     5.0000000000E-01 / [days] Fractional part of time reference MJD
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=     1.7640000000E+03 / [s] Total livetime
DEADC   =     9.8000001907E-01 / Deadtime correction factor
TIMEDEL =                    1 / Time resolution
OBJECT  = 'Galactic Plane Survey' / Observed object
RA_OBJ  =                    0 / [deg] Target Right Ascension
DEC_OBJ =                    0 / [deg] Target Declination
RA_PNT  =     1.8615609741E+02 / [deg] Pointing Right Ascension
DEC_PNT =    -6.4019000000E+01 / [deg] Pointing Declination
ALT_PNT =     9.0000000000E+01 / [deg] Average altitude of pointing
AZ_PNT  =                    0 / [deg] Average azimuth of pointing
RADECSYS= 'FK5     '            / Coordinate system
EQUINOX =     2.0000000000E+03 / Epoch
CONV_DEP=                    0 / Convergence depth of telescopes
CONV_RA =                    0 / [deg] Convergence Right Ascension
CONV_DEC=                    0 / [deg] Convergence Declination
OBSERVER= 'CTA Consortium'      / Observer
N_TELS  =                    0 / Number of telescopes in event list
TELLIST = 'Baseline'            / Telescope IDs
GEOLAT  =    -2.4627200000E+01 / [deg] Geographic latitude of array centre
GEOLON  =     7.9404100000E+01 / [deg] Geographic longitude of array centre
ALTITUDE=     2.1500000000E+00 / [km] Altitude of array centre
EUNIT   = 'TeV     '            / Energy unit
EVTVER  = 'draft1  '            / Event list version number
CALDB   = '1dc     '            / Calibration database
IRF     = 'South_z40_50h'       / Instrument Response Function
END
```

How to install ctools

Download the code

- http://cta.irap.omp.eu/ctools/admin/download.html
- Release tarballs for source installation
- Binary package for Mac OS X (more OS to come soon)
- Clone the development version using Git



ctools cherenkov telescope array

CTA

Cherenkov Telescope Array Science Analysis Software

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Download

ctools can be obtained in form of releases or directly from the git development repository. Prefer a release if you intend using ctools for production (and publications). Clone the code from git if you need the most recent code that implements new features and corrects known bugs.

Releases

The latest ctools release is `ctools-1.3.0` (7 June 2017).

Below a table of ctools releases. Please read the *Release History* to learn more about new features and corrected bugs in a given release.

Warning

At this stage of the project there is a strict link between the ctools and gammalib versions. Please make sure that you have the corresponding gammalib version installed before installing ctools. The Mac OS X packages comprise both ctools and gammalib.

ctools	gammalib	Mac OS X package
1.3.0	1.3.0	ctools-1.3.0-macosx10.7.dmg
1.2.1	1.2.0	ctools-1.2.1-macosx10.7.dmg
1.2.0	1.2.0	ctools-1.2.0-macosx10.7.dmg
1.1.0	1.1.0	ctools-1.1.0-macosx10.3.dmg

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Getting ctools

Next topic

Installing ctools

Quick search

Go

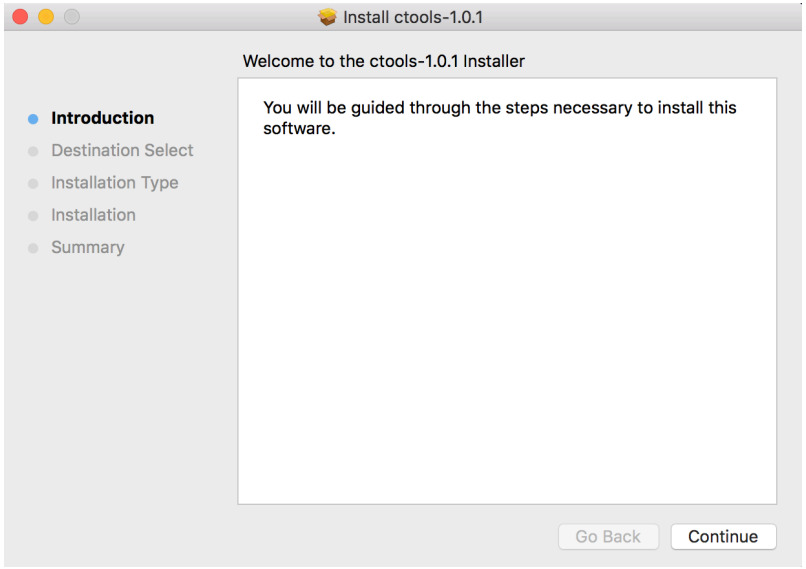
Enter search terms or a module, class or function name.

How to install ctools

Building from source
(first GammaLib, then ctools)

```
$ ./configure
$ make
$ make install
```

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

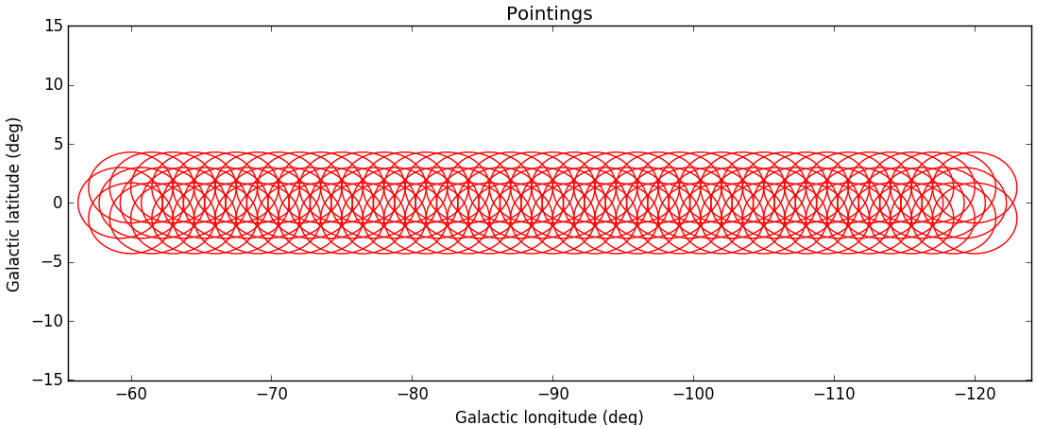


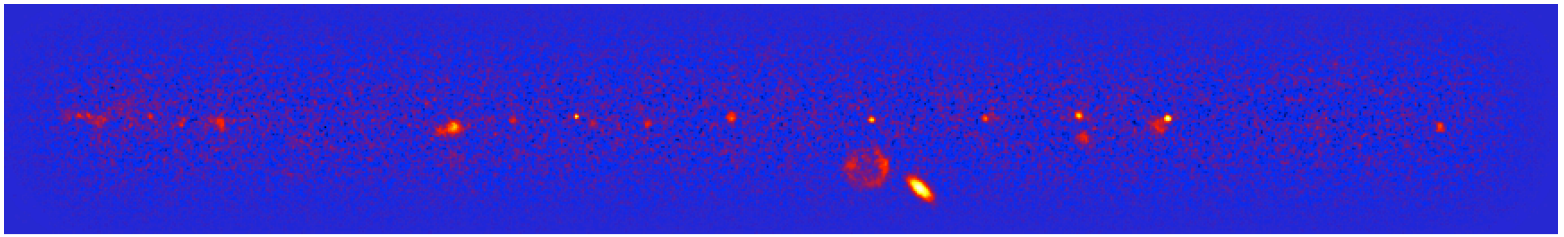
Configuring GammaLib & ctools
(put this into your .profile or .bashrc script)

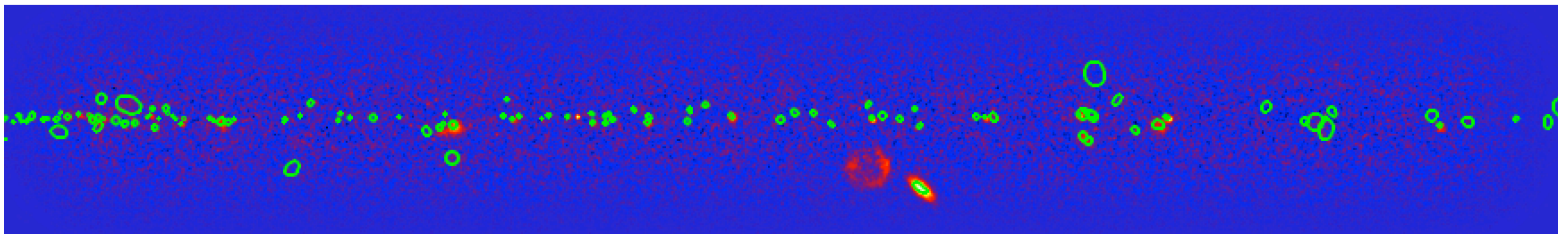
```
$ export GAMMALIB=/usr/local/gamma
$ source $GAMMALIB/bin/gammalib-init.sh
$ export CTOOLS=/usr/local/gamma
$ source $CTOOLS/bin/ctools-init.sh
```

The hands-on dataset

Dedicated hands-on dataset prepared for this workshop



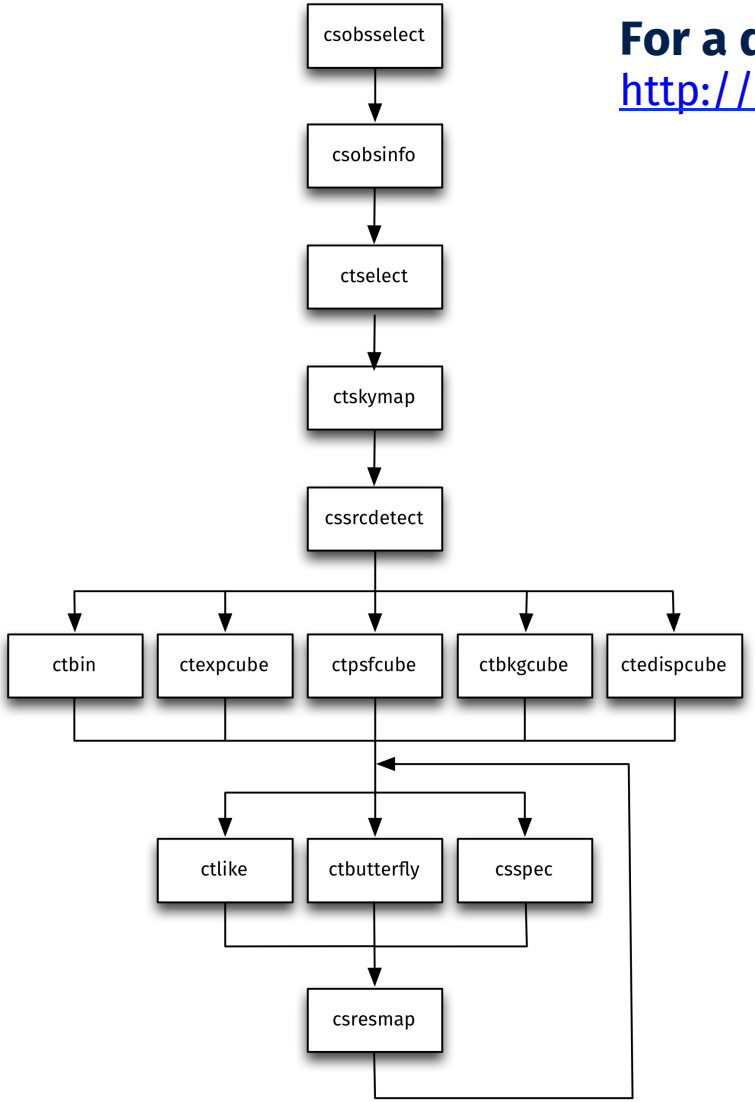




The hands-on dataset

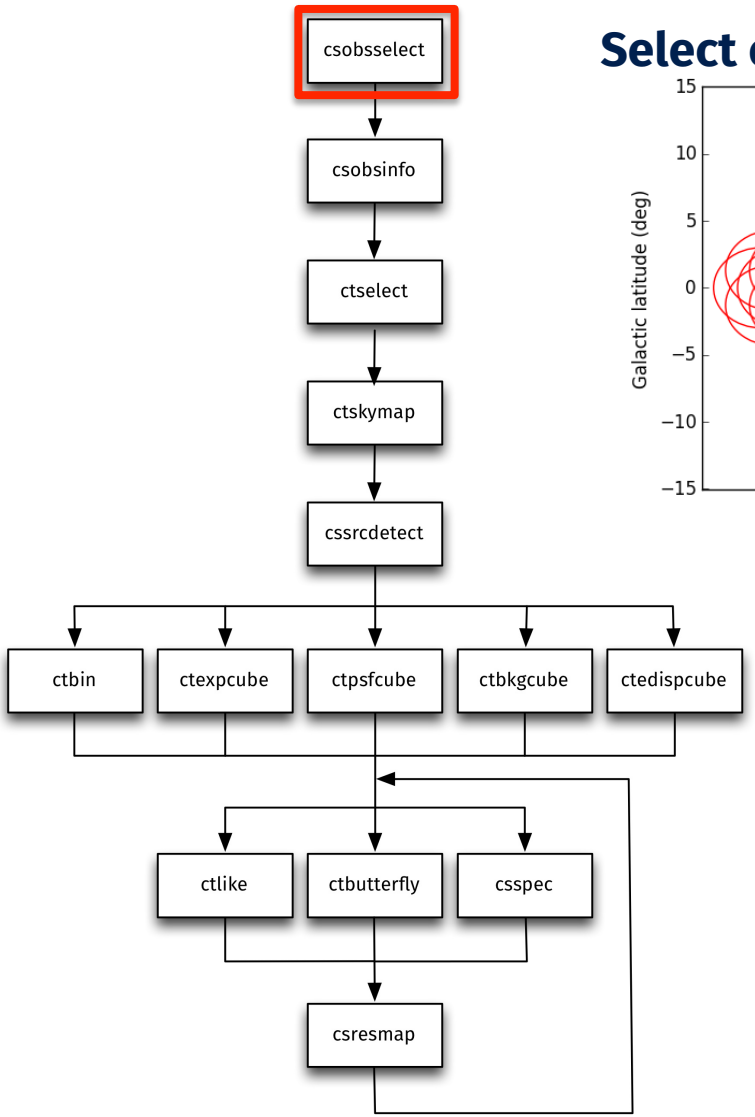
```
$ export CTADATA=/Users/jurgen/analysis/cta/handson/handson
$ export CALDB=$CTADATA/caldb

$ csobsinfo debug=yes
Input event list, ... XML file [obs_selected.xml] $CTADATA/obs/obs_handson.xml
Output DS9 region file [ds9.reg]
2017-09-28T10:42:08: === Observations ===
2017-09-28T10:42:08:  Unbinned observations .....: 123
2017-09-28T10:42:08:  Binned observations .......: 0
2017-09-28T10:42:08: === Events ===
2017-09-28T10:42:08:  Number of events ..........: 6062856
2017-09-28T10:42:08:  Number of bins ............: 0
2017-09-28T10:42:08: === Pointings ===
2017-09-28T10:42:08:  Mean offset angle .........: Unknown
2017-09-28T10:42:08:  Mean zenith angle .........: 0.00 deg
2017-09-28T10:42:08:  Mean azimuth angle ........: 0.00 deg
2017-09-28T10:42:08: === Energy range ===
2017-09-28T10:42:08:  Minimum energy ............: 30 GeV
2017-09-28T10:42:08:  Maximum energy ............: 160 TeV
2017-09-28T10:42:08: === Time range ===
2017-09-28T10:42:08:  MJD (days) ................: 59215.500 - 59221.699
2017-09-28T10:42:08:  UTC ......................: 2021-01-01T11:58:51 - 2021-01-07T16:44:51
2017-09-28T10:42:08:  MET (seconds) ............: 662774400.000 - 663309960.000
2017-09-28T10:42:08:  Total ontime .............: 221400.00 s = 3690.00 min = 61.50 h
2017-09-28T10:42:08:  Total livetime ...........: 216972.00 s = 3616.20 min = 60.27 h
```

Using ctools

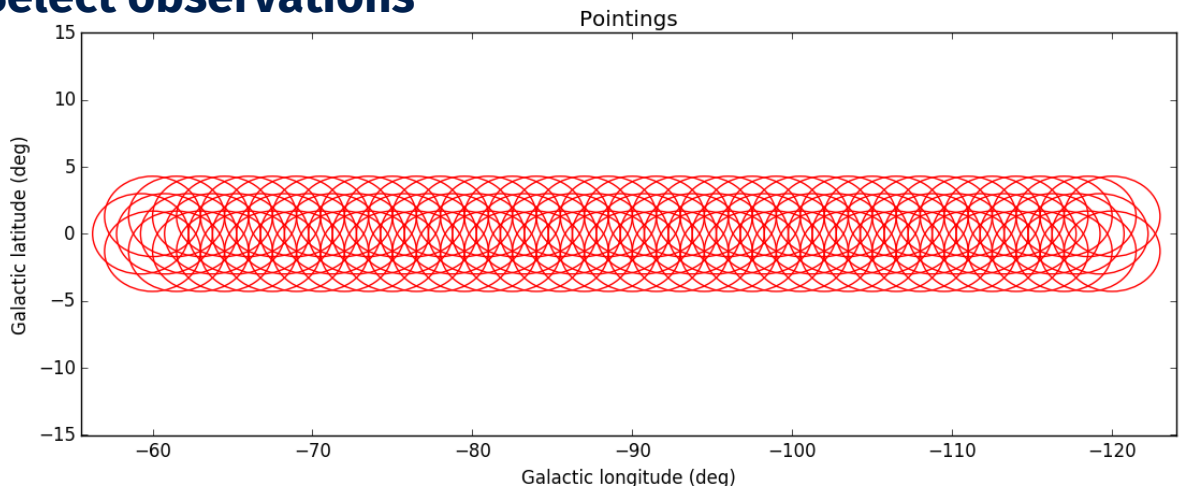


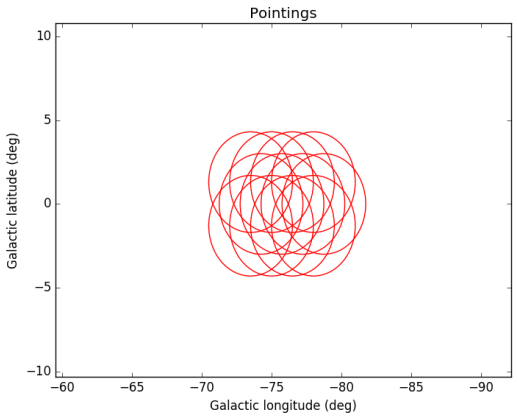
For a detailed description of the workflow see
http://cta.irap.omp.eu/ctools/users/tutorials/1dc/first.html

Selecting relevant observations

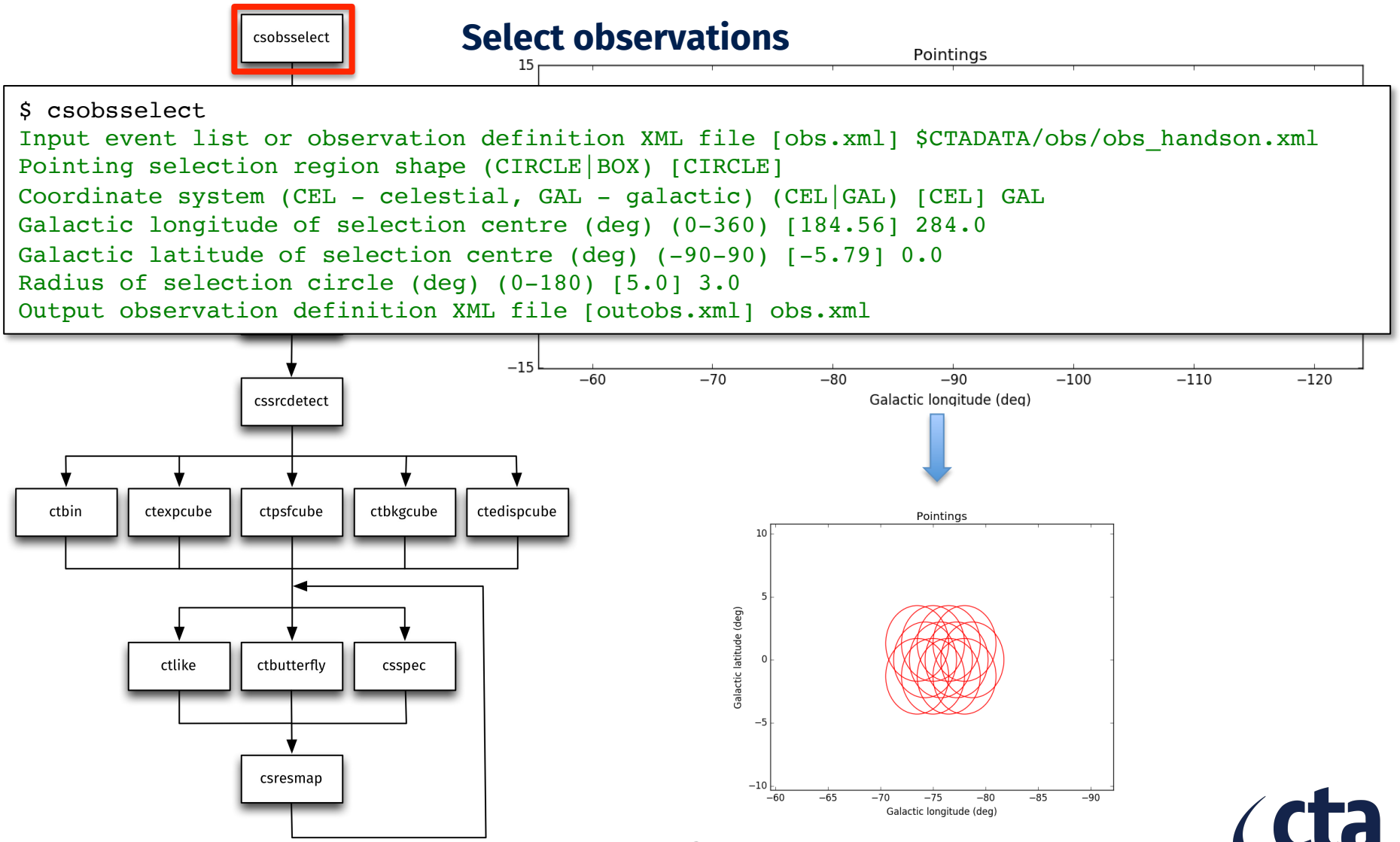


Select observations

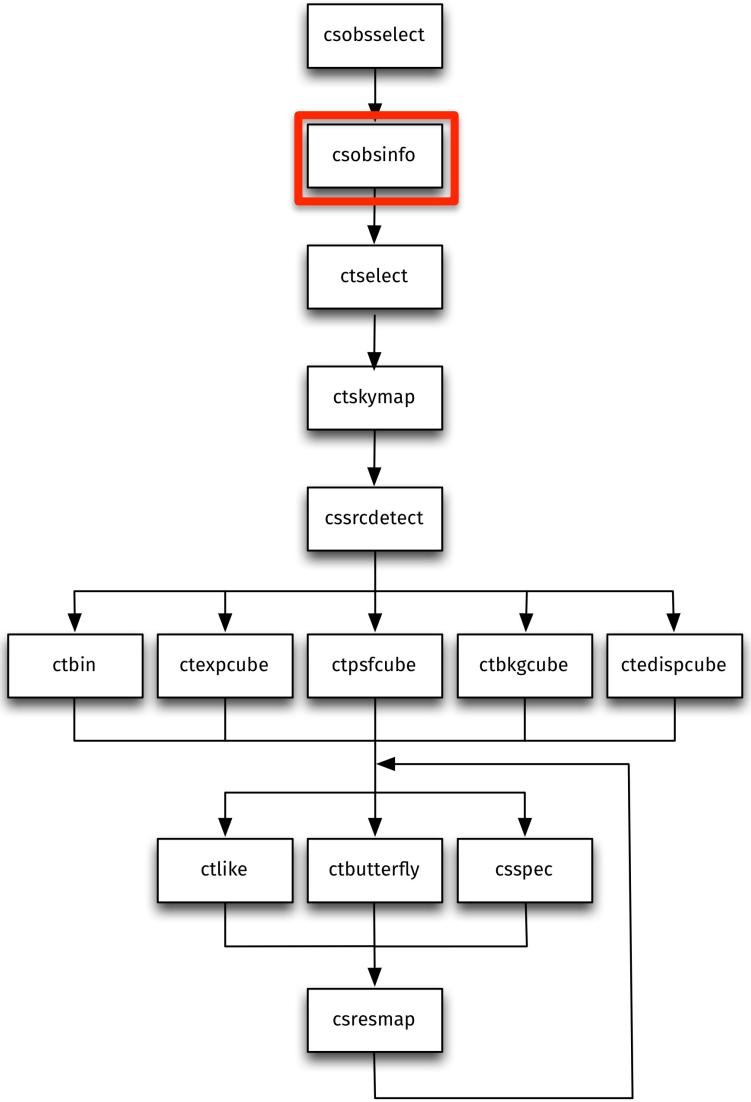




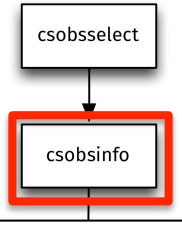
Selecting relevant observations



Inspect selected observations

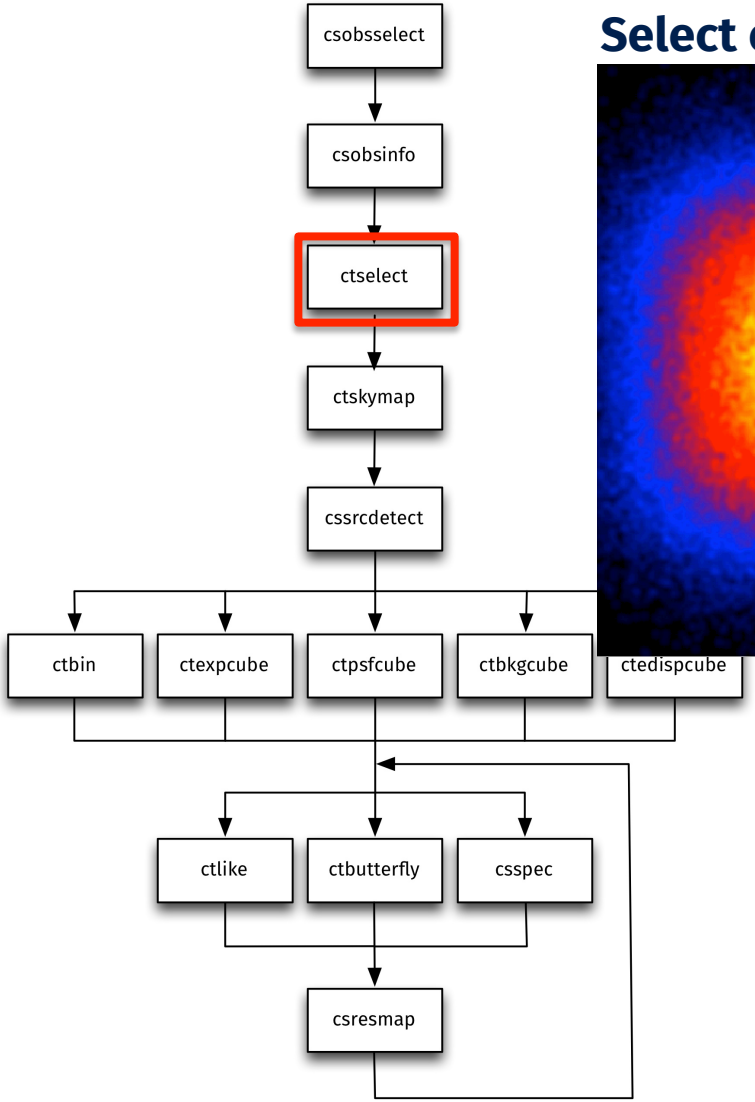


Inspect selected observations

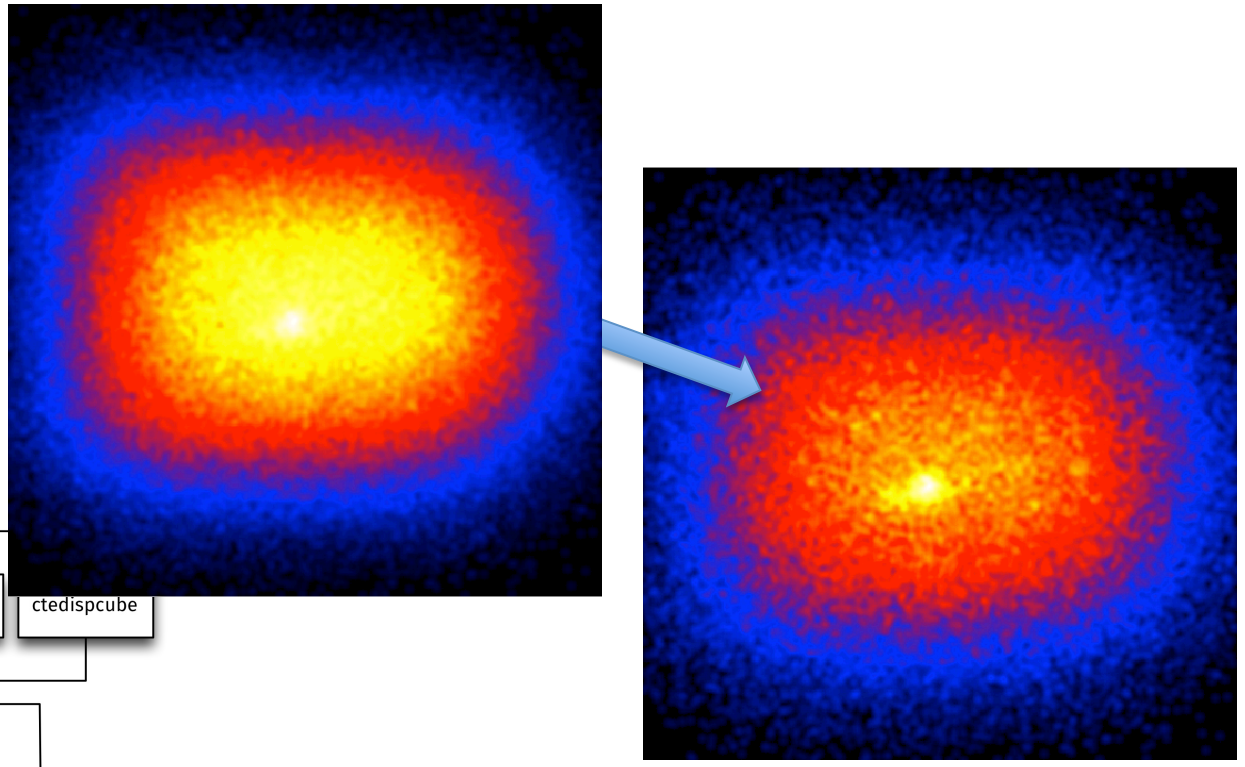



```
$ csobsinfo debug=yes
Input event list, ... XML file [obs_selected.xml] obs.xml
Output DS9 region file [ds9.reg]
2017-09-28T11:04:50: === Observations ===
2017-09-28T11:04:50:  Unbinned observations .....: 12
2017-09-28T11:04:50:  Binned observations .......: 0
2017-09-28T11:04:50: === Events ===
2017-09-28T11:04:50:  Number of events ..........: 595899
2017-09-28T11:04:50:  Number of bins ............: 0
2017-09-28T11:04:50: === Pointings ===
2017-09-28T11:04:50:  Mean offset angle .........: Unknown
2017-09-28T11:04:50:  Mean zenith angle .........: 0.00 deg
2017-09-28T11:04:50:  Mean azimuth angle ........: 0.00 deg
2017-09-28T11:04:50: === Energy range ===
2017-09-28T11:04:50:  Minimum energy ............: 30 GeV
2017-09-28T11:04:50:  Maximum energy ............: 160 TeV
2017-09-28T11:04:50: === Time range ===
2017-09-28T11:04:50:  MJD (days) ................: 59216.700 - 59220.921
2017-09-28T11:04:50:  UTC ......................: 2021-01-02T16:46:51 - 2021-01-06T22:04:51
2017-09-28T11:04:50:  MET (seconds) .............: 662878080.000 - 663242760.000
2017-09-28T11:04:50:  Total ontime ..............: 21600.00 s = 360.00 min = 6.00 h
2017-09-28T11:04:50:  Total livetime ............: 21168.00 s = 352.80 min = 5.88 h
```

Selecting relevant events

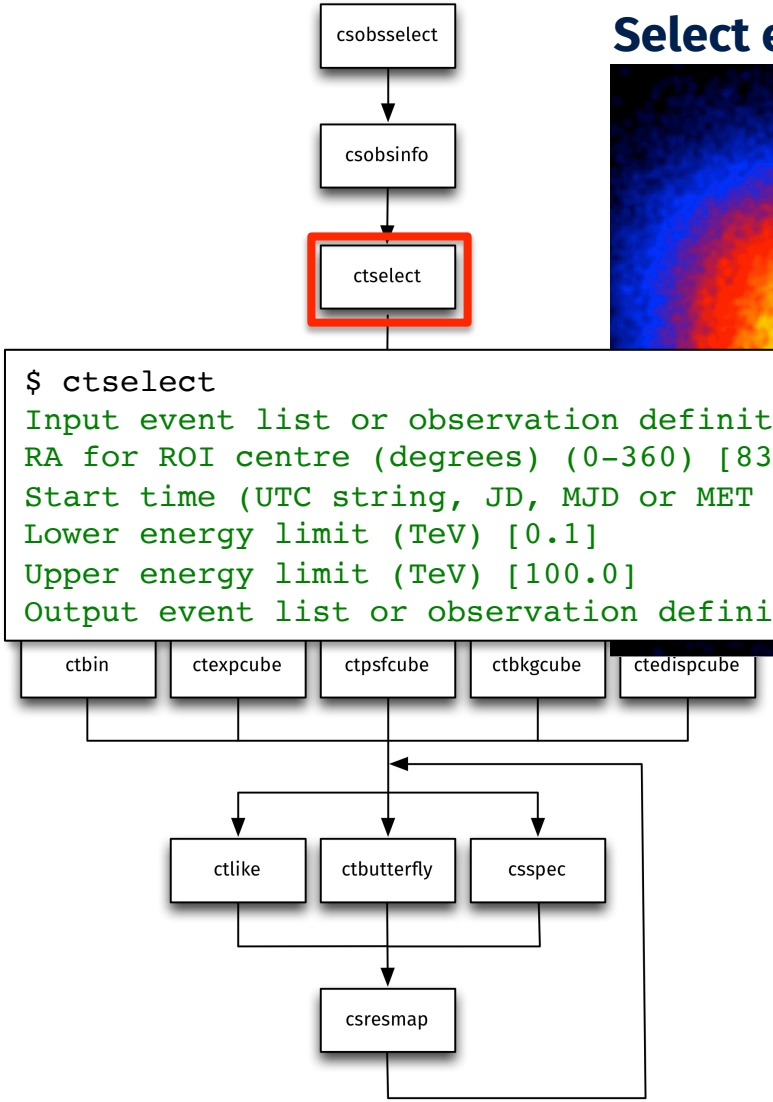


Select events

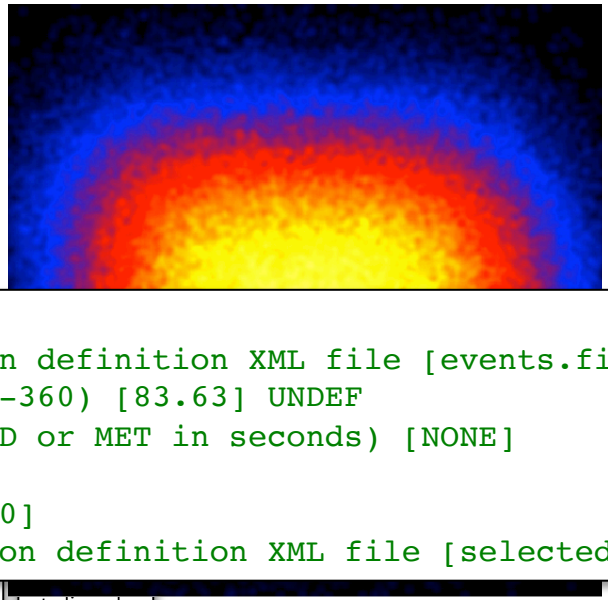


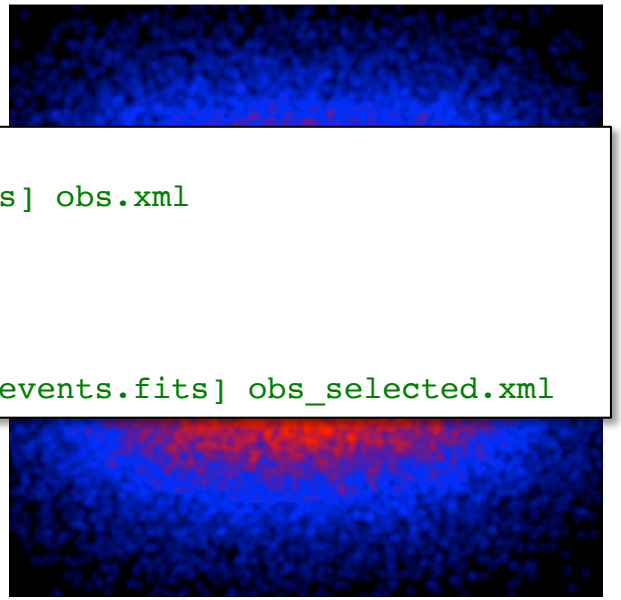
- Here: select events within 0.1 – 100 TeV
- Also possible: spatial and temporal selection

Selecting relevant events



Select events

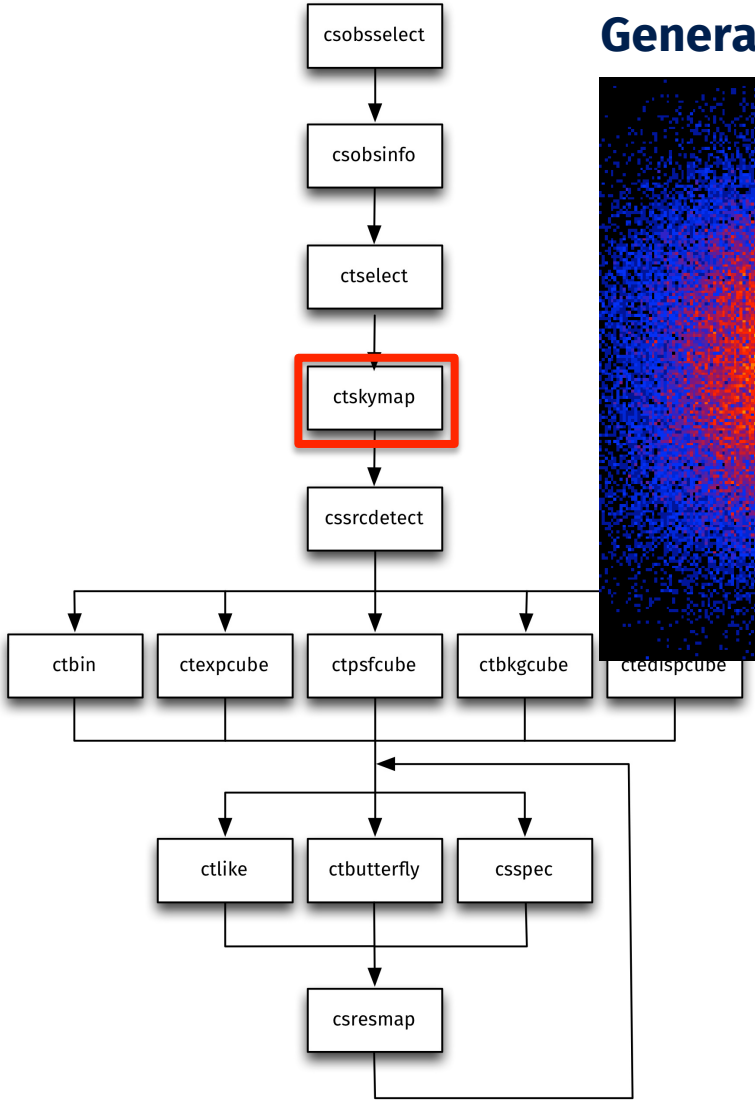




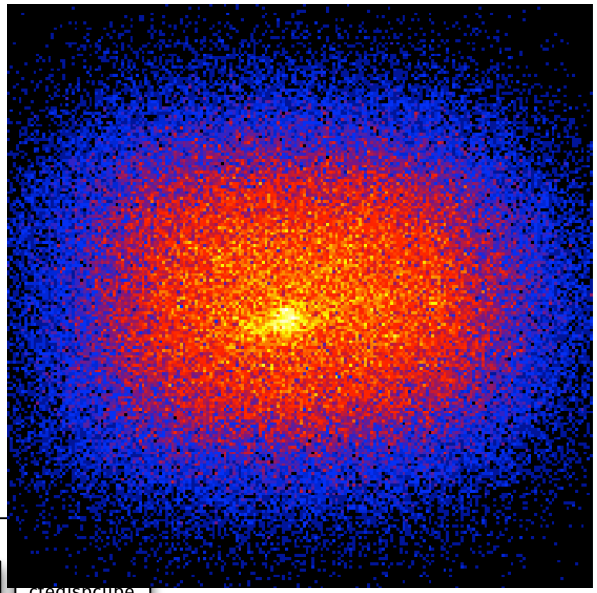
```
$ ctselect
Input event list or observation definition XML file [events.fits] obs.xml
RA for ROI centre (degrees) (0-360) [83.63] UNDEF
Start time (UTC string, JD, MJD or MET in seconds) [NONE]
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Output event list or observation definition XML file [selected_events.fits] obs_selected.xml
```

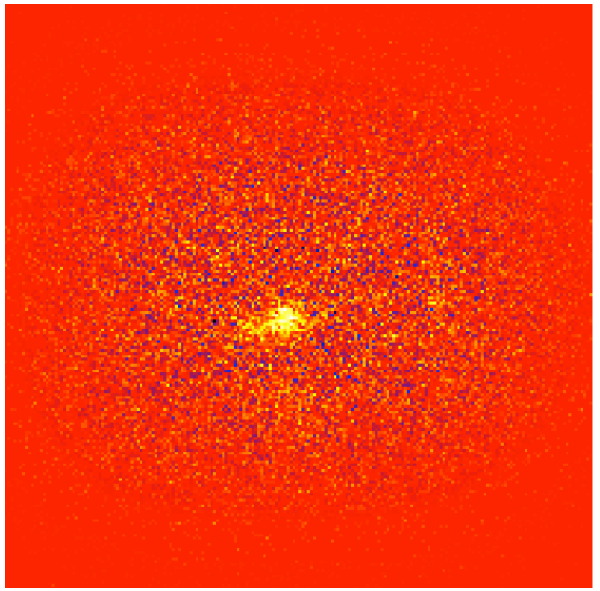
- Here: select events within 0.1 – 100 TeV
- Also possible: spatial and temporal selection

Generating a sky map from the events



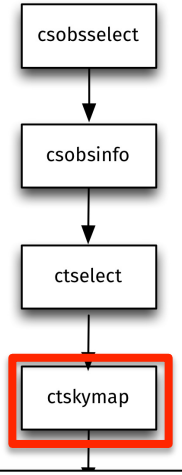
Generate a sky map from events



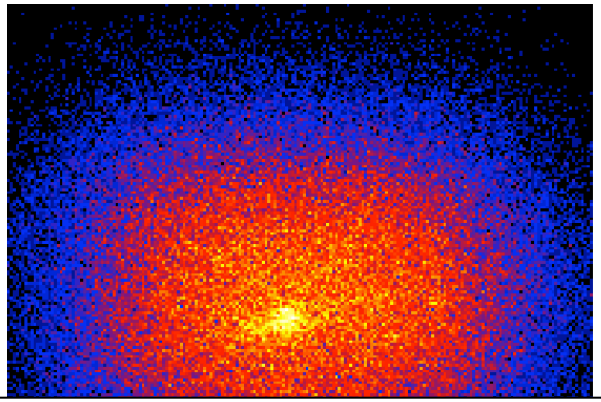


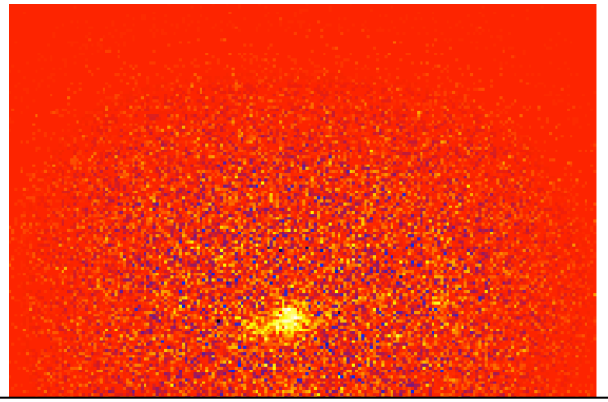
- Left: map of events
- Right: map of events minus background template

Generating a sky map from the events



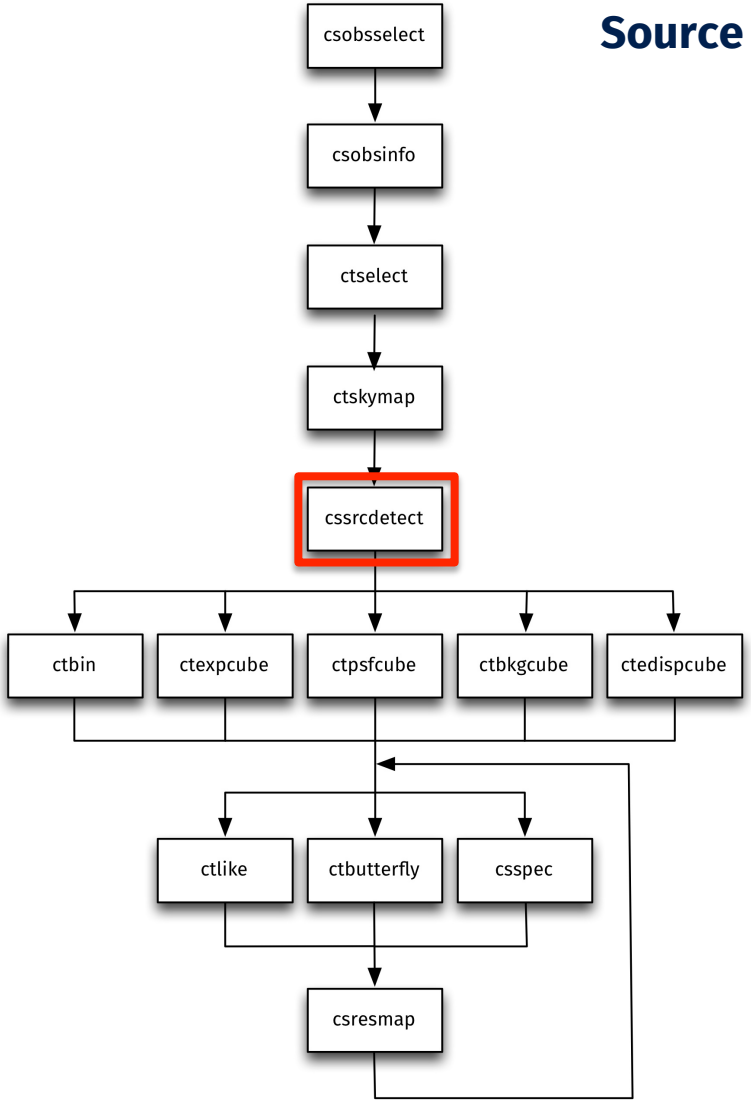
Generate a sky map from events



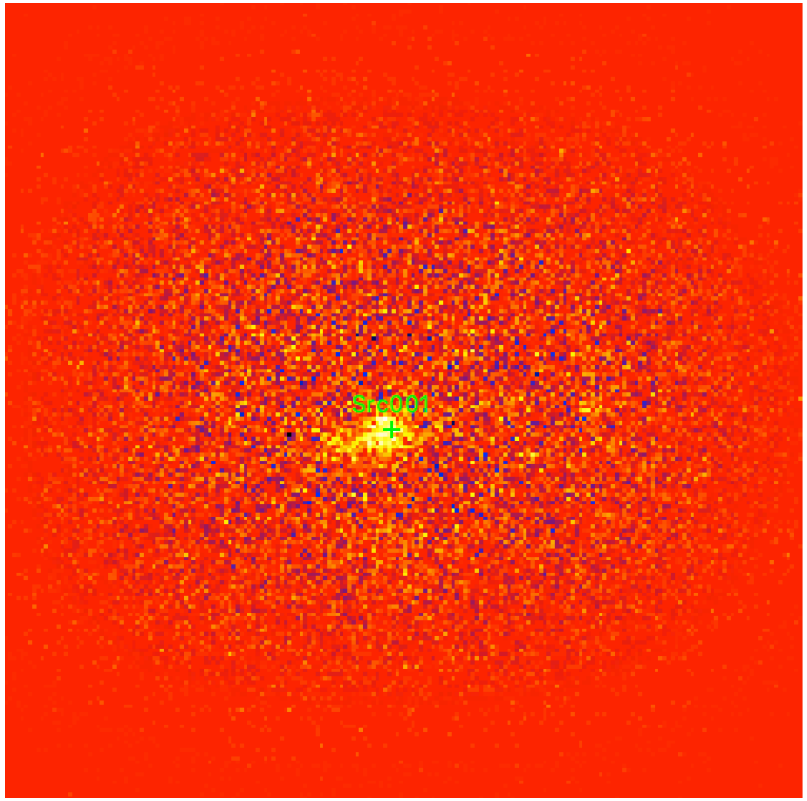


```
$ ctskymap
Input event list or observation definition XML file [events.fits] obs_selected.xml
First coordinate of image center in degrees (RA or galactic l) (0-360) [83.63] 284.0
Second coordinate of image center in degrees (DEC or galactic b) (-90-90) [22.01] 0.0
Projection method (AIT|AZP|CAR|GLS|MER|MOL|SFL|SIN|STG|TAN) [CAR]
Coordinate system (CEL - celestial, GAL - galactic) (CEL|GAL) [CEL] GAL
Image scale (in degrees/pixel) [0.02] 0.05
Size of the X axis in pixels [200]
Size of the Y axis in pixels [200]
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Background subtraction method (NONE|IRF) [NONE]
Output skymap file [skymap.fits]
```

Finding sources in the sky map

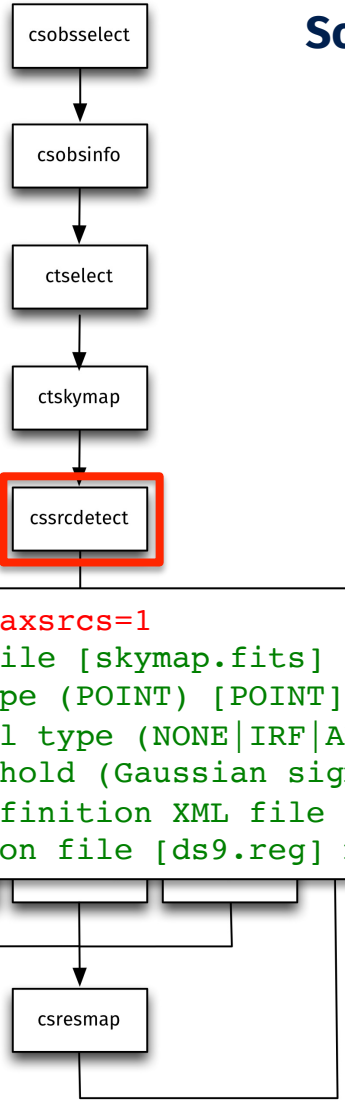


Source detection and model definition XML file creation

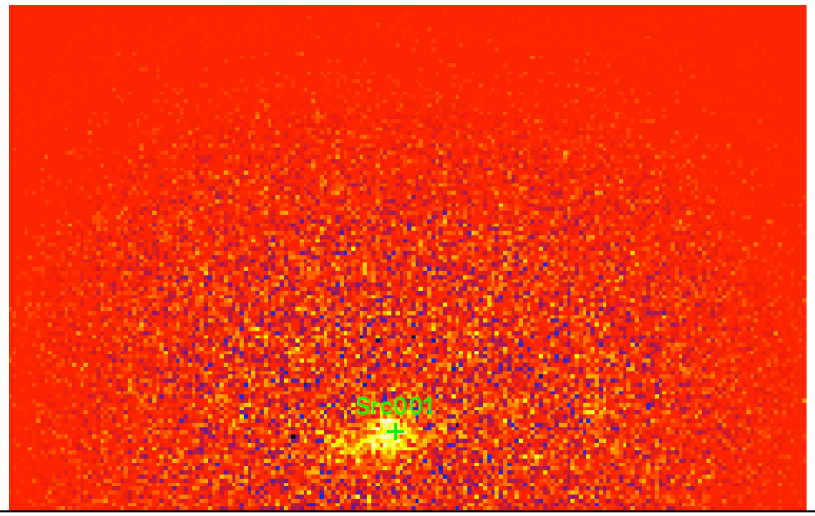


- So far implements simple peak above threshold algorithm

Finding sources in the sky map



Source detection and model definition XML file creation

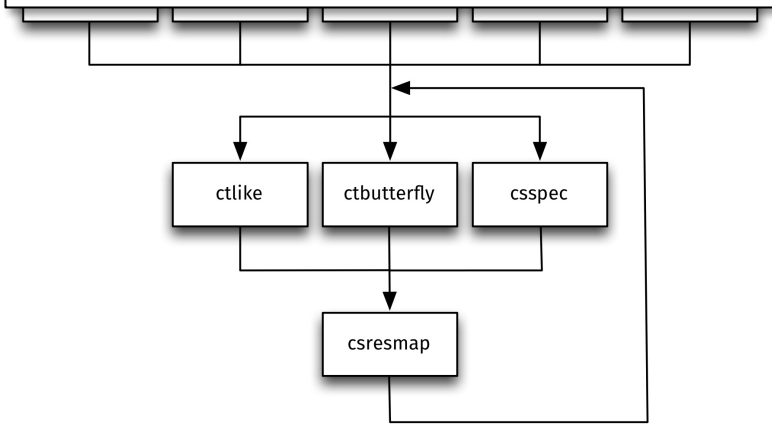


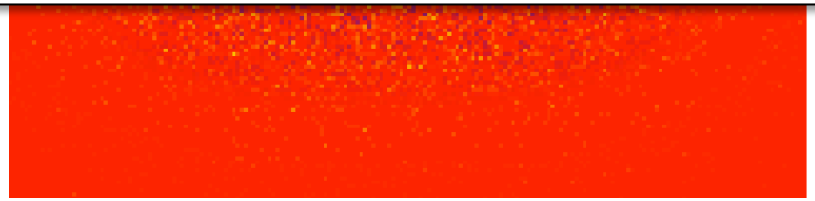

```
$ cssrcdetect maxsrcs=1
Input sky map file [skymap.fits] skymap_irf.fits
Source model type (POINT) [POINT]
Background model type (NONE|IRF|AEFF|CUBE) [NONE] IRF
Detection threshold (Gaussian sigma) [5.0] 10.0
Output model definition XML file [models.xml]
Output DS9 region file [ds9.reg] models.reg
```

- So far implements simple peak above threshold algorithm

Finding sources in the sky map

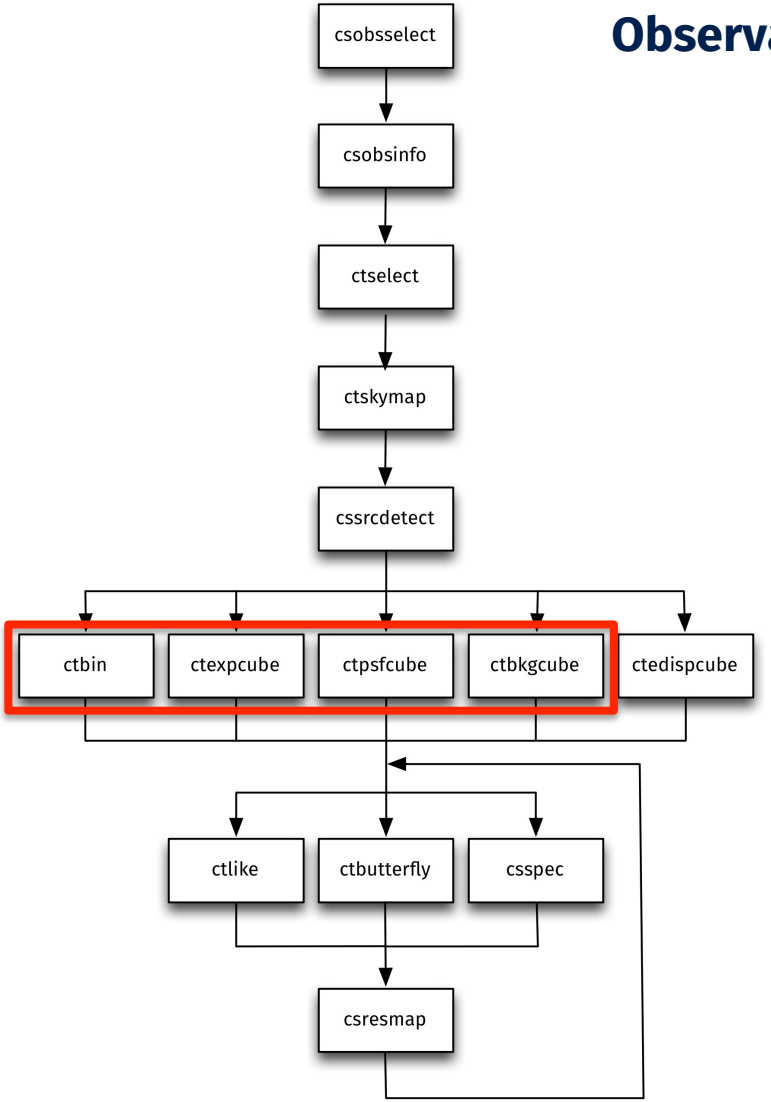
```
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<source_library title="source library">
 <source name="Src001" type="PointSource">
    <spectrum type="PowerLaw">
      <parameter name="Prefactor" value="1" error="0" scale="5.7e-18" min="0" free="1" />
      <parameter name="Index" value="1" error="-0" scale="-2.48" min="-4.03225806" max="4.03225806" free="1" />
      <parameter name="PivotEnergy" value="1" scale="300000" free="0" />
    </spectrum>
    <spatialModel type="PointSource">
      <parameter name="RA" value="155.730431674709" error="0" scale="1" free="1" />
      <parameter name="DEC" value="-57.7189221745815" error="0" scale="1" free="1" />
    </spatialModel>
  </source>
  <source name="Background" type="CTAIrfBackground">
    <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>
```



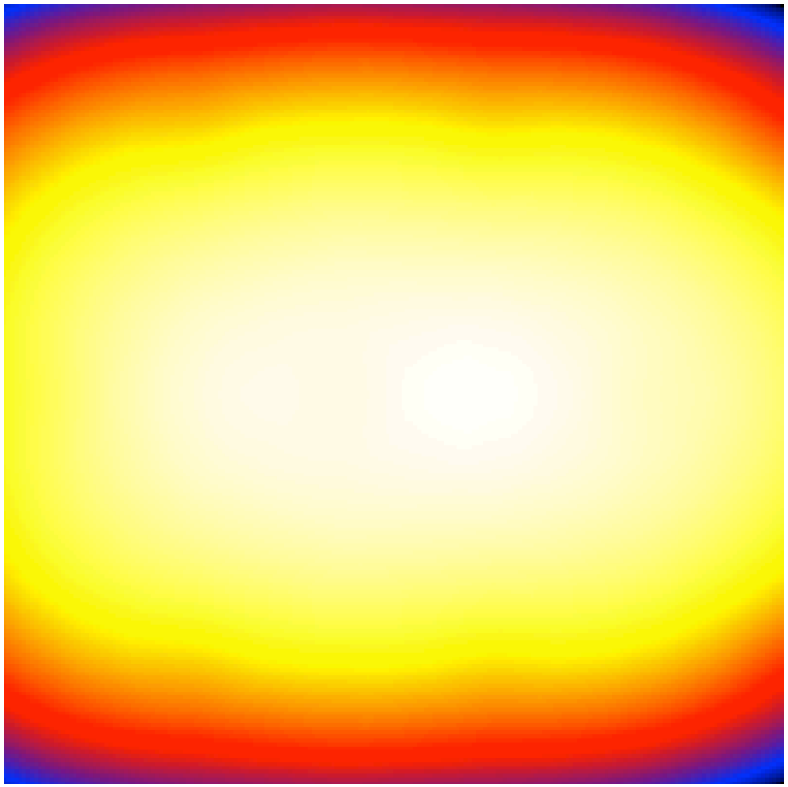


- So far implements simple peak above threshold algorithm

Stacking the observations



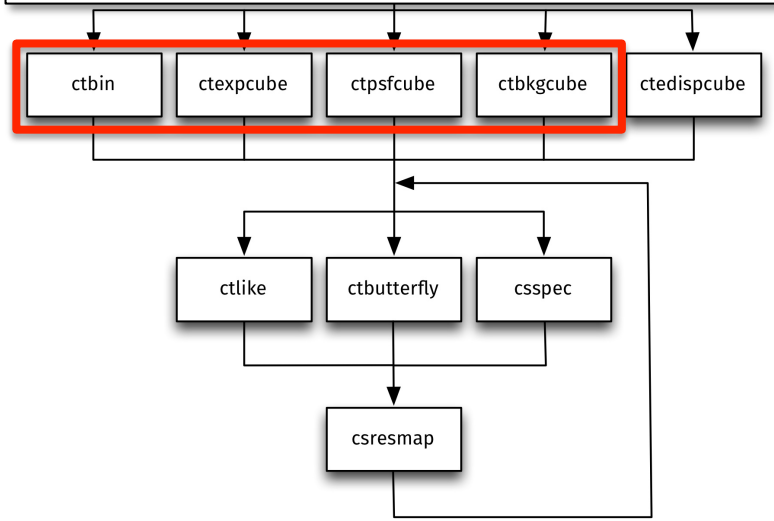
Observation stacking



- Example: exposure at 100 GeV

Stacking the observations

```
$ ctbin
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] 284.0
Second coordinate of image center in degrees (DEC or galactic b) (-90-90) [22.01] 0.0
Projection method (AIT|AZP|CAR|GLS|MER|MOL|SFL|SIN|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]
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 (1-200) [20]
Output counts cube file [cntcube.fits]
```



- Example: exposure at 100 GeV

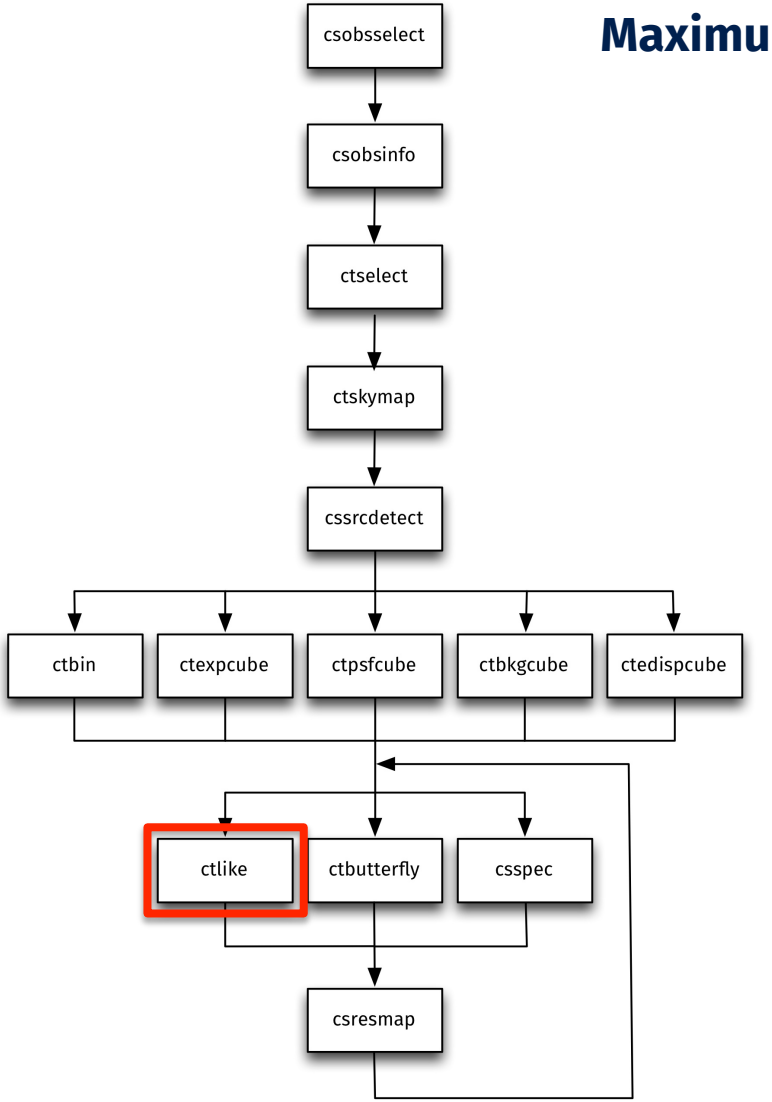
Stacking the observations

```
$ ctexpcube
Input event list or observation definition XML file [NONE] obs_selected.xml
Input counts cube file to extract exposure cube definition [NONE] cntcube.fits
Output exposure cube file [expcube.fits]
```

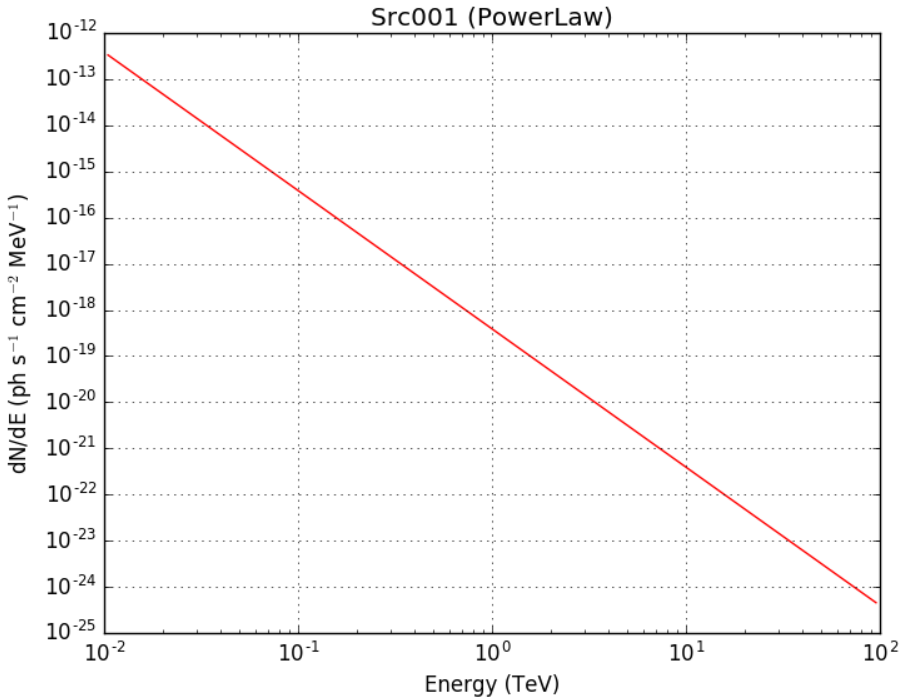
```
$ ctpsfcube
Input event list or observation definition XML file [NONE] obs_selected.xml
Input counts cube file to extract PSF cube definition [NONE]
First coordinate of image center in degrees (RA or galactic l) (0-360) [83.63] 284.0
Second coordinate of image center in degrees (DEC or galactic b) (-90-90) [22.01] 0.0
Projection method (AIT|AZP|CAR|GLS|MER|MOL|SFL|SIN|STG|TAN) [CAR]
Coordinate system (CEL - celestial, GAL - galactic) (CEL|GAL) [CEL] GAL
Image scale (in degrees/pixel) [1.0]
Size of the X axis in pixels [10]
Size of the Y axis in pixels [10]
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Number of energy bins [20]
Output PSF cube file [psfcube.fits]
```

```
$ ctbkgcube
Input event list or observation definition XML file [NONE] obs_selected.xml
Input counts cube file to extract background cube definition [NONE] cntcube.fits
Input model definition XML file [NONE] models.xml
Output background cube file [bkgcube.fits]
Output model definition XML file [NONE] models_cube.xml
```

Maximum likelihood fitting

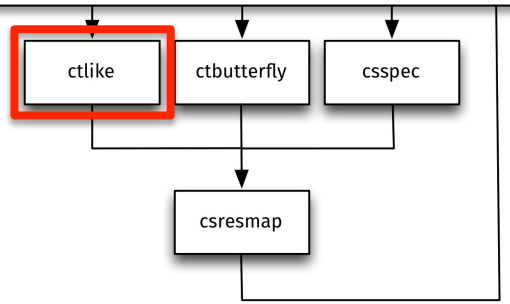


Maximum likelihood fitting



Maximum likelihood fitting

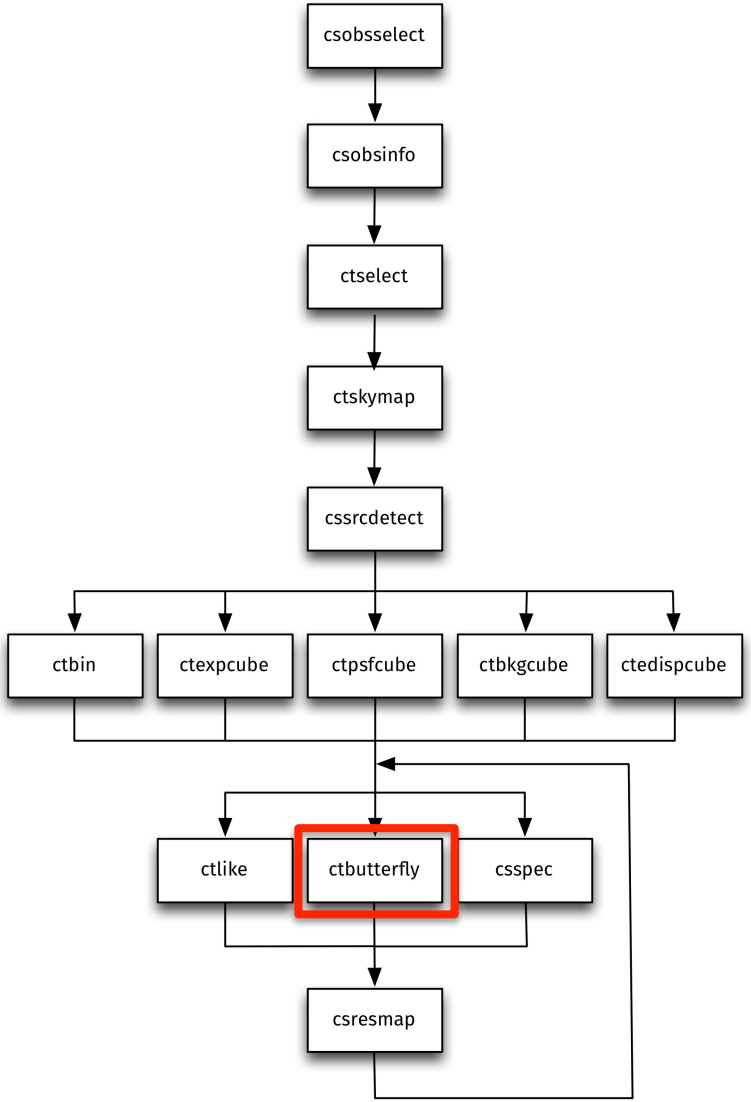
```
$ ctlike debug=yes
Input event list, counts cube or observation definition XML file [events.fits] cntcube.fits
Input exposure cube file [NONE] expcube.fits
Input PSF cube file [NONE] psfcube.fits
Input background cube file [NONE] bkgcube.fits
Input model definition XML file [$CTOOLS/share/models/crab.xml] models_cube.xml
Output model definition XML file [crab_results.xml] results.xml

2017-09-29T10:14:03:  >Iteration   0: -logL=162916.514, Lambda=1.0e-03
2017-09-29T10:14:04:  >Iteration   1: -logL=162674.679, Lambda=1.0e-03, delta=241.834, step=1.0e+00, max(|grad|)=-386.499338 [Prefactor:6]
2017-09-29T10:14:06:  >Iteration   2: -logL=162654.758, Lambda=1.0e-04, delta=19.921, step=1.0e+00, max(|grad|)=370.071145 [DEC:1]
2017-09-29T10:14:07:  >Iteration   3: -logL=162646.911, Lambda=1.0e-05, delta=7.848, step=1.0e+00, max(|grad|)=363.694688 [DEC:1]
2017-09-29T10:14:09:  >Iteration   4: -logL=162641.551, Lambda=1.0e-06, delta=5.360, step=1.0e+00, max(|grad|)=316.982189 [DEC:1]
2017-09-29T10:14:10:  >Iteration   5: -logL=162638.318, Lambda=1.0e-07, delta=3.233, step=1.0e+00, max(|grad|)=257.876057 [DEC:1]
2017-09-29T10:14:12:  >Iteration   6: -logL=162636.578, Lambda=1.0e-08, delta=1.740, step=1.0e+00, max(|grad|)=194.922043 [DEC:1]
2017-09-29T10:14:13:  >Iteration   7: -logL=162635.713, Lambda=1.0e-09, delta=0.865, step=1.0e+00, max(|grad|)=148.734927 [DEC:1]
2017-09-29T10:14:15:  >Iteration   8: -logL=162635.311, Lambda=1.0e-10, delta=0.402, step=1.0e+00, max(|grad|)=111.261327 [DEC:1]
2017-09-29T10:14:16:  >Iteration   9: -logL=162635.111, Lambda=1.0e-11, delta=0.200, step=1.0e+00, max(|grad|)=83.906156 [DEC:1]
2017-09-29T10:14:18:  >Iteration  10: -logL=162635.008, Lambda=1.0e-12, delta=0.103, step=1.0e+00, max(|grad|)=65.175372 [DEC:1]
2017-09-29T10:14:19:  >Iteration  11: -logL=162634.951, Lambda=1.0e-13, delta=0.057, step=1.0e+00, max(|grad|)=54.792776 [DEC:1]
2017-09-29T10:14:21:  >Iteration  12: -logL=162634.913, Lambda=1.0e-14, delta=0.039, step=1.0e+00, max(|grad|)=46.186164 [DEC:1]
2017-09-29T10:14:22:  >Iteration  13: -logL=162634.889, Lambda=1.0e-15, delta=0.024, step=1.0e+00, max(|grad|)=30.334885 [DEC:1]
2017-09-29T10:14:24:  >Iteration  14: -logL=162634.876, Lambda=1.0e-16, delta=0.012, step=1.0e+00, max(|grad|)=30.327022 [DEC:1]
2017-09-29T10:14:25:  >Iteration  15: -logL=162634.862, Lambda=1.0e-17, delta=0.014, step=1.0e+00, max(|grad|)=29.326994 [DEC:1]
2017-09-29T10:14:26:  >Iteration  16: -logL=162634.853, Lambda=1.0e-18, delta=0.009, step=1.0e+00, max(|grad|)=17.034481 [DEC:1]
2017-09-29T10:14:28:  >Iteration  17: -logL=162634.849, Lambda=1.0e-19, delta=0.004, step=1.0e+00, max(|grad|)=14.067471 [DEC:1]
```

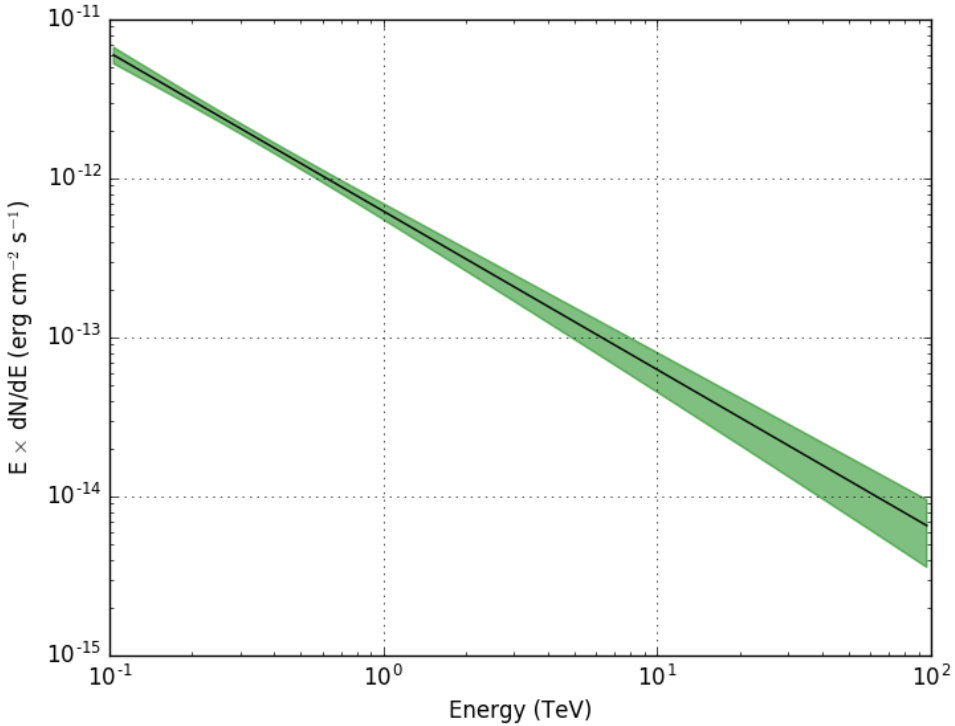


Maximum likelihood fitting

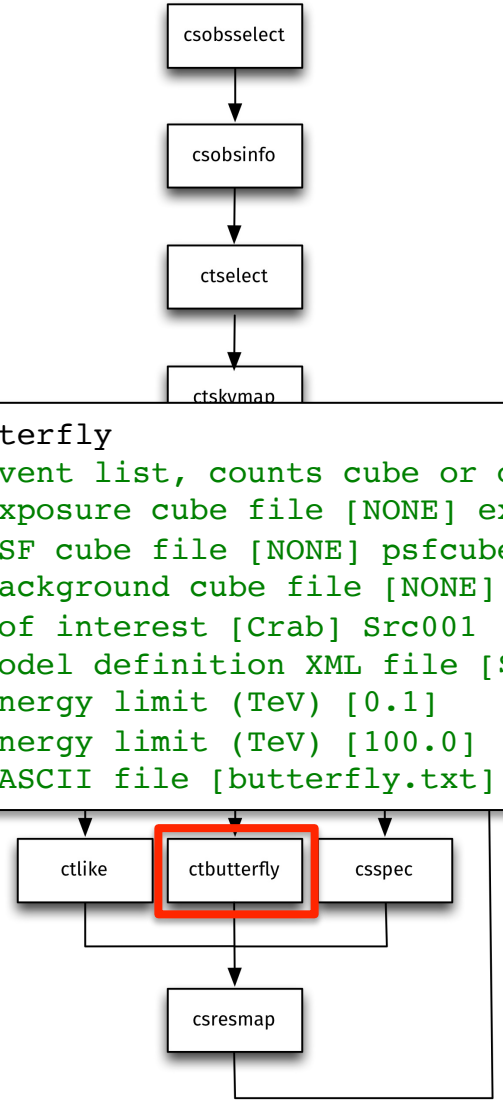
```
2017-09-29T10:14:29: === GOptimizerLM ===
2017-09-29T10:14:29:  Optimized function value ..: 162634.849
2017-09-29T10:14:29:  Absolute precision ........: 0.005
2017-09-29T10:14:29:  Acceptable value decrease .: 2
2017-09-29T10:14:29:  Optimization status .......: converged
2017-09-29T10:14:29:  Number of parameters ......: 10
2017-09-29T10:14:29:  Number of free parameters .: 6
2017-09-29T10:14:29:  Number of iterations ......: 17
2017-09-29T10:14:29:  Lambda ....................: 1e-20
2017-09-29T10:14:29:  Maximum log likelihood ....: -162634.849
2017-09-29T10:14:29:  Observed events  (Nobs) ...: 82861.000
2017-09-29T10:14:29:  Predicted events (Npred) ..: 82860.995 (Nobs - Npred = 0.00502115531708114)
2017-09-29T10:14:29: === GModels ===
2017-09-29T10:14:29:  Number of models ..........: 2
2017-09-29T10:14:29:  Number of parameters ......: 10
2017-09-29T10:14:29: === GModelSky ===
2017-09-29T10:14:29:  Name ......................: Src001
2017-09-29T10:14:29:  Instruments ...............: all
2017-09-29T10:14:29:  Instrument scale factors ..: unity
2017-09-29T10:14:29:  Observation identifiers ...: all
2017-09-29T10:14:29:  Model type ................: PointSource
2017-09-29T10:14:29:  Model components ..........: "PointSource" * "PowerLaw" * "Constant"
2017-09-29T10:14:29:  Number of parameters ......: 6
2017-09-29T10:14:29:  Number of spatial par's ...: 2
2017-09-29T10:14:29:   RA ........................: 155.830563187239 +/- 0.00703462449391177 deg (free,scale=1)
2017-09-29T10:14:29:   DEC .......................: -57.7562830556977 +/- 0.00367619623578647 deg (free,scale=1)
2017-09-29T10:14:29:  Number of spectral par's ..: 3
2017-09-29T10:14:29:   Prefactor .................: 1.435495936e-17 +/- 1.116843125e-18 [0,infty[ ph/cm2/s/MeV (free,scale=5.7e-18,gradient)
2017-09-29T10:14:29:   Index .....................: -2.99659451192301 +/- 0.0791118536010512 [10,-10]  (free,scale=-2.48,gradient)
2017-09-29T10:14:29:   PivotEnergy ..............: 300000 MeV (fixed,scale=300000,gradient)
2017-09-29T10:14:29:  Number of temporal par's ..: 1
2017-09-29T10:14:29:   Normalization .............: 1 (relative value) (fixed,scale=1,gradient)
2017-09-29T10:14:29: === GCTAModelCubeBackground ===
2017-09-29T10:14:29:  Name ......................: BackgroundModel
2017-09-29T10:14:29:  Instruments ...............: CTA, HESS, MAGIC, VERITAS
2017-09-29T10:14:29:  Instrument scale factors ..: unity
2017-09-29T10:14:29:  Observation identifiers ...: all
2017-09-29T10:14:29:  Model type ................: "PowerLaw" * "Constant"
2017-09-29T10:14:29:  Number of parameters ......: 4
2017-09-29T10:14:29:  Number of spectral par's ..: 3
2017-09-29T10:14:29:   Prefactor .................: 1.09431953979467 +/- 0.00933498203600886 [0.01,100] ph/cm2/s/MeV (free,scale=1,gradient)
2017-09-29T10:14:29:   Index .....................: 0.0839727564602386 +/- 0.00489569197634214 [-5,5]  (free,scale=1,gradient)
2017-09-29T10:14:29:   PivotEnergy ..............: 1000000 MeV (fixed,scale=1000000,gradient)
2017-09-29T10:14:29:  Number of temporal par's ..: 1
2017-09-29T10:14:29:   Normalization .............: 1 (relative value) (fixed,scale=1,gradient)
```

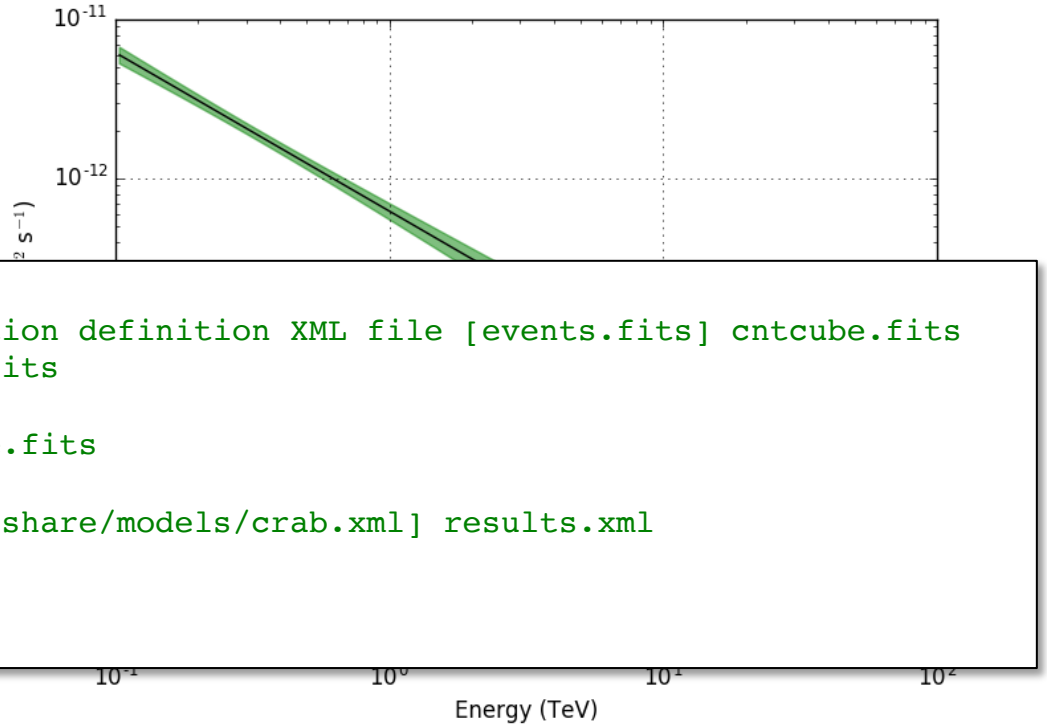
Generating a butterfly diagram





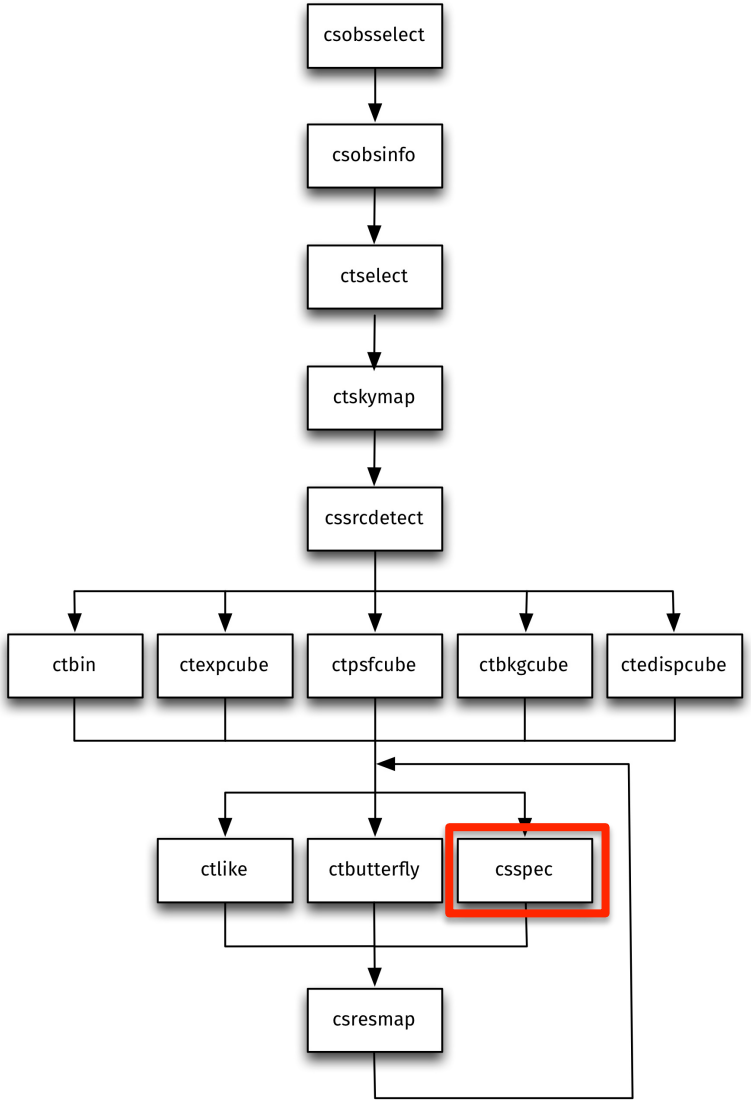
Generating a butterfly diagram

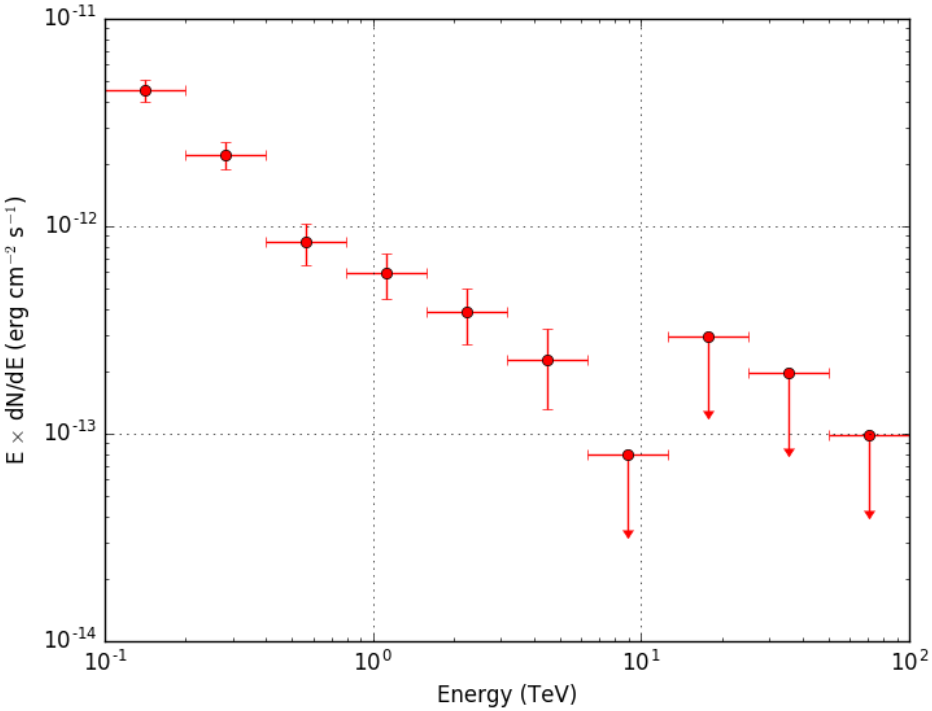




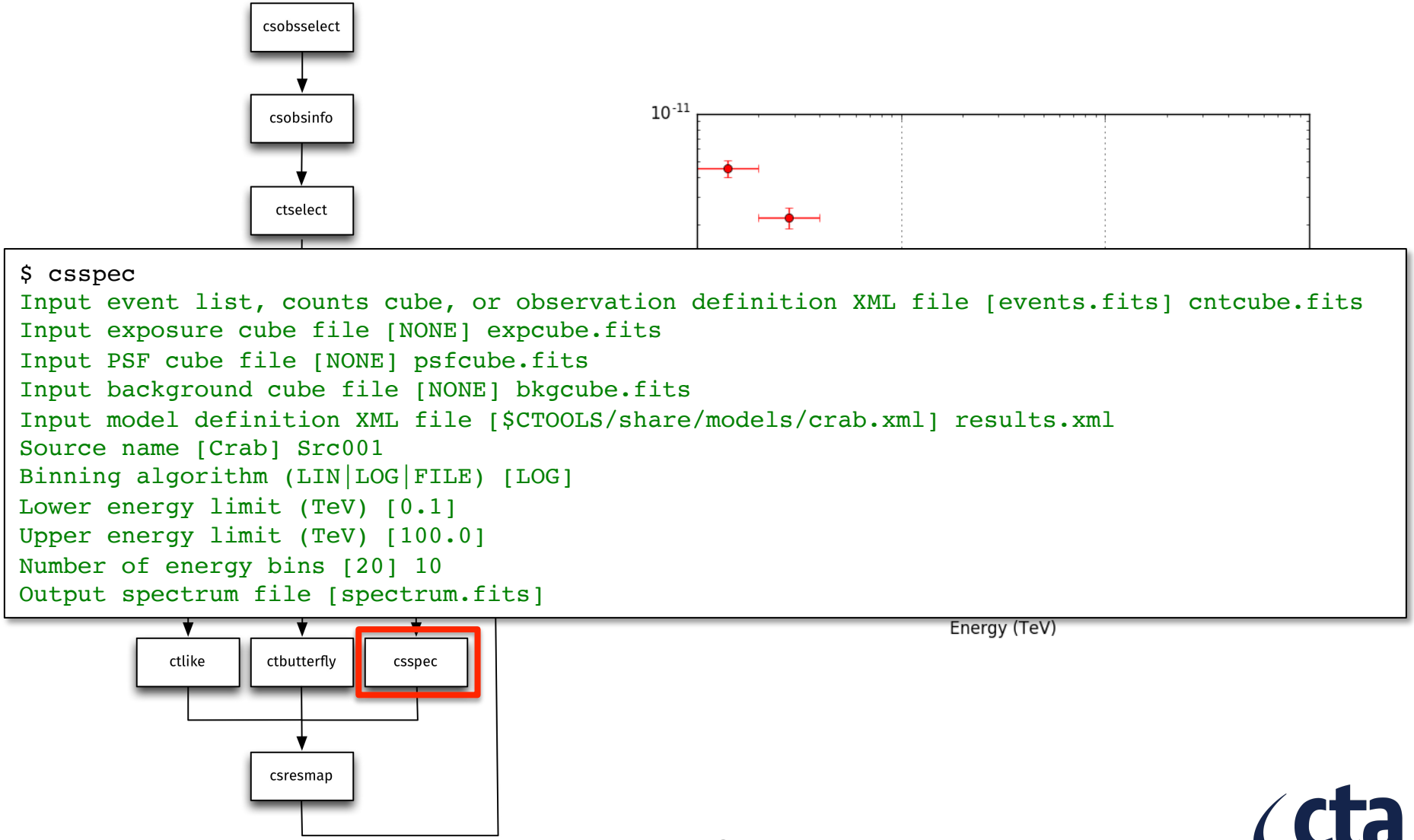

```
$ ctbutterfly
Input event list, counts cube or observation definition XML file [events.fits] cntcube.fits
Input exposure cube file [NONE] expcube.fits
Input PSF cube file [NONE] psfcube.fits
Input background cube file [NONE] bkgcube.fits
Source of interest [Crab] Src001
Input model definition XML file [$CTOOLS/share/models/crab.xml] results.xml
Lower energy limit (TeV) [0.1]
Upper energy limit (TeV) [100.0]
Output ASCII file [butterfly.txt]
```

Generating a SED

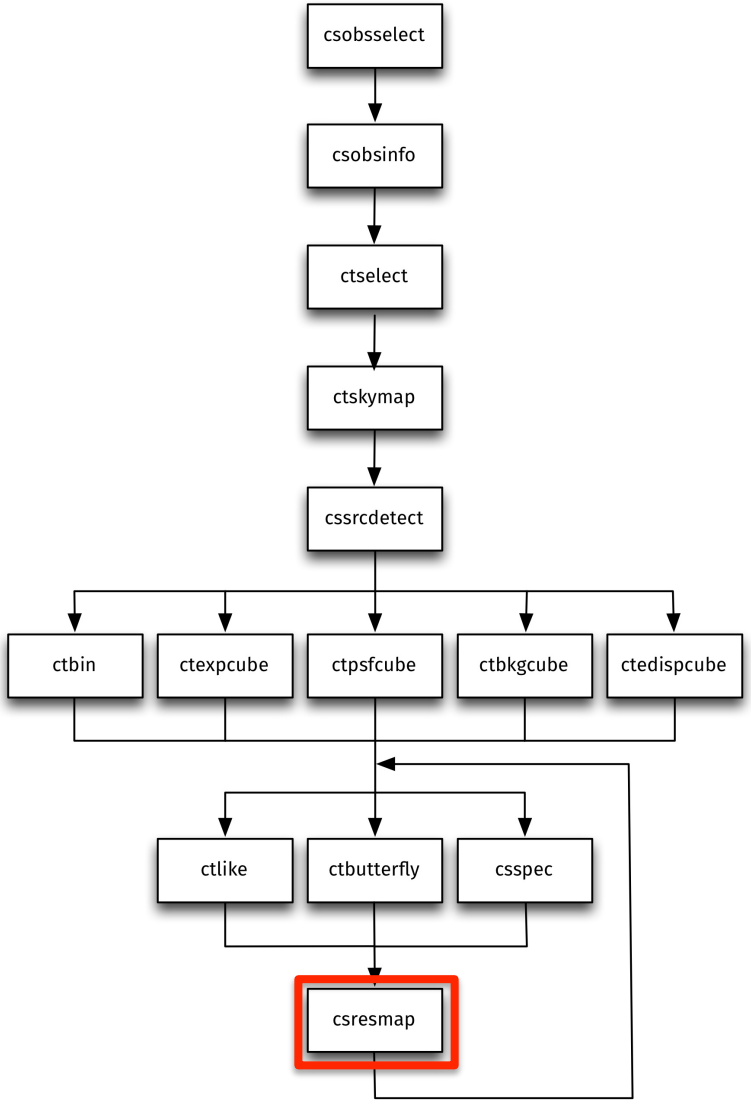


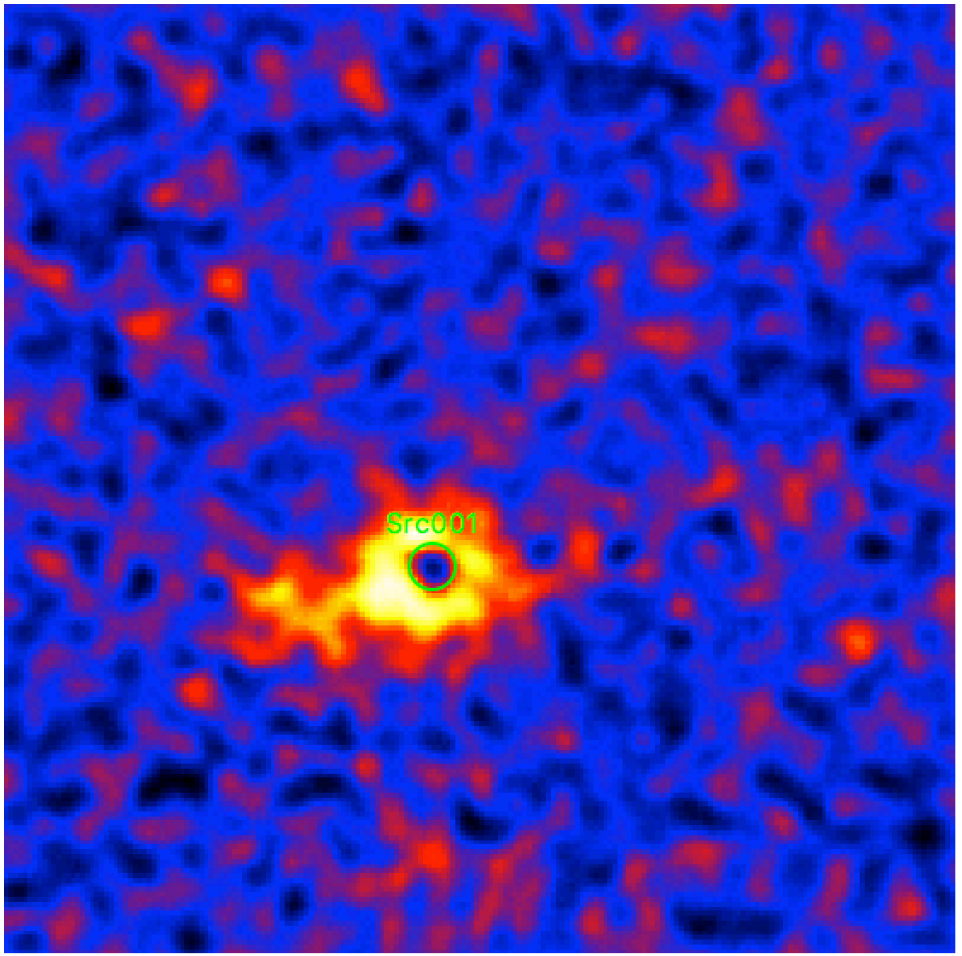


Generating a SED

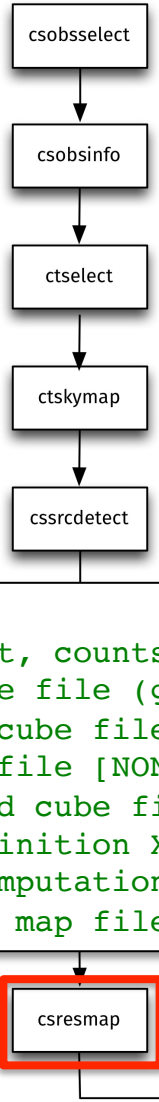


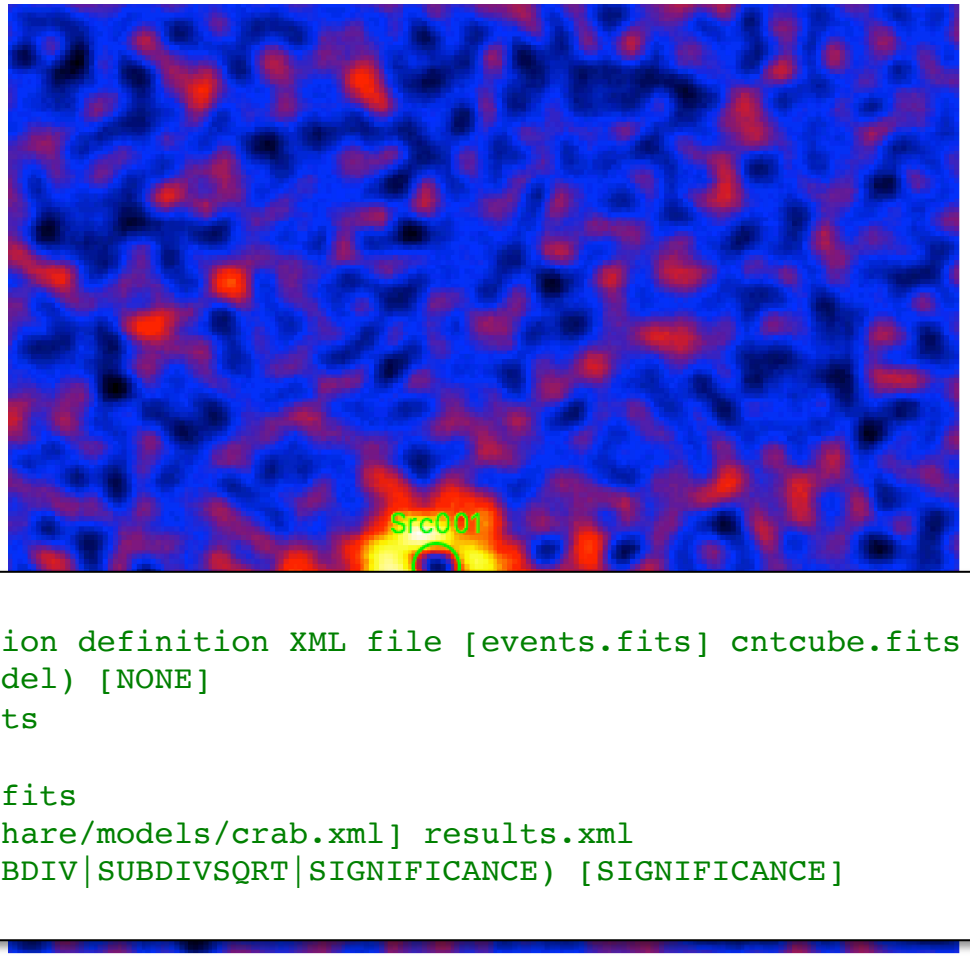
Inspecting the residuals





Inspecting the residuals

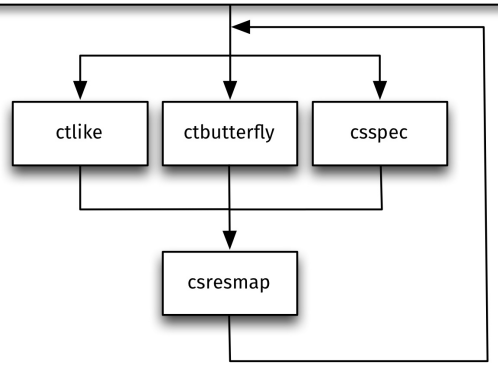




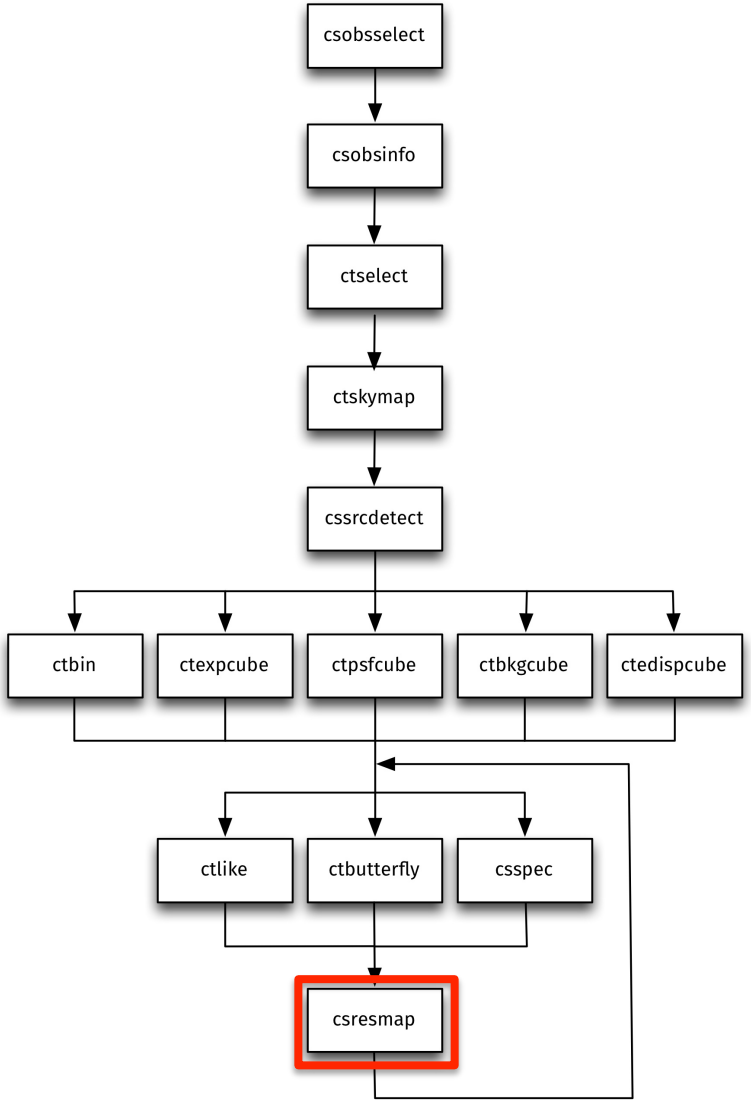

```
$ csresmap
Input event list, counts cube, or observation definition XML file [events.fits] cntcube.fits
Input model cube file (generated with ctmodel) [NONE]
Input exposure cube file [NONE] expcube.fits
Input PSF cube file [NONE] psfcube.fits
Input background cube file [NONE] bkgcube.fits
Input model definition XML file [$CTOOLS/share/models/crab.xml] results.xml
Residual map computation algorithm (SUB|SUBDIV|SUBDIVSQRT|SIGNIFICANCE) [SIGNIFICANCE]
Output residual map file [resmap.fits]
```

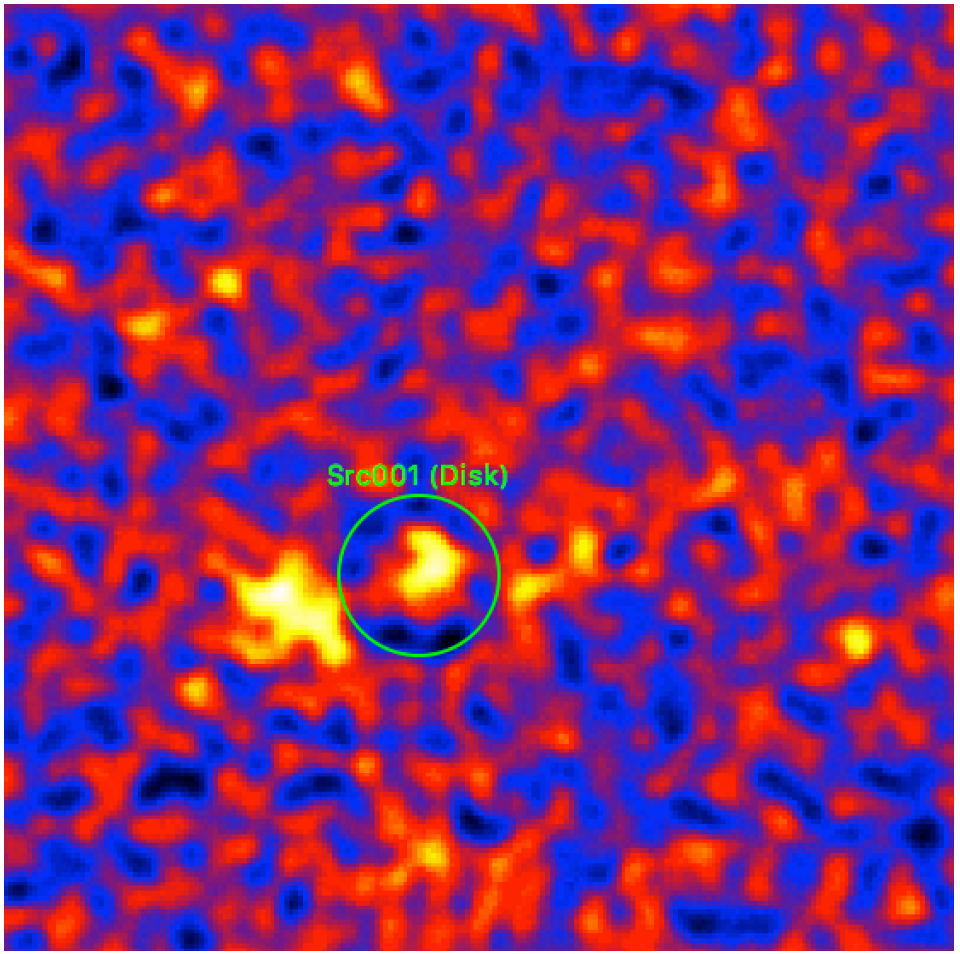
Improving the source model

```
<?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="-0" scale="-2.48" min="-4.03225806" max="4.03225806" free="1" />
      <parameter name="PivotEnergy" value="1" scale="300000" free="0" />
    </spectrum>
    <spatialModel type="RadialDisk">
      <parameter name="RA"     value="155.730" scale="1" free="1" />
      <parameter name="DEC"    value="-57.719" scale="1" free="1" />
      <parameter name="Radius" value="0.1"     scale="1" min="0.0001" max="1.0" free="1" />
    </spatialModel>
  </source>
  <source name="BackgroundModel" type="CTACubeBackground" instrument="CTA,HESS,MAGIC,VERITAS">
    <spectrum type="PowerLaw">
      <parameter name="Prefactor" value="1" error="0" scale="1" min="0.01" max="100" free="1" />
      <parameter name="Index" value="0" error="0" scale="1" min="-5" max="5" free="1" />
      <parameter name="PivotEnergy" value="1" scale="1000000" free="0" />
    </spectrum>
  </source>
</source_library>
```



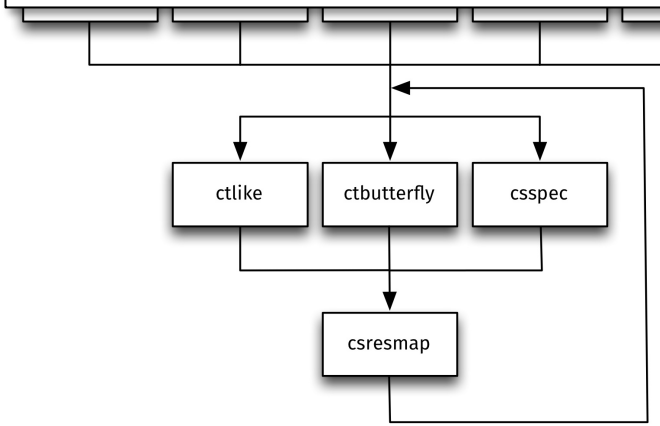
Inspecting the residuals



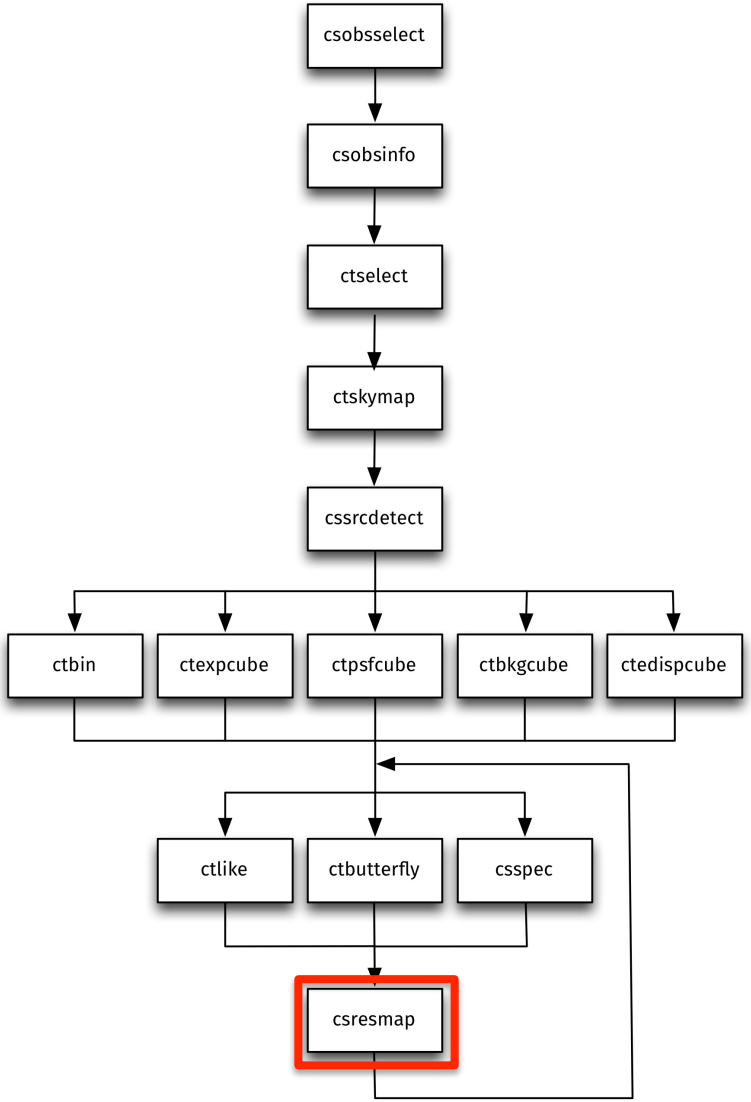


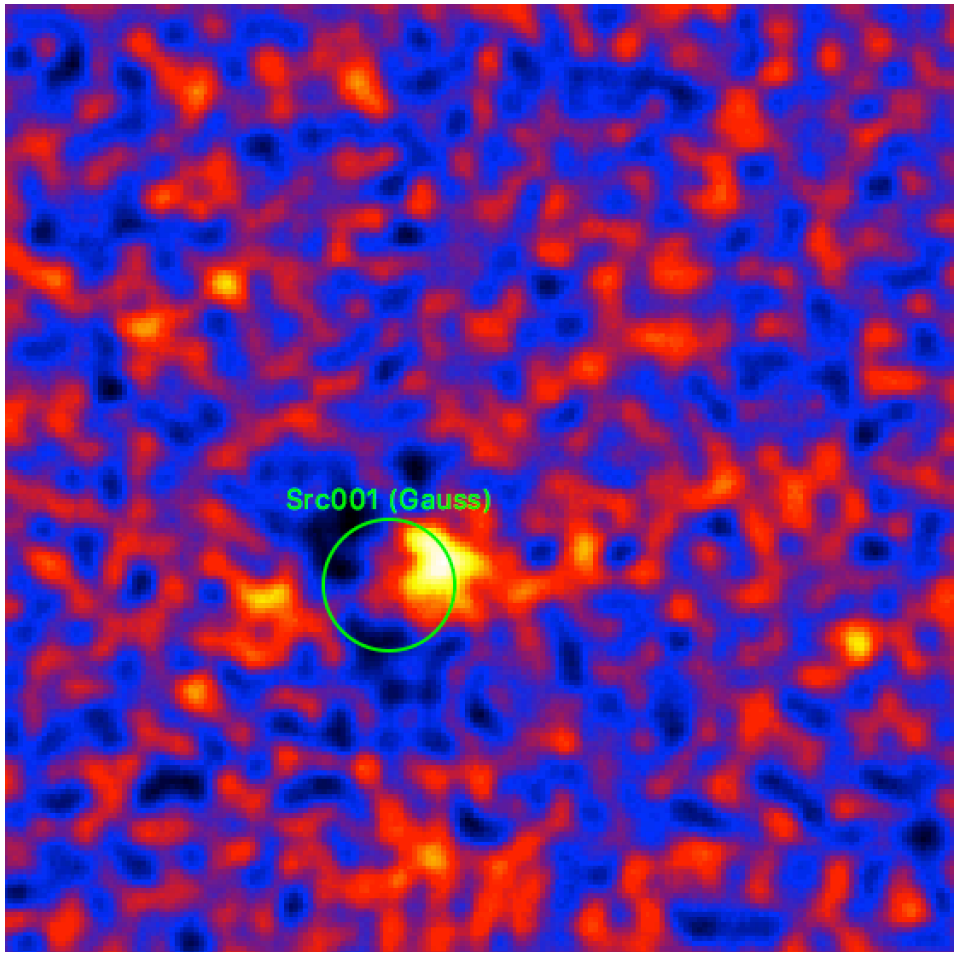
Improving the source model

```
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<source_library title="source library">
 <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="-4.03225806" max="4.03225806" free="1" />
      <parameter name="PivotEnergy" value="1" scale="300000" free="0" />
    </spectrum>
    <spatialModel type="RadialGaussian">
      <parameter name="RA"    value="155.730" scale="1" free="1" />
      <parameter name="DEC"   value="-57.719" scale="1" free="1" />
      <parameter name="Sigma" value="0.1"     scale="1" min="0.0001" max="1.0" free="1" />
    </spatialModel>
  </source>
  <source name="BackgroundModel" type="CTACubeBackground" instrument="CTA,HESS,MAGIC,VERITAS">
    <spectrum type="PowerLaw">
      <parameter name="Prefactor" value="1" error="0" scale="1" min="0.01" max="100" free="1" />
      <parameter name="Index" value="0" error="0" scale="1" min="-5" max="5" free="1" />
      <parameter name="PivotEnergy" value="1" scale="1000000" free="0" />
    </spectrum>
  </source>
</source_library>
```



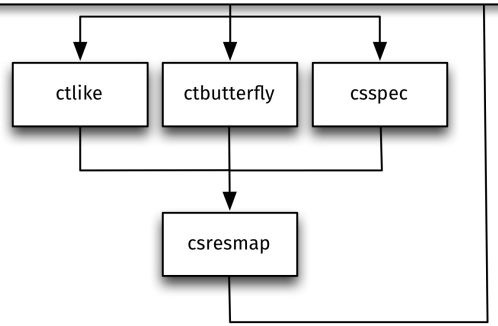
Inspecting the residuals



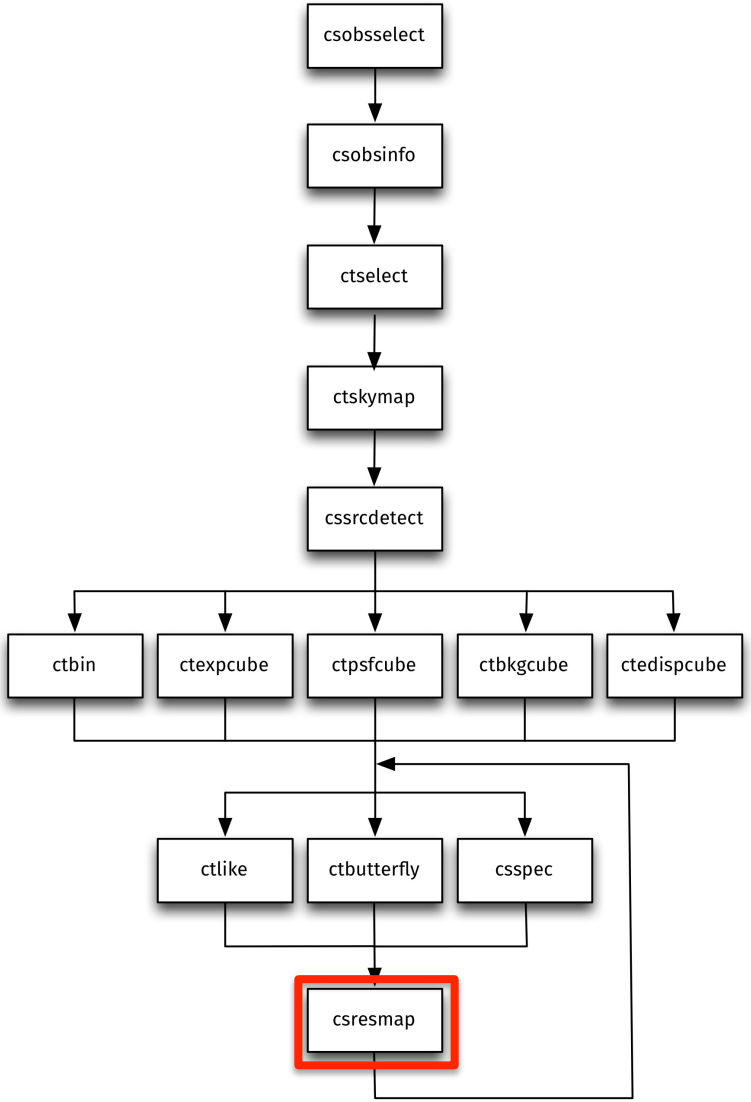


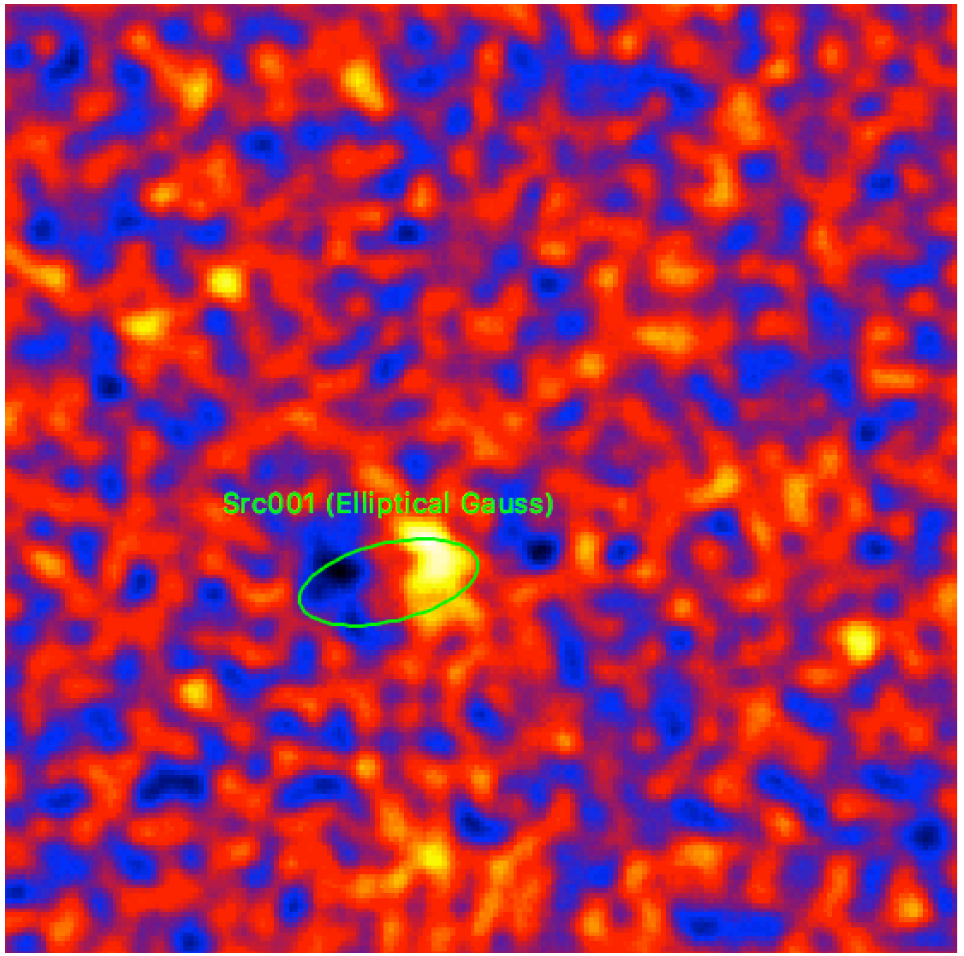
Improving the source model

```
<?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="-0" scale="-2.48" min="-4.03225806" max="4.03225806" free="1" />
      <parameter name="PivotEnergy" value="1" scale="300000" free="0" />
    </spectrum>
    <spatialModel type="EllipticalGauss">
      <parameter name="RA"          value="155.730" scale="1" free="1" />
      <parameter name="DEC"         value="-57.719" scale="1" free="1" />
      <parameter name="PA"          value="45.0" scale="1" min="-360.0" max="+360.0" free="1" />
      <parameter name="MinorRadius" value="0.2"  scale="1" min="0.05"   max="1.0"    free="1" />
      <parameter name="MajorRadius" value="0.4"  scale="1" min="0.1"    max="1.0"    free="1" />
    </spatialModel>
  </source>
  <source name="BackgroundModel" type="CTACubeBackground" instrument="CTA,HESS,MAGIC,VERITAS">
    <spectrum type="PowerLaw">
      <parameter name="Prefactor" value="1" error="0" scale="1" min="0.01" max="100" free="1" />
      <parameter name="Index" value="0" error="0" scale="1" min="-5" max="5" free="1" />
      <parameter name="PivotEnergy" value="1" scale="1000000" free="0" />
    </spectrum>
  </source>
</source_library>
```



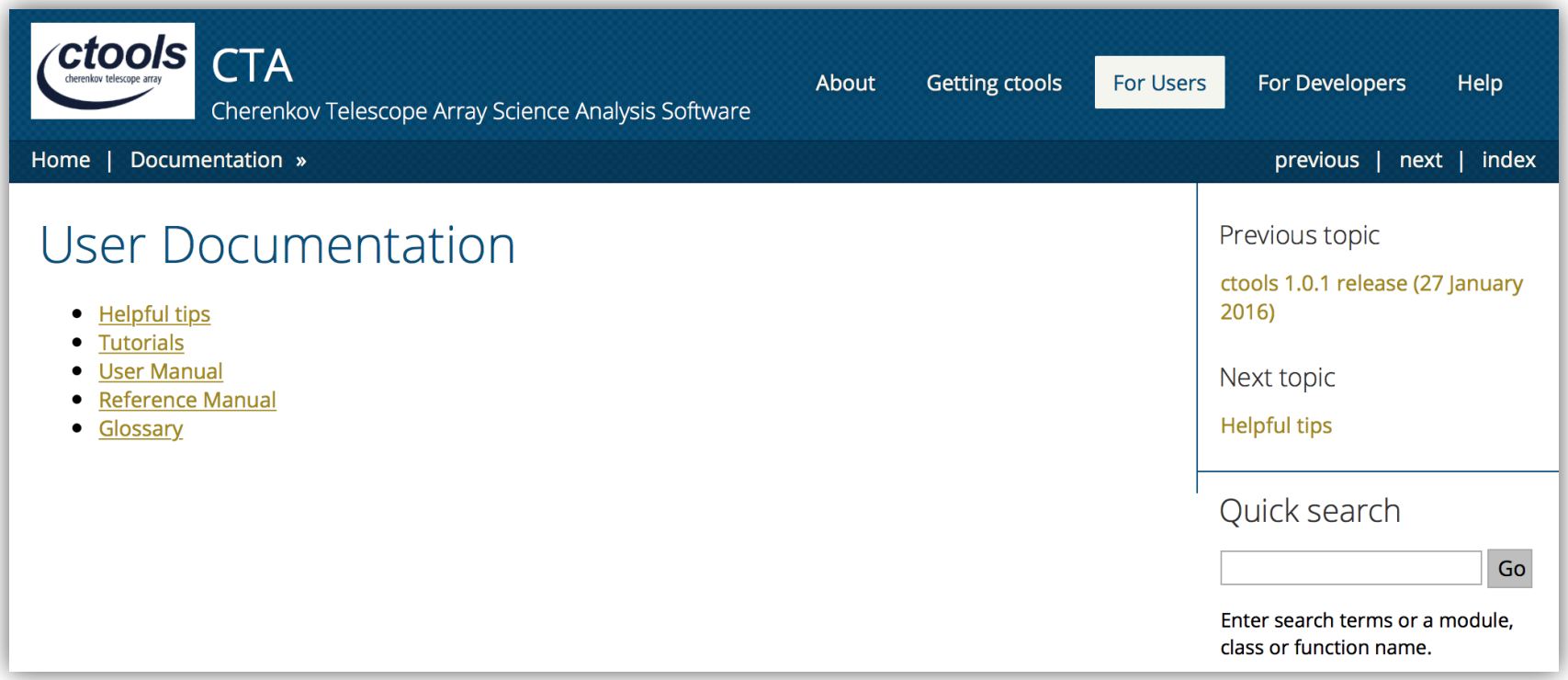
Inspecting the residuals





How do I get help?

- Read the ctools User Documentation
  - http://cta.irap.omp.eu/ctools/users/index.html



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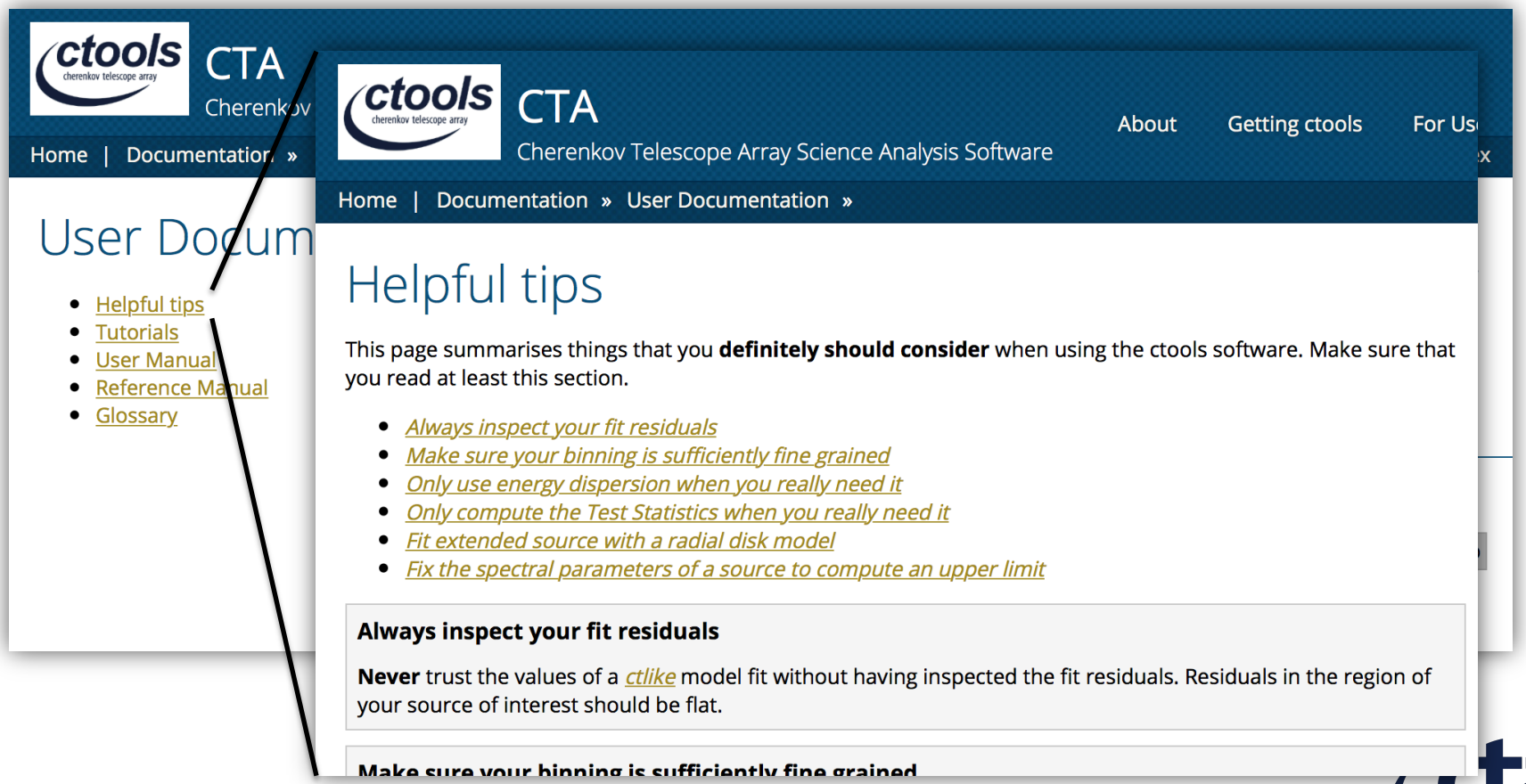

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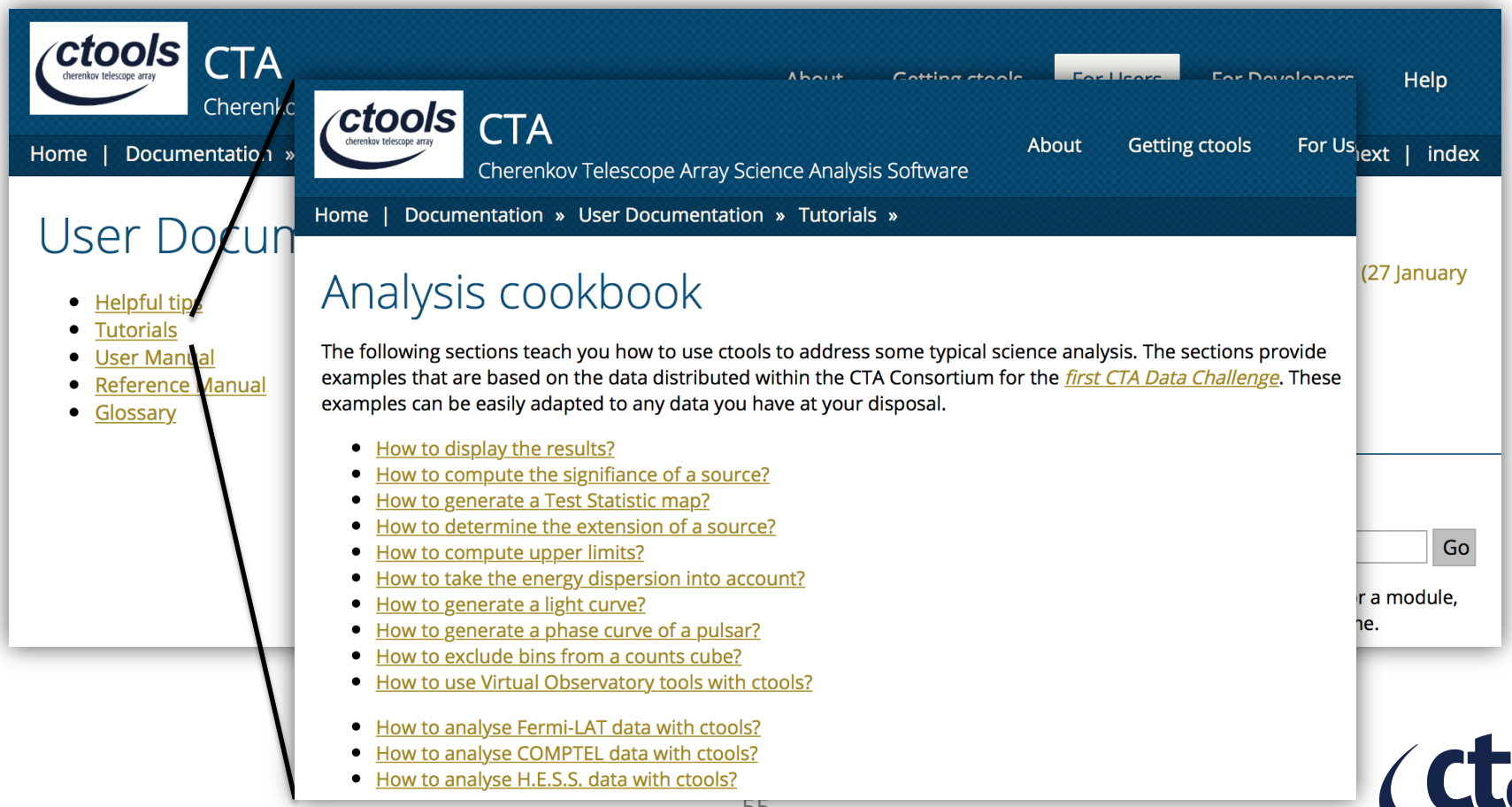

How do I get help?

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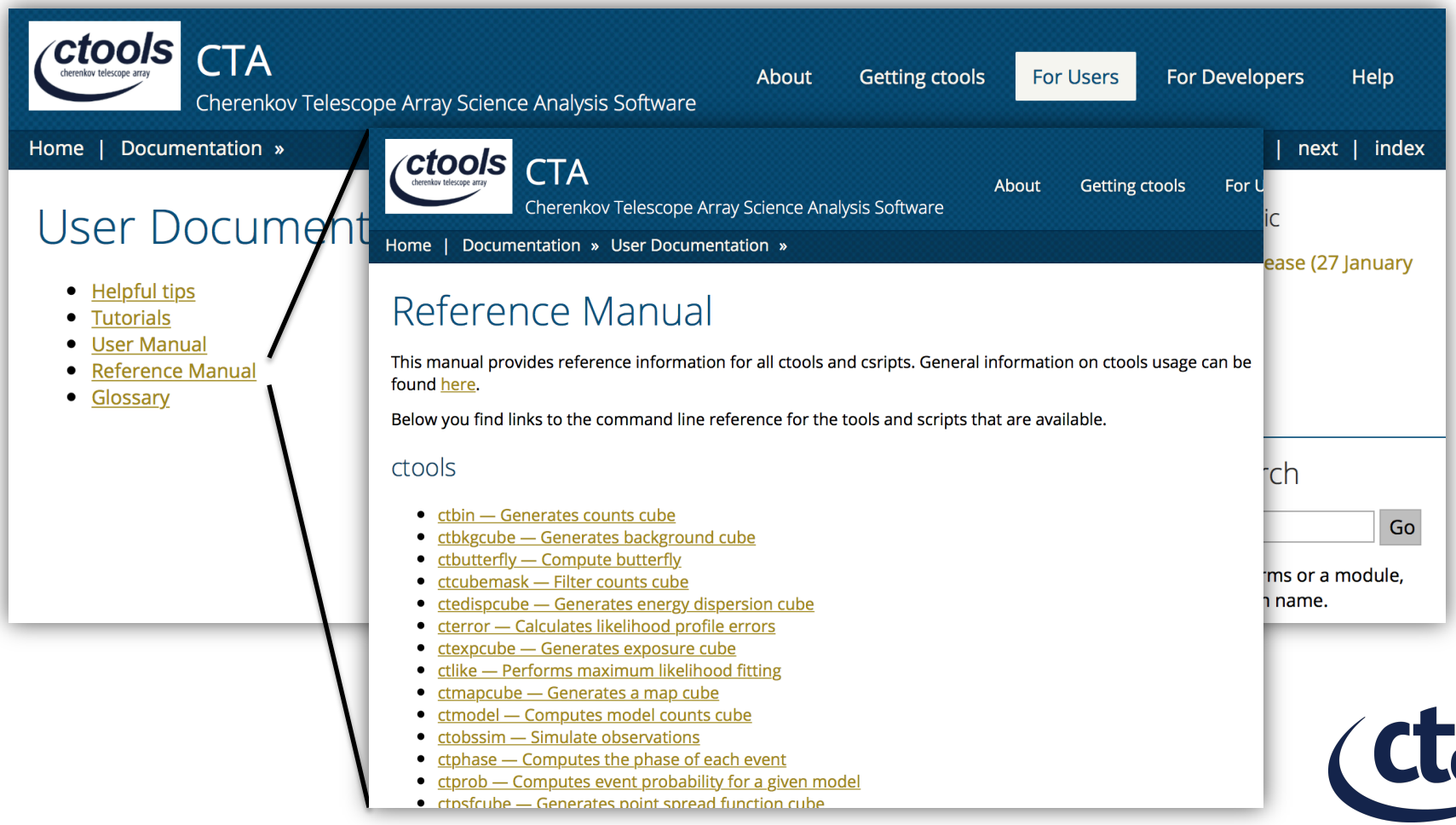
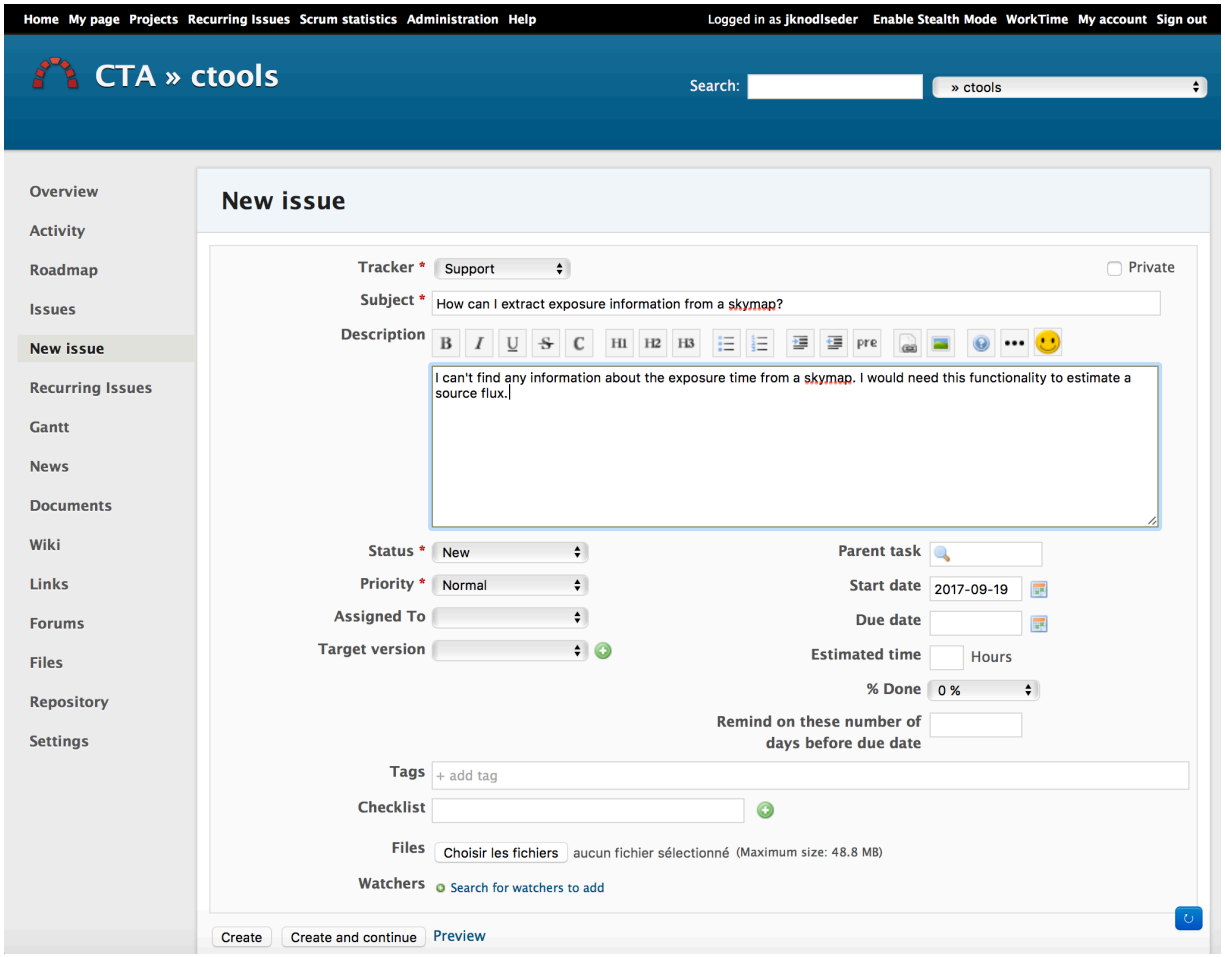


How do I get help?

- Create a “Support” issue on the ctools Redmine
  - https://cta-redmine.irap.omp.eu/projects/ctools/issues/new



How do I get help?

- Send an e-mail to the ctools User list
  - ctools@irap.omp.eu

How do I get help?

- Come to our next coding sprint
  - 9-13 October 2017, IRAP, Toulouse, France
  - Sign-up on ctools Redmine
    - https://cta-redmine.irap.omp.eu/projects/ctools/wiki/Eighth_ctools_coding_sprint