Dark Energy Introduction IV: Probing Cosmic Acceleration Using Weak Gravitational Lensing

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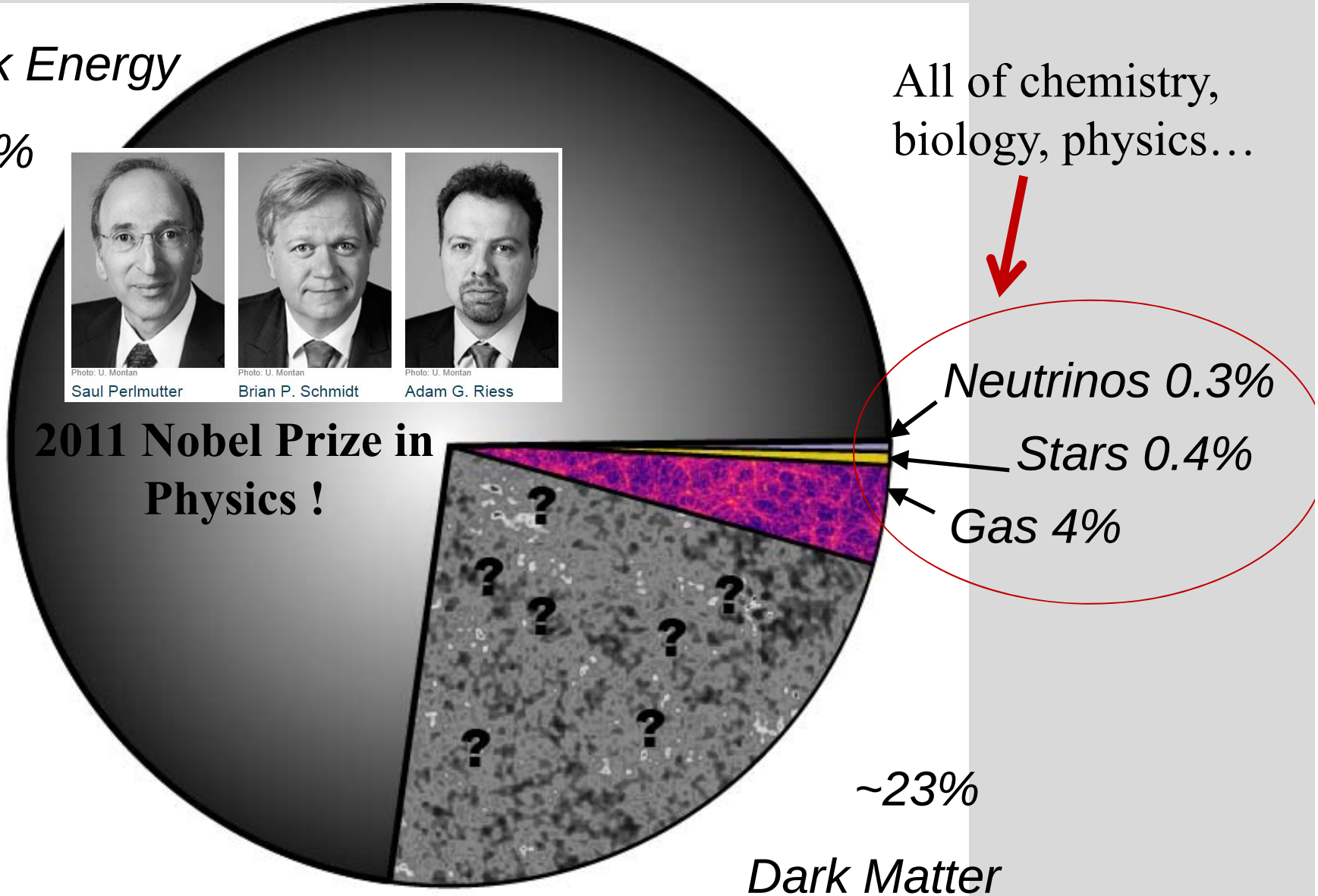
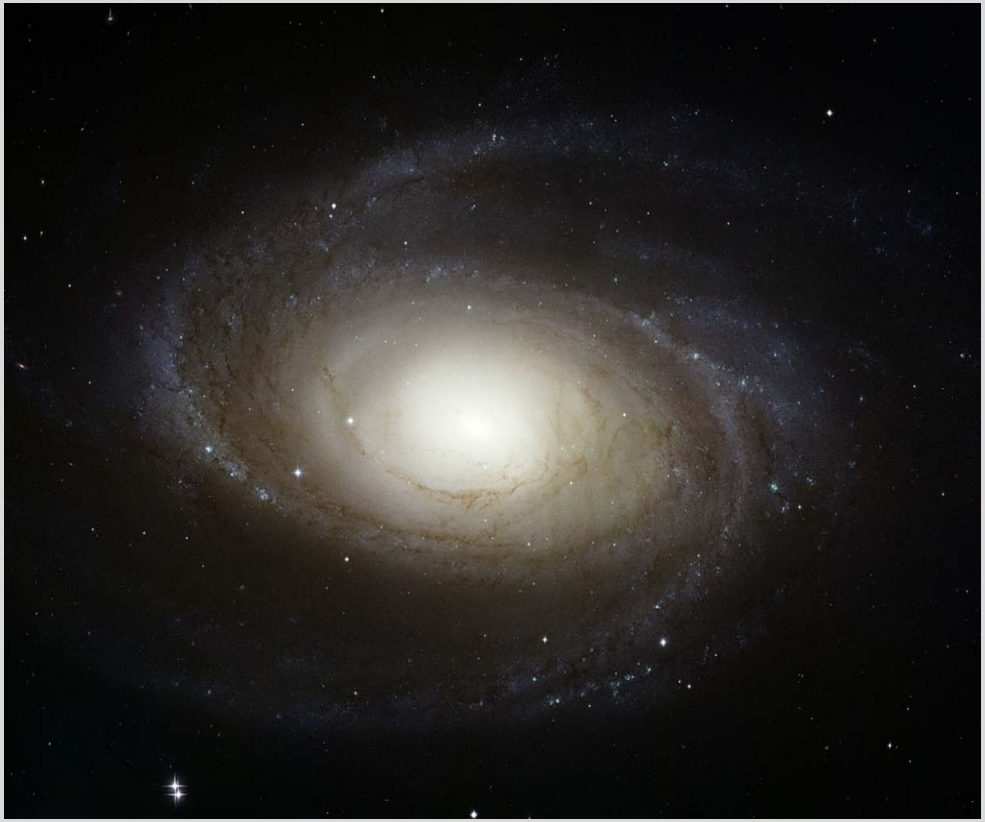
The Universe as a Pie Chart

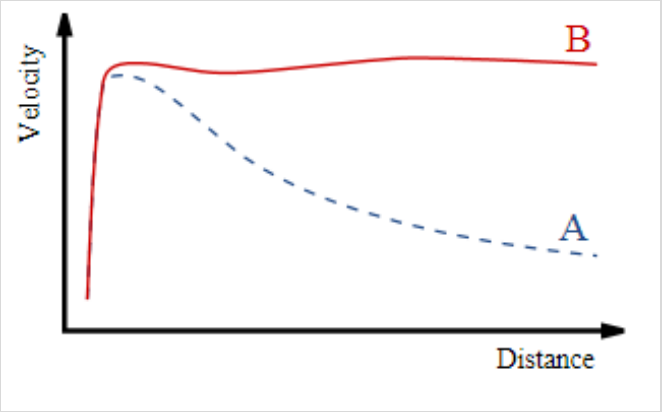


Dark Matter History

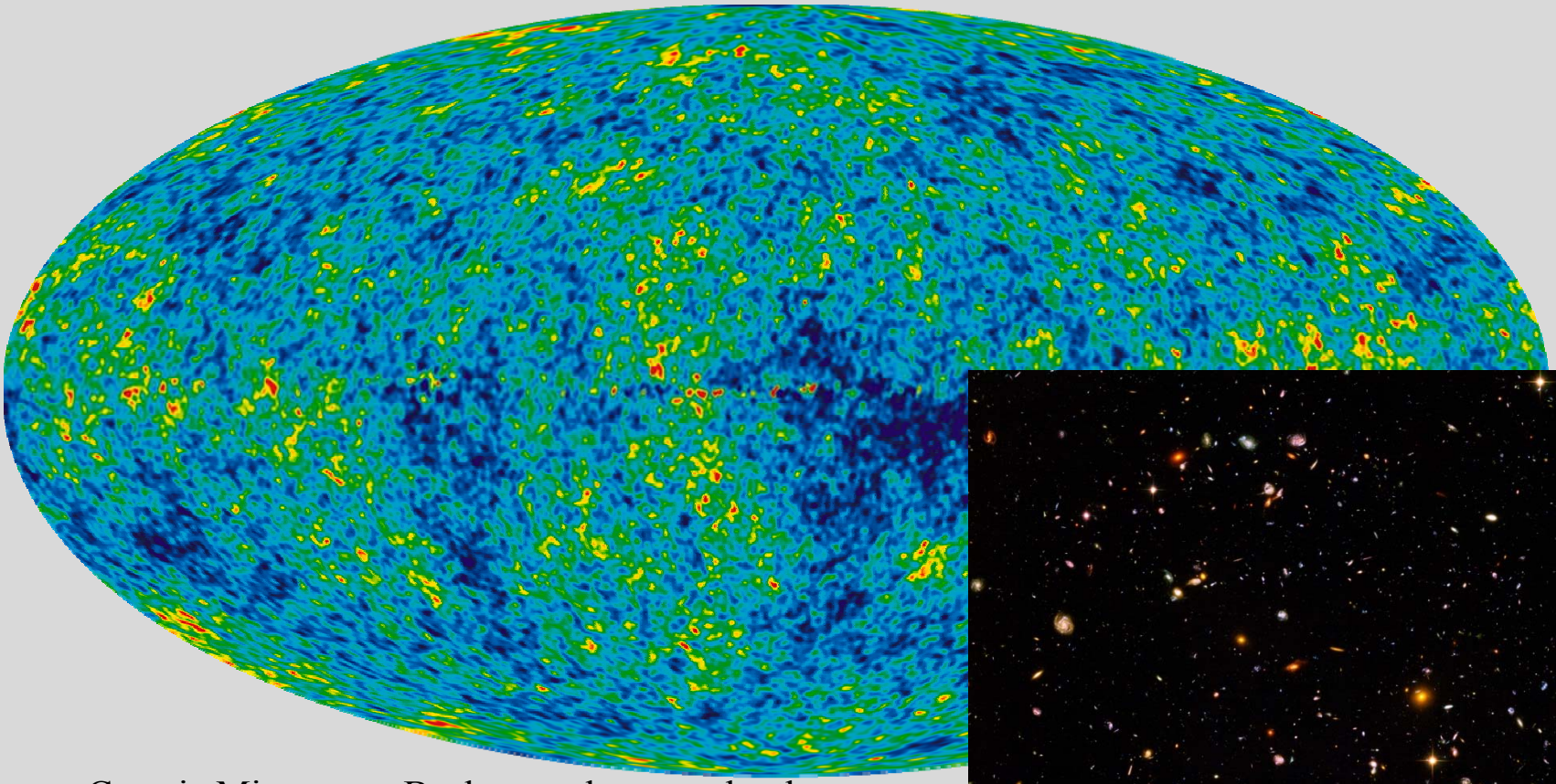
Originally postulated in the 1930s to explain galaxy ‘rotation curves’



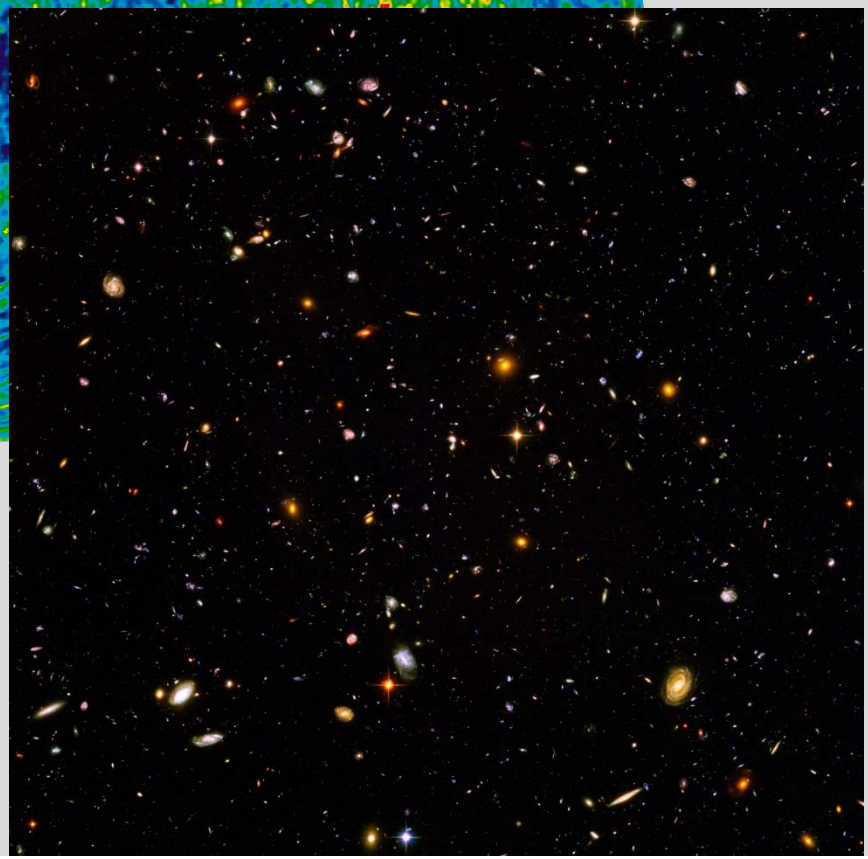
Galaxy M81 as seen from the Hubble Space Telescope



Growth of Structure



- Cosmic Microwave Background as seen by the WMAP satellite
- Remnants of the Big Bang
- 300,000 years after the Big Bang



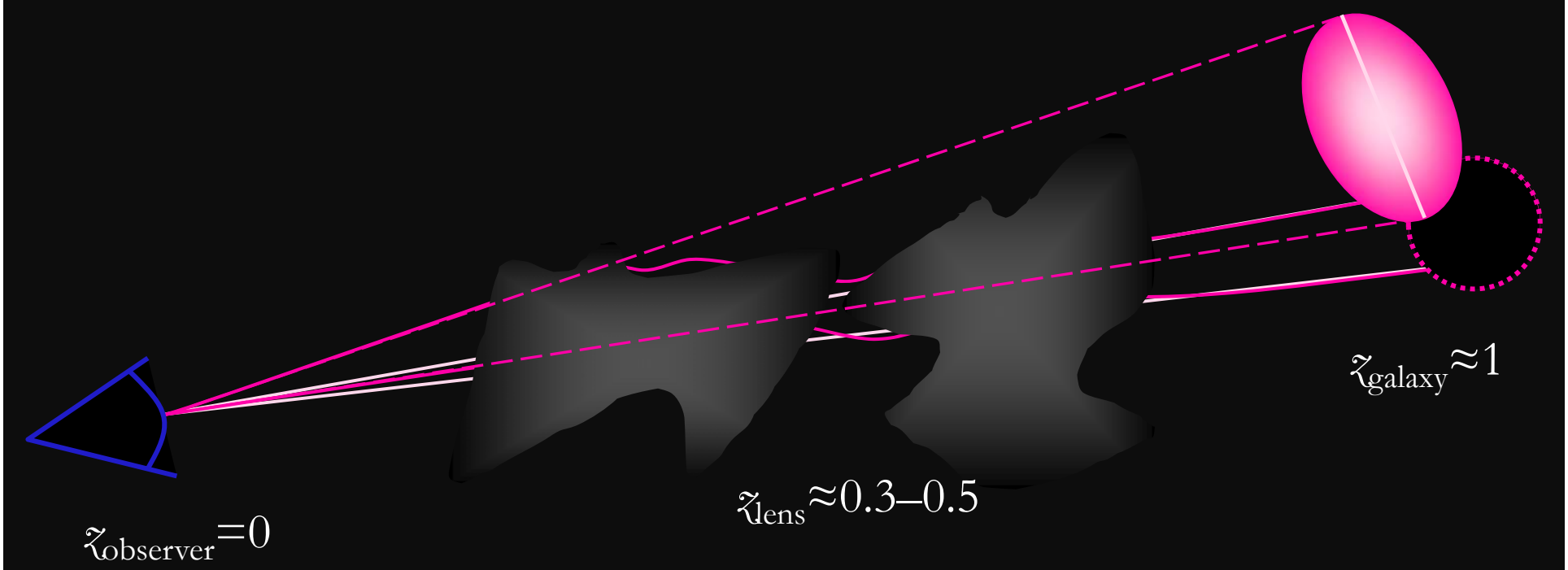
Galaxies as seen in the Hubble Ultra Deep Field

Dark Matter

- Doesn't interact electromagnetically (doesn't emit or absorb radiation)
- Not detected in a lab … yet
- Is cold (not moving relativistically)
- It isn't baryons (protons, electrons, neutrons…)
- Is collisionless (doesn't even like to interact with itself)

We can only detect it gravitationally

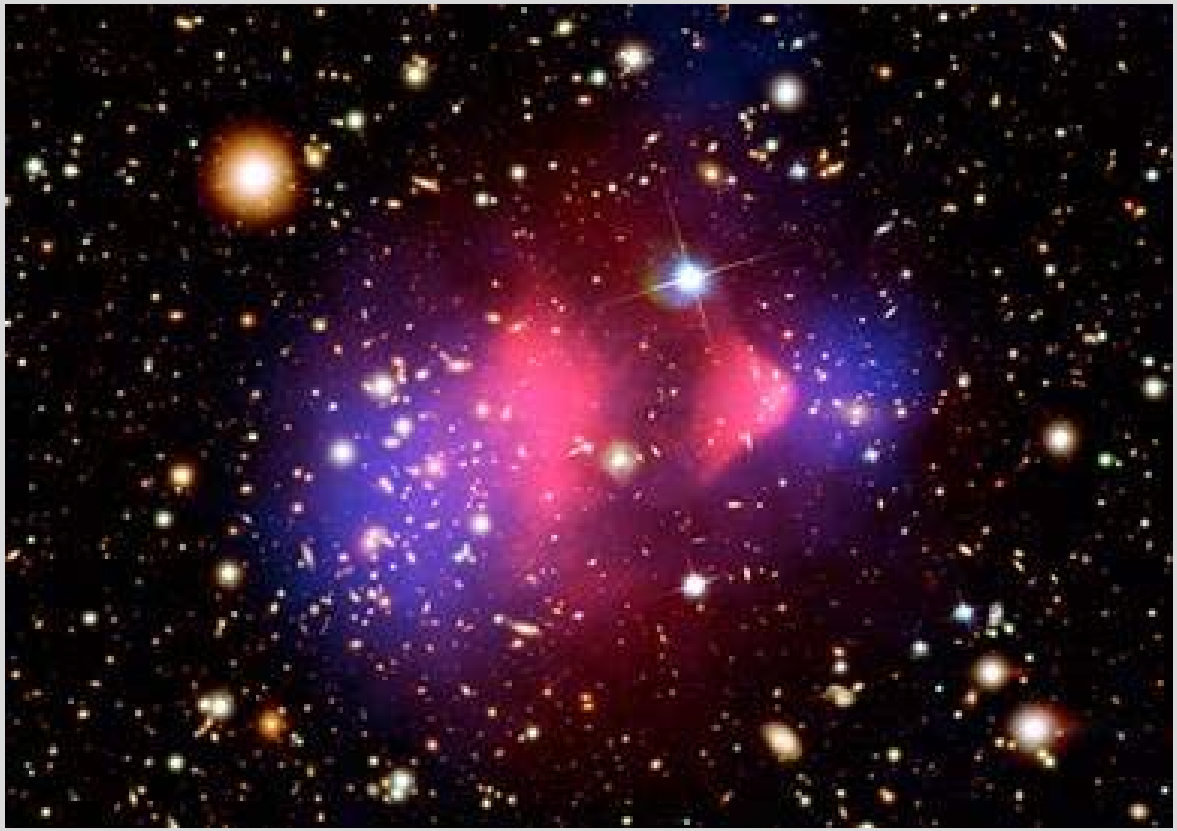
Gravitational Lensing



If there is any intervening large-scale structure, light follows the distorted path (exaggerated). Background images are magnified and sheared by ~2%, mapping a circle into an ellipse. Like glass lenses, gravitational lenses are most effective when placed half way between the source and the observer.

A Penny in the Pool

Bullet Cluster



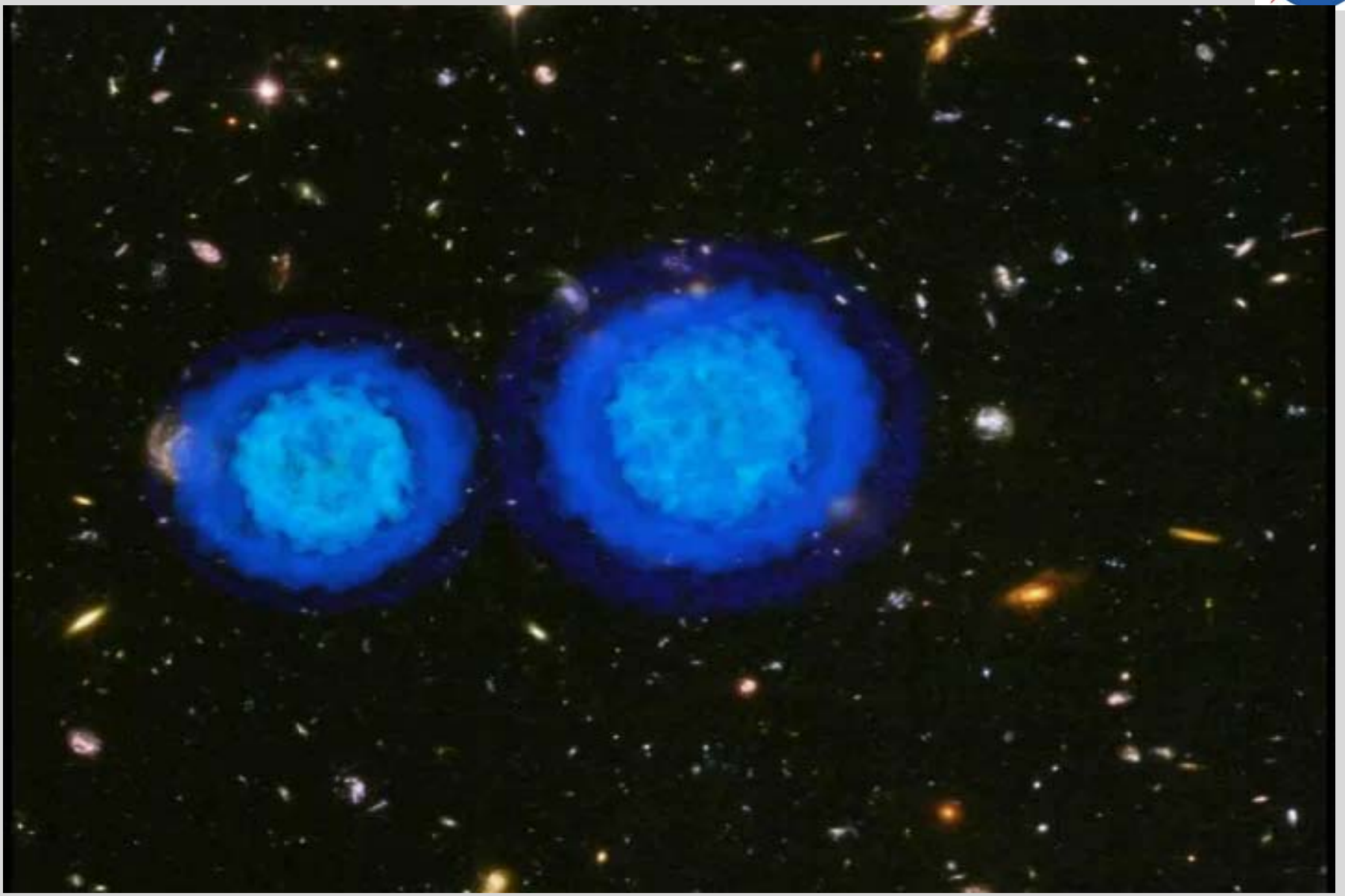
Clowe, Bradac et al 2006.

Purple is dark matter

Pink is X-ray emitting plasma (gas)

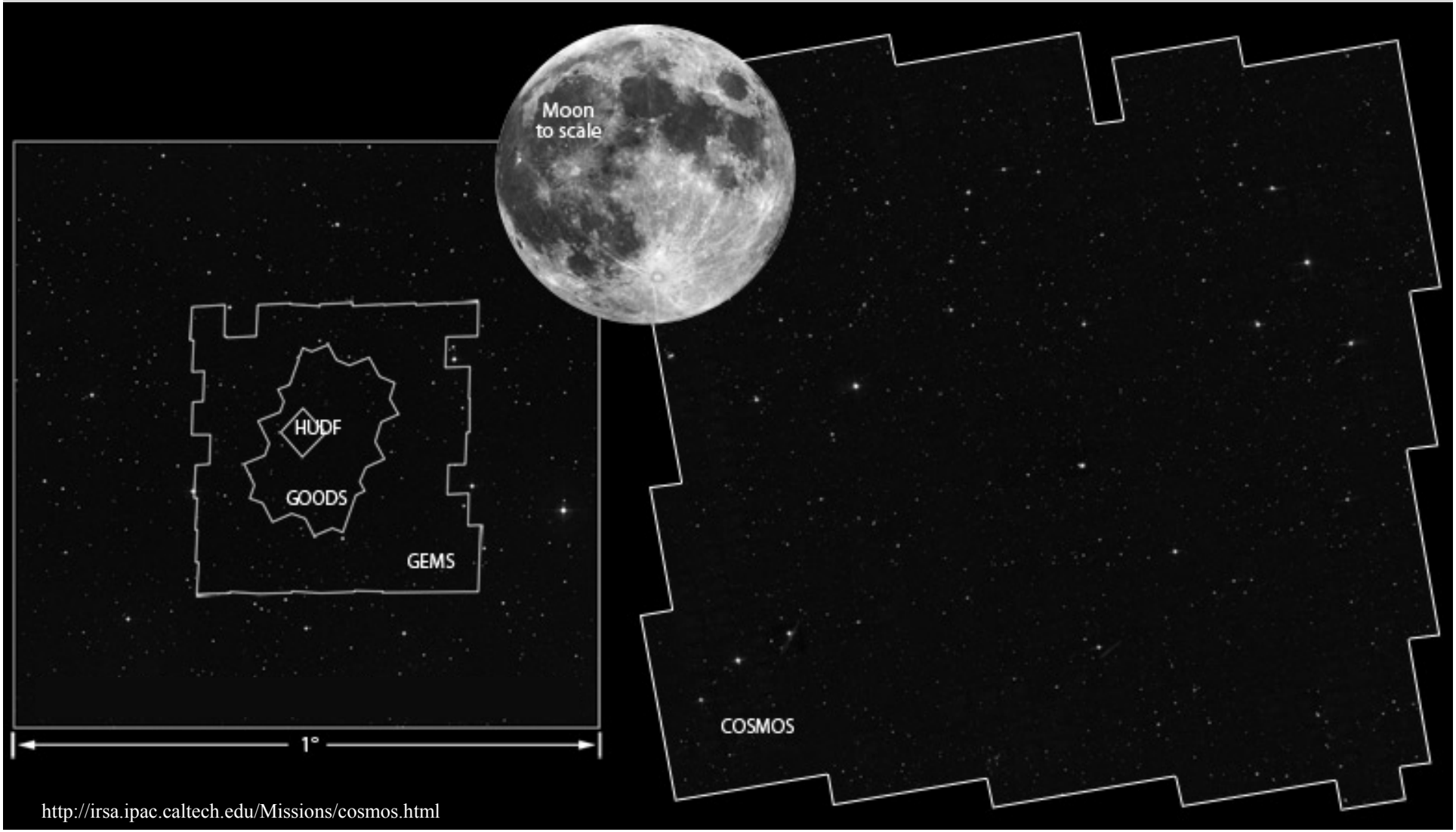
Due to the collision, the dominant baryonic component is in a different position than the total mass. Thus, most of the mass is dark matter.

Bullet Video



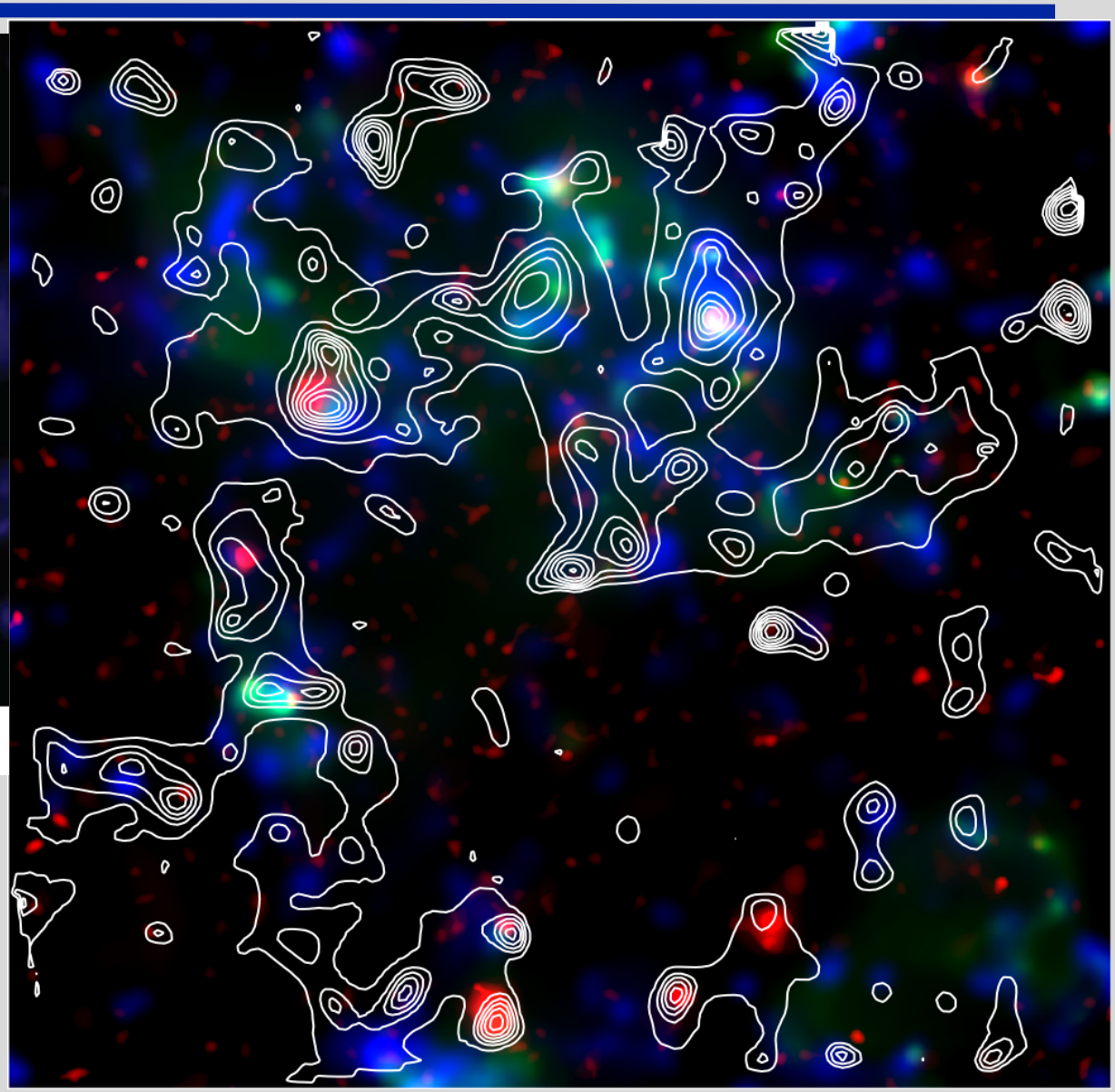
COSMOS

- About 2 square degrees
- Largest ever Hubble Space Telescope survey
- 10% of HST time for 2 years
- Exquisite high resolution
- Above the atmosphere
- Over one million galaxies



http://irsa.ipac.caltech.edu/Missions/cosmos.html

COSMOS: Mapping the Dark Matter



Weak lensing mass contours(HST)

Extended *x*-ray emission (XMM-Newton)

Galaxy number density (Subaru & CFHT)

Galaxy stellar mass (Subaru/CFHT)

Massey, Rhodes et al 2007

Two Effects

Dark Energy affects the:

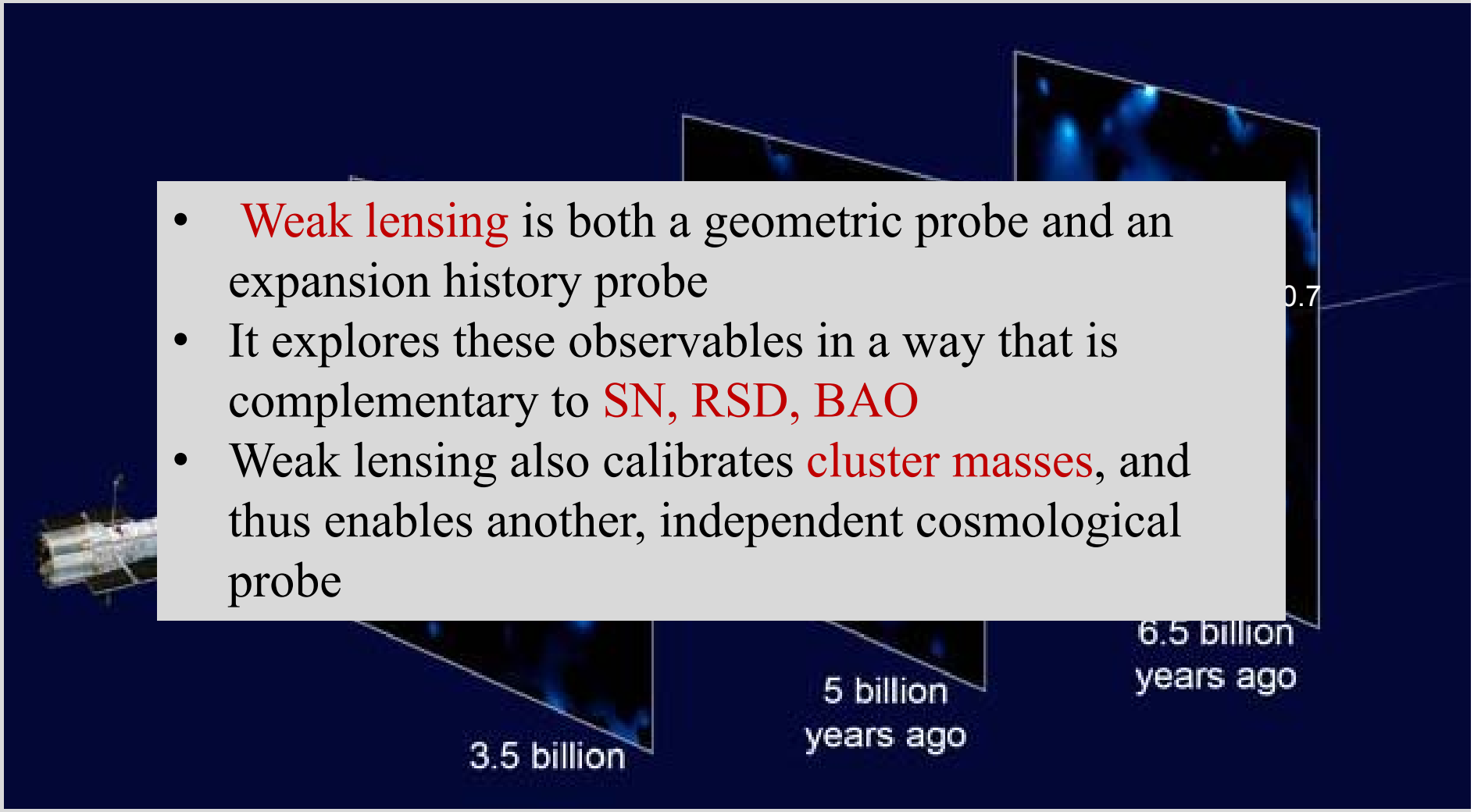
- Expansion history of the Universe
  - How fast did the Universe expand?
  - Also called the geometry of the Universe

- Growth of structures
  - How do the dark matter structures (like the ones we recently measured with Hubble) evolve and grow over time
  - Attractive gravity competes with repulsive dark energy

If Einstein's General Relativity is wrong, modified gravity theories could explain the accelerating expansion.

This would change the above effects differently, *so we must measure them both!*

Weak Lensing as a Probe of Dark Energy



- Weak lensing is both a geometric probe and an expansion history probe
- It explores these observables in a way that is complementary to SN, RSD, BAO
- Weak lensing also calibrates cluster masses, and thus enables another, independent cosmological probe

- The growth of dark matter structure is governed by the interplay of gravity (attractive) and dark energy (repulsive)
- Looking at this growth over time can tell us about dark energy AND gravity
- Weak lensing is a geometric effect, depending on source and lens distances, so it measures geometry

WL as a Probe of Acceleration

- Weak lensing is a very "clean" cosmological probe
  - —Measure the total mass so do not have to make assumptions about bias
- Measure the dark matter power spectrum, which is a probe of both expansion and geometry
- Weak lensing magnification is complementary to weak lensing shear
  - —Data comes for free and has different systematics
- Weak lensing tells us about the dark matter environment so can help us better understand other probes
  - —SN are lensed
  - —BAO and RSD measure biased mass tracers

Caveat: Weak lensing is challenging

Weak lensing- The Tall Poles

1. Systematic effects in shape measurement

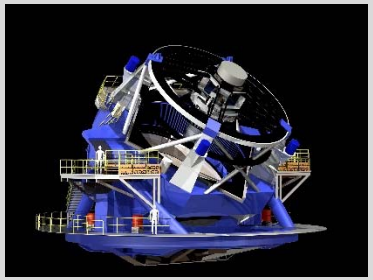
2. Photo-z accuracy and calibration

3. Intrinsic galaxy alignments

4. Computing resources and simulation accuracy needed for interpretation/covariance matrices

Euclid

WFIRST



LSST

Systematic Errors

- For cosmological applications, essentially all lensing systematics may be classified as one of three kinds:
  1. Additive, 2. Multiplicative, 3. Redshift errors

$$\hat{\gamma}(z_s) = \gamma(z_s + \underset{3}{\delta z})\left[1 + \underset{2}{\zeta}(z_s)\right] + \underset{1}{\gamma_{sys}}(z_s)$$

- Intrinsic alignment errors (1)
- Spectroscopic calibration of photo-z's (3)
- Shear calibration (2)
- PSF correction (1) (also connected to shear calibration)

Shape measurements on galaxy and star images

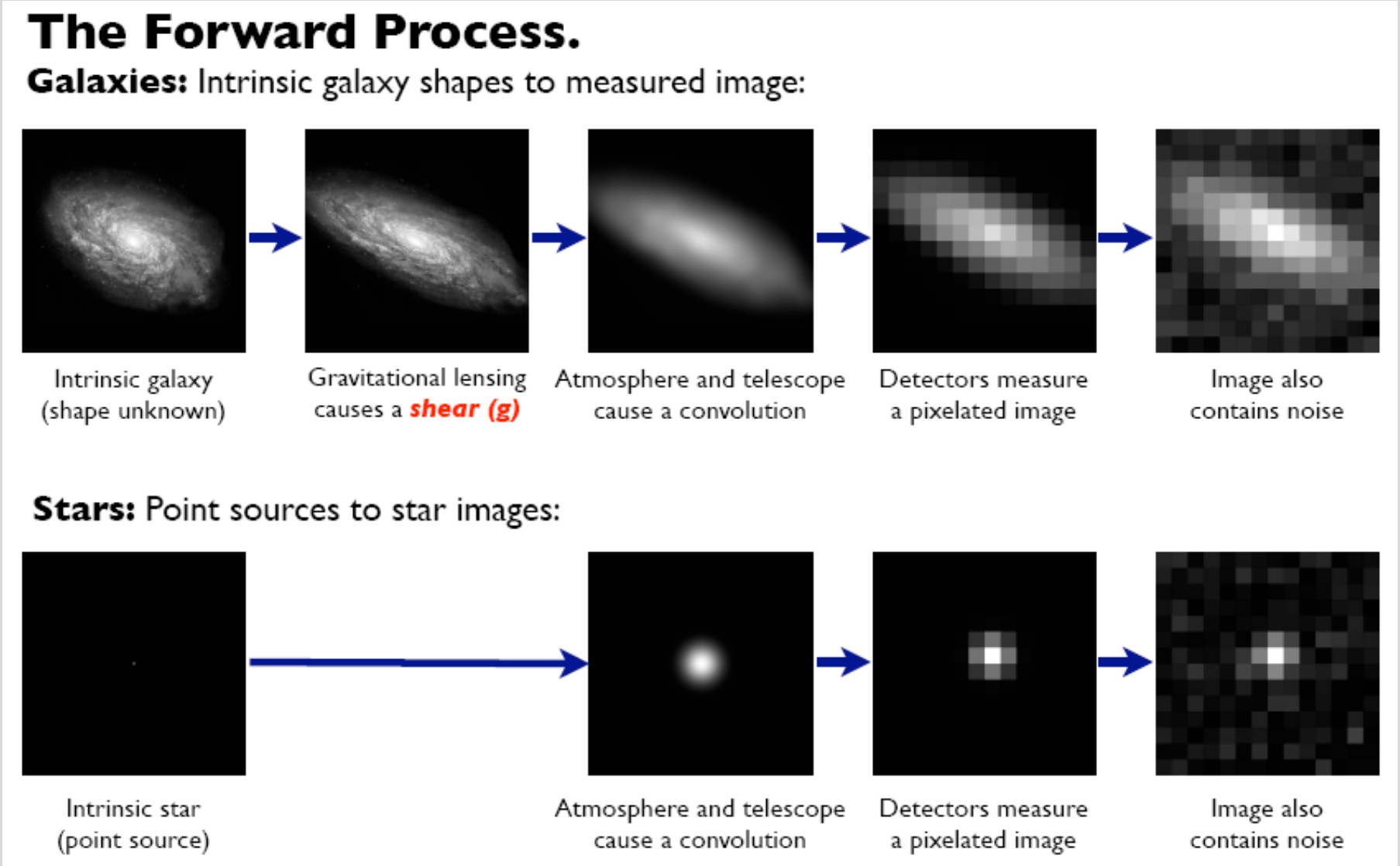


Figure from S. Bridle

Shape Measurement

- Star/galaxy separation
- PSF measurement and interpolation
- Color gradients
- Shear calibration
- Detector Effects

Requirement on Systematics

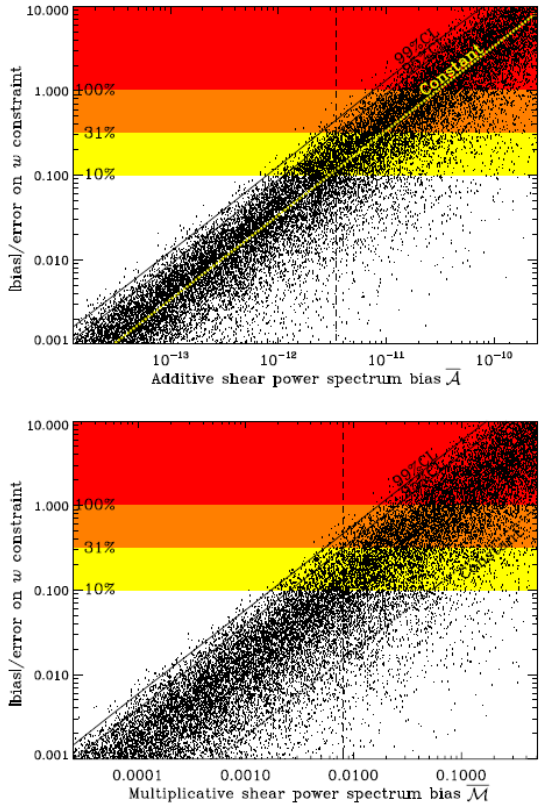


Figure 3. The bias on measurements of the dark energy equation of state parameter w from weak lensing surveys with **(top panel)** additive and **(bottom panel)** multiplicative shear measurement systematics. Each data point shows a random realisation of systematics with a unique dependence upon angular scale and redshift (for clarity, only one in three are plotted). The dotted diagonal lines show the bias on cosmological parameters if the shear measurement systematics are constant. The solid diagonal curves show limiting values that include 95% and 99% of random realisations with a given value of $\overline{\mathcal{A}}$ or $\overline{\mathcal{M}}$. An all-sky 3D cosmic shear survey will only be deemed successful if the measurement bias is $\lesssim 31\%$ of the statistical measurement error. At 95%CL, this will require (vertical dashed line) shear measurement better than $\overline{\mathcal{A}} \lesssim 3.5 \times 10^{-12}$ if $\mathcal{M} \equiv 0$, and $\overline{\mathcal{M}} \lesssim 8.0 \times 10^{-3}$ if $\mathcal{A} \equiv 0$.

- From Massey et al 2013
- Additive and multiplicative shear errors can both bias dark energy constraints
- Systematics must be kept well below statistical errors

GREAT3

- The Gravitational Lensing Accuracy Test 3 (GREAT3) was the latest in a 10+ year community effort to refine shear measurement techniques
- Finished in 2013
- Initial planning meeting for GREAT4 was held in Nov 2015

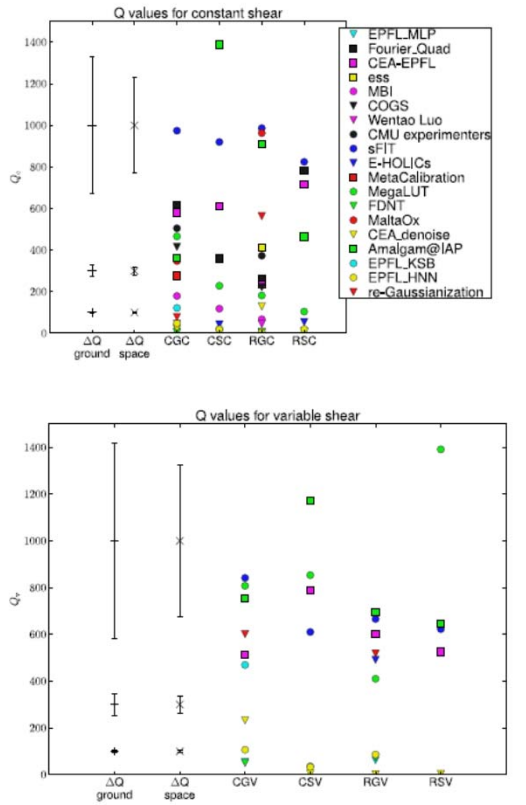


Figure 15. Q_c (top) and Q_v (bottom) for constant- and variable-shear branches in the control and realistic galaxy experiments. The errorbars show the possible range of Q values for a submission with shear calibration biases that would nominally give a particular Q value. As shown, the sizes of these ranges depend strongly on Q, and are smaller for space than for ground branches.

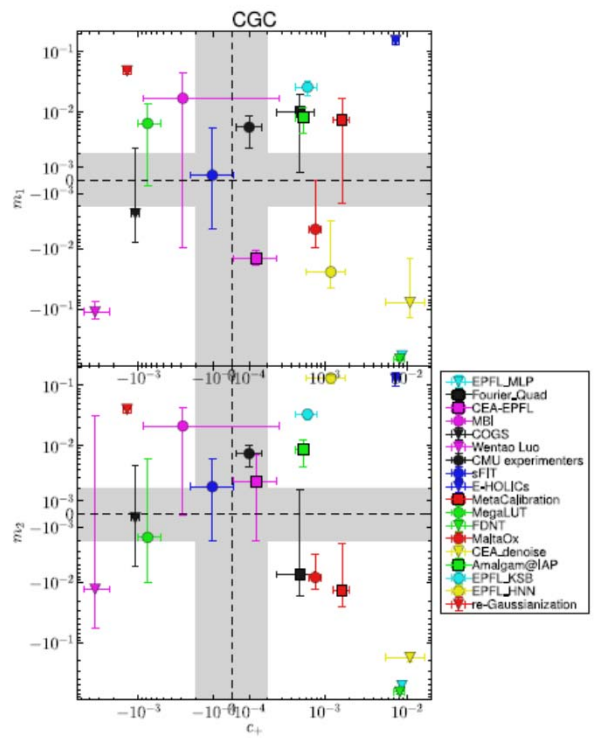
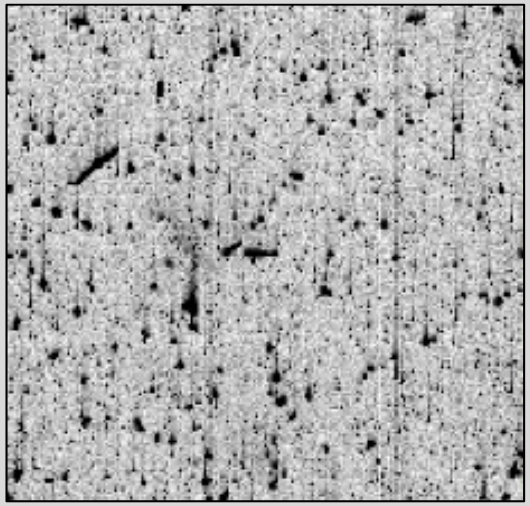


Figure 19. Shear biases for CGC, similar to Fig. 17 but using m_1 and m_2 (defined using the pixel coordinate system).

Plots from Mandelbaum et al 2015

Detector Effects

Charge Transfer Inefficiency (CTI) in CCDs



Raw ACS/WFC science exposure (Dupke 2010)

Inter-pixel capacitance (IPC) in CMOS detectors

0.002	0.02	0.002
0.02	0.912	0.02
0.002	0.02	0.002

Detector pixels

Idealized kernel showing fraction of central pixel's signal shared among neighbors

These are well-known effects that distort the PSF. CTI has taken years to mitigate for weak lensing. Work on IPC is ongoing.

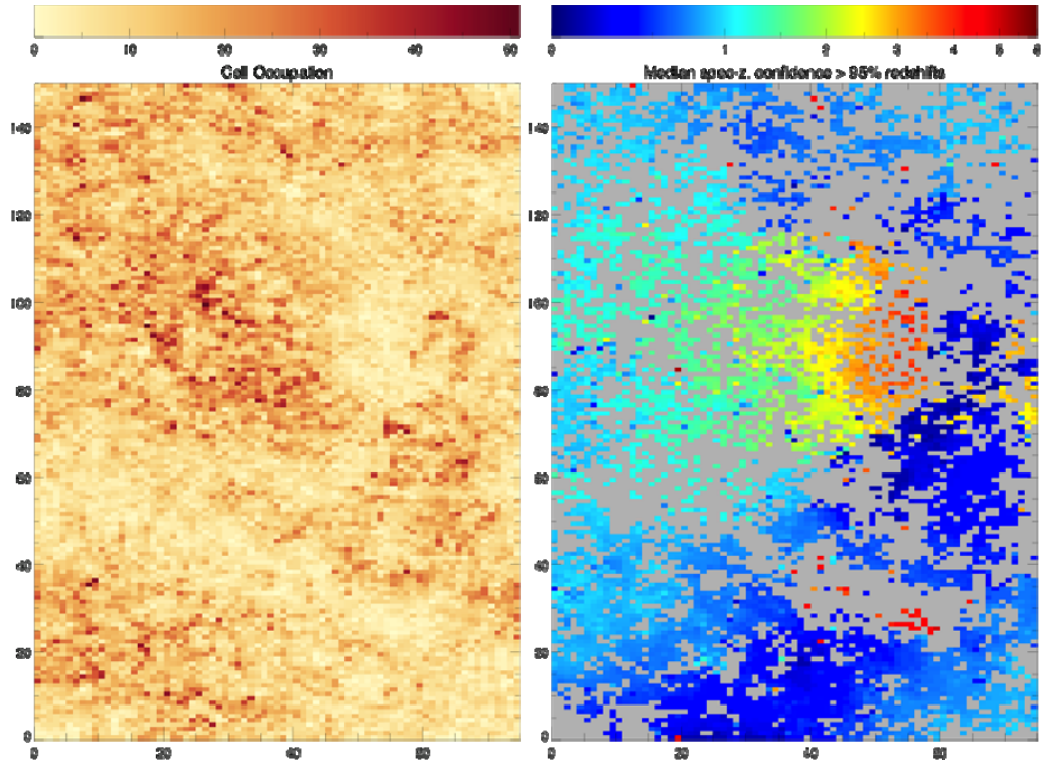
Slide From Chaz Shapiro (JPL/Caltech)

Photometric Redshifts

- Photometric depth and precision
  - Need multi-band photometry to sufficient depth across at least 4 optical and 3 near infrared bands
  - ~1% photometry
- Spectroscopic calibration
  - Need a complete sample of spectra down to the lensing depth (27-28 for next generation surveys)
- Photo-z methods
  - Like shear measurement methods, community challenges are still helping the accuracy improve

How will we achieve the challenging Euclid photometric redshift requirements?

- Photo-z bias requirement for WL presents a major challenge: the mean redshift of galaxies in WL tomographic bins must be known to better than 0.2%.
- One long-standing problem has been to understand the *representativeness* of existing spectroscopic samples with respect to the full photometric sample.
- Incomplete or unrepresentative spec-z training and calibration samples can easily lead to significant biases in photo-z estimates, particularly for machine learning methods.
- We developed a method based on the self-organizing map (SOM; Kohonen 1995), to empirically map the diistribution of galaxy SEDs in the high-dimensional color space probed by the Euclid broadband filters (**Masters, Capak, Stern** et al. 2015, ApJ, **813**, 53).
- This high-dimensional mapping directly addresses the representativeness of existing spec-z samples in galaxy parameter space, and points the way to calibration strategies moving forward.



Left: The density of galaxies from COSMOS on the SOM. This is our estimate of the density of galaxies as a function of position in color space, $\rho(C)$. *Right:* The map colored by the median spectroscopic redshift of high-quality spec-z objects in each cell. The gray regions are parts of color space for which no high-quality spectroscopic redshifts have been obtained, which represents ~50% of the cells

Slide from Capak and Masters (IPAC)

Keck spectroscopic surveys for photo-z

What photo-z calibration sample is required?

• SOM framework answers this challenging question: we need to target the ~50% of cells in the SOM lacking high-quality spectroscopic redshifts (based on COSMOS + DEEP2 redshift surveys).

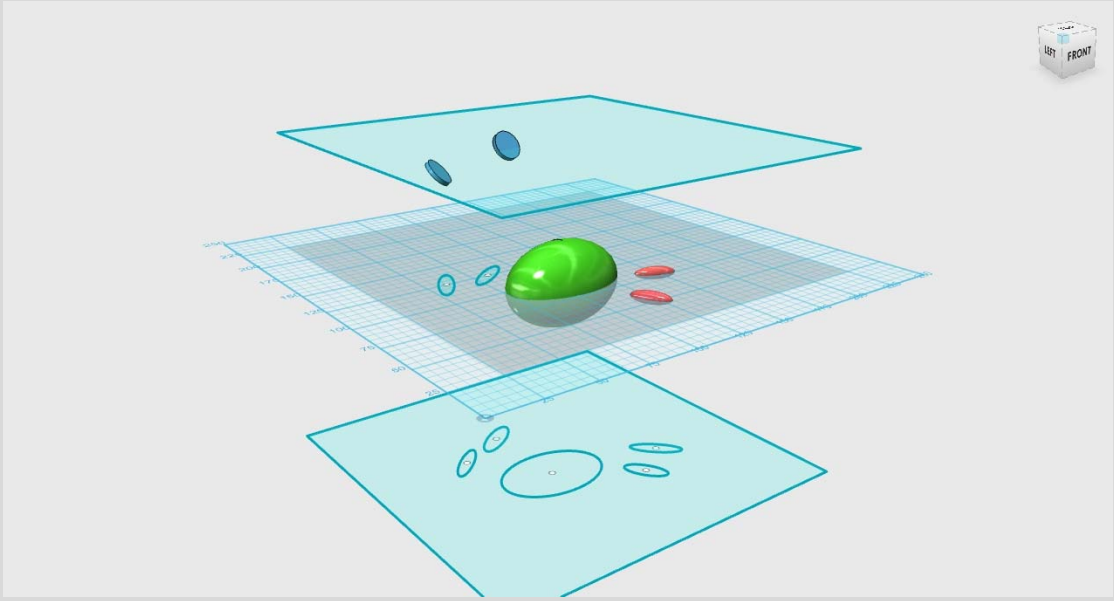
- SOM has made a previously intractable problem tractable.

•We require ~5000 spectroscopic redshifts (selected across the six Euclid calibration fields – COSMOS, ECDFS, SXDS, VVDS-2hr, GOODS-N and EGS) to provide at least one spectroscopic redshift for essentially the entire SOM (with small percentage of the most difficult cells dropped).

• **Masters** et al. (2015) describes how this could be done in a 40 night Keck program using the suite of Keck multi-object spectrographs (with suitable allowances for bad weather, repeated targets, etc…).

Galaxy Intrinsic Alignments

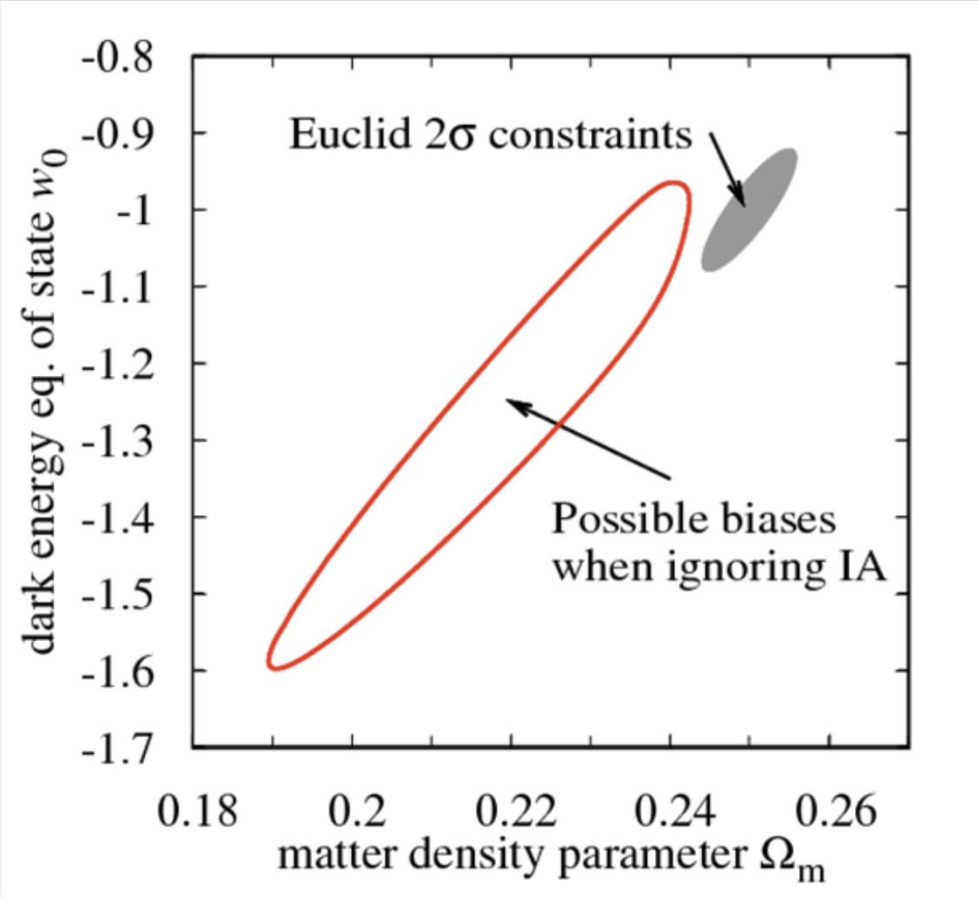
- Two types of primordial alignments that can enhance or dilute the cosmic signal
- Largest astrophysical systematic



From Joachimi et al 2015

- Light travels downward
- Cyan (distant) galaxies are gravitationally lensed to have correlated shapes- **signal**!
- Pink galaxies are intrinsically aligned during formation- contaminant
- Pink and cyan galaxy images are anti-aligned – contaminant
- Accurate photo-zs are necessary (but not sufficient) to mitigate this
- Work on modeling still needed

Intrinsic Alignments



- Example Euclid constraints (gray) and possible biases if IA are ignored (Joachimi et al 2011)
- Modeling and understanding sources of IA is key

Cosmological Simulations: Computing

- To understand results, high resolution, large scale numerical simulations are needed
- Dark matter only at first, but eventually need complicated baryon physics (it's not just gravity!)
- Many different cosmological models must be simulated, increasing the computing problem by orders of magnitude

Experimental Data	2013	2020	2030+
Storage	1PB	6PB	100-1500PB
Cores	10^3	70K	300+K
CPU hours	$3x10^6$ hrs	2×10^8 hrs	$\sim 10^9$ hrs
Simulations	2013	2020	2030+
Storage	1-10 PB	10-100PB	> 100PB - 1EB
Cores	0.1-1M	10-100M	> 1G
CPU hours	200M	>20G	> 100G

Table Credit: Connolly et al, 2013

Simulations: Is Dark Matter Collisionless?

ΛCDM simulations show no offset between DM and stars (both collisionless)

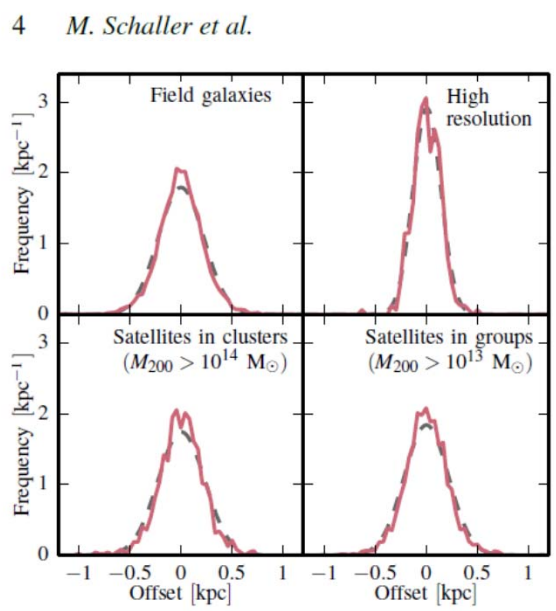
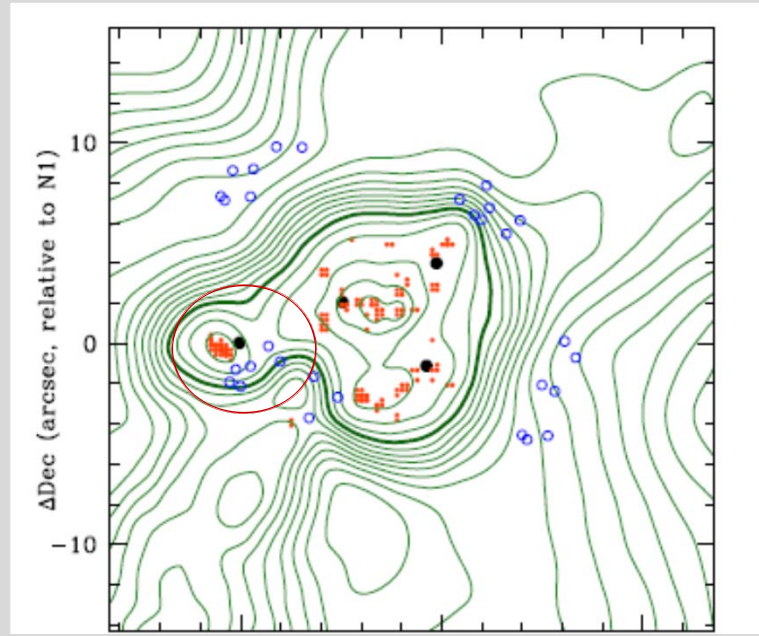


Figure 2. The offset between the centre of the dark matter distribution and stellar distribution along the axis of motion of the stellar distribution for galaxies with a stellar mass $M_\star > 10^9 M_\odot$. The different panels correspond to the same subsets of galaxies as in Fig. 1. The dashed grey curves in the background show a Gaussian distribution with the same mean and standard deviation as the offset distributions. The distribution of offsets displays no bias towards trailing or leading motion of the dark matter centre with respect to the luminous centre and only deviates from a normal distribution by displaying a positive kurtosis.

But we have tantalizing first glimpses that DM may have a small, but non-zero self interaction cross section



Massey et al 2015

Figure 4. *Top panel:* Map of total mass in the cluster core, reconstructed using GRALE. Green contours show the projected mass density, spaced logarithmically by a factor 1.15; the thick contour shows convergence $\kappa = 1$ for $z_{c\ell} = 0.099$ and $z_A = 1.24$ ($\Sigma_{crit} = 1.03\,g/cm^2$). Red dots show local maxima in individual realisations of the mass map. Black dots show cluster ellipticals N.1–N.4. Blue circles show the lensed images. *Middle panel:* Mass after

We need to understand the detailed characteristics of DM and how baryons behave in order to simulate, and interpret our results

Current Generation

DARK ENERGY SURVEY

5000 square degrees
2013-2018
Blanco 4m Telescope

HSC

HyperSuprimeCam Survey

1400 square degrees
2014-2018
Subaru 8m telescope

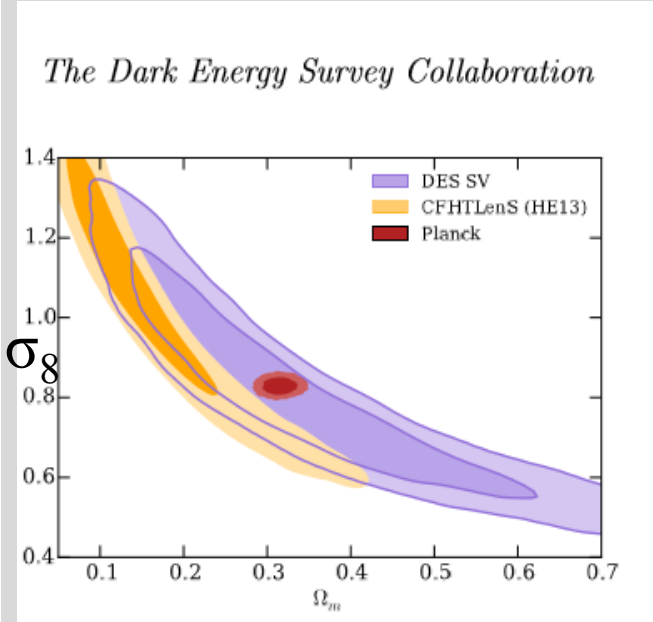
KiloDegree Survey

1500 square degrees
2011-2017
VLT Survey Telescope 2.6m

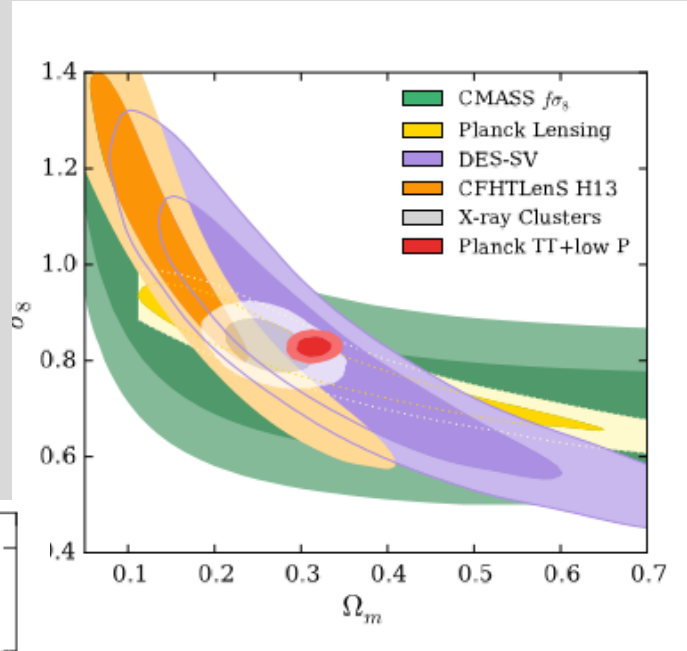
- Starting to see cosmological results
- Will inform survey design and data analysis for future experiments

DES Results

Science Verification Data is 139 square degrees (< 3% of total survey)



Huge leverage when combined with other probes



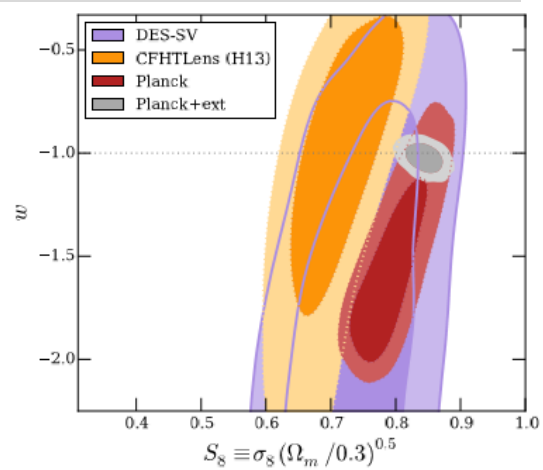


Figure 12. Constraints on the dark energy equation of state w and $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$, from DES SV (purple), Planck (red), CFHTLenS (orange), and Planck+ext (grey). DES SV is consistent with Planck at $w = -1$. The constraints on S_8 from DES SV alone are also generally robust to variation in w.

Already competitive with largest extant WL survey

Competitive with other cosmological constraints

From DES arxiv:1507.05552

The next decade

	LSST	Euclid	WFIRST
Proposed lifetime	2022 - 2032	2021 - 2027	2024 - 2030
Mirror size (m)	6.5 (effective diameter)	1.2	2.4
Survey size (sq deg)	20,000	15,000	2,227
Median z (WL)	0.9	1.0	1.2
Depth (AB mag)	~27.5	~24.5	~27
FoV (sq deg)	9.6	0.5 (Vis) 0.5 (NIR)	0.28
Filters	u-g-r-i-z-y	Y-J-H-Vis	Y-J-H-F184
Cosmological probes	WL, LSS, SN, SL, Cl	WL, LSS, SL, Cl,	WL, LSS, SN, SL, Cl