Coding / Decoding the Cosmos:

Python Applications in Astrophysics

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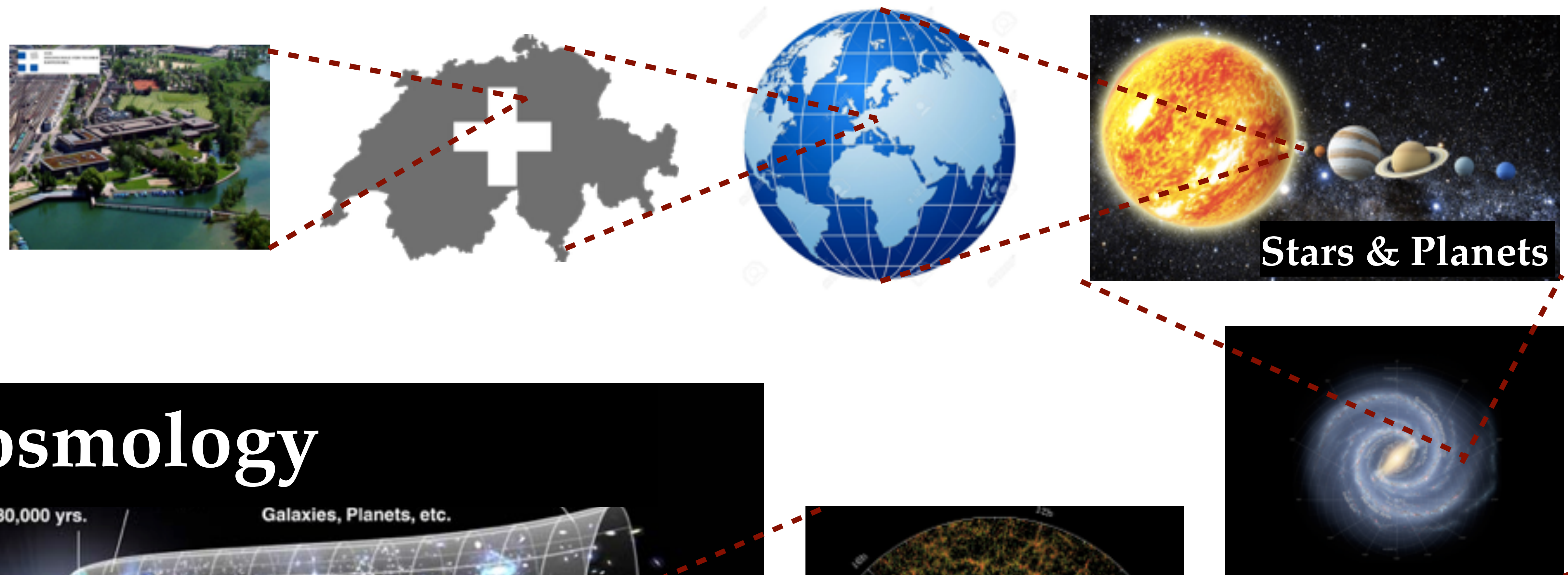
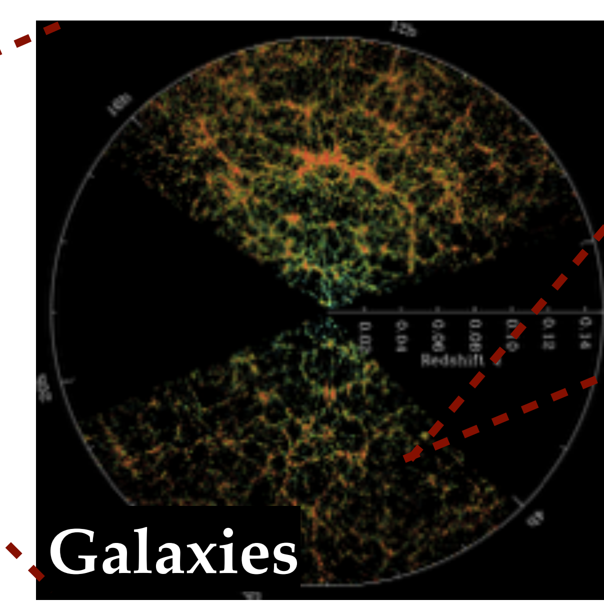
ETH | Cosmology

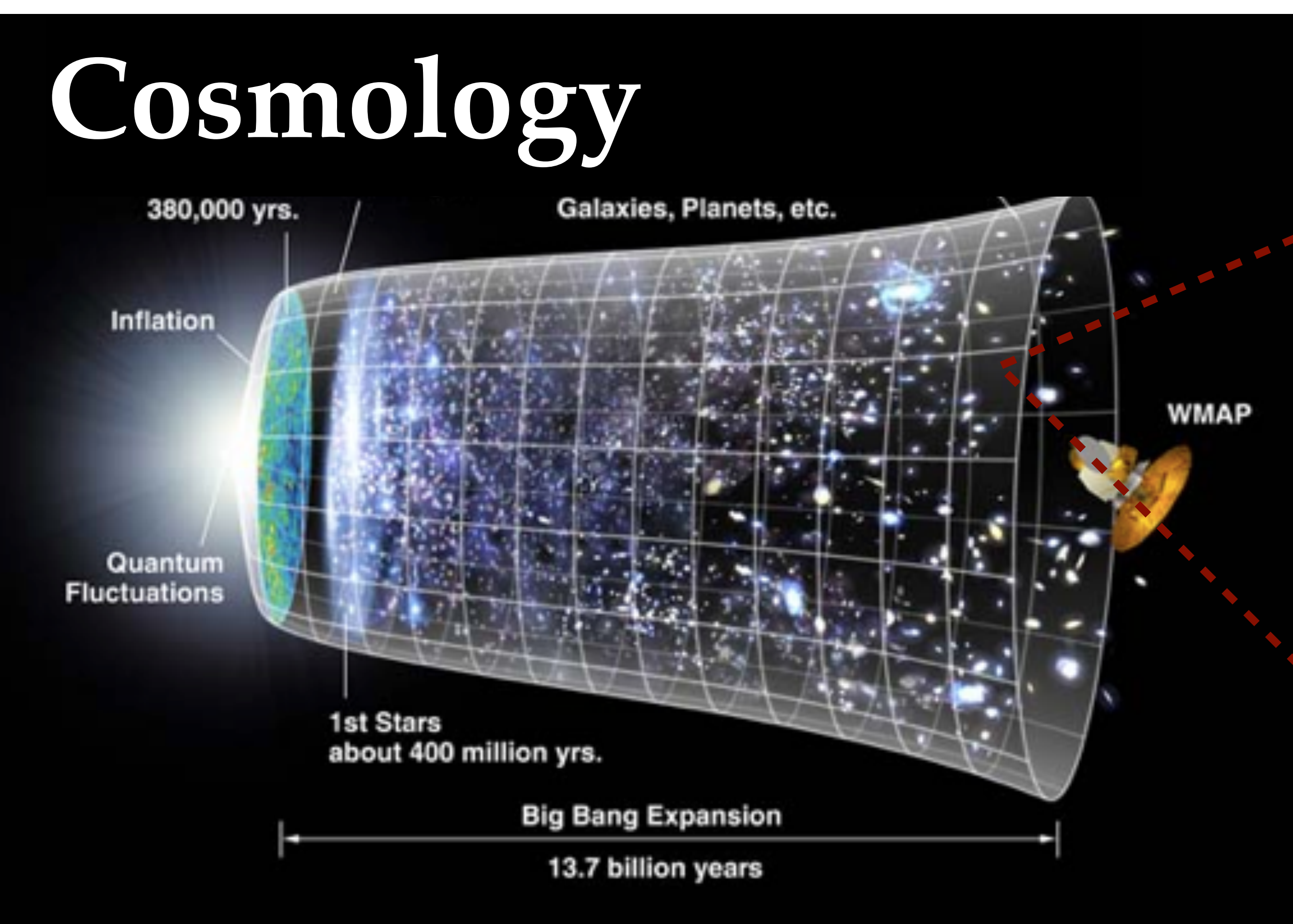
DISCLAIMER

- This is **not** your typical computer-science talk.
- You will probably **not** learn new fancy coding techniques here.
- What you will learn is that you can do a massive amount of **science** with relatively **simple Python**.

From Astrophysics to Cosmology







Computing for Typical Astronomers

- **Science computing can be quite different from that in industry**
  - ➡ Quick(-and-dirty) results, interactive
  - ➡ Less rigorous testing and control
  - ➡ Never know what to expect, moving targets and loose deadlines

—> it's like an experiment!

Computing for Typical Astronomers

- *Recent* **used languages in astrophysics**
  - ➡ C, C++, FORTRAN, perl, shell script, Mathematica, MATLAB, ROOT …
  - ➡ **IDL, python,** and libraries/wrappers/interface to above

- **Common Python packages / interface in astro:**
  - ➡ SciPy, NumPy, matplotlib, astropy
  - ➡ IPython / Jupyter

Computing for Typical Astronomers

- **Public python-related packages developed in our group**

HOPE: A Python Just-In-Time compiler for astrophysical computations

`/cosmo-ethz/hope`

CosmoHammer: Parallel MCMC for HPC clusters

`/cosmo-ethz/CosmoHammer`

ABCPMC: Parallel Approximate Bayesian Computation

`/jakeret/abcpmc`

PynPoint: Direct imaging of exo-planets

`http://pynpoint.ethz.ch`

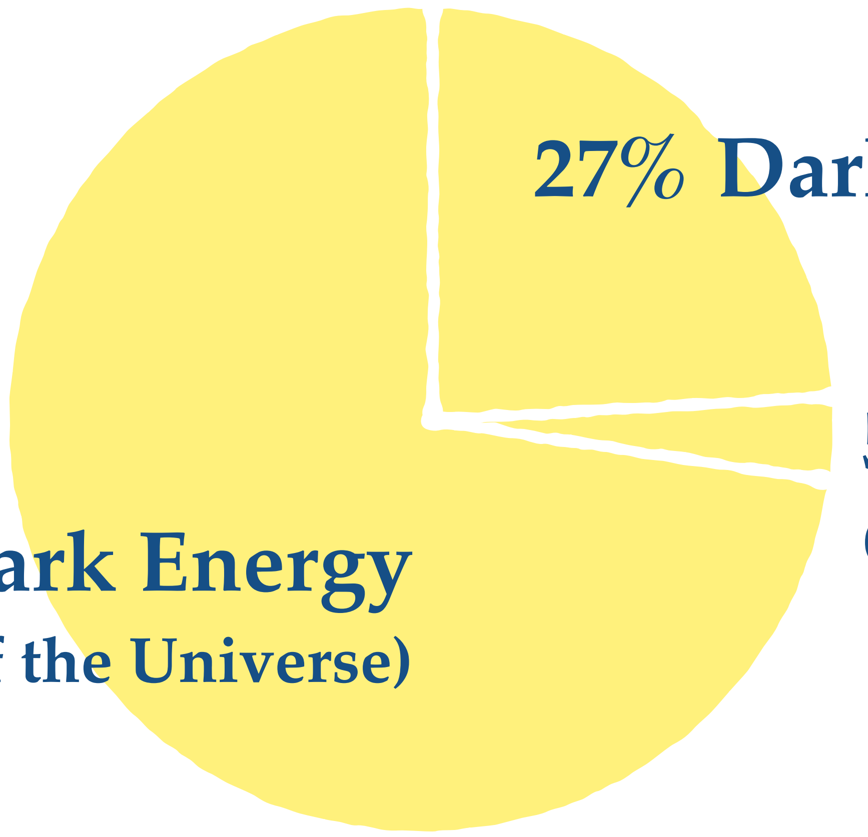
Two Examples

- **Mapping dark matter using millions of galaxy images**
  - *Physical Review Letters* ***115*** *, 051301 (2015), arXiv: 1505.01871*
  - *Phys.Rev.D 92 , 022006 (2015), arXiv: 1504.03002*
- **Calibrating radio telescopes with drones**
  - *Publications of the Astronomical Society of the Pacific* ***127****, 1131–1143, (2015), arXiv:1505.05885*

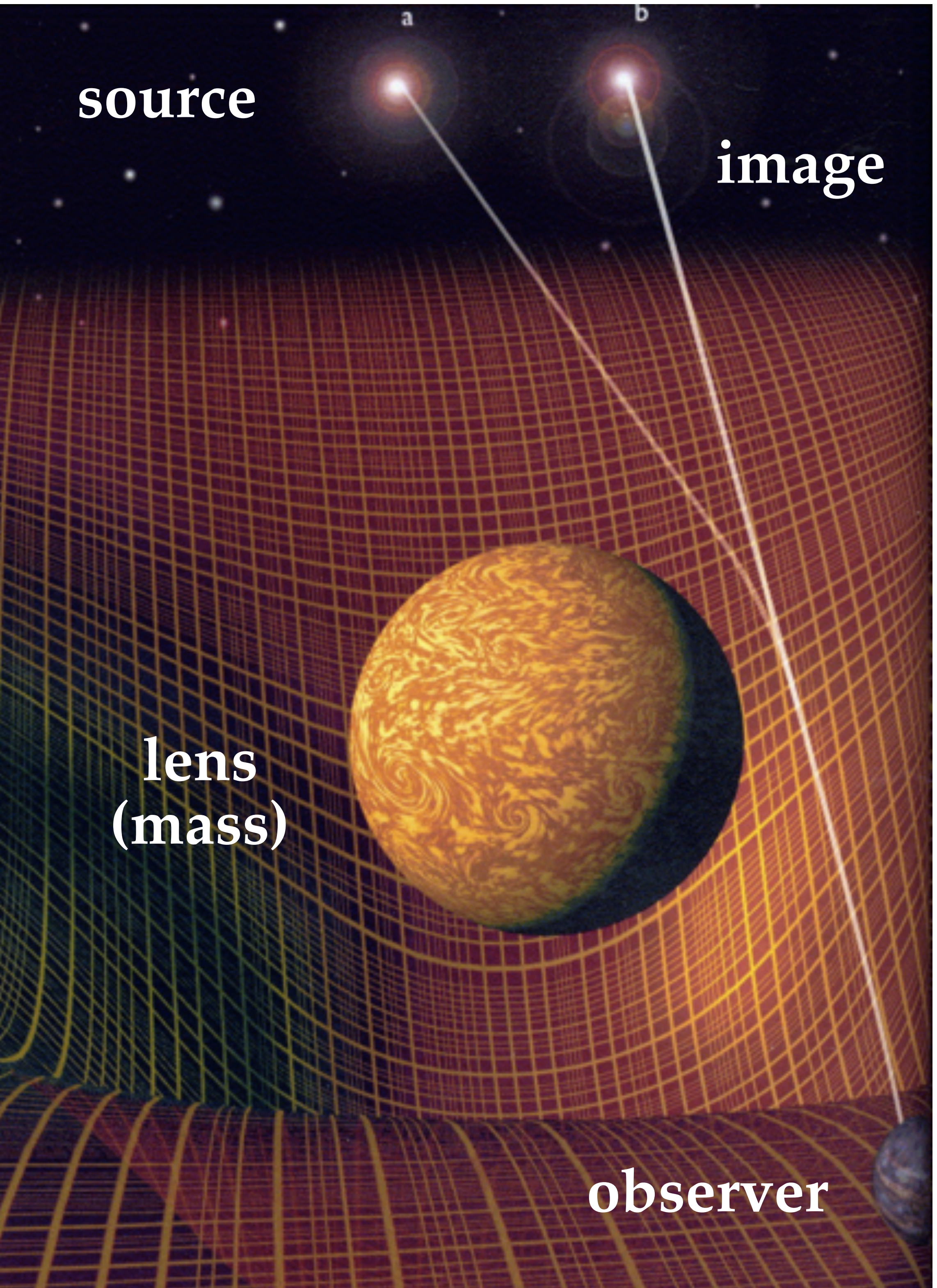
python

Mapping Dark Matter

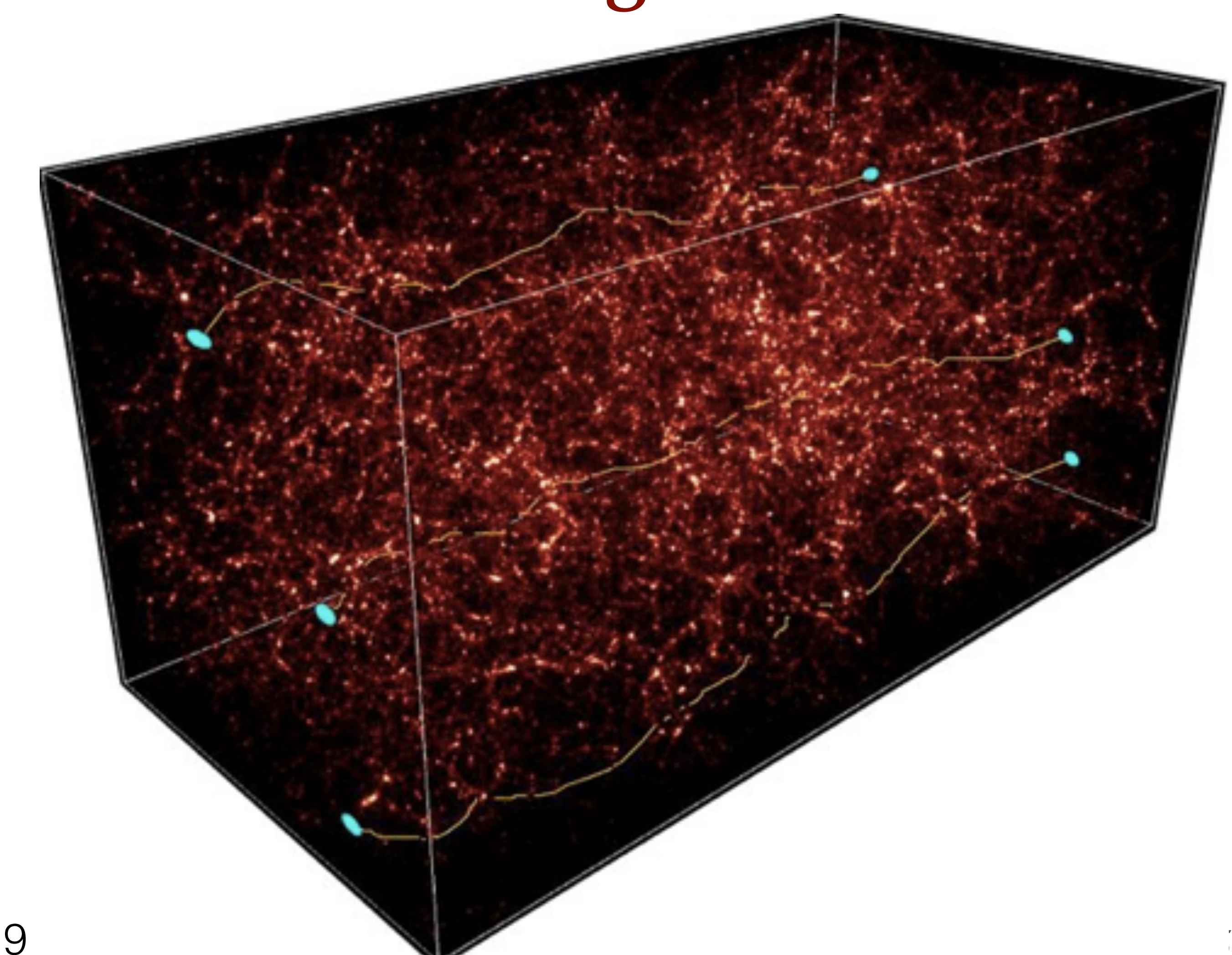
- **We don't know a whole lot about our Universe**, because we cannot **see** most of the stuff in the Universe!



Gravitational Lensing

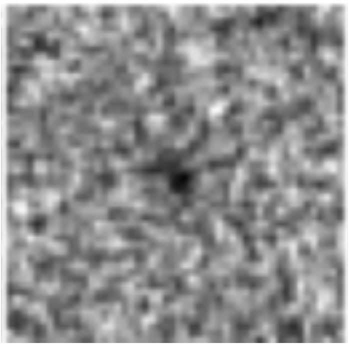


We can *see* dark matter through **Gravitational Lensing**!



The Computational Challenge

- We want to measure accurately **shapes** of a lot of small, faint, noisy galaxies, and get useful information out of them.

~100,000,000 x 

The Computational Challenge

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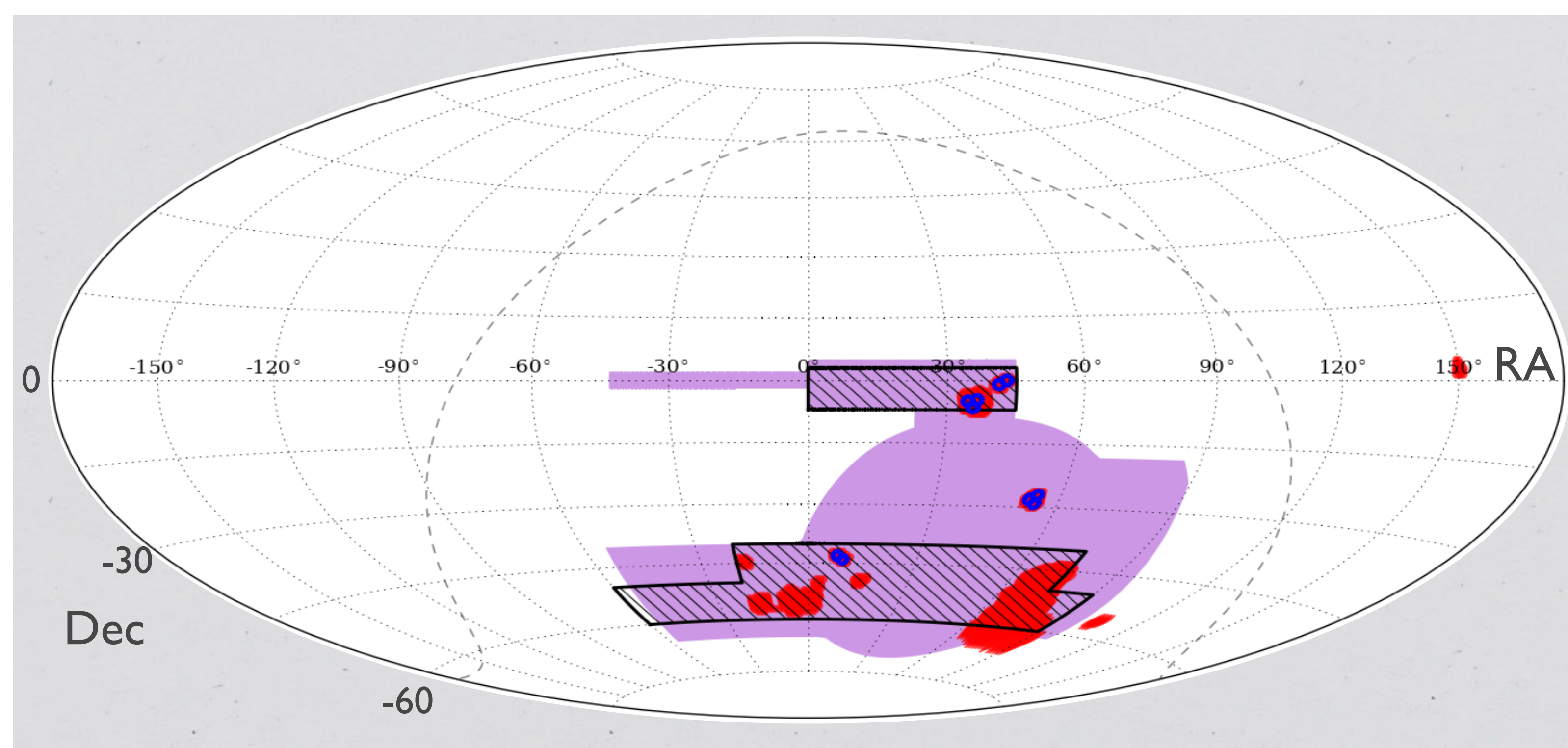
/barbabytprowe/great3-public
/GalSim-developers/GalSim

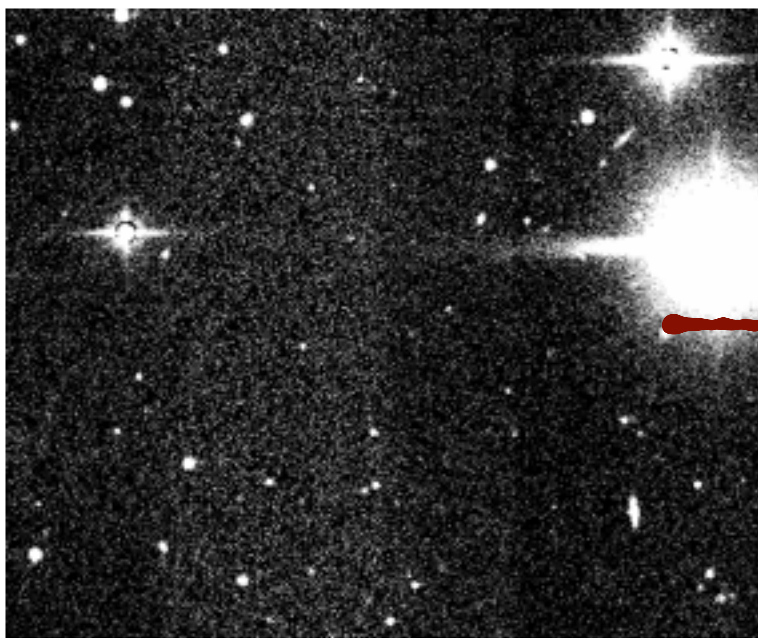
The Dark Energy Survey

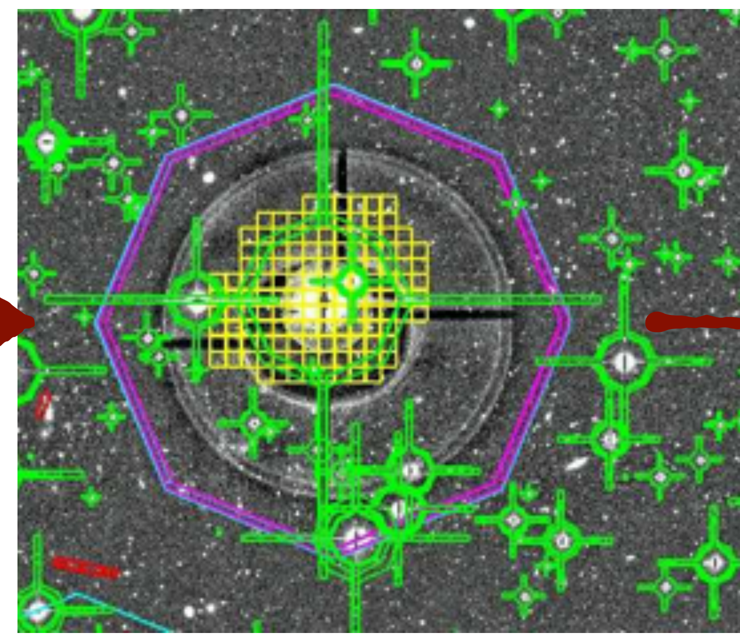
DES is an ongoing **galaxy imaging survey** and will cover **5000 sq. degrees** over 5 years

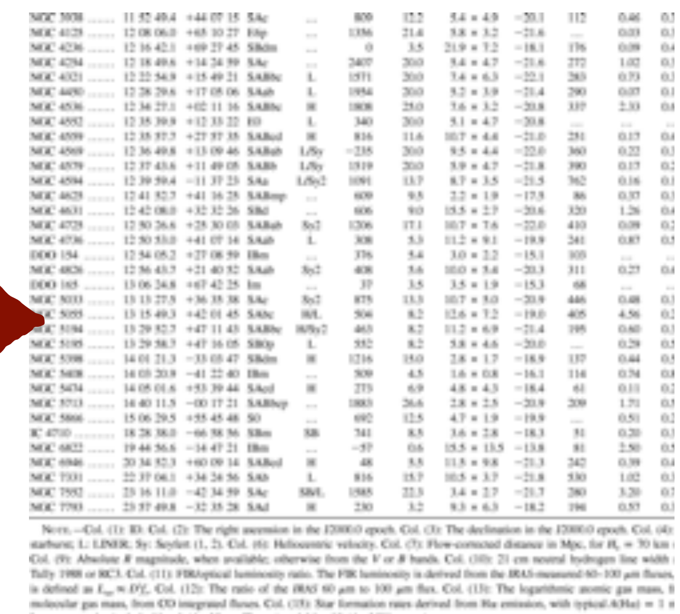


The Dark Energy Survey

- The data processing pipeline (partially Python)







- raw data
- calibration
- stacking

- object detection
- masking artefacts
- measure characteristics of each object (size, brightness, shape etc.)
- classification

- "cataloging"
- science analysis

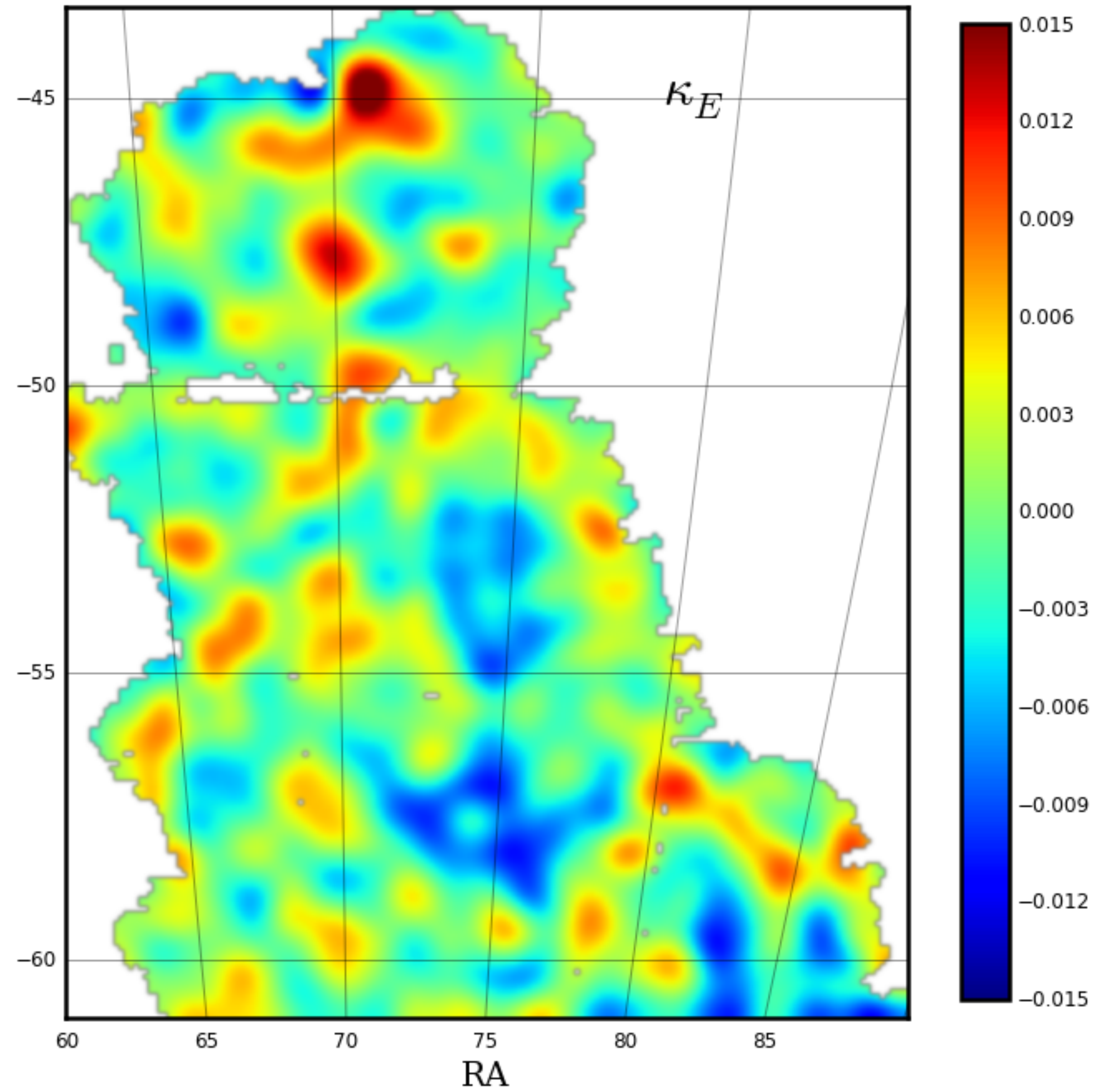
Mapping Dark Matter

Convert galaxy shapes to mass:

$$D_{\boldsymbol{\ell}} = \frac{\ell_1^2 - \ell_2^2 + 2i\ell_1\ell_2}{|\boldsymbol{\ell}|^2}$$

$$\hat{\kappa}_{\boldsymbol{\ell}} = D_{\boldsymbol{\ell}}^* \hat{\gamma}_{\boldsymbol{\ell}}$$

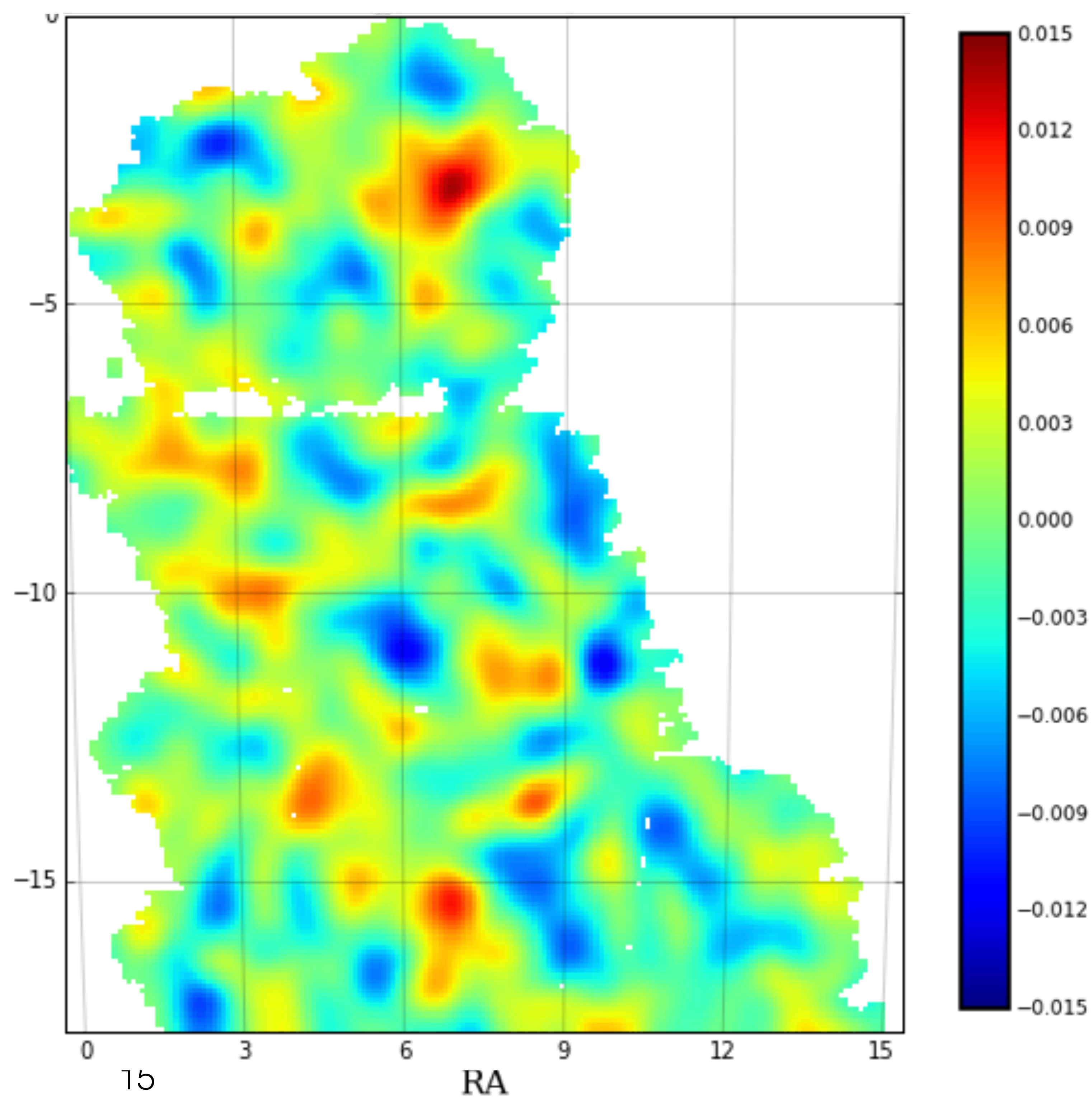
Mass **Galaxy shapes**



Mapping Dark Matter

Simulation is a crucial ingredient in cosmological analyses, since many of the analysis steps are **heavily non-linear** and **couples with one another.**

```
scipy.ndimage
scipy.fftpack
scipy.signal
astropy.io
astropy.wcs
numpy.random
numpy.ma
```



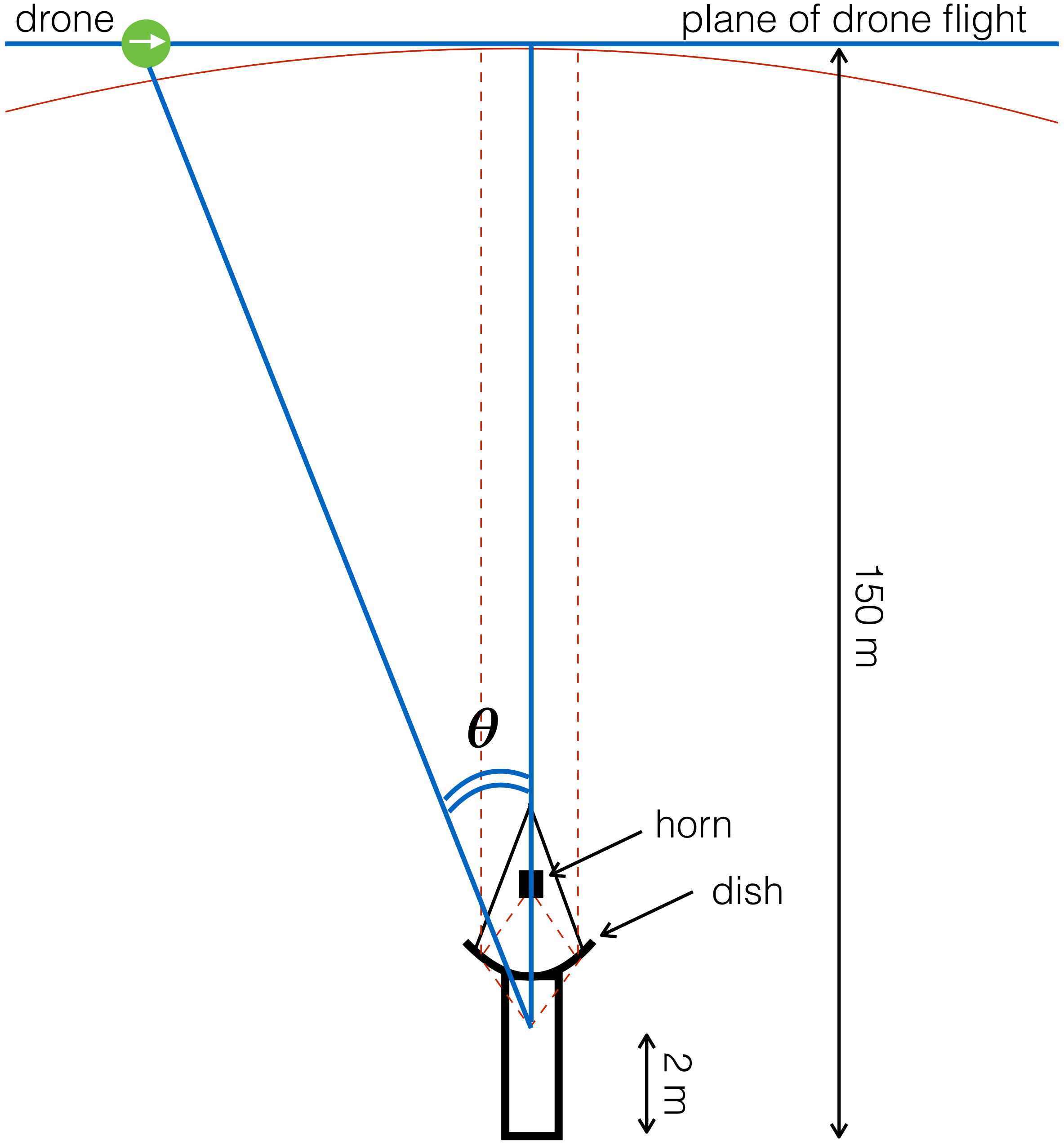
Summary: Mapping Dark Matter

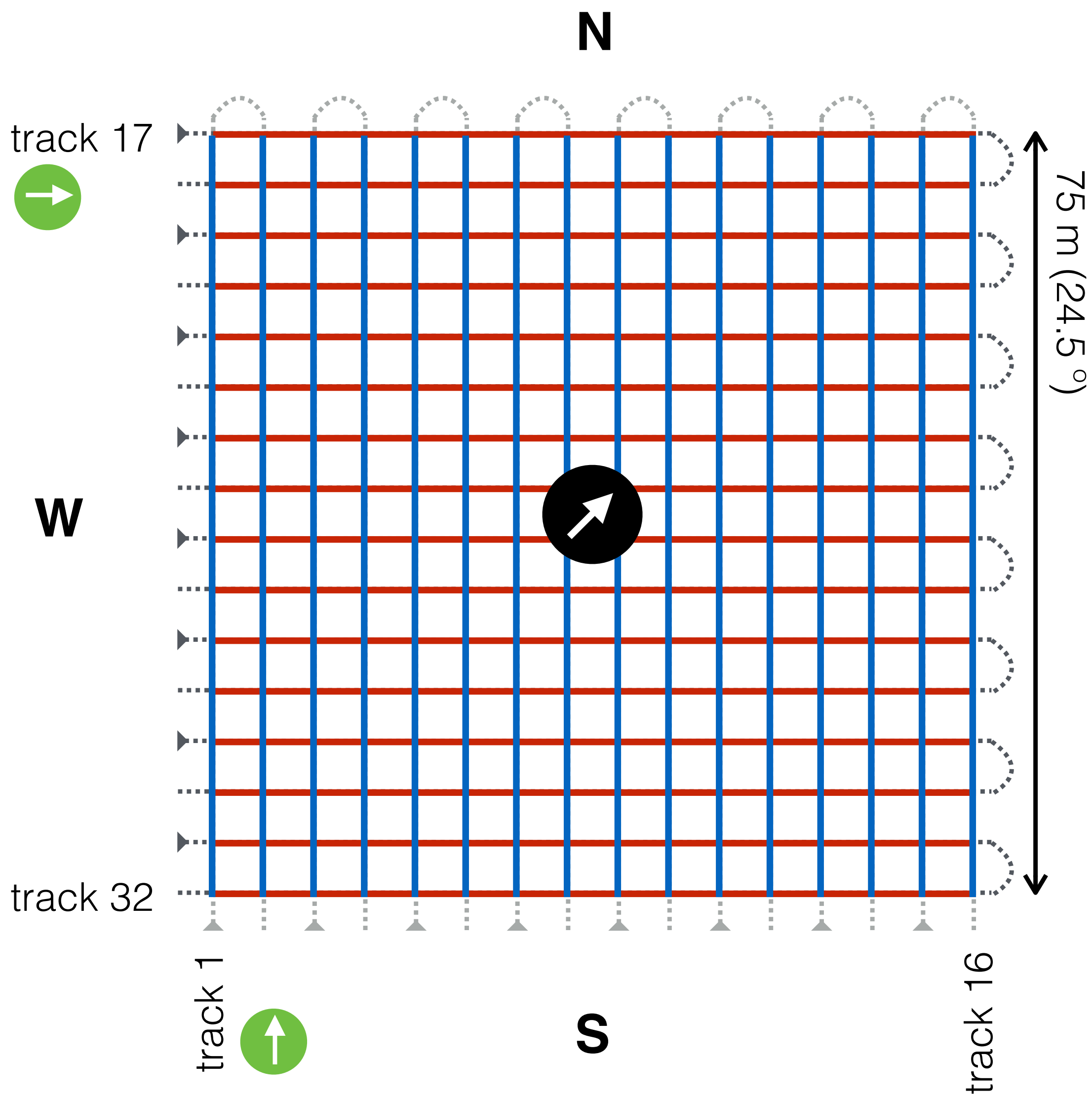
- **Weak gravitational lensing** is a tool we use to extract information about **Dark Matter**, and the name of the game is **measuring galaxy shapes**.
- The lensing community uses a lot of inspirations from the **computing and statistics community**.
- We used data from the **Dark Energy Survey** to make Dark Matter maps.

Radio Telescope Calibration

- The **Bleien Observatory**, operated by the ETH Cosmology group
- Gränichen, Switzerland (50 min outside Zürich), in a farm…
- 5m and 7m single-dish telescopes
- Before doing science, we need to **calibrate** our telescope, i.e. understand how our instrument responses to the incoming signal.

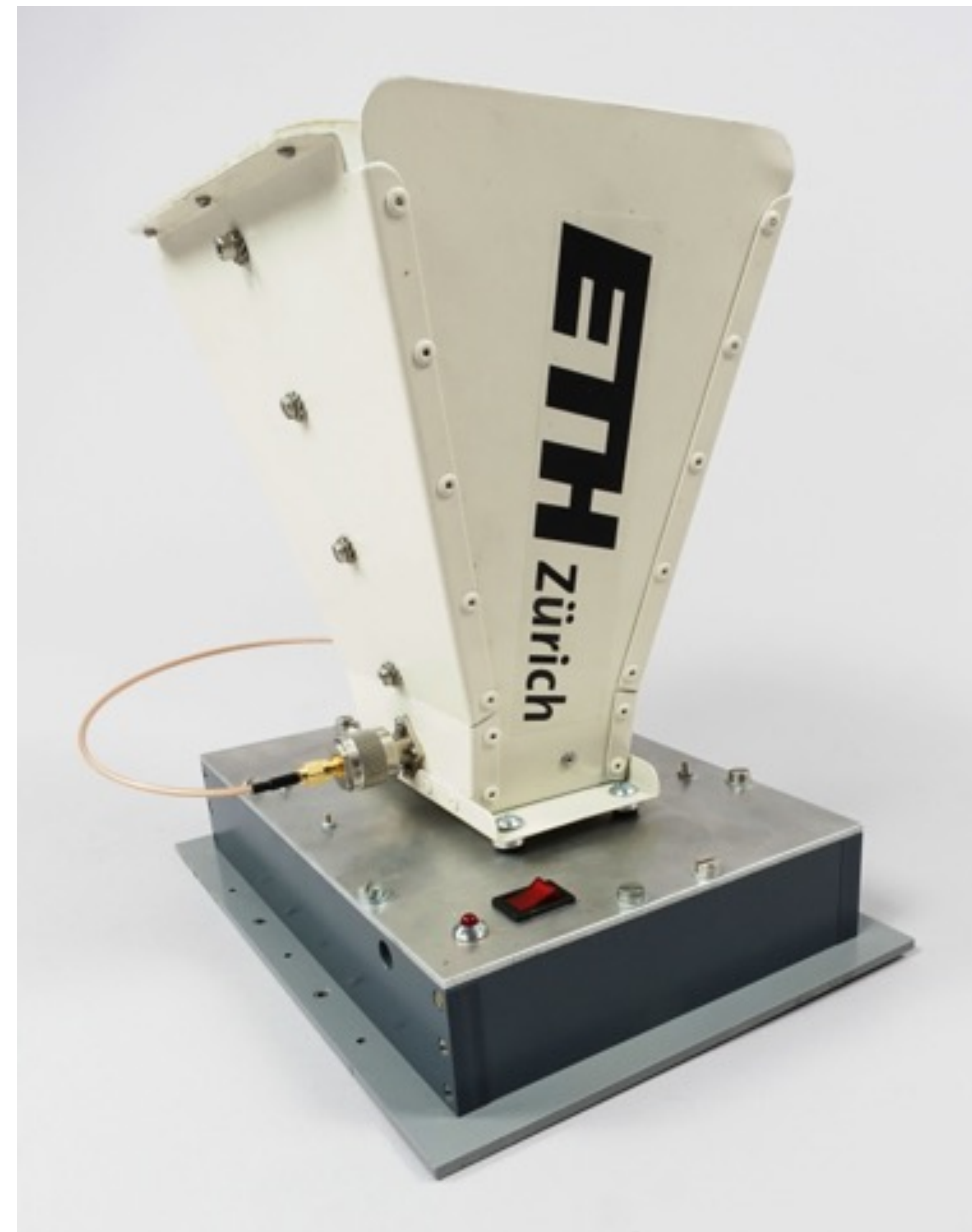
The Drone Experiment





The Drone Experiment

Image credit: Koptershop

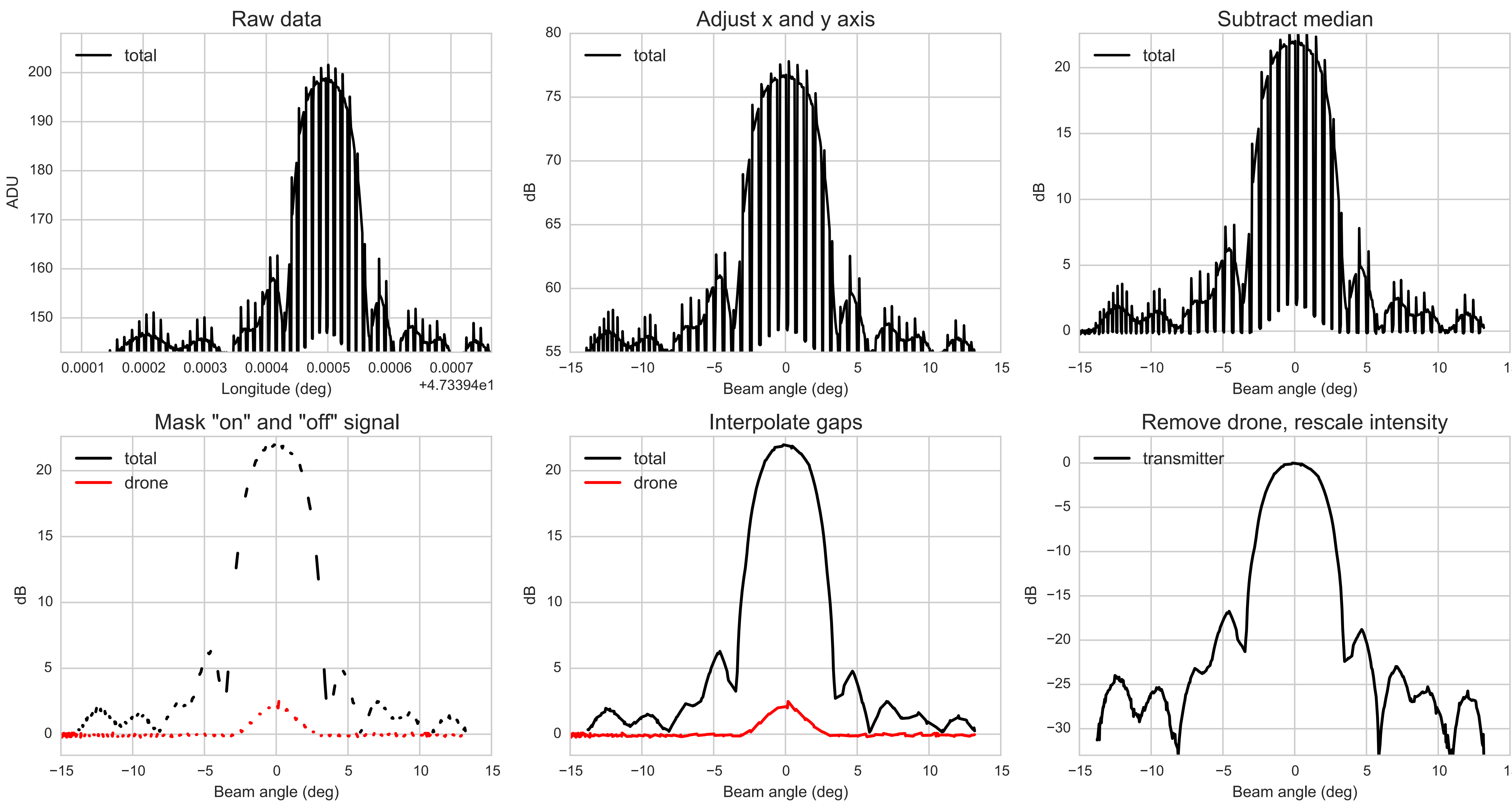


Total weight: 10.9 kg (<2 kg load)
Max. flight time: 13.5 min

The Computational Challenge

- Interface between inhomogeneous and messy data, tools and people — **communication and sharing results**.
- **Spontaneous improvisation** and **exploration of data** — you figure out things on the way.
- **Plotting** is very important!
- All of this means a lot of **IPython notebooking**…

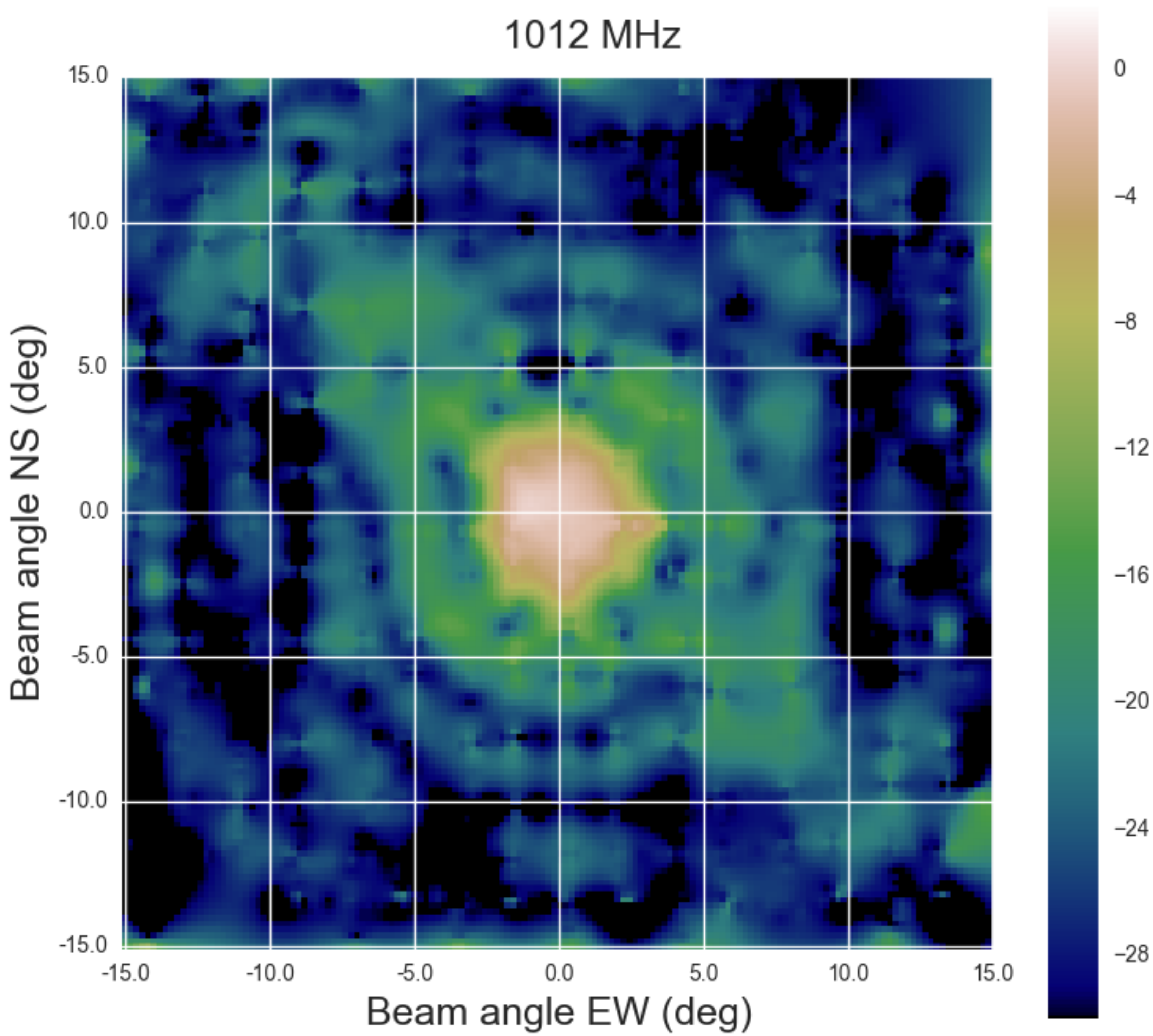
Analysis



Raw data
total
ADU
Longitude (deg)
+4.73394e1
Adjust x and y axis
Beam angle (deg)
dB
Subtract median
Mask "on" and "off" signal
drone
Interpolate gaps
Remove drone, rescale intensity
transmitter

Results

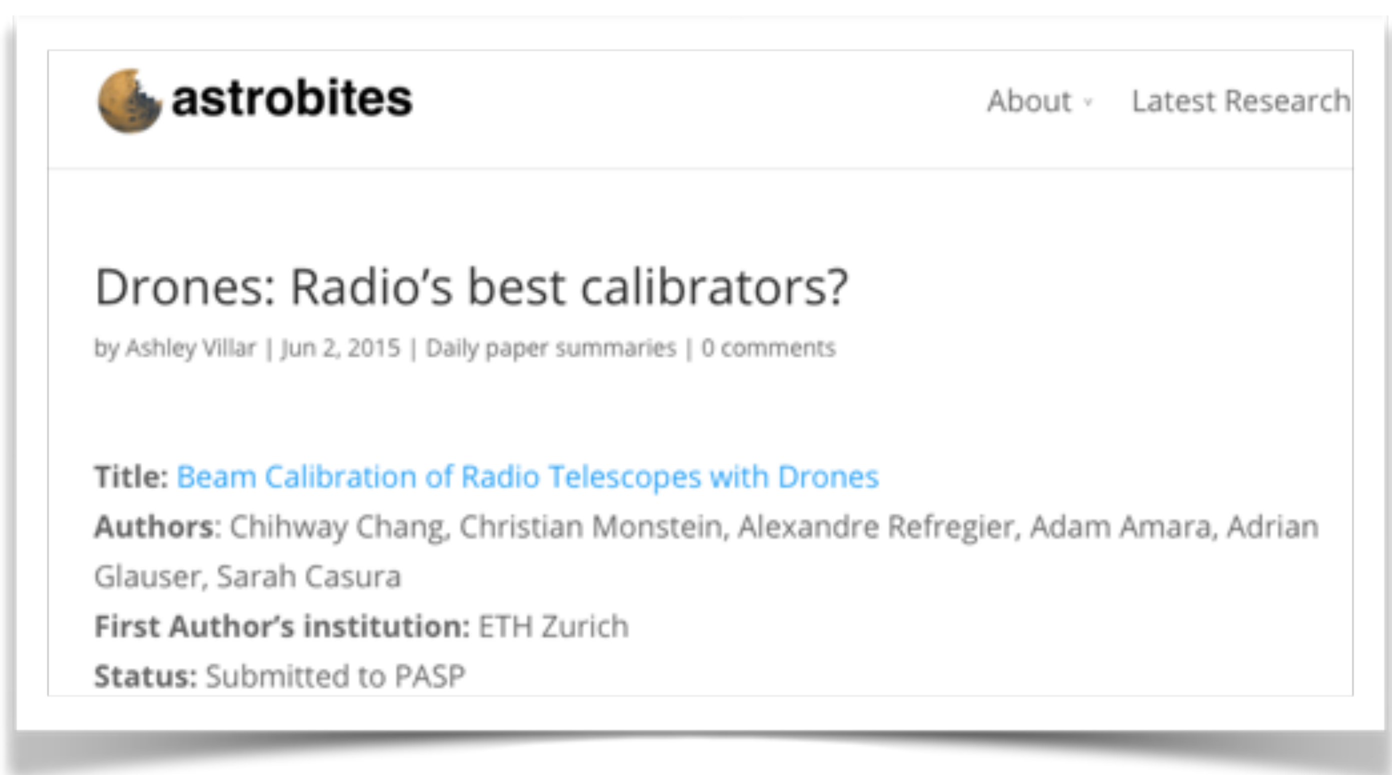
2D maps of the telescope beam profile with very high S/N




```
scipy.interpolate
scipy.special
scipy.optimize
astropy.convolution
seaborn
```

Summary: Radio Telescope Calibration

- The **easy interface** and **interactive nature** of Python allows efficient data exploration and discussion in science.
- In this example of calibrating our radio telescope, **IPython notebook** has been especially useful.
- **Drones** are cool :)


astrobites About Latest Research

Drones: Radio's best calibrators?

by Ashley Villar | Jun 2, 2015 | Daily paper summaries | 0 comments

Title: Beam Calibration of Radio Telescopes with Drones

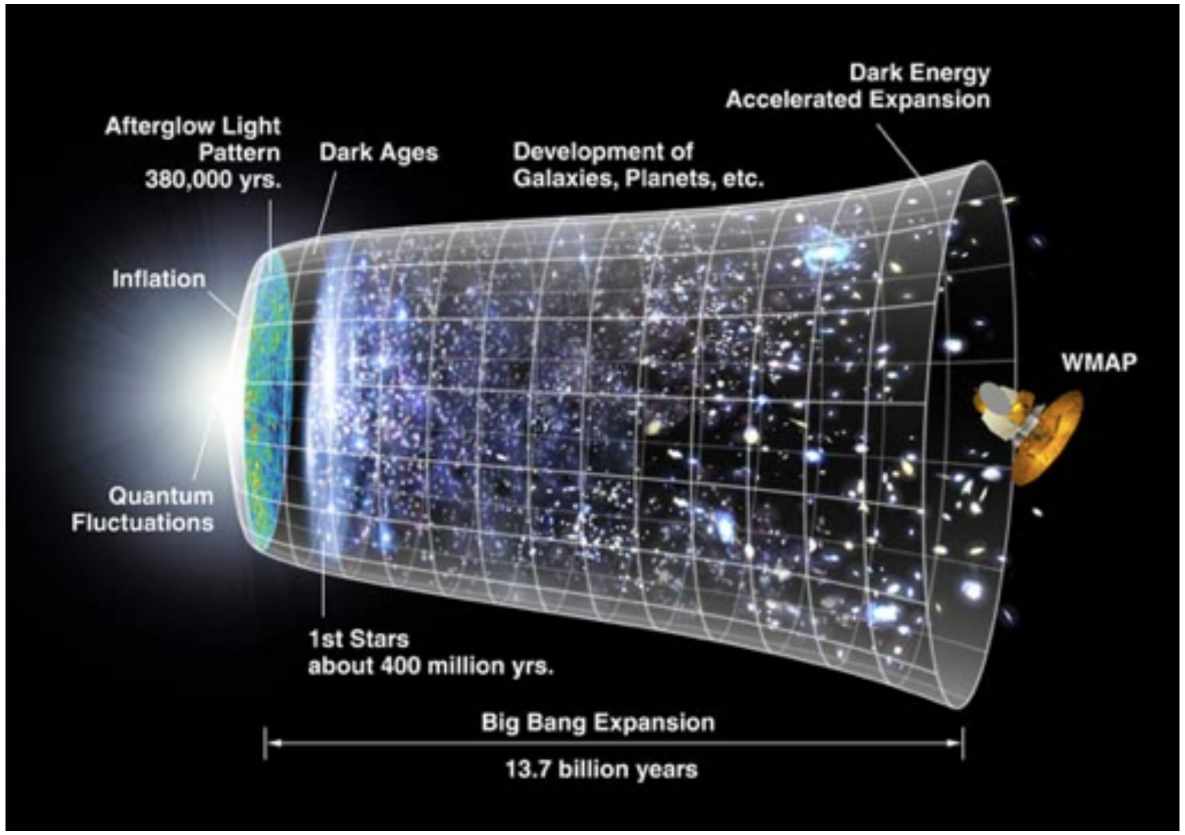
Authors: Chihway Chang, Christian Monstein, Alexandre Refregier, Adam Amara, Adrian Glauser, Sarah Casura

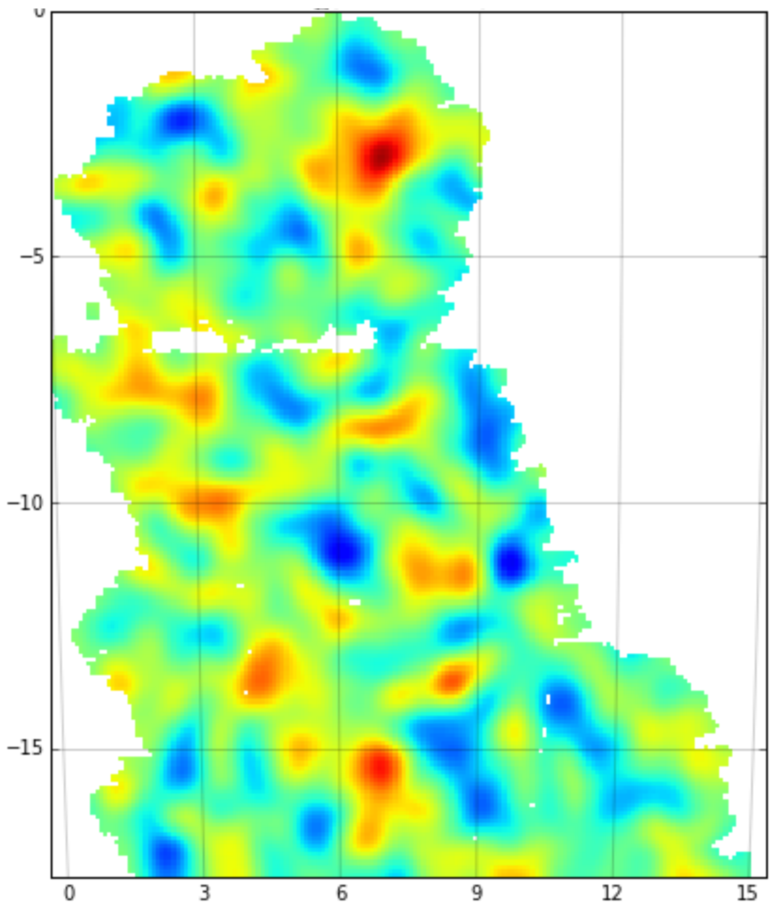
First Author's institution: ETH Zurich

Status: Submitted to PASP

Take-Home Message

There is a lot of stuff lying between **us** and the vast **cosmos**, most of which can be solved using **Python**.





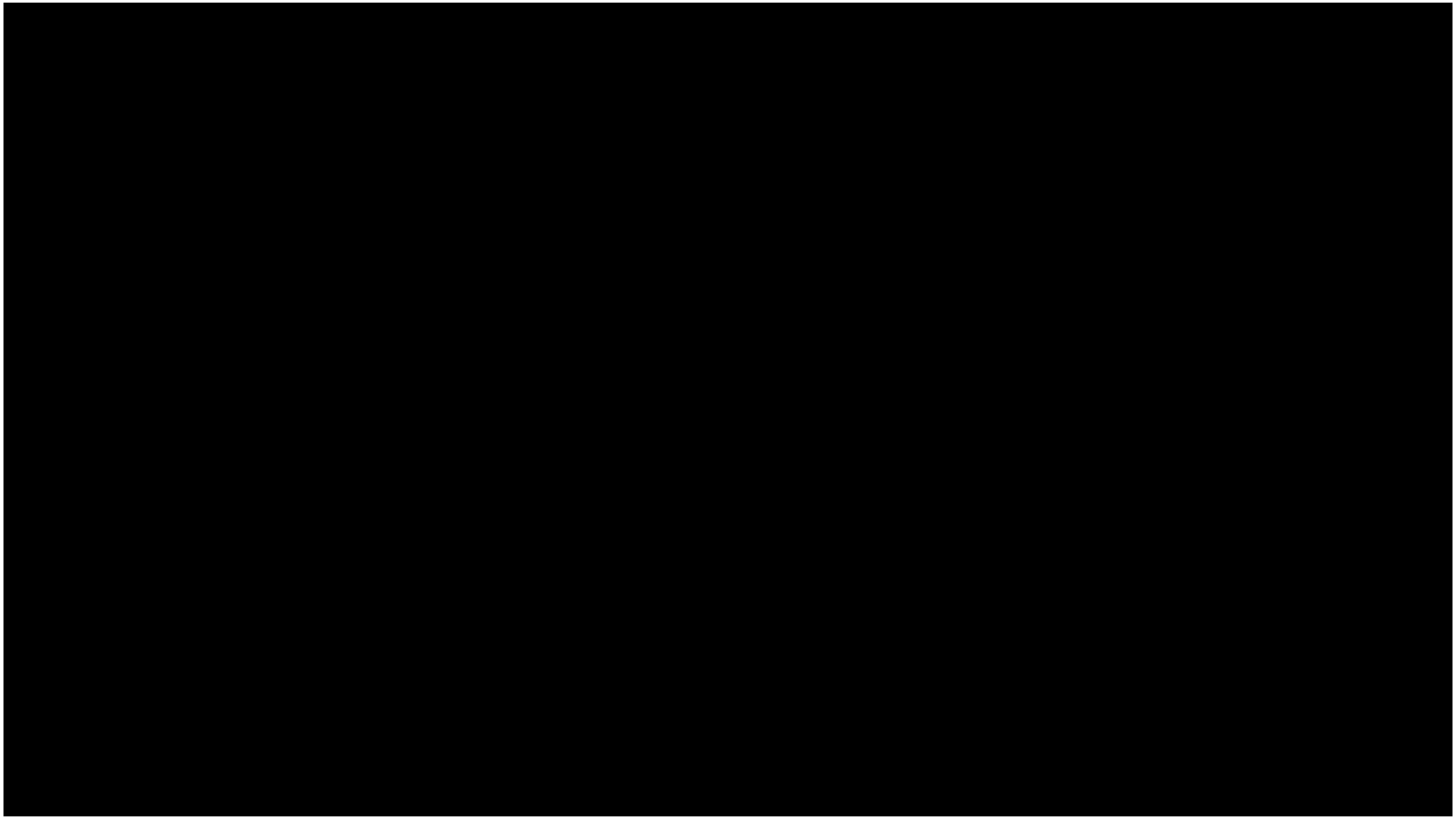
Cool People I Work with…

The ETH Cosmology Group

Other Dark Energy Survey Collaborators

Vinu Vikram (Argonne National Lab, USA)
Bhuvnesh Jain (University of Pennsylvania, USA)
David Bacon (University of Portsmouth, UK)

Drone in Action



Backup Slides

Gravitational Lensing

Theory and observable:

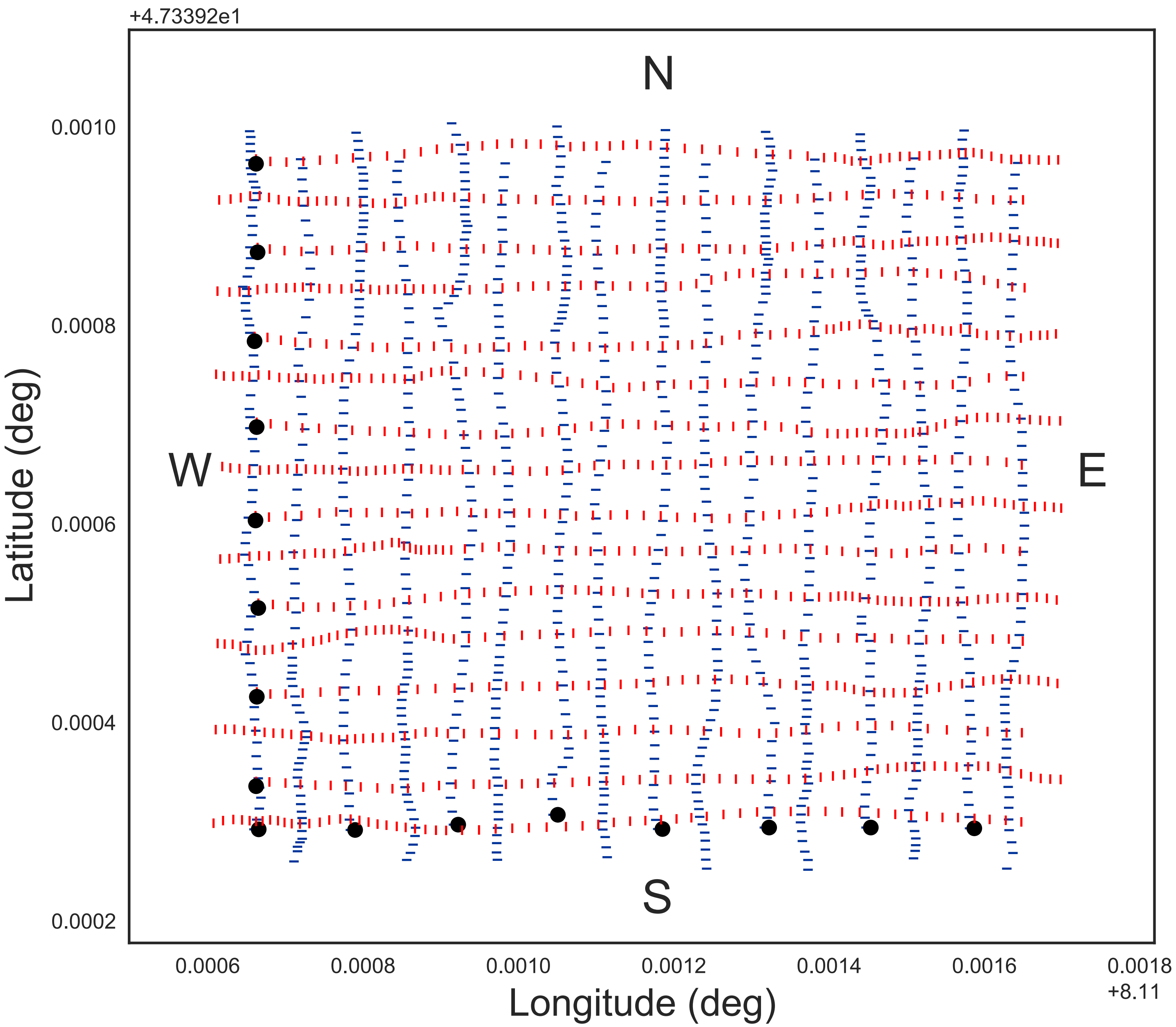
Lensing potential	$\psi(\boldsymbol{\theta}, r) = 2\int_0^r \mathrm{d}r' \frac{r-r'}{rr'} \Phi(\boldsymbol{\theta}, r')$
Deflection	$\alpha = \nabla\psi$
Convergence	$\kappa = \frac{1}{2}\nabla^2\psi = \frac{1}{2}(\psi_{,11} + \psi_{,22})$

Mass (what we care about)

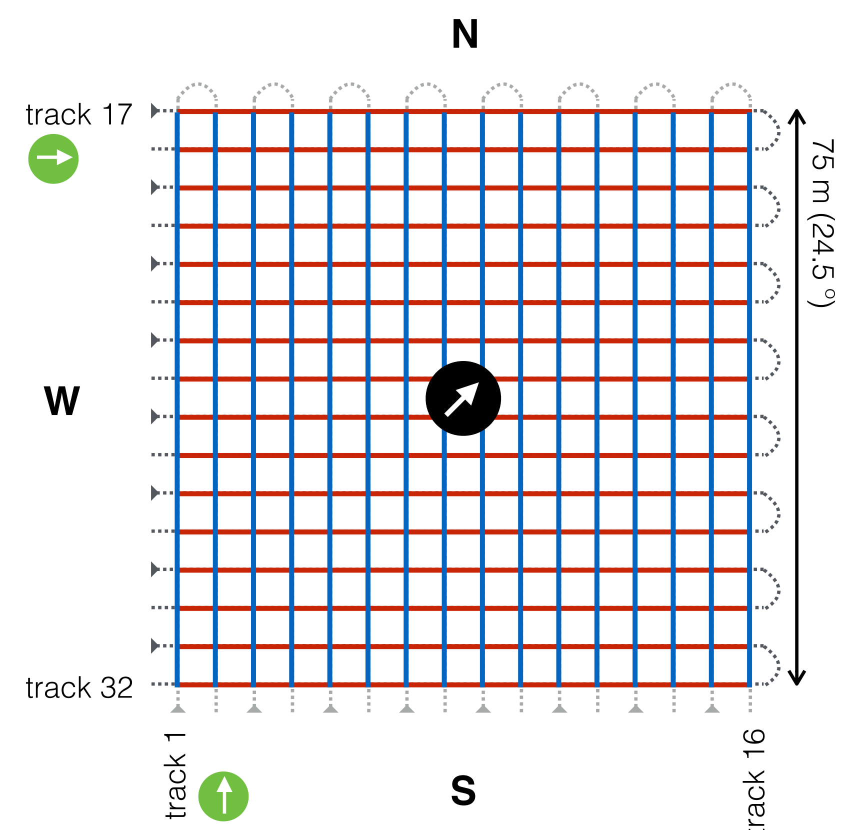
Shear	$\gamma = \gamma_1 + i\gamma_2 = \frac{1}{2}(\psi_{,11} - \psi_{,22}) + i\psi_{,12}$

Distortion (what we can measure)

Analysis

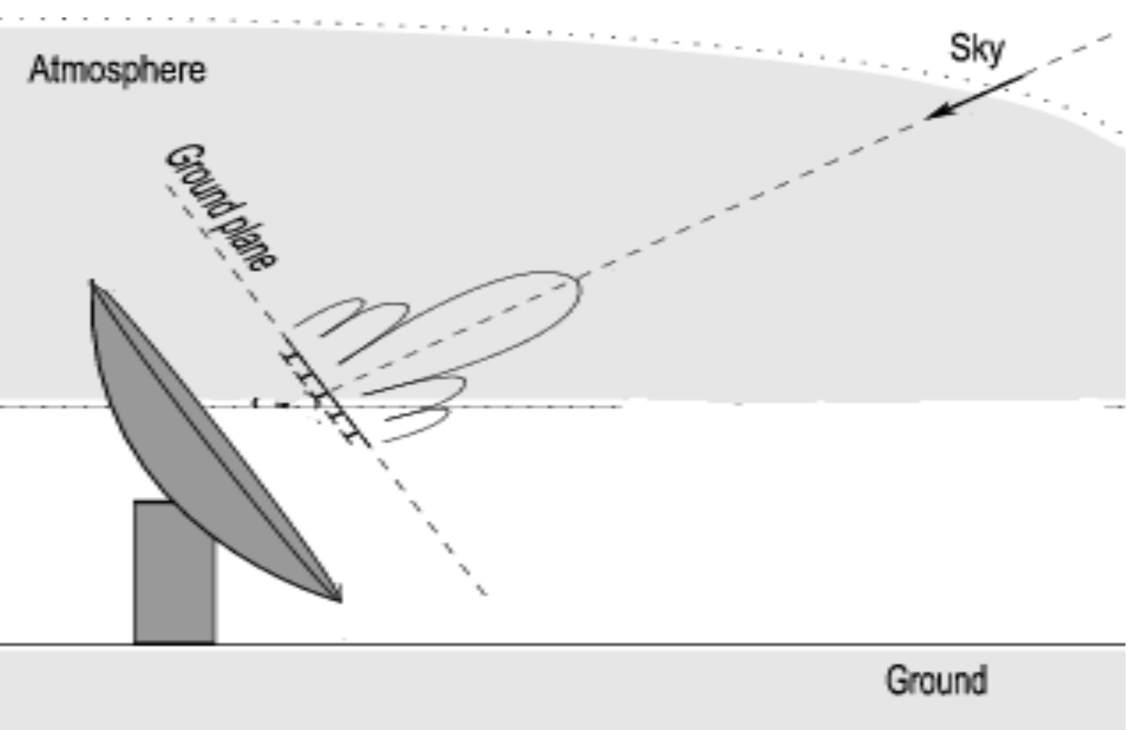


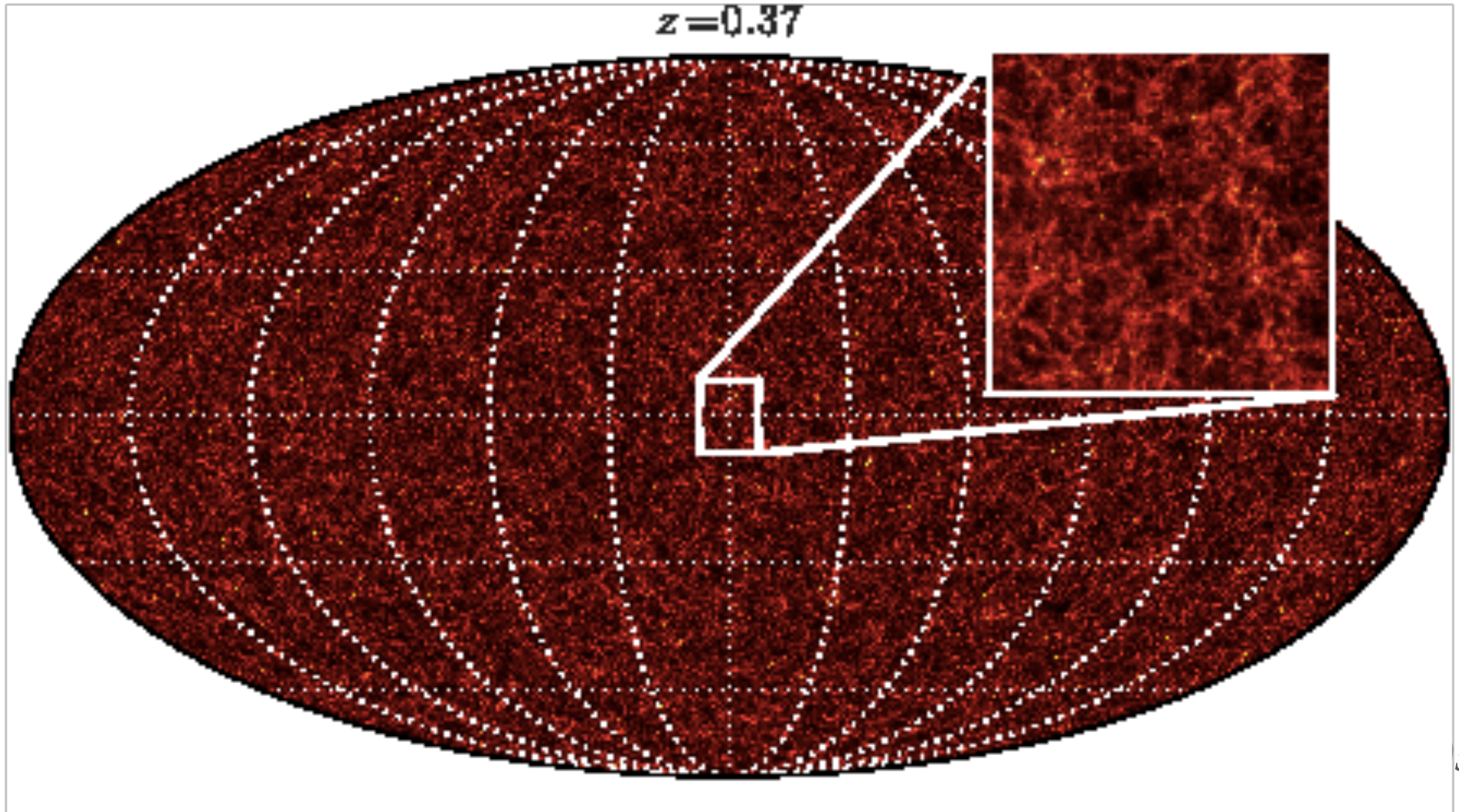
Positioning:
GPS + barometric altimeter



Radio Telescope Calibration

- Now we want to make another map, this is a map of **non-dark** hydrogen, but not in the visible wavelength — we map in the **radio wavelength (20~30 cm)**.
- Before doing that, we need to **calibrate** our telescope, i.e. understand how our instrument responses to the incoming signal.





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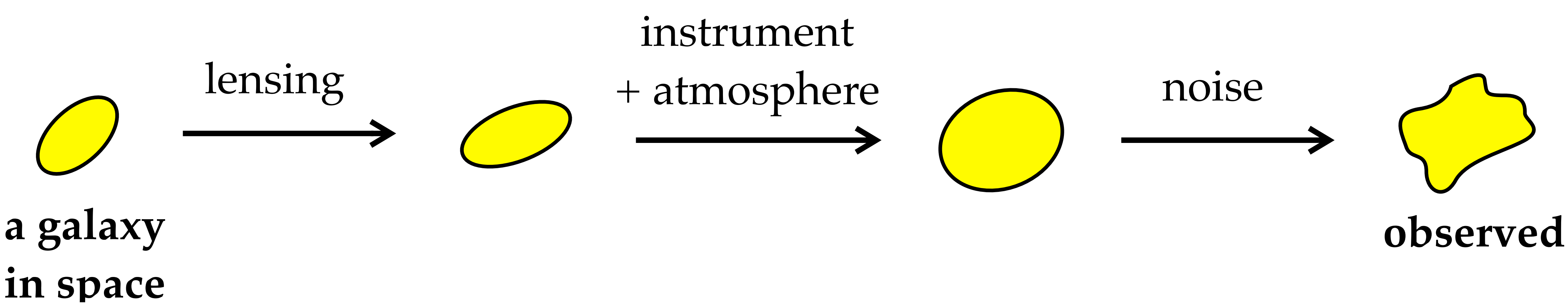
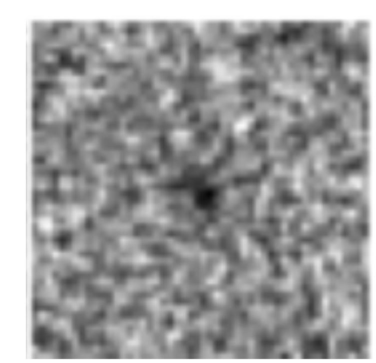


~100,000,000 x 

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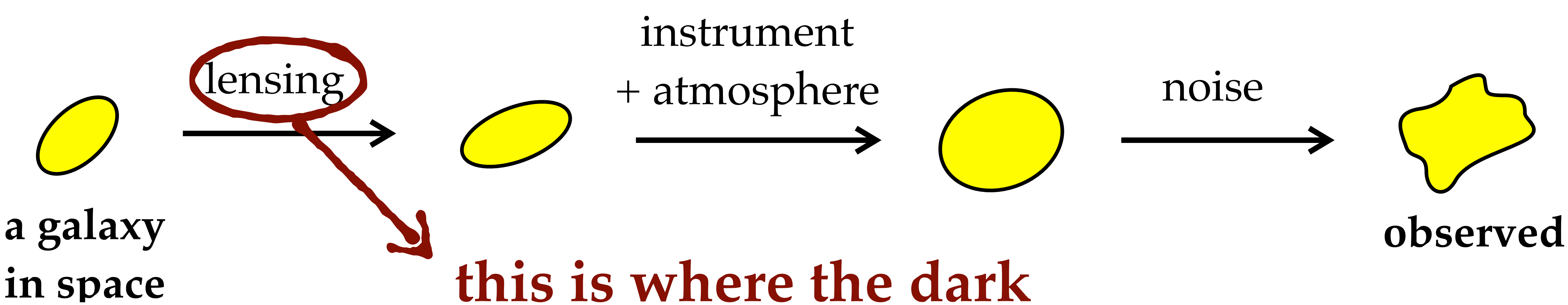
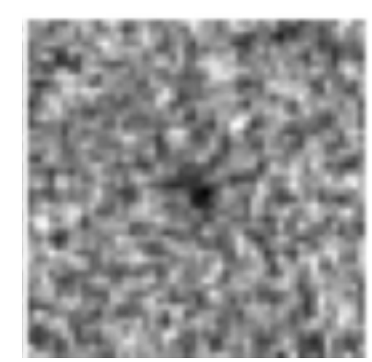


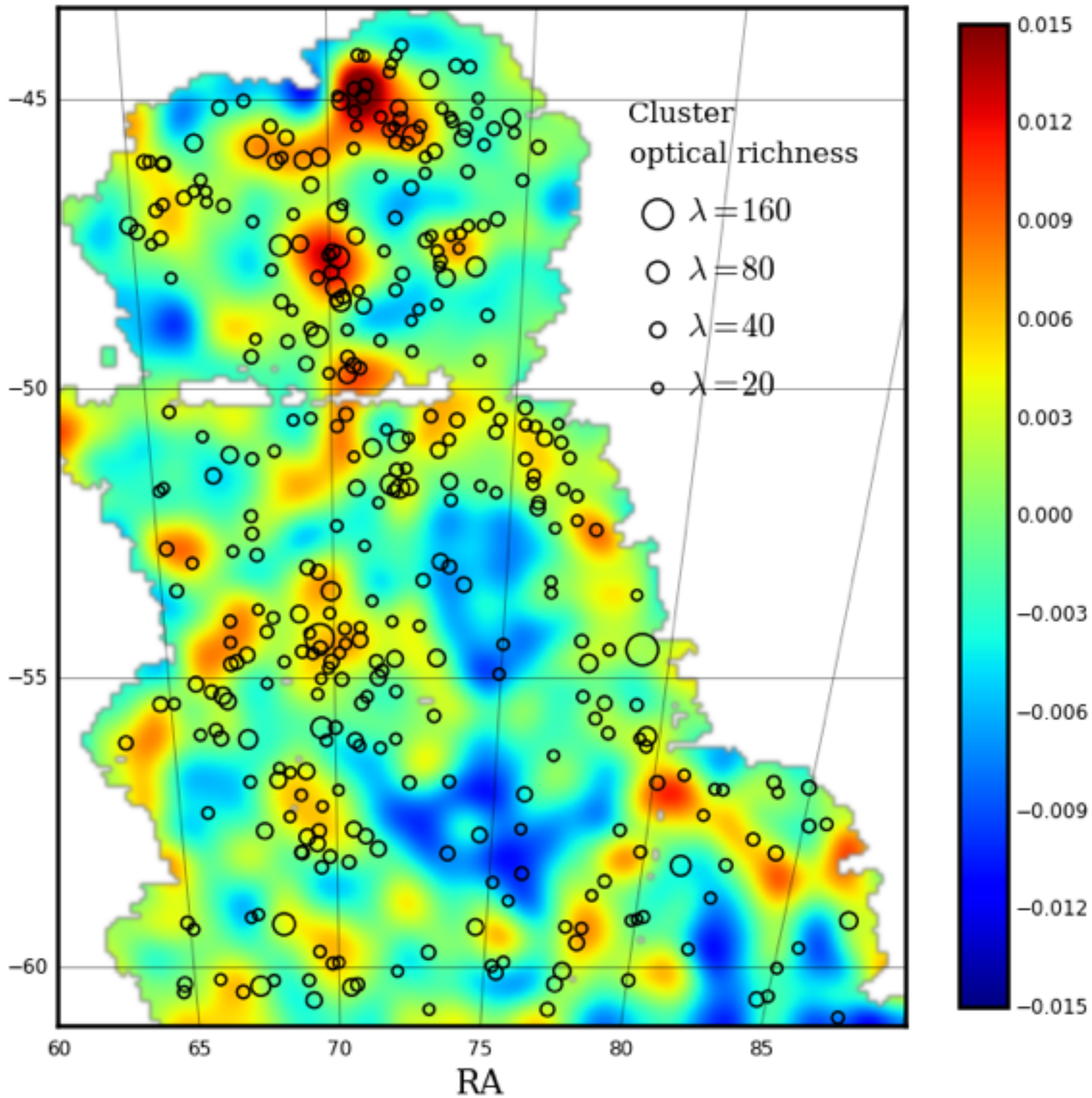
this is where the dark matter information is — a 1% effect!

~100,000,000 x 

Mapping Dark Matter

Compare with distribution of visible mass.

Galaxy clusters: the most massive gravitationally bound systems in the Universe



From Astrophysics to Cosmology

- Astrophysics is the branch of astronomy that employs the principles of physics and chemistry "to ascertain the nature of the heavenly bodies, rather than their positions or motions in space.” — Wikipedia
- Cosmology is the study of the origin, evolution, and eventual fate of the universe. — Wikipedia