cta cherenkov telescope array

ctools cherenkov telescope array

irap astrophysique & planétologie

Simulation and analysis of Cherenkov Telescope Array data using ctools

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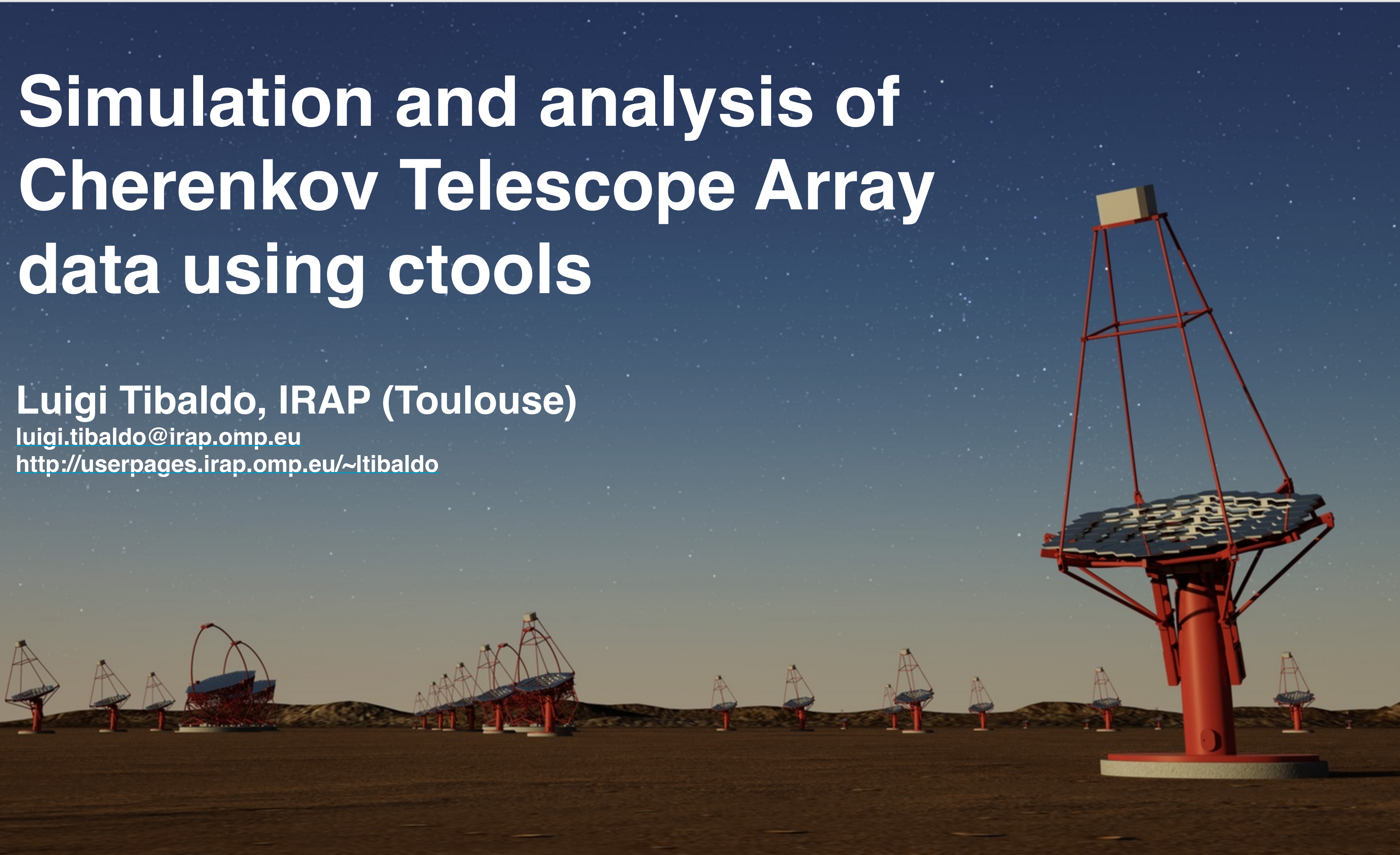


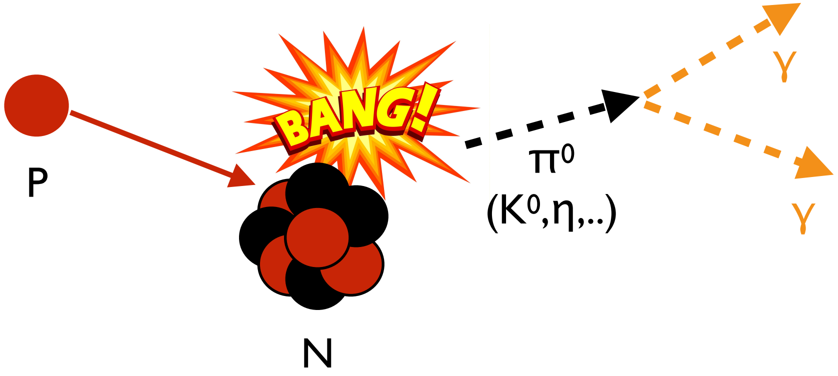
Outline

1. Scientific motivations of very-high-energy gamma-ray astronomy
2. Imaging Atmospheric Cherenkov Telescopes
3. The Cherenkov Telescope Array
4. ctools
5. Demo: simulation and analysis of CTA observations of a gamma-ray source
6. Hands-on sessions

Inception of gamma-ray astronomy: a quest for the sources of cosmic rays

gamma rays from CR nuclei interactions with interstellar matter

- through production of unstable particles that decay in gamma rays (lightest π^0)
- **only electromagnetic tracer of highly relativistic nuclei**

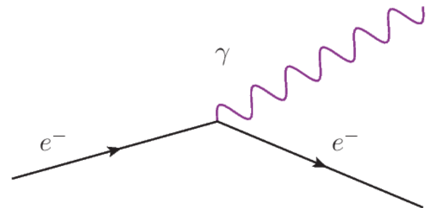


How a VHE gamma-ray is made

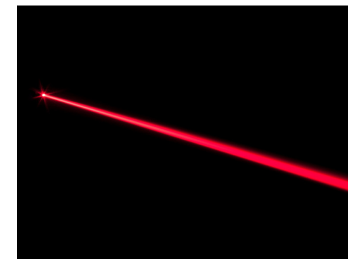
energy source

particle acceleration

particle interaction/
gamma-ray production



gamma-ray
propagation

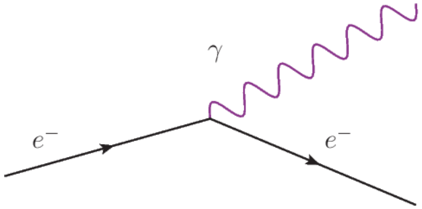


A probe of nonthermal phenomena

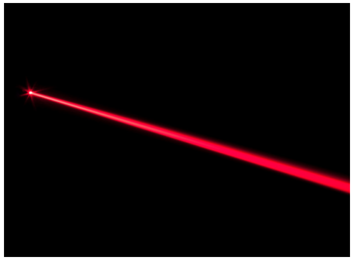
energy source

particle acceleration

particle interaction/ gamma-ray production



gamma-ray propagation



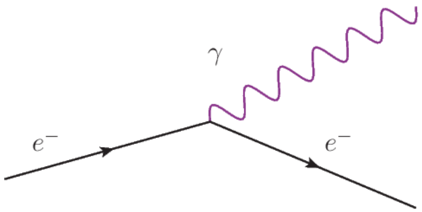
- cannot be produced by thermal processes:
  100 MeV → 2×10^{11} K (Wien's law)
- no nuclear gamma-ray lines beyond few tens of MeV
- only production mechanism: **particle acceleration + radiative process**

1 - Origin and role of relativistic cosmic particles

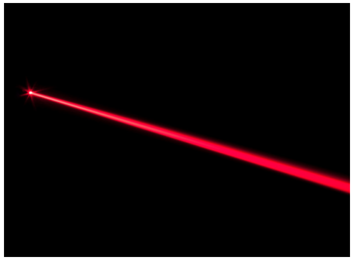
energy source

particle acceleration

particle interaction/ gamma-ray production



gamma-ray propagation



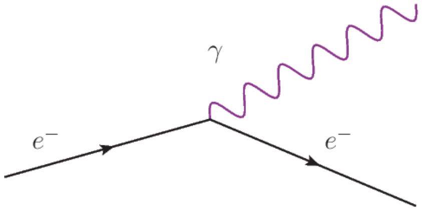
- **the original one**: what are the sites and mechanisms of cosmic-ray acceleration?
- what is the feedback of cosmic rays on star-formation and galaxy evolution?

2 - Probing extreme environments

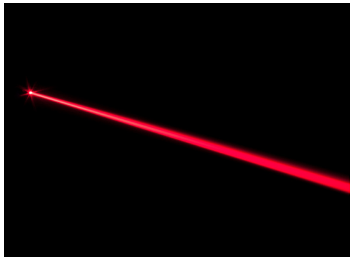
energy source

particle acceleration

particle interaction/ gamma-ray production



gamma-ray propagation



- what physical processes are at work close to neutron stars and black holes?
- what are the characteristics of relativistic jets, winds and explosions?
- what is the nature of gamma-ray bursts, the Fermi bubbles … ?
- what are the electromagnetic counterparts to gravitational wave and neutrino sources?

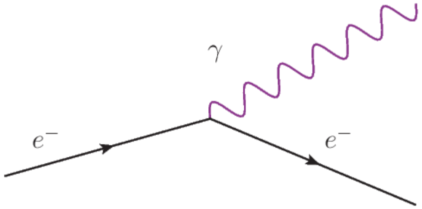
- how intense are radiation/ magnetic fields in extragalactic space and how do they evolve over cosmic time?

3- Exploring frontiers in Physics

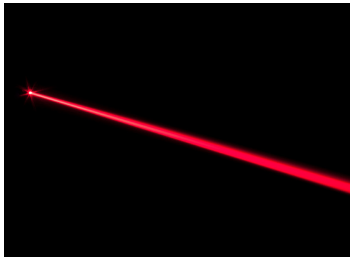
energy source

particle acceleration

particle interaction/ gamma-ray production



gamma-ray propagation



- what is the nature of dark matter and how is it distributed?

- are there quantum gravitational affects on photon propagation?
- do axion-like particles exist?

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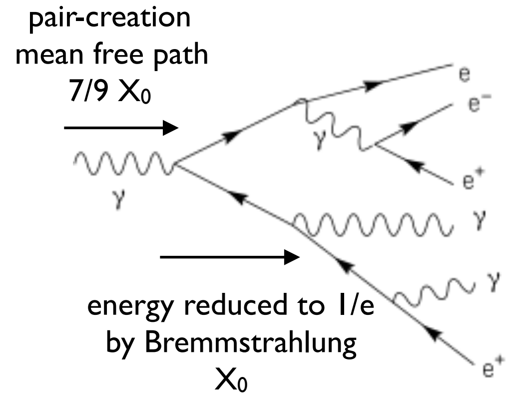
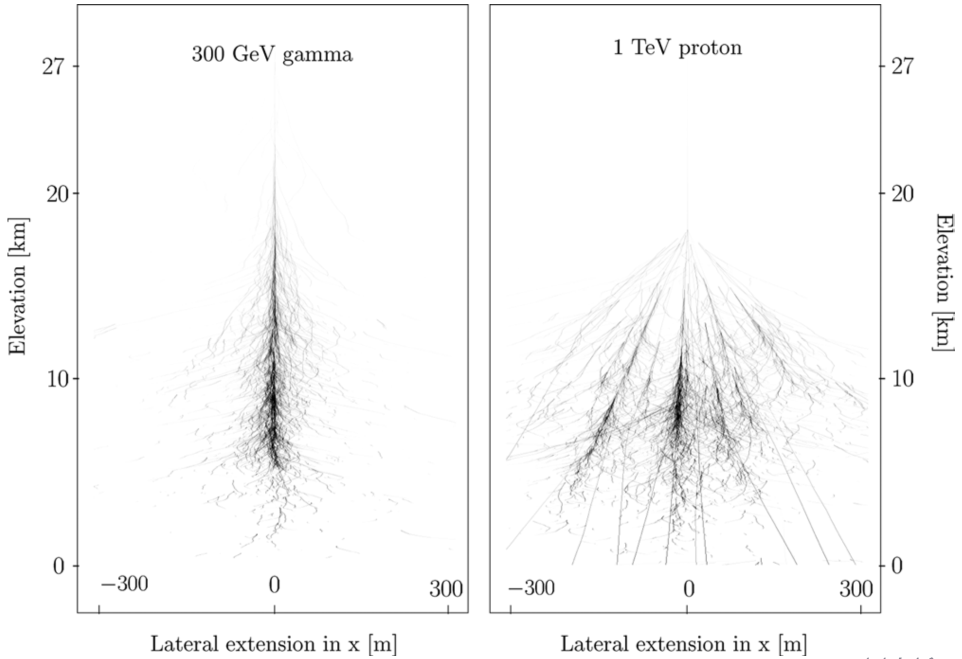
Detecting celestial gamma rays

- the Earth's atmosphere stops gamma rays
- satellite detectors are limited by their size to energies < 1 TeV

Atmospheric showers

- gamma rays produce electromagnetic showers
  - 1 e/gamma generates 2 with 1/2 energy over scale of radiation length
  - shower growth: 2^N e/gamma with $1/2^N$ energy after N r.l.
  - process stops when approaching electron critical energy O(100 MeV), ionisation prevails over Bremsstrahlung
- cosmic-ray nuclei also produce showers
  - hadronic interactions can transfer higher transversal momentum → wider/patchier profile

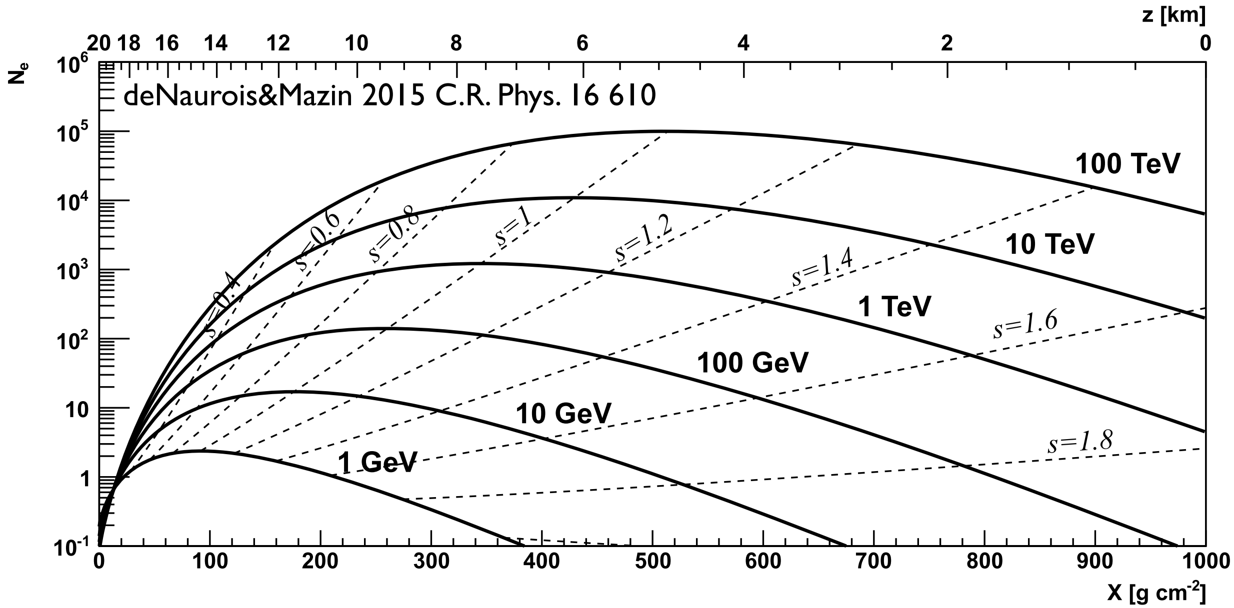




Aharonian+ 2008 R.P.Phys 71 096901

Atmospheric showers development

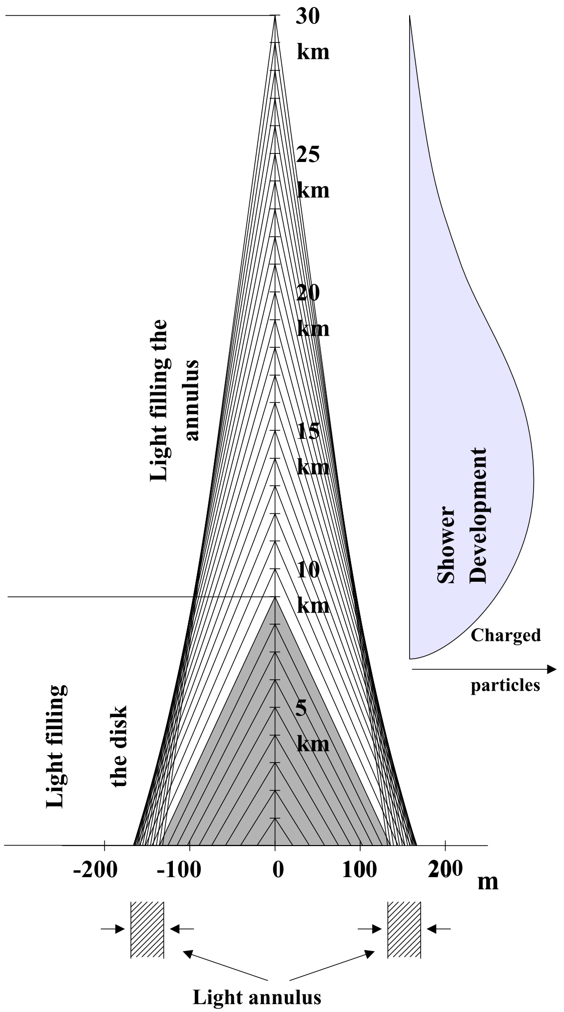
- the atmosphere has approximately an exponential density profile exp($-z/z_0$) with $z_0 \sim 8$ km
- the radiation length in air is ~ 37 g cm^{-2} , the total depth at sea level is ~ 30 r.l.
- the shower maximum occurs at heights of 5 to 15 km (depending on energy)
- fluctuations in the em shower development are mainly due to fluctuations of first interaction depth
- shower opening
  - multiple Coulomb scattering causes a lateral opening of ~5°
  - Earth's magnetic field broadens the shower in the East-West direction



Cherenkov radiation

- ultrarelativistic electrons emit Cherenkov light at characteristic angle
- the Cherenkov light yield is approximately proportional to primary energy
- refraction index depends on density, exponential variation with altitude → angle varies from 0.2° at 30 km to 1.5° at sea level
  - rough focussing on 120-150 m light pool
  - multiple Coulomb scattering creates exponential distribution of angles within O(5°)
- since electrons are superluminal, duration of Cherenkov photon flash is short O(5 ns) on axis
- Cherenkov light is absorbed in the atmosphere
  - Rayleigh scattering (small particles), absorption length → λ^4
  - Mie scattering (large particles = aerosols), absorption length → λ
  - Ozone photodissociation, absorbs UV
  - scattering by water vapour

deNaurois&Mazin 2015 C.R. Phys. 16 610



The imaging Cherenkov technique

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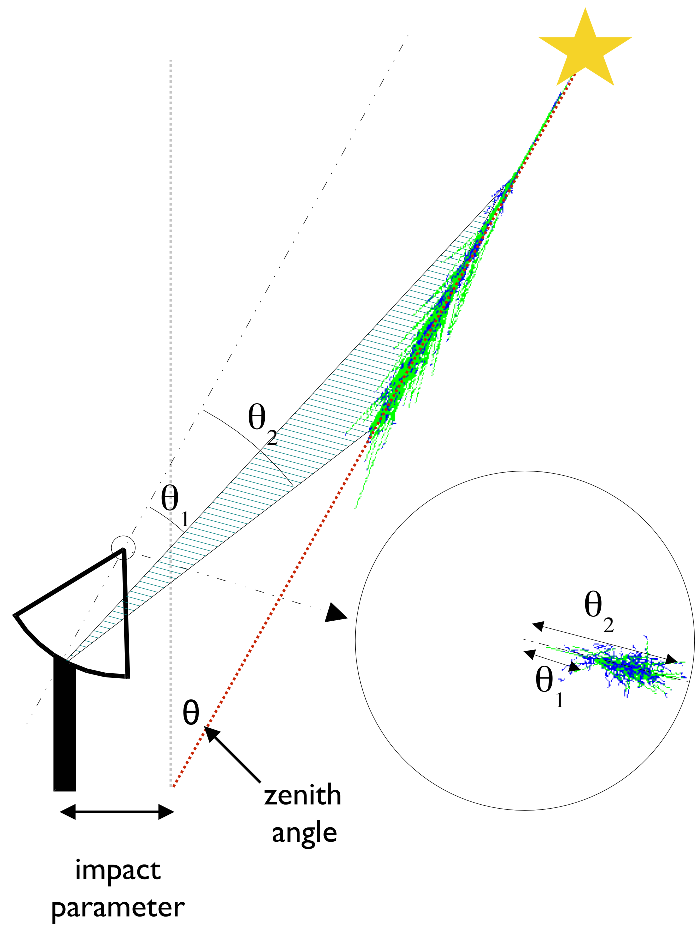
- elongated image pointing to source
- with increasing impact parameter
  - image more elongated
  - centroid farther from parallax
- with increasing energy
  - light amount increases
  - image length increases
- with increasing zenith angle
  - shower max distance increases as $l_{max} = z_{max}/\cos\theta$
  - image width/length smaller by a factor $\cos\theta$
  - radius of light pool larger by $1/\cos\theta$, thus light intensity smaller by $\cos^2\theta$
  - consequences: effective area and energy threshold increase approximately as $1/\cos^2\theta$
- increasing altitude reduces the distance to the shower max, so opposite effects



Imaging Cherenkov telescopes

- basic constituents
    - wide-field optical telescope (shower width 5°) with resolution O(0.1°) (internal structure of shower)
    - fast camera with 100 to > 1000 pixels that records images on timescales O(5 ns) to discriminate showers from fluctuations of night-sky background
    - altitude-azimuth mount to track sources during long exposures
- arrays of imaging Cherenkov telescopes
    - multiple telescopes spaced by 50-100 m (at least 2 to 4 see same shower light pool)
    - stereoscopic reconstruction of shower arrival direction and impact position
    - better gamma/hadron separation
- working principle
    - trigger when multiple pixels (or sum of multiple pixels) exceed some threshold within time coincidence window
    - array coincidence trigger helps with background rejection
- observing modes:
    - pointing known/putative sources
    - surveys (still limited because small field of view)
- require dark and clear-sky conditions

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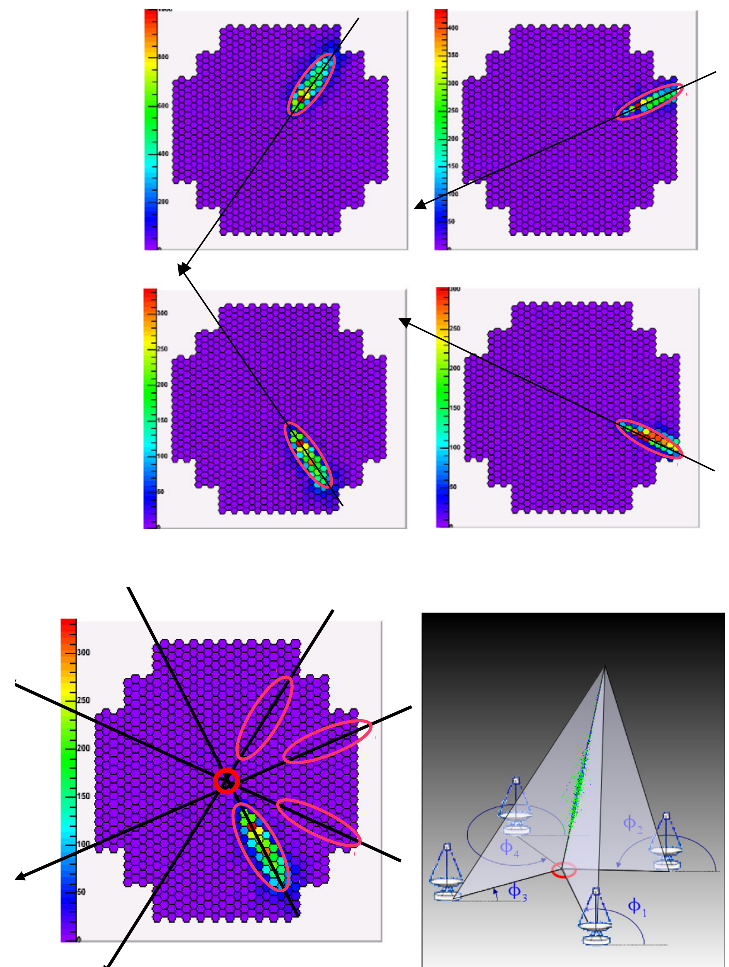


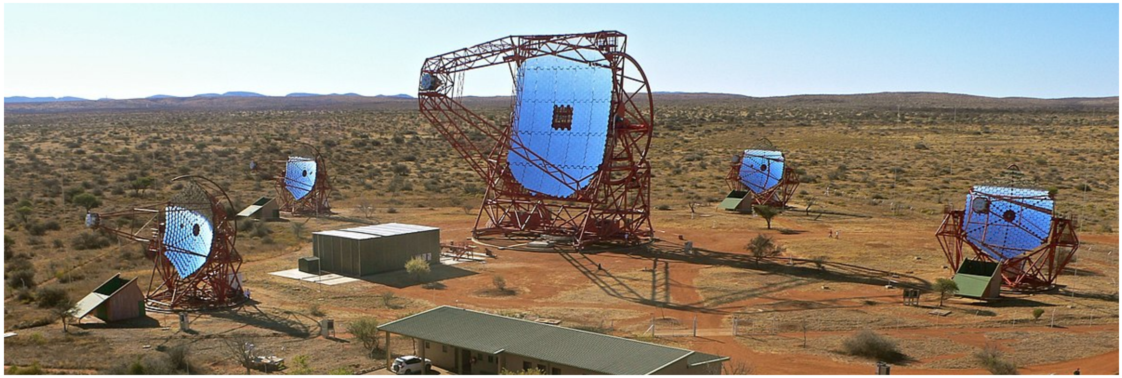
IACT history in a nutshell

- 1953: Galbraith measures Cherenkov light from atmospheric showers
- 1960s-1980s: several experiments try to measure gamma rays using shower Cherenkov light, no solid detection of gamma-ray sources
- 1990s: IACT astronomy begins
  - 1989: the Whipple collaboration detects gamma rays from the Crab Nebula with single IACT, few more sources follow
  - from 1993: the HEGRA collaboration performs the first stereoscopic observations with an array of 5 IACTs
  - from 1997: the CAT collaboration demonstrates the advantage of finely pixelated cameras
- 2000s-2010s: current generation IACTs, the coming of age of VHE astronomy

Whipple Telescope 1968

Current generation IACTs

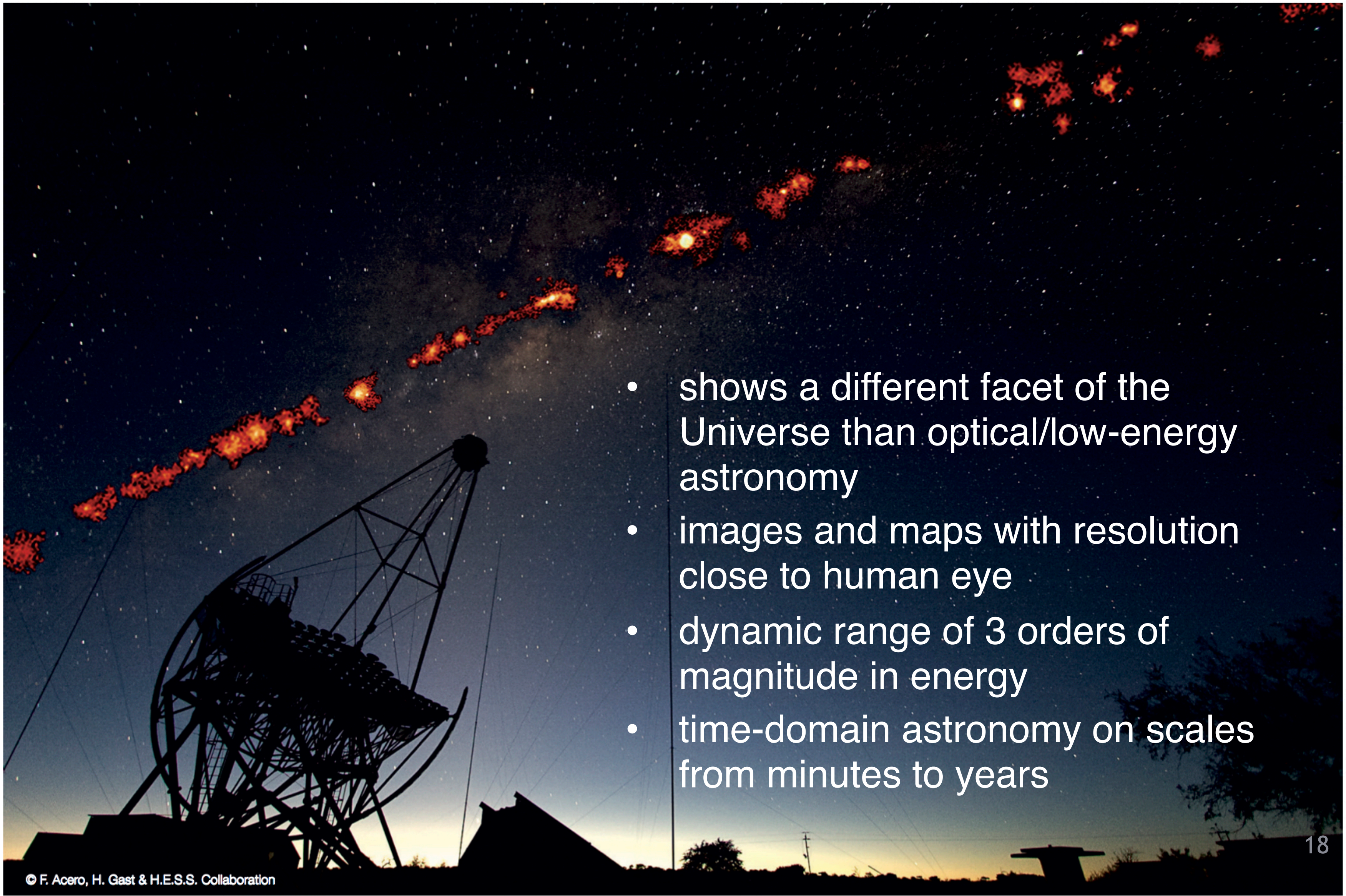
H.E.S.S.
Namibia
4 + 1 telescopes
12 m + 28 m



VERITAS
Arizona
4 telescopes
10 m

MAGIC
Canary Islands
2 telescopes
17 m

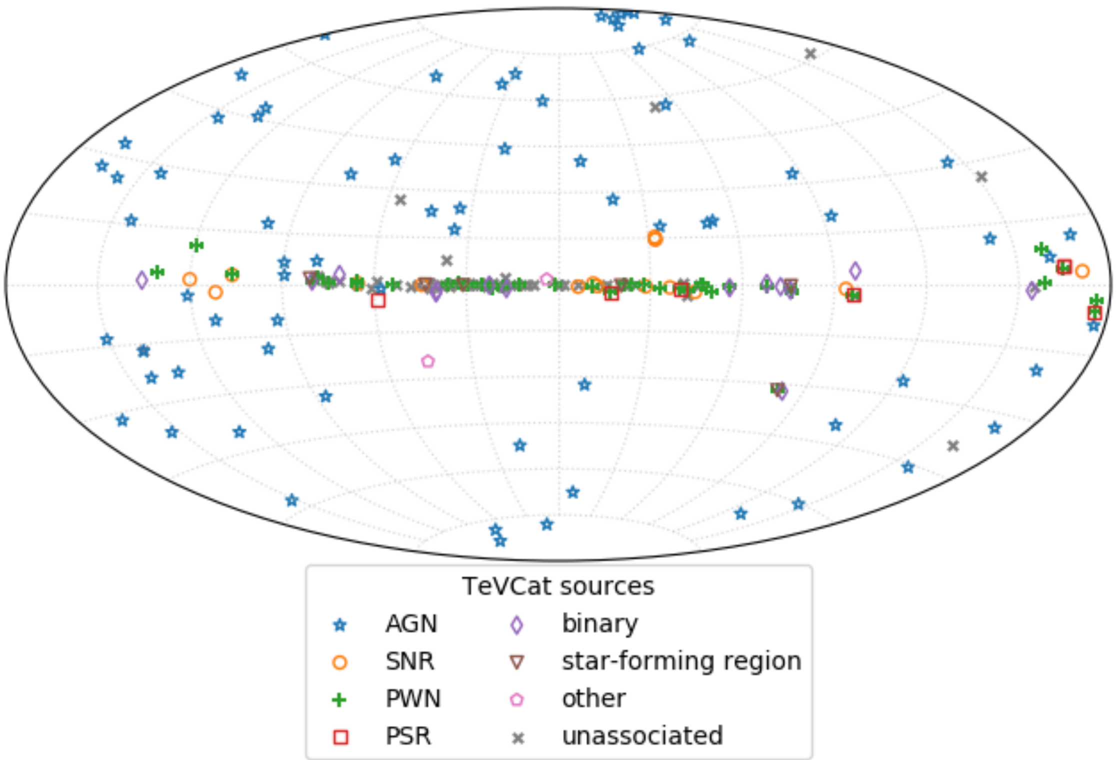
Astronomy with IACTs



- shows a different facet of the Universe than optical/low-energy astronomy
- images and maps with resolution close to human eye
- dynamic range of 3 orders of magnitude in energy
- time-domain astronomy on scales from minutes to years

The coming of age of VHE astronomy

Sources detected by ground-based gamma-ray telescopes (TeVCat)



astounding variety of VHE emitters, attests to ubiquitous phenomena of extreme objects accelerating particles in the Universe

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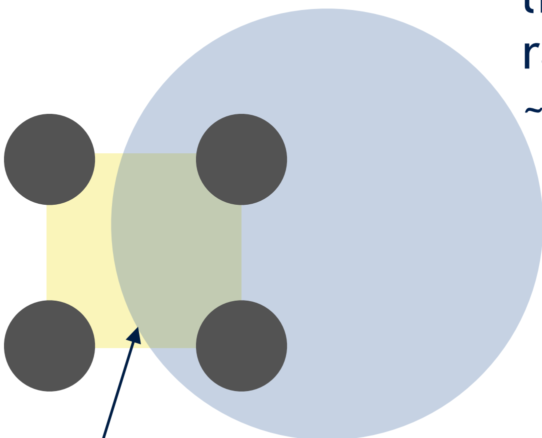
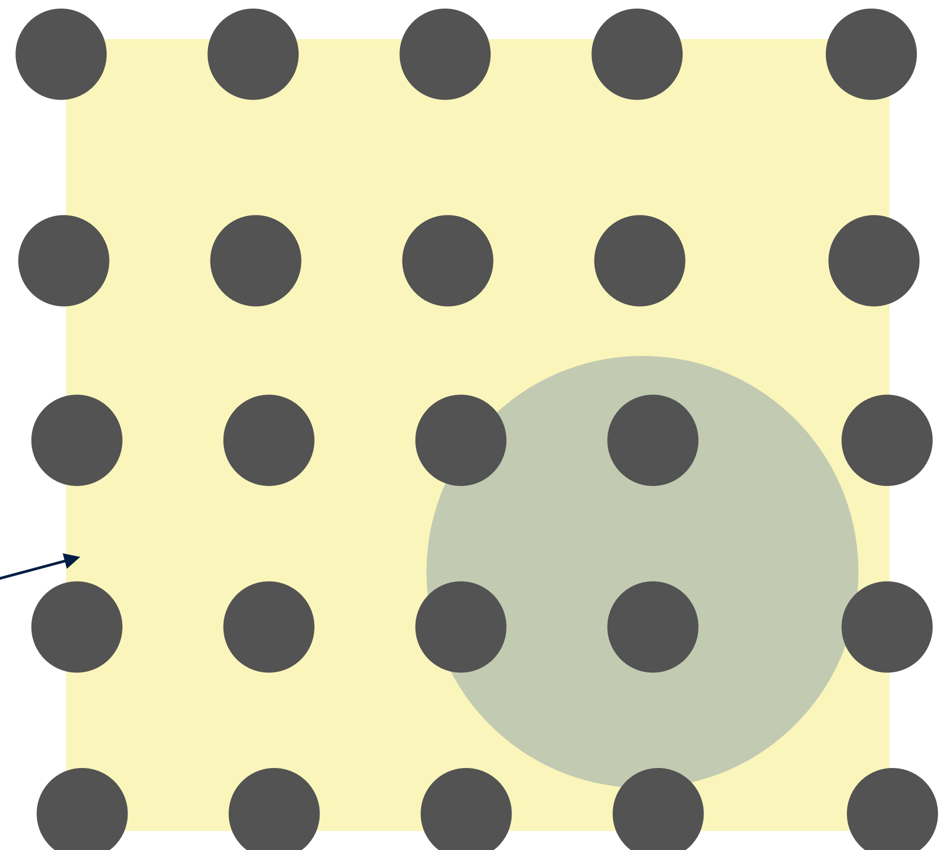
CTA: the concept

Credit: Werner Hofmann

light-pool
radius 100-150 m
~ telescope spacing

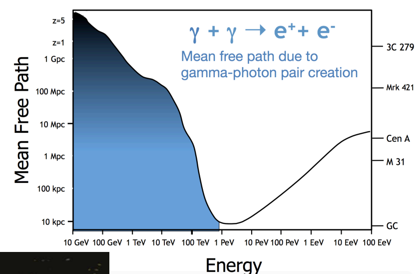


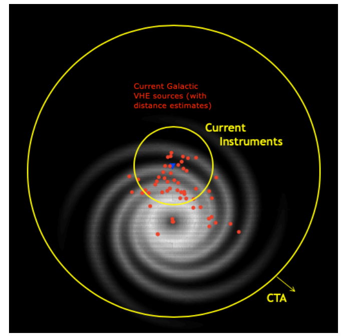
sweet spot for trigger
and reconstruction:
most showers miss it

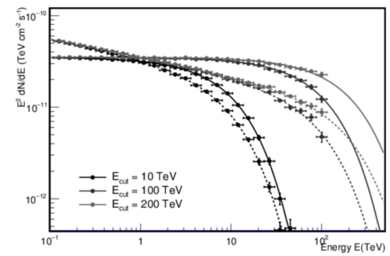


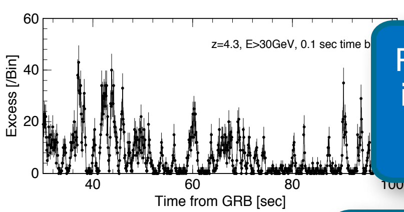
large detection area
more images per shower
lower trigger threshold

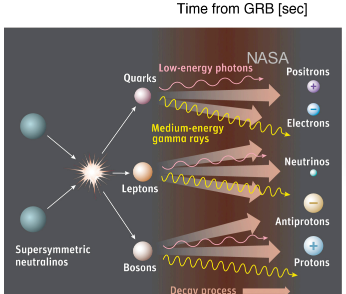
Design drivers











Energies down to 20 GeV
→ Cosmology++

10 x Sensitivity, Large Collection Area
→ all topics

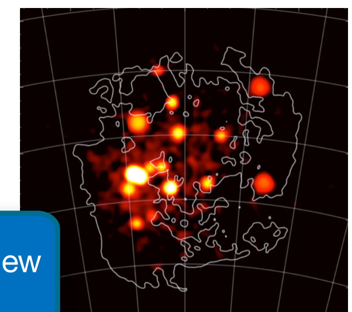
Energies up to 300 TeV
→ Pevatrons

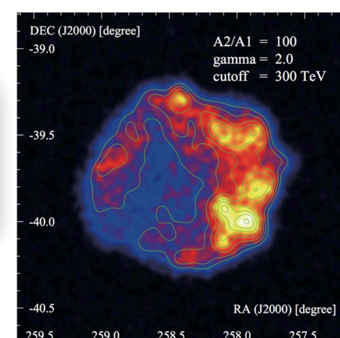
Rapid Slewing in 20 seconds
→ transients

8° Field of View
→ surveys, extended objects

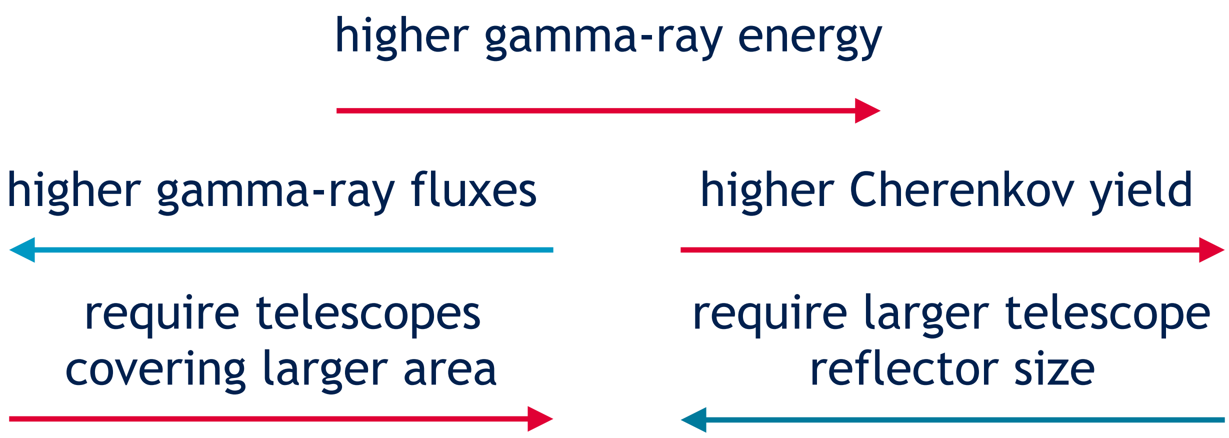
10% Energy Resolution
→ lines, features

Few ' Angular Resolution
→ morphology





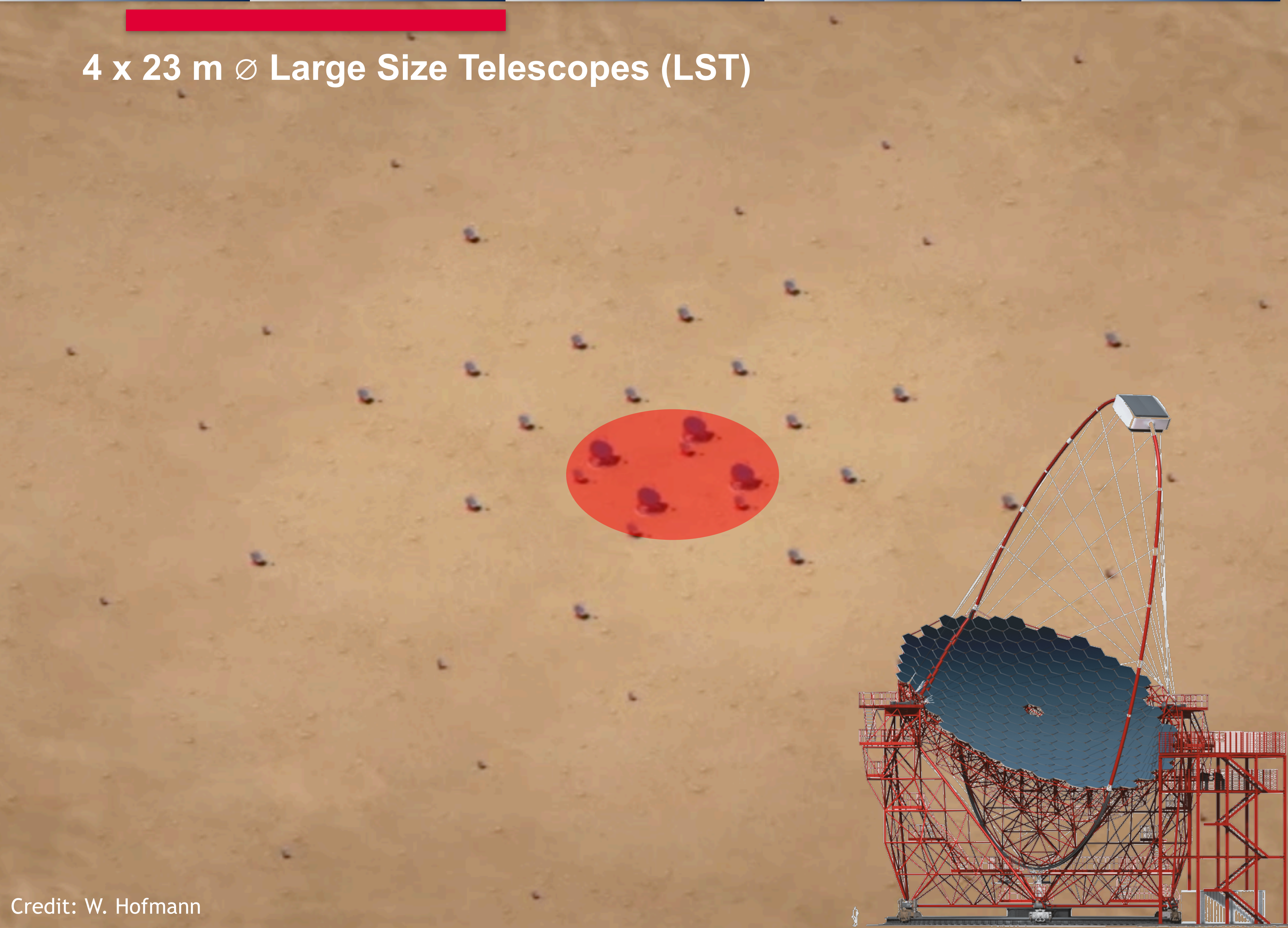
A size for every energy



- at low energies Cherenkov yield is lower → require larger telescope reflector size
- at high energies gamma-ray fluxes are lower → require to cover larger ground area with telescopes
- need to find a cost-effective compromise to cover large energy range!

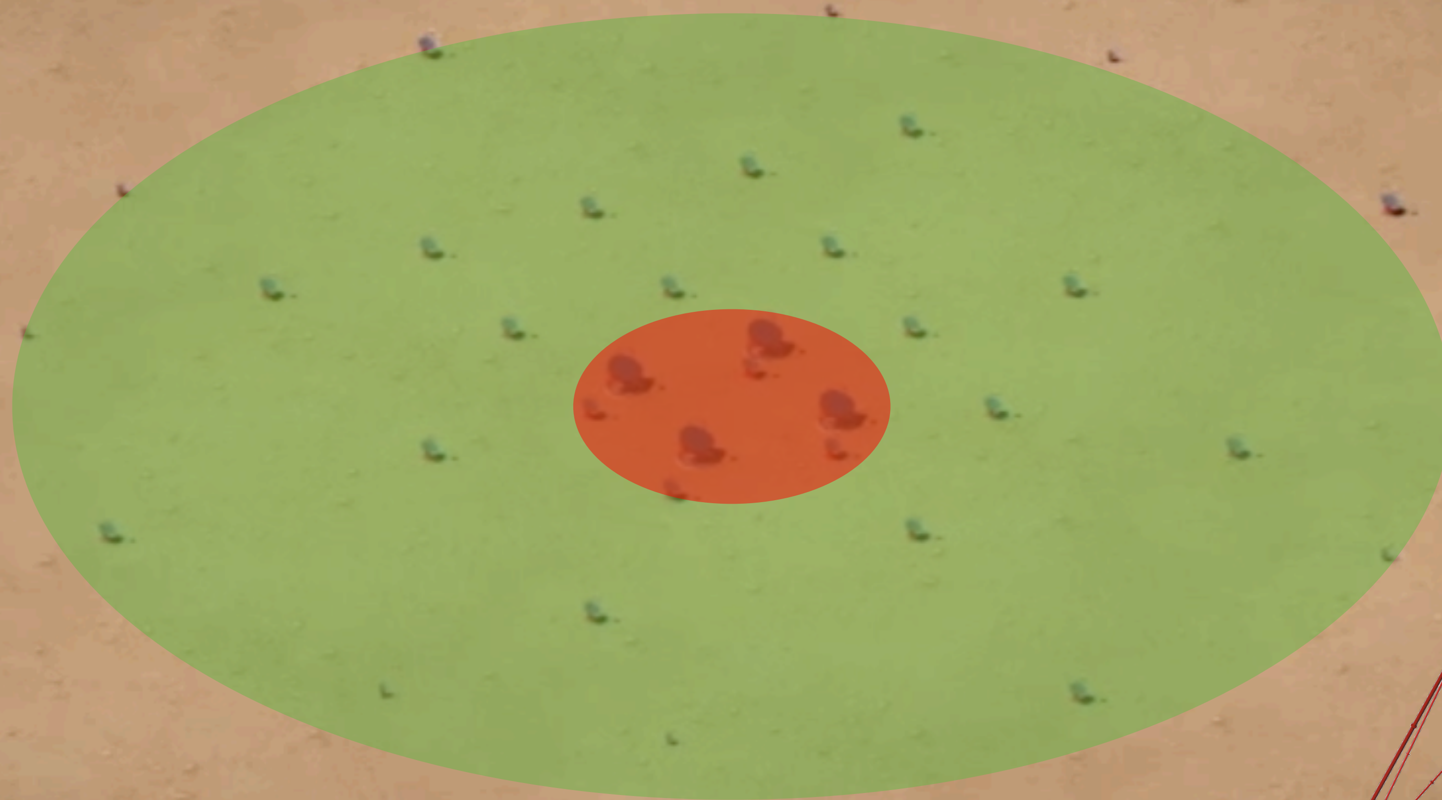
10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

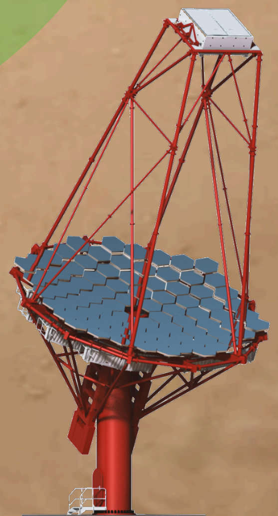
4 x 23 m ∅ Large Size Telescopes (LST)



10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

25 x 12 m ∅ Medium Size Telescopes (MST)
(North: 15)





Credit: W. Hofmann

10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

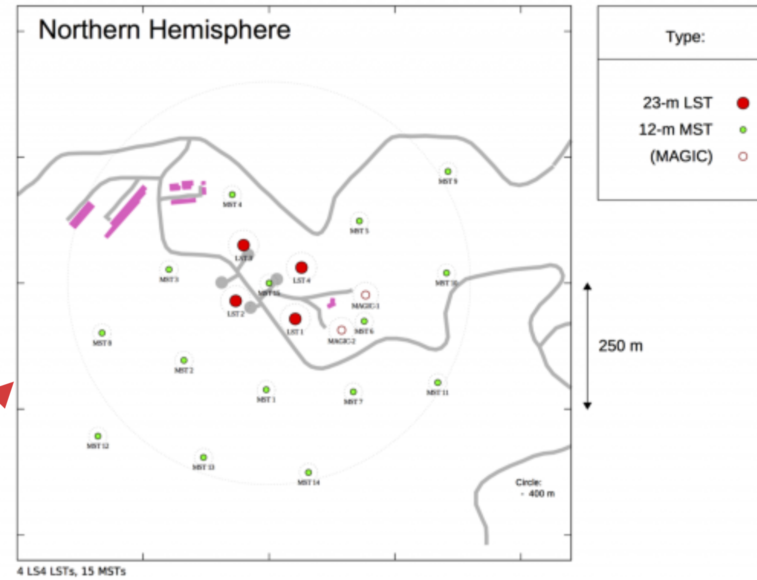
70 x 4 m ∅ Small Size Telescopes (SST) (South)

Credit: W. Hofmann

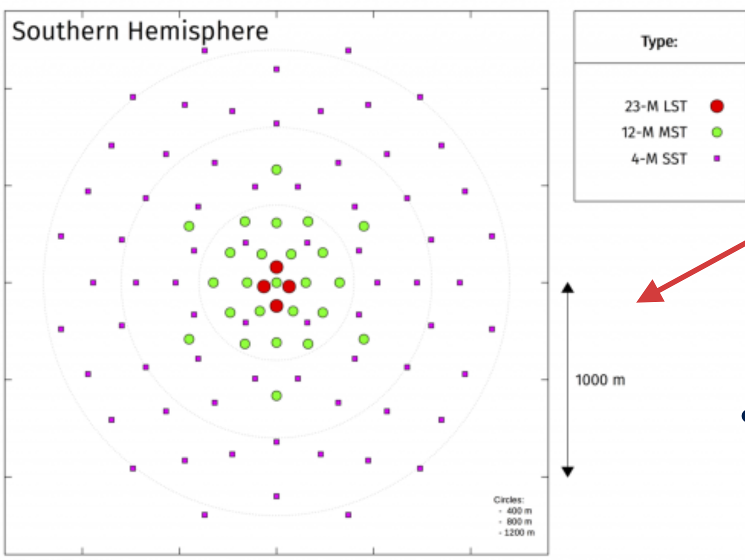
Sites and layout

- two sites for full sky coverage
- SSTs only in Southern hemisphere owing to easier access to Milky Way (extragalactic VHE gamma rays absorbed by EBL)

La Palma, Canary Islands, Spain

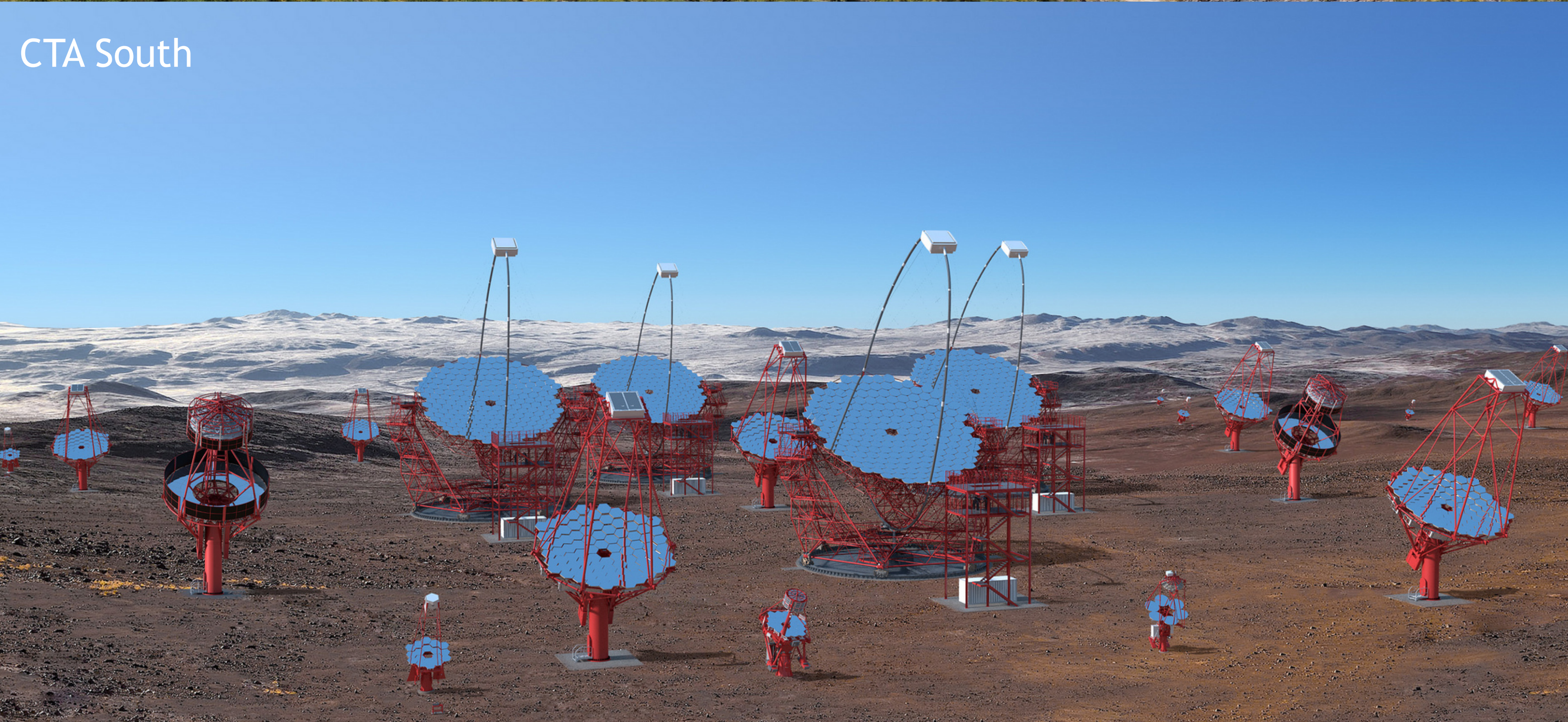


Paranal, Chile



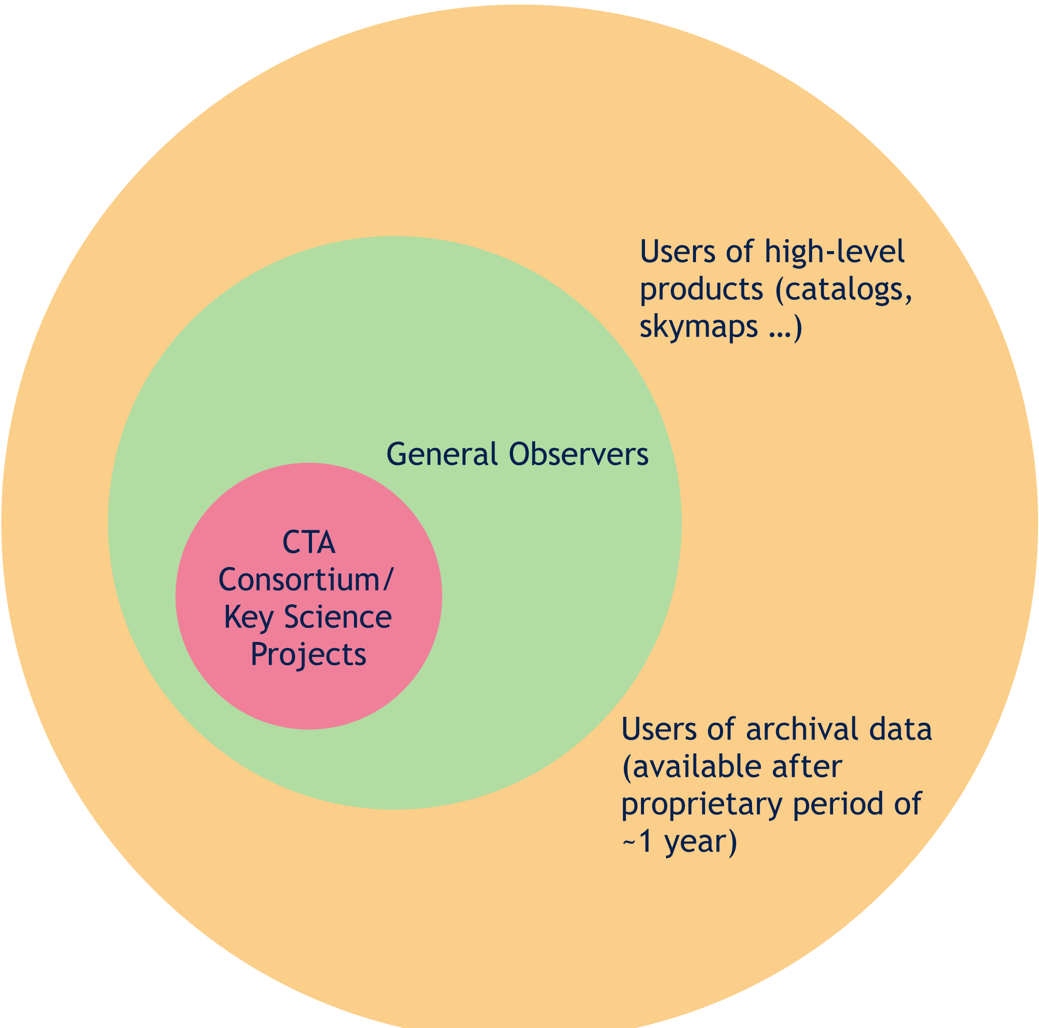
- exact layout chosen to optimise Science performance within environmental contraints (CTAC, 2019 Astropart. Phys 111, p. 35-53)


CTA North


CTA South

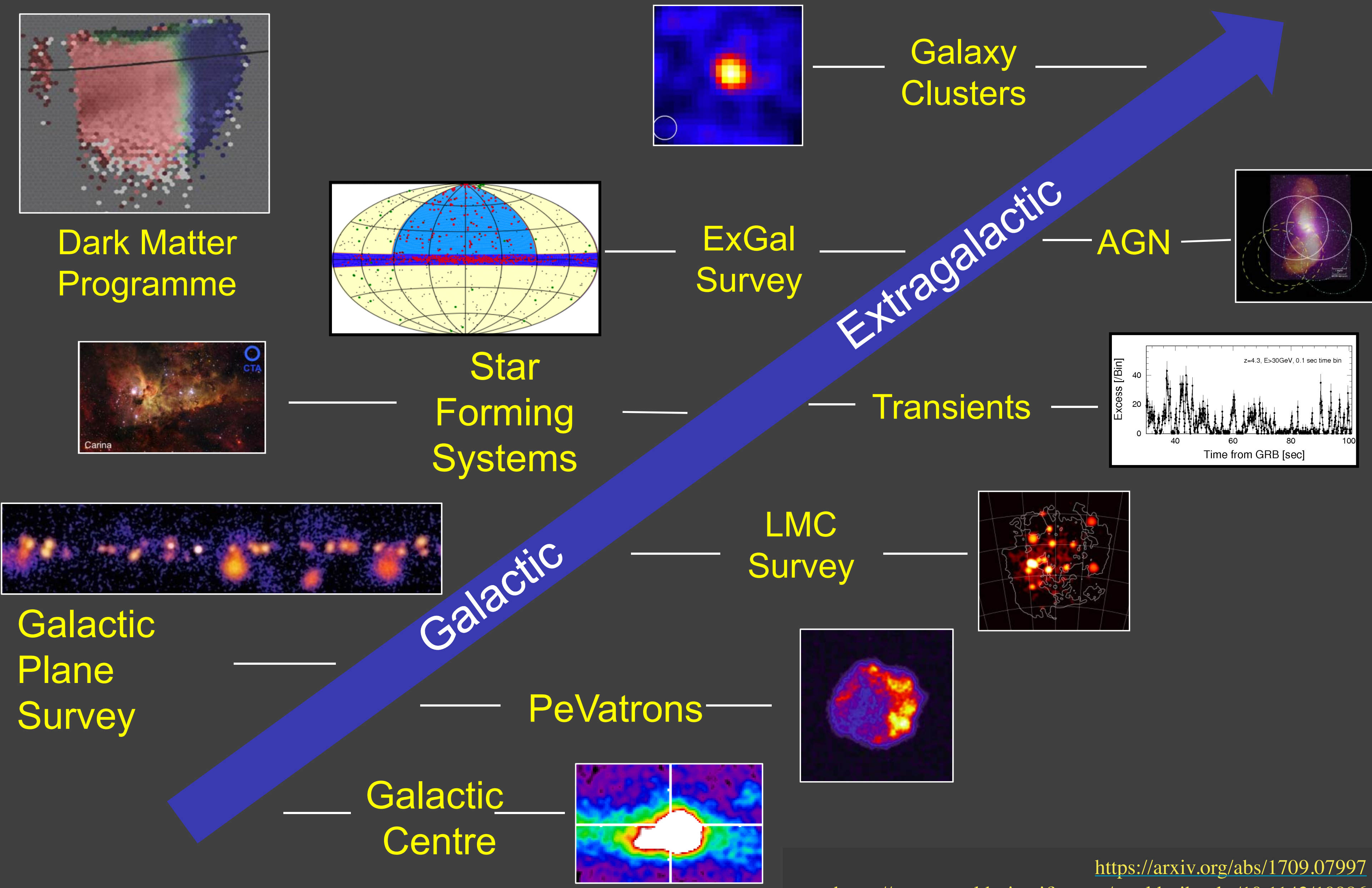
LST-1 in La Palma

CTA: the first VHE observatory



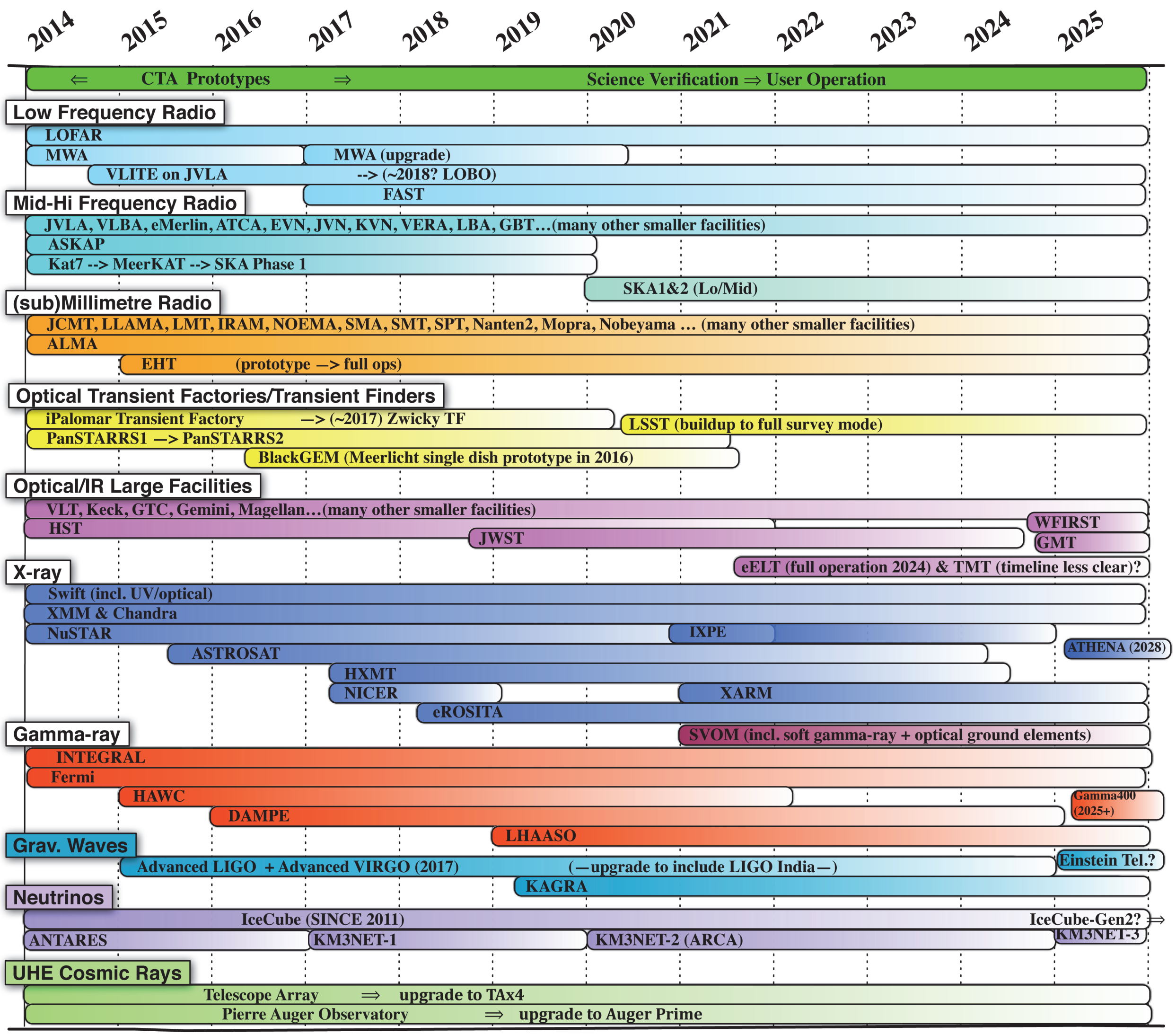
- ~40% of observing time over first 10 years for Consortium Key Science Projects (KSPs)
- rest of the time open to general observers (GO)
- ultimately **all data public** (candidate photon lists with measured properties) + **software tools to perform scientific analysis**

CTA Key Science Projects



https://arxiv.org/abs/1709.07997
https://www.worldscientific.com/worldscibooks/10.1142/10986

Multiwavelength/messenger synergies



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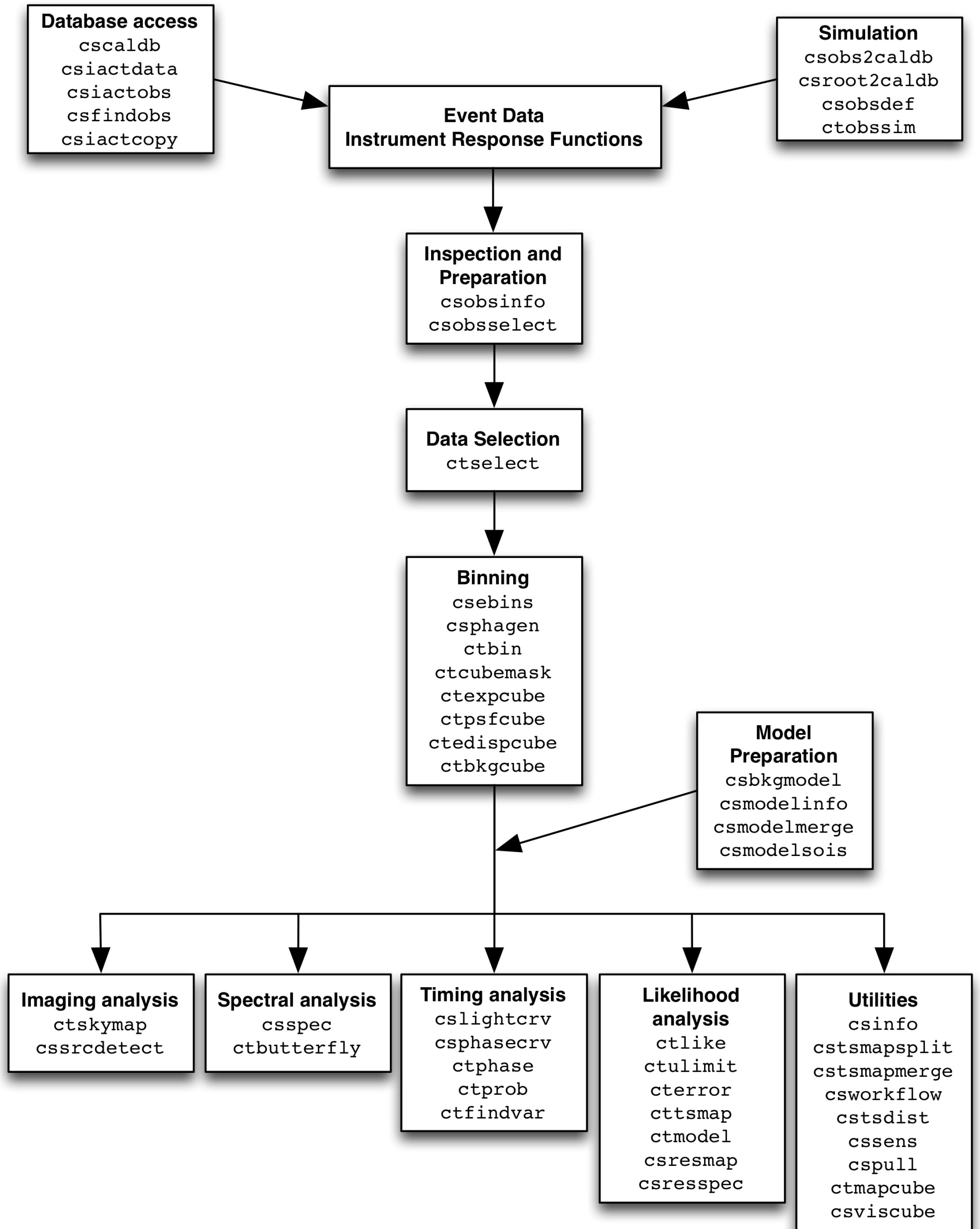
ctools in a nutshell

- 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)
- Validated on simulated data and real data from H.E.S.S. and *Fermi* (https://doi.org/10.1051/0004-6361/201936010)
- Find all the information on the website

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

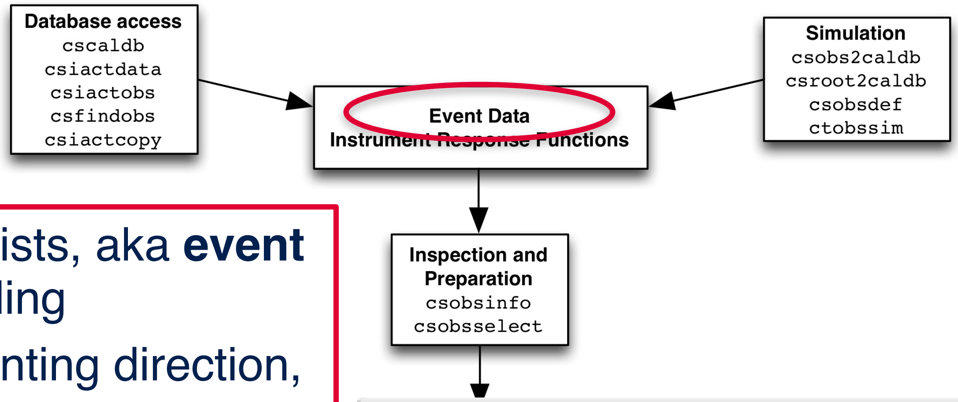
  - how to get them
  - how to use them (manual, tutorials, description of tools)
  - how to contribute to development
- Latest release 1.6.3

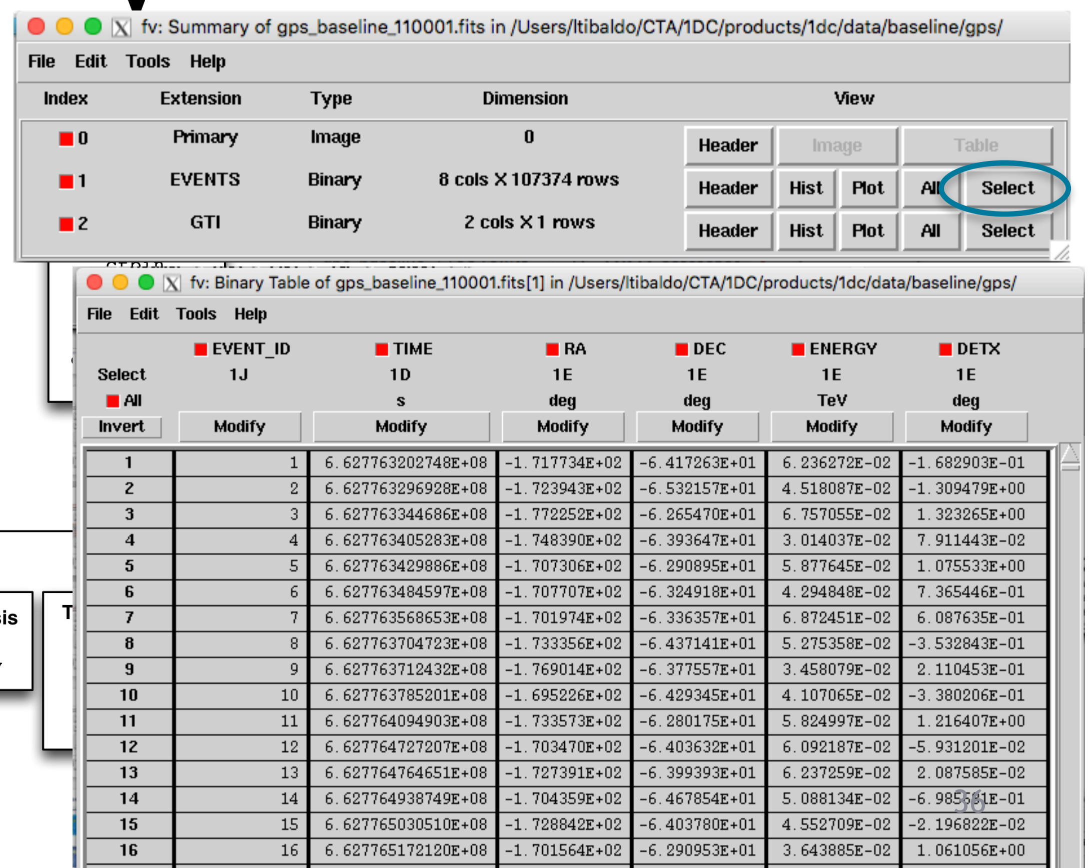
Tools overview



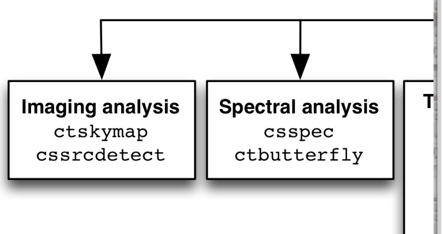
Data

- 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)



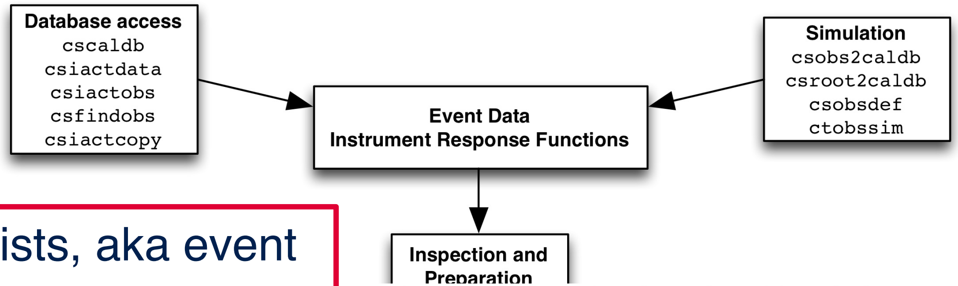


Select	EVENT_ID	TIME	RA	DEC	ENERGY	DETX
	1J	1D	1E	1E	1E	1E
All		s	deg	deg	TeV	deg
Invert	Modify	Modify	Modify	Modify	Modify	Modify
1	1	6.627763202748E+08	-1.717734E+02	-6.417263E+01	6.236272E-02	-1.682903E-01
2	2	6.627763296928E+08	-1.723943E+02	-6.532157E+01	4.518087E-02	-1.309479E+00
3	3	6.627763344686E+08	-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	[illegible]
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



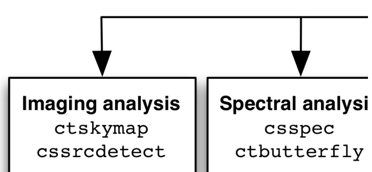
https://gamma-astro-data-formats.readthedocs.io

Data

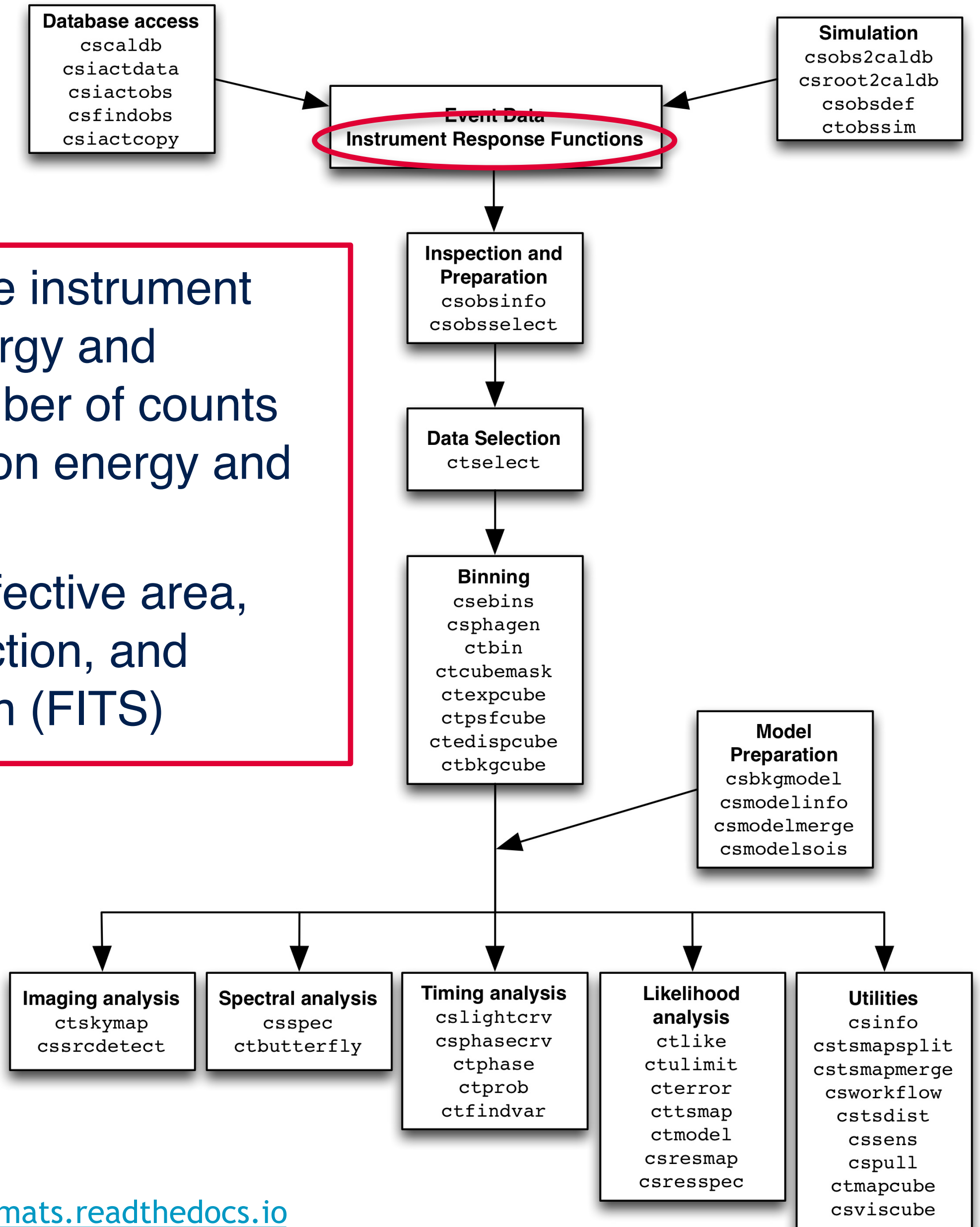


- candidate photon lists, aka event lists (FITS), including
  - metadata (pointing direction, livetime …)
  - good time intervals (GTIs): continuous intervals of data taking with stable instrument response
- event lists from different observations combined in **observation lists** (XML)


```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>
```

Instrument Response Functions

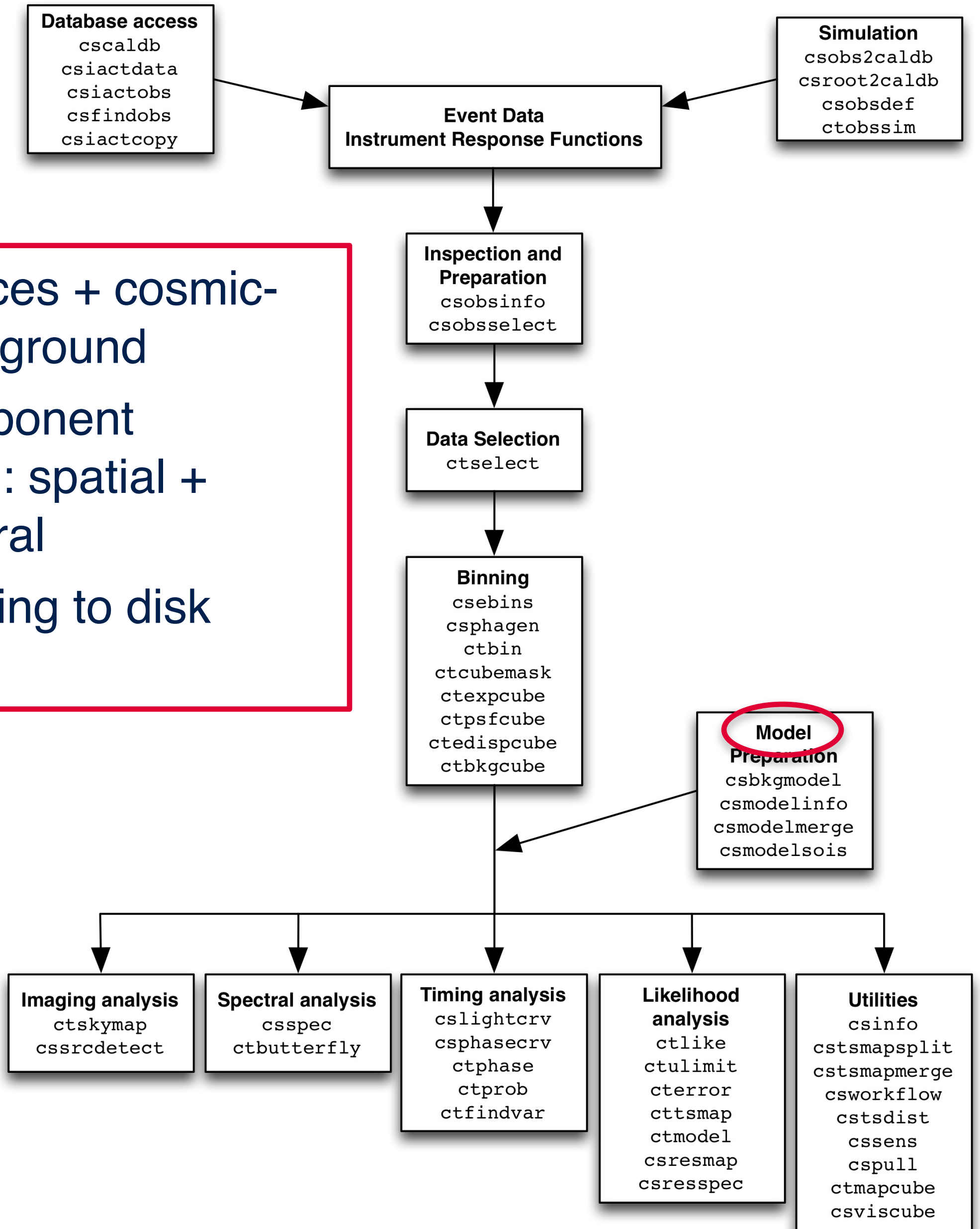


- flux arriving at the instrument (**true** photon energy and direction) → number of counts (**measured** photon energy and direction)
- factorised into effective area, point spread function, and energy dispersion (FITS)

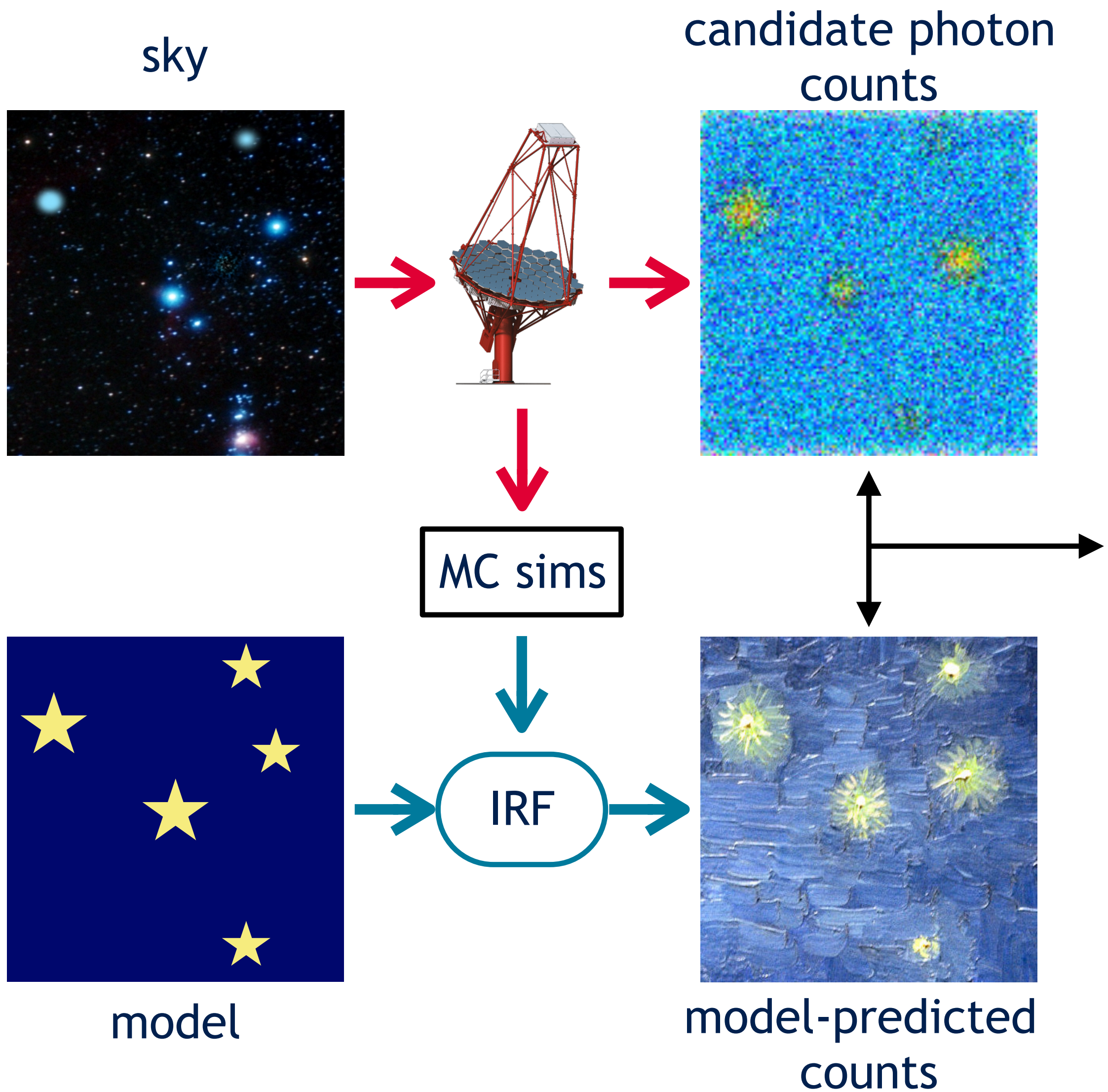
https://gamma-astro-data-formats.readthedocs.io

Models

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



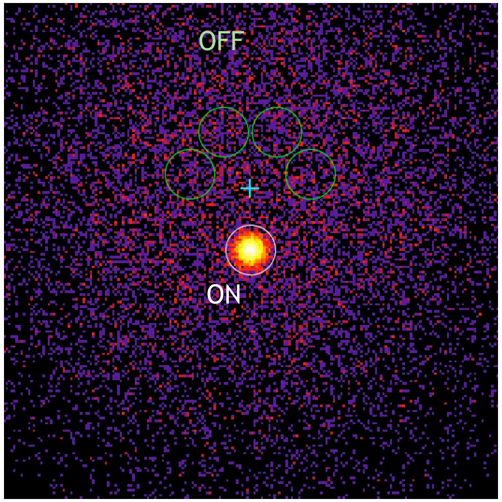
The likelihood method

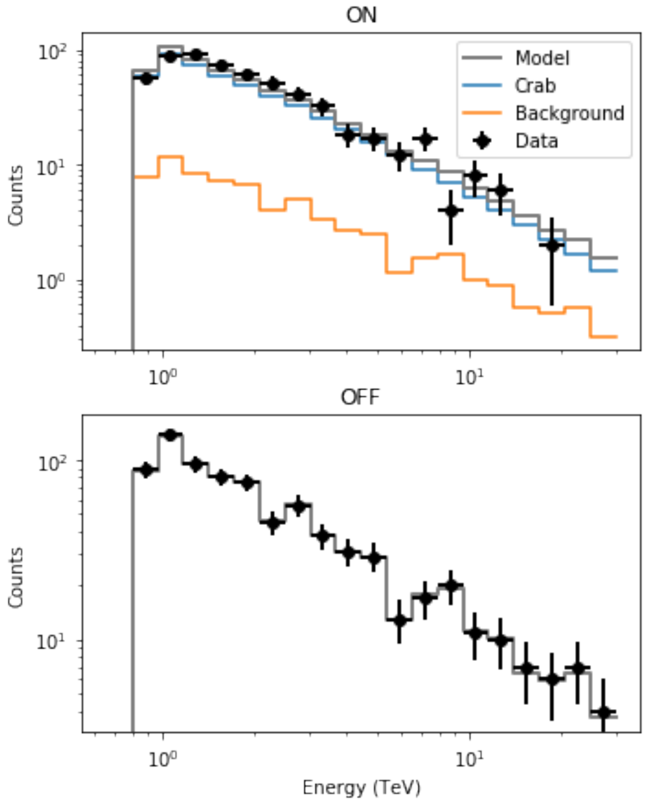


- compute likelihood of given model
- determine best-fit values and uncertainties of model parameters (e.g., source fluxes) via maximum likelihood

Classical IACT analyses

- principle: constrain background in dedicated background (Off) regions
- method: identify dedicated source (On) and background (Off) regions
- similar to X-rays
- separate image (2D) and spectral (1D) analysis
- fewer assumptions on background, but sacrifices information



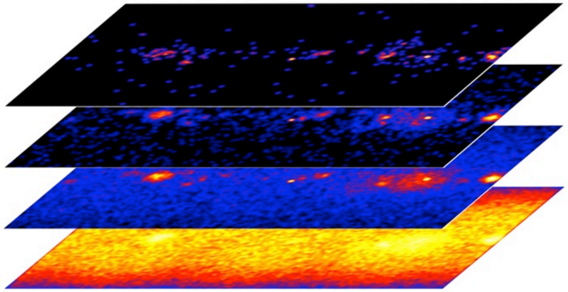


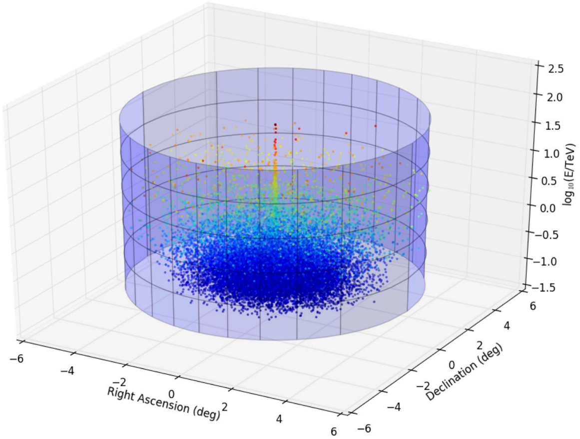
Multiple observations:
- joint analysis → each observation treated independently
- stacked analysis

3D analyses

- model background and sources together over the entire region of interest in 3D space: sky direction + energy
- similar to satellite gamma-ray detectors
- full data information exploited, can handle multiple overlapping sources, but requires adequate background model

binned	unbinned
bin events in sky direction and energy	full information exploited for each event





Multiple observations:
- 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, Python scripts, Jupyter notebooks)

```python
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]
$
```

hidden parameter, not inquired automatically
automatic parameter
default/latest used value
user-specified value

Python API (terminal, Python scripts, Jupyter notebooks)

```python
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

- Now: first step with ctools (demo) → simulation/analysis of CTA observations of the Crab Nebula
- Next sessions: 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

- 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