Big data in astronomical observations

William O'Mullane

Data management
LSST
Tucson, AZ USA

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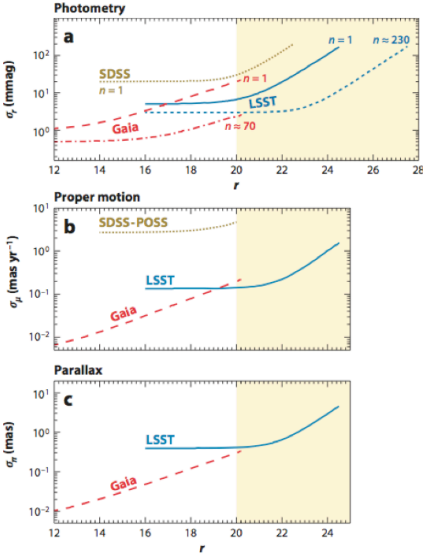
ISSI
Bern, Switzerland

A little about myself

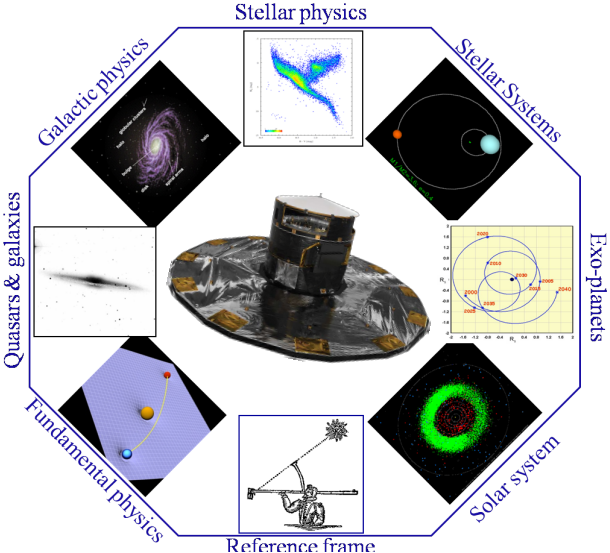
- 1985ish started with BASIC on a Commodore
- 1993 MSc BSc Computer Science, University College Cork, Ireland
- 1993 - 1997 Spacecraft Control Systems (C++), ESA ESOC Germany
- 1997 - 2001 Hipparcos, Integral, Planck, Gaia, Bepi-Sax (C,Java,Oracle, HTM, HEALPix), ESA ESTEC Netherlands
- 2001-2003 Commercial programming - some Astronomy (Java)
- 2003-2005 The Johns Hopkins, SDSS and National Virtual Observatory (C,C#,Java,Sqlserver)
- 2005-2014 Gaia Astrometric Solution and Science Operations (Java, Oracle, Intersystems Cache)
- 2012 PhD in Physics on Implementing the Gaia Astrometric Solution, Barcelona University
- 2014-2017 ESA Division head - all Science Ground Segments in Development
- 2017- LSST Data Management Project Manager (Python,C++), Deputy Project Manager for Software (control systems)

Gaia and LSST continuum



- Gaia: excellent astrometry (and photometry), but only to r > 20
- LSST: photometry to r < 27.5 and time resolved measurements to r < 24.5
- Complementary: photometric, proper motion and trigonometric parallax errors are similar around r=20

Science topics - surveys

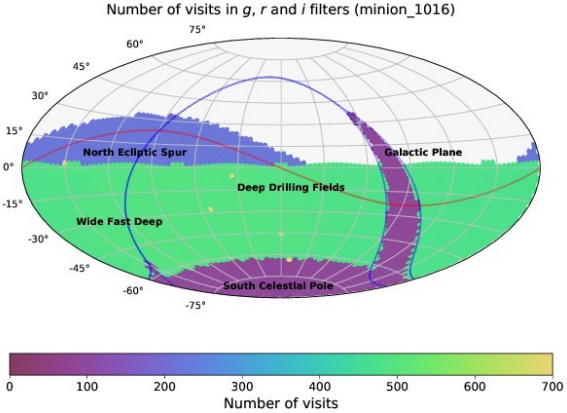


LSST:uniform sky survey

An optical/near-IR survey of half the sky in ugrizy bands to r 27.5 (36 nJy) based on 825 visits over a 10-year period: deep wide fast.

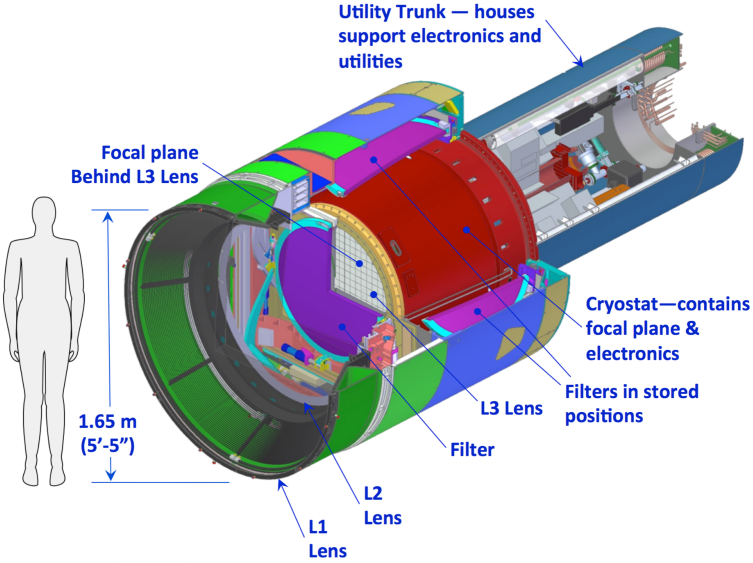
- 90% of time spent on uniform survey: every 3-4 nights, the whole observable sky scanned twice per night
- 100 PB of data: about a billion 16 Mpix images, enabling measurements for 40 billion objects!

see also http://www.lsst.org and Ivezic et al. (2008)-arXiv:0805.2366



10-year simulation of LSST survey: number of visits in u,g,r band (Aitoff projection of eq. coordinates)

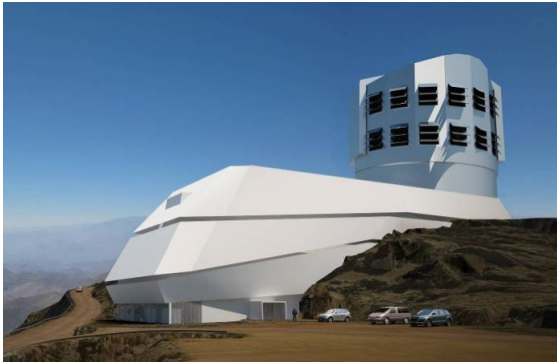
LSST Camera



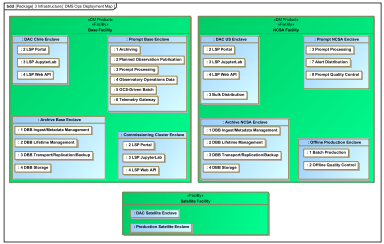
The largest astronomical camera:

- 2800 kg
- 3.2 Gpix

Site as imagined and in March 2019



DM build and deploy - already challenging



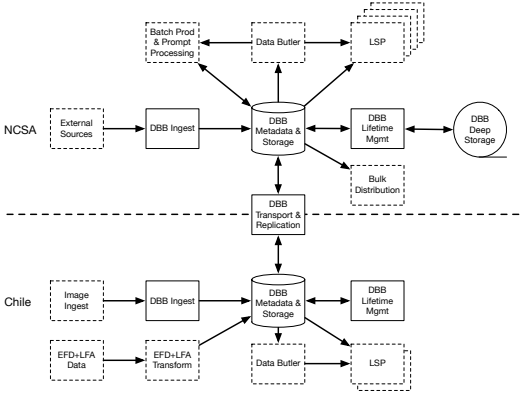
DM must build everything to get LSST products (see http://ls.st/dpdd) to the users.

- large data sets (20TB/night)
- complex analysis
- aiming for small systematics
- Science Alerts in under 2 minutes .. (aiming for 1 minute)

About $\frac{1}{2}$ million lines of code (C++/python) all open source on github

diagram K.T. Lim

Data Backbone

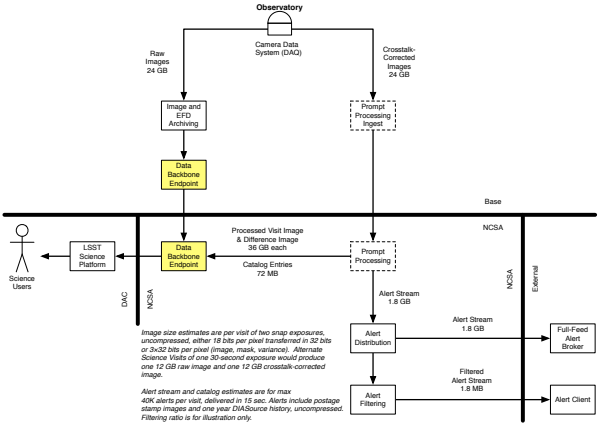


One small box on the previous slide was Data Backbone.
That hides several things

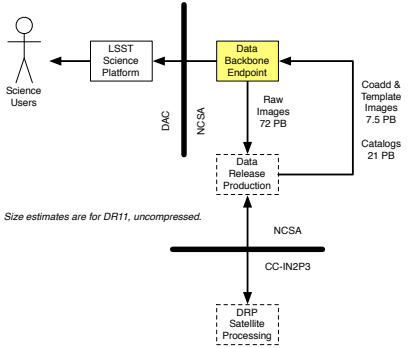
- Qserv - the LSST end user database
  - Custom Massive Parallel Processing (MPP)
  - allow queries on ≈ 20 Petabytes of tabular data
  - 4×10^{10} objects, 4×10^{13} sources (observations)
- All the networks : we now have fiber to the mountain and from La Serena to NCSA (two routes)

diagram K.T. Lim

Data flow



Lots to do every night ..
Plus annually there is a data release



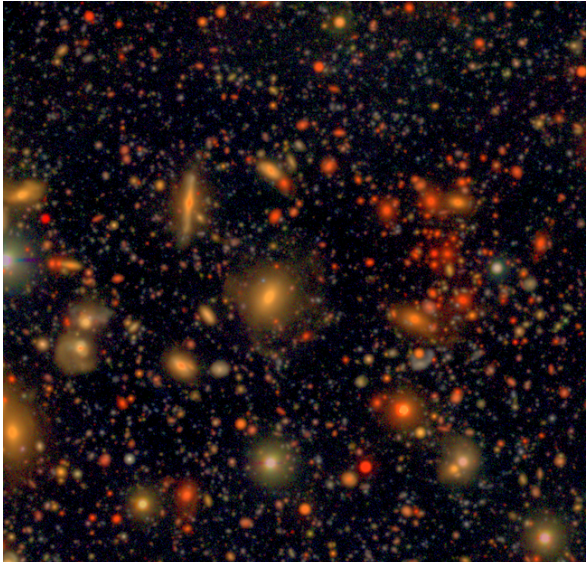
Images from K.T. Lim

SDSS image

Nice colors Lupton et al. (2004)
$\approx 3.5'$

Image Robert Lupton

Hyper Suprime Cam (HSC) on Subaru

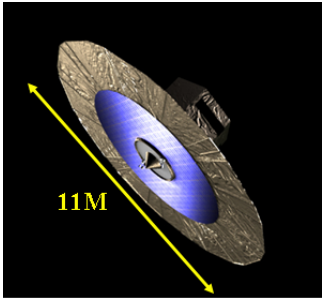


HSC image (COSMOS) from g,r(1.5 hrs) ,i(3 hrs) PSF matched co-add (≈ 27.5)
Challenges:

- Unknown statistical distributions, Truncated, censored and missing data, Unreliable quantities (e.g. unknown systematics and random errors)
- PSF - short exposure - atmosphere dominated ?
  - cosmic shear signal from weak lensing
- Photometry challenging - will Gaia help LSST ..
- Everything is blended!!

Satellite overview

- Mission:
  - ESA Corner Stone 6
    - ESA provided the hardware and launch
      Mass: 2120 kg (payload 743 kg)
      Power: 1631 W (payload 815 W)
  - Launched December 19th 2013
  - Stereoscopic Census of Galaxy over 5 years
    - Extended 2 yrs - request for five
  - μarcsec Astrometry G $<$ 20 (10^9 sources)
  - Radial Velocities G $<$ 16
  - Photometry millimag G $<$ 20



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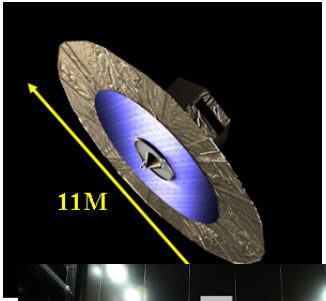
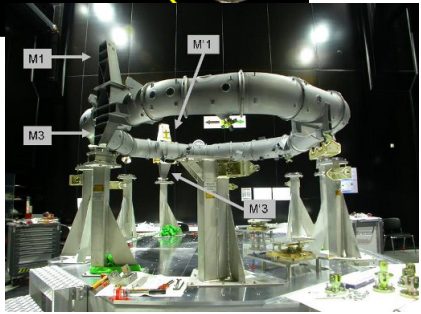
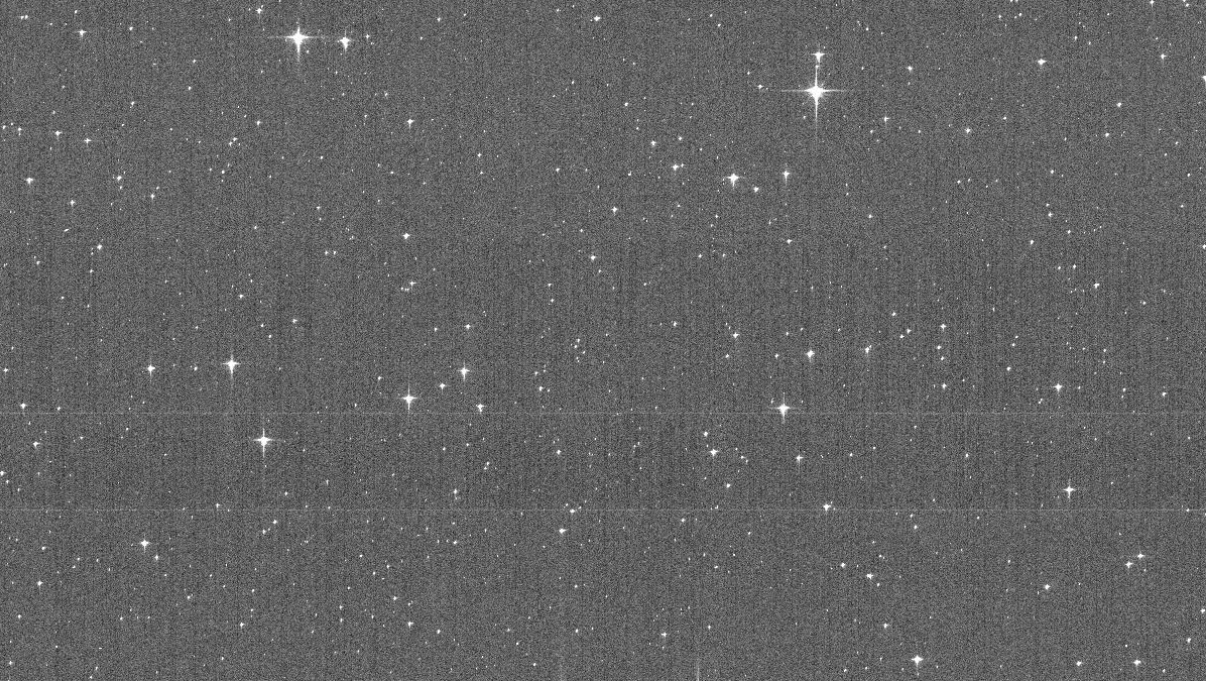
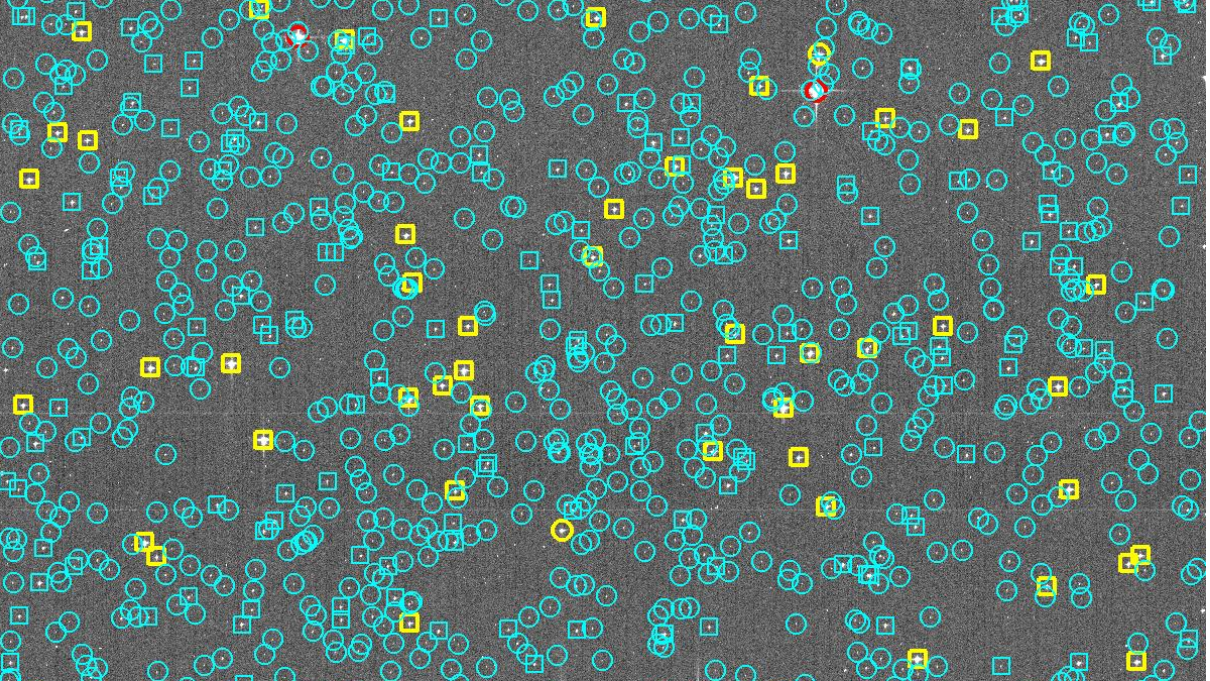
- Final catalogue $\approx$ 202?









Data processing - challenging complex data

- Astrometric centroid of the CCD image to be determined to an accuracy of 1% of the pixel size!
  - There will be 10^{12} images $\approx$ 100TB downlink need to handle $\approx$ 1PB
  - At 1 millisecond each that is $\approx$ 30 years
- Reconstructed attitude is required to order 10 μarcsec
  - Path of light through instrument needed to nanometre level
  - System must be extremely stable
  - Must consider relativistic light bending from solar system objects.
- Attitude and Geometric calibration can only by done using Gaia's own observational data. (AGIS) (O'Mullane et al., 2011; Lindegren et al., 2012)
  - this requires a significant portion of the data to be processed iteratively

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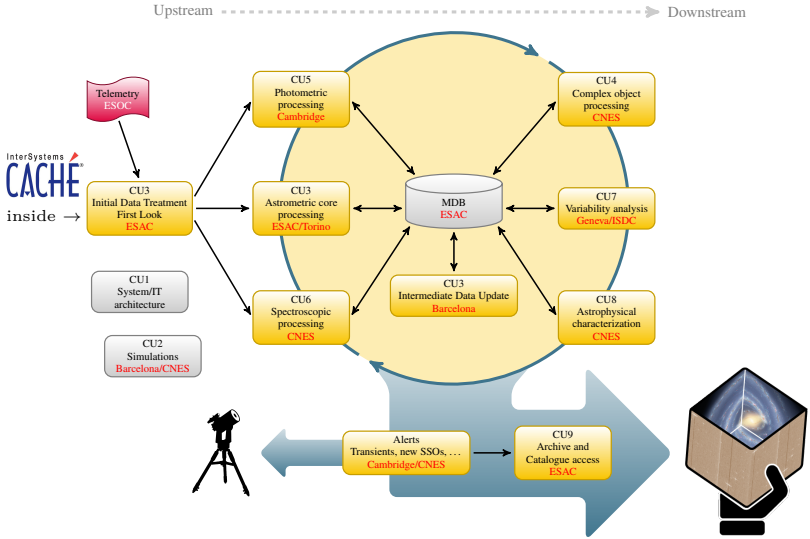
Simplified processing overview



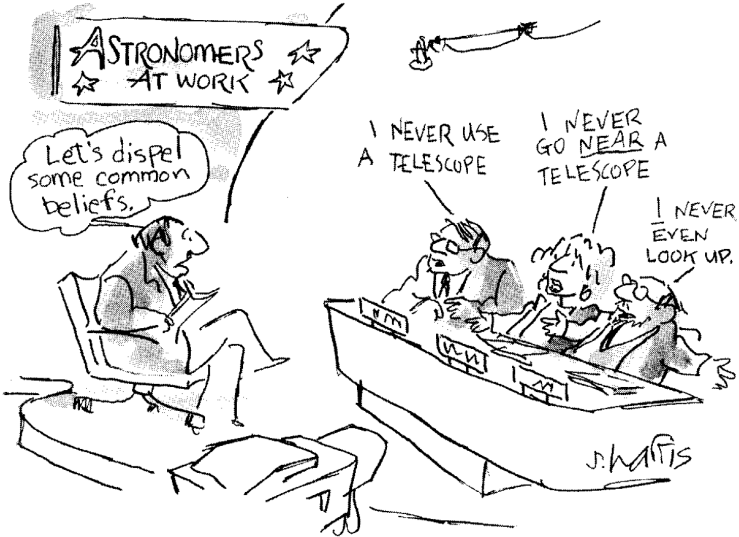
CU=Coordination Unit

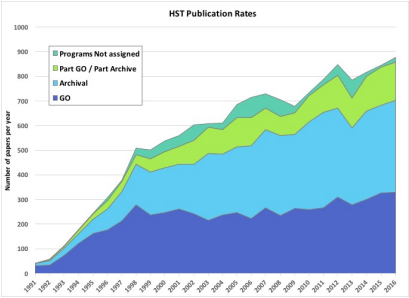
Daily 50 – 100GB compressed

5yrs 1PB

(see also O'Mullane et al. (2006), O'Mullane et al. (2009))

The Era Of Surveys and Archives

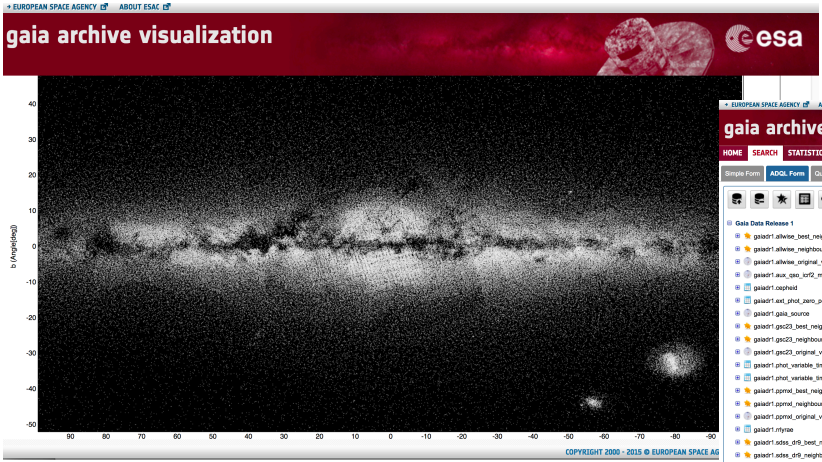


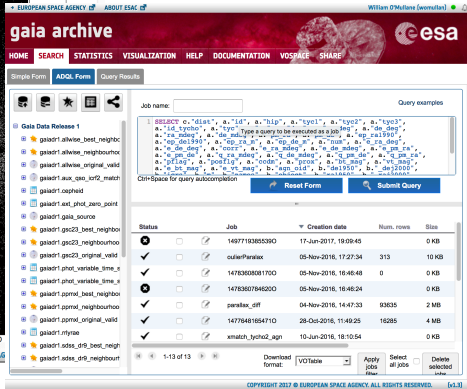


https://archive.stsci.edu/hst/bibliography/pubstat.html

...indicates archival research probably play an important role in the scientific success of XMM-Newton Ness et al. (2014)

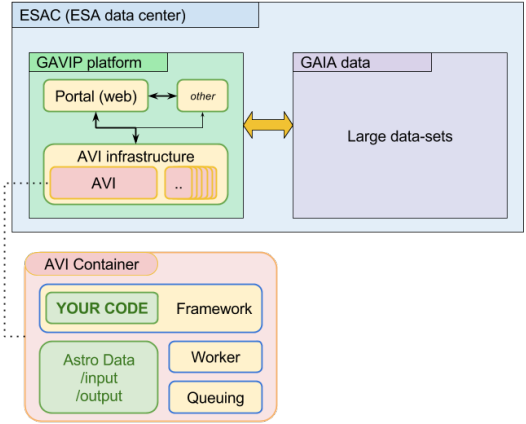
Gaia Archive

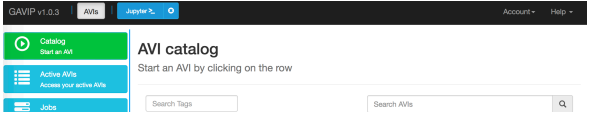




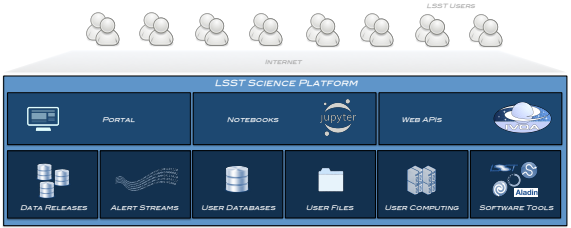
All Gaia data is publicly accessible at https://gea.esac.esa.int/archive/

Gaia Added Value Interface Platform (GAVIP)





LSST Science Platform



For DR2:

- Computing:2,400 cores ($\approx$ 18 TFLOPs)
- File storage: $\approx$ 4PB (VOSpace)
- Database storage: $\approx$ 3PB (MYDB)

The Science Platform has three user facing aspects: the Portal (novice), the JupyterLab (intermediate), and the Web APIs (expert and remote tools).

This is the sort of envronment users now expect to have - it is no longer novel.
Bruno will have more to say on this

More generally for astronomy I

Material drawn from ?

We have issues/challenges :

- Data volume - data will be looking for astronomers not vice versa
  - Should LSST be one of the last missions with proprietary data?
  - Networks and infrastructure
  - Commodity services ..
  - Long term preservation
- Data models and interoperability
- Long term software support and software eco system
  - Open source and publicly scrutinized algorithms
  - Agree community cyber infrastructure model
  - Educate astronomers/managers on how to open source
  - Though I made my career in astronomy/computing .. its not easy .. and I really had to do the management thing

More generally for astronomy II

- Machine learning:
  - Automated discovery - need it great !
  - Reproducibility, understand ability
- education - everyone needs to be a data scientist/programmer ..

Its all team work on big projects

The End

Acronyms I

Acronym	Description
AGIS	Astrometric Global Iterative Solution
Archive	The repository for documents required by the NSF to be kept. These include documents related to design and development, construction, integration, test, and operations of the LSST observatory system. The archive is maintained using the enterprise content management system DocuShare, which is accessible through a link on the project website www.project.lsst.org.
CCD	Charge-Coupled Device
CU	Coordination Unit
Camera	The LSST subsystem responsible for the 3.2-gigapixel LSST camera, which will take more than 800 panoramic images of the sky every night. SLAC leads a consortium of Department of Energy laboratories to design and build the camera sensors, optics, electronics, cryostat, filters and filter exchange mechanism, and camera control system.
DM	Data Management
Data Backbone	The software that provides for data registration, retrieval, storage, transport, replication, and provenance capabilities that are compatible with the Data Butler. It allows data products to move between Facilities, Enclaves, and DACs by managing caches of files at each endpoint, including persistence to long-term archival storage (e.g. tape).
Data Management	The LSST Subsystem responsible for the Data Management System (DMS), which will capture, store, catalog, and serve the LSST dataset to the scientific community and public. The DM team is responsible for the DMS architecture, applications, middleware, infrastructure, algorithms, and Observatory Network Design. DM is a distributed team working at LSST and partner institutions, with the DM Subsystem Manager located at LSST headquarters in Tucson.
ESA	European Space Agency
ESOC	European Space Operations Centre
ESTEC	European Space Technology Engineering Centre

Acronyms II

GAVIP	Gaia Added Value Interface Platform
GB	Gigabyte
HEALPix	Hierarchical Equal-Area iso-Latitude Pixelisation
HSC	Hyper Suprime-Cam
HTM	Hierarchical Triangular Mesh
IR	Infra Red
ISSI	International Space Science Institute
LSST	Large Synoptic Survey Telescope
MPP	Massively Parallel Process
NCSA	National Center for Supercomputing Applications
Operations	The 10-year period following construction and commissioning during which the LSST Observatory conducts its survey
PB	PetaByte
PSF	Point Spread Function
Project Manager	The person responsible for exercising leadership and oversight over the entire LSST project; he or she controls schedule, budget, and all contingency funds
Qserv	Proprietary Database built by SLAC for LSST
SDSS	Sloan Digital Sky Survey
Science Platform	A set of integrated web applications and services deployed at the LSST Data Access Centers (DACs) through which the scientific community will access, visualize, and perform next-to-the-data analysis of the LSST data products.
TB	TeraByte
XMM	X-ray Multi-mirror Mission (ESA; officially known as XMM-Newton)
arcmin	arcminute minute of arc (unit of angle)
arcsec	arcsecond second of arc (unit of angle)

Acronyms III

astrometry	In astronomy, the sub-discipline of astrometry concerns precision measurement of positions (at a reference epoch), and real and apparent motions of astrophysical objects. Real motion means 3-D motions of the object with respect to an inertial reference frame; apparent motions are an artifact of the motion of the Earth. Astrometry per se is sometimes confused with the act of determining a World Coordinate System (WCS), which is a functional characterization of the mapping from pixels in an image or spectrum to world coordinate such as (RA, Dec) or wavelength.
calibration	The process of translating signals produced by a measuring instrument such as a telescope and camera into physical units such as flux, which are used for scientific analysis. Calibration removes most of the contributions to the signal from environmental and instrumental factors, such that only the astronomical component remains.
camera	An imaging device mounted at a telescope focal plane, composed of optics, a shutter, a set of filters, and one or more sensors arranged in a focal plane array.
metric	A measurable quantity which may be tracked. A metric has a name, description, unit, references, and tags (which are used for grouping). A metric is a scalar by definition. See also: aggregate metric, model metric, point metric.

References

Bauer, A.E., Bellm, E.C., Bolton, A.S., et al., 2019, arXiv e-prints, arXiv:1905.05116 (arXiv:1905.05116), ADS Link

Ivezic, Z., et al., 2008, ArXiv e-prints (arXiv:0805.2366), ADS Link

Lindegren, L., Lammers, U., Hobbs, D., et al., 2012, A&A, 538, A78 (arXiv:1112.4139), doi:10.1051/0004-6361/201117905, ADS Link

Lupton, R., Blanton, M.R., Fekete, G., et al., 2004, PASP, 116, 133 (arXiv:astro-ph/0312483), doi:10.1086/382245, ADS Link

Ness, J.U., Parmar, A.N., Valencic, L.A., et al., 2014, Astronomische Nachrichten, 335, 210 (arXiv:1311.5751), doi:10.1002/asna.201312001, ADS Link

O'Mullane, W., Lammers, U., Bailer-Jones, C., et al., 2006, ArXiv Astrophysics e-prints (arXiv:astro-ph/0611885), ADS Link

O'Mullane, W., Hernández, J., Hoar, J., Lammers, U., 2009, In: D. A. Bohlender, D. Durand, & P. Dowler (ed.) Astronomical Data Analysis Software and Systems XVIII, vol. 411 of Astronomical Society of the Pacific Conference Series, 470, ADS Link

O'Mullane, W., Lammers, U., Lindegren, L., Hernandez, J., Hobbs, D., 2011, Experimental Astronomy, 31, 215 (arXiv:1108.2206), doi:10.1007/s10686-011-9248-z, ADS Link

Vagg, D., O'Callaghan, D., O'Hógáin, F., et al., 2016, In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 9913 of SPIE, 99131V (arXiv:1605.09287), doi:10.1117/12.2233619, ADS Link