The cosmic balance: weighing neutrinos with precision cosmology

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Neutrino dark matter...

- Massive neutrinos (m_ν > 1 meV) are **dark matter**:

$$\rho_\nu = \sum m_\nu n_\nu \quad \Rightarrow \quad \Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$$

112 cm^{-3} per flavour (→ n_ν)

Energy density (→ $\Omega_\nu h^2$)

  - Closure bound: $\sum m_\nu < 90$ eV

    Gerstein & Zel'dovich, 1966
    Cowsik & McClelland, 1972

- From lab experiments:

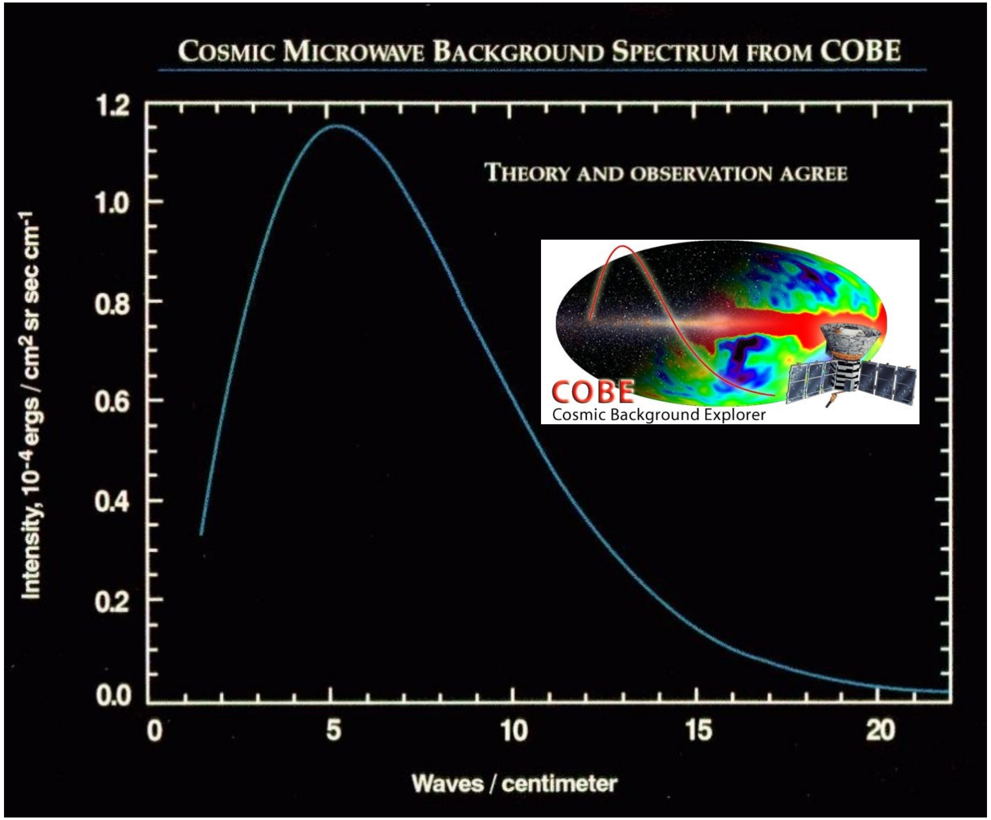
$$\min \sum m_\nu \simeq 0.05\,\mathrm{eV} \quad \text{(Neutrino oscillations)}$$
$$\max \sum m_\nu \simeq 6\,\mathrm{eV} \quad \text{(Tritium β decay)}$$

→ Small but not negligible!

$$\Omega_\nu \sim 0.1\,\% \rightarrow 12\,\%$$

- Neutrino dark matter is **hot**. → Pin down with precision cosmological data?

Probe 1: Cosmic microwave background...



Mather et al., 1994

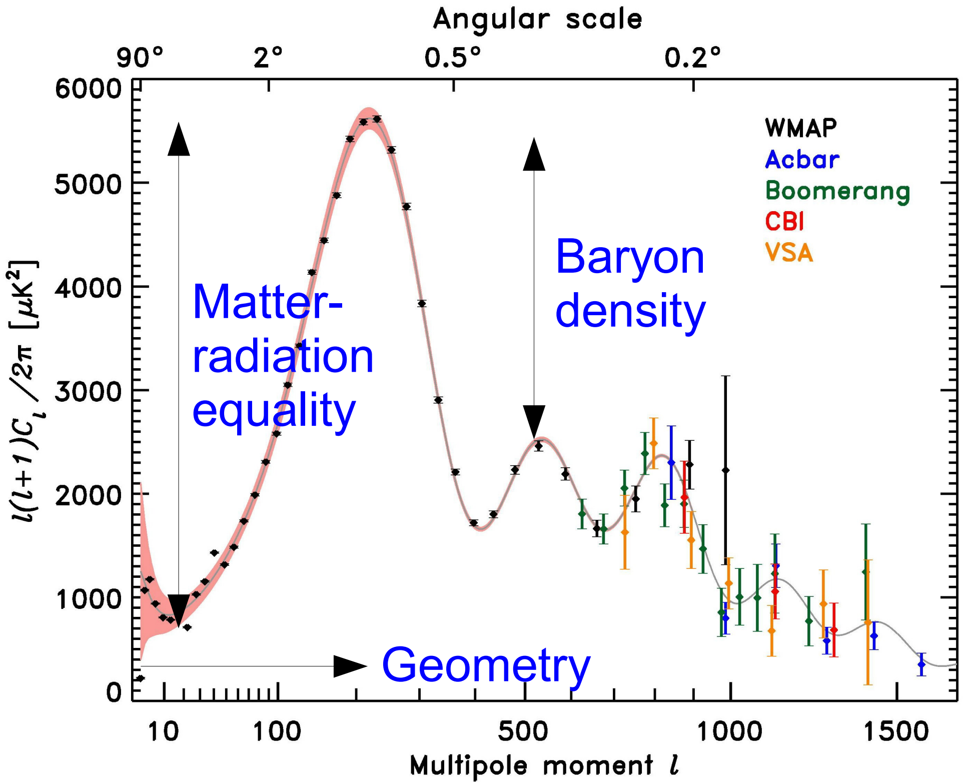
- FIRAS on COBE measured **Planck spectrum**, with temperature:

$$T_{\mathrm{CMB}} = 2.725 \pm 0.001\,\mathrm{K}$$

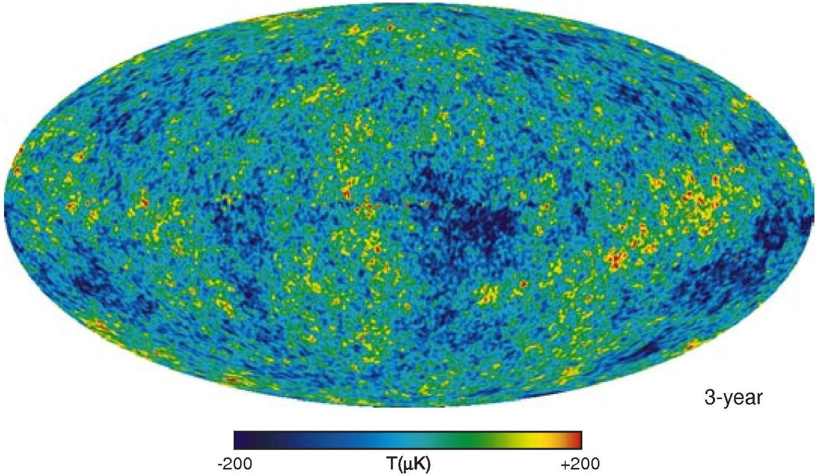
- T_{CMB} fixes:
  - Photon energy density.
  - Relic neutrino number density per flavour:

$$n_{\nu} = 112\,\mathrm{cm}^{-3}$$

... and its anisotropies...

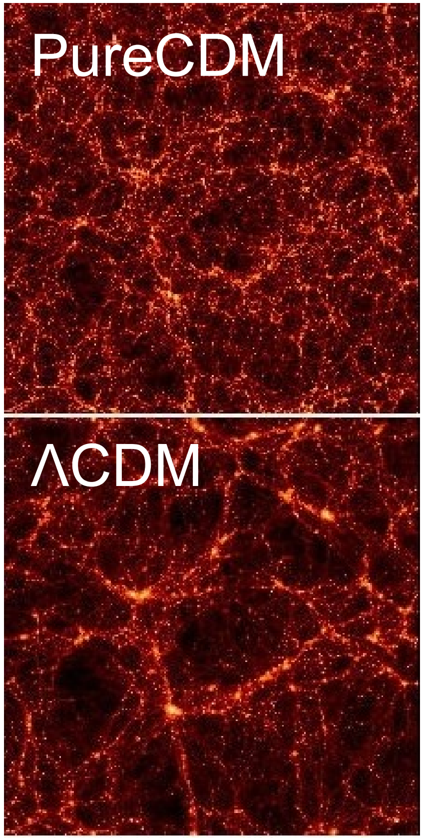


WMAP, 2006



- Temperature fluctuations from **acoustic oscillations** of the photon-baryon fluid frozen on the last scattering surface.

Probe 2: Large-scale structure...

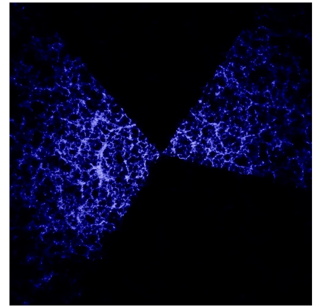


Matter distribution
(luminous and dark)

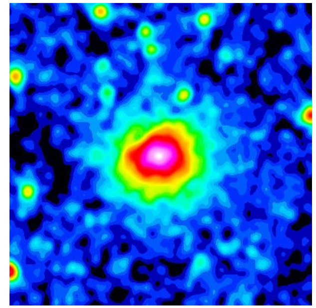
Virgo collaboration, 1996

Probed by

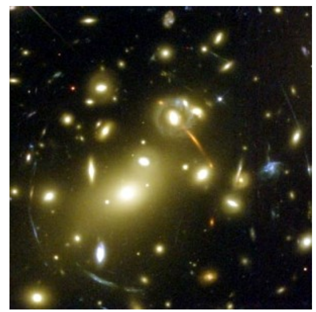
300 h^{-1} Mpc



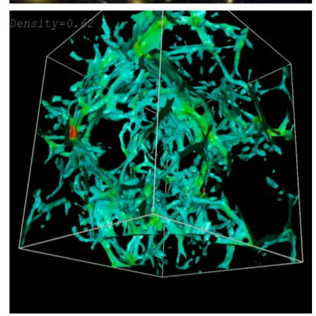
Galaxy clustering



Cluster abundance



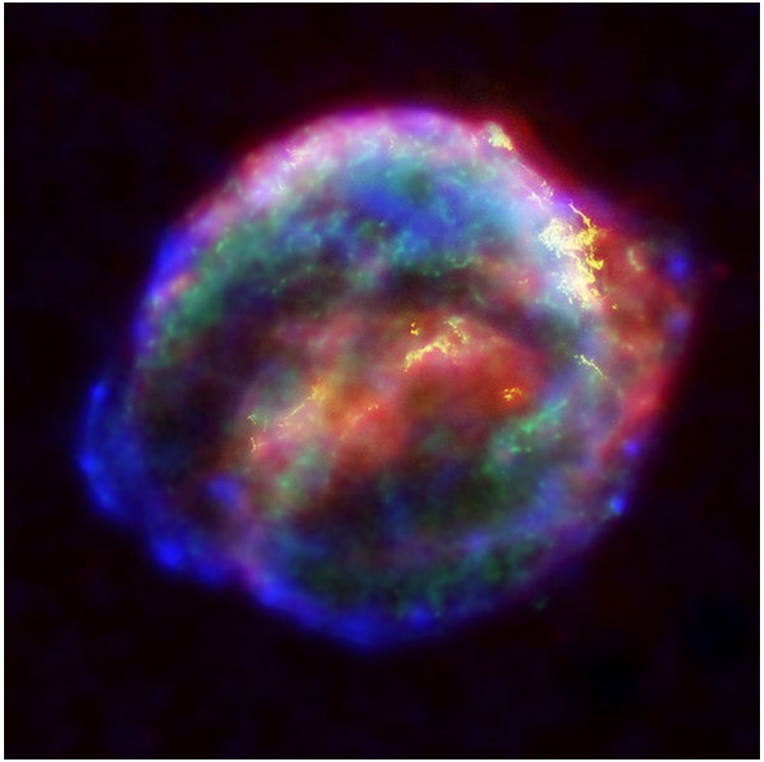
Gravitational lensing



Intergalactic hydrogen clumps; Lyman-α

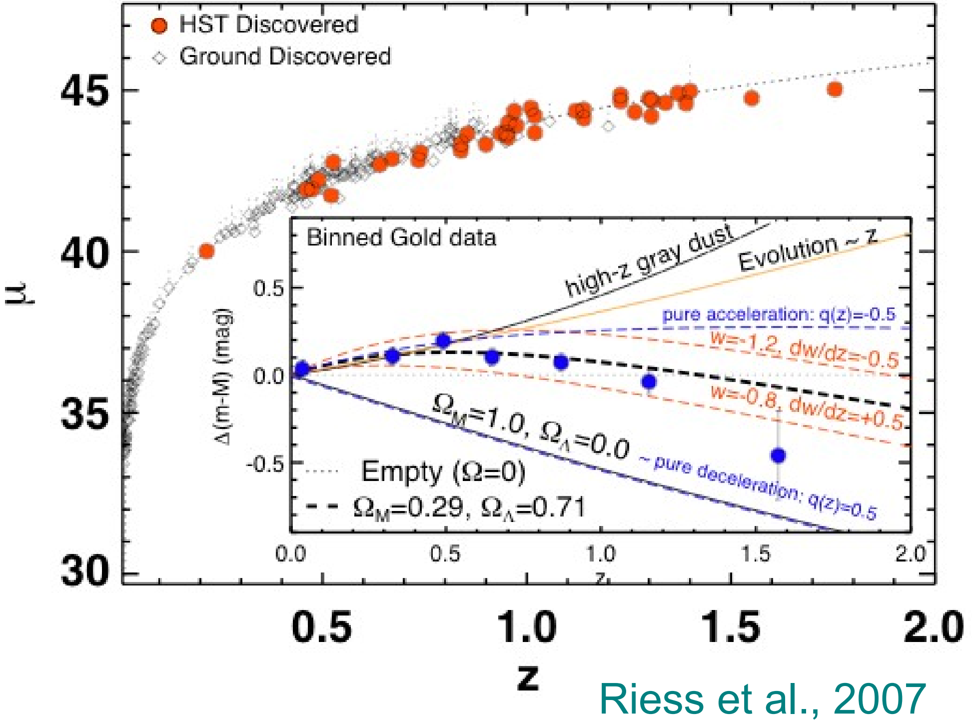
1 h^{-1} Mpc

Probe 3: Standard candles...



Type Ia supernova (SNIa).

- Hubble diagram of **SNIa** provided the first evidence for a negative pressure fluid, the "**dark energy**".



Riess et al., 2007

The concordance model...

- The simplest model consistent with **present data**:

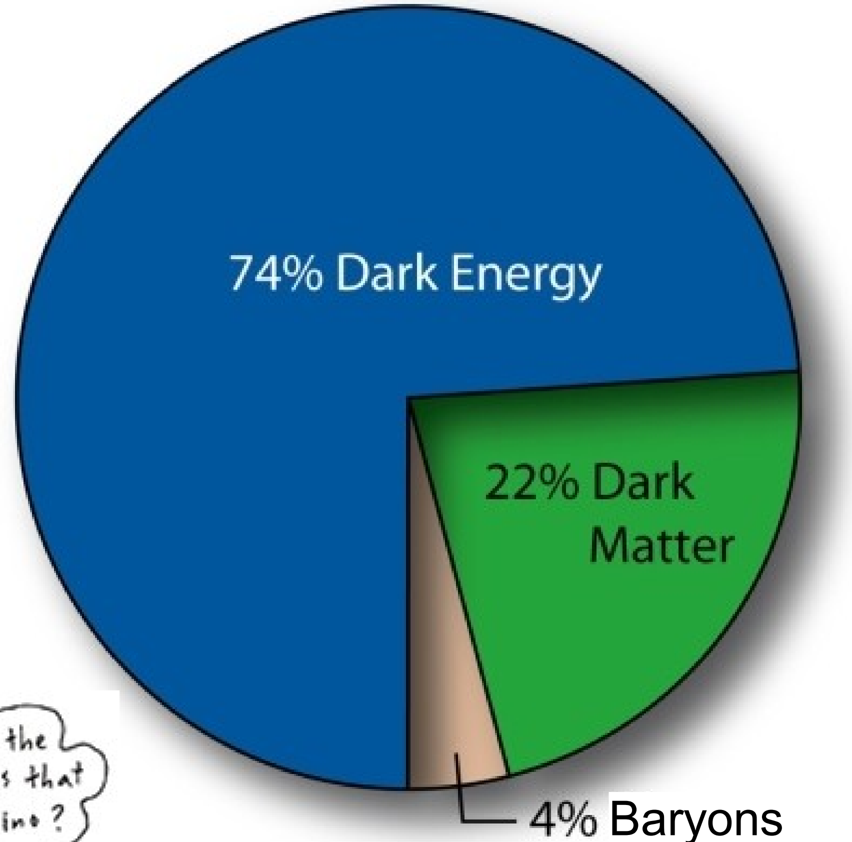
→ Flat geometry.

→ 6 free parameters:

$$\Omega_m h^2, \Omega_b h^2, h, n_s, A_s, \tau$$

→ Dark matter is cold.

→ Does not require neutrino dark matter: $\Delta\chi^2 \sim -2$ or less.



Present cosmological neutrino mass bounds...

Reference	95% C.L.	Model	Data
Spergel et al. 2006	< 0.7 eV	m	WMAP3, LSS, SN, HST
Tegmark et al. 2006	< 0.94 eV	m	WMAP3, SDSS
Goobar et al. 2006	< 0.6 eV	x	WMAP3, LSS, SN, BAO, HST
Seljak et al. 2006	< 0.17 eV	m	WMAP3, LSS, SN, BAO, Lya, HST
Ichikawa et al. 2006	< 2.0 eV	m	WMAP3 only
Kristiansen et al. 2006	< 1.43 eV	m	WMAP3, Cluster mass function
Zunckel & Ferreira 2007	< 2.2 eV	x	WMAP3, LSS
Hannestad et al. 2007	< 0.65 eV	x	WMAP3, LSS, SN, BAO

... and probably more.

m=minimal; x=extended

Future cosmological probes...

- Weak gravitational lensing
  - Of galaxies (tomography).
  - Of the CMB.
- High redshift galaxy surveys.
- Cluster abundance.
- CMB/galaxy cross-correlation (ISW effect).

Coming up in the lab...

- Tritium β decay:

Sensitivity to $\Sigma m_\nu \sim 0.6$ eV

- Neutrinoless ββ decay:

Sensitivity to $\Sigma m_\nu \sim 0.05$ eV (SuperNEMO)
Majorana neutrinos only

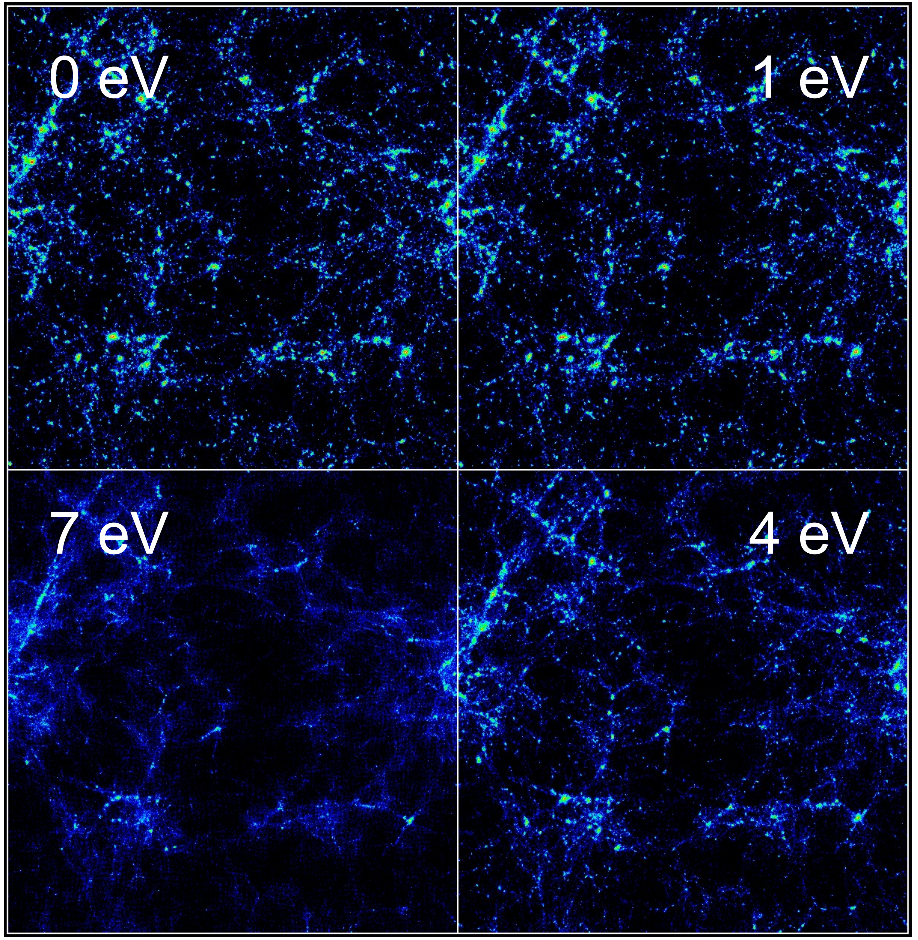
Plan...

- What we can do **now**.
- What we can do **in the future**.
- What are the **challenges**.

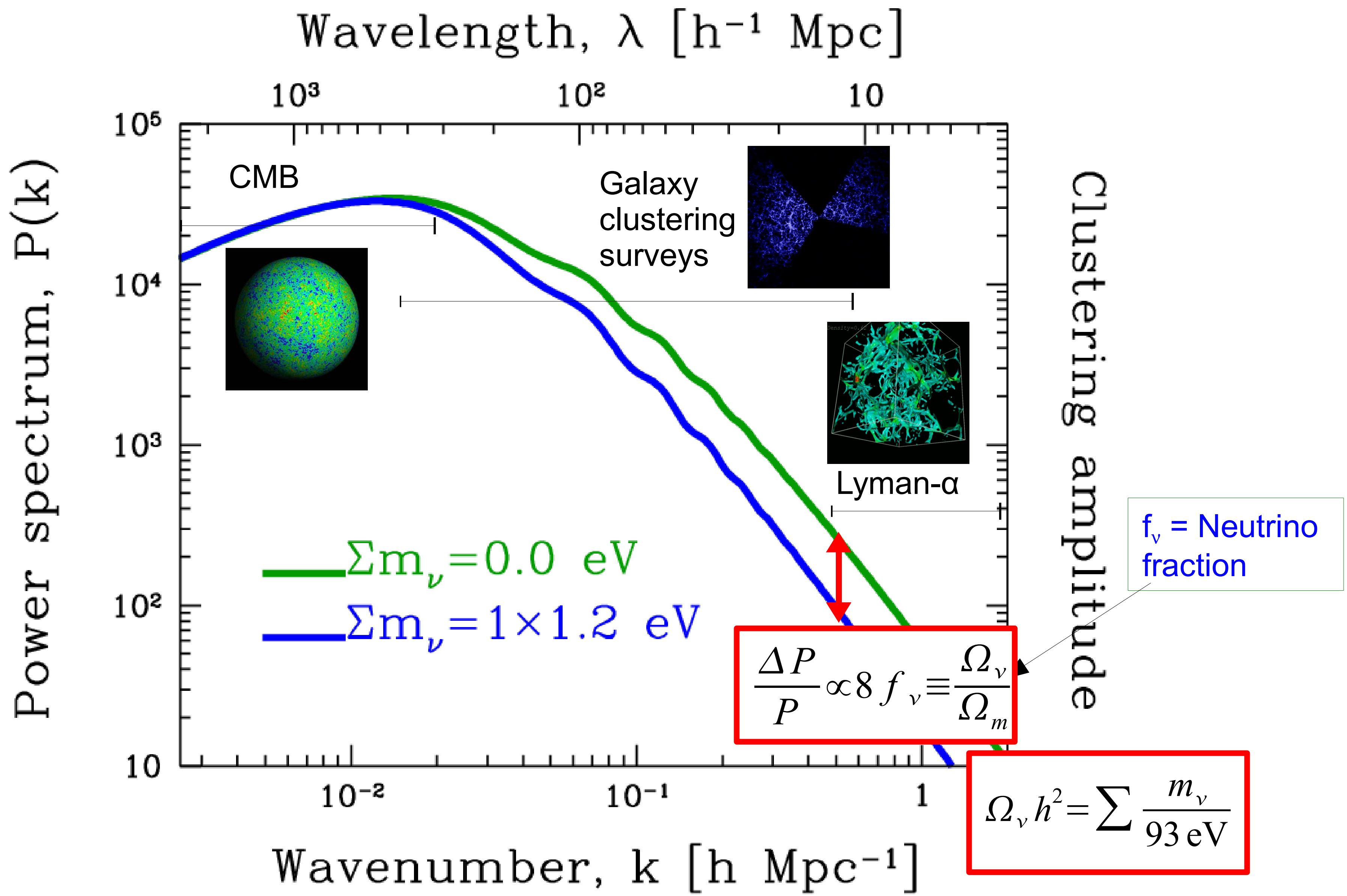
1. What we can do now...

The idea...

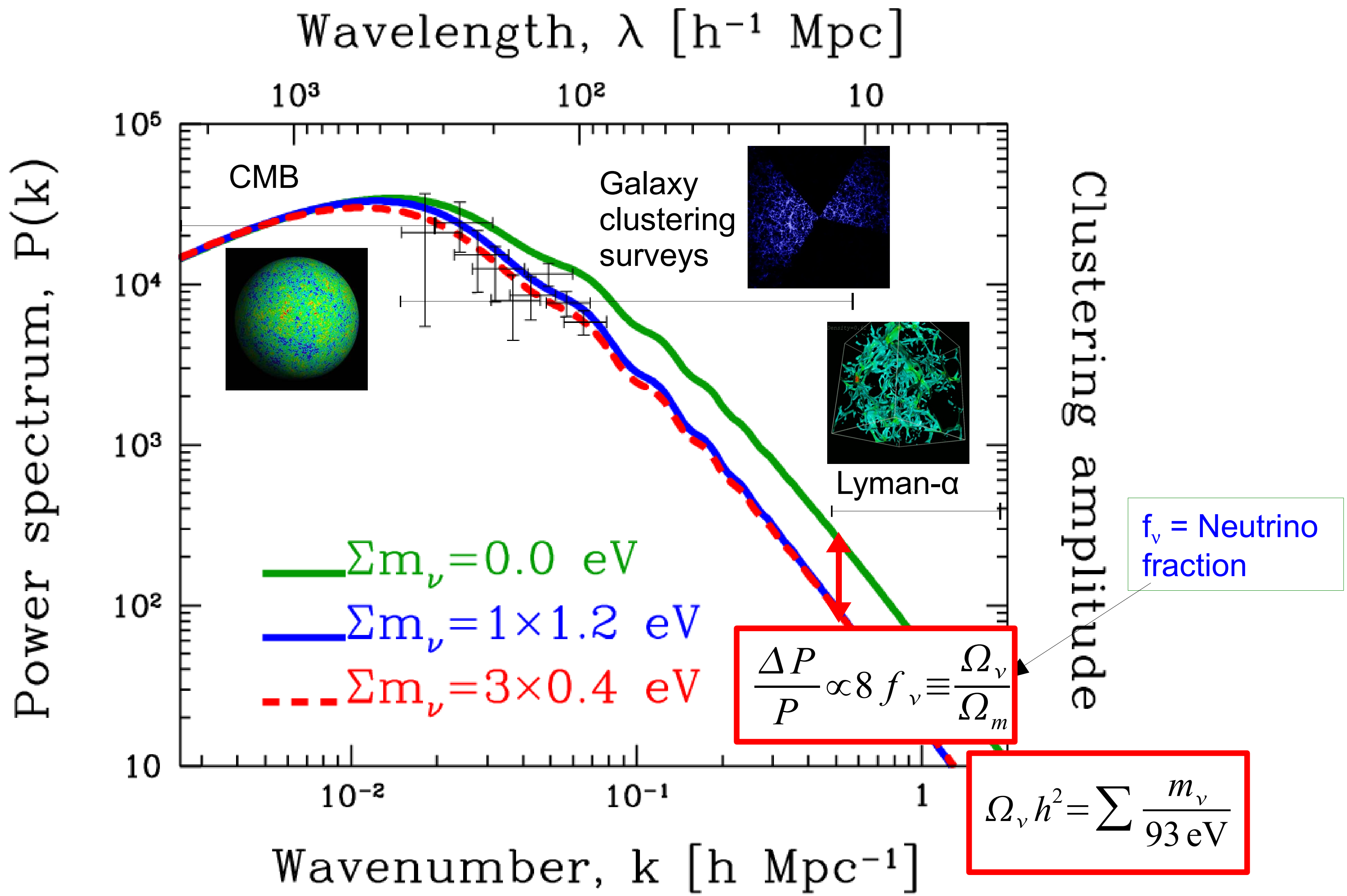
- Massive neutrinos are **hot dark matter**.
  - 1 eV neutrino becomes nonrelativistic at z_{nr} ~ 2000.
  - Structure formation begins at z_{eq} ~ 3000.
- Free-streaming from z_{eq} to z_{nr} suppresses formation of structures on small scales.



N-body simulation, Ma 1996



Wavelength, λ [h⁻¹ Mpc]
10³
10²
10
10⁵
10⁴
10³
10²
10
CMB
Galaxy clustering surveys
Lyman-α
Σm_ν=0.0 eV
Σm_ν=1×1.2 eV
Power spectrum, P(k)
Clustering amplitude
Wavenumber, k [h Mpc⁻¹]
10⁻²
10⁻¹
1
f_ν = Neutrino fraction
$\frac{\Delta P}{P} \propto 8 f_\nu \equiv \frac{\Omega_\nu}{\Omega_m}$
$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$

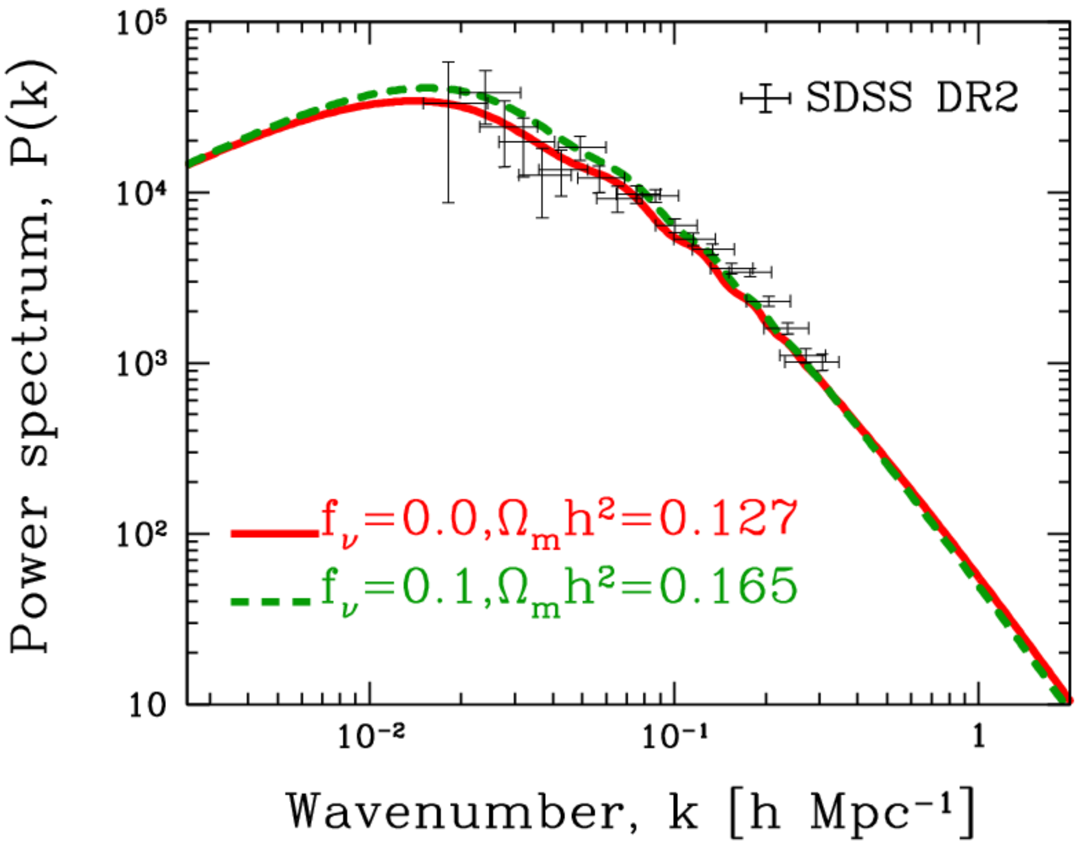


Wavelength, λ [h⁻¹ Mpc]
10³
10²
10
CMB
Galaxy clustering surveys
Lyman-α
Power spectrum, P(k)
Clustering amplitude
$\Sigma m_\nu = 0.0$ eV
$\Sigma m_\nu = 1\times1.2$ eV
$\Sigma m_\nu = 3\times0.4$ eV
f_ν = Neutrino fraction
$\frac{\Delta P}{P} \propto 8 f_\nu \equiv \frac{\Omega_\nu}{\Omega_m}$
$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$
Wavenumber, k [h Mpc⁻¹]

In practice...

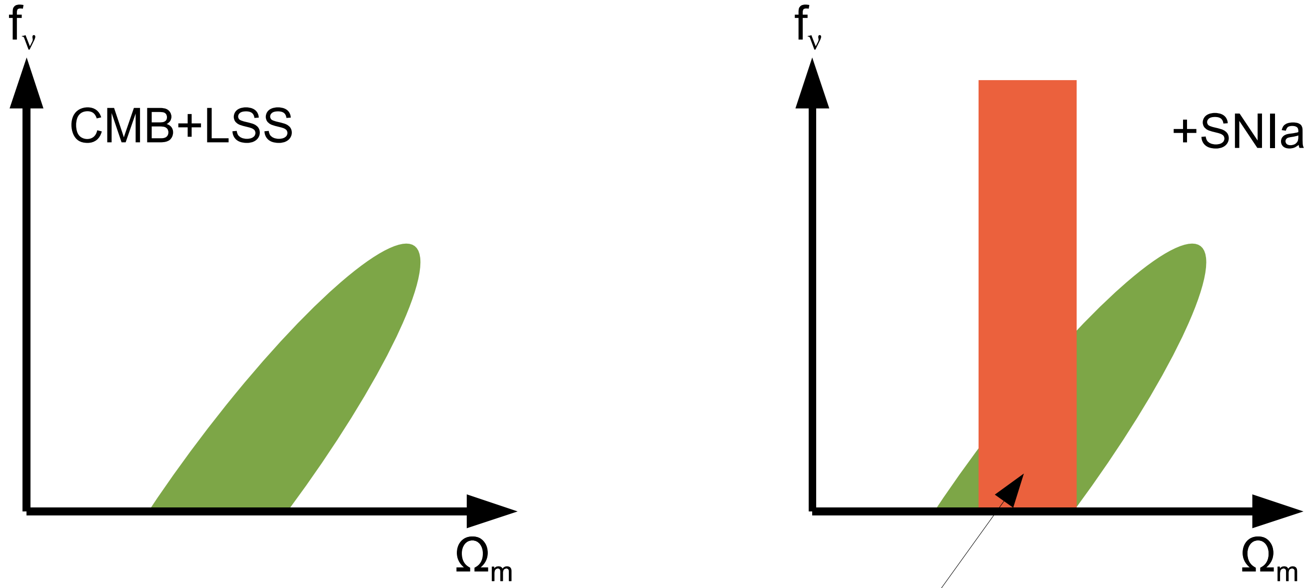
- Measurement of Σm_ν is limited by our knowledge of the **total matter density Ω_m**, because:
  - Suppression is most sensitive to $f_\nu = \Omega_\nu/\Omega_m$.
  - (Approximate) degeneracy between f_ν and Ω_m in P(k).

Ignoring normalisation



- Add SNIa for more leverage on Ω_m?

Schematic only!
Not to scale!



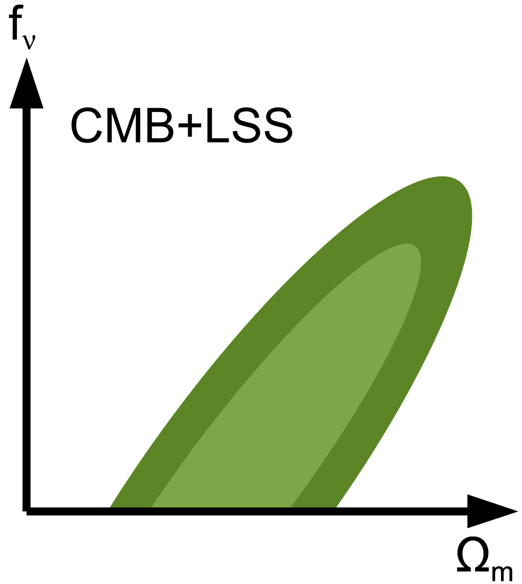
Flat geometry, DE=Cosmological constant

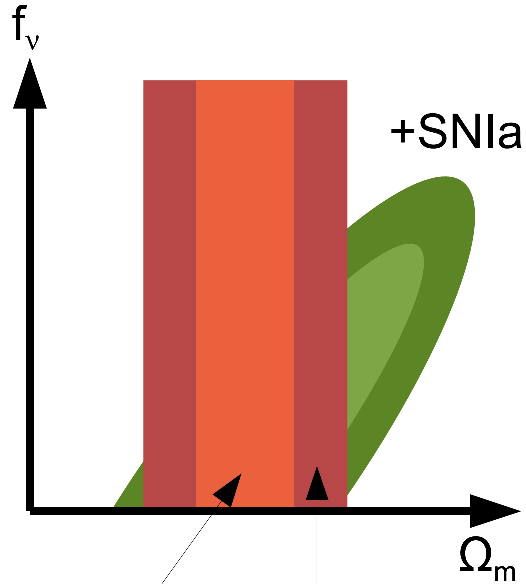
$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)}$$

H(z) = Expansion rate

- Add SNIa for more leverage on Ω_m?

Schematic only!
Not to scale!





Flat geometry, DE=Cosmological constant

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)}$$

Flat geometry, but DE=something else?

H(z) = Expansion rate

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)}}$$

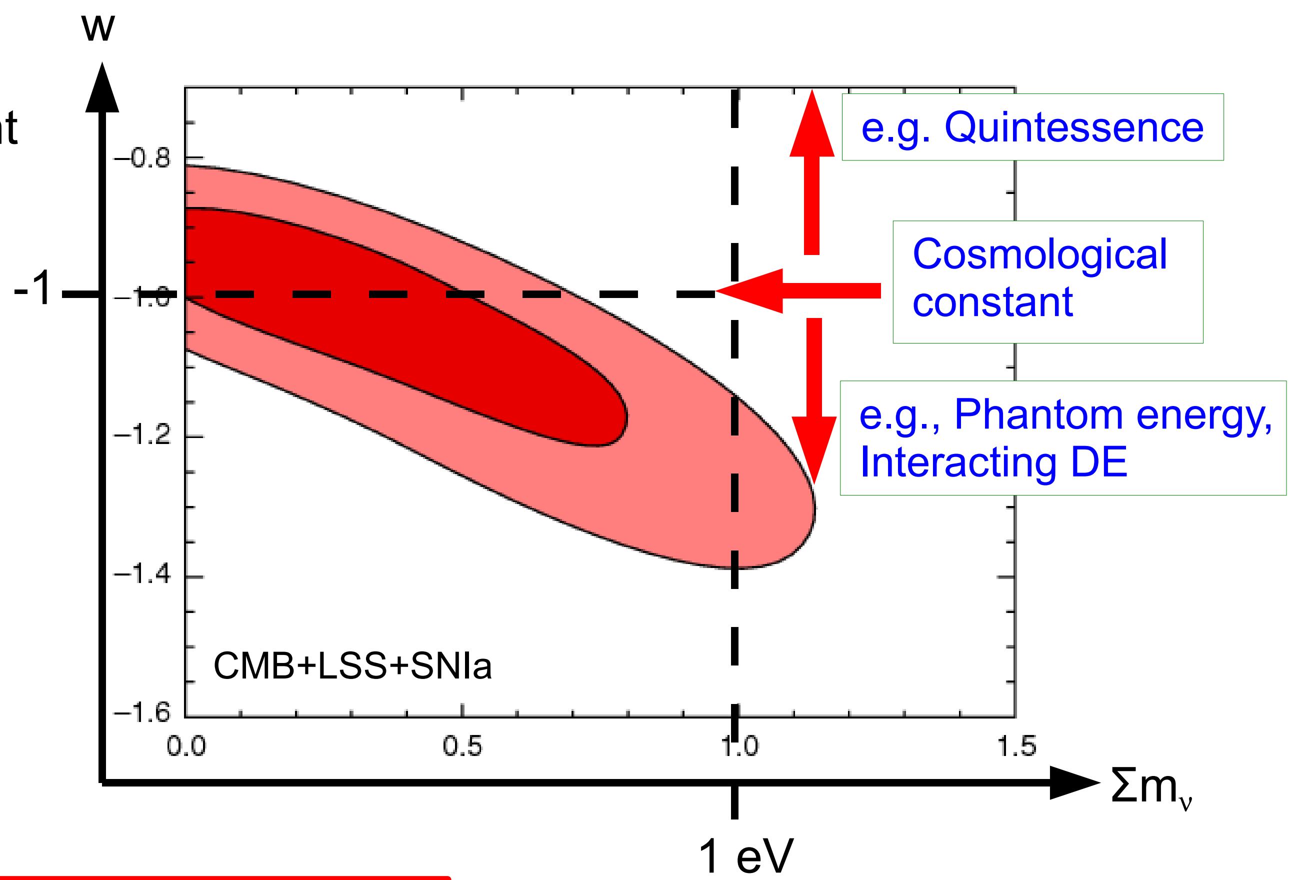
- The net effect on the Σm_ν measurement:

w = (apparent) constant **DE equation of state** parameter:

- Either real EOS:

$$w_{DE} \equiv \frac{P_{DE}}{\rho_{DE}}$$

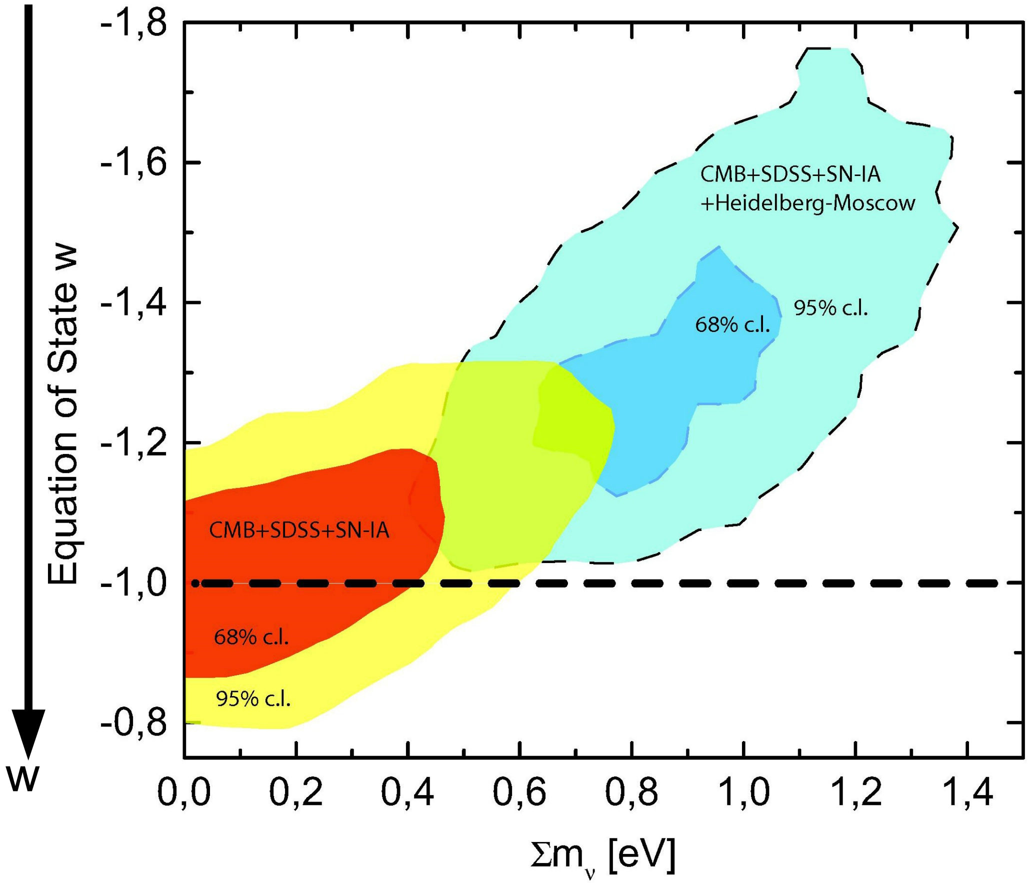
- Or effective behaviour of the expansion rate.



$$\sum m_\nu < 0.6\,\text{eV}\,(95\,\%\,\text{C.L.}),\quad w=-1$$
$$\sum m_\nu < 1.0\,\text{eV}\,(95\,\%\,\text{C.L.}),\quad \text{free } w$$

Hannestad, 2005; WMAP, 2006

It's two-way traffic...



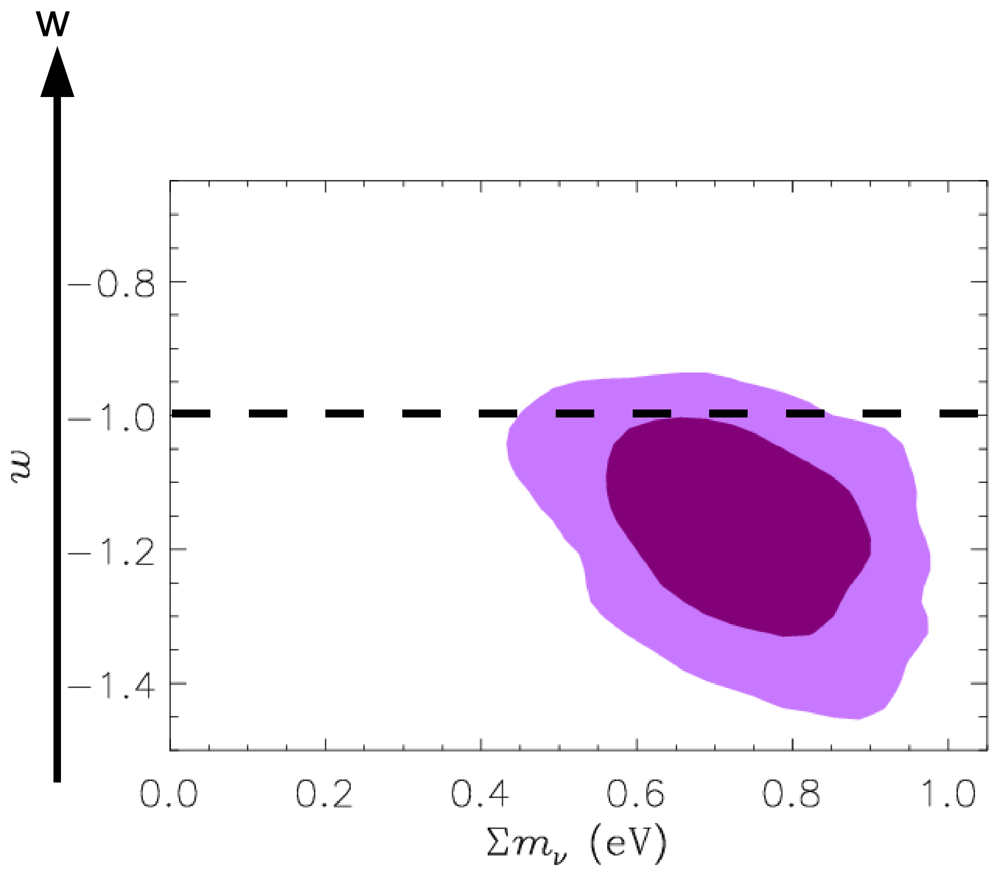
- If the Heidelberg-Moscow $0\nu\beta\beta$ result is correct, $(0.43 < m_{\beta\beta}/\mathrm{eV} < 0.81)$, then...
  - CMB+LSS+SNIa **+Heidelberg-Moscow**:

$$-1.67 < w < -1.05 \quad (95\%\,\mathrm{C.L.})$$

→ Cosmological constant disfavoured at 95% C.L.!

De La Macorra, Melchiorri, Serra & Bean, 2006

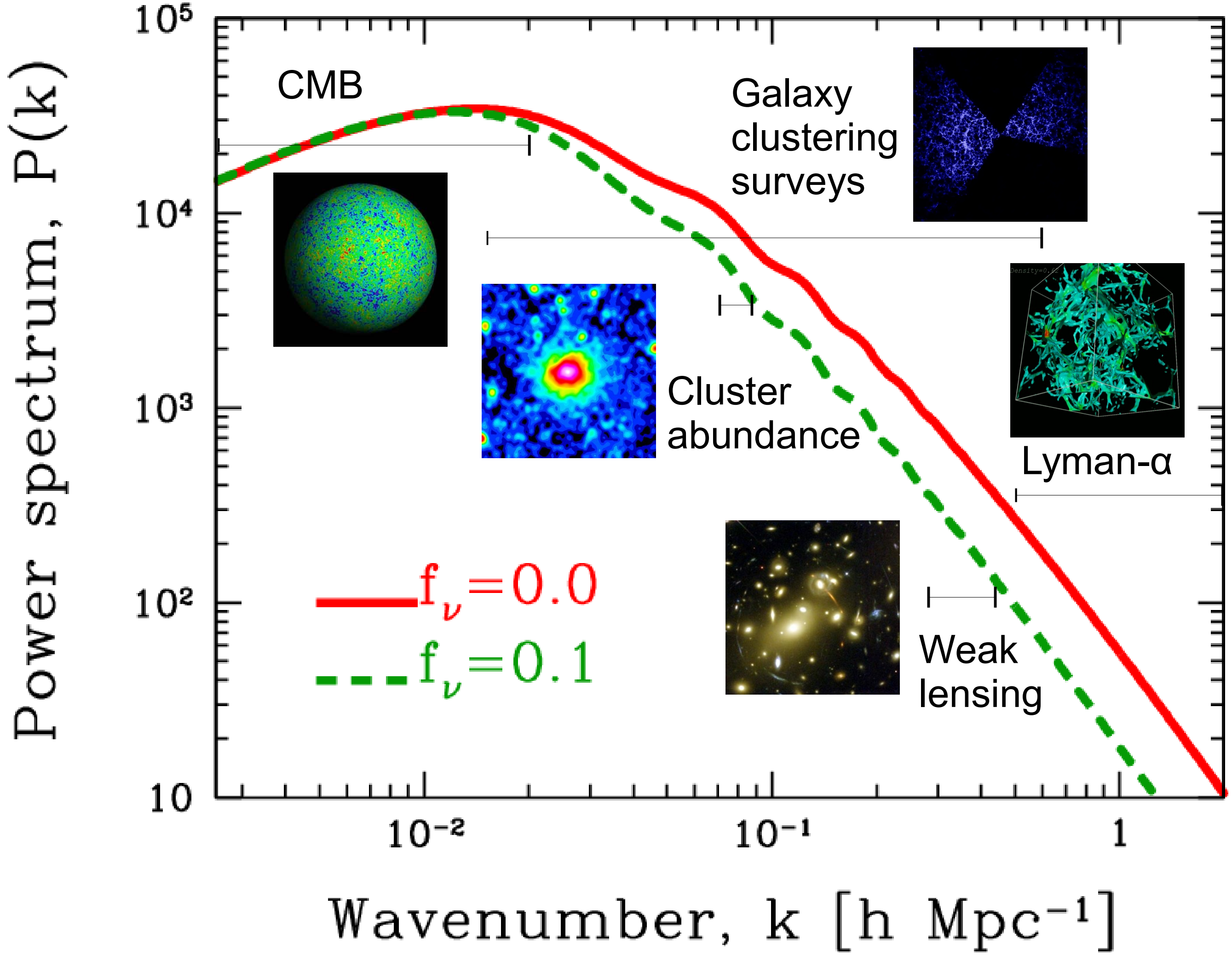
- If, in the future...
  - **KATRIN** finds
    $m_\beta \sim 0.28$ eV
  - **GERDA** finds
    $m_{\beta\beta} \sim 0.18$ eV
- Then...
  - Present cosmological data+KATRIN+GERDA give



Hannestad, 2007

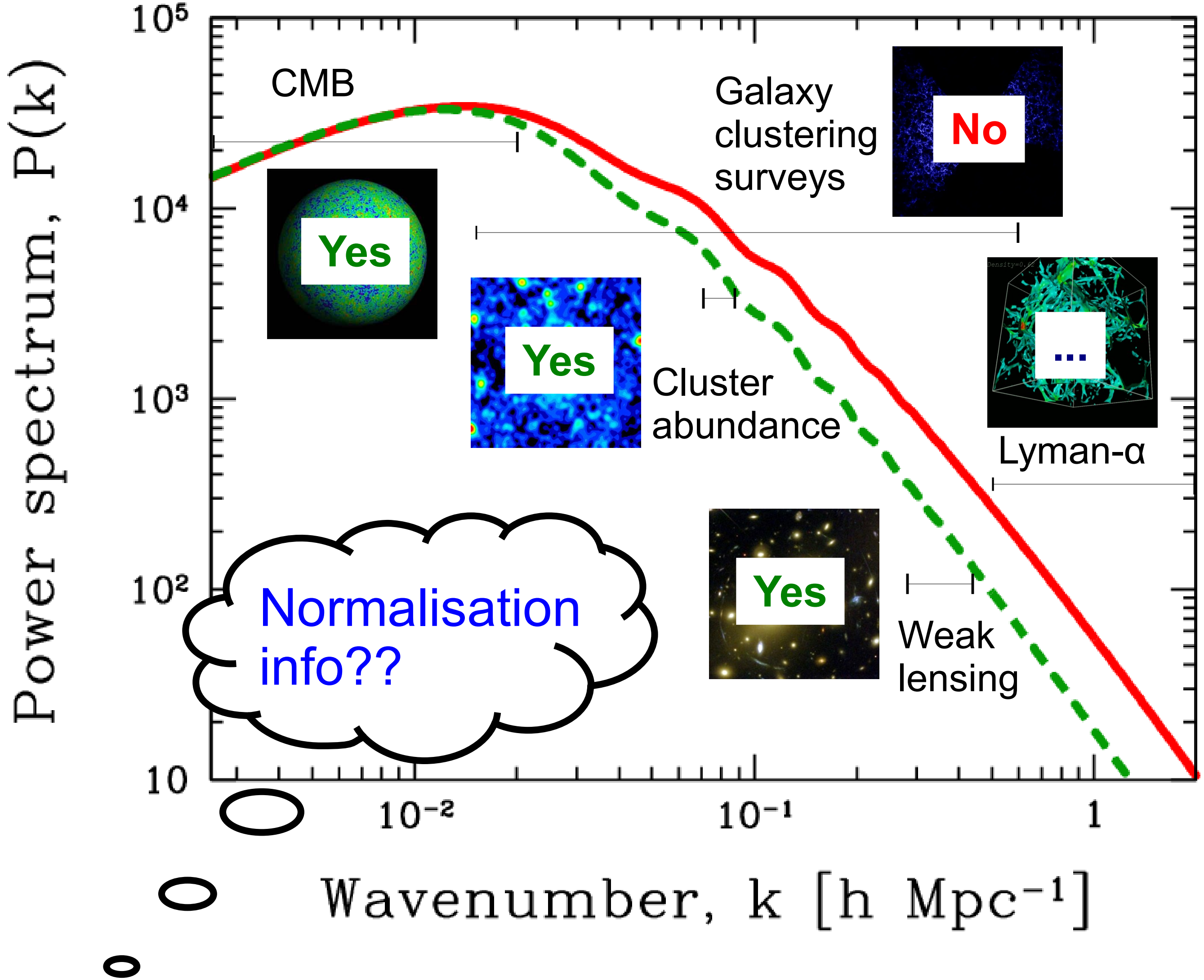
Spectrum normalisation...

Present capacities



Spectrum normalisation...

Present capacities



Galaxy bias...

- **Assumption**: galaxy distribution traces that of the underlying matter up to a normalisation factor:

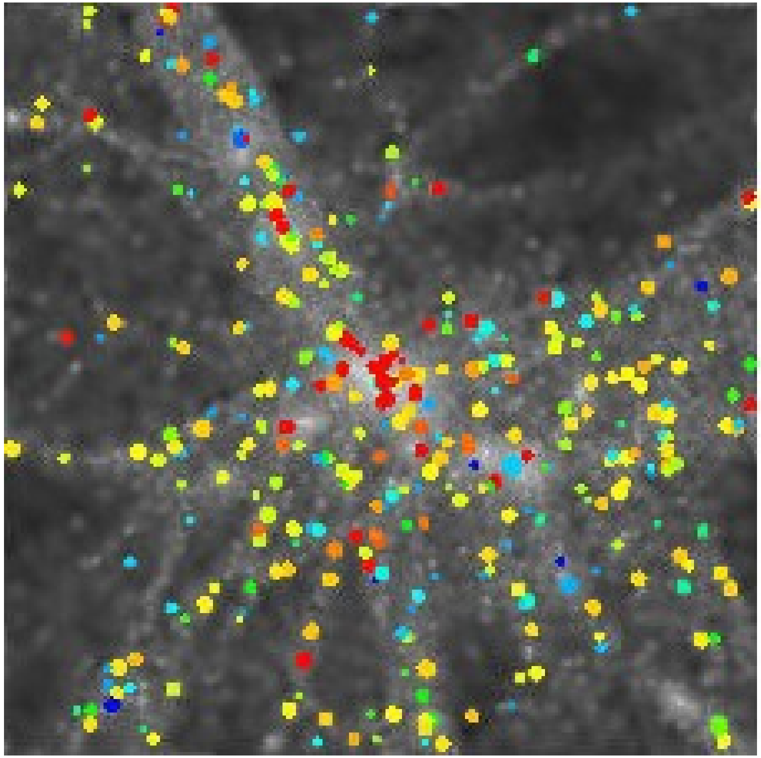
$$\frac{n_{\text{gal}}(x)-\bar{n}_{\text{gal}}}{\bar{n}_{\text{gal}}} \propto \frac{\rho_m(x)-\bar{\rho}_m}{\bar{\rho}_m}$$

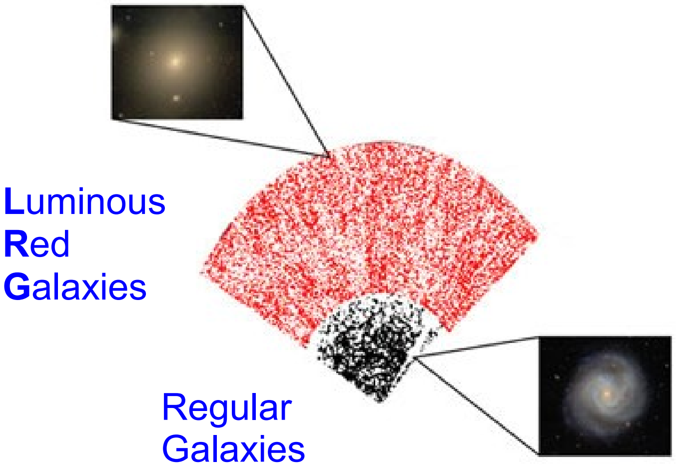
$$P_{\text{gal}}(k)=b^2 P_m(k)$$

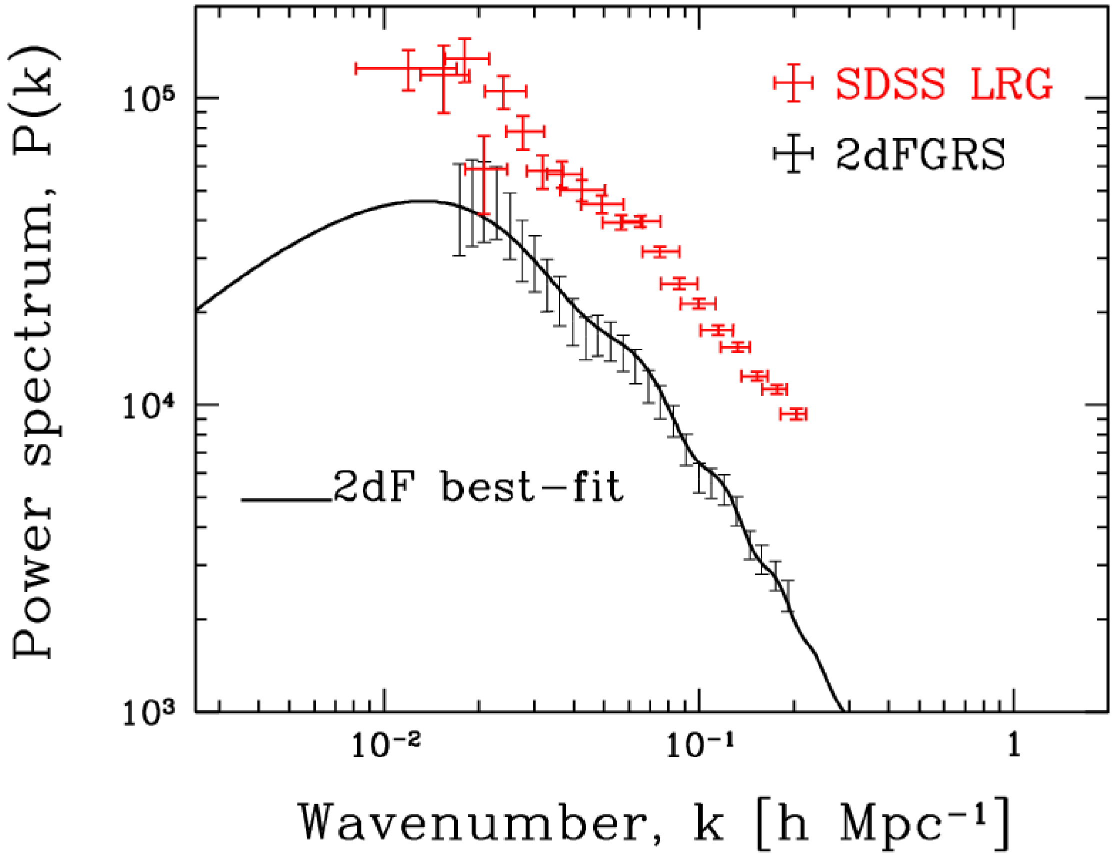
$P_{gal}(k)$ = Galaxy power spectrum

b = Galaxy bias, depends on galaxy type

$P_m(k)$ calculated from linear perturbation theory

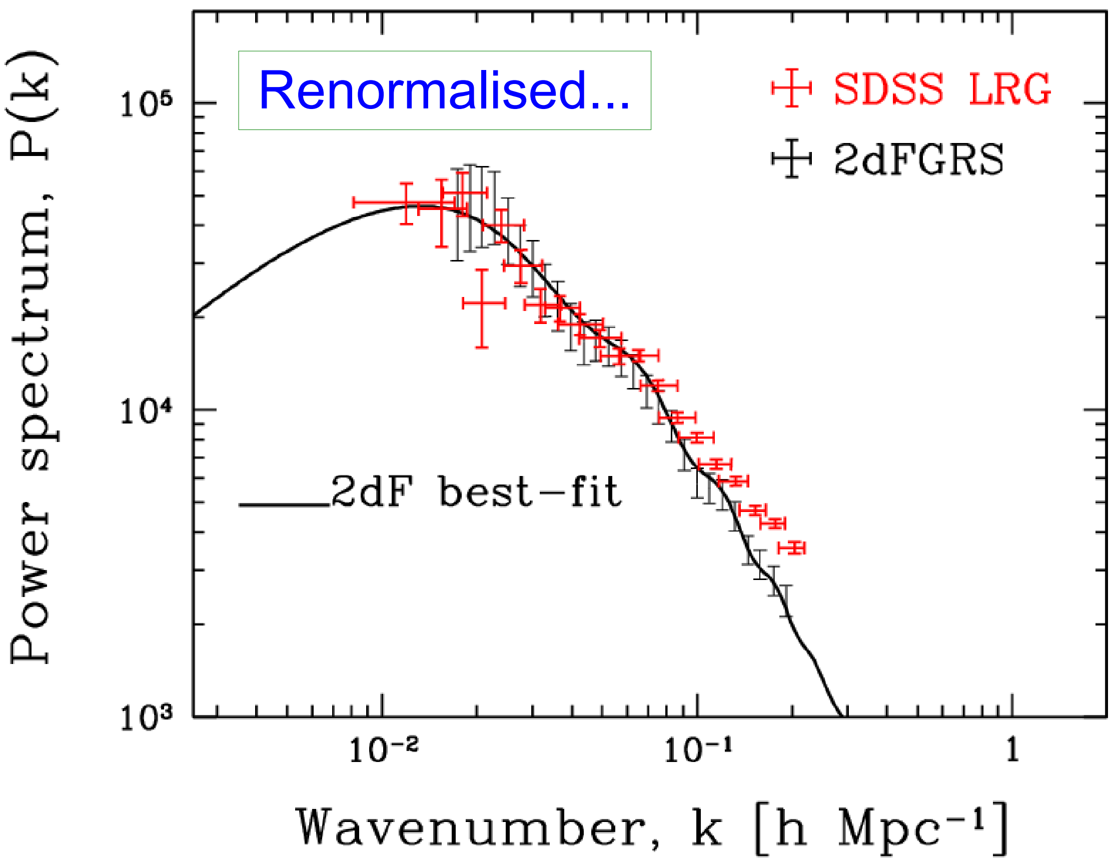




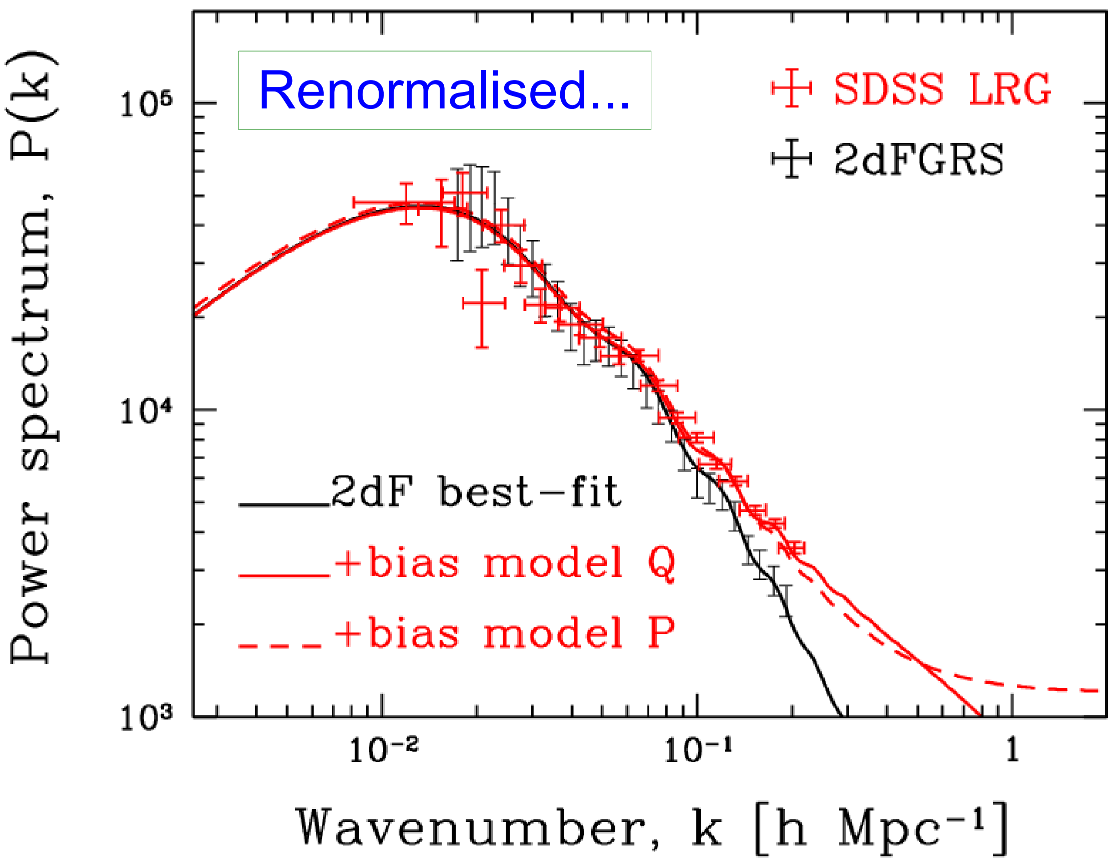


- Current galaxy formation theories **cannot** accurately predict bias factor.

  → Use shape information only in fits.



- **Reality**: Galaxy bias is scale-dependent!



- **Reality**: Galaxy bias is scale-dependent!
- Correction models:
  - Q-model: Cole et al., 2005

$$P_{\rm gal}(k) = b^2 \frac{1+Q_{\rm nl} k^2}{1+1.4k} P_m(k)$$

Nuisance parameters to be marginalised

  - P-model:

$$P_{\rm gal}(k) = b^2 P_m(k) + P_{\rm shot}$$

Hamann, Hannestad & Y^3W, in prep.

A word about Lyman-α...

- Seljak, McDonald & Slosar, 2006 reported:

$$\sum m_\nu < 0.17 \text{ eV}$$

WMAP3+LSS+SNIa+
BAO+Lya+HST

- Lya sensitive to fluctuation amplitude σ_8 and slope n_s of power spectrum:

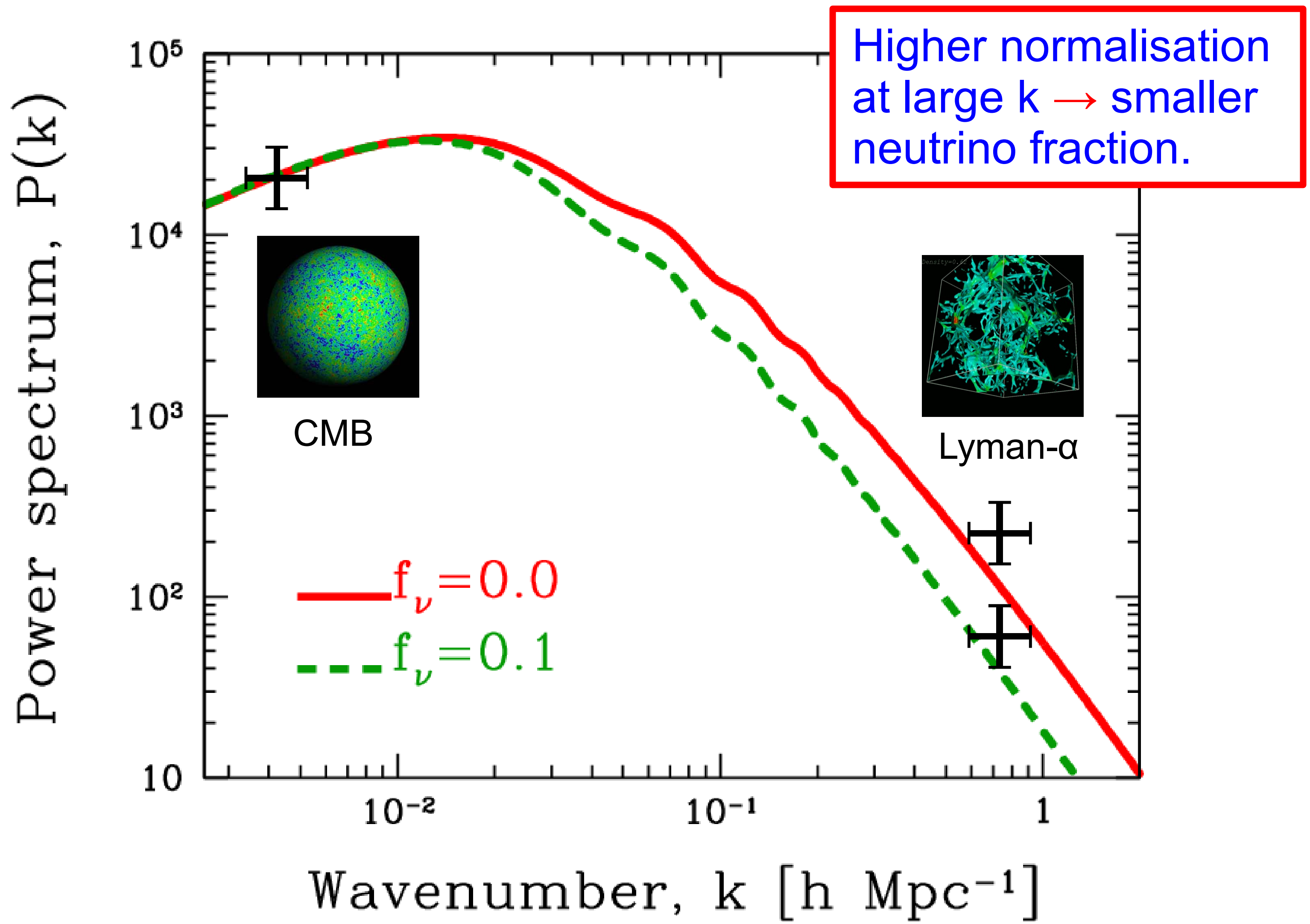
WMAP3+Lya: $\sigma_8 = 0.86 \pm 0.03, \; n_s = 0.96 \pm 0.02$

WMAP3 only: $\sigma_8 = 0.76 \pm 0.05, \; n_s = 0.96 \pm 0.02$

McDonald et al., 2005

cf. another analysis WMAP3+Lya: $\sigma_8 = 0.80 \pm 0.04, \; n_s = 0.96 \pm 0.01$

Viel & Haehnelt, 2006



Higher normalisation at large k → smaller neutrino fraction.
Power spectrum, P(k)
Wavenumber, k [h Mpc⁻¹]
10⁵
10⁴
10³
10²
10
10⁻²
10⁻¹
1
CMB
Lyman-α
f_ν=0.0
f_ν=0.1

The bottom line...

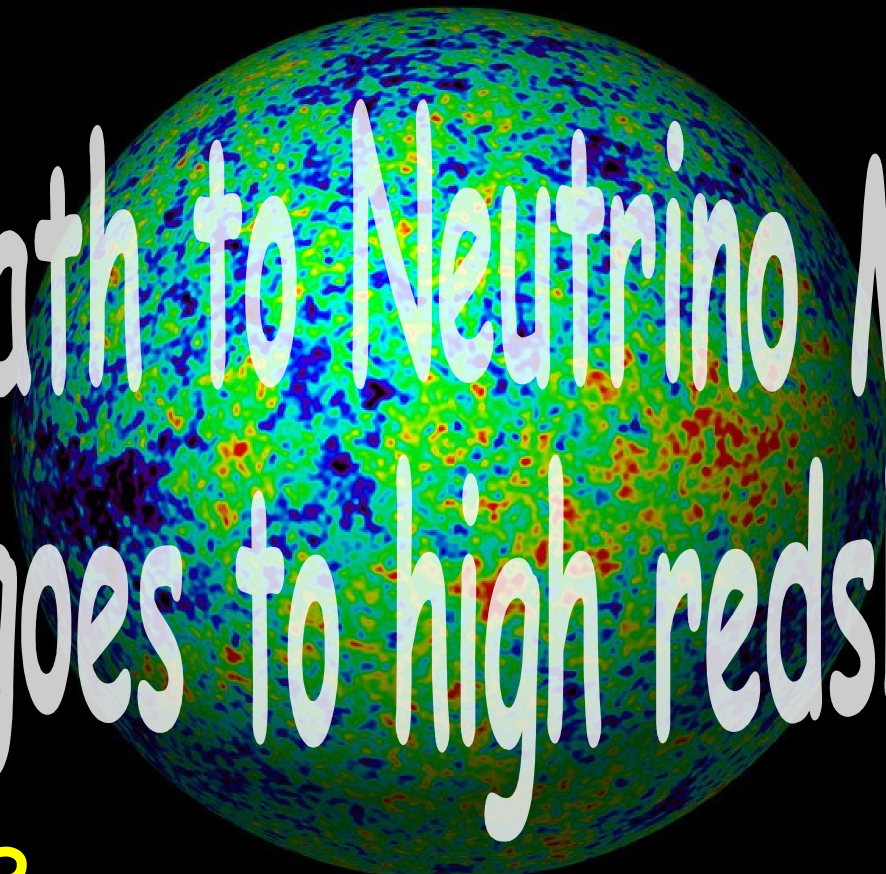
- Conservative upper limit on Σm_ν is about 1 eV (95% C.L.).

- Neutrino mass and the apparent dark energy EOS are degenerate parameters:

  → **Breaking** this degeneracy will improve the sensitivity to the neutrino mass.

- Precise knowledge of spectrum normalisation at small scales would be extremely useful.

2. What we can do in the future...

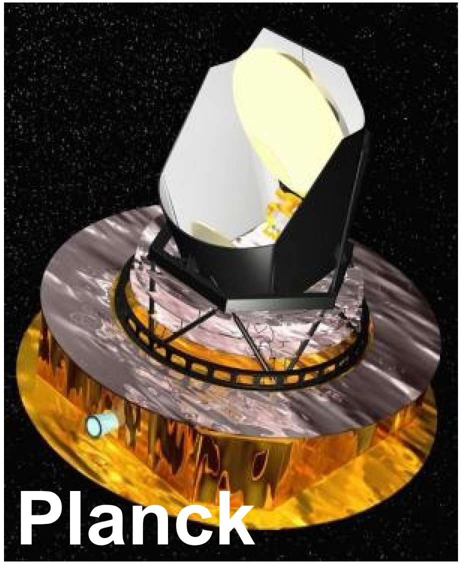


The Path to Neutrino Mass…
… goes to high redshift !

Århus, 4 September 2007

Julien Lesgourgues (LAPTH, Annecy, France)

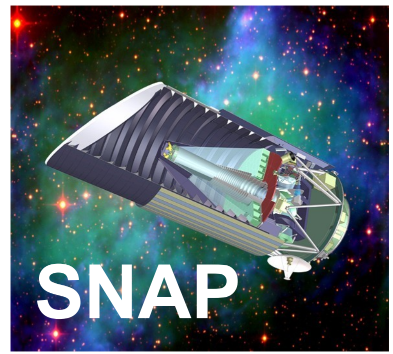
CMB probe



HETDEX

Spectroscopic
surveys @ high z

Pan-STARRS



Photometric
surveys with
lensing capacity

Dark Energy Survey

LSST
Large Synoptic Survey Telescope

DUNE

3 reasons to go high z...

1. **Spectrum evolution.**

2. **Growth of fluctuations.**

3. **Baryon wiggles.**

Probes:

- Weak gravitational lensing
  - of galaxies (tomography)
  - of the CMB
- High-z galaxy clustering
- Cluster abundance
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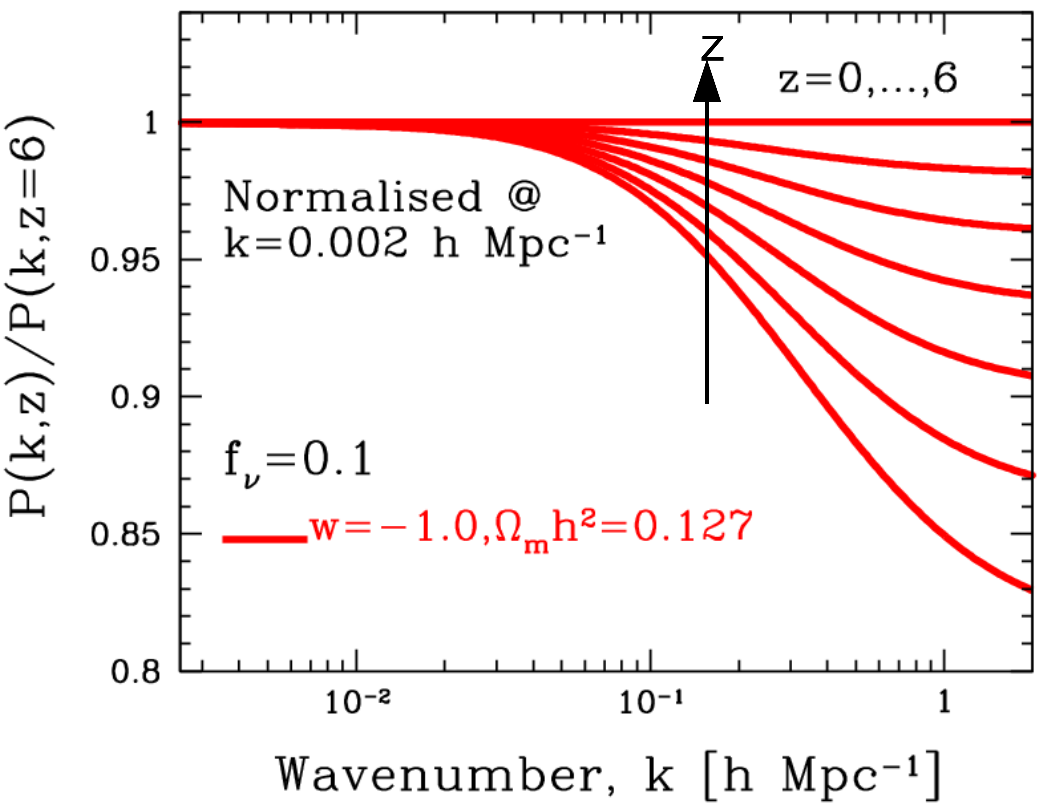
1. Spectrum evolution...

Best probes:
High-z galaxy clustering
Lensing tomography

- In the presence of neutrino DM, the **shape** of P(k) changes with time.
  - Not so if DM is entirely cold!
- Spectrum evolution is a unique and robust signature of neutrino DM.



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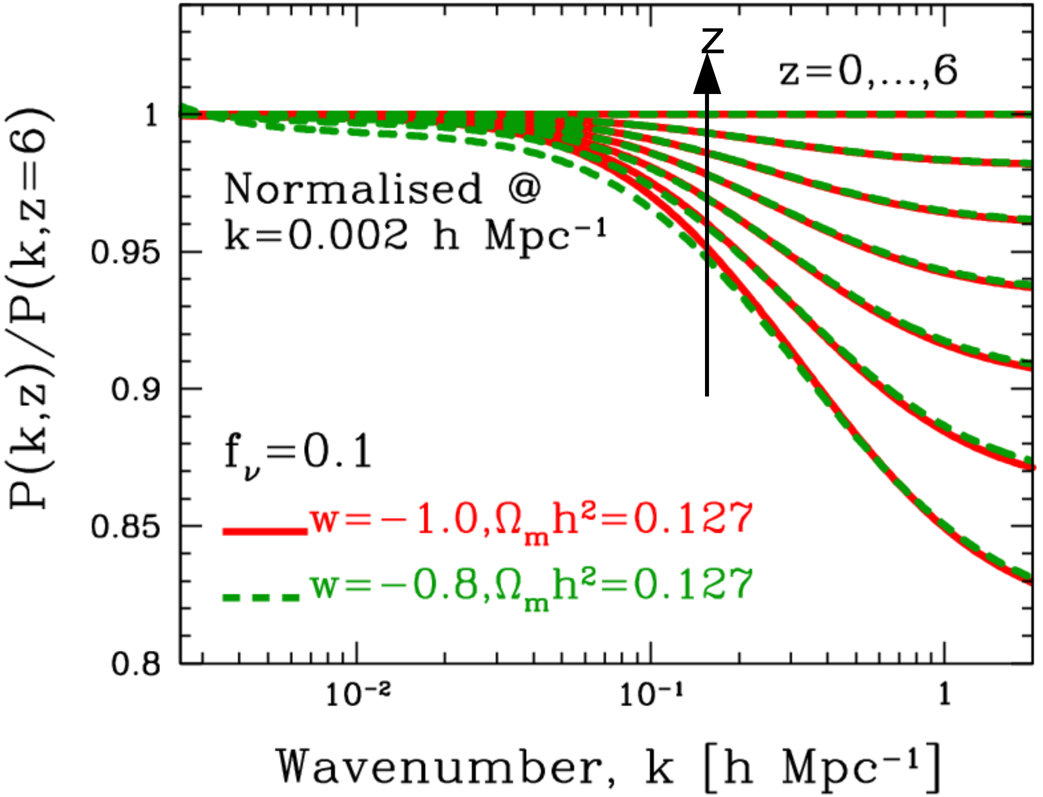

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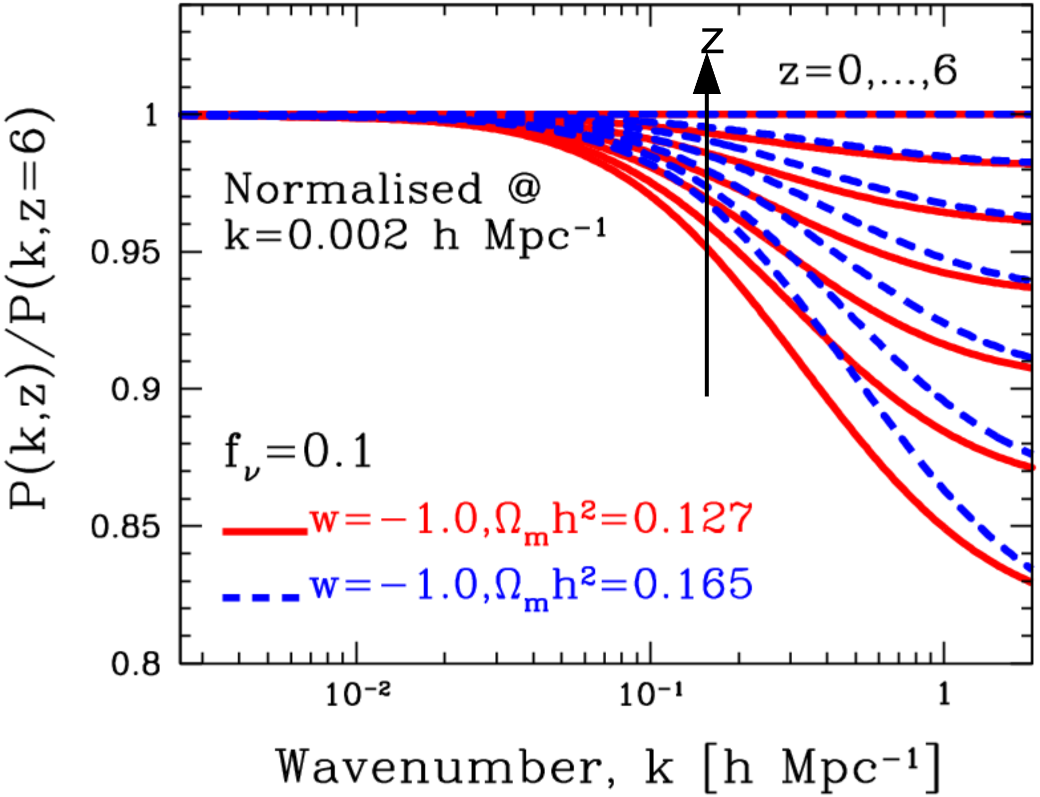
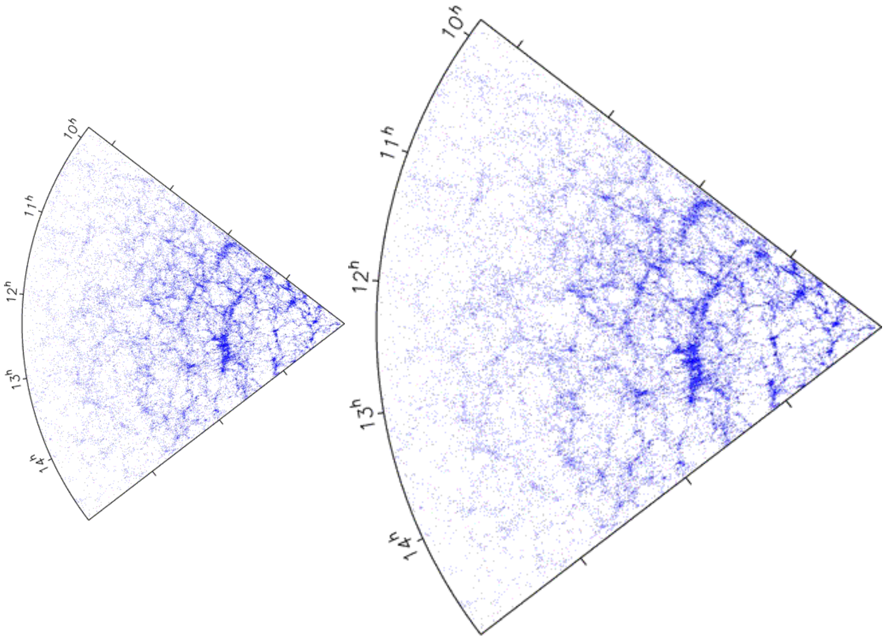


- Consider two galaxy clustering surveys:



z ←

G2 @ $4 < z < 6$
$V \sim 3.4\ h^{-3}\ \mathrm{Gpc}^3$

G1 @ $0.5 < z < 2$
$V \sim 7.5\ h^{-3}\ \mathrm{Gpc}^3$

Statistical power $\sim \sqrt{\text{Volume}}$

Sensitivity to Σm_ν
(95% C.L.)

- **G1 only**: 0.13 eV
- **G2 only**: 0.14 eV
- **G1+G2**: 0.08 eV
- **G1x1.5**: 0.12 eV

Same survey volume

Combination of high and low z surveys = excellent probe of spectrum evolution.

Hannestad & Y[3]W, 2007

3 reasons to go high z...

1. **Spectrum evolution.**

2. **Growth of fluctuations.**

3. **Baryon wiggles.**

Probes:

- Weak gravitational lensing
  - of galaxies (tomography)
  - of the CMB
- High-z galaxy clustering
- Cluster abundance
- CMB/galaxy cross-correlation (ISW effect)

2. Growth of fluctuations...

Best probes:
Lensing tomography
Cluster abundance

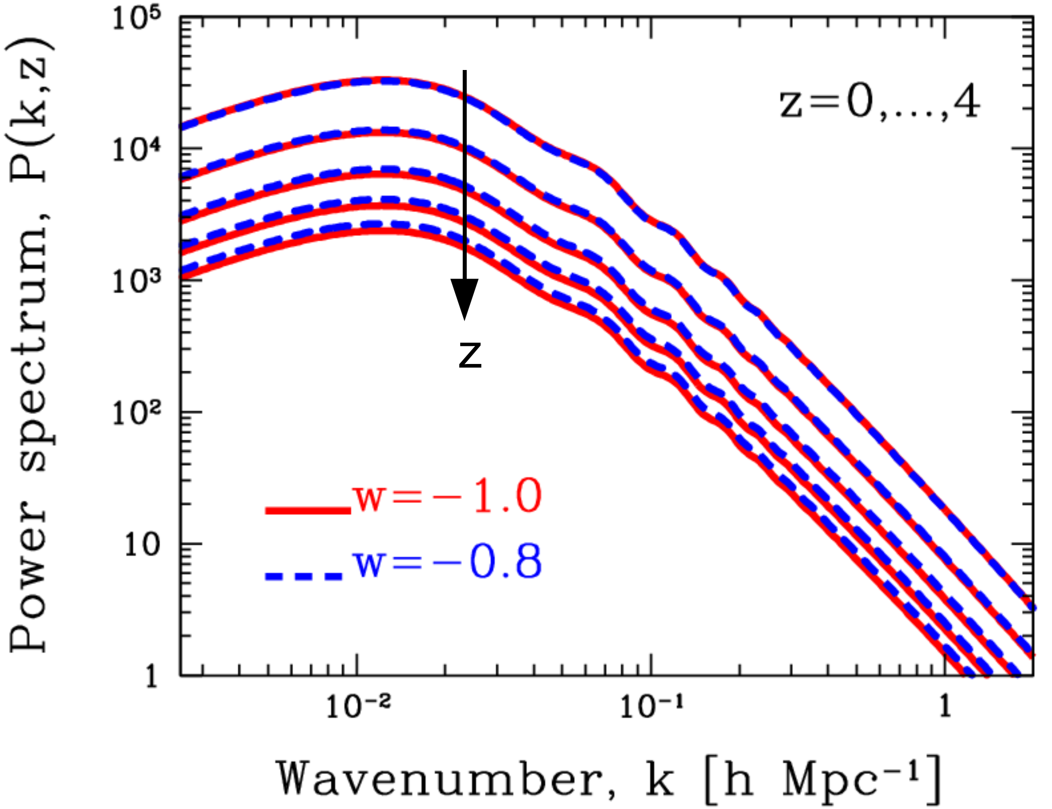
- Density fluctuations grow with time:

$$P(k,z) = D^2(k,z)\,P(k,0)$$

D(k,z) = Growth function
~ D(z)

- D(z) depends on the background expansion:

  → sensitive to dark energy properties.



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Lensing tomography
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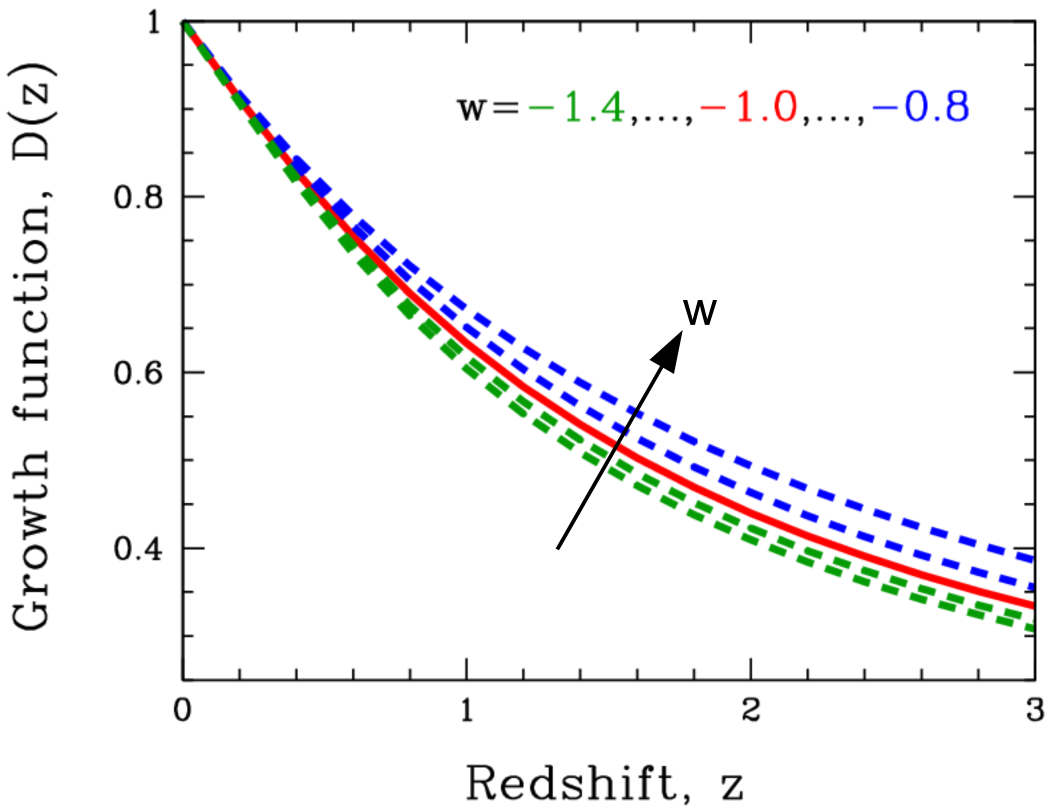
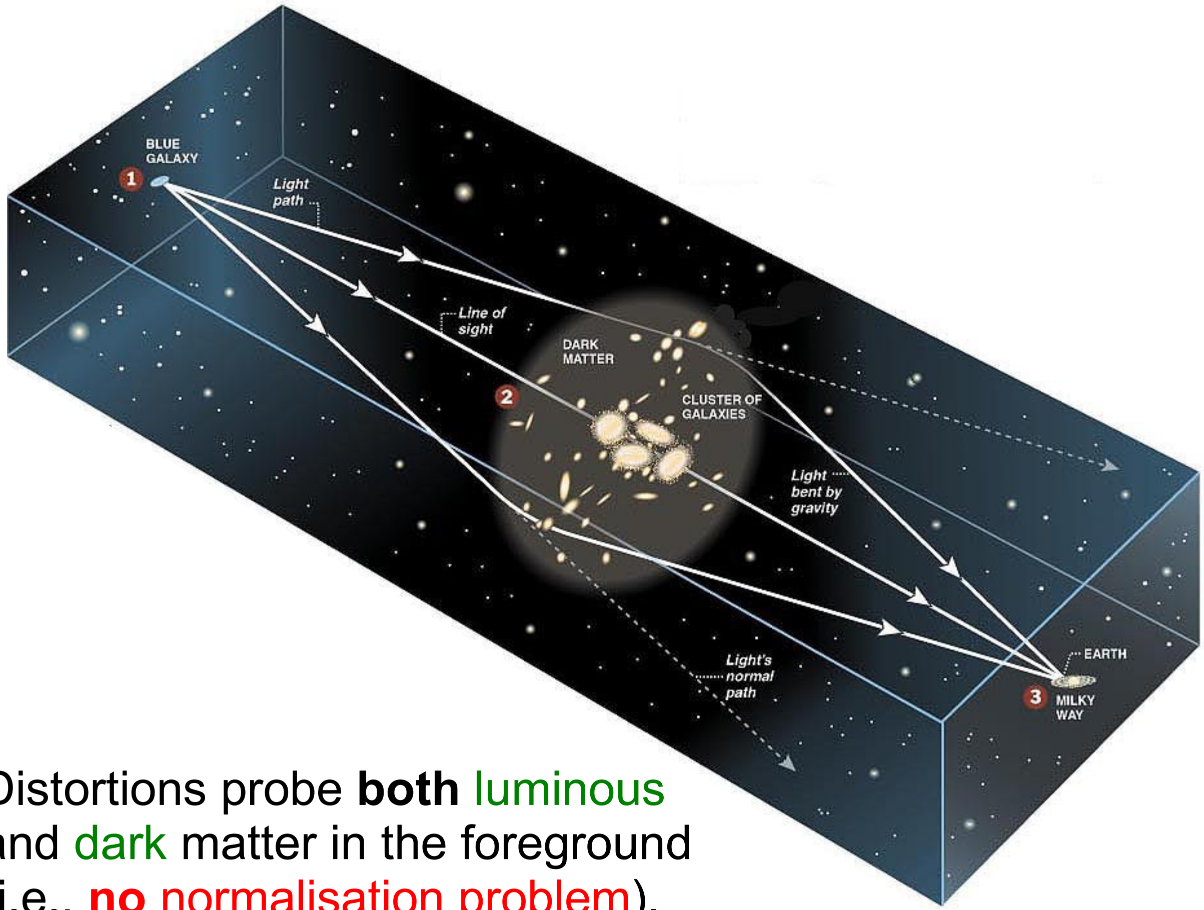
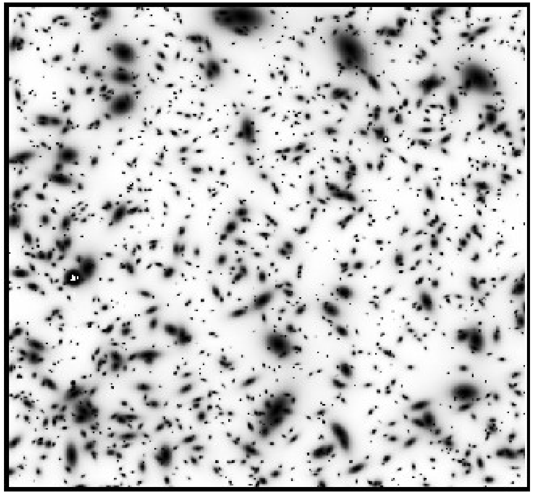


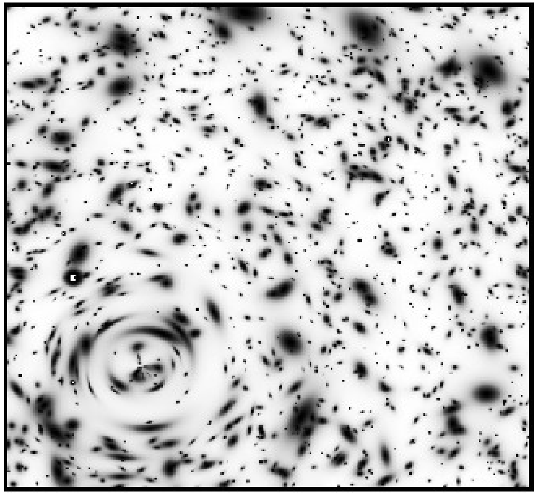
- **Weak gravitational lensing/Cosmic shear**: Distortion (magnification or stretching) of distant galaxy images by foreground matter.



Distortions probe **both** luminous and dark matter in the foreground (i.e., **no** normalisation problem).



Unlensed

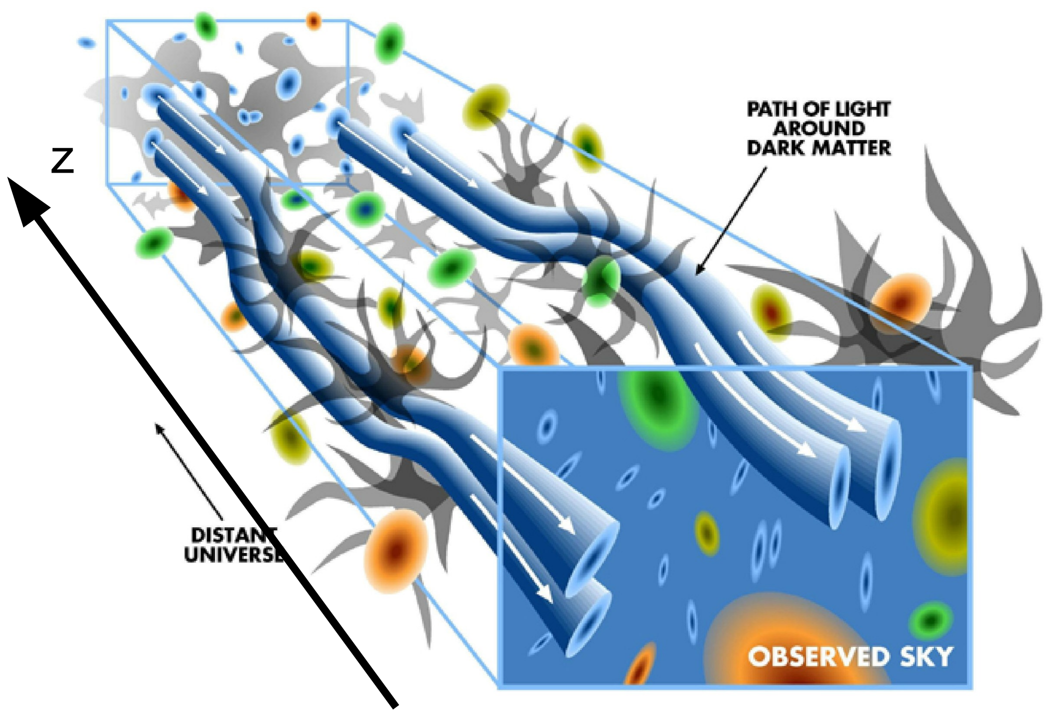


Lensed

$$\text{Shear power spectrum} \propto \sum_{\substack{\text{Lenses along}\\ \text{line-of-sight}}} \left[\sum_{\text{Sources}} \frac{D_{\text{Lens}-\text{Source}}}{D_{\text{Source}}} \right]^2 P_{\text{Lens}}(k)$$

D = Angular diameter distance

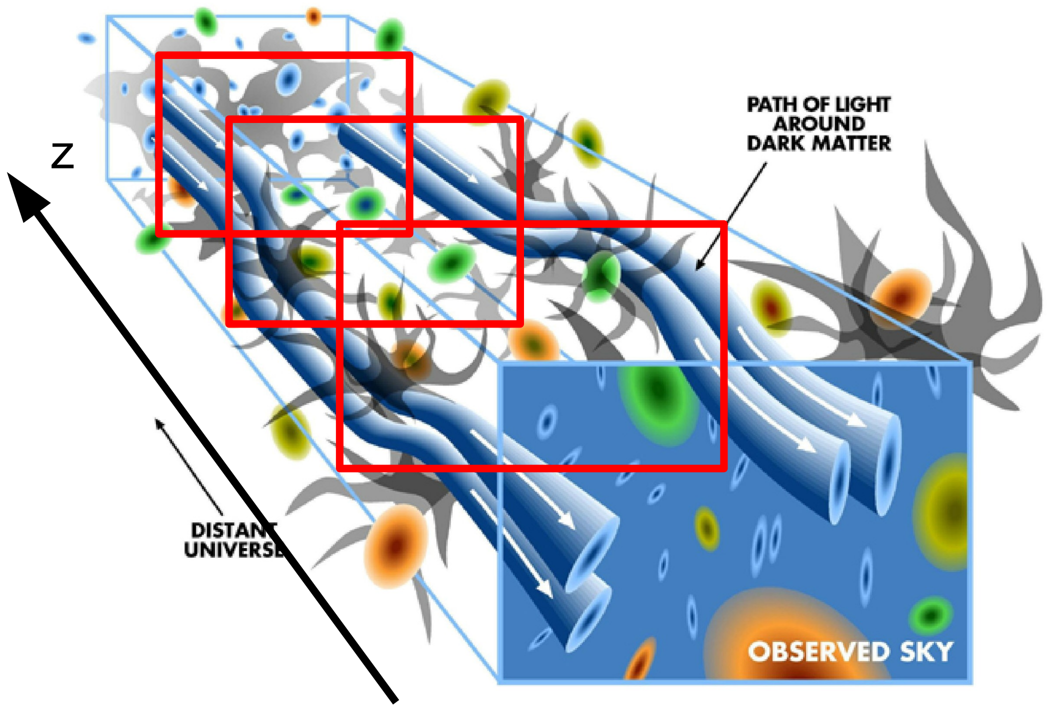
Lens = Matter



Shear power spectrum of redshift bin i $\propto \sum_{\text{Lenses along line-of-sight}} \left[\sum_{\text{Sources in bin i}} \frac{D_{\text{Lens}-\text{Source}}}{D_{\text{Source}}} \right]^2 P_{\text{Lens}}(k)$

D = Angular diameter distance

Lens = Matter



- **Tomography** = bin source galaxies by redshift; can probe:

  → Growth of fluctuations + spectrum evolution.

  → Distance-redshift relation.

- What can lensing tomography do for neutrino masses?

	Sensitivity to Σm_ν (95% C.L.)	
– **Planck only**	0.96 eV	0.50 eV
– **Planck+LSST* no tomography**	0.30eV	0.16 eV
– **Planck+LSST 5 redshift bins**	0.086 eV	0.074 eV
	↑ Unconstrained w	↑ Assuming DE = Cosmological constant

* LSST = Large Synoptic Survey Telescope
Ground-based, full-sky lensing survey
Looking out to z~3, first light 2012.

→ Σm_ν-w degeneracy broken by tomography!

Hannestad, Tu & Y^3W, 2006

- Large-scale structures **lense the CMB** too!

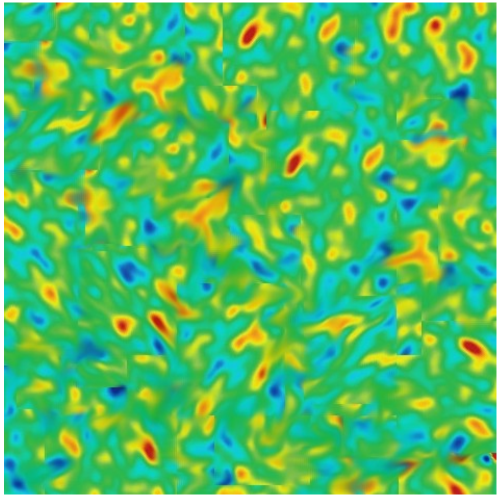
  → An extra "tomography bin" at z~1000 when combined with cosmic shear.

- Lensing exatraction on **Planck**'s agenda:

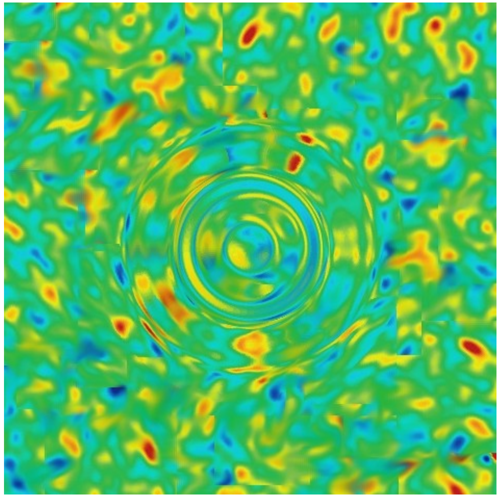
  – Adding Planck lensing to cosmic shear with LSST does not improve sensitivity to Σm_ν. ☹

Planck lensing alone:
Sensitivity to Σm_ν is
0.22 eV (95% C.L.).

Song & Knox , 2004
Lesgourgues, Perotto, Pastor & Piat, 2006
Perotto, Lesgourgues, Hannestad, Tu & Y^3W, 2006



Unlensed



Lensed

- Other probes of the growth function/spectrum evolution:

  - **Cluster abundance.**

    - Cluster mass function: number density of collapsed objects of mass M at redshift z.

Wang, Haiman, Hu, Khoury & May, 2005

- Other probes of the growth function/spectrum evolution:

  - **Cluster abundance.**
    - Cluster mass function: number density of collapsed objects of mass M at redshift z.

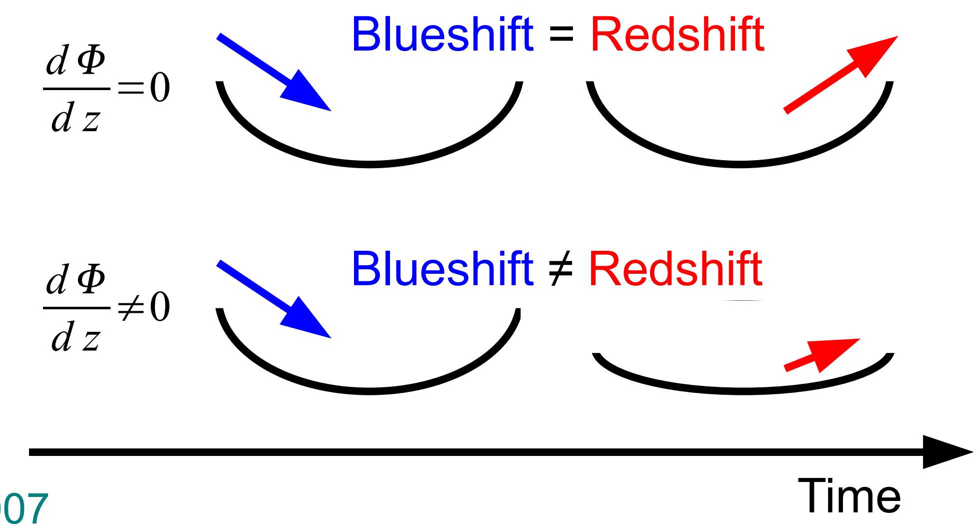
Wang, Haiman, Hu, Khoury & May, 2005

  - **CMB/galaxy cross-correlation (ISW effect).**

$$\frac{\delta T}{T}(\hat{n}) \propto \cdots - \int dz \, \frac{d\Phi(\hat{n}, z)}{dz}$$

$$\frac{d\Phi}{dz} \propto \frac{d}{dz}\left[(1+z)D(z)\right]$$

D(z) = Growth function



Lesgourgues, Valkenburg & Gaztanaga, 2007

3 reasons to go high z...

1. **Spectrum evolution.**

2. **Growth of fluctuations.**

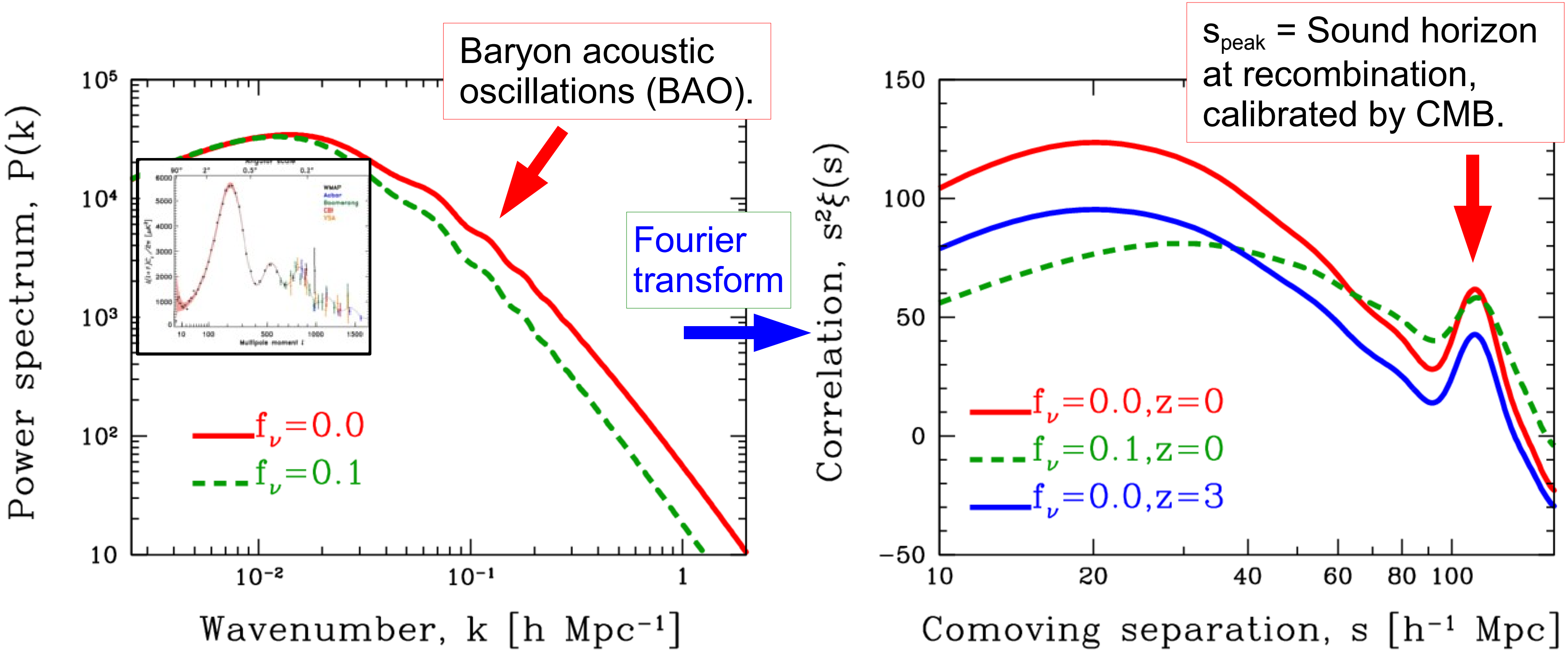
3. **Baryon wiggles.**

Probes:
- Weak gravitational lensing
  - of galaxies (tomography)
  - of the CMB
- High-z galaxy clustering
- Cluster abundance
- CMB/galaxy cross-correlation (ISW effect)

3. Baryon wiggles...

Best probes:
High-z galaxy clustering (spectroscopic)

- **Acoustic oscillations** of coupled photon-baryon fluid at recombination (cf CMB anisotropies).

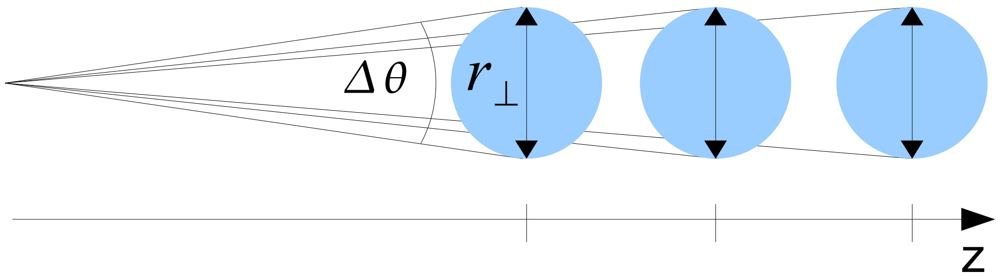


- BAO as a **standard ruler**:

$$r_\perp = r_\parallel = s_{\text{peak}} \sim 150\ h^{-1}\,\text{Mpc}$$

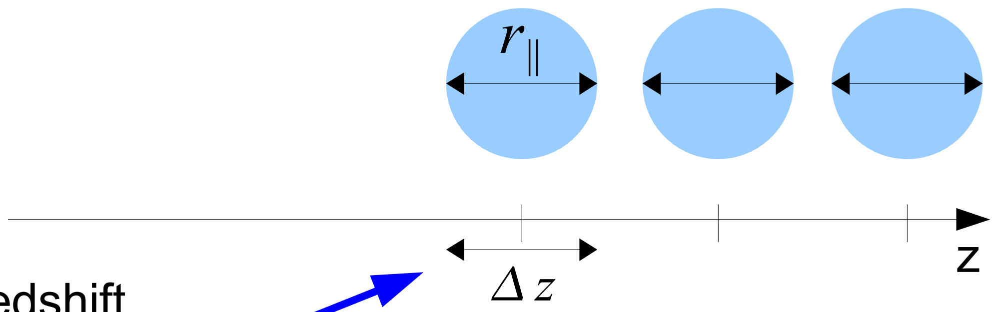
Correlation in transverse direction
→ Angular diameter distance

$$D_A(z) = \int_0^z \frac{dz'}{H(z')} = \frac{r_\perp}{\Delta\theta}$$



Correlation in radial direction
→ Hubble expansion rate

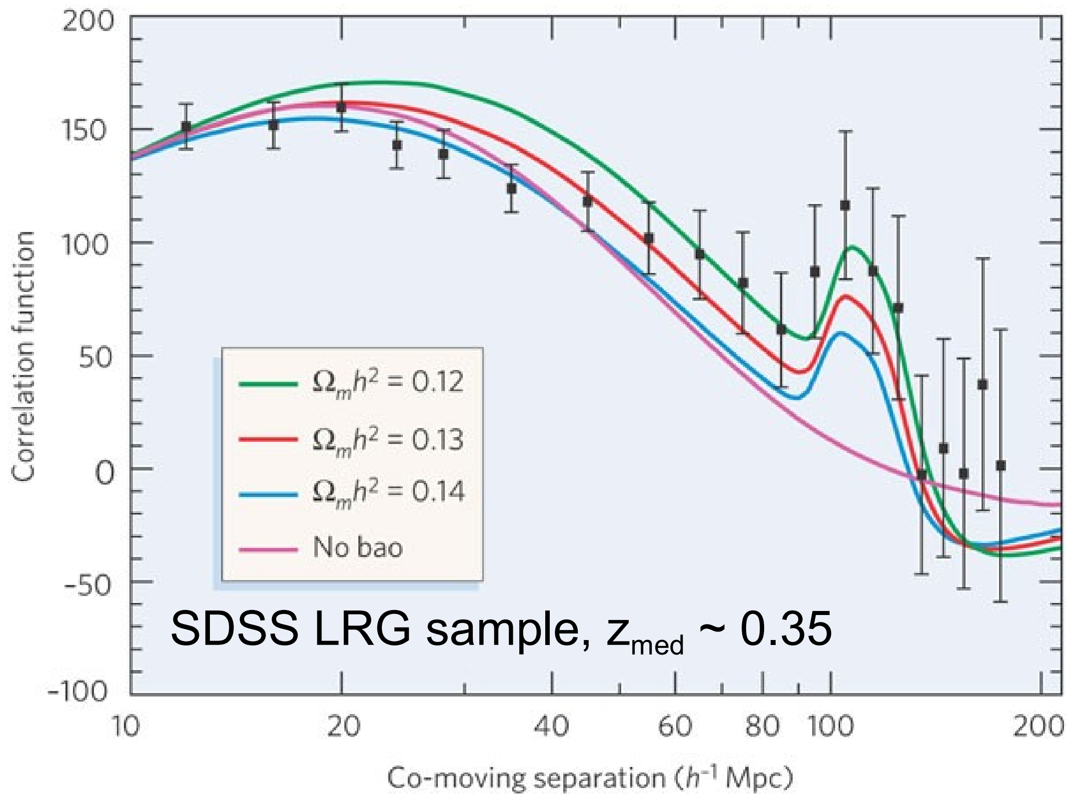
$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_{\text{DE}} (1+z)^{3(1+w)}} = \frac{\Delta z}{r_\parallel}$$



Requires good redshift resolution → spectroscopic galaxy surveys only

- BAO has been **detected** @ z ~ 0.35.

- Planned/proposed spectroscopic surveys, (WFMOS, HETDEX, etc.) will observe @ 2 < z < 4.



Eisenstein et al. (SDSS), 2005

- What can future BAO do for neutrino masses?

  - Adding BAO to broad-band probes of P(k) will eliminate any remaining degeneracy between Σm_ν and the dark energy EOS.

  - Our preliminary estimate of the Σm_ν sensitivity for **Planck + Cosmic shear tomography + BAO** is ~ 0.05 eV (95% C.L.).

Hannestad & Y^3W, in prep.

3. The challenges…

Nonlinearities...

- Linear perturbation theory fails at k > 0.2 h Mpc^{-1} today.
- Nonlinearities can affect:
  - Spectrum shape.
  - Location of BAO peak.
- **Remedies**:
  - Brute-force method: N-body simulations.
  - Semi-analytical halo models? Peacock & Smith, 2000; Seljak, 2000; Ma & Fry, 2000
  - Higher order perturbation theory? Renormalisation group?

Crocce & Scoccimarro, 2005; 2007
Matarrese & Pietroni, 2007

	Spectrum evolution	Growth function	Baryon wiggles
High-z galaxy clustering	Yes	No	Yes
Weak lensing			
of galaxies (tomography)	Yes	Yes	No
of the CMB	Yes	Yes	No
Cluster abundance	Yes	Yes	No
CMB/galaxy cross-correlation (ISW effect)	Yes	Yes	No

Spectrum evolution + Growth function + Baryon wiggles

→ Great prospects for probing the neutrino mass down to the 0.05 eV level (95% C.L.) in the next decade!