Large-scale Structure

Lecture 3:
Neutrino mass.
Weak lensing and 3x2 cosmology.

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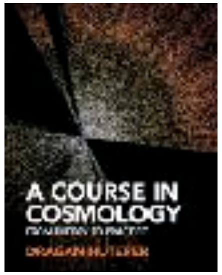
Overview of this lecture

- Aimed with the basics of P(k), plus BAO and RSD probes, and having discussed how they are sensitive to dark matter and dark energy - what next?
- This lecture, we 1) review the physics in LSS of massive neutrinos, and 2) briefly review weak gravitational lensing (or “cosmic shear”)



Linear galaxy power spectrum $\Delta_g^2(k)$

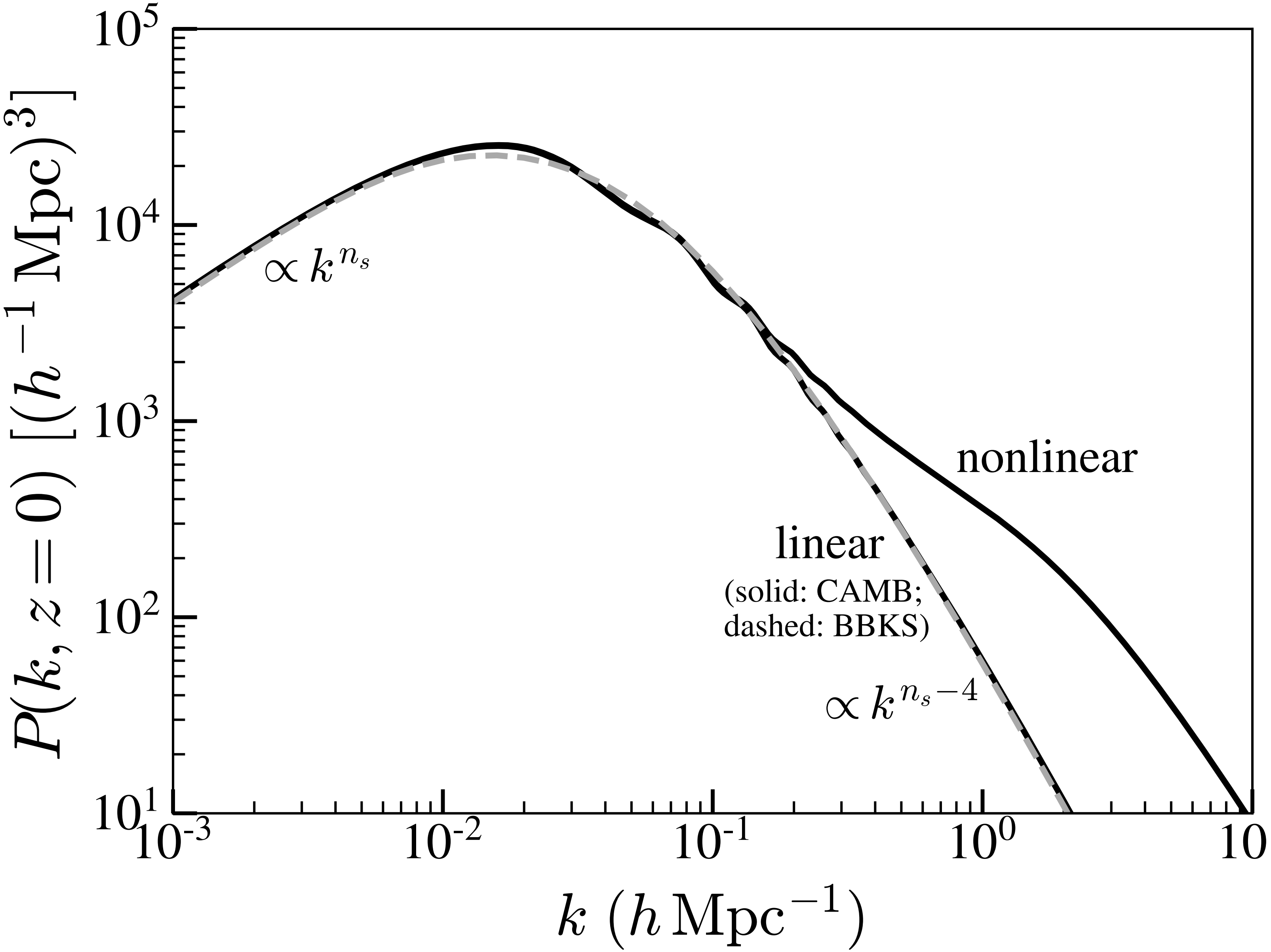
$$\Delta_g^2(k,a) \equiv \frac{k^3 P_g(k)}{2\pi^2}$$

$$= b^2(k,a) A_s \frac{4}{25} \frac{1}{\Omega_M^2} \left(\frac{k}{k_{\rm piv}}\right)^{n_s-1} \left(\frac{k}{H_0}\right)^4 [ag(a)]^2 T^2(k)$$

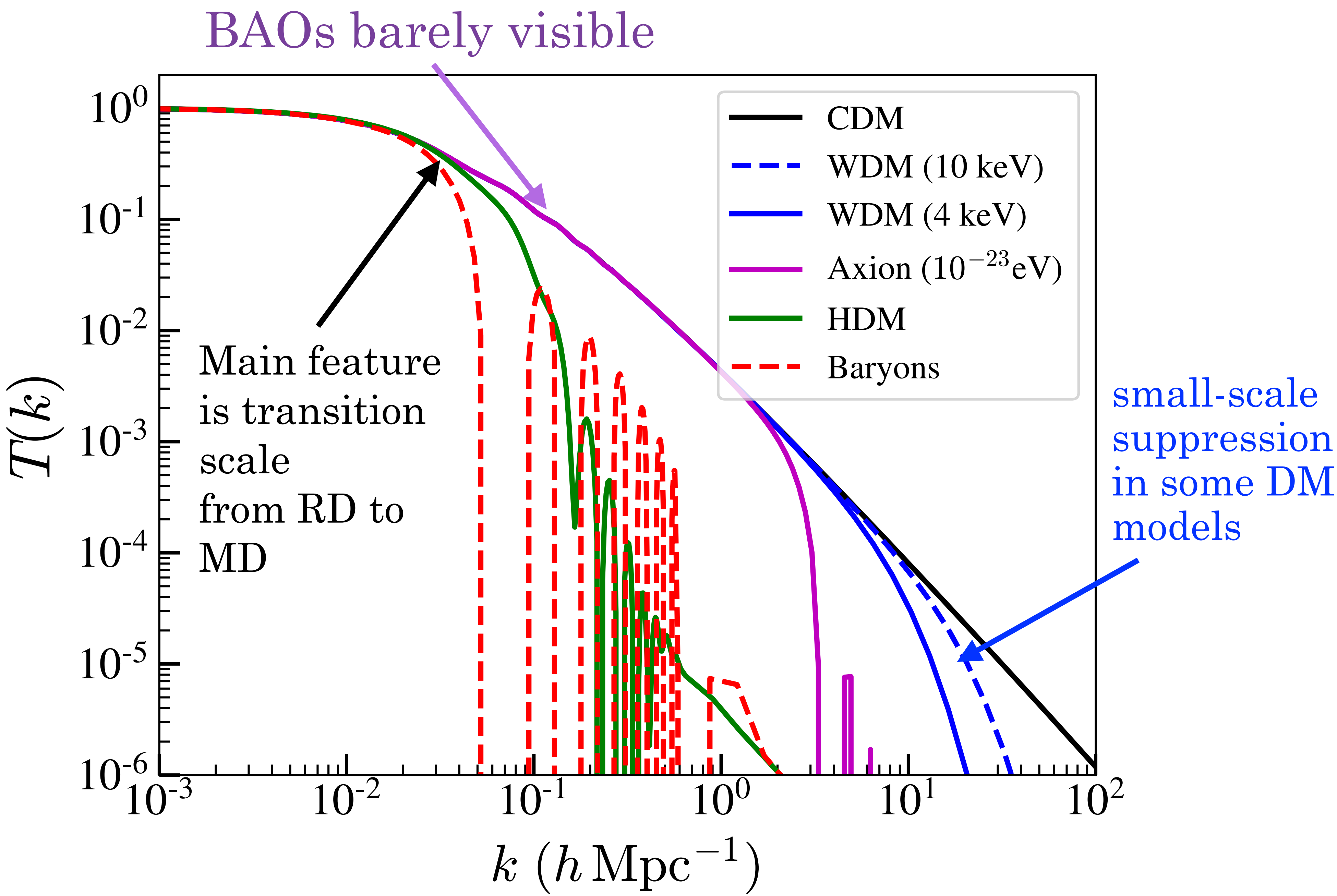
Principal sensitivity to cosmo parameters comes from:

- growth function $D(a) = ag(a)/g(1)$ (D is linear growth, g is growth suppression, i.e. value relative to EdS)
- transfer function T(k)
- (for non-Gaussianity only): galaxy bias b
- [Also anisotropic power spectrum, not shown above, with RSD]

$$\Delta_g^2(k,a) = b^2(k,a)\,A_s\,\frac{4}{25}\frac{1}{\Omega_M^2}\left(\frac{k}{k_{\rm piv}}\right)^{n_s-1}\left(\frac{k}{H_0}\right)^4\,[ag(a)]^2\,T^2(k)$$



Transfer function



Neutrino Mass

Neutrino basics

- Three neutrino flavors (e, mu, tau)
- Definitely massive (neutrino oscillations detected)
- $\Omega_\nu h^2 = \dfrac{\sum_i m_{\nu,i}}{94\text{eV}},$
- Cosmology largely sensitive to $\sum m_{\nu,i}$
- Cosmological upper bound: $\sum m_{\nu,i} < 0.15\,\text{eV}$ (or so)

From the oscillation constraints, we conclude:

$$\left.\begin{aligned}(\Delta m^2)_{\rm sol} &\simeq 8\times10^{-5}\ \text{eV}^2\\ (\Delta m^2)_{\rm atm} &\simeq 3\times10^{-3}\ \text{eV}^2\end{aligned}\right\}$$

$\sum m_i = 0.06$ eV* (normal)

vs.

$\sum m_i = 0.11$ eV* (inverted)

*(assuming $m_3=0$)

So the goal is to

1. distinguish $\sum m_i$ of 0.06 eV from 0.11 eV
2. distinguish $\sum m_i$ of 0.06 eV from zero eV

Are neutrinos relativistic??

Well, it depends: they are relativistic at redshift higher than

$$\boxed{z_{\rm nr} \simeq 1890 \left(\frac{m_\nu}{\rm eV}\right) \simeq 100 \quad \text{for} \quad m_\nu \simeq 0.05\,{\rm eV}}$$

The neutrinos affect the expansion rate as

$$H^2(z) = H_0^2 \left[\Omega_{cb}(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\nu \frac{\rho_\nu(z)}{\rho_{\nu,0}} + \Omega_{\rm de}\frac{\rho_{\rm de}(z)}{\rho_{\rm de,0}}\right]$$

where

$$\rho_\nu(z \gg z_{\rm nr}) = N_{\rm eff}\frac{7\pi^2}{120}T_{\nu,0}^4(1+z)^4$$

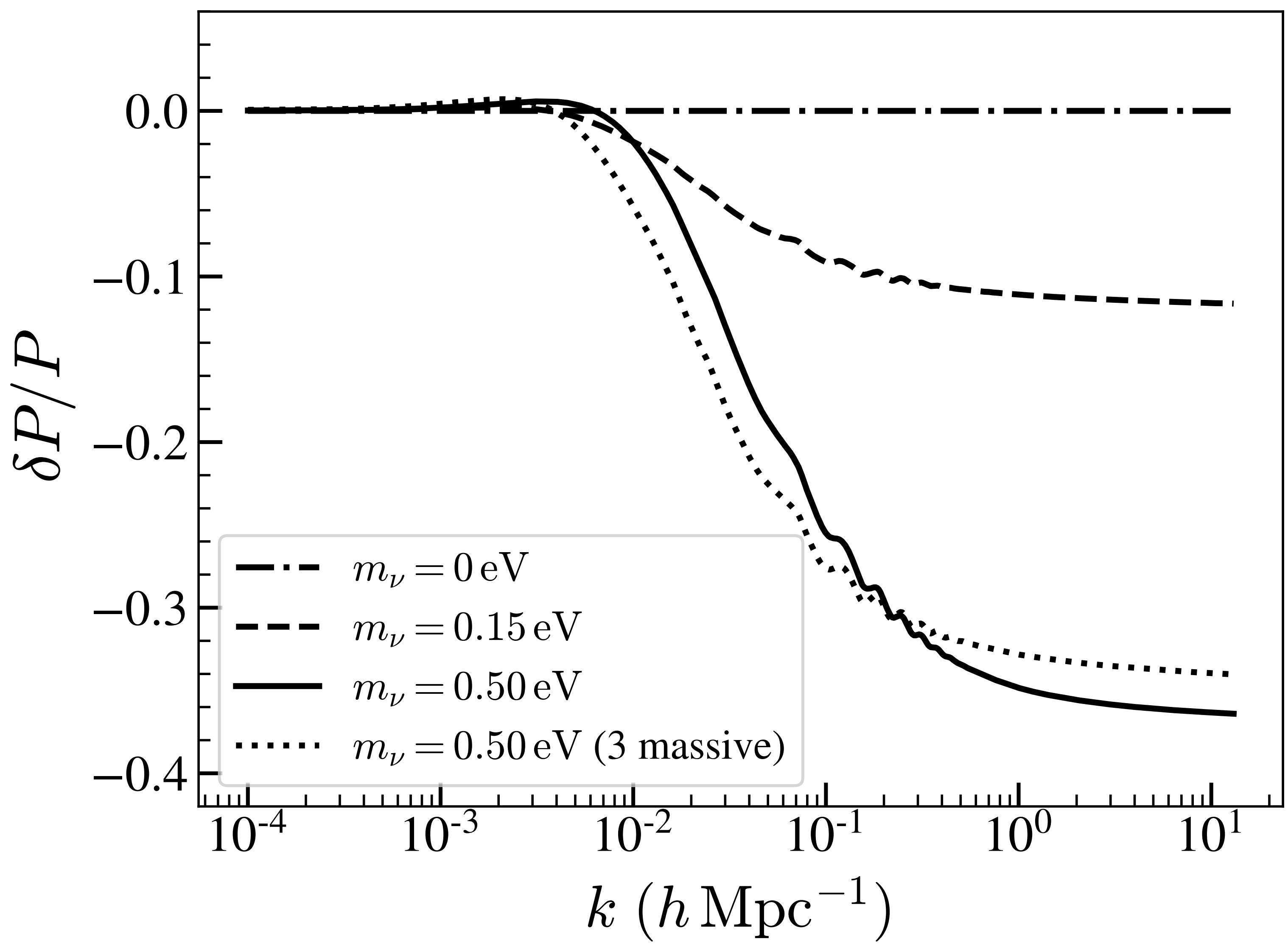
scales like radiation

$$\rho_\nu(z \ll z_{\rm nr}) = \frac{\sum m_\nu}{93\,{\rm eV}}\frac{3H_0^2}{8\pi G}(1+z)^3$$

scales like matter

Neutrino free-streaming leaves signatures in P(k)

$$\lambda_{\rm FS} \simeq 300 \left(\frac{1{\rm eV}}{m_\nu}\right) {\rm Mpc}; \quad k_{\rm FS} \equiv \frac{2\pi}{\lambda_{\rm FS}} \simeq 0.02 \left(\frac{m_\nu}{1{\rm eV}}\right) {\rm Mpc}^{-1},$$



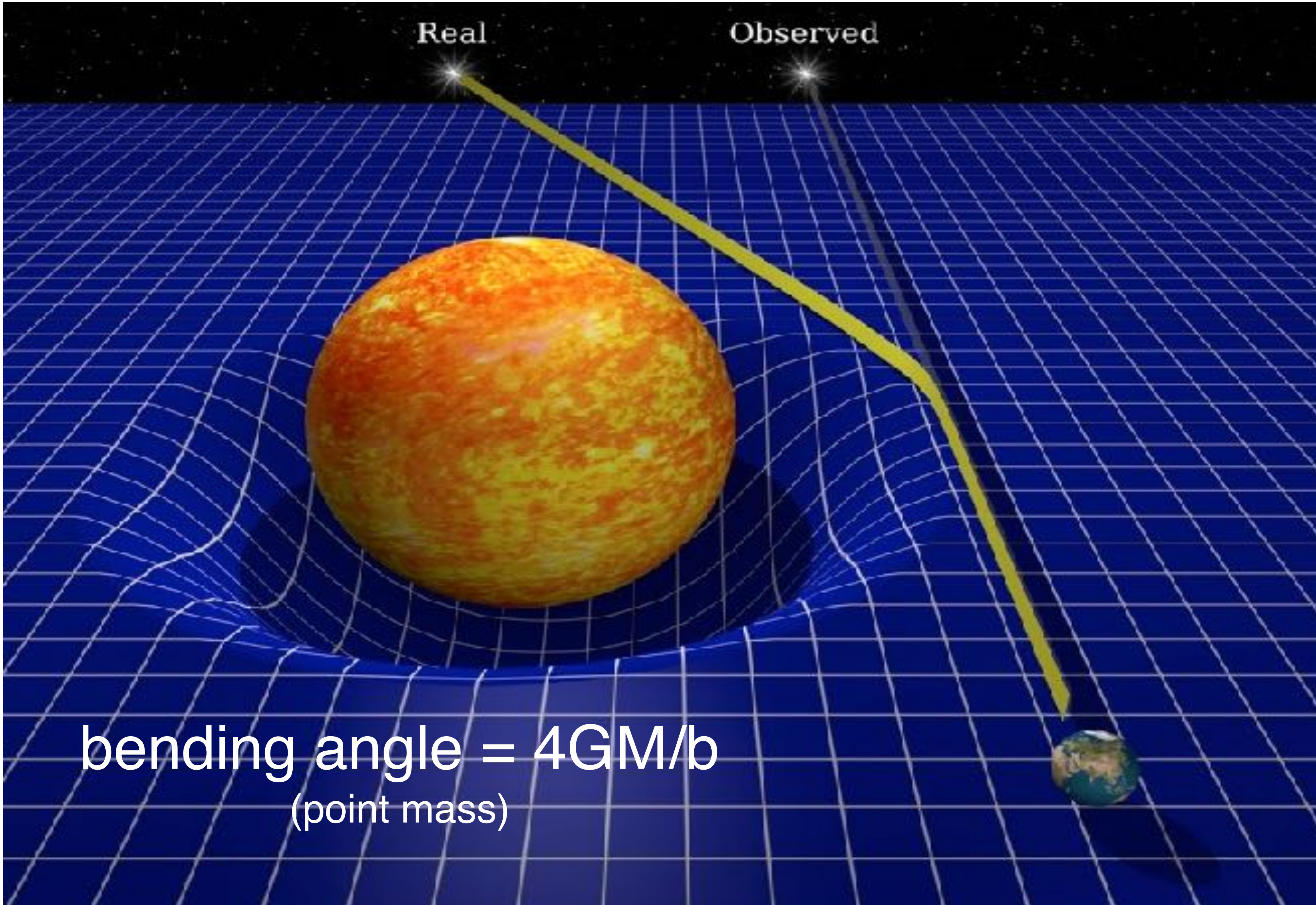
$$\frac{\delta P}{P} \simeq -8 f_\nu$$

Neutrino masses: prospects

- Neutrino masses are in principle output of a standard P(k) full-shape analysis (with or without the RSD)
- However, theoretically modeling the impact of neutrinos is famously challenging — need Nbody simulations, tricky to get sufficient precision
- Recent progress appears to have largely solved the above challenge
- Specific predictions of the effect of m_ν on observables make these tests highly physics-y. Cosmology tests of m_ν: a great (and correspondingly cheap) complement to particle-physics experiments

Weak gravitational lensing

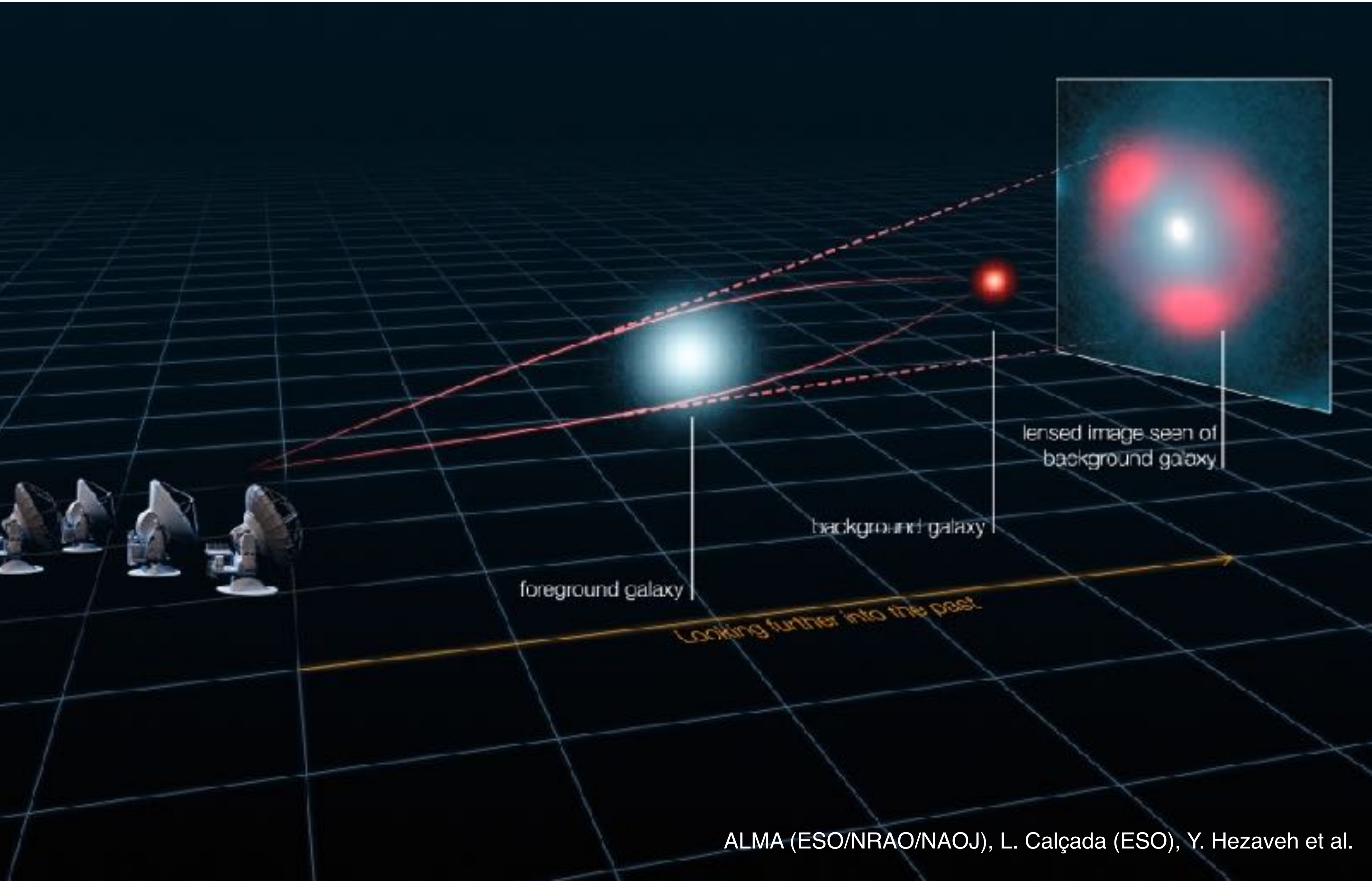
Strong (not weak!) gravitational lensing



bending angle = $4GM/b$

(point mass)

Strong lensing: multiple images are formed



ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

Weak lensing: no multiple images

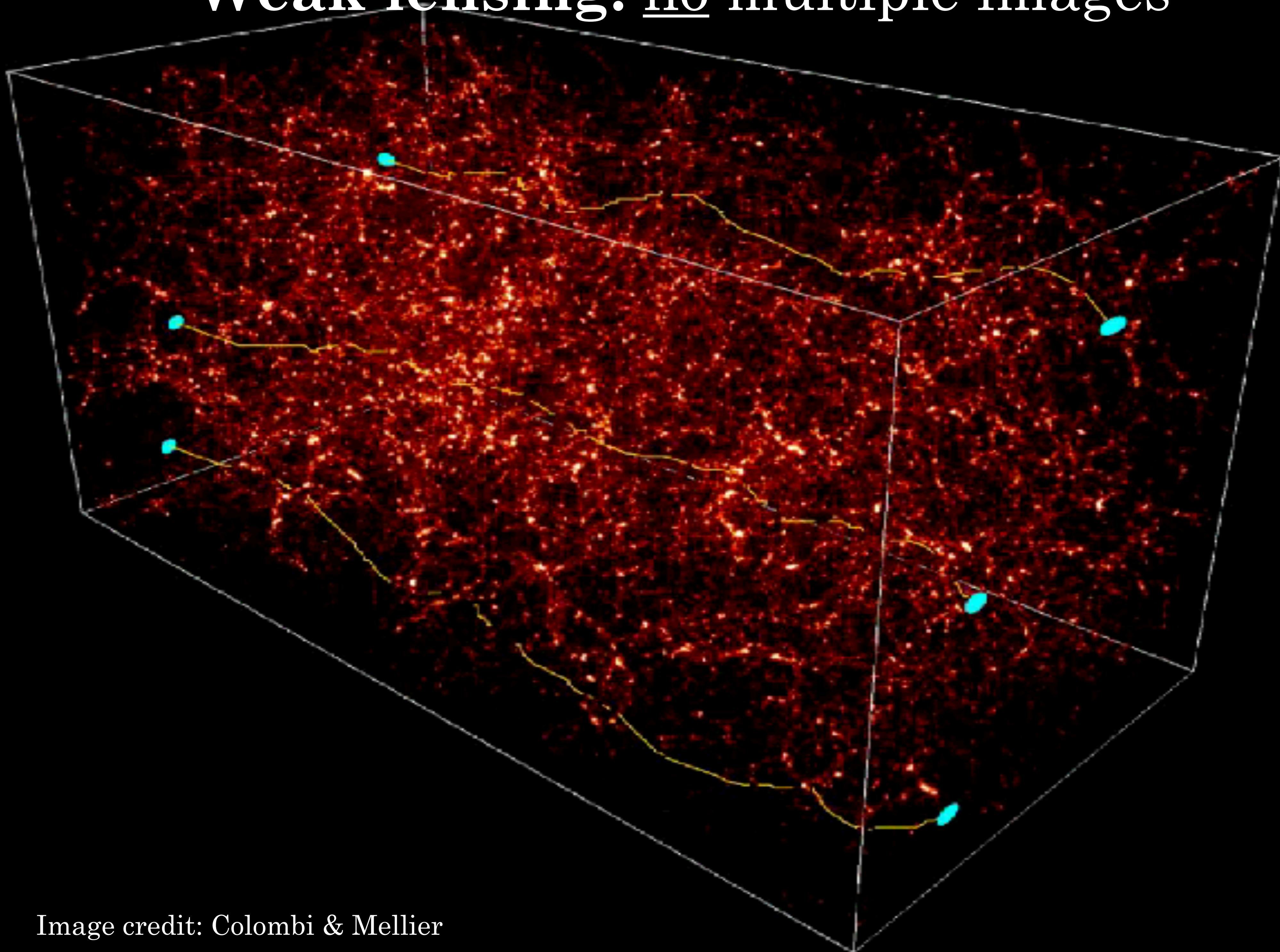


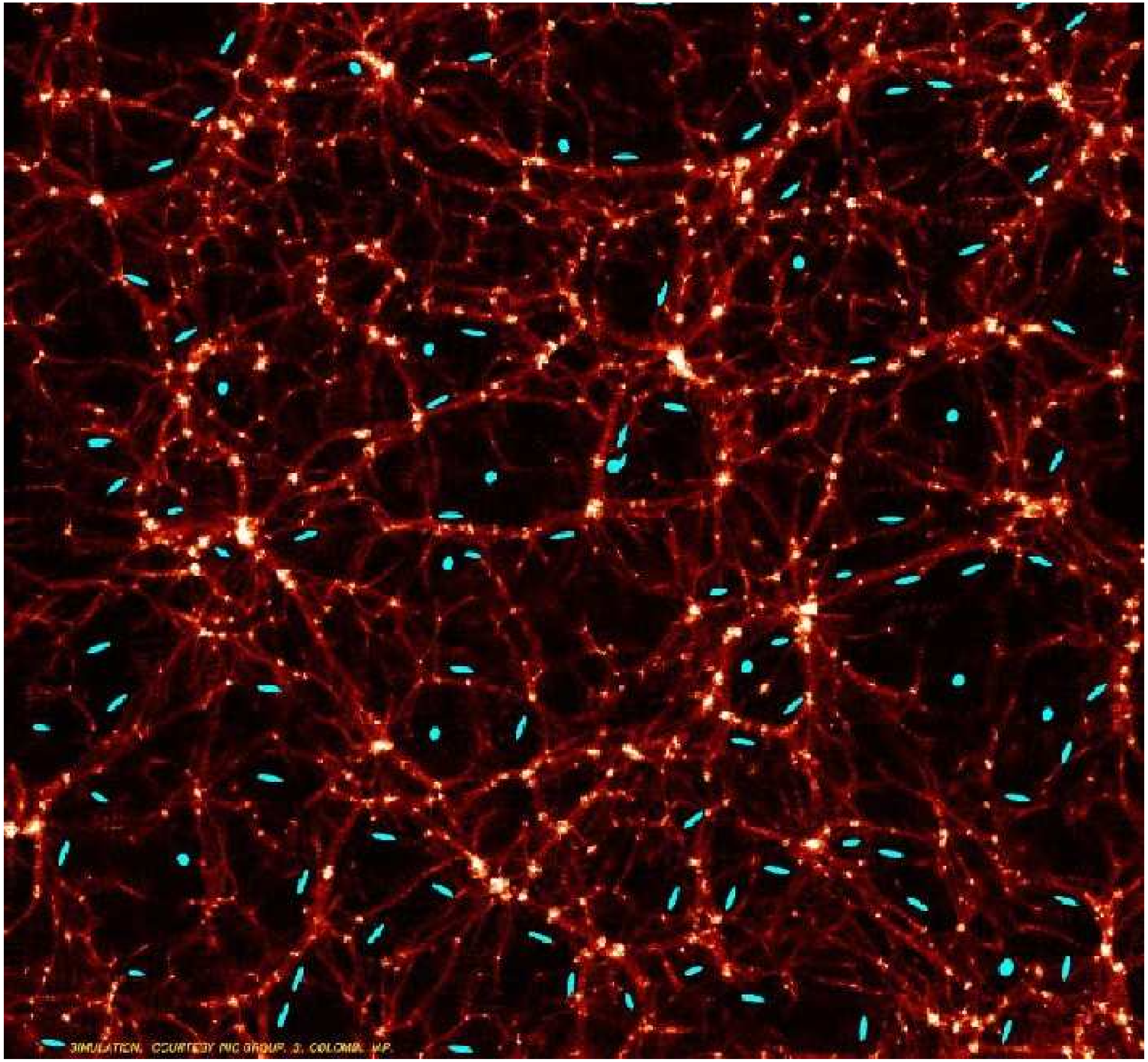
Image credit: Colombi & Mellier

Weak Gravitational Lensing

Credit: NASA, ESA and R. Massey (Caltech)

Key advantage: measures distribution of matter, not light

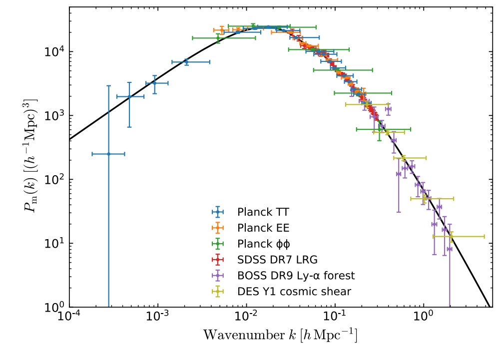
Weak Grav. Lensing (a.k.a. "cosmic shear") **by large-scale structure**



Credit: Colombi & Mellier

Weak Lensing and Dark Matter/Energy

WL measures integral over the line of sight:



$$P_{\rm shear} \simeq \int_0^\infty W(r) P_{\rm matter}(r)\, dr$$

galaxy shear clustering (measure)

distance, volume factors (theory→DM,DE)

(dark) matter clustering (theory→DM,DE)

- Probes integrated matter density; also sensitive to DM/DE through distance, volume factors

More precisely: shear power spectrum

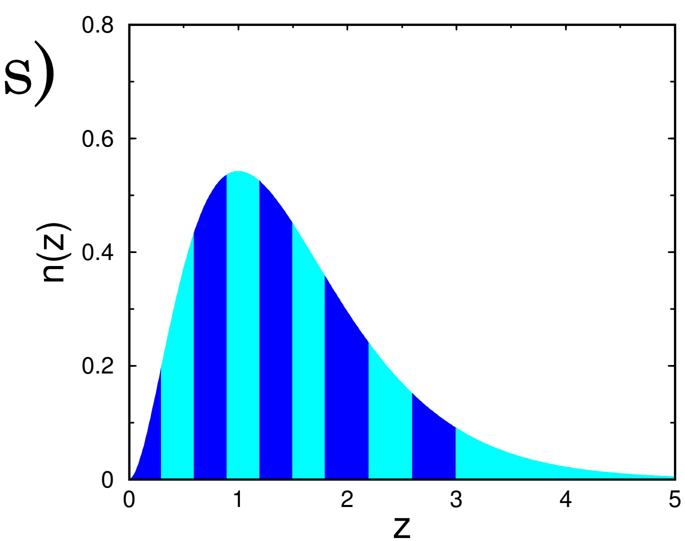
$$P^{\kappa}(\ell) = \int_0^{\infty} dz \, \frac{W^2(z)}{r(z)^2 \, H(z)} \, P\left(\frac{\ell}{r(z)}, z\right)$$

matter
power spectrum

where k=l/r (Limber approximation).

With **tomography** (splitting into z bins)

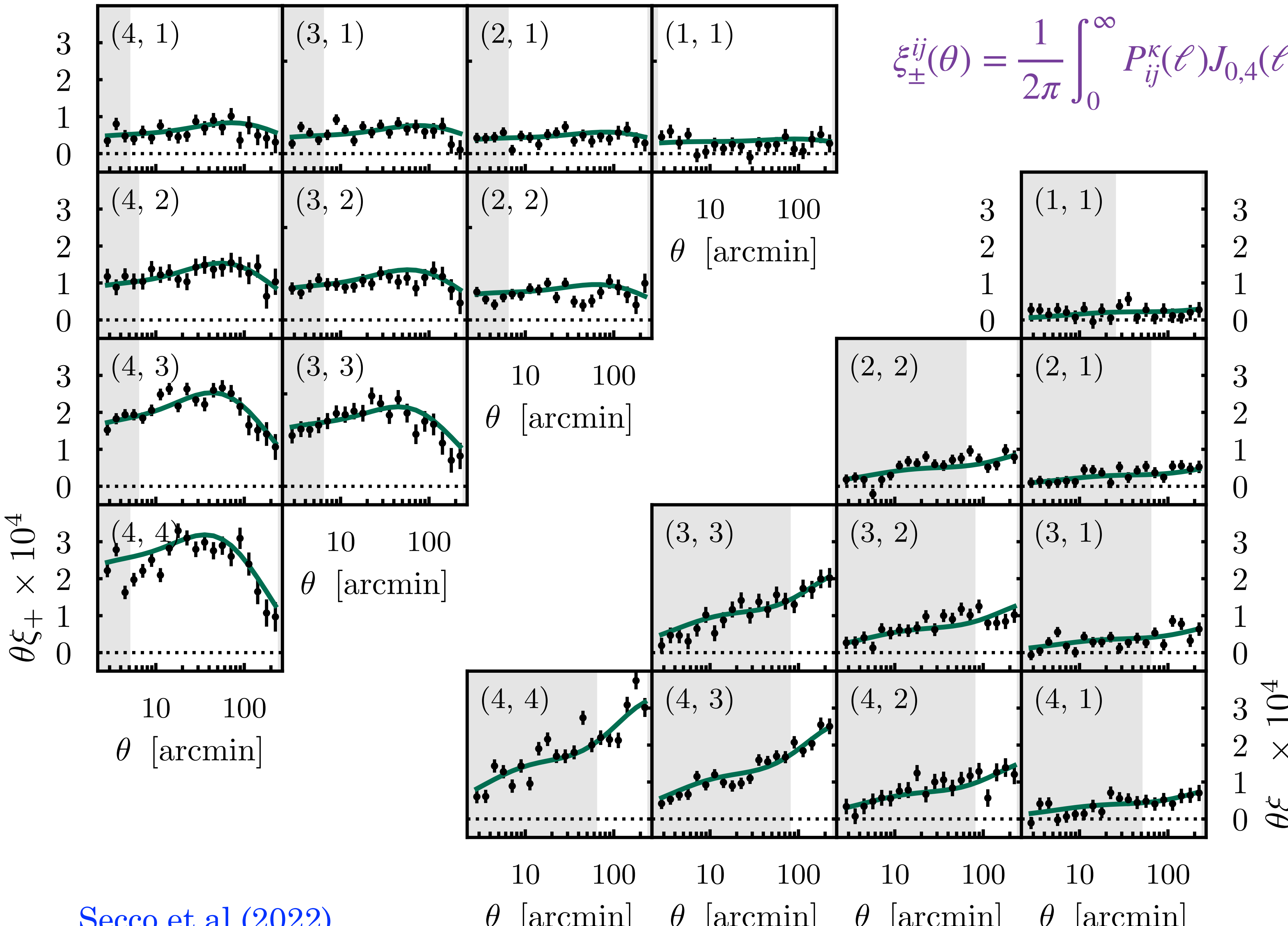
$$P_{ij}^{\kappa}(\ell) = \int_0^{\infty} dz \, \frac{W_i(z) \, W_j(z)}{r(z)^2 \, H(z)} \, P\left(\frac{\ell}{r(z)}, z\right)$$



Weak lensing from DES Y3 (4 tomographic bins)

In configuration space

$$\xi_{\pm}^{ij}(\theta) = \frac{1}{2\pi}\int_0^{\infty} P_{ij}^{\kappa}(\ell) J_{0,4}(\ell\theta)\ell\, d\ell$$



Secco et al (2022)

Weak lensing summary:

- History:
  - Proposed in 1960s
  - First detected in year 2000 (four teams!)
  - New era with DES, KiDS, HSC
  - Bright future with LSST, Euclid, Roman

- Pros:
  - Sensitive to ALL matter, including dark matter!
  - No bias! (recall $P_g = b^2 P_m$; measures P_m, not P_g)
  - Sensitive to both geometry (distances) and growth of structure

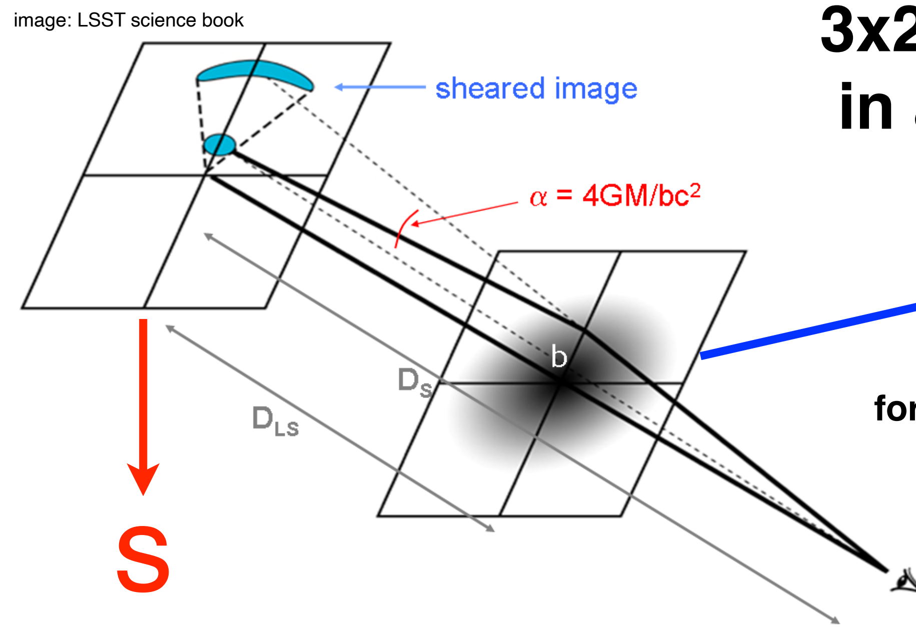
- Cons:
  - Lots of systematics! atmospheric distortions and "rounding" of shapes; intrinsic alignments, etc etc.

“3x2” cosmology

Can correlate:

1. galaxy position with galaxy position (galaxy clustering)
2. galaxy shape with galaxy shape (weak lensing)
3. galaxy position with galaxy shape (galaxy-galaxy lensing)

3x2 analysis in a picture



g

(**positions** of **foreground** galaxies; 5 redshift bins)

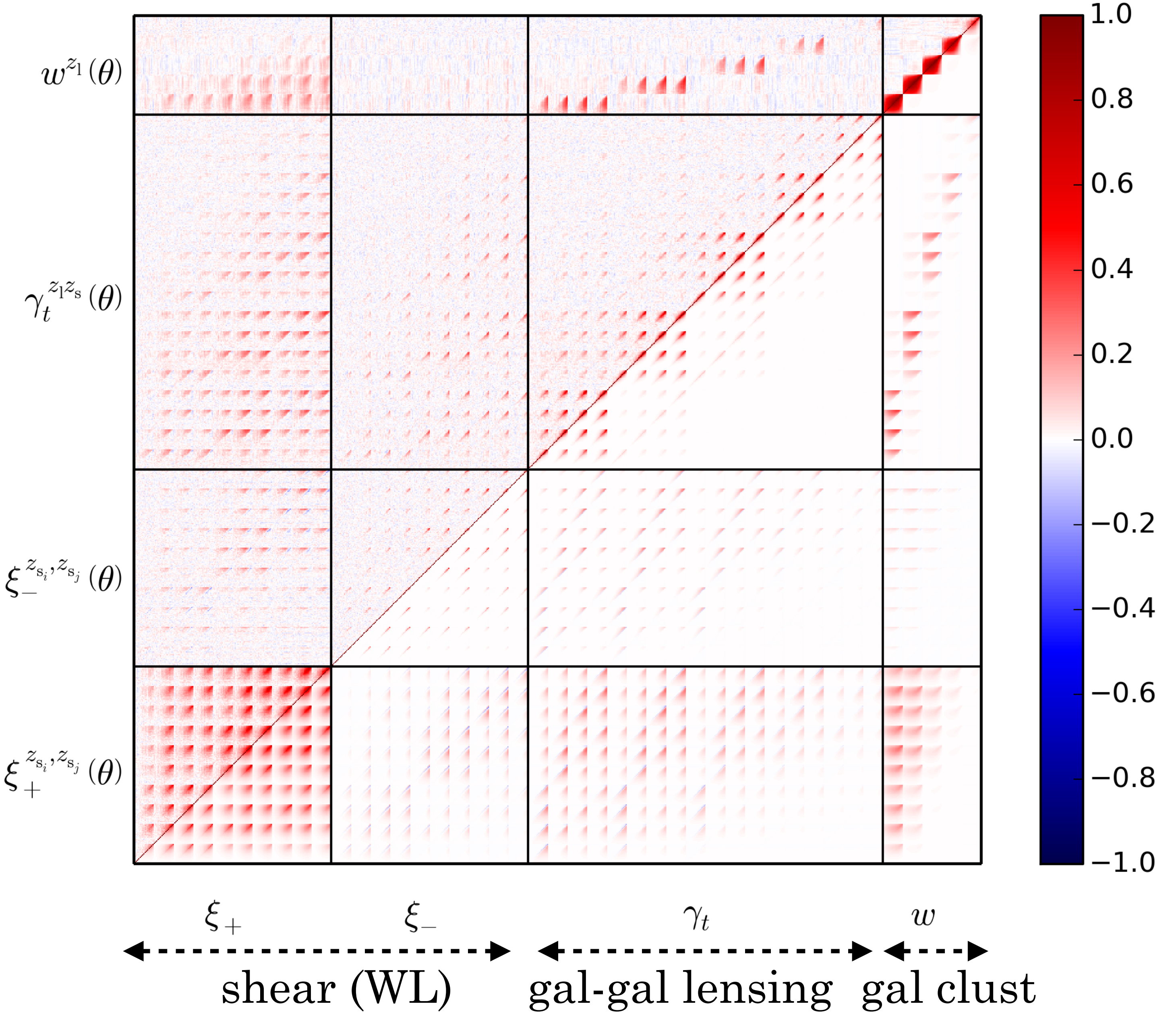
S

(**shear** of **background** galaxies; 5 redshift bins)

“3x2 (point-function)” clustering measurements: $\begin{bmatrix} gg & gs \\ gs & ss \end{bmatrix}$

3x2 cosmology

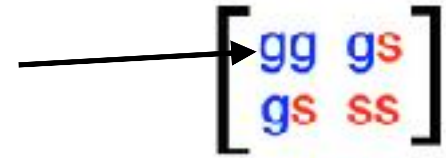
Covariance is non-trivial to calculate…

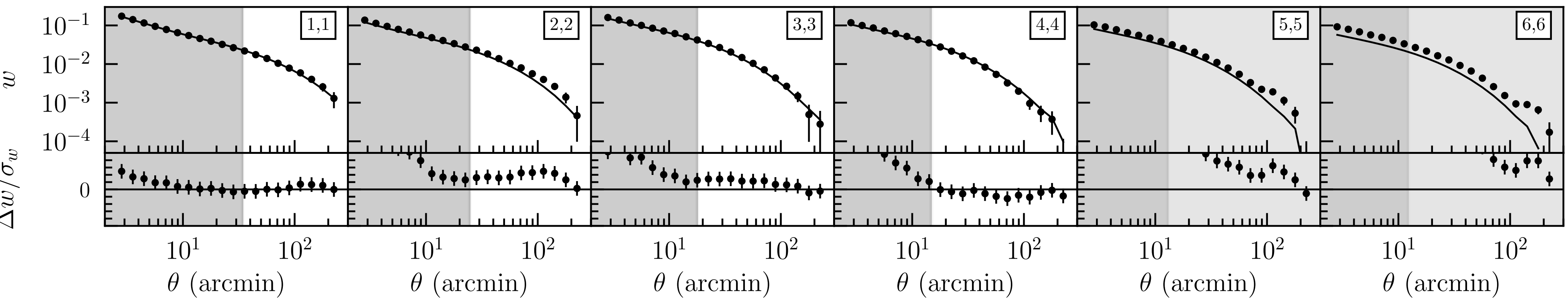


Krause, Eifler et al (2017)
[3x3 Cov for DES]

DES Y3 constraints from 3x2 cosmology:

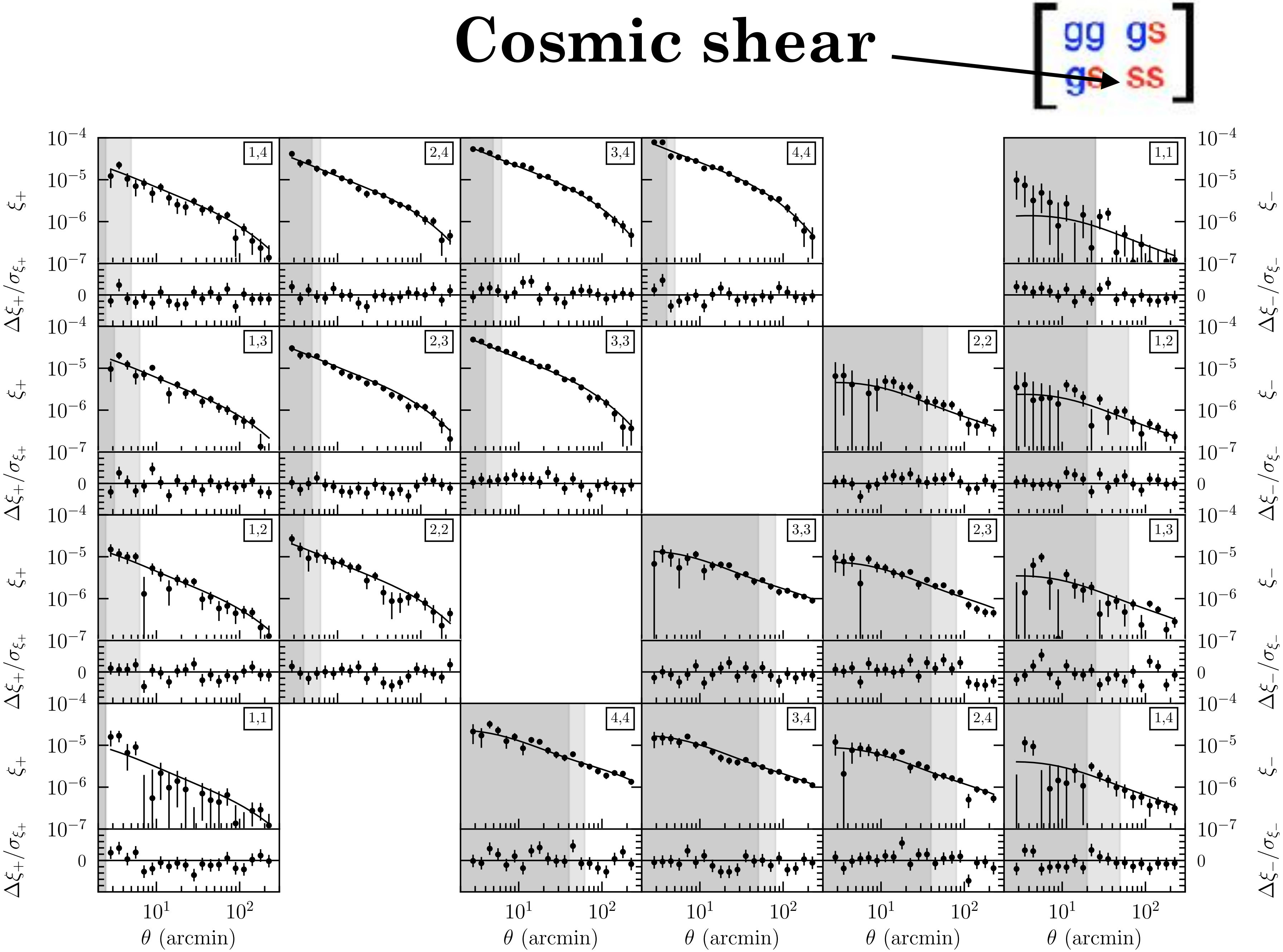
Galaxy clustering





Abbott et al, 2022

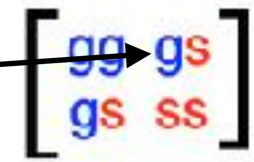
DES Y3 constraints from 3x2 cosmology:

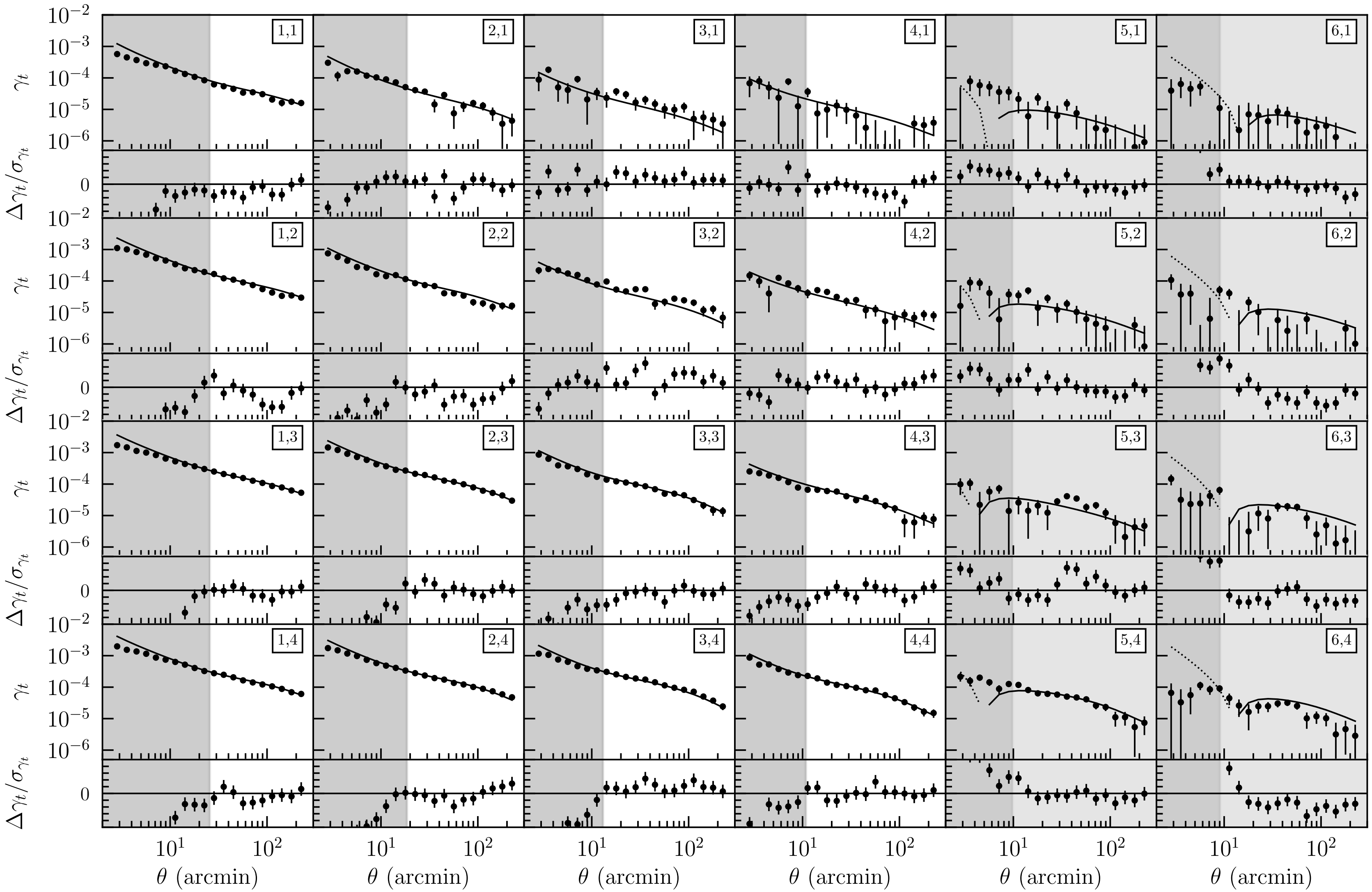


Abbott et al, 2022

DES Y3 constraints from 3x2 cosmology:

Galaxy-shear cross-corr

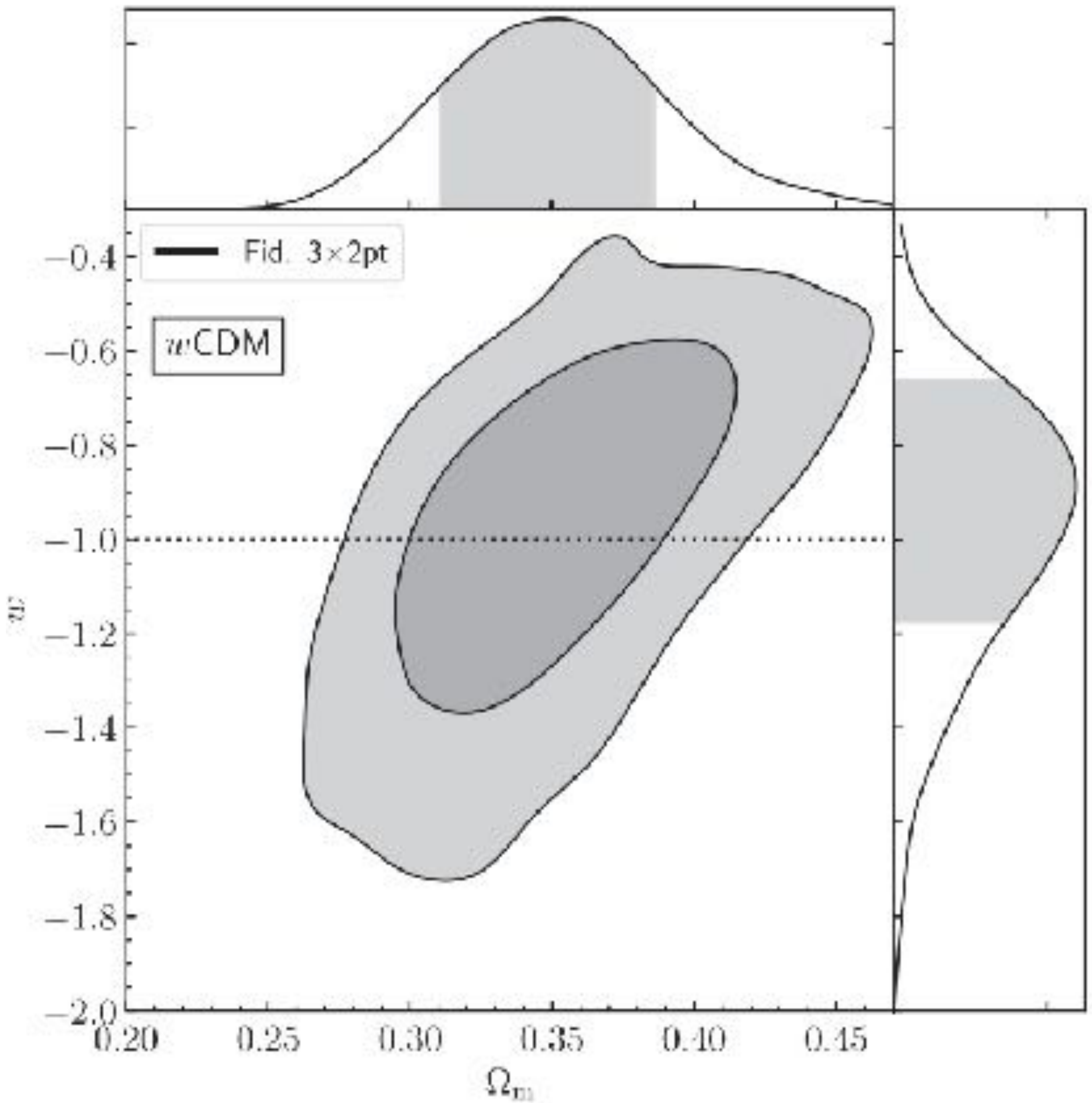




Abbott et al, 2022

DES Y3 constraints from 3x2 cosmology:

Equation of state w=p/rho



Matter density rel. to critical

Abbott et al, 2022

Weak lensing ("cosmic shear") summary

Yes, it's a bit messy, and shapes of galaxies are hard to measure, but:

No dependence on galaxy bias:

$$P_{\rm shear} \simeq \int_0^\infty W(r) P_{\rm matter}(r) dr$$

makes it a powerful probe of DM and DE.

Principal upcoming surveys with weak lensing: Euclid; LSST on Rubin Observatory; Nancy Roman Space Telescope.