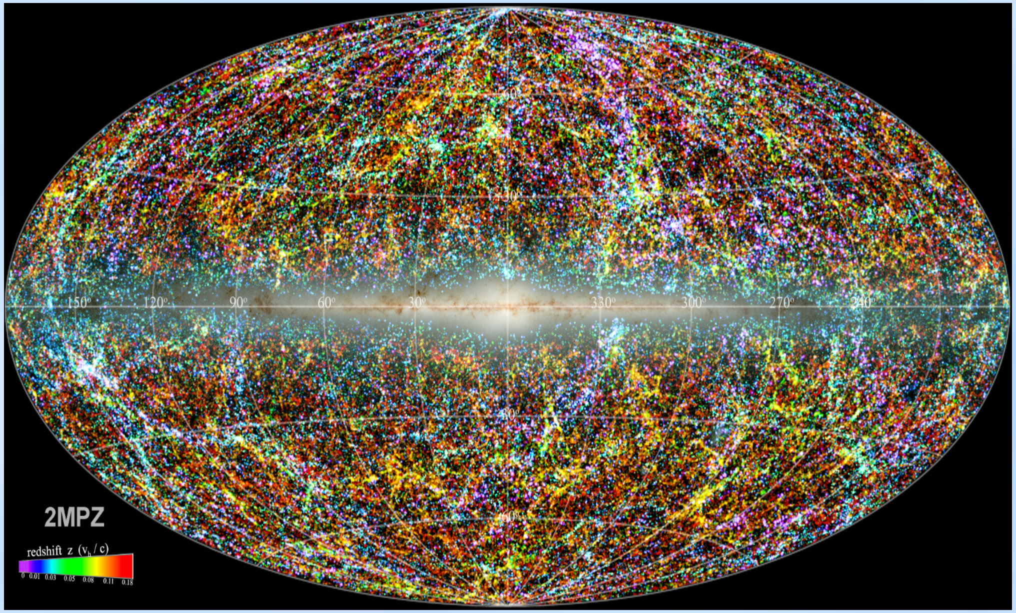
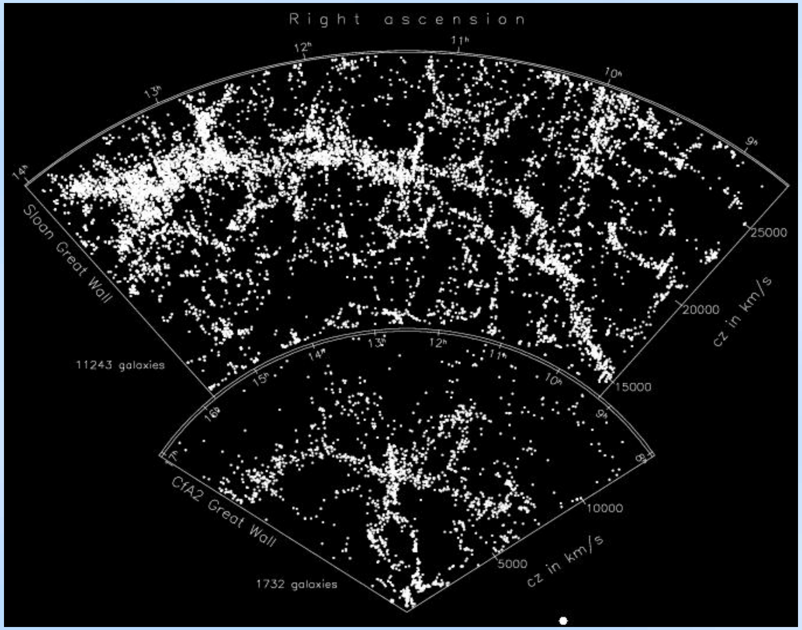
Cosmology with the large-scale structure



A subjective review



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Surveys of galaxies: why do we need them?

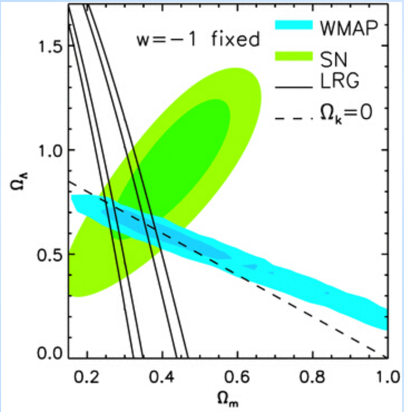
* **The distribution of galaxies** results from physical processes since the Big Bang until now (gravitational collapse, galaxy formation, ...)

* By studying the **statistical properties of the large-scale structure** we measure **cosmological parameters** (determining the past and future evolution of the Universe), such as:

– mean **matter density** ("baryonic" and dark matter)

– **cosmological constant** (dark energy)

– current and past **expansion rate** (Hubble constant)



Reid et al. 2010

* **Key words**: density power spectrum; galaxy correlation function; baryon acoustic oscillations; growth rate of structure; …

Observational cosmology: what we already know

More precisely: what is most consistent with observations

* Most of the **matter** in the Universe is in a “**dark**” form – interacting only gravitationally and (probably) weakly

* Universal **expansion** has been **accelerating** for a couple billion years – **dark energy** is now dominating the mass-energy balance

* The Universe has **null curvature** – space is globally flat

* The Universe is **homogeneous** and **isotropic** on the largest scales

* The **growth of structure** is consistent with general relativity

Questions...
What we don't fully (or at all) know yet

* What is **dark matter**? (Particles? What kind? Something else??)

* What is **dark energy**? (Cosmological constant? Negative pressure? Artefact of the overly simplistic model? More exotic models?)

* Is **general relativity** correct on the largest scales? (Modified gravity?)

* How large are the scales of global **isotropy and homogeneity**?

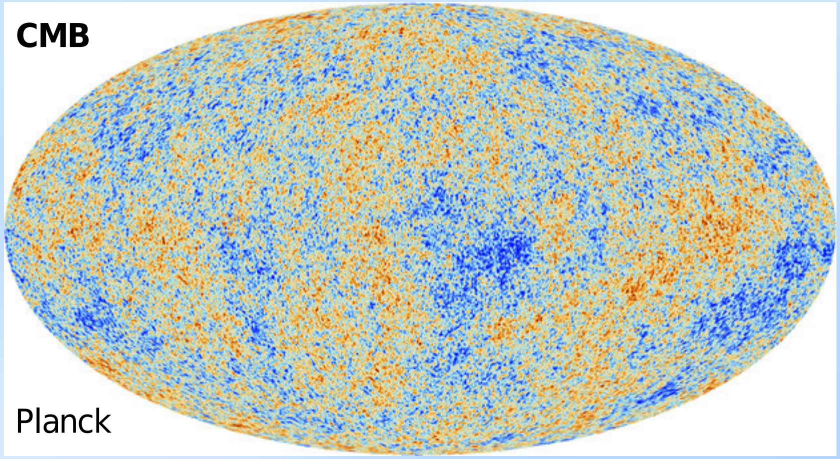
* Are we a **typical observer**? (Basis of the **Copernican principle**...)

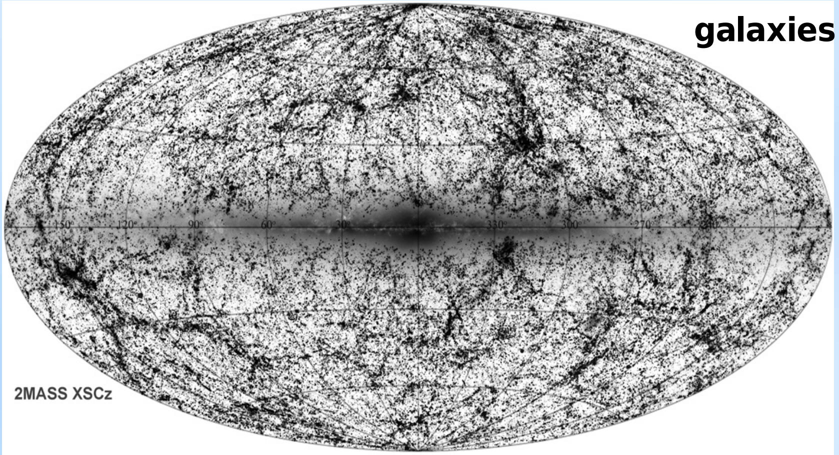
* More detailed **(g)astrophysical aspects**:
– history of galaxy formation, build-up of galaxies from primordial gas;
– collisions and mergers of galaxies;
– build-up of galaxy clusters and large-scale voids...

Build-up of the large-scale structure

Formed out of *primordial density fluctuations*

imprinted today in the ***c****osmic* ***m****icrowave* ***b****ackground*





Universe 13.8 billion years ago

(380,000 years after the Big Bang)

Universe today

(13.8 billion years after the Big Bang)

Fluctuations of 1 part in 100,000

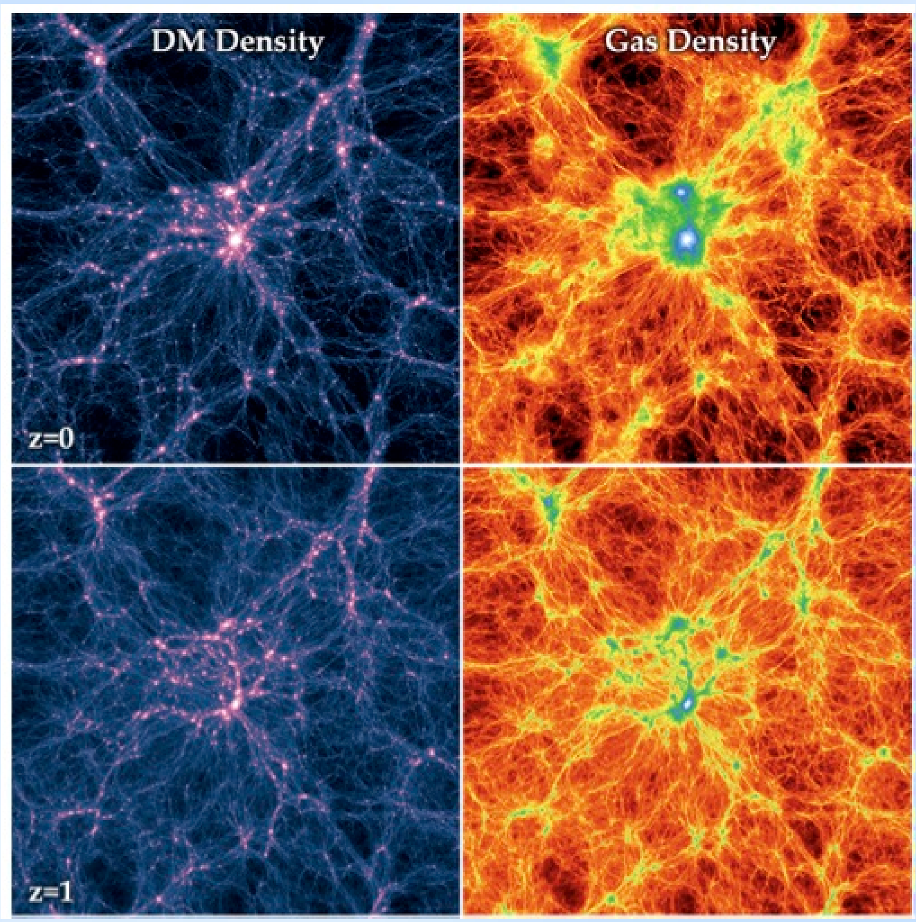
Clusters and superclusters of galaxies

Voids and filaments

Large density contrasts

Build-up of the large-scale structure

Formed via the ***gravitational instability*** mechanism:



Illustris collaboration

• **Overdense regions collapse** under their own gravity to become galaxies, clusters and superclusters of galaxies

• **Underdense regions expand** faster than the background to become voids of densities much lower than the average

More **complete picture** thanks to **numerical simulations**
(Lectures by Wojtek Hellwing & Matthieu Schaller)

Large-scale structure of the Universe

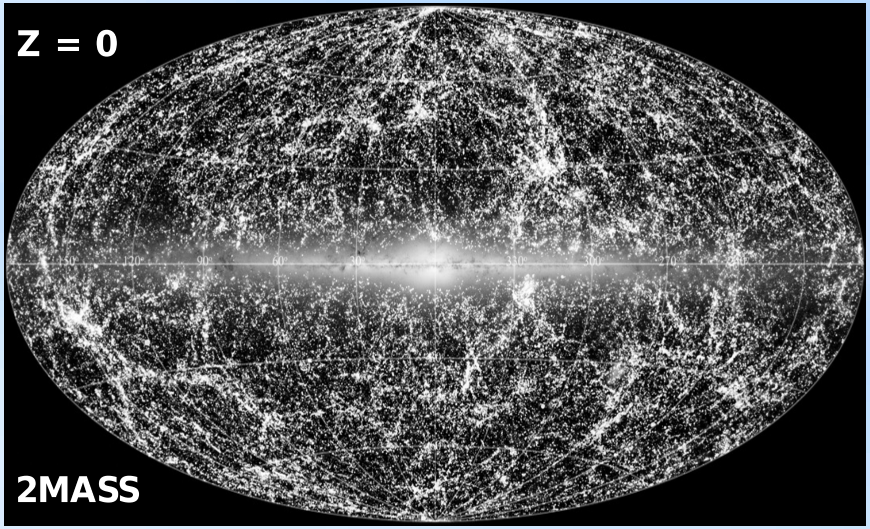
Galaxies organized into

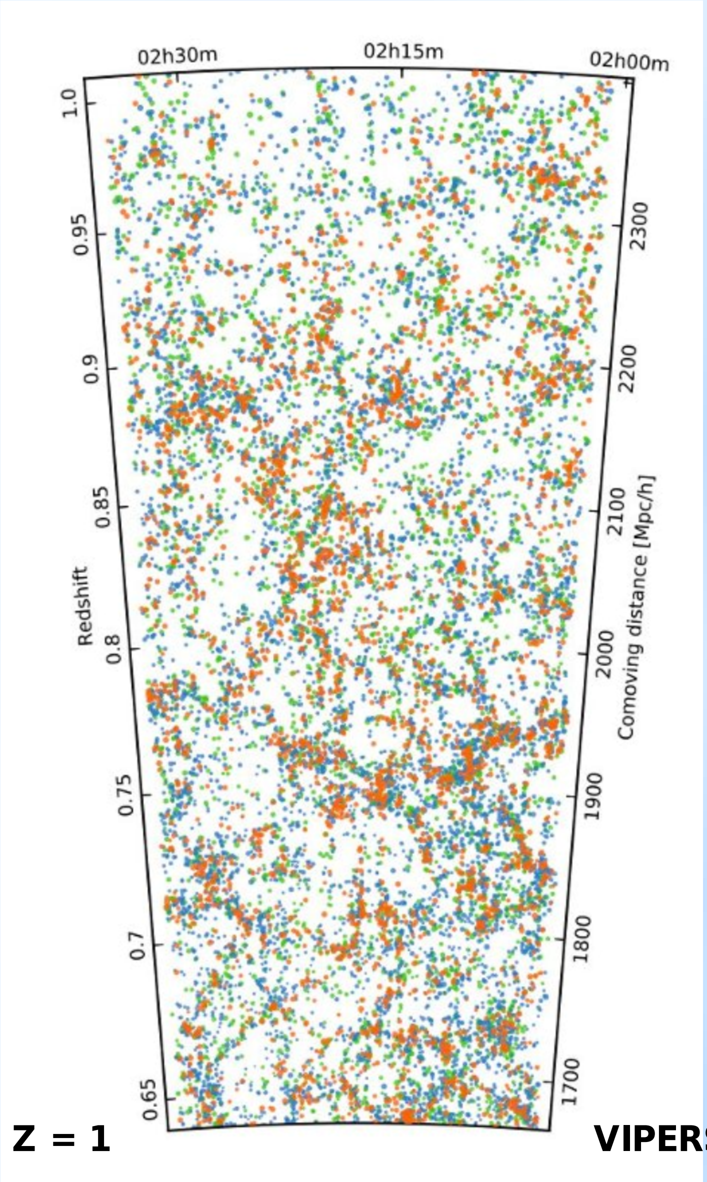
a network of interconnected

filaments and *walls*,

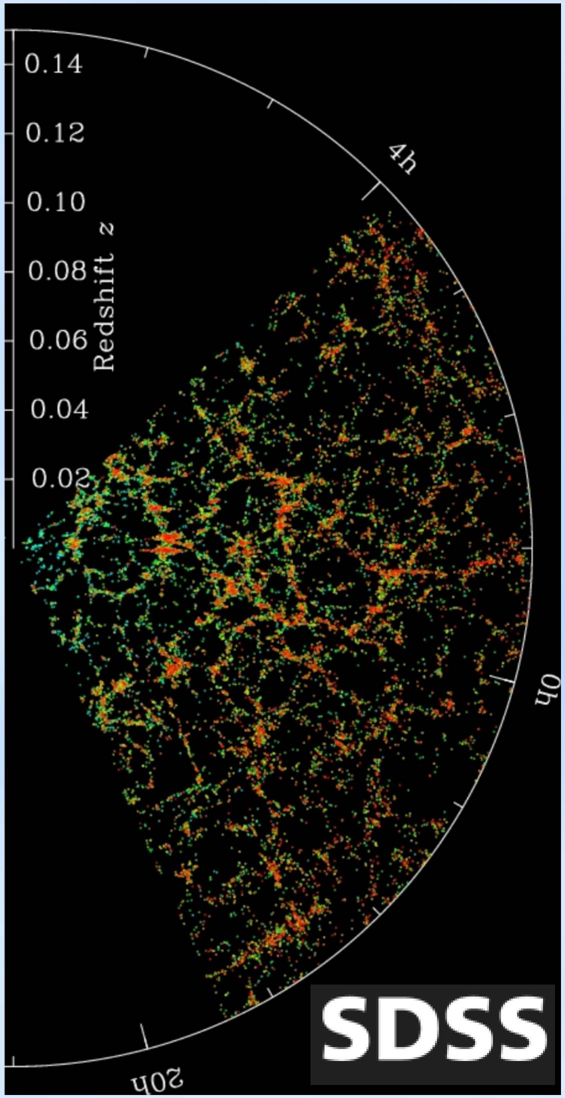
surrounding giant *voids*:

the ***cosmic web***





Observing the large-scale structure



- We need **representative samples** of the Universe: covering *large areas* of the sky and reaching as *far from us* as possible

- The most successful to date: the **Sloan Digital Sky Survey** (SDSS), 3 mln spectra on 25% of sky

- A **trade-off** between *how much of the sky* is covered and *how deep* a survey can reach
→ observing the wide-angle 3D galaxy distribution is *expensive* and *time-consuming*

Cosmological inference from the large-scale structure

Clustering measurements: correlations

- Galaxies are **not distributed randomly** in space: they **cluster**
- Their **distribution is correlated** on various scales
- A statistical measure of clustering: two-point **correlation function *ξ*(*r*)**
- **Excess probability** of finding a galaxy pair over random distribution

$$\mathrm{d}P = \bar{n}^2 (1 + \xi(r_{12}))\, \mathrm{d}V_1\, \mathrm{d}V_2$$

- $\xi(r)$ only **depends on separation** (and not direction) due to statistical isotropy
- Also useful: **power spectrum *P*(*k*)**, i.e. Fourier-space counterpart of $\xi(r)$

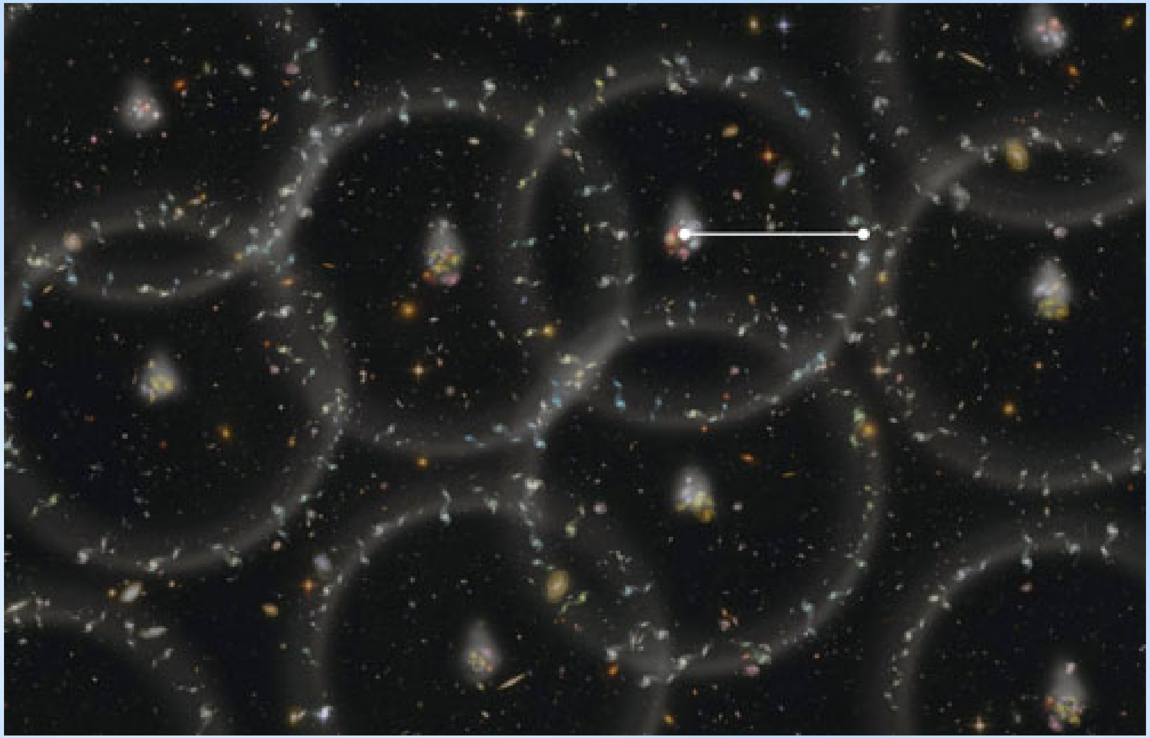
$$\xi(r) = \frac{1}{2\pi^2} \int \mathrm{d}k\, k^2 P(k) \frac{\sin(kr)}{kr}$$

Here k is the wavenumber – length of wavevector

Cosmological inference from the large-scale structure

Baryon acoustic oscillations

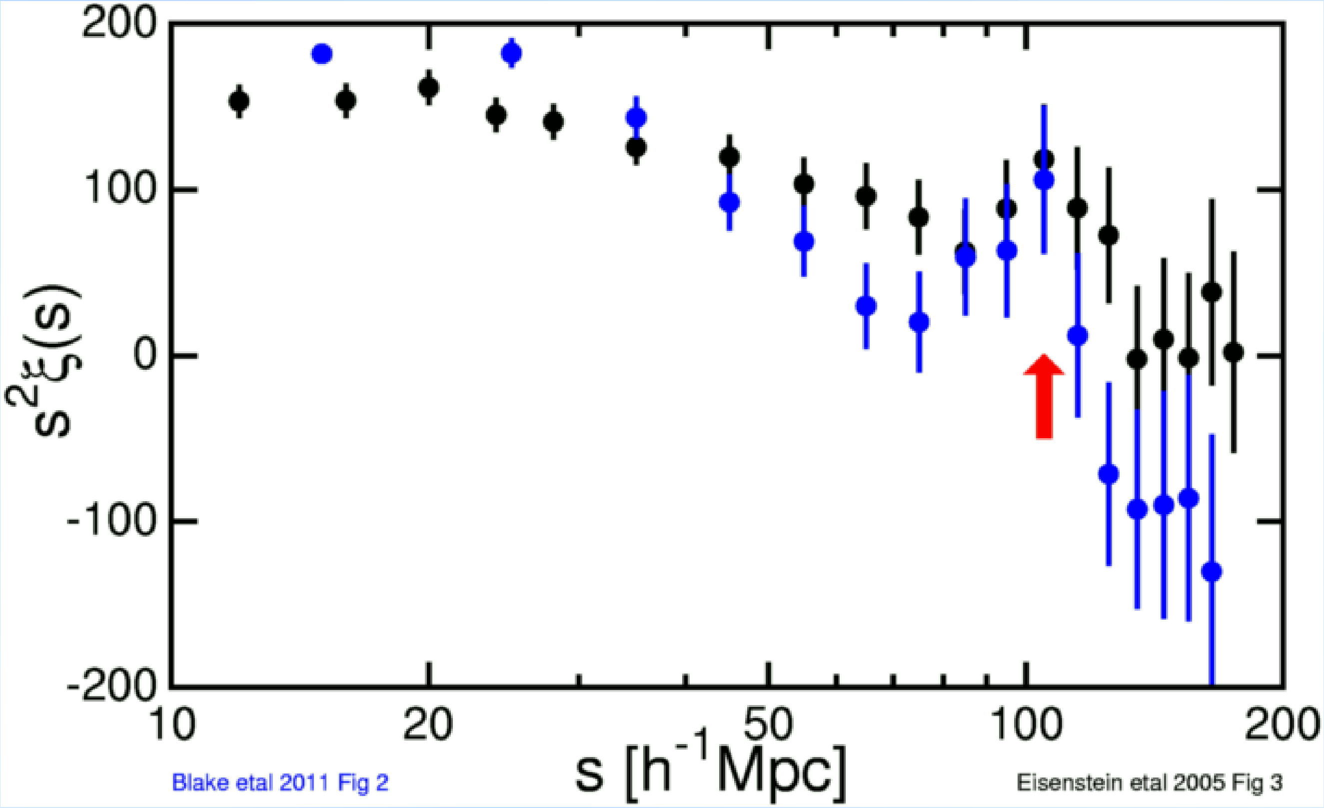
- Frozen relics of sound waves propagating through the primordial plasma of the early Universe, imprinted today in luminous matter (galaxy) correlations
- The ‘sound horizon’ has a fixed physical scale, hence BAOs are a **standard ruler** to measure universal expansion, and give evidence of cosmic acceleration



Cartoon by BOSS

Baryon acoustic oscillations

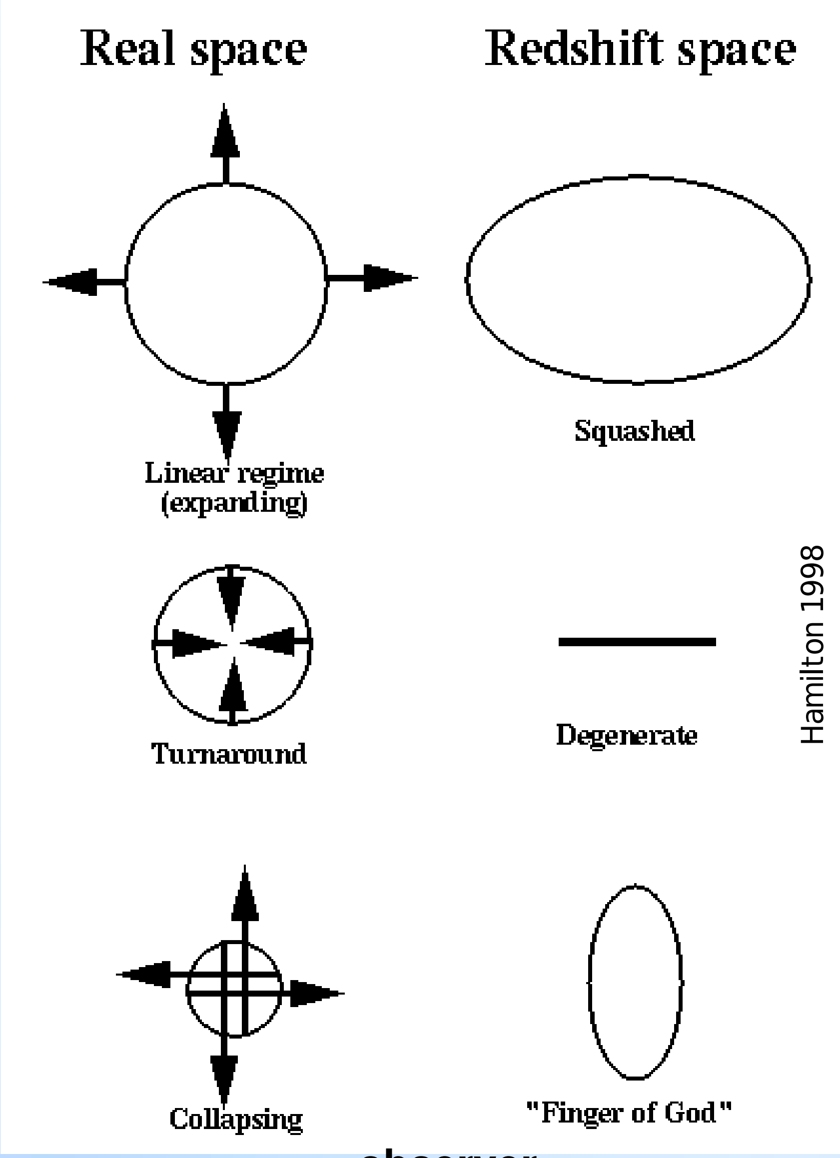
- Measured from the two-point galaxy correlation function, BAOs are seen as a **characteristic peak** at a redshift-dependent scale
- This **acoustic scale** can be compared to the one well-known from the CMB
- This allows to measure "**distance to a given redshift**" and the Hubble parameter $H(z)$ at this redshift
(rate of expansion)



Cosmological inference from the large-scale structure

Redshift-space distortions

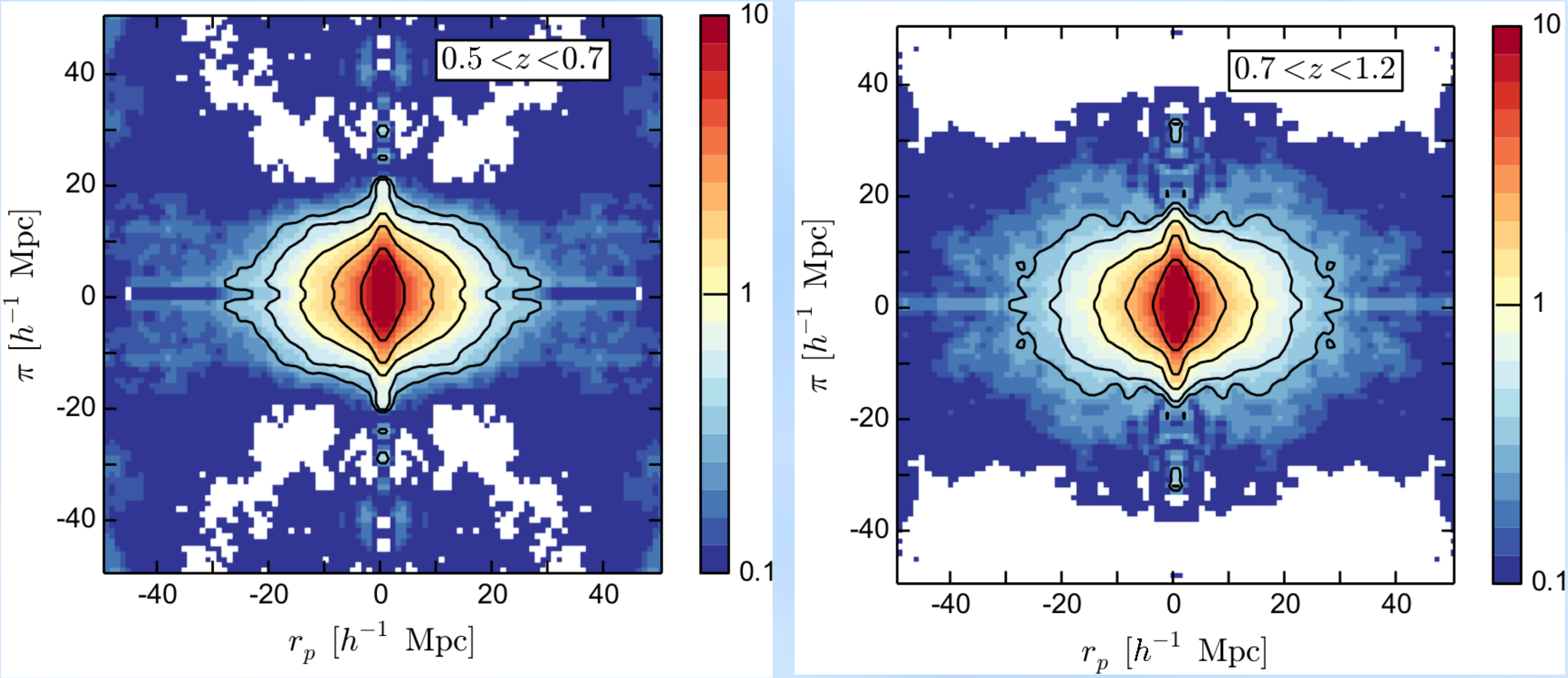
- The two-point correlation function is different in the **line of sight direction** and the one perpendicular to it (**plane of the sky**)
- These differences come from **processes of gravitational collapse** projected on the "redshift space" (in which observations are made) – imprint of **peculiar velocities** $\boldsymbol{c\,z = H_0\,r + v_{\mathrm{pec}}}$
- Two main regimes: large scales ('*squashing*') and small scales of galaxy clusters/groups ('*fingers of god*')



observer

Redshift-space distortions illustrated

Correlation function projected on the radial (π) / perpendicular (r_p) directions



VIPERS, Pezzotta et al. 2017

Redshift-space distortions

- The amount of “squash” and elongation in the correlation function depends on cosmological parameters, in particular the **growth rate** of structure
- The **power spectrum** is equally employed (e.g. Kaiser 1987):

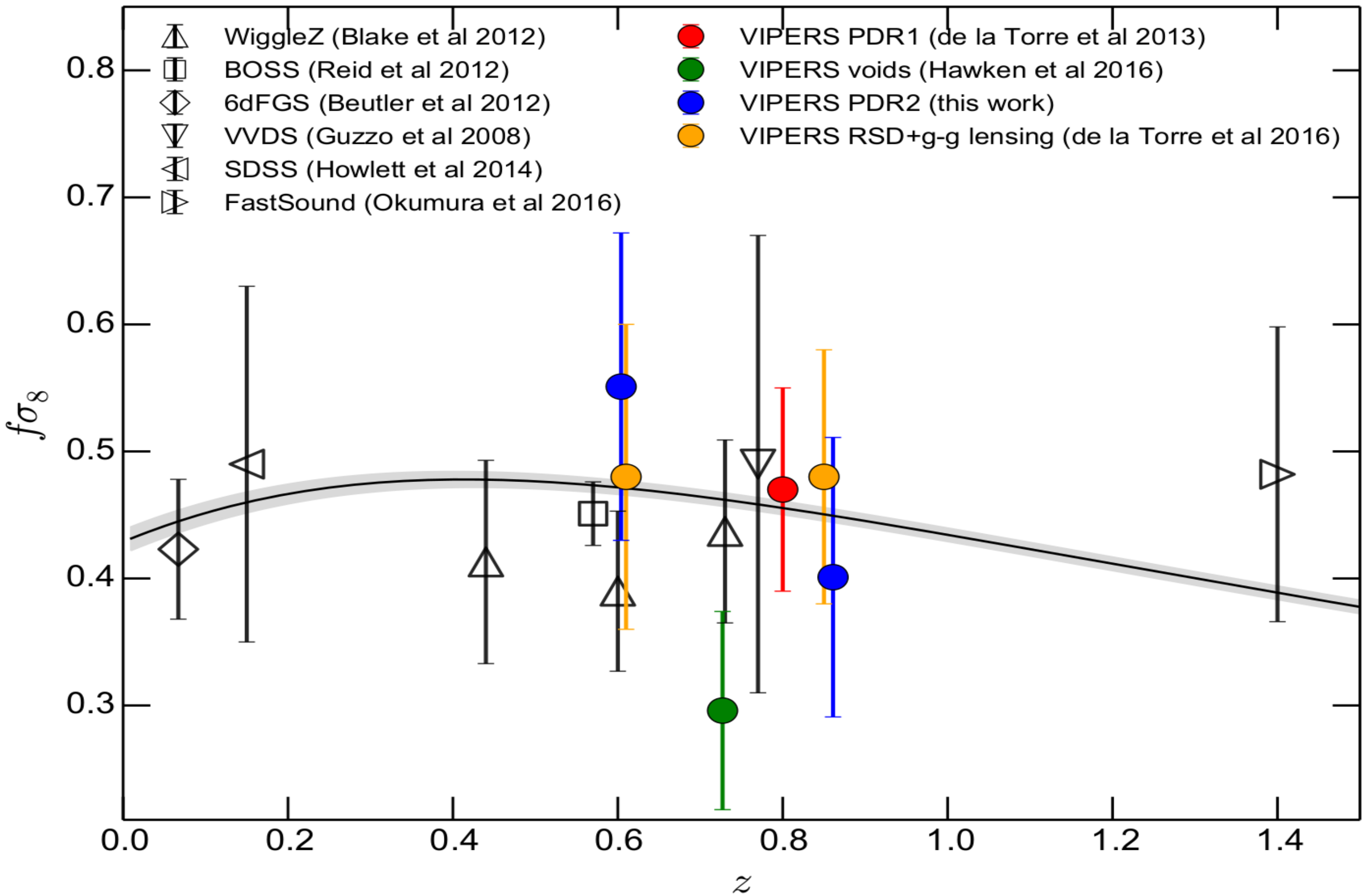
$$P^{(s)}(\mathbf{k};z) = (1 + f\mu_{\mathbf{k}}^2)^2\, P(k;z), \quad \mu_{\mathbf{k}} = \frac{\mathbf{e}_z \cdot \mathbf{k}}{k}$$

  where *f* is the LSS **growth factor**

- Measuring the correlation functions and comparing to various models we can check if the growth of the LSS is **consistent with theory predictions** (e.g. general relativity / modified gravity...)
- Together with BAOs, these are the two major probes benefiting from **clustering properties of matter**, imprinted in the correlation functions measured from **spectroscopic redshift surveys**

Redshift-space distortions for the growth rate

growth rate at various redshifts



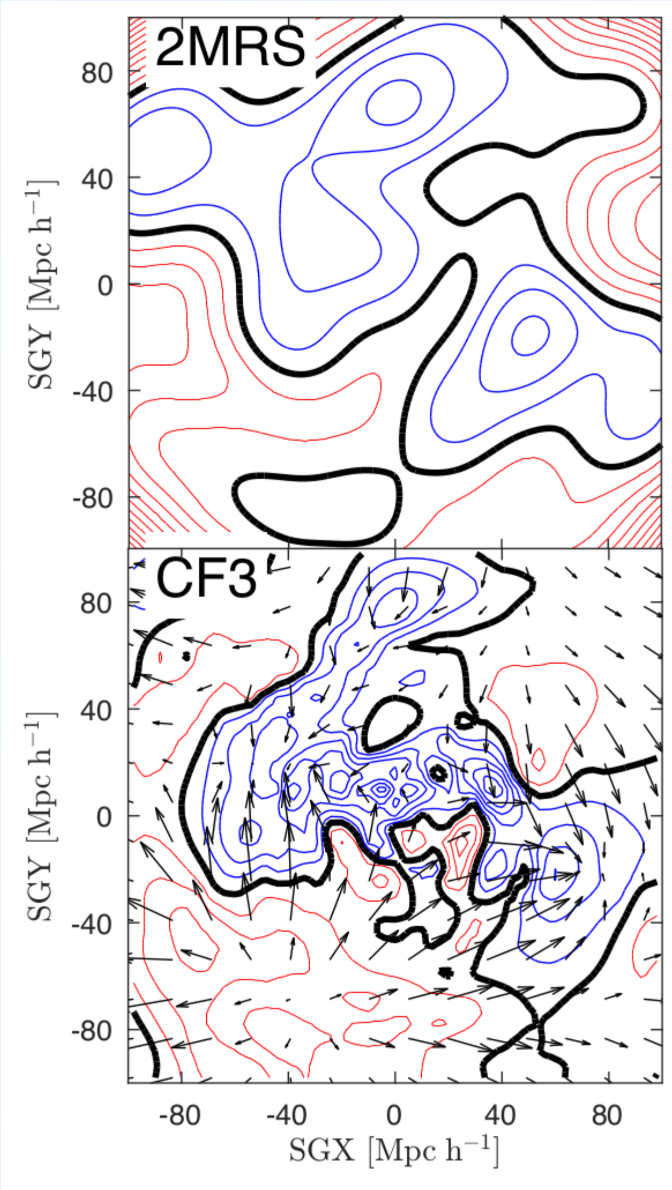
VIPERS, Pezzotta et al. 2017

Cosmological inference from large-scale structure
Peculiar velocities

- The measured redshift of each galaxy includes the cosmological component (from the “Hubble flow”) and a **peculiar velocity** one: $c\,z \approx H_0\, r + v_{\mathrm{pec}}$
- Peculiar velocities arise due to **matter concentrations**: coherent infall
- A **direct tracer** of the overall density field, no galaxy bias
- Peculiar velocity can be measured if **reshift-independent distance** is known: **distance indicators** (Tully-Fisher, Fundamental Plane, Supernovae Ia, ...)
- Distance indicators give ~10 – 20% precision, so v_{pec} available only for z<0.1 (their errors grow linearly with distance, while v_{pec} ~ 500 km/s typically)
- Cureently the largest catalog of peculiar velocities: **CosmicFlows-3**, 18,000 galaxies (Tully et al. 2016)

Cosmological inference from large-scale structure

Peculiar velocities

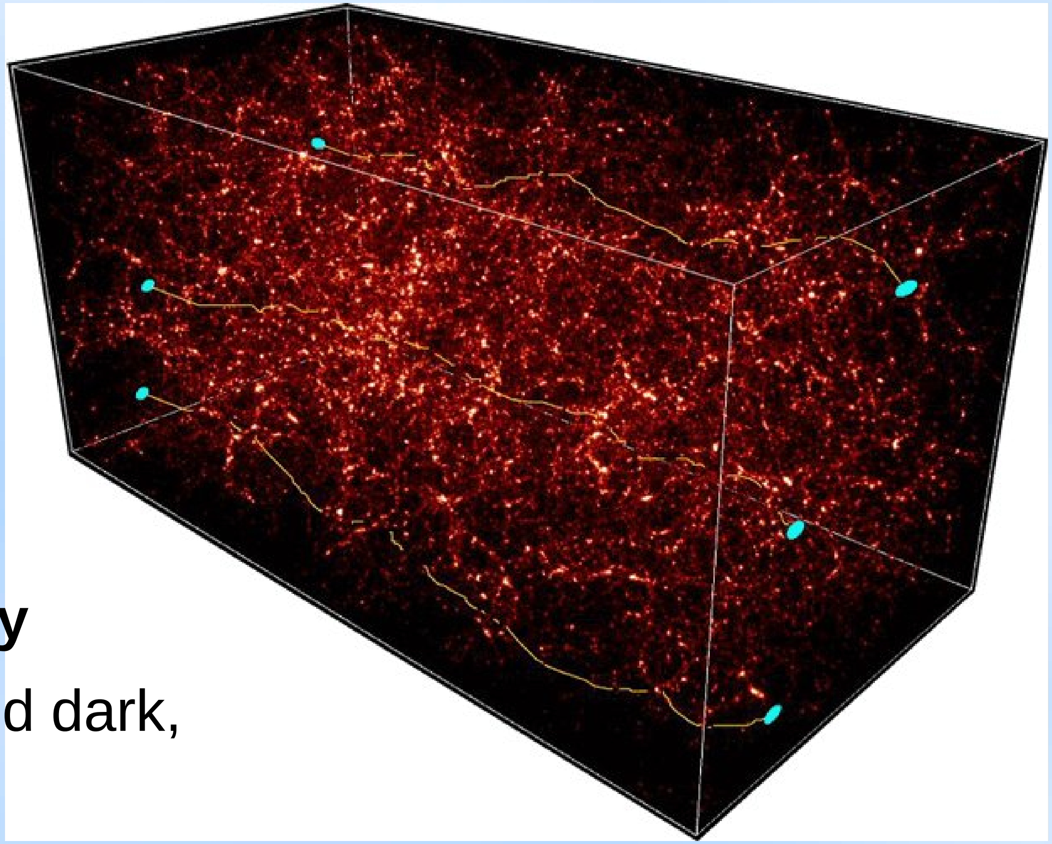


- Individual peculiar velocities very **noisy** and **difficult to measure**
- Catalogs of v_{pec} relatively **sparse** and **small**
- **Cosmological constraints** from peculiar velocities best if used together with density field: **reconstructions**, **cross-correlations**…
- Used for the **growth rate** constraints, large-scale **flows**, **cosmography**, ...

Nusser 2017

Cosmological inference from the large-scale structure

Gravitational lensing

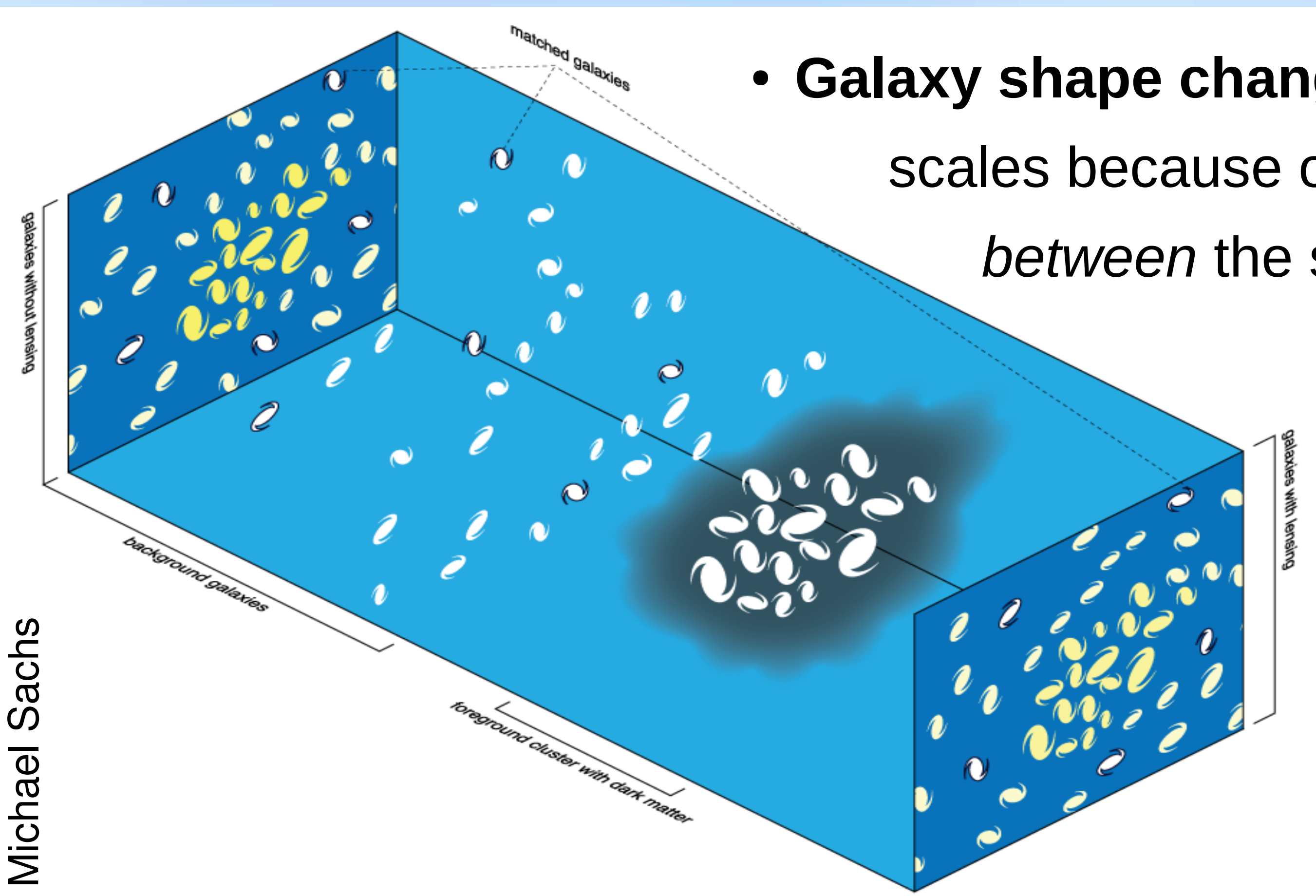


- On their way from the sources to the observer, paths of photons are **distorted** by the intervening matter: **gravitational lensing**
- Gravitational lensing **probes directly** all types of matter: both luminous and dark, baryonic and non-baryonic…
- We generally speak of **strong lensing** (caustics, rings, Einstein crosses) and **weak lensing** (tiny statistical effects)

Cosmological inference from the large-scale structure

Weak gravitational lensing

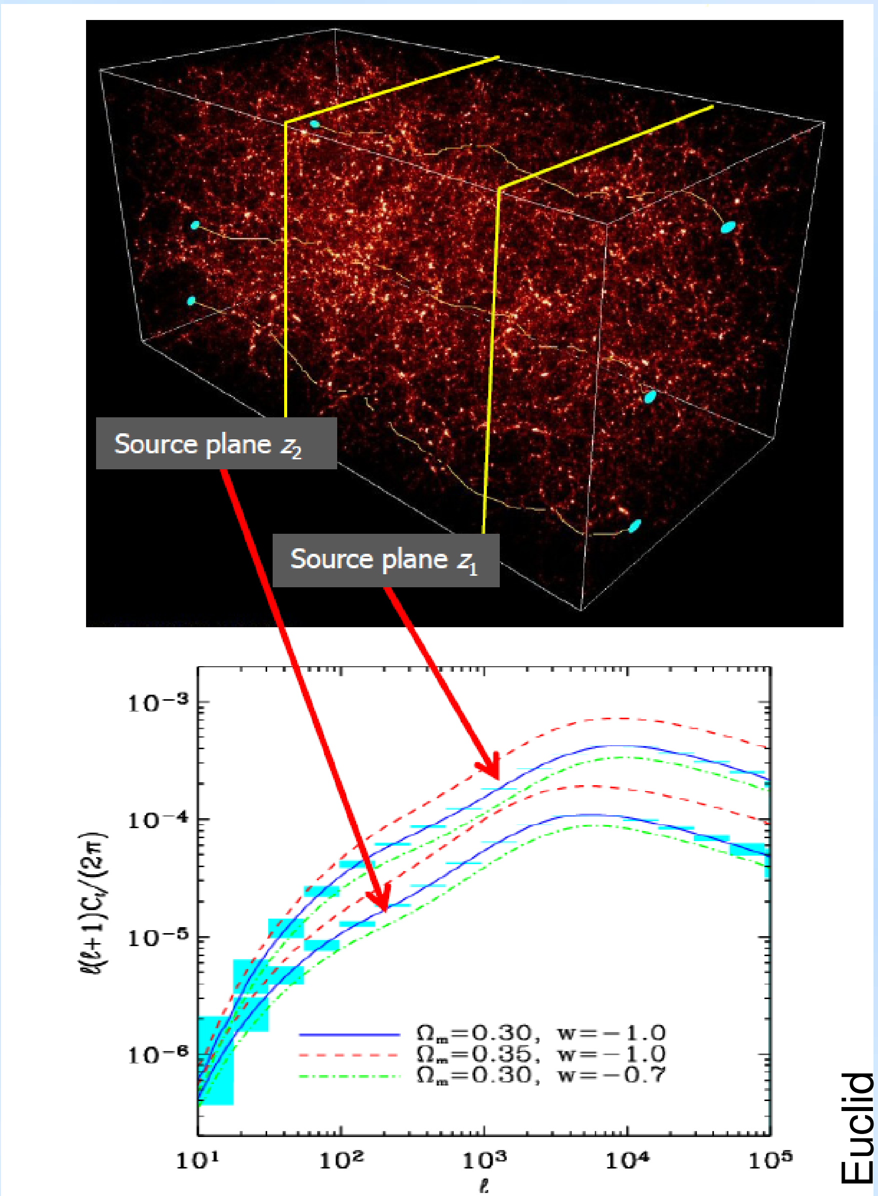
- Of most interest for cosmology is the ***weak lensing*** regime, in which observed **galaxy shapes** undergo tiny changes



- **Galaxy shape changes** are correlated on large scales because of the masses lying *between* the sources and the observer – ***cosmic shear***

Cosmological inference from the large-scale structure

Cosmic shear



- The amount of cosmic shear depends mostly on the **amount and clustering properties of matter** between the source and observer
- The **cosmic shear signal** is looked for in correlation functions / power spectra of galaxy shapes (rather than of clustering like in BAO or RSD)
- Weak lensing measurements require **extremely good quality imaging** – from the ground possible only in places like Chile, Hawaii (very good seeing)

Cosmological inference from the cosmic shear

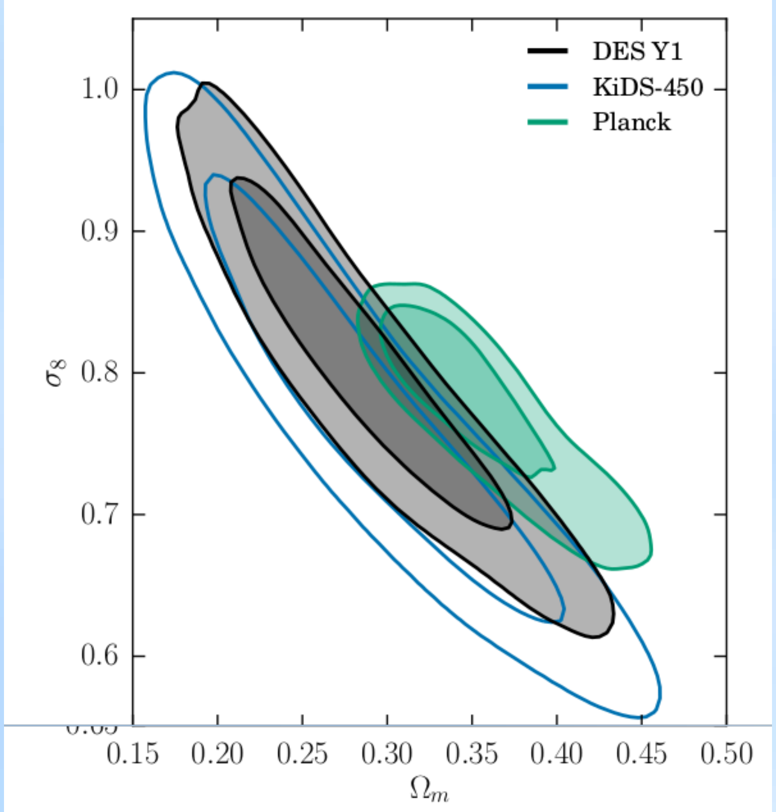
- Cosmic shear constrains mostly the **(Ω_m, σ_8) plane**, where **Ω_m is mean matter density** today and **σ_8 is amount of fluctuations** at scales of 8/h Mpc (h = H_0/100)

- State-of-the-art measurements:
  Dark Energy Survey (DES)
  & Kilo-Degree Survey (KiDS)

- **Some tension with CMB**-based results...

- Large sizes of contours due to **still low statistical power** of cosmic shear

- Need to wait for **LSST** and **Euclid** for these to shrink considerably



DES, Troxel et al. 2017

Cosmological inference from large-scale structure

Cross-correlations

- Some signals are **too weak** for significant auto-correlation measurement and/or are plagued by systematics
- One can however **cross-correlate** different datasets to extract information
- General idea: if two surveys **probe the same** large-scale structure (or its effect on the measurements), then x-correlation will give **non-zero signal**
- Cosmological/astrophysical parameters are inferred from **cross-power spectra** or **cross-correlation functions** of the two surveys / catalogs
- Cross-correlations benefit from **as large sky coverage as possible** [signal to noise ~ sqrt(coverage)]

Cross-correlations

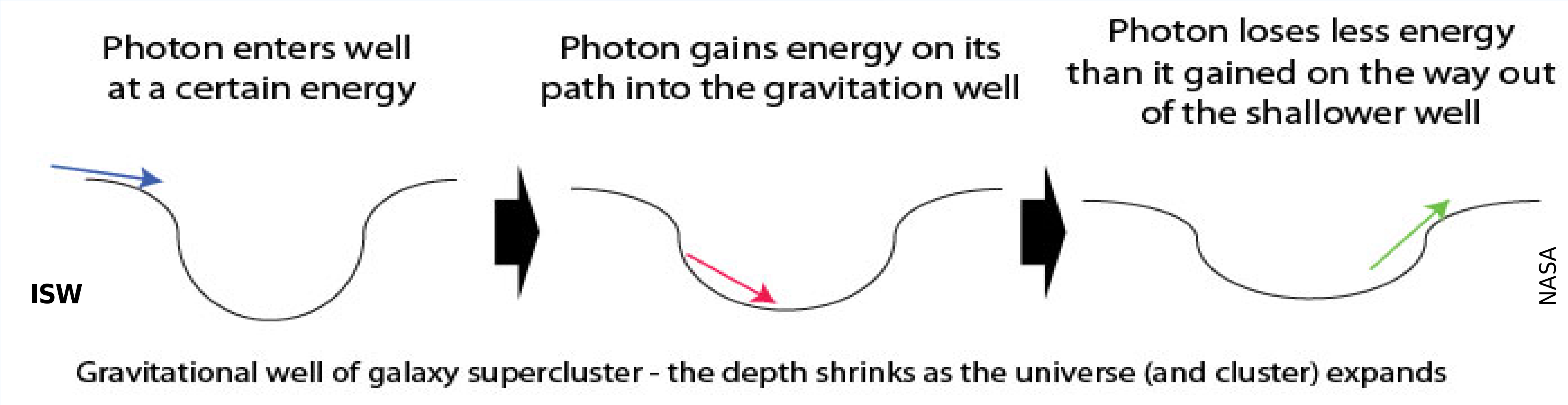
- Cross-correlations are a **powerful technique** especially if the signal we look for is much lower than other signals in the data
- They also allow us to **mitigate systematics** if these are different between the two surveys (e.g. instrumental effects)
- By using **redshift-binned** foreground galaxy distribution, one can slice-up "**tomographically**" various cosmological backgrounds
- Note: if one of the maps comes from a galaxy survey, usually spectroscopic redshifts are **not** needed – a **2D (projected) map** is sufficient + some information on galaxy **redshift distribution** for instance via photometric redshifts

Cosmological inference from the large-scale structure

Late-time integrated Sachs-Wolfe effect

- Cosmic background photons change their energy passing through evolving matter over- and underdensities (gravitational wells and hills)
  → resulting effect would be null if there was no dark energy (in a flat Universe)
  → can be also generated in modified gravity models

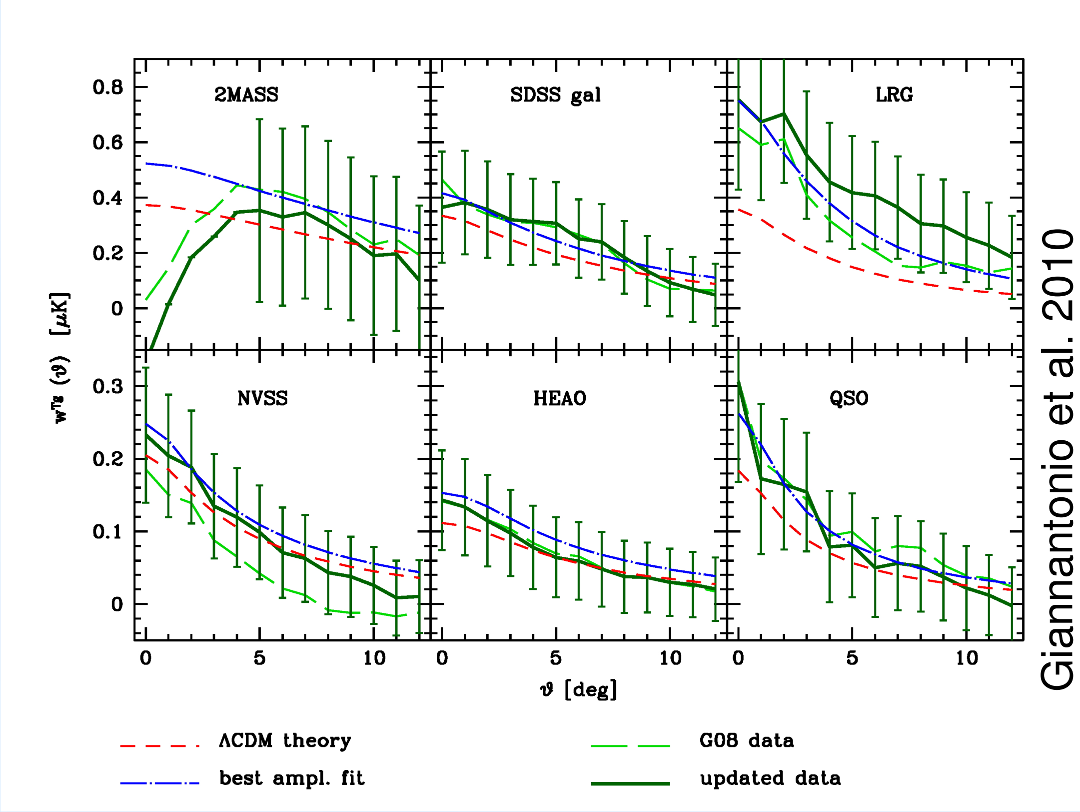
- Late-time ISW cannot be detected from CMB auto-correlations alone (signal much lower than primary CMB anisotropies)



Integrated Sachs-Wolfe effect from cross-correlations

- First proposed by Crittenden & Turok (1996) to look for the **ISW effect** by cross-correlating CMB (COBE) and LSS (ROSAT X-ray) maps

- **First detection of ISW** much later, only after WMAP CMB data came online – from x-correlation with NVSS radio data and the HEAO1 A1 X-ray data (Boughn & Crittenden 2004)



Giannantonio et al. 2010

- **Detection of ISW**: evidence for dark energy as the Universe is flat

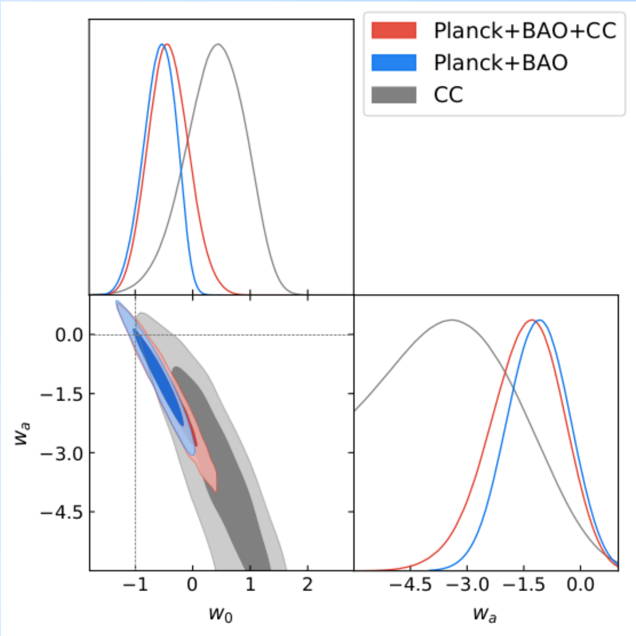
- Now a **standard technique** to measure ISW with WMAP or Planck cross-correlated with various galaxy & quasar surveys

ISW for dark energy

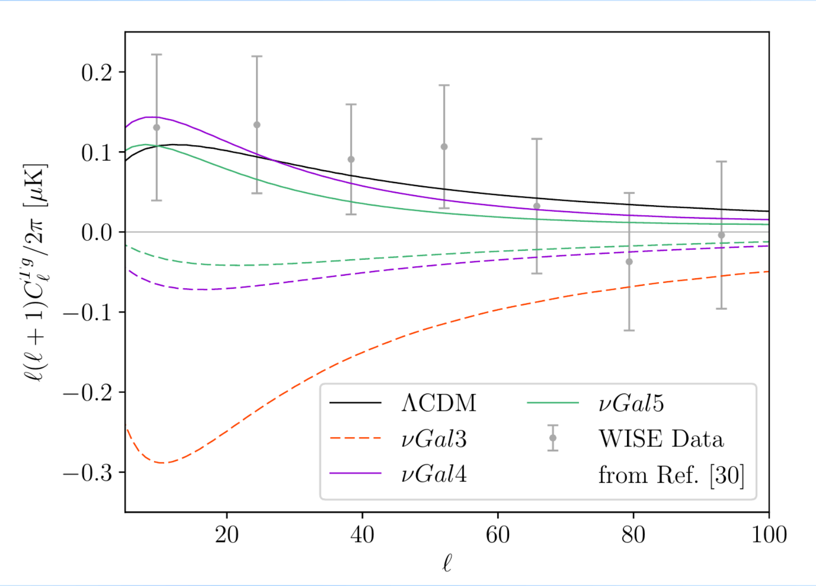
- The ISW signal can be also used to constrain **dark energy properties** – challenging, as the cross-correlation signal is low

- Tomographic analysis by Stölzner et al. 2018: first **5σ ISW detection** from cross-correlation, constraints on the **dark energy equation of state** [$p = w\,\rho$; $w(z) = w_0 + w_a\, z / (1+z)$; cosmological constant: $w(z)=-1$]

- ISW is also used to put constraints on some **modified gravity models** (e.g. Renk et al. 2017 - various Galileon flavors)



Stölzner et al. 2018

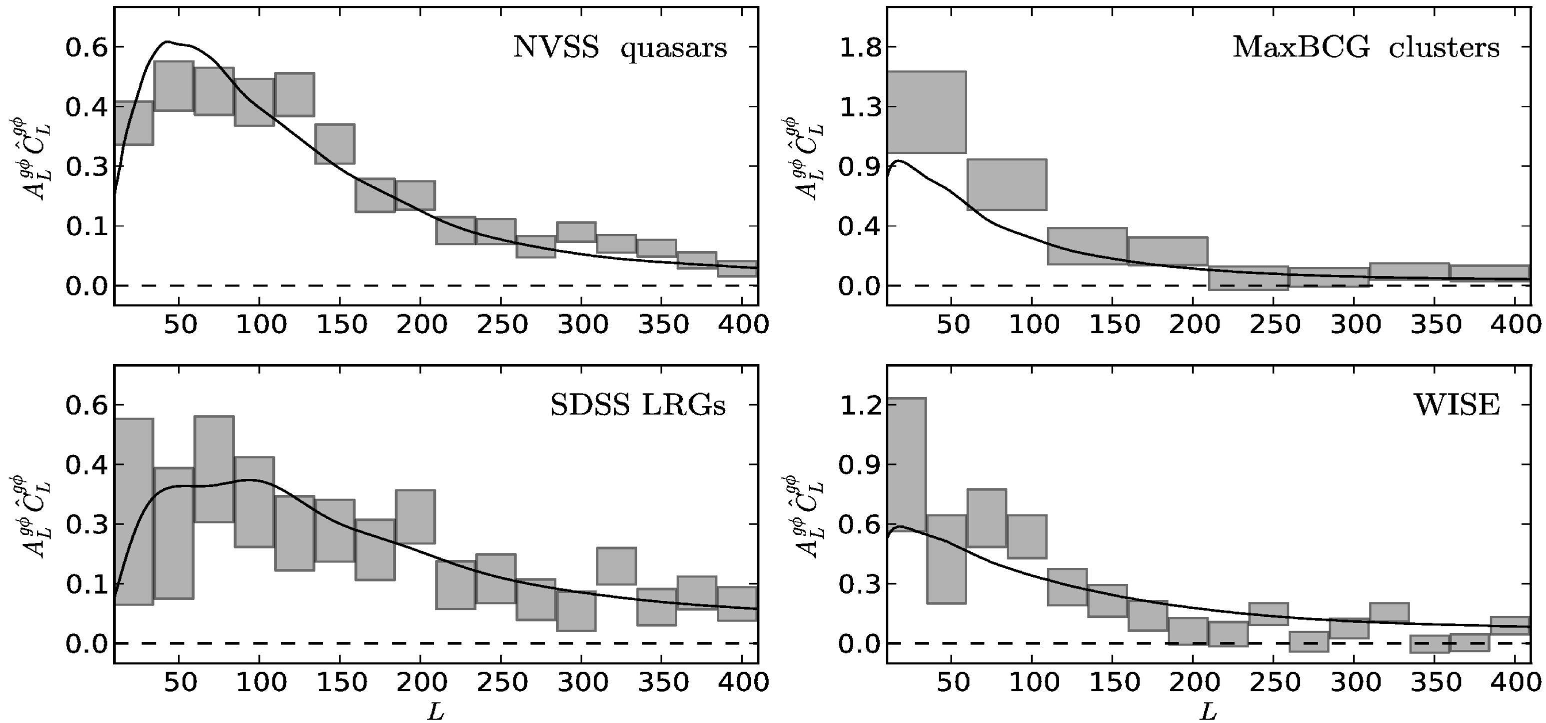


Renk et al. 2017

Cosmological inference from the large-scale structure

Cross-correlation with CMB lensing

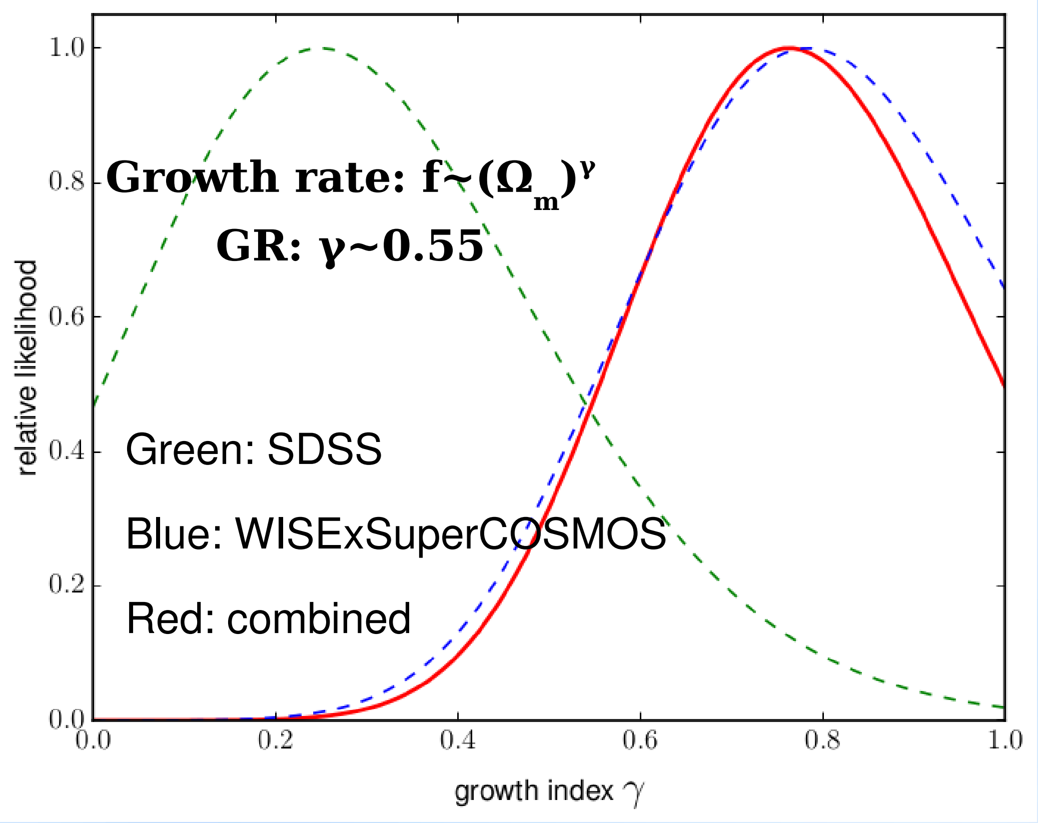
- **CMB is lensed by the LSS** in the same way as photons from galaxies, only that the “source” is the last-scattering surface and not galaxies
- Signal can be extracted from **cross-correlations with LSS maps**
- **Significant detection** for many foreground source catalogs x Planck lensing



Planck Collaboration 2013 XVII

CMB lensing for the growth of structure

- The amplitude of the CMB-lensing x LSS cross-correlation depends on the **growth rate** of structure – provides a test independent from redshift-space distortions in galaxy auto-correlations
- The cross-correlation signal is currently **limited by CMB maps** rather than the LSS ones (e.g.: Planck CMB lensing map is noise-dominated)
- Of particular interest are correlations with **low-redshift** galaxy surveys to probe dark-energy dominated era (e.g. Bianchini et al. 2017; Peacock & Bilicki 2018)
- Not competitive yet with RSDs but promising for future campaigns



Peacock & Bilicki 2018

Cosmological inference from the large-scale structure

CMB lensing x cosmic shear

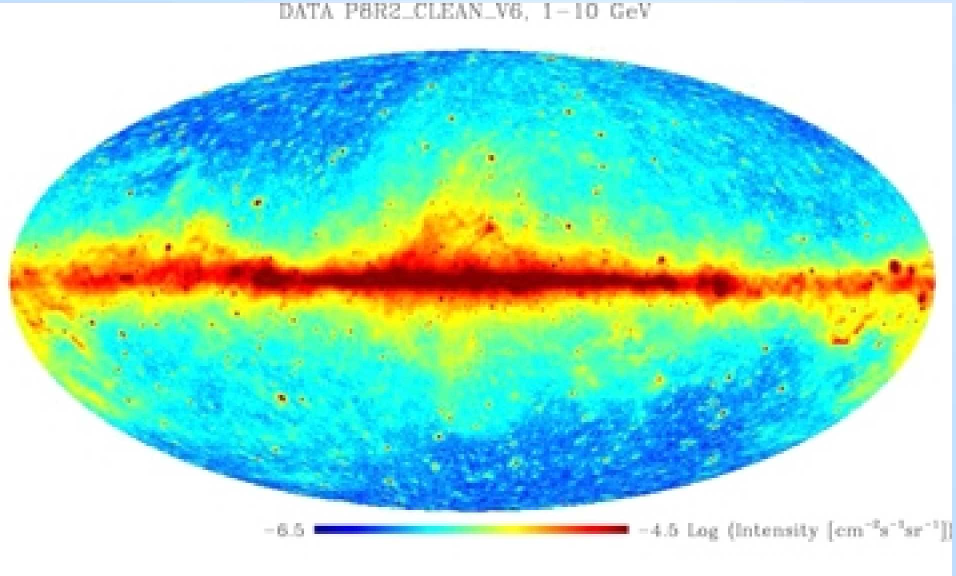
- Gravitational lensing of the CMB cross-correlated with the LSS maps: now extended to x-correlations of **CMB lensing with cosmic shear**
- Cosmic shear probes all matter distribution while LSS maps are sensitive to **galaxy bias** ($\delta_g = b\,\delta_m$, where $\delta = \langle\rho\rangle/\rho - 1$)
- An **emerging approach** as both the CMB lensing maps and wide-angle cosmic shear catalogs started being available only in the last ~5 years
- Several detections made so far, but **no cosmological constraints yet** (e.g. KiDS x Planck: Harnois-Déraps et al. 2017)
- **Great promise** for ongoing and future surveys (cosmic shear: KiDS, DES, Euclid...; CMB lensing: ACT, SPT, Stage4...)

Cosmological inference from the large-scale structure

Other cross-correlations

- Many other maps and surveys have been cross-correlated; for instance:
  - Planck **thermal Sunyaev-Zeldovich** maps vs. galaxy data for constraints on baryonic physics (warm-hot intergalactic medium, filaments, …)
  - CMB lensing vs. **submillimeter** galaxy maps
  - **Cosmic *Infrared* Background** vs. galaxy maps for constraints on the sources of the CIB
  - **Gamma-ray background** as measured by Fermi-LAT vs. galaxy maps for constraints on the sources on the unresolved gamma-ray signal
  - The latter can also be used to constrain some **dark matter models**, also by cross-correlating with cosmic shear

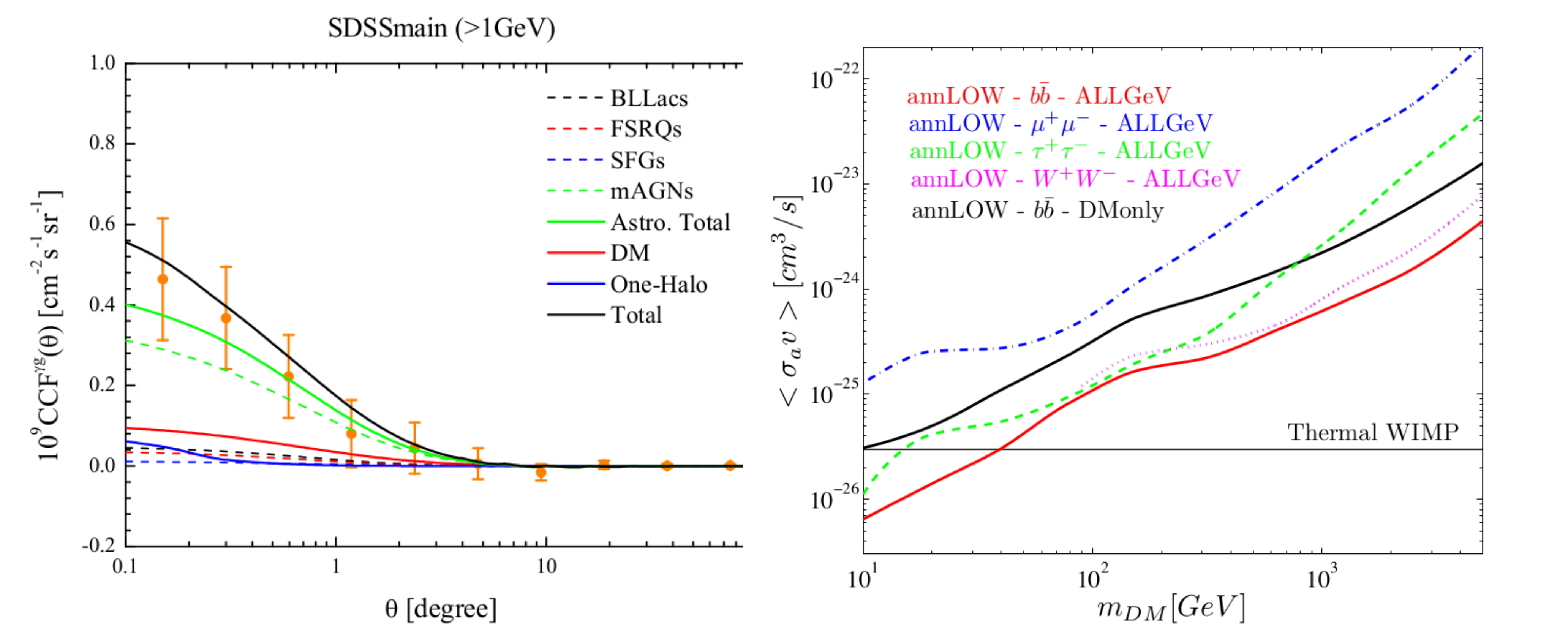
Unresolved gamma-ray background



- The Fermi-LAT satellite measures **unresolved gamma-ray background** (in addition to γ-ray sources)
- This background has **Milky-Way + extragalactic origin**
- Extragalactic γ-ray background (EGRB) can be presently **fully explained by astrophysical processes** (blazars, AGNs, star formation)
- However, if dark matter **self-annihilates or decays**, gamma-ray signal would be produced, and localized to structures (galaxies, clusters)

Probing the EGRB with x-correlations

- Significant detection of **EGRB x LSS cross-correlation** (e.g. Xia et al. 2015; Cuoco et al. 2017): EGRB is generated by cosmic structures
- No signal yet in gamma-ray bckgrd vs. cosmic shear (e.g. Tröster et al. 2017)
- **Upper limits on dark matter annihilation or decay** cross-sections etc. – an emerging probe of particle physics



Cuoco et al. 2015