A Cosmic Microwave Background (CMB) fluctuation map showing temperature variations across the sky. The map is color-coded, with red and orange representing warmer regions and blue and purple representing cooler regions. A grid of latitude and longitude lines is overlaid on the map.

# Coding / Decoding the Cosmos:

## Python Applications in Astrophysics



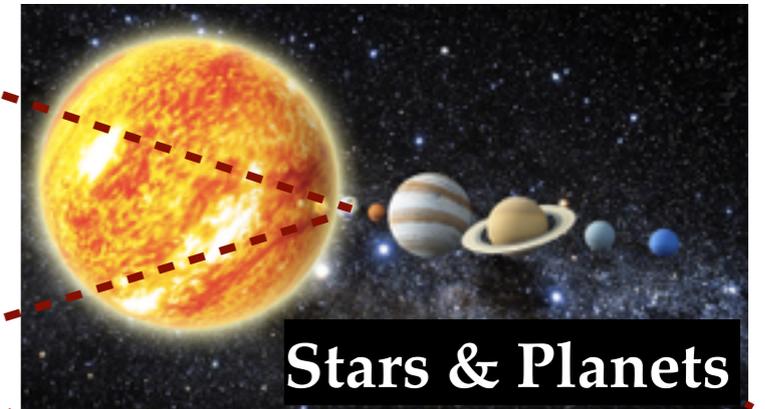
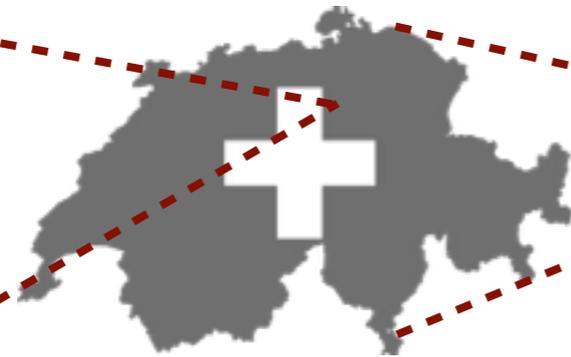
*Chihway Chang (ETH Zürich)*

**ETH** | Cosmology

# DISCLAIMER

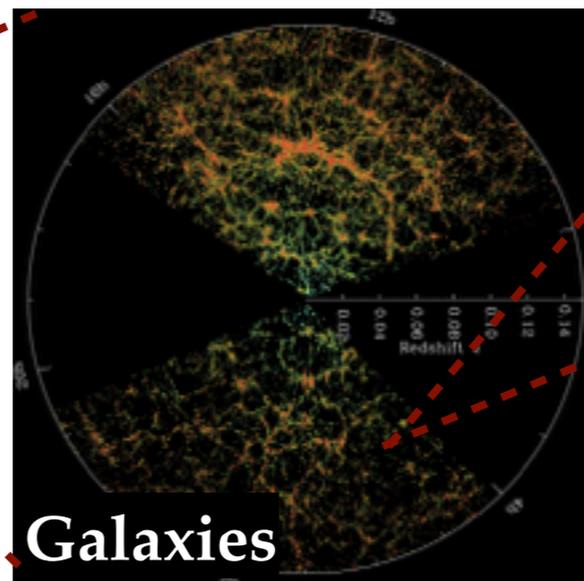
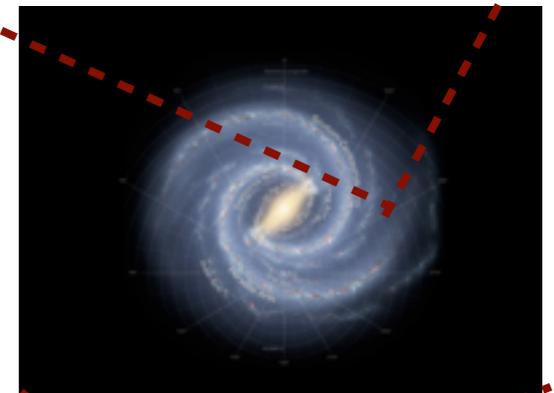
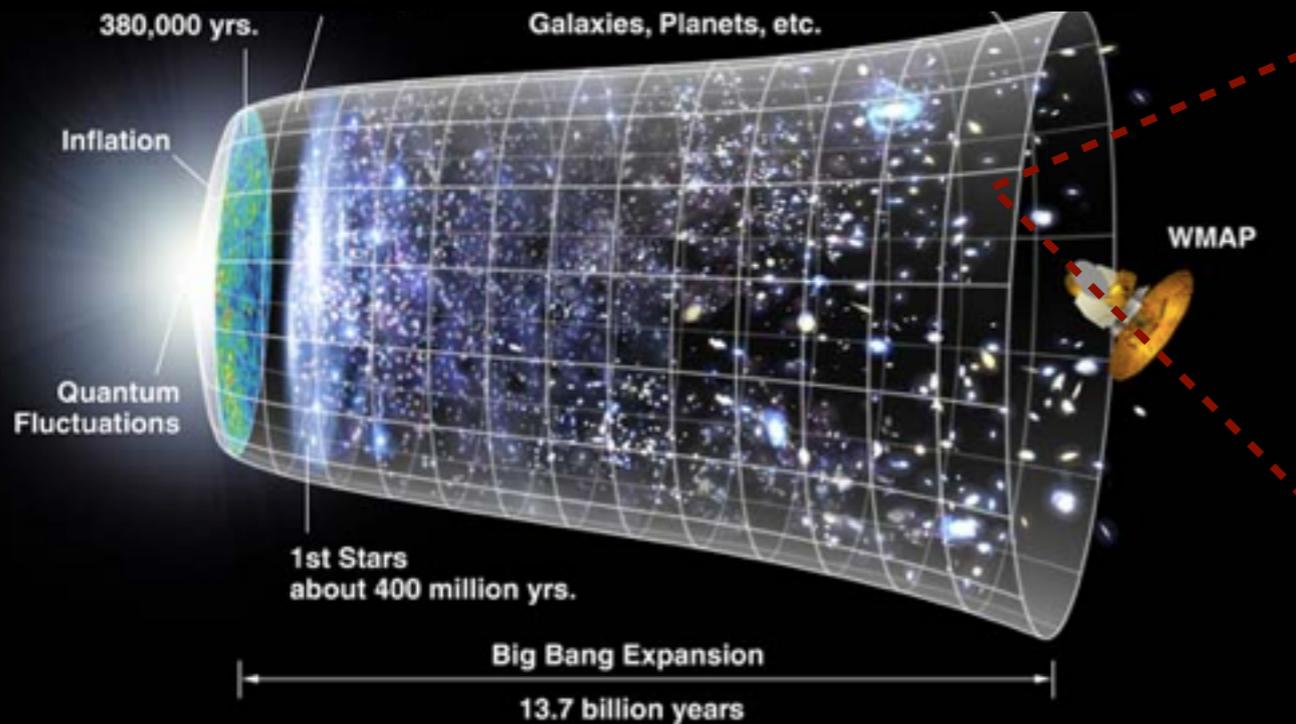
- This is **not** your typical computer-science talk.
- You will probably **not** learn new fancy coding techniques here.
- What you will learn is that you can do a massive amount of **science** with relatively **simple Python**.

# From Astrophysics to Cosmology



Stars & Planets

## Cosmology



Galaxies

# 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](https://github.com/cosmo-ethz/hope)

**CosmoHammer:** Parallel MCMC for HPC clusters  
[/cosmo-ethz/CosmoHammer](https://github.com/cosmo-ethz/CosmoHammer)

**ABCPMC:** Parallel Approximate Bayesian Computation  
[/jakeret/abcpmc](https://github.com/jakeret/abcpmc)



**PynPoint:** Direct imaging of exo-planets  
<http://pynpoint.ethz.ch>

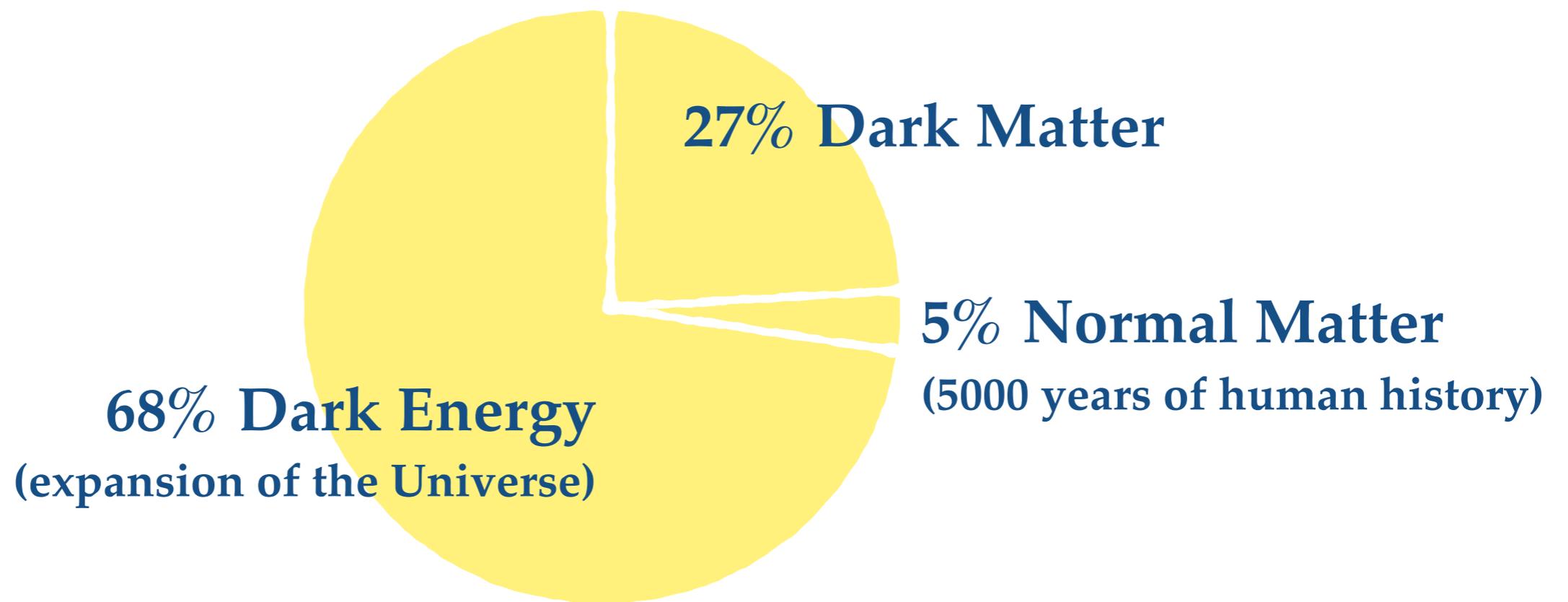
# Two Examples

- **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*

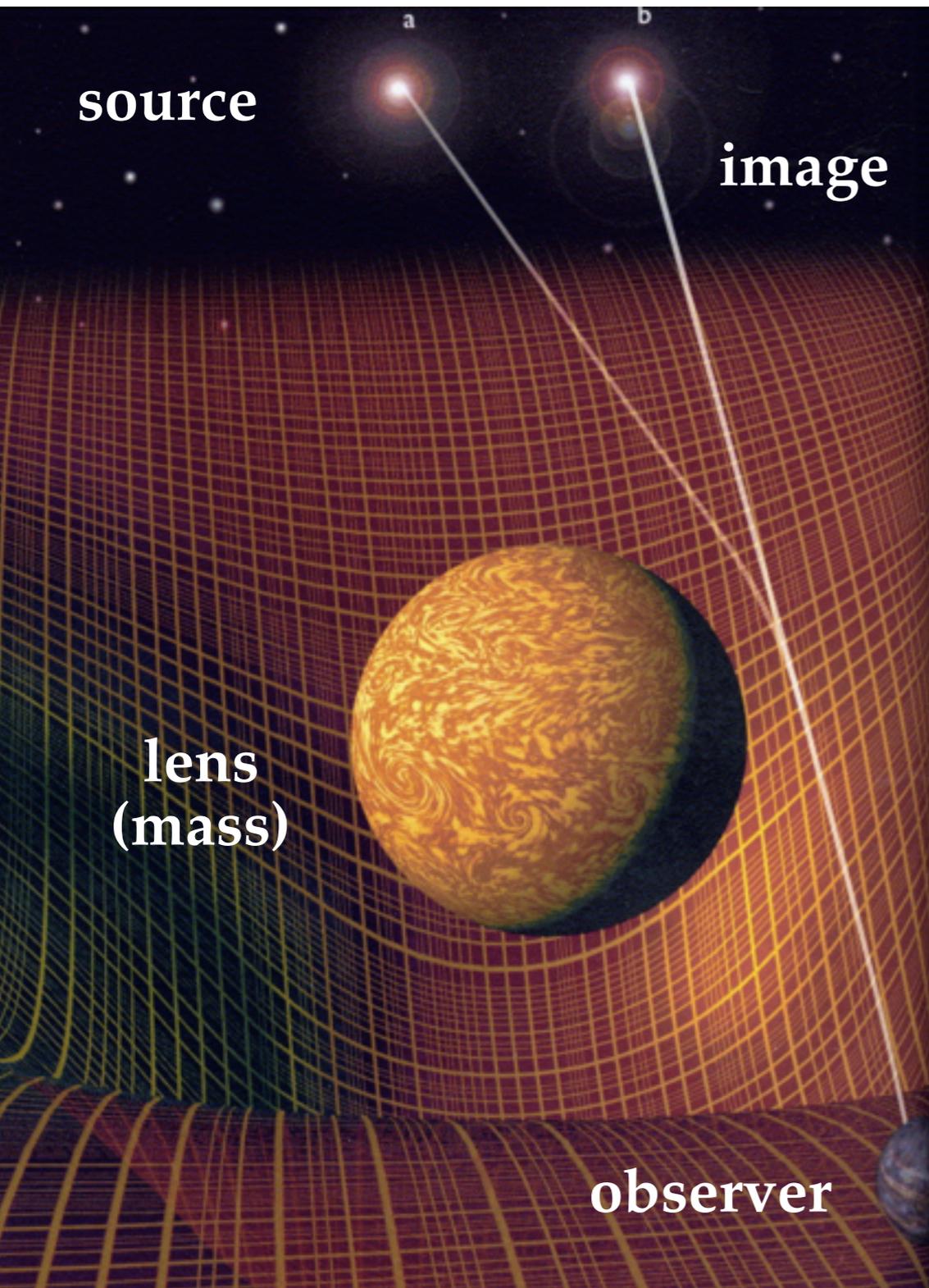


# Mapping Dark Matter

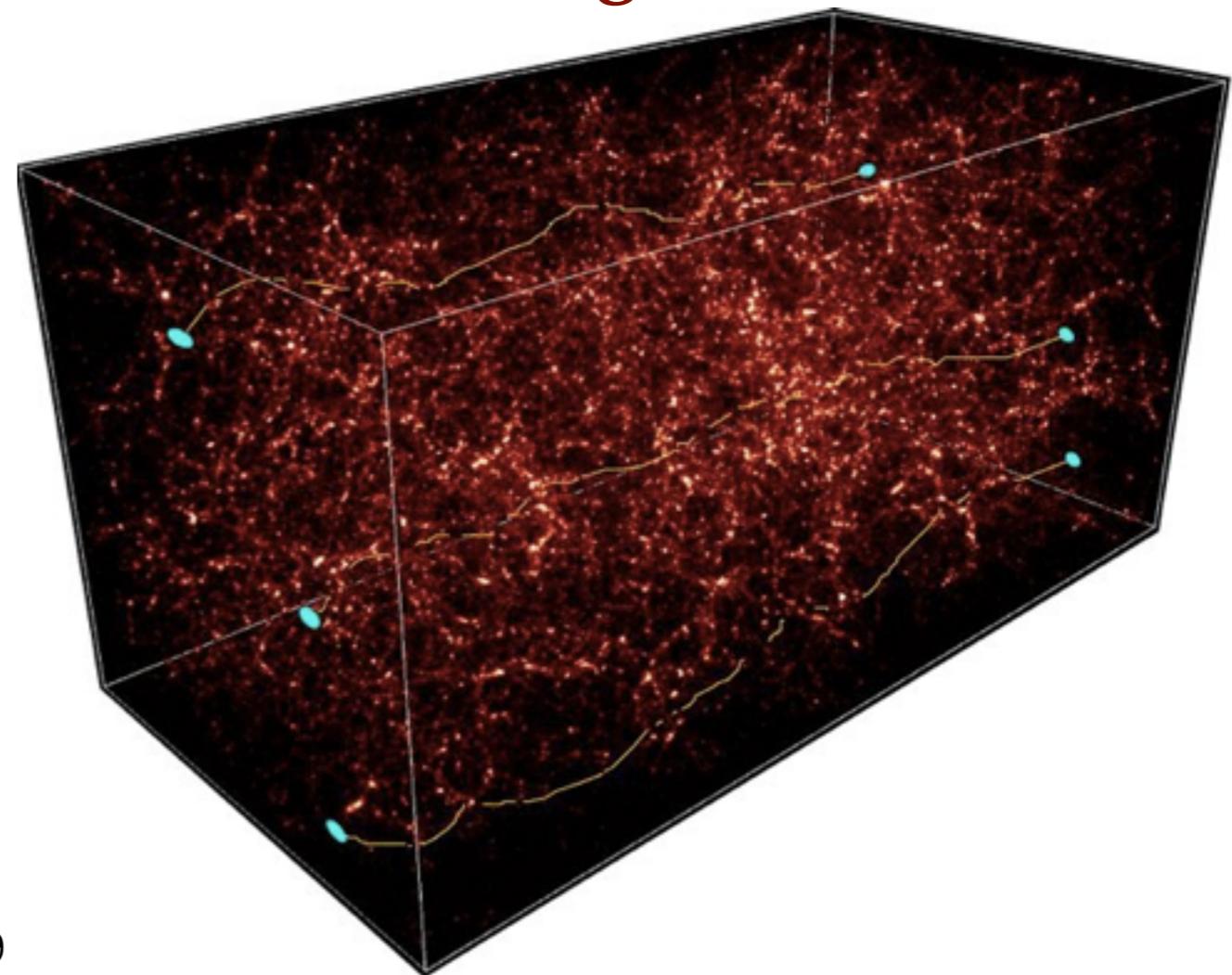
- **We don't know a whole lot about our Universe**, because we cannot **see** most of the stuff in the Universe!



# Gravitational Lensing



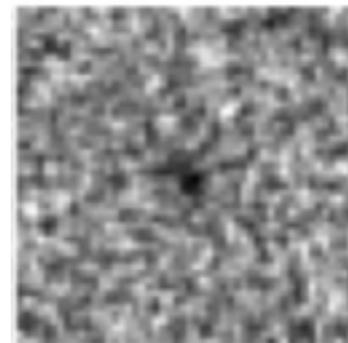
We can *see* dark matter through  
**Gravitational Lensing!**



# The Computational Challenge

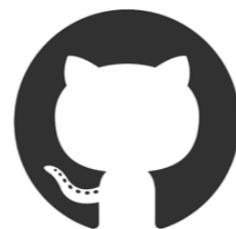
- We want to measure accurately **shapes** of a lot of small, faint, noisy galaxies, and get useful information out of them.

~100,000,000 x



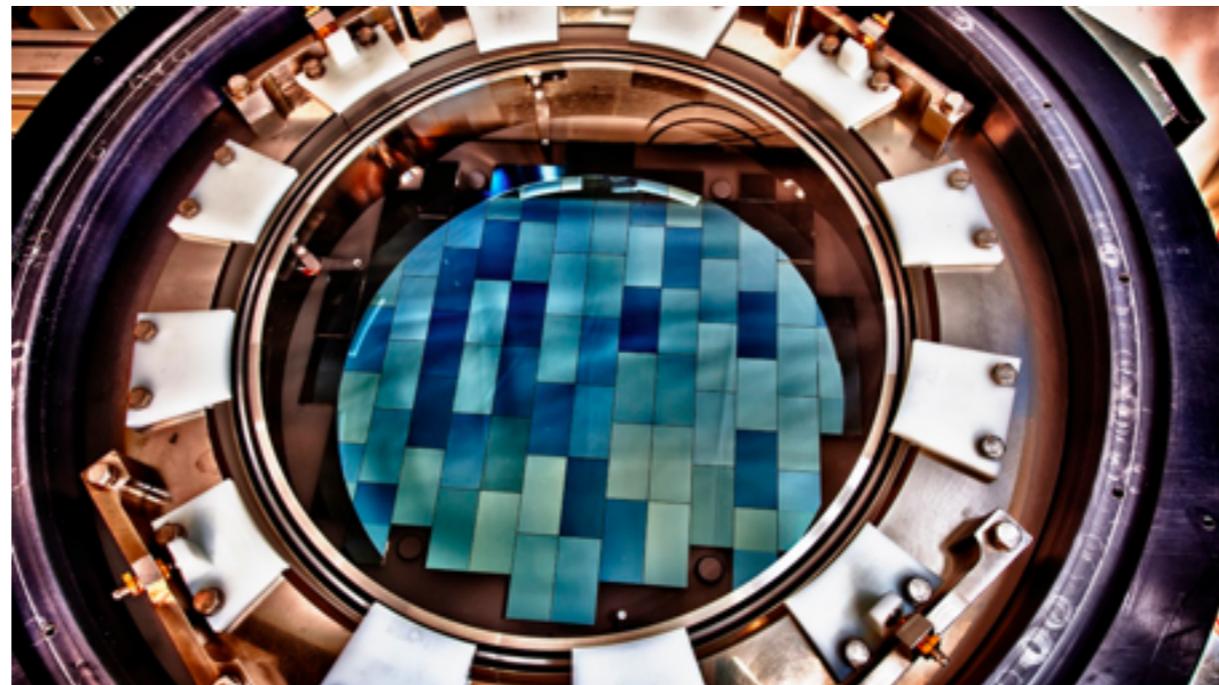
# The Computational Challenge

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

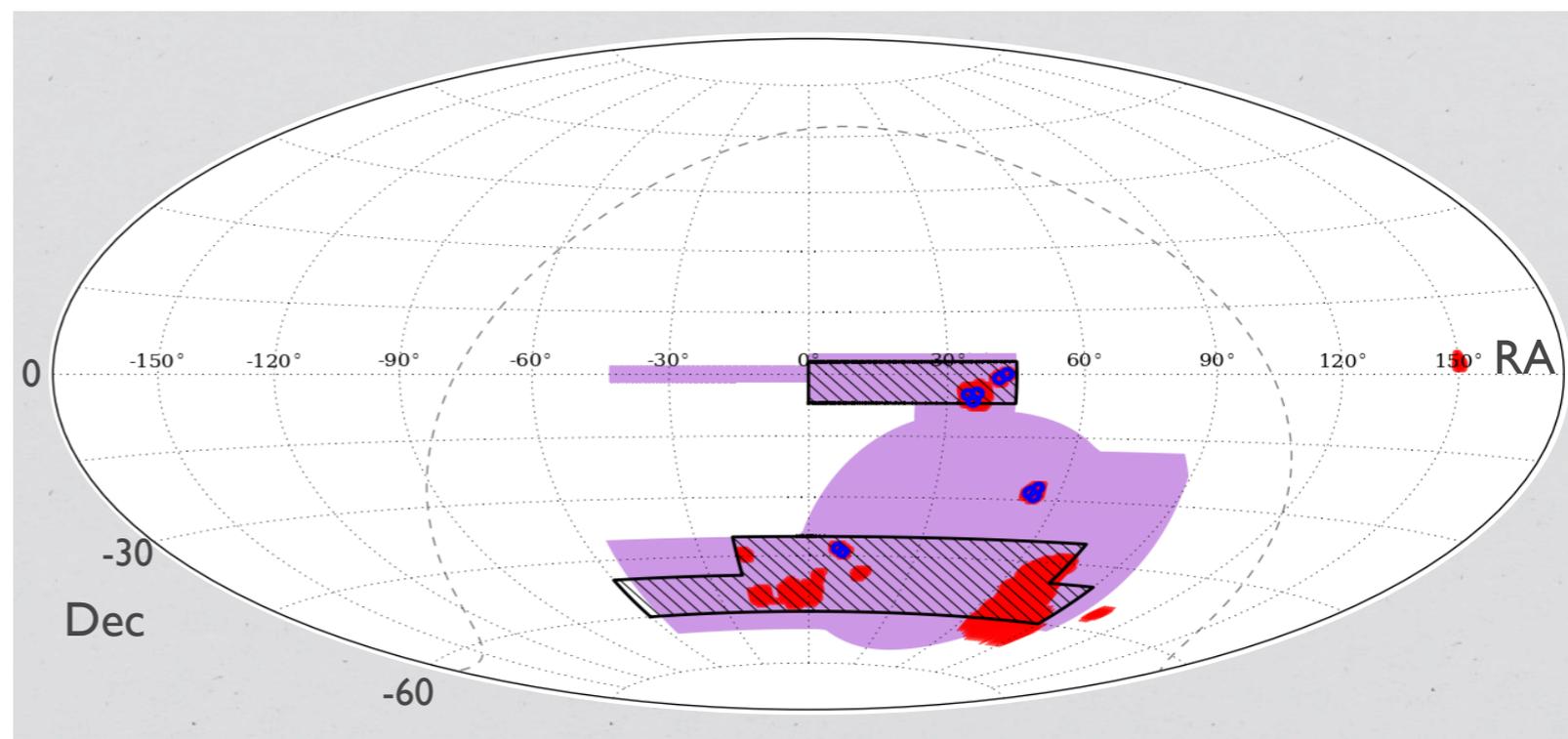


[/barbabytprowe/great3-public](#)  
[/GalSim-developers/GalSim](#)

# The Dark Energy Survey

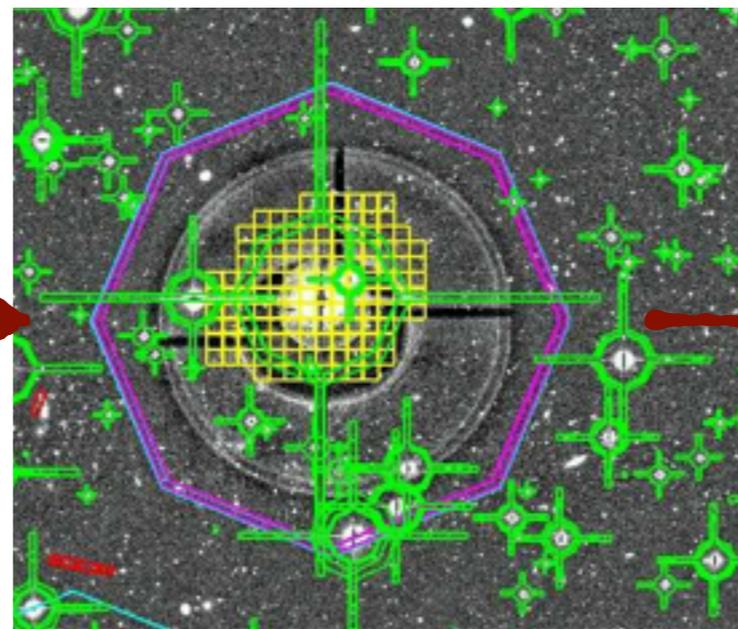
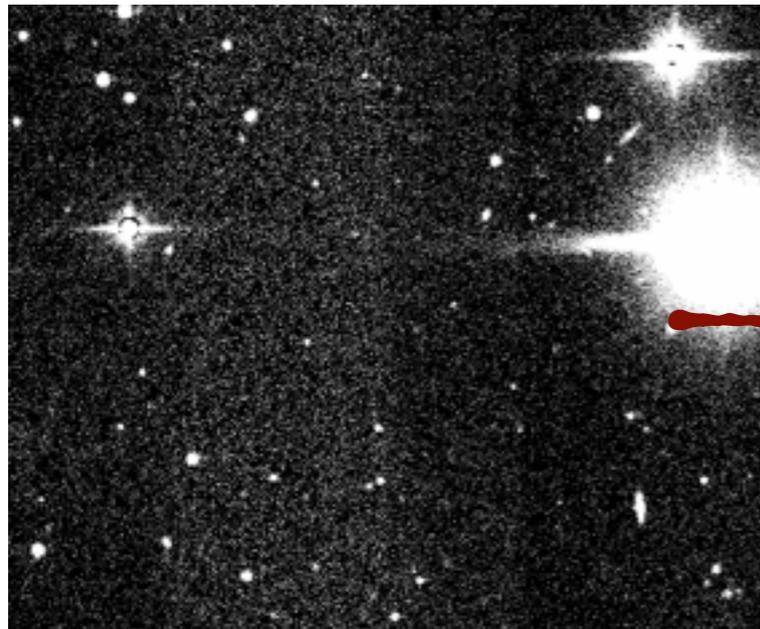


DES is an ongoing **galaxy imaging survey** and will cover **5000 sq. degrees** over 5 years



# The Dark Energy Survey

- The data processing pipeline (partially Python)



NCC 3938	11 57 49.4	+44 07 15	SAc	...	809	12.2	5.4 ± 4.9	-20.1	112	0.46	0.1
NCC 4129	12 08 06.0	+65 32 27	IRsp	...	1196	21.4	9.8 ± 3.2	-25.6	...	0.03	0.1
NCC 4236	12 16 42.3	+69 27 45	SB(rs)m	...	9	3.5	21.9 ± 3.2	-18.1	176	0.08	0.4
NCC 4294	12 18 49.6	+14 24 59	SAc	...	2407	20.0	9.4 ± 4.7	-21.6	277	1.02	0.1
NCC 4321	12 22 54.8	+15 49 21	SAB(rs)c	L	1971	20.0	7.4 ± 6.5	-22.1	283	0.93	0.1
NCC 4480	12 28 29.6	+17 05 06	SABs	L	1954	20.0	9.2 ± 3.9	-21.4	290	0.07	0.1
NCC 4536	12 34 23.1	+02 11 16	SAB(rs)c	IR	1808	25.0	7.6 ± 3.2	-20.8	337	2.03	0.4
NCC 4552	12 35 39.9	+12 33 22	IR	L	340	20.0	5.1 ± 4.7	-20.8	...	...	...
NCC 4559	12 35 37.7	+27 37 35	SAB(rs)c	IR	816	11.6	10.7 ± 4.4	-21.0	281	0.17	0.4
NCC 4569	12 36 49.8	+13 09 46	SAB(rs)c	L,IRy	-235	20.0	9.5 ± 4.4	-22.0	360	0.22	0.1
NCC 4579	12 37 43.6	+11 49 05	SAB(s)c	L,IRy	1919	20.0	9.9 ± 4.7	-21.8	390	0.17	0.2
NCC 4594	12 39 59.4	-11 37 25	SAa	L,IRy2	1091	13.7	8.7 ± 3.5	-21.5	362	0.16	0.1
NCC 4629	12 41 52.7	+41 16 25	SAB(rs)c	...	809	9.5	2.2 ± 1.9	-17.9	86	0.07	0.1
NCC 4631	12 42 06.0	+32 32 26	SB(s)	...	906	9.0	15.5 ± 2.7	-20.6	320	1.26	0.4
NCC 4725	12 50 26.6	+25 30 05	SAB(rs)c	Sp2	1306	17.1	10.7 ± 7.6	-22.0	410	0.09	0.2
NCC 4736	12 50 53.0	+41 07 16	SAB(s)c	L	308	5.3	11.2 ± 9.1	-19.9	241	0.87	0.3
IC03 154	12 54 05.2	+27 08 59	IRm	...	376	5.4	3.0 ± 2.2	-15.1	105	...	...
NCC 4826	12 56 43.7	+21 40 32	SAB(s)c	Sp2	408	5.6	10.0 ± 9.4	-20.3	311	0.27	0.4
IC03 165	13 06 34.8	+07 42 25	IRm	...	37	3.5	3.5 ± 1.9	-15.3	68	...	...
NCC 5033	13 15 27.5	+36 35 36	SAc	Sp2	875	13.3	10.7 ± 5.0	-20.9	446	0.48	0.1
NCC 5035	13 15 49.3	+42 01 45	SABc	IRL	506	8.2	12.6 ± 7.2	-19.0	405	4.56	0.1
NCC 5104	13 29 52.7	+47 11 43	SAB(rs)c	IRy2	465	8.2	11.2 ± 6.9	-21.4	195	0.60	0.1
NCC 5105	13 29 58.7	+47 16 05	SB(rs)c	L	592	8.2	5.8 ± 4.6	-20.0	...	0.29	0.3
NCC 5108	14 01 21.3	-33 03 47	SB(rs)c	IR	1216	15.0	2.8 ± 1.7	-18.9	117	0.44	0.1
NCC 5408	14 05 20.8	-41 22 40	IRm	...	309	4.5	1.6 ± 0.8	-16.1	134	0.14	0.4
NCC 5474	14 05 01.6	+53 39 44	SAB(s)c	IR	279	6.9	4.8 ± 4.5	-18.4	61	0.10	0.2
NCC 5713	14 40 11.5	-00 17 21	SAB(rs)c	...	1085	26.6	2.8 ± 2.5	-20.9	209	1.70	0.7
NCC 5866	15 06 29.5	+55 45 46	SB	...	692	12.5	4.7 ± 1.9	-19.9	...	0.51	0.1
IC 4707	18 28 38.0	-66 58 36	SB(rs)c	IR	741	8.5	3.6 ± 2.8	-18.3	31	0.20	0.1
NCC 6822	19 44 56.6	-14 47 21	IRm	...	-97	0.6	15.5 ± 13.5	-13.8	81	2.50	0.3
NCC 6846	20 34 52.3	+60 09 14	SAB(rs)c	IR	48	5.3	11.5 ± 9.8	-21.3	242	0.39	0.4
NCC 7131	22 37 06.1	+34 24 56	SA(s)c	L	816	15.7	10.5 ± 3.7	-21.8	330	1.02	0.1
NCC 7592	23 16 11.0	-42 34 59	SAc	SB(s)	1985	22.3	3.4 ± 2.7	-21.7	290	3.20	0.1
NCC 7793	25 37 49.8	-32 35 28	SAB	IR	230	3.2	9.3 ± 6.5	-18.2	196	0.57	0.1

Notes.—Col. (1): ID; Col. (2): The right ascension in the J2000.0 epoch; Col. (3): The declination in the J2000.0 epoch; Col. (4): galaxy; L: LINER; Sp: Seyfert 1; S: Col. (5): Heliocentric velocity; Col. (7): Flow-converted distance in Mpc, for  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ; Col. (8): Absolute  $B$  magnitude, when available, otherwise from the  $V$  or  $R$  bands; Col. (10): 21 cm neutral hydrogen line width; Tully 1980 or RC3; Col. (11): Photometric luminosity ratio; The FR luminosity is derived from the IRAS-measured 60–100  $\mu\text{m}$  flux, is defined as  $L_{\text{FR}} = 4.75 L_{\text{IR}}$ ; Col. (12): The ratio of the IRAS 60  $\mu\text{m}$  to 100  $\mu\text{m}$  flux; Col. (13): The logarithmic atomic gas mass;  $M$  molecular gas mass, from CO integrated fluxes; Col. (15): Star formation rates derived from the emission, with typical  $\Delta \text{H}\alpha = 1$  important codes include 01–11 (the Virgo Cluster) and 14–19 (the M81 group).

- raw data
- calibration
- stacking

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

- “cataloging”
- science analysis

# Mapping Dark Matter

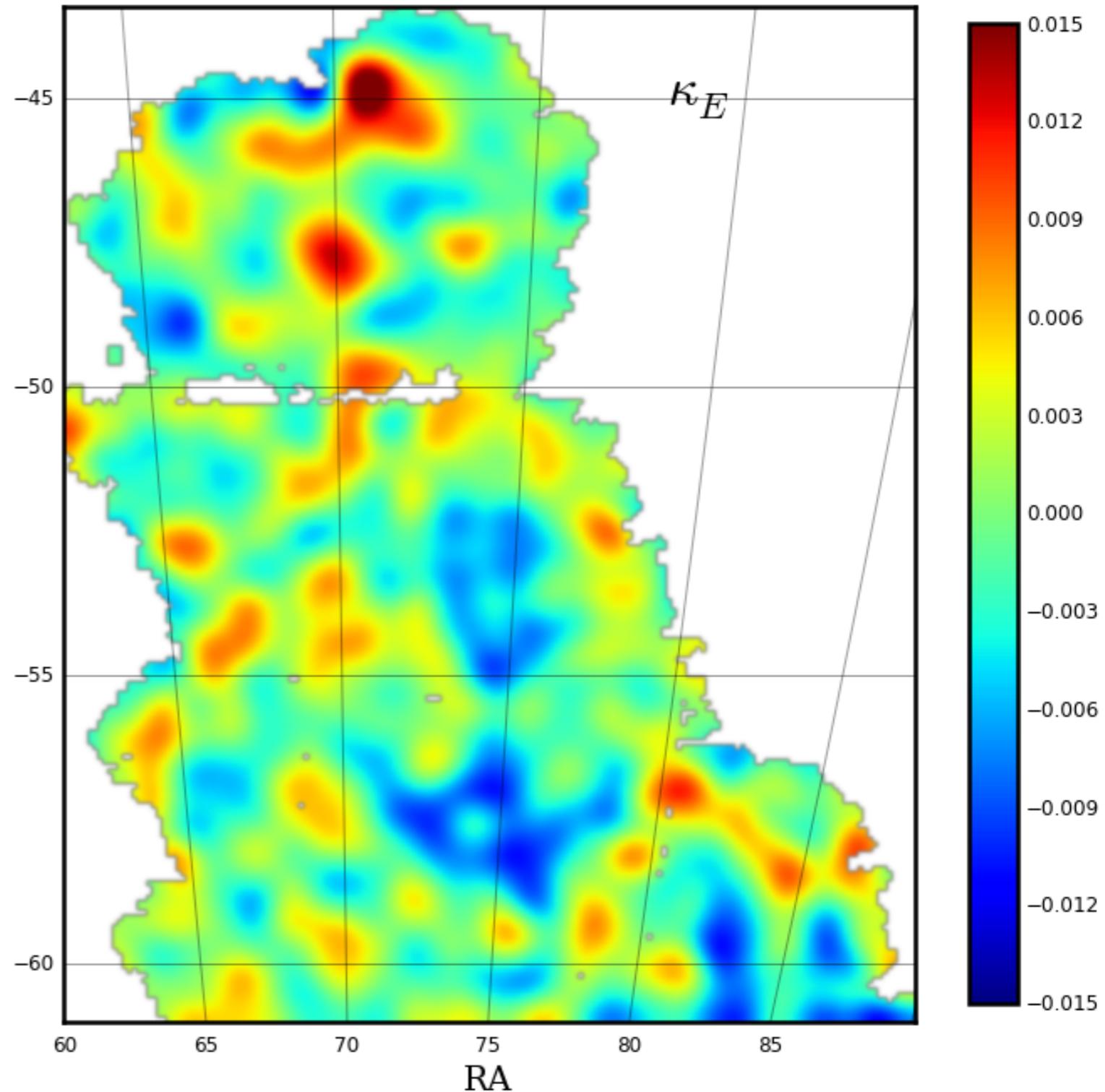
Convert galaxy shapes to mass:

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

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

Mass

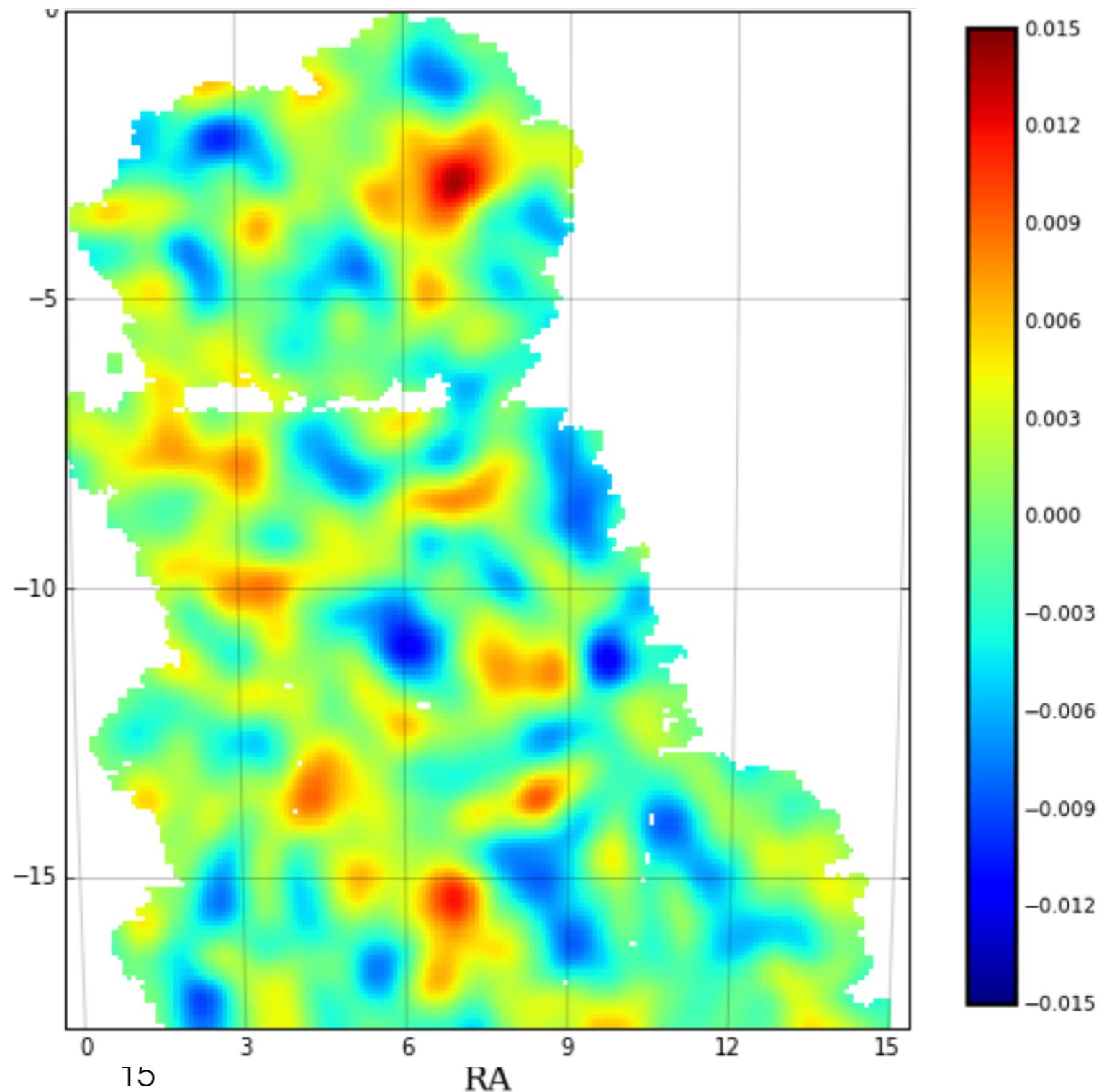
Galaxy shapes



# Mapping Dark Matter

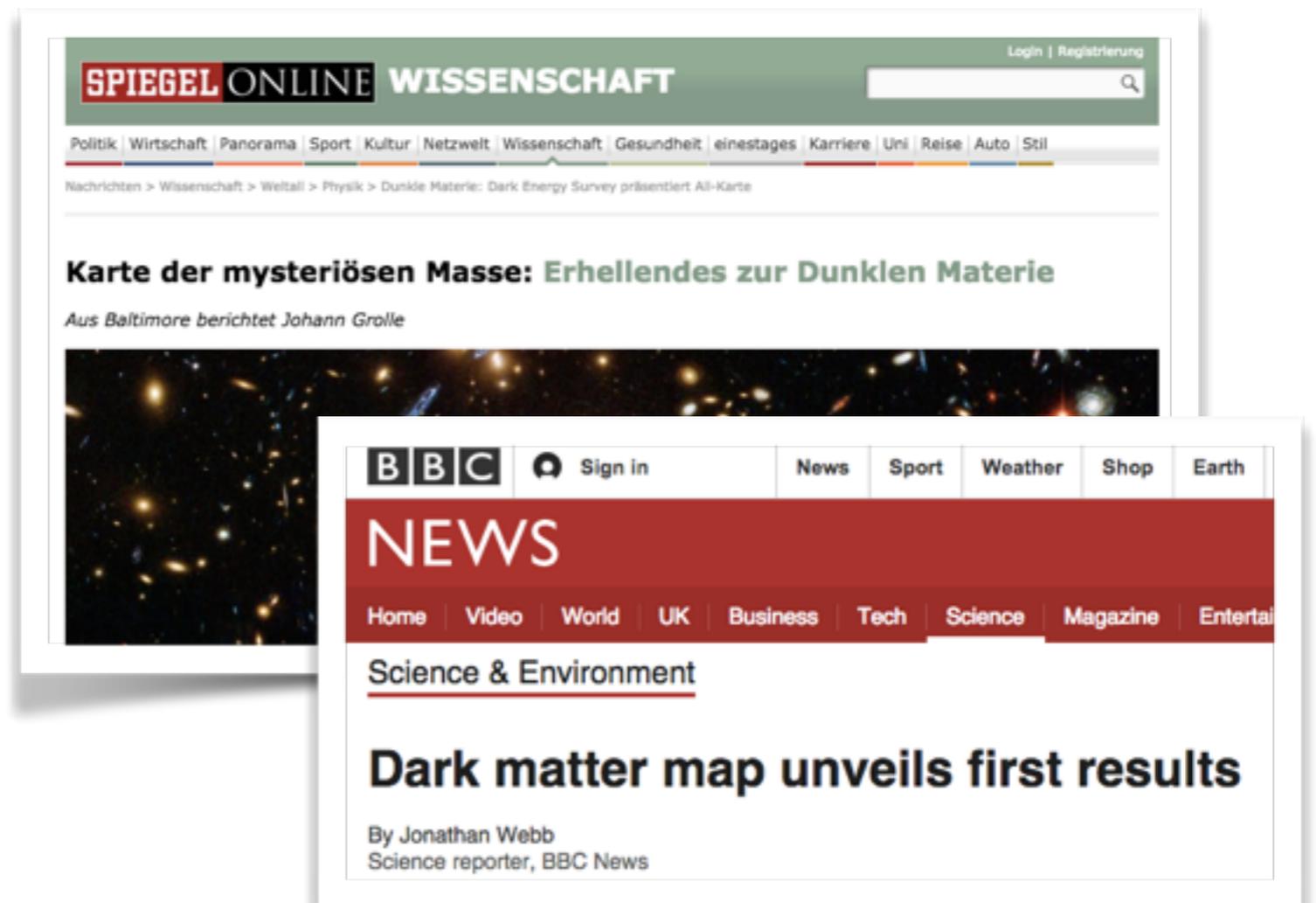
**Simulation** is a crucial ingredient in cosmological analyses, since many of the analysis steps are **heavily non-linear** and **couple** with one another.

```
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.

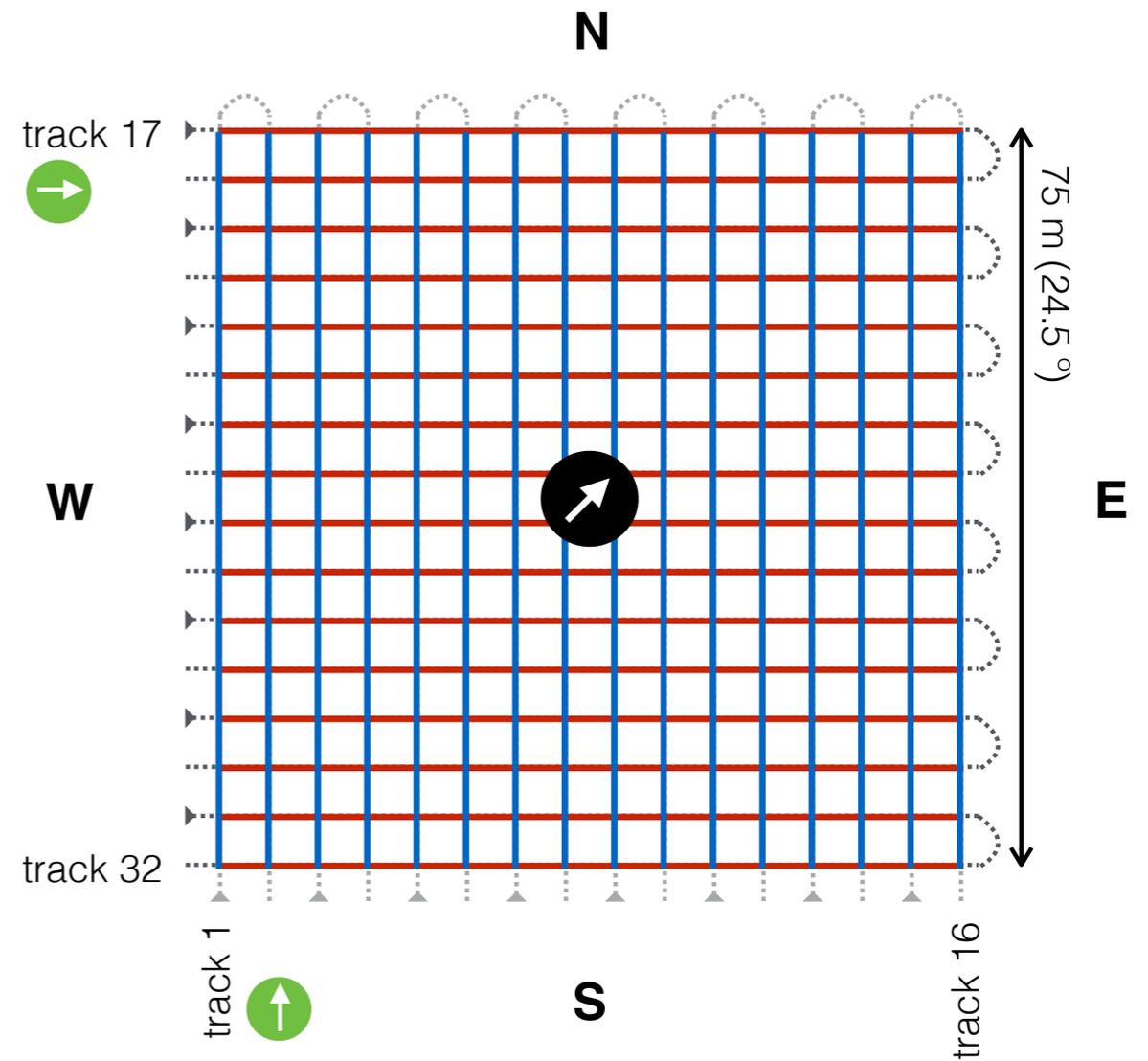
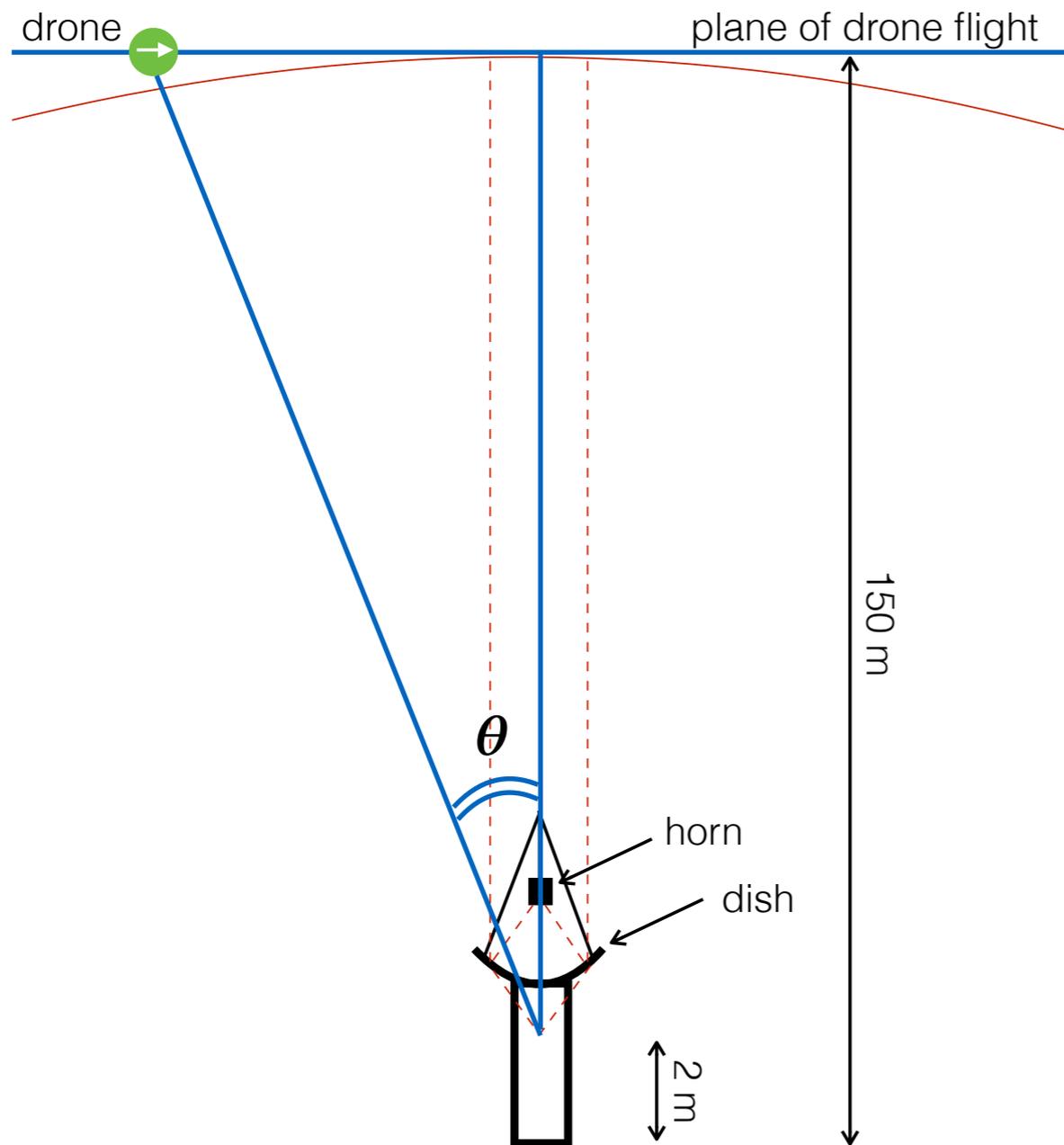


# Radio Telescope Calibration

- 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**

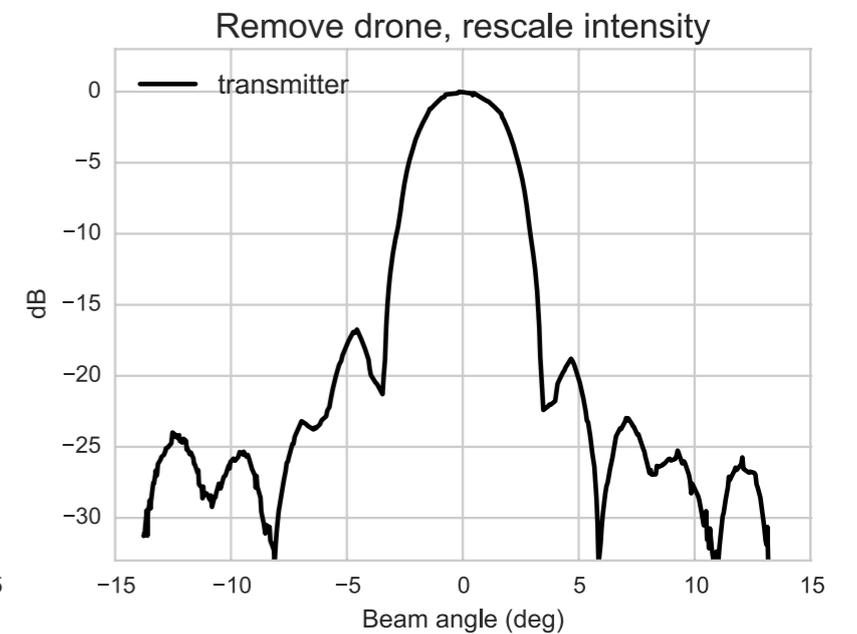
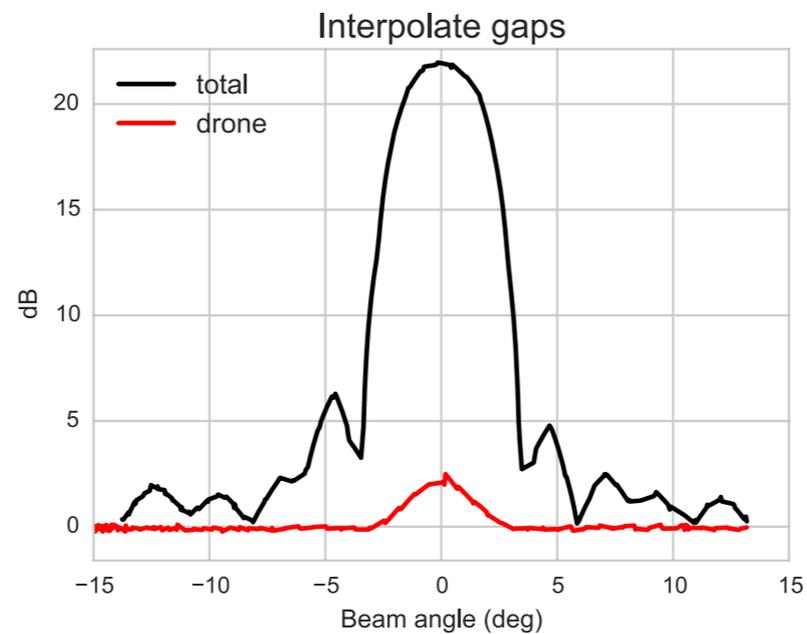
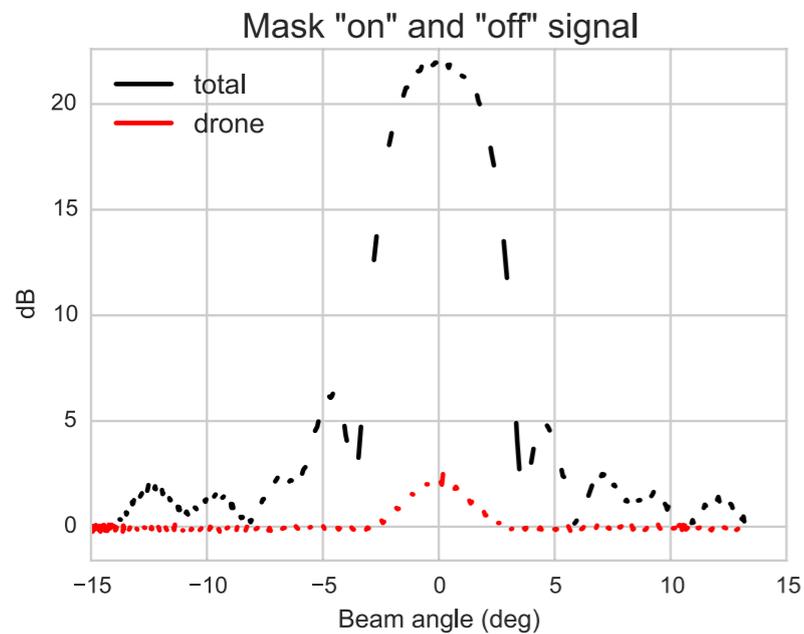
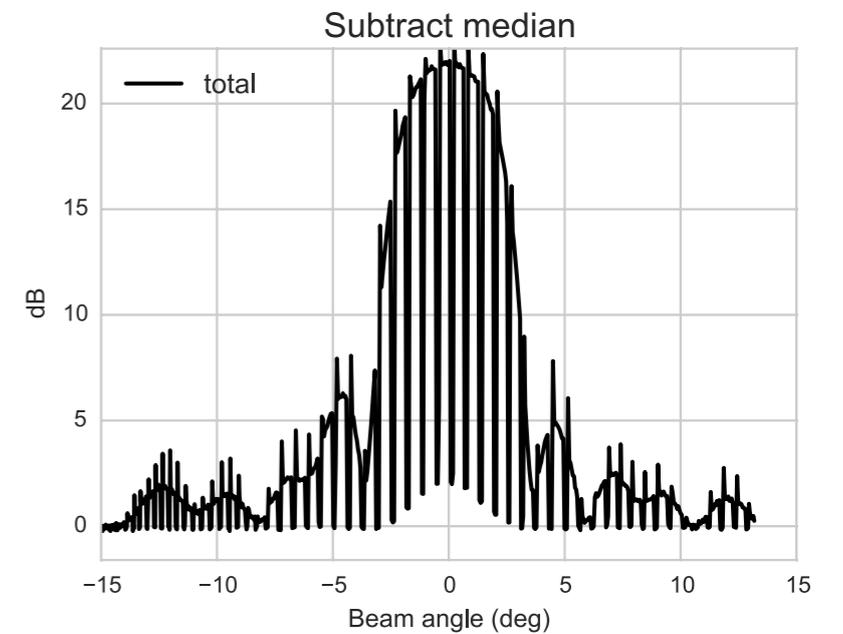
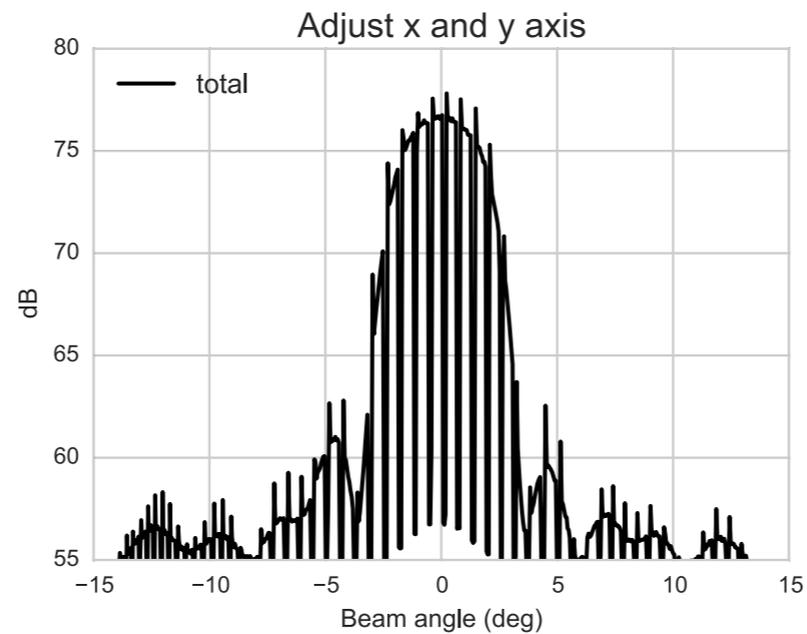
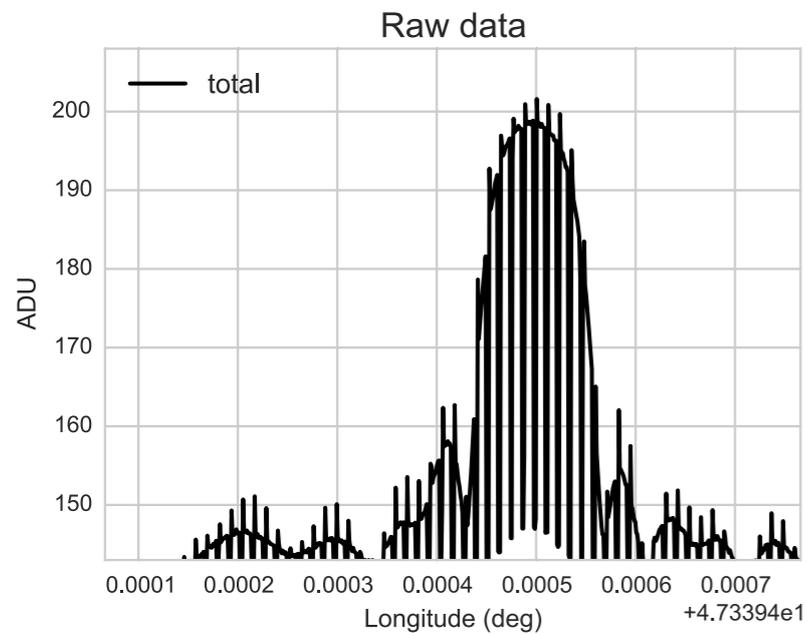


# The Computational Challenge

- 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**...



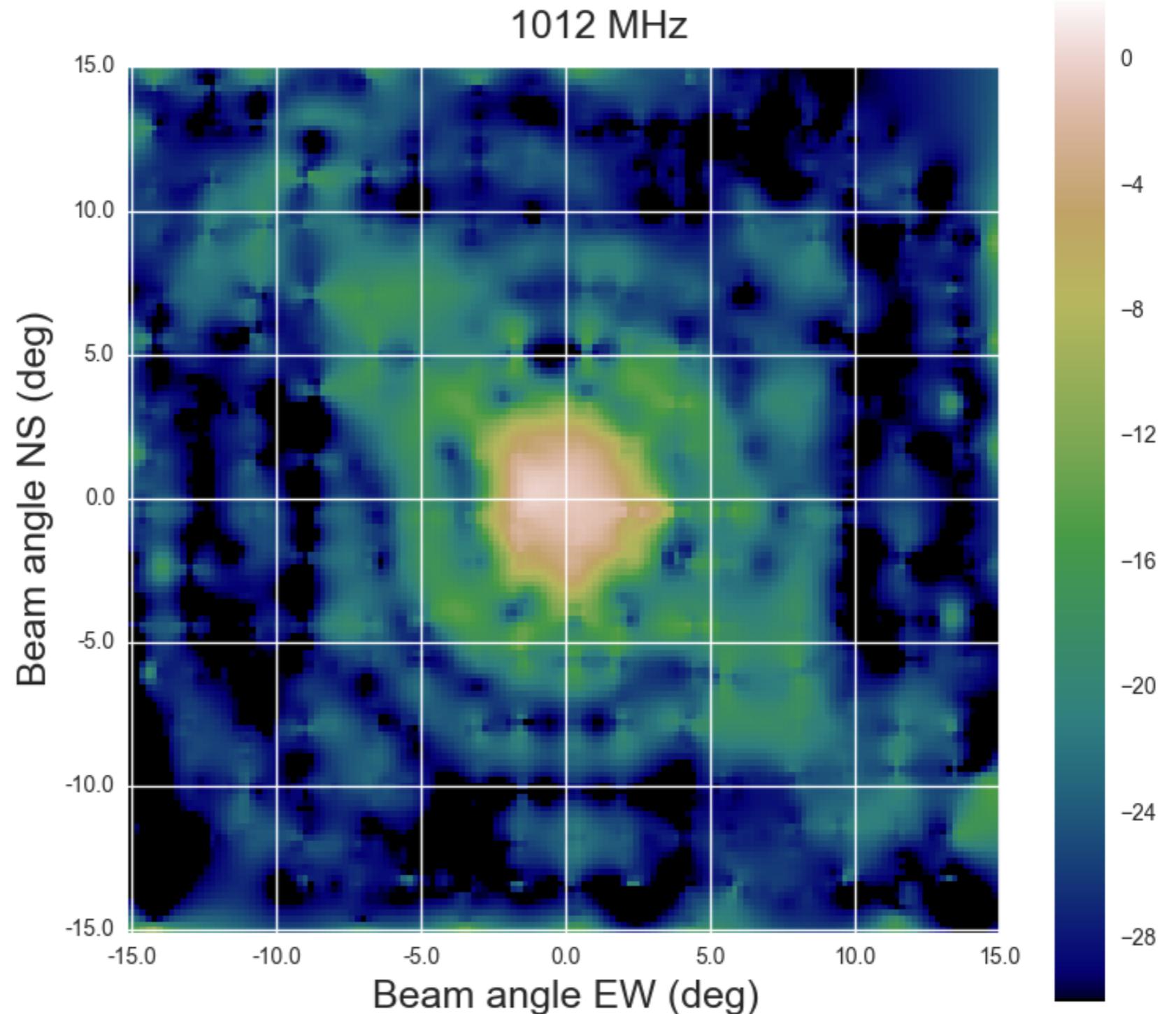
# Analysis



# Results

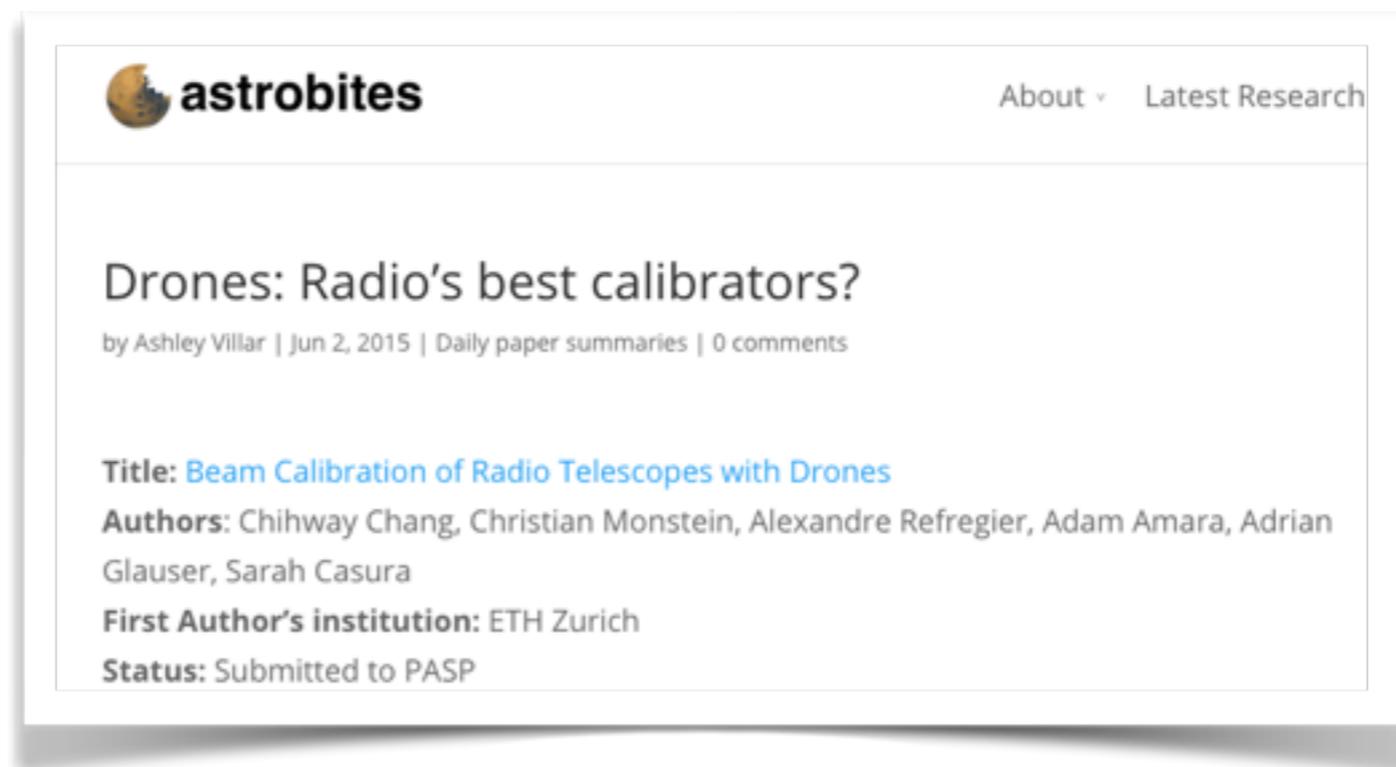
2D maps of the  
telescope beam  
profile with very  
high S/N

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



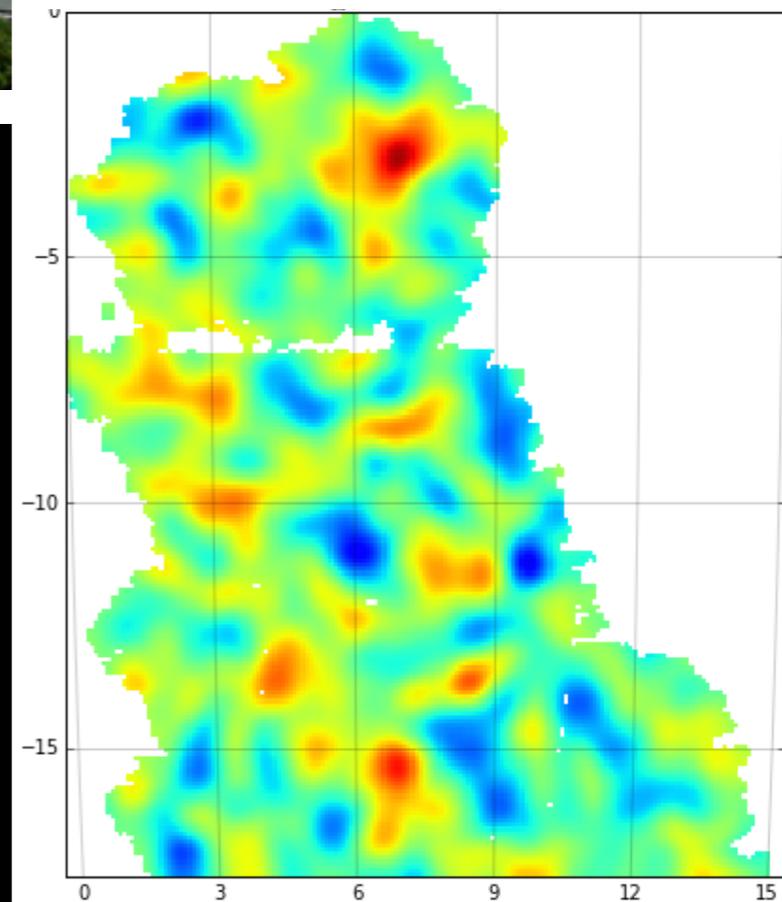
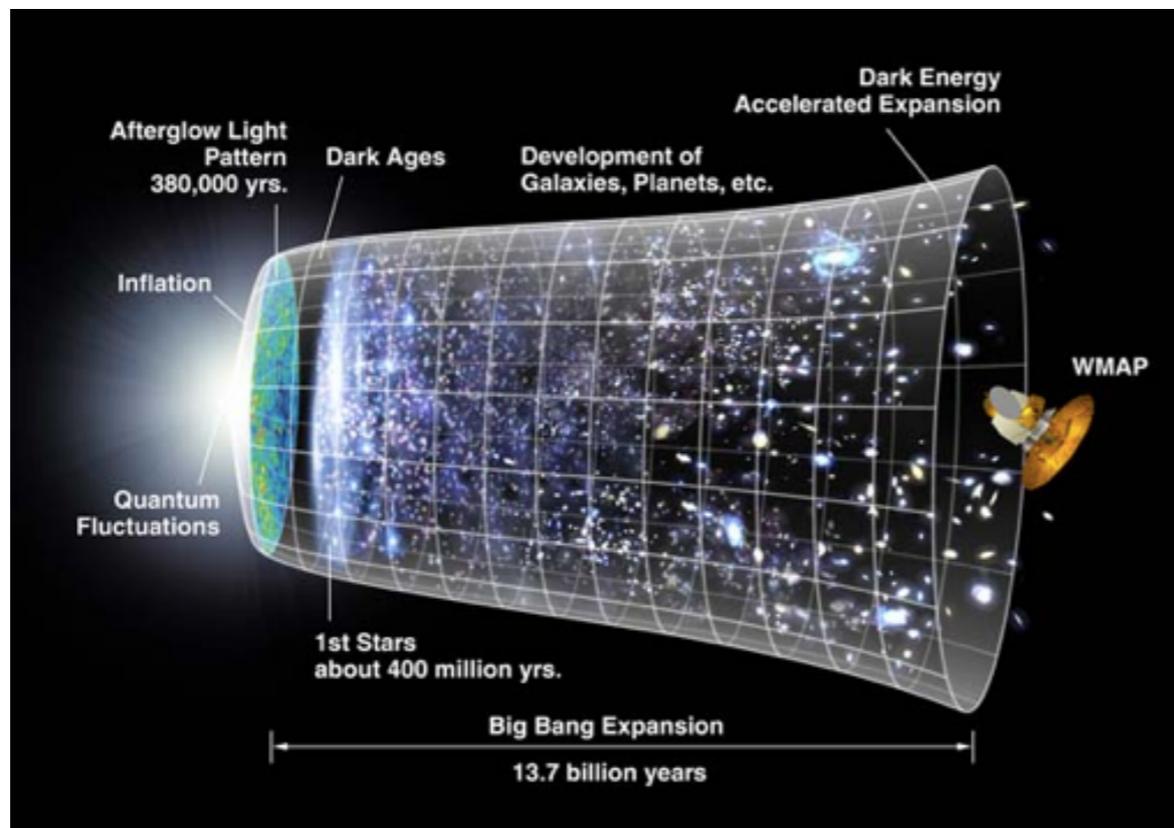
# Summary: Radio Telescope Calibration

- 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 :)



# 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...

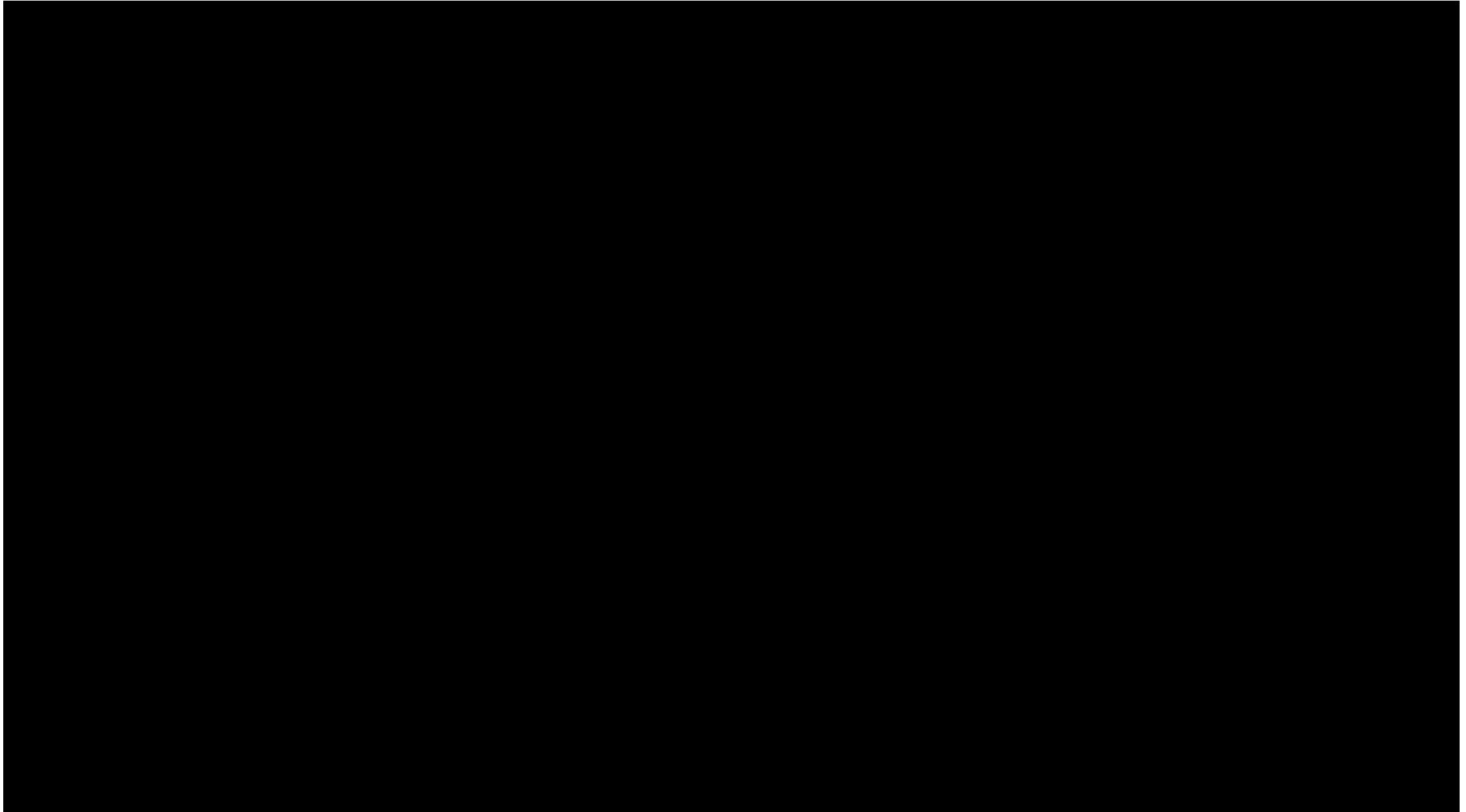
## The ETH Cosmology Group



## 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  $\psi(\theta, r) = 2 \int_0^r dr' \frac{r-r'}{rr'} \Phi(\theta, r')$

Deflection  $\alpha = \nabla \psi$

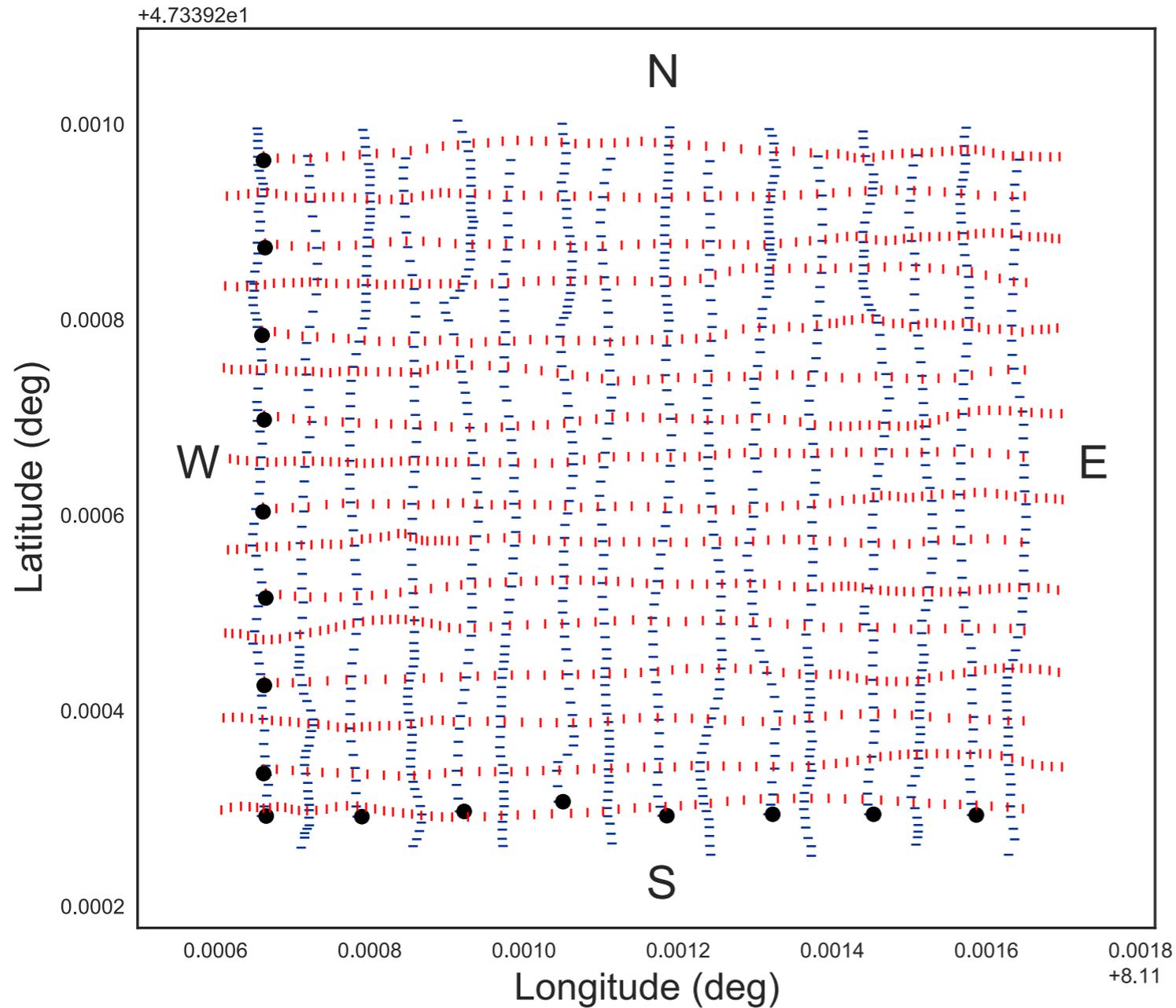
Convergence  $\kappa = \frac{1}{2} \nabla^2 \psi = \frac{1}{2} (\psi_{,11} + \psi_{,22})$

→ **Mass (what we care about)**

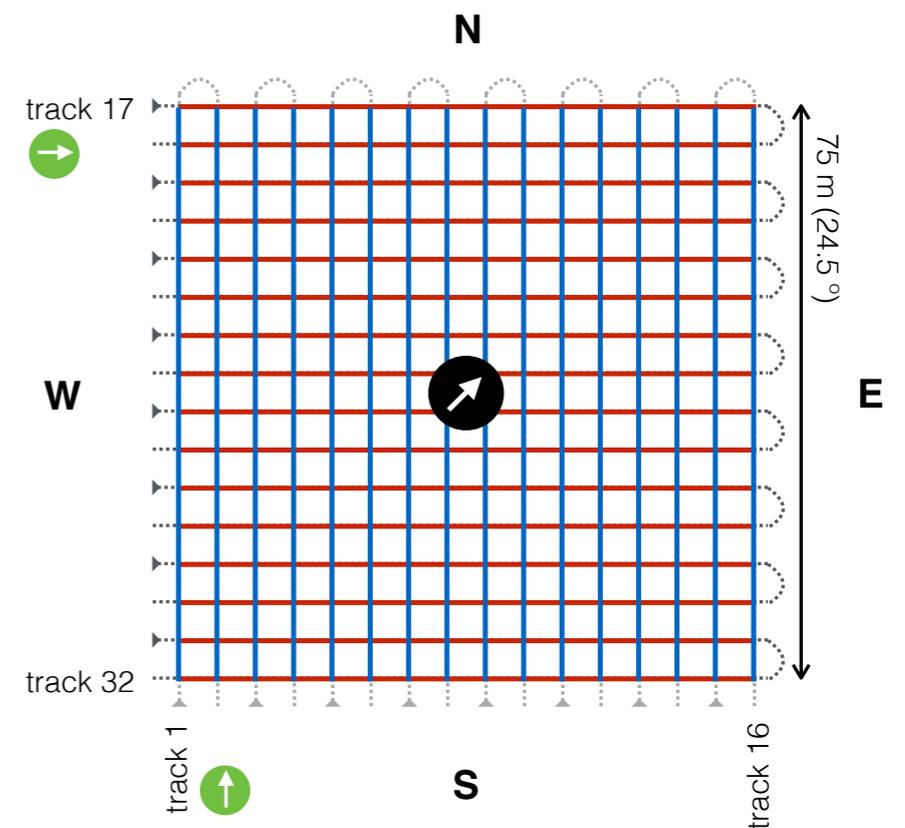
Shear  $\gamma = \gamma_1 + i\gamma_2 = \frac{1}{2} (\psi_{,11} - \psi_{,22}) + i\psi_{,12}$

→ **Distortion (what we can measure)**

# Analysis

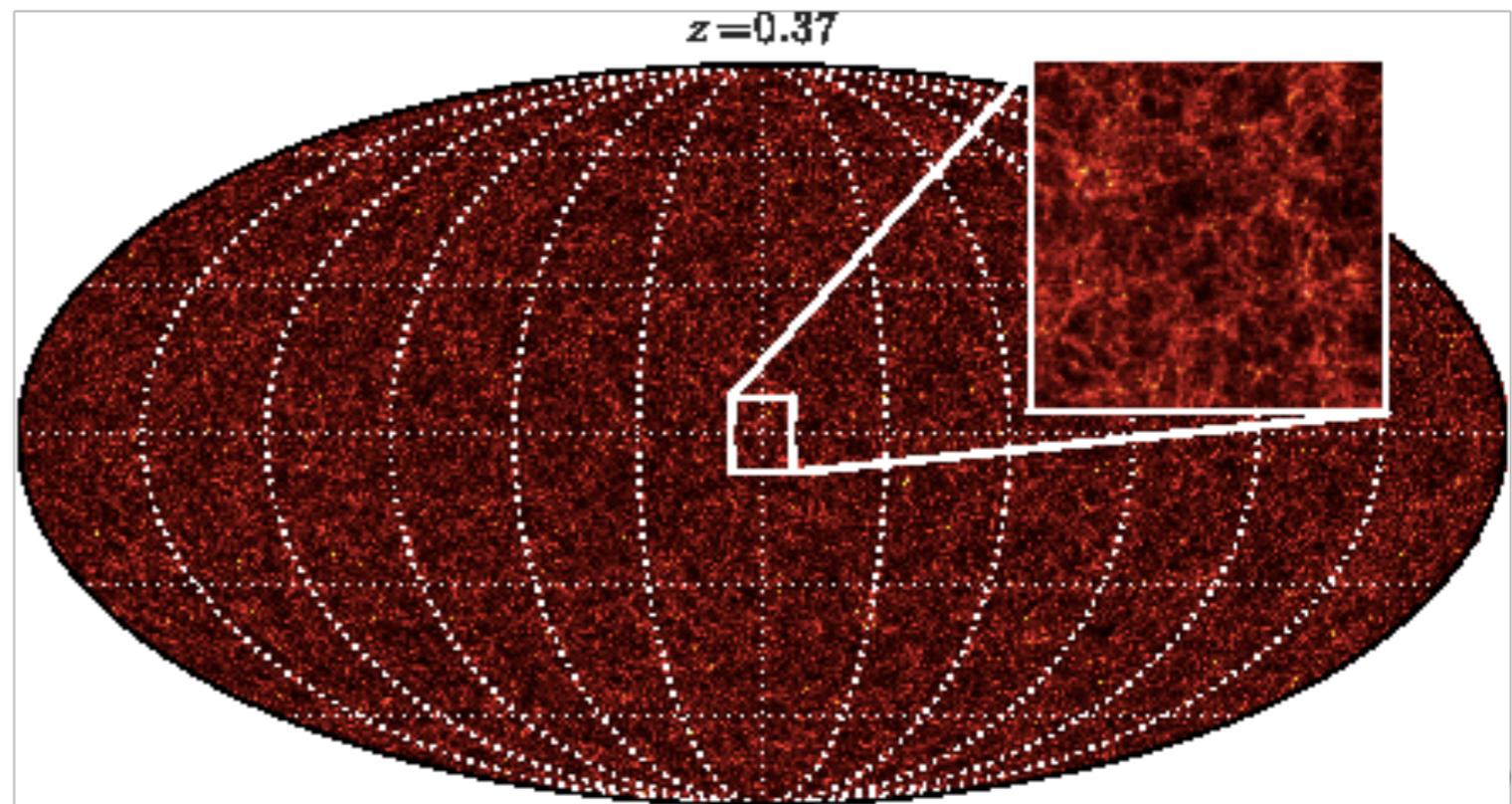
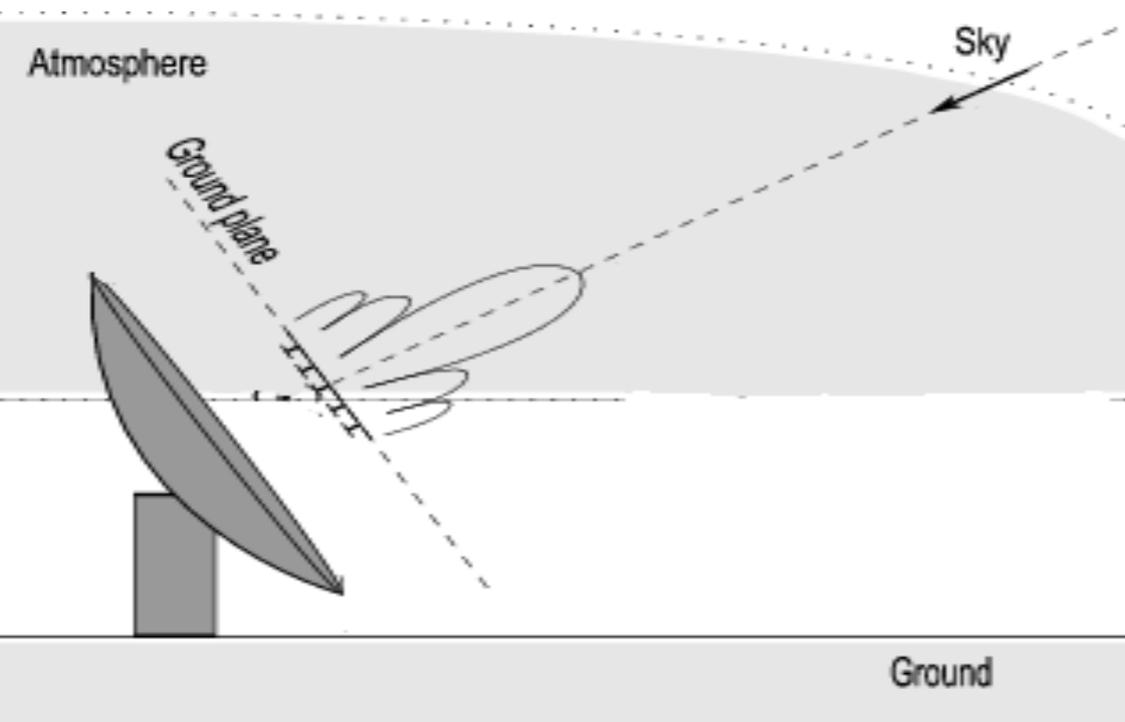


**Positioning:**  
**GPS + barometric altimeter**



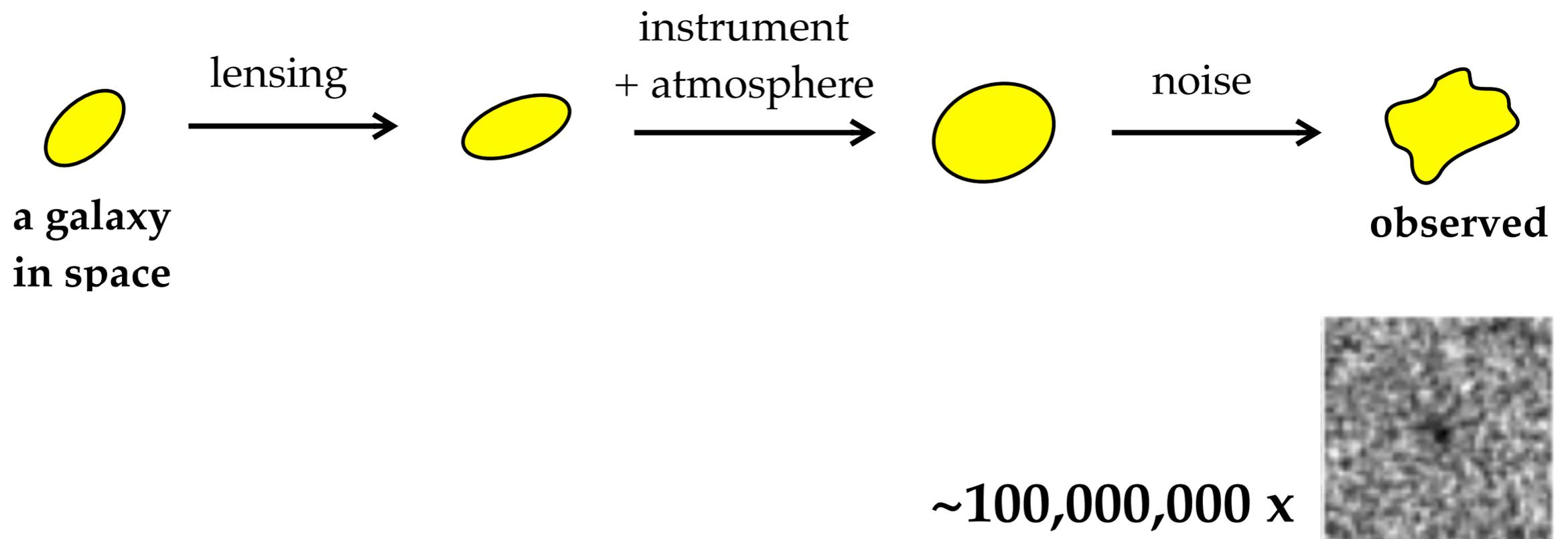
# Radio Telescope Calibration

- 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.



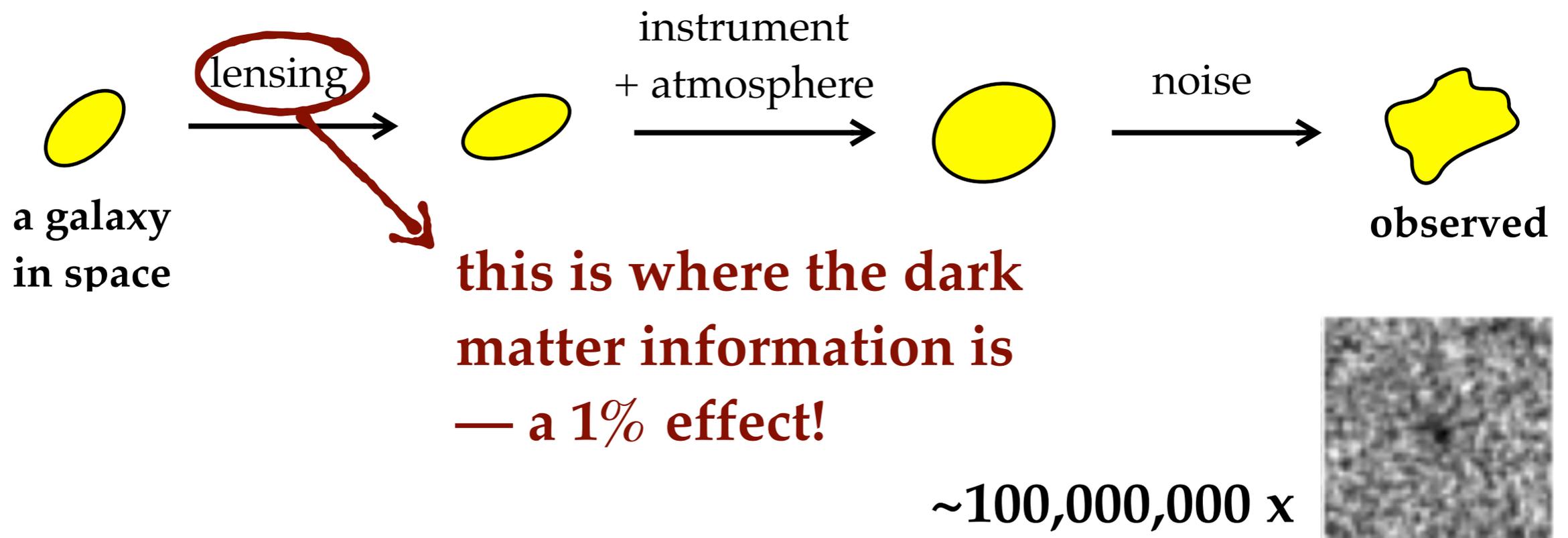
# The Computational Challenge

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



# The Computational Challenge

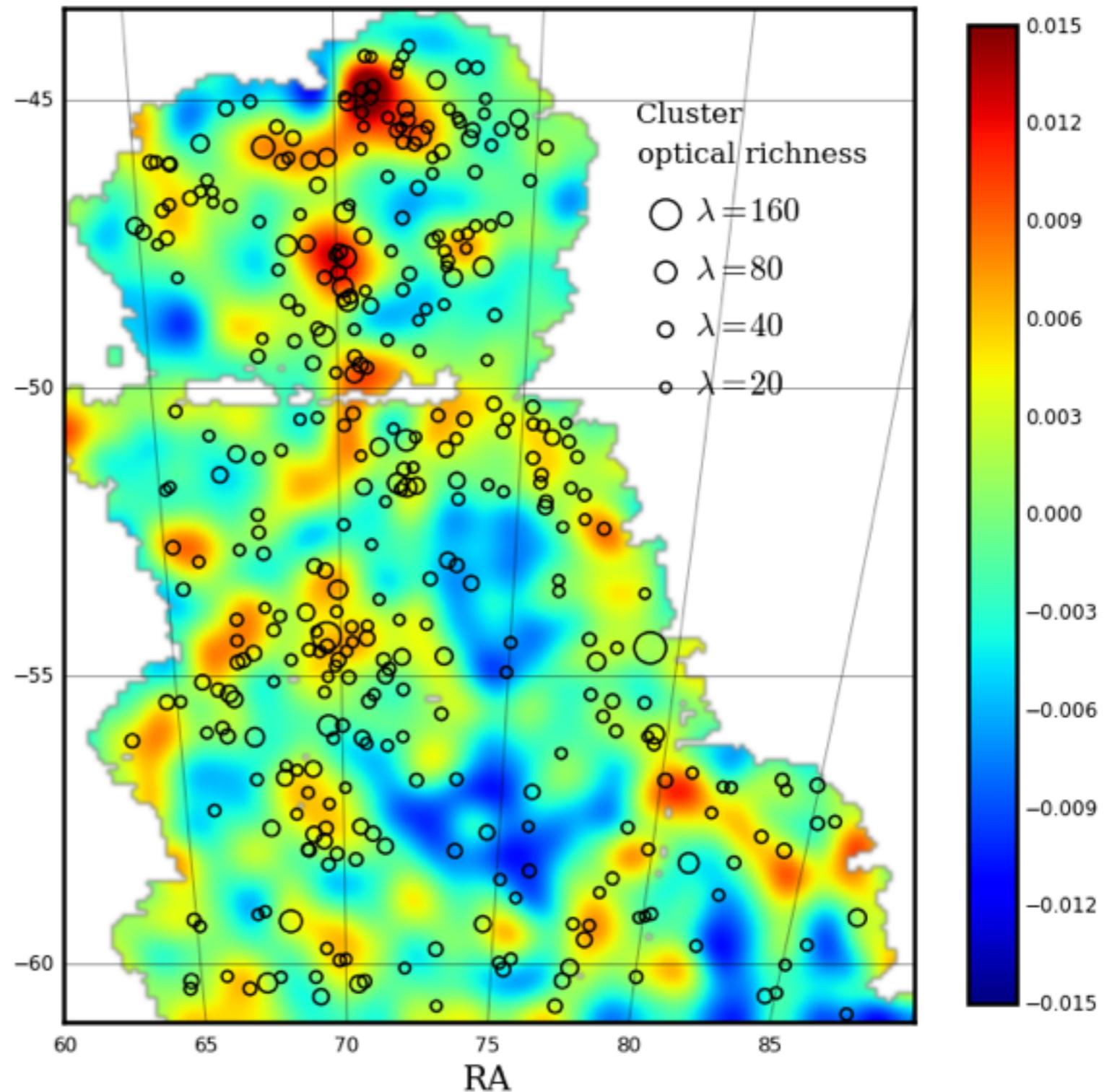
- We want to measure accurately **shapes** of a lot of small, faint, noisy galaxies, and get useful information out of them.



# 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