

Coding / Decoding the Cosmos: Python Applications in Astrophysics



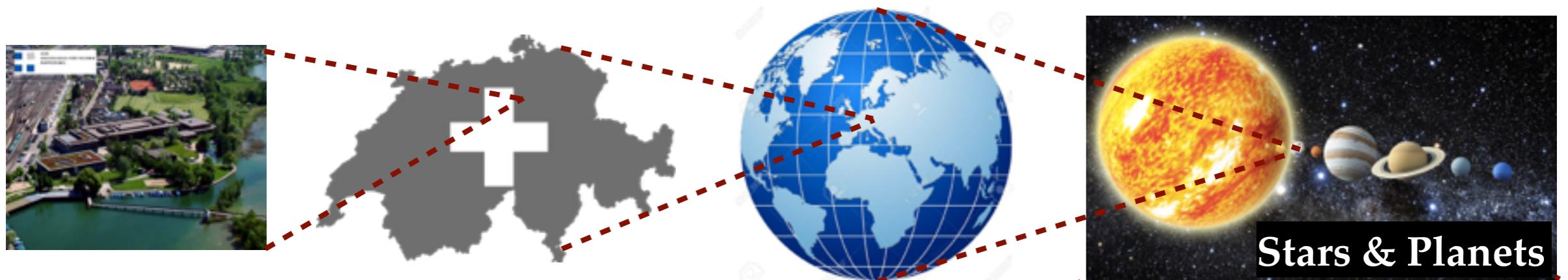
Chihway Chang (ETH Zürich)

ETH | Cosmology

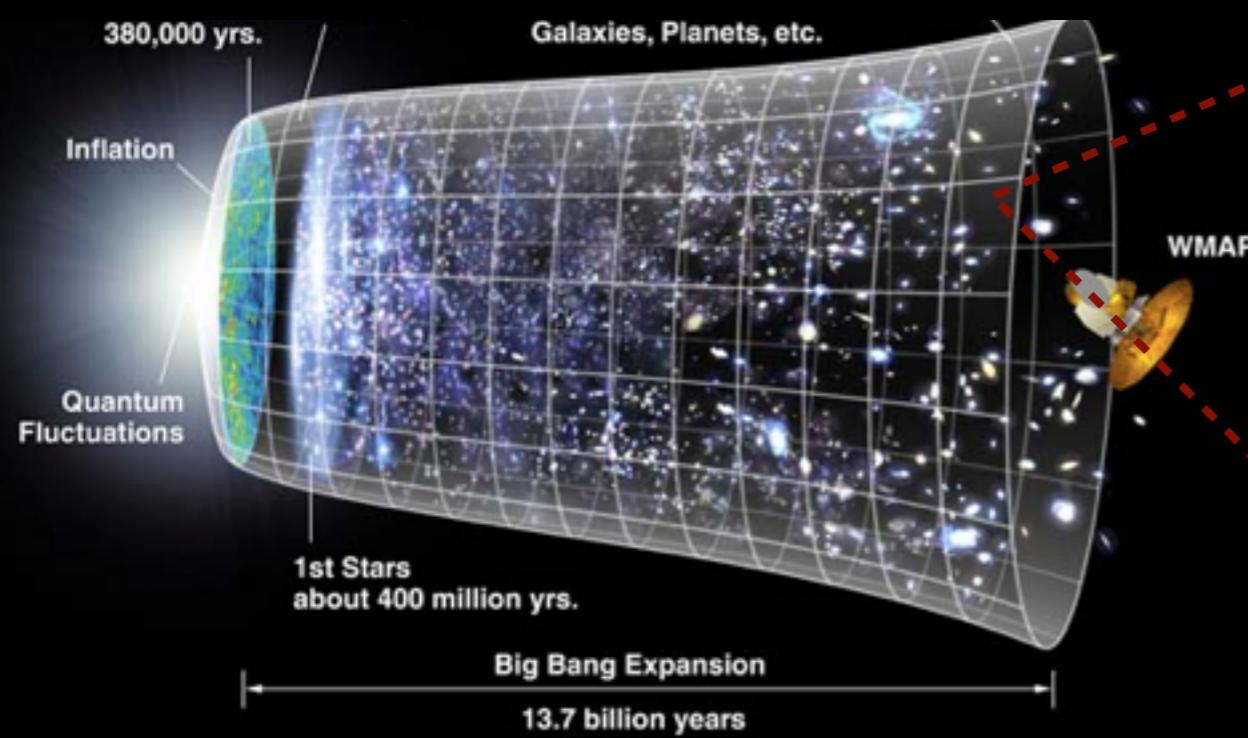
DISCLAIMER

- 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**.

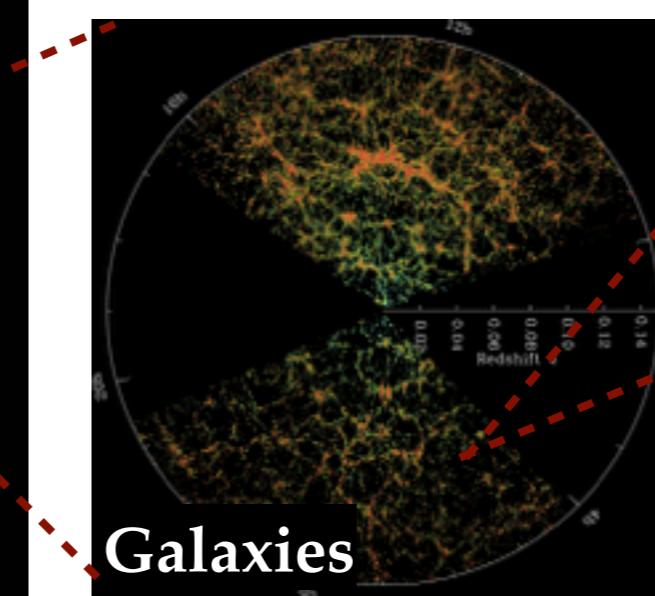
From Astrophysics to Cosmology



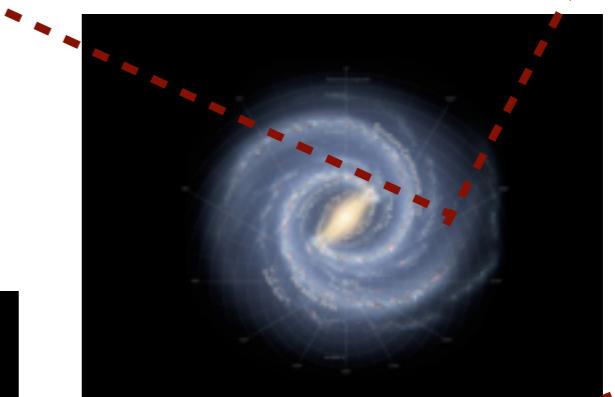
Cosmology



3



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>

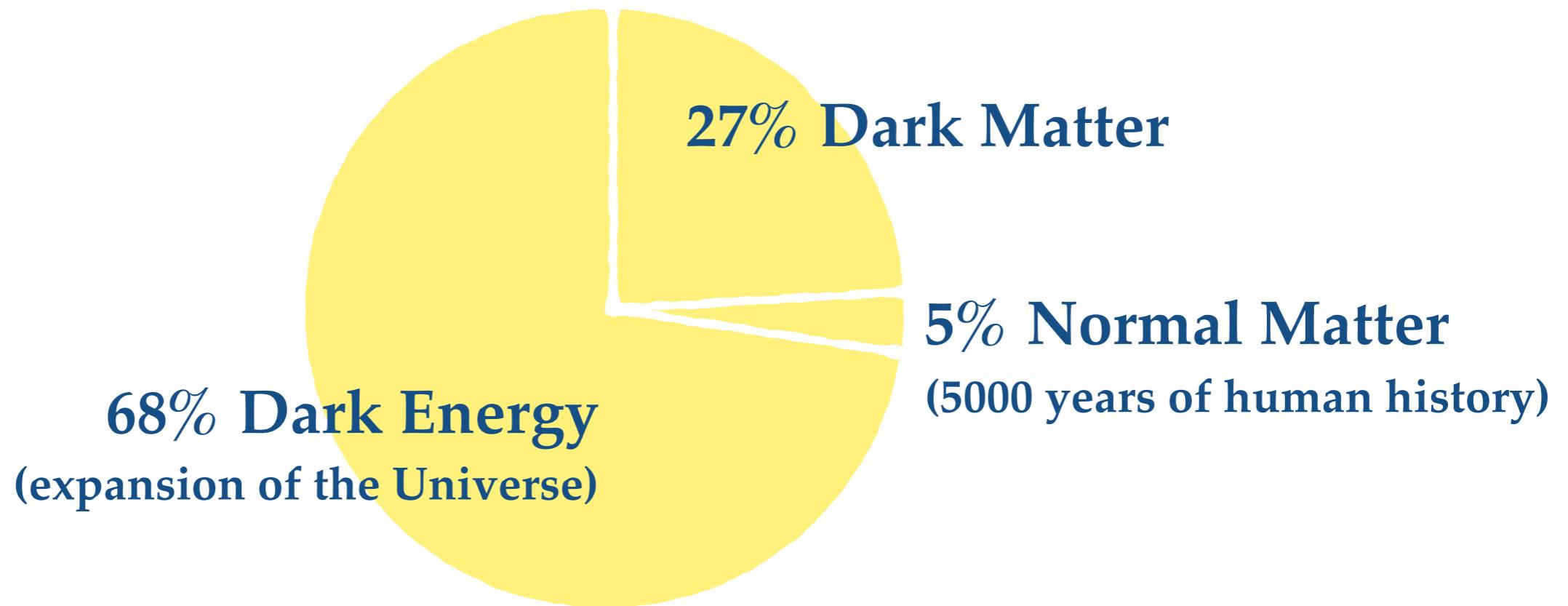
Two Examples

- **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*

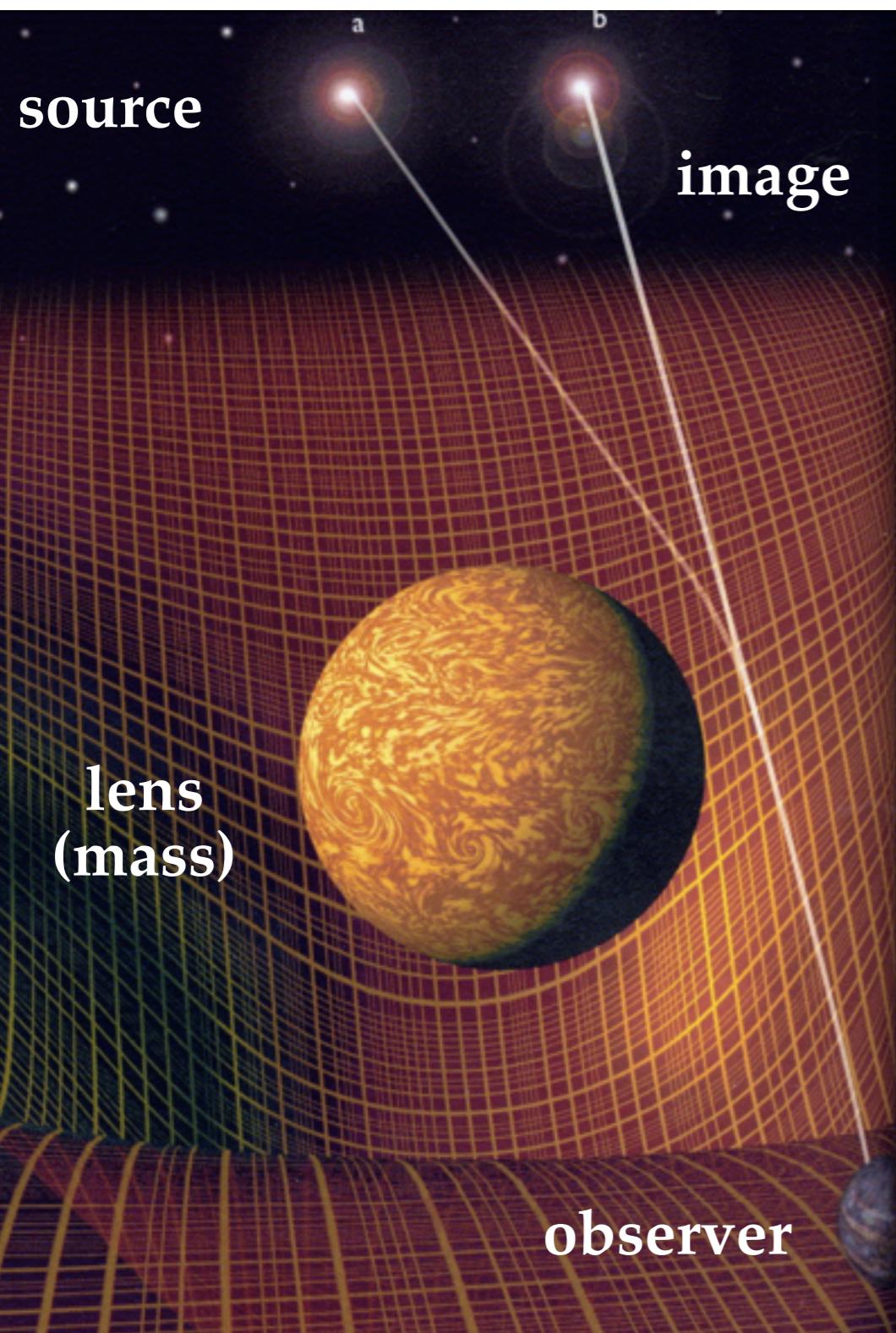


Mapping Dark Matter

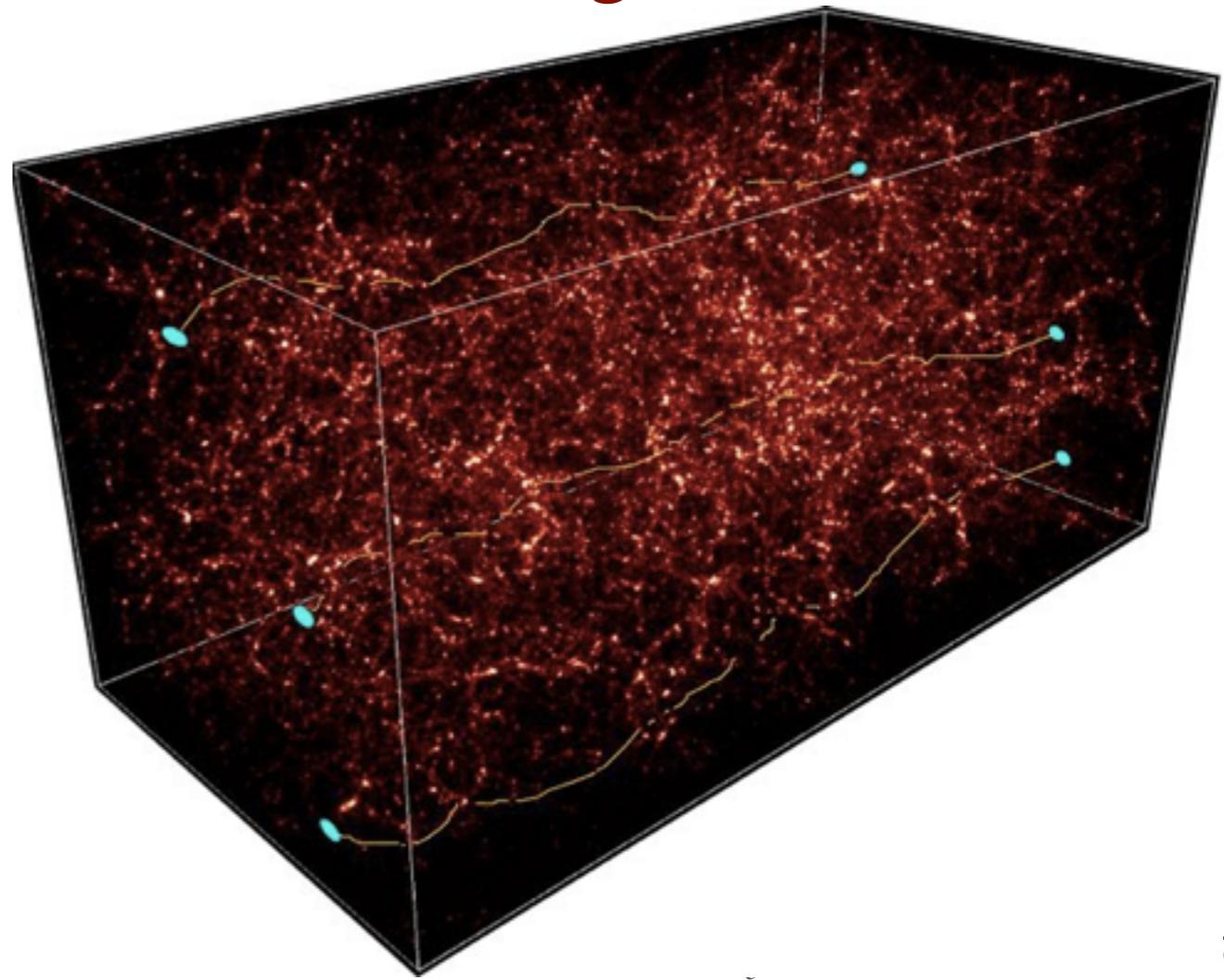
- **We don't know a whole lot about our Universe**, because we cannot **see** most of the stuff in the Universe!



Gravitational Lensing



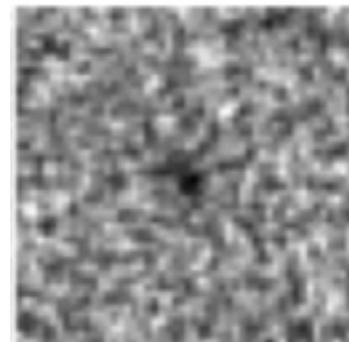
We can *see* dark matter through
Gravitational Lensing!



The Computational Challenge

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

$\sim 100,000,000 \times$



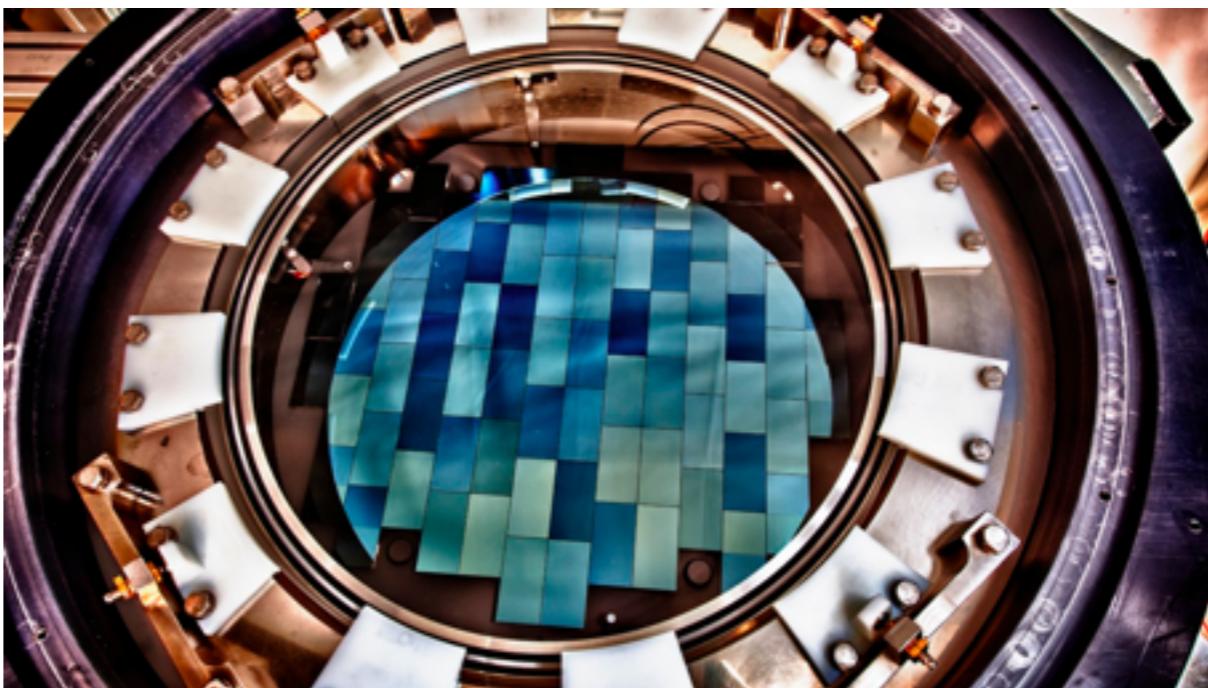
The Computational Challenge

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

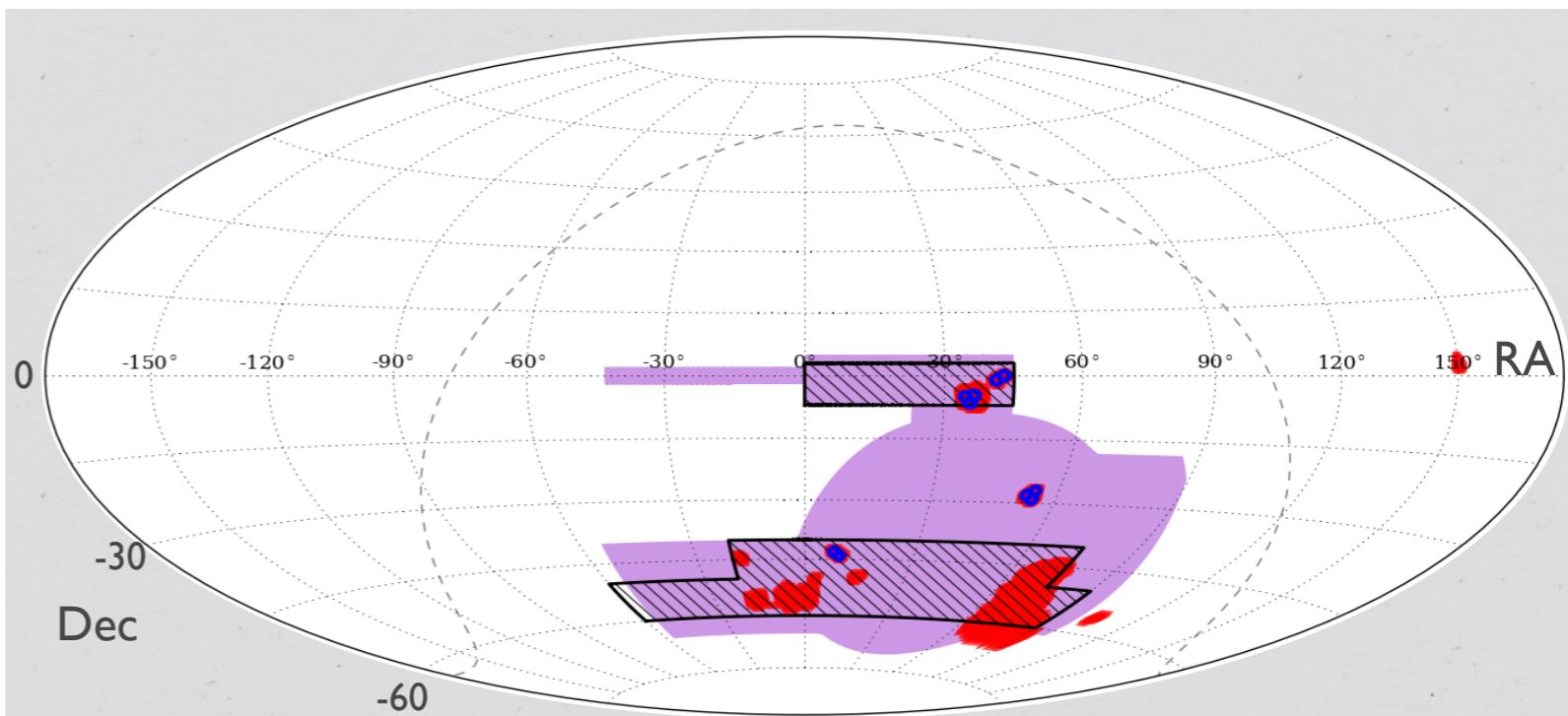


[/barbababytprowe/great3-public](https://github.com/barbababytprowe/great3-public)
[/GalSim-developers/GalSim](https://github.com/GalSim-developers/GalSim)

The Dark Energy Survey

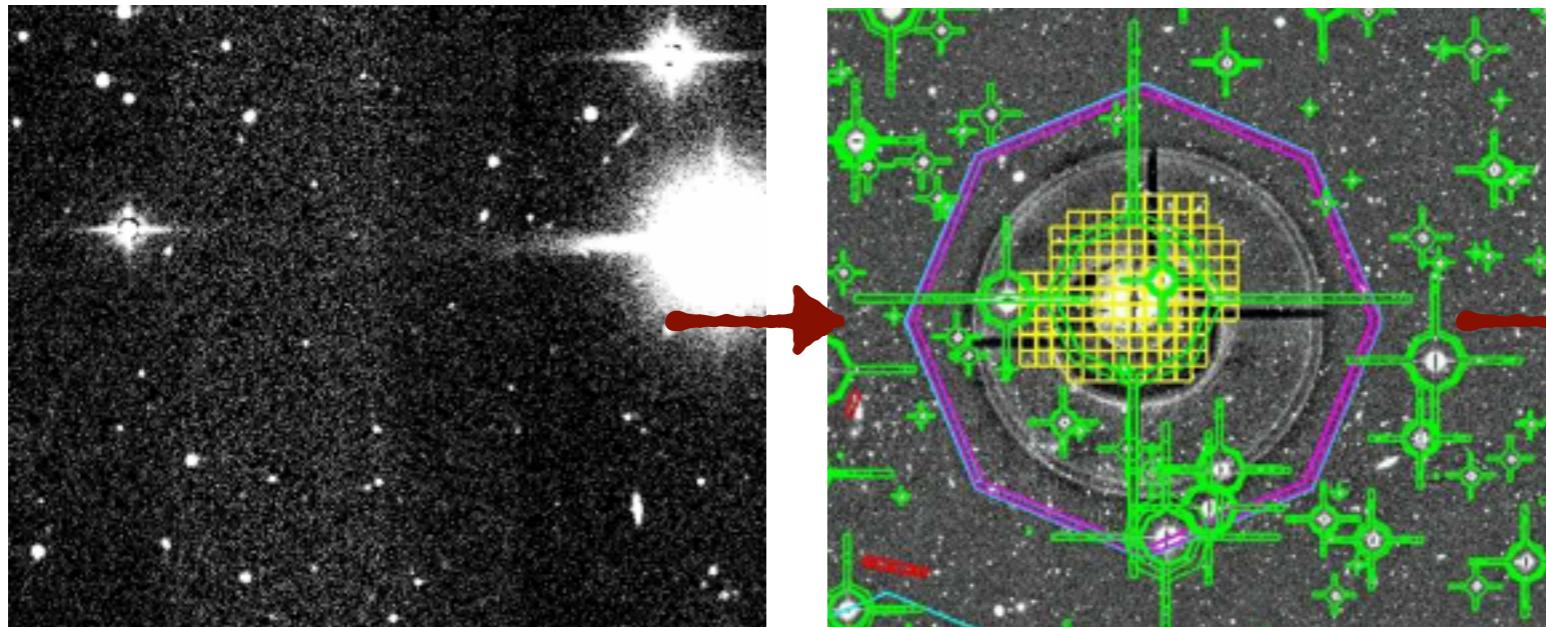


DES is an ongoing **galaxy imaging survey** and will cover **5000 sq. degrees** over 5 years



The Dark Energy Survey

- The data processing pipeline (partially Python)



NGC 300	11 32 49.4	+44 07 15	SAb	...	809	12.5	5.4 ± 4.9	-20.1	112	0.46	0.1
NGC 4123	12 08 06.0	+05 10 27	SBp	...	1336	21.6	3.8 ± 3.2	-21.6	—	0.03	0.1
NGC 4236	12 16 42.3	+09 27 45	SB0m	...	0	3.5	21.9 ± 7.2	-18.1	176	0.09	0.4
NGC 4294	12 18 49.6	+14 24 39	SAbc	...	2407	20.0	3.4 ± 4.7	-21.6	272	1.02	0.1
NGC 4321	12 22 54.9	+15 49 21	SA0bc	L	1571	20.0	3.4 ± 6.3	-22.1	283	0.79	0.1
NGC 4490	12 28 29.6	+17 05 06	SA0ab	L	1954	20.0	3.2 ± 3.9	-21.4	290	0.07	0.1
NGC 4536	12 34 22.0	+02 11 16	SA0bc	R	1808	25.0	3.6 ± 3.2	-20.8	337	2.33	0.4
NGC 4592	12 35 39.9	+12 33 22	ED	L	340	20.0	3.1 ± 4.7	-20.8	—	—	—
NGC 4599	12 35 37.7	+27 07 35	SA0bcd	R	816	11.6	10.7 ± 4.6	-21.0	281	0.17	0.4
NGC 4609	12 36 49.8	+13 09 46	SA0ab	R	>235	20.0	3.5 ± 4.6	-22.0	360	0.22	0.1
NGC 4679	12 37 43.8	+11 49 05	SA0b	L	1919	20.0	3.9 ± 4.7	-21.8	390	0.17	0.2
NGC 4894	12 39 59.4	+11 37 23	SAb	R	1091	11.7	8.7 ± 3.5	-21.5	362	0.16	0.1
NGC 4828	12 41 52.9	+01 16 25	SA0bcsp	...	809	9.8	2.2 ± 1.9	-17.9	46	0.37	0.1
NGC 4831	12 42 08.0	+32 32 26	SBd	...	806	9.0	10.5 ± 2.7	-20.6	320	1.26	0.4
NGC 4728	12 50 26.0	+25 30 03	SA0ab	R	1206	17.1	10.7 ± 7.6	-22.0	410	0.09	0.2
NGC 4736	12 50 53.0	+41 07 16	SA0b	L	308	5.3	11.2 ± 9.1	-19.9	241	0.03	0.5
ICD 154	12 54 05.2	+27 08 59	EBm	...	376	5.4	3.0 ± 2.2	-15.1	905	—	—
NGC 4828	12 36 43.7	+21 40 32	SA0b	R	408	3.6	10.0 ± 5.6	-20.3	311	0.23	0.4
NGC 165	13 06 24.0	+07 42 25	Im	...	37	3.5	—	-15.3	68	—	—
NGC 5033	13 13 27.9	+36 35 38	SAb	R	875	13.3	10.7 ± 3.0	-20.9	446	0.48	0.1
NGC 5095	13 15 49.3	+42 01 45	SA0bc	R	506	8.2	12.6 ± 7.2	-19.0	405	4.56	0.2
NGC 5194	13 29 52.7	+47 11 43	SA0bc	R	463	8.2	11.2 ± 6.3	-21.4	395	0.60	0.1
NGC 5195	13 29 58.7	+47 16 05	SB0p	L	352	8.2	5.8 ± 4.6	-20.0	—	0.29	0.1
NGC 5398	14 01 21.3	-33 03 47	SBdm	R	1216	15.0	2.8 ± 1.7	-18.9	137	0.44	0.1
NGC 5408	14 03 23.3	-41 22 40	EBm	...	309	4.5	3.6 ± 0.8	-16.1	116	0.34	0.1
NGC 5474	14 09 01.6	+53 39 44	SAbd	R	273	6.9	4.8 ± 4.3	-18.4	61	0.13	0.1
NGC 5723	14 40 11.3	-00 17 21	SA0bey	...	1083	26.6	2.8 ± 2.5	-20.9	209	1.71	0.1
NGC 5866	15 06 29.8	+55 45 48	SD	...	692	12.5	4.7 ± 1.9	-19.9	—	0.51	0.2
IC 4710	18 29 38.0	-06 58 56	EBm	R	341	8.5	3.6 ± 2.8	-18.3	81	0.26	0.1
NGC 6822	19 44 56.6	-14 47 21	EBm	...	>57	0.6	10.5 ± 13.5	-13.8	81	2.56	0.5
NGC 6946	20 34 52.3	+00 09 14	SA0bcd	R	48	3.5	11.8 ± 9.8	-21.3	242	0.39	0.4
NGC 7332	22 37 08.1	+34 26 56	SA0	L	816	13.7	10.5 ± 3.7	-21.8	530	1.02	0.1
NGC 7592	23 16 11.0	+42 34 59	SAb	R	1585	22.3	3.4 ± 2.7	-21.7	280	3.26	0.7
NGC 7793	23 37 49.8	-32 35 28	SA0	R	230	3.2	9.8 ± 6.3	-18.2	398	0.93	0.1

Note: Col. (1): RA; Col. (2): The right ascension in the J2000 epoch; Col. (3): The declination in the J2000 epoch; Col. (4): starburst; L: LINER; Sy: Seyfert (1, 2); Col. (5): Hubble velocity; Col. (6): Flow-connected distance in Mpc, for $H_0 = 70$ km/s; Col. (9): Absolute I magnitude, when available; otherwise from the V or B bands; Col. (10): 21 cm neutral hydrogen line width; Tully-Fisher or RCF; Col. (11): FIR/Optical luminosity ratio. The FIR luminosity is derived from the IRAS-measured 60–100 μm fluxes, as defined in $L_{\text{FIR}} = D_L^2 \cdot F_{\text{IR}}$; Col. (12): The ratio of the IRAS 60 μm to 100 μm flux; Col. (13): The logarithmic atomic gas mass, $\log M_{\text{H}_2}$ in solar units, from CO integrated fluxes; Col. (14): Star formation rates derived from $\text{H}\alpha$ emission, with typical $\Delta t = 1$ Gyr.

- raw data
- calibration
- stacking
- object detection
- masking artefacts
- measure characteristics of each object (size, brightness, shape etc.)
- classification
- “cataloging”
- science analysis

Mapping Dark Matter

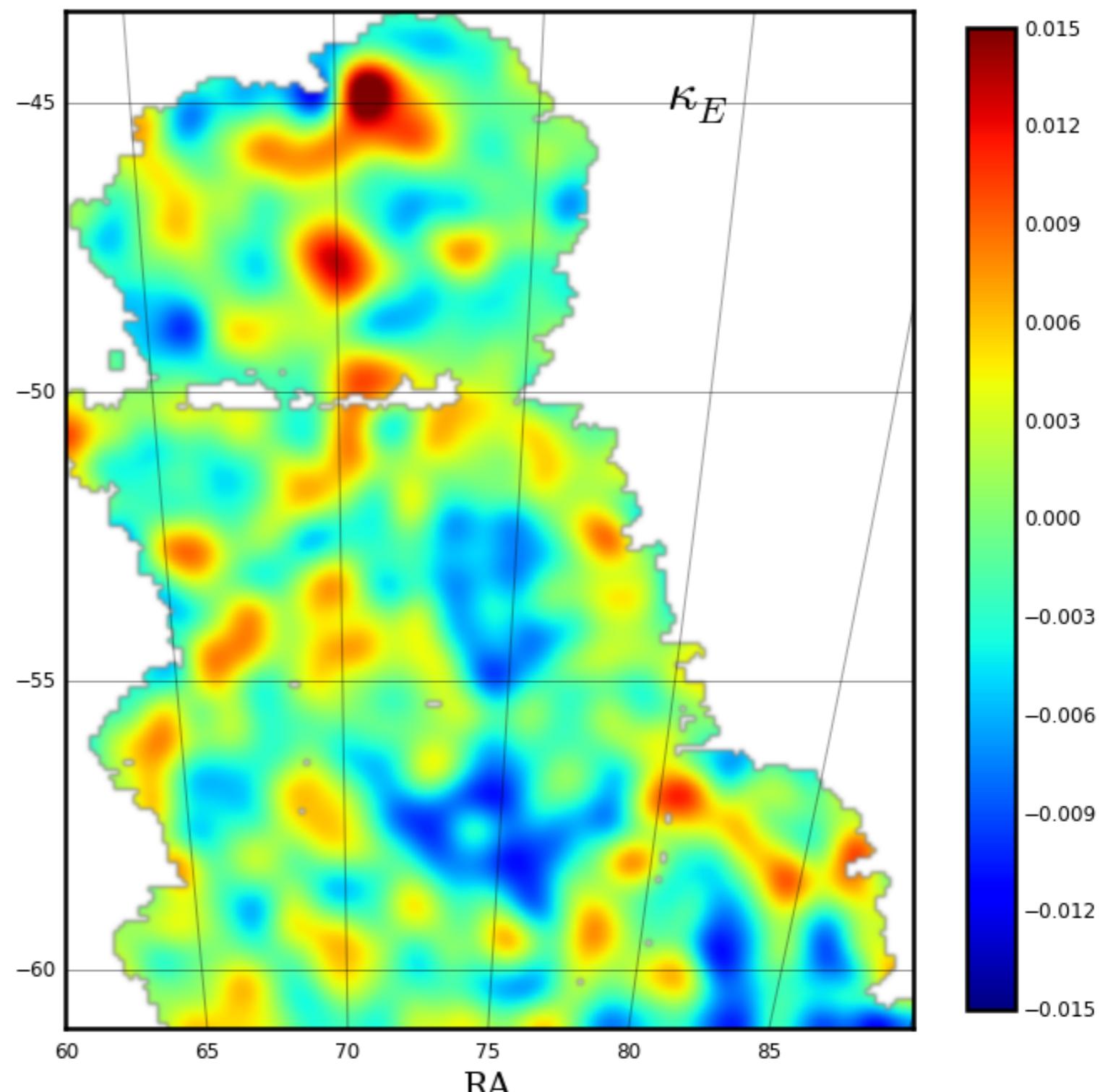
Convert galaxy shapes to mass:

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

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

Mass

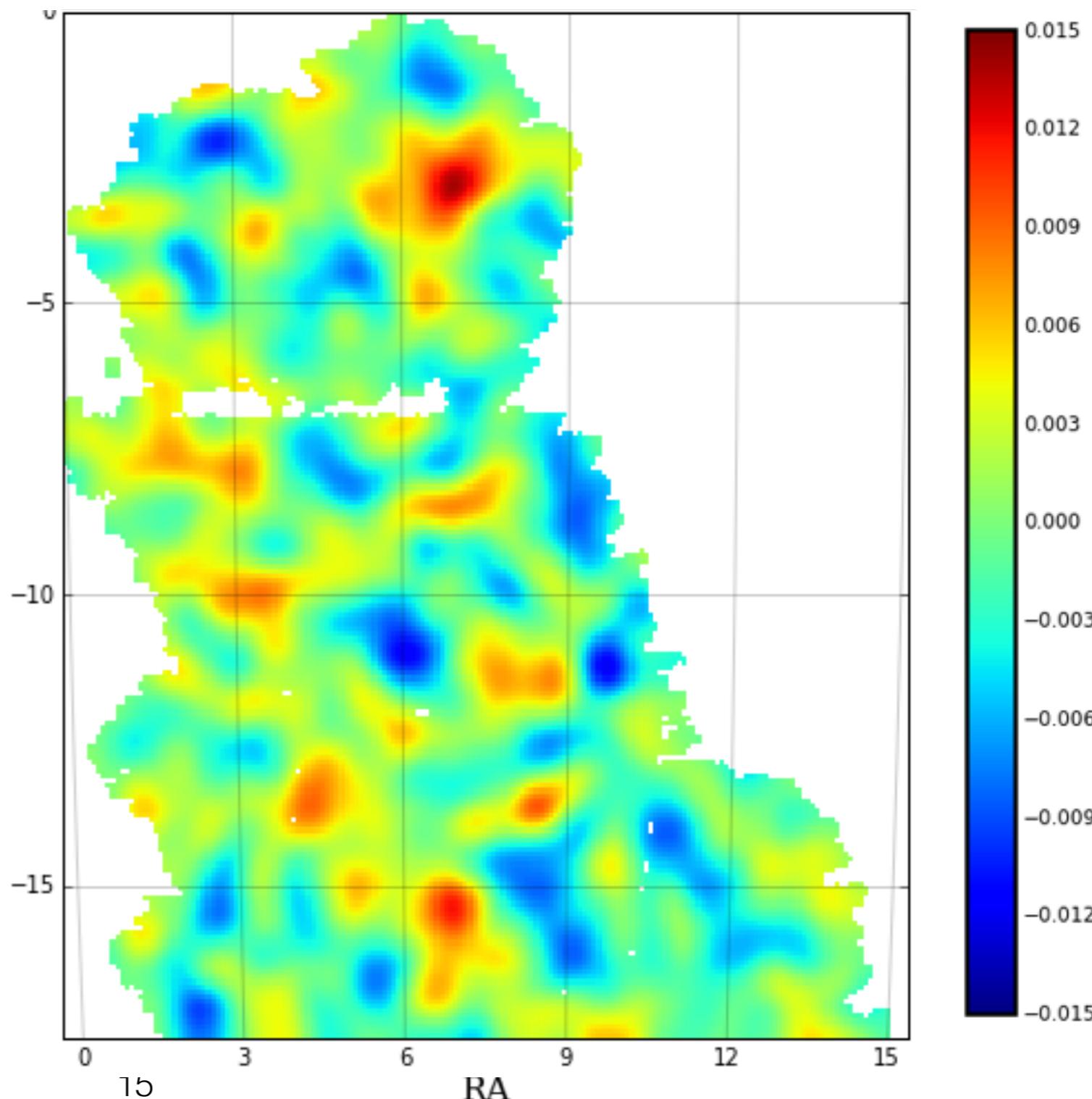
Galaxy shapes



Mapping Dark Matter

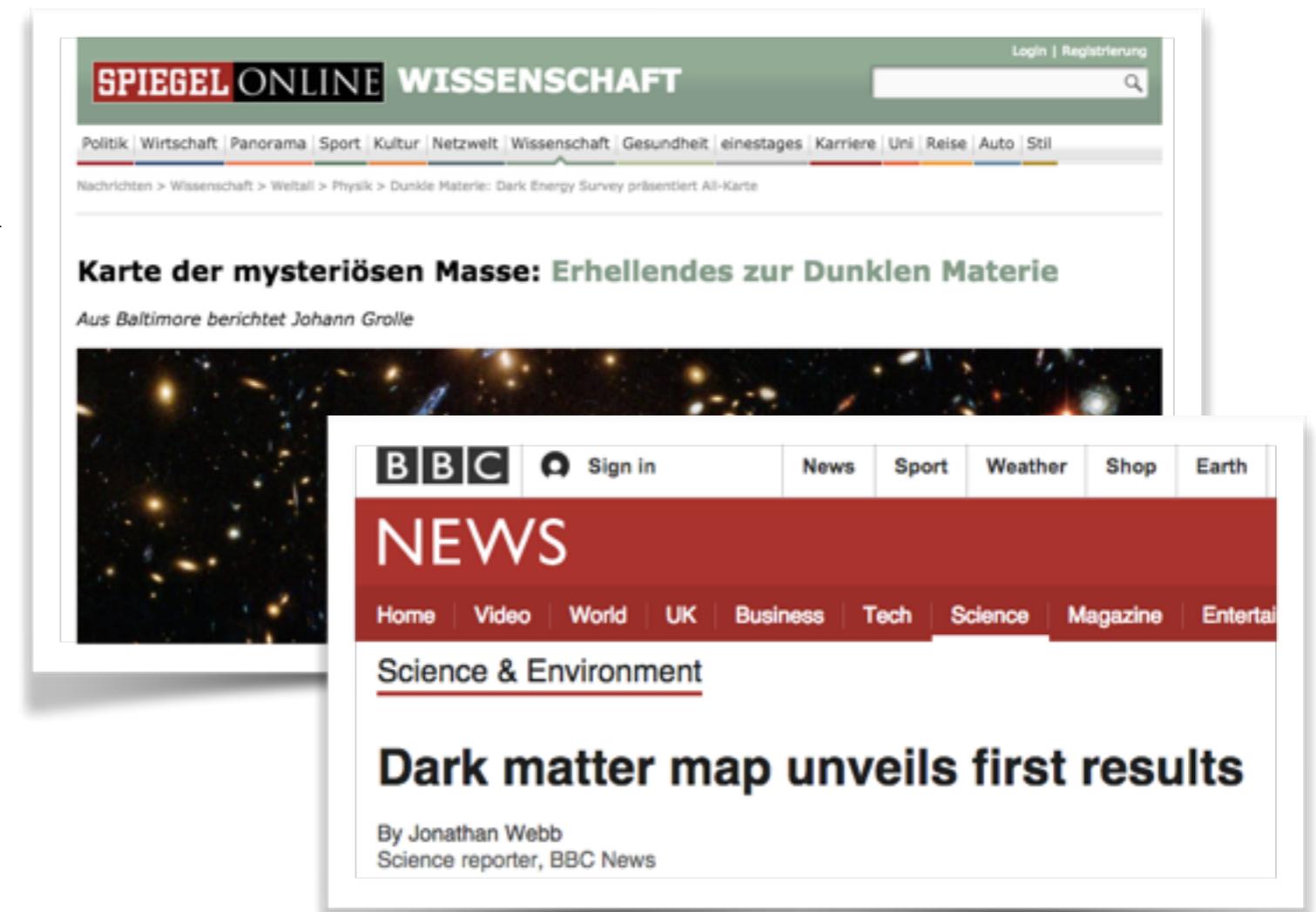
Simulation is a crucial ingredient in cosmological analyses, since many of the analysis steps are **heavily non-linear** and **couples with one another**.

```
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.

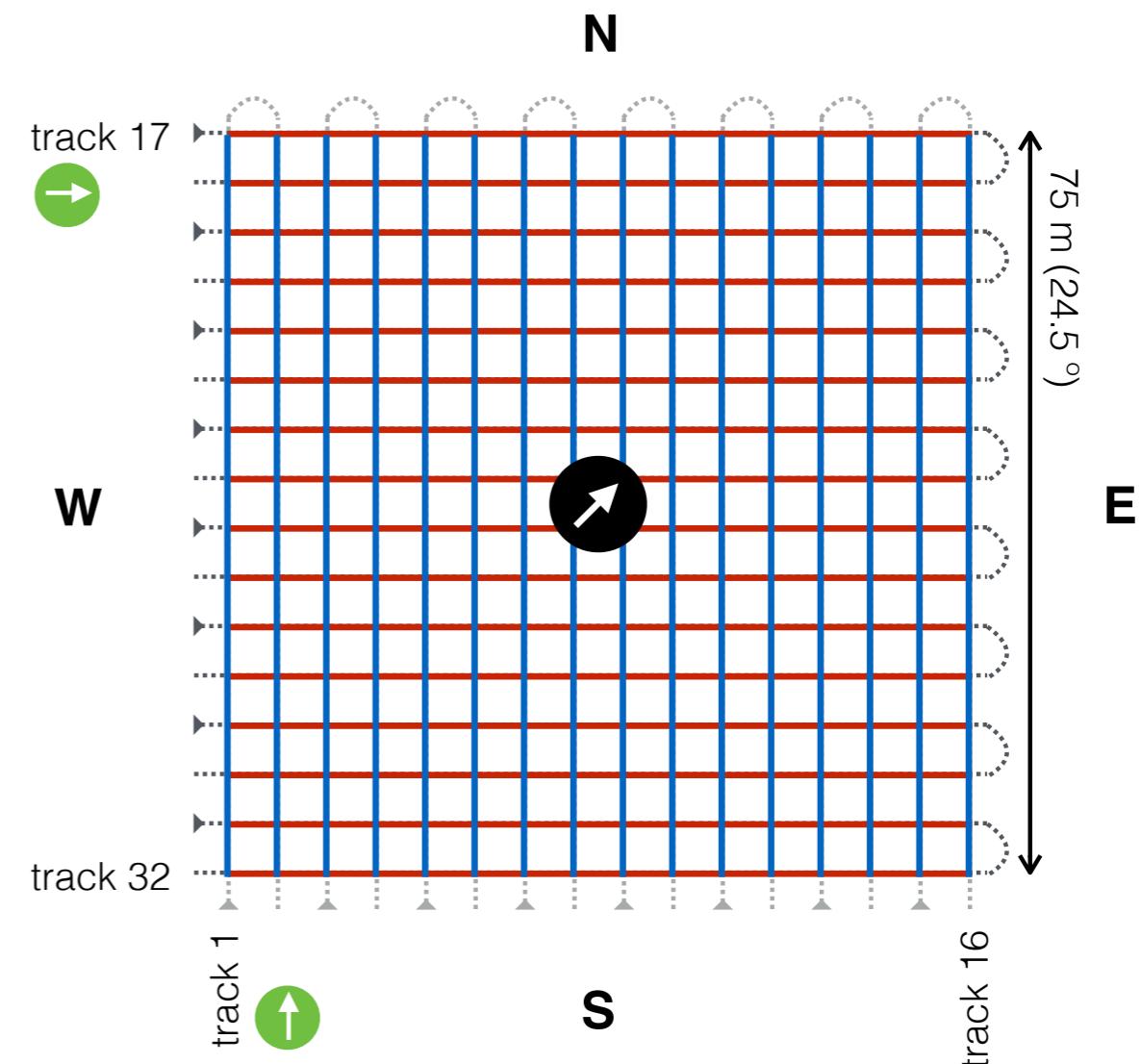
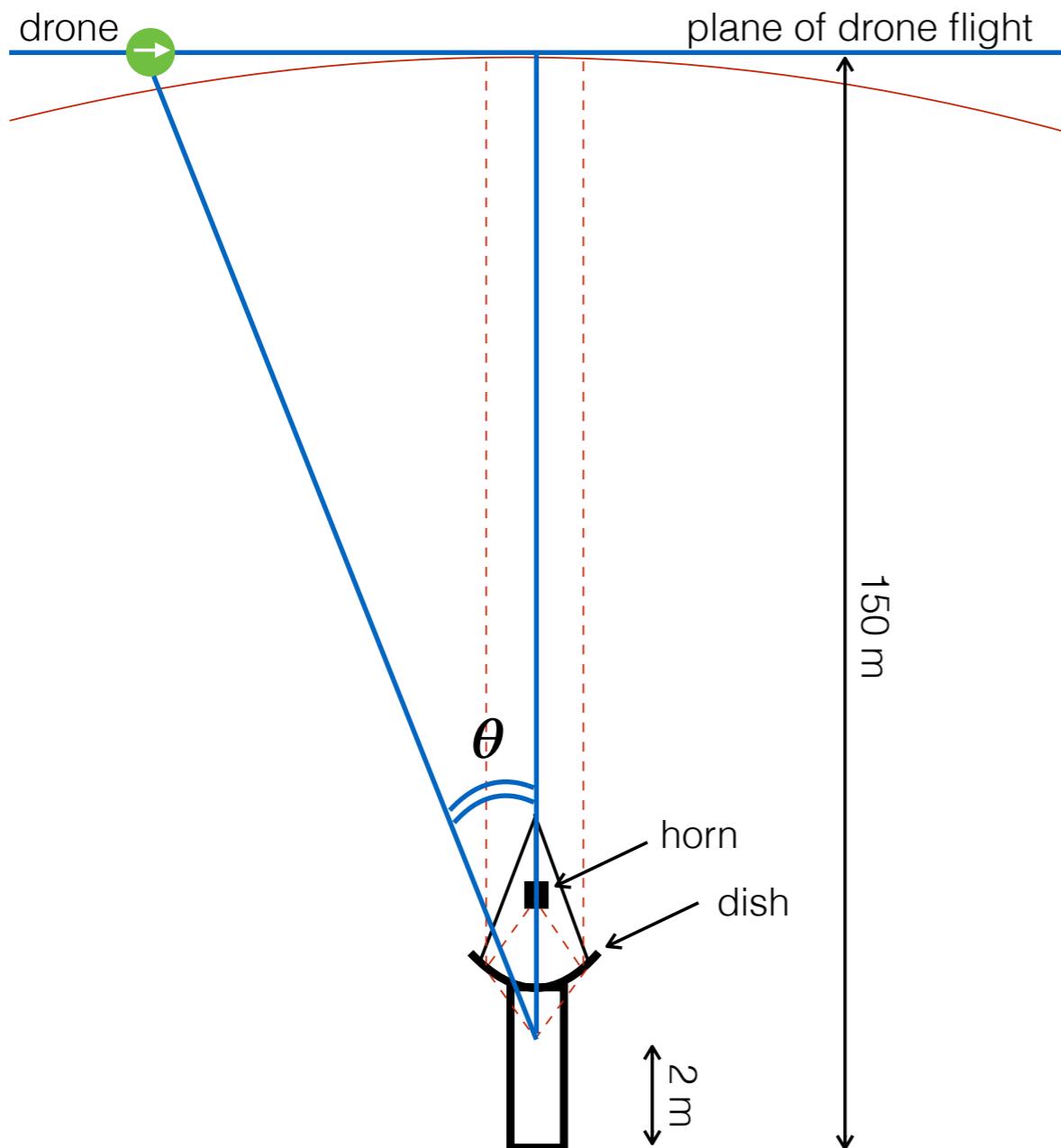


Radio Telescope Calibration

- 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



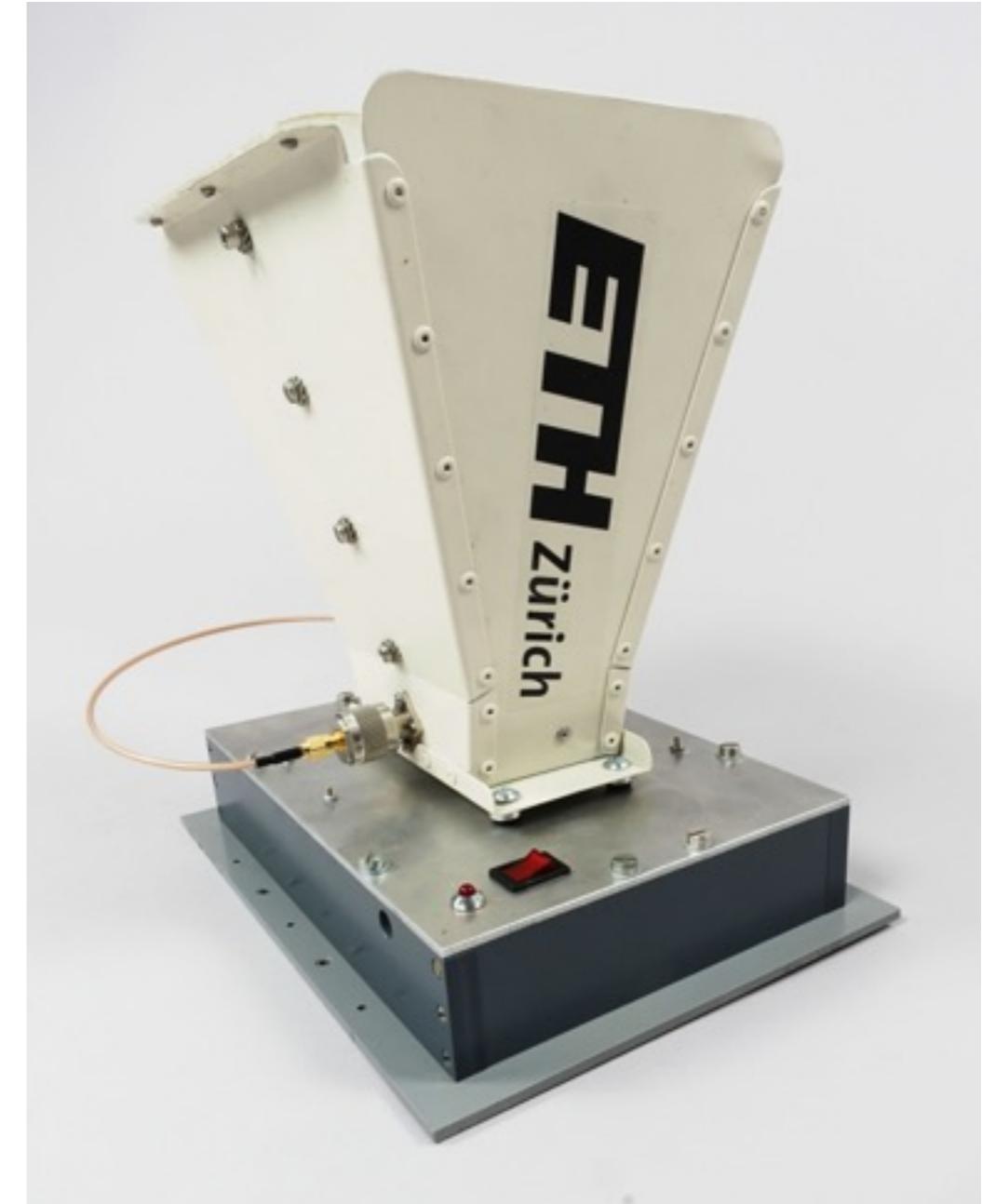
The Drone Experiment

Image credit: Koptershop



Total weight: 10.9 kg (<2 kg load)

Max. flight time: 13.5 min

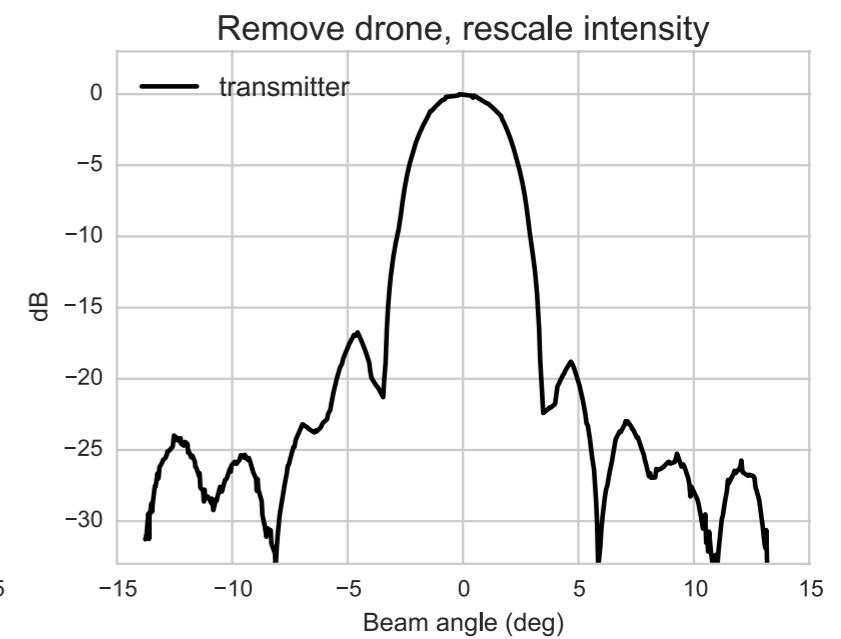
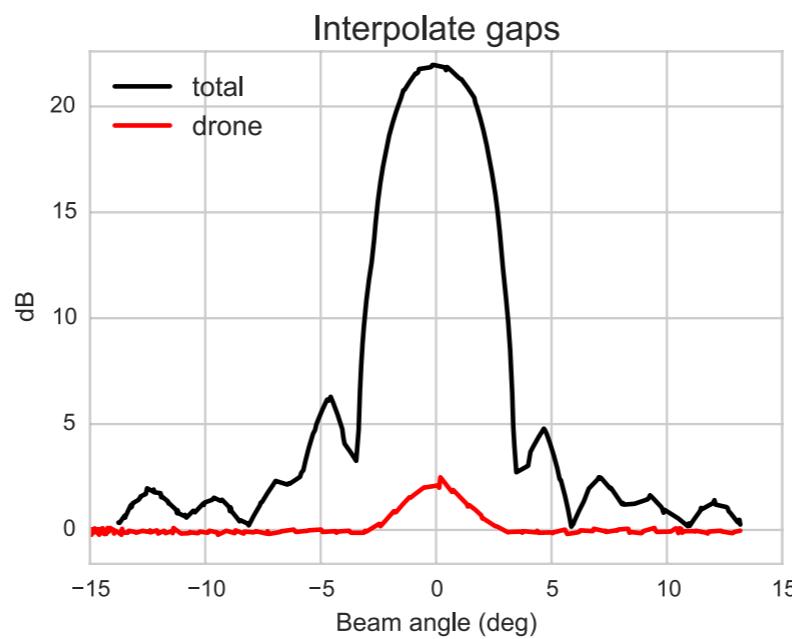
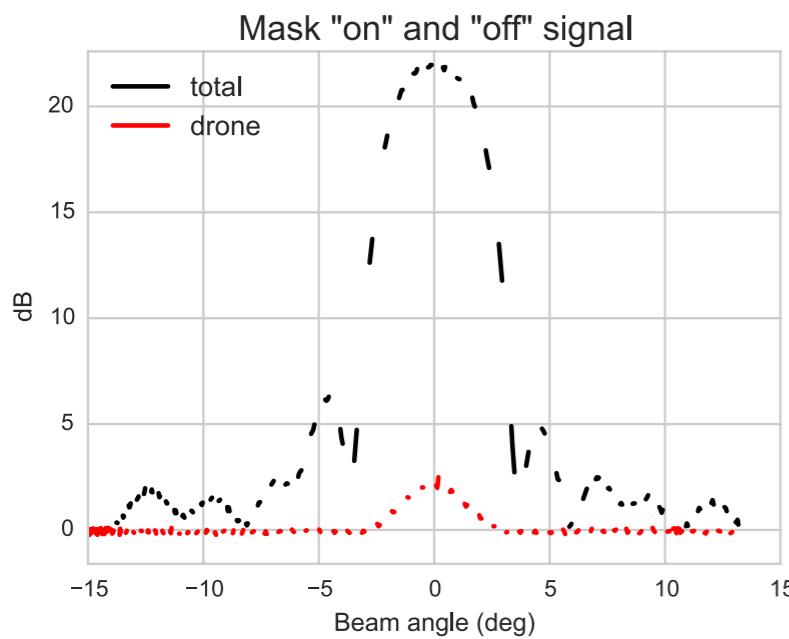
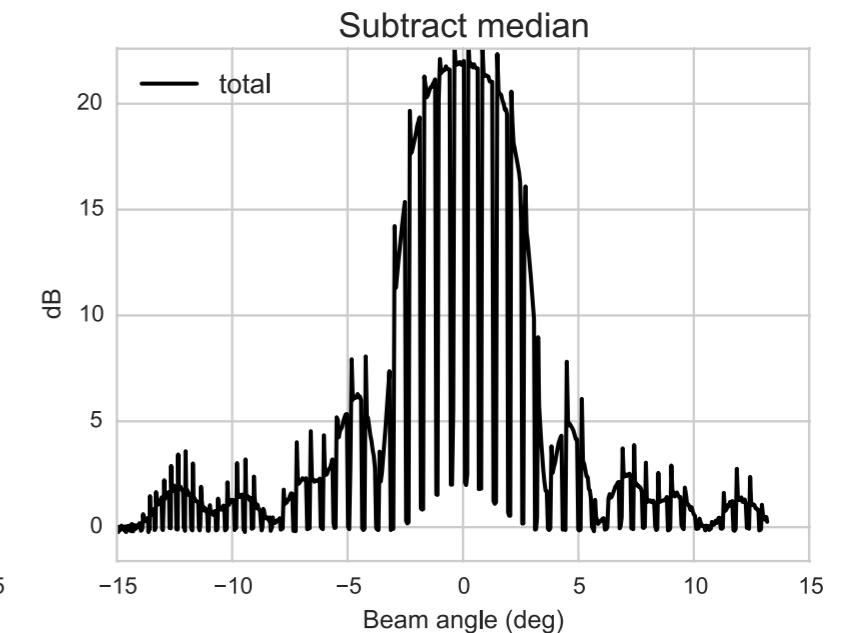
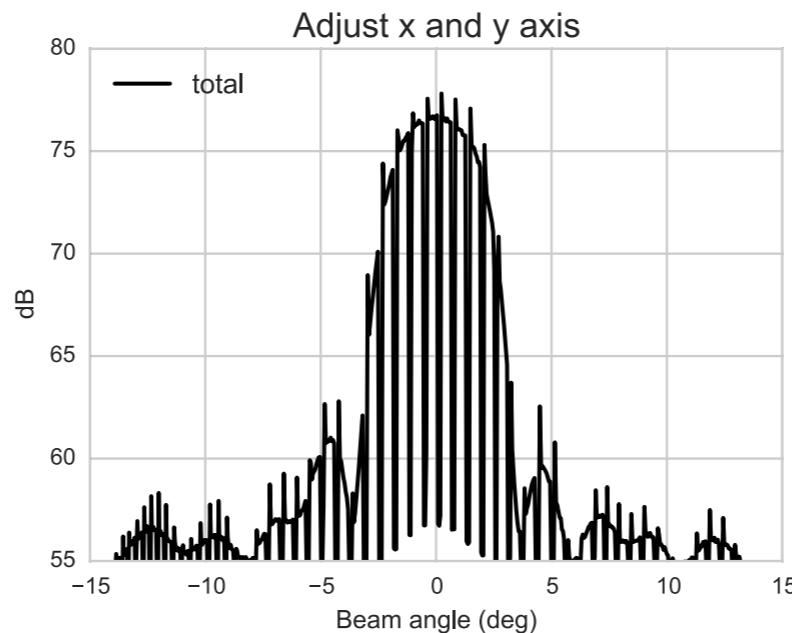
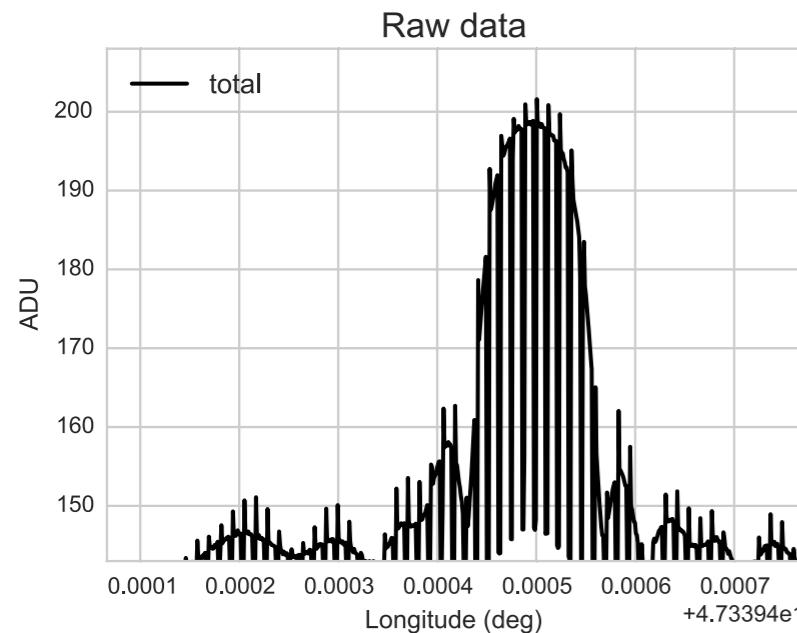


The Computational Challenge

- 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**...



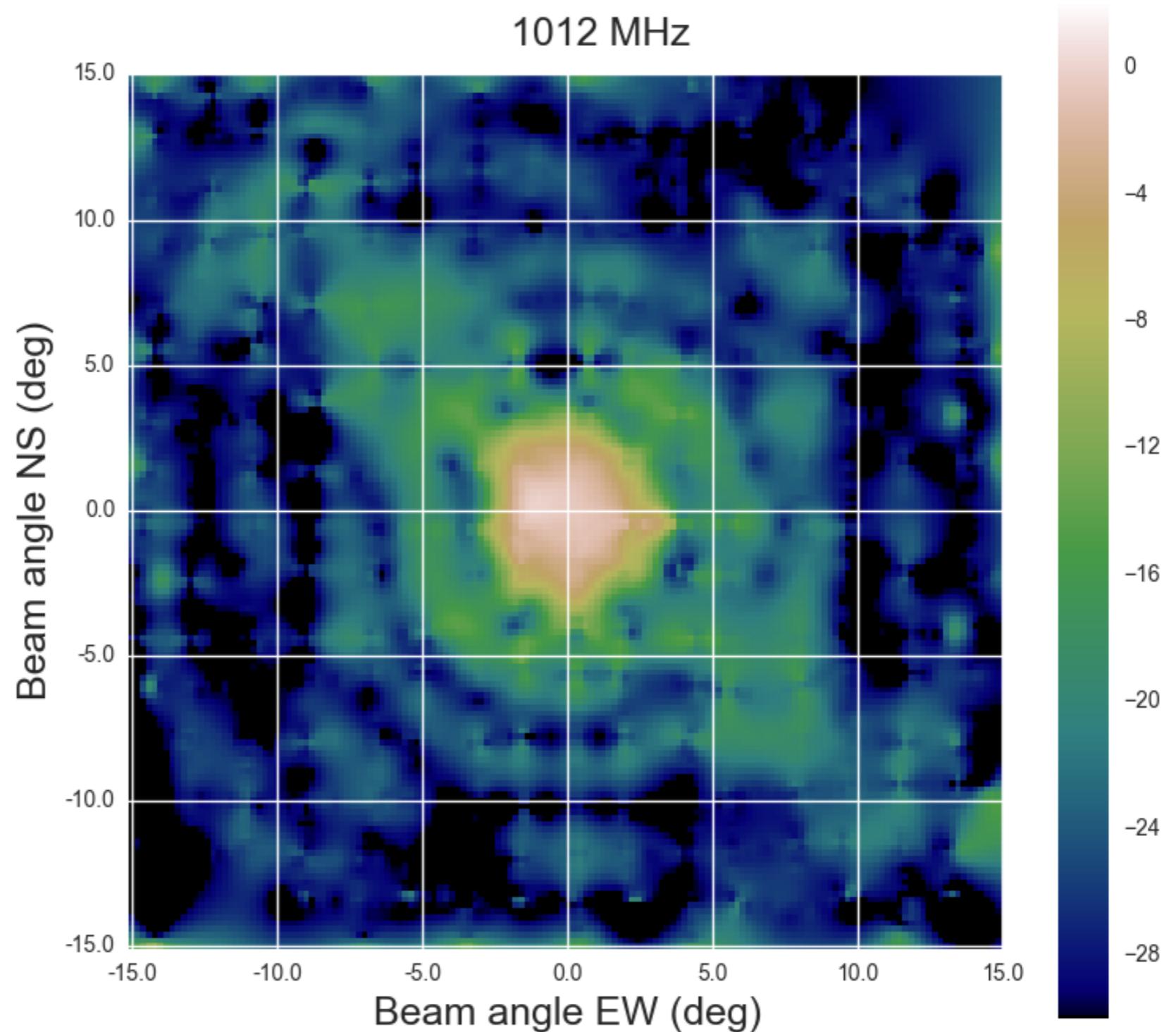
Analysis



Results

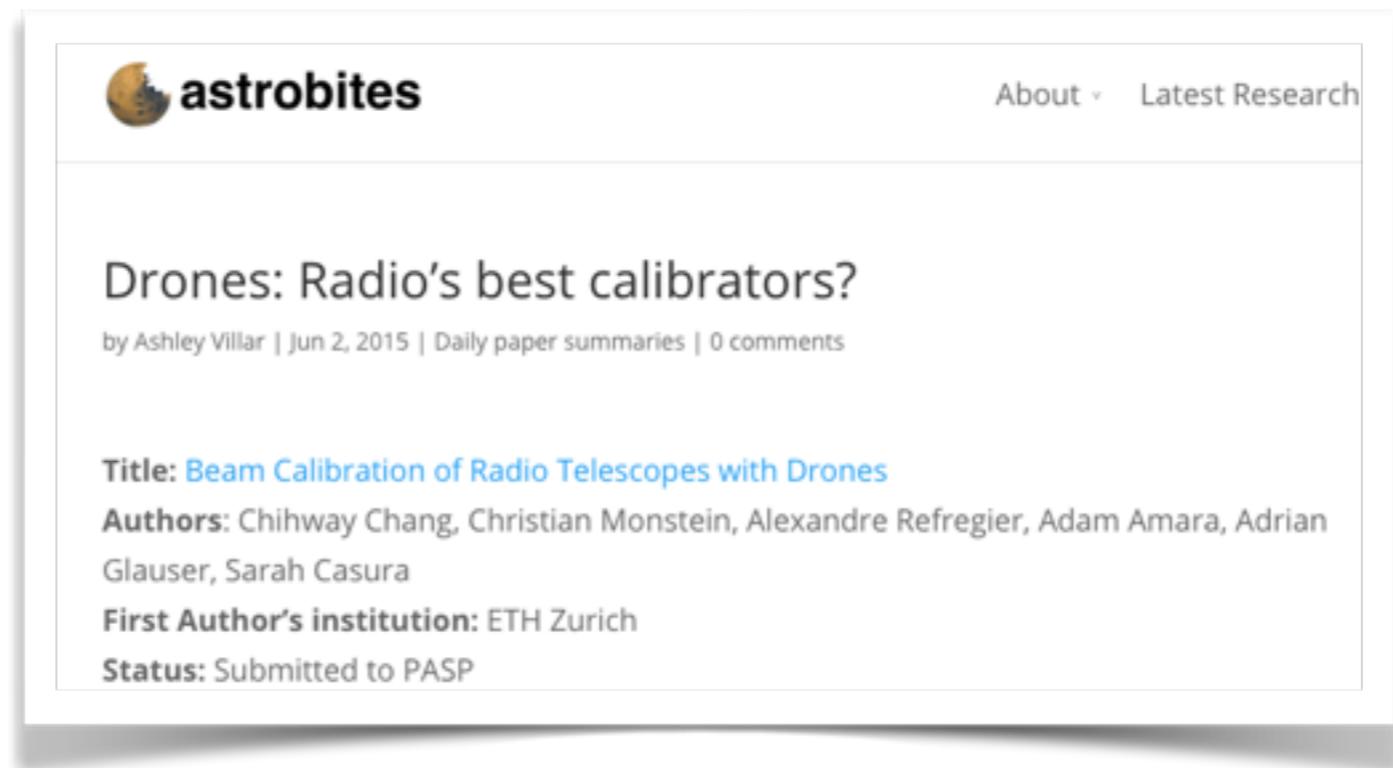
2D maps of the telescope beam profile with very high S/N

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



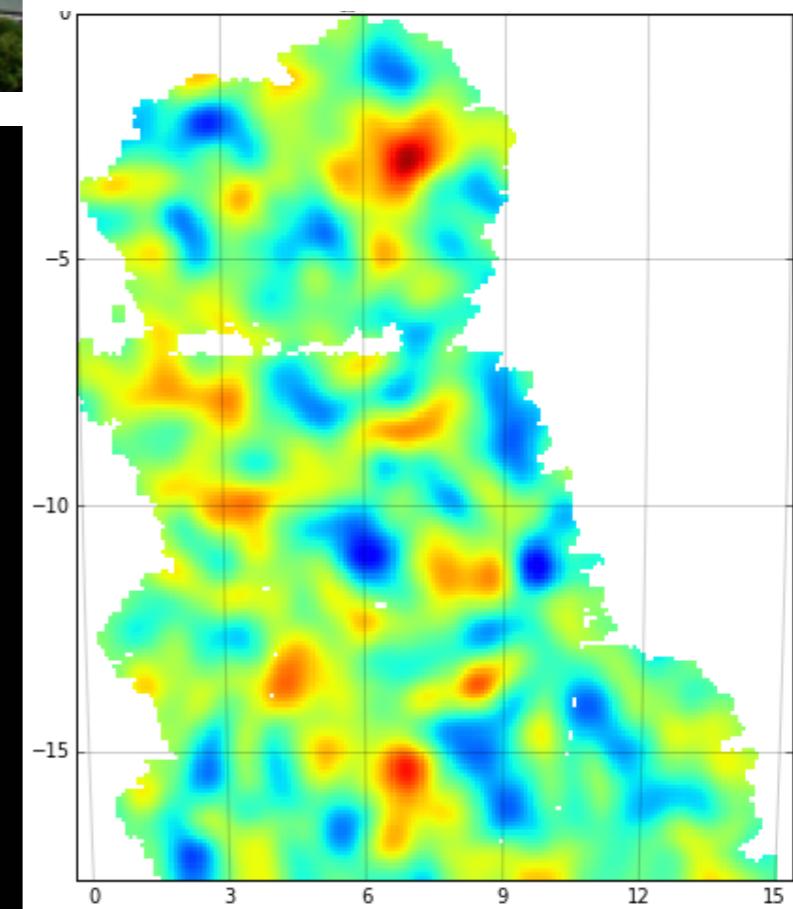
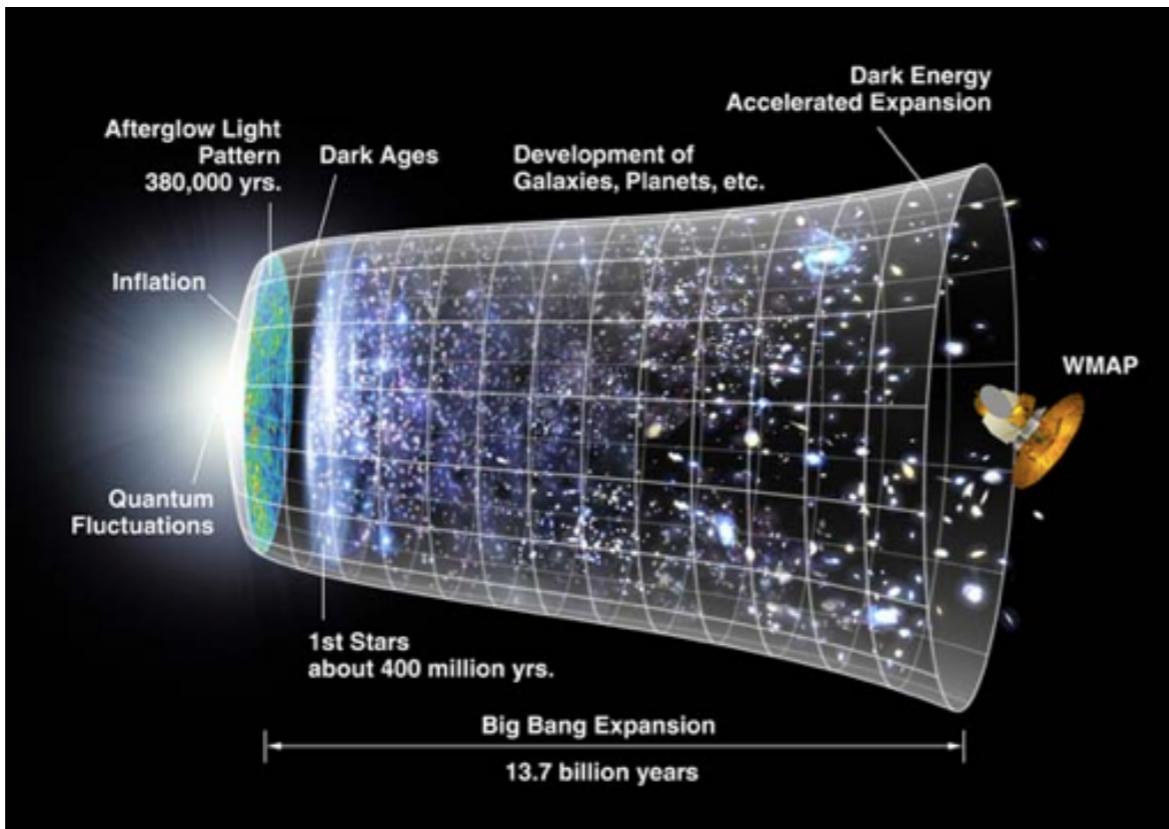
Summary: Radio Telescope Calibration

- 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...

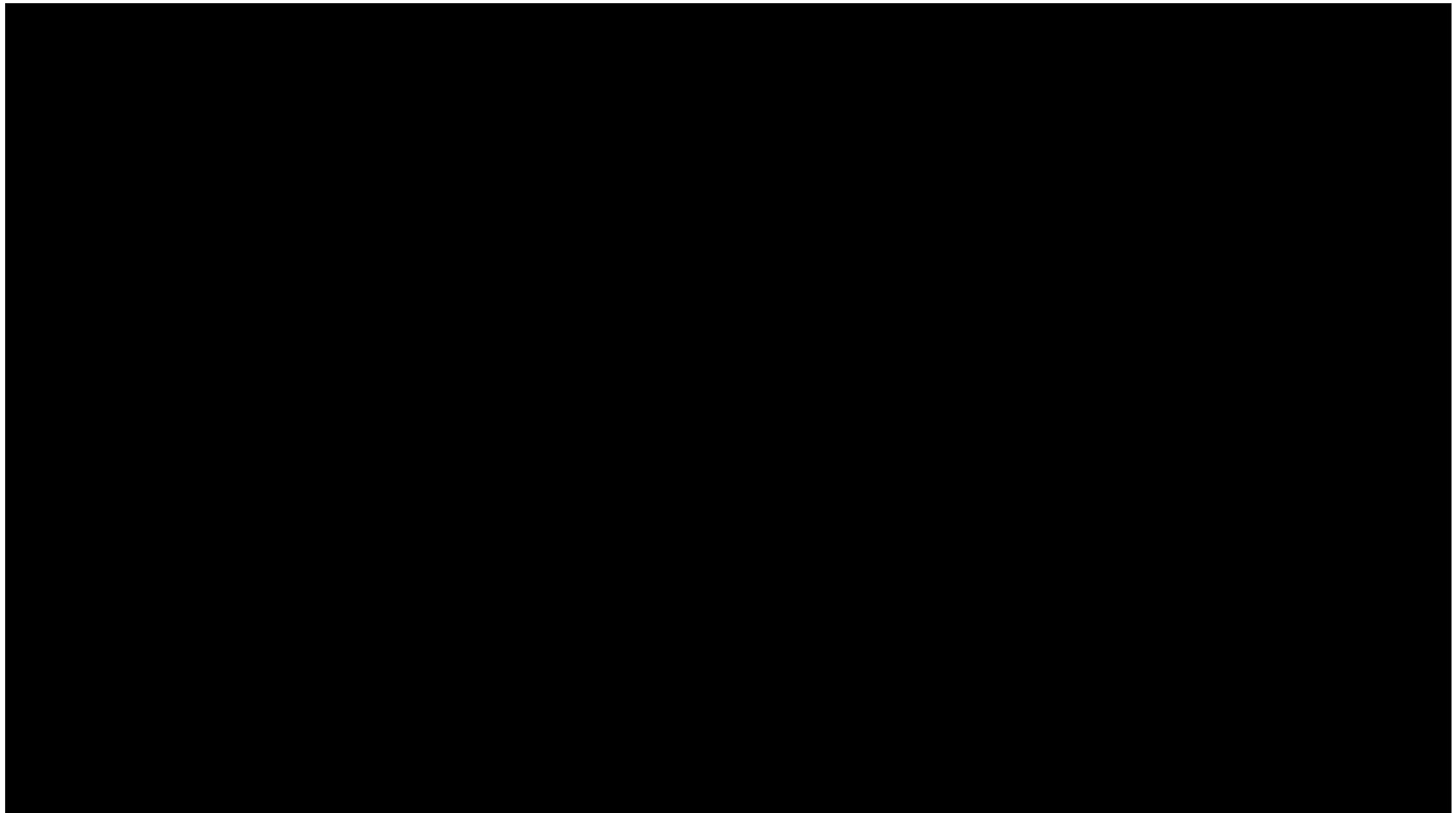
The ETH
Cosmology Group



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

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

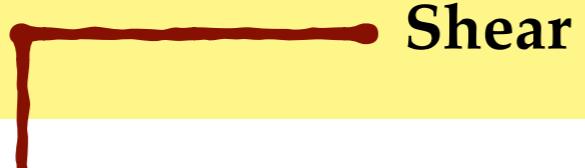
Deflection

$$\alpha = \nabla \psi$$



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

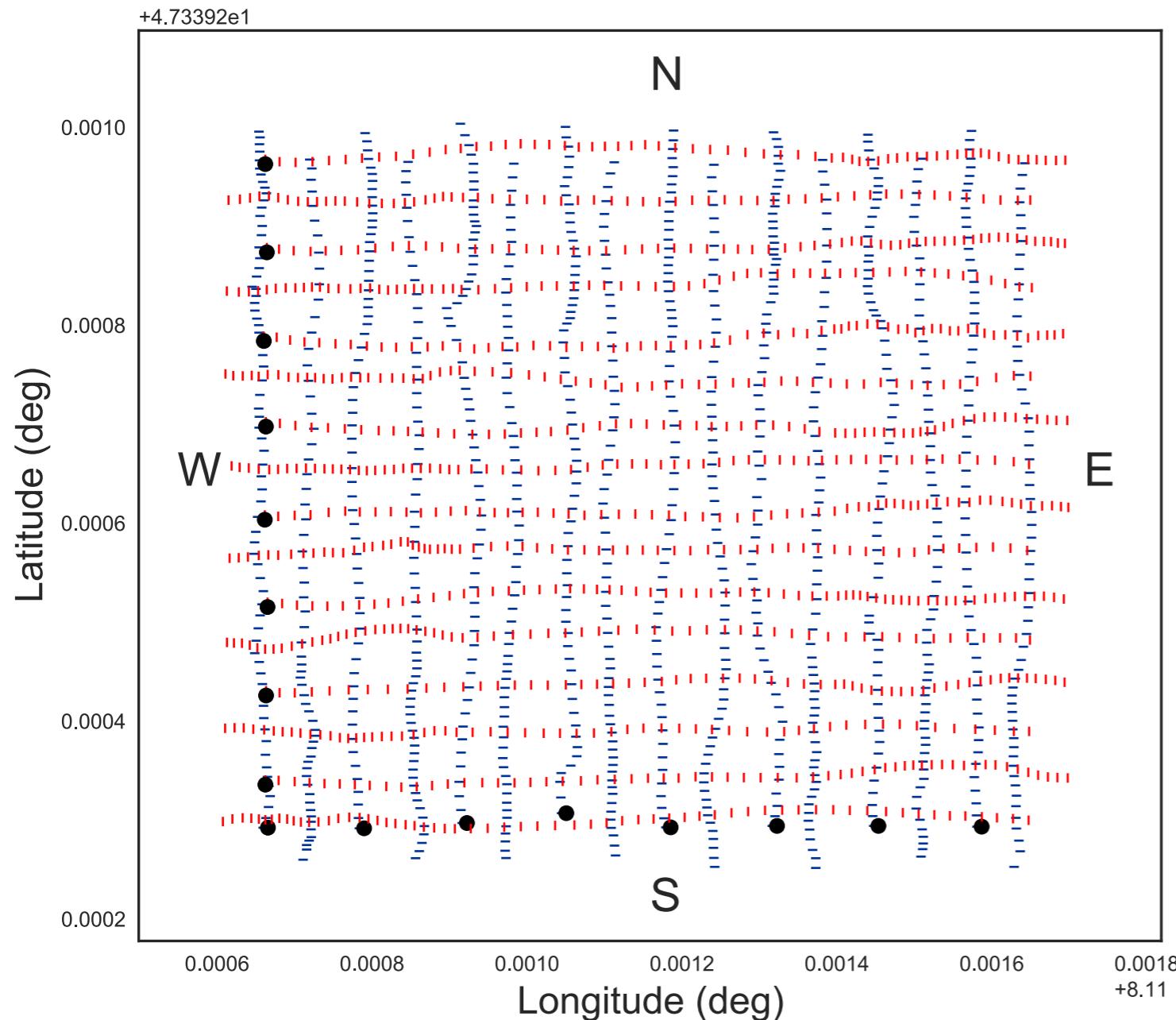
→ Mass (what we care about)



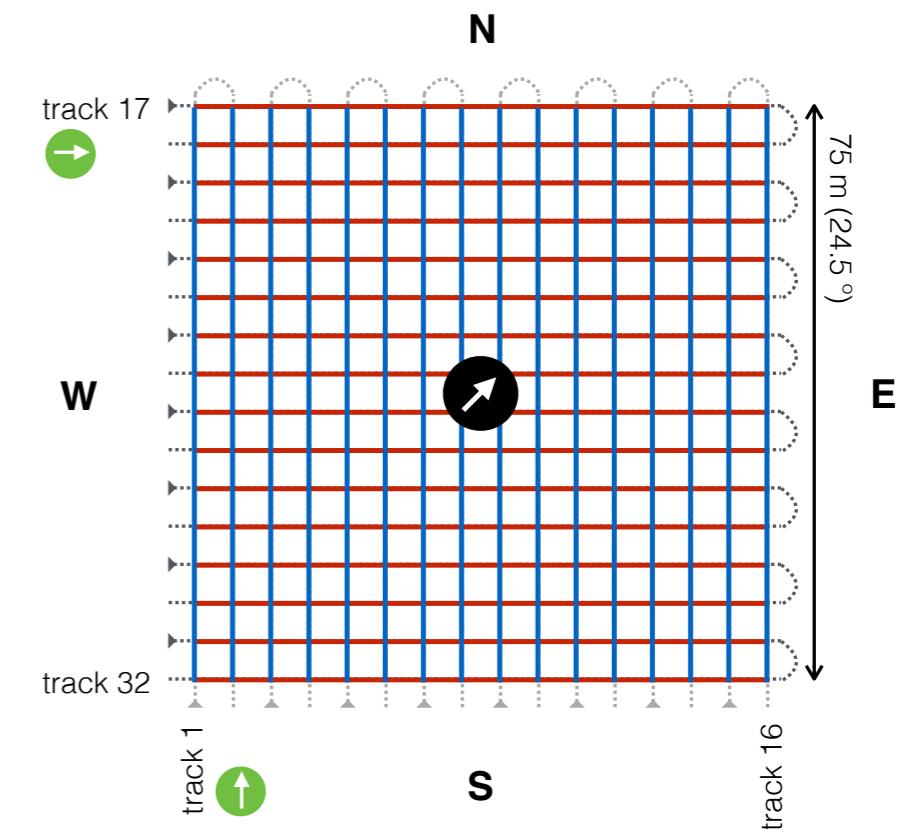
$$\gamma = \gamma_1 + i\gamma_2 = \frac{1}{2} (\psi_{,11} - \psi_{,22}) + i\psi_{,12}$$

→ Distortion (what we can measure)

Analysis

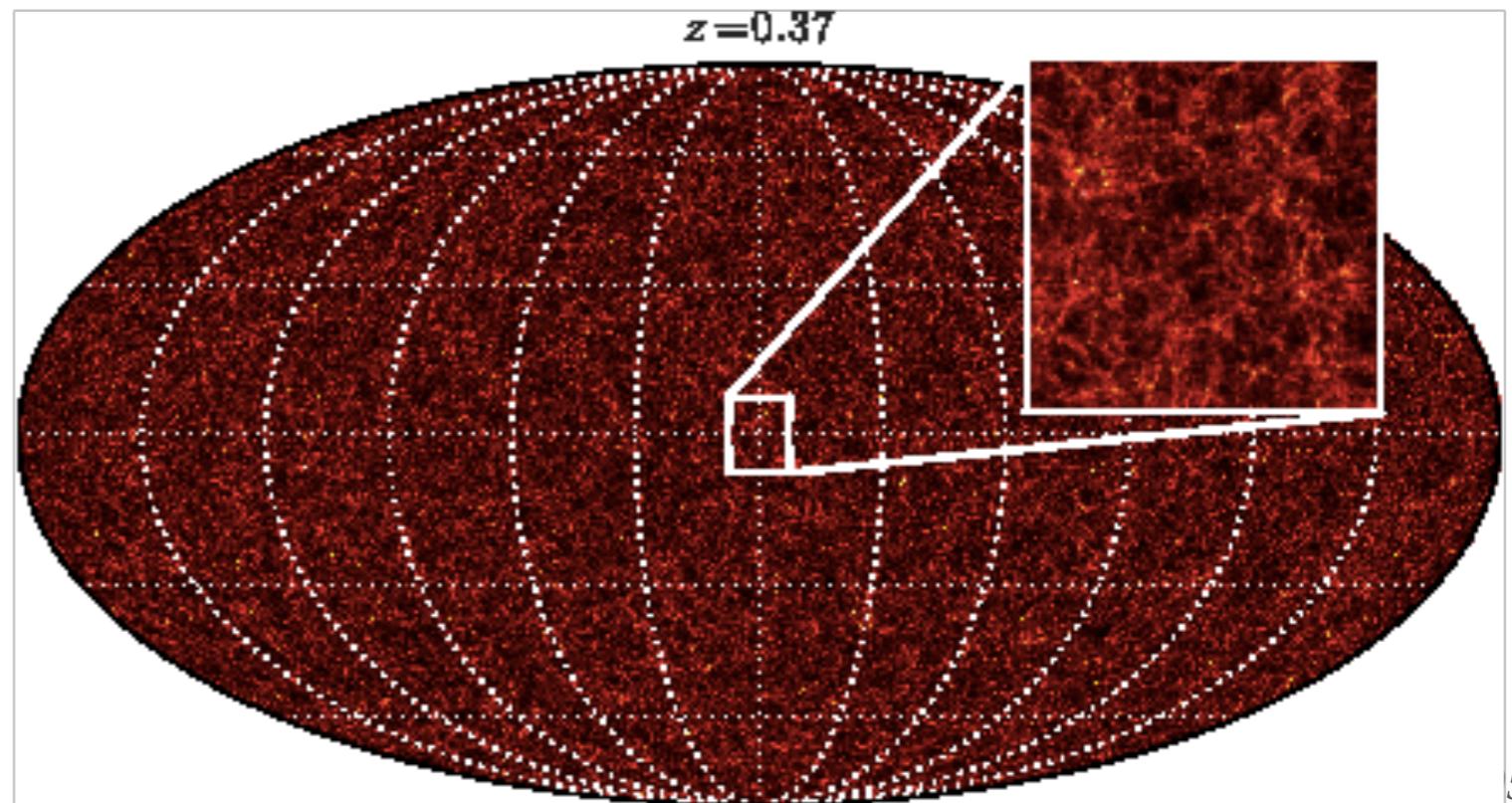
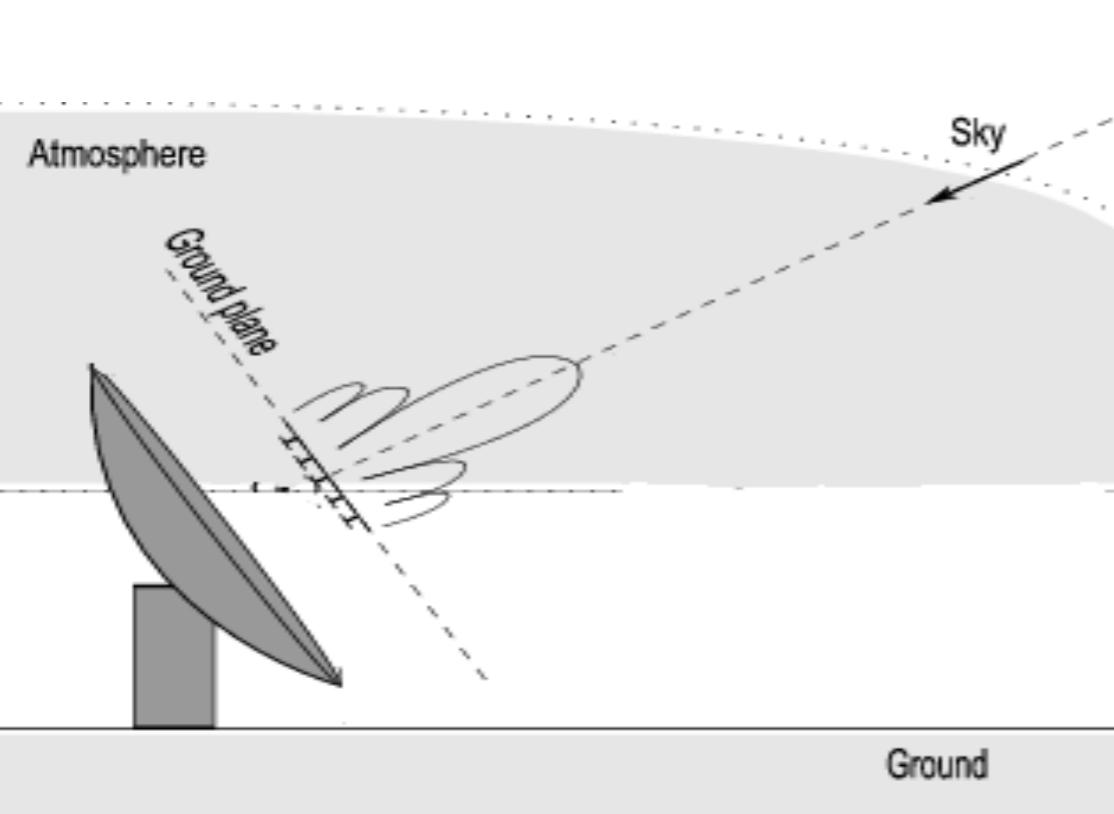


Positioning:
GPS + barometric altimeter



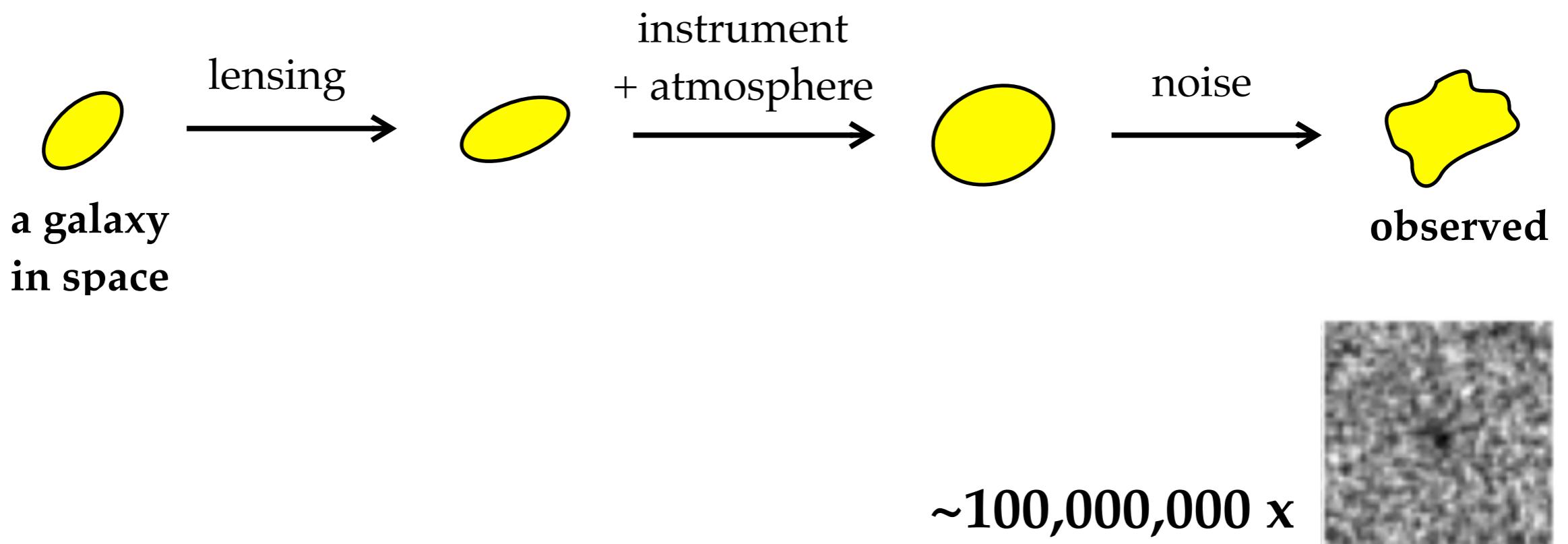
Radio Telescope Calibration

- 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 responds to the incoming signal.



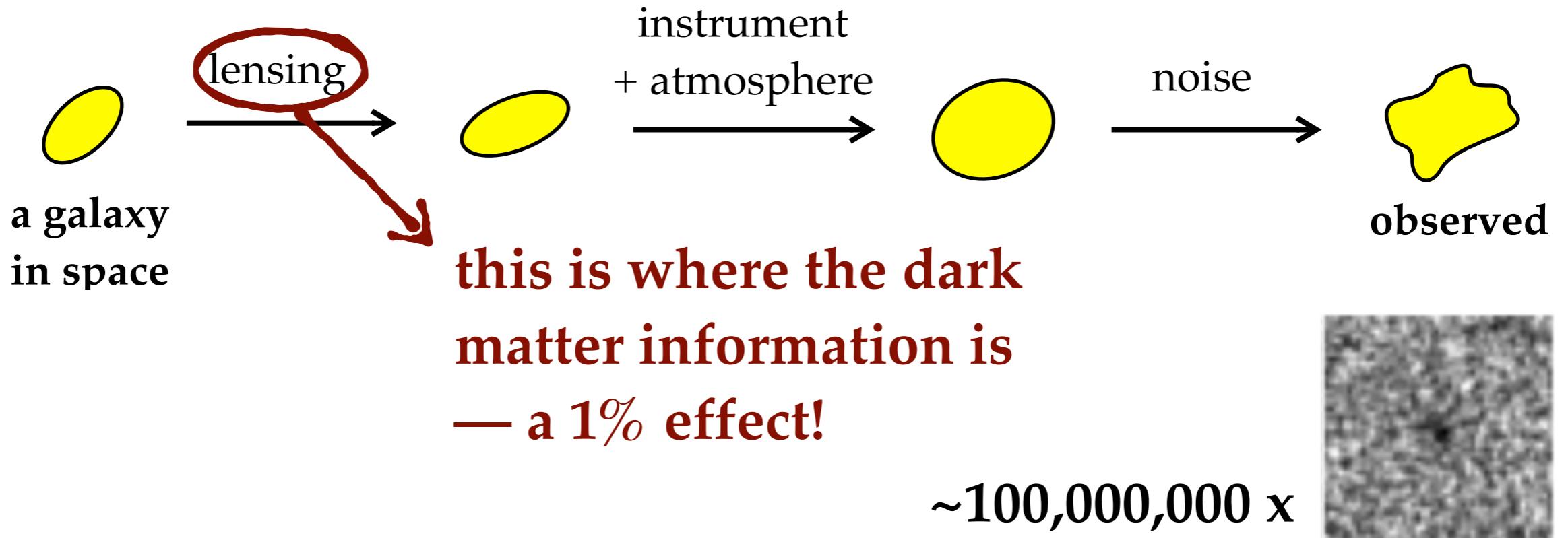
The Computational Challenge

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



The Computational Challenge

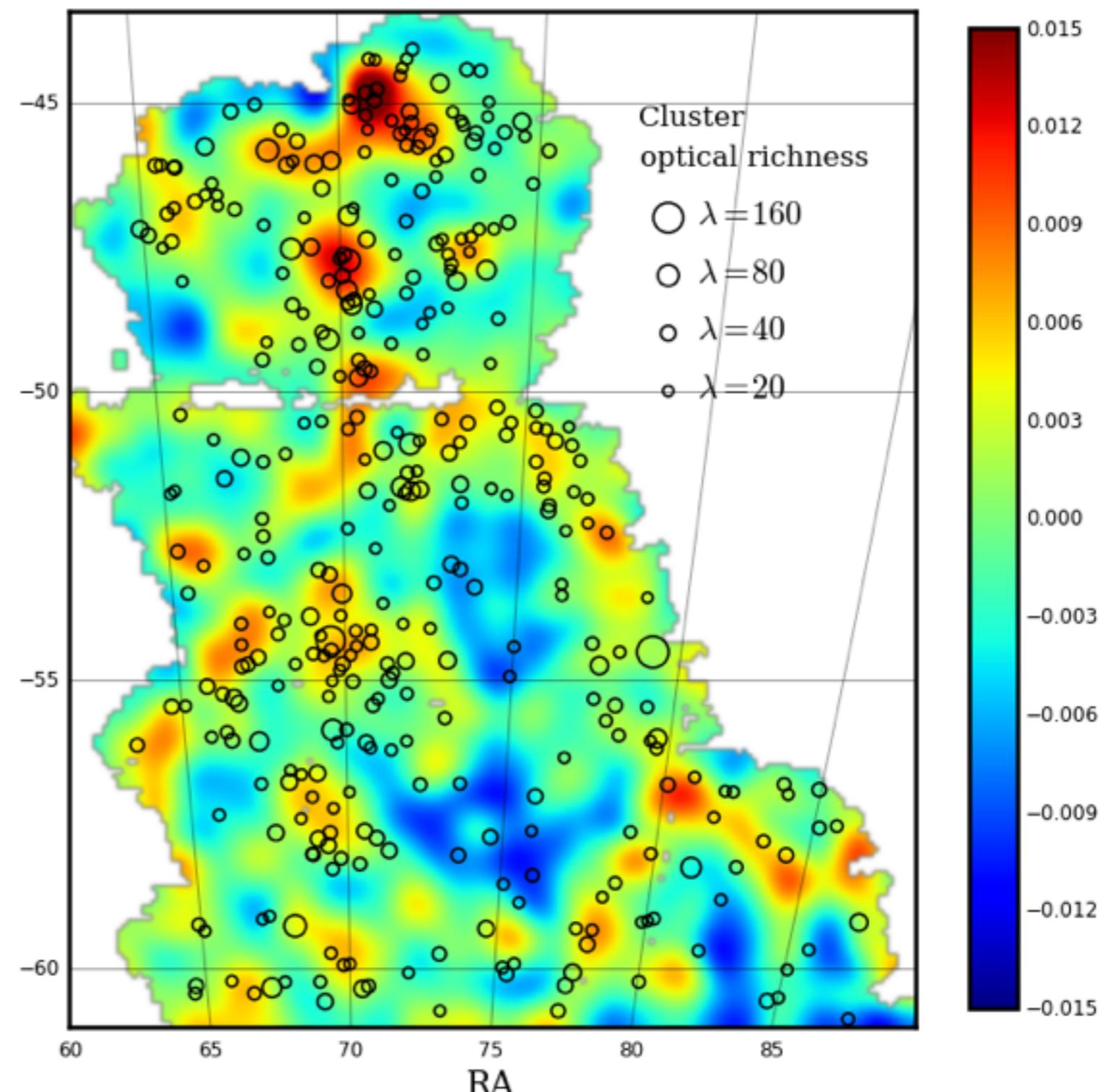
- We want to measure accurately **shapes** of a lot of small, faint, noisy galaxies, and get useful information out of them.



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