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



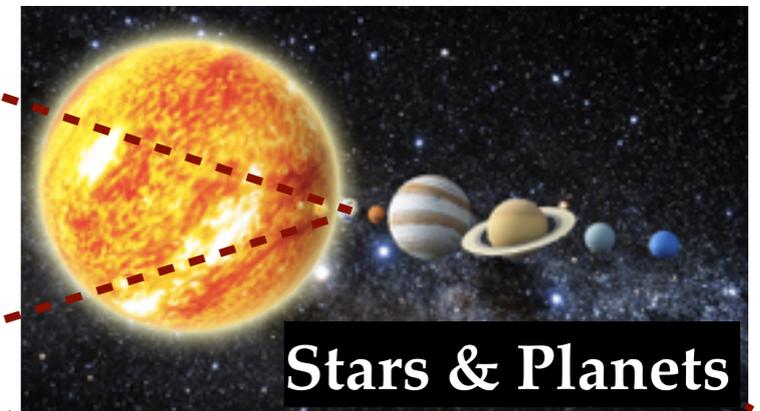
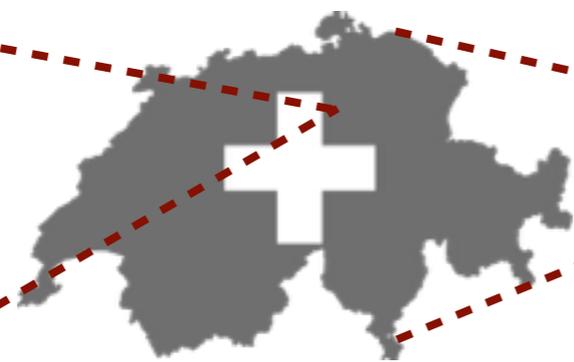
Chihway Chang (ETH Zürich)

ETH | Cosmology

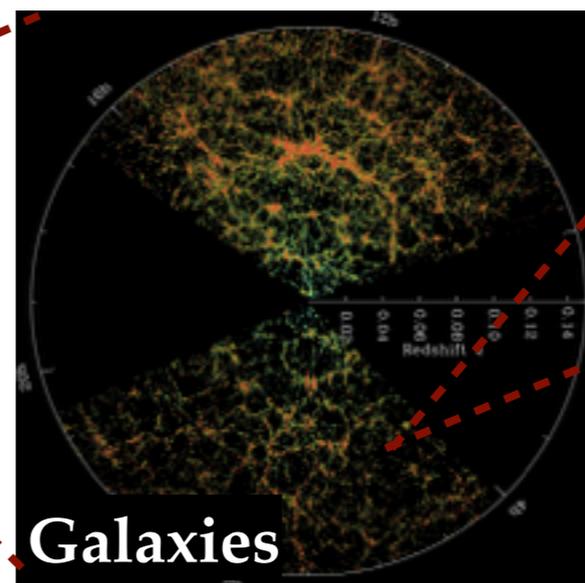
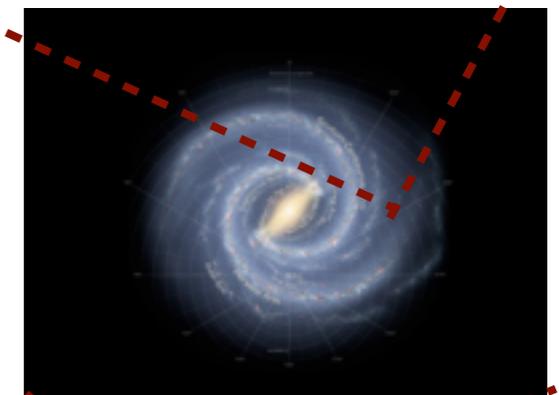
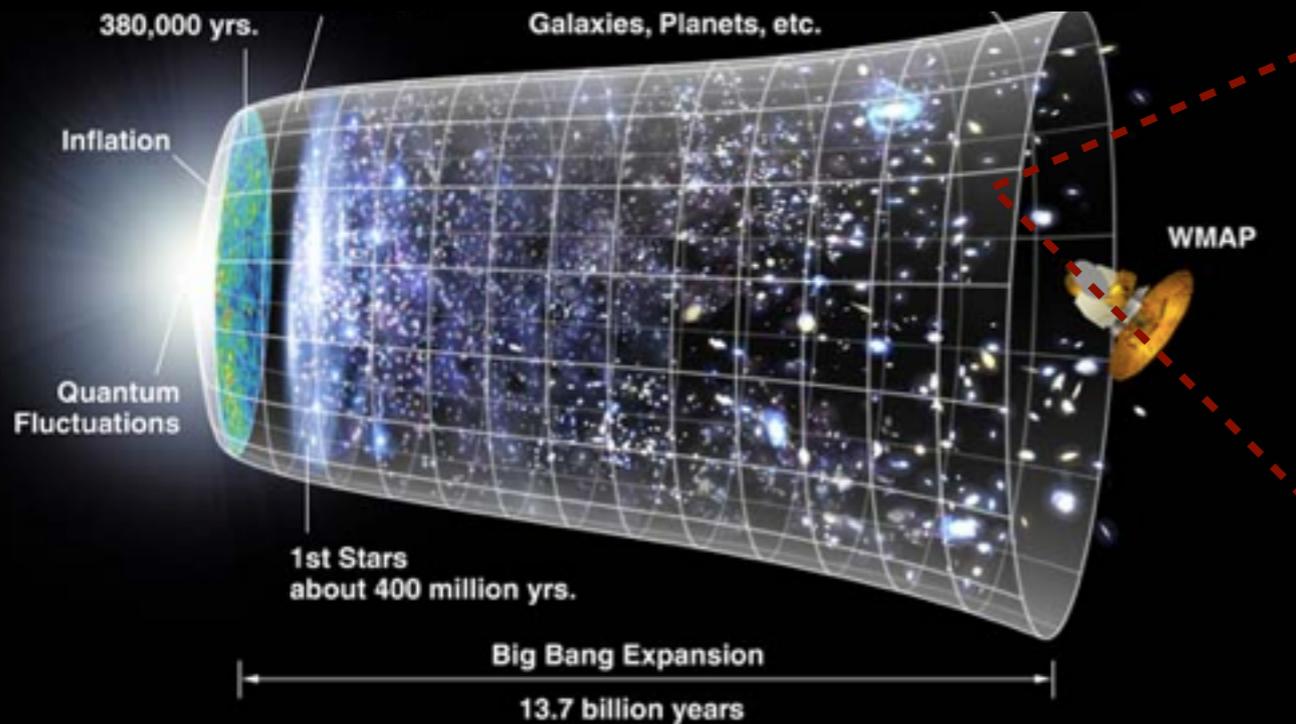
DISCLAIMER

- 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



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](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>

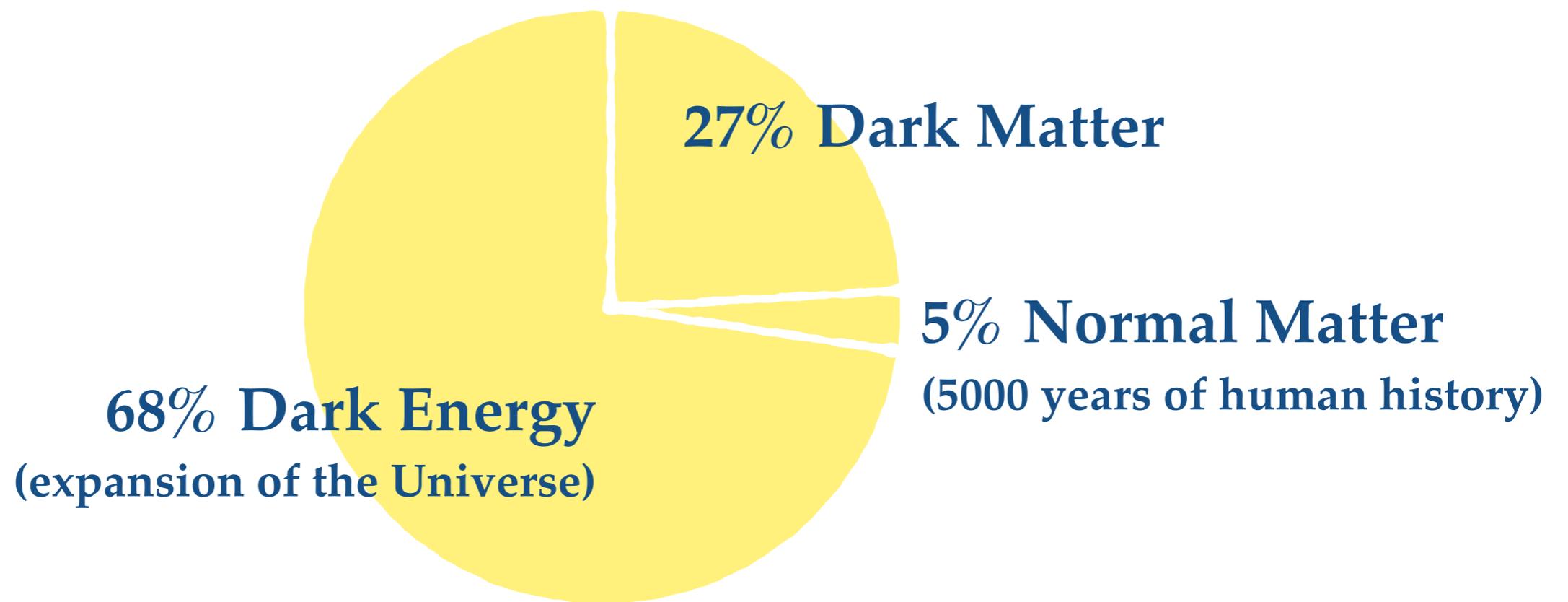
Two Examples

- **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

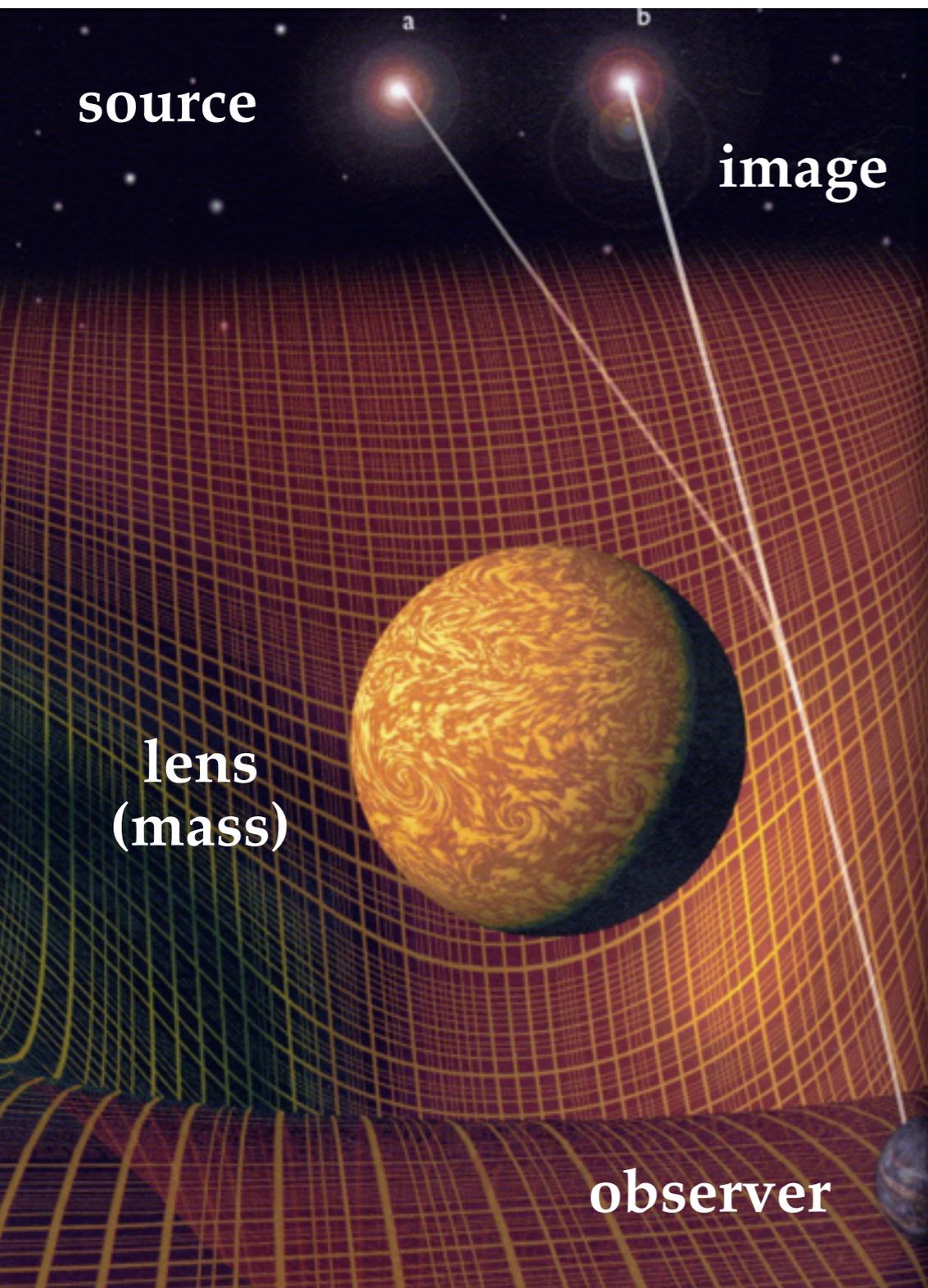


Mapping Dark Matter

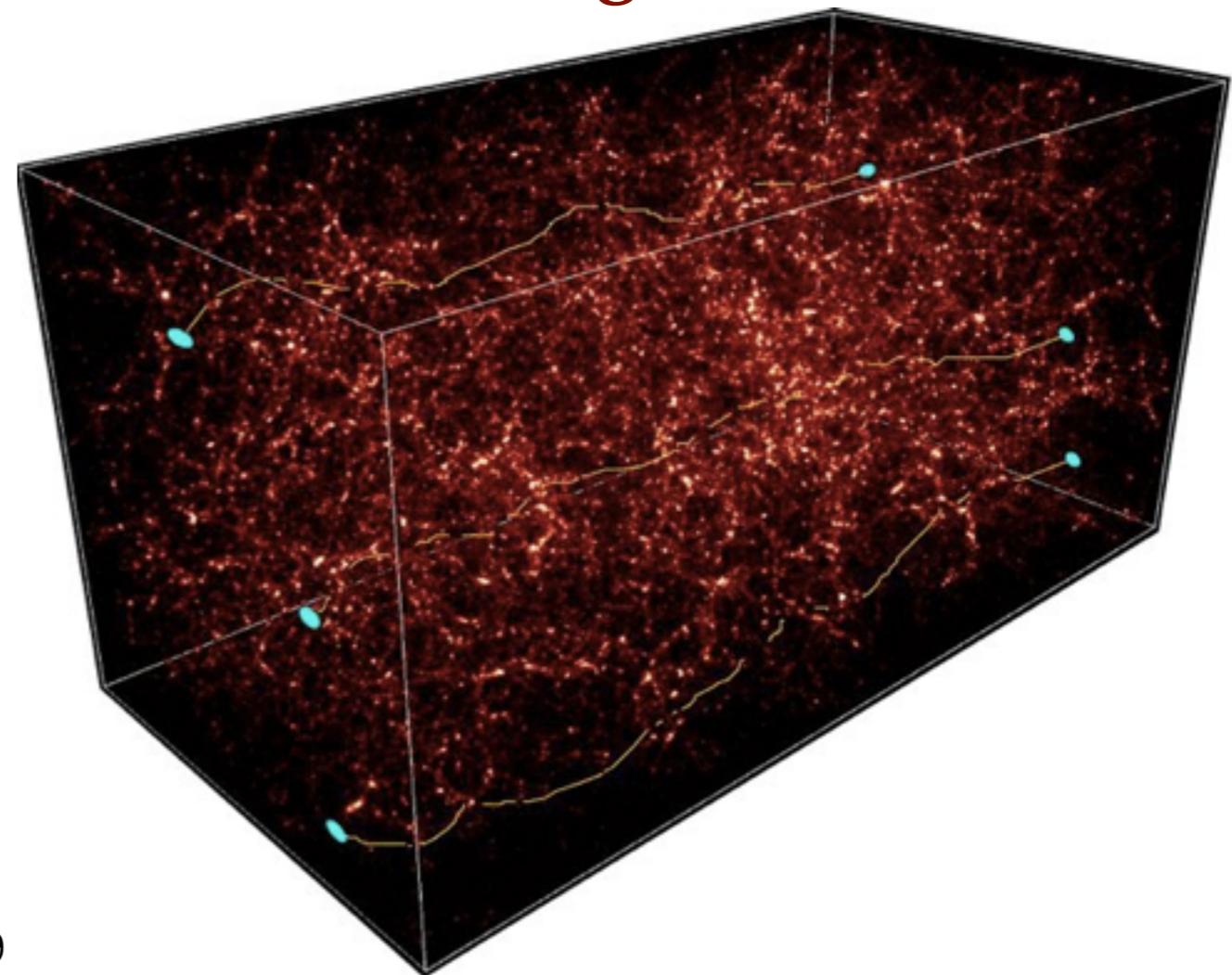
- **We don't know a whole lot about our Universe**, because we cannot **see** most of the stuff in the Universe!



Gravitational Lensing



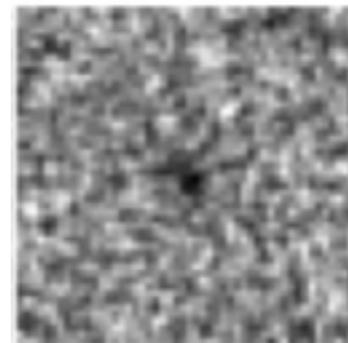
We can *see* dark matter through **Gravitational Lensing!**



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



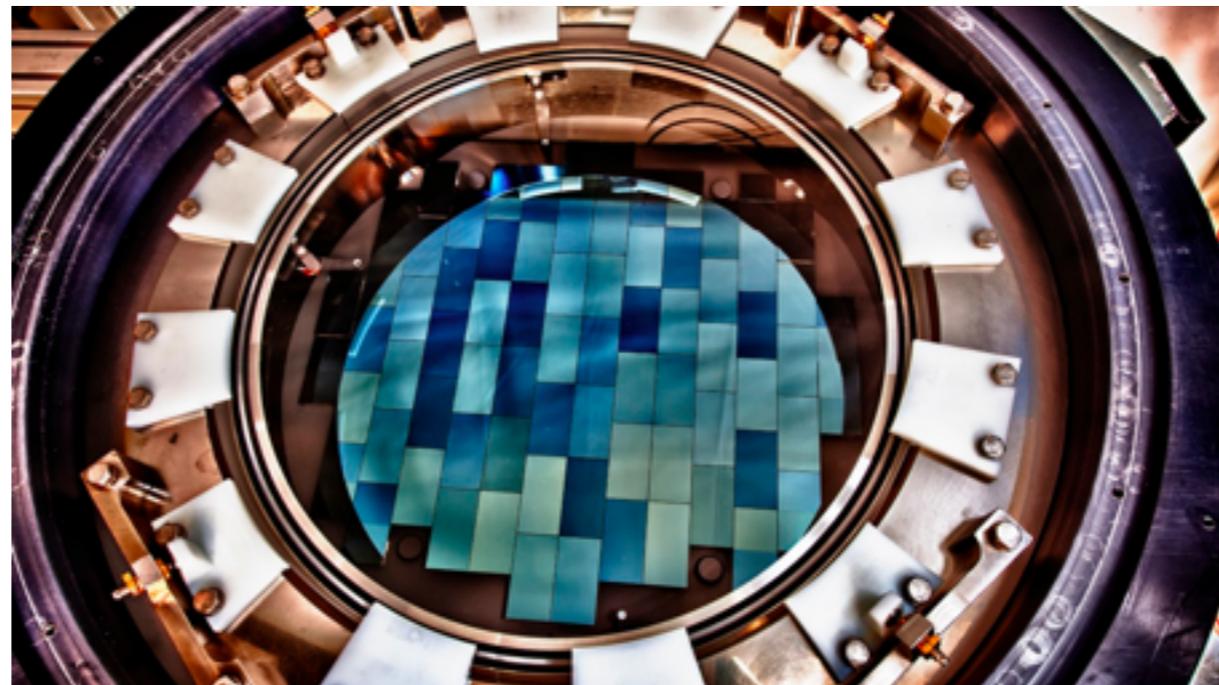
The Computational Challenge

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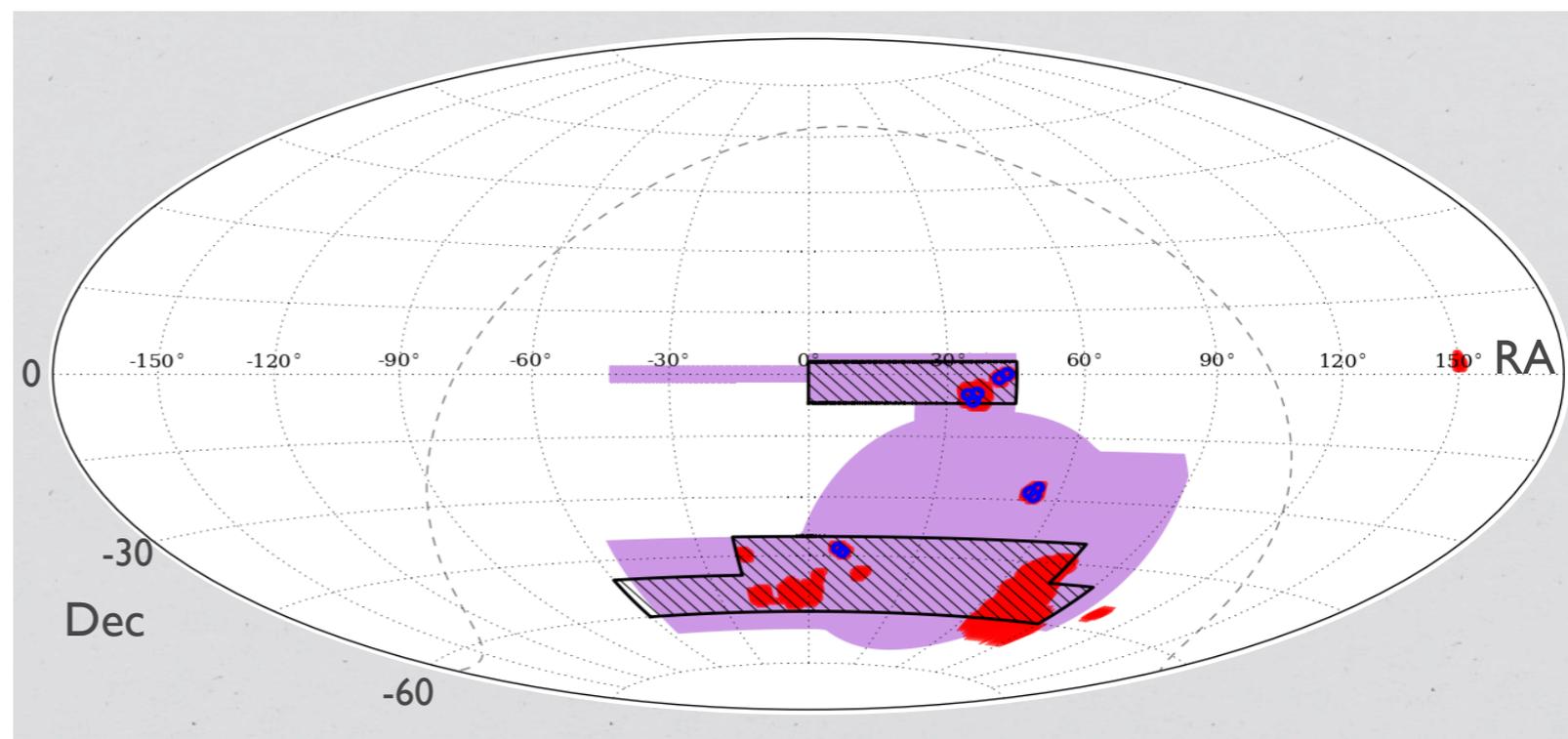


[/barbabyteprowe/great3-public](#)
[/GalSim-developers/GalSim](#)

The Dark Energy Survey

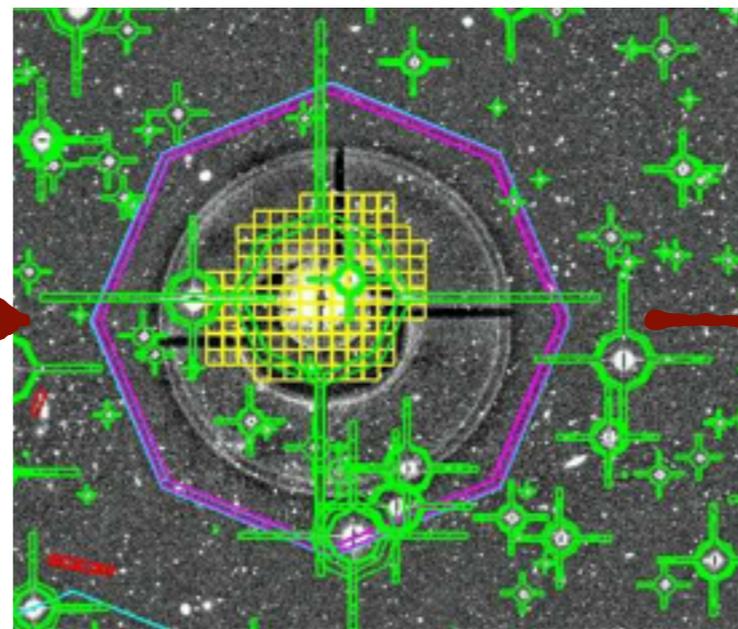
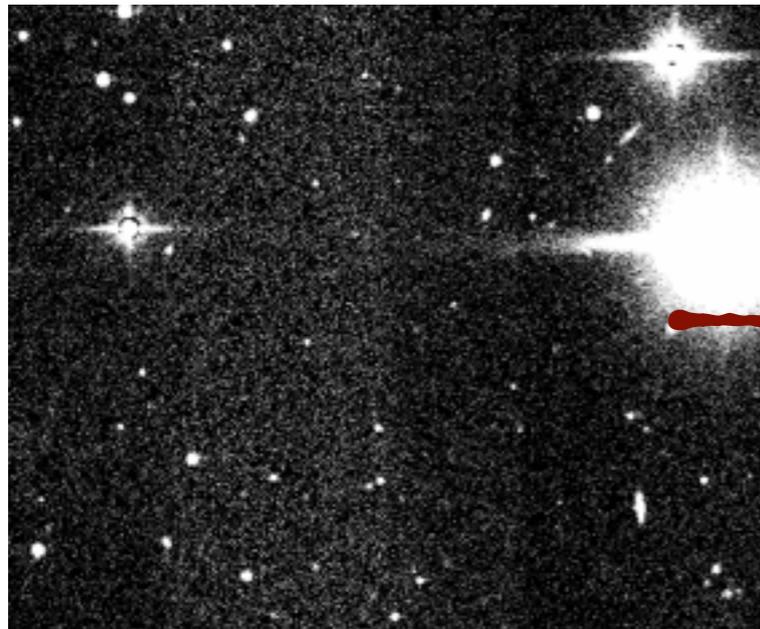


DES is an ongoing **galaxy imaging survey** and will cover **5000 sq. degrees** over 5 years



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	...	1186	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	3.4 × 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	3.4 × 6.5	-22.1	283	0.93	0.1
NCC 4480	12 28 29.6	+17 05 06	SABs	L	1954	20.0	3.2 × 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	3.6 × 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,Sp	-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,Sp	1919	20.0	3.9 × 4.7	-21.8	390	0.17	0.2
NCC 4594	12 39 59.4	-11 37 25	SAa	L,Sp,?c	1091	13.7	8.7 × 3.5	-21.5	362	0.16	0.1
NCC 4629	12 41 32.7	+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	SBc	...	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	Sp,?c	1306	17.1	10.7 × 7.6	-22.0	410	0.09	0.2
NCC 4736	12 50 53.0	+41 07 16	SABs	L	308	5.3	11.2 × 9.1	-19.9	241	0.87	0.3
IC03 154	12 54 05.2	+27 08 59	IRms	...	376	5.4	3.0 × 2.2	-15.1	105
NCC 4826	12 56 43.7	+21 40 32	SABs	Sp,?c	408	5.6	10.0 × 3.4	-20.3	311	0.27	0.4
IC03 165	13 06 34.8	+07 42 25	IR	...	37	3.5	3.5 × 1.9	-15.3	68
NCC 5033	13 15 27.5	+36 35 36	SAc	Sp,?c	875	13.3	10.7 × 5.0	-20.9	446	0.48	0.1
NCC 5055	13 15 49.3	+42 01 45	SABc	IR,L	506	8.2	12.6 × 7.2	-19.0	405	4.56	0.1
NCC 5104	13 29 32.7	+47 11 43	SAB(rs)c	IR,Sp,?c	465	8.2	11.2 × 6.9	-21.4	195	0.60	0.1
NCC 5105	13 29 58.7	+47 16 05	SAB(rs)c	L	532	8.2	5.8 × 4.6	-20.0	...	0.29	0.3
NCC 5108	14 01 21.3	-33 03 47	SB(rs)m	IR	1216	15.0	2.8 × 1.7	-18.9	117	0.44	0.1
NCC 5408	14 05 20.8	-41 22 40	IRms	...	309	4.5	1.6 × 0.8	-16.1	134	0.14	0.4
NCC 5474	14 05 01.6	+53 39 44	SABc	IR	273	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)m	IR	741	8.5	3.6 × 2.8	-18.3	31	0.20	0.1
NCC 6822	19 44 56.6	-14 47 21	IRms	...	-97	0.6	15.5 × 13.5	-13.8	81	2.50	0.3
NCC 6846	20 34 32.3	+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	SABs	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	23 37 49.8	-32 35 28	SABc	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 type; 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 μm flux, is defined as $L_{\text{FR}} = 4.75 L_{\text{IR}}$; Col. (12): The ratio of the IRAS 60 μm to 100 μm 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 $\Delta \text{Mpc} = 1$ 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

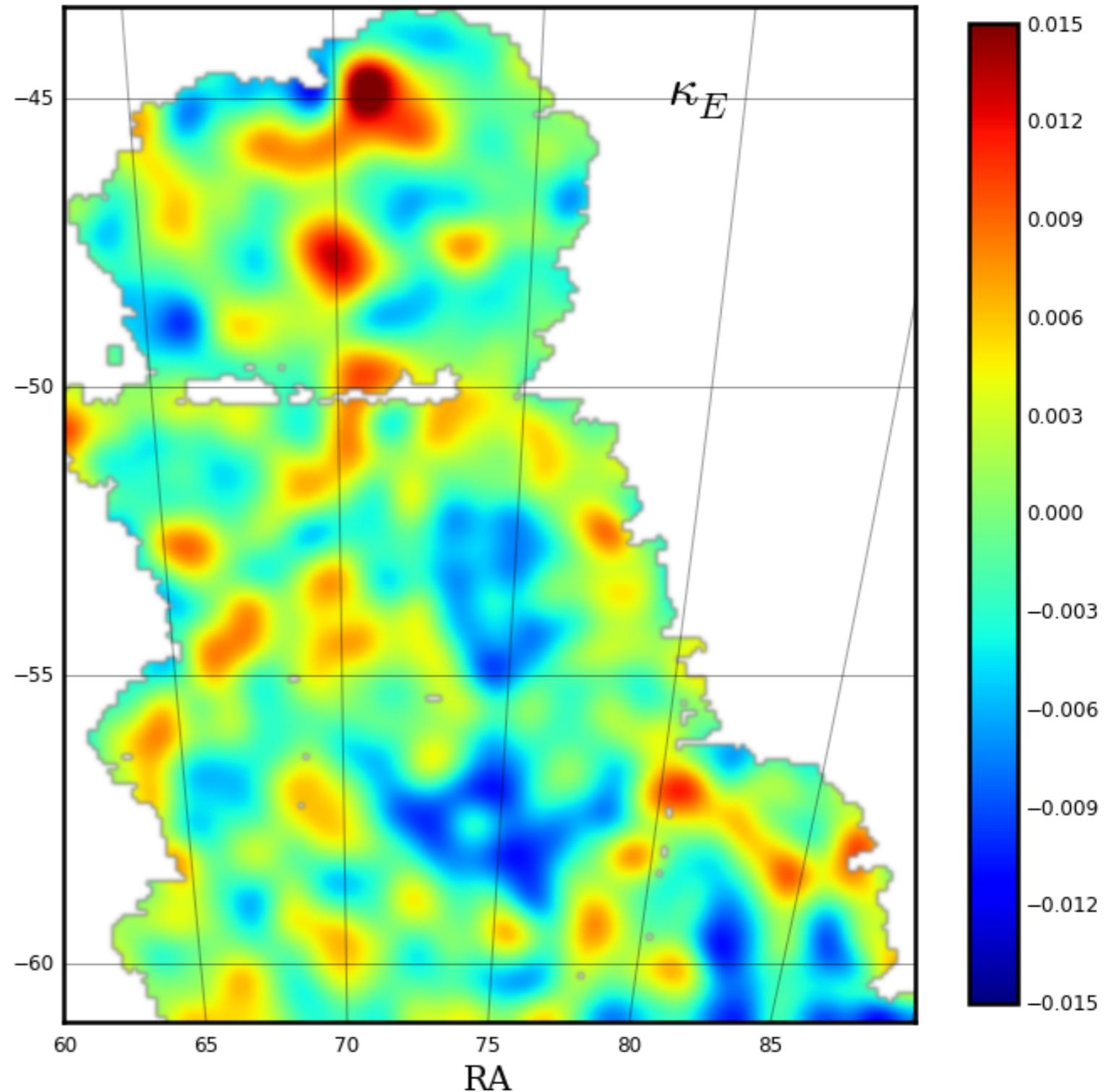
Convert galaxy shapes to mass:

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

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

Mass

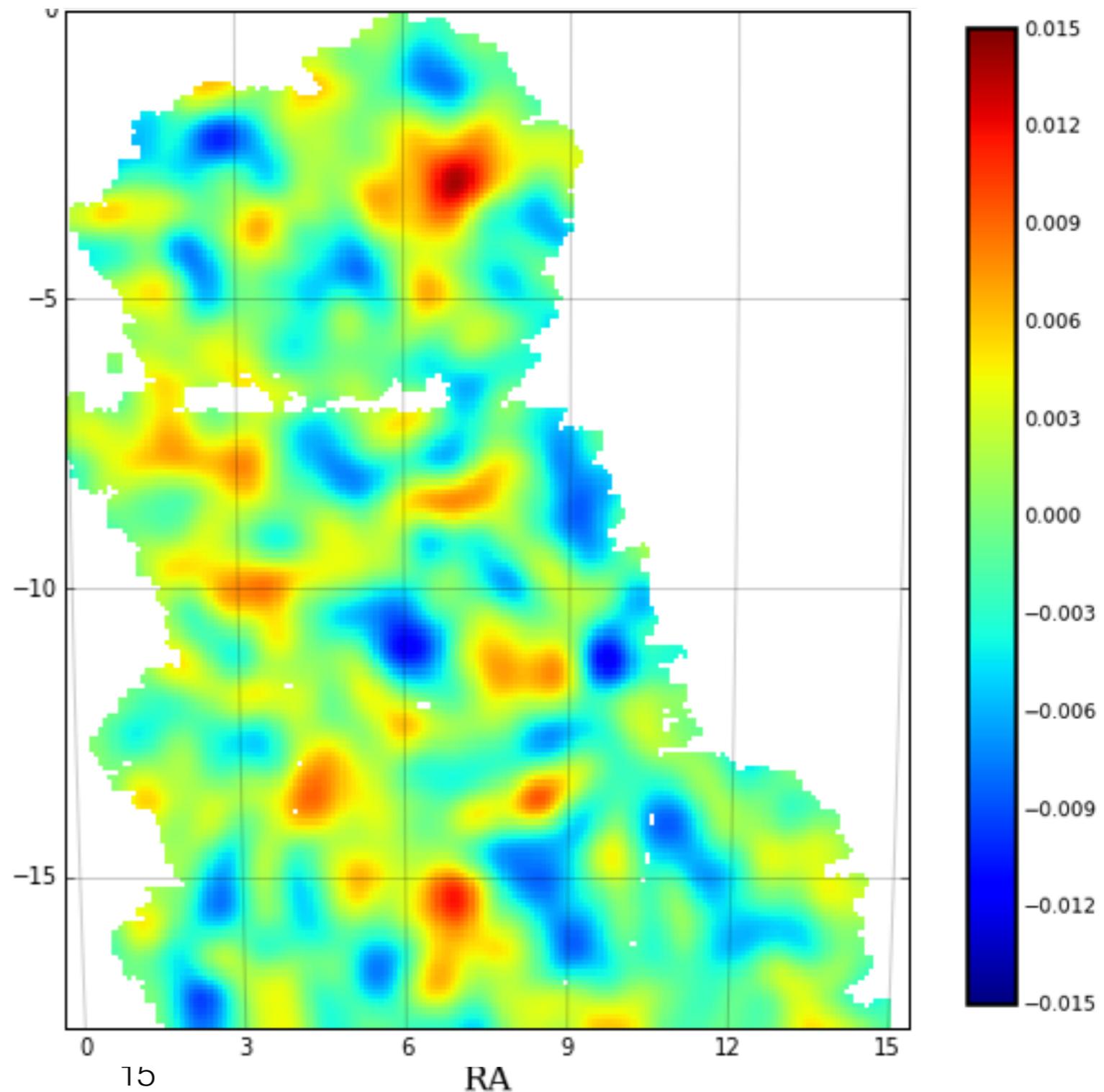
Galaxy shapes



Mapping Dark Matter

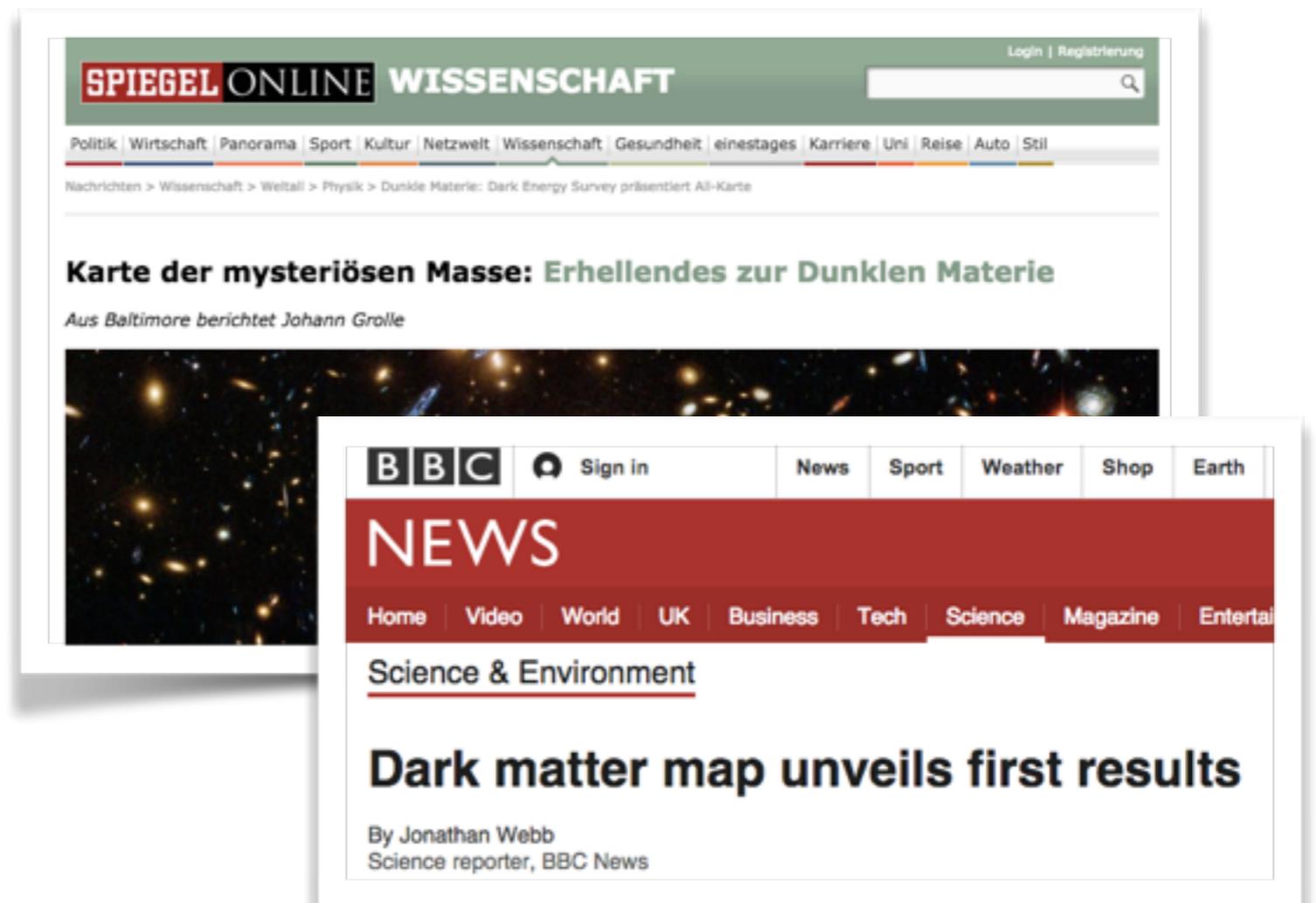
Simulation is a crucial ingredient in cosmological analyses, since many of the analysis steps are **heavily non-linear** and **couple** with one another.

```
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.

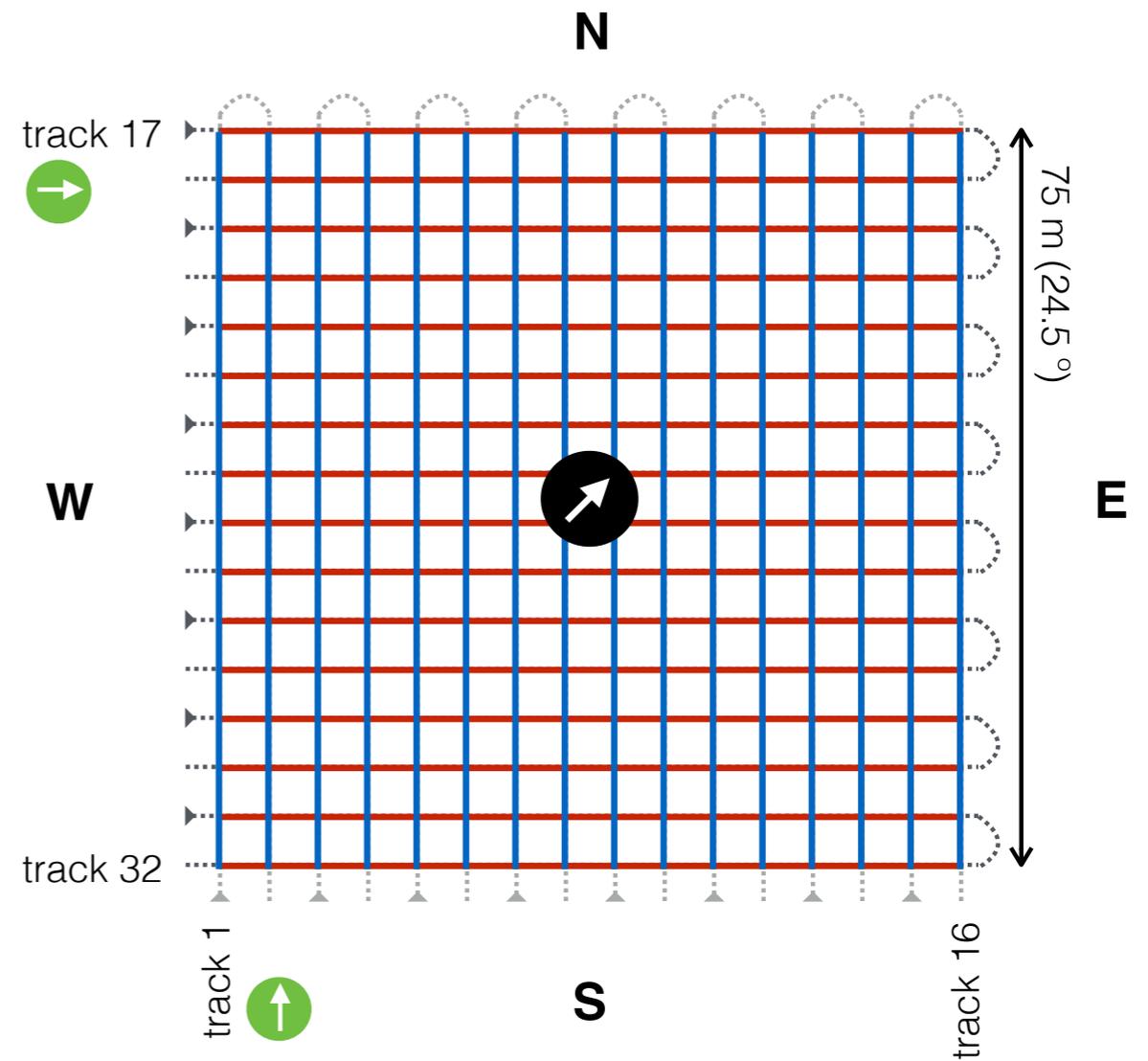
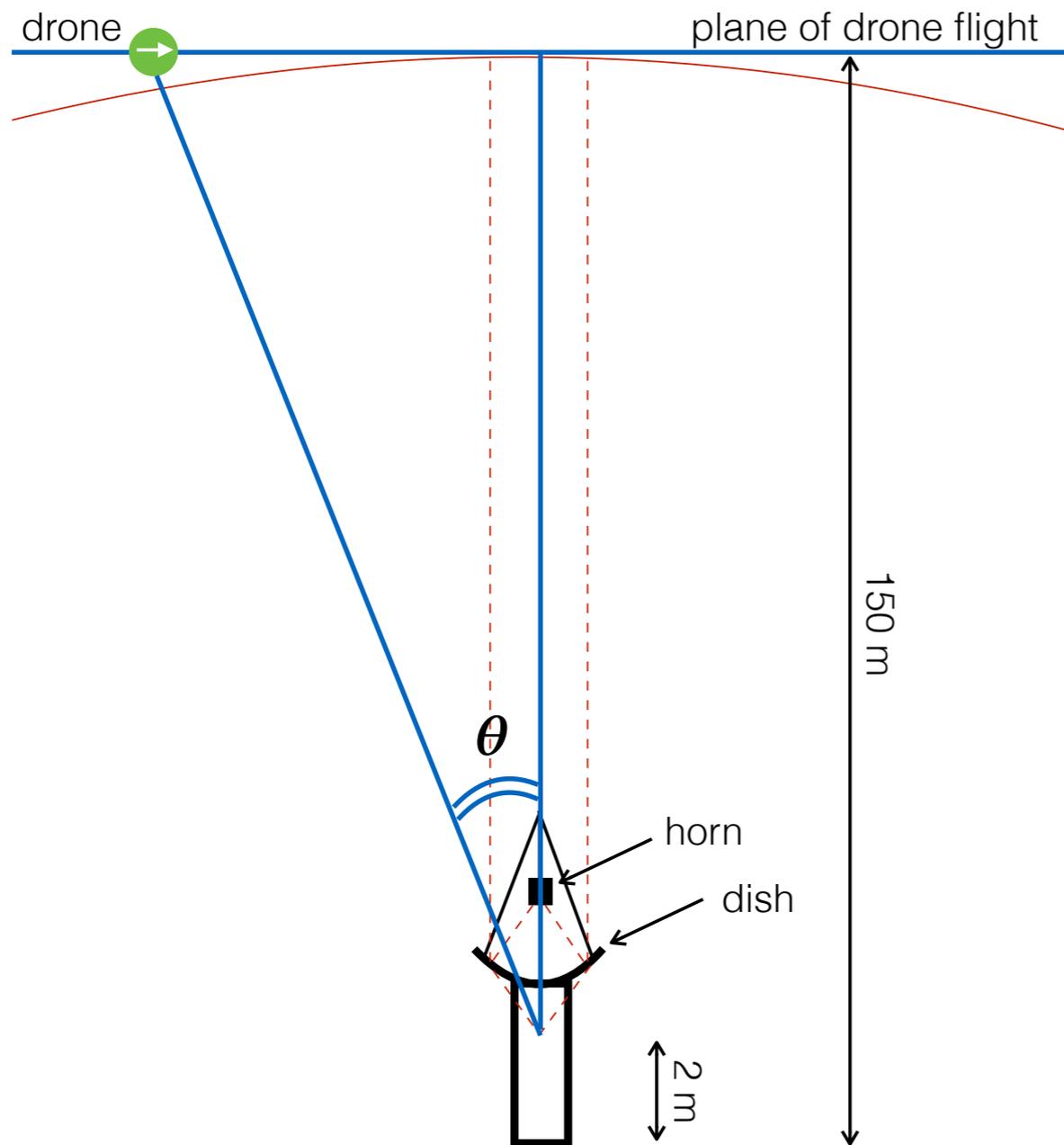


Radio Telescope Calibration

- 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

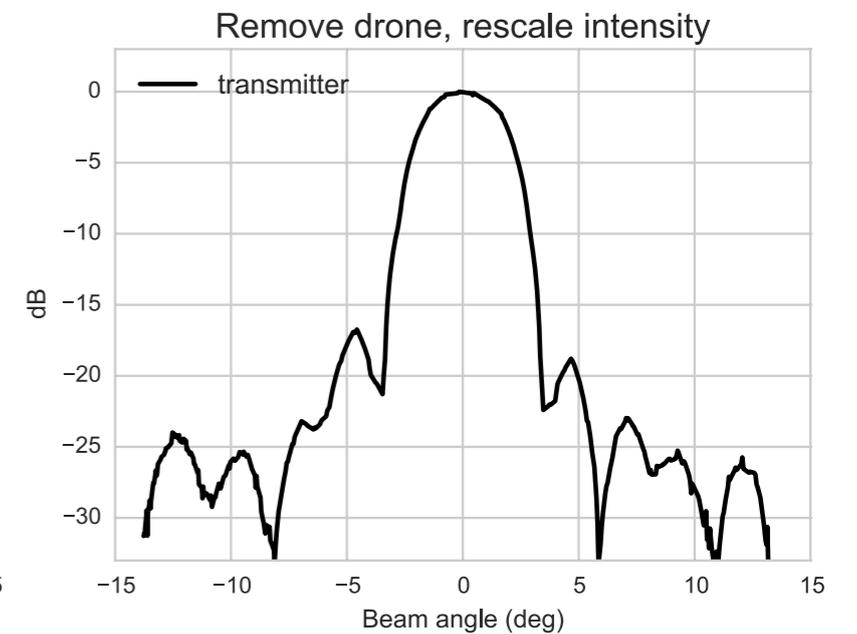
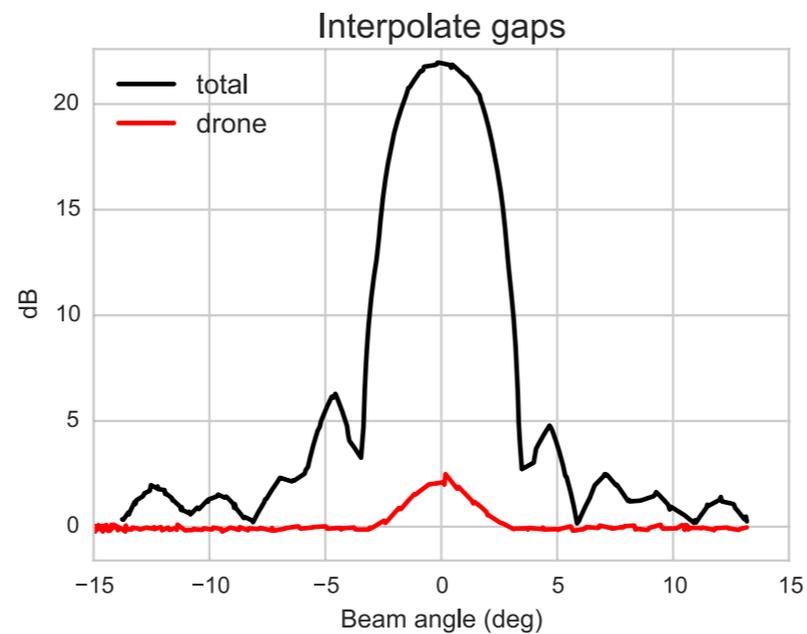
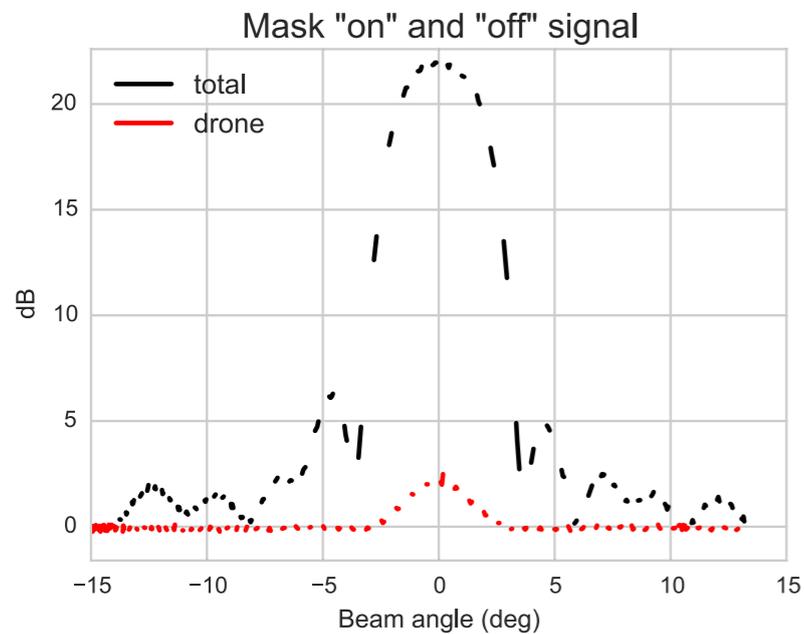
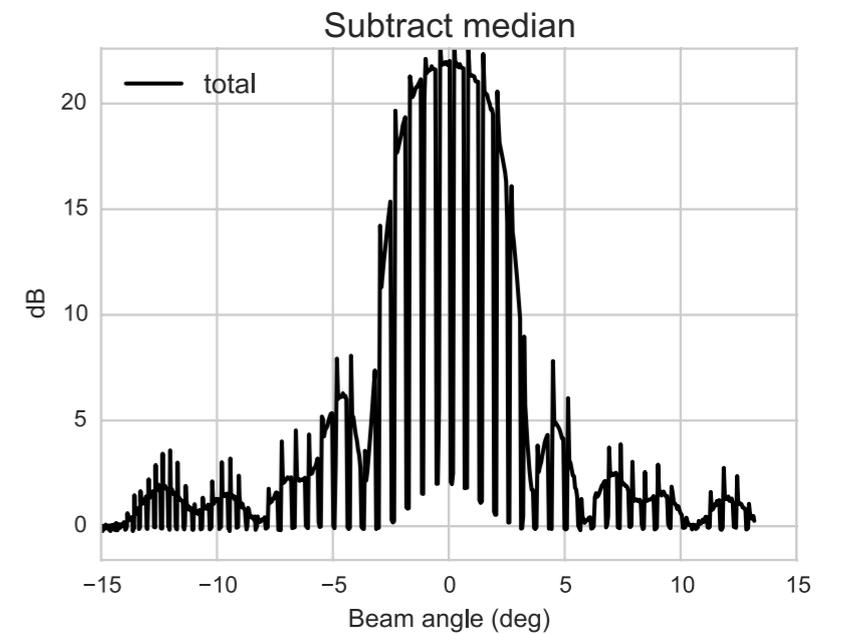
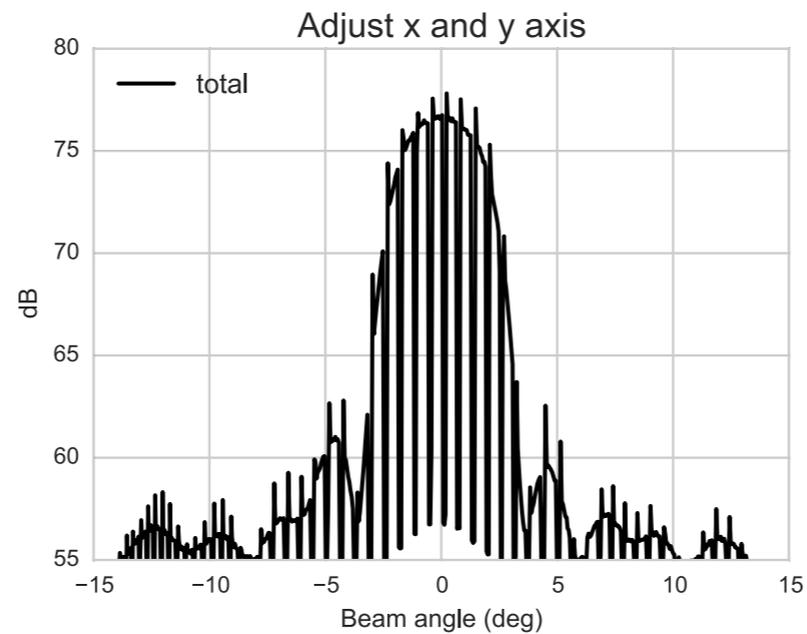
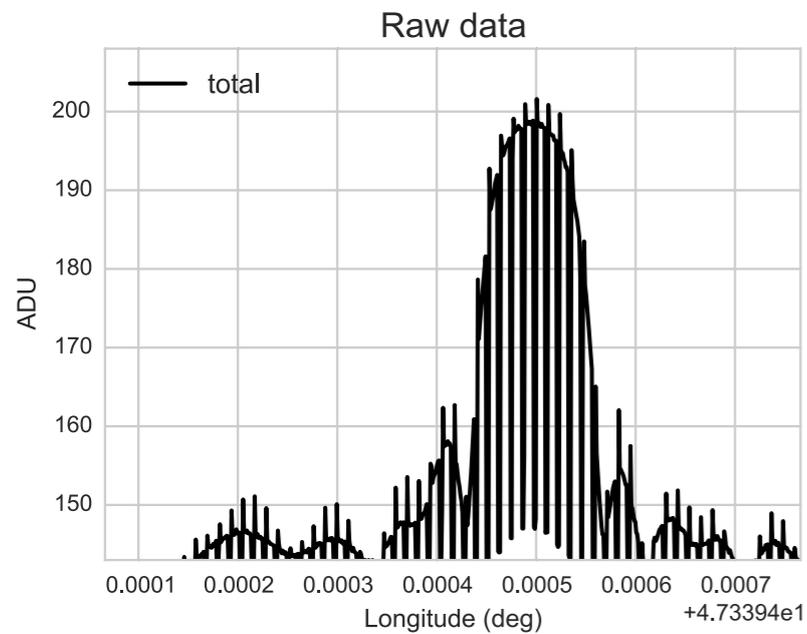


The Computational Challenge

- 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**...



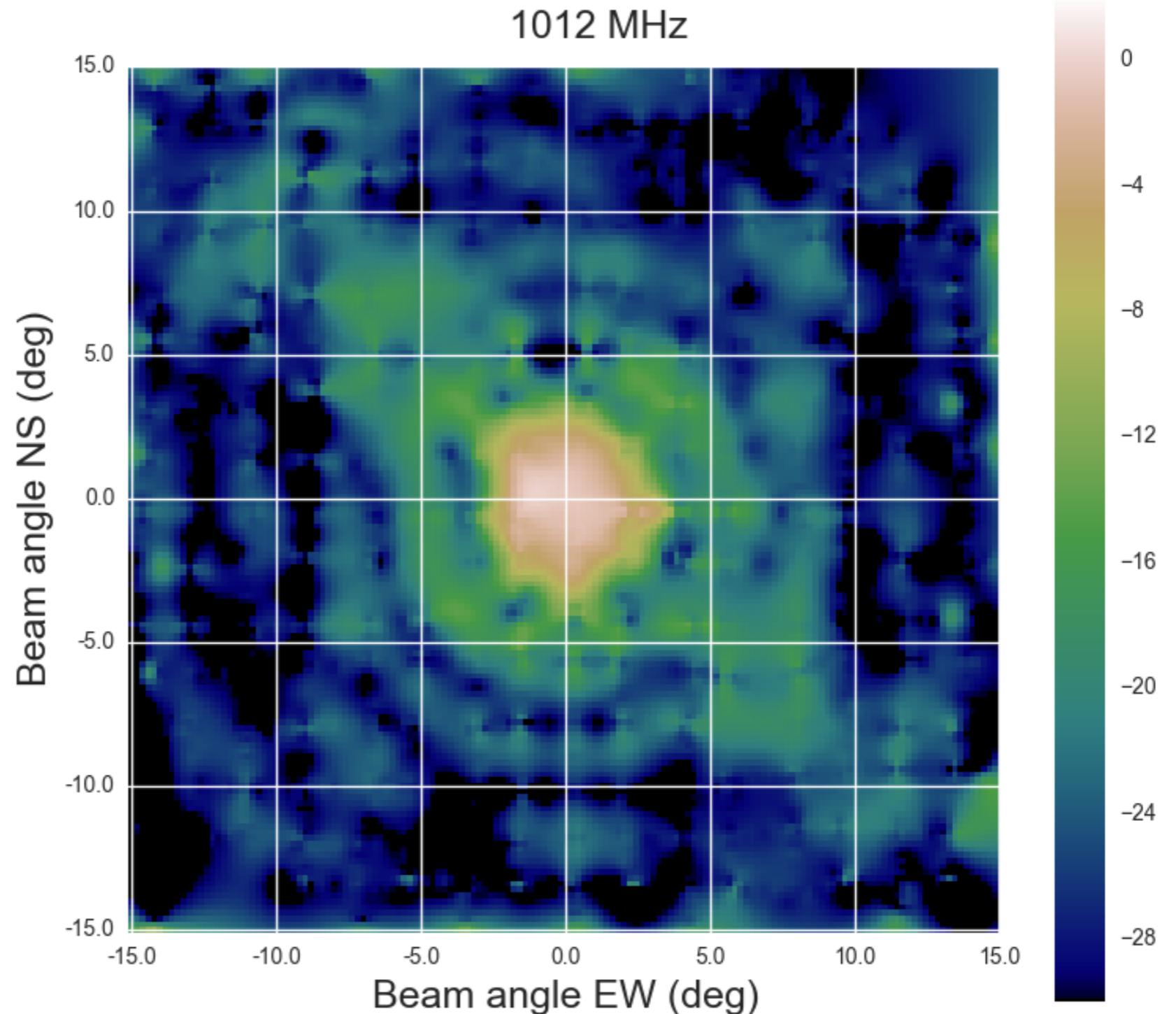
Analysis



Results

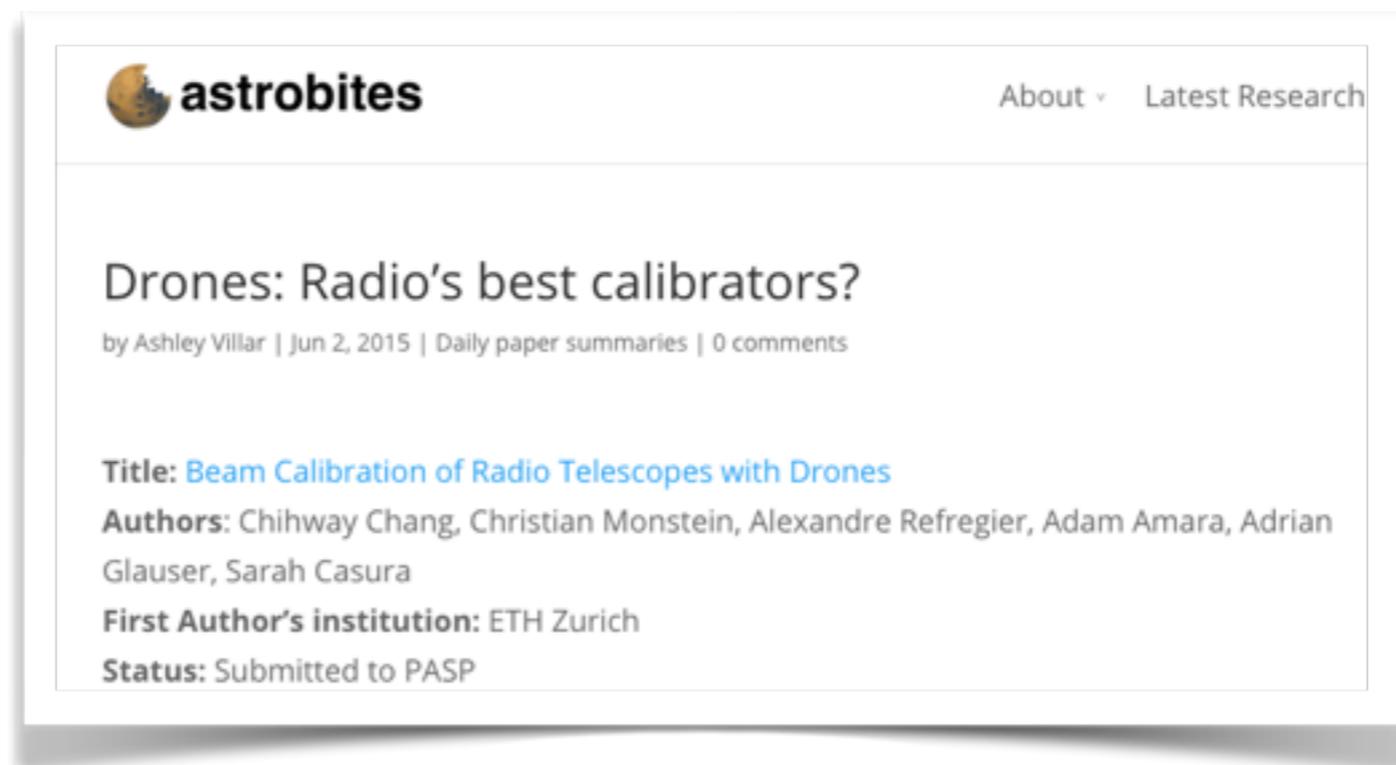
2D maps of the
telescope beam
profile with very
high S/N

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



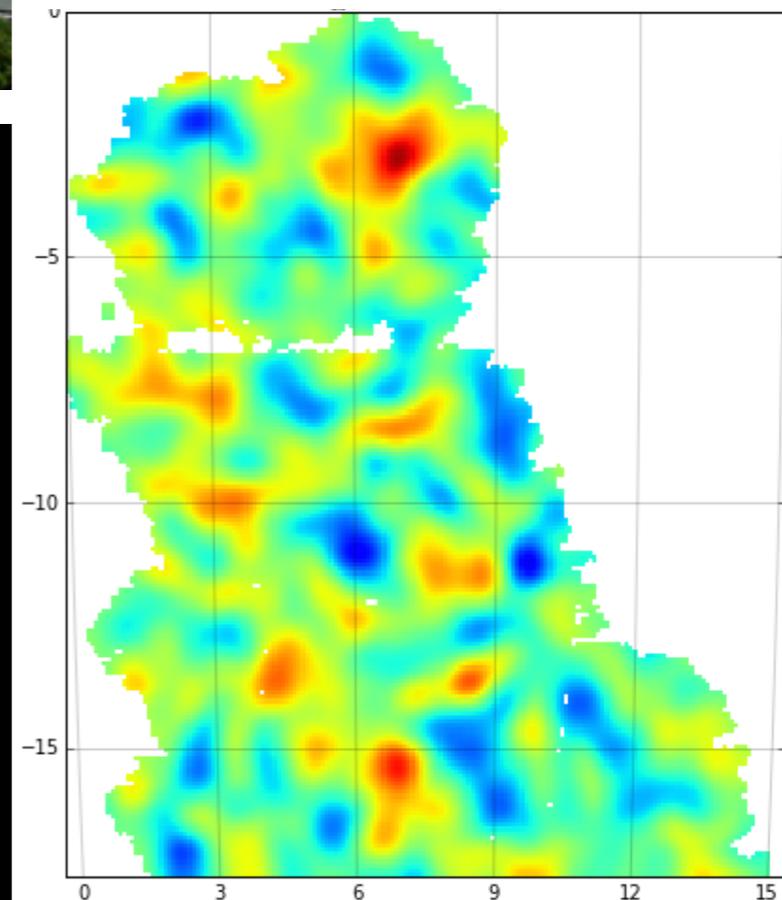
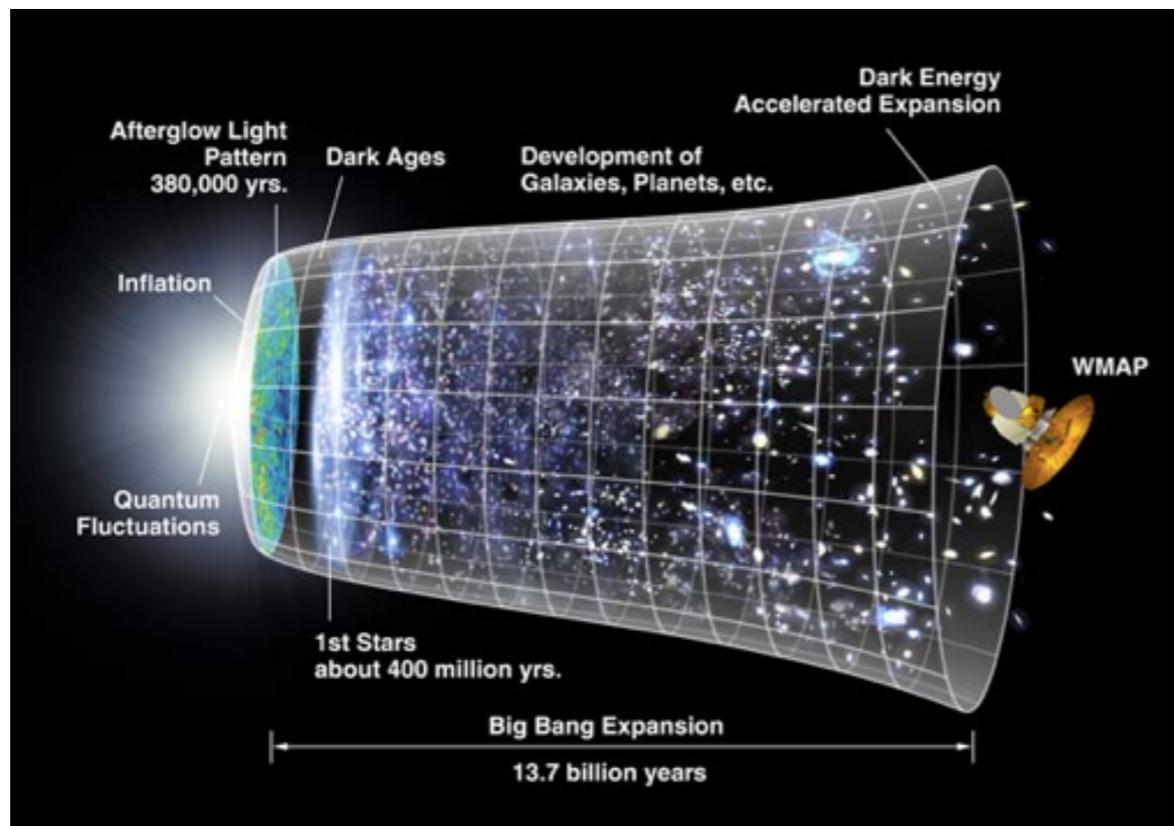
Summary: Radio Telescope Calibration

- 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...

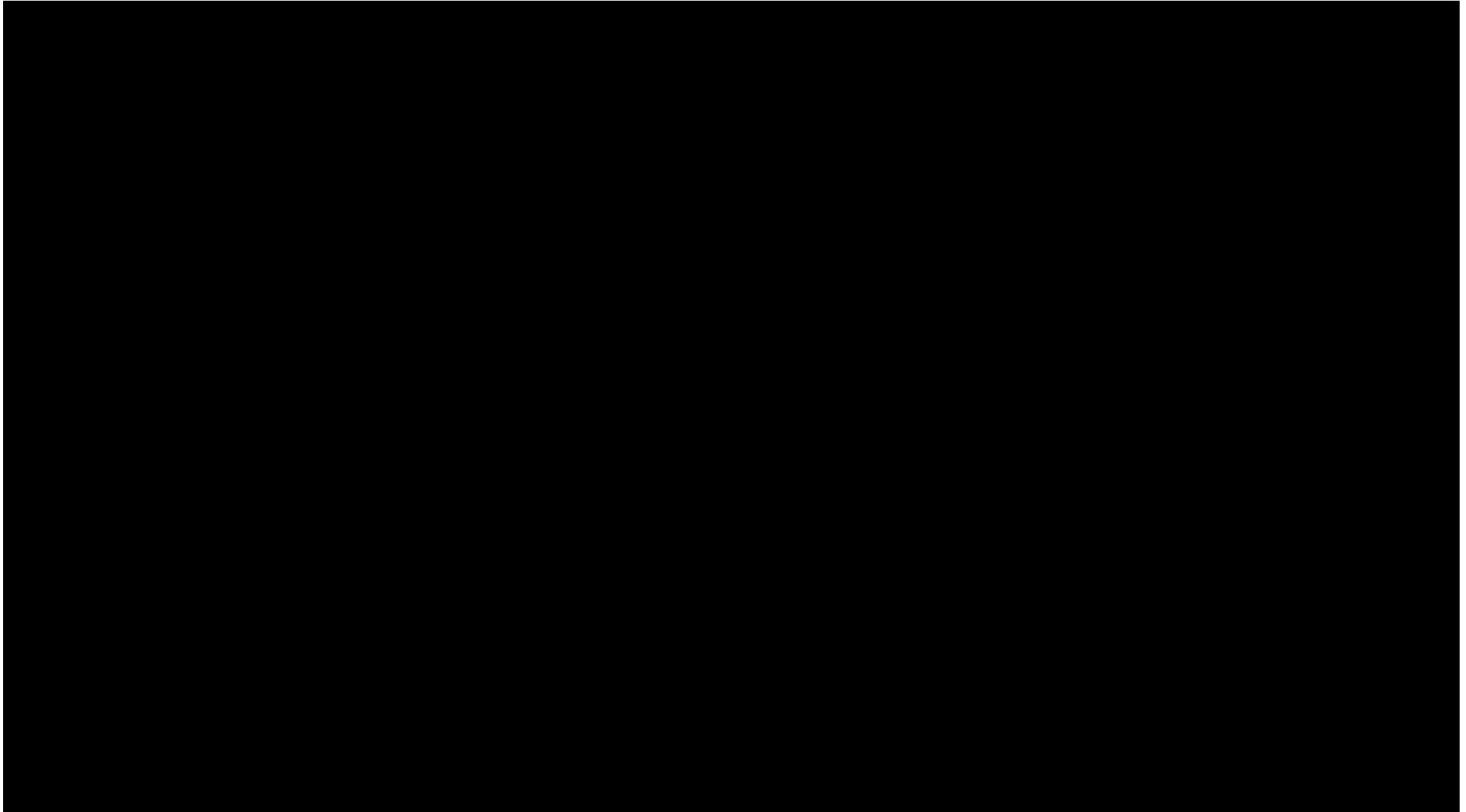
The ETH Cosmology Group



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 $\alpha = \nabla \psi$

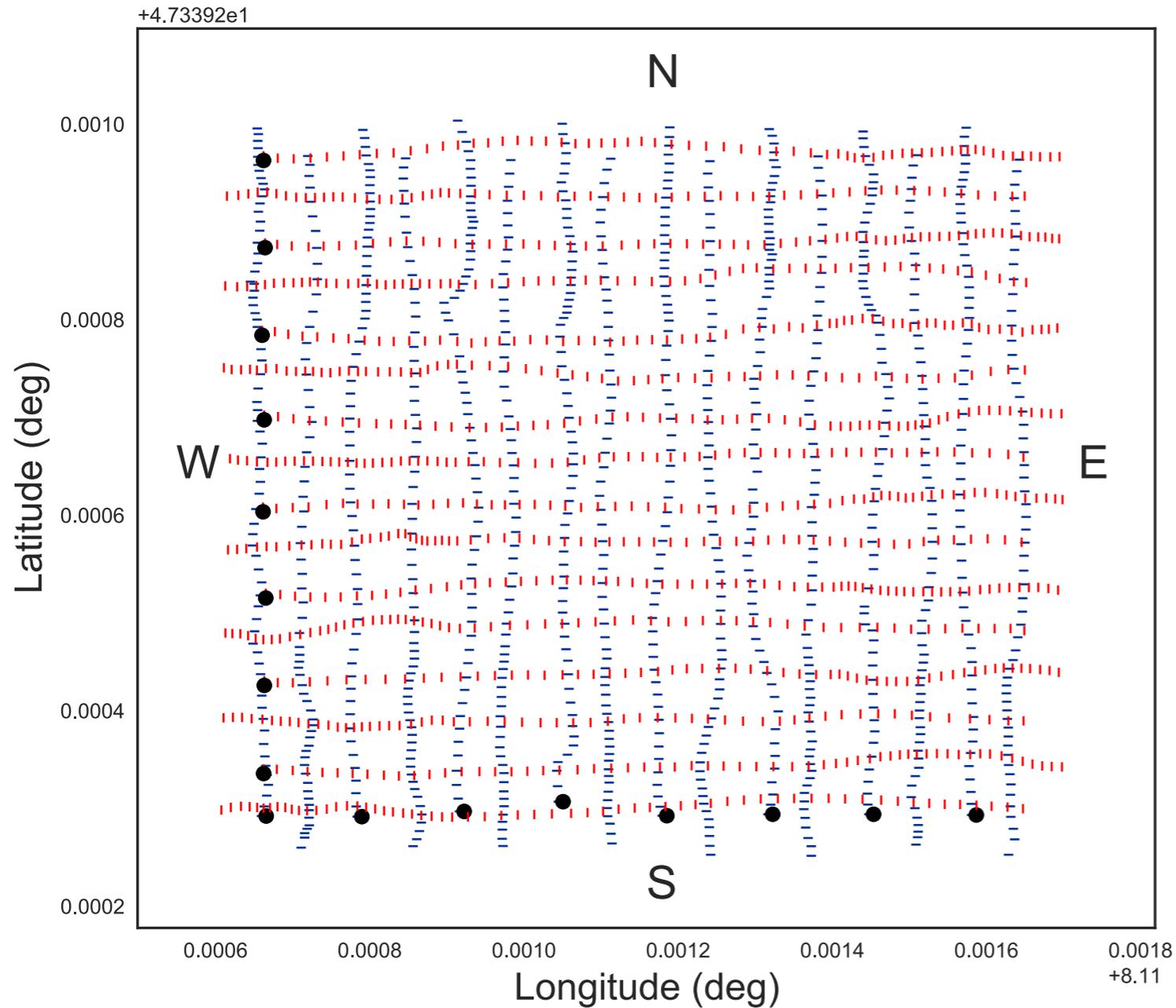
Convergence $\kappa = \frac{1}{2} \nabla^2 \psi = \frac{1}{2} (\psi_{,11} + \psi_{,22})$

→ **Mass (what we care about)**

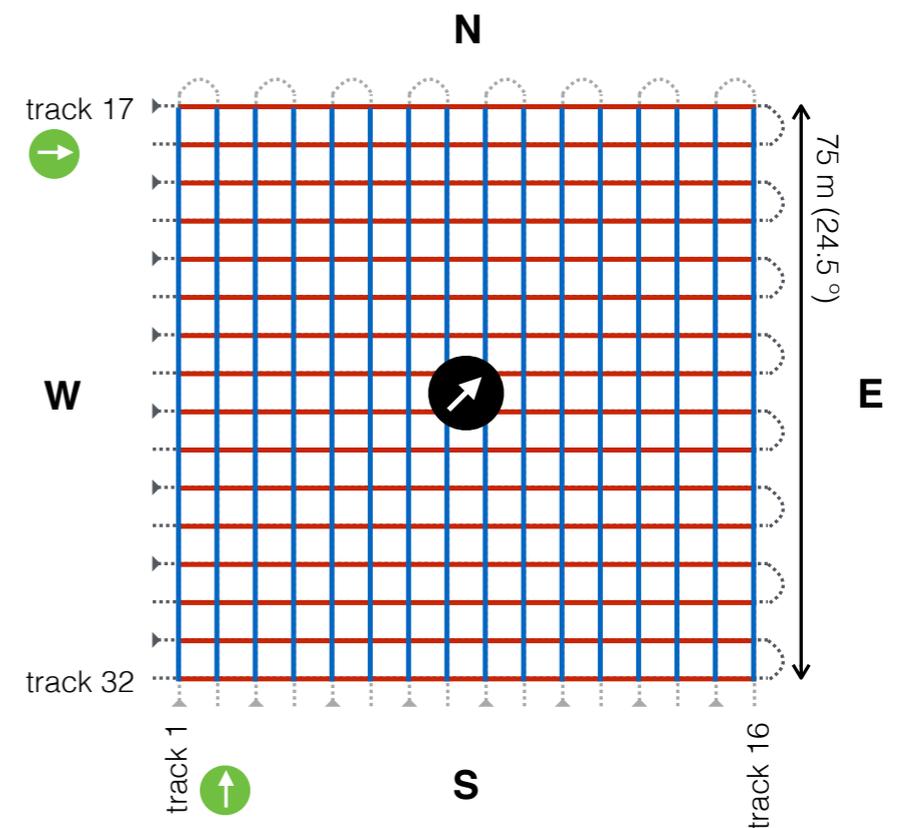
Shear $\gamma = \gamma_1 + i\gamma_2 = \frac{1}{2} (\psi_{,11} - \psi_{,22}) + i\psi_{,12}$

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

Analysis

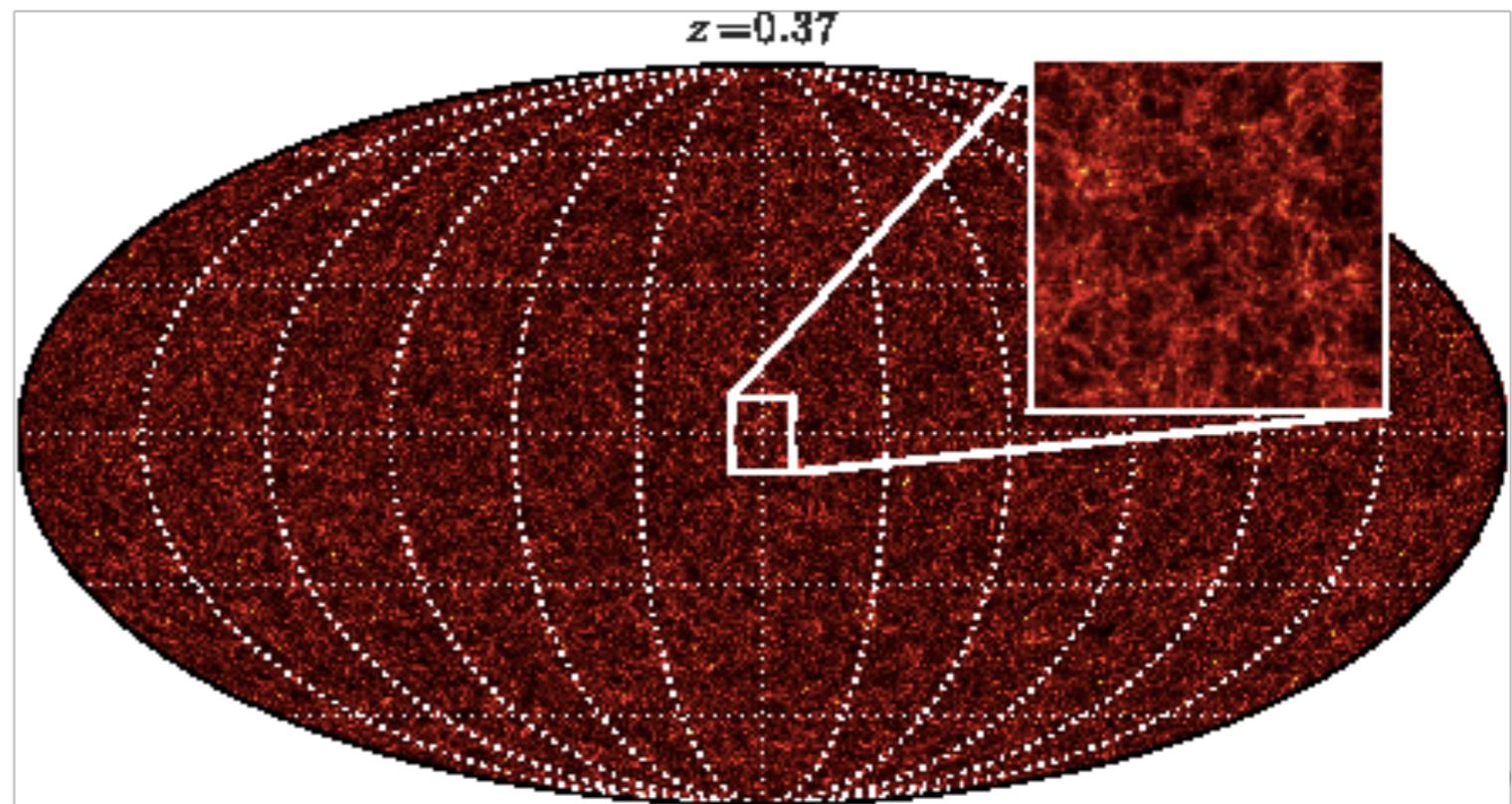
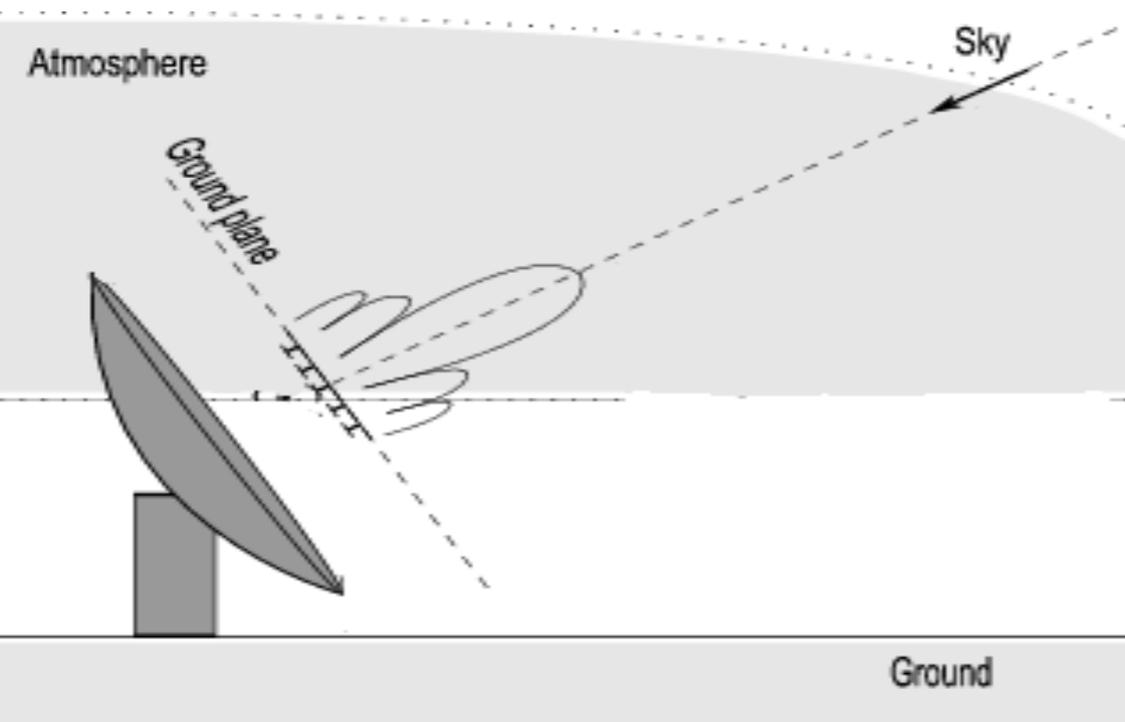


Positioning:
GPS + barometric altimeter



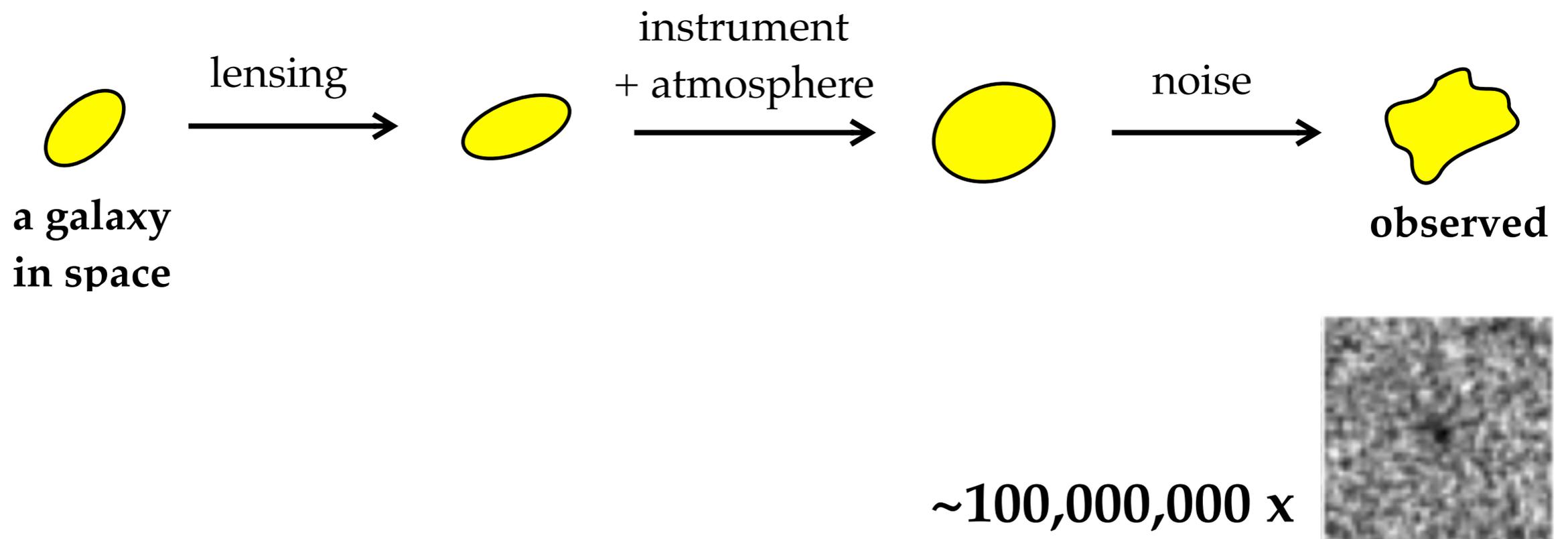
Radio Telescope Calibration

- 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.



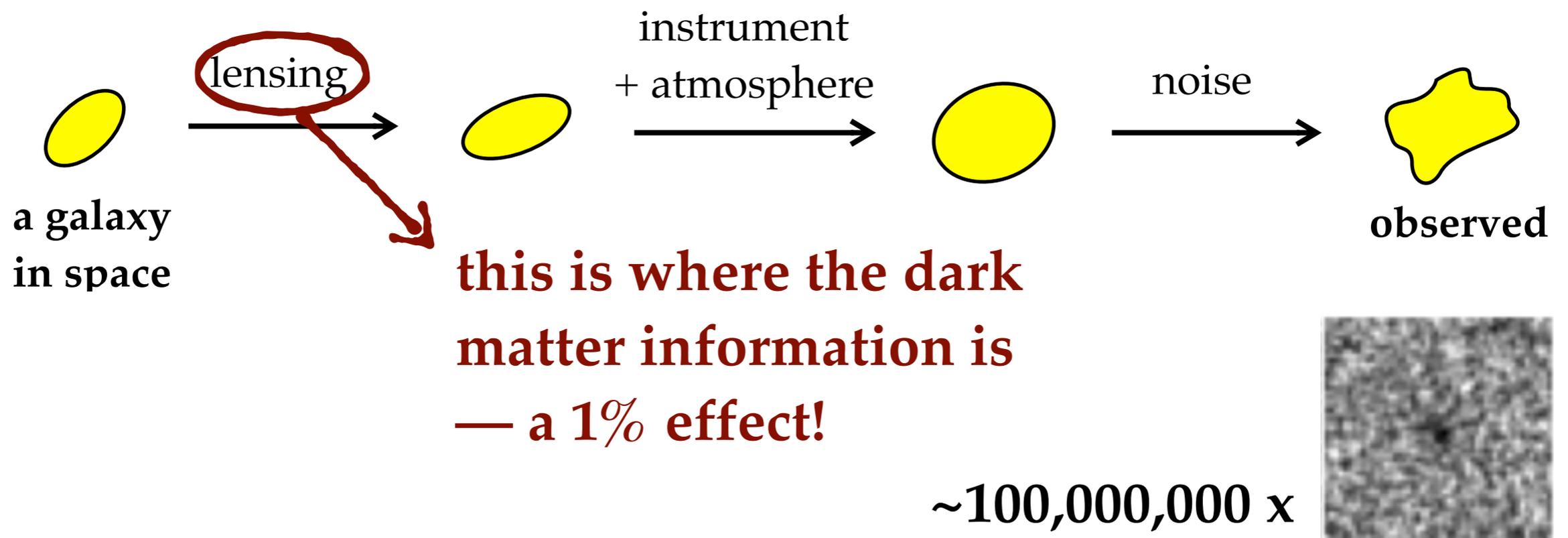
The Computational Challenge

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



The Computational Challenge

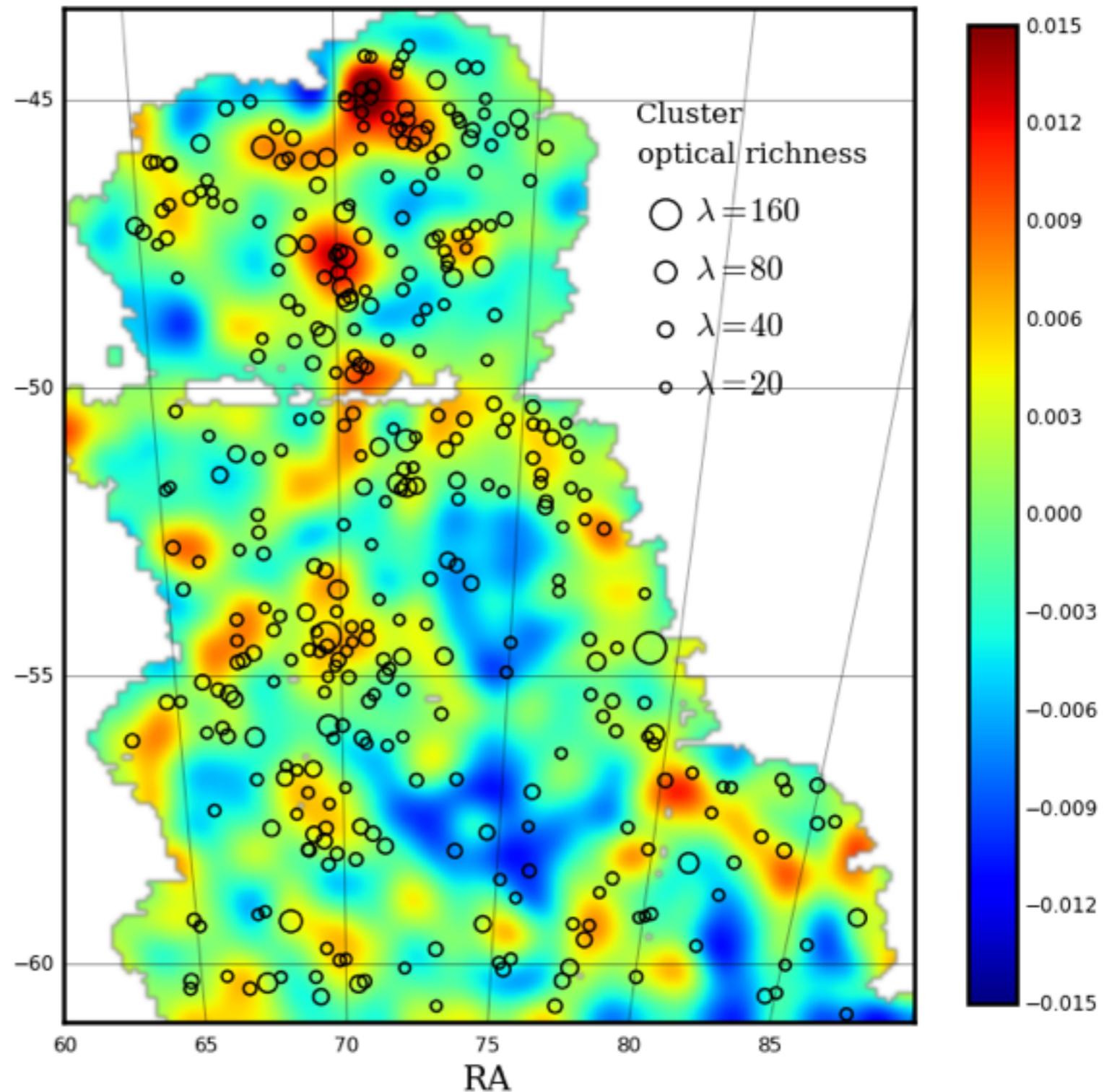
- We want to measure accurately **shapes** of a lot of small, faint, noisy galaxies, and get useful information out of them.



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