Weak Lensing

(and beyond)

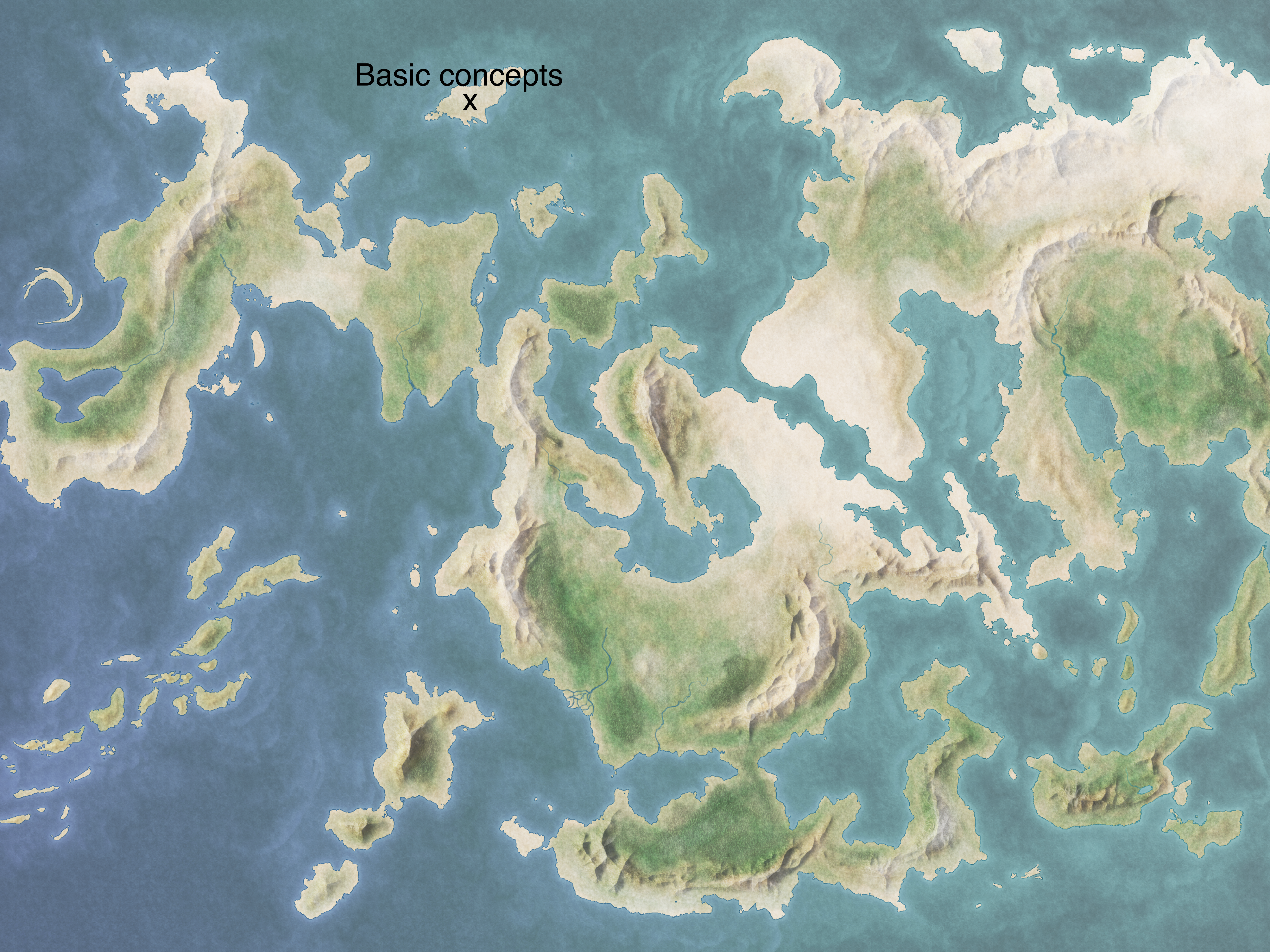
Tim Eifler (JPL/Caltech)

Excellent Review for Weak Lensing:

http://adsabs.harvard.edu/abs/2005astro.ph..9252S

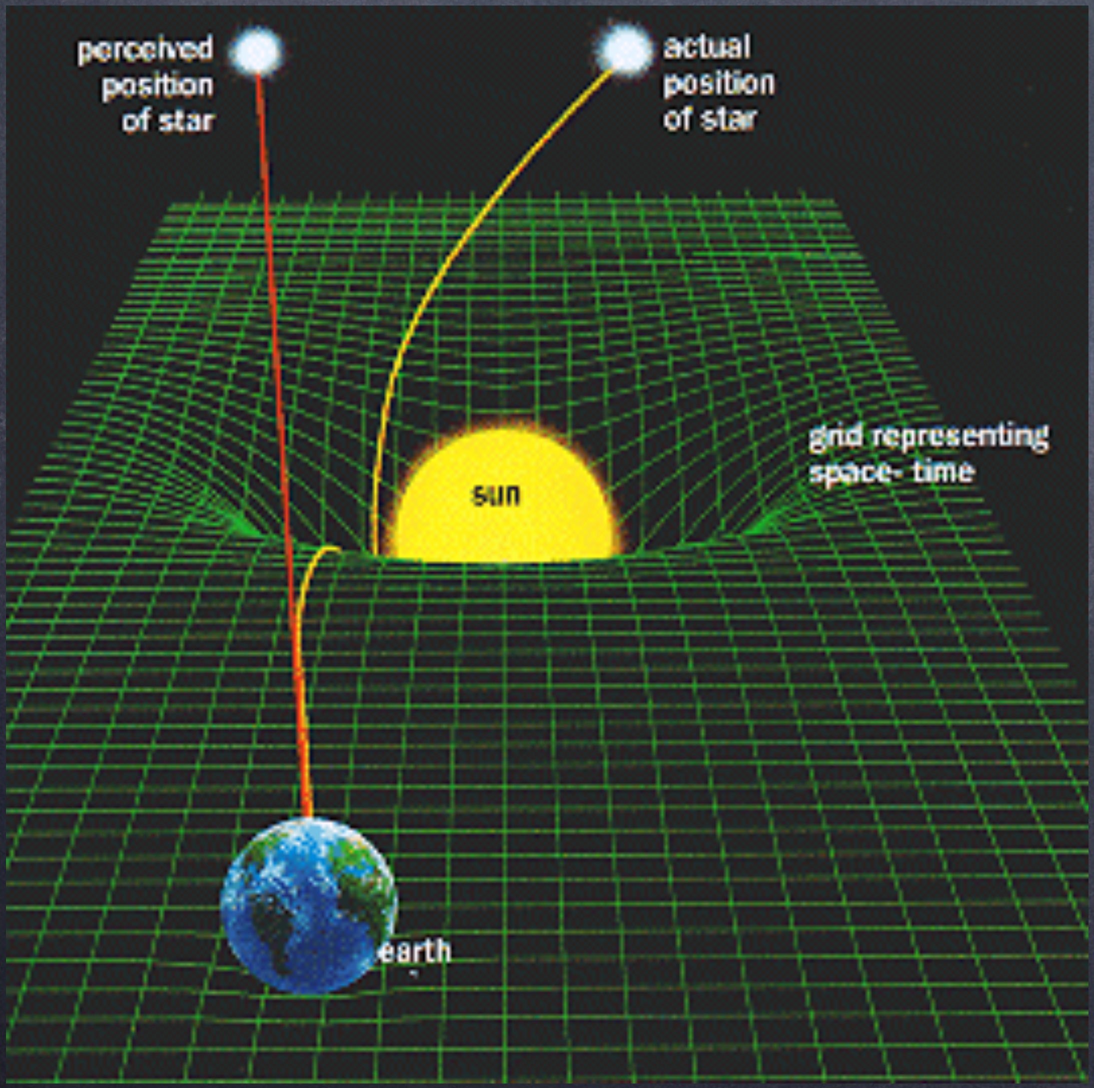
Basic concepts

x



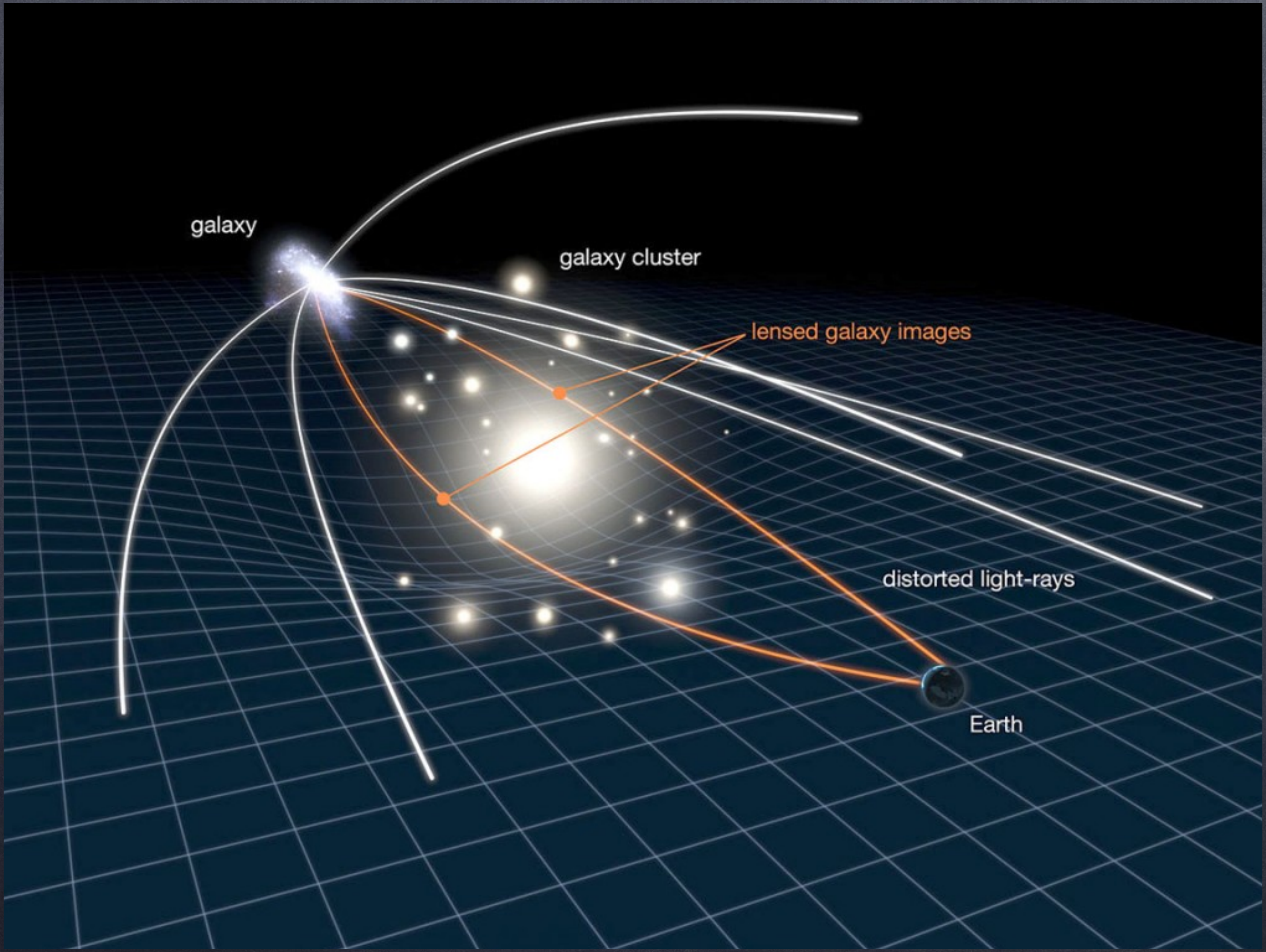
History

1915: The development of GR allowed Einstein calculated the bending of light through massive objects precisely

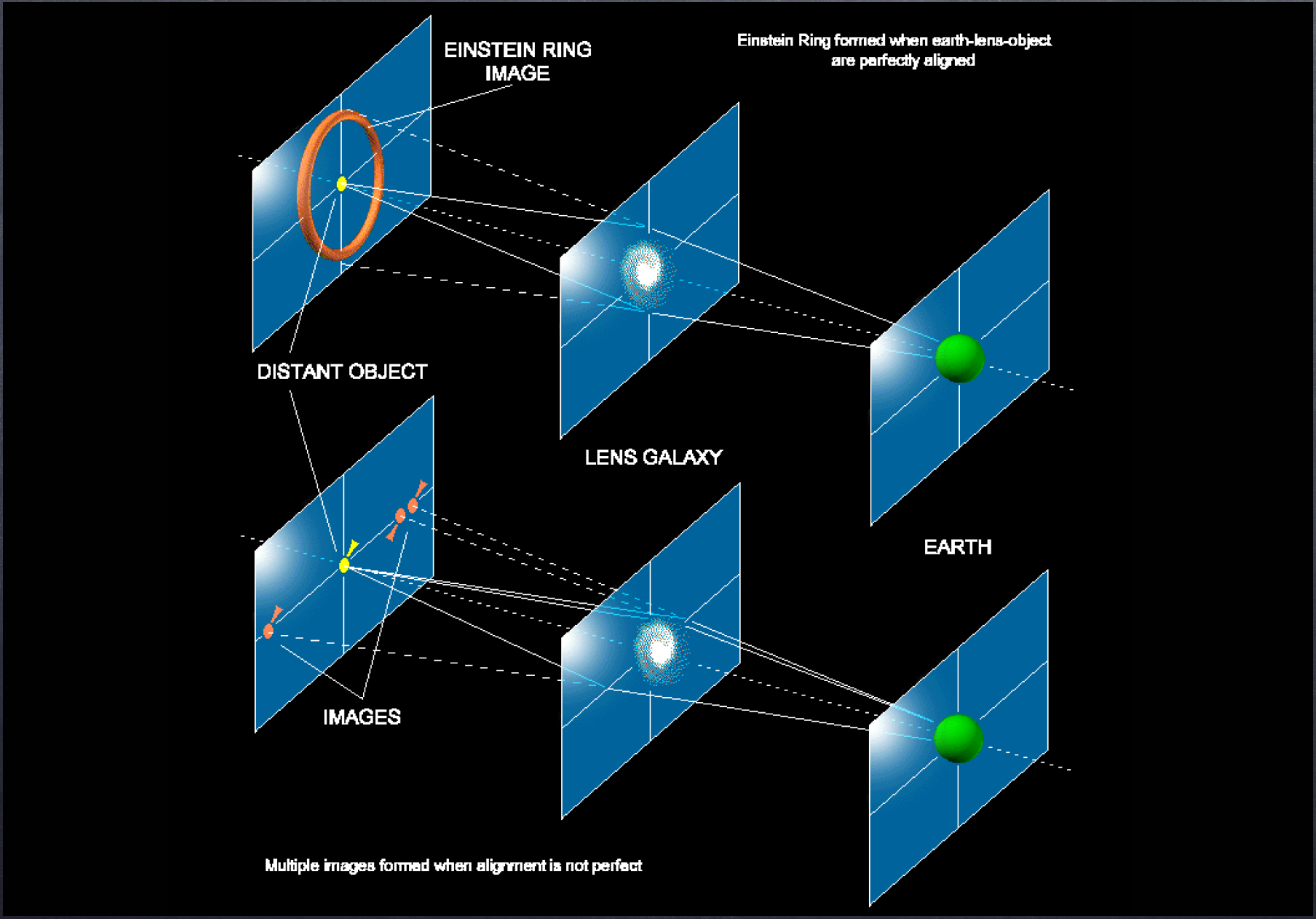


1919: Arthur Eddington confirmed the light bending phenomenon during a solar eclipse (traveling to the island of principe)

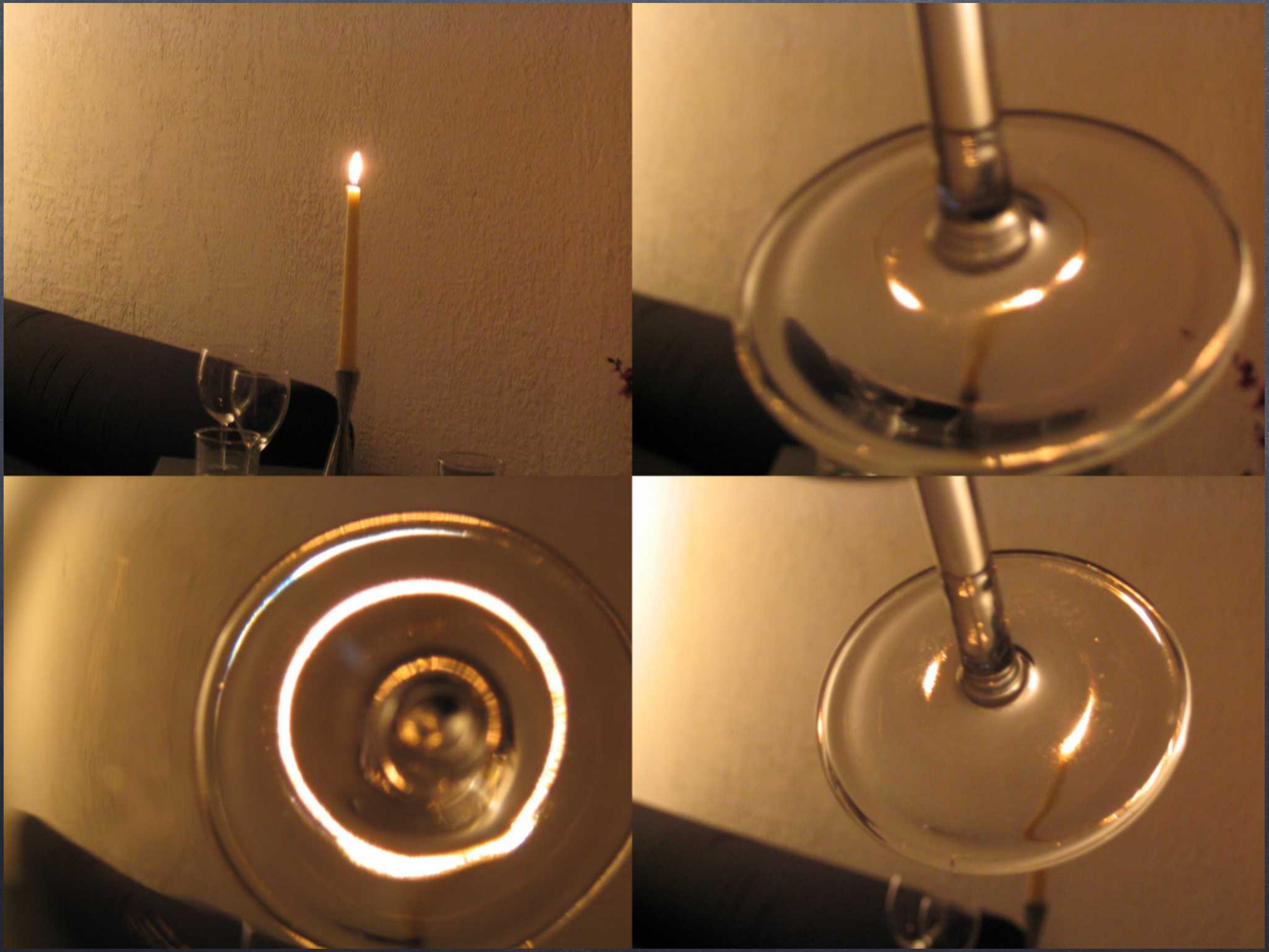
Same with Galaxies



Same with Galaxies

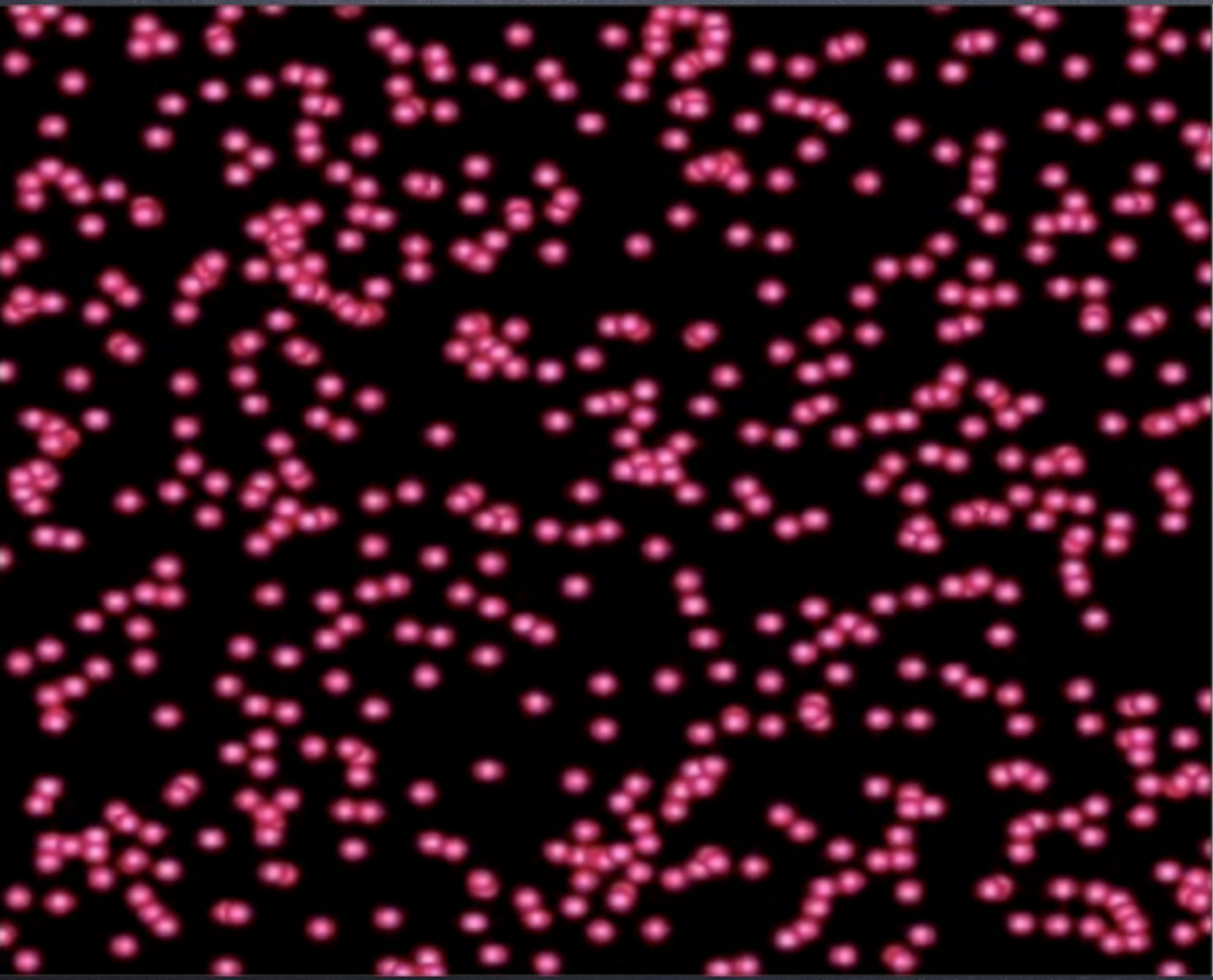
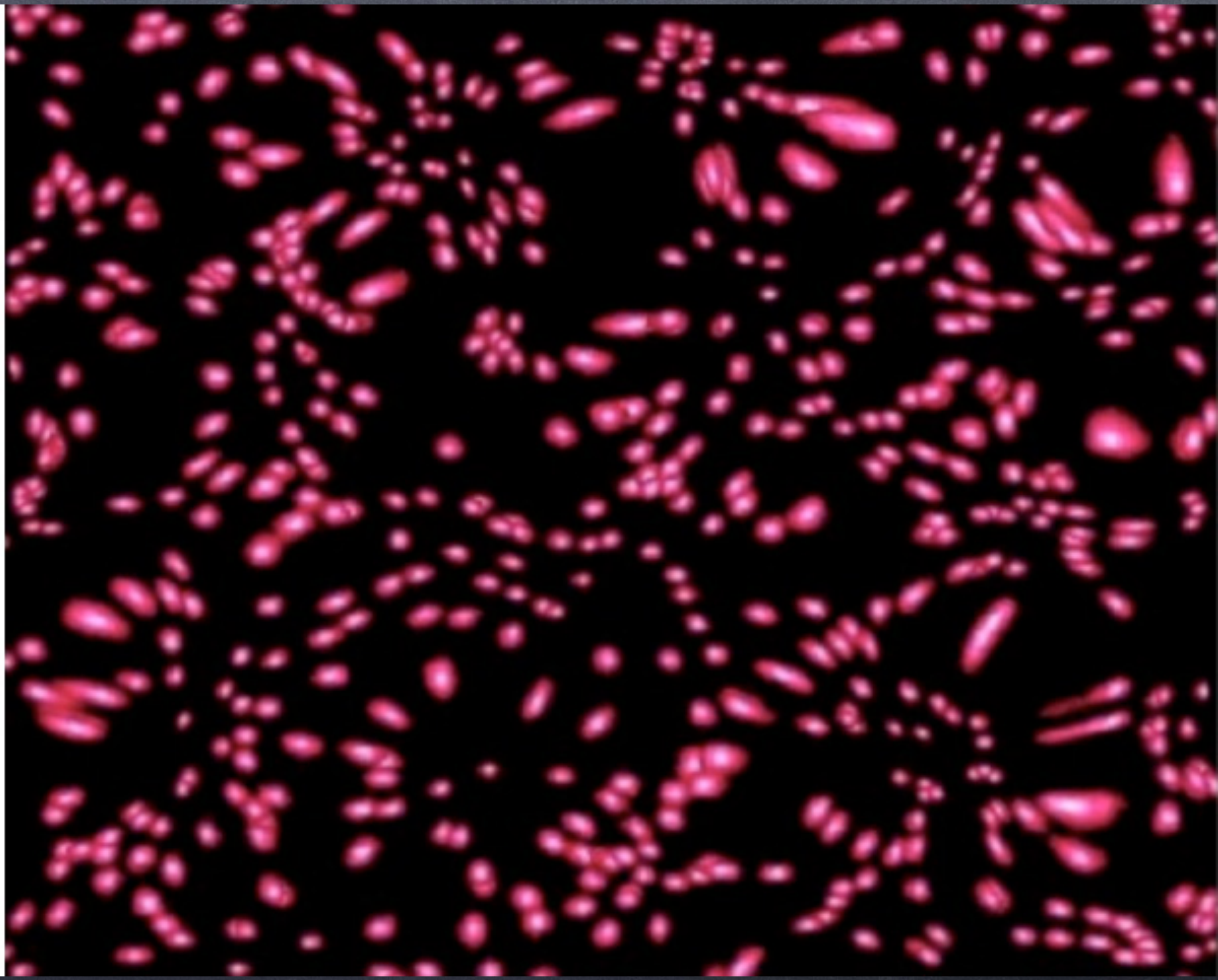


Same with wine glasses

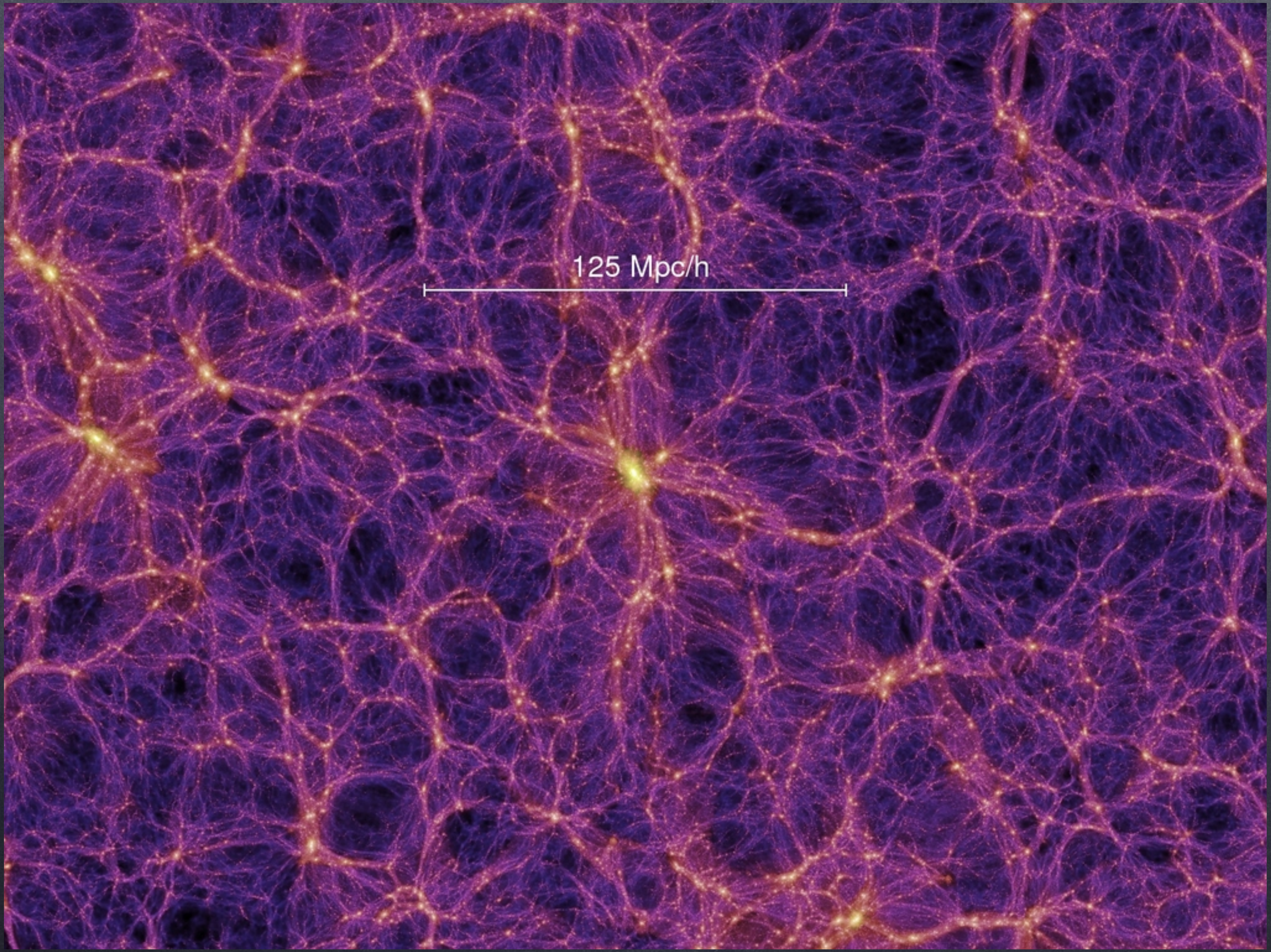


Abell 2218 as a lens - HST

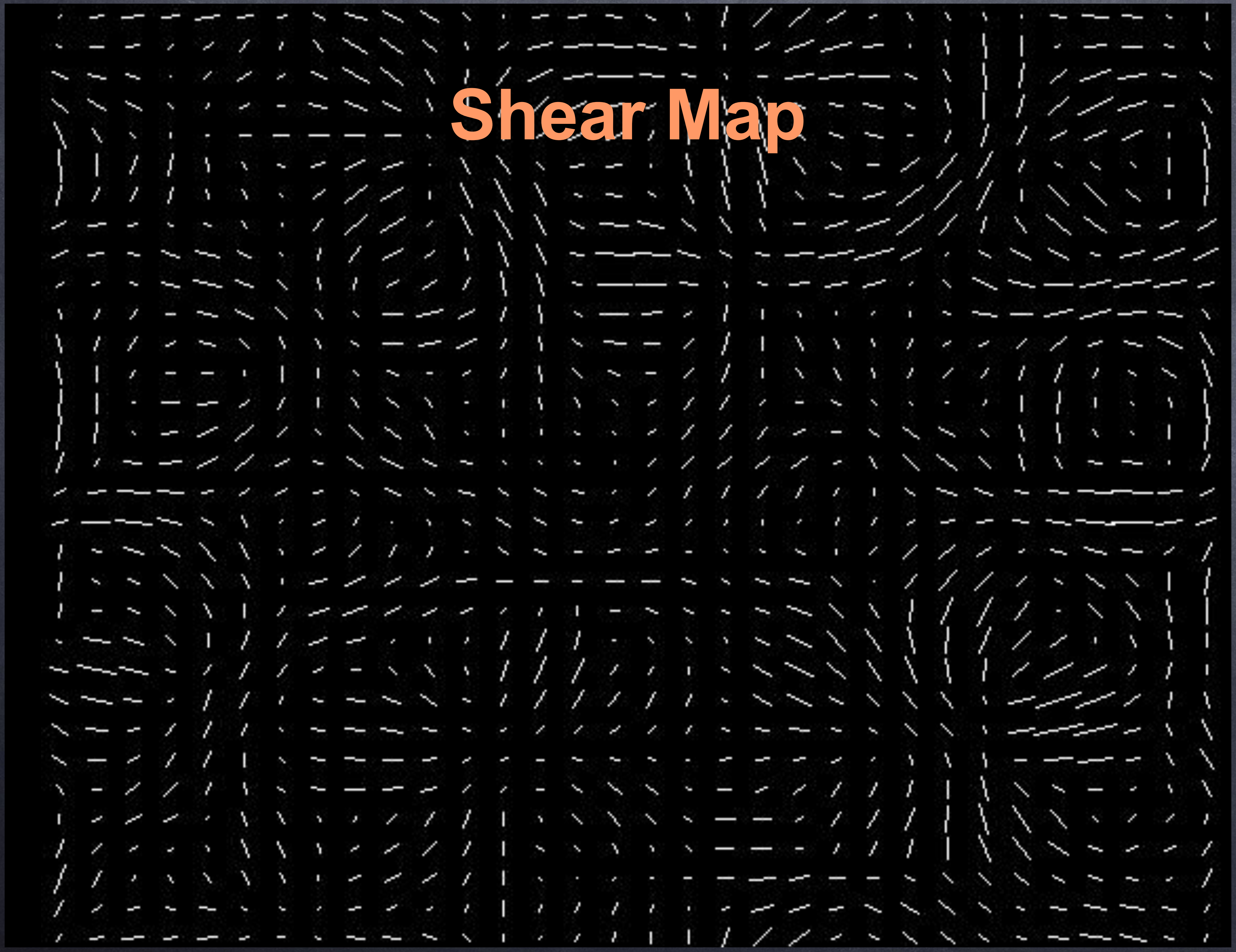
Every object in the universe is lensed

Galaxy field - no lensing	Galaxy field - with lensing (exaggerated)
	

Every object in the universe is lensed - Large Scale Structure

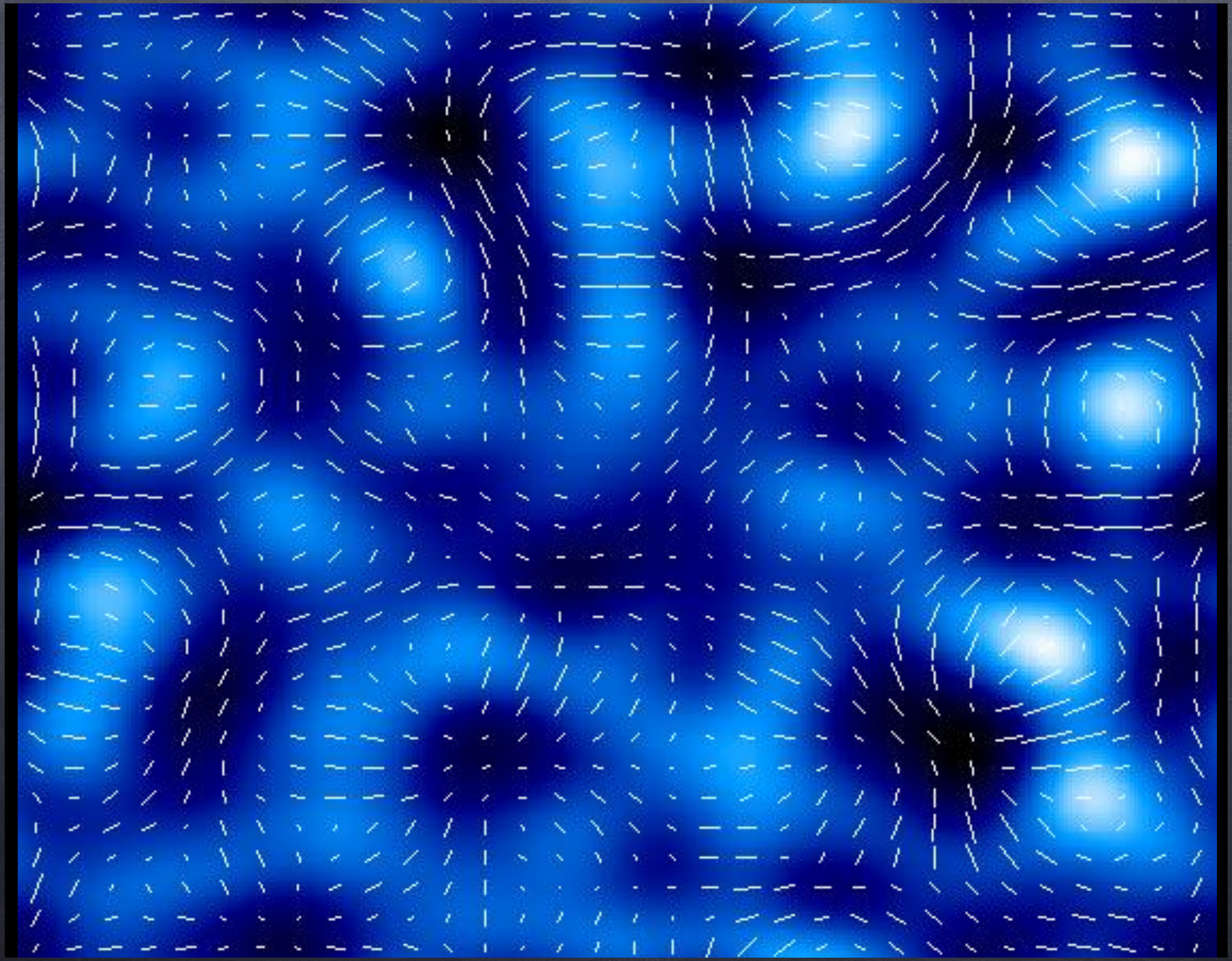


Every object in the universe is lensed

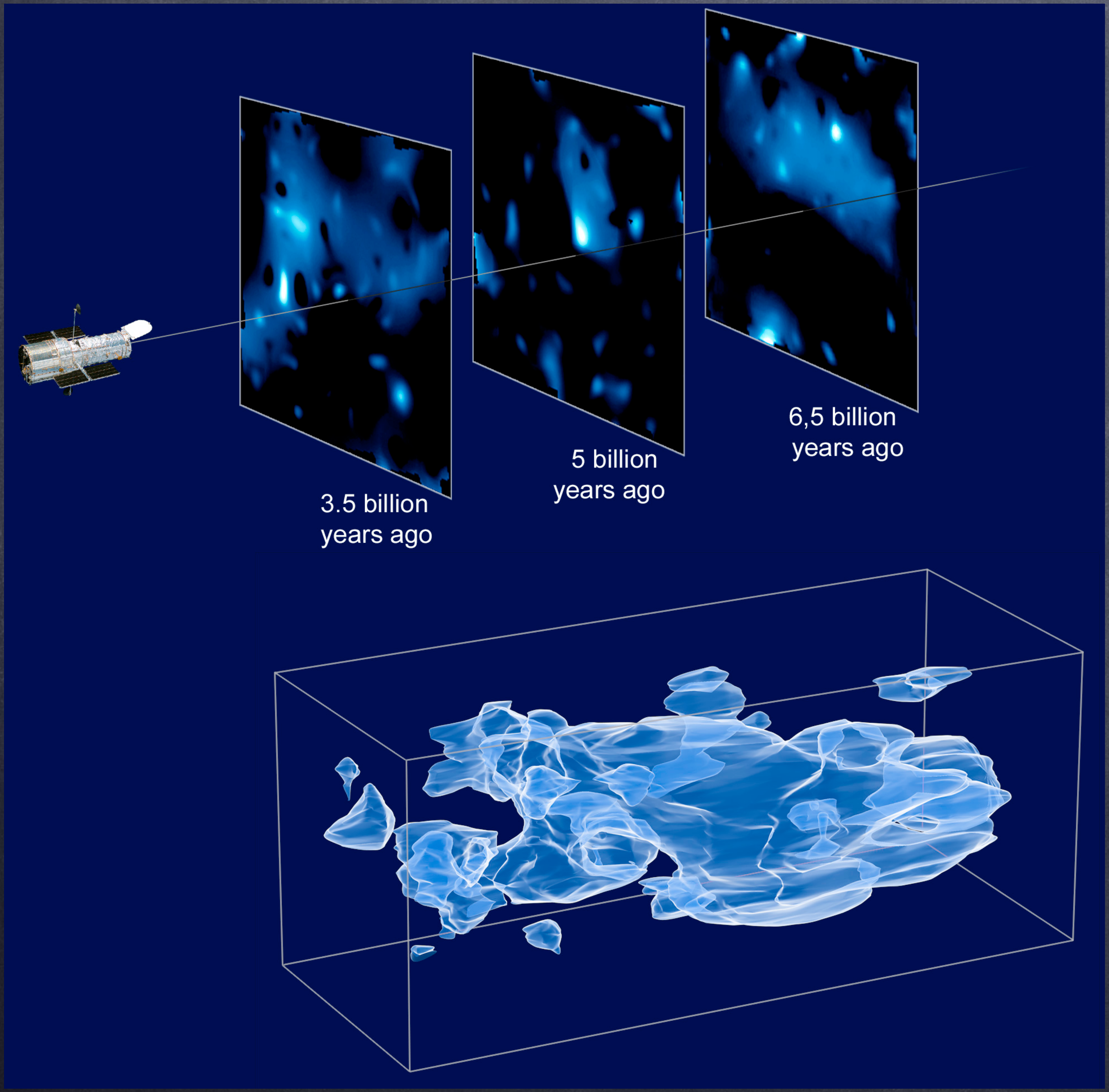


“Sticks” represent ellipticity strength and orientation

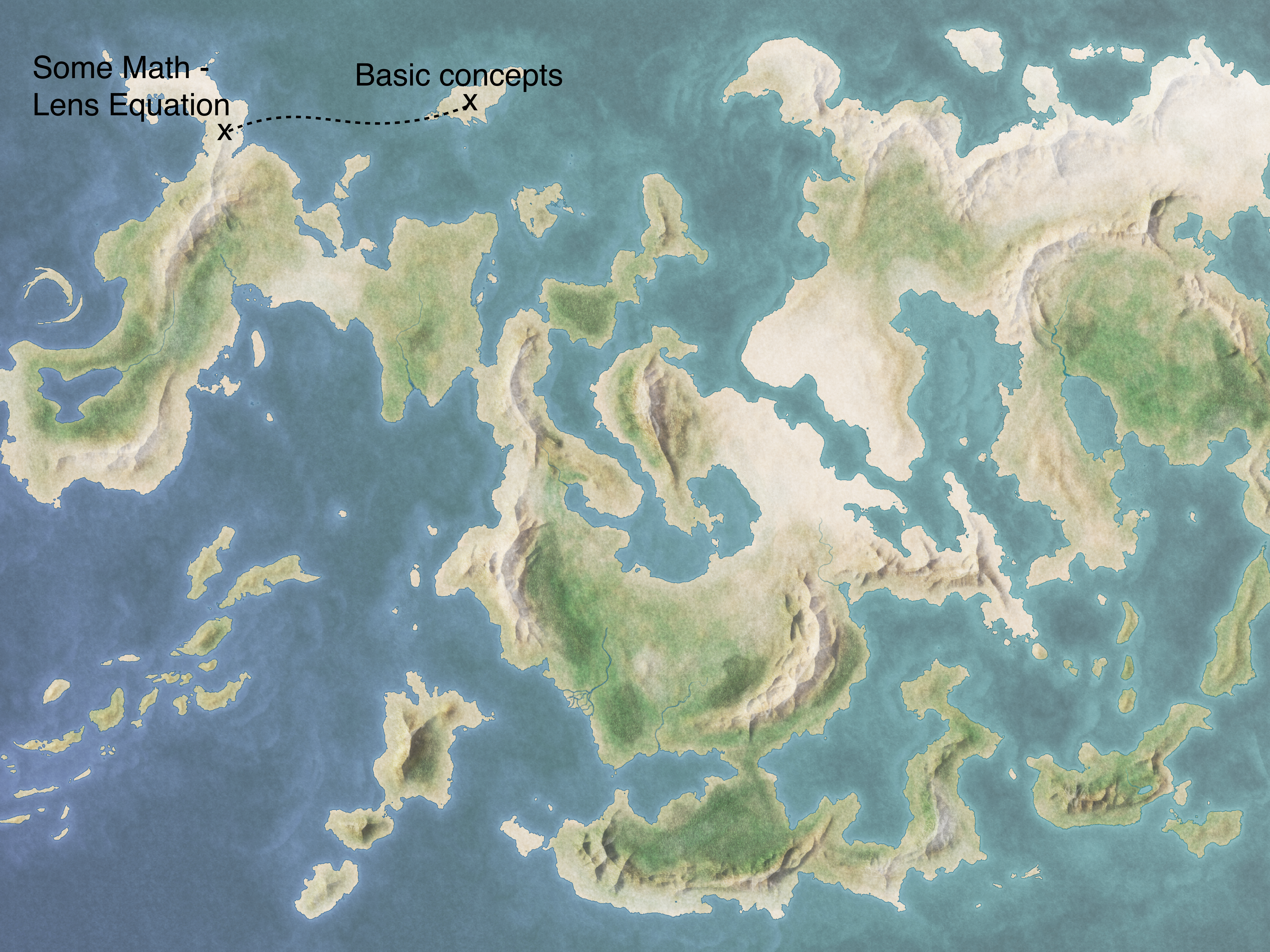
Every object in the universe is lensed



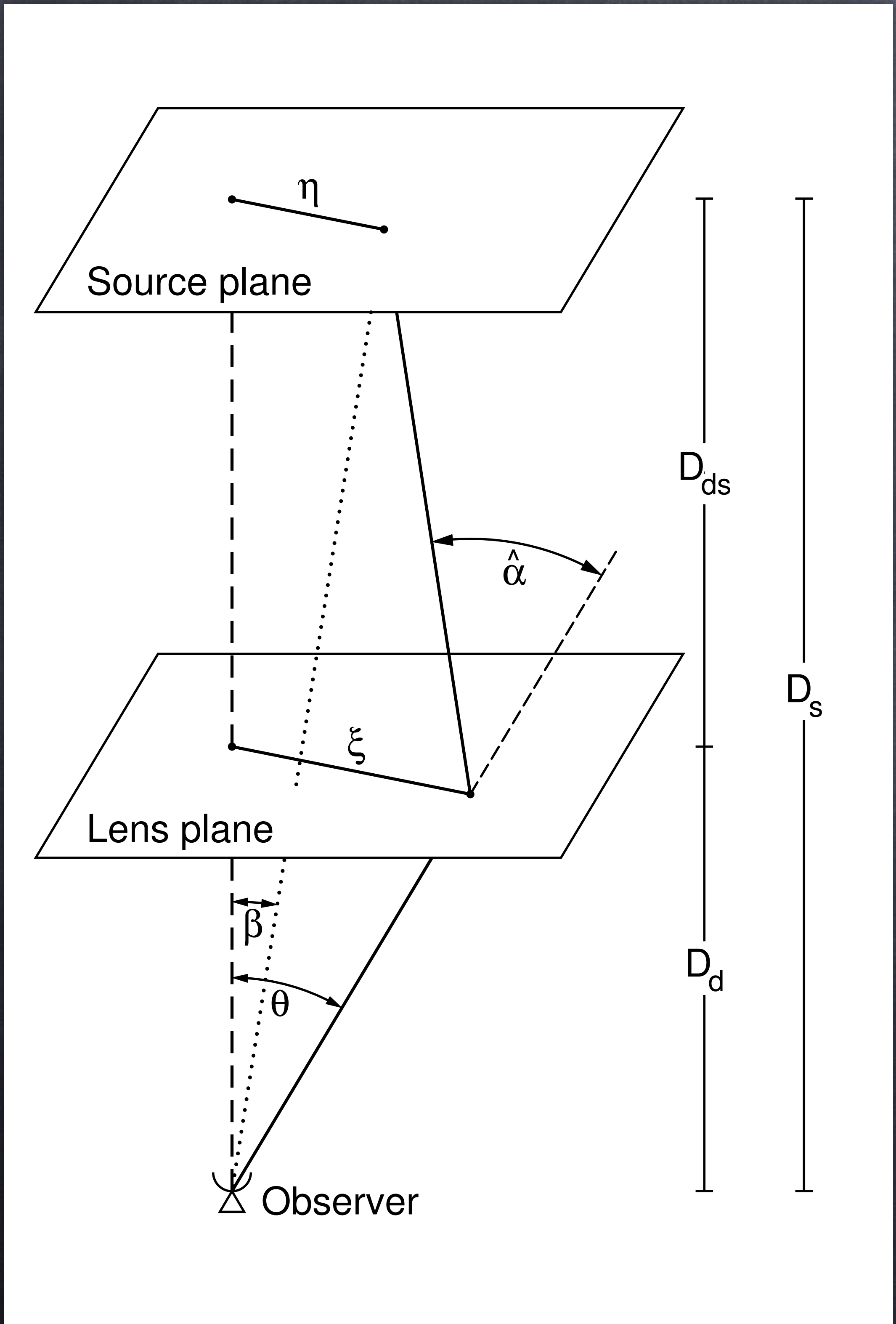
Lensing Tomography - 3D information



- Lensing is sensitive to the integrated mass distribution
- Directly sensitive to dark and luminous matter


Some Math -
Lens Equation
Basic concepts

Lens Equation



deflection angle

position in source plane

$$\boldsymbol{\eta} = \frac{D_\mathrm{s}}{D_\mathrm{d}}\boldsymbol{\xi} - D_\mathrm{ds}\hat{\boldsymbol{\alpha}}(\boldsymbol{\xi})$$

$$\boldsymbol{\eta} = D_\mathrm{s}\boldsymbol{\beta}\ ;\ \boldsymbol{\xi} = D_\mathrm{d}\boldsymbol{\theta}$$

relates source and observed position

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \frac{D_\mathrm{ds}}{D_\mathrm{s}}\hat{\boldsymbol{\alpha}}(D_\mathrm{d}\boldsymbol{\theta}) \equiv \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta})$$

scaled deflection angle

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} \mathrm{d}^2\theta'\,\kappa(\boldsymbol{\theta}')\,\frac{\boldsymbol{\theta}-\boldsymbol{\theta}'}{|\boldsymbol{\theta}-\boldsymbol{\theta}'|^2}$$

$$\kappa(\boldsymbol{\theta}) := \frac{\Sigma(D_\mathrm{d}\boldsymbol{\theta})}{\Sigma_\mathrm{cr}} \qquad \Sigma_\mathrm{cr} = \frac{c^2}{4\pi G}\,\frac{D_\mathrm{s}}{D_\mathrm{d}\,D_\mathrm{ds}} \approx 0.35\left(\frac{D_\mathrm{d}\,D_\mathrm{ds}}{D_\mathrm{s}\;1\,\mathrm{Gpc}}\right)^{-1}\ \mathrm{g\,cm^{-2}}$$

dimensionless surface mass density

Lens Equation - more generally

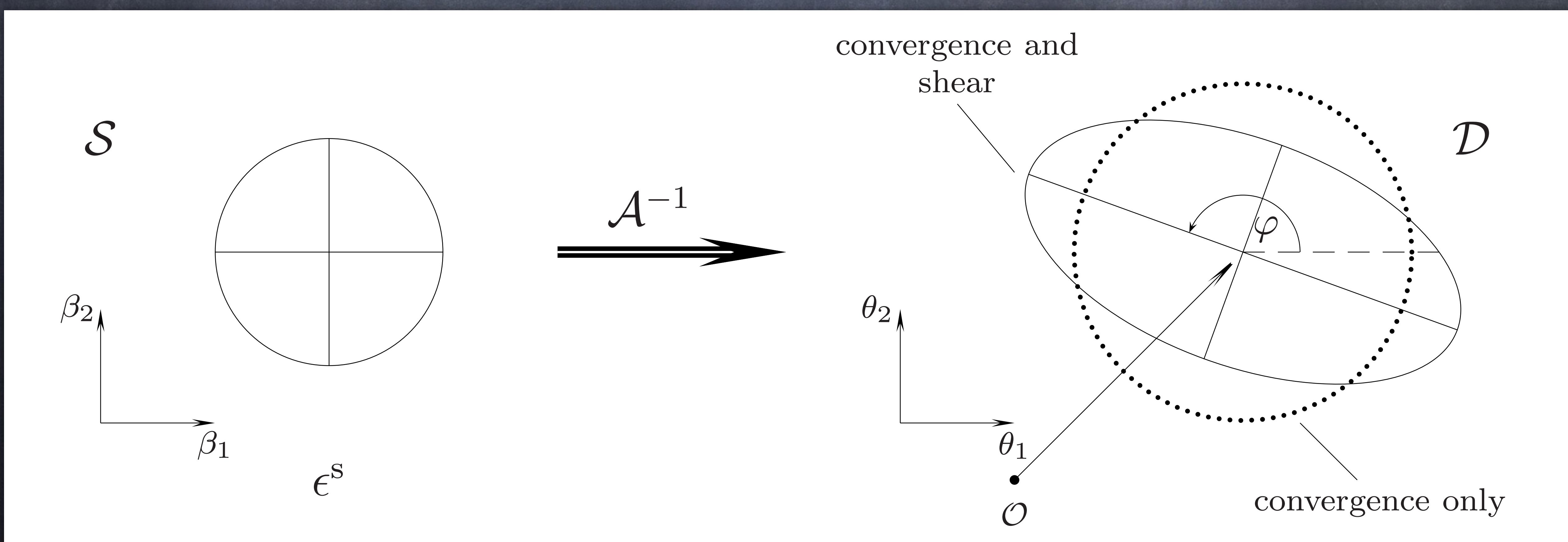
$$\boldsymbol{\beta} - \boldsymbol{\beta}_0 = \mathcal{A}(\boldsymbol{\theta}_0) \cdot (\boldsymbol{\theta} - \boldsymbol{\theta}_0)$$

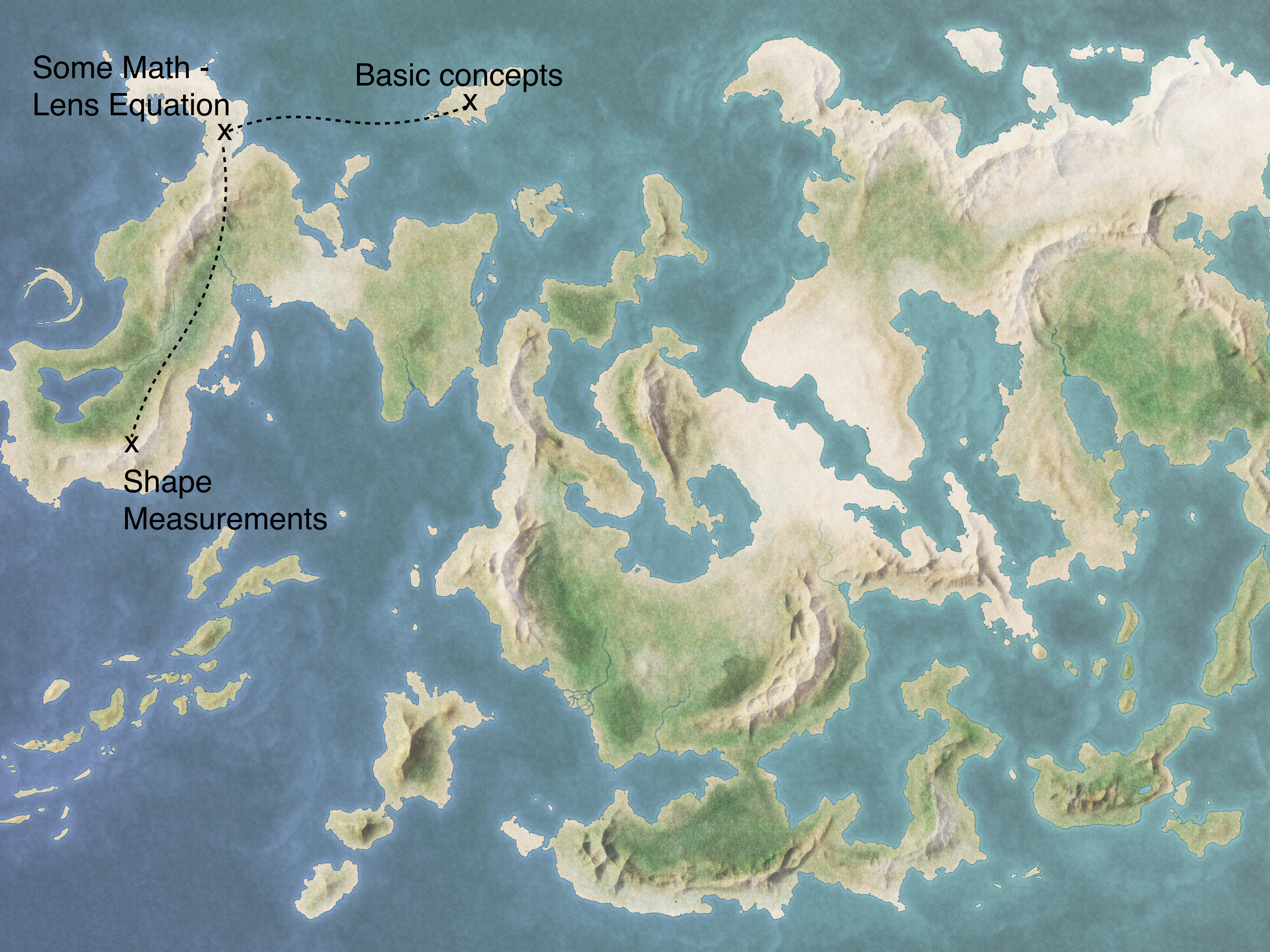
linearized lens mapping

$$\mathcal{A}(\boldsymbol{\theta}) = (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}$$

reduced shear $g(\boldsymbol{\theta}) = \frac{\gamma(\boldsymbol{\theta})}{[1-\kappa(\boldsymbol{\theta})]}$

shear $\gamma = \gamma_1 + \mathrm{i}\gamma_2 = |\gamma|\,\mathrm{e}^{2\mathrm{i}\varphi}$




Some Math -
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Shape
Measurements

Measurement is simple on paper

1) Measure the centroid:

$$\bar{\boldsymbol{\theta}} \equiv \frac{\int \mathrm{d}^2\theta \, q_I[I(\boldsymbol{\theta})] \, \boldsymbol{\theta}}{\int \mathrm{d}^2\theta \, q_I[I(\boldsymbol{\theta})]}$$

2) Measure second order Brightness moments:

$$Q_{ij} = \frac{\int \mathrm{d}^2\theta \, q_I[I(\boldsymbol{\theta})] \, (\theta_i - \bar{\theta}_i) \, (\theta_j - \bar{\theta}_j)}{\int \mathrm{d}^2\theta \, q_I[I(\boldsymbol{\theta})]} \, , \quad i, j \in \{1, 2\}$$

3) Define an ellipticity measure (there exist many...)

$$\boxed{\chi \equiv \frac{Q_{11} - Q_{22} + 2\mathrm{i}Q_{12}}{Q_{11} + Q_{22}}} \quad \text{and} \quad \boxed{\epsilon \equiv \frac{Q_{11} - Q_{22} + 2\mathrm{i}Q_{12}}{Q_{11} + Q_{22} + 2(Q_{11}Q_{22} - Q_{12}^2)^{1/2}}}$$

Measurement is simple on paper

4) Relate observed and intrinsic ellipticities

$$Q^{(\mathrm{s})} = \mathcal{A}\,Q\,\mathcal{A}^T = \mathcal{A}\,Q\,\mathcal{A} \qquad \boxed{\mathcal{A}(\boldsymbol{\theta}) = (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}}\,, \quad \boxed{g_i = \frac{\gamma_i}{(1-\kappa)}}$$

$$\chi^{(\mathrm{s})} = \frac{\chi - 2g + g^2\chi^*}{1+|g|^2 - 2\mathcal{R}\mathrm{e}(g\chi^*)} \qquad \epsilon^{(\mathrm{s})} = \begin{cases} \dfrac{\epsilon - g}{1-g^*\epsilon} & \text{if } |g| \le 1 \\[2ex] \dfrac{1-g\epsilon^*}{\epsilon^* - g^*} & \text{if } |g| > 1 \end{cases}$$

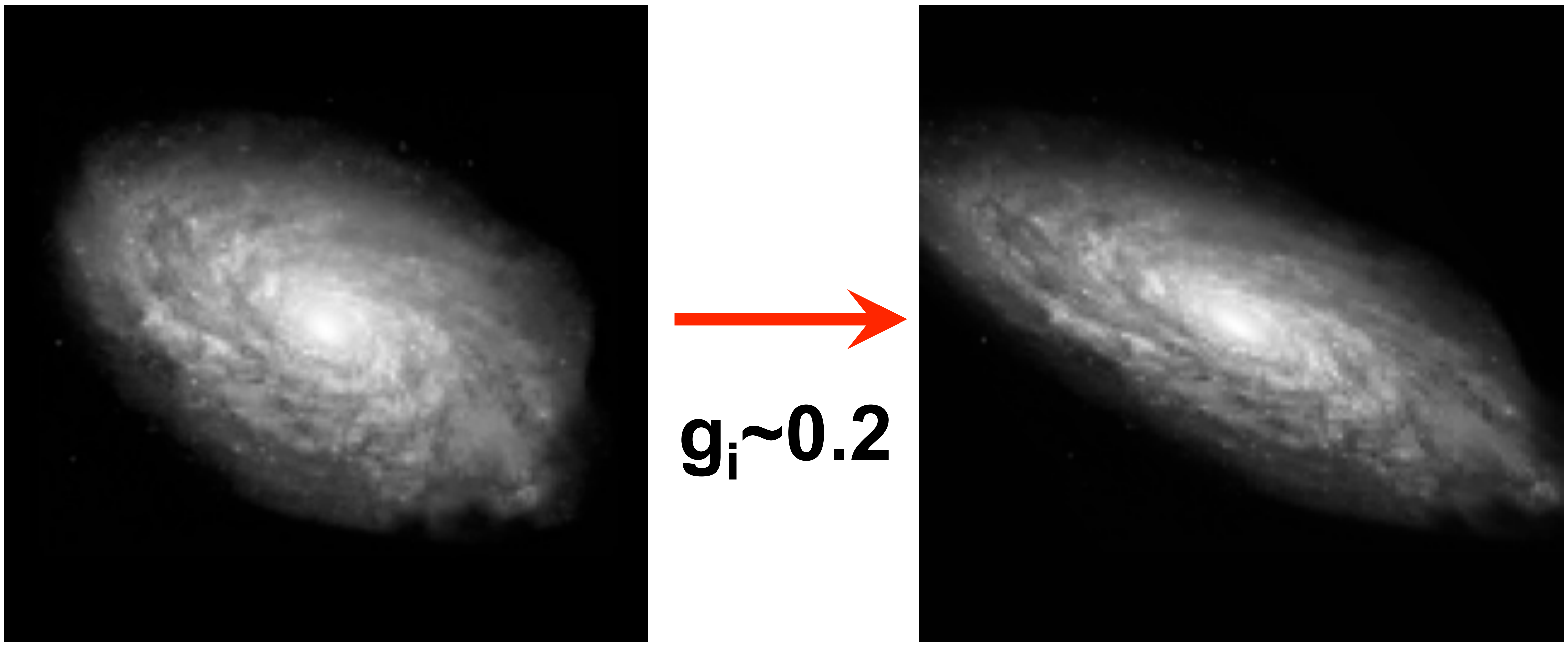
5) Assume that universe is isotropic
→ Expectation value of intrinsic ellipticity is zero

$$\boxed{\mathrm{E}\left(\chi^{(\mathrm{s})}\right) = 0 = \mathrm{E}\left(\epsilon^{(\mathrm{s})}\right)}$$

6) In the weak lensing regime....

$$\boxed{\gamma \approx g \approx \langle\epsilon\rangle \approx \frac{\langle\chi\rangle}{2}}$$

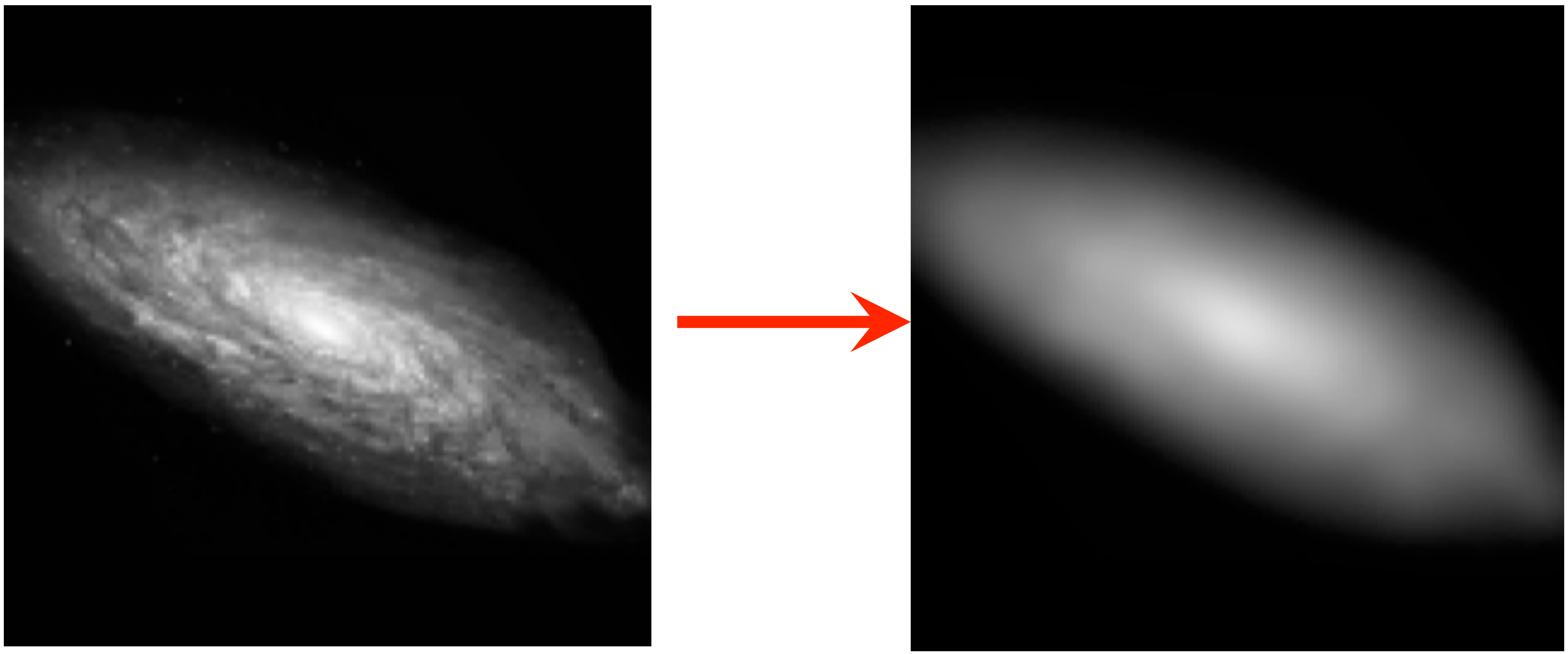
Reality 1: Effect of Lensing



$$\begin{pmatrix} x_u \\ y_u \end{pmatrix} = \begin{pmatrix} 1 - g_1 & -g_2 \\ -g_2 & 1 + g_1 \end{pmatrix} \begin{pmatrix} x_l \\ y_l \end{pmatrix}$$

Real data: g_i~0.03

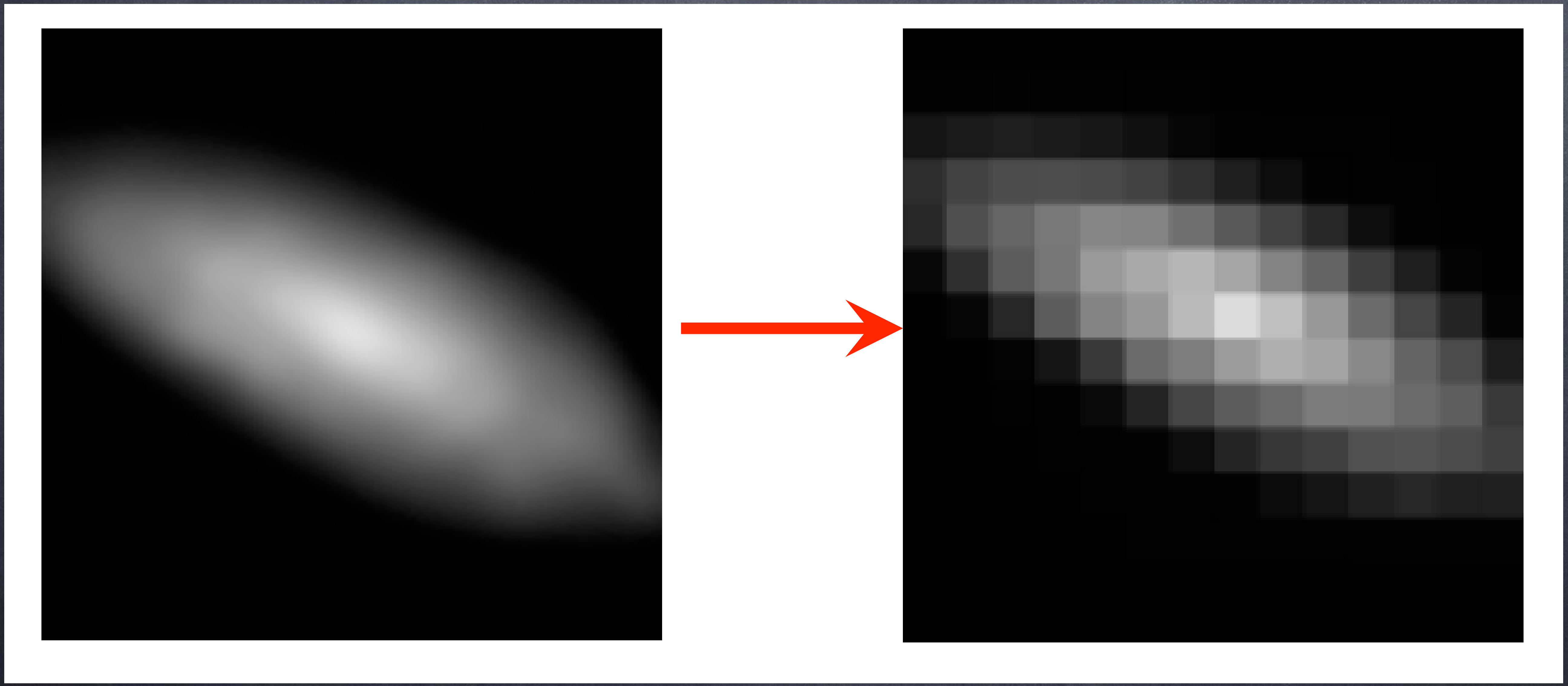
Reality 2:Telescope and Atmosphere PSF



Convolution with kernel

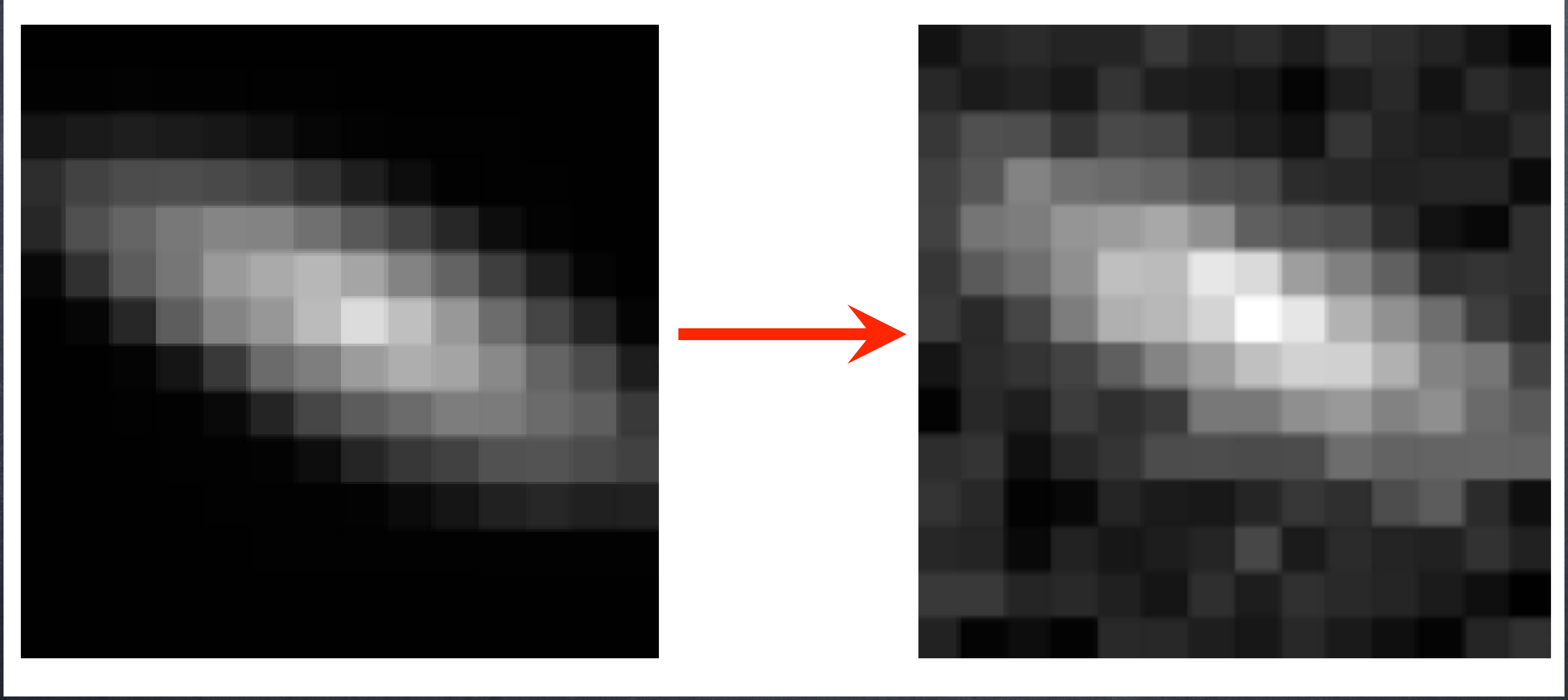
Real data: Kernel size ~ Galaxy size

Reality 3: Pixelization

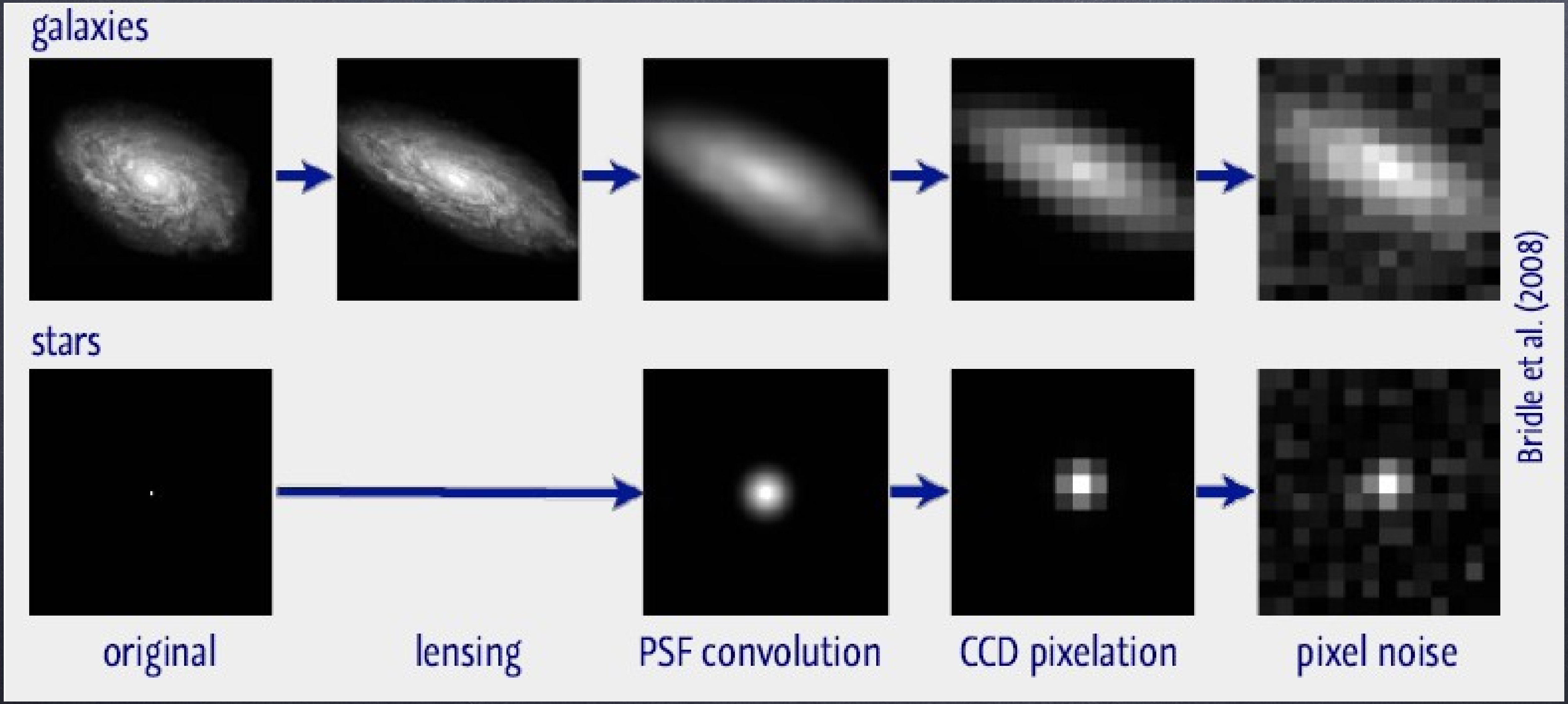


Many other detector effects+artifacts enter at this step

Reality 4: Noise

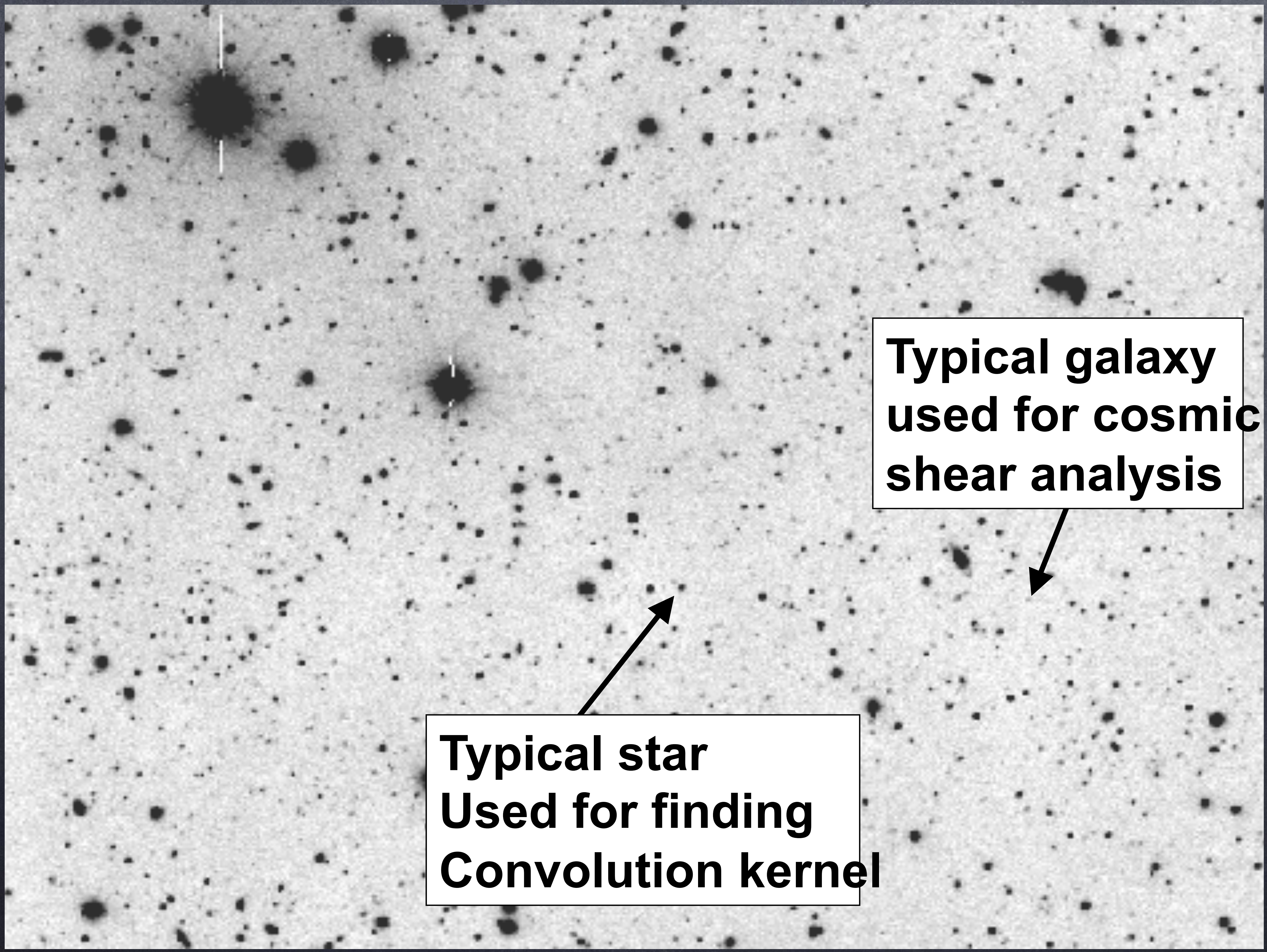


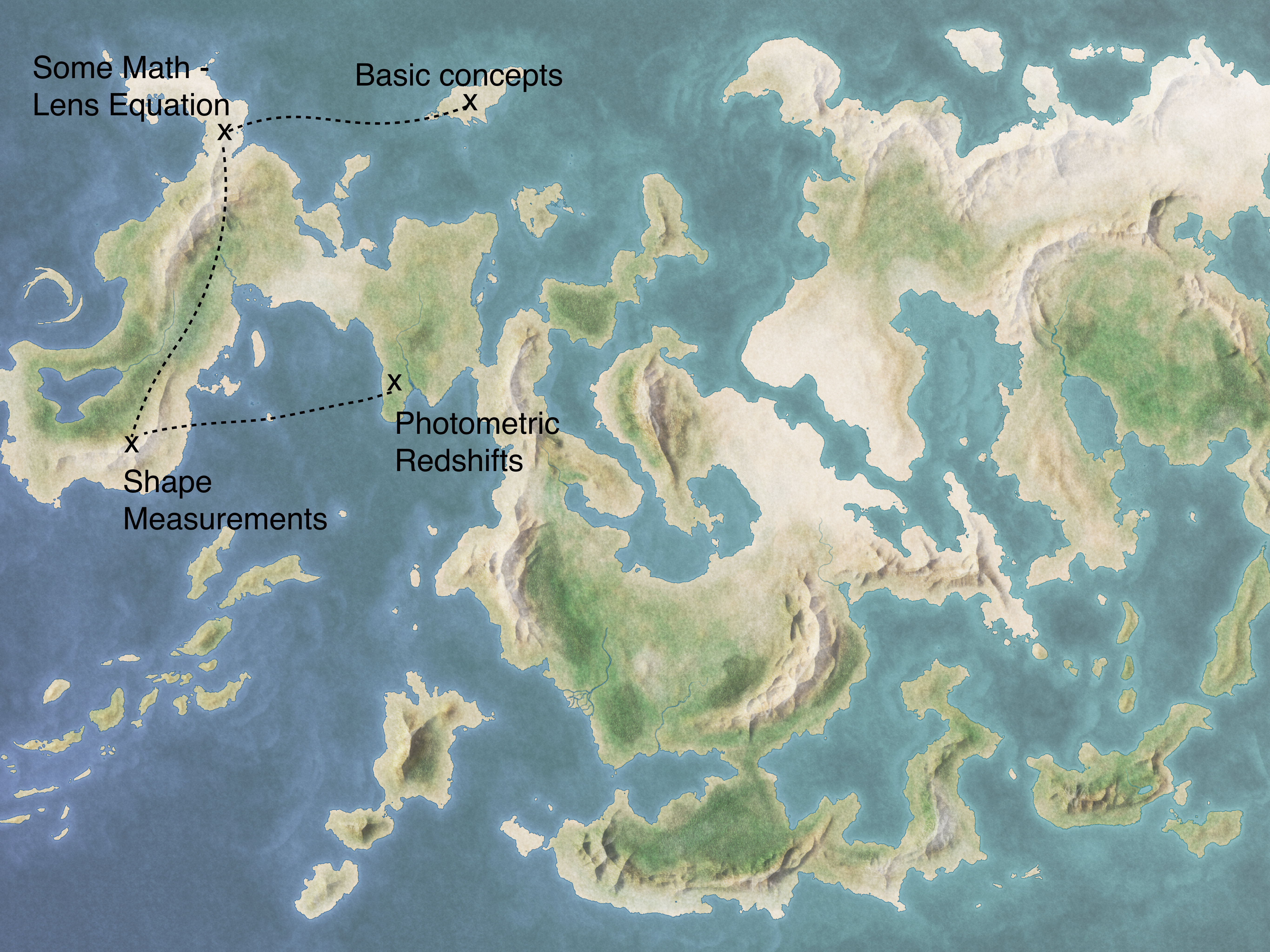
Summary



galaxies
stars
original
lensing
PSF convolution
CCD pixelation
pixel noise
Bridle et al. (2008)

Putting things in perspective

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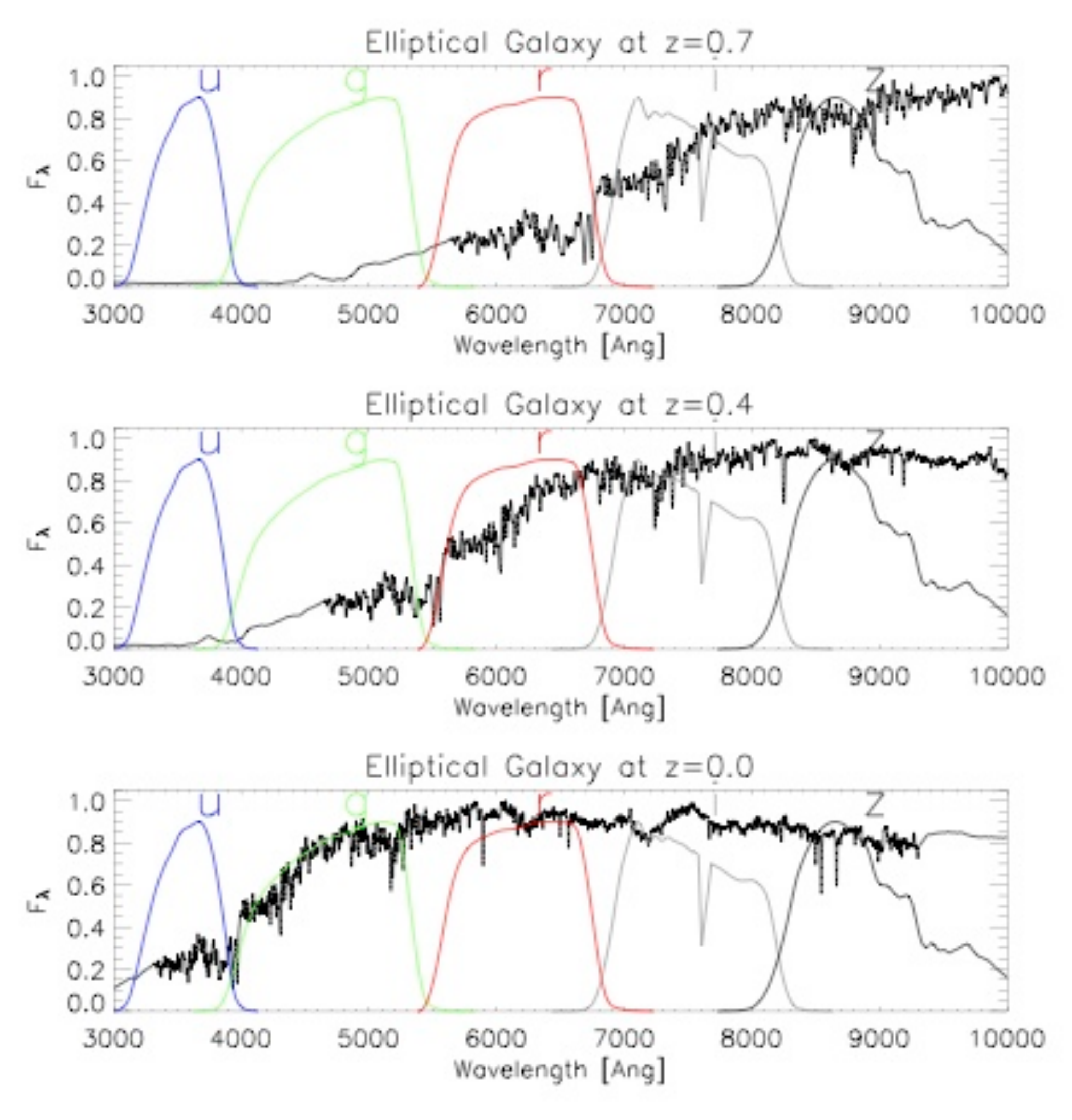
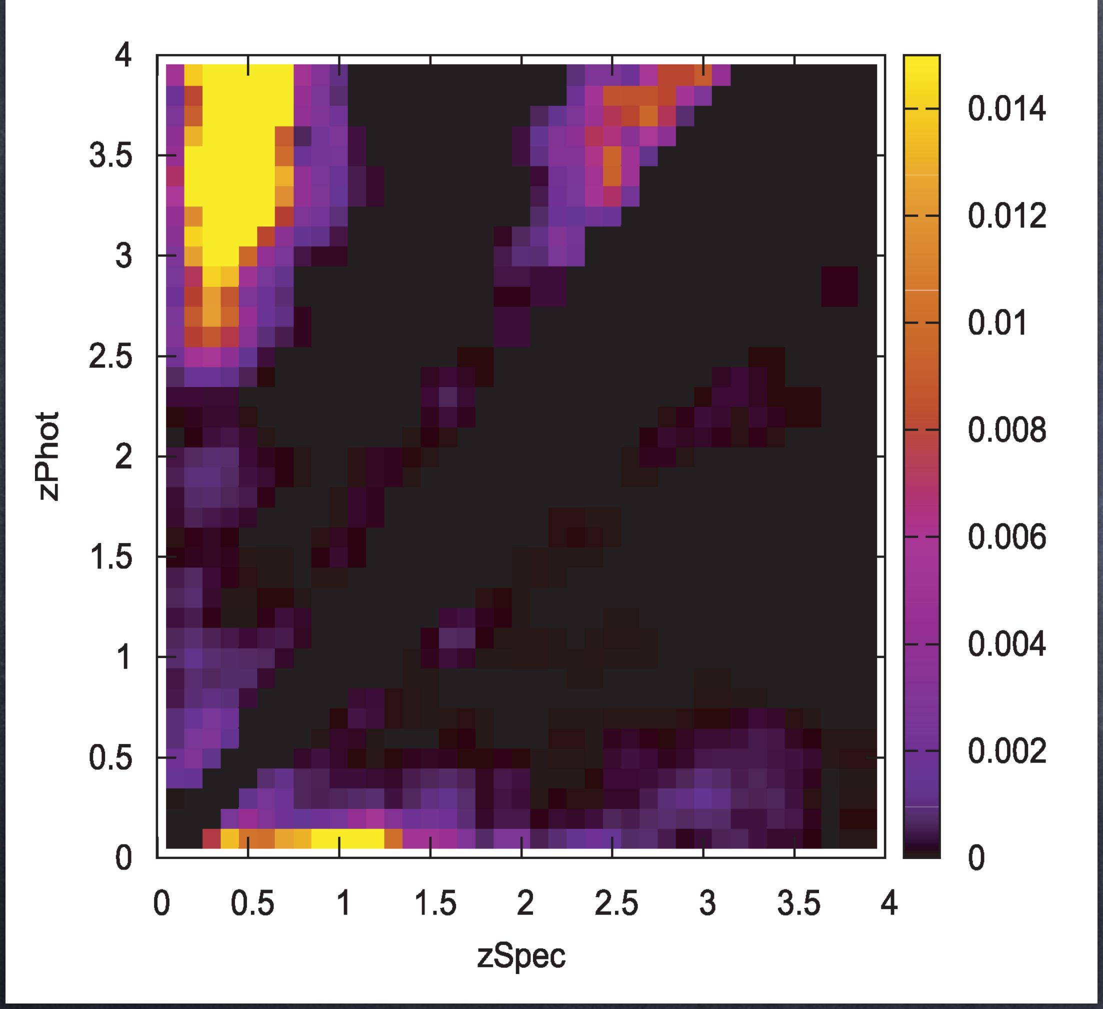
Photometric Redshifts



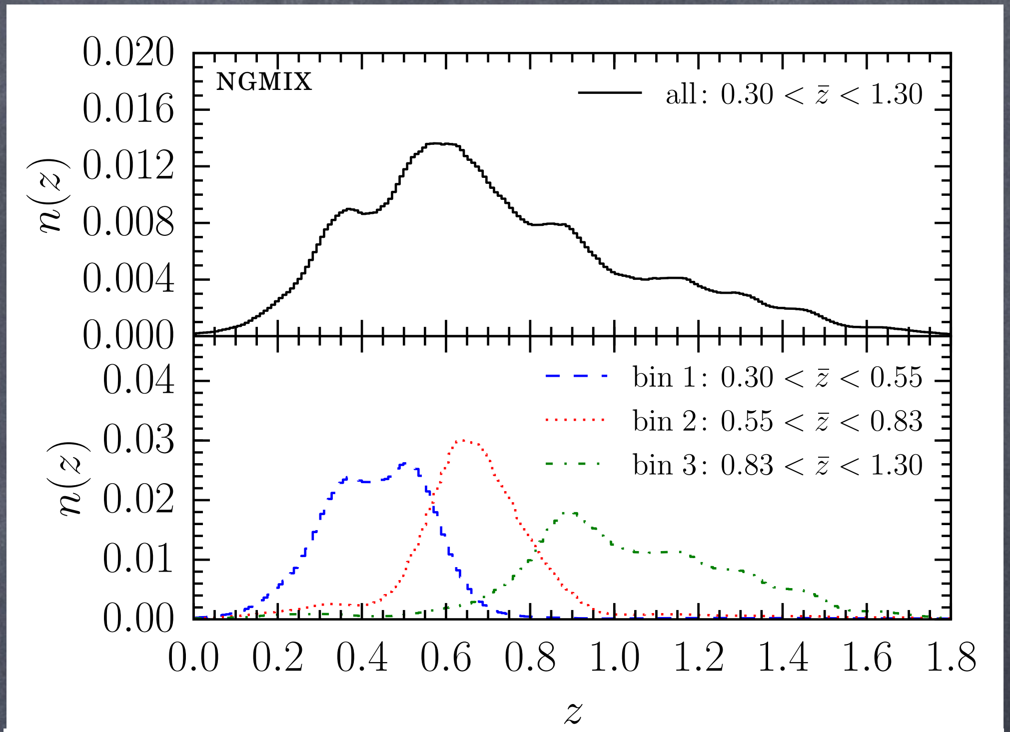
- Measure Fluxes in many different photometric bands
- Collects spectra for representative galaxy sample
- Infer redshifts through mapping these flux measurements to galaxy spectra
- Much less accurate compared to spectroscopic redshifts

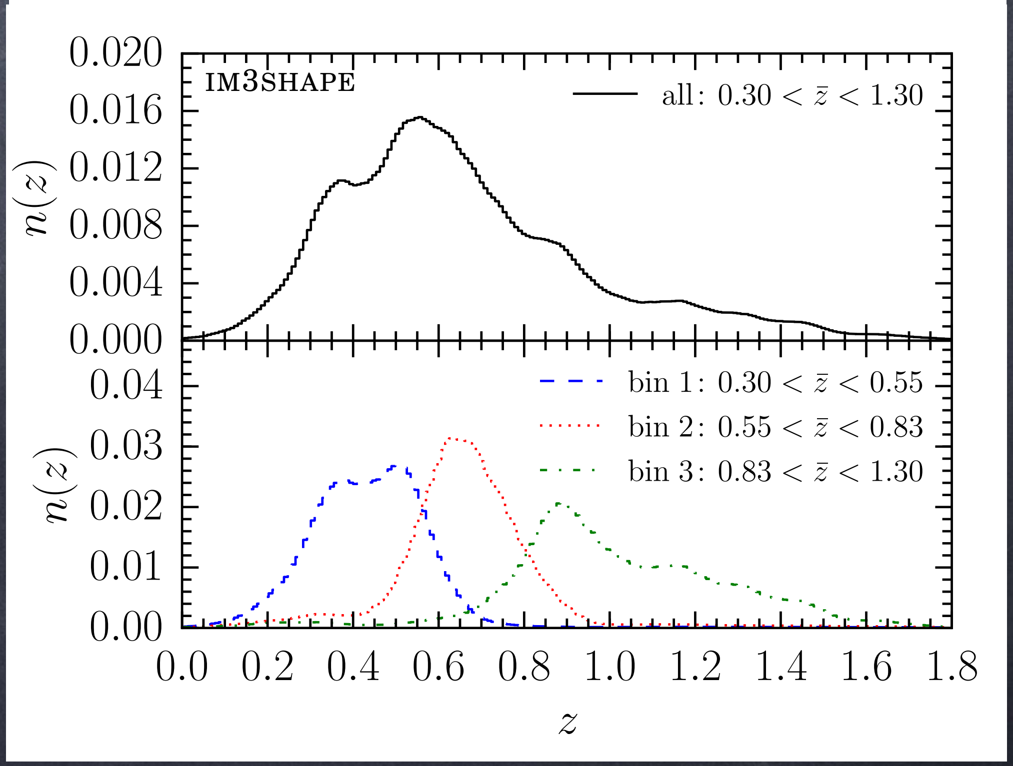
Photo-z uncertainties

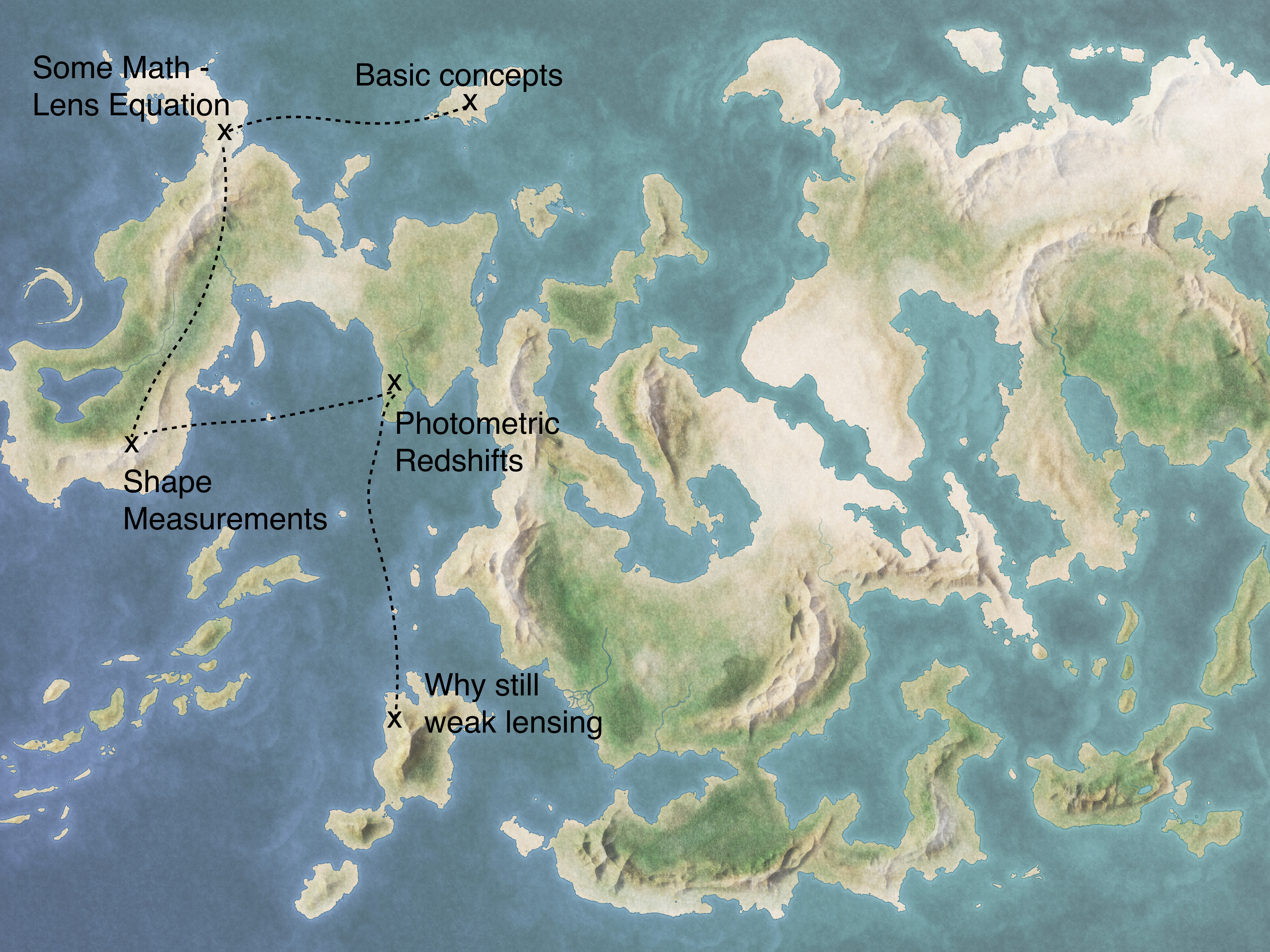
Two types of uncertainties:
1) broadening of tomographic bin limits
2) catastrophic outliers



contamination fraction is most severe for z_p > 2.5 and < 0.2



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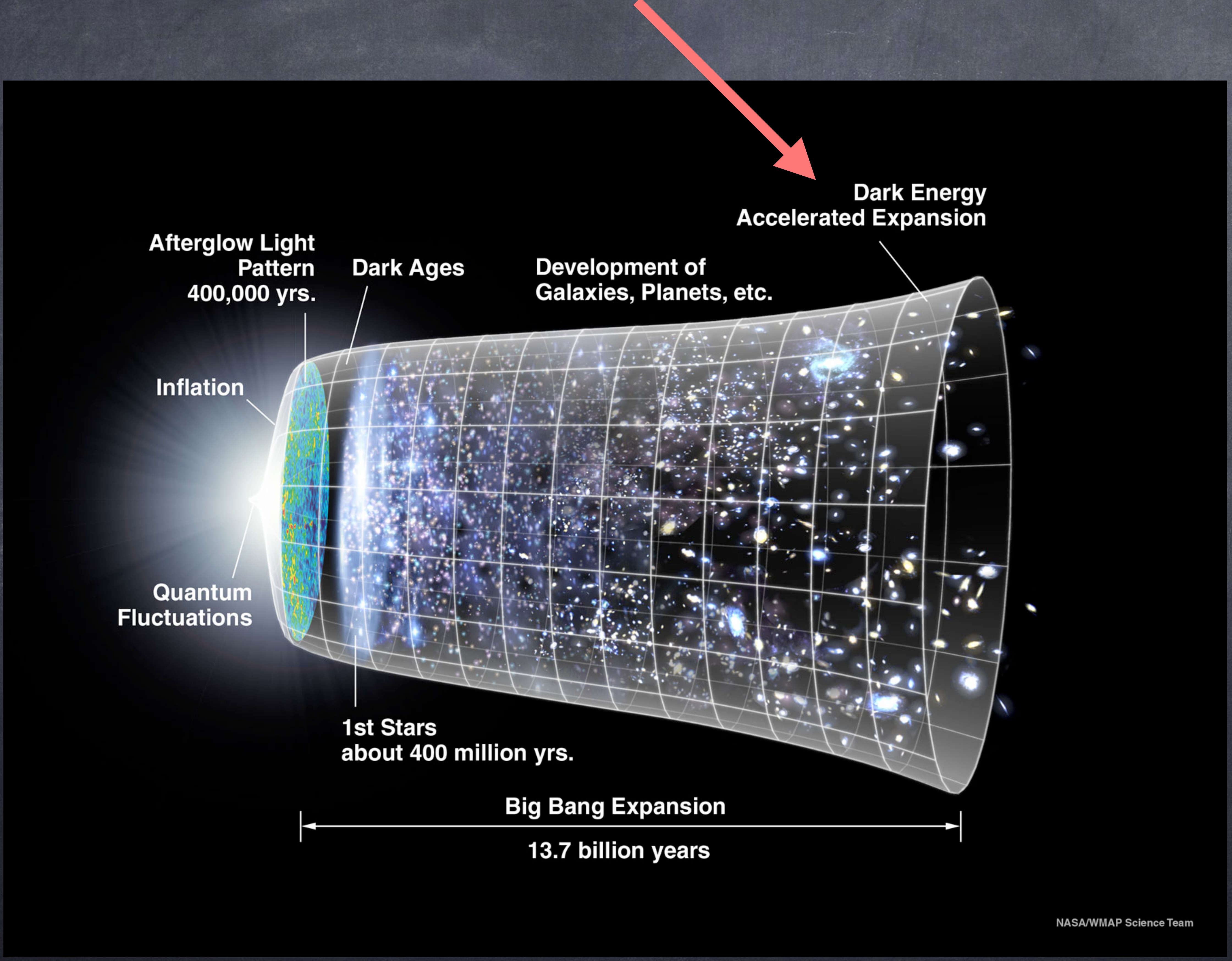
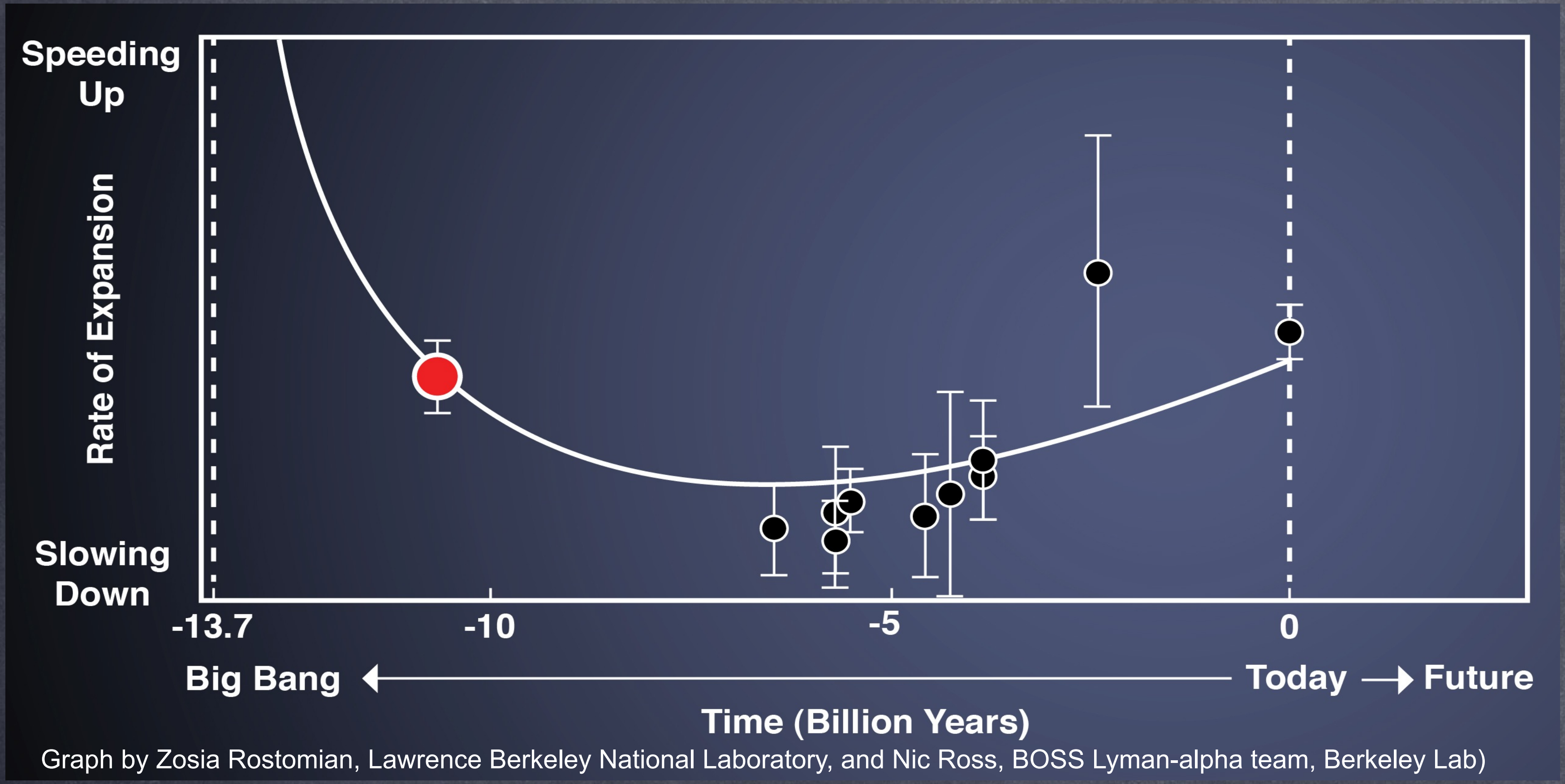
Why still
weak lensing

Cosmic Acceleration



Cosmic Acceleration

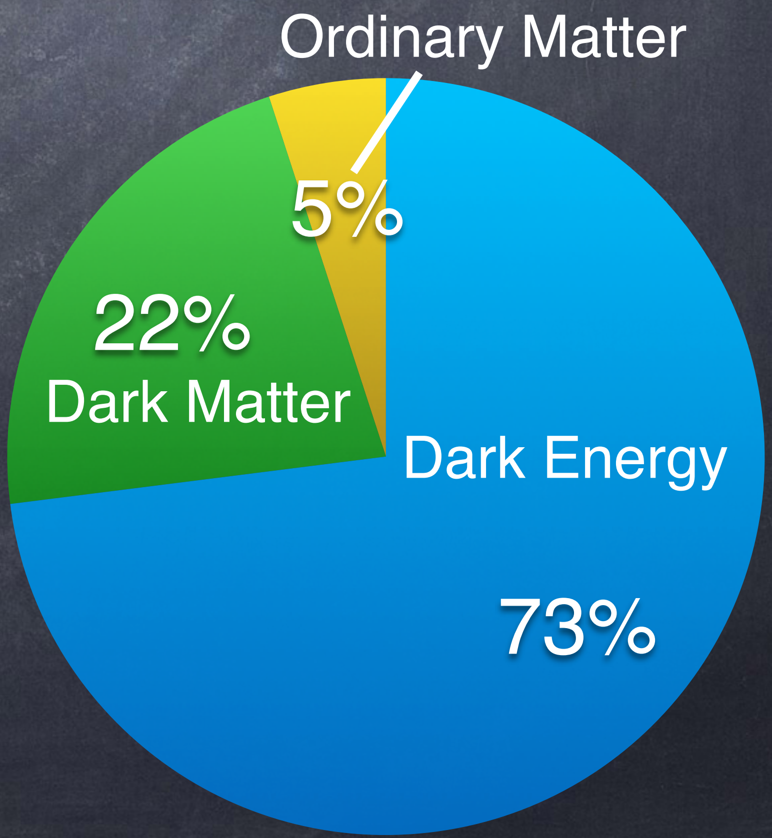


Since 1930s we know

$$\dot{a} > 0$$

SN1a (Nobel Prize 2011) and BAO have shown

$$\ddot{a} > 0$$



If GR is correct, and we trust the observations, the Universe is dominated by an energy density component with negative pressure

Alternative: Breaking GR

Many new DE/modified gravity theories developed over last decade

Most can be categorized based on how they **break GR**:

The only **local**, **second-order** gravitational field equations that can be derived from a **four-dimensional action** that is constructed **solely from the metric tensor**, and admitting Bianchi identities, are GR + Λ.

Lovelock's theorem (1969)

Alternative: Breaking GR

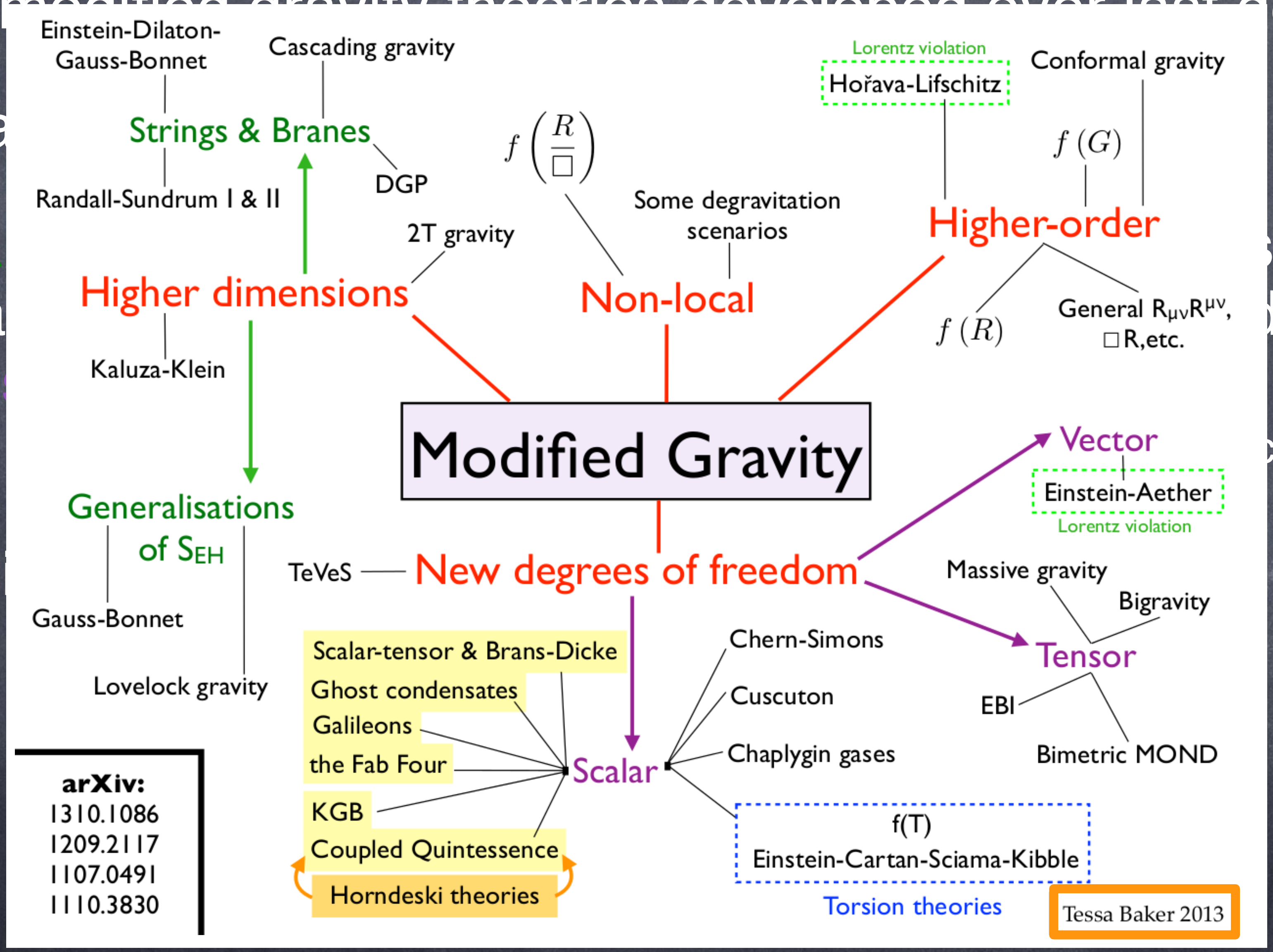
Many new DE/modified gravity theories developed over last decade

Most can be ca

The only loca ... that can be derived from a ... solely from the metric ten

ck's theorem (1969)

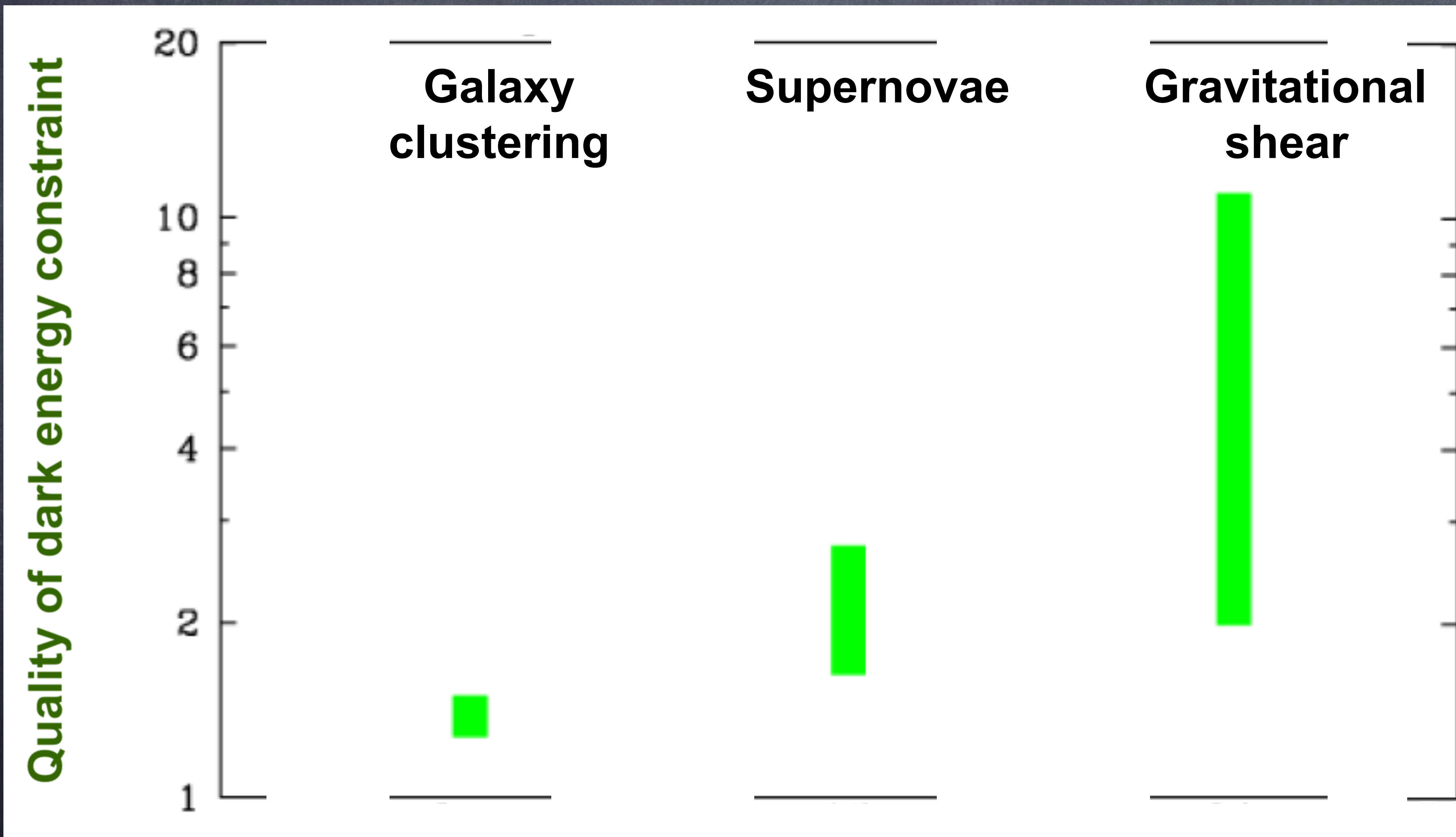
Subject to viabi



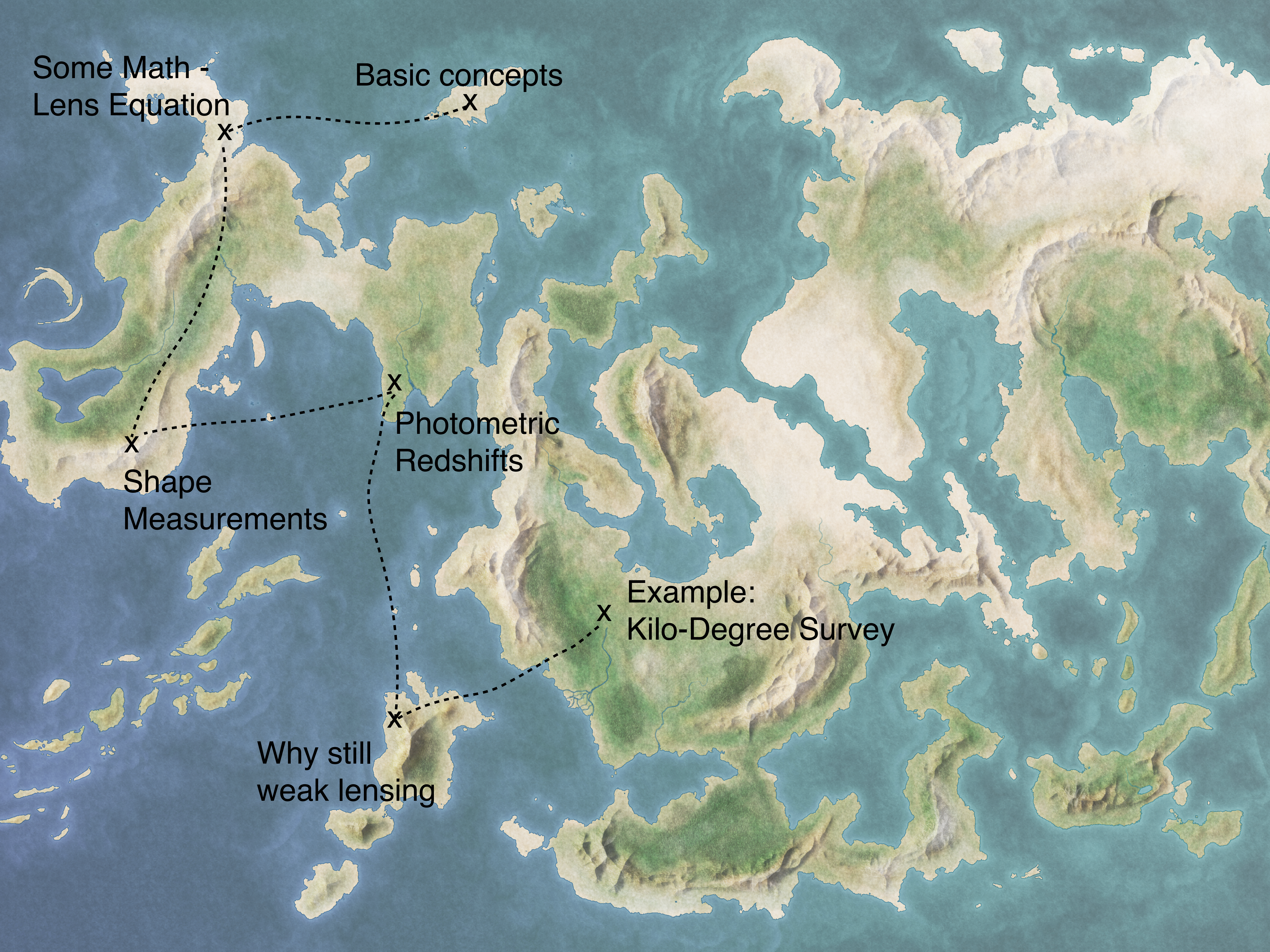
No favored alternative theory, theory space hard to summarize succinctly

Need unifying frameworks + phenomenology to compare to data

Why Still Weak Lensing?



Dark Energy Task Force in 2006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Example:
Kilo-Degree Survey
Why still
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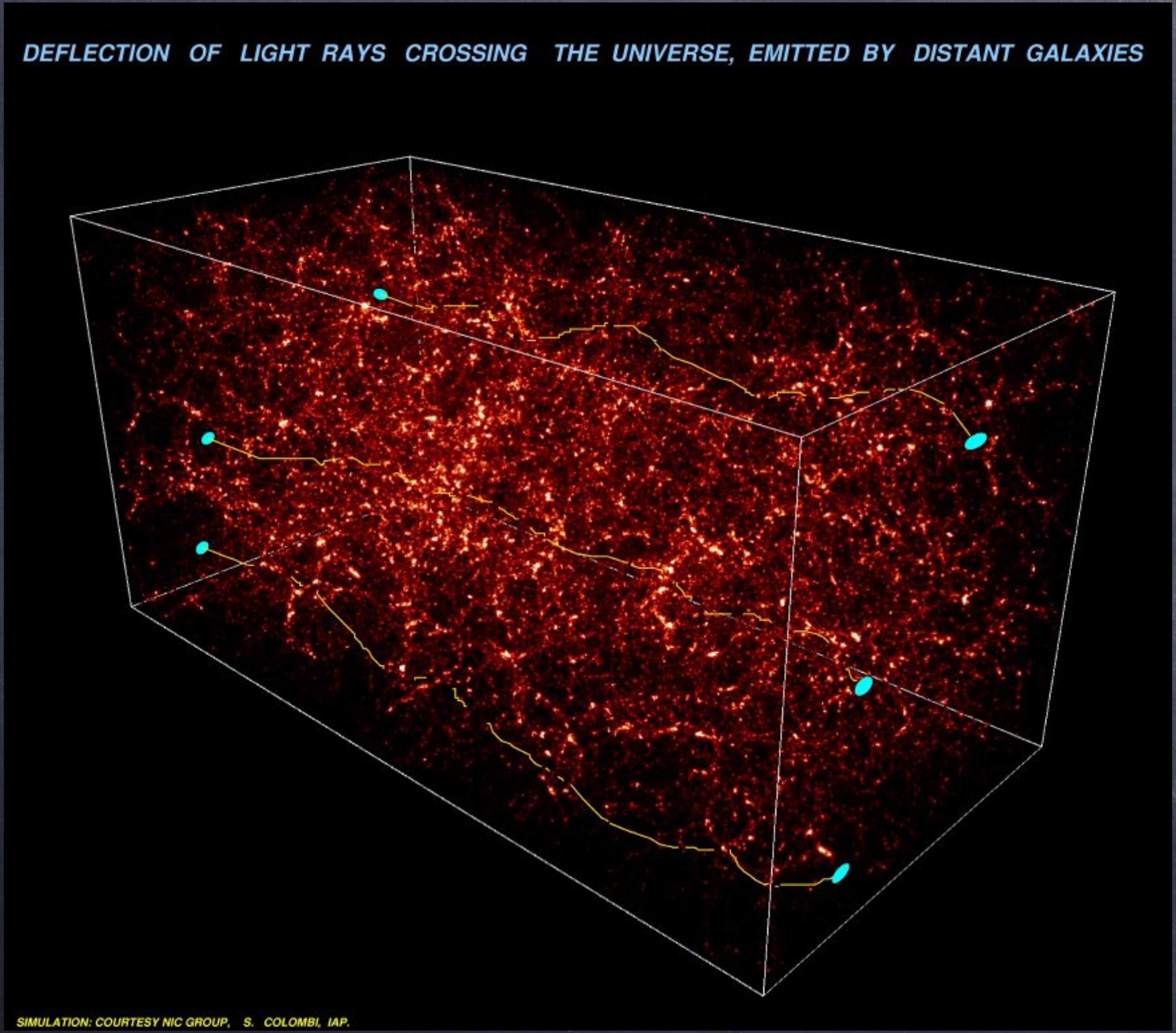
Weak Lensing in a nutshell

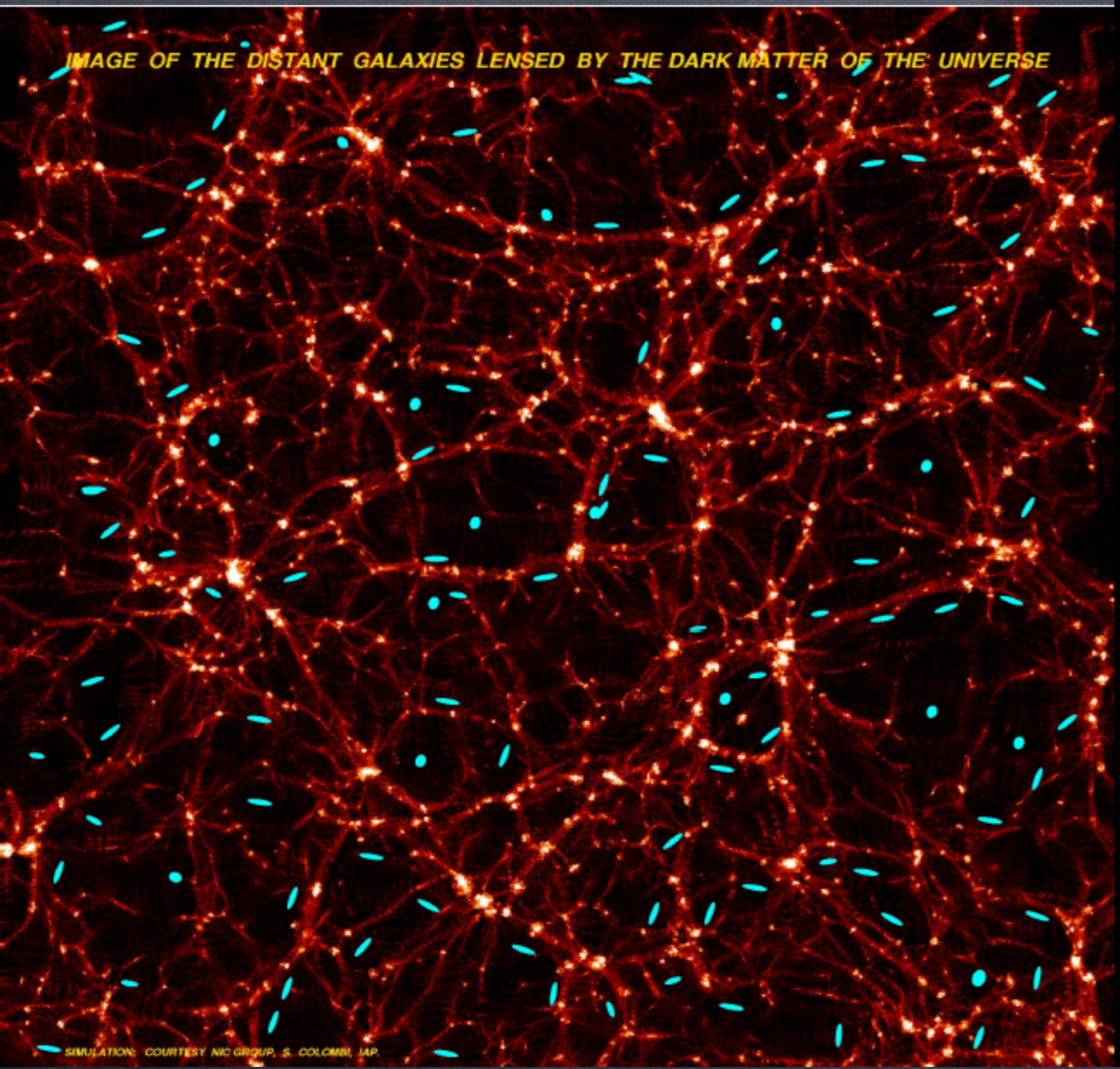


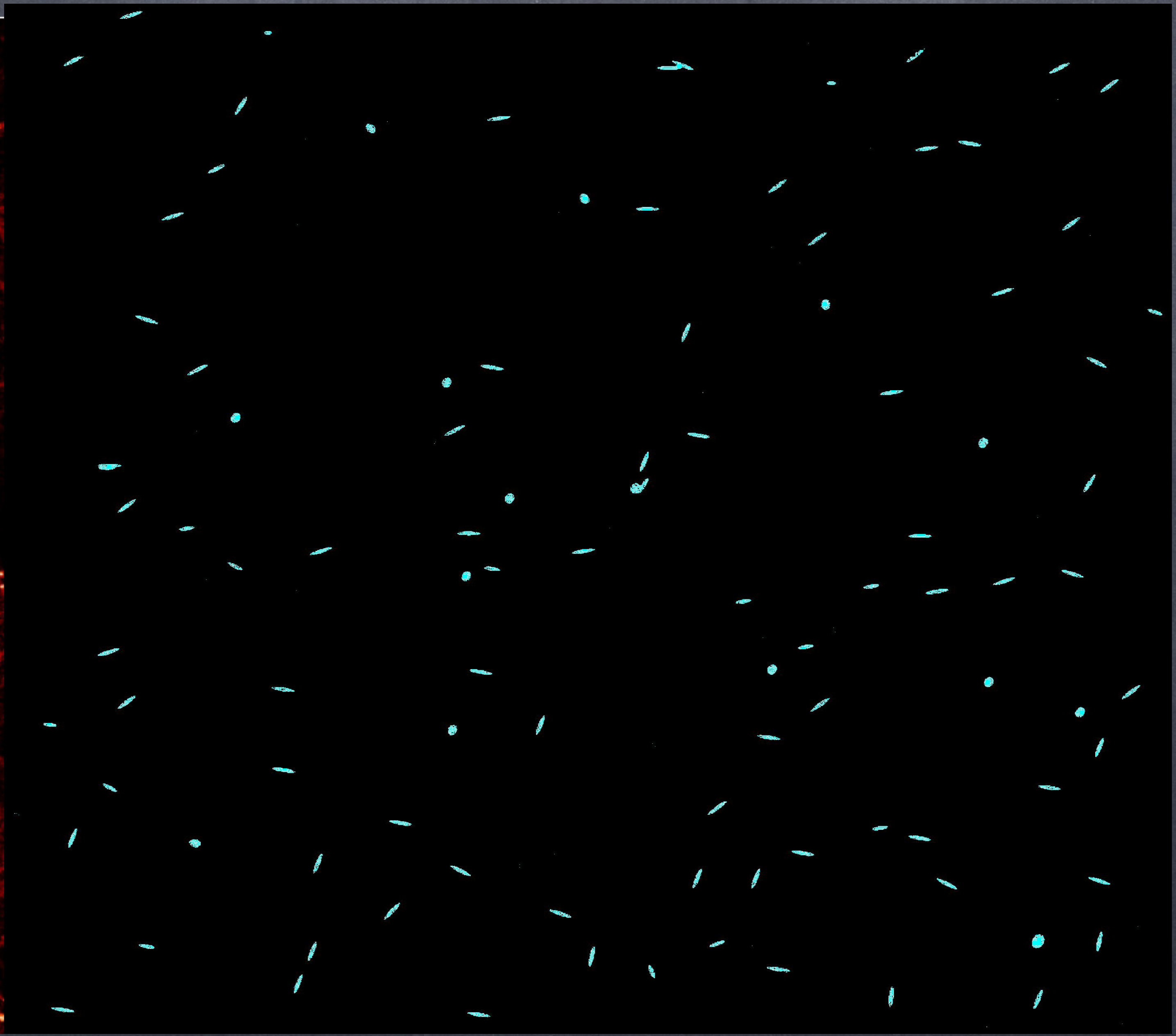
Light rays are distorted by dark matter density field of the Universe

Statistical properties of the distortion reflect statistical properties of the density field

Sir Ernest Rutherford:
"If your experiment needs statistics, you ought to have done a better experiment"

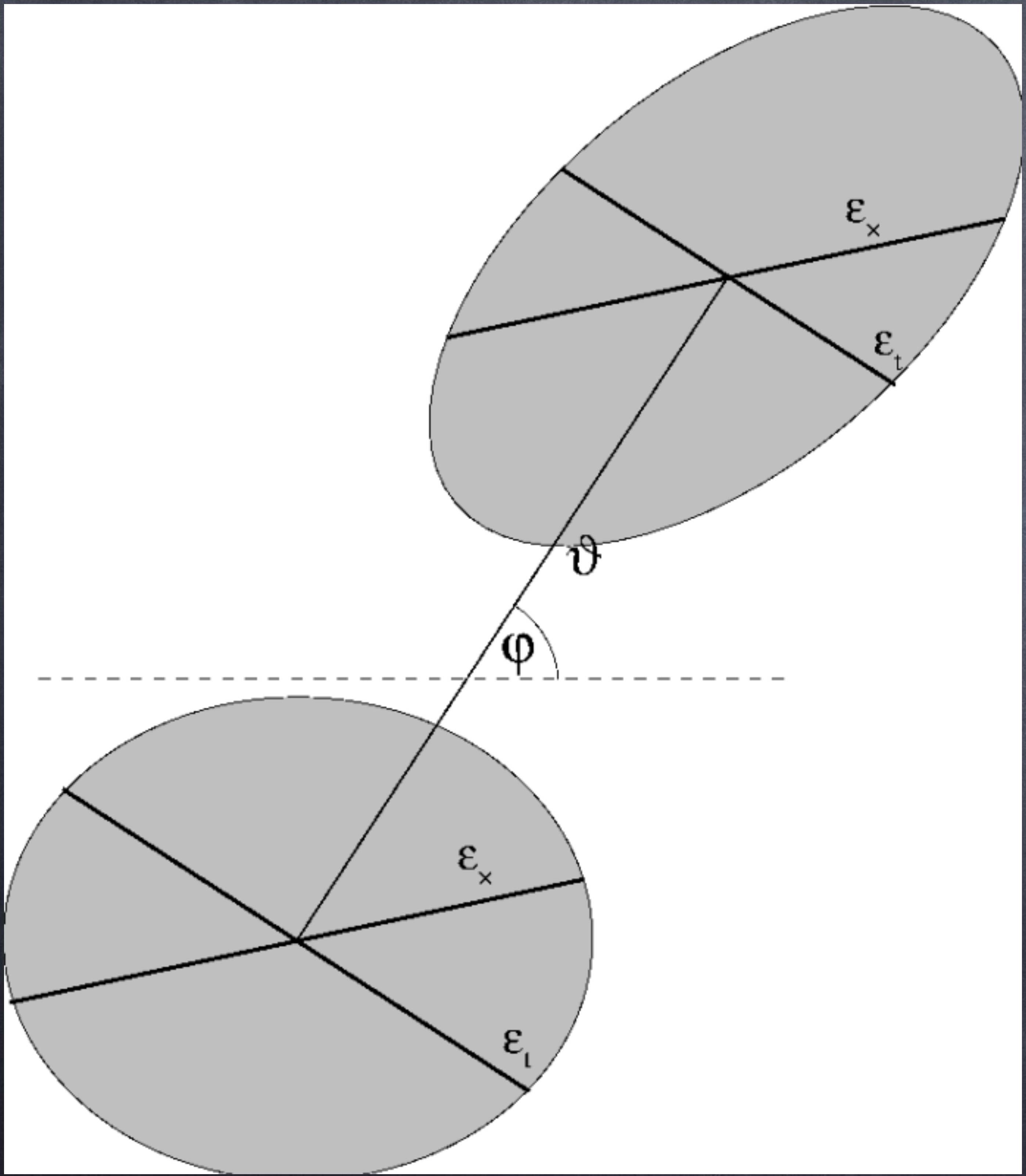
Principle Of Cosmic Shear





<u>But lots of difficulties:</u> Bad seeing, PSF anisotropy, tracking errors, bright objects, pixelization, noise, blending, intrinsic alignment, baryons, non-linear density evolution, photo-z errors, shape calibration, etc

Cosmic Shear Observations



Observation

- measure ellipticities $\epsilon = \epsilon^{(s)} + \gamma$
- assume random orientation $\langle \epsilon^{(s)} \rangle = 0$
- for weak lensing: $\langle \epsilon \rangle = \gamma$

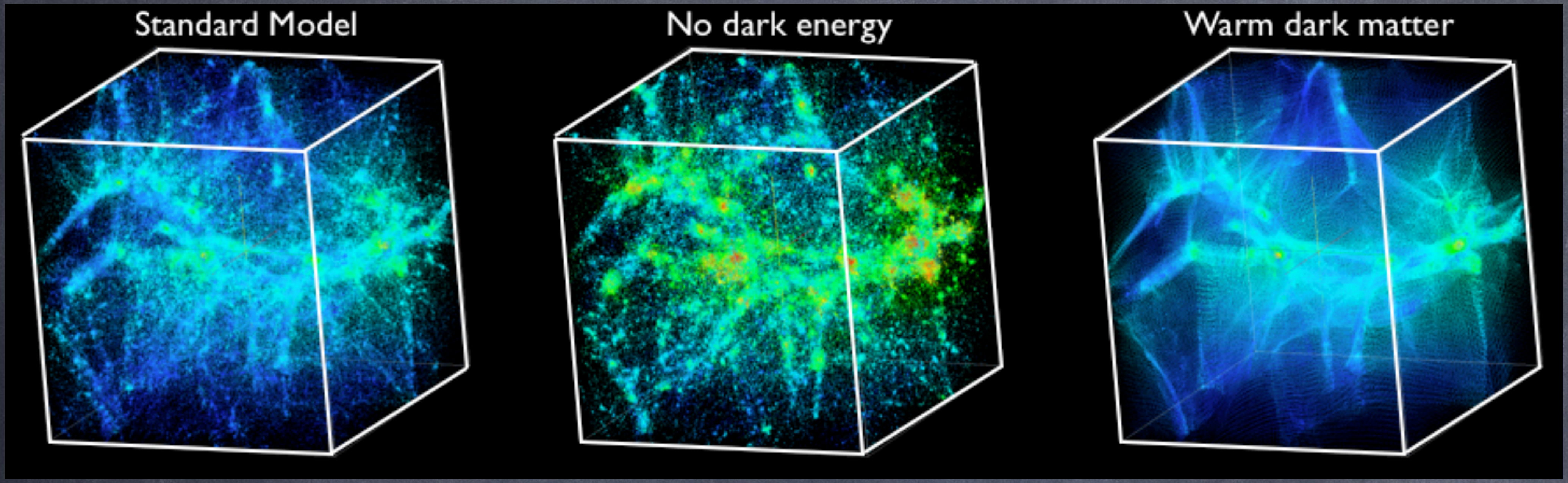
calculate $\xi_\pm$

$$\xi_\pm(\vartheta) = \langle \gamma_t \gamma_t \rangle \pm \langle \gamma_\times \gamma_\times \rangle$$

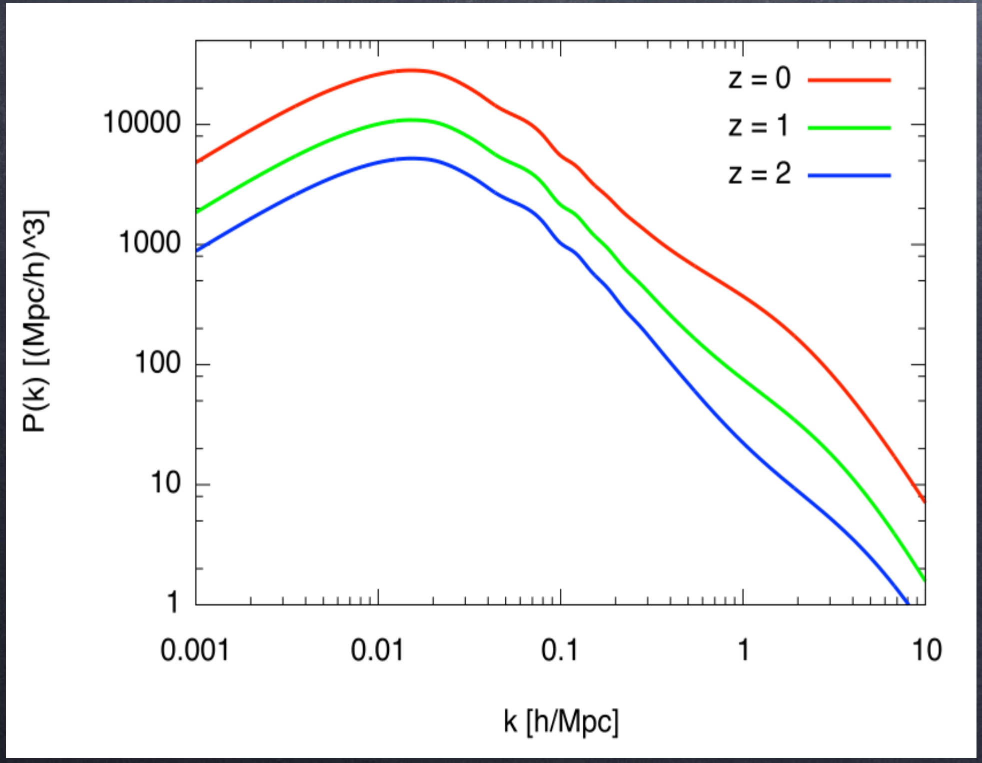
obtain observed data vector $\boldsymbol{\xi}^{obs}$

Cosmic Shear Theory I

1. Choose a variety of cosmological models - cosmological parameters



2. Run numerical simulations



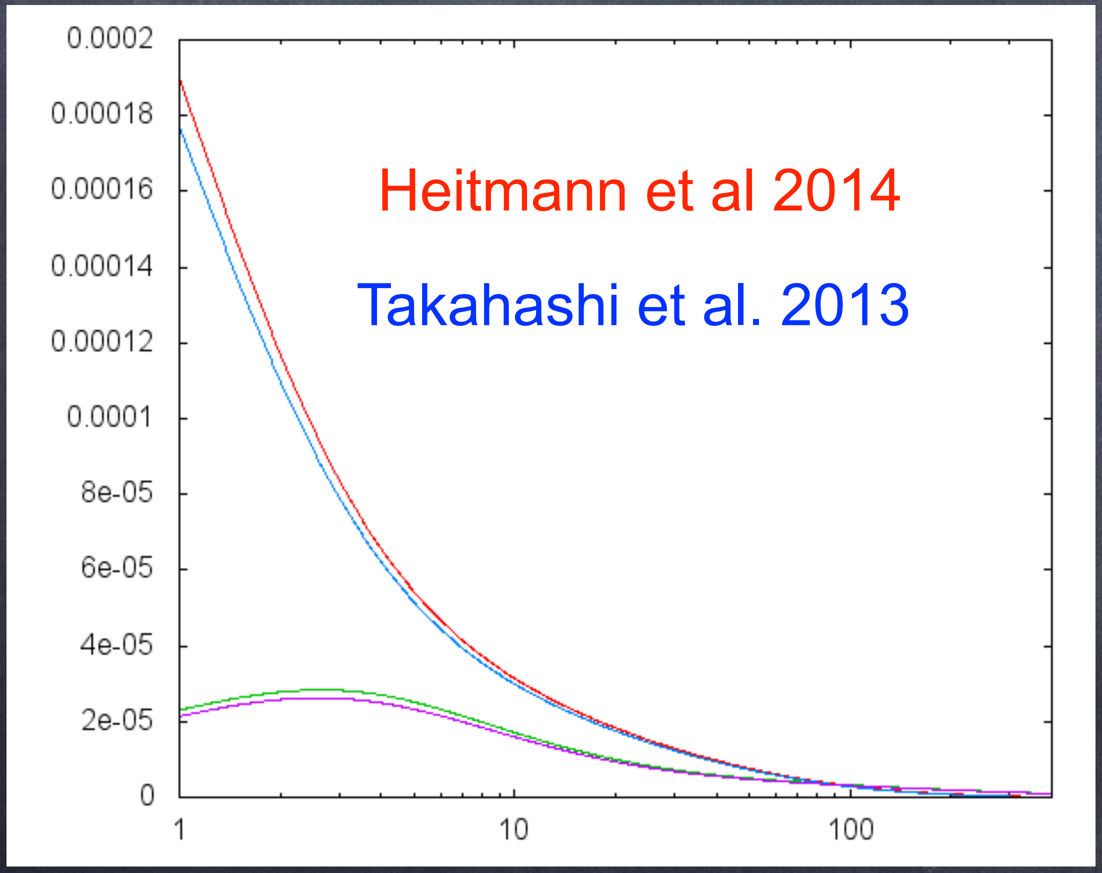
3. Measure Density Power Spectrum as a function of k-mode and redshift in simulations (contains all second order information of the density field)

Cosmic Shear Theory II

Redshift distribution of source galaxies and distances of lenses and sources enter here

$$C^{ij}(l) = \frac{9H_0^4\Omega_m^2}{4c^4}\int_0^{\chi_h} d\chi\, \frac{g^i(\chi)g^j(\chi)}{a^2(\chi)} P_\delta\left(\frac{l}{f_K(\chi)}, \chi\right)$$

4. Project **Density Power Spectrum** along the line-of sight to obtain the **Shear Power Spectrum**



Correlation Function Amplitude

arcmin

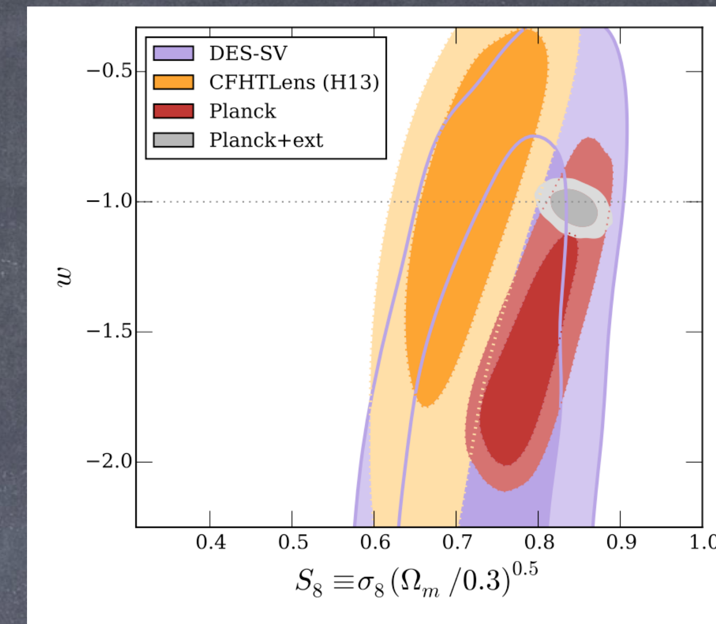
5. Fourier transform the **Shear power Spectrum** to obtain the **Shear Correlation function**

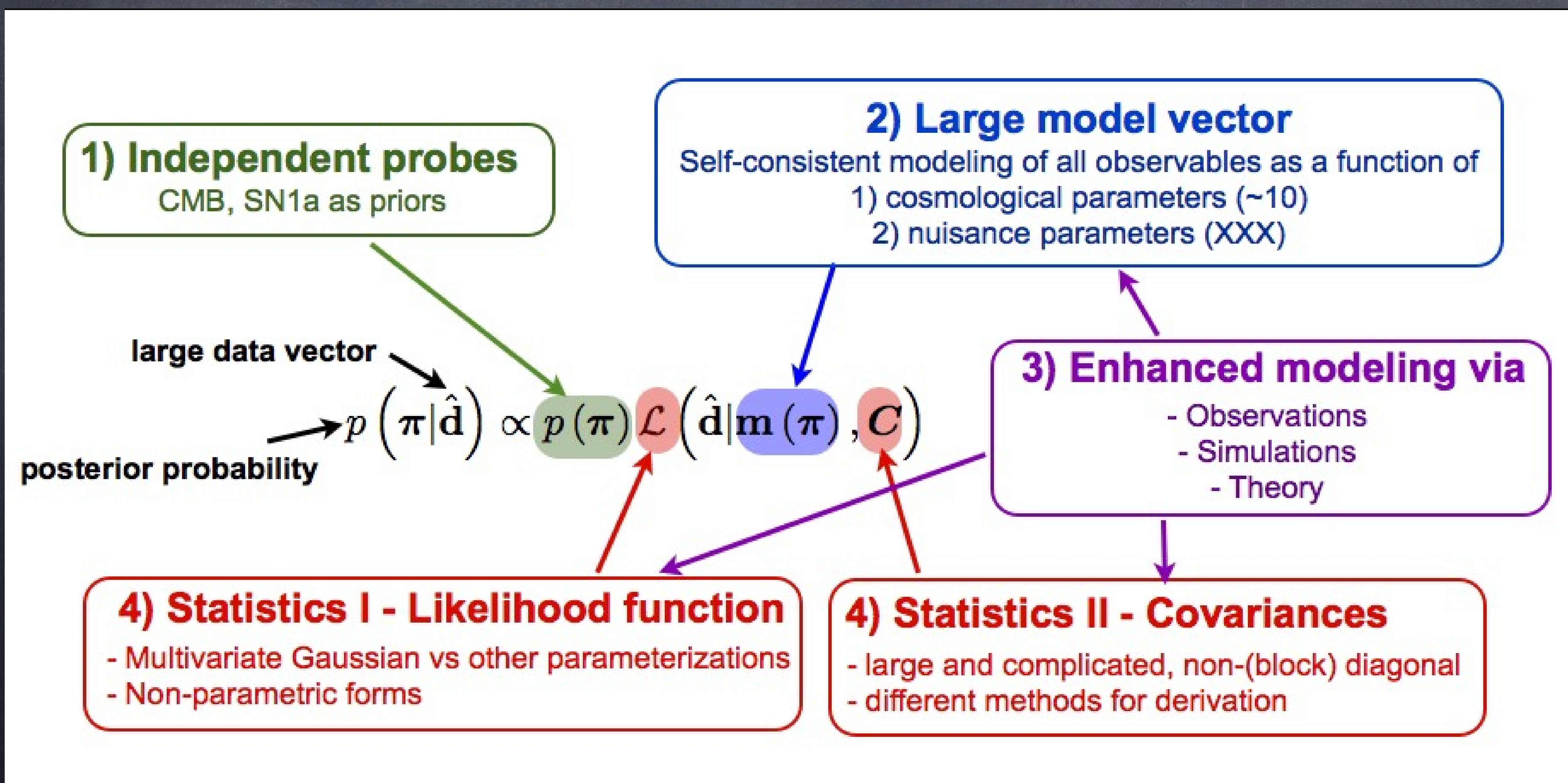
$$\xi_{\pm}^{ij}(\vartheta) = \int_0^{\infty} \frac{d\ell\, \ell}{2\pi} J_{0/4}(\ell\vartheta)\, C^{ij}(\ell)$$

6. Compare observed data vector and model vector in a likelihood analysis (next slide)

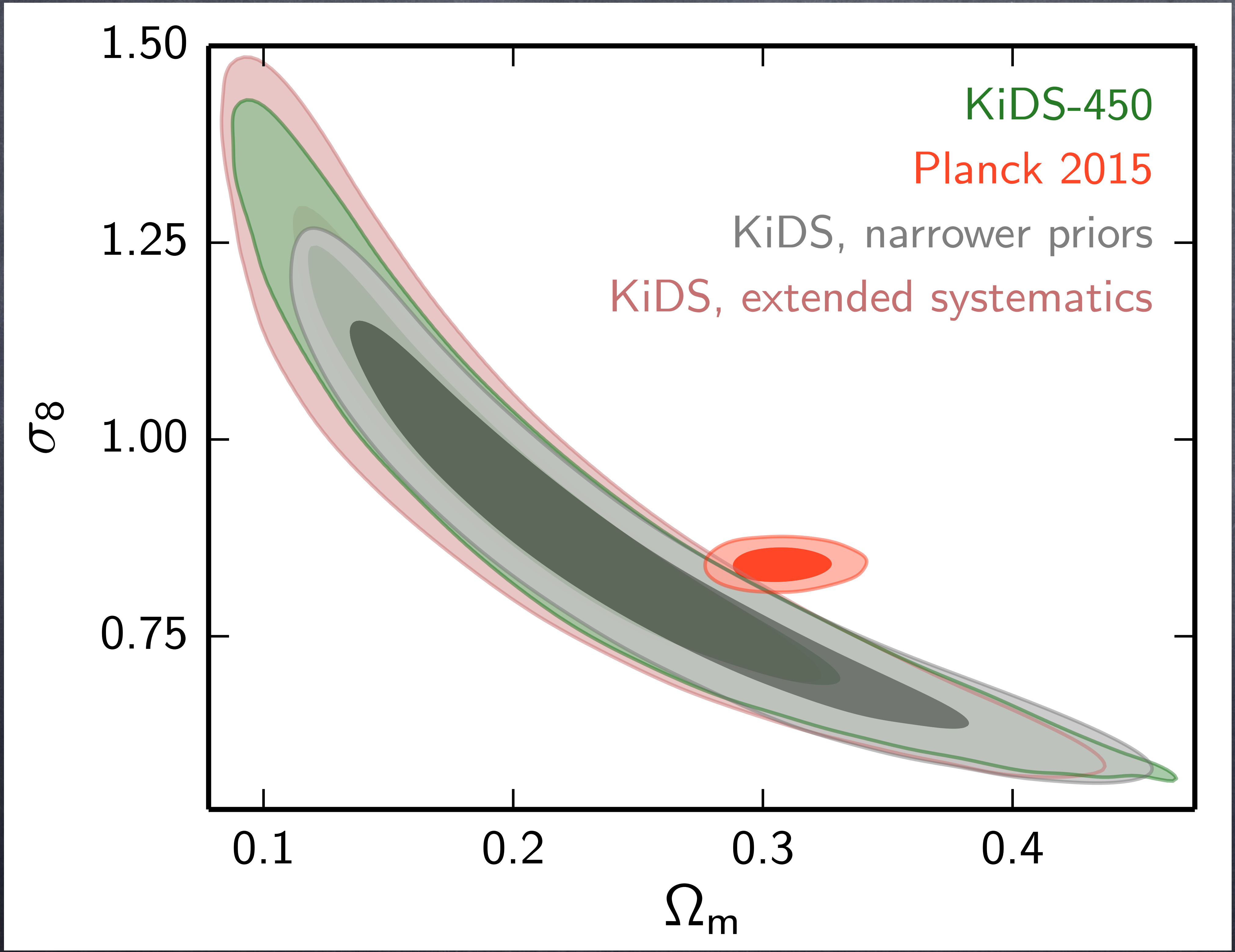
Likelihood Analysis

reduced data and catalogs

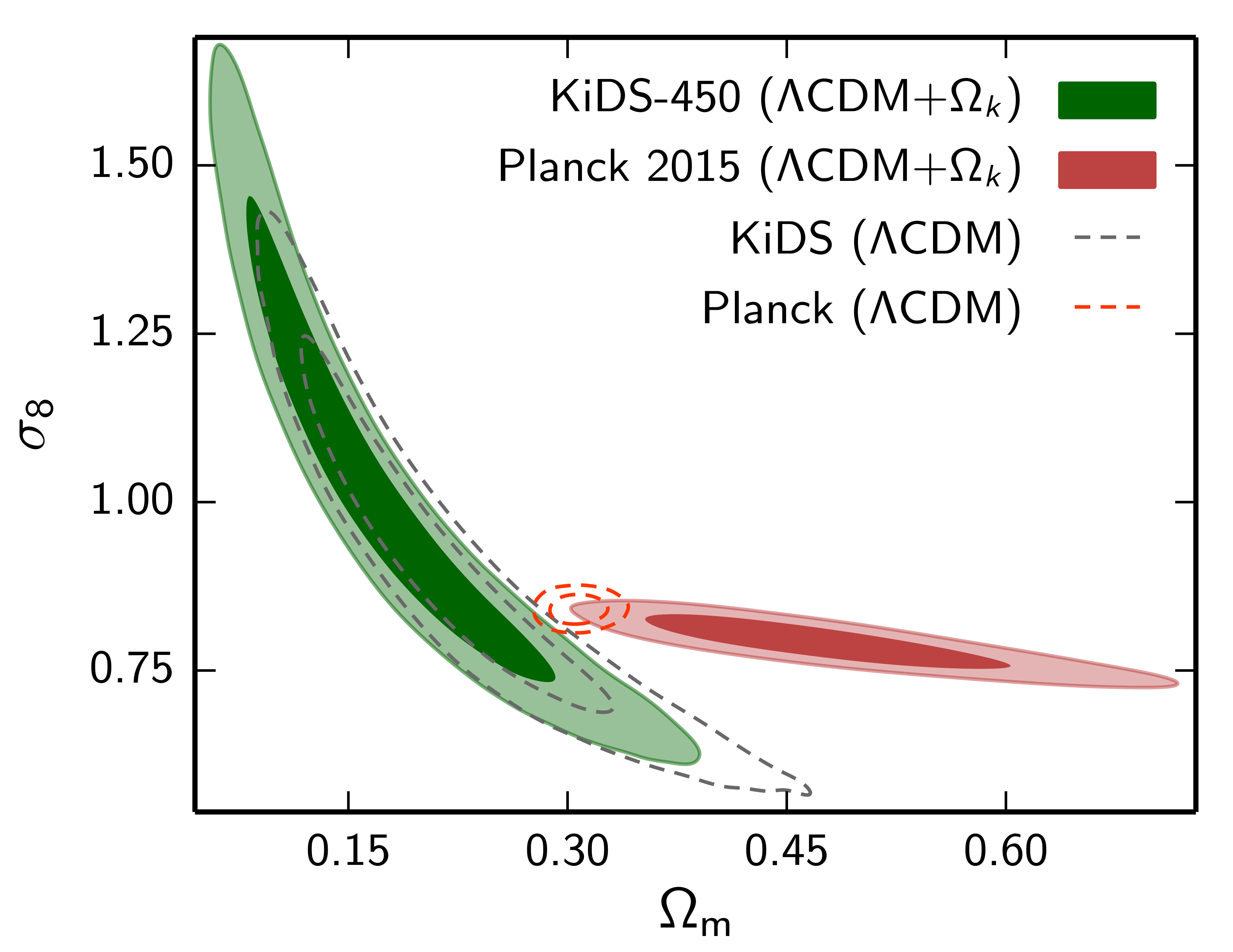




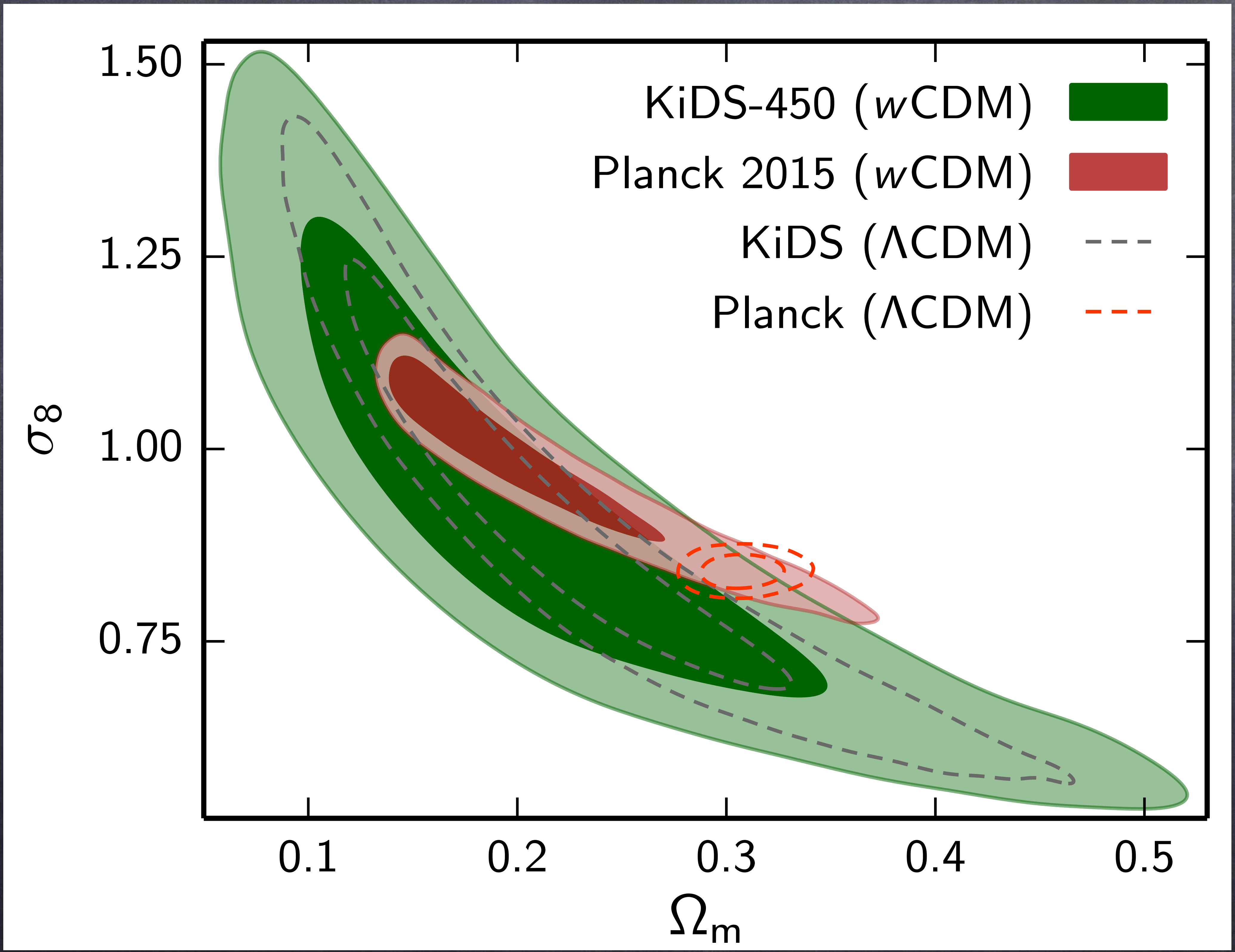
Example: Kilo Degree Survey Joudaki et al 2016

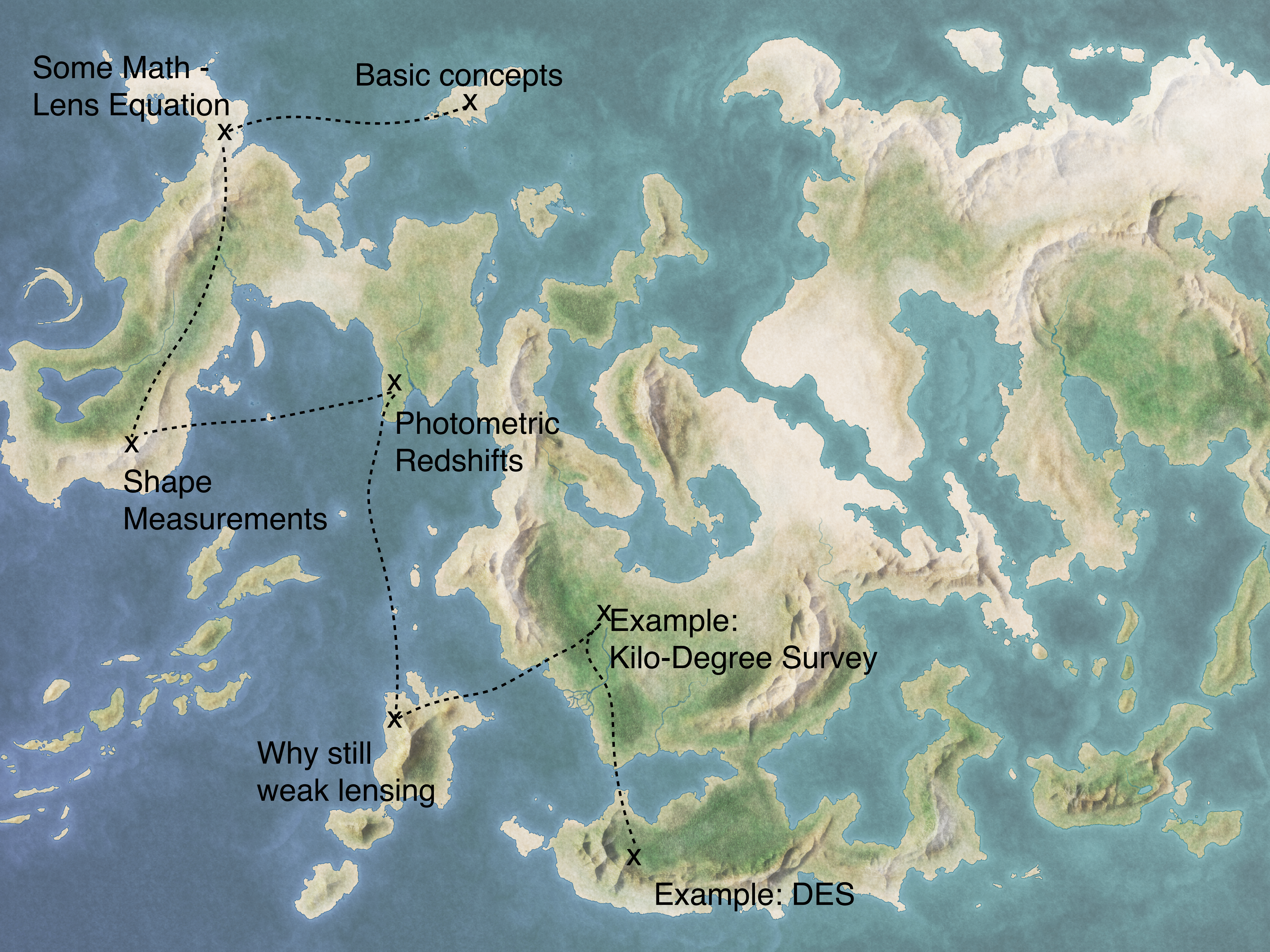


Example: Kilo Degree Survey



Example: Kilo Degree Survey

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Example: DES

Existing and future WL++ data sets

(extended) Baryon Oscillation Spectroscopic Survey (eBOSS)

Kilo-Degree Survey (KIDS)

HSC

DARK ENERGY SURVEY

Prime Focus Spectrograph (PFS)

Dark Energy Spectroscopic Instrument (DESI)

SUPER BIT

WFIRST Wide Field Infrared Survey Telescope

LSST Large Synoptic Survey Telescope

euclid

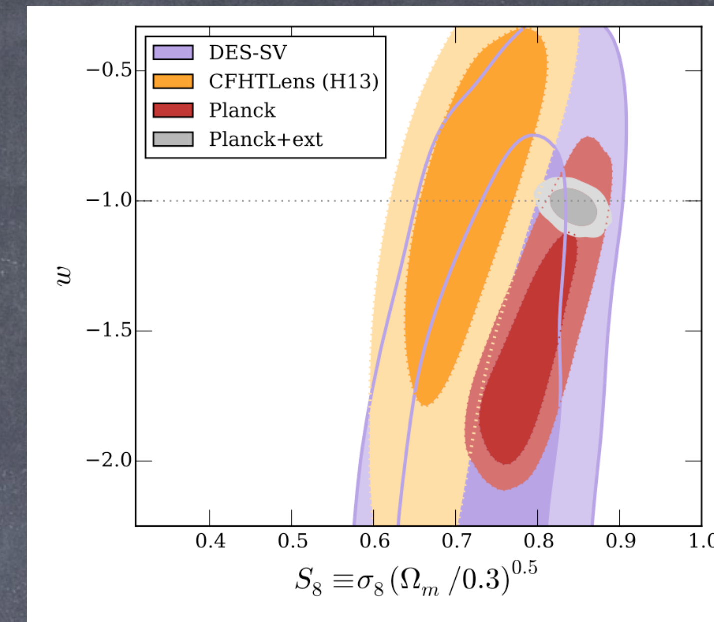
Now

Near Future

Future

Likelihood Analysis

reduced data and catalogs



1) Independent probes
CMB, SN1a as priors

2) Large model vector
Self-consistent modeling of all observables as a function of
1) cosmological parameters (~10)
2) nuisance parameters (XXX)

large data vector

posterior probability

$$p\left(\boldsymbol{\pi}|\hat{\mathbf{d}}\right) \propto p\left(\boldsymbol{\pi}\right)\mathcal{L}\left(\hat{\mathbf{d}}|\mathbf{m}\left(\boldsymbol{\pi}\right), \boldsymbol{C}\right)$$

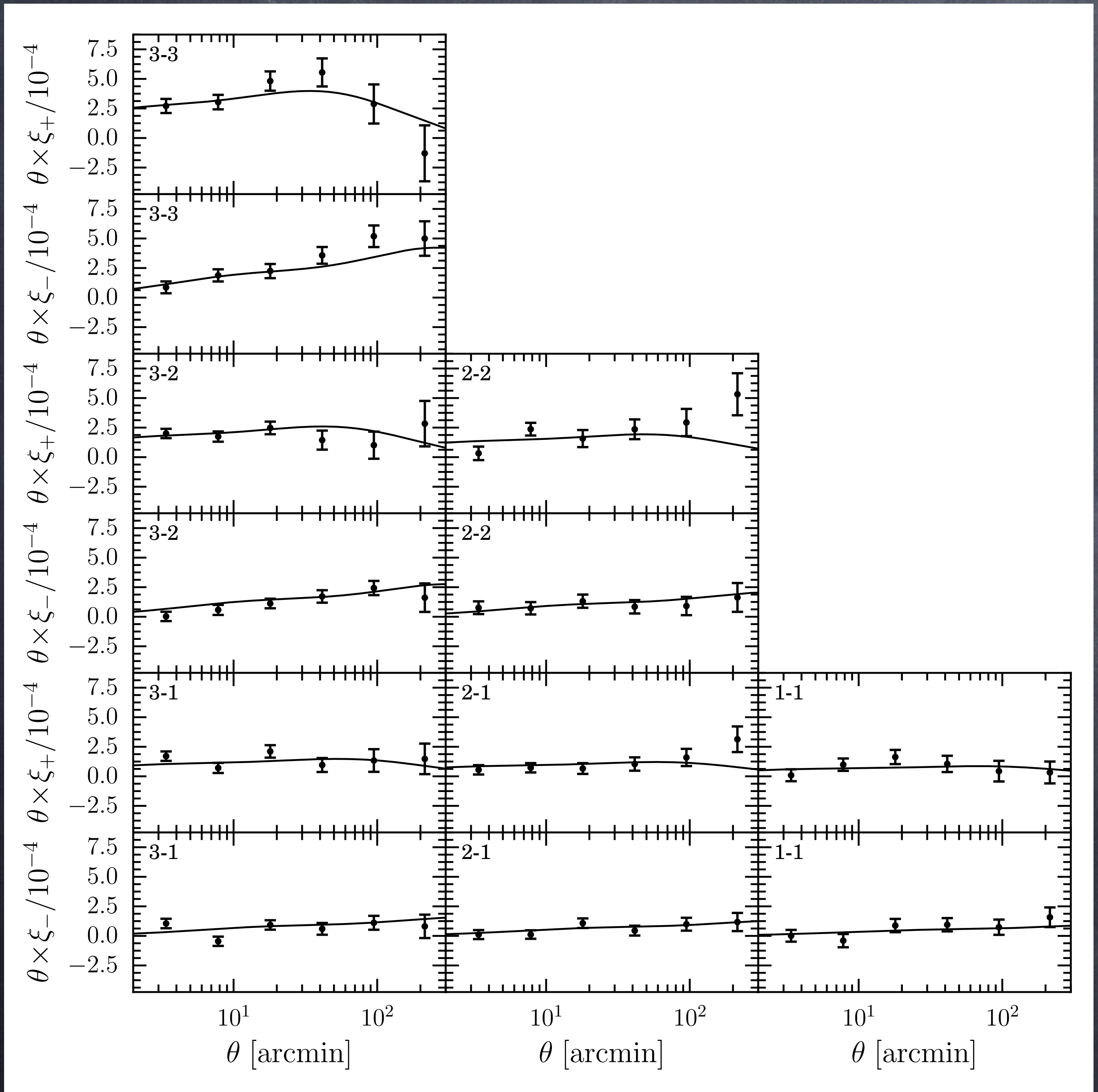
3) Enhanced modeling via
- Observations
- Simulations
- Theory

4) Statistics I - Likelihood function
- Multivariate Gaussian vs other parameterizations
- Non-parametric forms

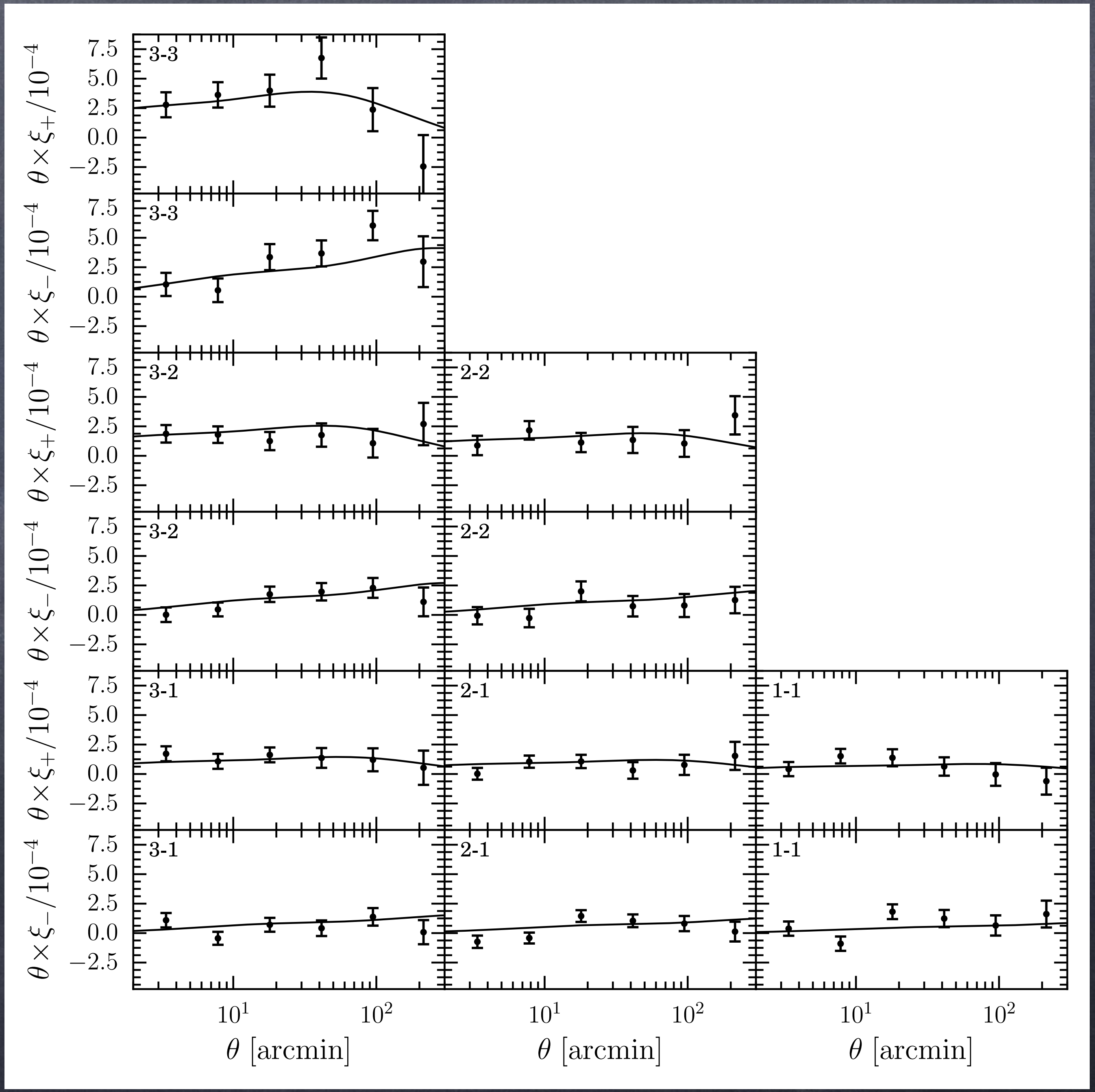
4) Statistics II - Covariances
- large and complicated, non-(block) diagonal
- different methods for derivation

DES - Tomography

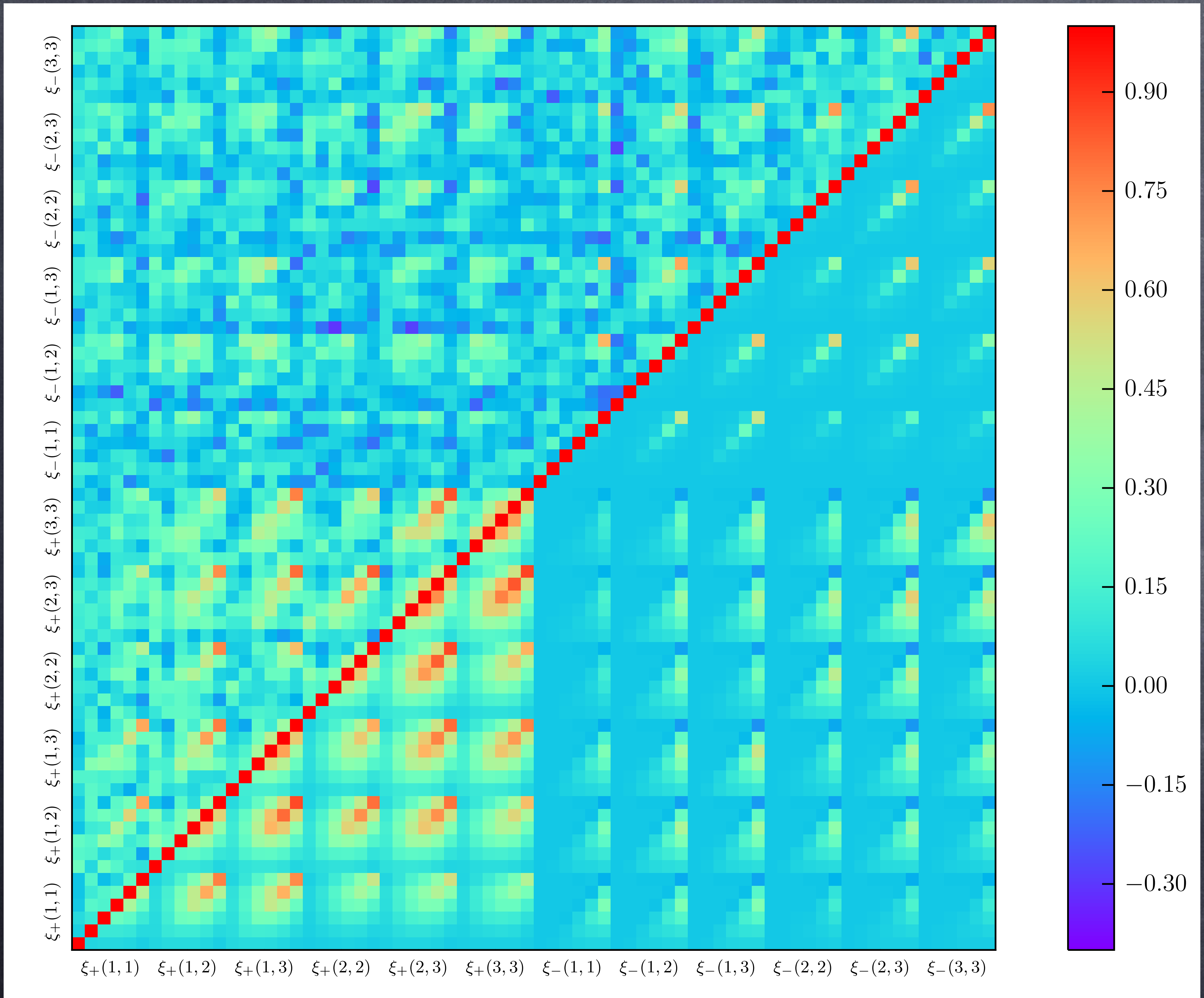
ngmix



im3shape



DES Covariances



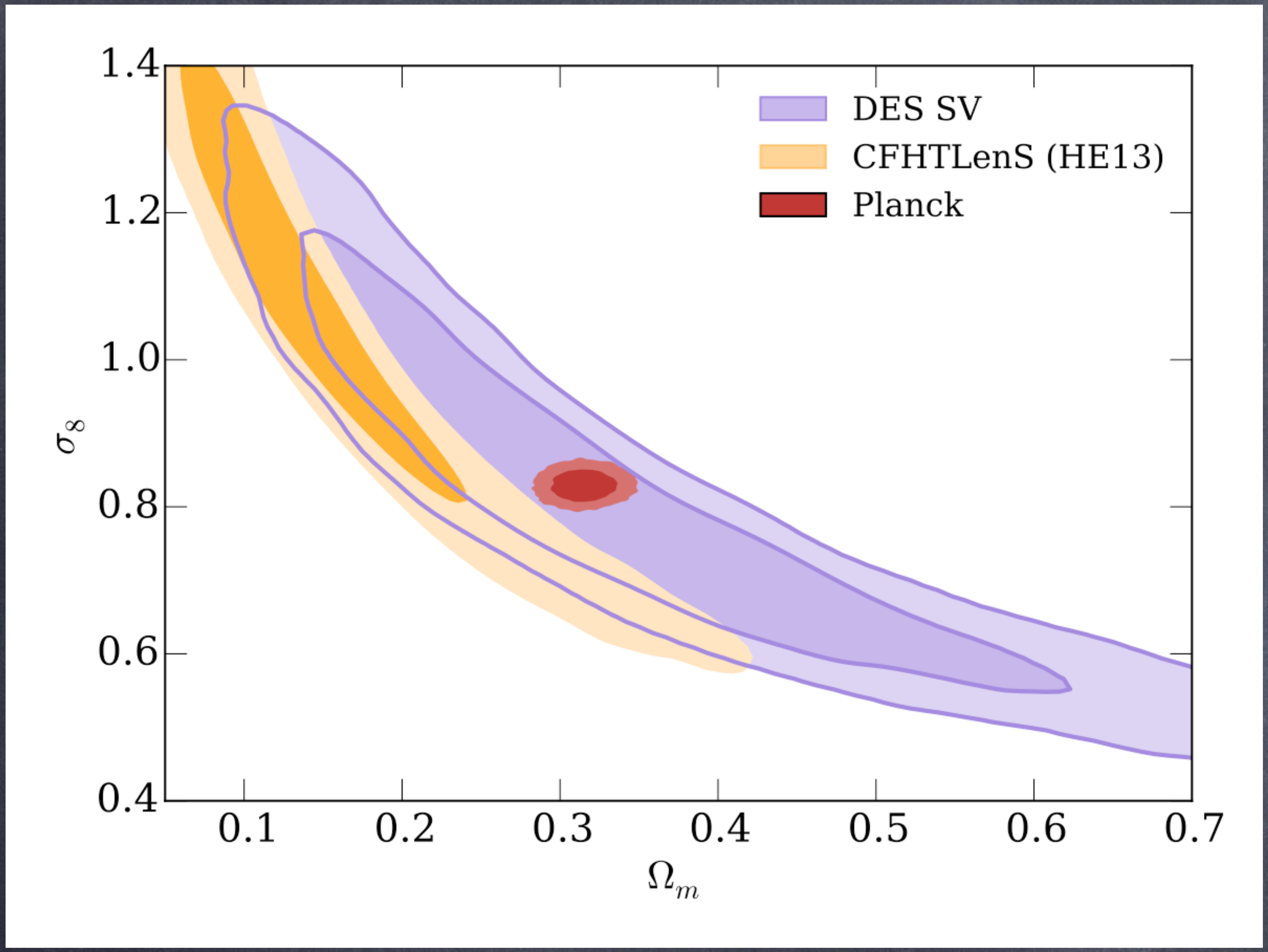
2 Methods:

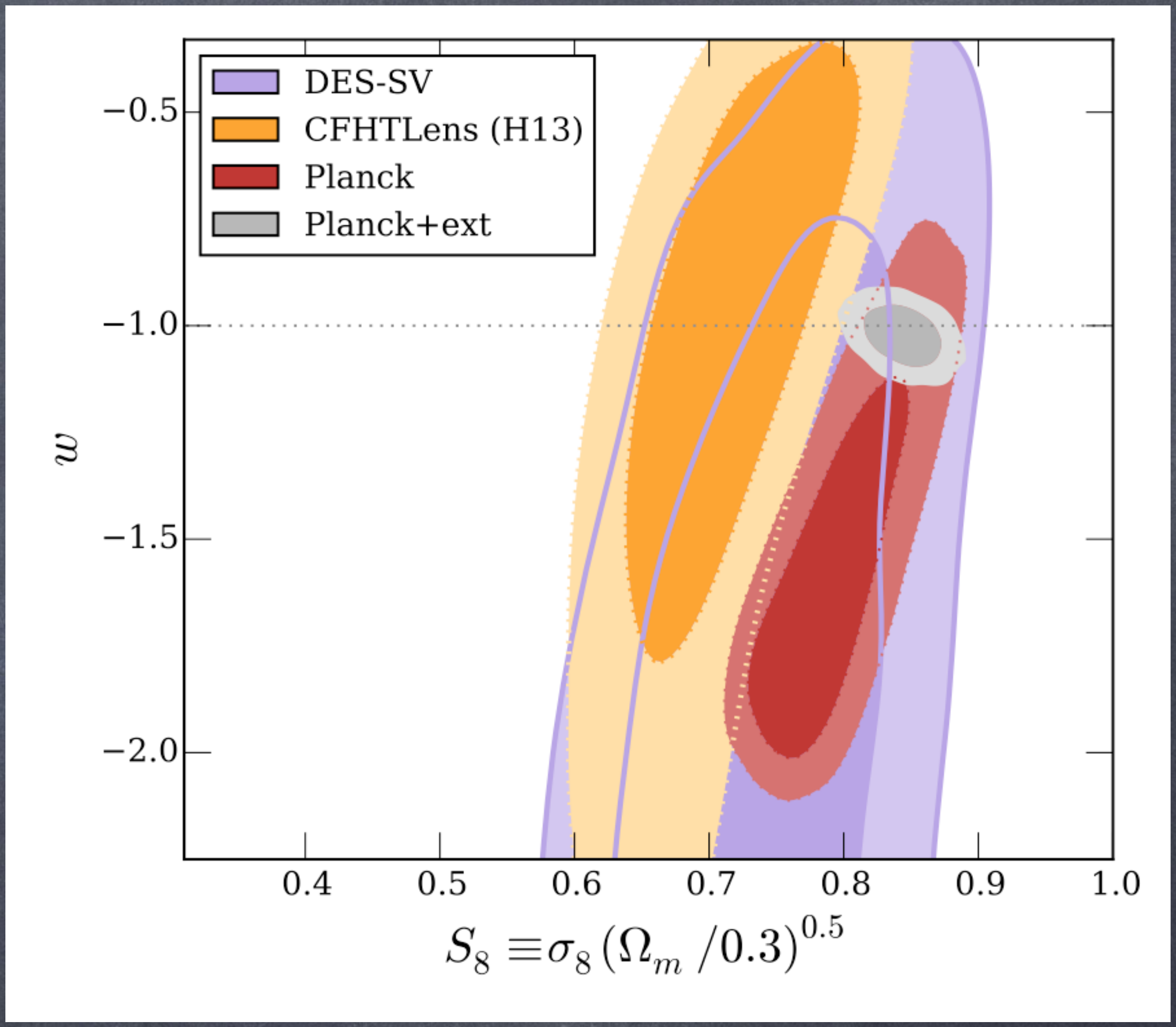
- Numerical simulations 126 Realizations of the exact SV area
- Analytical Halo Model

- Both include higher order moments of the density field

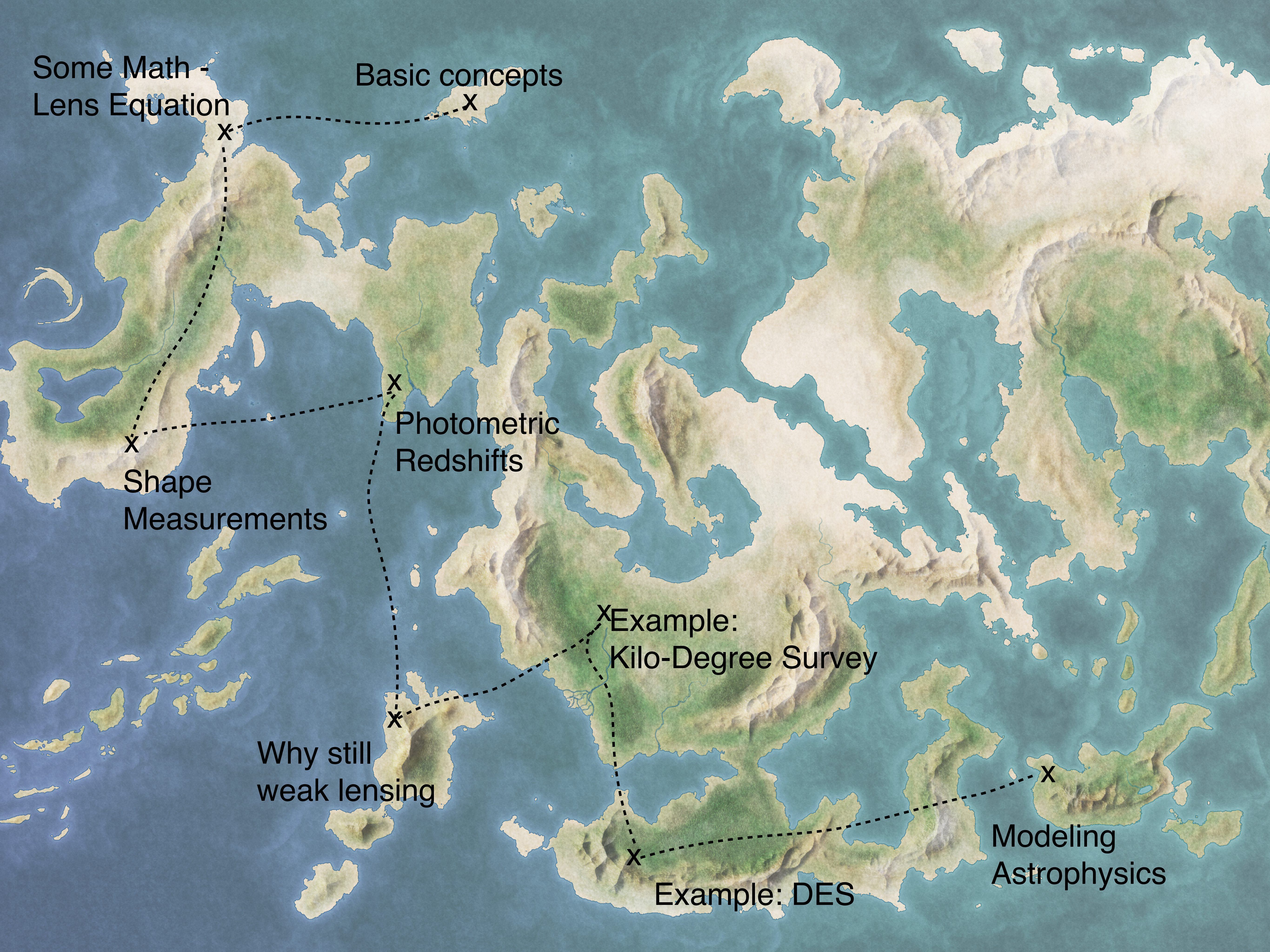
- Numerical sims are noisier, substantially more expensive, and limit size of the data vector, but should be more precise in the highly nonlinear regime (depends on simulations/ray-tracing resolution, etc)

DES Early Results





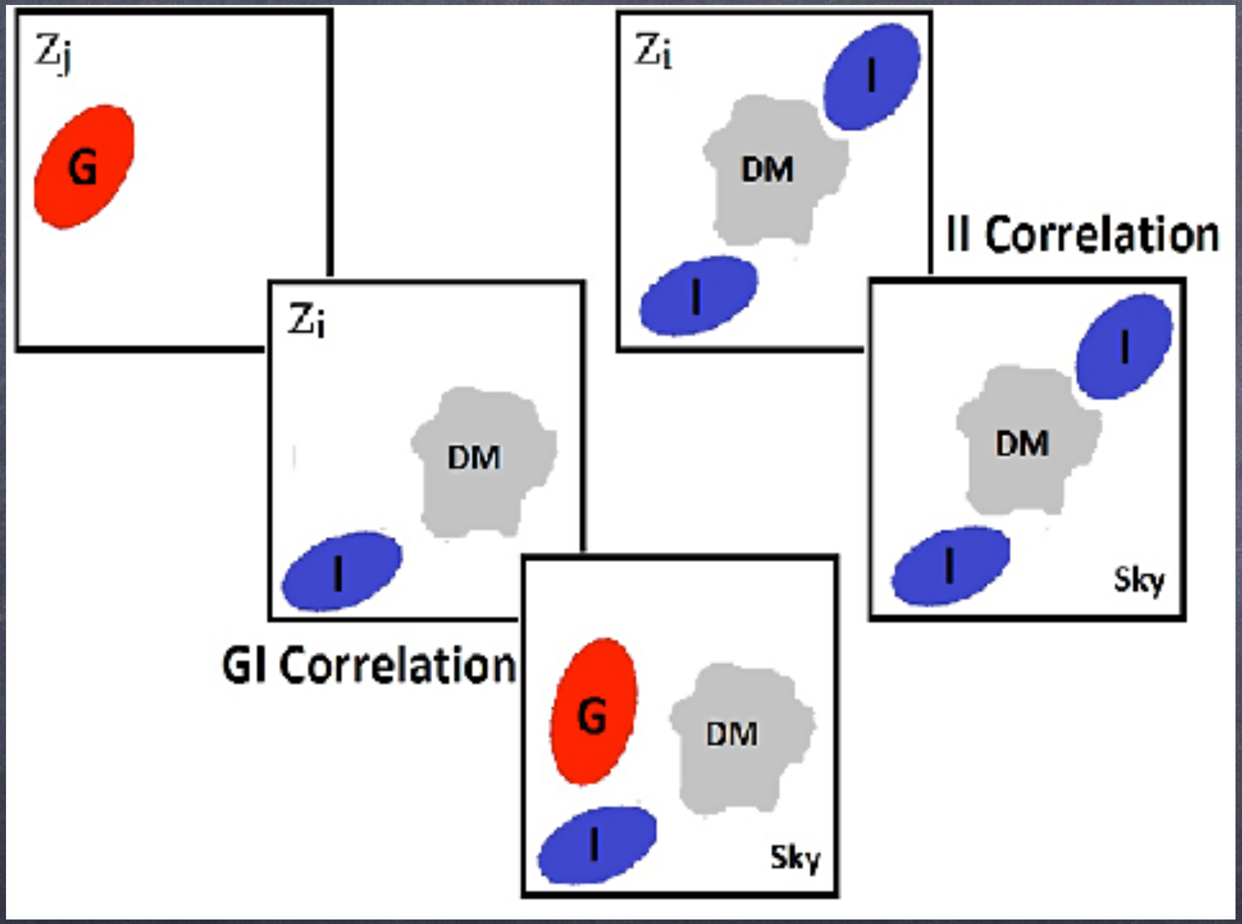
- This was for 150 deg^2
- Coming Months will reveal the 1300 deg^2 analysis



Some Math -
Lens Equation
Basic concepts
Photometric
Redshifts
Shape
Measurements
Example:
Kilo-Degree Survey
Why still
weak lensing
Modeling
Astrophysics
Example: DES

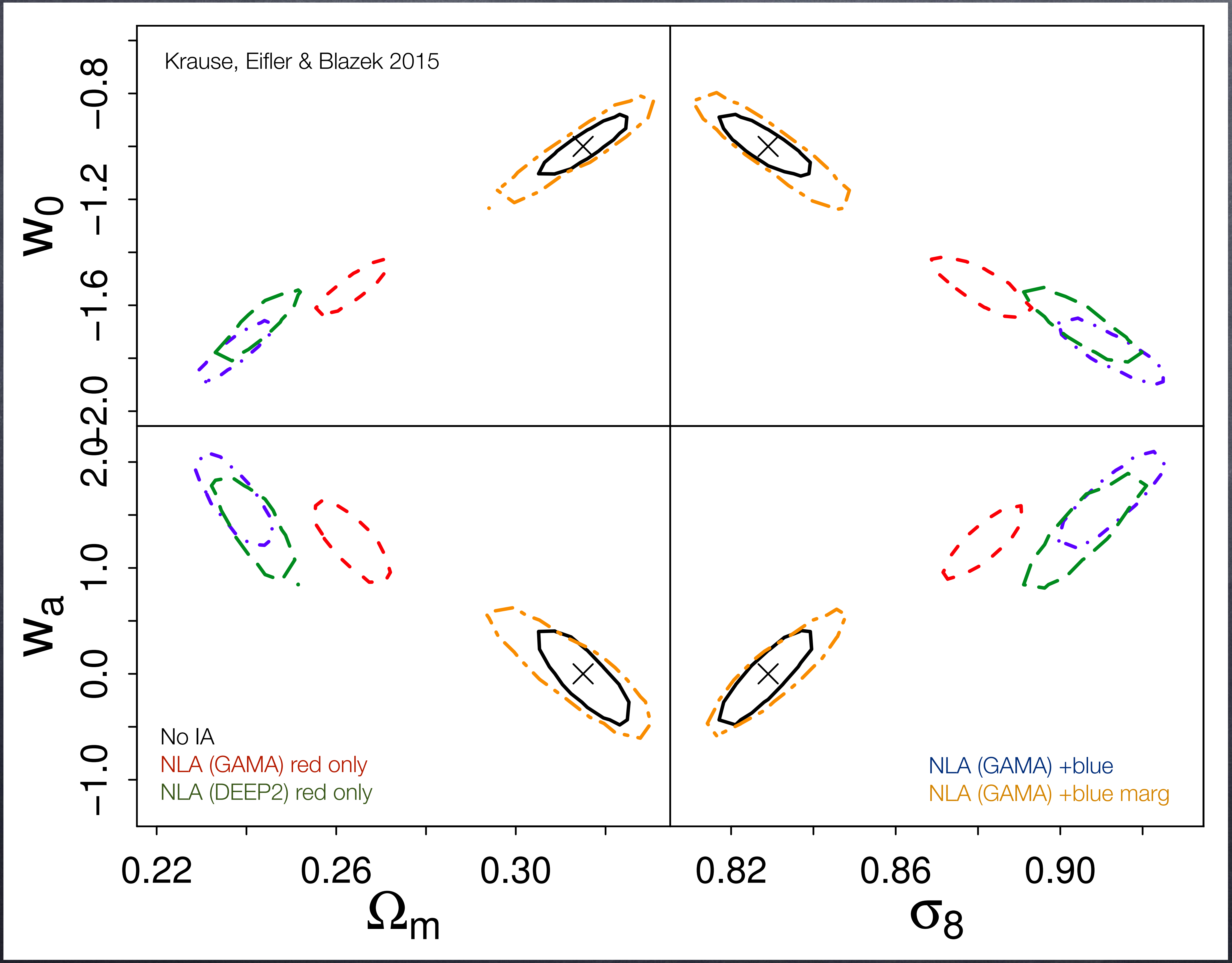
Astrophysics 1: Intrinsic Alignments

- not all (source) galaxies randomly oriented - e.g. tidal alignments

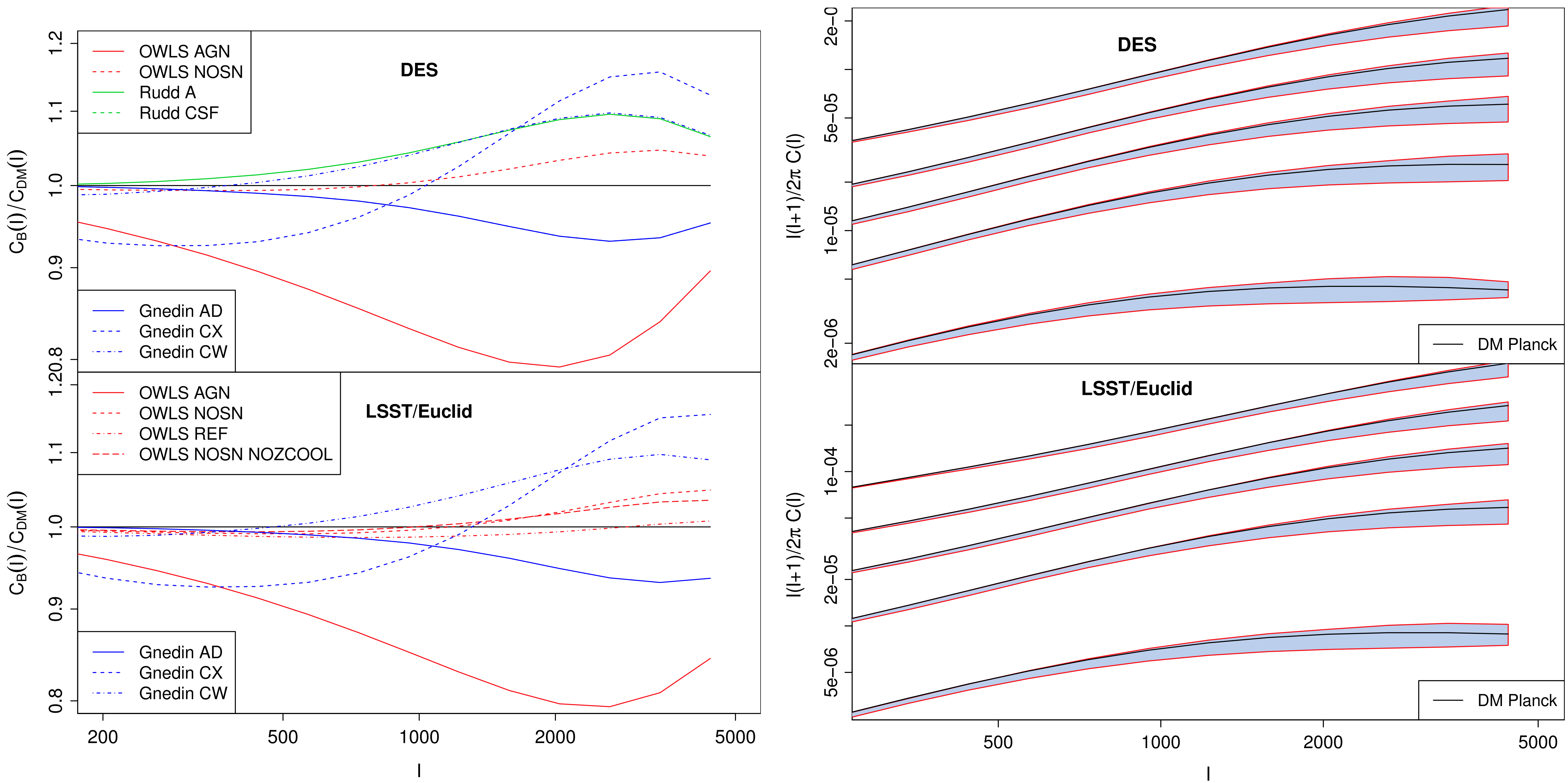


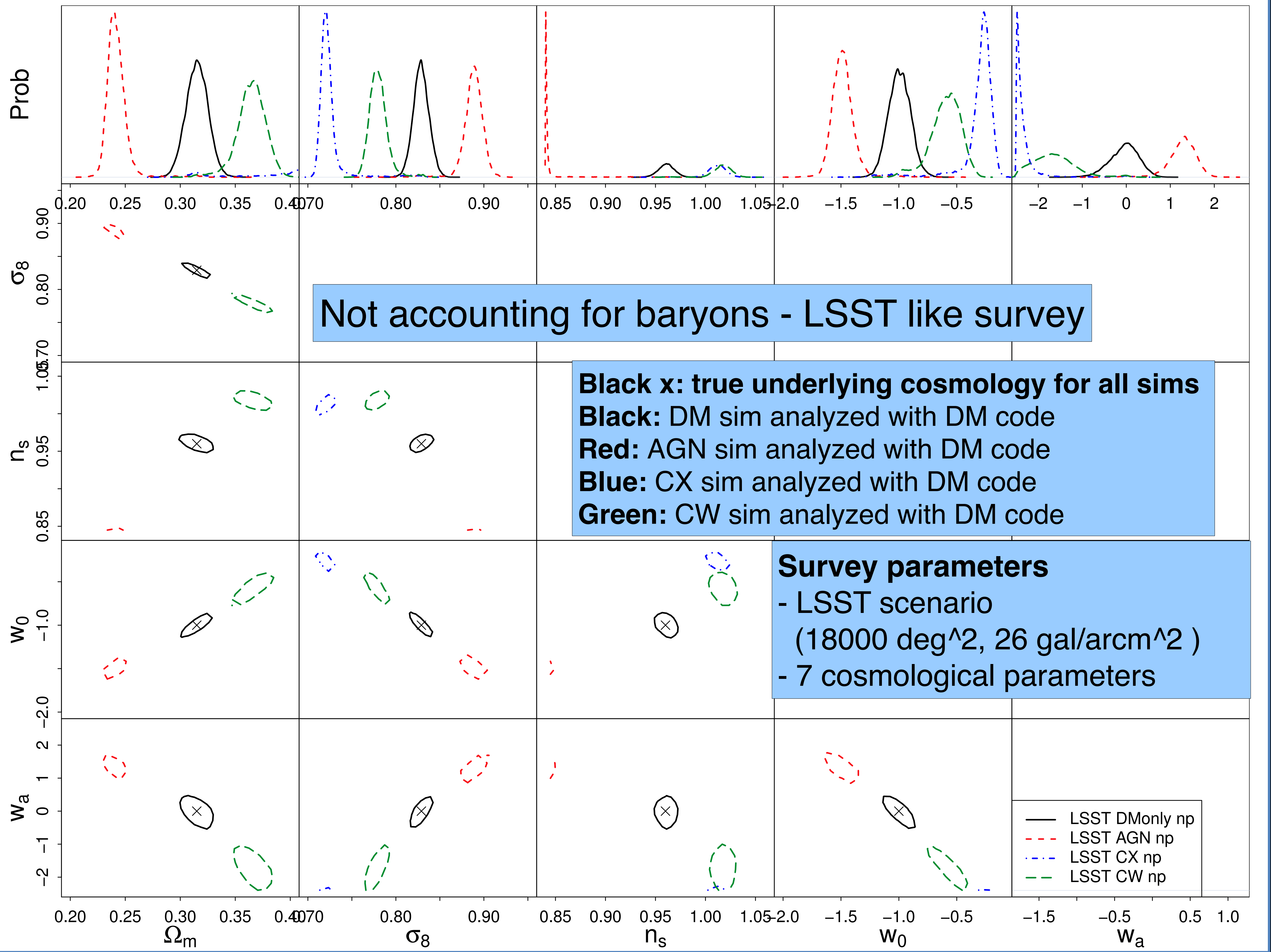
- potentially scary systematic

Intrinsic Alignments - Mitigation



Astrophysics 2: Baryons - feedback/cooling





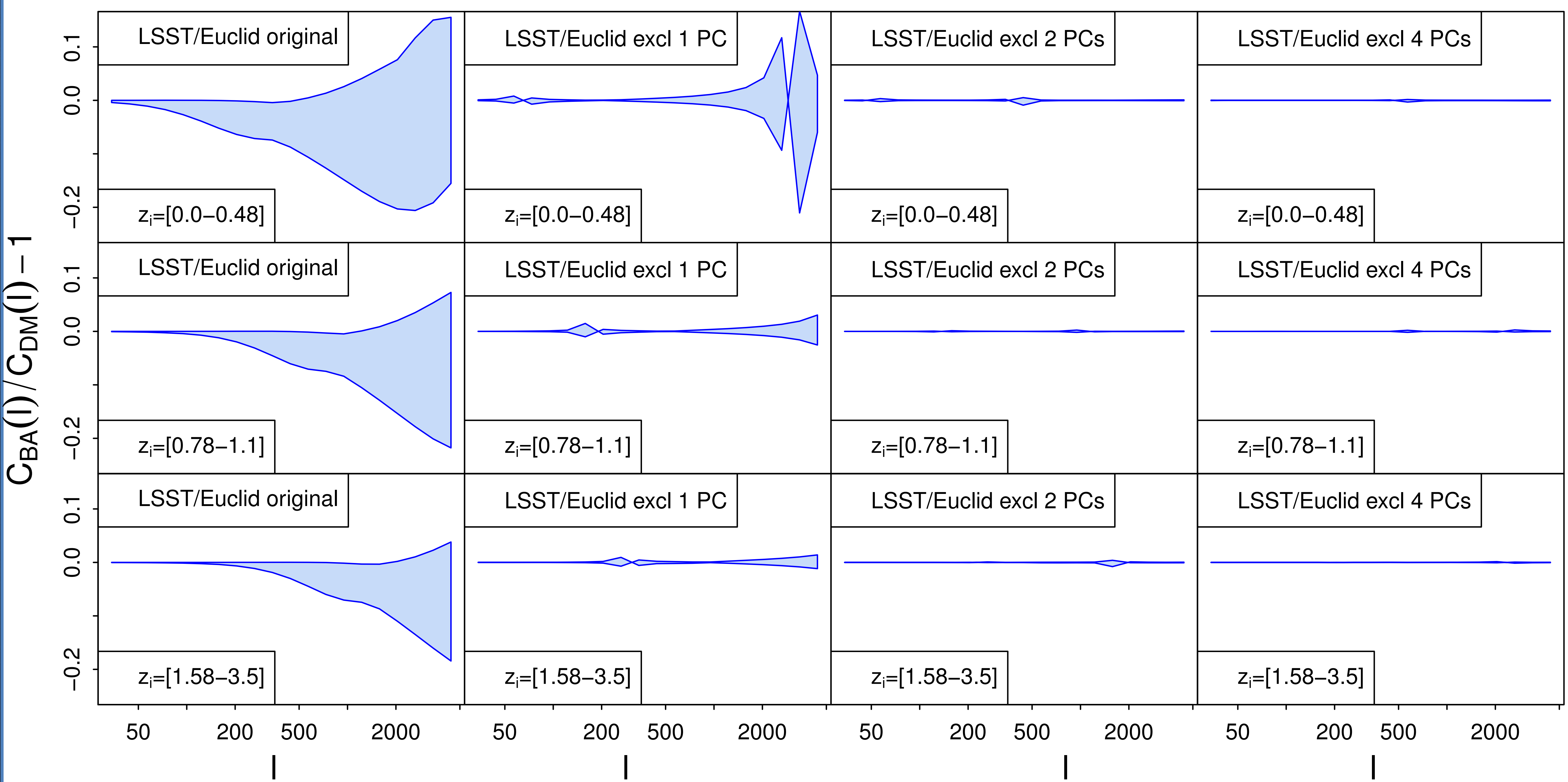
Not accounting for baryons - LSST like survey

Black x: true underlying cosmology for all sims
Black: DM sim analyzed with DM code
Red: AGN sim analyzed with DM code
Blue: CX sim analyzed with DM code
Green: CW sim analyzed with DM code

Survey parameters
- LSST scenario
  (18000 deg^2, 26 gal/arcm^2)
- 7 cosmological parameters

PCA-marginalization/Mode removal

2) Transform C(l) to PC space -> remove contaminated modes -> transform back to C(l)



PCA-marginalization/Mode removal

1) At each point in cosmology define set

$$\mathbf{M}_j(\mathbf{p}_{\mathrm{nu}}) \,\epsilon\, \left\{\mathbf{M}(\mathbf{p}_{\mathrm{nu}}|\mathbf{p}_{\mathrm{co}})\right\}$$

2) Calculate differences to DM → create matrix

$$\Delta_{ij} = M_{ij} - M_i^{\mathrm{DM}}$$

3) SVD on difference matrix → cols of U contain PCs

$$\mathbf{\Delta} = \mathbf{U\Sigma V}^t$$

4) Perform likelihood calculation in PC space

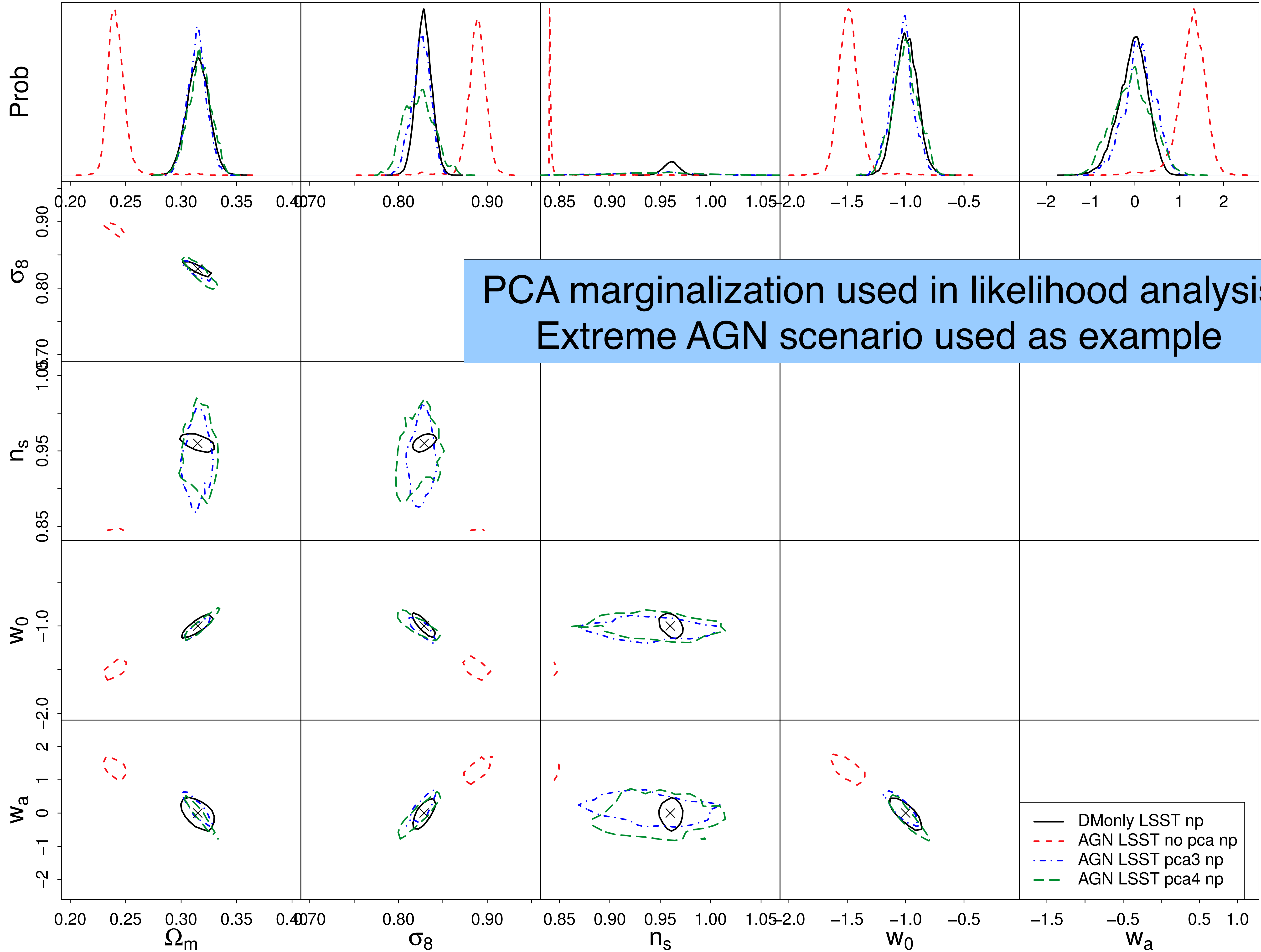
$$\chi^2(\mathbf{p}_{\mathrm{co}}, \mathbf{p}_{\mathrm{nu}}) = (\mathbf{D} - \mathbf{M})^t\mathbf{U}\mathbf{U}^t\mathbf{C}^{-1}\mathbf{U}\mathbf{U}^t(\mathbf{D} - \mathbf{M})$$

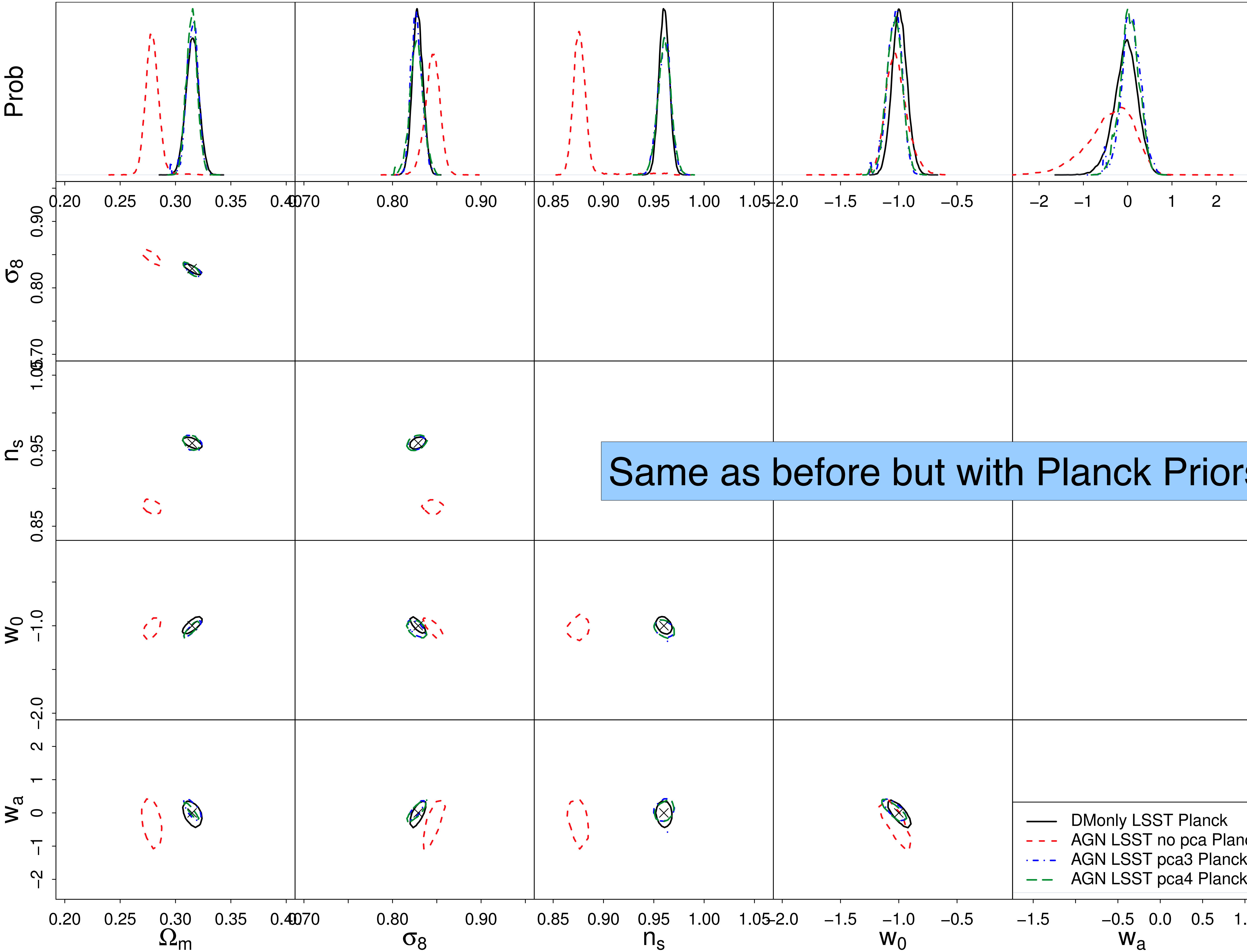
$$\mathbb{1} = \mathbf{U}\mathbf{U}^t$$

5) Project out the baryon sensitive PCs

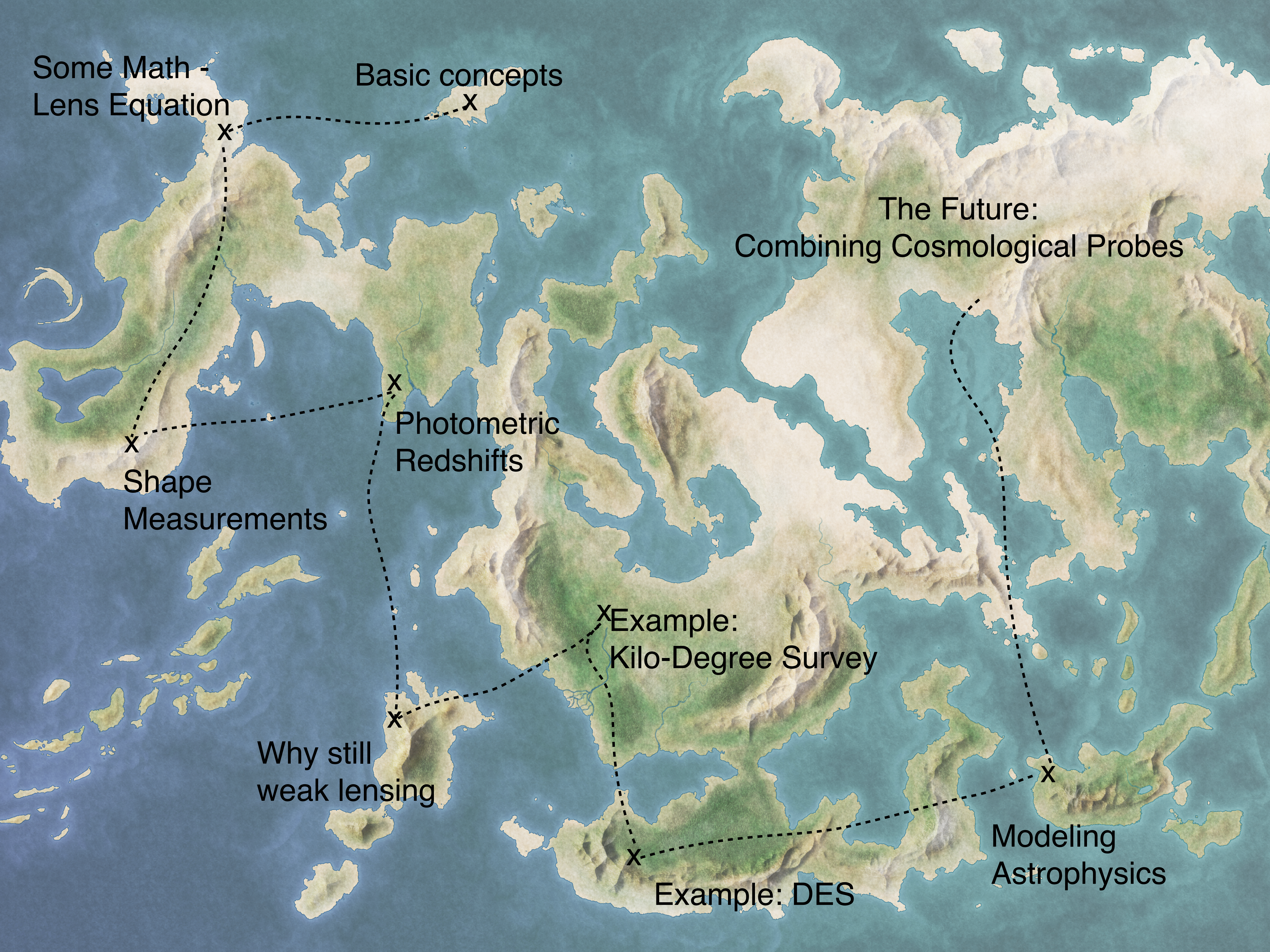
$$\chi^2(\mathbf{p}_{\mathrm{co}}, \mathbf{p}_{\mathrm{nu}}) = (\mathbf{P}\mathbf{U}^t\mathbf{D} - \mathbf{P}\mathbf{U}^t\mathbf{M})^t(\mathbf{P}\mathbf{U}^t\mathbf{C}\mathbf{U}\mathbf{P})^{-1}(\mathbf{P}\mathbf{U}^t\mathbf{D} - \mathbf{P}\mathbf{U}^t\mathbf{M})$$

PCA marginalization used in likelihood analysis
Extreme AGN scenario used as example





Same as before but with Planck Priors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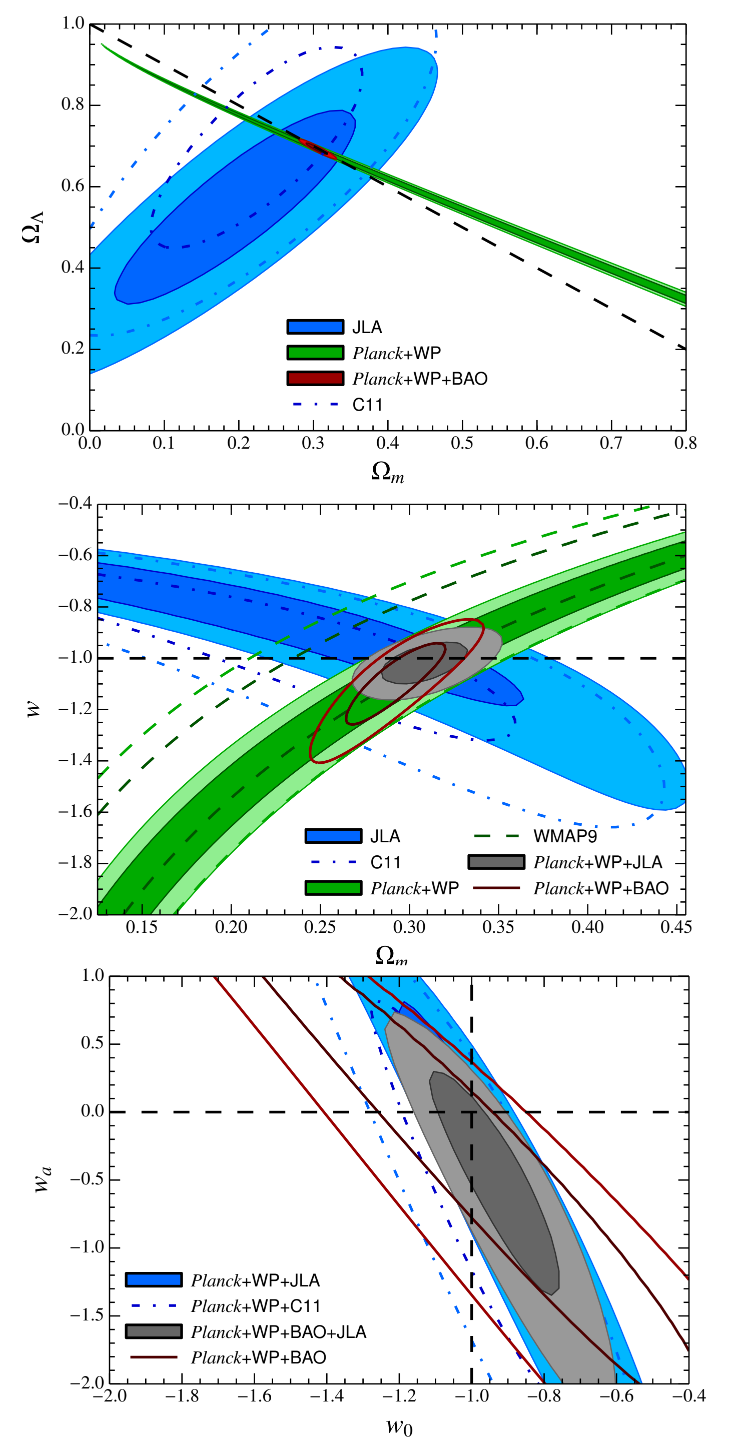
The Power of Combining Probes

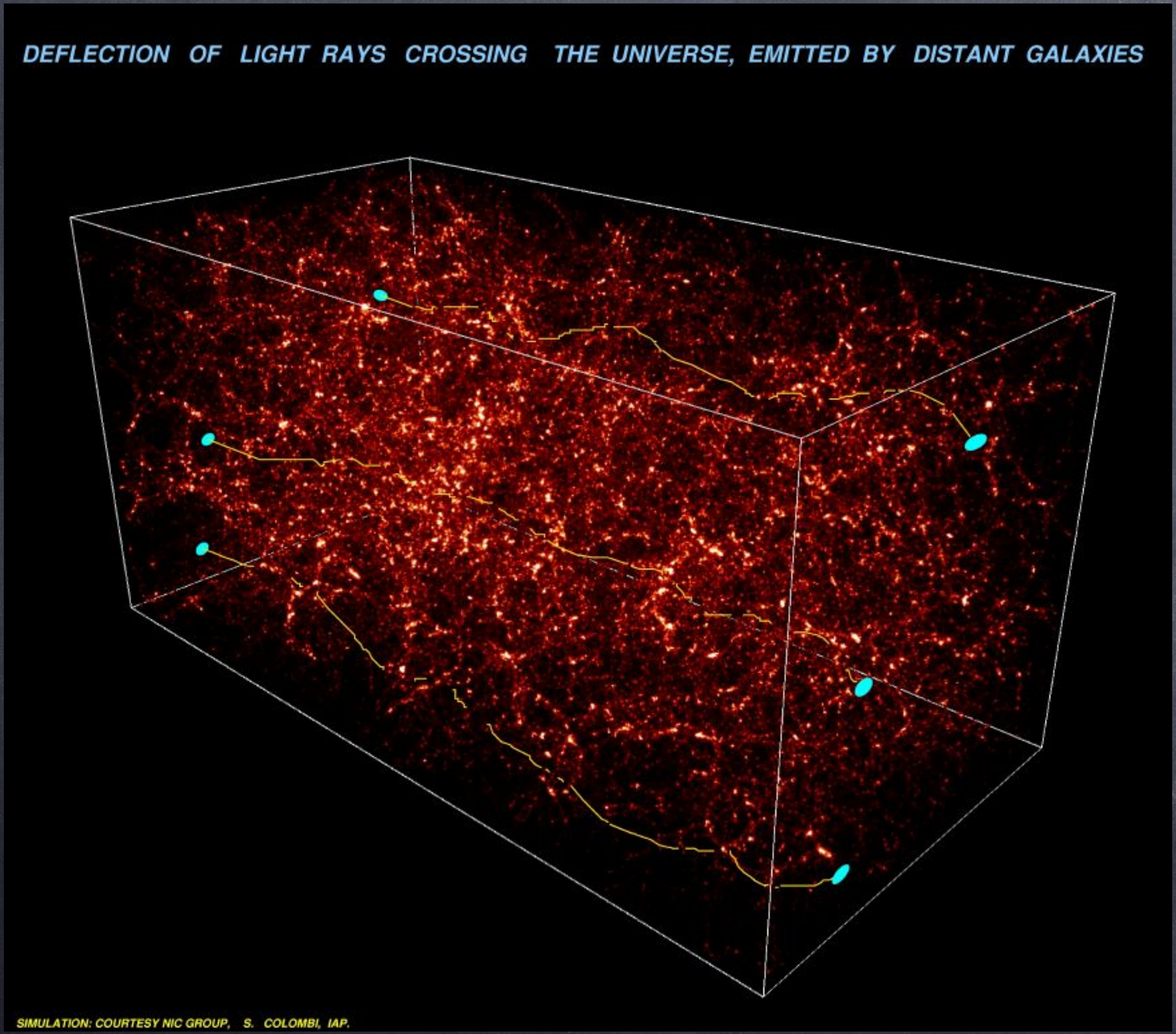
- Best constraints obtained by combining cosmological probes
  - independent probes: multiply likelihoods (if individual results are consistent)
- Combining Large-Scale Structure (LSS) probes (from same survey) requires more advanced strategies
  - clustering, clusters and WL probe same underlying density field, are



Betoule et al. 2014

Takeaway: We want multi-probe/ survey analyses for LSS probes

Already discussed Weak Lensing



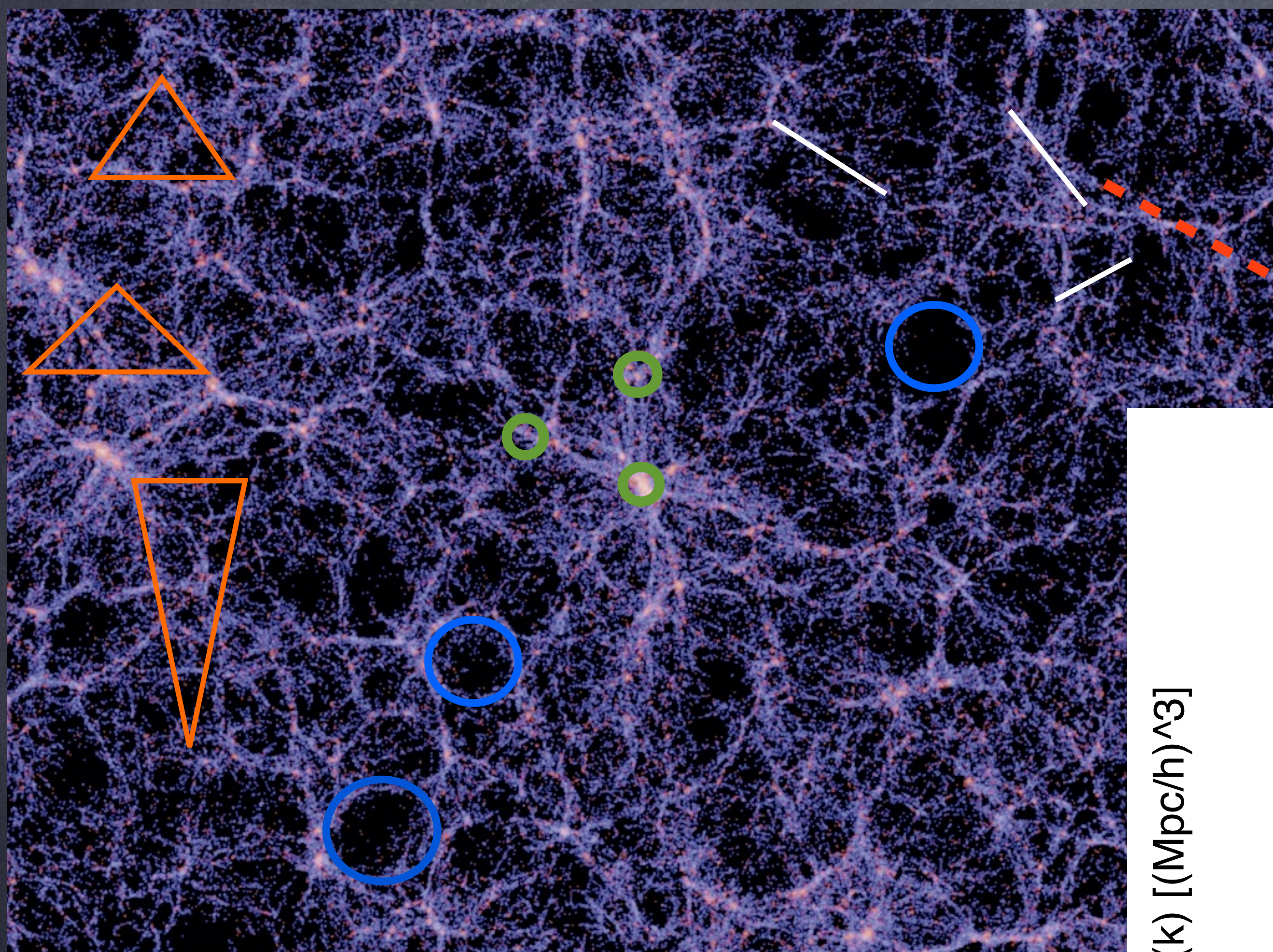
Light rays are distorted by dark matter density field of the Universe

Statistical properties of the distortion reflect statistical properties of the density field

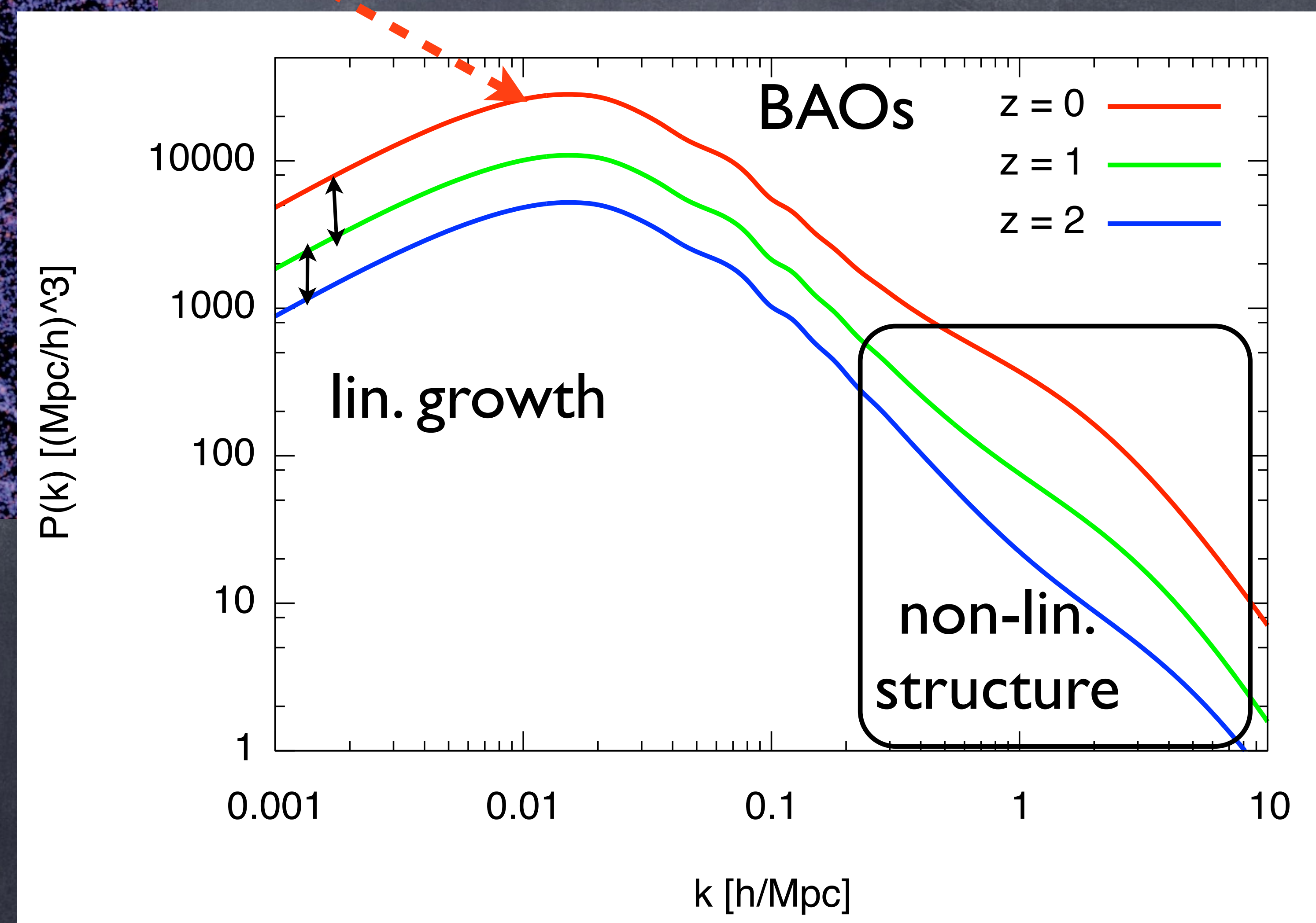
Sir Ernest Rutherford:
"If your experiment needs statistics, you ought to have done a better experiment"

Cosmology through Structure

More information compared to expansion history



need redshift, understand galaxy bias



clusters (over densities),

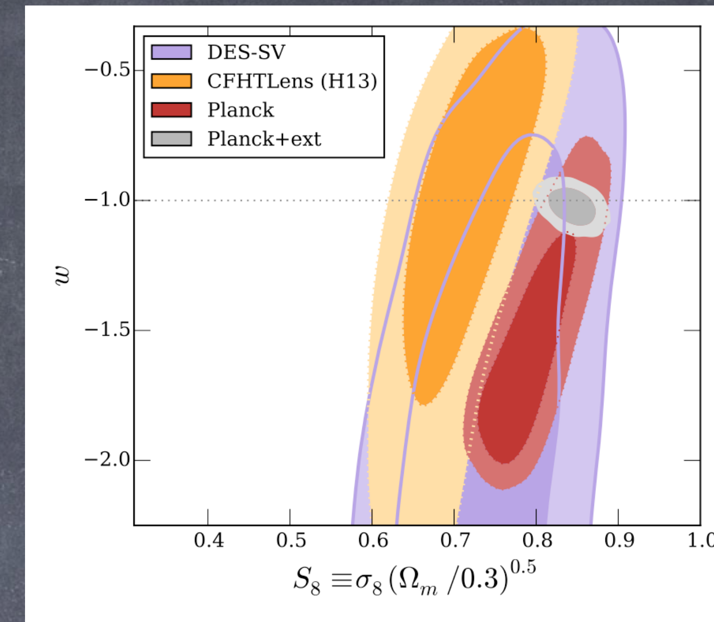
voids (under densities)

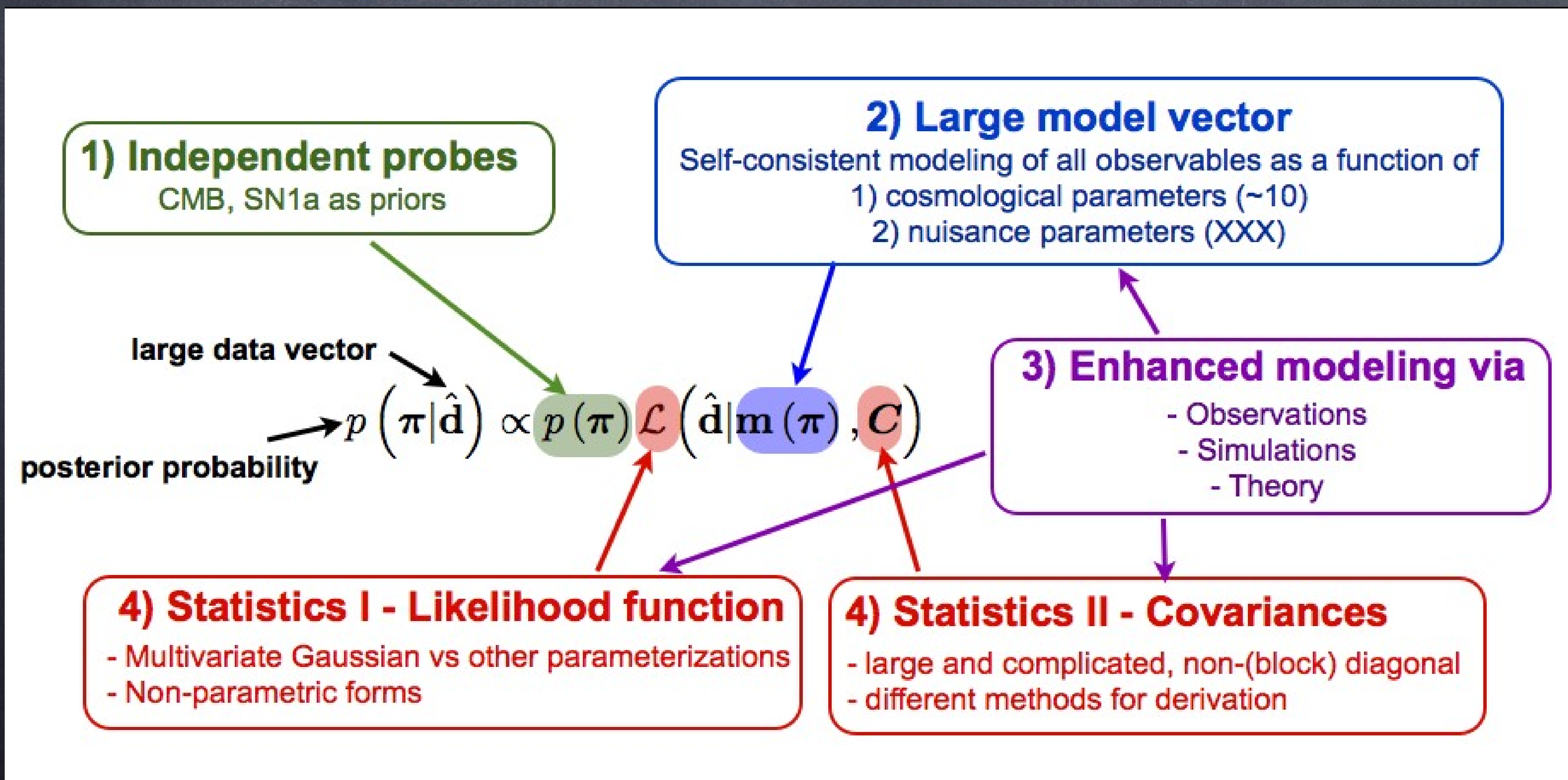
two-point correlations

three-point correlations,...

Likelihood Analysis

reduced data and catalogs





Example Data Vector and

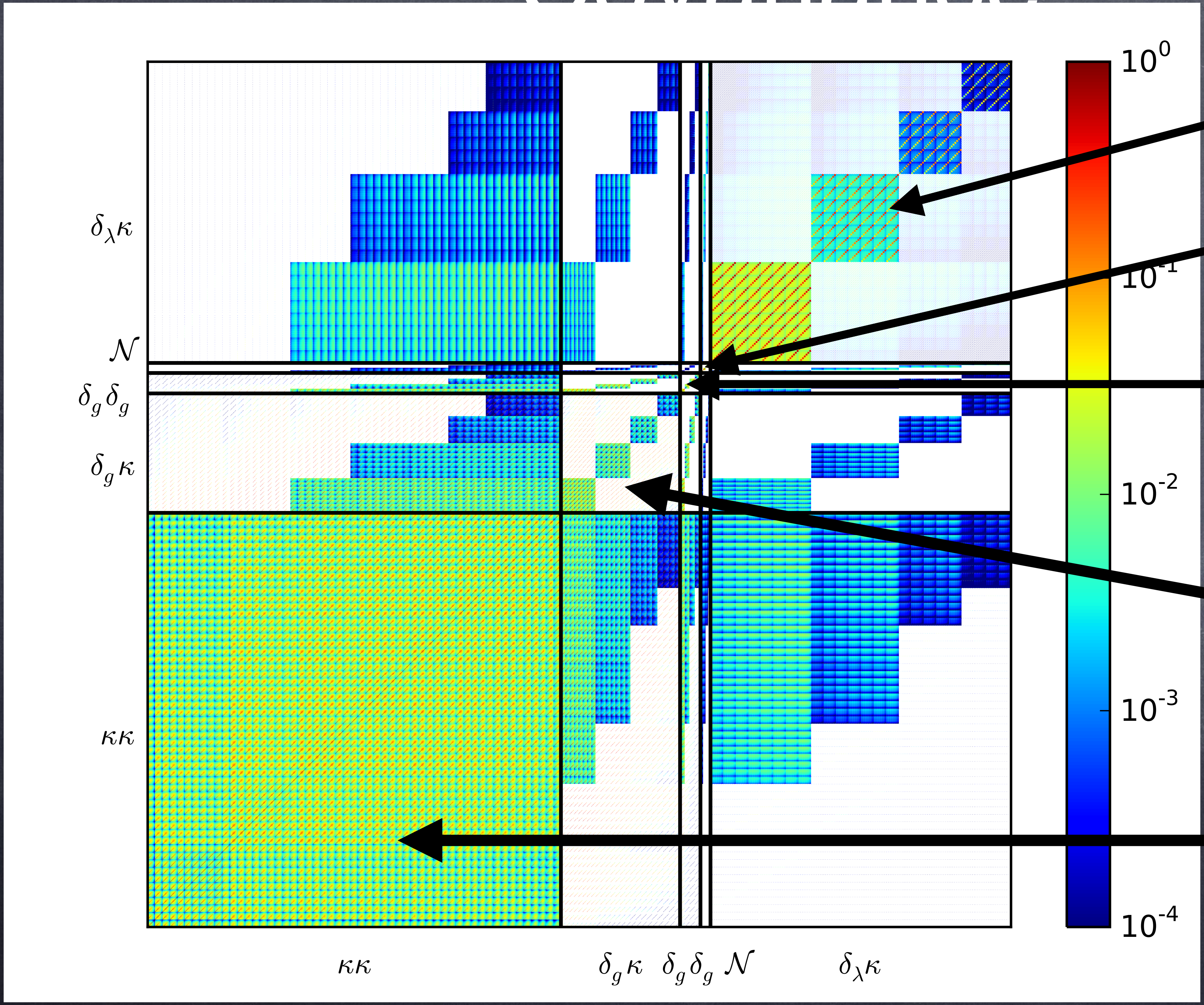
- Weak Lensing (cosmic shear)
  - 10 tomography bins
  - 25 l bins, 25 < l < 5000
- Galaxy clustering
  - 4 redshift bins (0.2-0.4,0.4-0.6,0.6-0.8,0.8-1.0)
  - compare two samples: σ_z <0.04, redMaGiC
  - linear + quadratic bias only : l bins restricted to R> 10 Mpc/h
  - HOD modeling going to R>0.1 MPC/h
- Galaxy-galaxy lensing
  - galaxies from clustering (as lenses) with shear sources
- Clusters - number counts + shear profile
  - so far, 8 richness, 4 z-bins (same as clustering)
  - tomographic cluster lensing (500 < l < 10000)

shear calibration,
photo-z (sources)
IA, baryons

b_1, b_2,...
photo-z (lenses)

N-M relation
c-M relation
off-centering

Multi-Probes Forecasts: Covariance



Cluster Lensing

Clusters

Galaxy Clustering

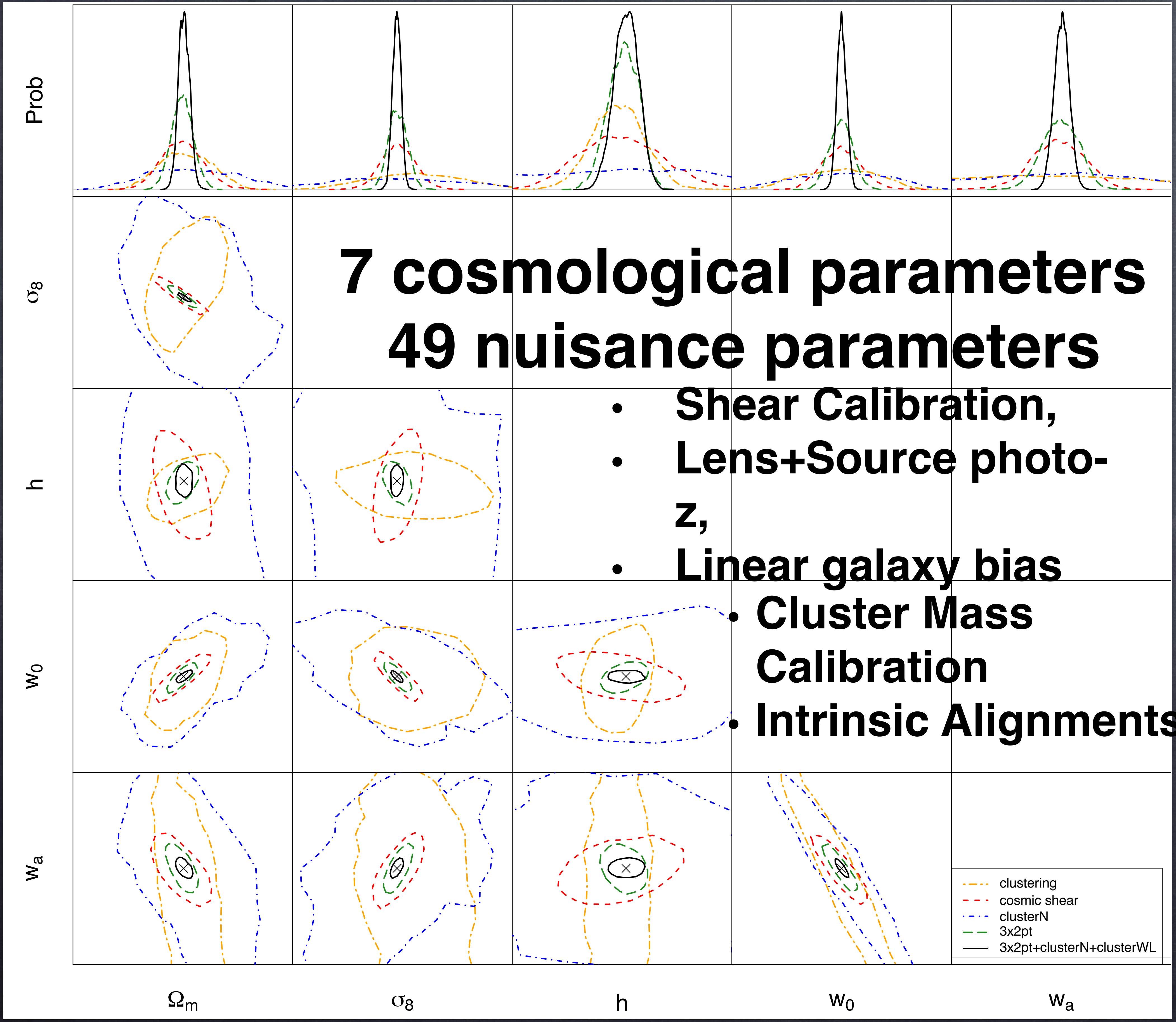
Galaxy-Galaxy Lensing

Cosmic Shear

7+ million elements

details: Krause&Eifler '16

The Power of Combining Probes

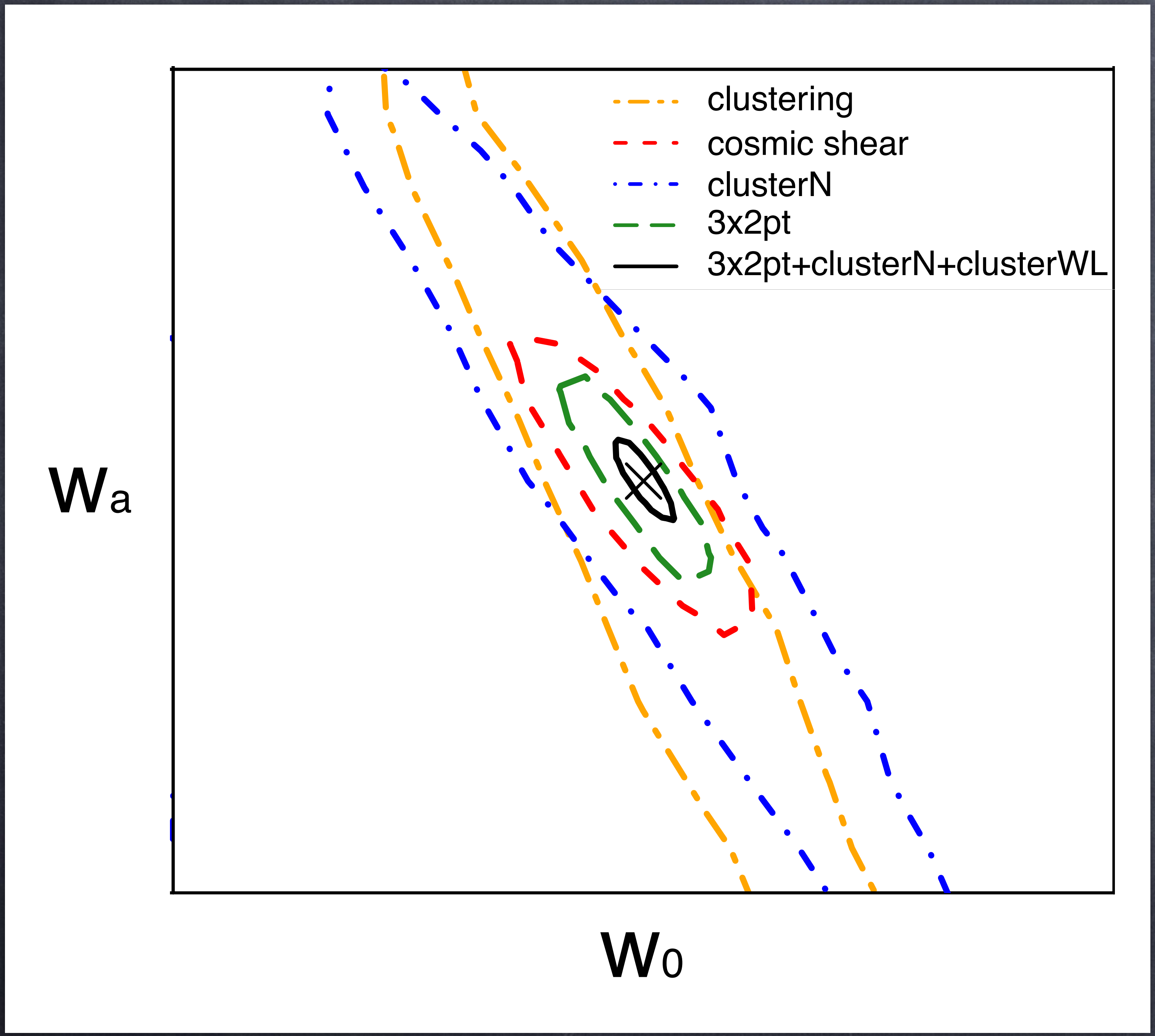


7 cosmological parameters
49 nuisance parameters

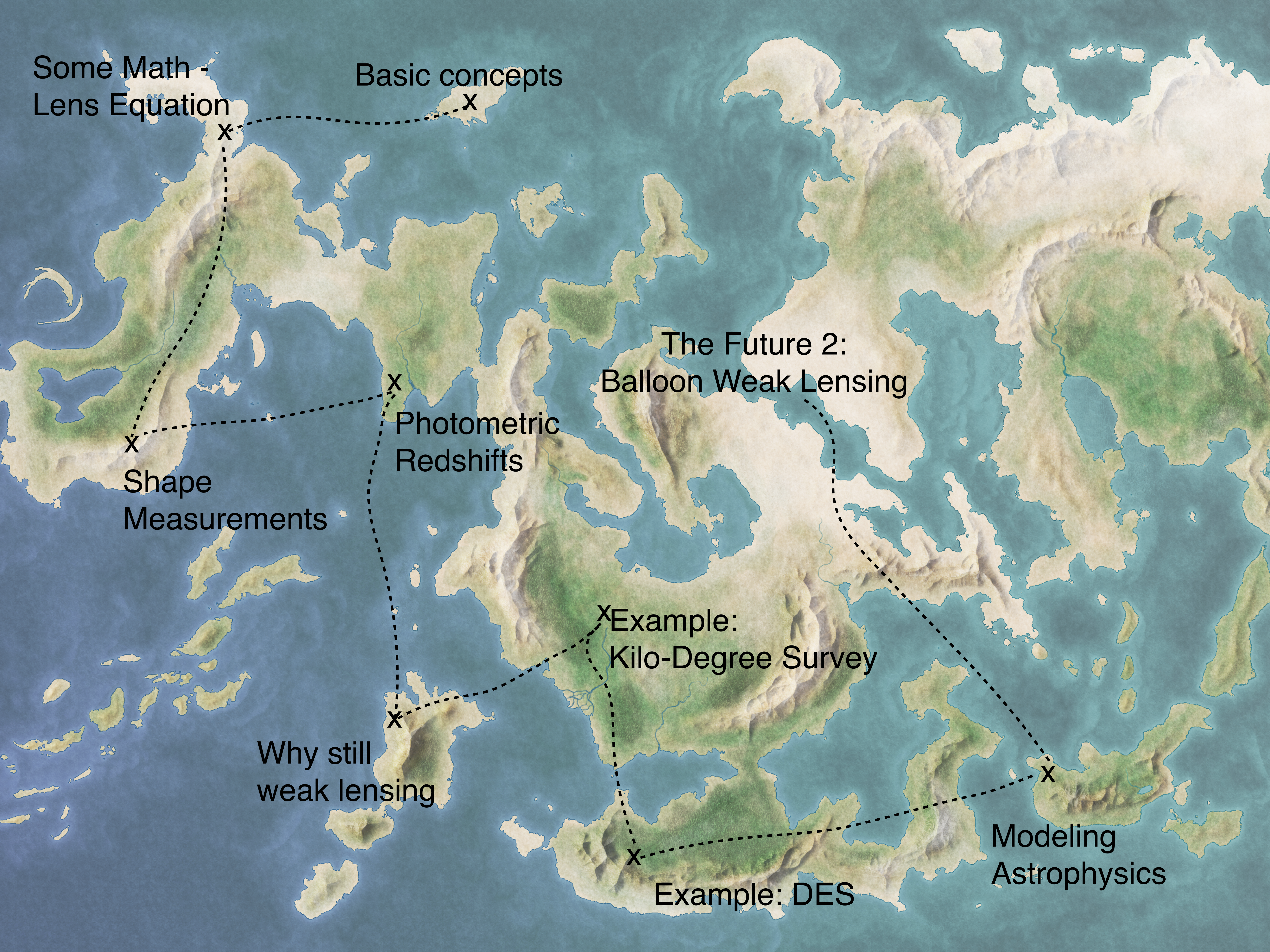
- **Shear Calibration,**
- **Lens+Source photo-z,**
- **Linear galaxy bias**
- **Cluster Mass Calibration**
- **Intrinsic Alignments**

Details see Krause & TE'16

Zoom into w_0-w_a plane



- Very non-linear gain in constraining power
- Most stringent constraints on fundamental physics questions will come from combining Weak Lensing with other tracers of the density field.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SuperBIT - Suborbital imaging platforms for cosmological observations

Sub-arcsecond, wide-field imaging from the Super Pressure Balloon platform for Weak Lensing Cluster Observations

- SuperBIT launch is 2018 (100 days, 200 galaxy clusters, multi-band photometry)
- Overlap with X-Ray and SZ observations
- Dark Energy/ Dark Matter studies

William Jones (PI, Princeton), Tim Eifler (JPL/Caltech),
Aurelien Fraisse (Princeton), Richard Massey (Durham),
Barth Netterfield (Toronto), Jason Rhodes (JPL/Caltech)

Weak Lensing is hard as it is … why balloon?

Overwhelming advantage in the near UV (λ < 400 nm)

Significant advantage in the near IR (λ > 900 nm)

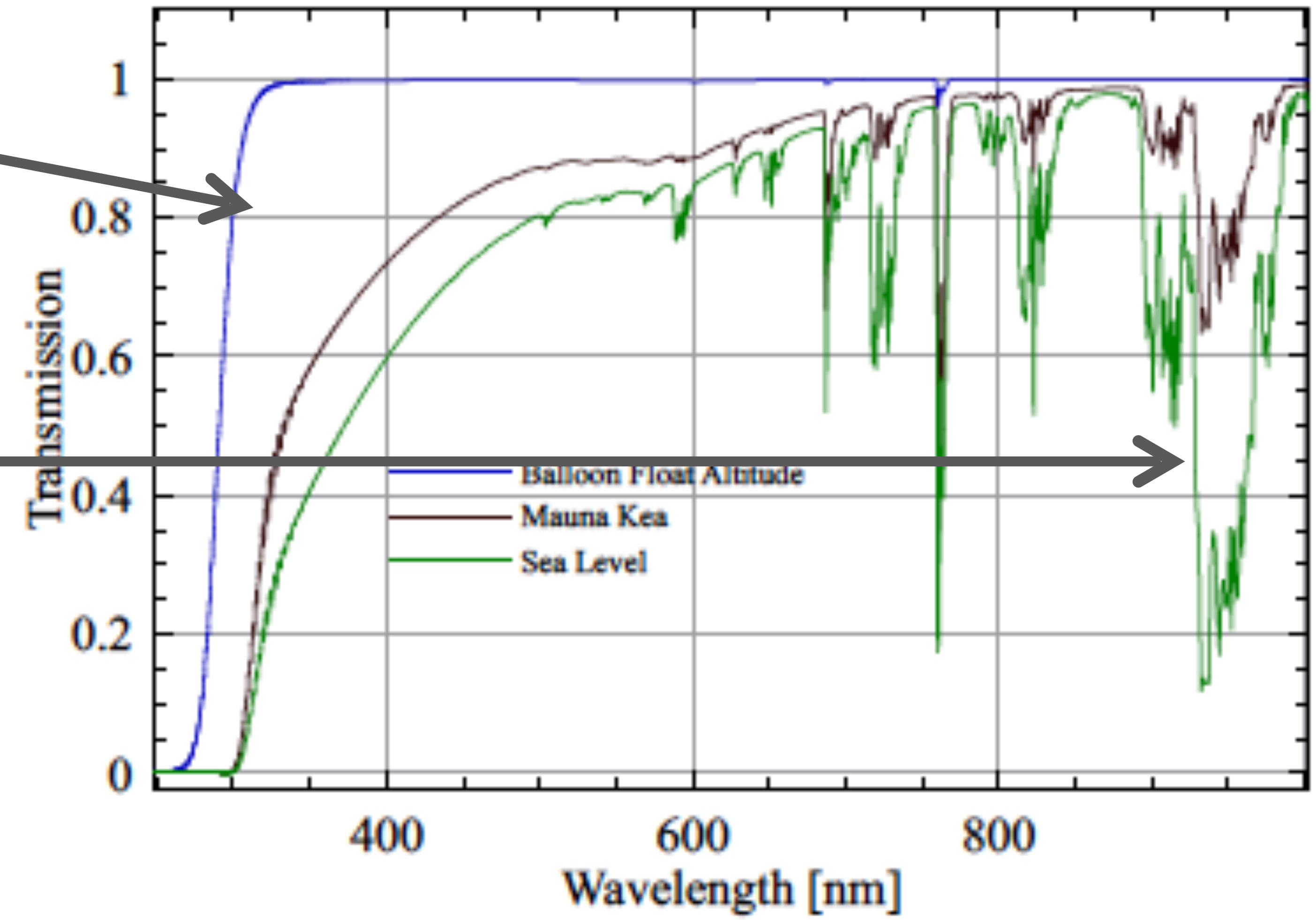


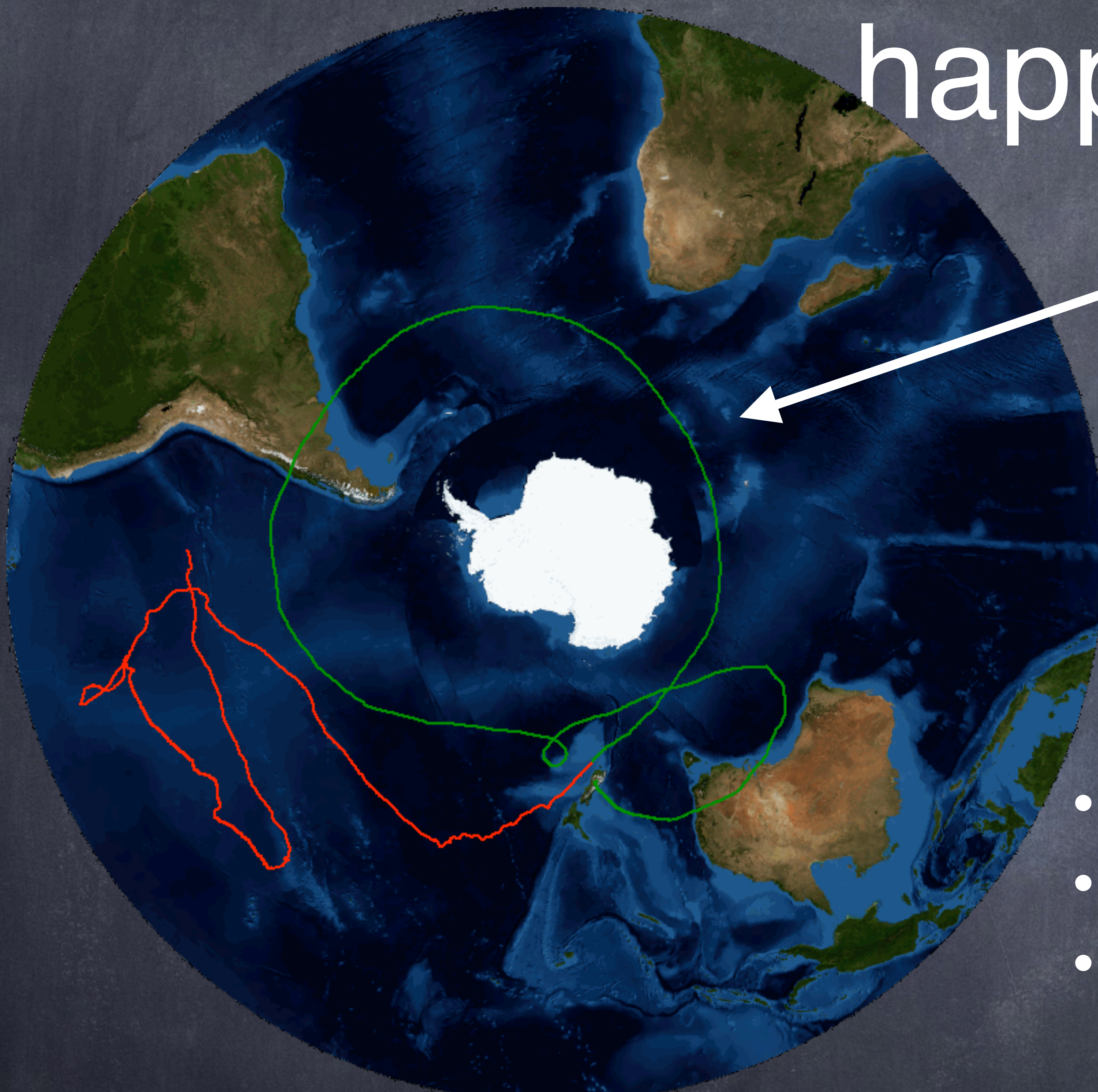
Figure 1: Atmospheric transmission as calculated by MODTRAN4 [2]. Reduced air column, and decreased pressure broadening provides significantly reduced atmospheric absorption at float, particularly in the blue and near-UV bands.

- **Diffraction limited resolution**
- **Space-like sensitivity**
- **Enormous imaging speed in the Blue/UV**

Main Argument: It's cheap

Ok, why did nobody try this earlier?

ULDB mid latitude flights are happening



- 2016 first science flight: Cosmic Ray Detector (UCB)
- SuperBIT launch is 2018 (100 days, 200 galaxy clusters, multi-band photometry)

- Diffraction limited resolution
- Space-like sensitivity
- Enormous imaging speed in the Blue/UV
- Highly synergistic with LSST/Euclid
- LSST already funded my proposal on organizing a workshop to explore synergies (blending, calibration)

The Future - “99 Luftballon” idea

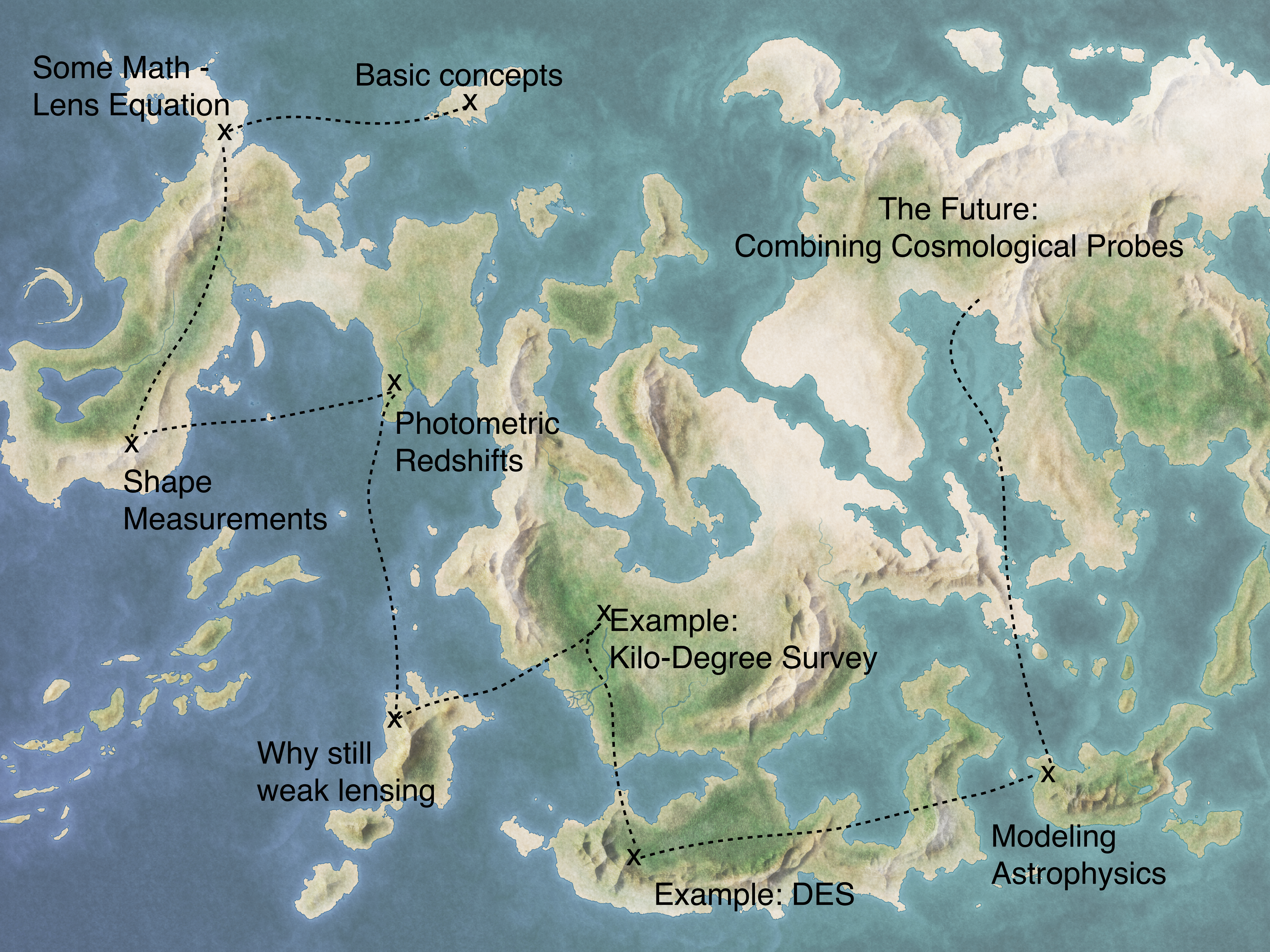
- Impact: Addresses many different science areas in UV-optical-NIR (exoplanets to cosmology, many PI opportunities)
- Risk minimization: If one flight fails no disaster
- Modularity: (vary instrumentation update detectors, spectrographs, optics,)
- Synergies: Ideal complement for JWST, LSST, WFIRST, Euclid
- Cost: Instrument Reusability > 0%, mass production savings…

Highly synergistic with ground (calibration) and space based (cheap blue/ UV imaging) surveys

Table 1. Assumed mission parameters for a Small, Medium, Large ULDB. The last row contains the computed survey area at Euclid depth.

	Euclid	Small	Medium	Large
Dark time per day (h)	24	12	12	12
Mission duration (d)	2195	100	100	100
Camera FoV (deg^2)	0.57	1	1.5	2
Primary Mirror (m^2)	1.13	1.13	2.55	4.52
Survey Strategy	0.6	1	1	1
A_{survey} (deg^2, Euclid depth)	15,000	1,000	3,382	7,993

Eifler 2016, NASA white papers, probe mission concepts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Summary

- Weak Lensing is a powerful direct measure of the structure growth in the Universe
- Many challenges in terms of measurement and modeling uncertainties
- Great discovery potential for new fundamental physics
  - when combining weak lensing with other probes and
  - when combining multiple data from future surveys

SuperBIT - Suborbital imaging platforms for cosmological observations

Sub-arcsecond, wide-field imaging from the Super Pressure Balloon platform

William Jones (PI, Princeton), Tim Eifler (JPL/Caltech),
Aurelien Fraisse (Princeton), Richard Massey (Durham),
Barth Netterfield (Toronto), Jason Rhodes (JPL/Caltech)

The Artist formerly known as …

High Altitude Lensing Observatory

Jason Rhodes (Principal Investigator) Jeff Booth (Project Manager)

JPL: Paul Brugarolas, Ben Dobke , Eric Jullo, Kurt Liewer, Chris Paine, Michael Seiffert, James Wu **Caltech**: Richard Ellis, Sergio Pellegrino, Roger Smith , Harry Teplitz(IPAC) **Wallops Flight Facility:** Raymond Lanzi, David Stuchlick, **NOAJ(Japan):** Satoshi Miyazaki **ETH Zurich:** Adam Amara, Simon Lilly, Udo Wehmeier **Edinburgh (UK):** Tom Kitching, Richard Massey, John Peacock **Durham (UK):** Ray Sharples, Paul Clark, Richrd Meyers **UKATC:** David Lunney, David Henry, Naidu Bezawada **UChicago:** Ali Vanderveld **e2v**: Roger Pittock

HALO: The High Altitude Lensing Observatory (idea as in ~2008)

2011-2014

Single night flights; 2x2 detector array;N2 cooling, standard balloon

Stage 1

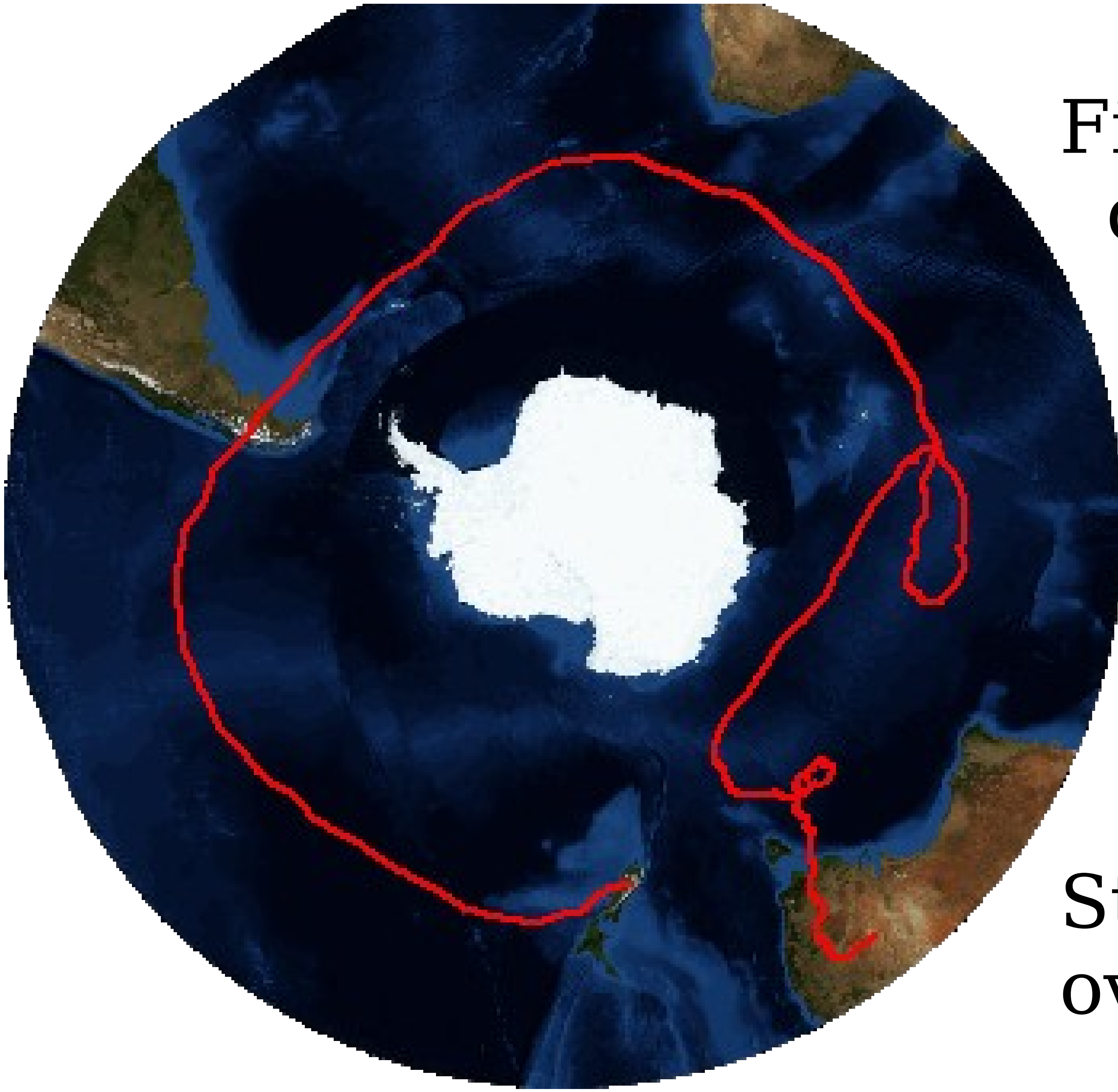
2012-2016

Multiple flights of ~100 days; 50 CCDs; ULDB; dark energy constraints

Stage 2

This clearly did not happen… so why is this now a good idea?

ULDB mid latitude flights are happening



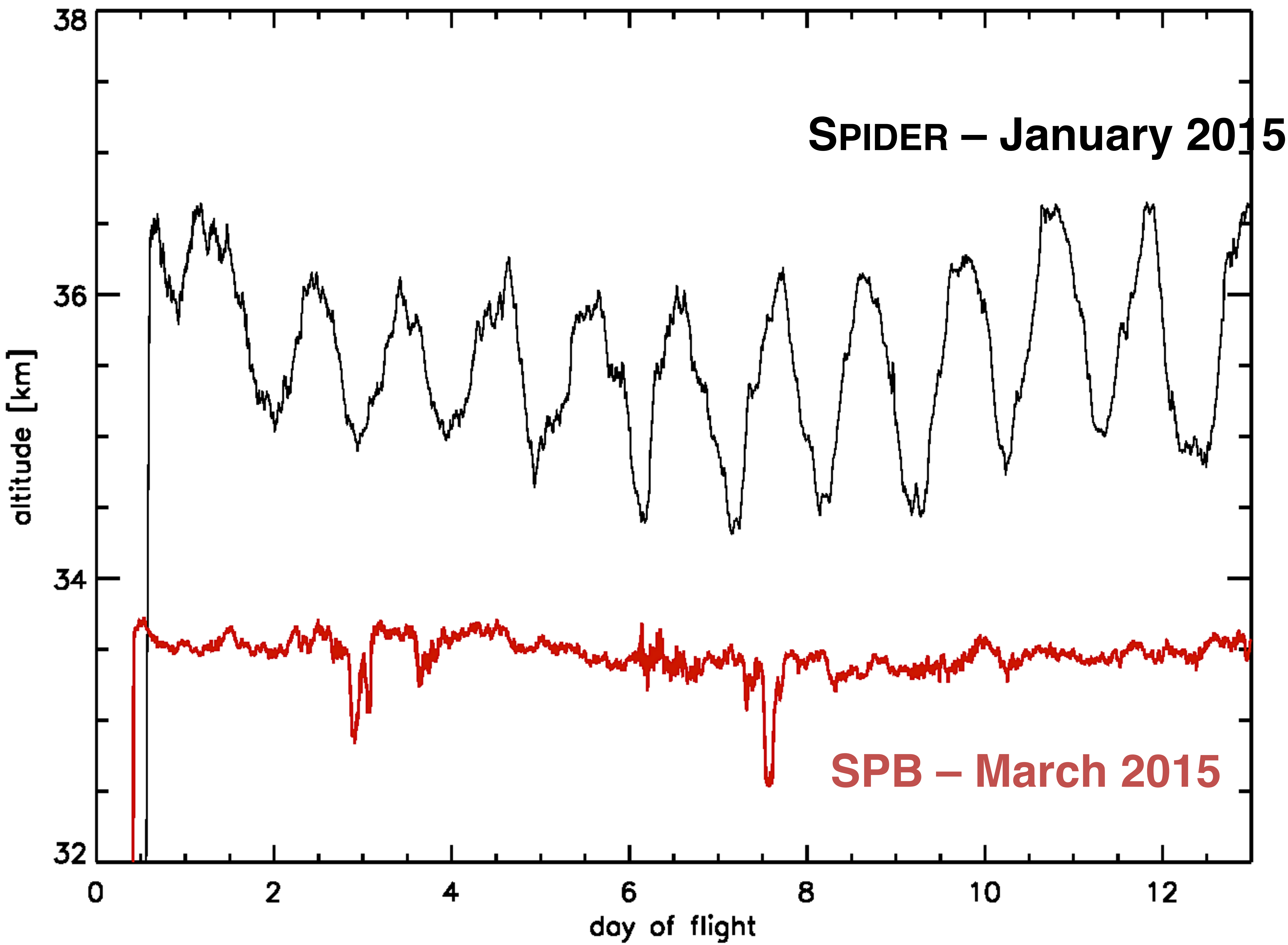
First Mid-latitude long duration balloon flight this spring

33 day flight.

Excellent altitude stability

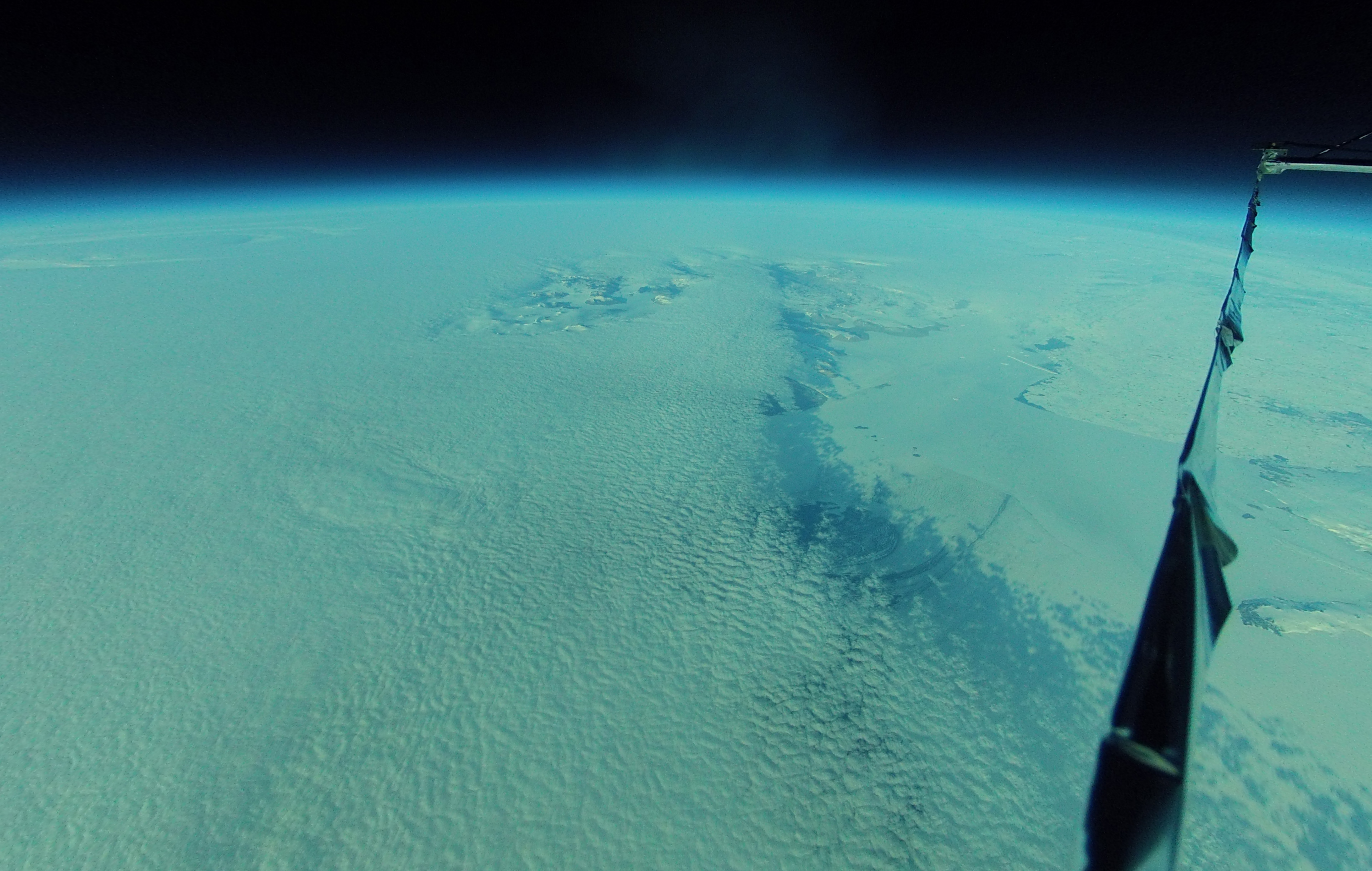
Started to loose pressure over Australia.

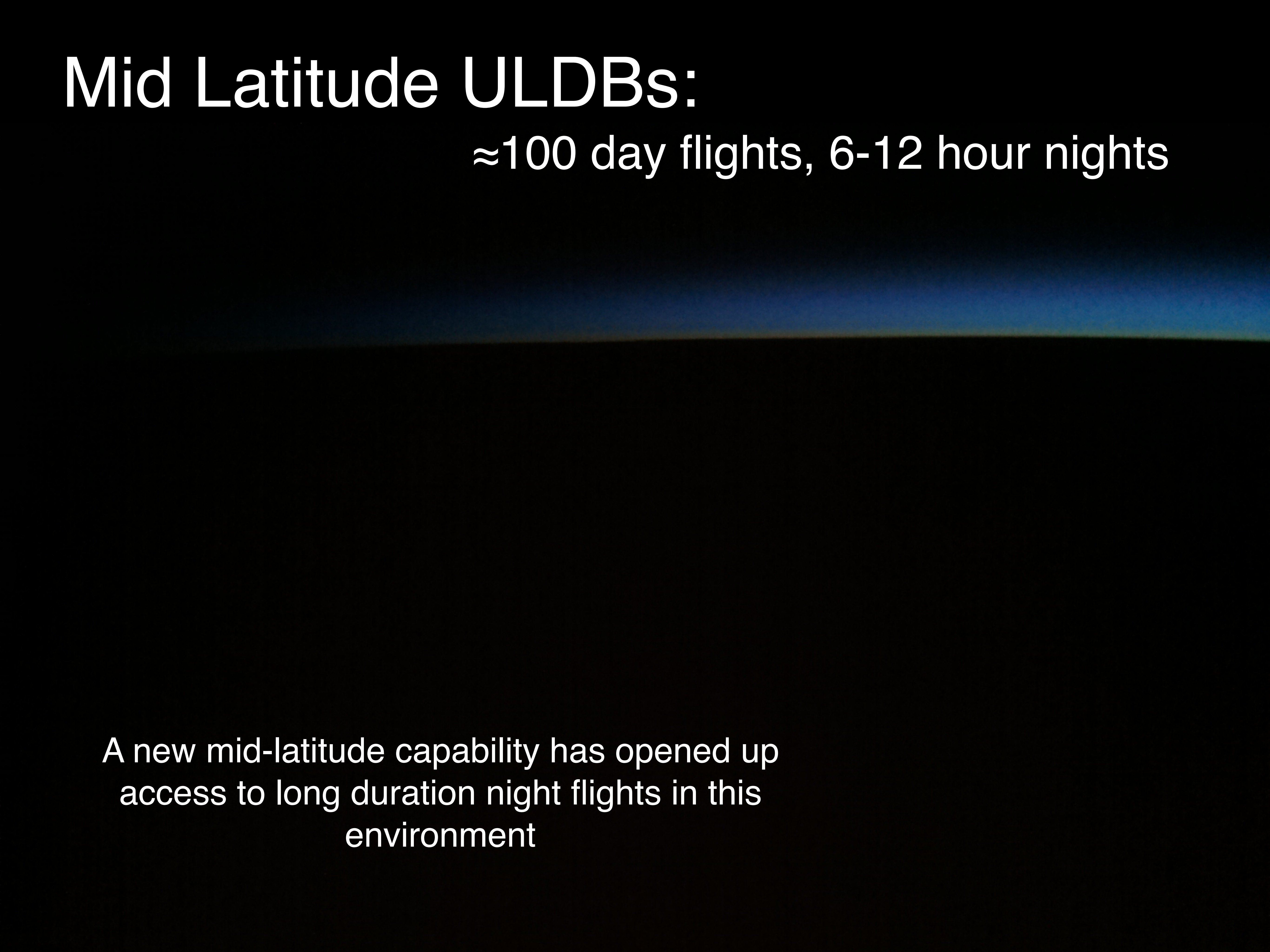
2500 lb science payload.



SPIDER – January 2015
SPB – March 2015
altitude [km]
day of flight
38
36
34
32
0
2
4
6
8
10
12

Antarctic LDB: Sun above the horizon 100% of the time.
Daytime sky-glow is significant, show stopper in the near UV/IR




Mid Latitude ULDBs:
≈100 day flights, 6-12 hour nights
A new mid-latitude capability has opened up access to long duration night flights in this environment

SuperBIT mission - launch 2017/18

Science cases: Cluster Weak Lensing
Clusters in their filamentary environment,
DES overlap and calibration ideas

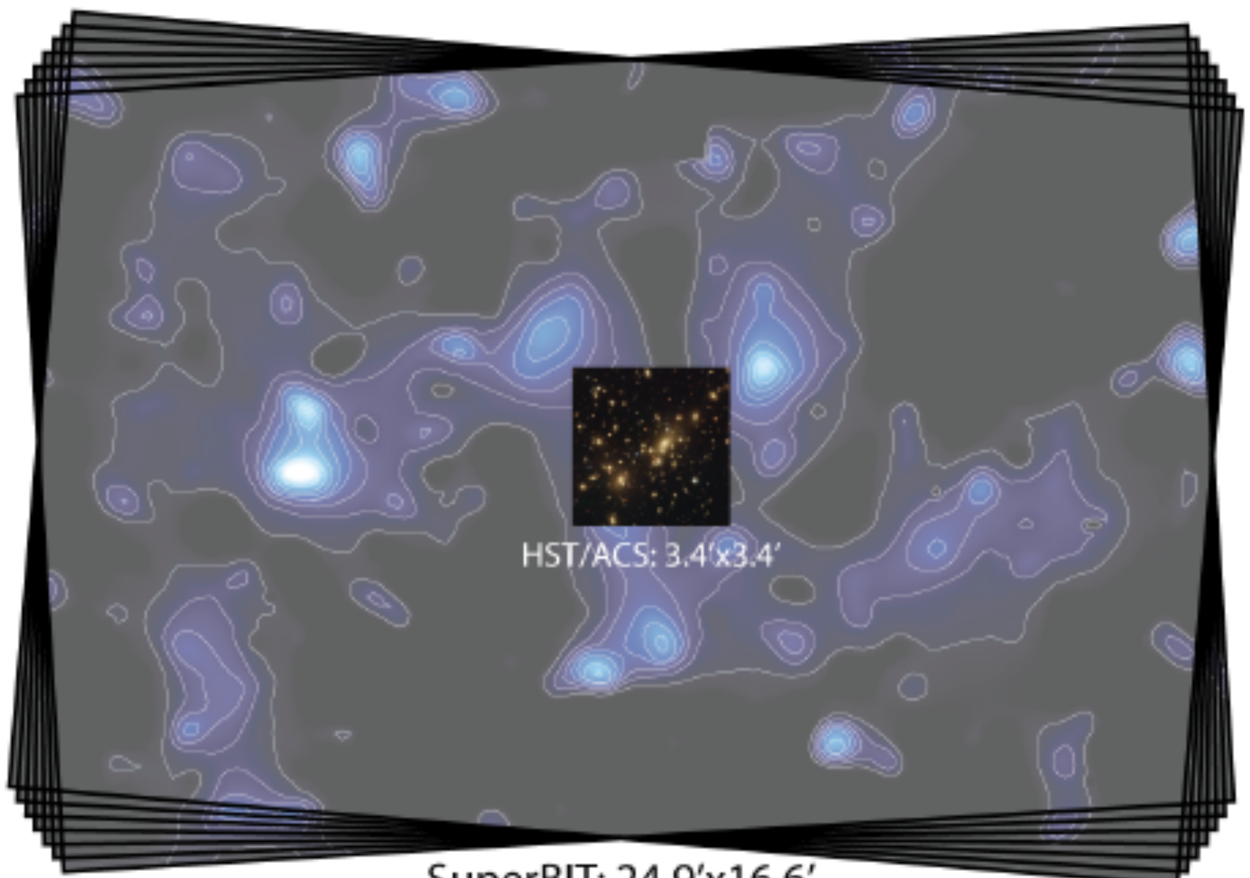
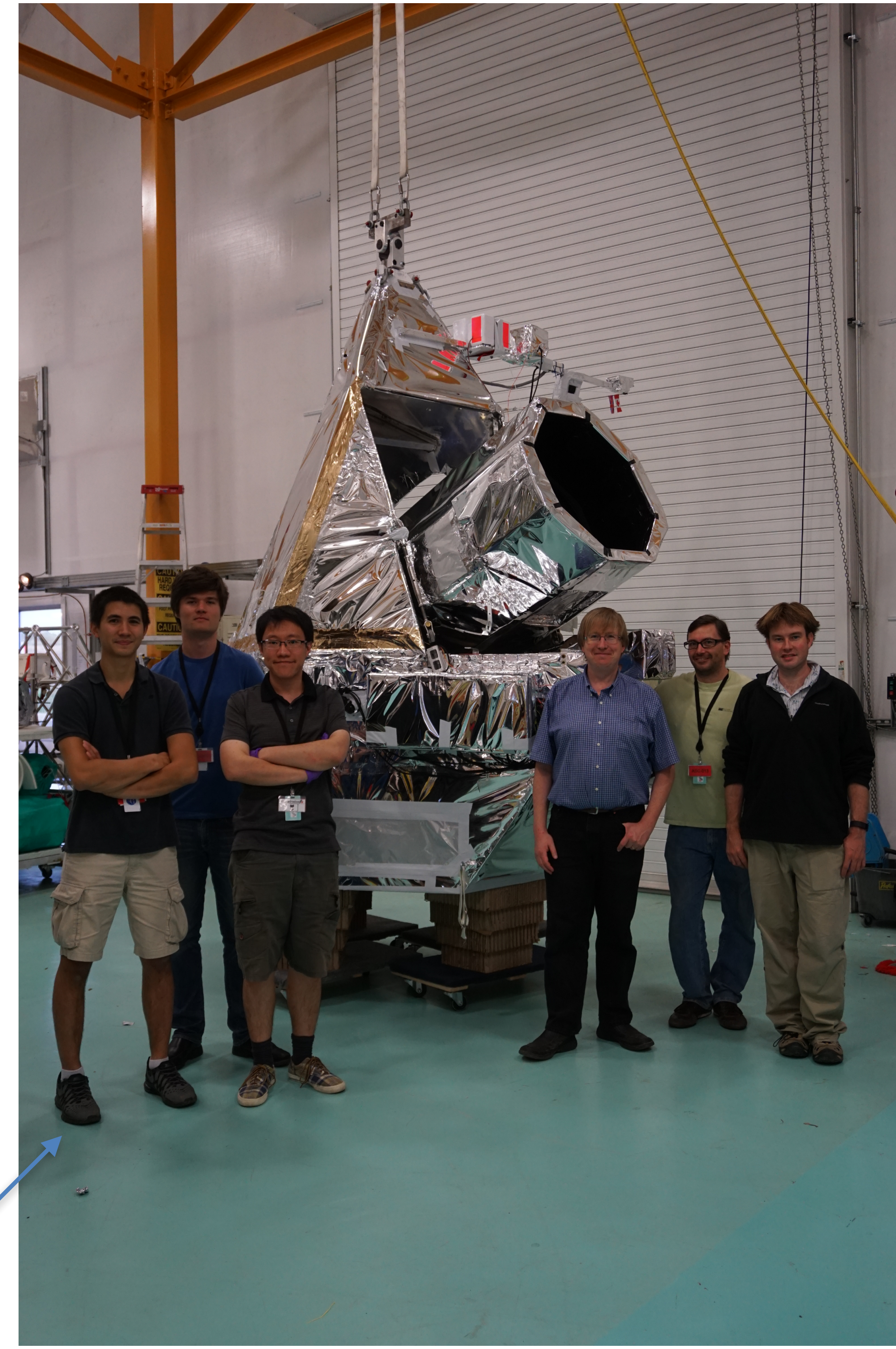


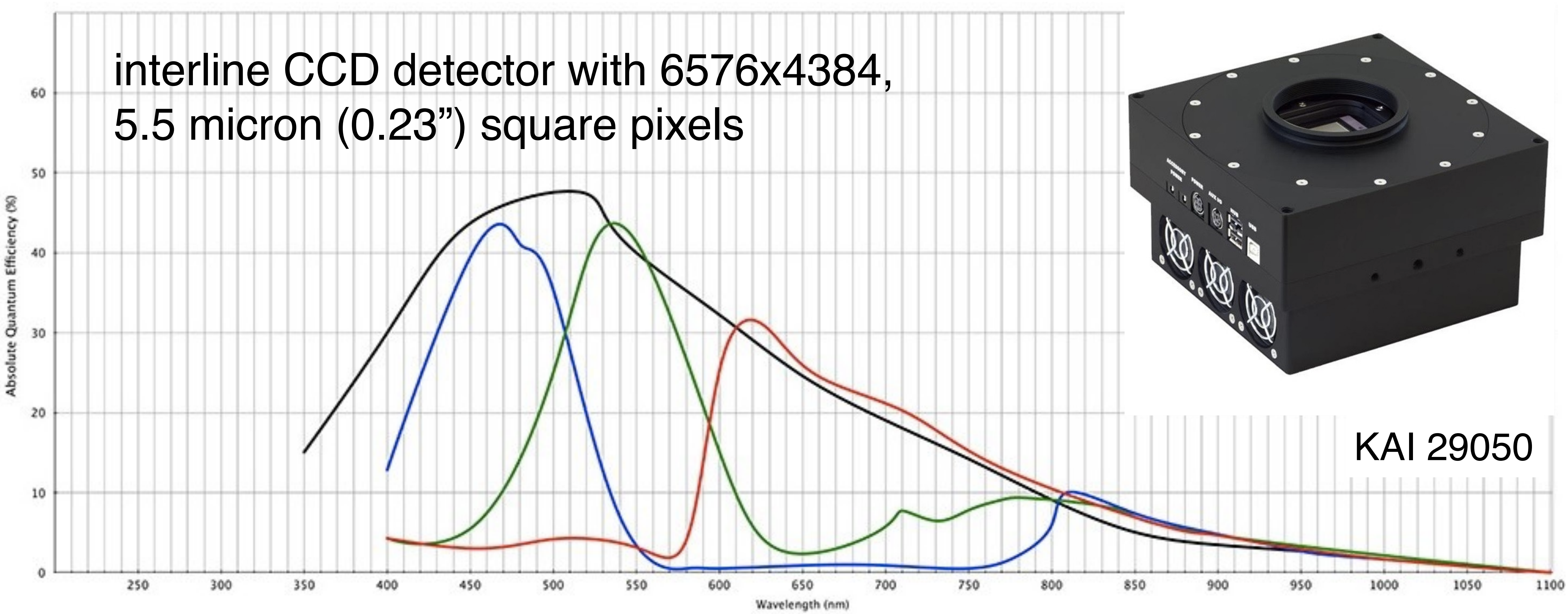
Figure 3: SuperBIT's field of view is 36 times bigger than that of the largest camera on HST. This will allow us to study entire (even nearby) galaxy clusters in a single pointing – including their outer environment and attachment to the cosmic web – without any need for mosaicking. The center square shows an HST image of Abell 2218; surrounding background shows a weak lensing map of the cosmic web from an HST mosaic.



BIT test flight

SuperBIT - 0.3” resolution imaging over a 0.4 field of view in five bands between 300 and 1000 nm with sensitivities exceeding 24th magnitude (5 point source).

Band	λ_c [nm]	$\Delta\lambda/\lambda$	Band Start	Band Stop	Nyquist [pixels/PSF]	M_{phot}	N_{exp}
u	360	0.28	300	400	0.67	28	8
u'	393	0.38	300	450	0.73	7	3
g	478	0.31	400	550	0.89	4	3
r	619	0.26	550	710	1.15	7	6
shape	666	0.53	550	900	1.22	–	3
ACS f814w	783	0.29	702	930	1.46	25	20



Problem 1: Pointing stability

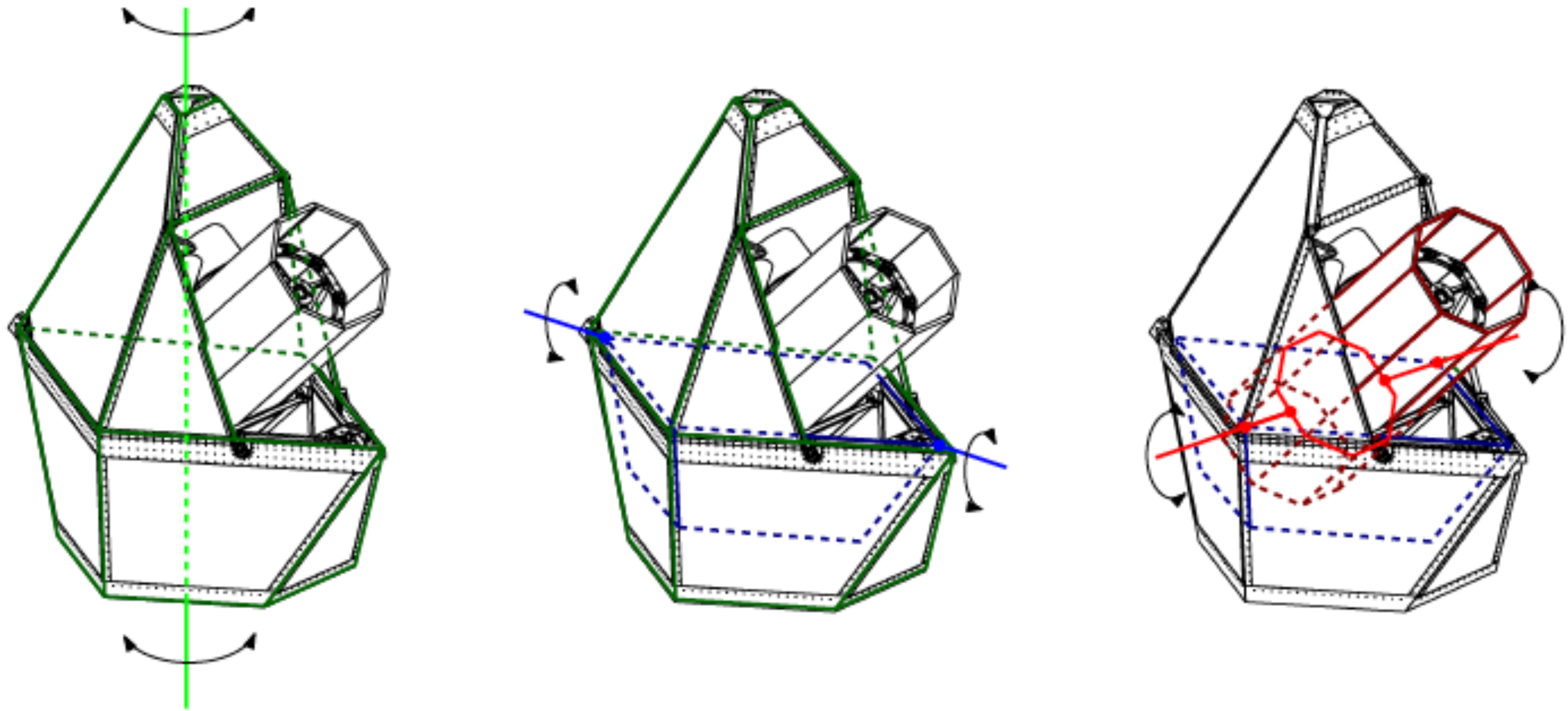
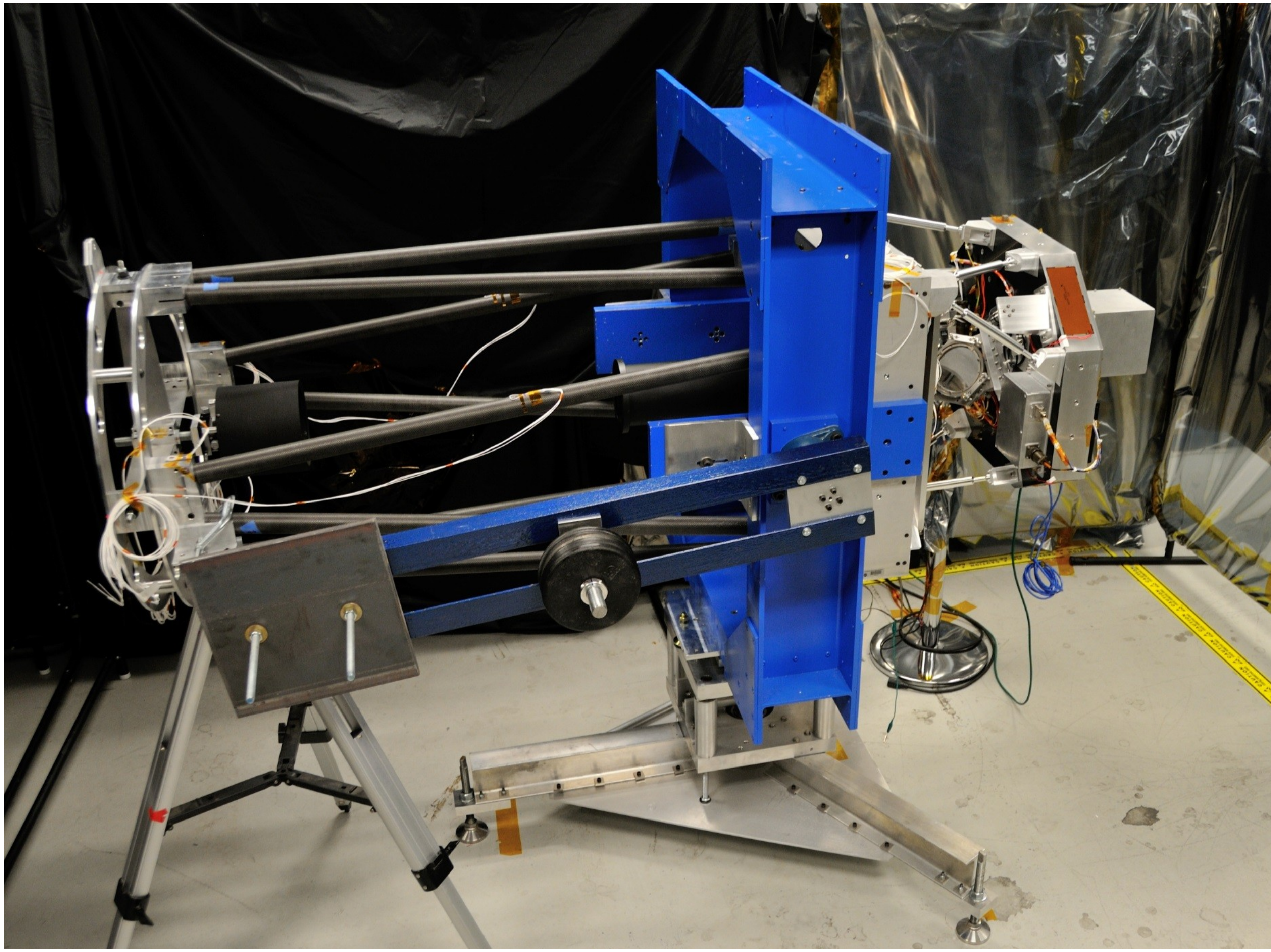


Figure 5: The SuperBIT gondola's Yaw/Roll/Pitch mount. The attitude of the telescope is controlled in three nearly orthogonal axes as required by SuperBIT's wide field. The outer frame is controlled in yaw (green), the middle frame is controlled in roll (blue) and the inner frame is controlled in pitch (red).

Gondola achieves 1" stability

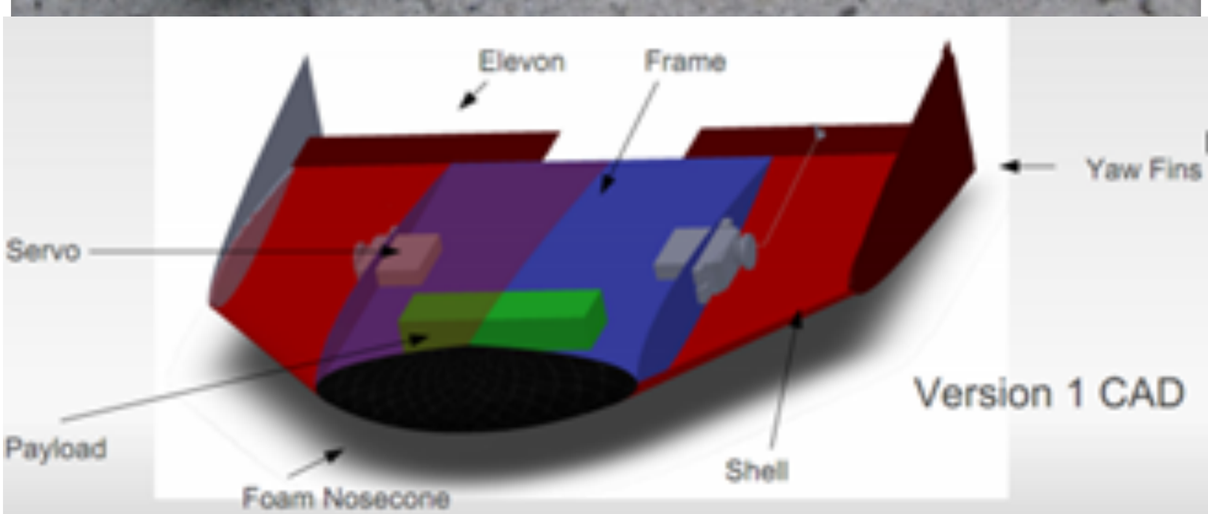
Problem 1: Pointing stability

- Fast steering mirror (~60Hz) to stabilize image
- Requires bright guide stars
- Sunrise has achieved <50mAs



Problem 2: Data Recovery…

Idea AIRS: Automated Information Retrieval System



- JPL summer student project (Mentor Jason Rhodes)
- GPS guided autonomous glider
- Can return a solid state hard drive from balloon altitude to ground
- Simple technology
- Cheap (~$1k)
- Safe (meets all FAA regulations)

- Had only done low altitude glide tests (~10 meters)
- More development done this summer

- Could retrieve 1 TB during every overpass (every 2-3 weeks)

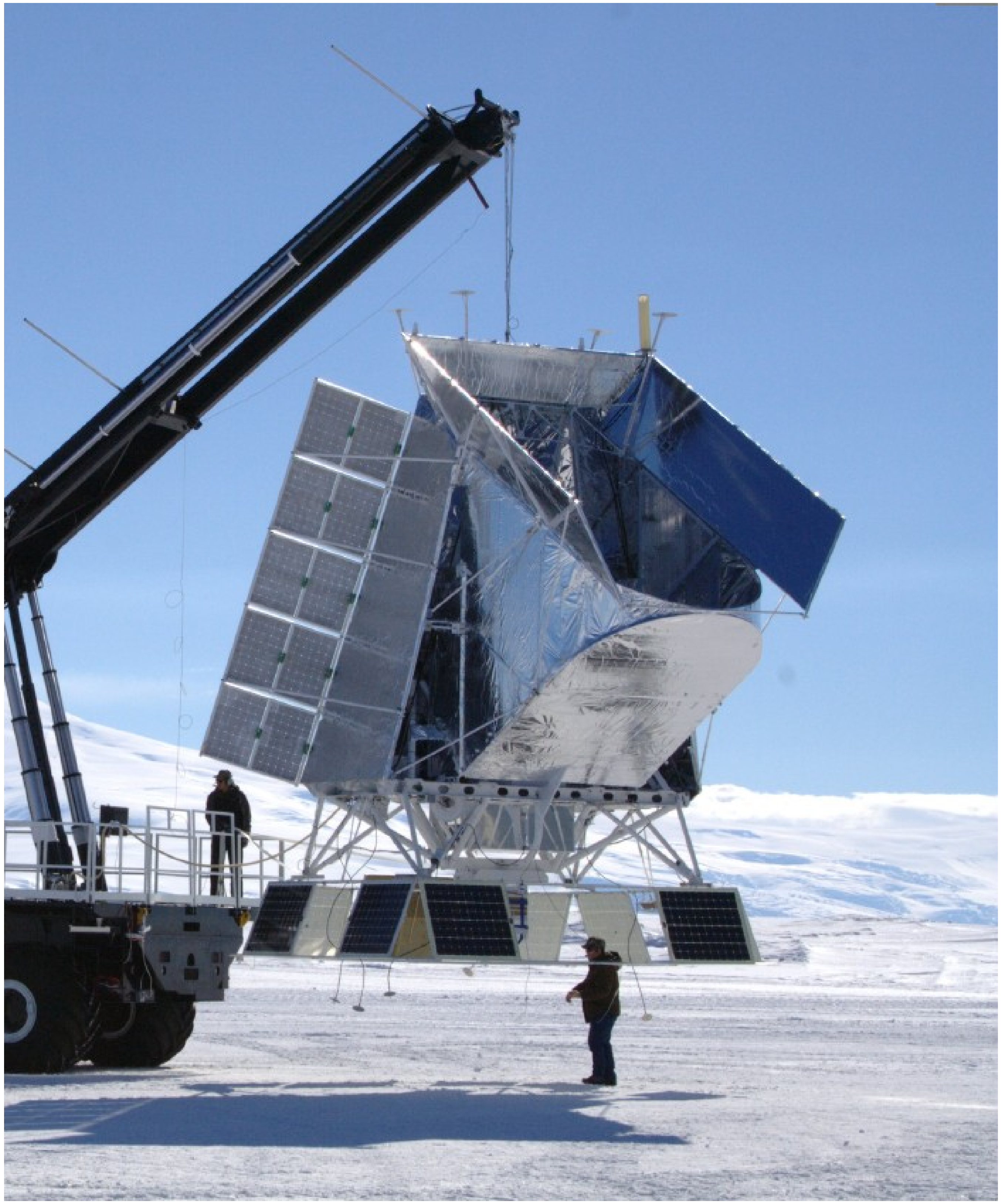
Future

Mirror Size

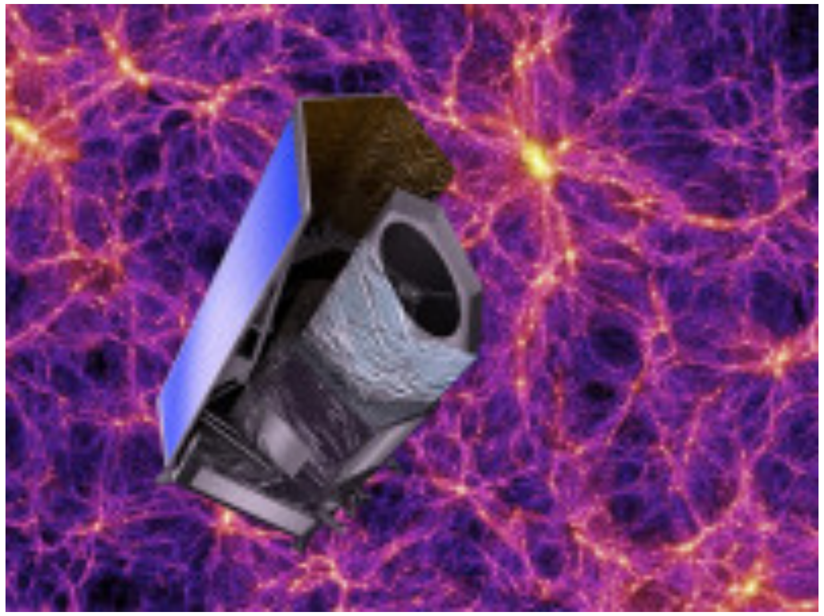
BLAST has flow a 2m primary.

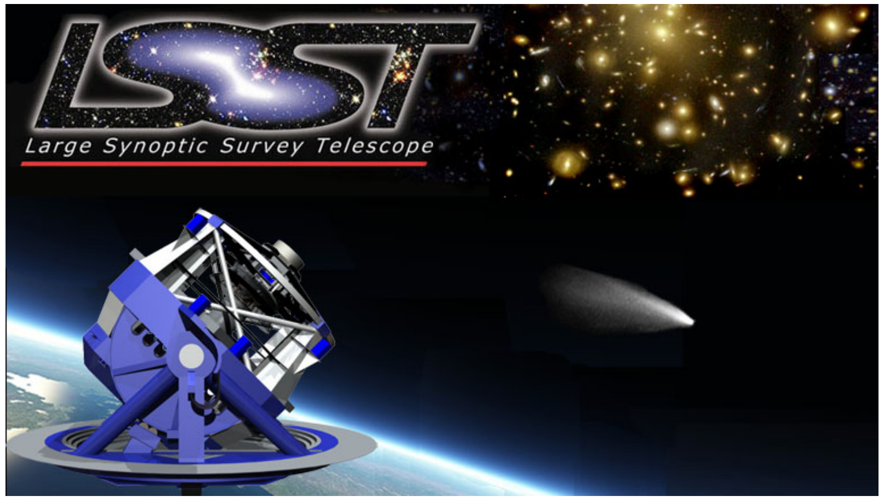
The Gondola can accommodate up to A 2.5m mirror.

A very fast telescope so very sensitive to thermal expansion.



Synergies





Euclid:
Photo-zs,
Blue+UV observations

LSST:
Blue+UV observations, photoz
Shapes, blending

WFIRST
photo-z, Blue+UV
Optical bands

	Euclid	SuperBIT	Small	Large
day/night	*3*	*1*	*1*	*1*
100 d/year	*3.5*	*1*	*1*	*1*
Camera FoV deg^2	*0.57*	*0.4*	*1*	*1.5*
Mirror Diameter (m)	***1.2***	***0.5 - 0.8***	***1.2***	***2.4***
Survey Strategy	*0.6*	*0.3*	*1*	*1*
Area/Year	*5.17*	*0.03 - 0.06*	*1.44*	*8.64*

Multi-Balloon Campaign as a future mission concept

- Near-Space quality imaging
- Advantages in UV and IR transmission
- Reusability (unclear but > 0%)
- Risk minimization; if something goes wrong, no disaster
- Modularity (update detectors; fly spectrograph)

How much science return for e.g. Flagship mission money? Answer early next year…

Dark Energy – Models/Theory (very incomplete)

1) ΛCDM: $$H^2 = H_0^2\left[\Omega_{\mathrm{r}}a^{-4} + \Omega_{\mathrm{m}}a^{-3} + (1-\Omega_0)a^{-2} + \Omega_\Lambda\right]$$

Energy density component with $w = -1$

- Fits data nicely → see Planck
- Currently no physical explanation other than:
  vacuum energy density → Cosmological Constant Problem
  → Anthropic Principle → Multiverse →hard to accept

2) wCDM: Same as above but time-dependent *w(a)* $$w_0 + w_a(1-a)$$

3) Modifications to Gravity:

- Deviations from GR at late times and large scales
- Recover GR on solar scales via Screening
  (e.g. strength of fifth force is density dependent)
- Wealth of models and screening mechanisms
  (e.g. Chameleon / f(R), Symmetron fields, DGP, Vainshtein)

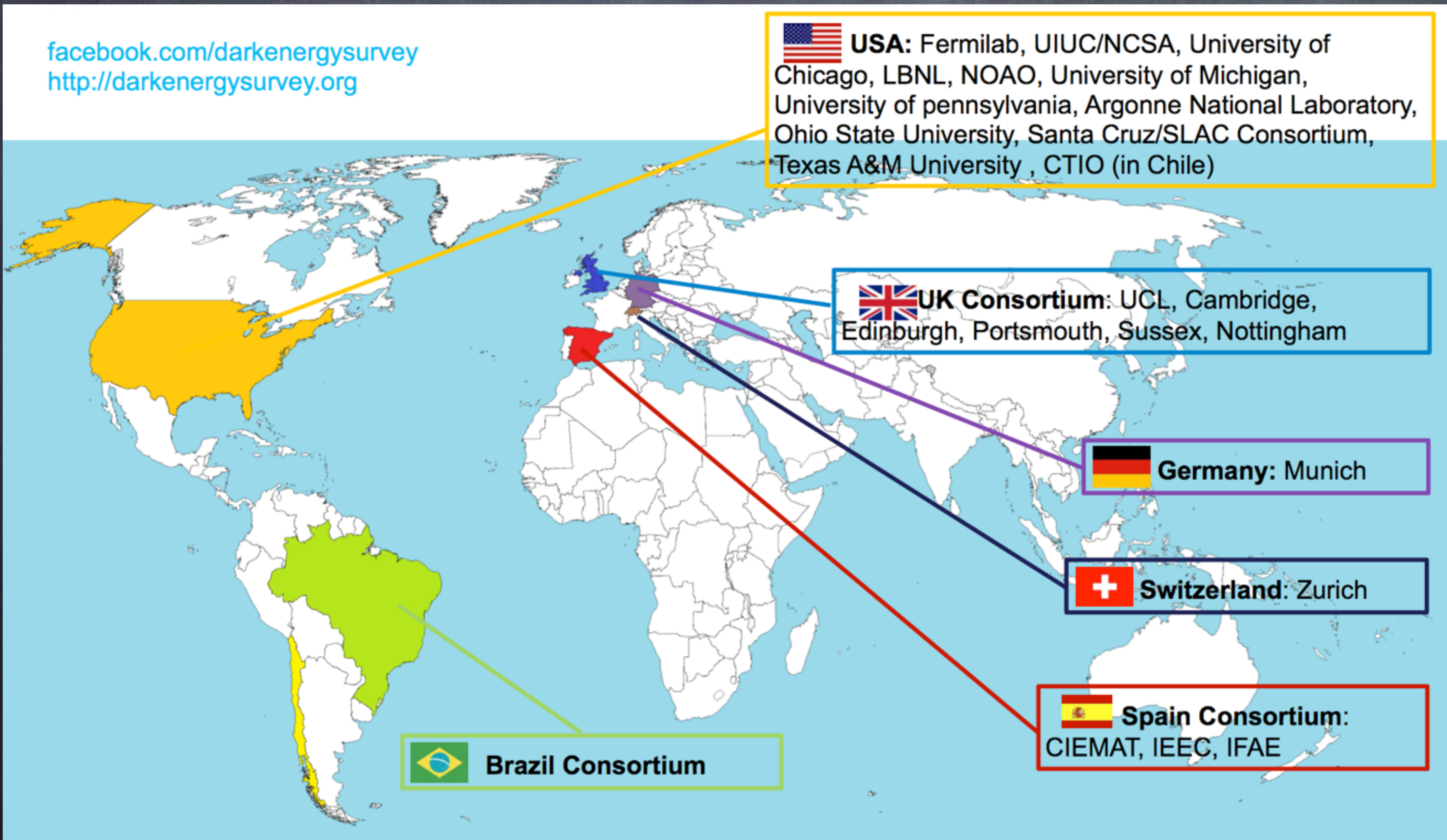
MG (usually) does not affect Lensing,
but Dynamics are affected

Takeaway: We have no clue about the physics causing the acceleration →

After establishing that we don't have a very good idea what dark energy is …

Let's continue with the Dark Energy Survey

DES Collaboration:
~300 scientists from 28 institutions



DES main science goal:

Constrain origin of the accelerated expansion of the Universe through various techniques/observables

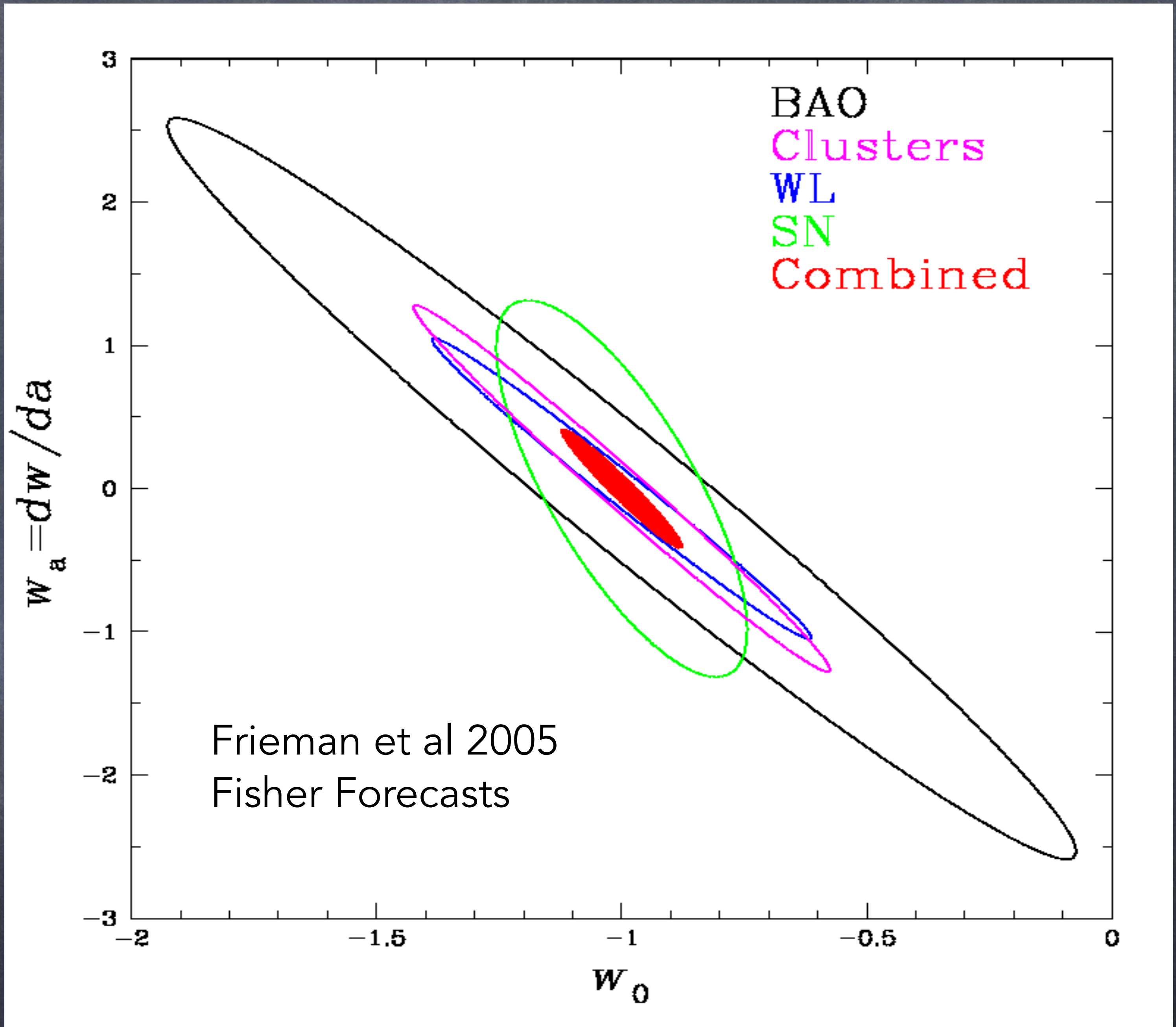
- Clusters (>30000, z<1, SPT)
- BAO (300 Mio galaxies, z<1)
- 4000 SN1a
- WL (200 Mio galaxy shapes)

Combining them greatly improves constraints

But
- observables of the same density field
- subject to similar systematics

→ highly correlated probes

Multiplying posteriors is not good enough → consistent joint analysis is necessary



Updated forecasts will appear in DES collaboration et al 2016
-> using CosmoLike framework

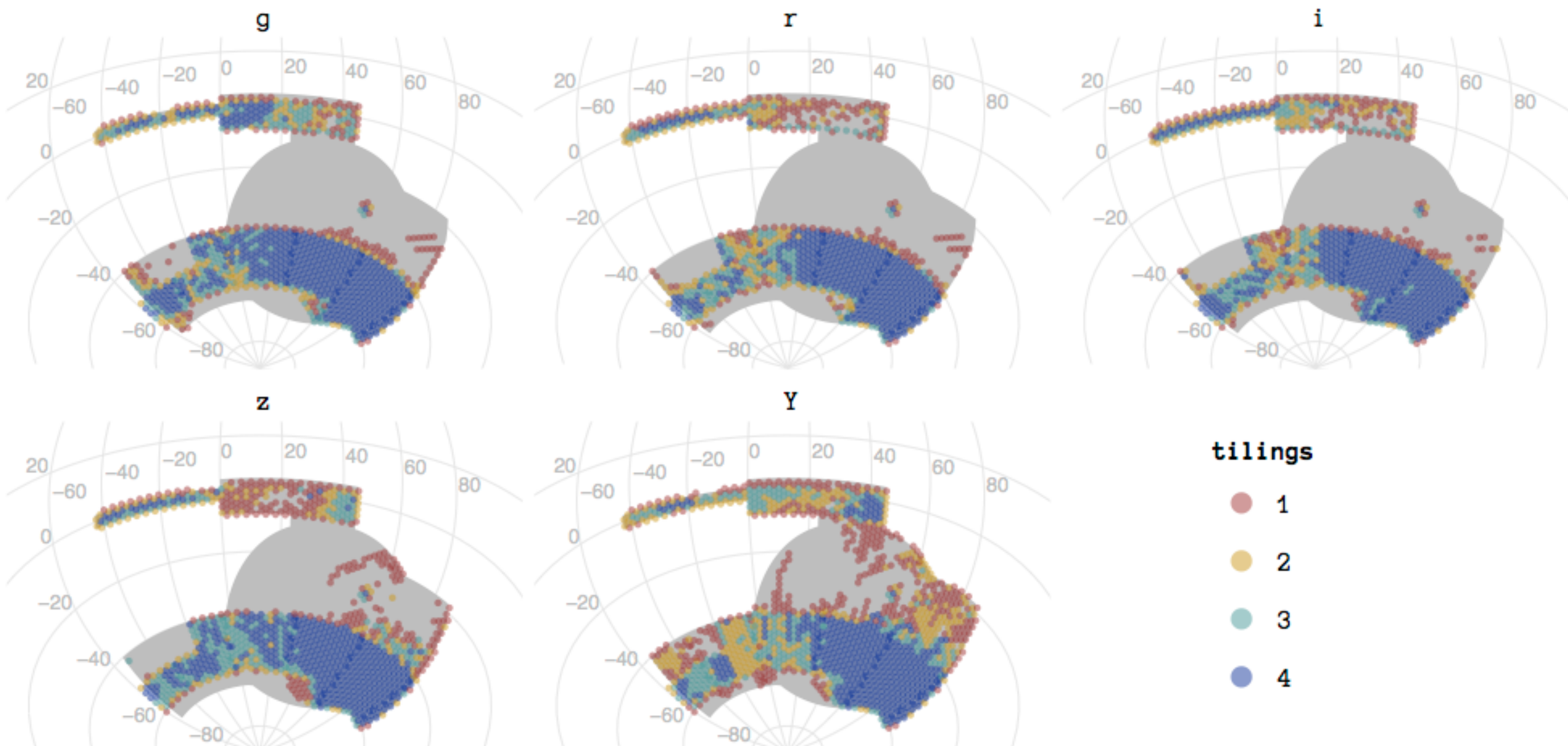
The Dark Energy Survey

- Cerro Tololo Inter-American Observatory Blanco 4-meter telescope
- First light Sept. 12, 2012
- Survey 2013-2018, 525 nights
- DECam: 570 Mpix, 3 deg^2 FOV, griZY filters
- 5000 deg^2 survey footprint, to mag 24 (redshift ~2.0) + 30 deg^2 deep SN fields

DES Timeline

- Project start 2003
- Research & Development 2004-8
- DECam Construction 2008-11
- Installation 2012
- First Light Sept. 2012
- Commissioning Sept-Oct. 2012
- Science Verification Nov. 2012-Feb. 2013
- First Season (Year 1) Aug. 2013-Feb. 2014
- Second Season (Y2) Aug. 2014-Feb. 2015
- Five 105-night seasons

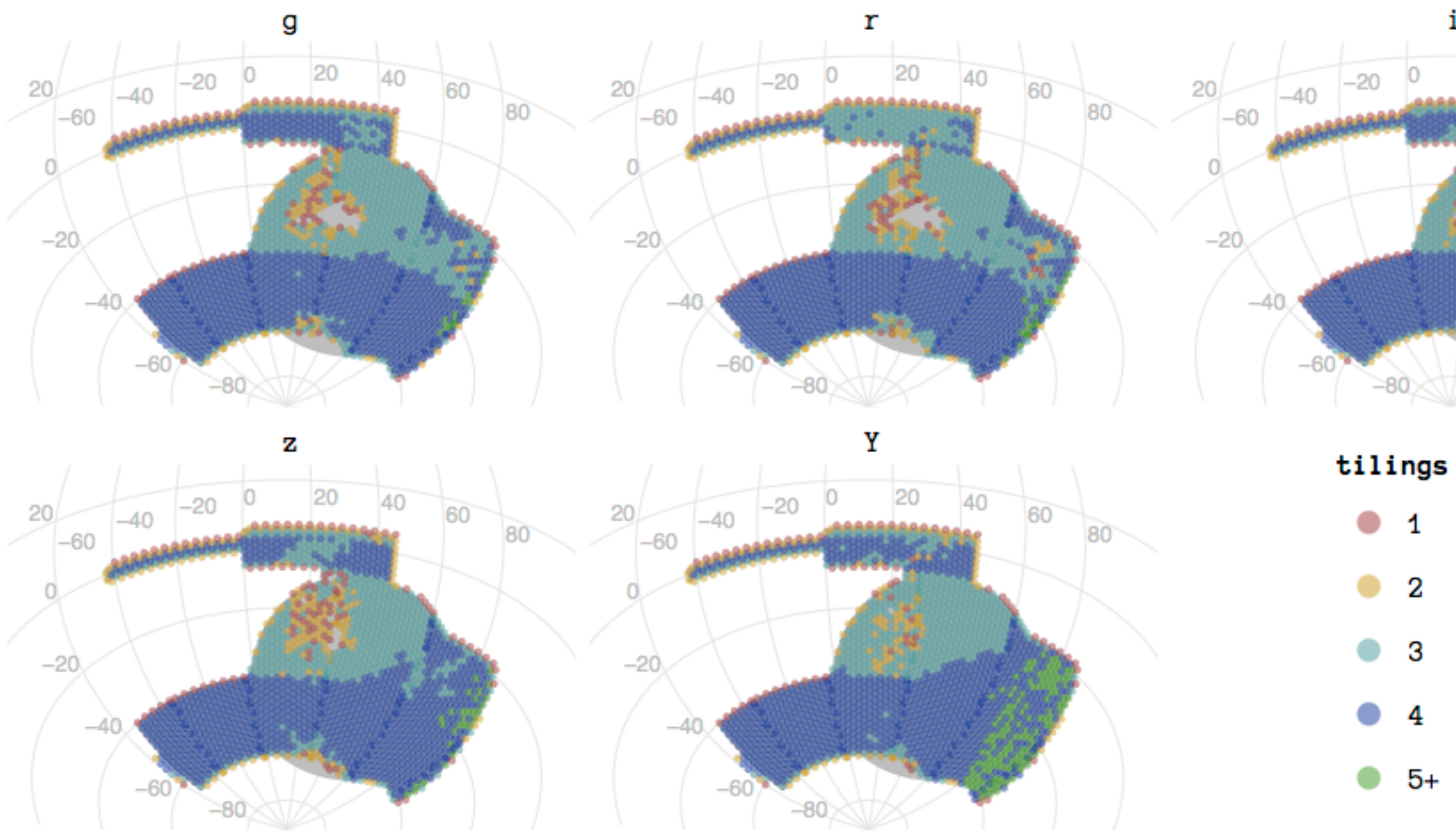
DES Survey Footprint



After Year 1 (Feb. 2014)

DARK ENERGY SURVEY

DES Survey Footprint



After Year 2 (Feb. 2015)