The Swiss Army Knife of Astronomical Data

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The Swiss Army Knife of Astronomical Data

By three methods we may learn wisdom: First, by reflection, which is noblest; second, by imitation, which is easiest; and third by experience, which is the bitterest.

Overview

I. Storage (how to store the data)

II. Procurement (how to get the data)

III. Analysis (how to interrogate the data)

I. Data storage

- State of the art: HDF5, VOTable, ASDF
- Outdated: FITS
- Really, really outdated: plain text (csv, etc.)

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the best is also the least used!

the worst are amongst the most common.

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- Really, really outdated: plain text (csv, etc.)

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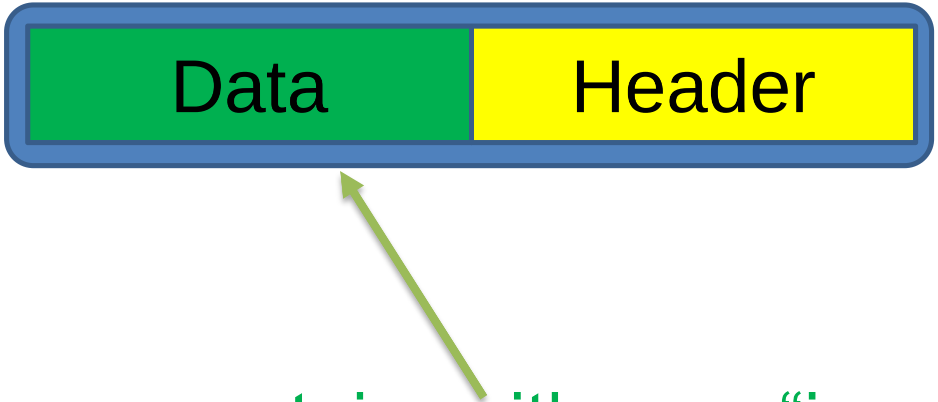
I. Data storage: FITS files

- interface (quick): topcat, ds9, QFitsView
- interface (analysis): cfitsio, astlib, astropy
- tables & images
- multiple extensions
- headers → WCS

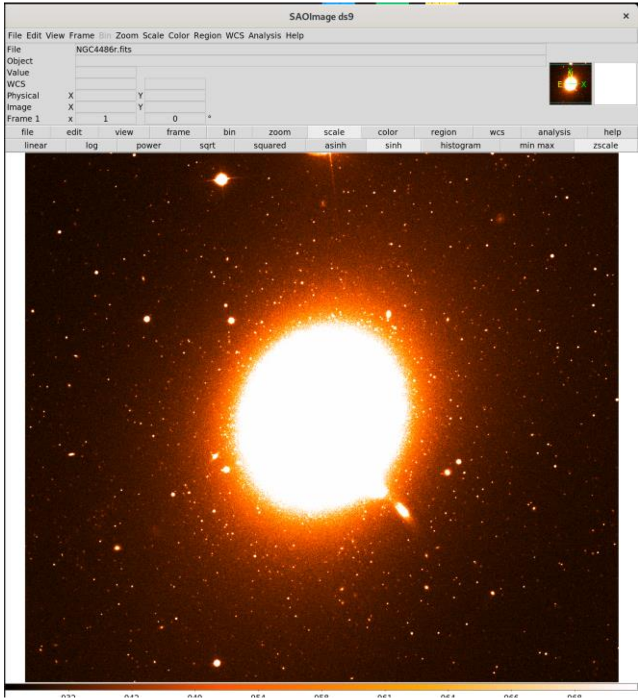
I. Data storage: FITS files

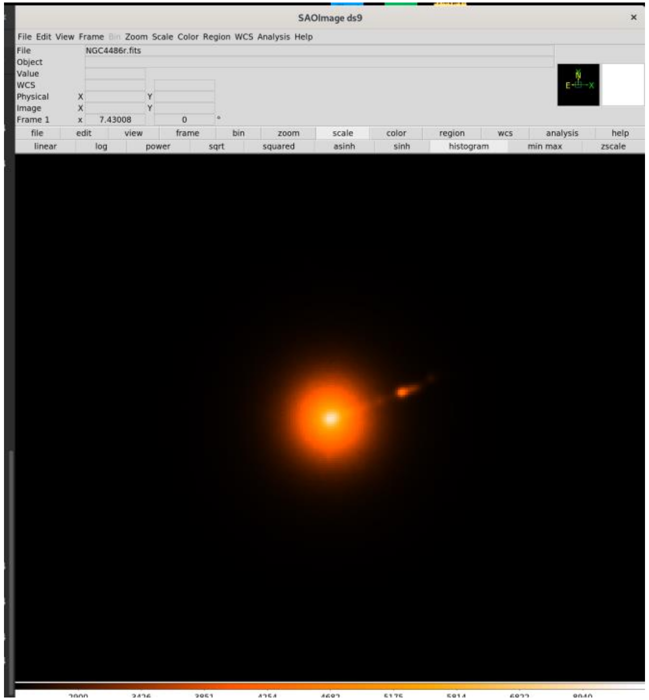


a FITS file
(single extension)

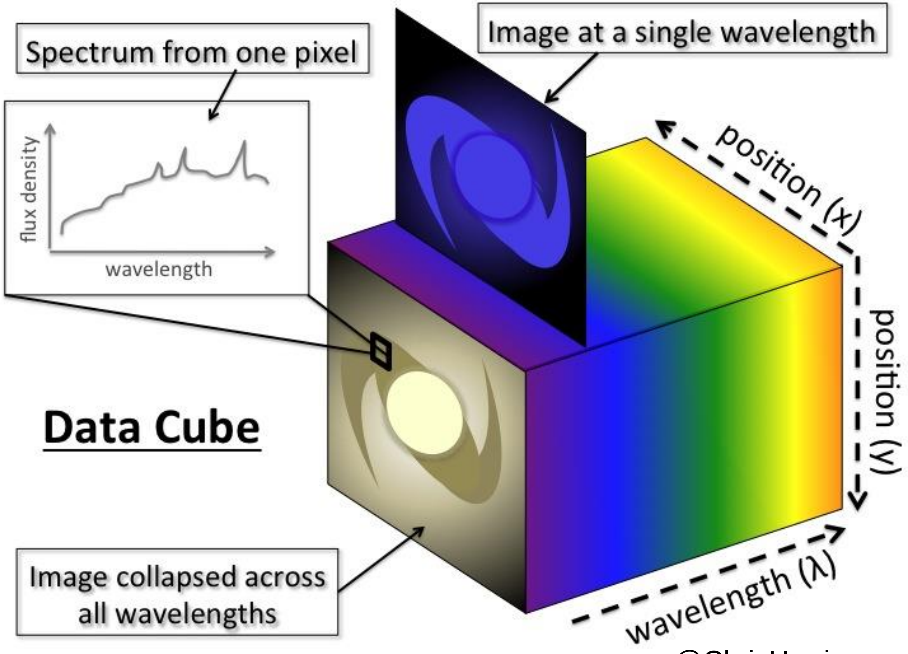
contains either an “image” or a table (also called binary table)

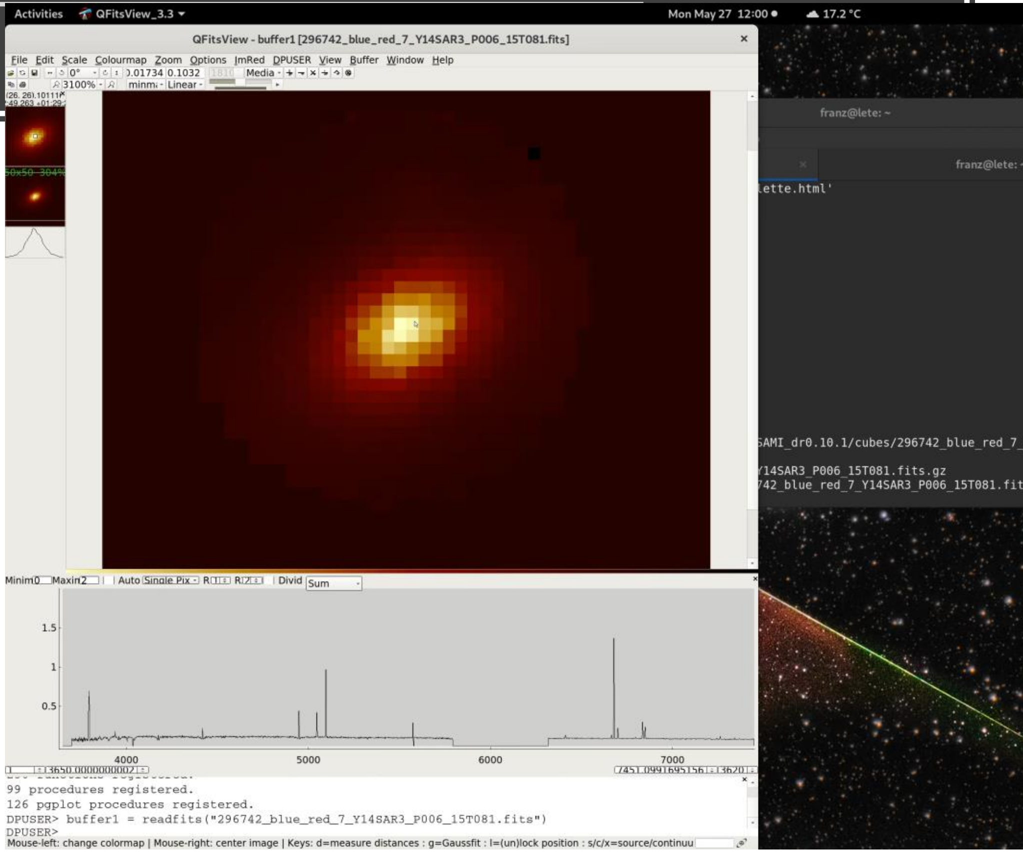
FITS Images


SAOImage ds9
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
File
NGC4486r.fits
Object
Value
WCS
Physical
Image
Frame 1
file edit view frame bin zoom scale color region wcs analysis help
linear log power sqrt squared asinh sinh histogram min max zscale


SAOImage ds9
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
File
NGC4486r.fits
Object
Value
WCS
Physical
Image
Frame 1
7.43008
file edit view frame bin zoom scale color region wcs analysis help
linear log power sqrt squared asinh sinh histogram min max zscale

FITS "Images" (Cubes)





FITS Tables

```
<Table masked=True length=497>
  CATID      phot     mag       n_comp_r
  int64     bytes4  float64      int64
---------- ------ ---------- --------
      7839   GAMA     15.003        4
      8487   GAMA     14.068        7
     15481   GAMA     14.888        5
     16525   GAMA     16.892        3
     16526   GAMA     16.816        4
     16926   GAMA     16.395        4
       ...    ...        ...      ...
9403800763    VST 15.0276728        8
9403800813    VST 13.8577576        8
9403800833    VST 15.4592133        5
9403800911    VST 15.5672979        5
9403801002    VST 15.1227217        7
9403801010    VST 14.4940319        9
```

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<Table masked=True length=497>
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---------- ------ ---------- --------
      7839   GAMA     15.003        4
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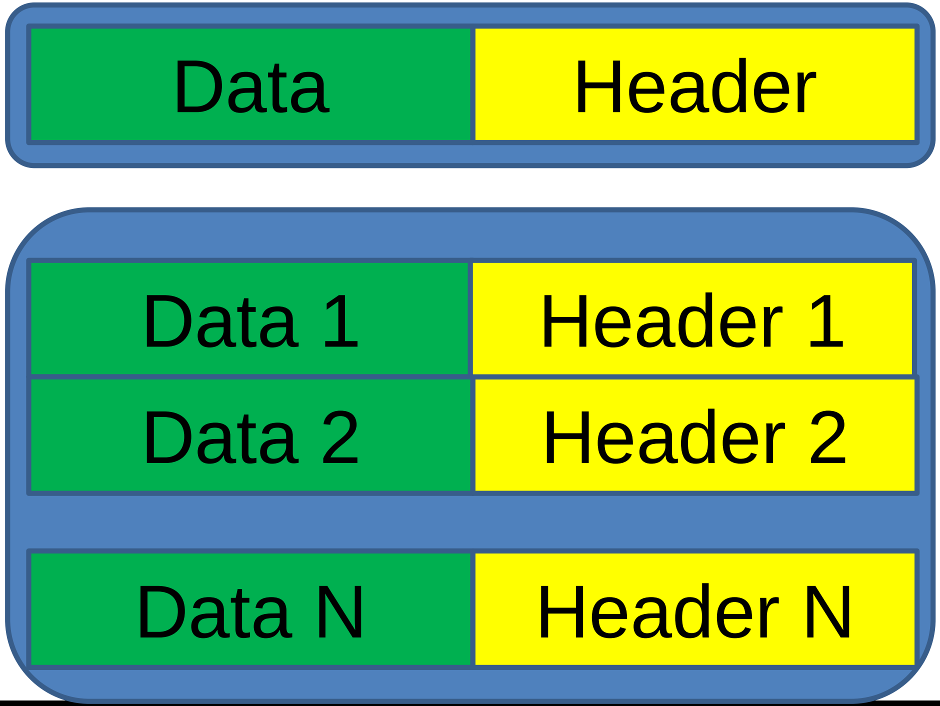
     16526   GAMA     16.816        4
     16926   GAMA     16.395        4
       ...    ...        ...      ...
9403800763    VST 15.0276728        8
9403800813    VST 13.8577576        8
9403800833    VST 15.4592133        5
9403800911    VST 15.5672979        5
9403801002    VST 15.1227217        7
9403801010    VST 14.4940319        9
```

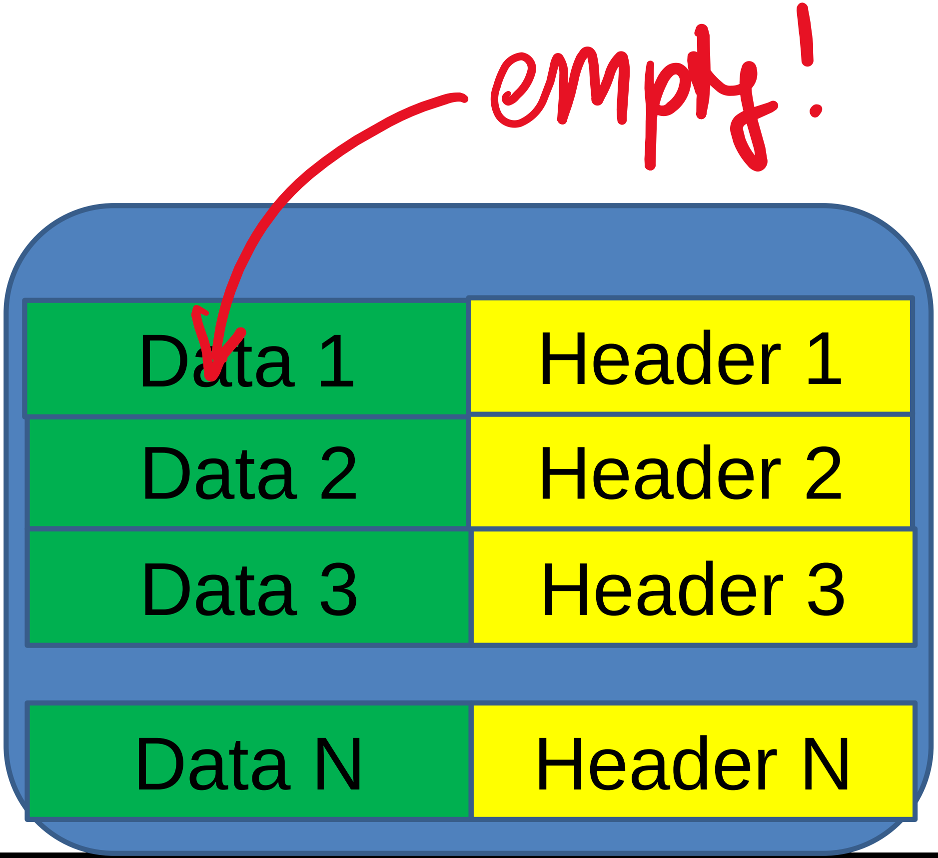
FITS structure: multiple extensions



a FITS file
(single extension)

a FITS file
(multiple extensions)

FITS structure: multiple extensions



a FITS file
(multiple extensions)

…done right.

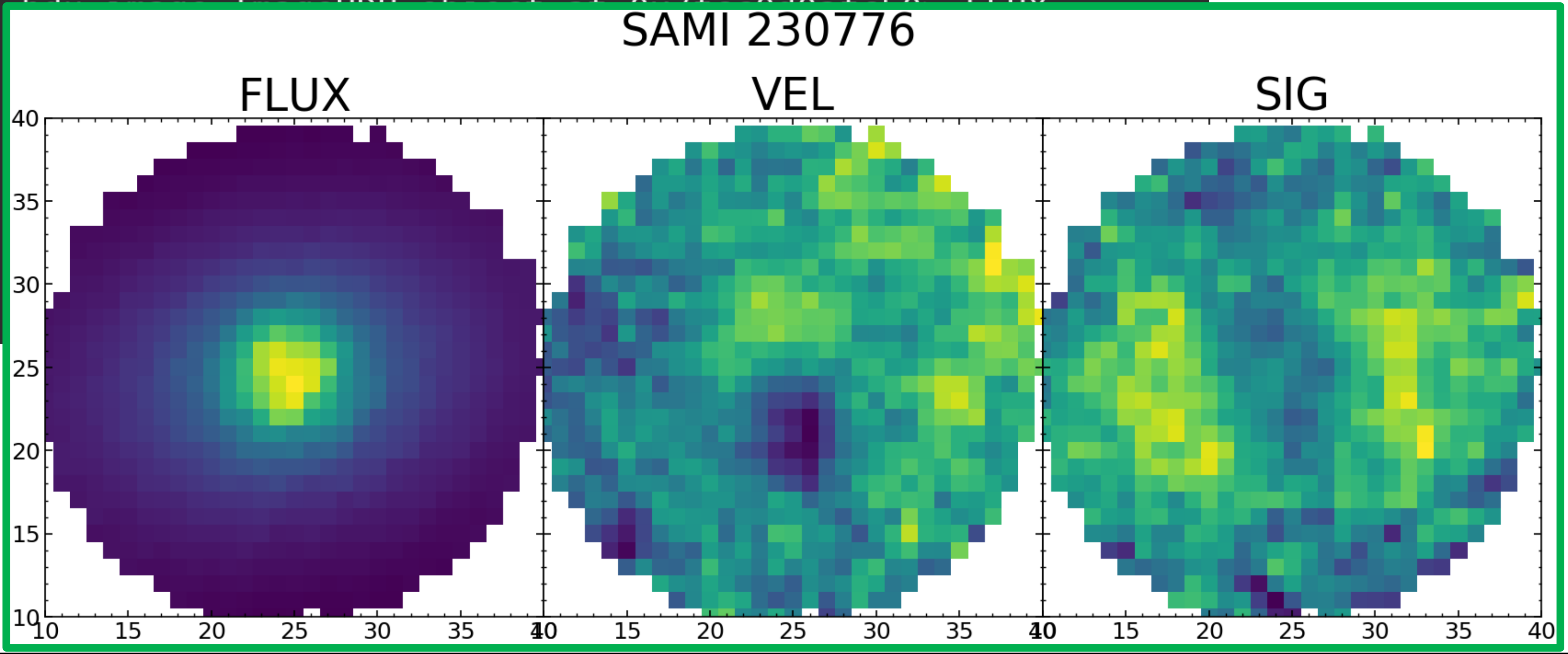
Why use FITS extensions?

```
<astropy.io.fits.hdu.image.ImageHDU object at 0x7fcc0d0afc50> FLUX
<astropy.io.fits.hdu.image.ImageHDU object at 0x7fcc0d42e860> FLUX_ERR
<astropy.io.fits.hdu.image.ImageHDU object at 0x7fcc0d42edd8> VEL
<astropy.io.fits.hdu.image.ImageHDU object at 0x7fcc0d424470> VEL_ERR
<astropy.io.fits.hdu.image.ImageHDU object at 0x7fcc0d424a90> SIG
<astropy.io.fits.hdu.image.ImageHDU object at 0x7fcc0d424f98> SIG_ERR
<astropy.io.fits.hdu.image.ImageHDU object at 0x7fcc0d42b588> FORMAL_SNR
<astropy.io.fits.hdu.image.ImageHDU object at 0x7fcc0d42bef0> QC
```

A way to group together different FITS files

What are FITS extensions?

```
<astropy.io.fits
<astropy.io.fits
<astropy.io.fits
<astropy.io.fits
<astropy.io.fits
<astropy.io.fits
<astropy.io.fits
<astropy.io.fits
```



What are FITS headers?

```
SIMPLE  =                    T / conforms to FITS standard
BITPIX  =                    8 / array data type
NAXIS   =                    0 / number of array dimensions
EXTEND  =                    T
CRPIX1  =                 25.5 / Pixel coordinate of reference point
CRPIX2  =                 25.5 / Pixel coordinate of reference point
CDELT1  = -0.000138888888888889 / [deg] Coordinate increment at reference poi
CDELT2  =  0.000138888888888889 / [deg] Coordinate increment at reference poi
CTYPE1  = 'RA---TAN'           / Right ascension, gnomonic projection
CTYPE2  = 'DEC--TAN'           / Declination, gnomonic projection
CRVAL1  =           181.112792 / [deg] Coordinate value at reference point
CRVAL2  =             1.895972 / [deg] Coordinate value at reference point
EQUINOX =               2000.0 / [yr] Equinox of equatorial coordinates
WCS_SRC = 'Nominal '           / WCS Source
CATID   = '230776  '           / Object ID
HGCUBING= '0627572adcf5+'      / Hg changeset ID for cubing code
INSTRUME= 'AAOMEGA-SAMI'       / Instrument in use
SPECID_B= 'BL      '           / Spectrograph ID blue
GRATID_B= '580V    '           / Disperser ID blue
SPECID_R= 'RD      '           / Spectrograph ID red
GRATID_R= '1000R   '           / Disperser ID red
PLATEID = 'Y13SAR1_P014_12T001_15T029' / Plate ID (from config file)
LABEL   = 'Run 10 galaxy plate 1' / Configuration File label
IFUPROBE= '7       '           / Id number(s) of the SAMI IFU probe(s)
A_POLY  =                   12 / Order of additive polynomial in pPXF fit
N_MOM   =                    2 / Number of moments fit with pPXF
Z_IN    =              0.01973 / Initial guess redshift input to pPXF
Z_PPXF  =              0.01975 / Best fitting redshift from ppxf
AP_SIG  =     295.4755098343882 / Aperture velocity dispersion
AP_SERR =     1.598230857424561 / Error on aperture velocity dispersion
AP_VEL  =     5.261451588145117 / Measured aperture velocity
AP_VERR =     1.600067683112066 / Error on measured aperture velocity
APER    = 'Circular 2 arcsec'  / Aperture used to extract central spectrum
ORIG_CUB= '230776_blue_red_7_Y13SAR1_P014_12T001.fits' / Original data cube
PRODUCT = 'Stellar Kinematics  (2 moments)' / Data Product
DATE    = '2018-6-21'          / Date this data product was generated
AUTHOR  = 'Jesse van de Sande'
CONTACT = 'Jesse van de Sande <jesse.vandesande@sydney.edu.au>'
VERSION = 'v02     '           / Version of this data product
SAMI_VER= 'v00.10  '           / Version of SAMI cubes to generate product
```

```
CRPIX1  =                 25.5 / Pixel coordinat
CRPIX2  =                 25.5 / Pixel coordinate
CDELT1  = -0.000138888888888889 / [deg] Coordinate
CDELT2  =  0.000138888888888889 / [deg] Coordinate
CTYPE1  = 'RA---TAN'           / Right ascension,
CTYPE2  = 'DEC--TAN'           / Declination, gno
CRVAL1  =           181.112792 / [deg] Coordinate
CRVAL2  =             1.895972 / [deg] Coordinate
EQUINOX =               2000.0 / [yr] Equinox of
WCS_SRC = 'Nominal '           / WCS Source
```

The place for "everything else"

Want to know more?

https://fits.gsfc.nasa.gov/fits_standard.html

http://docs.astropy.org/en/stable/io/fits/

II. Data procurement

- Observations
- Archives
- Various

II. Data procurement: observations

- Guaranteed time or competitive proposals
- Proposals have generally biannual cadence

Proposal tools

- Exposure time calculator (telescope website)
- Observability charts (iobserve, staralt)
- Proposal template (Latex)

Proposal success criteria

Compelling science case	Somewhat arbitrary
Quantitative time justification	Objective
Quantitative sample size	Objective
Quantitative expected results	Objective
Convincing telescope justification	Somewhat arbitrary
Informative, pretty figures	Absolutely objective
Robustness	Objective

Moon: on or off?

- Off for blue wavelengths and/or faint targets
- Moon has the same spectrum as the Sun → bluer than the sky background
- At red enough wavelength (>800 nm), sky emission dominated by other processes

II. Data procurement: various

- dedicated website
- email / usb stick / dropbox

→ difficult to obtain, unless searching for something specific.

II. Data procurement: archives

- CDS – Strasbourg astronomical data center (e.g. VizieR)
- SciServer (e.g. casjobs)
- Telescope archives (e.g. archive.eso.org, HST legacy)

Telescope archives

- ESO archive
- Keck archive
- HST Legacy archive
- Gemini archive
- Subaru

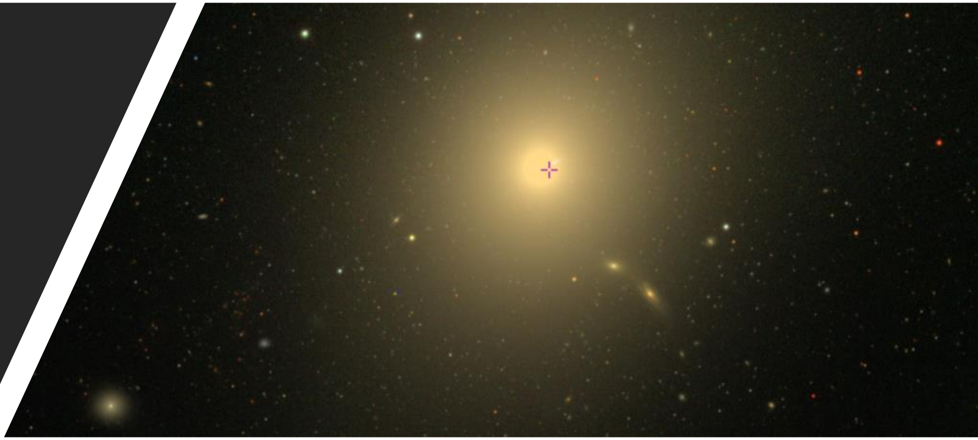
…and many more

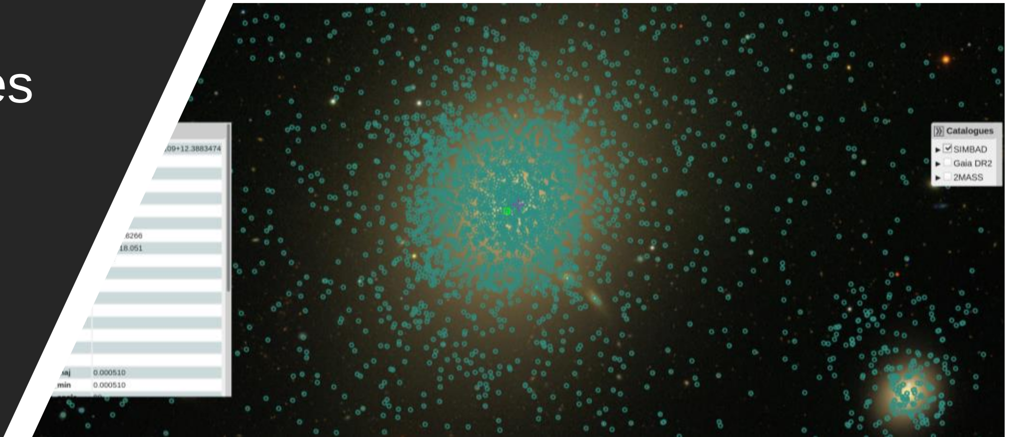
CDS: Aladin Sky Atlas

Useful to view the data, and to search data around a particular sky location

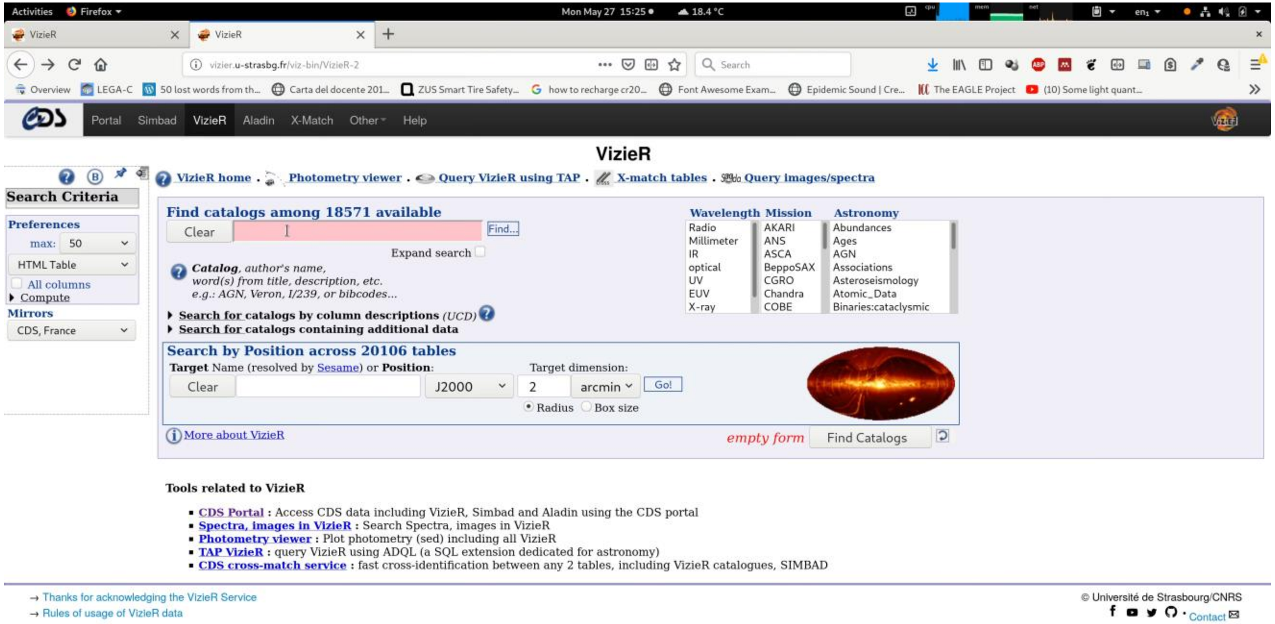
There is a “lite” version that runs in the browser, and a desktop version, which allows to download catalogues, over plot.

See here, looking for all the sources around M87 (these are mostly globular clusters)





CDS: VizieR “interactive” query



Useful to look what’s around.

CDS: VizieR SQL-like query

Why?
- easy to reproduce
- easy to pass around
- pre-select the data

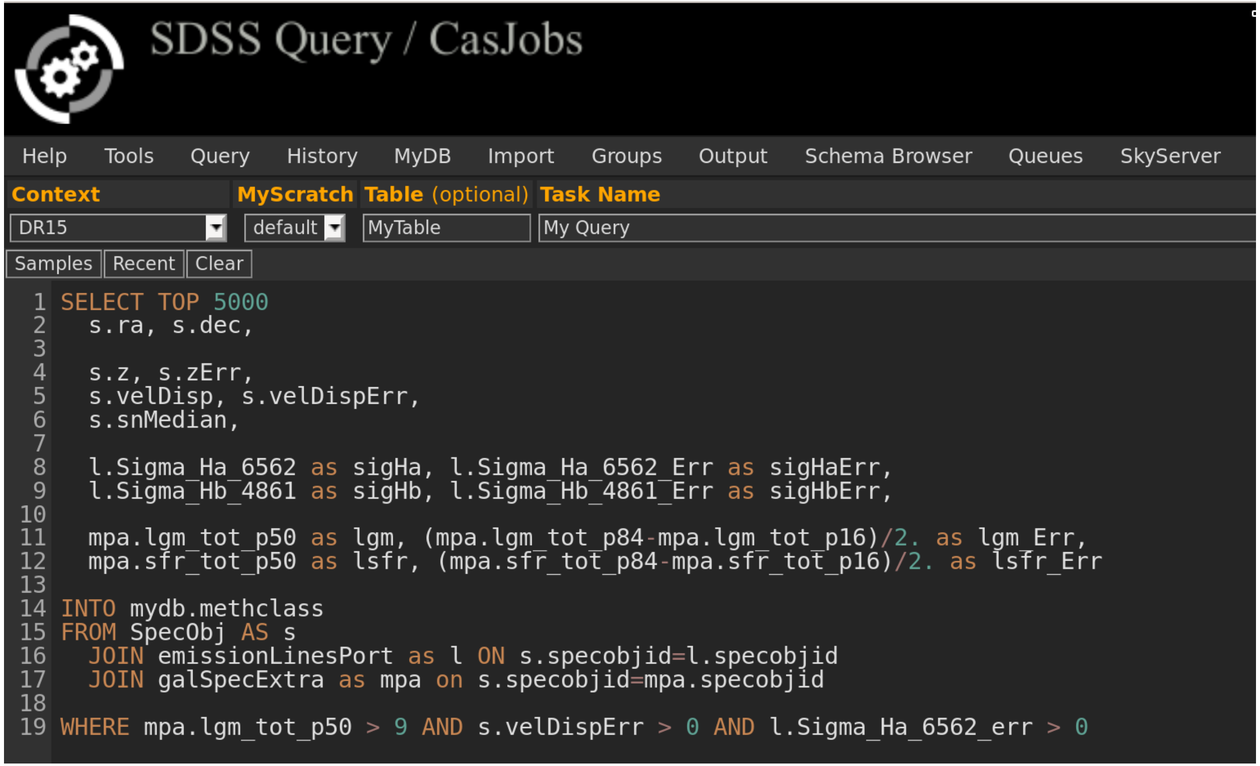
How?
- know table/column names (schema browser)
- learn the SQL language (the basics)

CDS: VizieR SQL-like query

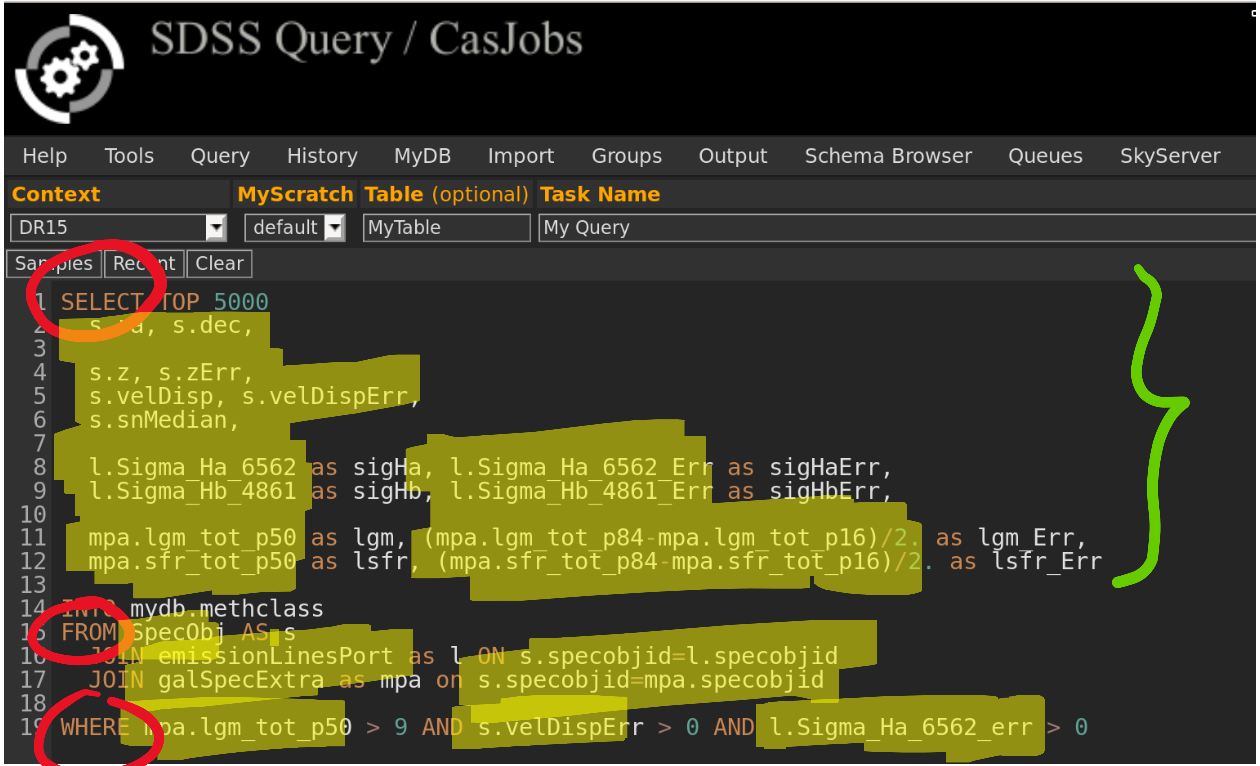
Structured Query Language – the most common query language.

Astronomers also made their own version, called Astronomy Data Query Language ADQL

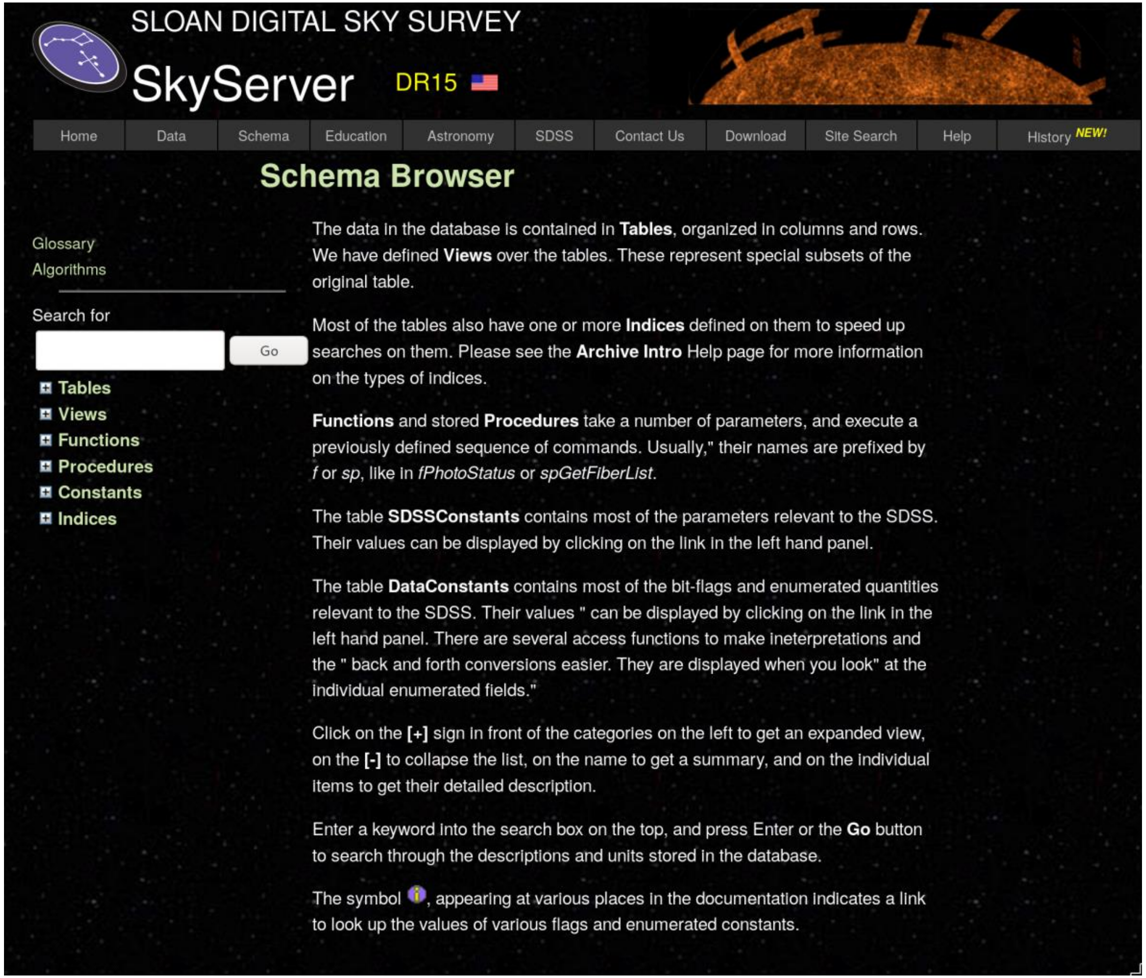
A working example with SDSS

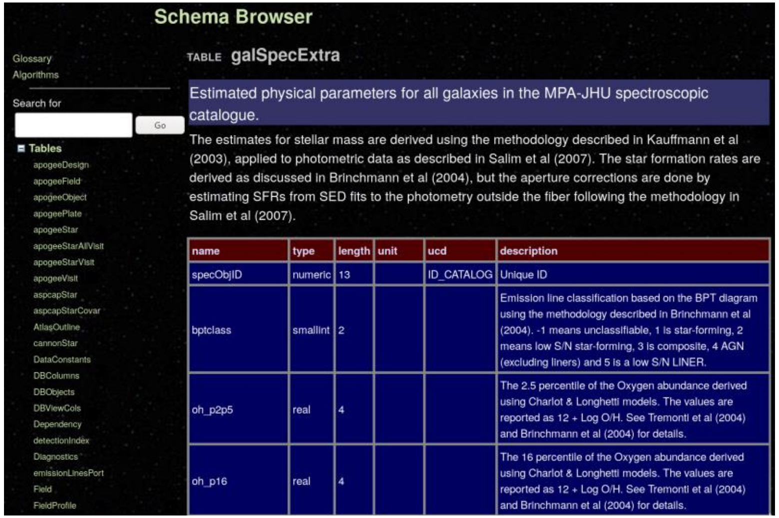


A working example with SDSS



How d I know table/column names?





Schema Browser

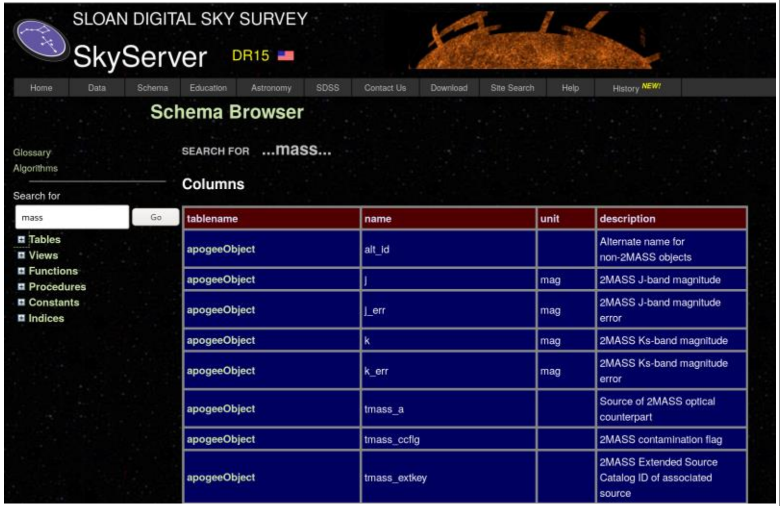
Glossary
Algorithms
Search for
Go
Tables
apogeeDesign
apogeeField
apogeeObject
apogeePlate
apogeeStar
apogeeStarAllVisit
apogeeStarVisit
apogeeVisit
aspcapStar
aspcapStarCovar
AtlasOutline
cannonStar
DataConstants
DBColumns
DBObjects
DBViewCols
Dependency
detectionIndex
Diagnostics
emissionLinesPort
Field
FieldProfile

TABLE galSpecExtra

Estimated physical parameters for all galaxies in the MPA-JHU spectroscopic catalogue.

The estimates for stellar mass are derived using the methodology described in Kauffmann et al (2003), applied to photometric data as described in Salim et al (2007). The star formation rates are derived as discussed in Brinchmann et al (2004), but the aperture corrections are done by estimating SFRs from SED fits to the photometry outside the fiber following the methodology in Salim et al (2007).

name	type	length	unit	ucd	description
specObjID	numeric	13		ID_CATALOG	Unique ID
bptclass	smallint	2			Emission line classification based on the BPT diagram using the methodology described in Brinchmann et al (2004). -1 means unclassifiable, 1 is star-forming, 2 means low S/N star-forming, 3 is composite, 4 AGN (excluding liners) and 5 is a low S/N LINER.
oh_p2p5	real	4			The 2.5 percentile of the Oxygen abundance derived using Charlot & Longhetti models. The values are reported as 12 + Log O/H. See Tremonti et al (2004) and Brinchmann et al (2004) for details.
oh_p16	real	4			The 16 percentile of the Oxygen abundance derived using Charlot & Longhetti models. The values are reported as 12 + Log O/H. See Tremonti et al (2004) and Brinchmann et al (2004) for details.



SLOAN DIGITAL SKY SURVEY
SkyServer DR15

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Schema Browser

Glossary
Algorithms
Search for
mass
Go
Tables
Views
Functions
Procedures
Constants
Indices

SEARCH FOR ...mass...

Columns

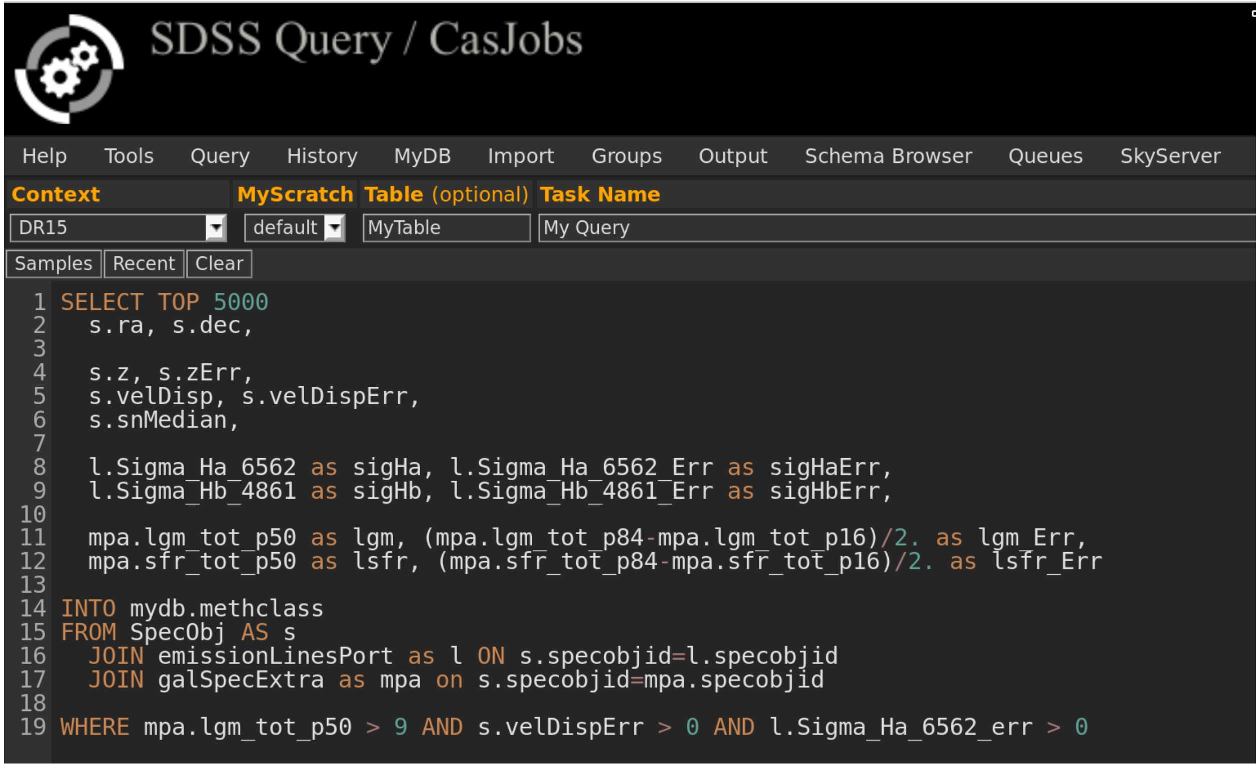
tablename	name	unit	description
apogeeObject	alt_id		Alternate name for non-2MASS objects
apogeeObject	j	mag	2MASS J-band magnitude
apogeeObject	j_err	mag	2MASS J-band magnitude error
apogeeObject	k	mag	2MASS Ks-band magnitude
apogeeObject	k_err	mag	2MASS Ks-band magnitude error
apogeeObject	tmass_a		Source of 2MASS optical counterpart
apogeeObject	tmass_ccflg		2MASS contamination flag
apogeeObject	tmass_extkey		2MASS Extended Source Catalog ID of associated source

Example from SDSS Schema:

Search for keywords

Search by table/view

Our query:



methclass.fit

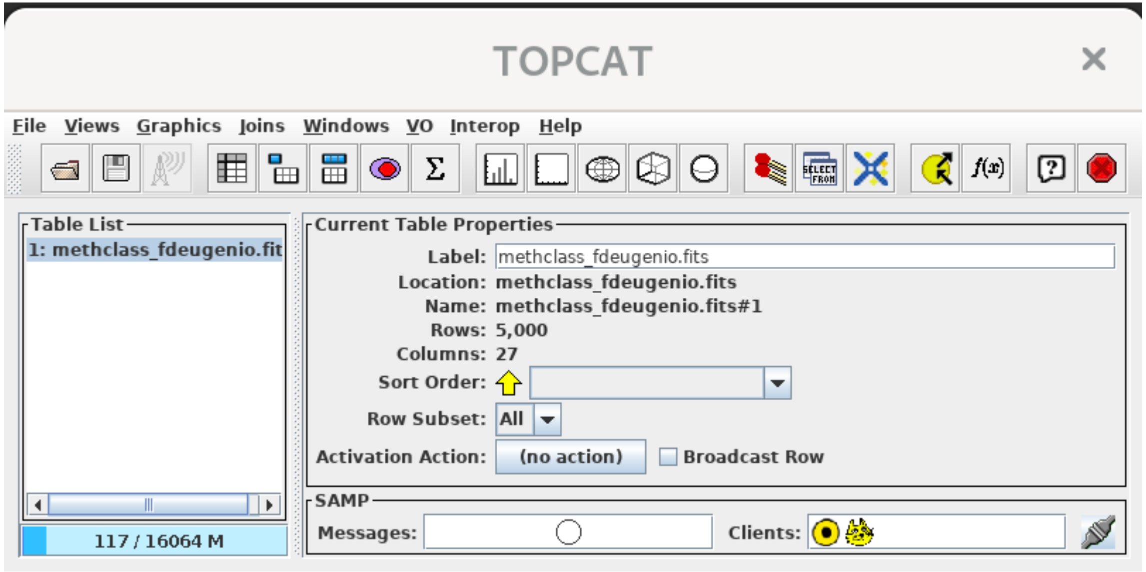
II. Data procurement: Summary

- Archives (catalogues) (SQL, Schema)
- Archives (images/spectra)
- Observations

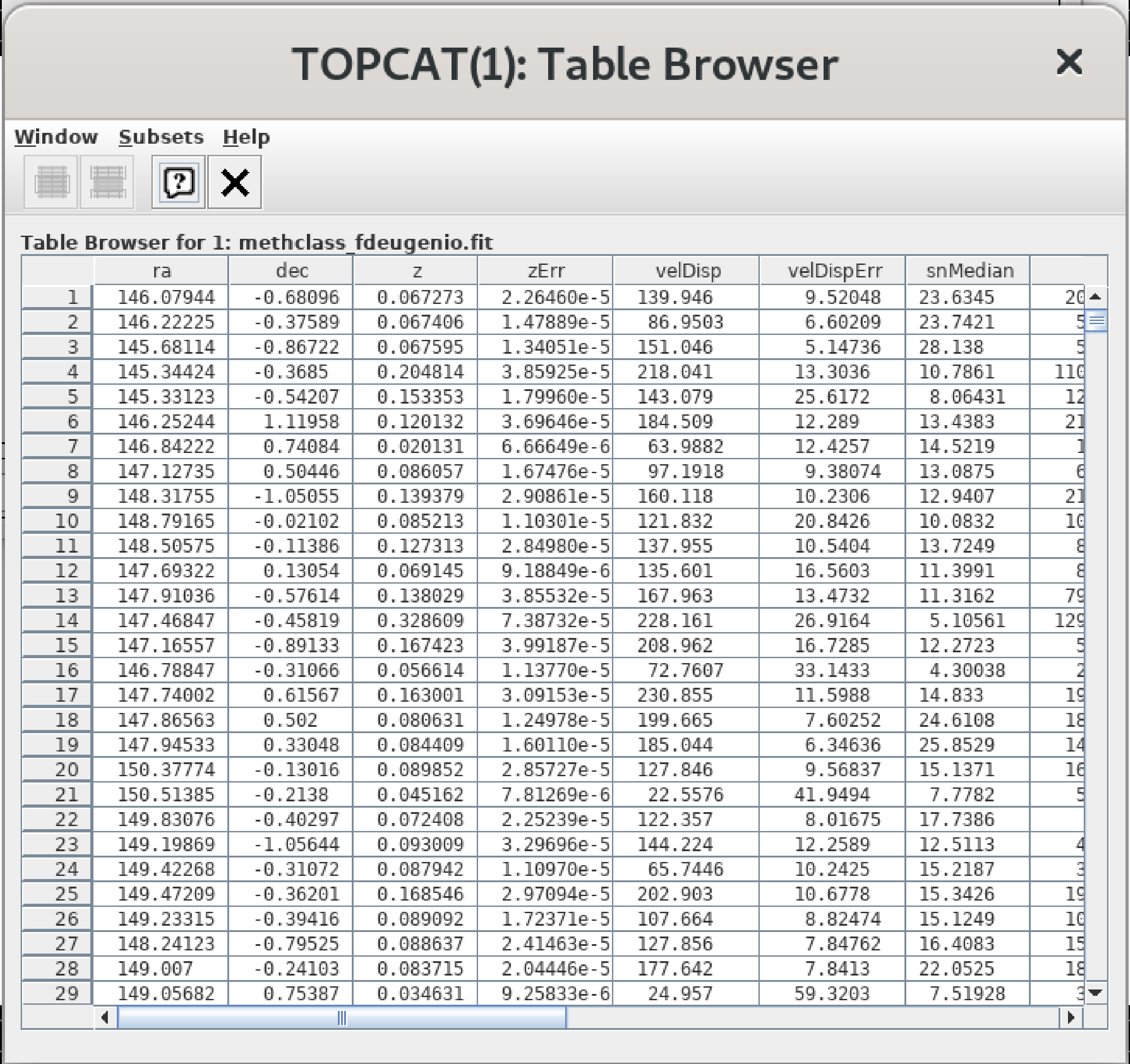
III. Quick analysis tools

- What is it? A test that takes < 30'
- Why? Evaluate data quality, feasibility
- What tools? Plotting & robust fitting algorithms

Topcat:
see the data



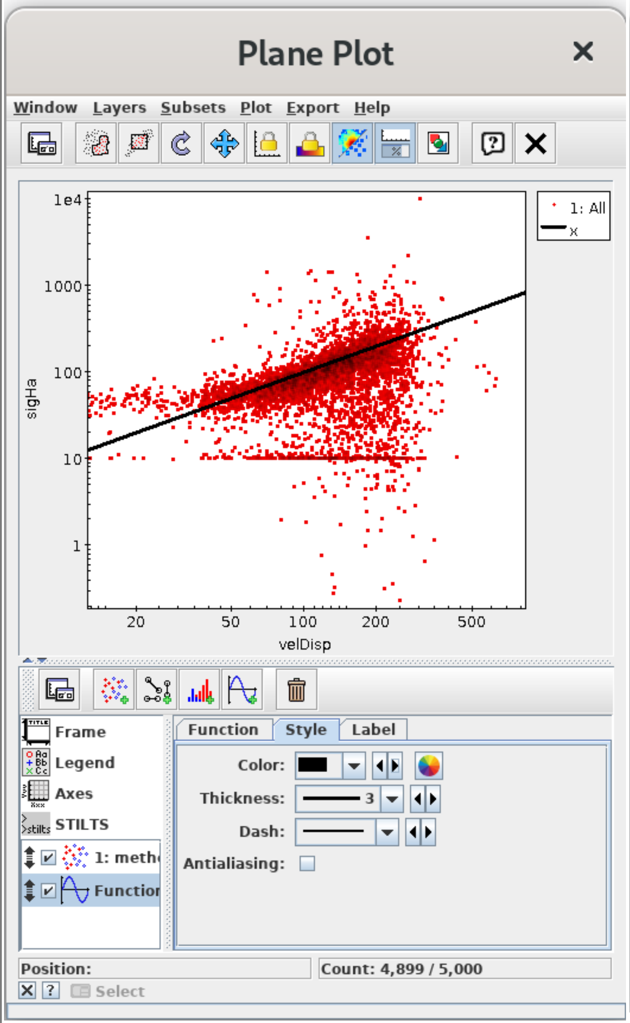
Topcat: see the data

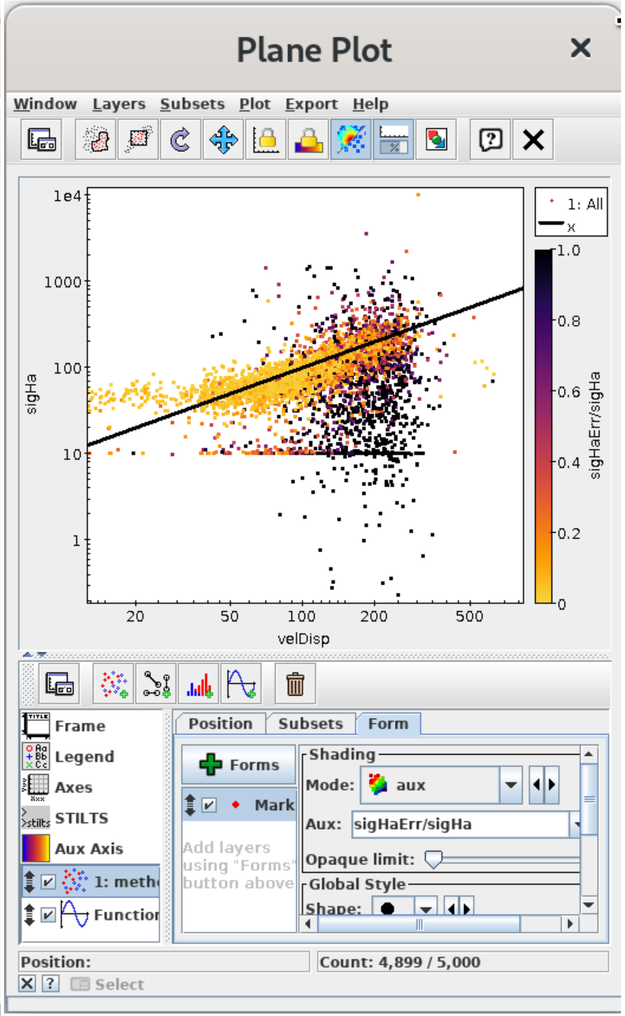


	ra	dec	z	zErr	velDisp	velDispErr	snMedian	
1	146.07944	-0.68096	0.067273	2.26460e-5	139.946	9.52048	23.6345	20
2	146.22225	-0.37589	0.067406	1.47889e-5	86.9503	6.60209	23.7421	5
3	145.68114	-0.86722	0.067595	1.34051e-5	151.046	5.14736	28.138	5
4	145.34424	-0.3685	0.204814	3.85925e-5	218.041	13.3036	10.7861	110
5	145.33123	-0.54207	0.153353	1.79960e-5	143.079	25.6172	8.06431	12
6	146.25244	1.11958	0.120132	3.69646e-5	184.509	12.289	13.4383	21
7	146.84222	0.74084	0.020131	6.66649e-6	63.9882	12.4257	14.5219	1
8	147.12735	0.50446	0.086057	1.67476e-5	97.1918	9.38074	13.0875	6
9	148.31755	-1.05055	0.139379	2.90861e-5	160.118	10.2306	12.9407	21
10	148.79165	-0.02102	0.085213	1.10301e-5	121.832	20.8426	10.0832	10
11	148.50575	-0.11386	0.127313	2.84980e-5	137.955	10.5404	13.7249	8
12	147.69322	0.13054	0.069145	9.18849e-6	135.601	16.5603	11.3991	8
13	147.91036	-0.57614	0.138029	3.85532e-5	167.963	13.4732	11.3162	79
14	147.46847	-0.45819	0.328609	7.38732e-5	228.161	26.9164	5.10561	129
15	147.16557	-0.89133	0.167423	3.99187e-5	208.962	16.7285	12.2723	5
16	146.78847	-0.31066	0.056614	1.13770e-5	72.7607	33.1433	4.30038	2
17	147.74002	0.61567	0.163001	3.09153e-5	230.855	11.5988	14.833	19
18	147.86563	0.502	0.080631	1.24978e-5	199.665	7.60252	24.6108	18
19	147.94533	0.33048	0.084409	1.60110e-5	185.044	6.34636	25.8529	14
20	150.37774	-0.13016	0.089852	2.85727e-5	127.846	9.56837	15.1371	16
21	150.51385	-0.2138	0.045162	7.81269e-6	22.5576	41.9494	7.7782	5
22	149.83076	-0.40297	0.072408	2.25239e-5	122.357	8.01675	17.7386	
23	149.19869	-1.05644	0.093009	3.29696e-5	144.224	12.2589	12.5113	4
24	149.42268	-0.31072	0.087942	1.10970e-5	65.7446	10.2425	15.2187	3
25	149.47209	-0.36201	0.168546	2.97094e-5	202.903	10.6778	15.3426	19
26	149.23315	-0.39416	0.089092	1.72371e-5	107.664	8.82474	15.1249	10
27	148.24123	-0.79525	0.088637	2.41463e-5	127.856	7.84762	16.4083	15
28	149.007	-0.24103	0.083715	2.04446e-5	177.642	7.8413	22.0525	18
29	149.05682	0.75387	0.034631	9.25833e-6	24.957	59.3203	7.51928	3

Visually inspecting the data

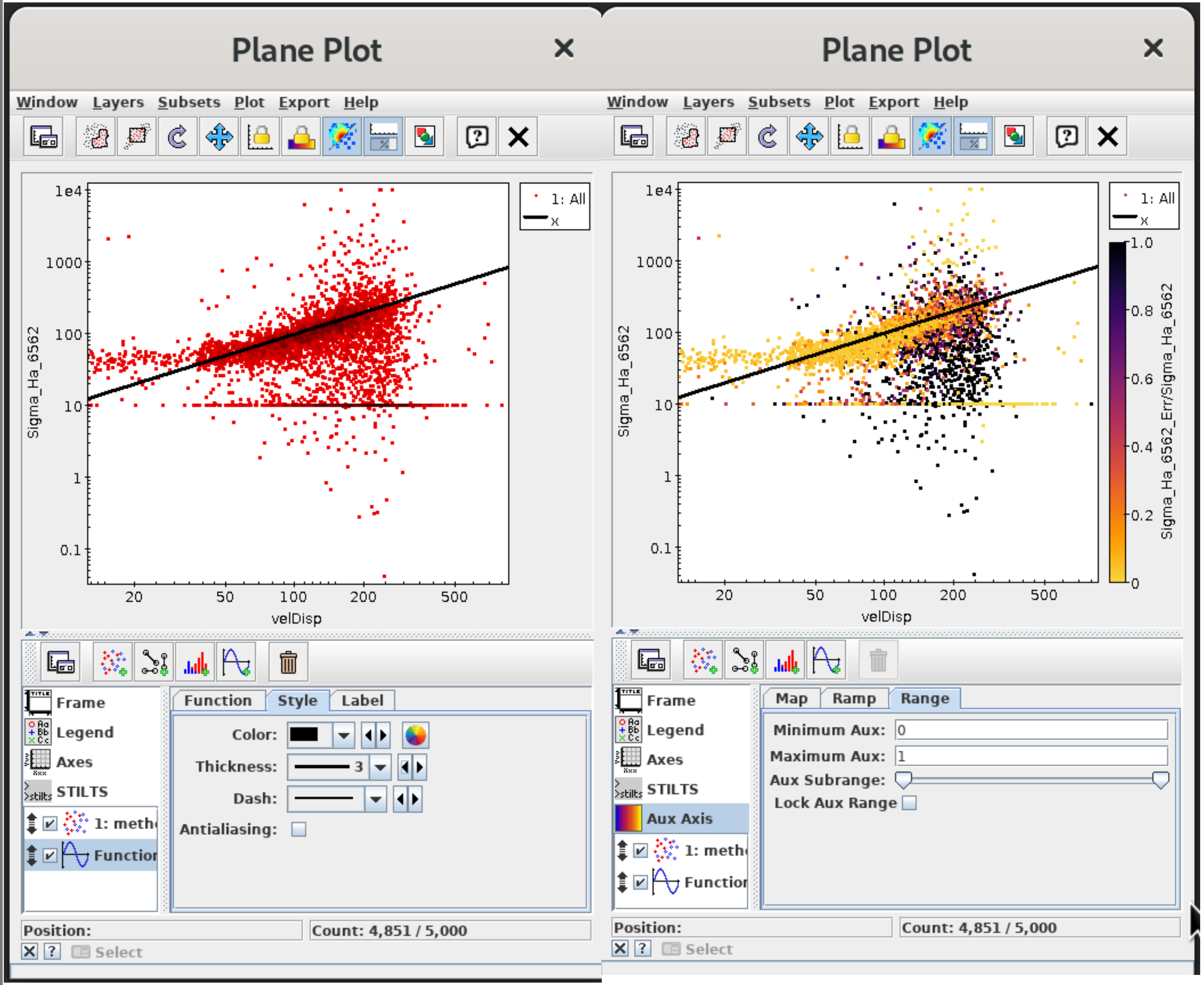
identify outliers
identify problems with the data

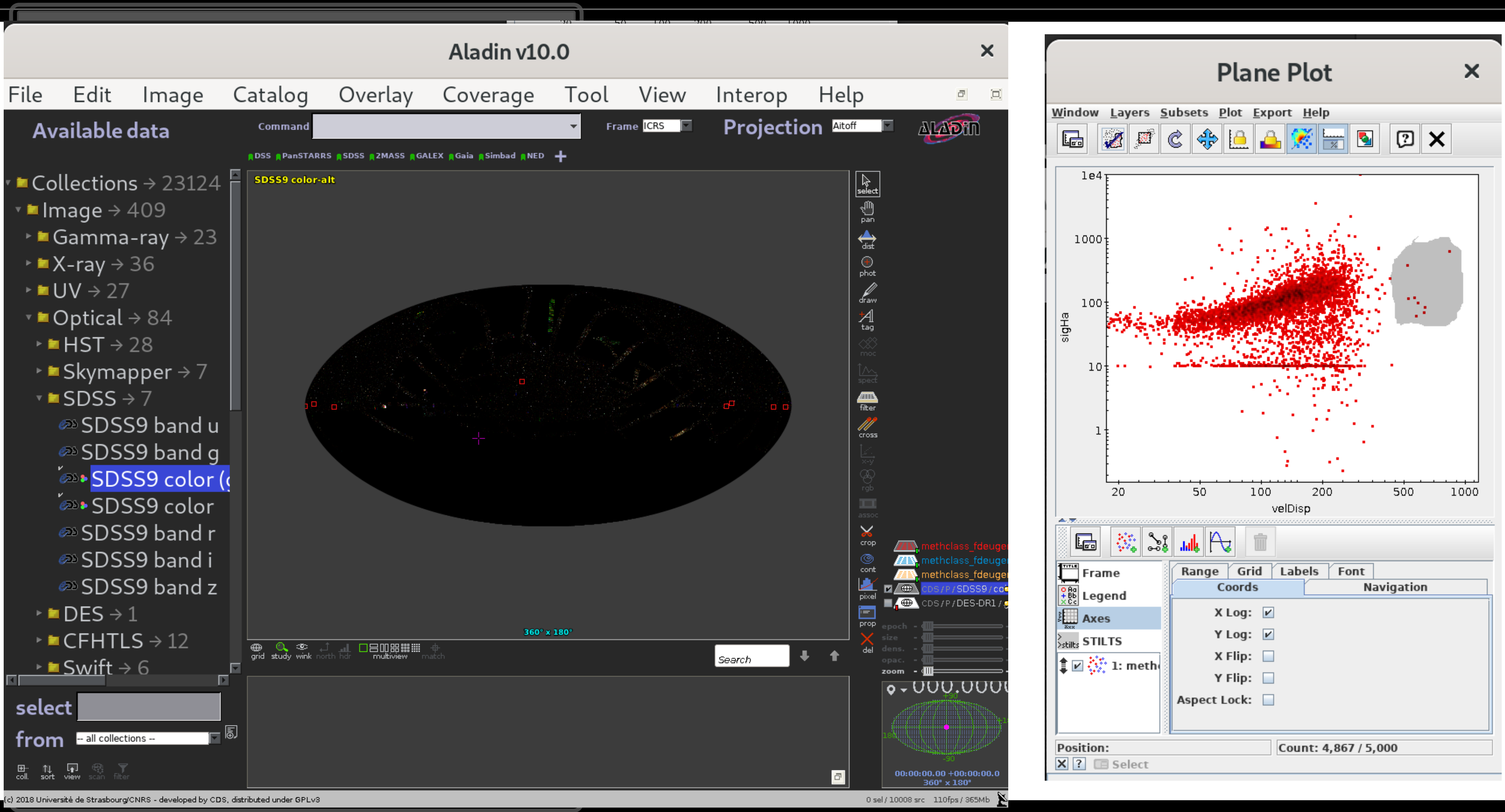




Visually inspecting the data

identify outliers
identify problems with the data




Aladin v10.0
File Edit Image Catalog Overlay Coverage Tool View Interop Help
Available data
Command
Frame ICRS
Projection Aitoff
DSS PanSTARRS SDSS 2MASS GALEX Gaia Simbad NED
Collections → 23124
Image → 409
Gamma-ray → 23
X-ray → 36
UV → 27
Optical → 84
HST → 28
Skymapper → 7
SDSS → 7
SDSS9 band u
SDSS9 band g
SDSS9 color
SDSS9 band r
SDSS9 band i
SDSS9 band z
DES → 1
CFHTLS → 12
Swift → 6
SDSS9 color-alt
360° x 180°
select
from
-- all collections --
Search
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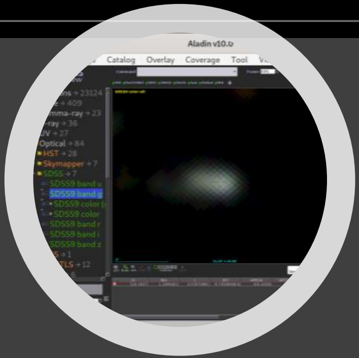
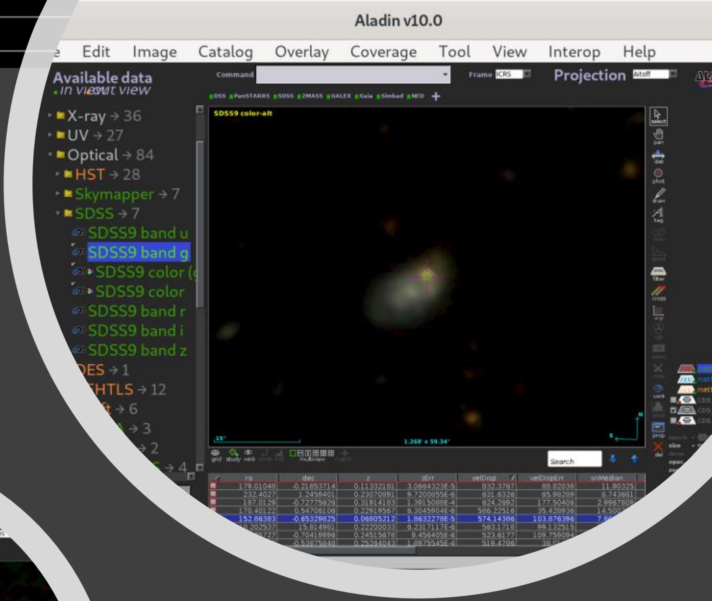
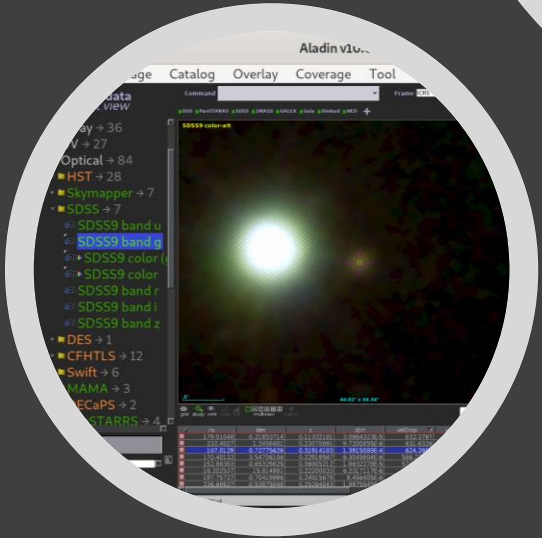
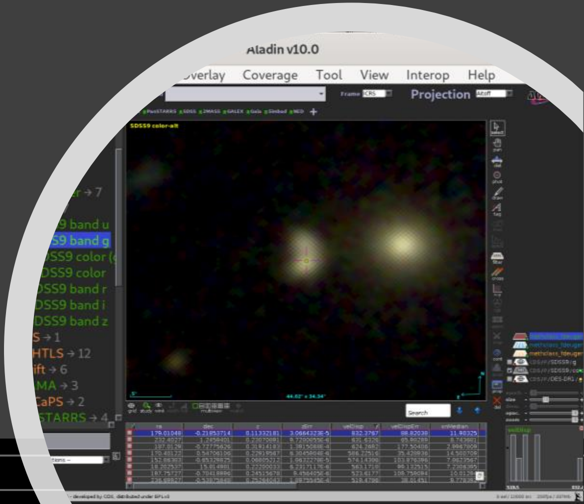
0 sel / 10008 src 110fps / 365Mb
Plane Plot
Window Layers Subsets Plot Export Help
sigHa
velDisp
Frame
Legend
Axes
STILTS
Range Grid Labels Font
Coords
Navigation
X Log:
Y Log:
X Flip:
Y Flip:
Aspect Lock:
Position:
Count: 4,867 / 5,000
Select

Visual inspection in SDSS









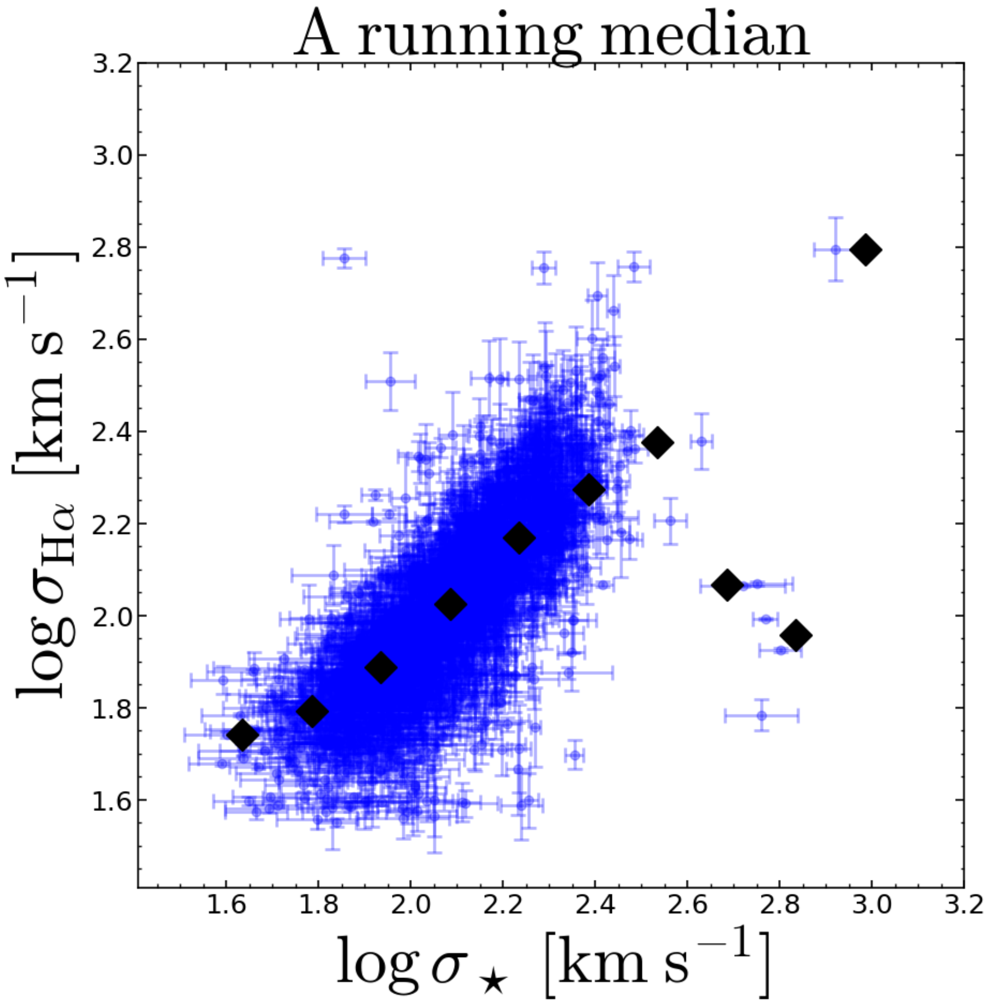
Total time: 1 minute (top)

A running median can help…

in python:

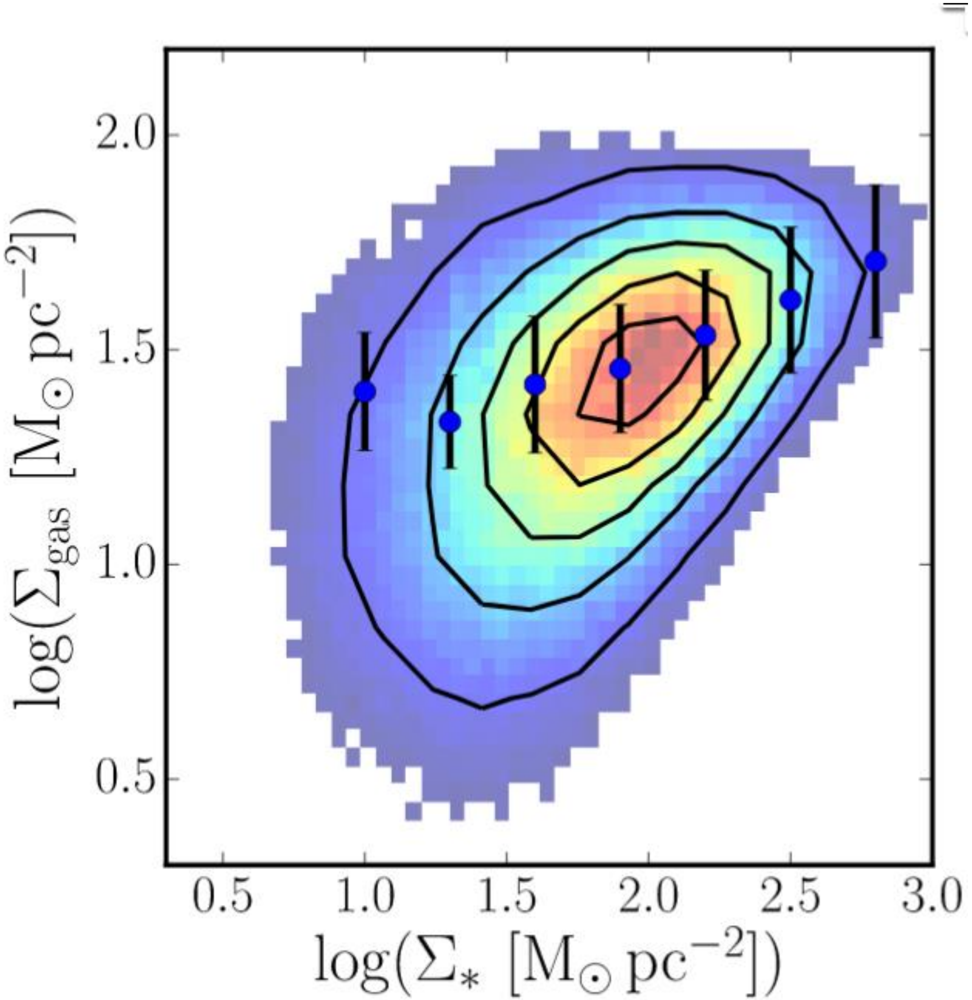
>>> binned_statistic(sigstar, sigHa, bins=…, statistic=np.median)

python3 methclass_running_median.py



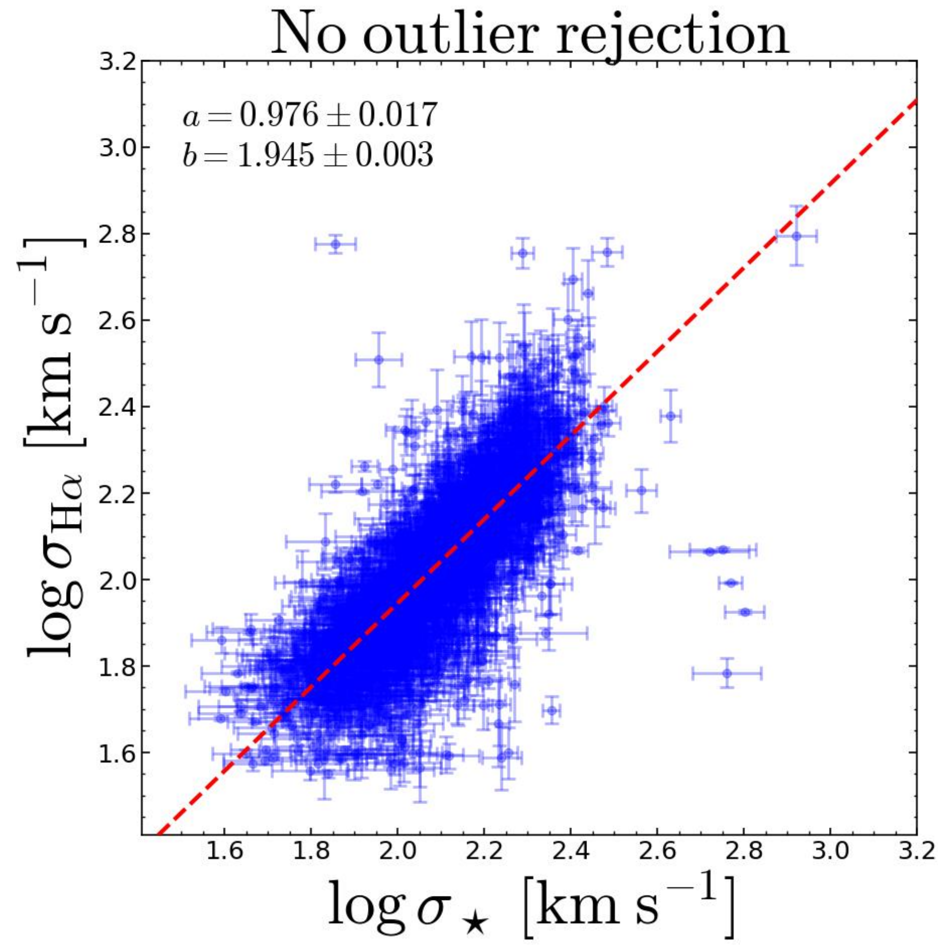
A running median can help…

…but be sensible!



Least Squares

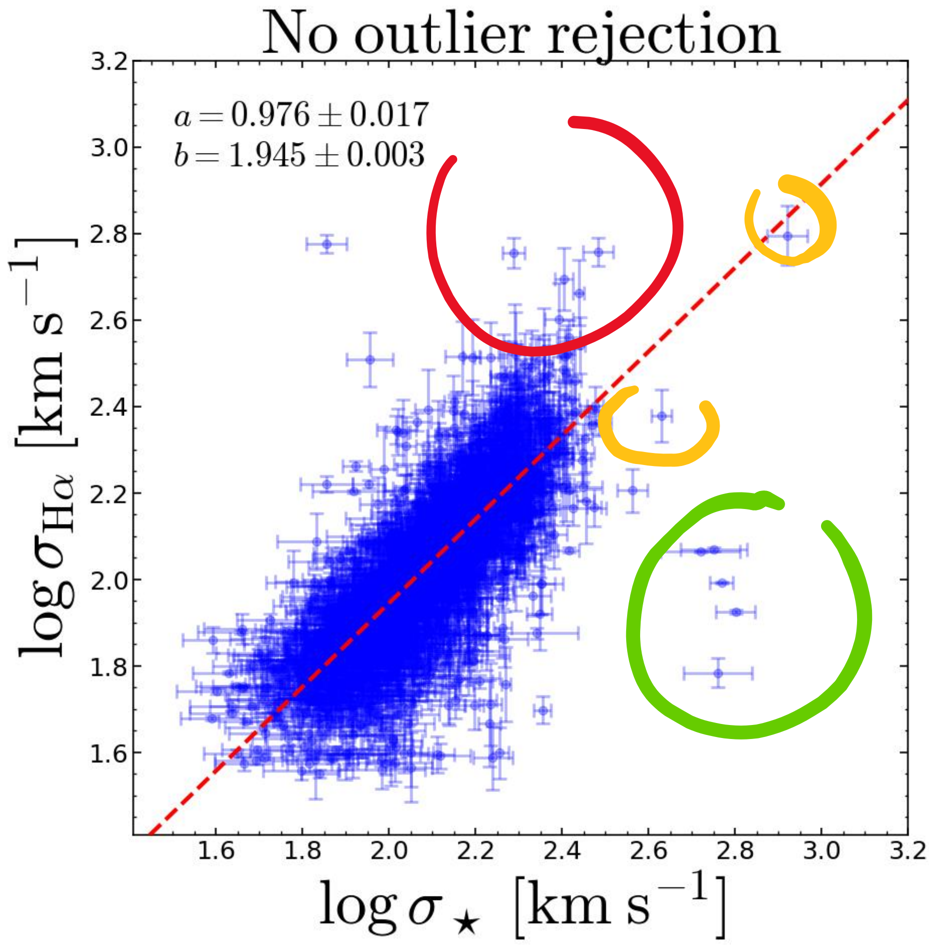
Something's wrong…



Need to reject outliers!

Difficult and often lengthy process

Labour intensive



Least Trimmed Squares (LTS)

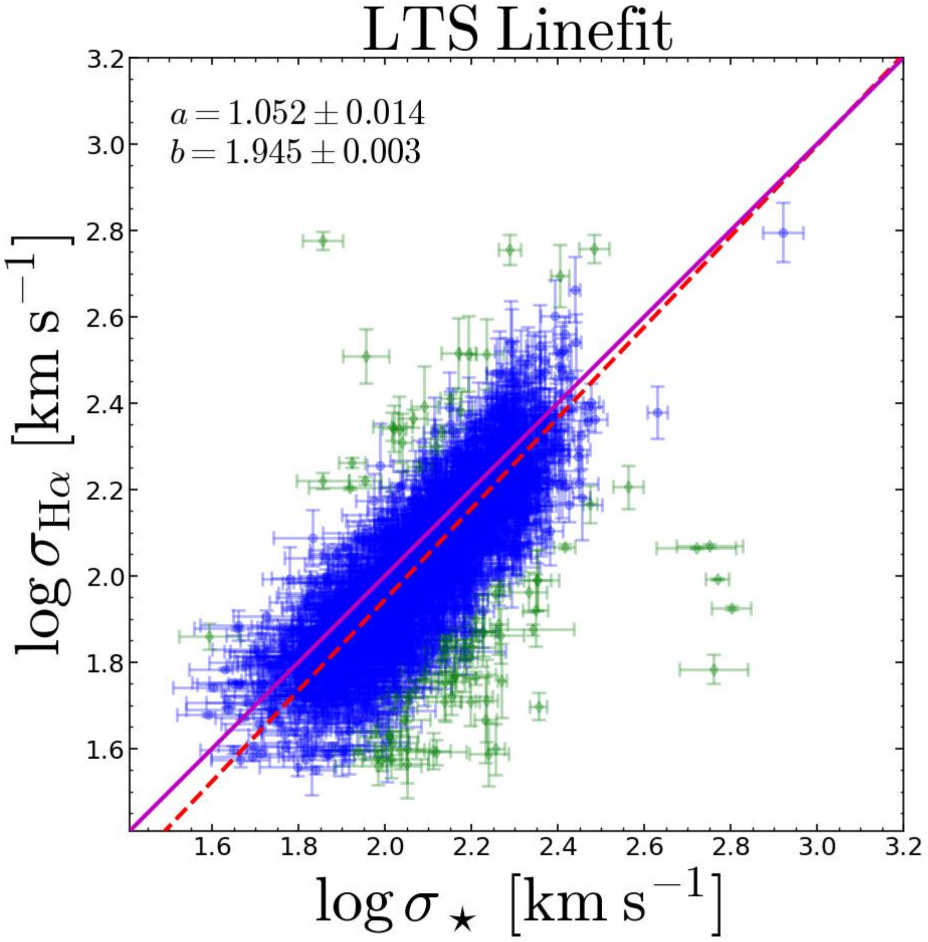
Least squares minimization + sigma clipping but:

- ➢proceeds inside-out
- ➢guaranteed to converge

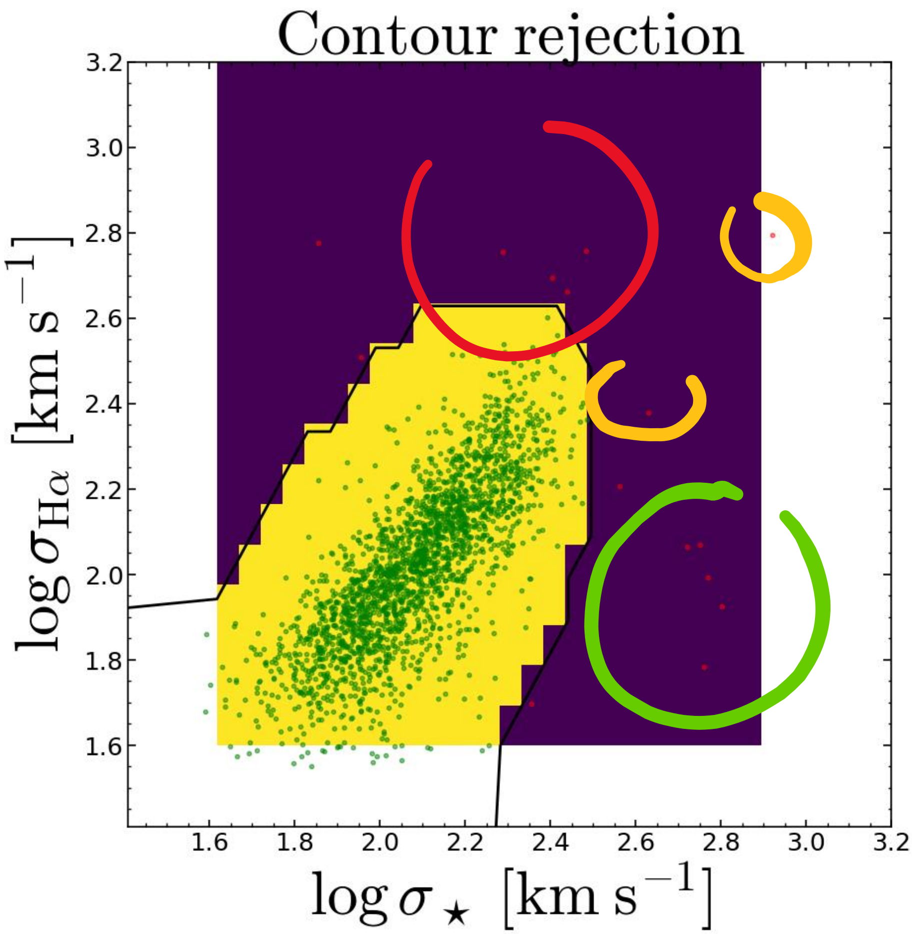
For the record:

slope = b = 1.08 +- 0.02

python3 methclass_lts_linefit.py



Contour-based rejection



Quick to implement

Can be recycled for Bayesian approach

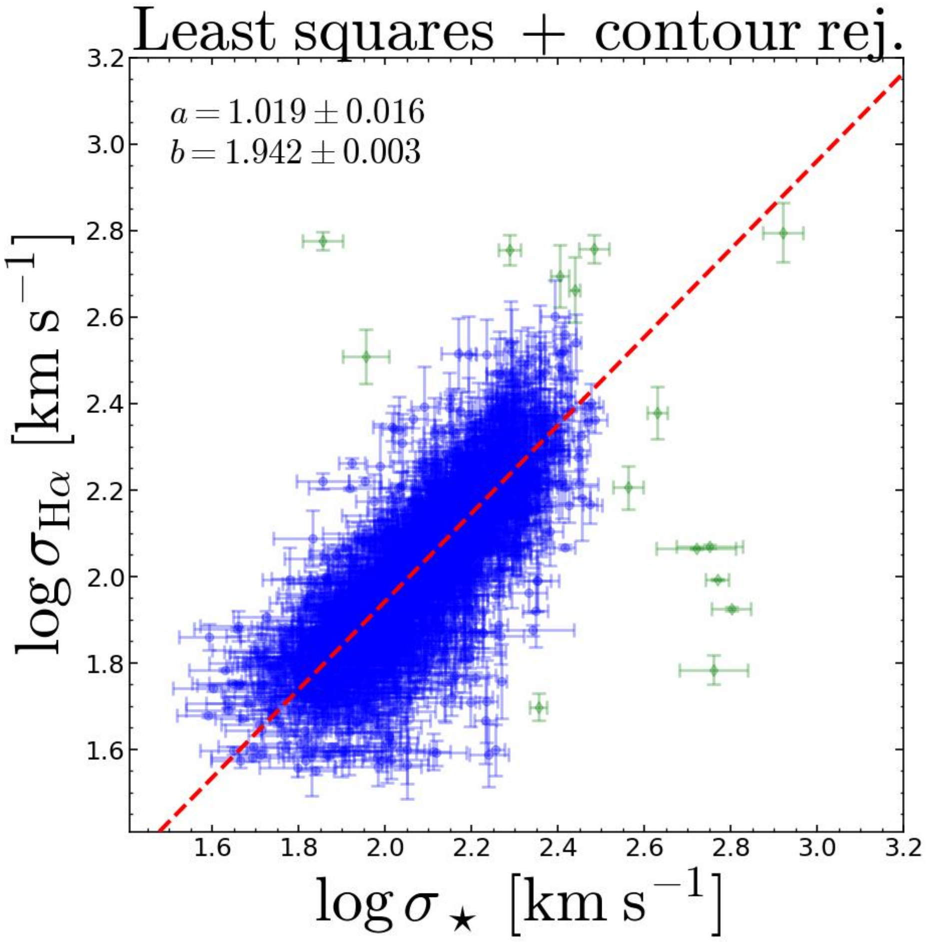
Applying contour rejection.

Least squares minimization + sigma clipping but:

- ➢proceeds inside-out
- ➢guaranteed to converge

For the record:

slope = b = 1.08 +- 0.02



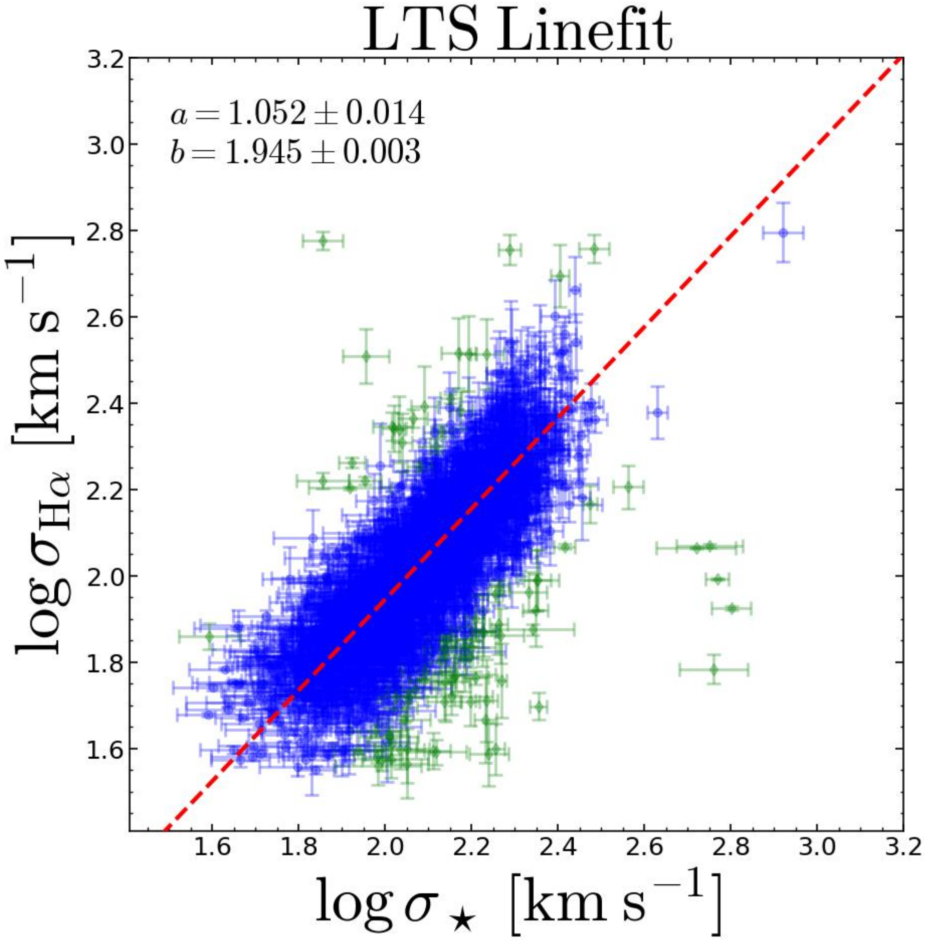
Towards a probabilistic model

Least squares minimization + sigma clipping but:

- proceeds inside-out
- guaranteed to converge

For the record:

slope = b = 1.08 +- 0.02



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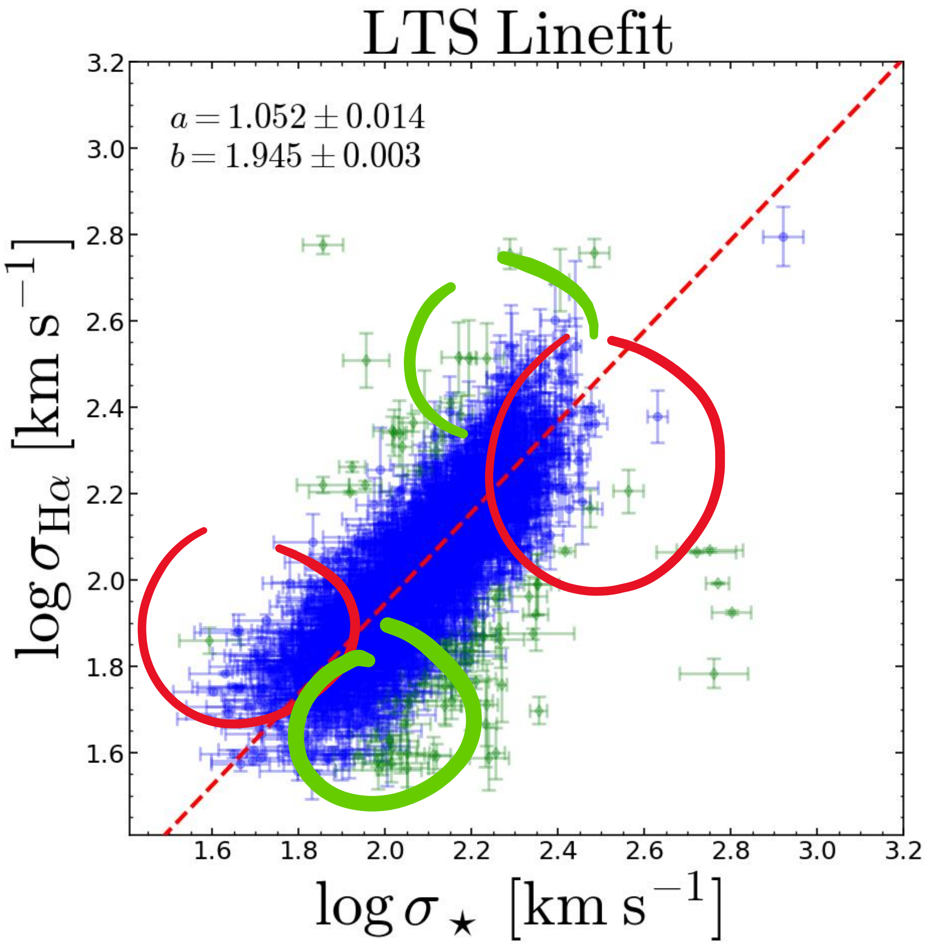

How to construct an adequate model?

create a probabilistic model

$$p(model|data) \propto p(model) \times p(data|model)$$

ALL algorithms we have seen so far assume a model

…know thy model

Towards a probabilistic model

Least squares minimization + sigma clipping but:

- ➢proceeds inside-out
- ➢guaranteed to converge

For the record:

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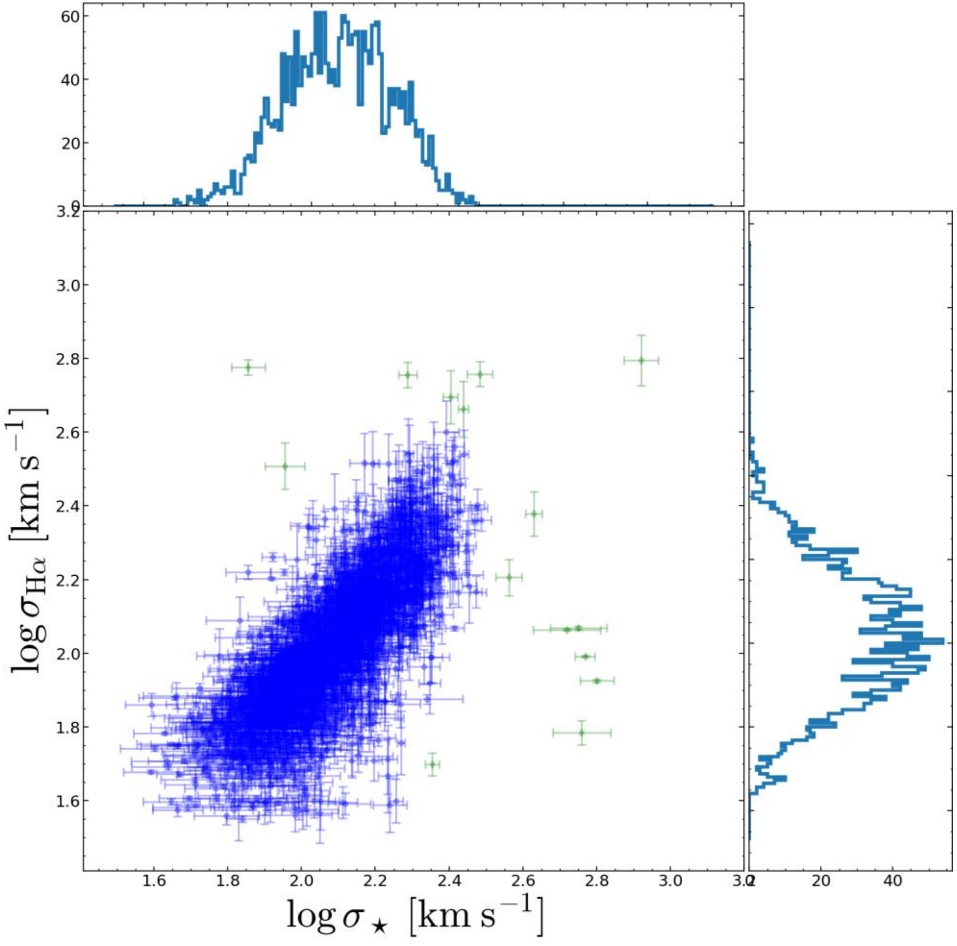

Towards a probabilistic model

Least squares minimization + sigma clipping but:

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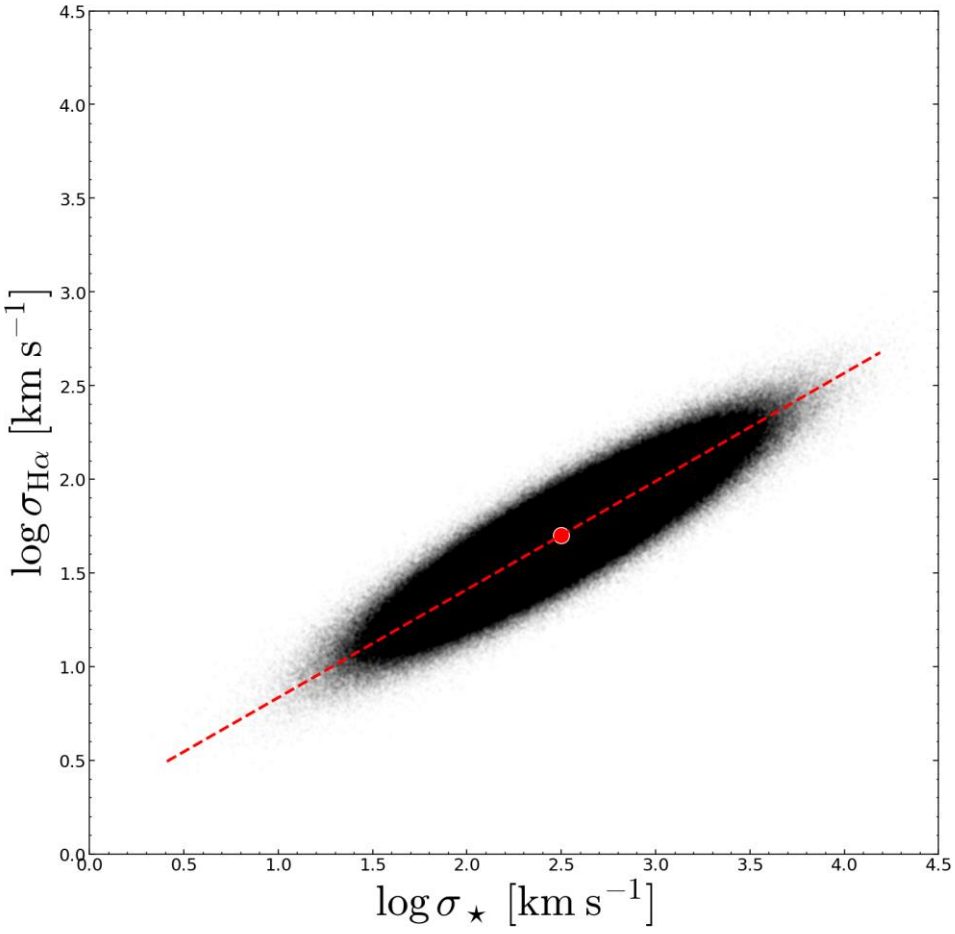
For the record:

slope = b = 1.08 +- 0.02



Towards a probabilistic model

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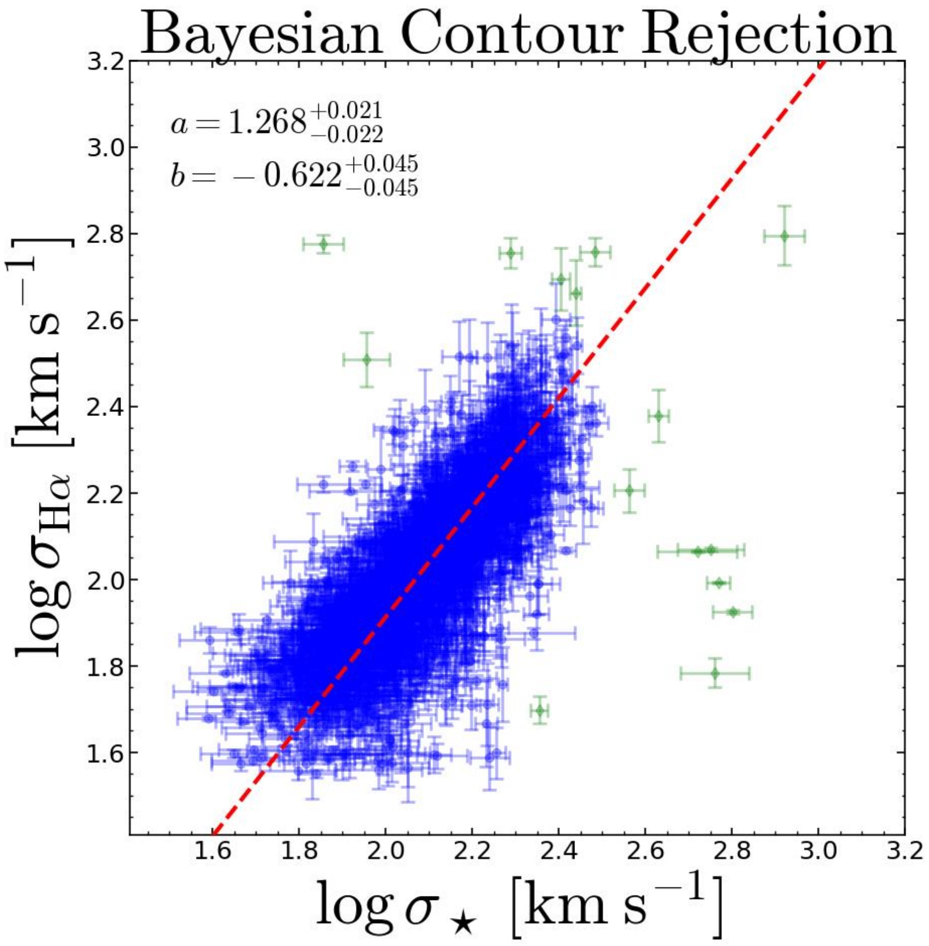

Towards a probabilistic model

Least squares minimization + sigma clipping but:

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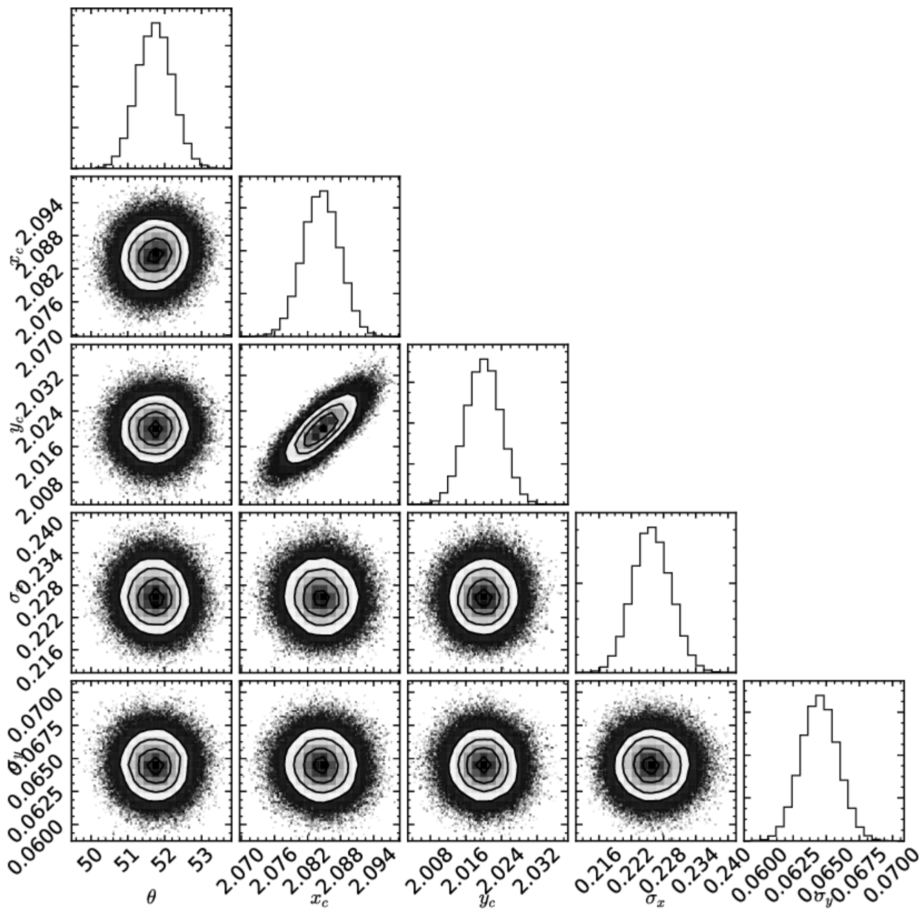

Locally wEighted Scatter-plot Smoother = LOESS