



# Measuring our galaxy and beyond

William O'Mullane, AURA/LSST  
DM Project Manager

18<sup>th</sup> July 2018 Scoil Mhuire, Clontibret, Monaghan, Ireland





## Early background



- 1982-87 High School in Fethard Co. Tipperary
- 1984ish started with BASIC on a Commodore (still kept horses)
- 1987-93 MSc BSc Computer Science, University College Cork, Ireland
- 1993 iESA Young Graduate Trainee - ESOC Germany.
- 1994-97 Spacecraft Control Systems (C++), ESA ESOC Germany
- 1997-2001 Hipparcos, Integral, Planck, Gaia, Bepi-Sax (C,Java,Oracle, HTM, HEALPix), ESA ESTEC Netherlands
- 2012 PhD in Physics on Implementing the Gaia Astrometric Solution, Barcelona University

YGT is still running - "about 100 YGT job offers, aimed mainly at engineers and physicists, graduates in Information Technology, Natural or Social Science and Business"

[https://www.esa.int/About\\_Us/Careers\\_at\\_ESA/Graduates\\_Young\\_Graduate\\_Trainees](https://www.esa.int/About_Us/Careers_at_ESA/Graduates_Young_Graduate_Trainees)



# South of Spain



William O'Mullane • Scoil Mhuire Clontibert • 18<sup>th</sup> June 2018



# Outline of the talk



European Space Agency

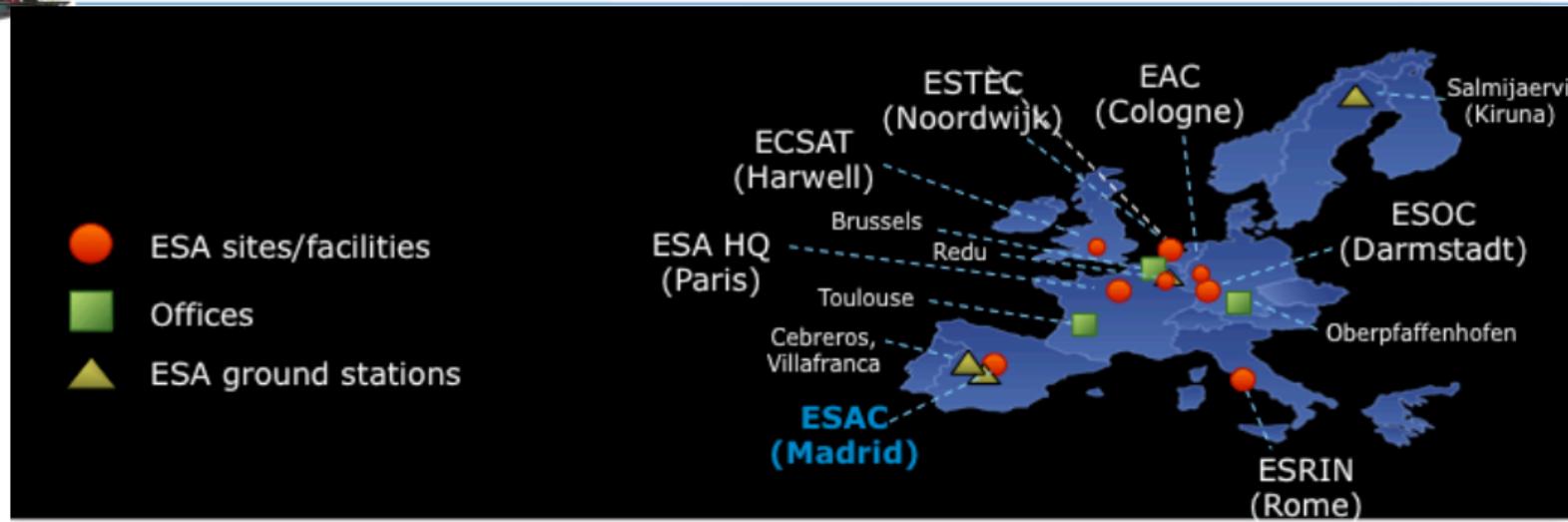
Gaia and LSST

Launch

Astrometry



# European Space Agency





Late 1990s SCOSII software contractors



- ESOC - Located in Darmstadt, near Frankfurt, Germany.
- Controls all ESA satellites.
- System design/engineering, requirements management, advanced studies ..
- SCOSII (Satellite Control and Operations System) for ENVISAT



## 1998 Integral in ESTEC



- ESTEC - Located near Noordwijk, Netherlands.
- Worked on Hipparcos, Integral, Planck and Gaia study phase:
  - First ideas on Global Astrometric Solution (O'Mullane & Lindegren, 1999) and **how to make a consortium**.
  - How to tessellate the celestial sphere : HEALPix and HTM work proved popular (O'Mullane et al., 2001).

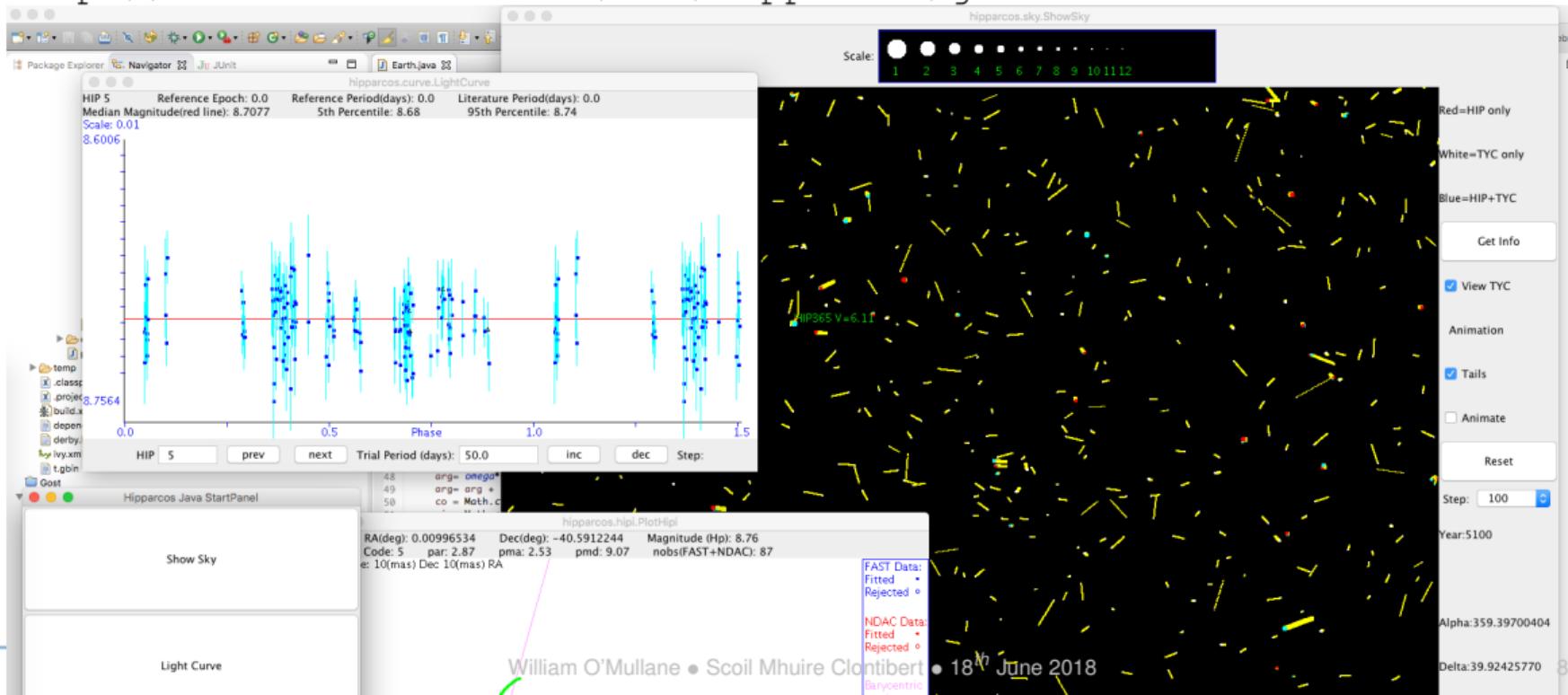


# Addition to HIP Catalogue



## 1997/98 Hipparcos Java Tools - learning Astrometry

<http://www.cosmos.esa.int/web/hipparcos/java-tools>





## In the USA early 2000s

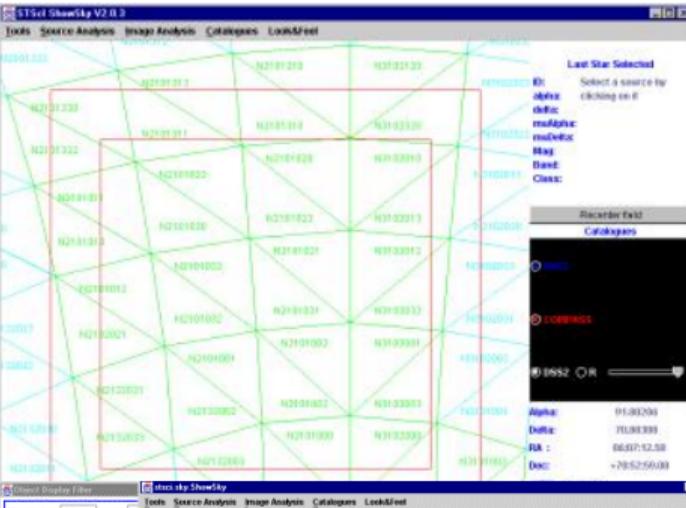


Entering the new millennium ..

## Quality tools for GSC2 (Java) →

CasJobs (C#) (O'Mullane et al., 2004)

A screenshot of a web browser window showing the SDSS Query / CasJobs interface. The browser title bar says "View Jobs - Mozilla Firefox". The main header has a menu bar with "File", "Edit", "View", "History", "Bookmarks", "Tools", and "Help". The page title is "SDSS Query / CasJobs". Below the title is a horizontal menu with links: "Help", "Tools", "Query", "History", "MyDB", "Import", "Groups", "Output", "Profile", "Admin", "SkyServer", "Logout", and "thakar". A watermark of a spiral galaxy is visible in the background.

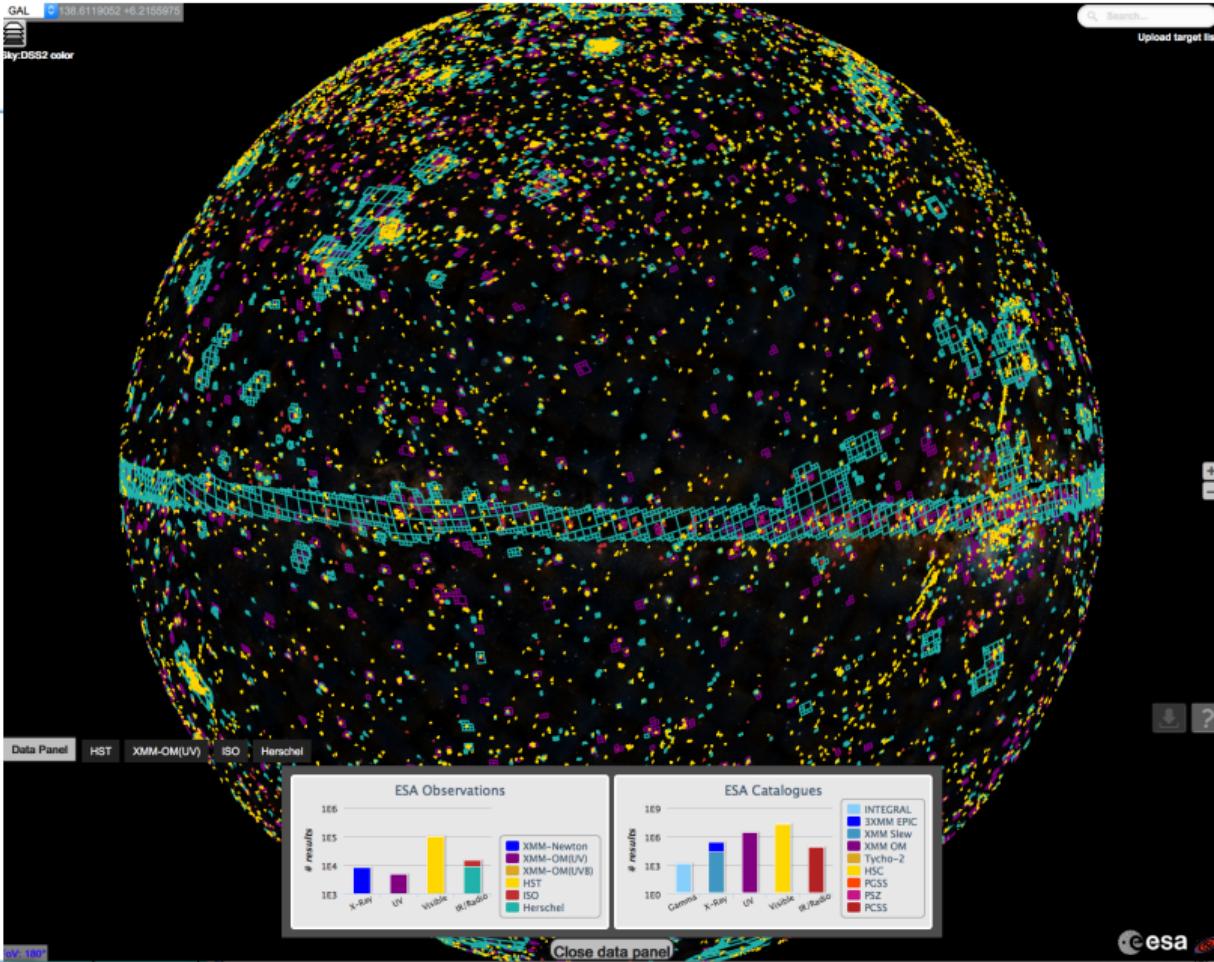


Status	Target	Name Like							
ANY	DR6		Apply						
Name	Query	Target	Submitted	Time(h:m:s)	Rows	Status			
Info Quasar Search in Imaging	SELECT TOP 1000 run,	DR6/600	7/15/2007 7:56:02 PM			Ready			
Info Quick Query	-- Galaxies meeting multiple s	DR6/1	7/15/2007 7:55:02 PM	0:0:0	10	Finished			
Info Sample Query 1	SELECT top 1000 G.ObjID, G.u,	DR6/600	7/15/2007 7:54:13 PM			Started			
Info My Query	select objid,ra,dec,modelmag_g	DR6/600	7/15/2007 12:17:42 AM	0:0:4	11308	Finished			
Info My Query	SELECT count(*) as 'total'	DR6/600	7/8/2007 11:20:37 AM	0:1:1		Failed			
Info My Query	SELECT TOP 1000 P.ObjID into m	DR6/600	7/8/2007 11:27:47 AM	0:7:53	1000	Finished			
Info My Query	SELECT TOP 1000 run,	DR6/600	7/8/2007 11:27:22 AM	0:0:1		Failed			
Info My Query	SELECT TOP 10000 run,	DR6/600	7/8/2007 11:27:06 AM	0:0:2	10000	Finished			
Info My Query	select top 10 * into mydb.MyTa	DR6/1500	6/26/2007 4:30:35 PM	0:0:0	10	Finished			
Info My Query	select top 10 * from dr5quasar	DR6/1	6/26/2007 1:08:12 PM	0:0:0	10	Finished			
Info My Query	select top 10 * from dr3quasar	DR6/1	6/26/2007 1:08:03 PM	0:0:0		Failed			



From 2005 to 2017

- ESAC Located near Madrid, Spain.
- Home of the Science Operations Department of the European Space Agency
- Surprising number of Irish people ..
- This picture from a public stargazing night - ~400 visitors came



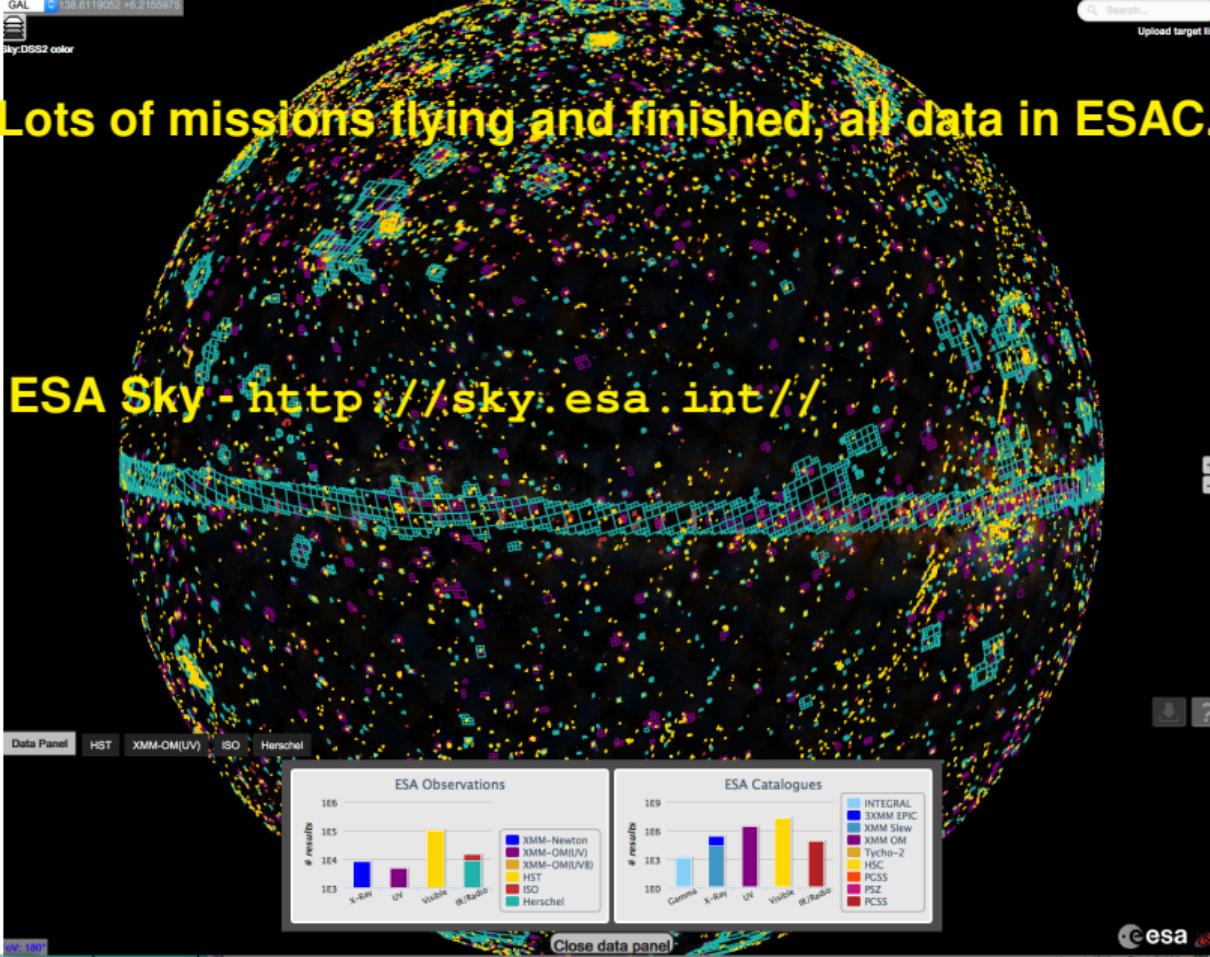


GAL 138.6119052 +6.2155975

Sky:DS2 color

Search...  
Upload target list

Lots of missions flying and finished, all data in ESAC.





# Outline of the talk



European Space Agency

Gaia and LSST

Launch

Astrometry



Milky way analogue

NGC1232

'Our sun' →

Jos de Bruijne

# Milky way analogue

NGC1232

‘Our sun’ →

Our view is severely obstructed by the dust in the disk and relatively little is known about the origin, history, and structure of our own Galaxy

Gaia’s main aim: unravel the formation, composition, and evolution of the Galaxy



## Some numbers and scales



- **Kilo** = 1000 =  $10^3$  **Mega** = 1000000 =  $10^6$  **Giga** = 1000000000 =  $10^9$  **Tera** =  $10^{12}$
- But note in computing .. KB = 1024 Bytes ..  $2^{10}$



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- 1 AU (astronomical unit) distance of earth from sun  $\sim 1.496 \times 10^{11}$  Meters
- 1 light year  $\sim 9.461 \times 10^{15}$  Meters sin63241 AU



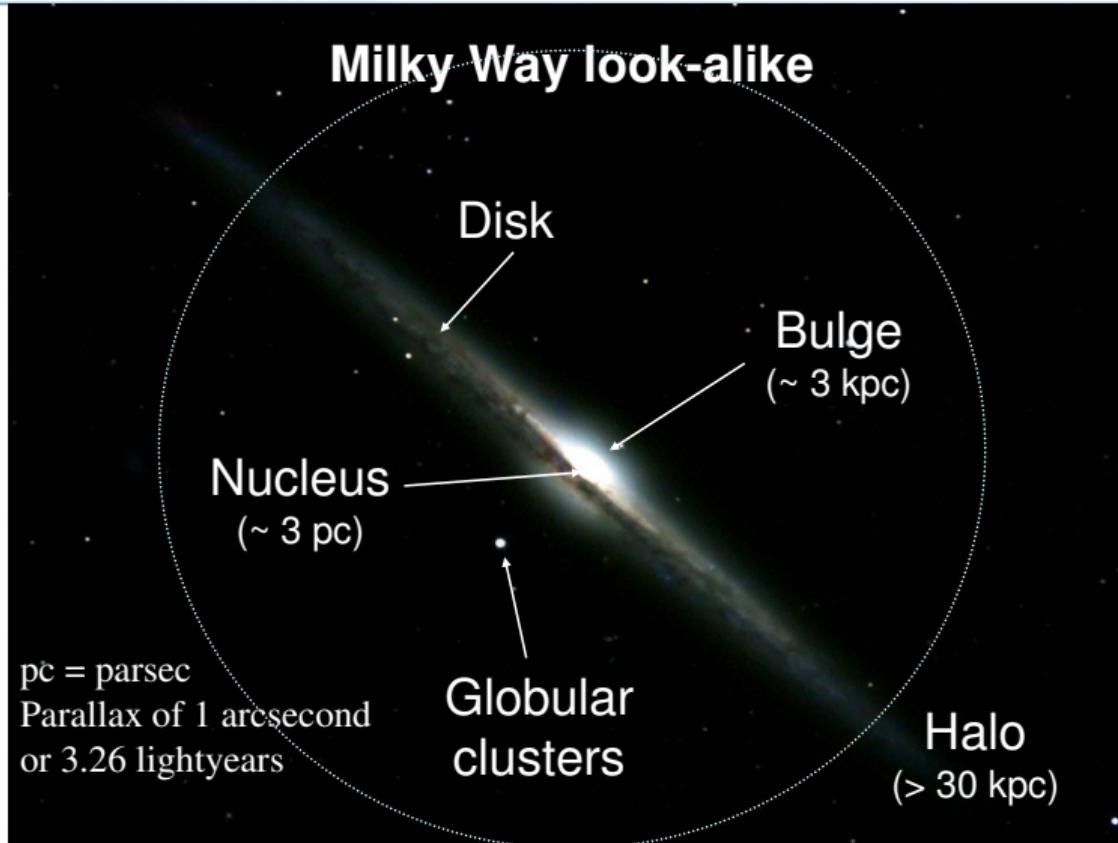
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- Parallax of 1'' known as 1 parsec  $\sim 3.26$  Light years  $\sim 206165$  AU
- 3.26 light years =  $3.26 \times 9.461 \times 10^{15} \sim 3.084 \times 10^{16}$  Meters

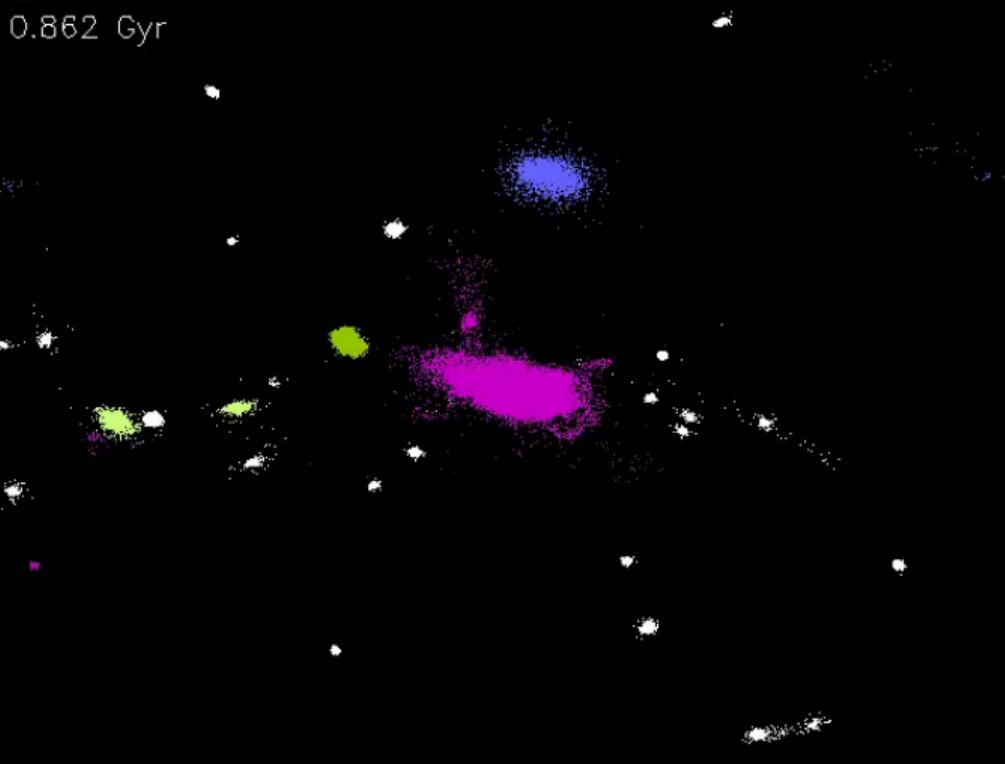


# Another Milky way Analogue (NGC4565)





# Origin of the Milky Way



Movie credit: Amina Helmi, University of Groningen

slides from Anthony Brown, Leiden University



# Origin of the Milky Way

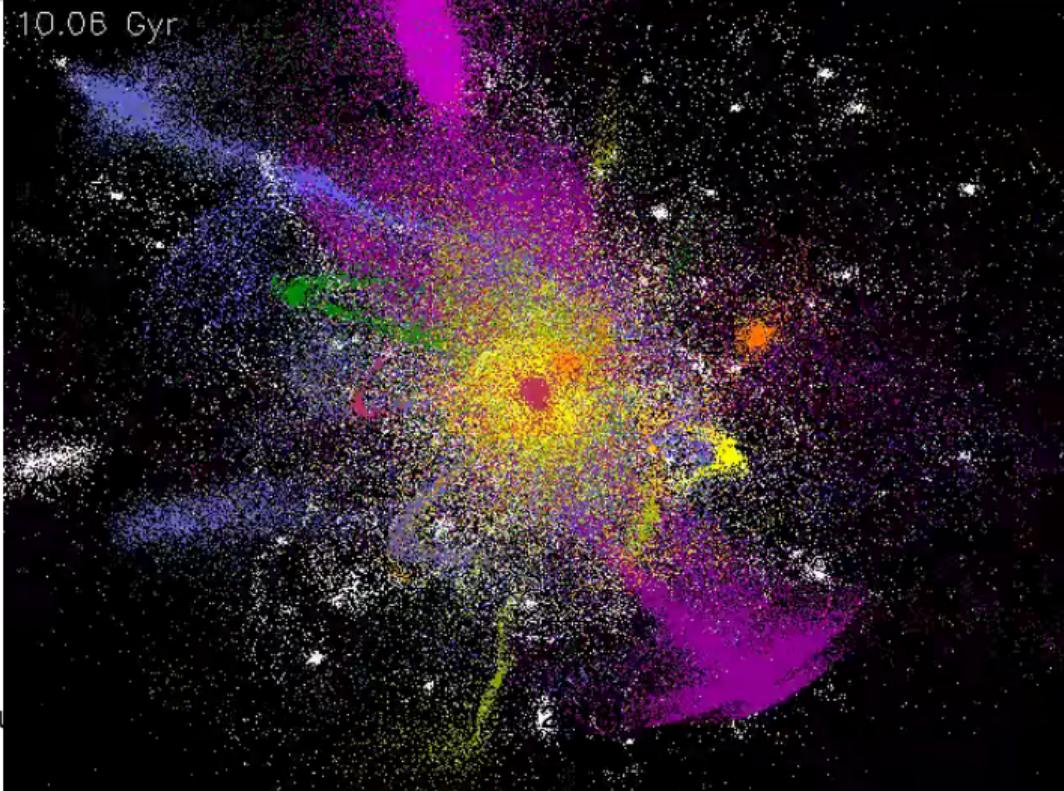
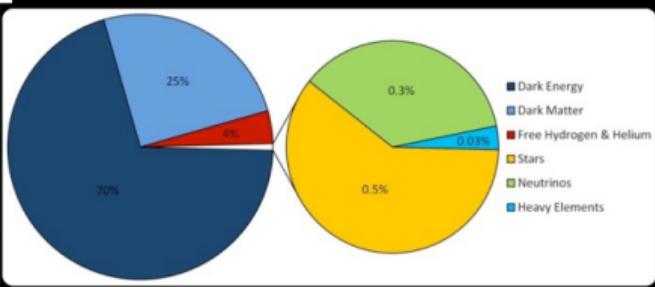
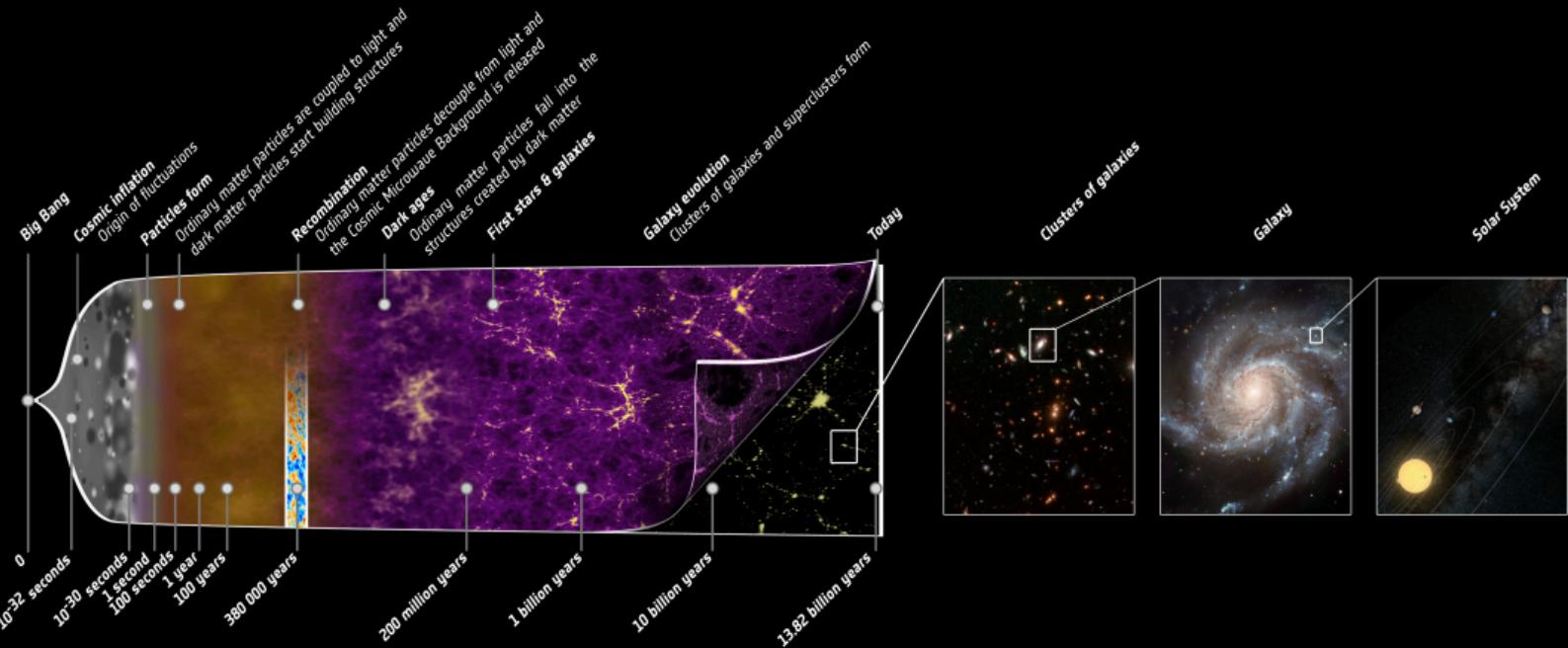


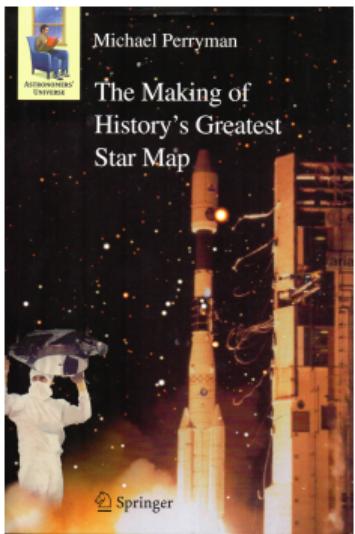
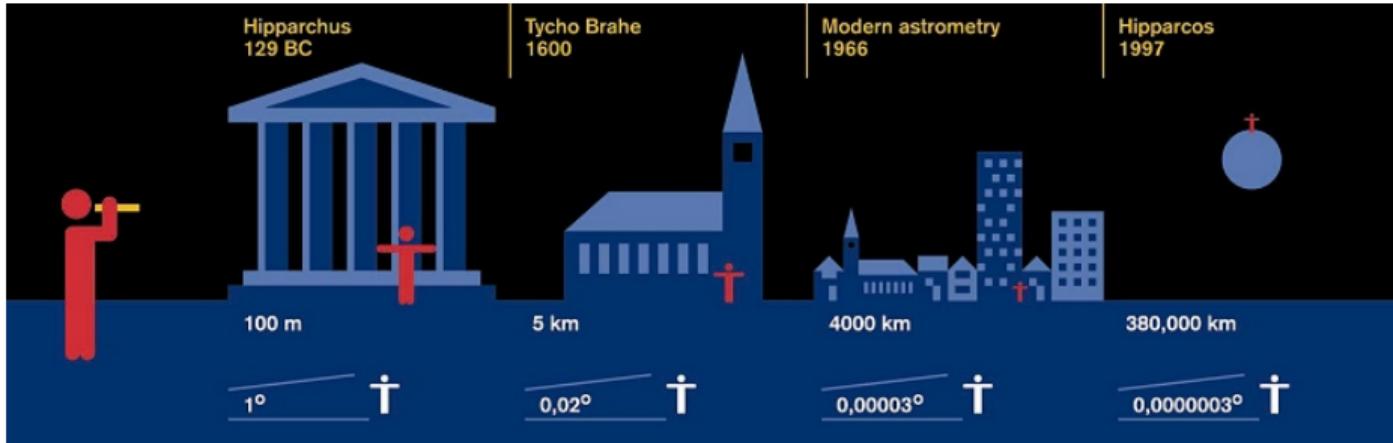
Image credit: R. Jay GaBany



The modern cosmological models can explain all observations, but need to *postulate* dark matter and dark energy (though gravity model could be wrong, too)



# Hipparchus to ESA's Hipparcos



Gaia will take us to the next order of magnitude the microarcsecond.  
e.g. A euro coin on the moon viewed from earth

Hipparcos measured  $10^5$  objects : Gaia measures  $10^9$

← superb account of the Hipparcos mission.



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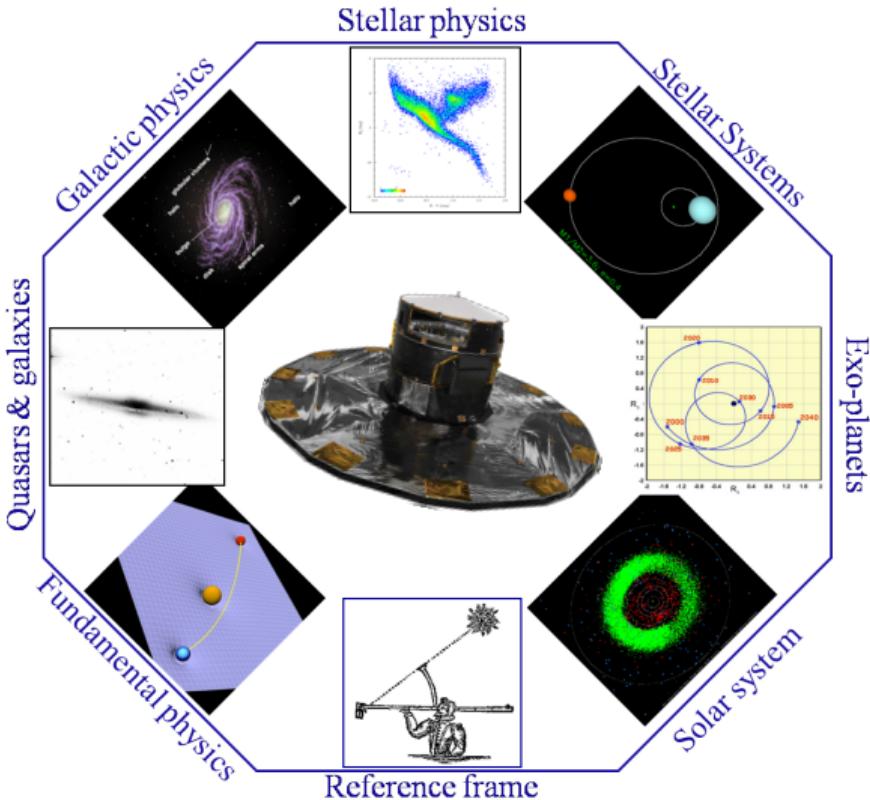
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# Science topics

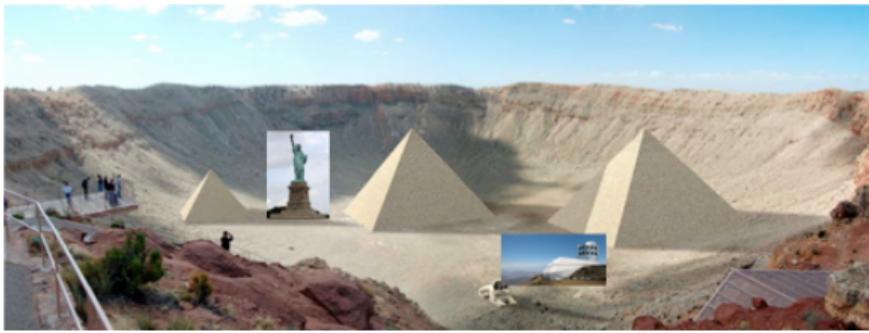




# Killer asteroids: the impact probability is not 0! LSST



LSST is the only survey capable of delivering completeness specified in the 2005 USA Congressional NEO mandate to NASA (to find 90% NEOs larger than 140m)



The Barringer Crater, Arizona: a 40m object 50,000 yr. ago

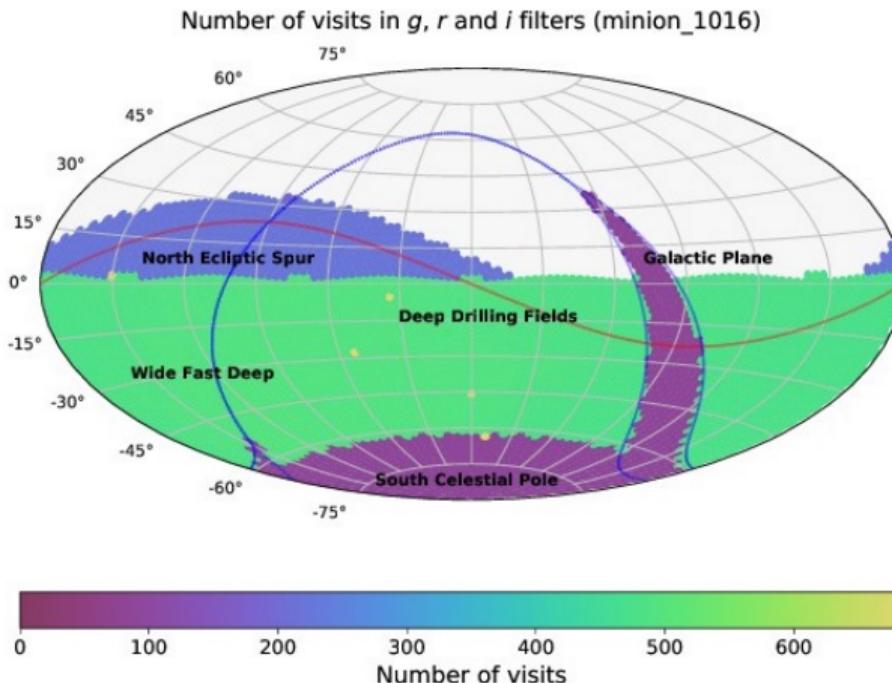


# LSST:uniform sky survey



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!**

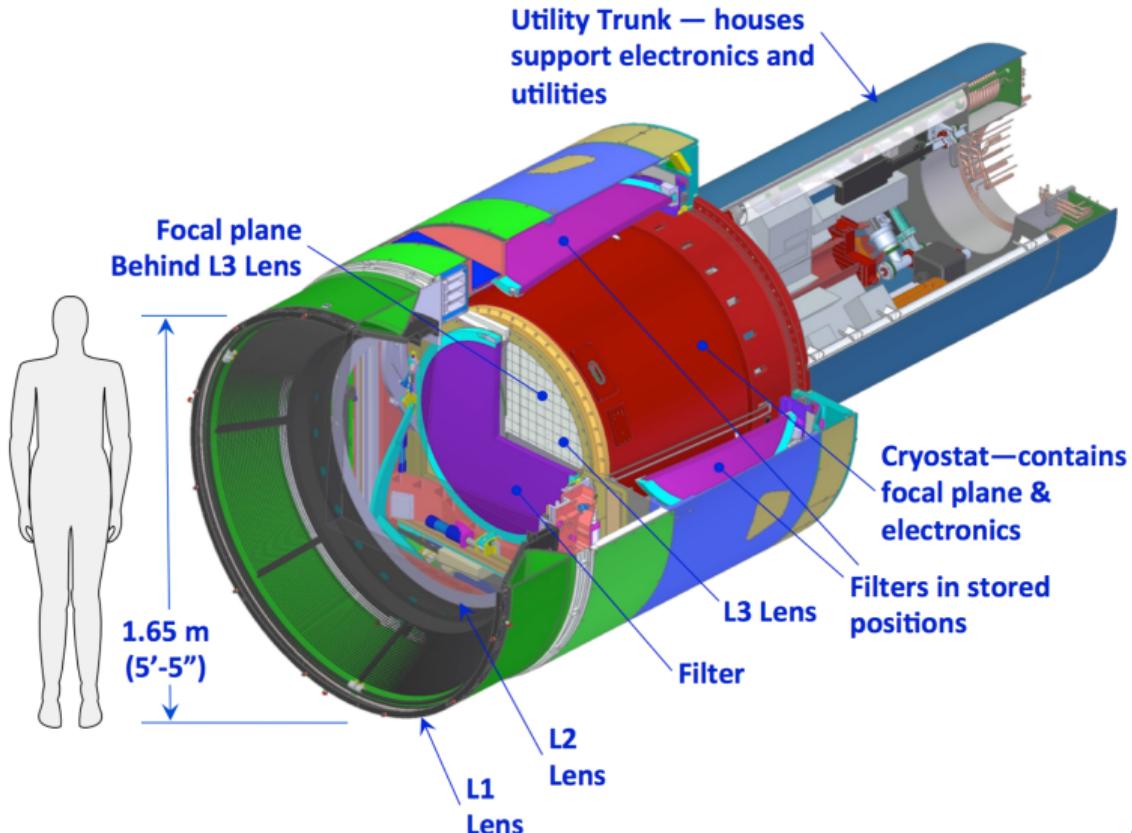


see also <http://www.lsst.org> and Ivezic et al. (2008)-arXiv:0805.2366

**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 shaping up





# Data management



DM Mission :  
*Stand up operable, maintainable, quality services to deliver high-quality LSST data products for science, all on time and within reasonable cost.*

LSST DM development is distributed across the Americas.  
Plus we have partners like IN2P3



## SDSS image



Nice colours 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 ( $\approx 27.5$ )

Processed with *LSST Stack*

<https://pipelines.lsst.io/>

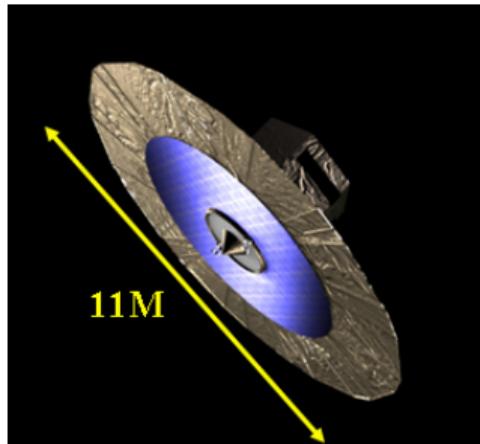
Image HSC collaboration, Robert Lupton



# 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 19<sup>th</sup> 2013
  - Stereoscopic Census of Galaxy over 5 years
    - Possible extension of 1 year - have fuel for at least that
  - $\mu\text{arcsec}$  Astrometry  $G < 20$  ( $10^9$  sources)
  - Radial Velocities  $G < 16$
  - Photometry millimag  $G < 20$

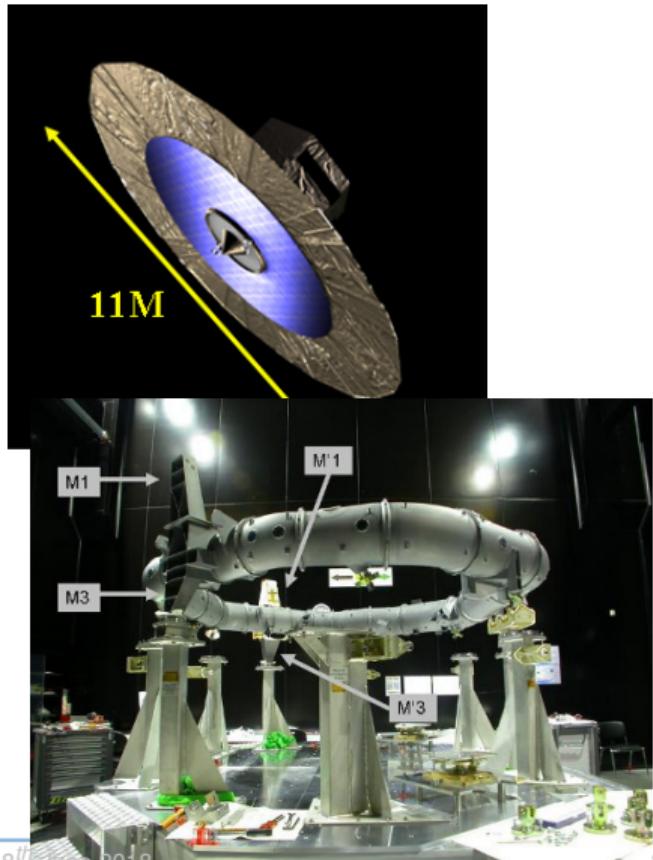




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- Final catalogue  $\approx$  2022





# Outline of the talk



European Space Agency

Gaia and LSST

Launch

Astrometry



# To Kourou



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# Lots of interesting signs ..





# Up close



Dec 18th saw (touched) our Fregat.  
Meanwhile a full dress rehearsal ongoing.  
Later road closed for Ariane movement





# Countdown..



Dec 18th 17:12 (20:12 UTC) the count down started. In Jupiter control room





Flawless lift off 19/12 06:12am

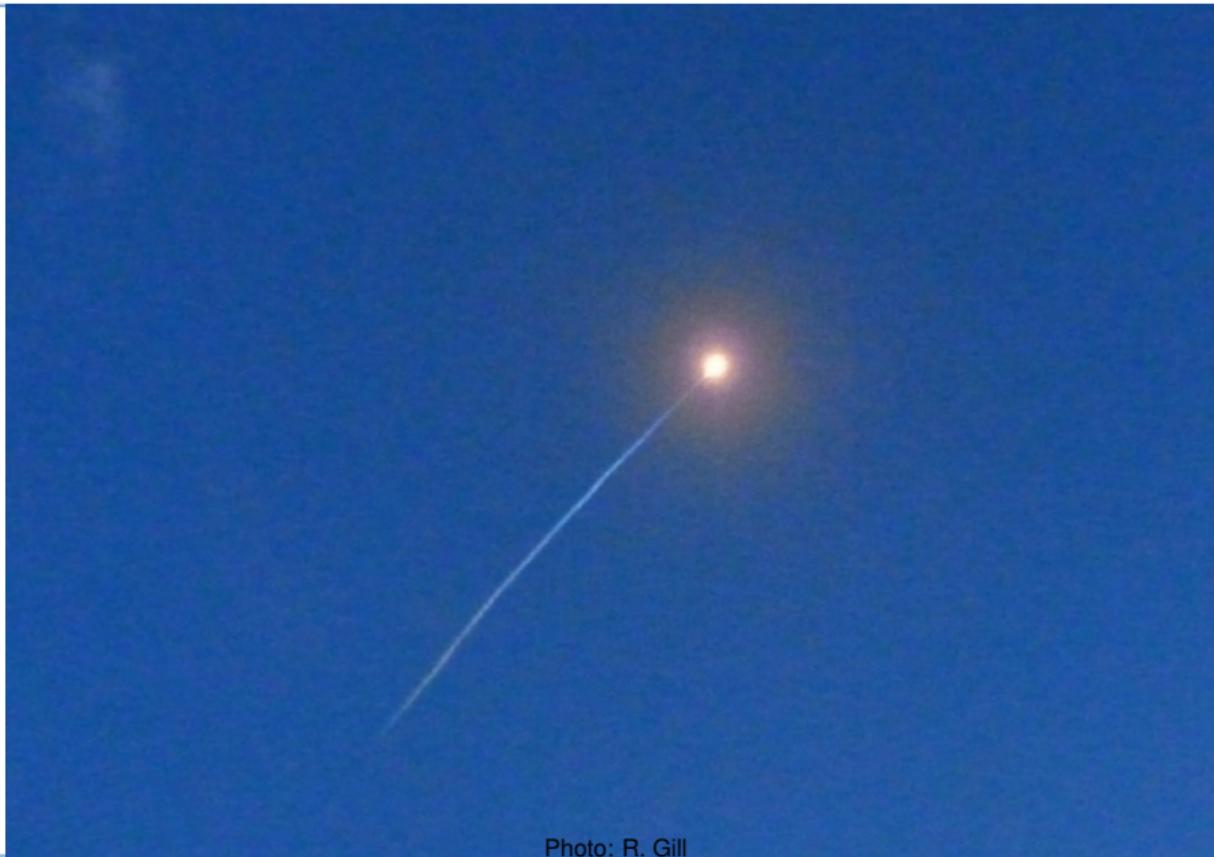


Photo: R. Gill

William O'Mullane • Scoil Mhuire Clontibert • 18<sup>th</sup> June 2018

Clontibert rocket flight - Quidnunc rocket 1.22.5 (www.youtube.com/watch?v=J1GzHLLC)



## Video clips



- Gaia Launch <https://youtu.be/xDmQvJVJg8Y?t=87>
- Gaia Data Release 2 <https://youtu.be/KULtrwVSq6g?t=10>
- Cerro Pachon LSST

<https://gallery.lsst.org/bp/#/folder/2689925/64565141>



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Just one part of the Gaia processing !

From the Hipparcos catalogue (ESA, 1997, Volume 3 Chapter 23).

## Minimisation problem for astrometry

$$\min_{\mathbf{a}, \mathbf{n}} \|\mathbf{g}^{\text{obs}} - \mathbf{g}^{\text{calc}}(\mathbf{a}, \mathbf{n})\|_M \quad (1)$$

- $\mathbf{a}$  is the vector of unknowns describing a star's barycentric motion represented by the measurement vector  $\mathbf{g}_k = (G_k, H_k)'$  and associated statistics.
- $\mathbf{g}^{\text{obs}}$  represents the vector of all measurements
- $\mathbf{g}^{\text{calc}}$  represents the vector of detector coordinates calculated from the astrometric parameters.
- $\mathbf{n}$  is a vector of nuisance parameters - required for realistic modeling (e.g. attitude, instrument calibration)
- $M$  metric defined by the statistics of the data, (error weighting)

The complete new formulation for Gaia is in (Lindegren et al., 2012).



# Basic Gaia Problem

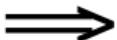


Put more simply the data reduction must:

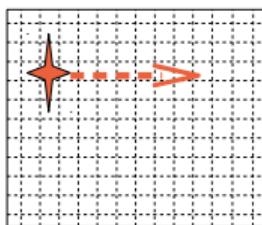
*find the astrometric parameters (catalogue) best predicting the ( $10^{12}$ ) focal plane observations of the sources. (O'Mullane et al., 2011)*

Catalogue Data

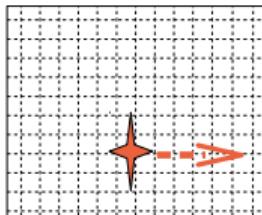
ID	$\alpha$	$\delta$	$\varpi$	$\mu_\alpha$	$\mu_\delta$	$\mu_r$
0000101	1.4	3.1	0.1	0.02	0.02	-
1001000	27	1.2	0.2	0.05	0.01	0.01



Gaia Focal Plane



$t_{\text{obs}} 1$



$t_{\text{obs}} n$

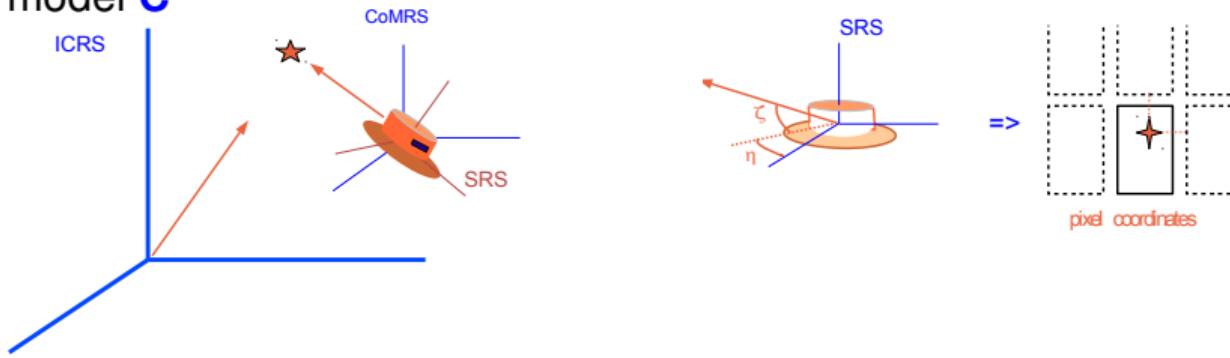


# Look at one block: Source modeling



The mapping or modeling of the observables **g** is done by three successive transformations:

1. from astrometric parameters to the celestial directions of a star at the instant of observation, using an astrometric model **S**
2. from celestial to instrument frame directions using an attitude model **A**
3. and finally from instrument directions to detector coordinates using an instrument model **C**





## Source Update



We fit the model to the observations:

Least squares for source update

$$\mathbf{Ax} \sim \mathbf{b} \pm \sigma \quad (2)$$

$$\text{where } \mathbf{b}_i = \mathbf{y}_i - f_i(\mathbf{a}, \mathbf{q}) \quad (3)$$

Here  $\mathbf{y}_i$  are the observed field angles  $f_i$  is a function to calculates field angles from the current model.



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In java (SourceUpdateCalculatorWrapper):

```
// get calculated angles + derivatives ...
ExtendedFieldAngles ecfA = angleCalc.getCalculatedEtaZeta(ae, origSrc, UpdateBlock.Source.getId());

// ... from those, get just calculated angles
double[][] calcEtaZeta = ecfA.getEtaZeta();

// ... and the observed ones from the angle calculator
double[][] obsEtaZeta = angleCalc.getObservedEtaZeta(ae);

// compute residuals [rad] and attach these to the Elementary...
```



# Its all team work on big projects





# The END



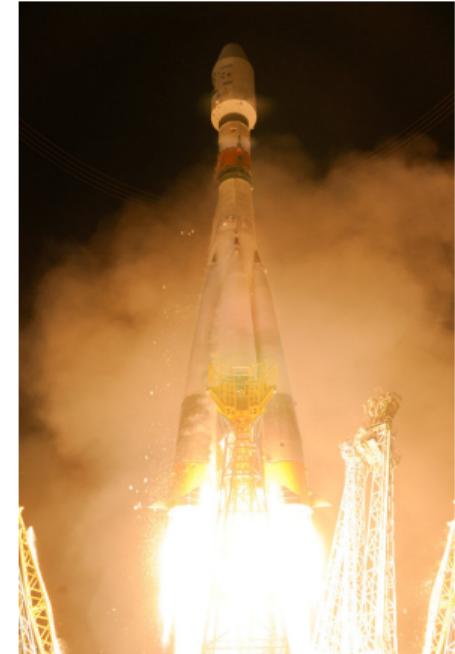
Blast 20 Cerro Pachón April 2011.

<http://www.lsst.org>

<http://community.lsst.org>

Gaia blast off on Soyuz December 2013

<http://www.cosmos.esa.int/web/gaia>





# Acronyms I



Acronym	Description
AURA	Association of Universities for Research in Astronomy
C	Specific programming language (also called ANSI-C)
DM	Data Management
ESA	European Space Agency
ESAC	European Space Astronomy Centre (ViSpa)
ESOC	European Space Operations Centre (ESA)
ESTEC	European Space research and TEchnology Centre (ESA)
HEALPix	Hierarchical Equal-Area iso-Latitude Pixelisation
HTM	Hierarchical Triangular Mesh
LSST	Large Synoptic Survey Telescope
PhD	Doctorate in Philosophy
SDSS	Sloan Digital Sky Survey
TEC	Thermo-Electric Cooler
USA	United States of America
arcmin	arcminute, minute of arc (unit of angle)
arcsec	arcsecond, second of arc (unit of angle)



# References



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