Introduction to Large Astronomical Surveys

A.Ederoclite

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GOBIERNO DE ARAGON
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MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN
CEFCA
Centro de Estudios de Física del Cosmos de Aragón
Ayuda ICTS-MRR-2021-03-CEFCA, financiada por:
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Plan de Recuperación, Transformación y Resiliencia
ESPAÑA PUEDE.
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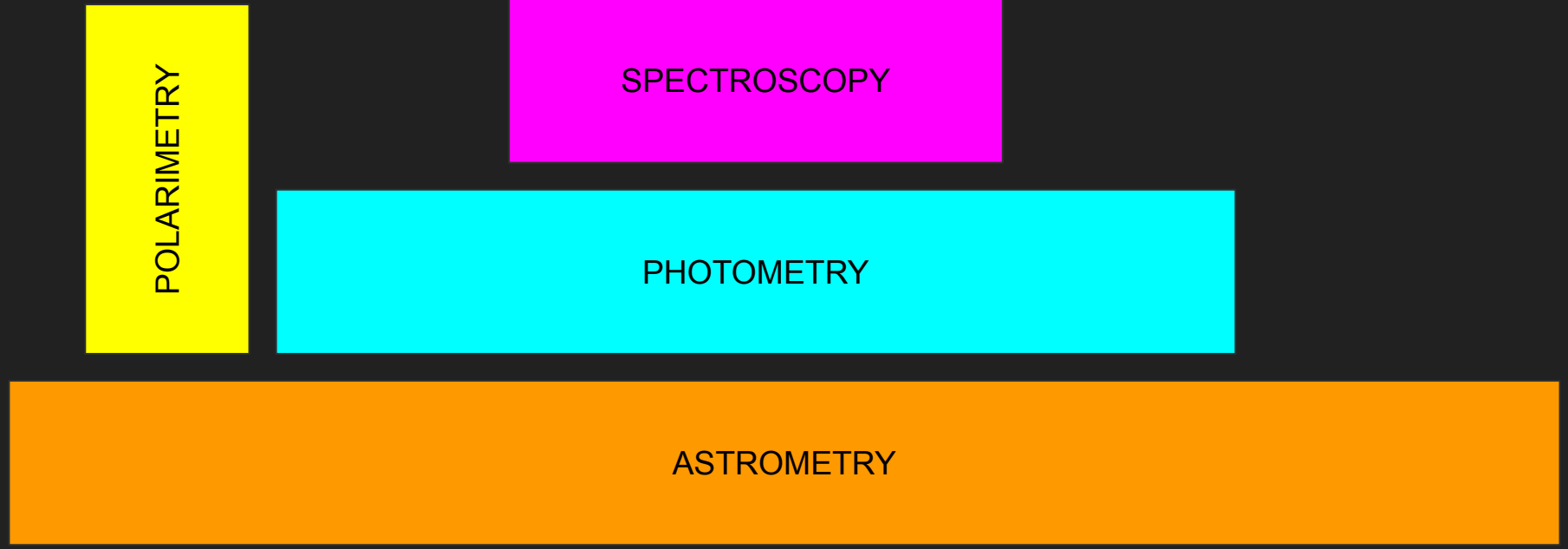
The astrophysical techniques pyramid

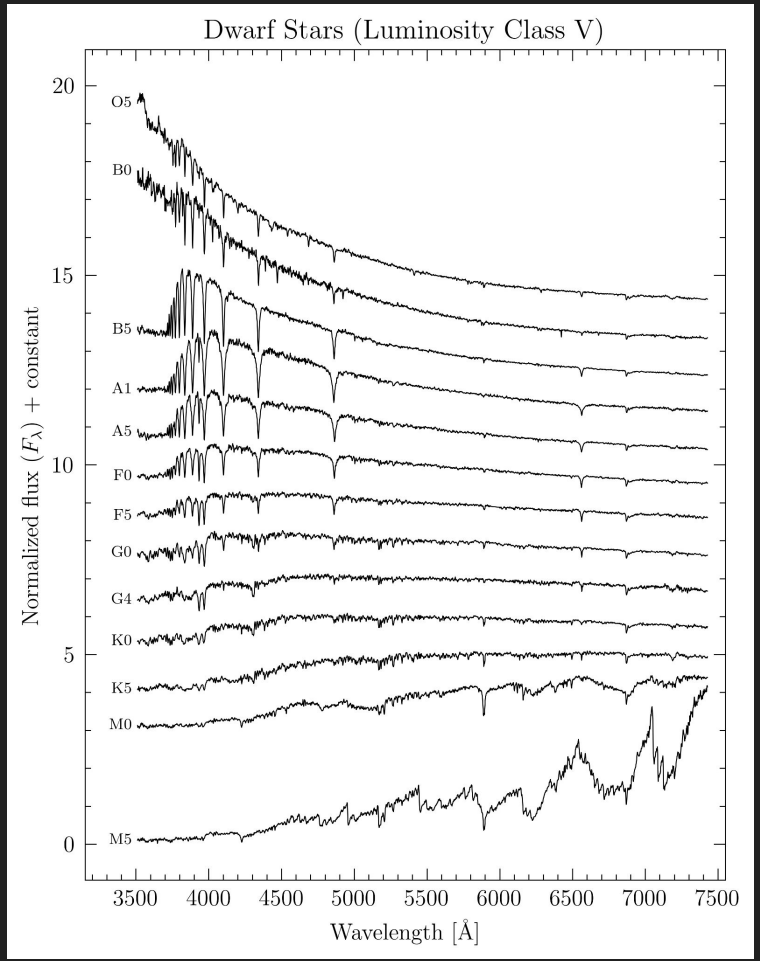


Stars

A stellar spectrum is the flux emitted from a star per unit of wavelength.

A stellar spectrum gives us information on temperature, gravity and chemical composition of a star.

Easy:
* Blue => hot
* Red => cool



What is a filter

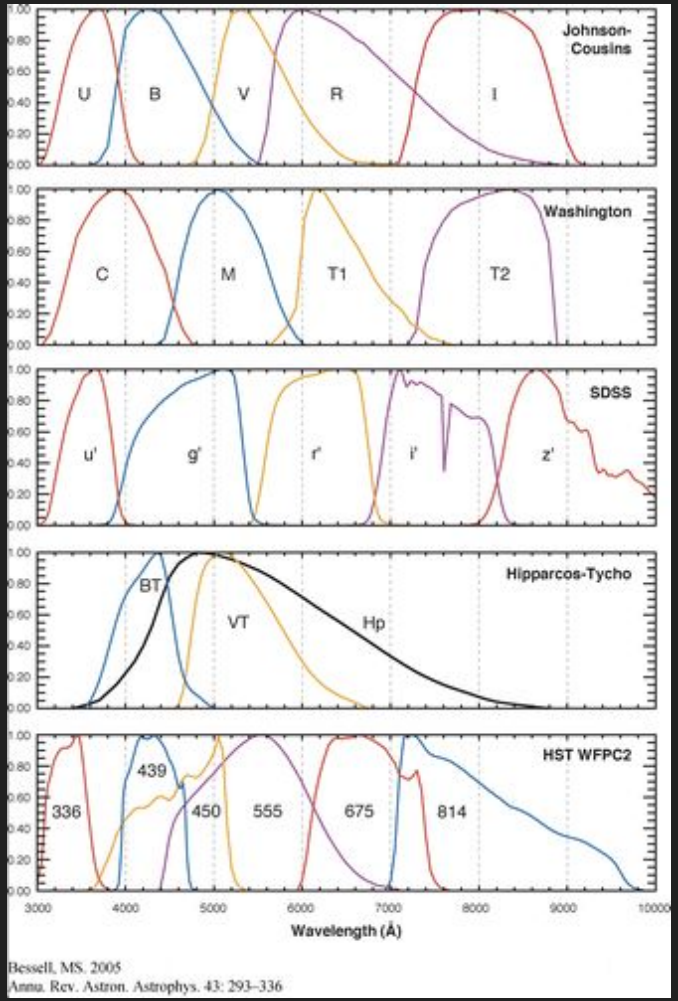
Select an interval of wavelengths/frequencies/energies.

Filters were born to tell red stars from blue stars (the “UBV”, Johnson system, Johnson & Morgan 1953)

“Poor man spectroscopy”

Now, the SDSS system is a new standard: Fukugita et al. (1996)

https://www.astro.umd.edu/~ssm/ASTR620/mags.html

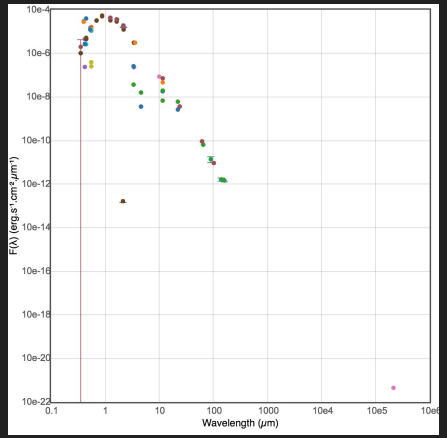


Spectral Energy Distribution

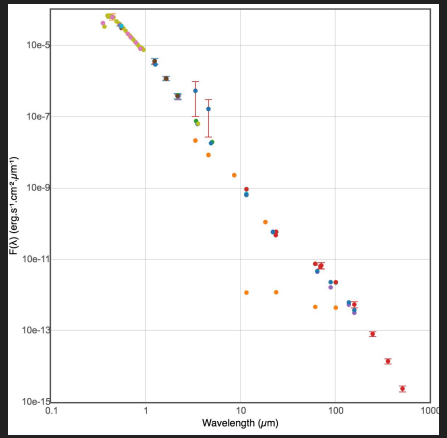
You can make a plot of the energy emitted in a filter vs. the central wavelength of the filter.

This is a Spectral Energy Distribution. Mind you: this is **not** a spectrum!

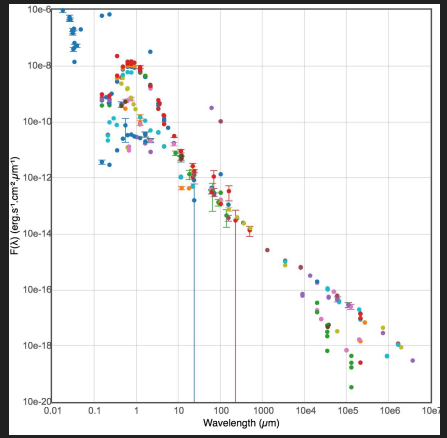
Antares (red star)



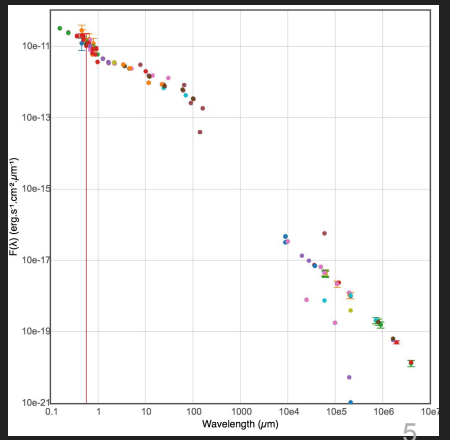
Vega (hot star)



M87 (giant elliptical galaxy)



3C 48 (quasar)



(Unfortunate) definition of magnitude

Defined by Ptolemy/Hipparchus: bright stars “first magnitude” and faint stars “sixth magnitude”.

The response of the human eye is logarithmic.

Pogson (1856)

$$mag_1 - mag_2 = -2.5 \log(f_1/f_2)$$

$$\Delta mag = 5 \rightarrow f_1/f_2 = 100$$

Absolute Magnitude vs. Apparent Magnitude

The magnitudes we observe are “apparent” ones.

An apparently faint star may just be a very far away bright star (or…? ;-))

We define “absolute magnitude” the magnitude of a star as if it was at a standard distance of 10 parsecs.

$M = m + 5 \log d[pc] + 5$

This is an incomplete version of an absolute magnitude!

Distance modulus: $M - m = 5 \log (d/10pc)$

Parallax

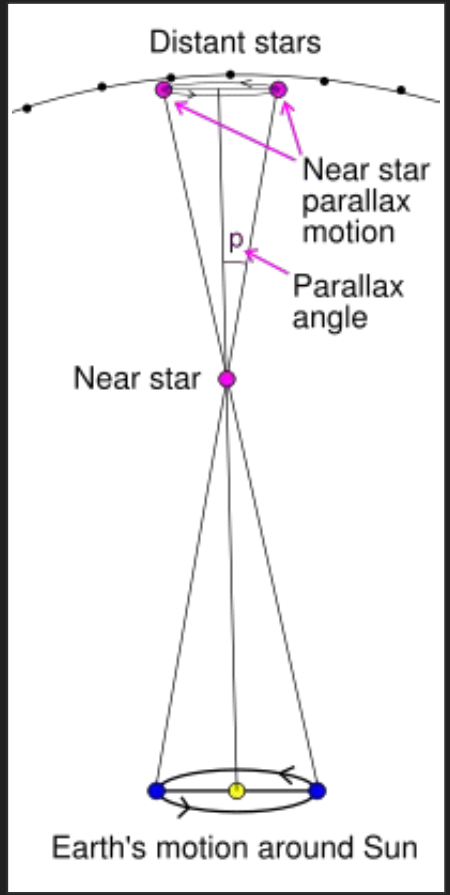
π = 1arcsec

corresponds to

206265 astronomical units

1 parsec

d[pc] = 1 / π(arcsec)



Interstellar extinction

The universe is full of gas and dust.

How does this gas and dust affect starlight?

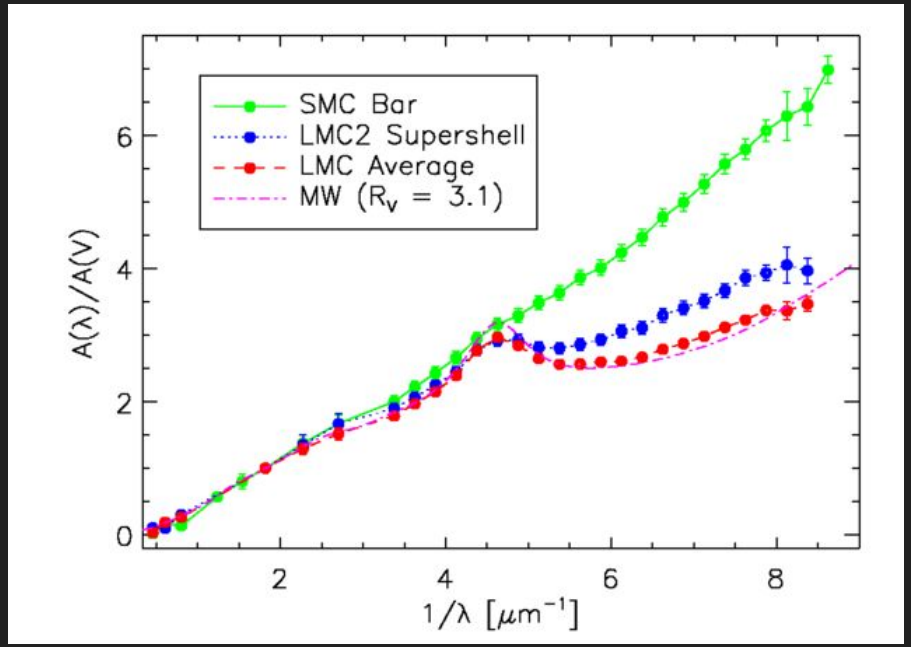
Light gets absorbed and reddened!

https://www.eso.org/public/images/eso9934b/

$R_V = A_V / E_{B-V}$

The complete expression of “absolute magnitude” is:

$M = m + 5 \log d[pc] + 5 + A_v$



https://en.wikipedia.org/wiki/Extinction_(astronomy)

White is not a colour

If you let “white light” pass through a prism made of glass, you split it in the colours of the rainbow.

Discovered by Sir. Isaac Newton.

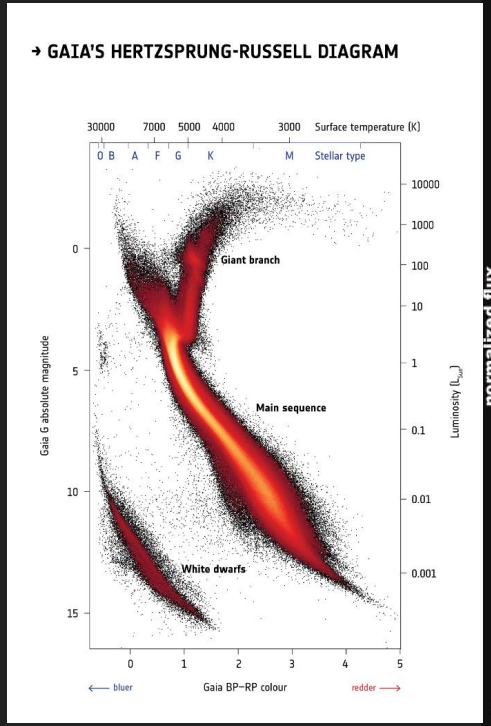
[Actually] White light is a superposition of light at different wavelengths, which are separated by a prism thanks to Snell’s law

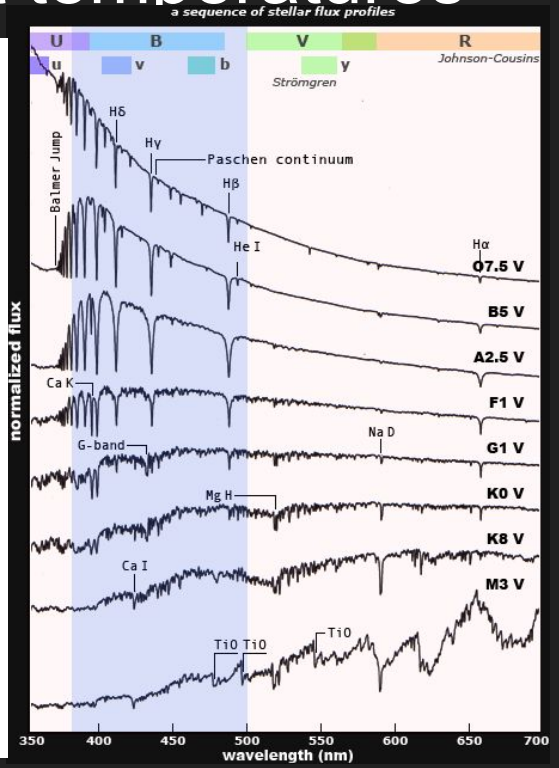
(Main Sequence) Stars of different temperatures

In the first decades of the XX century, the Harvard group (aka Pickering's harem) had the merit of standardising the classification of stellar spectra.

As a reminder, from hotter to cooler: OBAFGKM.

Most of that classification is what we still use today.



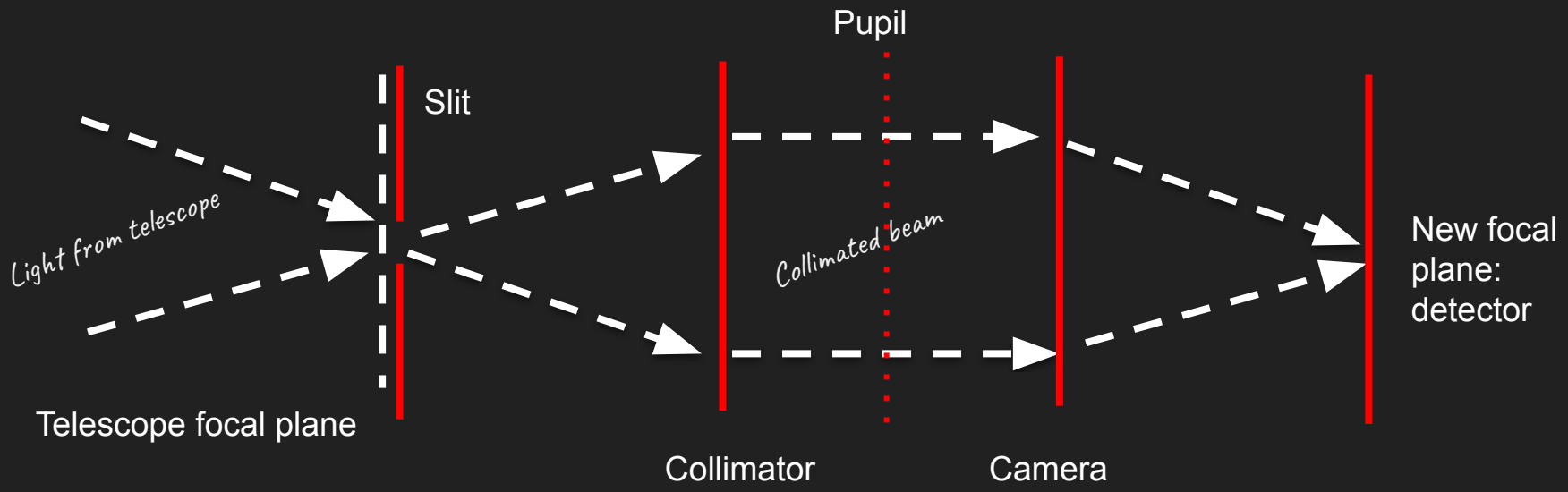


https://www.gaia.ac.uk/multimedia/gaia-dr2-hr-diagram

https://www.handprint.com/ASTRO/specclass.html

Spectrographs

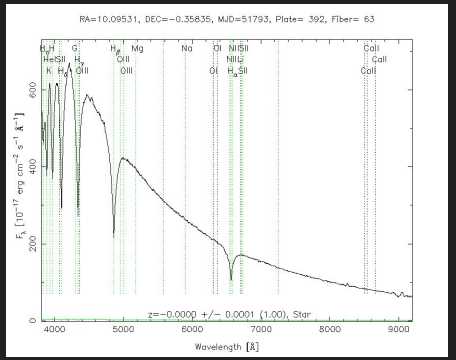
Need to put a light disperser in the collimated beam

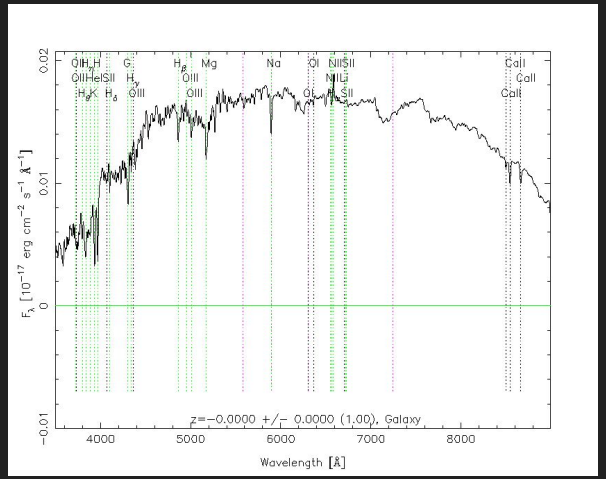


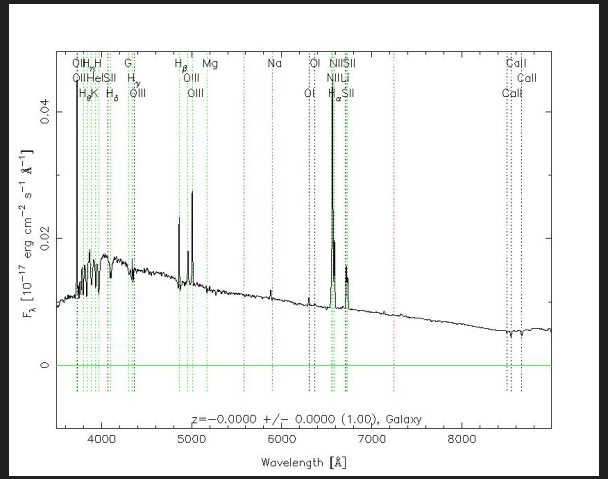
Spectra

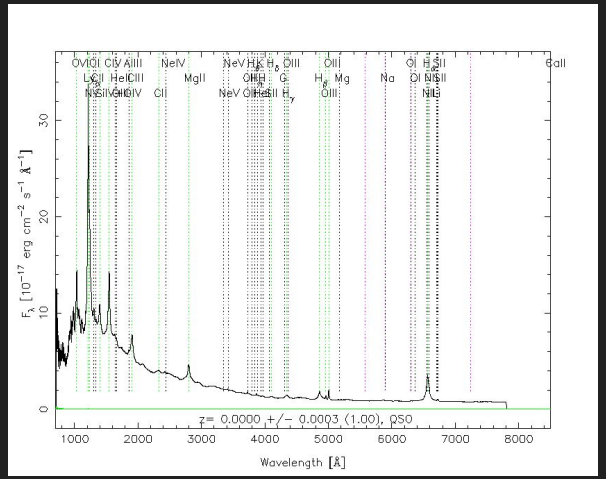
A spectrum is defined by its continuum and its lines.

https://classic.sdss.org/dr5/algorithms/spectemplates/









The “actuation range” of an instrument

There is no such thing as “the best 4m telescope of the world”.

A telescope/instrument is as good as the use you need.

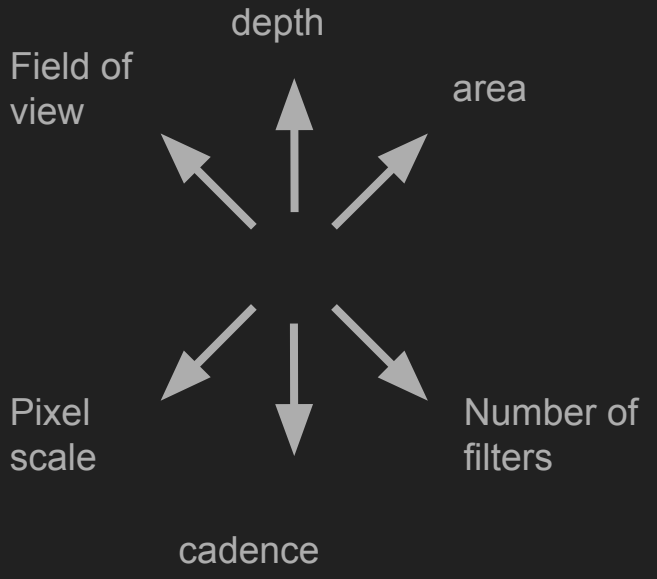
Use an “Exposure Time Calculator” to evaluate the magnitude range for S/N between 3 and 100 in 15 minutes.

That magnitude range is what **I** call the “actuation range”. It’s what the telescope/instrument is good at.

Survey Parameters

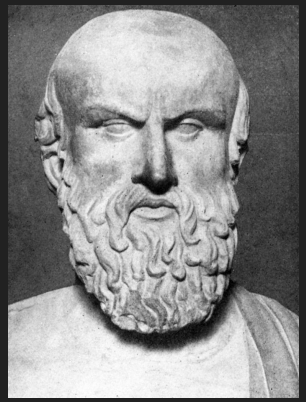
When you design a survey you have to play in a very complex space of parameters.

Given that exposure time, depending on the brightness of your source and the signal-to-noise you want to achieve, you will pick your telescope/instrument.



A little bit of history

Hipparcos/Ptolemy: Almagest

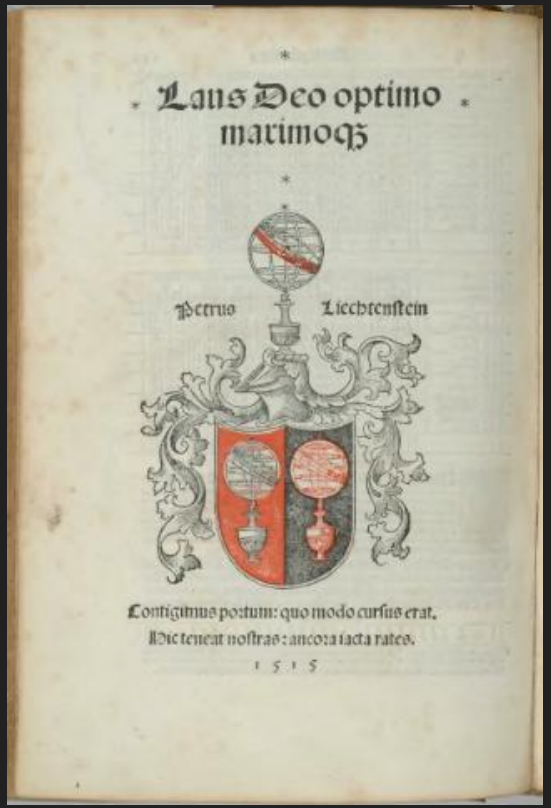


1022 stars and their positions in the constellations

<- Hipparcos

<- Ptolemy

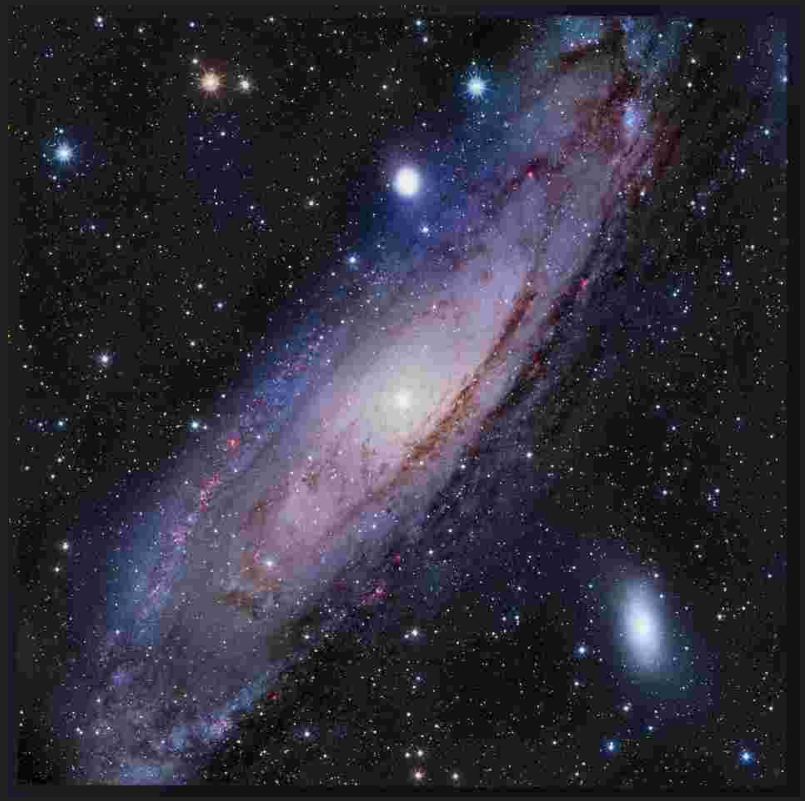
https://en.wikipedia.org/wiki/Almagest



Messier

He was hunting for comets and decided to make a catalogue of all objects that would confuse him.

Messier 31 (Andromeda Galaxy) ->



Carte du Ciel

22,000 photographic plates

1891-1920

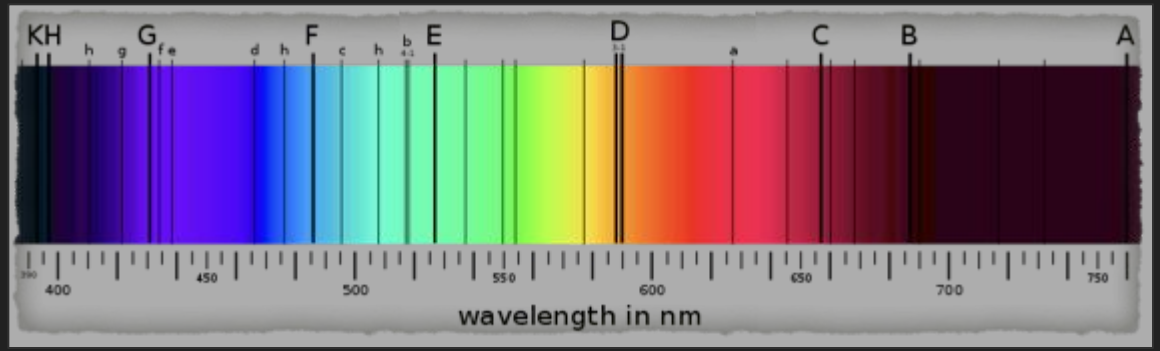
20 observatories involved worldwide

4.6 million objects @ 13mag

Precision of 0.5 arcsec


Catálogo Astrofotográfico
para
1900,0
SECCIÓN
del
Observatorio de Marina de San Fernando
DECLINACIÓN DE -0° A -6°
TOMO I
INTRODUCCIÓN Y TABLAS.

Spectroscopy - Fraunhofer



1787 - 1826

Fraunhofer discovered the presence of a series of dark lines in the solar spectrum.

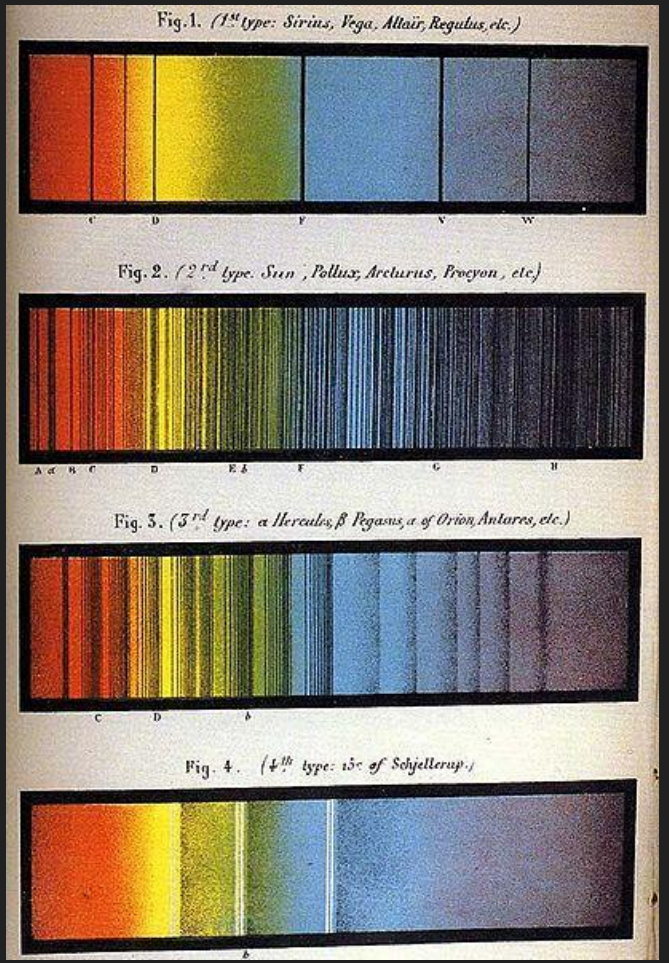
He called them with alphabet letters (capital for more intense and minuscule for less intense)

Note the wavelengths of the Na D doublet.

Spectroscopy - Secchi

Angelo Secchi (1818 - 1878)

First attempt to classify stars.



Harvard

Pickering (Director of Harvard Observatory)

500,000 photographic plates!

The Harvard Computers

Pickering hired a group of women who became known as “the Computers” (or “Pickering’s Harem”).

Hiring women was cheaper than hiring a man.

Among them there were some of the most important astronomers of the XX century (e.g. Anne Cannon, Henrietta Leavitt,...)

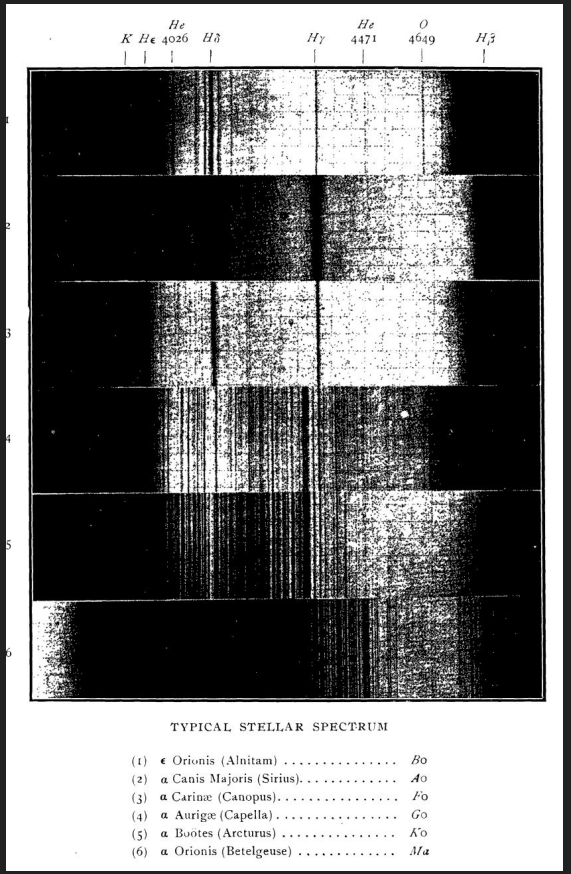
The work at Harvard set the basics of modern astrophysics.

The stellar classification

We owe to Willemina Fleming, Antonia Maury, and Anne Jump Cannon the Henry Draper Catalogue and the modern classification of OBAFGKM

https://ui.adsabs.harvard.edu/abs/1915JRASC...9..203C/abstract

You can use it too: http://cdsarc.u-strasbg.fr/viz-bin/Cat?III/135A



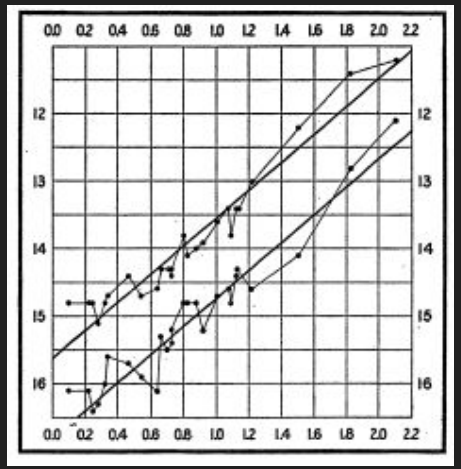
TYPICAL STELLAR SPECTRUM

(1) ε Orionis (Alnitam) ..... *Bo*
(2) α Canis Majoris (Sirius) ..... *Ao*
(3) α Carinæ (Canopus) ..... *Fo*
(4) α Aurigæ (Capella) ..... *Go*
(5) α Boötes (Arcturus) ..... *Ko*
(6) α Orionis (Betelgeuse) ..... *Ma*

The extragalactic distance saga

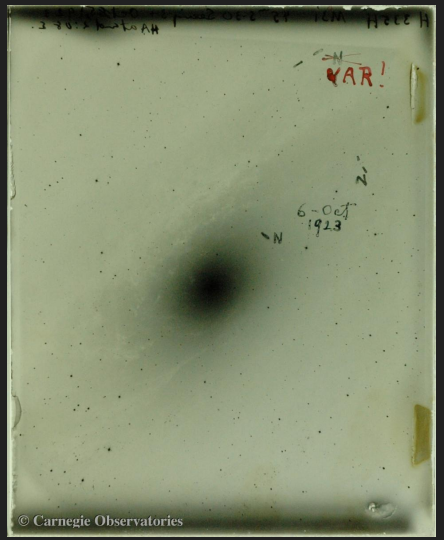
Leavitt & Pickering (1912) discovered the period-luminosity relation for Cepheids

https://ui.adsabs.harvard.edu/abs/1912HarCi.173....1L/abstract



Hubble was studying variable stars in M31

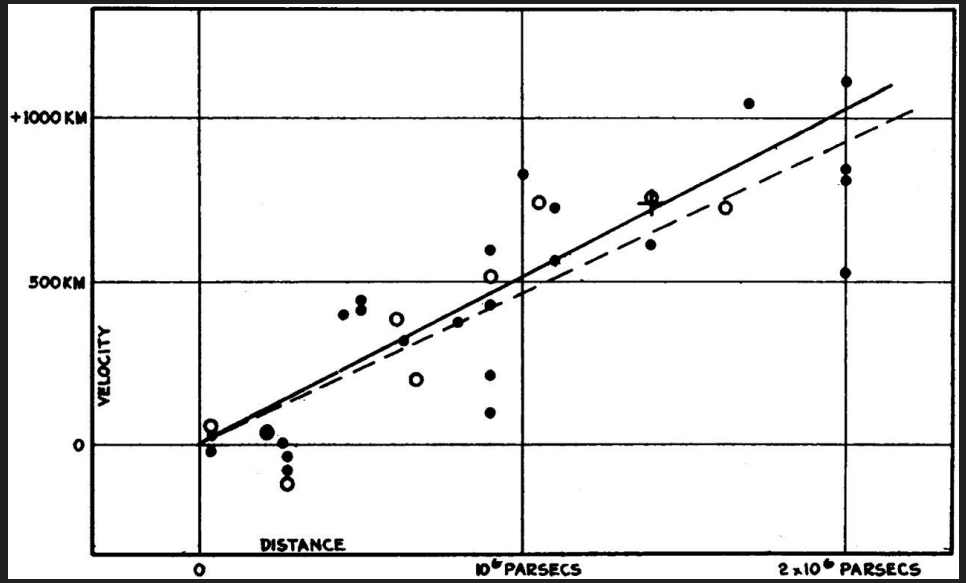
Found the first periodic star!



The Hubble-Lemaitre Law

The birth of extragalactic astrophysics.

Hubble started to study the relation between distance and “redshift”

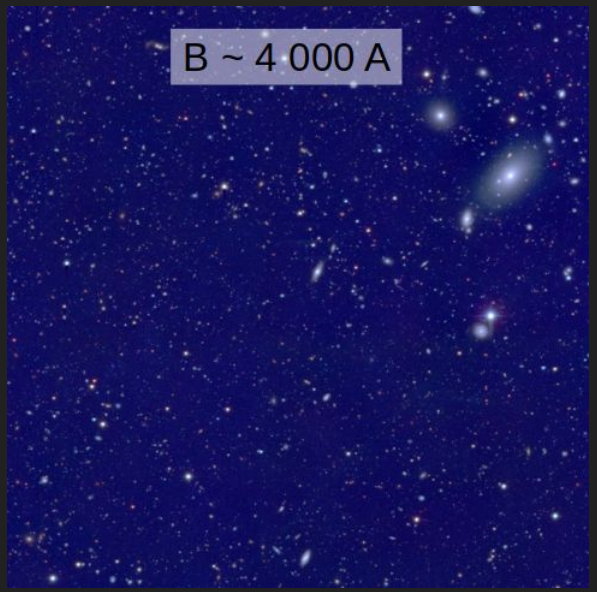


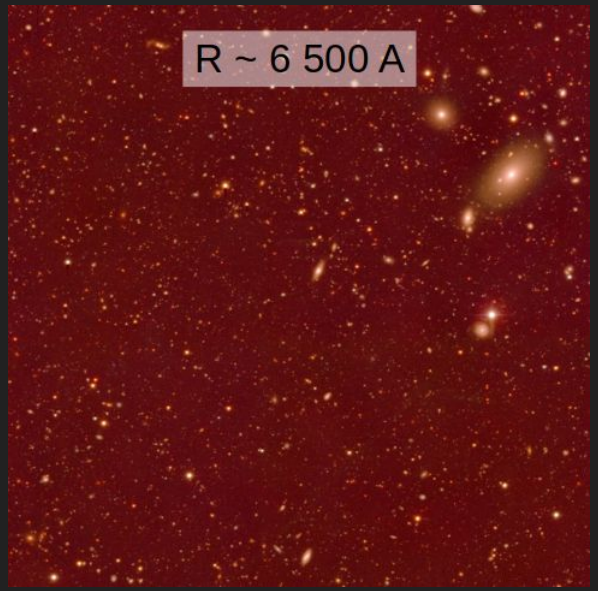
https://ui.adsabs.harvard.edu/abs/1929PNAS...15..168H/abstract

Palomar Observatory Sky Survey

First survey in more than a photometric band (1950-1958)

31,000sq.deg. @ mag~20.





The Hubble Deep Field

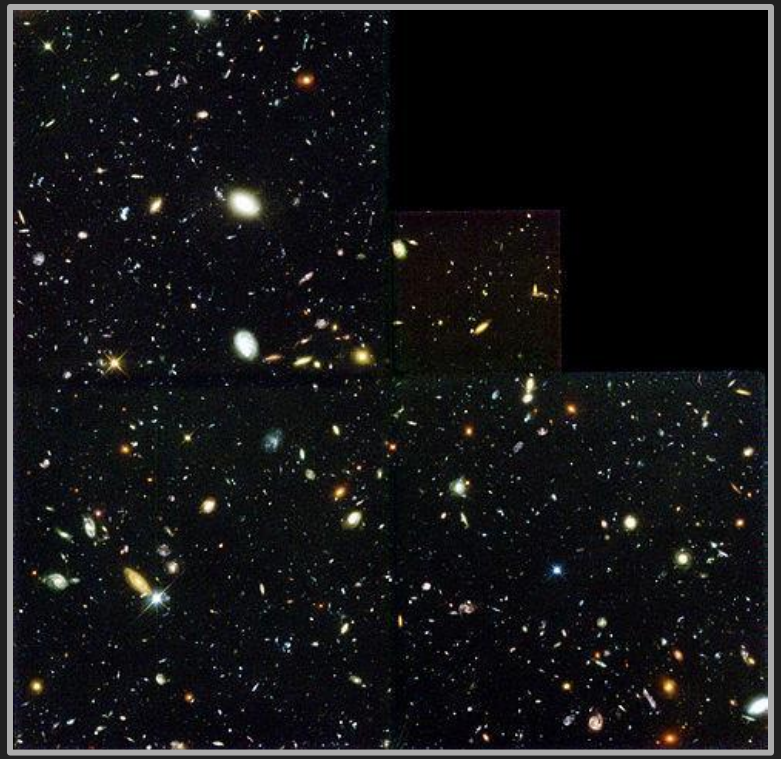
The origin of observational cosmology, as we understand it today.

The prototypical “pencil-beam” survey.

10 days of HST/WFPC2 in 4 filters

Calibrated data immediately available to everyone

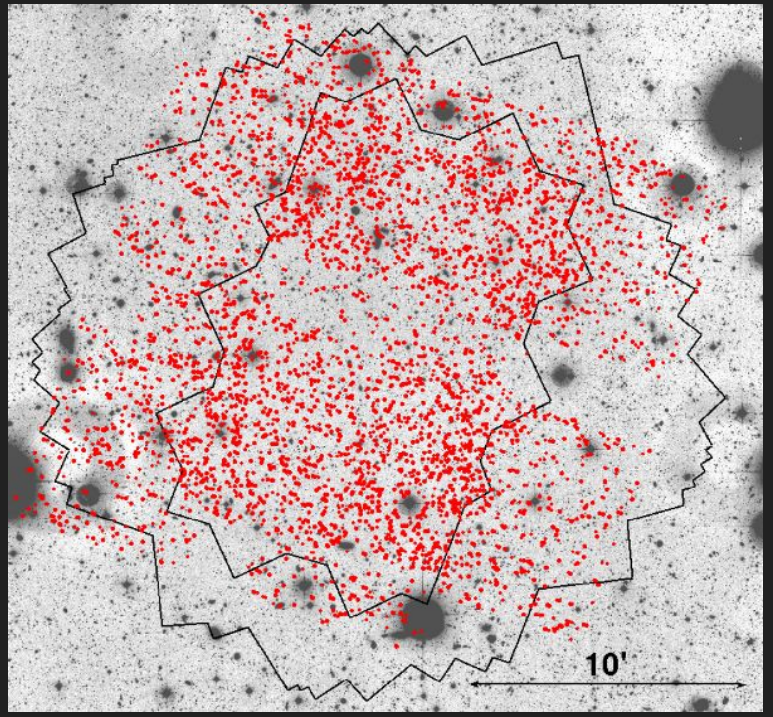
https://ui.adsabs.harvard.edu/abs/1996AJ....112.1335W/abstract



Great Observatories Origins Deep Survey

Multi-wavelength observations (from radio to X-rays) of a series of cosmological fields.

https://www.stsci.edu/science/goods/



ESO/Hamburg Survey

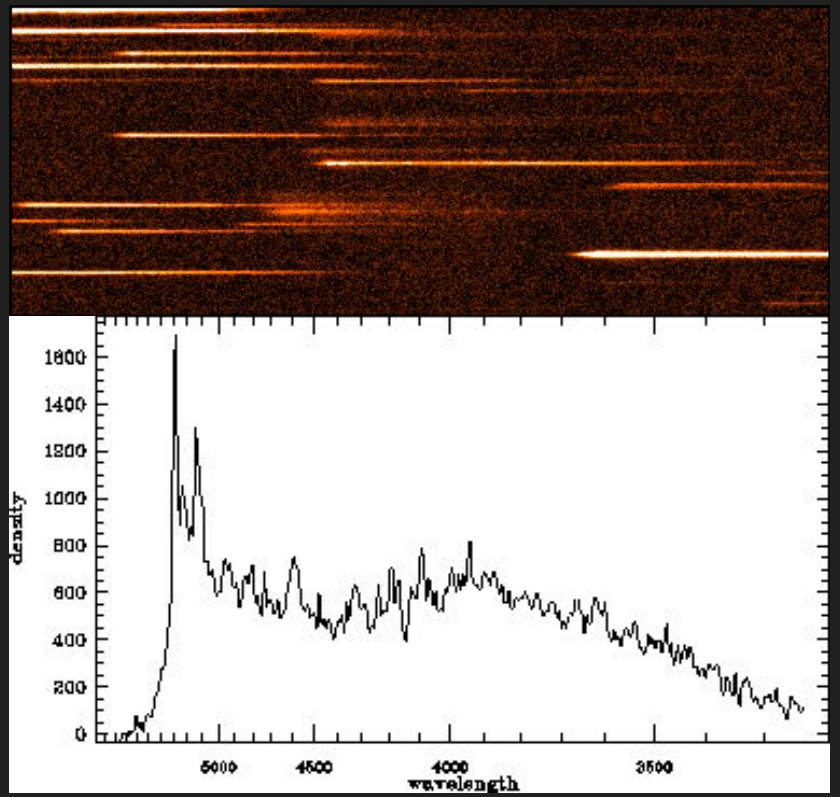
https://www.hs.uni-hamburg.de/DE/For/Exg/Sur/hes/index.html

9000sq.deg.

Prism objective survey

Low-spectral resolution

Schmidt telescope at La Silla

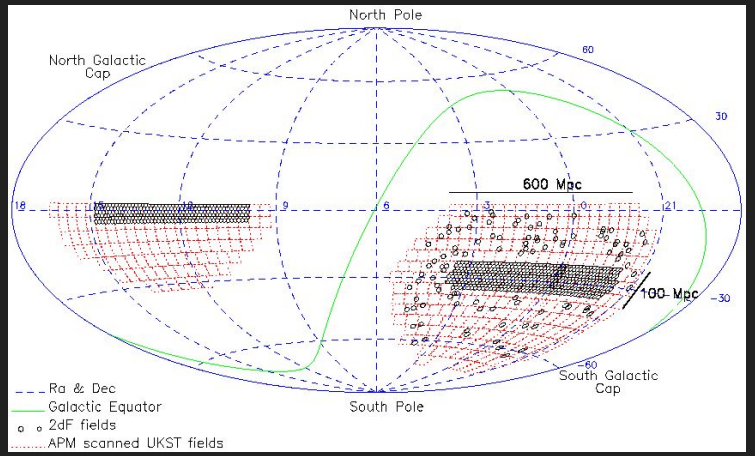


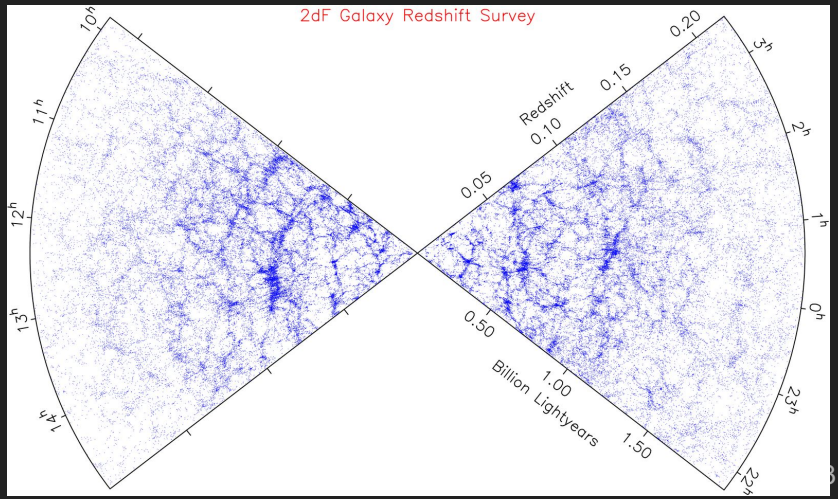
https://www.hs.uni-hamburg.de/EN/For/Exg/Sur/hes/qso_surveys.html

2dF Galaxy Redshift Survey

Used the 2degrees Field of view multi-object spectrograph (400 spectra per observation) on the 4m AAT telescope.

http://www.2dfgrs.net/





Sloan Digital Sky Survey

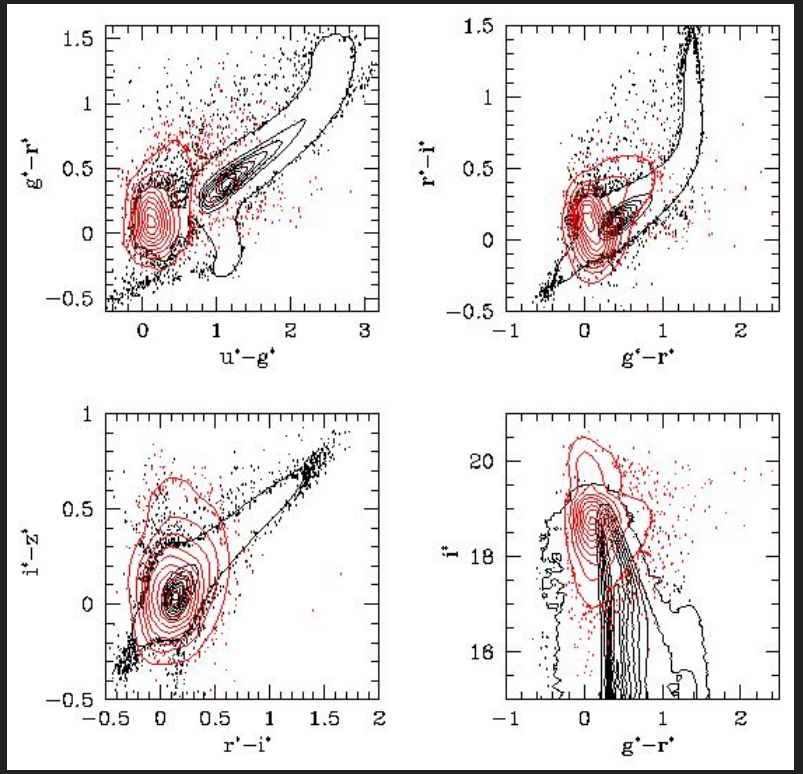
The Mother of All Modern Surveys

Originated as a quasar survey (post-2dF)

In its first incarnation:

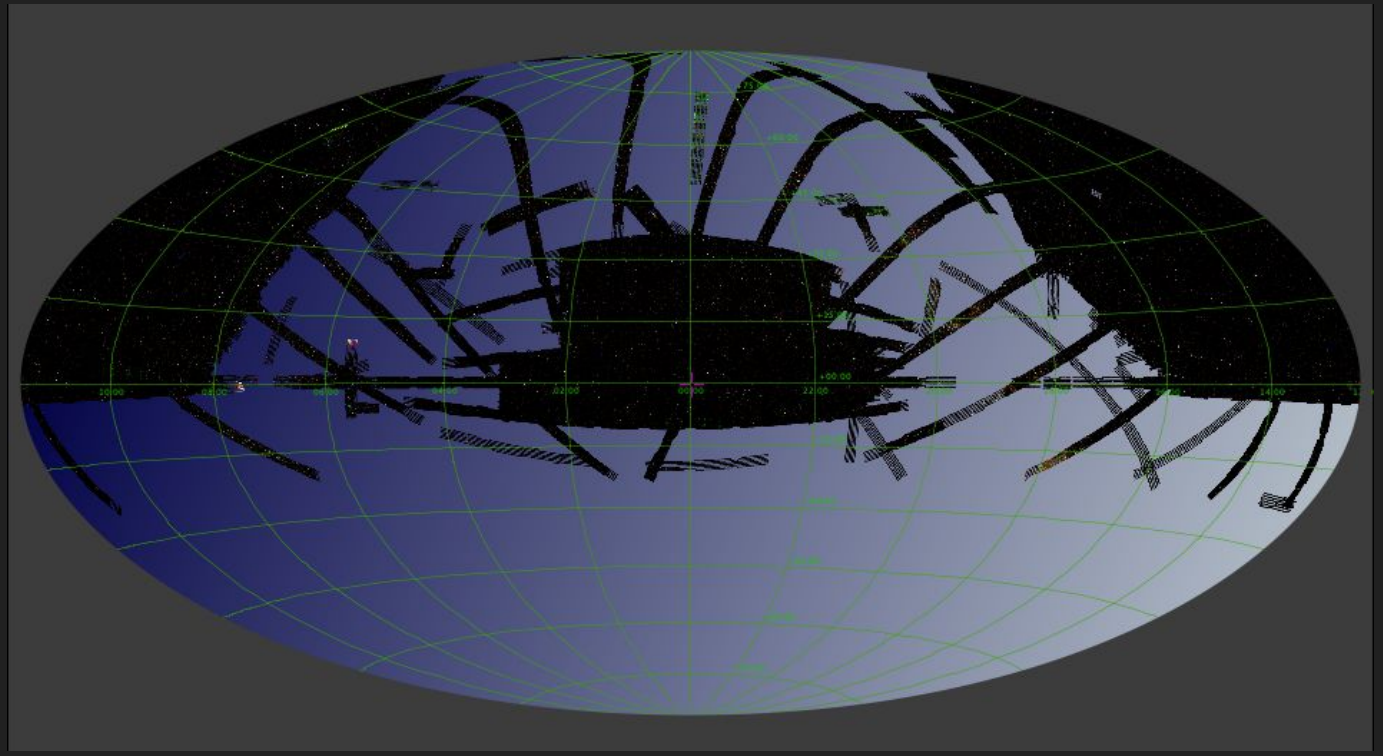
- 10,000 sq.deg. photometry (ugriz)
- 8,000 sq.seg. spectroscopy (R~2,000)

https://www.sdss.org/



In black the stellar locus and in red the quasar locus from SDSS EDR

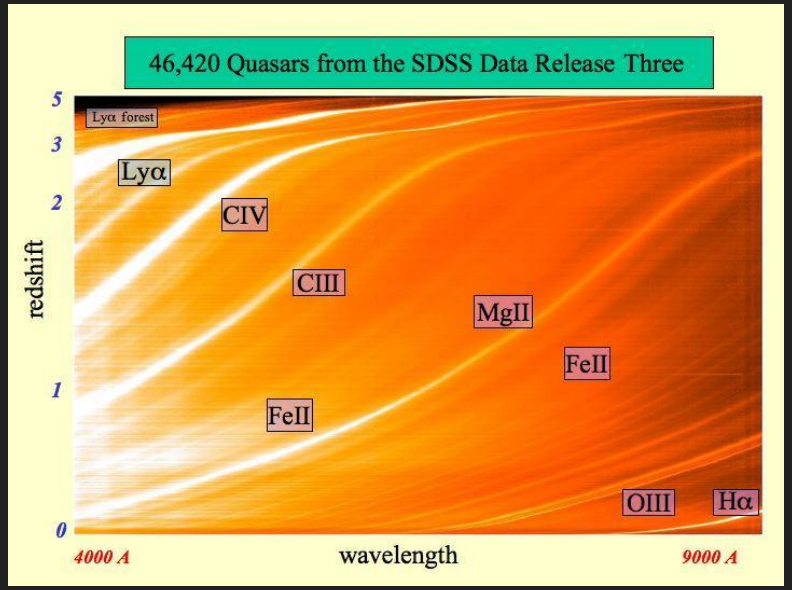
SDSS

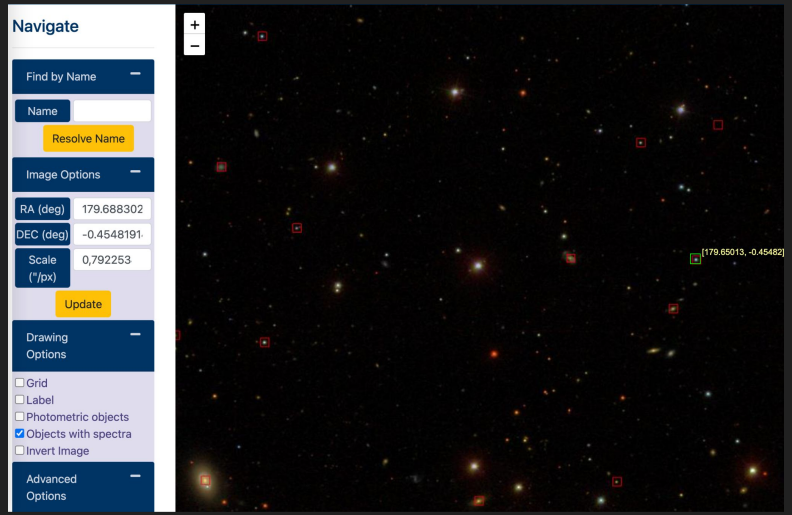


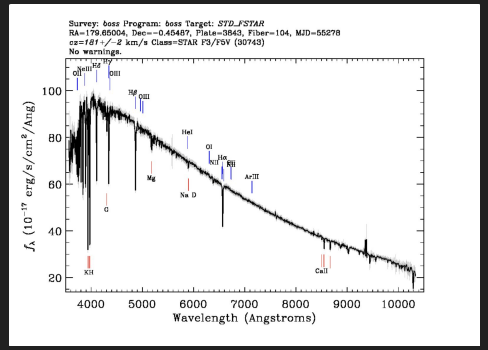
Not only quasars

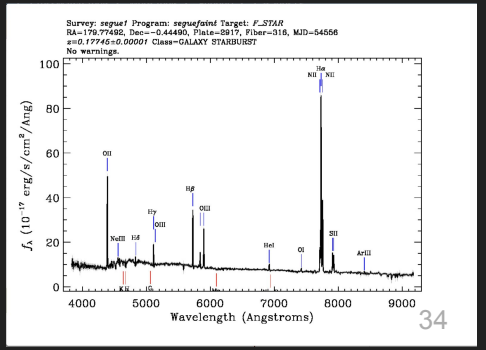
Data easy to access and use

https://skyserver.sdss.org/dr18/









Sloan Digital Sky Survey

https://www.sdss.org/surveys/

- SDSS I/II (2000-2008)
  - Legacy / Supernova (Stripe 82) / Segue
- SDSS III (2008-2014)
  - APOGEE / BOSS / MARVELS / SEGUE2
- SDSS IV (2014-2020)
  - APOGEE2 / eBOSS / MANGA /
- SDSS V (2020-2025)
  - https://www.sdss.org/future/

New incarnations of SDSS have required the development of new instruments (e.g. the APOGEE or BOSS spectrographs) with respect to the original survey.

LAMOST

Large Sky Area Multi Object Fiber Spectroscopic Telescope

“The Chinese SDSS”

Mostly focused on stars.

http://www.lamost.org/public/?locale=en

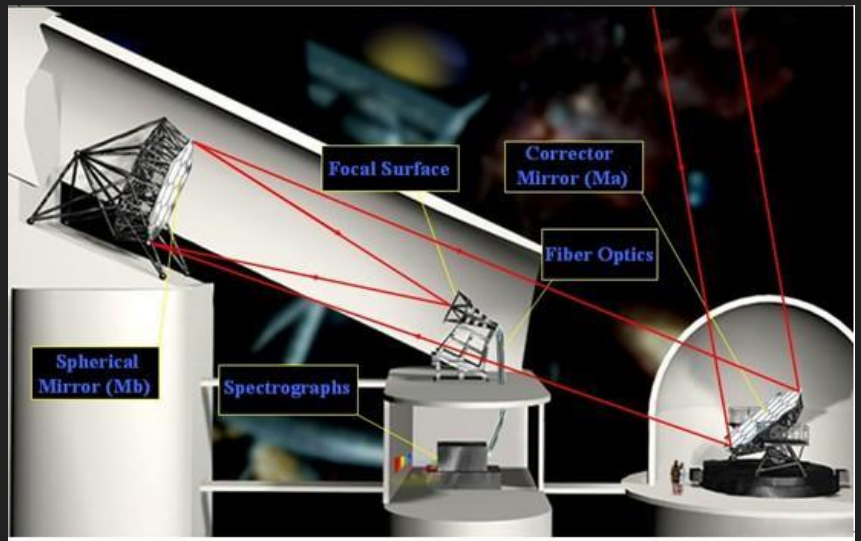
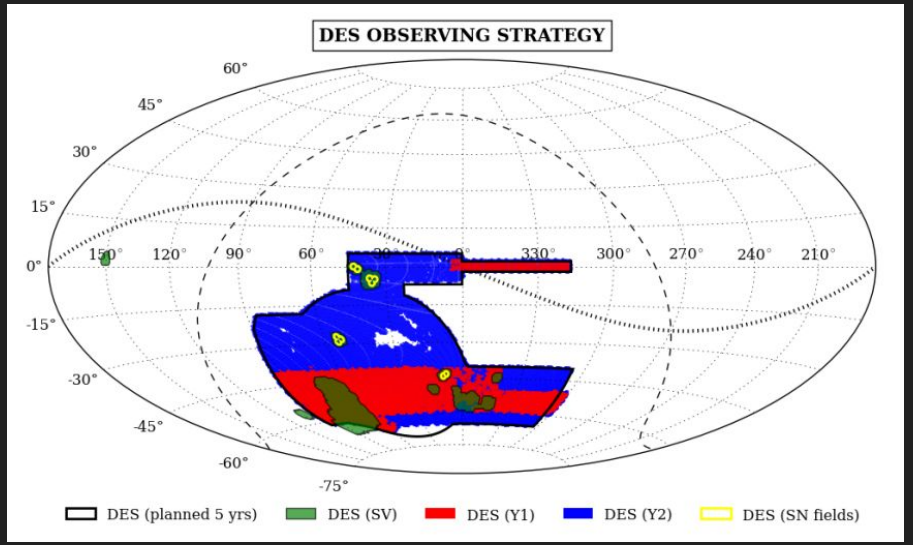


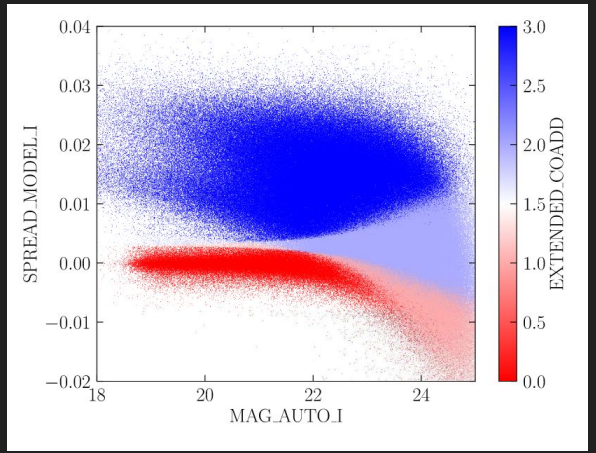
Figure 2 LAMOST overview

Dark Energy Survey

It has been a photometric cosmological survey carried out with the DECam at the 4m Blanco telescope at CTIO.

https://www.darkenergysurvey.org/

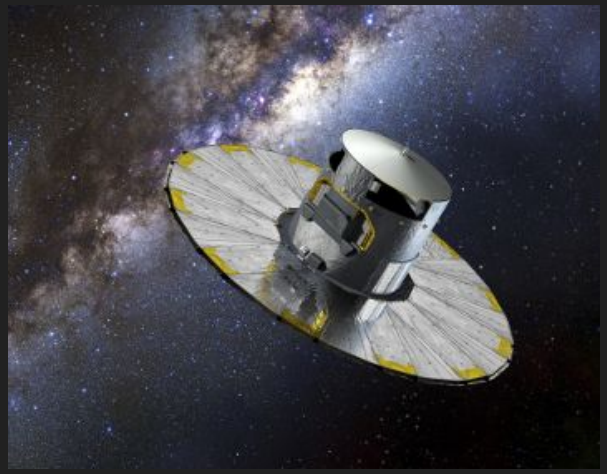




Abbott et al. (2018)

Current Surveys

Gaia



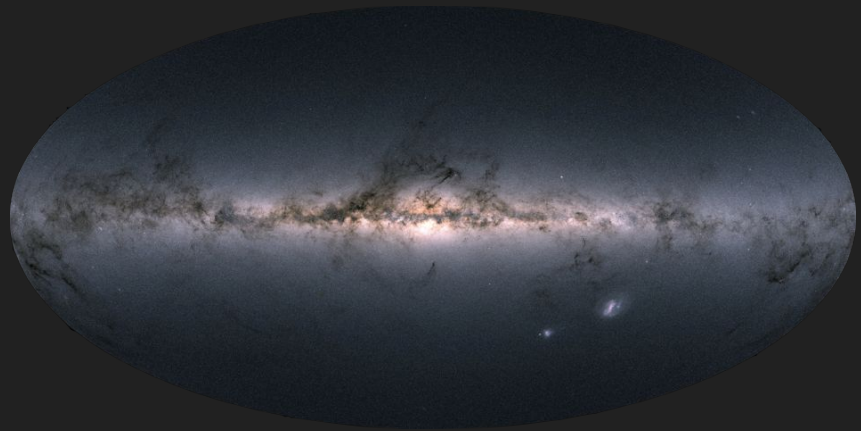
Since Gaia DR2 (25th Apr 2018), it has been producing papers at the same rate as the HST!

It is (mostly) an astrometric survey

DR2 has:

- 1.8 billion objects (position and brightness)
- 1.3 billion parallaxes

https://gea.esac.esa.int/archive/



This is a plot of the catalog, it is not an image!

Gaia Data Release 3

13 June 2022

https://www.cosmos.esa.int/web/gaia/dr3

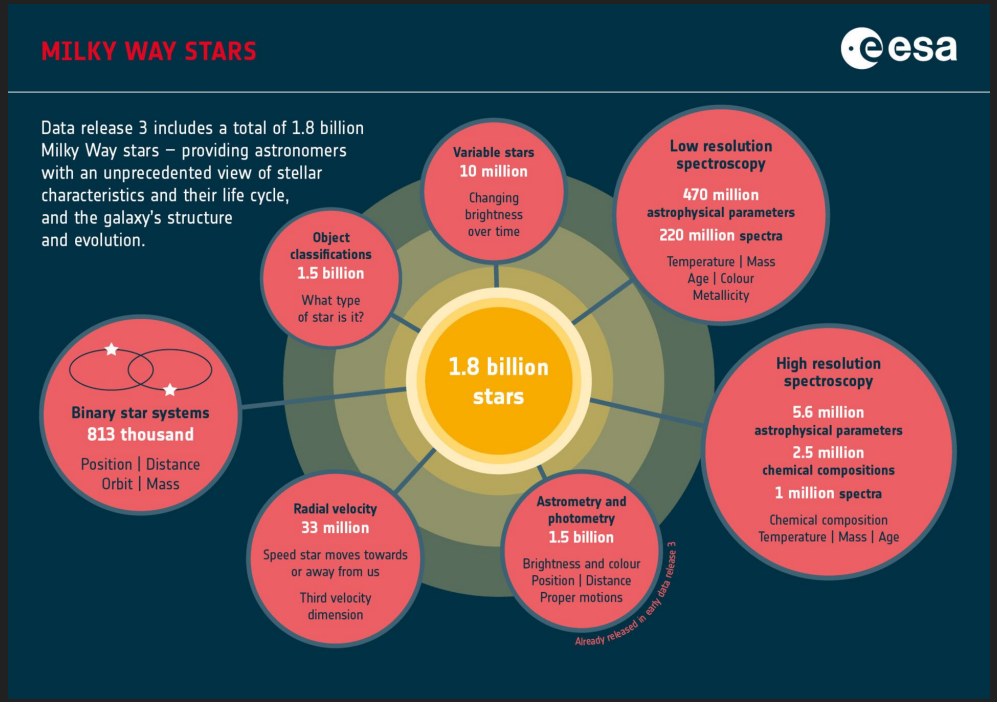
Content

Positions, parallaxes, proper motions

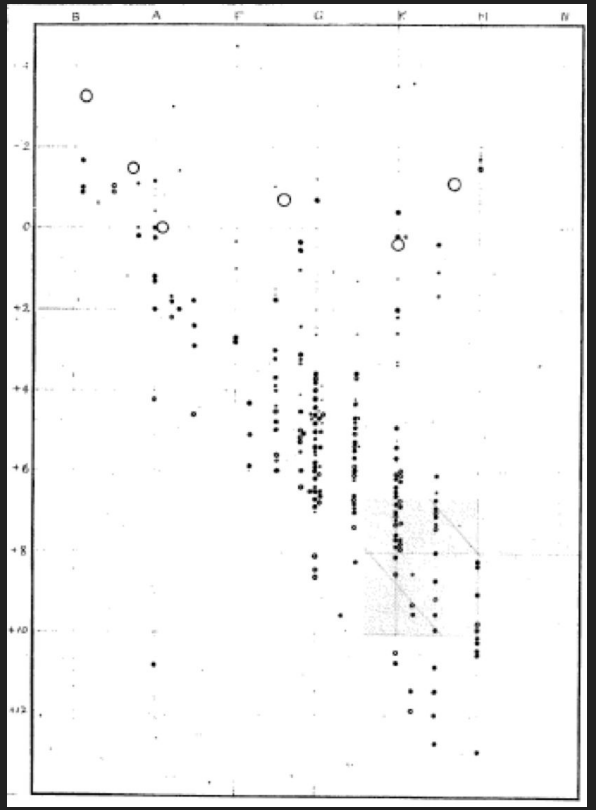
Spectra

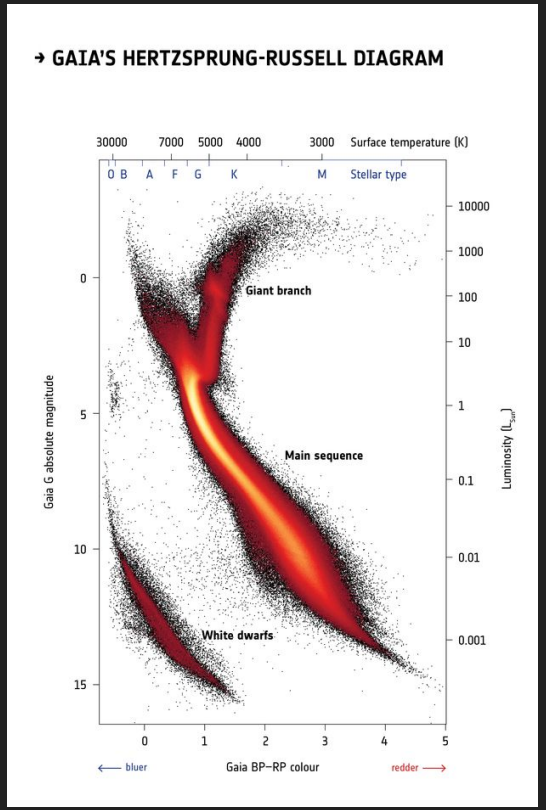
Atmospheric parameters

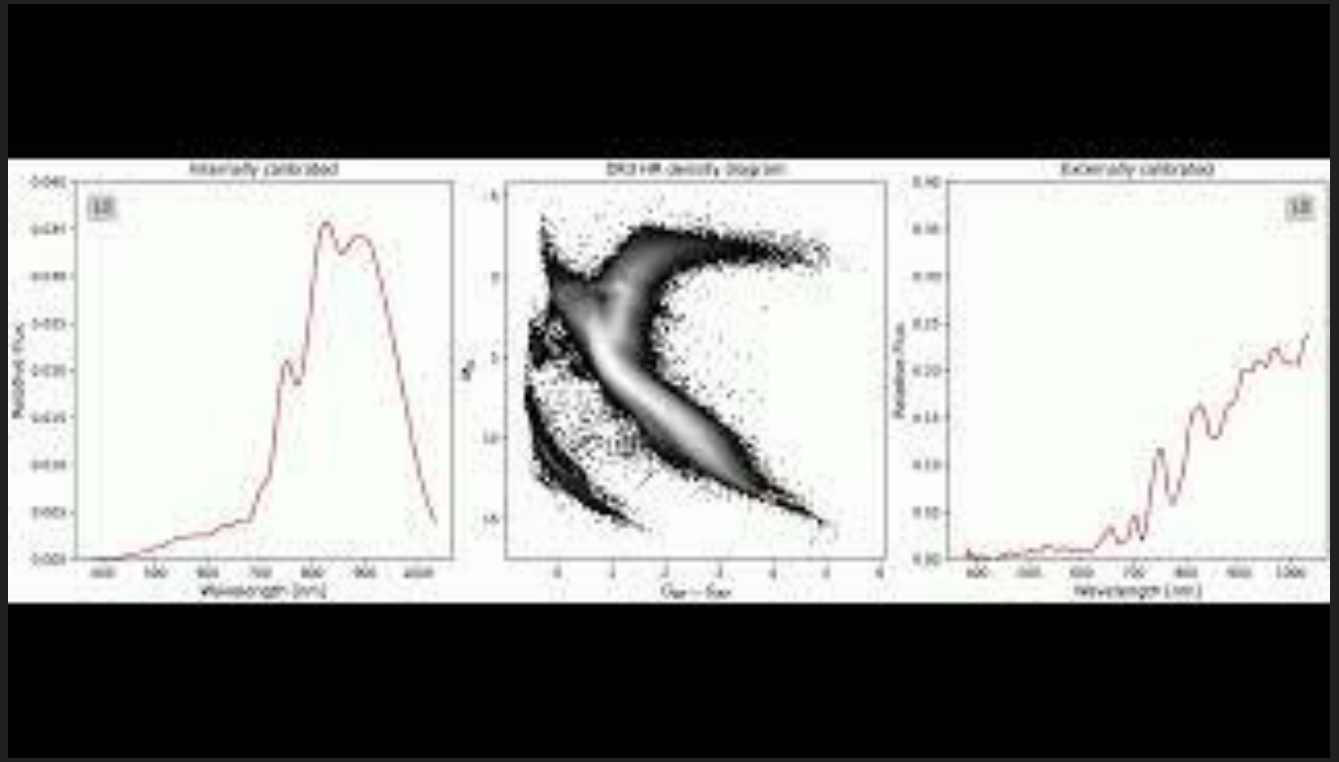
Light curves

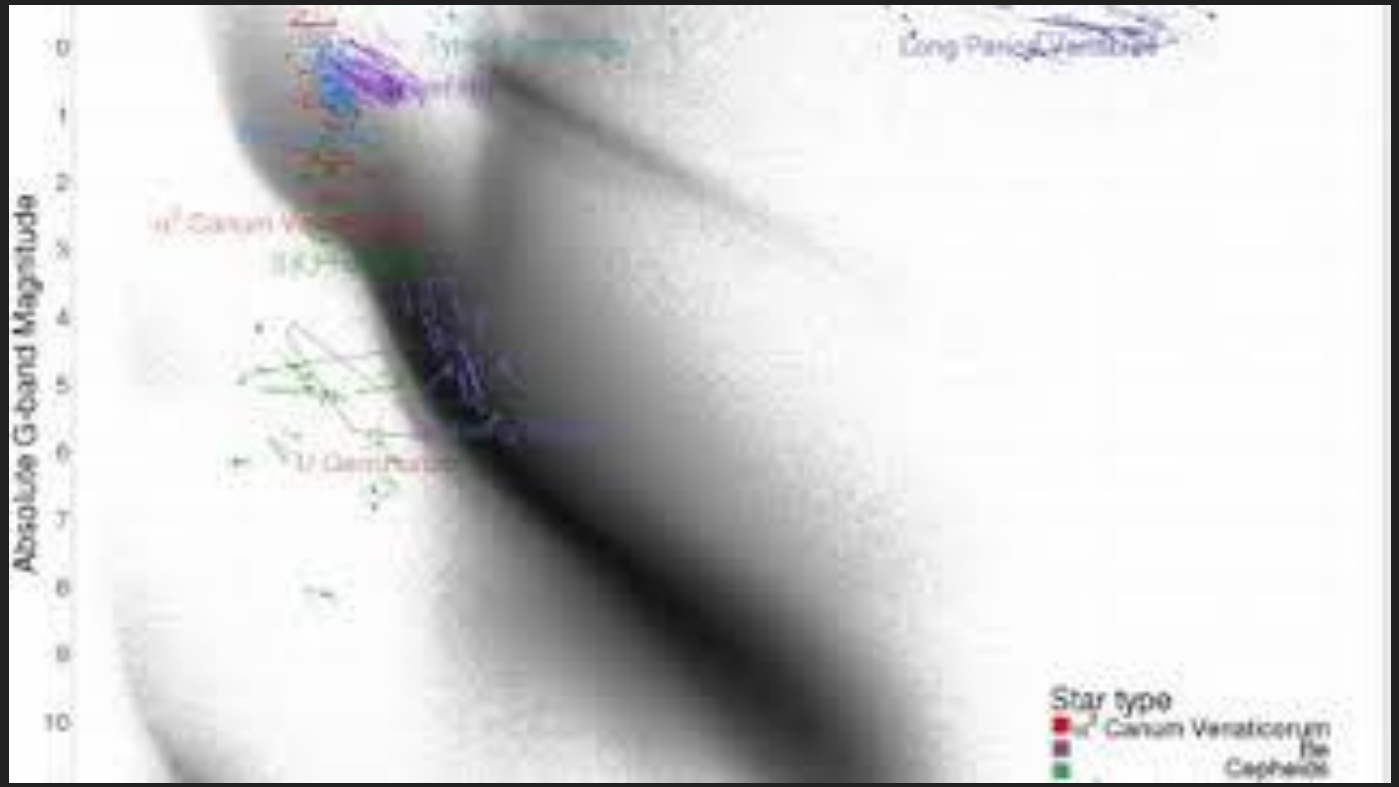


The HR diagram in 1 century






Internally calibrated
Relative Flux
Wavelength [nm]
HR Density Diagram
Externally calibrated
Relative Flux
Wavelength [nm]


Absolute G-band Magnitude
0
1
2
3
4
5
6
7
8
9
10
Star type
Cepheids

Gaia

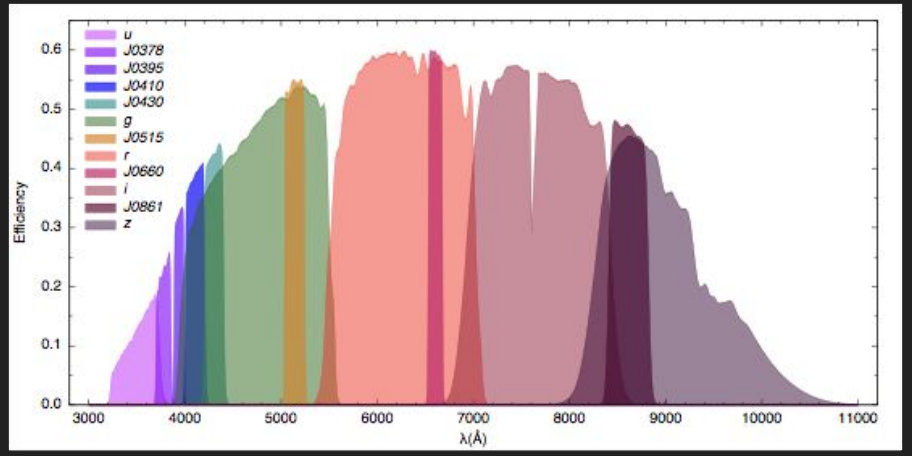
See the Gaia archive https://gea.esac.esa.int/archive/

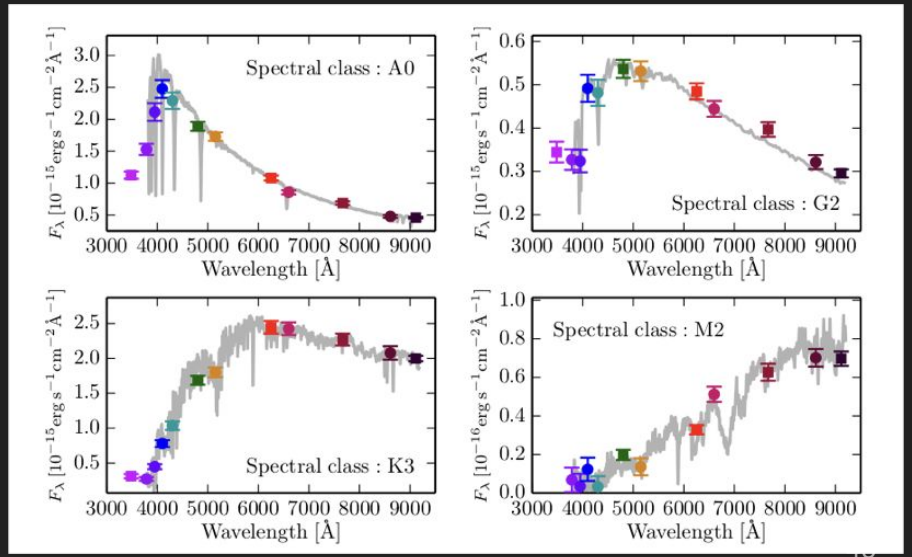
J-PLUS

The Javalambre Photometry of the Local Universe Survey is a photometric (12 filters) survey of the northern extragalactic sky (8,500 sq.deg.), carried out from the Observatorio Astrofísico de Javalambre.

Cenarro et al. (2019)

http://j-plus.es/



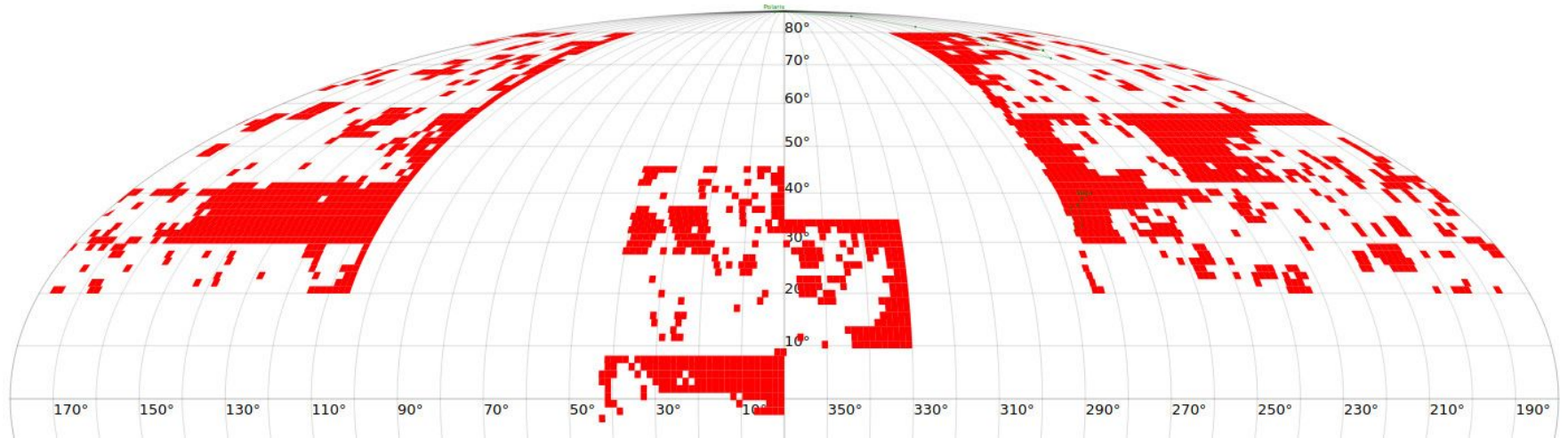


J-PLUS DR3

July 2022

About 3,000sq.deg.

47.4 M objects.



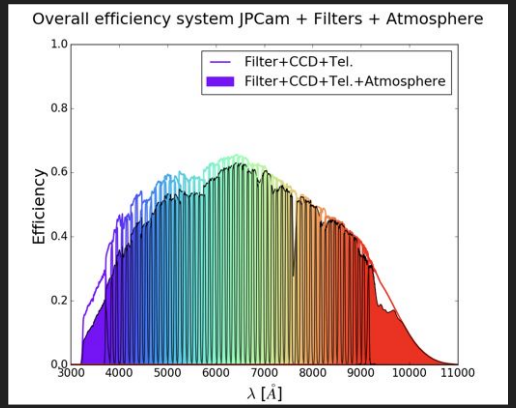
J-PAS

Javalambre Physics of the accelerating universe Astrophysical Survey

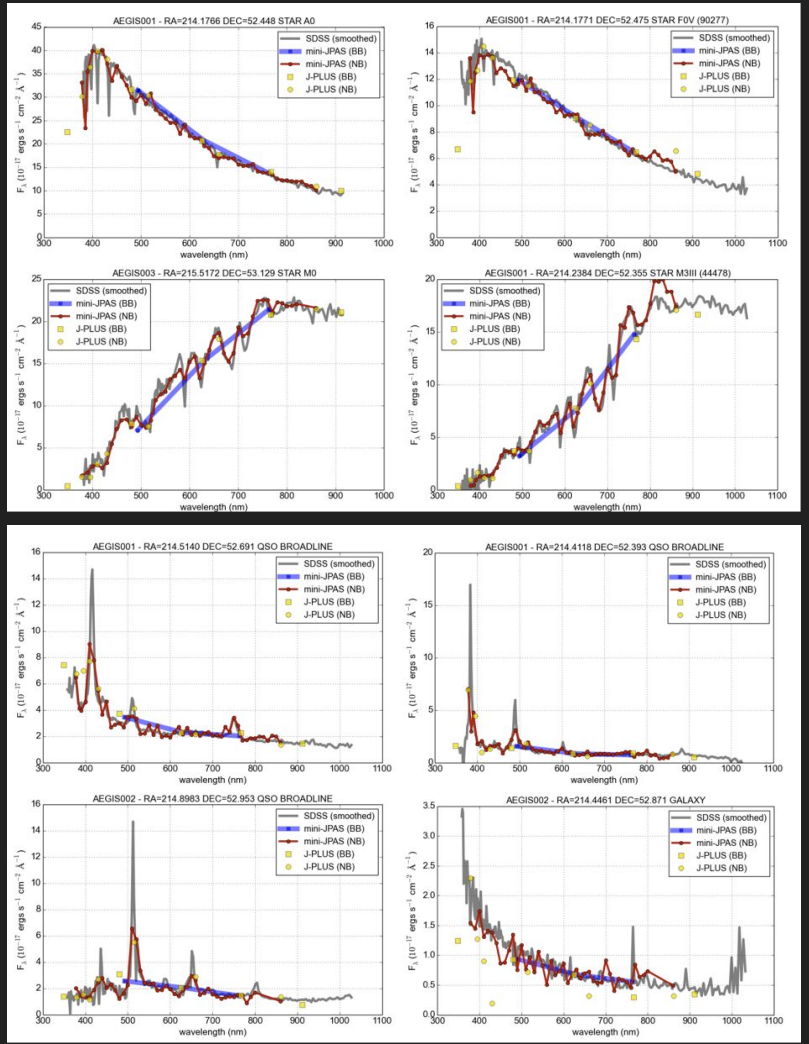
Cosmological photometric survey (8,500sq.deg.; same FoV as J-PLUS)

Benitez et al. (2014)

http://www.j-pas.org/



SEDs from the "mini-J-PAS" observations



miniJPAS & J-NEP

miniJPAS

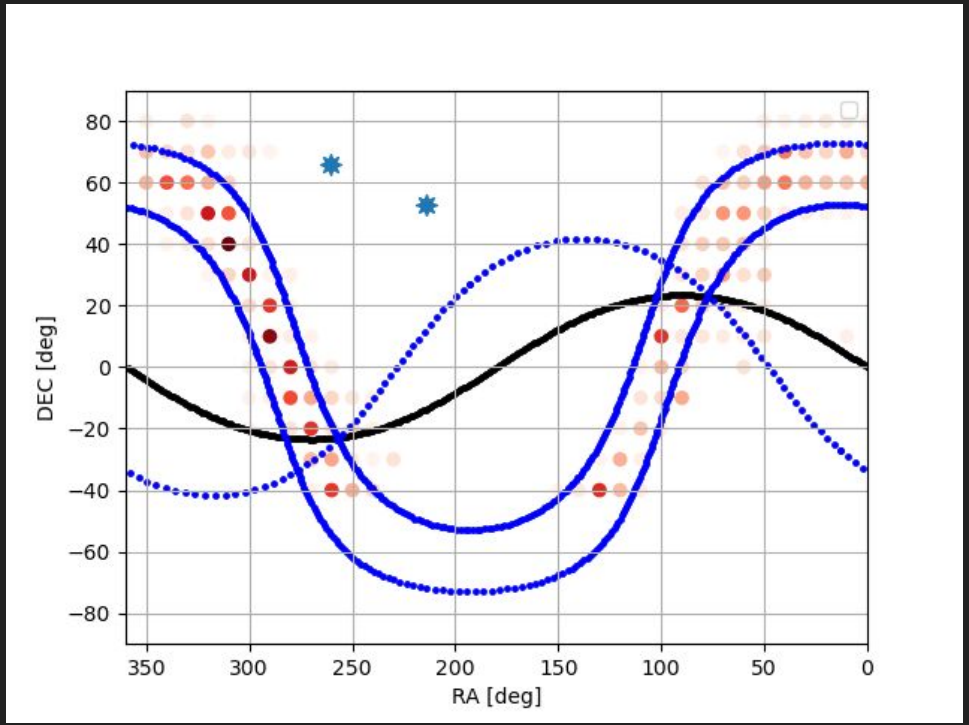
1 sq.deg.

J-NEP

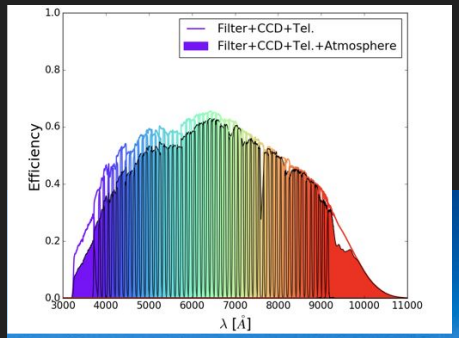
¼ sq.deg.

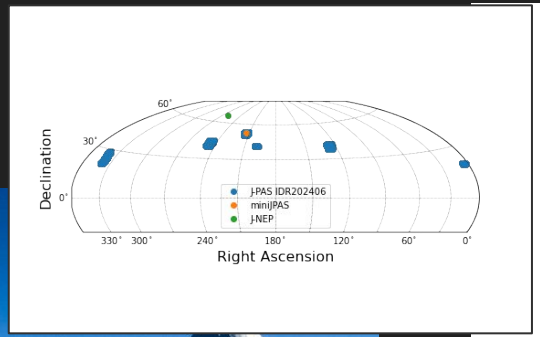
J-PAS-like observations!

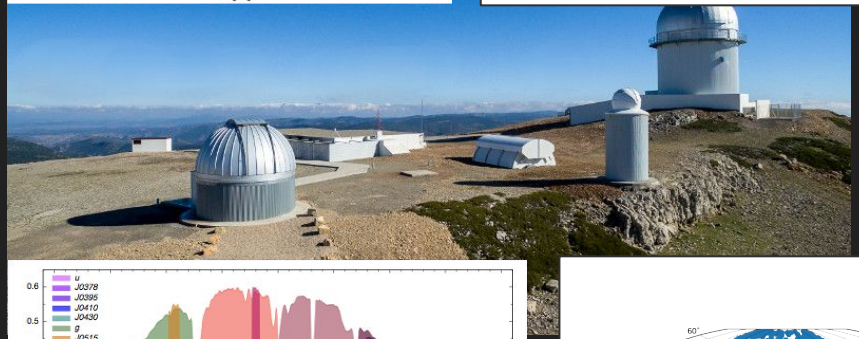
https://archive.cefca.es/catalogues

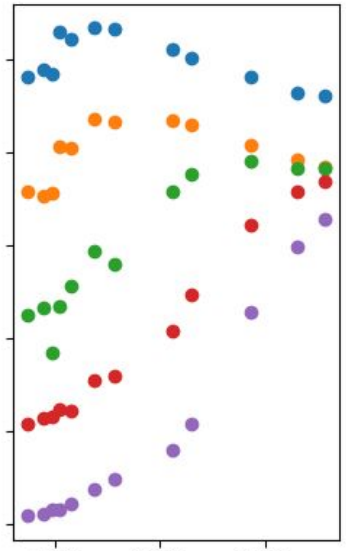


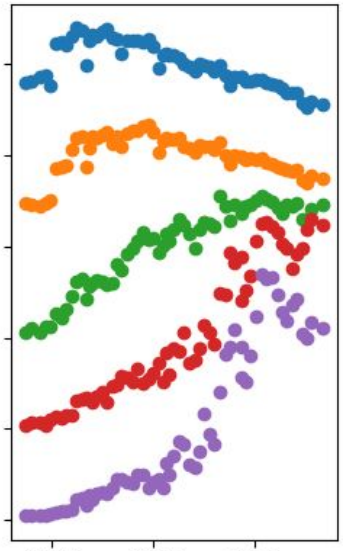
OAJ: J-PLUS and J-PAS

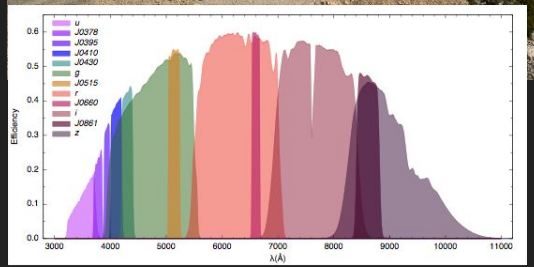


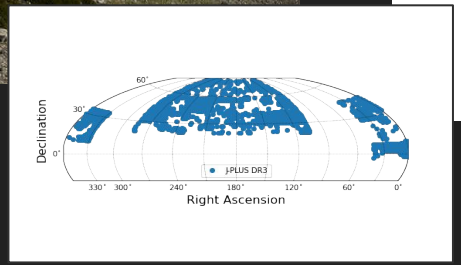












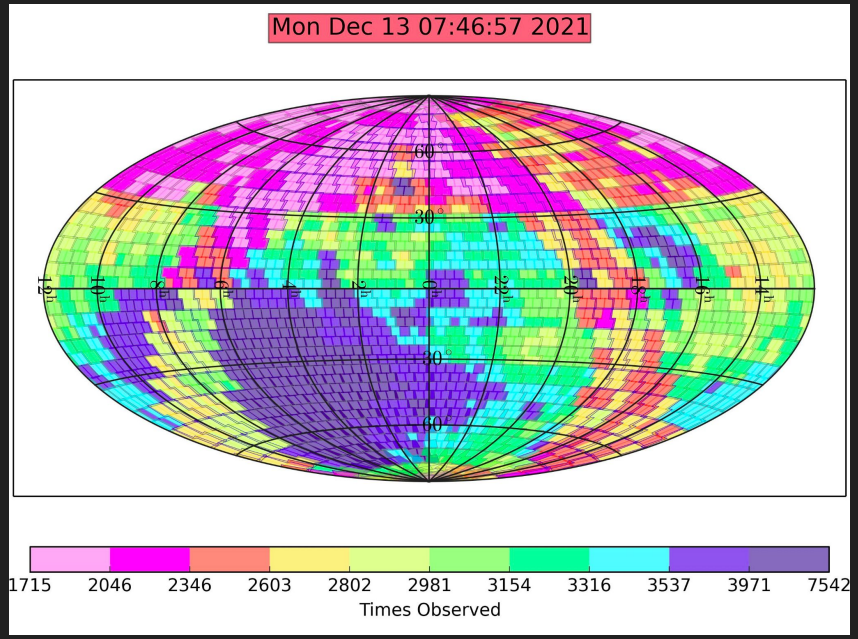
https://archive.cefca.es

ASAS-SN

All Sky Automated Survey for SuperNovae

ASAS-SN -> 24 x 14cm telescopes around the world

https://www.astronomy.ohio-state.edu/asassn/



Why J-VAR?

Neither J-PAS nor J-PLUS have time-domain capability.

T80/JAST vs. Mt Wilson

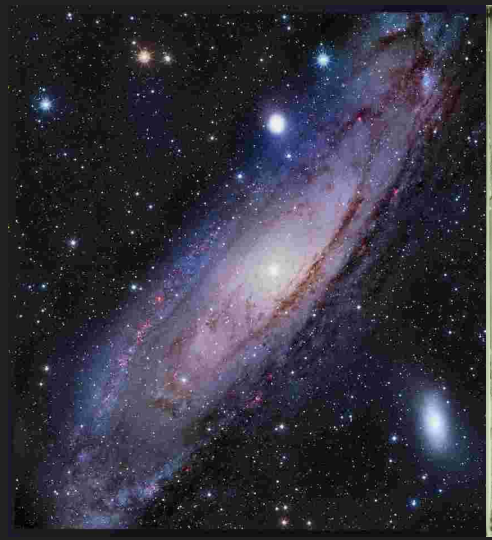
<u>Astrophysics in real time</u>

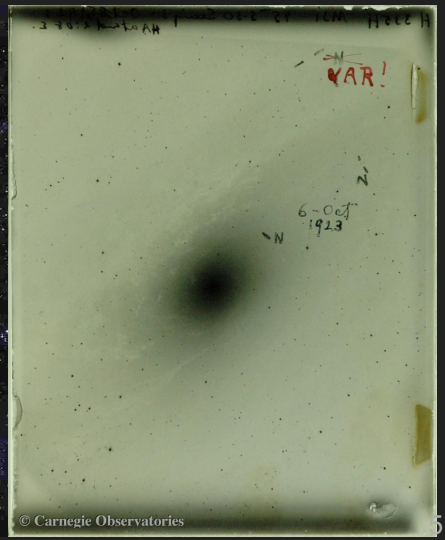
Using the strengths of JAST:

Wide field of view

Good image quality

Narrow band filters



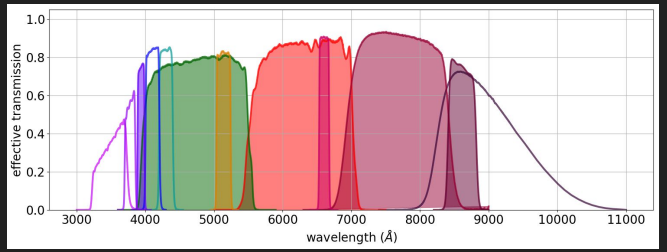


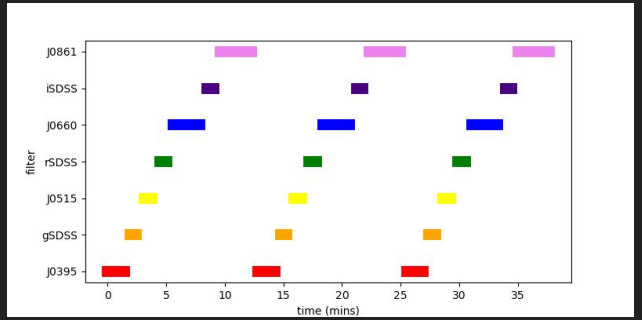
The observing strategy

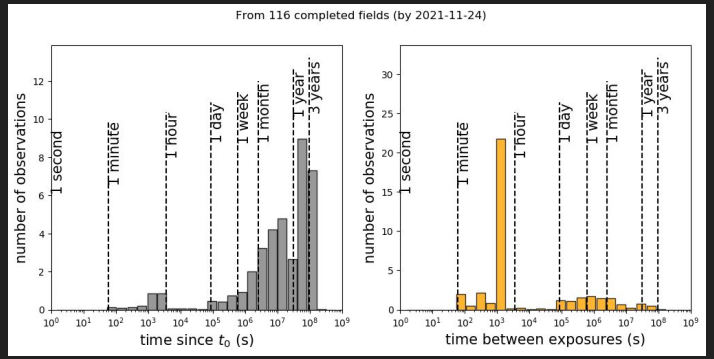
11 epochs (simulation from HVR)

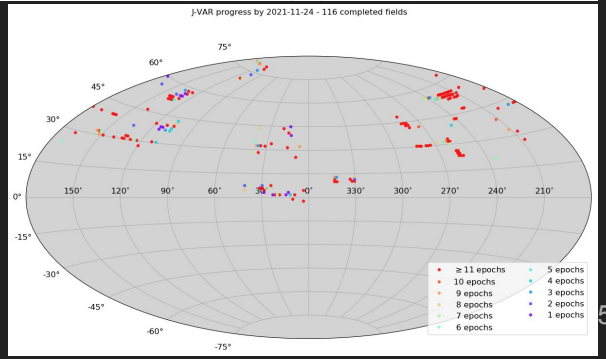
Each epoch made of 3 repetitions of observations in 7 filters

Fields in the observed footprint of J-PLUS -> out of the plane of the Milky Way.









Optical Transients

Main detection system via differential imaging.

80 fields analysed

10 SN candidates

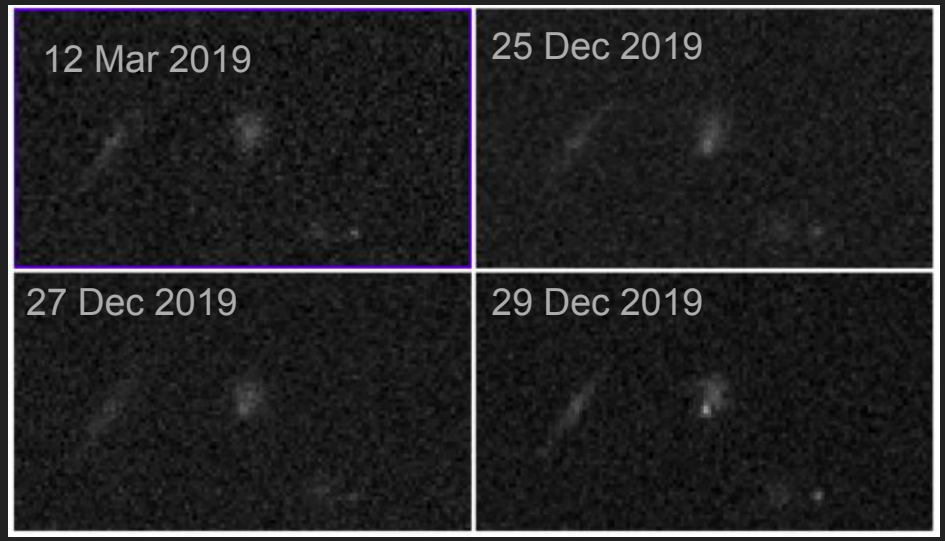
6 SN already detected by other surveys

204 variable stars

40 AGNs

211 variable stars candidates

‘ ...and JVAR20a

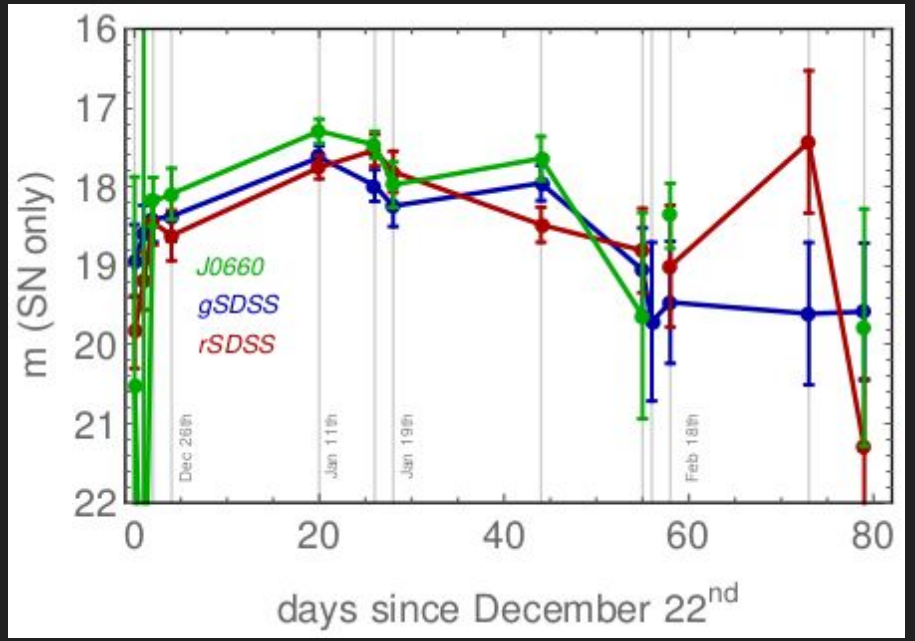


JVAR20a

Discovered by Javier Hernandez by visual inspection.

https://www.wis-tns.org/object/2020admb

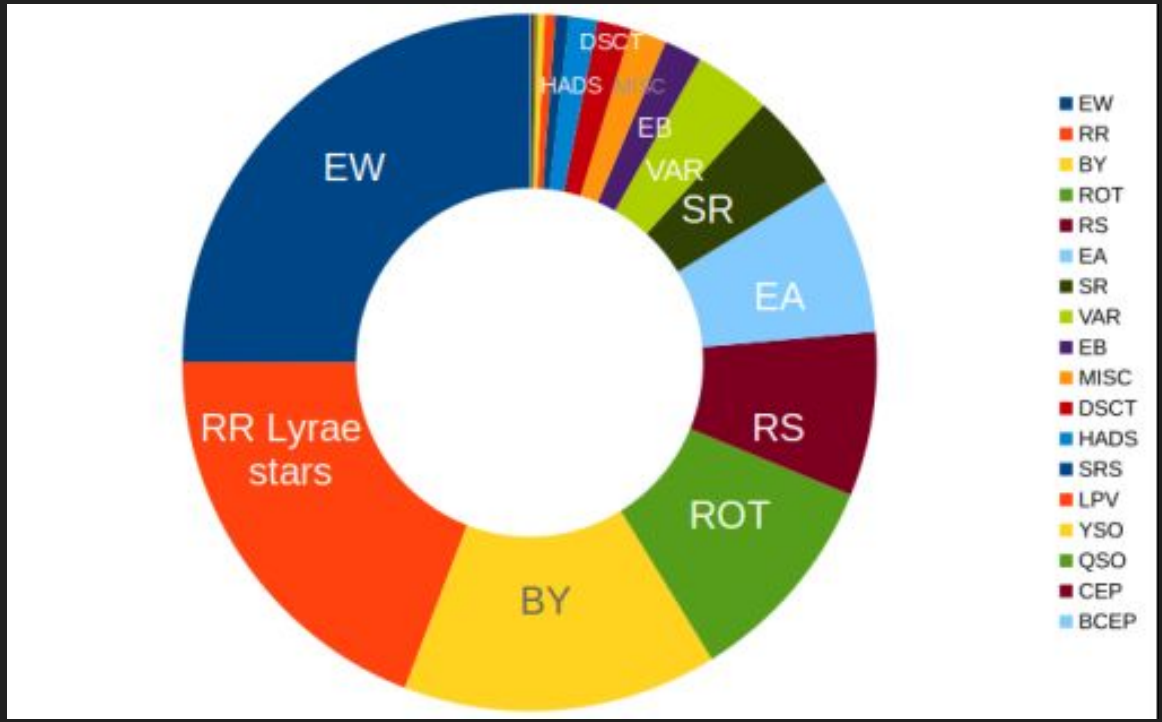
ZTF group confirmed it to be a SN Ia at z=0.04



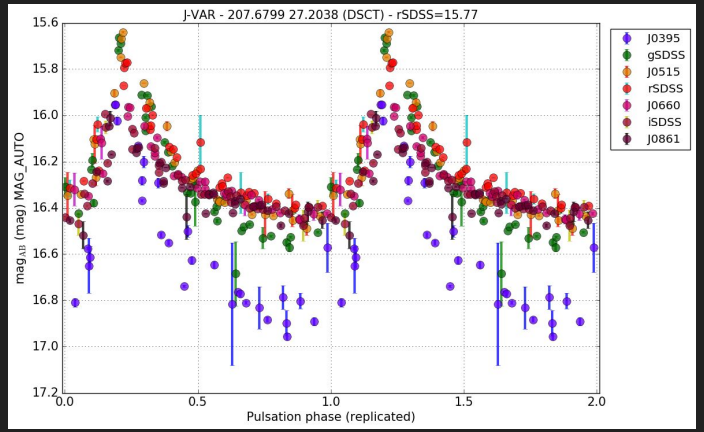
Variable Stars

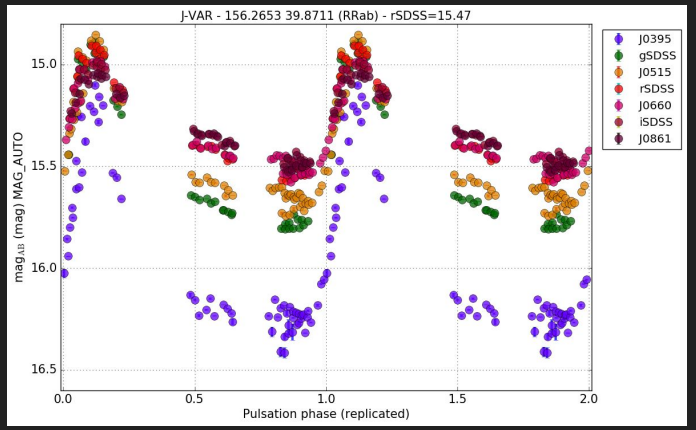
Cross-match our detections with the Variable Stars Index (AAVSO) and complemented with Gaia + PanSTARRS for RR Lyrae stars.

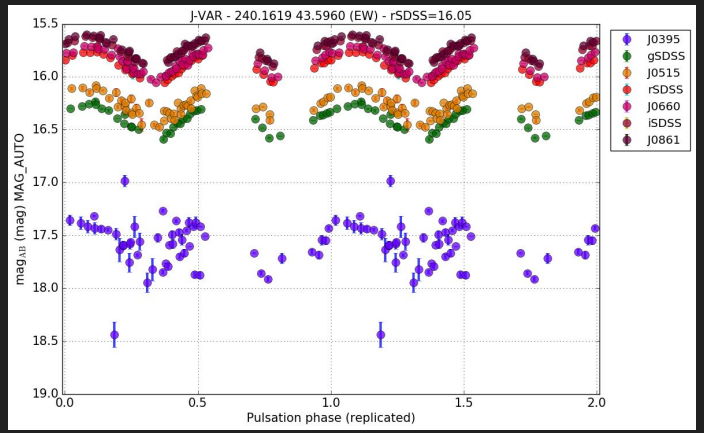
Large variety -> assess different astrophysical topics



Multiband photometry provides extraordinary physical information!







The future

LSST

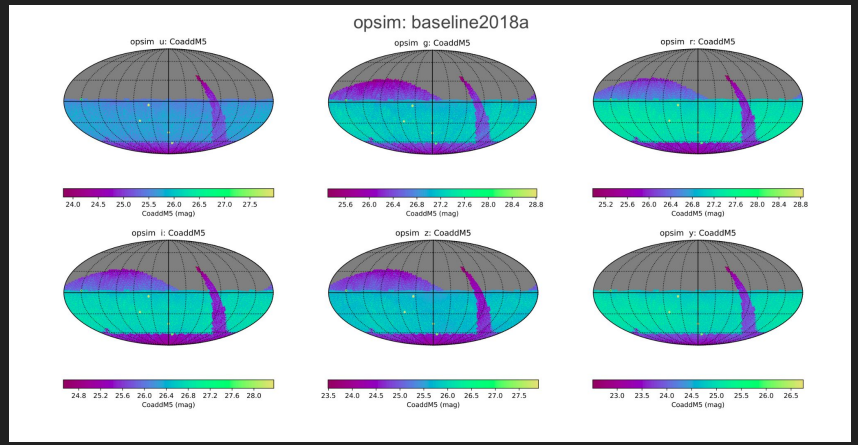
8m telescope with 9.6sq.deg. field of view

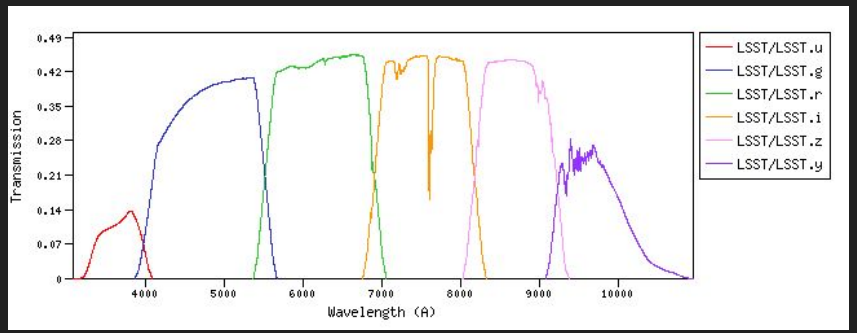
6 filters

Seeing limited (typical expected seeing 0.6”)

Limiting magnitude (depends on filter):

- 23-24 in single exposure
- 25-27 in 10 years





Not only optical…

X-rays

UHURU

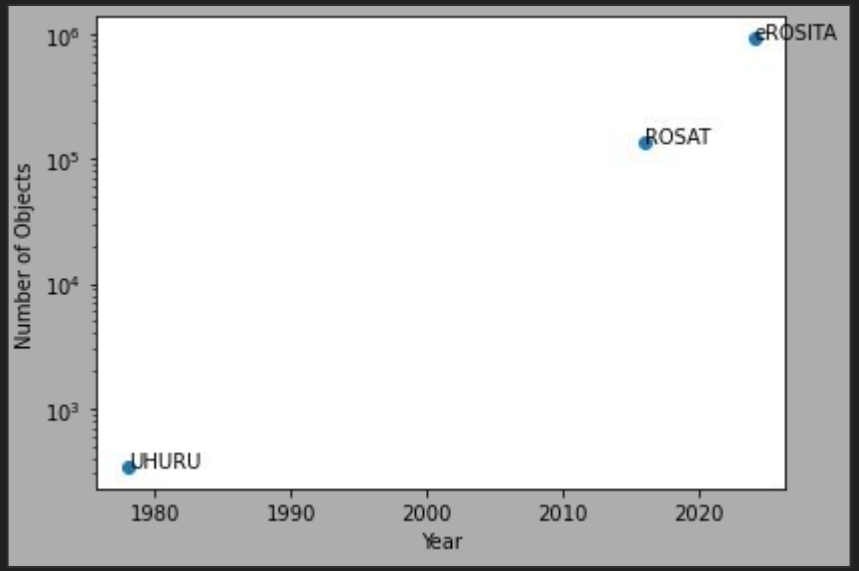
First Italian-US X-ray mission

ROSAT

German led X-ray mission

eROSITA https://www.mpe.mpg.de/eROSITA

German-Russian X-ray mission

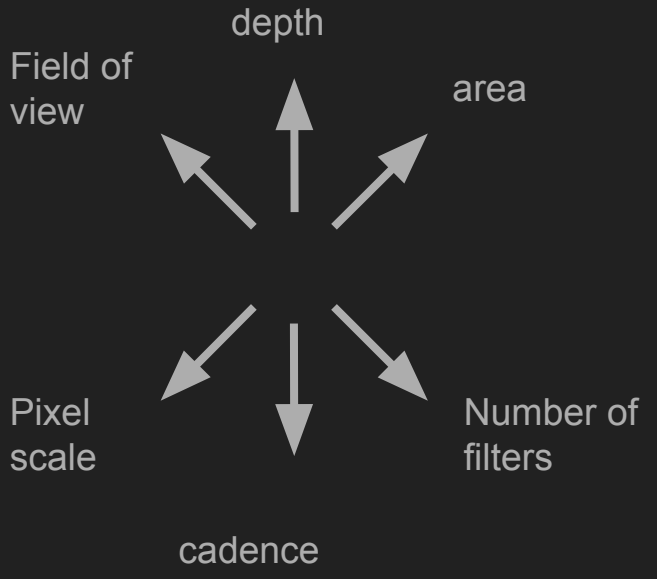


Building your own survey

Survey Parameters

When you design a survey you have to play in a very complex space of parameters.

Given that exposure time, depending on the brightness of your source and the signal-to-noise you want to achieve, you will pick your telescope/instrument.



A few steps

- Have one (or more) good science case(s)
- Find (or build) the telescope/instrument that suit your needs
  - A lot of intruments are built to make a survey and then become common use instruments
- Estimate how much time your survey is going to last
  - How many hours are good for your project at that given observatory?
  - Is your survey going to finish in a reasonable time-frame? Will there be other projects which are going to do your science in less time?
- Get prepared
  - “Software” is not “soft”
- Observe
- Publish
- Optional: book your flight to Stockholm to get the Nobel Prize

A note of wisdom

The real success of a survey is in the amount of people who were not involved in the definition and execution of the project but then use your data for excellent science which you did not think of.

Summary

Summary

- Surveys are key for our astrophysical knowledge
- Technological advances help shaping new surveys
- Surveys can be done in different wavelengths
- A clear science goal is key for the success of a survey
- Nowadays, surveys involve tens (if not hundreds) of people!

What is your favourite survey?