Probing Dark Energy with Gravitational Lensing

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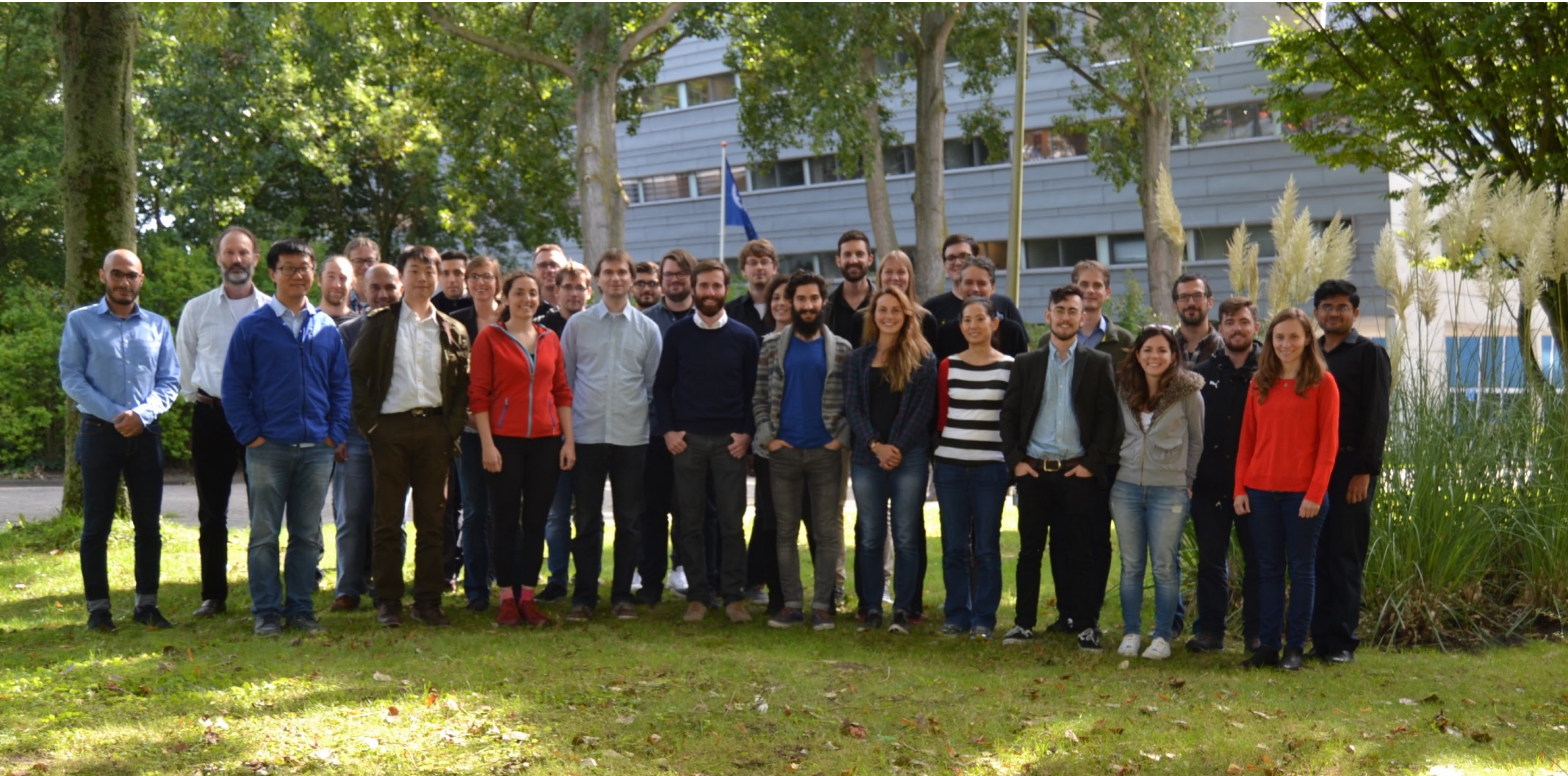
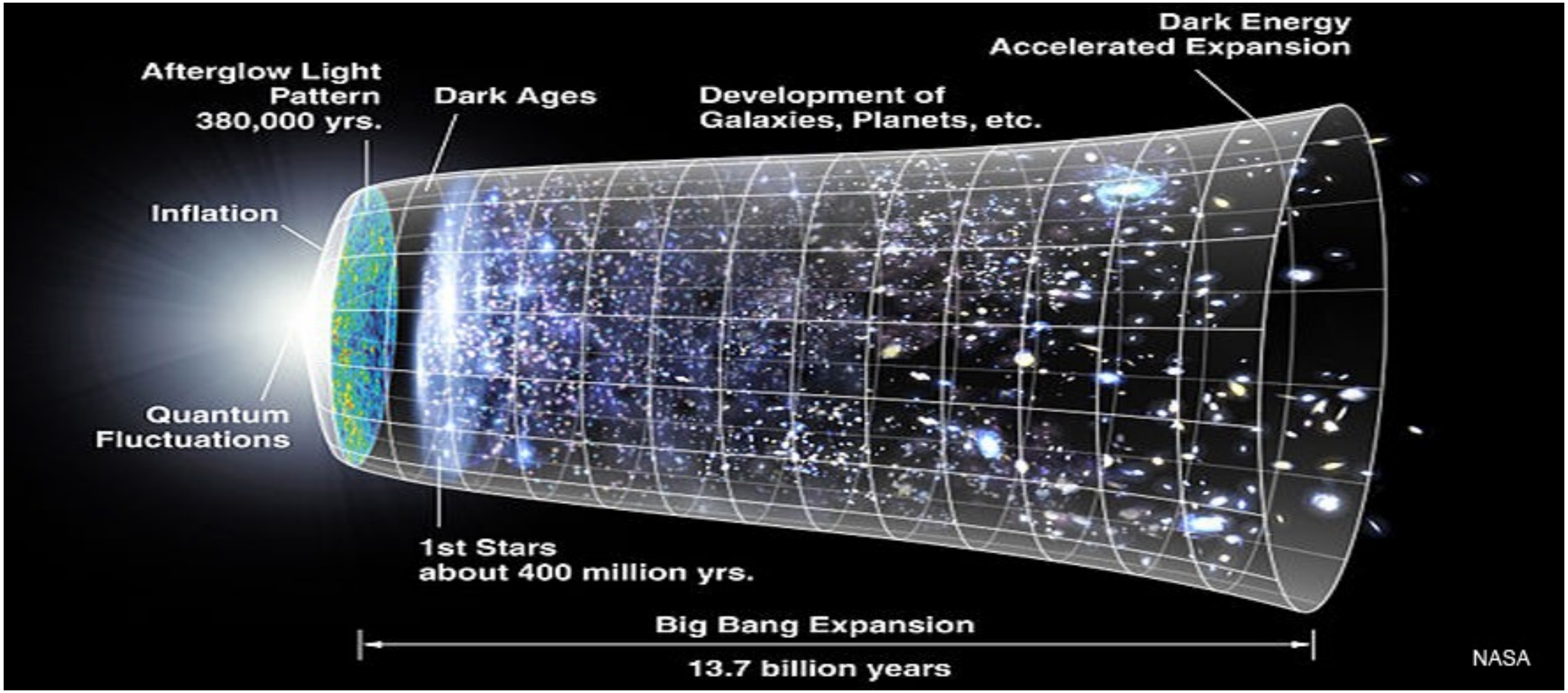
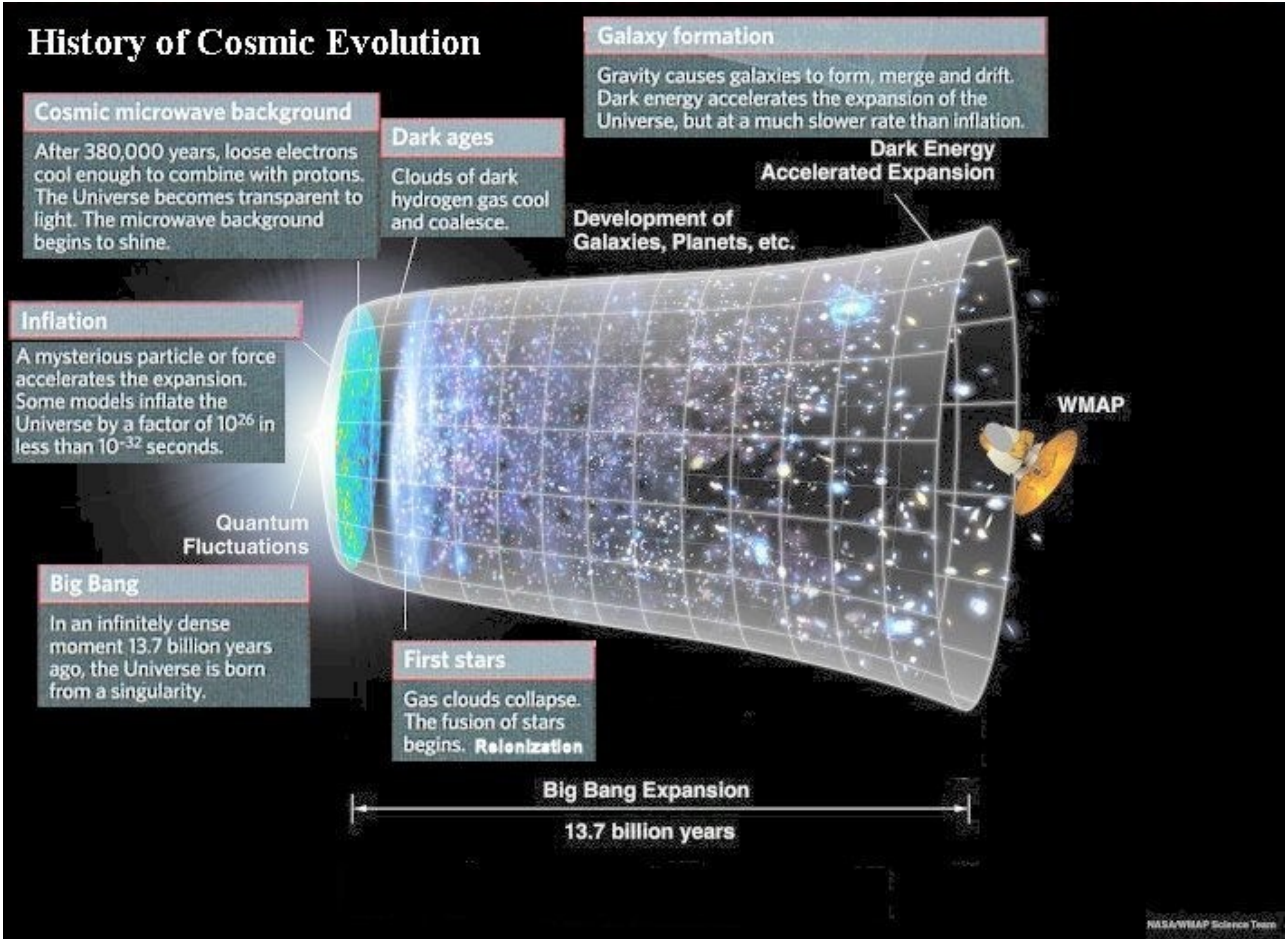
We are the KiDS



Brief history of the Universe




History of Cosmic Evolution
Cosmic microwave background
After 380,000 years, loose electrons cool enough to combine with protons. The Universe becomes transparent to light. The microwave background begins to shine.
Dark ages
Clouds of dark hydrogen gas cool and coalesce.
Galaxy formation
Gravity causes galaxies to form, merge and drift. Dark energy accelerates the expansion of the Universe, but at a much slower rate than inflation.
Dark Energy
Accelerated Expansion
Development of Galaxies, Planets, etc.
Inflation
A mysterious particle or force accelerates the expansion. Some models inflate the Universe by a factor of 10^{26} in less than 10^{-32} seconds.
WMAP
Quantum Fluctuations
Big Bang
In an infinitely dense moment 13.7 billion years ago, the Universe is born from a singularity.
First stars
Gas clouds collapse. The fusion of stars begins. Reionization
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Standard Model of Cosmology

= GR + Cosmological constant + cold Dark Matter +
some 'regular' matter / SM particle physics

$$S = \frac{1}{16\pi G}\int \mathrm{d}^4 x \sqrt{-g}(R - 2\Lambda)$$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G\left(T_{\mu\nu} + \frac{\Lambda}{8\pi G}g_{\mu\nu}\right)$$

$$T^{\mu\nu} = (\rho + p)\,U^{\mu}U^{\nu} - pg^{\mu\nu}$$

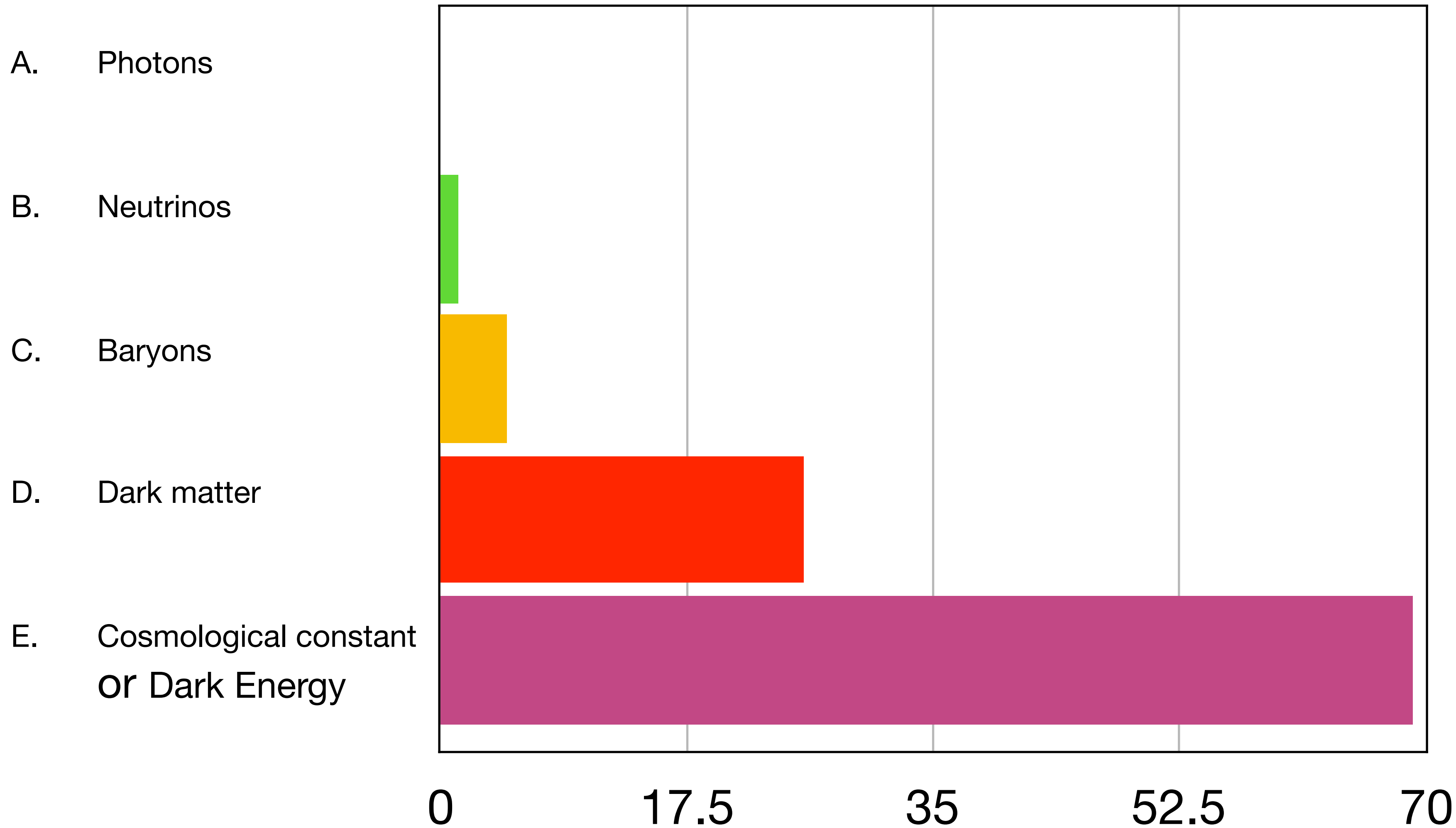
Cosmological principle: The Universe is homogenous and isotropic at large scales

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\mathrm{d}\chi^2 = -\mathrm{d}t^2 + a^2(t)\left(\frac{\mathrm{d}r^2}{1 - kr^2} + r^2\left(\sin^2\theta\mathrm{d}\varphi^2 + \mathrm{d}\theta^2\right)\right)$$

$$H(t) = \frac{\dot{a}(t)}{a(t)}$$

$$1 + z = \frac{a(t)}{a_0} \qquad a_0 \equiv a(t_0) = 1 \ (t_0 - \mathrm{today})$$

Cosmic inventory



Six free parameters

1. Age of the Universe
2. Amplitude of the primordial PS
3. Exponent of the primordial PS
4. Quantity of matter
5. Quantity of DE / CC
6. Reionization optical depth

$$H(t) = H_0 \left[\Omega_{r,0} a(t)^{-4} + \Omega_{m,0} a(t)^{-3} + \underbrace{\left(-\frac{k}{H_0^2} \right)}_{\Omega_{k,0}} a(t)^{-2} + \underbrace{\frac{\Lambda}{3H_0^2}}_{\Omega_\Lambda} \right]^{1/2}$$

$$t = \frac{1}{H_0} \int_0^{a(t)} \mathrm{d}a \left[\Omega_{r,0} a^{-4} + \Omega_{m,0} a^{-3} + \Omega_{k,0} a^{-2} + \Omega_\Lambda \right]^{-1/2}$$

What is Dark Energy?

- The Universe is expanding and the expansion is accelerating.
- The Universe is flat, but there isn't enough matter.
- Incidentally, the energy required to cause the acceleration matches the missing amount of matter (mass ~ energy)

"We don't know what is. We don't know what it wants. What we do have is a particular set of skills; skills we have acquired over a century. If it turns out to be cosmological constant, that will be the end of it - we will not look for it, we will not pursue it. But if it isn't, we will look for it. We will find it. And we will name it Dark Energy."

- Taken from Liam Neeson (2008)

Equation of state

- Dark energy is modeled as a ‘dynamical’ homogenous field.
- $p = w\rho$
- For cosmological constant, $w = -1$
- We look for difference from $w = -1$
- Standard parametrisation:

$$\begin{aligned} w(a) &= w_0 + (1-a)w_a \\ &= w_p + (a_p - a)w_a \end{aligned}$$

Toy model for Dark Energy

Scalar field as a candidate for Dark Energy

$$S = \frac{1}{2}\mathrm{d}^4 x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

EoM in expanding flat space

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

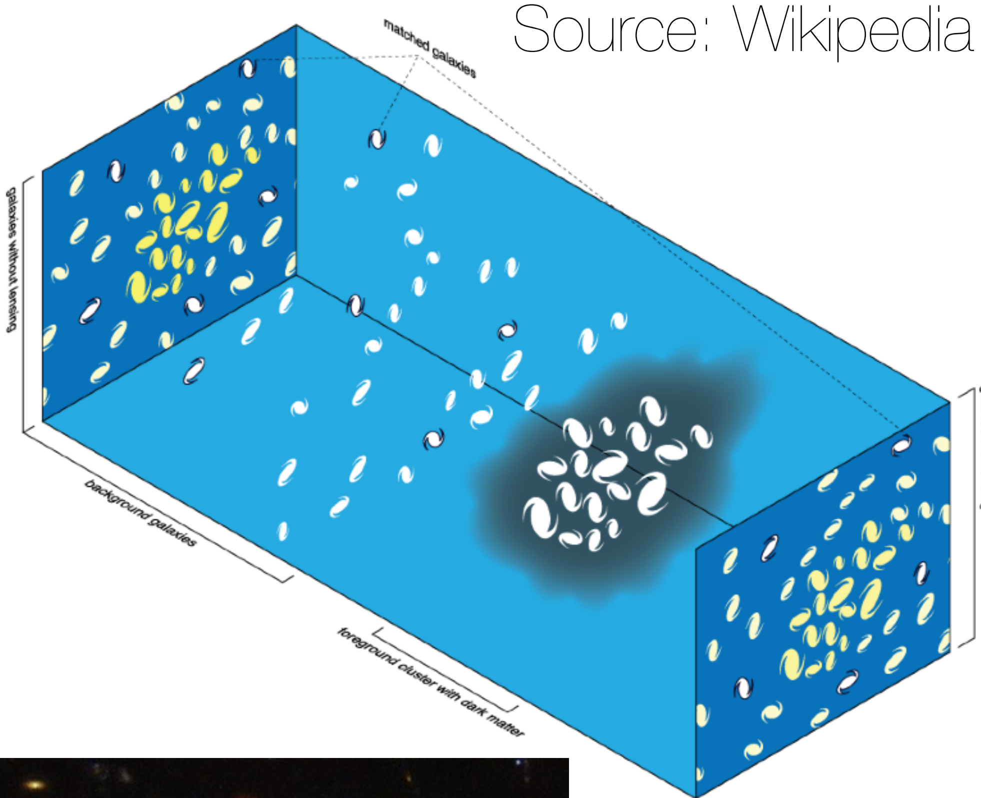
$$\frac{p}{\rho} = w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

The field loses its kinetic energy due to the ‘Hubble drag’

If the minimum has non-zero potential, the scalar field can mimic the Cosmological constant at late times

How can we find Dark Energy?

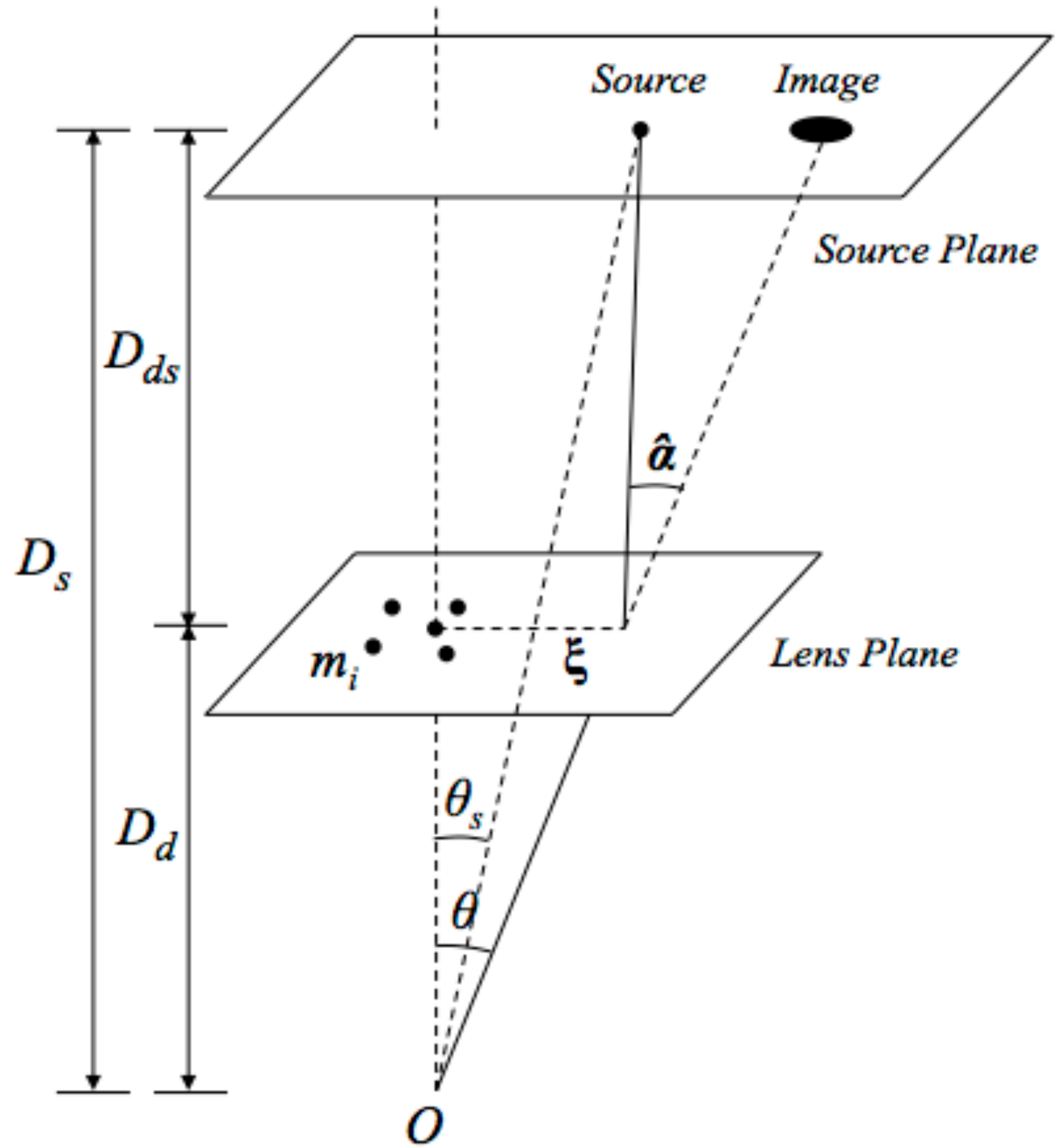
Source: Wikipedia



- With dark matter!
- Clumps of dark matter create tidal gravitational field that can deflect light
- Background galaxies appear distorted by foreground masses
- Lensing can inform about DE by probing the growth of structures at different epochs

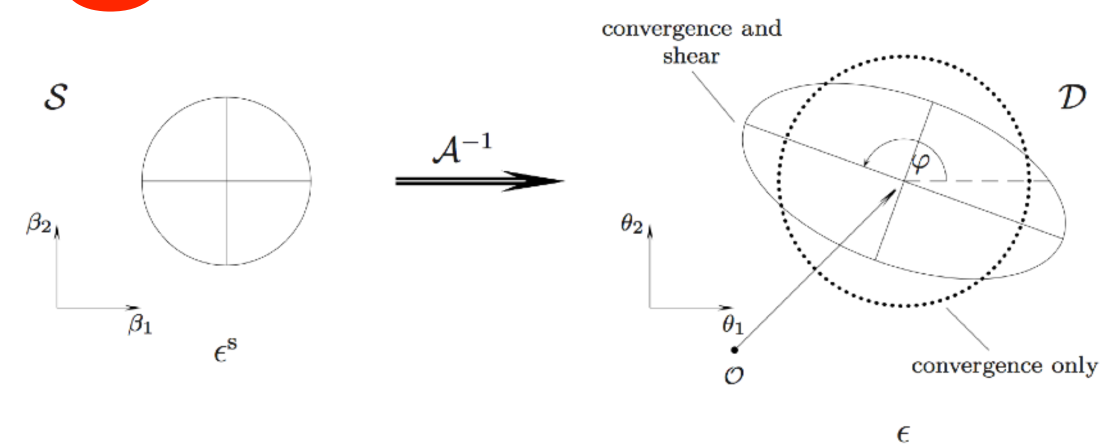
Lensing Primer

- Mathematically, lensing is a coordinate transformation in the sky
- To lowest order, lensing is characterized by the Jacobian of this transformation
- Observables are (transformed) size and ellipticity of galaxies
- Higher order lensing effects are capture by ‘flexion’



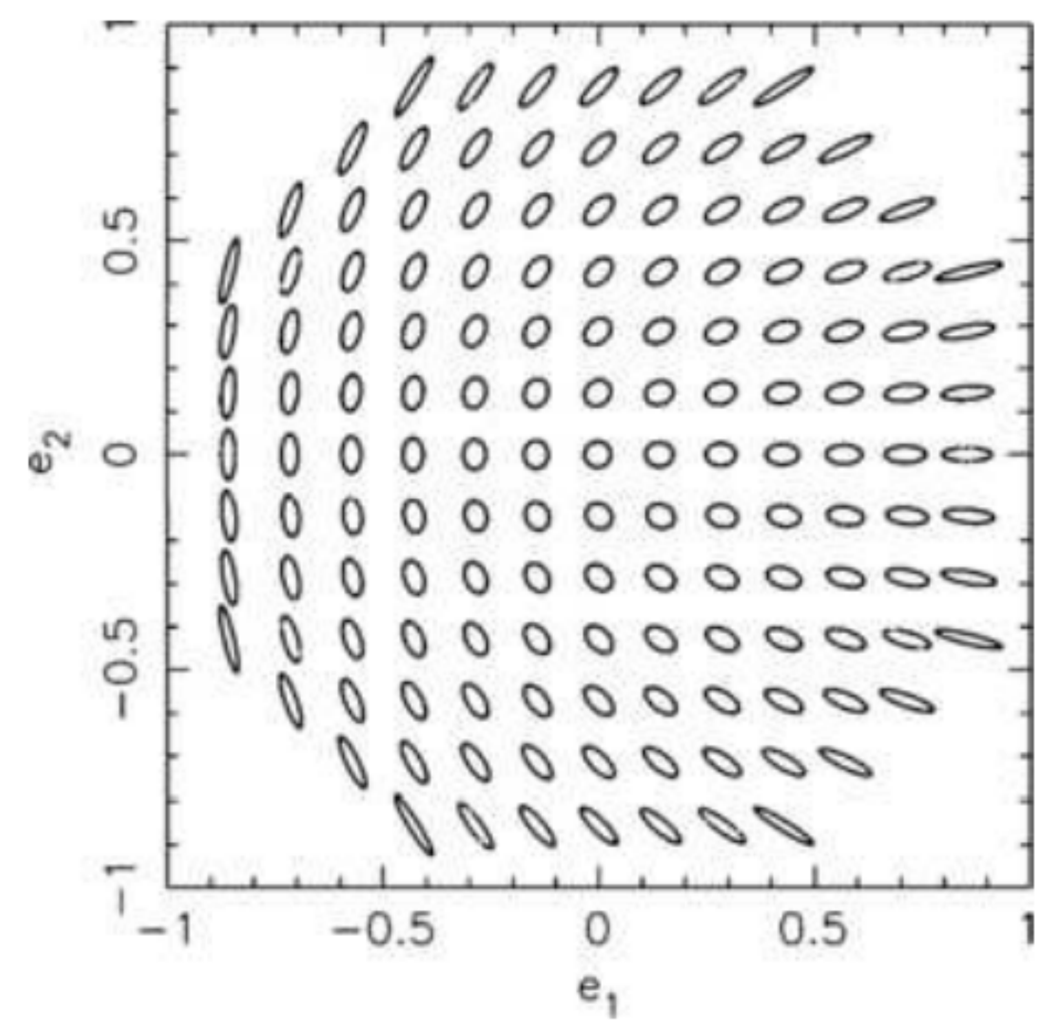
(Weak) Lensing Primer

$$\mathcal{A} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ +\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$



- To lowest order, lensing is characterized by convergence and a 2-component shear

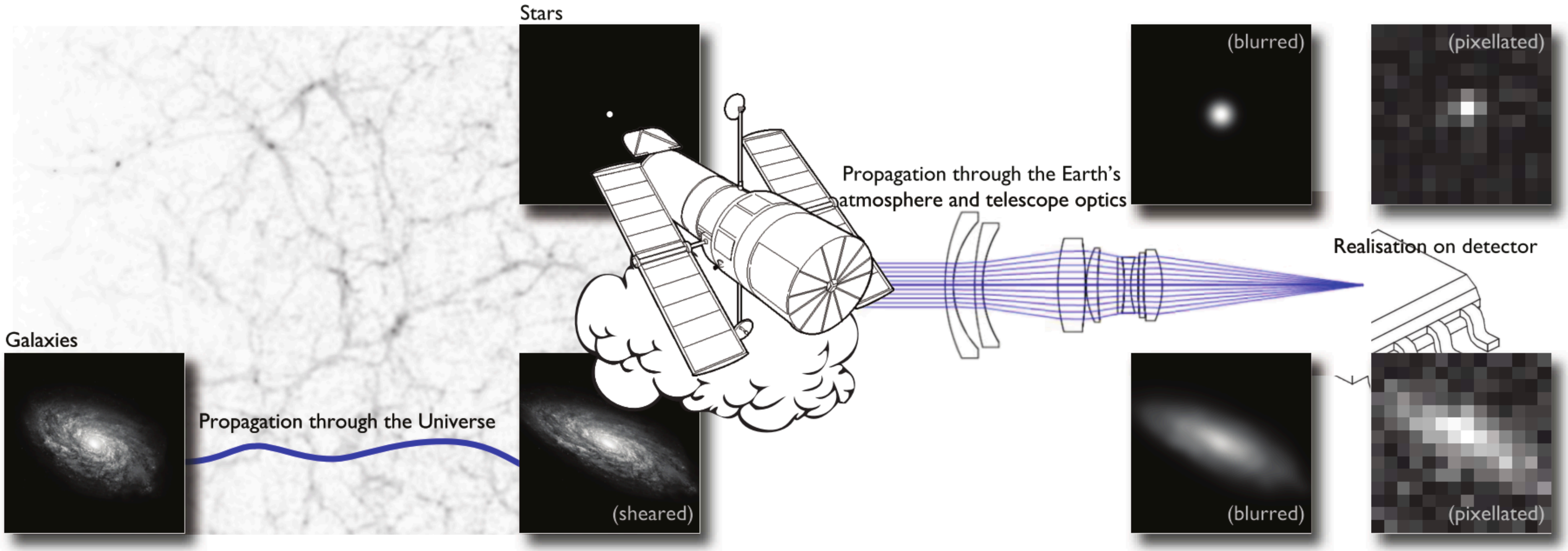
- Observables are size and ellipticity of galaxies



$$|\epsilon| = \frac{a-b}{a+b} \qquad \epsilon = |\epsilon|e^{2i\phi} = \epsilon_1 + i\epsilon_2$$

$$\epsilon^{(\mathrm{obs})} = \frac{\epsilon^{(\mathrm{int})} + g}{1 - g^*\epsilon^{(\mathrm{int})}} \approx \epsilon^{(\mathrm{int})} + \gamma$$

Weak Lensing is difficult



Source: GREAT3 handbook (Mandelbaum+ 2014)

- Currently a systematic dominated field
- Observational systematics: PSF correction, noise bias, detector effects, …
- Astrophysical systematics: Intrinsic alignments, Baryonic physics, Colour gradients, …

Cosmic shear

Cosmic shear refers to lensing by the LSS of the Universe

$$\xi_{\gamma_i\gamma_j}(\boldsymbol{\theta}) = \langle \boldsymbol{\gamma}_i(\boldsymbol{\theta}_1) \cdot \boldsymbol{\gamma}_j^*(\boldsymbol{\theta}_2) \rangle$$

i,j refer to redshift bins

$$\xi_+(\theta) = \langle \gamma_{i+}(\boldsymbol{\theta}_1)\gamma_{j+}(\boldsymbol{\theta}_2) \rangle$$

$$\xi_\times(\theta) = \langle \gamma_{i\times}(\boldsymbol{\theta}_1)\gamma_{j\times}(\boldsymbol{\theta}_2) \rangle$$

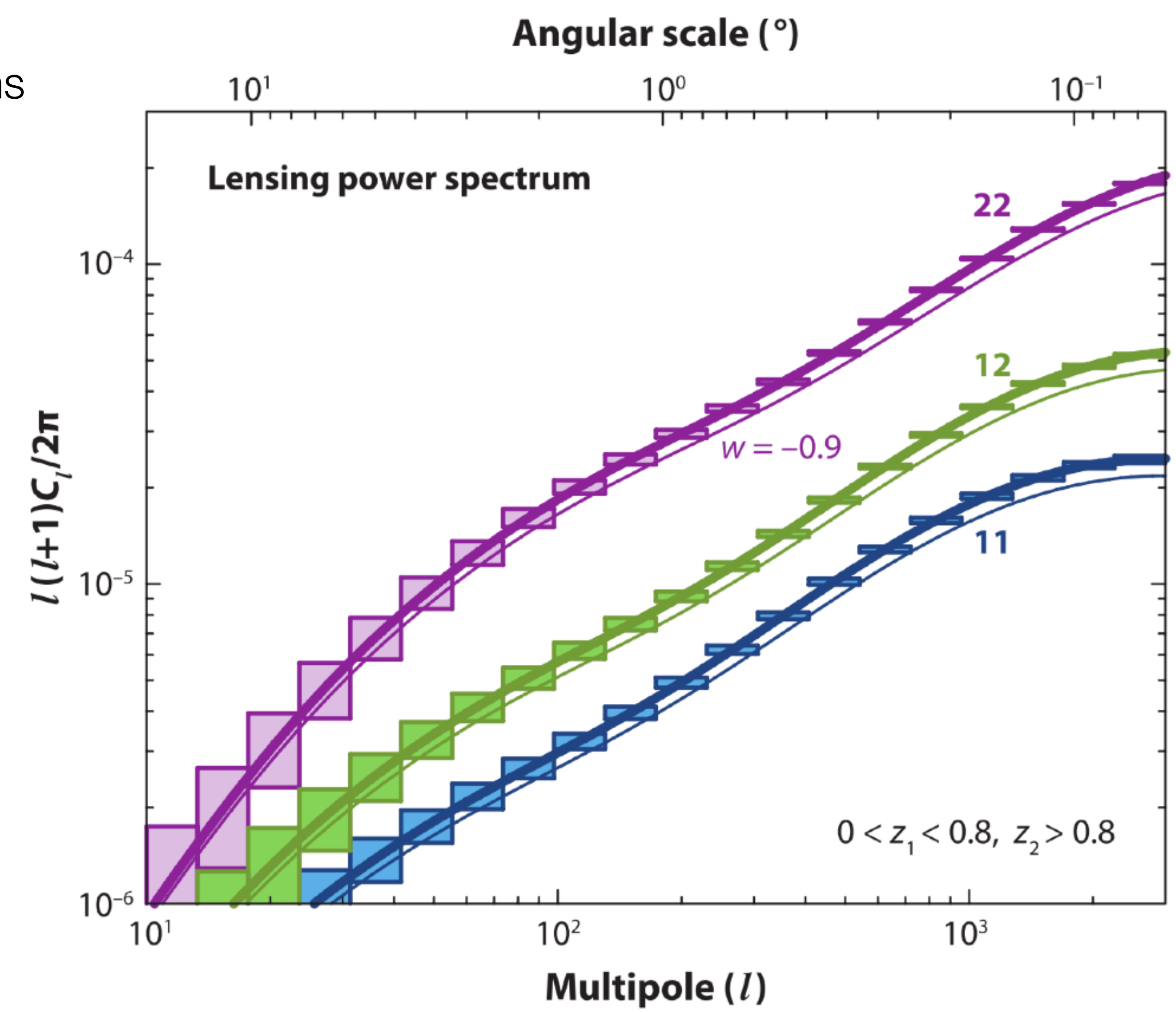
Lensing kernel:

$$W(\chi) = \frac{3}{2}\Omega_{m0} H_0^2 a^{-1}(\chi)\chi \int d\chi_s n_s(\chi_s) \frac{\chi_s - \chi}{\chi_s}$$

Lensing power spectrum:

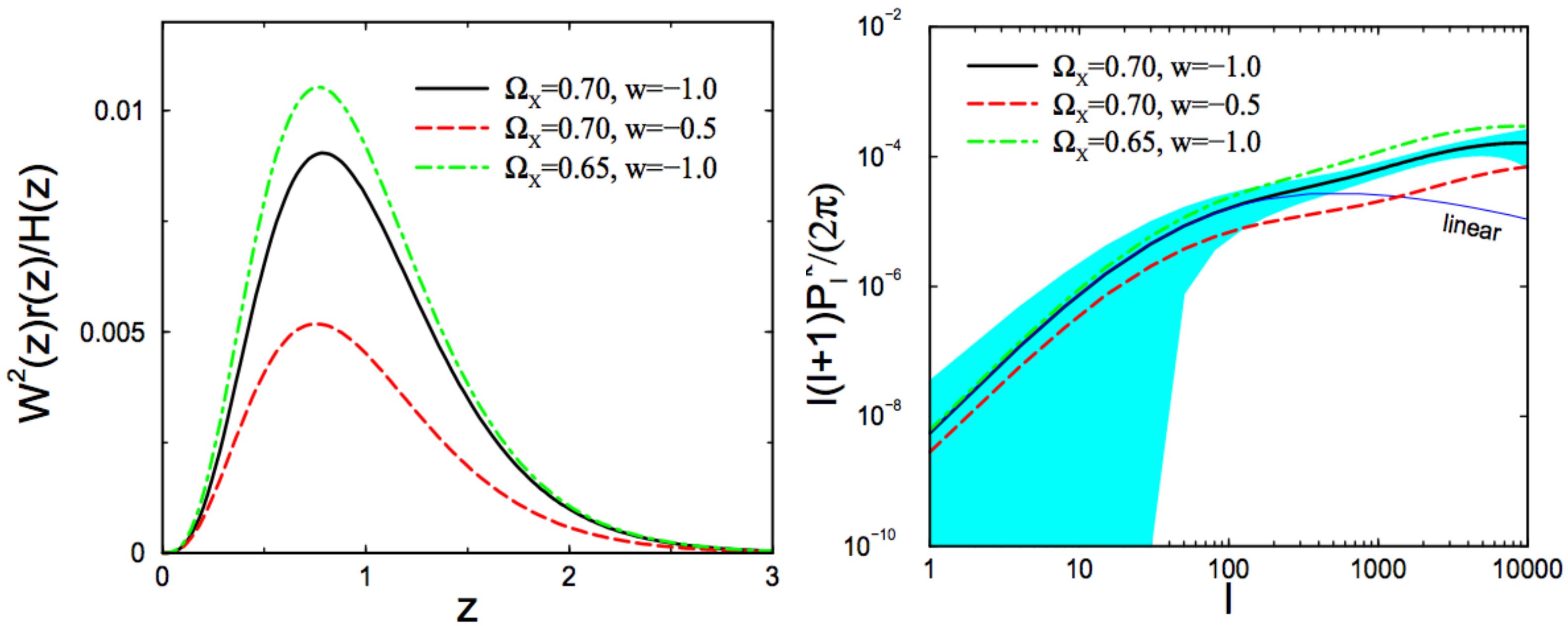
$$C_{\gamma_i\gamma_j}(\ell) = \int_0^\infty dz \frac{W_i(z)\, W_j(z)}{\chi(z)^2\, H(z)} P_\delta \left(\frac{\ell}{\chi(z)},\, z\right)$$

Matter power spectrum:

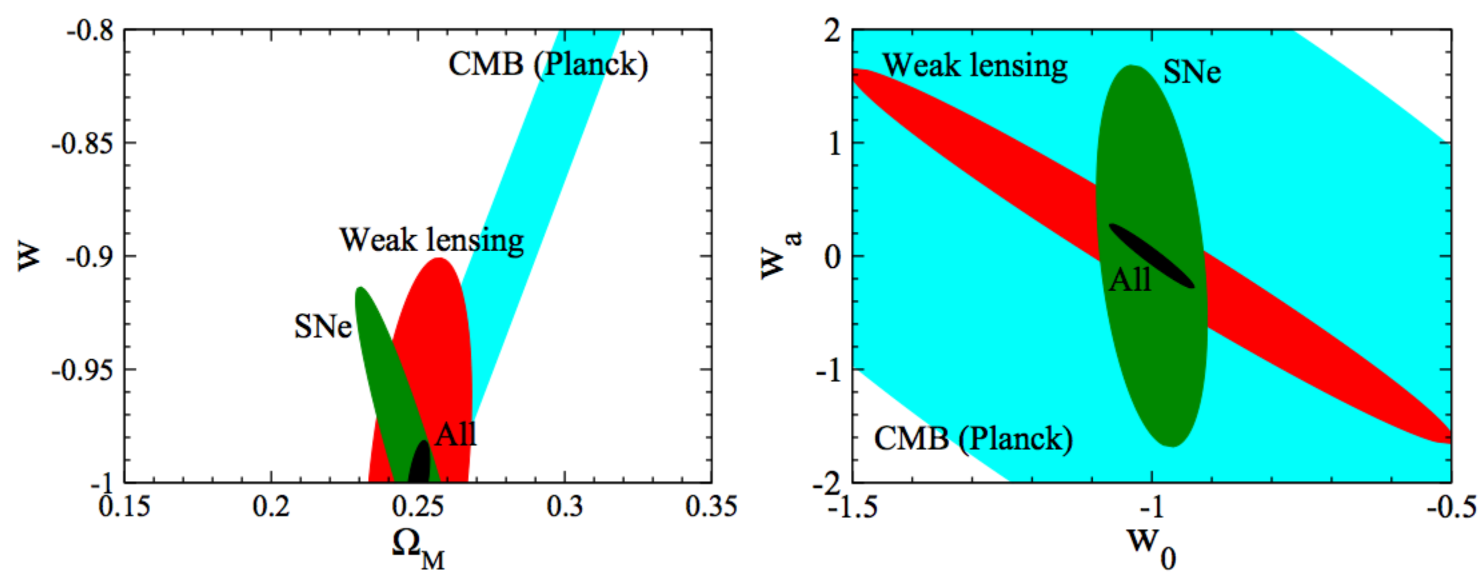


Hoekstra & Jain (2008)

Sensitivity to Dark Energy



Huterer (2001)

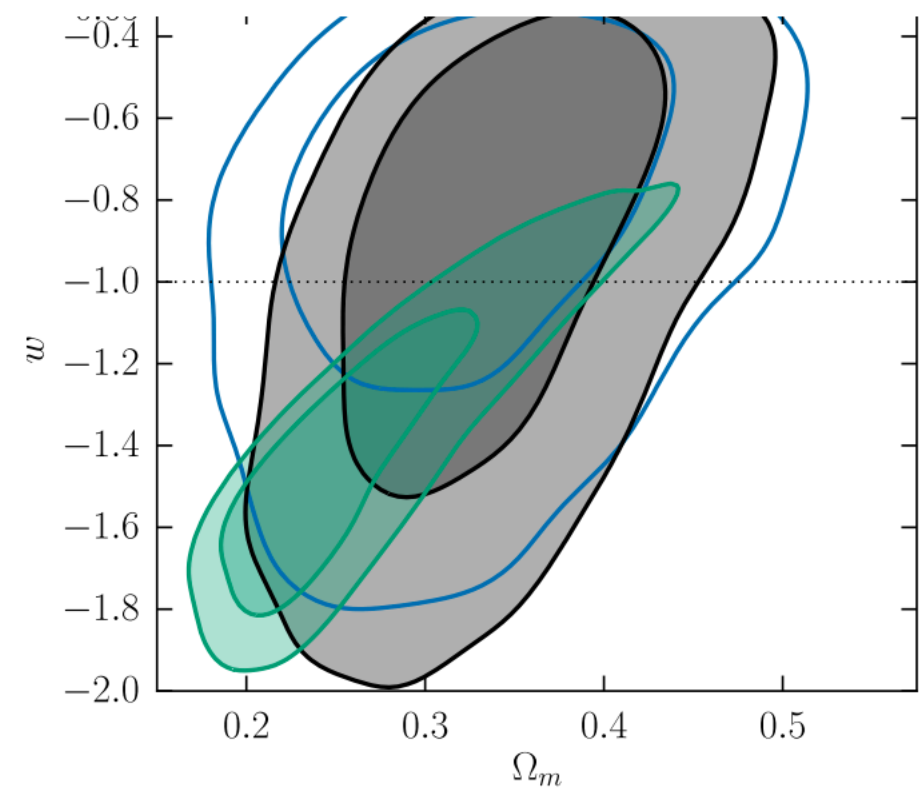


Frieman, Turner and Huterer (2008)

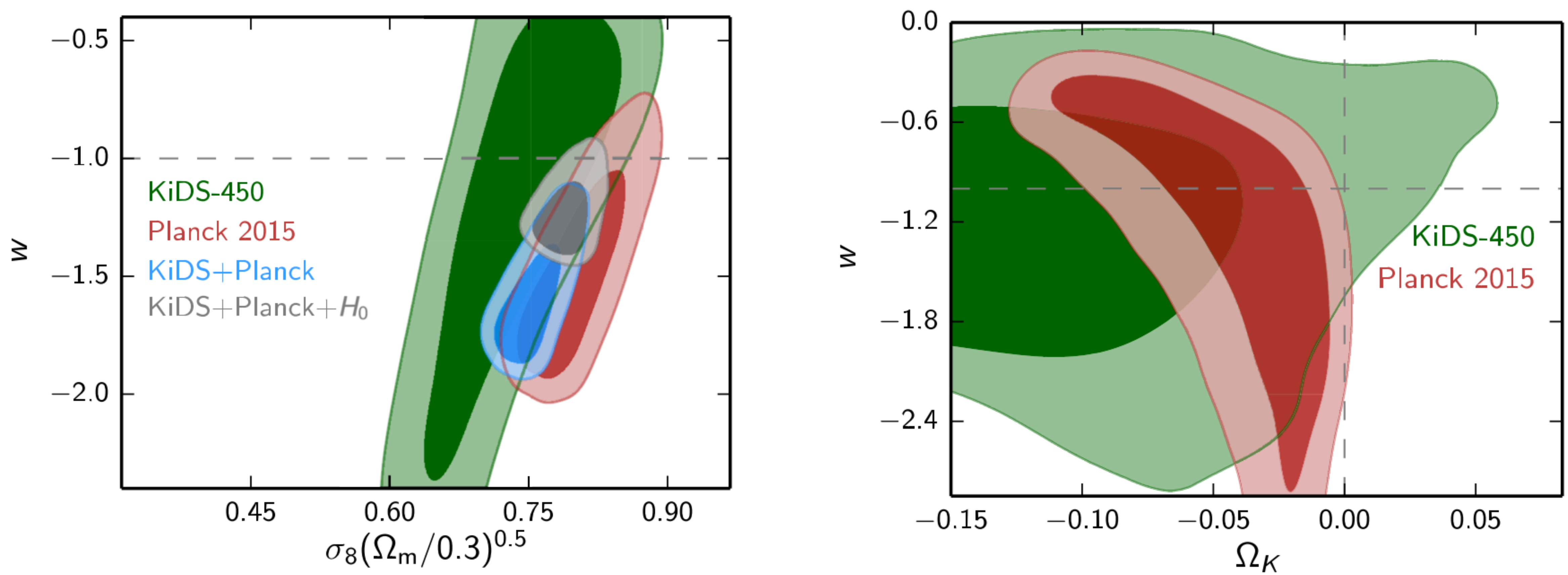
Observational Constraints

- Weak lensing measurements mainly constrain Ω_m and σ_8 under ΛCDM
- Cosmological constraints from lensing are in (mild) tension with those from Planck
- Lensing can also test wCDM cosmologies

DES results, along with KiDS and Planck
(Hildebrandt+ 2017, Troxel+ 2017)

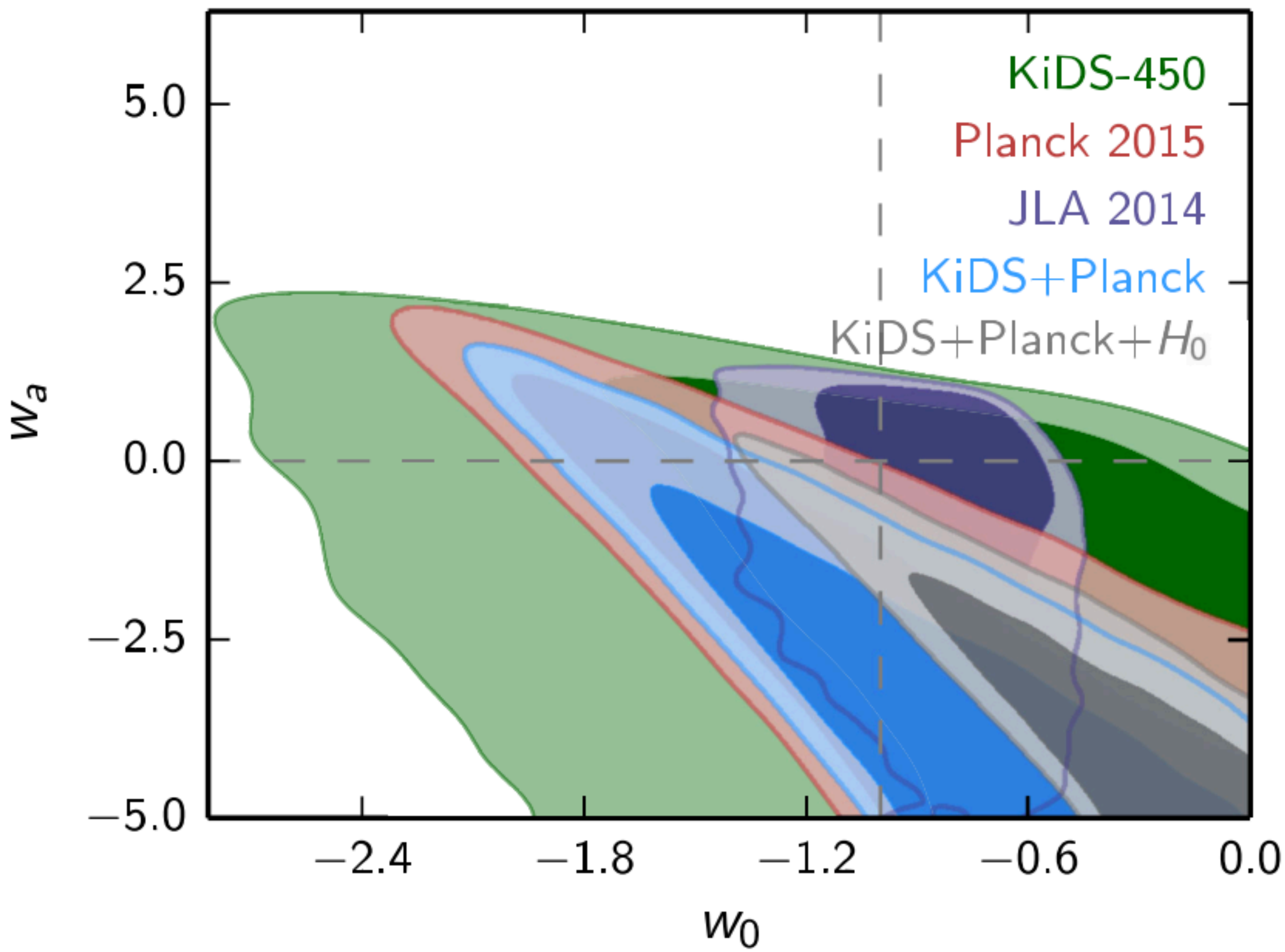


‘Static’ dark energy



Joudaki+ KiDS collaboration (2017)

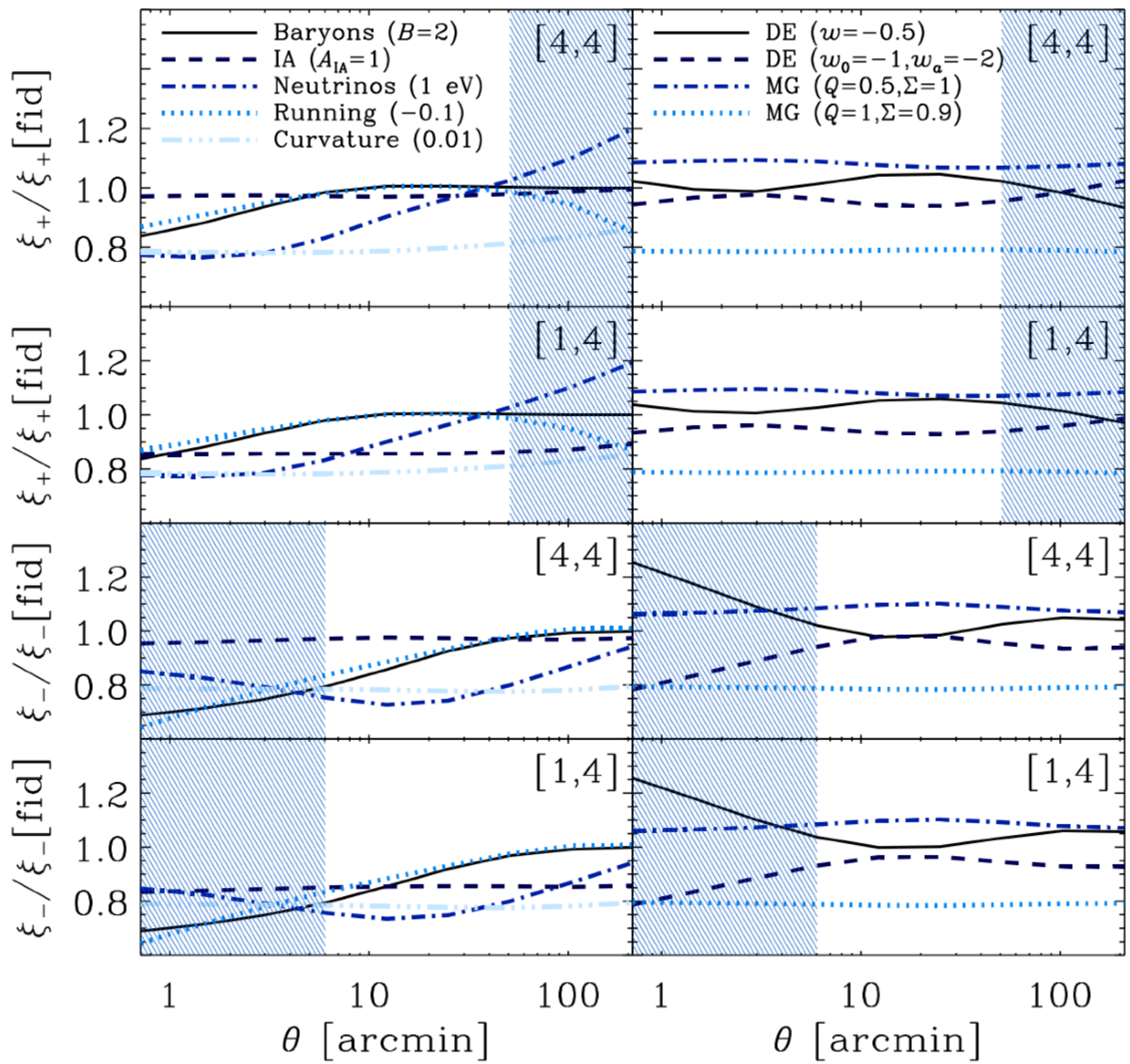
‘Dynamical’ dark energy



Joudaki+ KiDS collaboration (2017)

Dark Energy or Modified gravity?

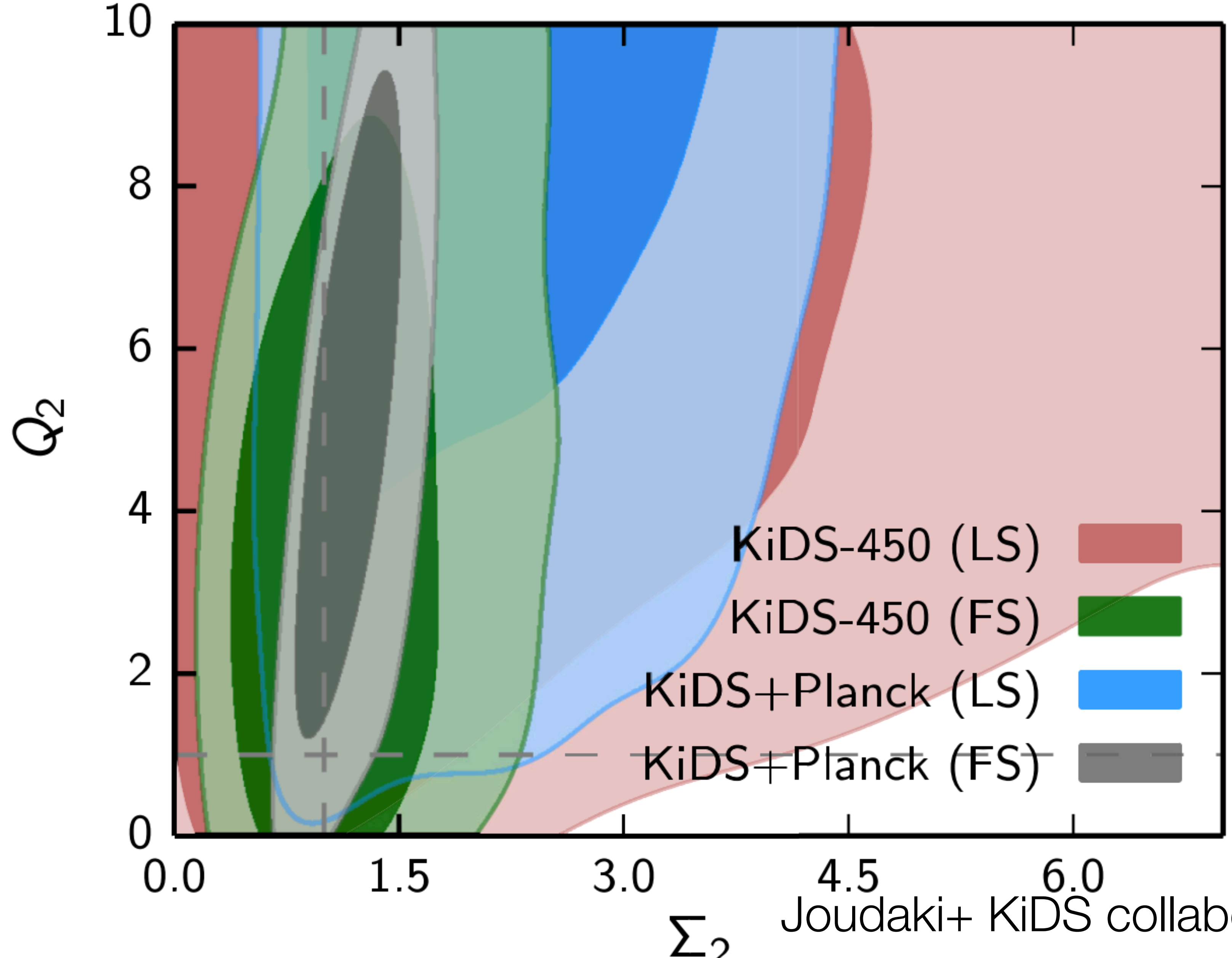
- Weak lensing can distinguish between dark energy models and modified gravity
- Light responds to metric perturbation in space and time equally. Matter (growth of structure) responds to perturbation in the time component
- MG is best studied with lensing + clustering (spectroscopic survey)



Joudaki+ KiDS collaboration (2017)

Modified gravity parametrisation

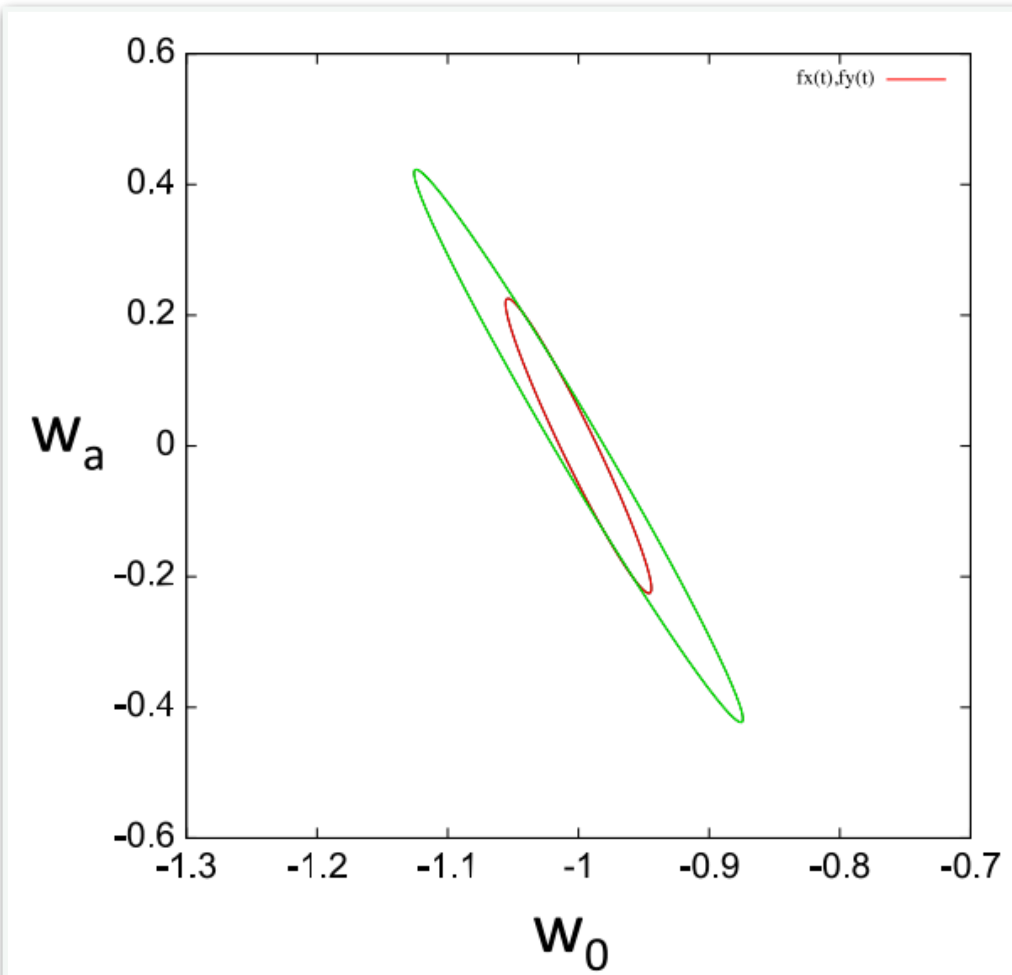
$$k^2\phi = -4\pi G a^2 \sum_i \rho_i \Delta_i Q(k,a),\qquad k^2[\psi - R(k,a)\phi] = -12\pi G a^2 \sum_i \rho_i \sigma_i (1+w_i) Q(k,a)$$



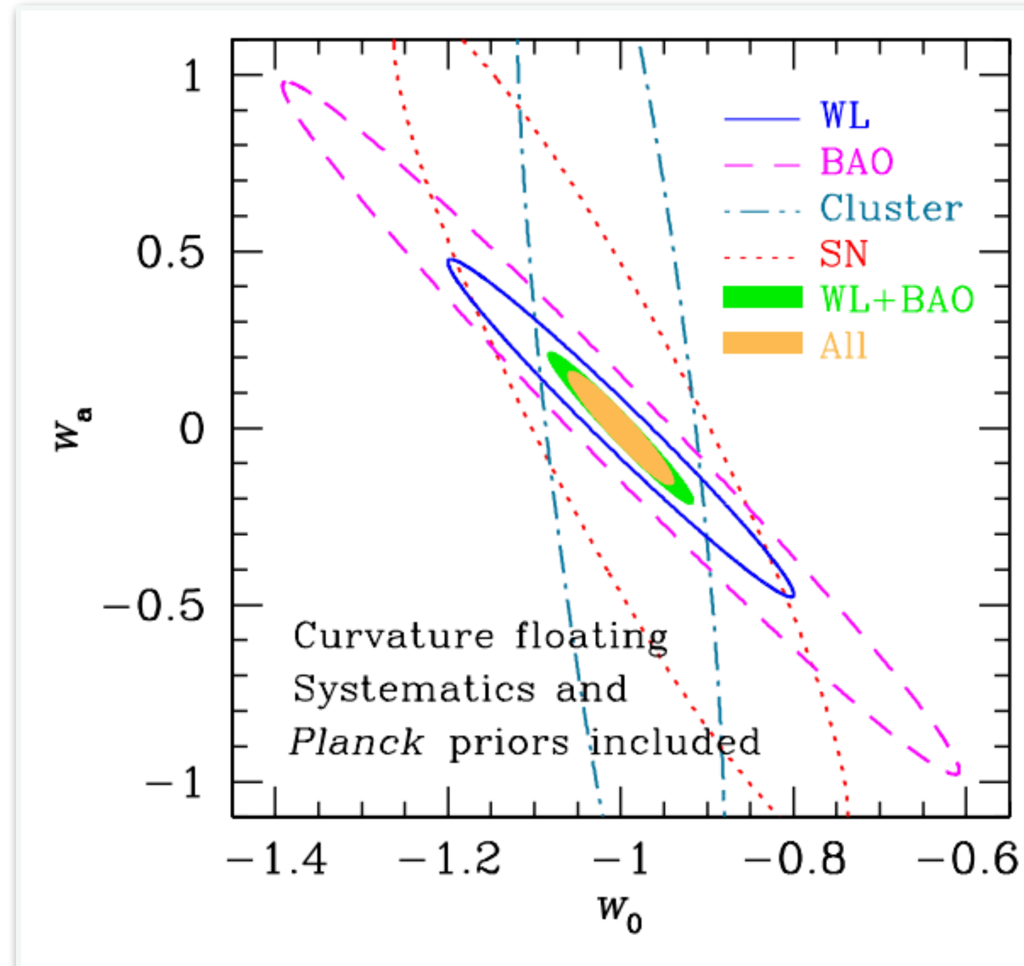
$$\Sigma = Q(1+R)/2$$

Joudaki+ KiDS collaboration (2017)

Forecast from future surveys

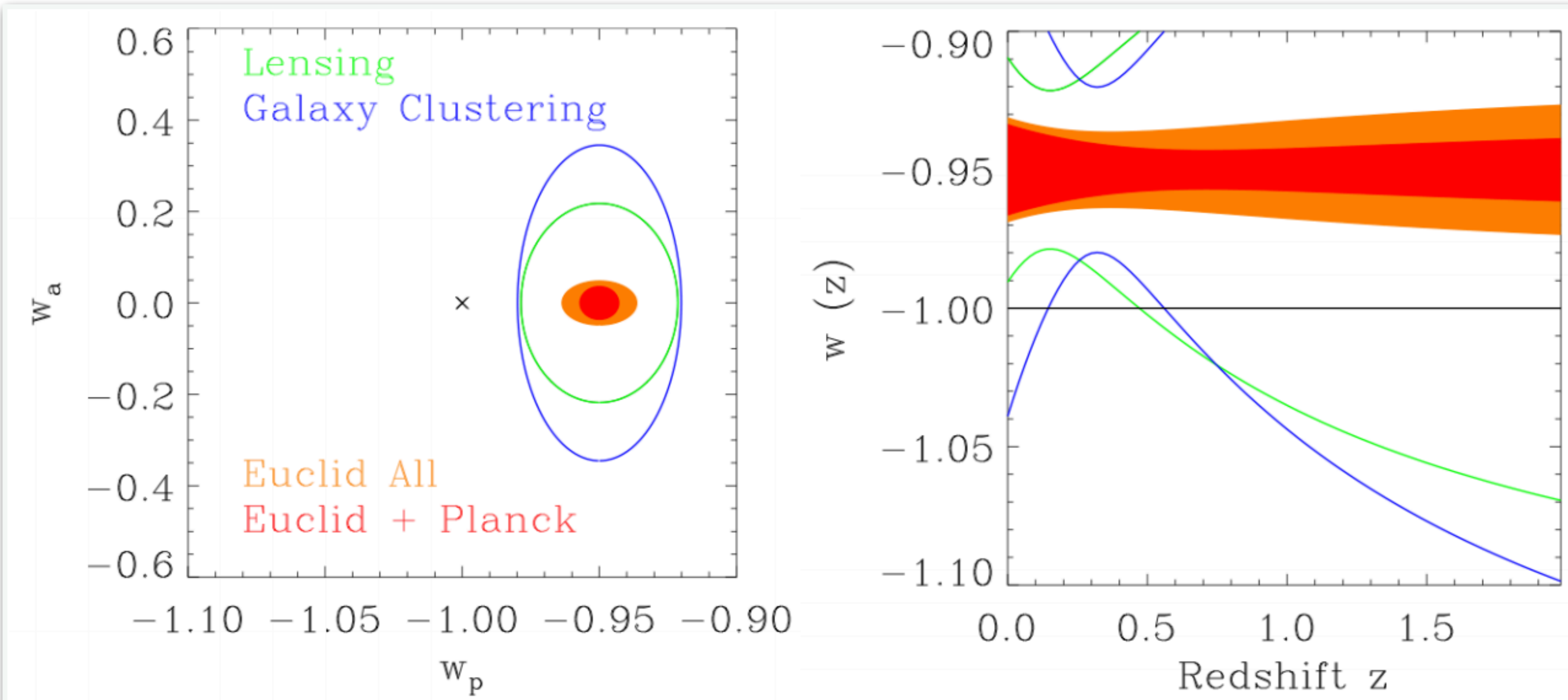


WFIRST Science Definition Report



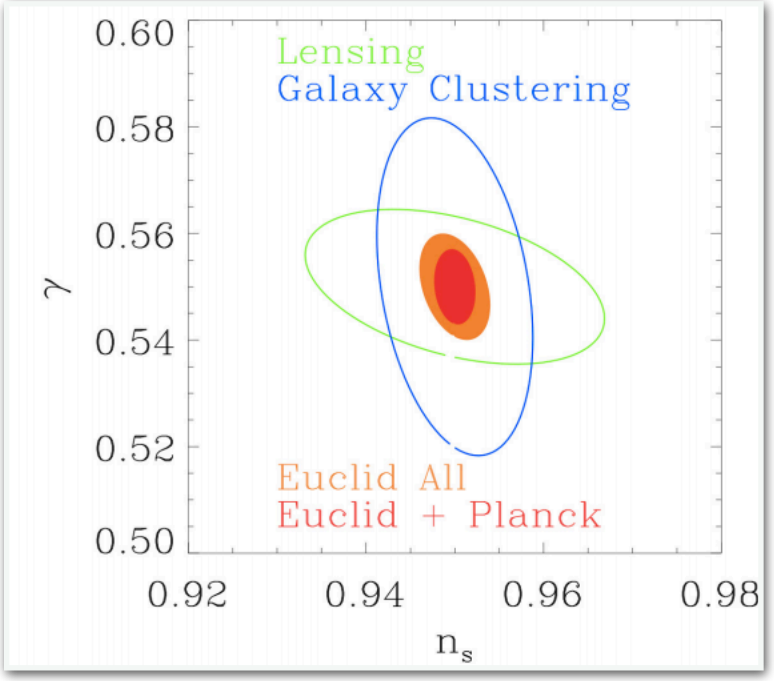
LSST White paper

Forecast from Euclid

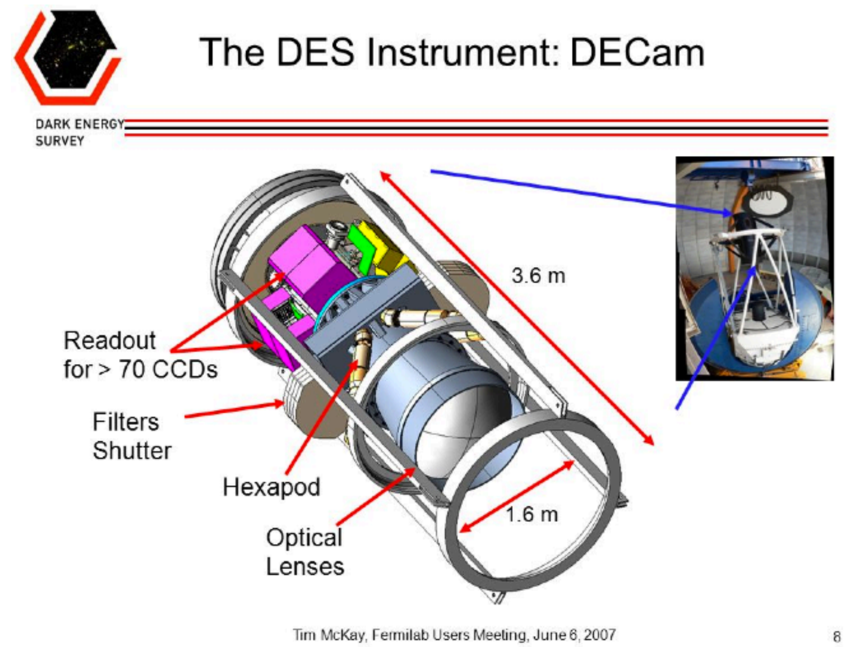


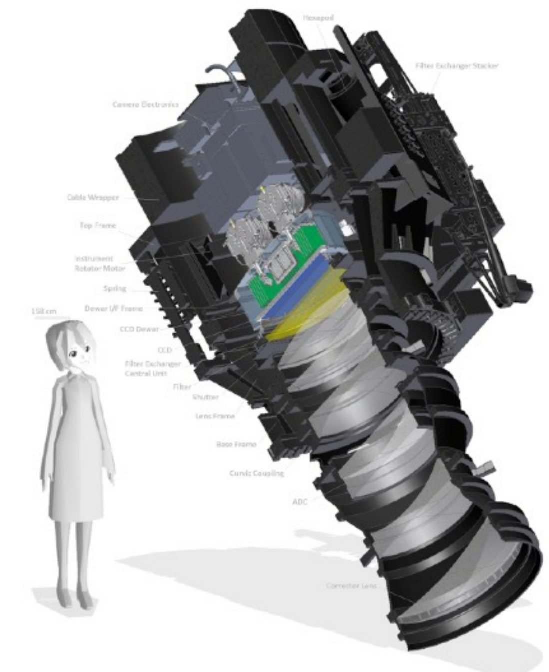
Growth rate: $f(z)=\Omega_m(z)^\gamma$

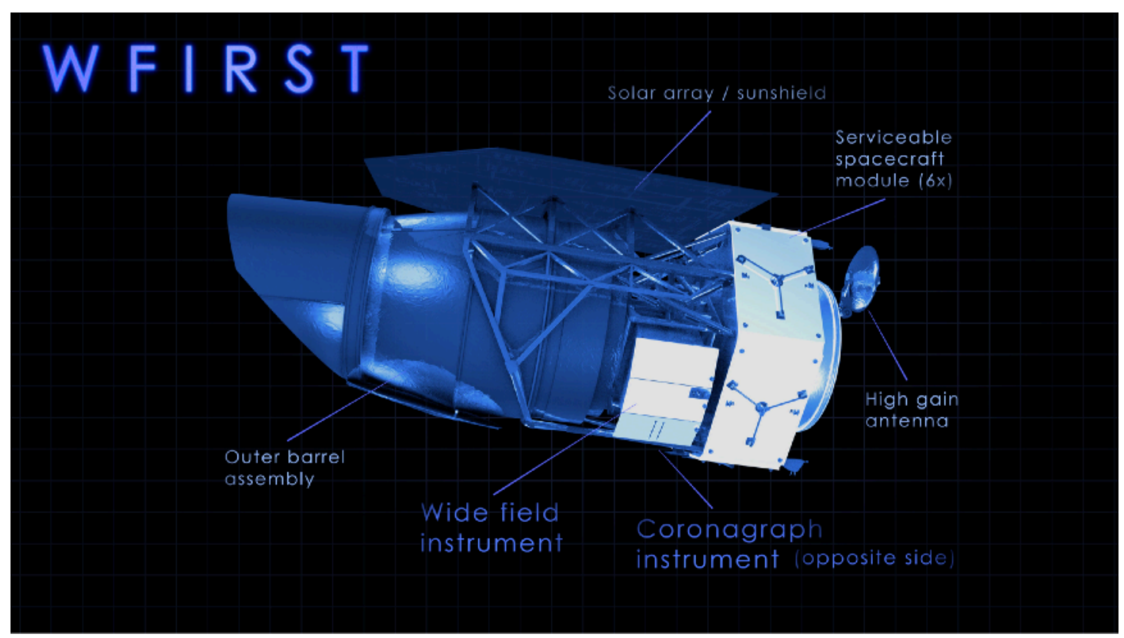
GR prediction: $\gamma=0.55$

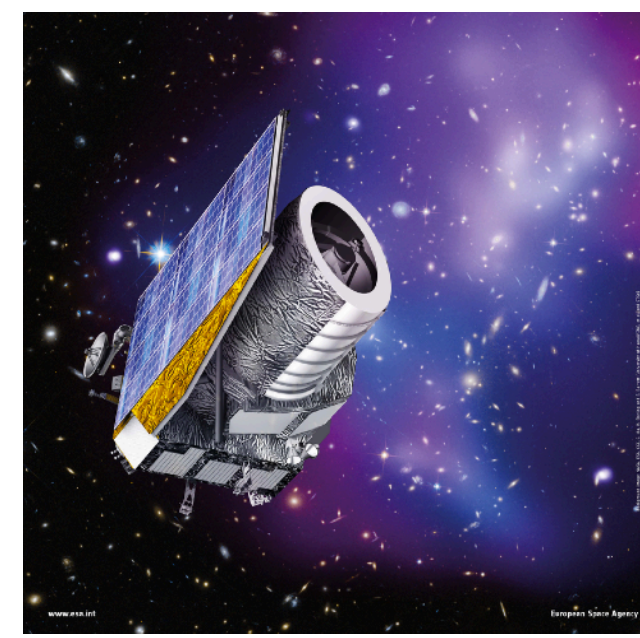


Current and Future DE surveys









Summary

- Gravitational lensing is light bending in response to the total mass (baryonic+dark matter)
- Tomographic lensing can probe dark energy by measuring the growth of structure at different epoch
- Since light and structure growth responds differently to the metric perturbations, it could potentially different dark energy from modified gravity
- Many Stage-IV surveys on their way with high Figure-of-Merit. Exciting times for Cosmology!