Measuring neutrino masses with a photometric redshift survey

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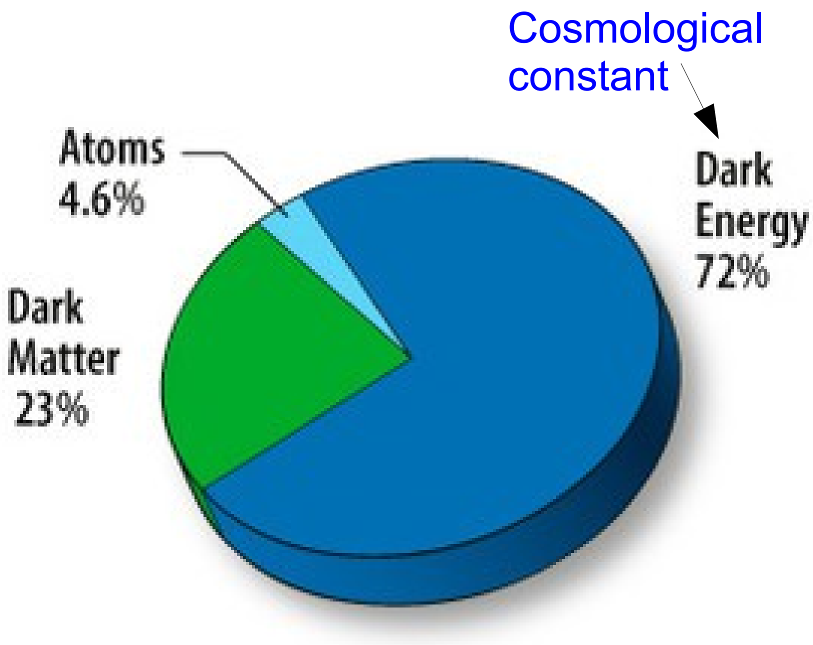
RWTH Aachen

[J. Hamann, S. Hannestad & Y^3W, JCAP 1211 (2012) 052]

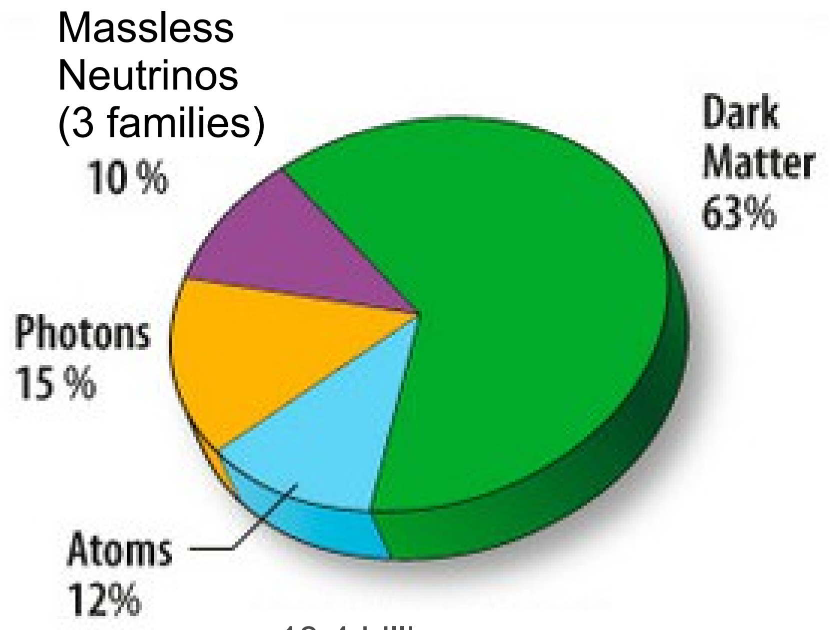
Theory seminar, Université Libre de Bruxelles, February 1, 2013

The cosmic pie(s)...

The ΛCDM model is the simplest model consistent with **present observations**.



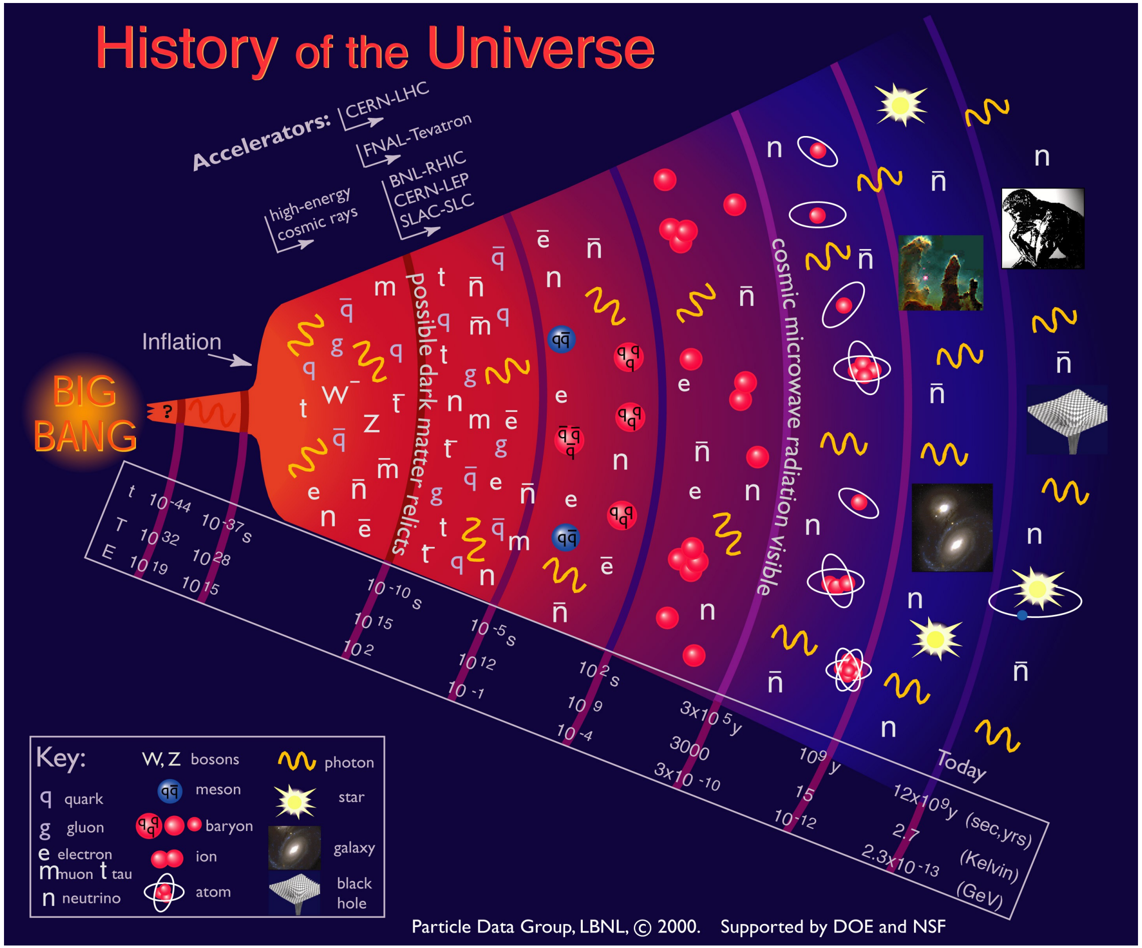
Composition today



13.4 billion years ago
(at photon decoupling)

Plus flat spatial geometry+initial conditions
from single-field inflation

The cosmic neutrino background...



Embedding the **standard model** in **FLRW cosmology** necessarily leads to a thermal neutrino background (decoupling at T ~ 1 MeV).

Fixed by weak interactions

Present temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma = 1.95\,\mathrm{K}$$

Number density per flavour:

$$n_\nu = \frac{6}{4}\frac{\zeta(3)}{\pi^2} T_\nu^3 = 112\ \mathrm{cm}^{-3}$$

The cosmic neutrino background: energy density...

The present-day neutrino energy density depends on whether the neutrinos are relativistic or nonrelativistic.

- **Relativistic** (m << T):

Photon energy density

$$\rho_\nu = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4 = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma \qquad \frac{3\rho_\nu}{\rho_\gamma} \sim 0.68$$

- **Nonrelativistic** (m >> T ~ 10^{-4} eV):

$$\rho_\nu = m_\nu n_\nu \qquad \boxed{\Omega_\nu h^2 = \frac{m_\nu}{93\,\mathrm{eV}}}$$

Neutrino dark matter
(not part of the vanilla ΛCDM)

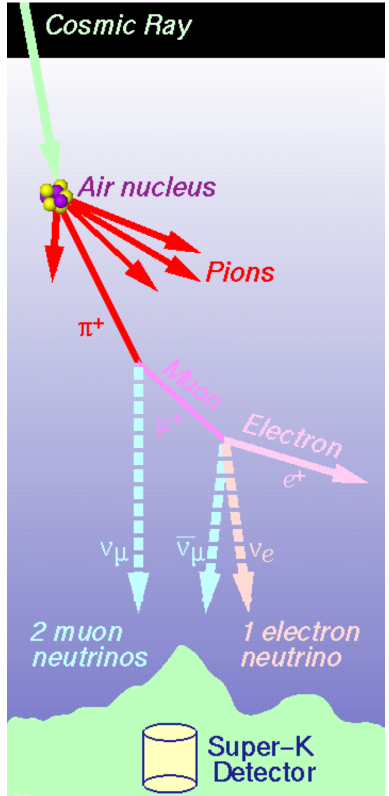
Flavour oscillations imply nonzero neutrino mass...

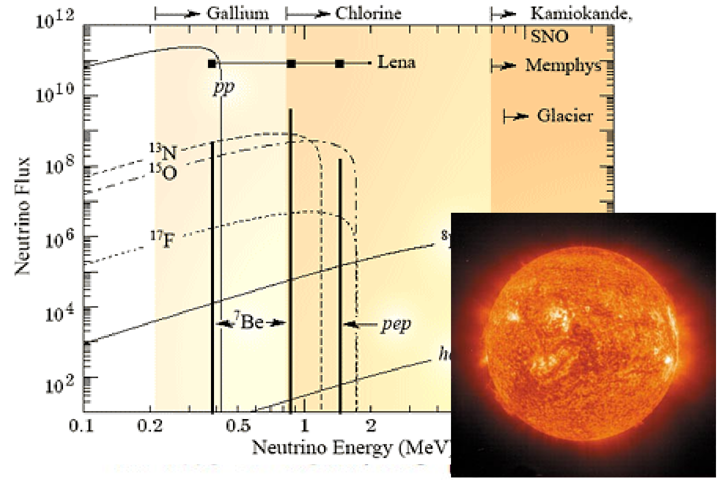
Atmospheric & solar neutrino oscillations indicate that at least one neutrino mass eigenstate has a **mass of > 0.05 eV**.

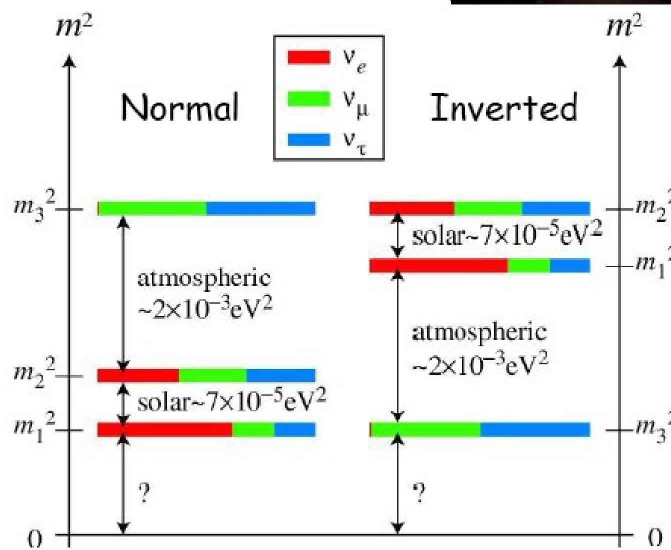
Cosmological implications:

- Relic neutrinos are nonrelativistic today.
- Present-day energy density:

$$\Omega_\nu = \frac{m_\nu}{93\,h^2\,\mathrm{eV}} > 0.1\,\%$$

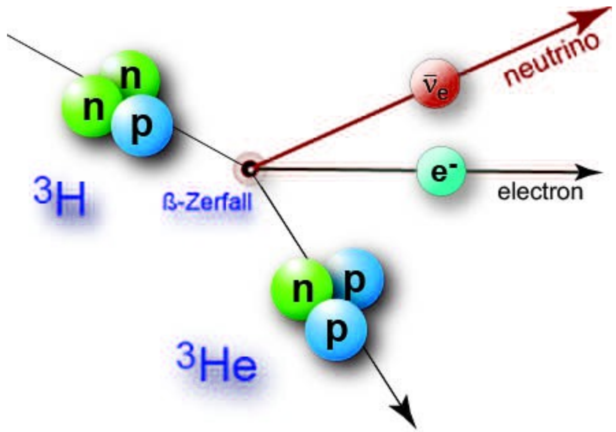


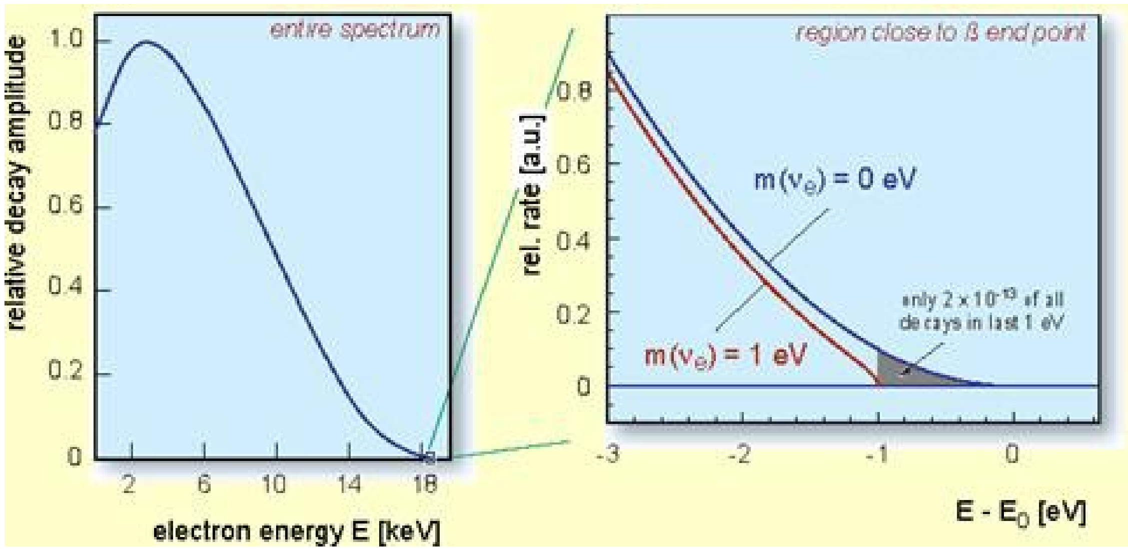




Tritium β-decay limit on neutrino mass...

Tritium β-decay end-point spectrum measurements impose an upper limit on the effective mass of the electron neutrino.





Current upper limit:

$$m_e \equiv \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2} < 2.2 \text{ eV}$$

$$\max \sum m_\nu \sim 7 \text{ eV} \rightarrow \max \Omega_\nu \sim 15\,\%$$

Lobashev [Troitsk] 2003; Krauss et al. [Mainz] 2005

Neutrino dark matter is hot...

Neutrino dark matter come with large **thermal motion**.

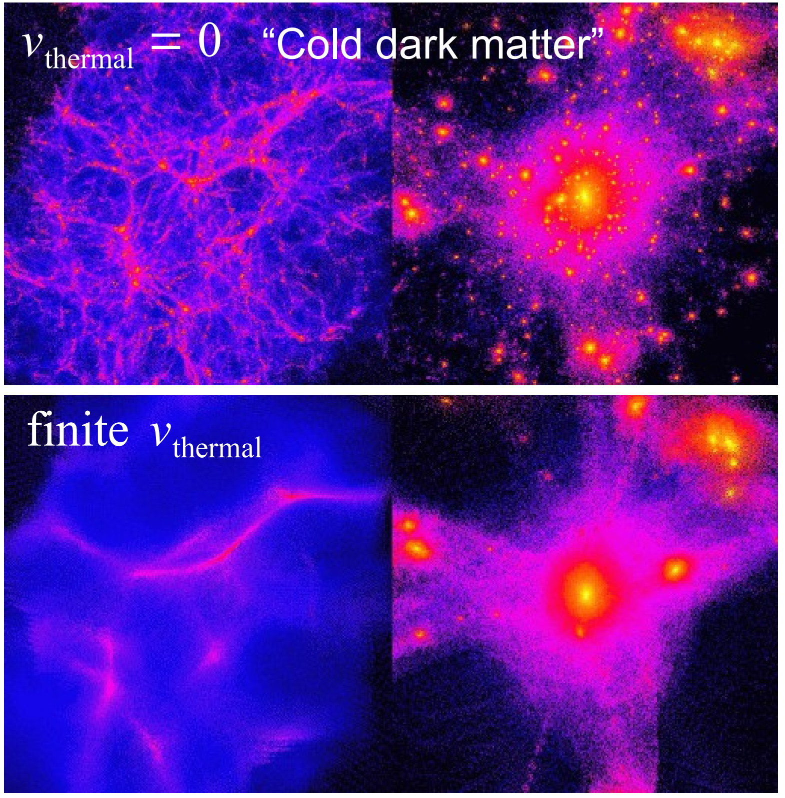
- Characteristic thermal speed:

$$v_{\text{thermal}} = \frac{T_\nu}{m_\nu} \simeq 50.4(1+z)\left(\frac{\text{eV}}{m_\nu}\right) \ \text{km s}^{-1}$$

Structures on scales below the (maximum) free-streaming scale could **not** have been formed via gravitational instability:

$$\lambda_{\text{FS,max}} = 31.8\,\Omega_{m,0}^{-1/2}\left(\frac{\text{eV}}{m_\nu}\right)^{1/2} h^{-1}\,\text{Mpc}$$

cf galaxies (~100 kpc), galaxy clusters (~ 1 Mpc)



http://www.itp.uzh.ch/

Why bother with neutrino dark matter then?

Because it's there.

- Neutrino dark matter = culmination of **FLRW cosmology + SM + terrestrial experiment**, a prediction as fundamental as the prediction of the cosmic microwave background.
  - Confirmation of FLRW cosmology
  - Determination of neutrino mass from cosmology
- **You have to deal with it** even if you don't care about it.
  - When performing parameter inference, the presence of neutrino dark matter may shift the values of those cosmological parameters you care about, e.g., inflation parameters, dark energy properties, etc.

Plan...

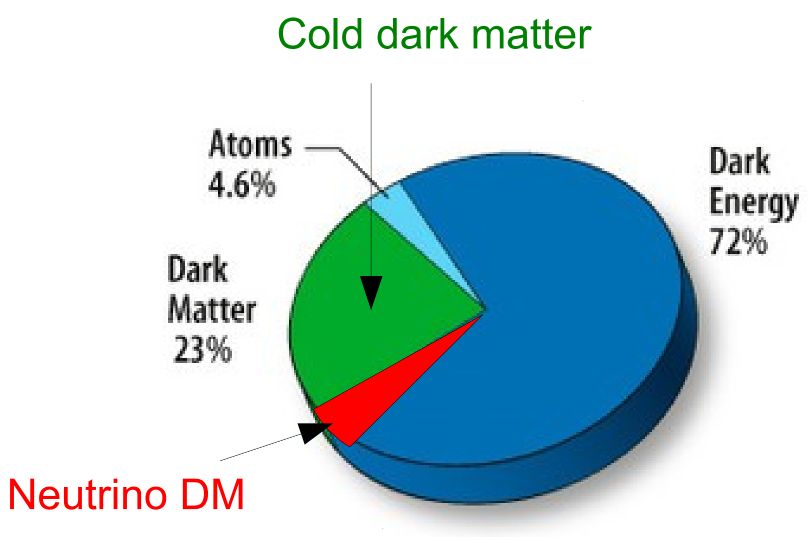
Looking for neutrino dark matter

- Direct detection
- Indirect detection

Euclid sensitivity forecast

- Why Euclid is so good for the determination of the neutrino mass from cosmology.

Disclaimer: We are dealing with subdominant, sub-eV to eV-mass neutrino dark matter here! The bulk of the DM content is explained by something else.



1. Looking for neutrino dark matter...

Direct detection of neutrino dark matter...

… is a difficult business.

- Small interaction cross-section:

$$\sigma_{\nu N} \sim \frac{G_F^2 m_\nu^2}{\pi} \simeq 10^{-56} \left(\frac{m_\nu}{\text{eV}}\right)^2 \text{cm}^2$$

cf WIMP detection, ~ 10^{-46} cm^2

- Neutrino energy too small to cross most detection thresholds.

$$\Delta p \sim m_\nu v_{\text{earth}} \simeq 10^{-3} m_\nu$$

Speed of Earth with respect to the CMB, ~ 370 km s^{-1}

  - Conventional WIMP detection techniques don't work here.

A zero threshold process?

- One unique candidate here...

Direct detection by neutrino capture...

Weinberg 1962
Cocco, Mangano & Messina 2007
Lazauskas, Vogel & Volpe 2007
Blennow 2008
Lusignoli & Vignati 2010

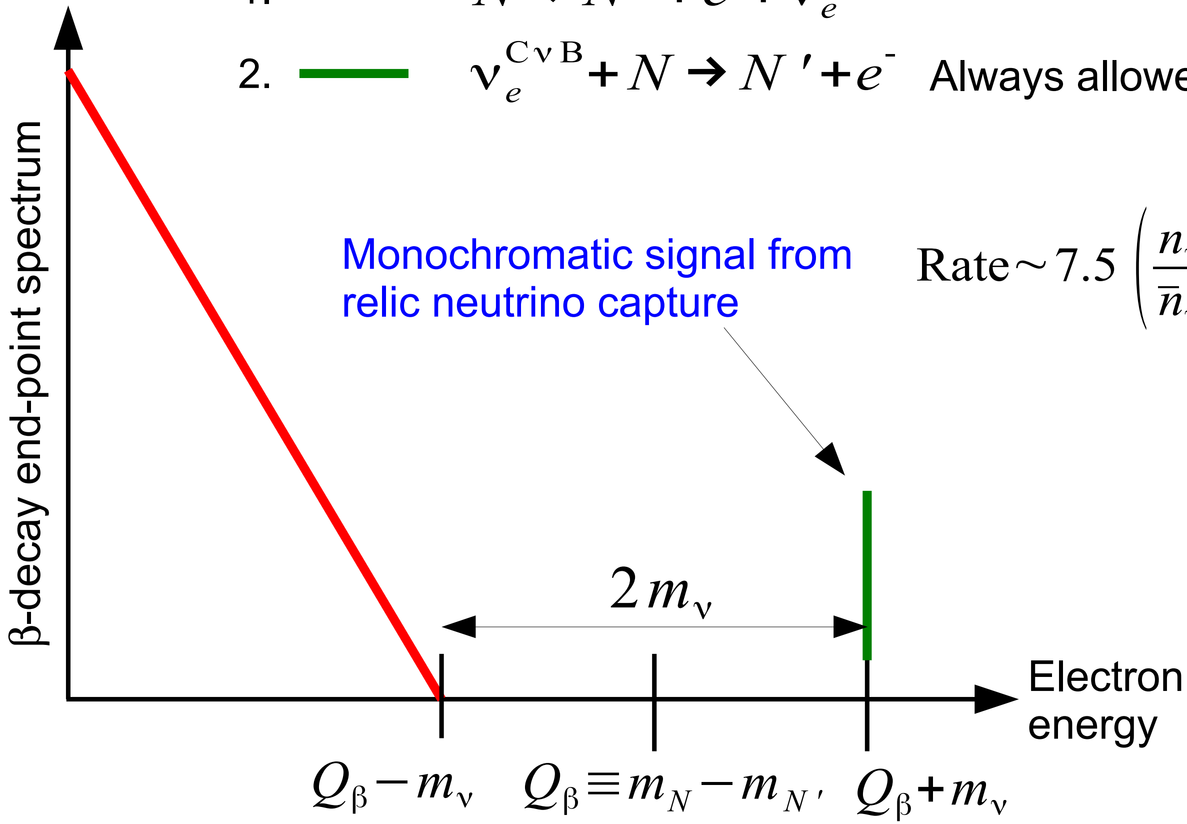
β-decay end-point spectrum

1. $N \rightarrow N' + e^- + \bar{\nu}_e$

2. $\nu_e^{C\nu B} + N \rightarrow N' + e^-$ Always allowed if $m_\nu + m_N > m_{N'} + m_e$

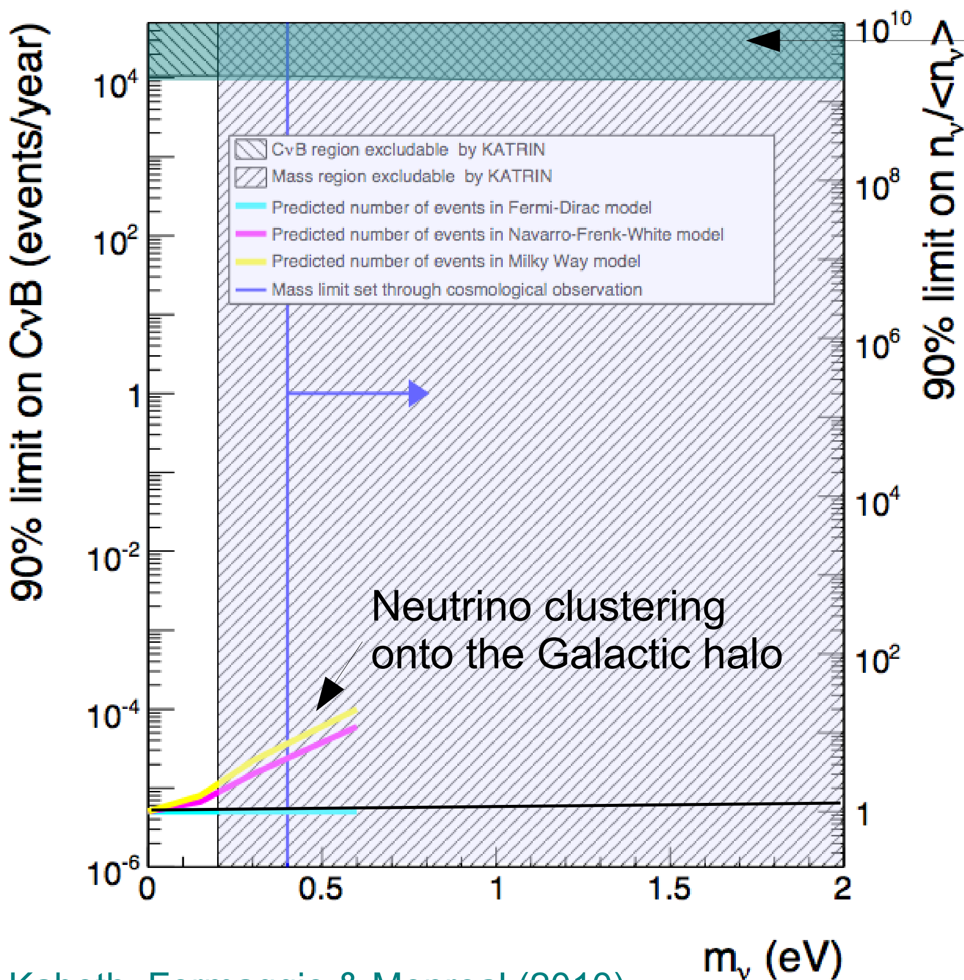
Local neutrino overdensity

$$\text{Rate} \sim 7.5 \left(\frac{n_\nu}{\bar{n}_\nu}\right) / \text{ year } / \left(100 \text{ g tritium}\right)$$

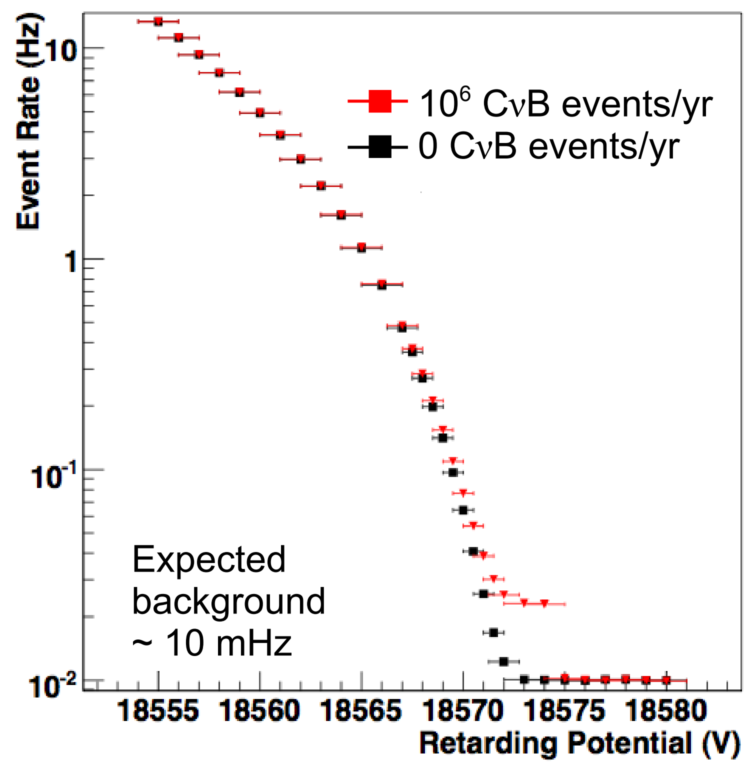


KATRIN ~ 0.1 mg tritium

Neutrino capture with KATRIN...

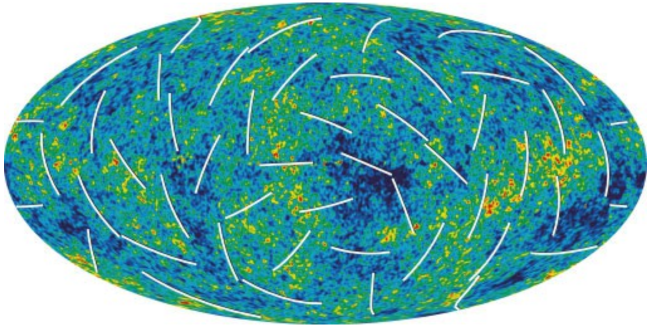


Requires a **10^9 local overdensity of neutrinos** in a 3-year run for a 90% C.L. detection.



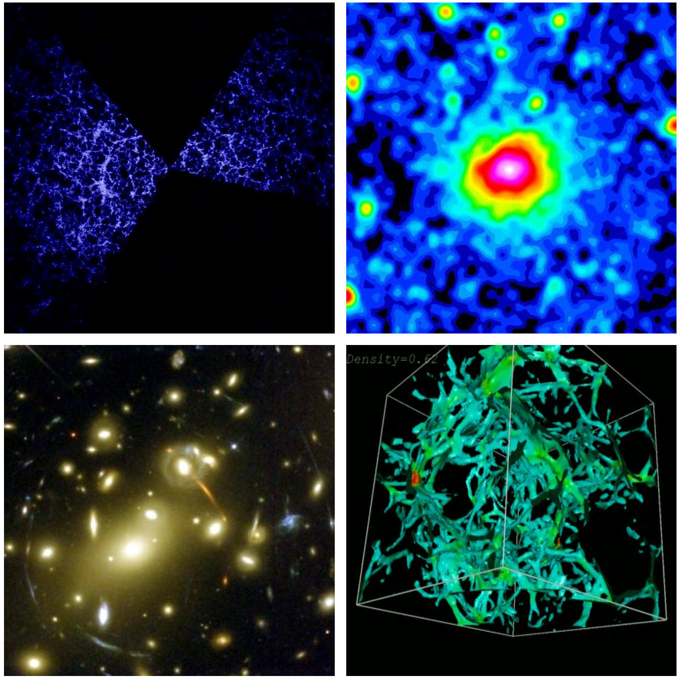
Kaboth, Formaggio & Monreal (2010)

Indirect detection...



Exploit the effects of (subdominant) neutrino dark matter on precision cosmological observables:

- **Cosmic microwave background anisotropies**
  - Effects on the evolution of the homogeneous background



- **Large-scale matter distribution**
  - Effects on the level of the inhomegeneities

Neutrino dark matter and the CMB anisotropies...

Background effect

- eV-mass neutrinos become nonrelativistic close to equality and photon decoupling.

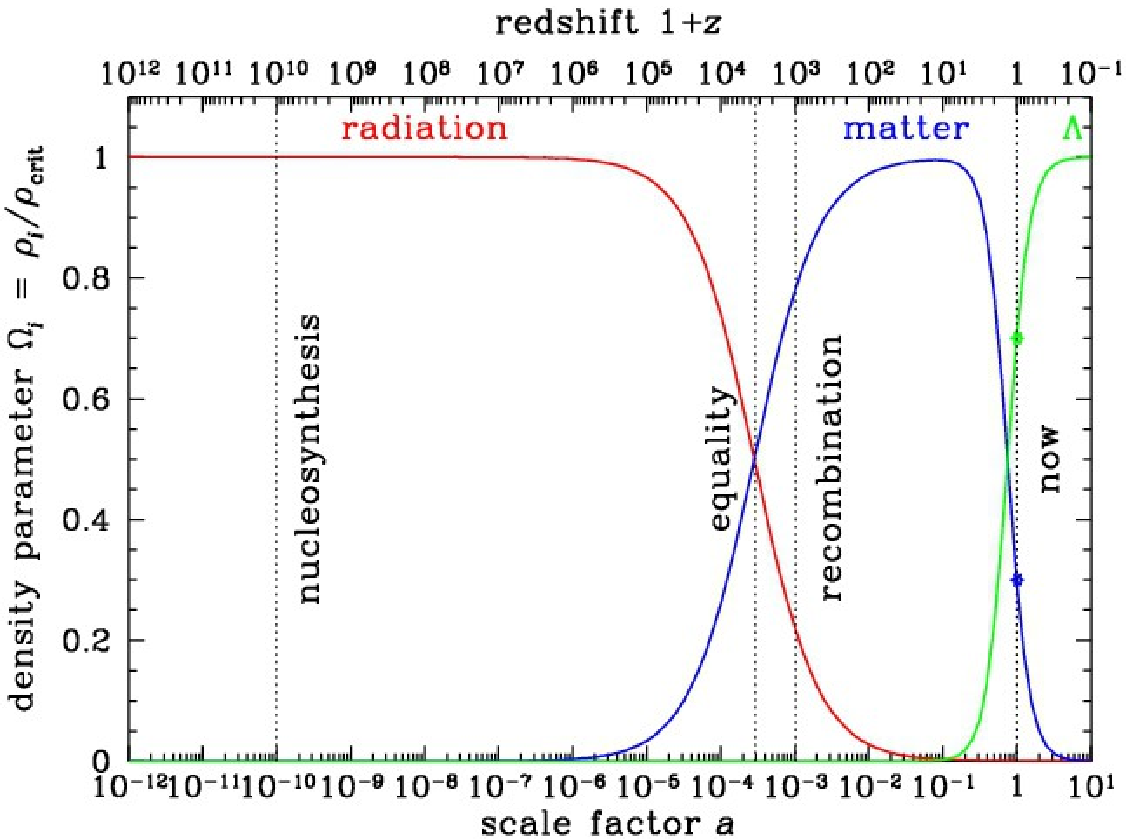
- A non-trivial transition from radiation to matter domination.

  → Affects sound horizon.

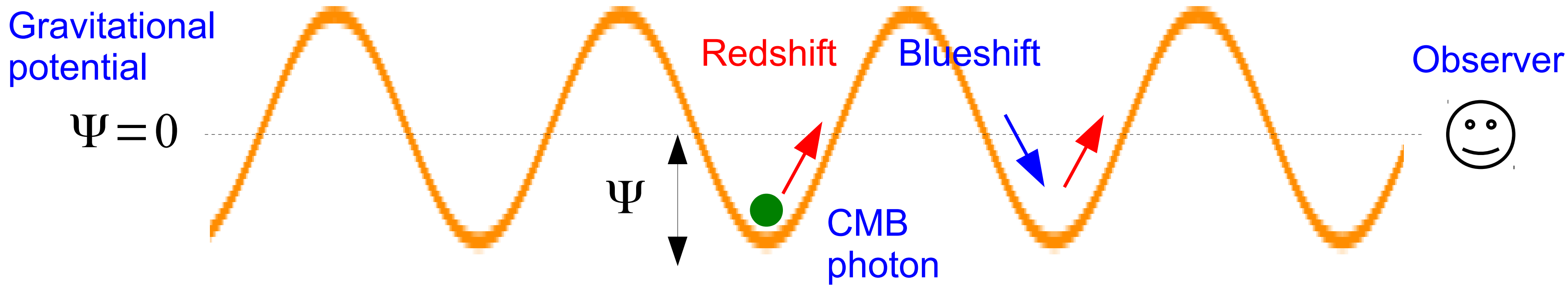
  → A nonstandard early Integrated Sachs-Wolfe effect.

1 eV mass neutrino

Relativistic → Nonrelativistic



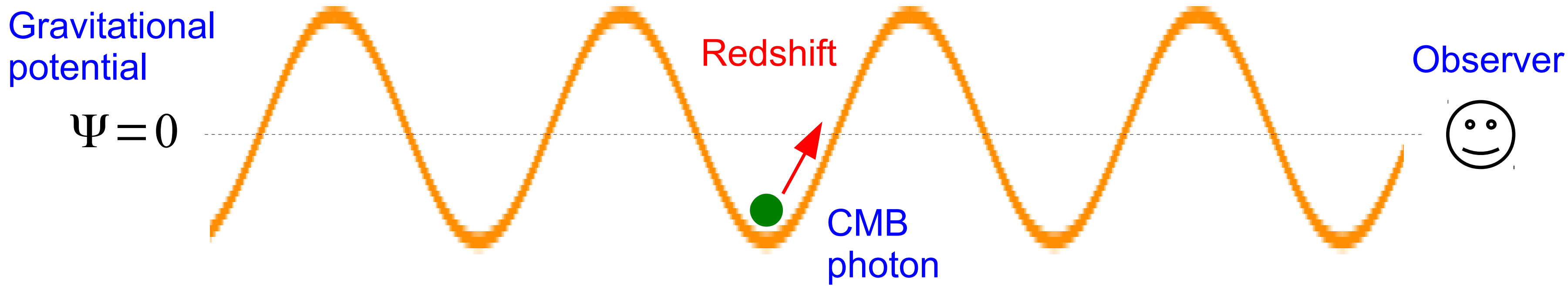
Sachs-Wolfe effect:



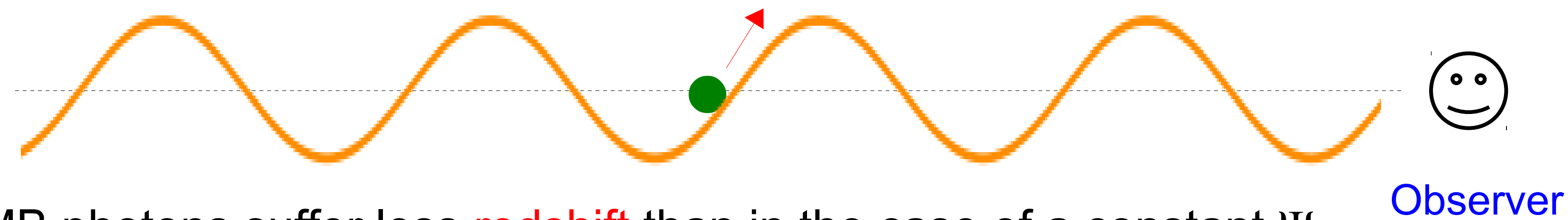
Observed CMB temperature fluctuation

$$\left.\frac{\Delta T}{T}\right|_{\text{observed}} = \left.\frac{\Delta T}{T}\right|_{\text{intrinsic}} + \Psi$$

<u>Integrated</u> Sachs-Wolfe (ISW) effect:



- Except during matter domination, gravitational potentials **decay with time**.

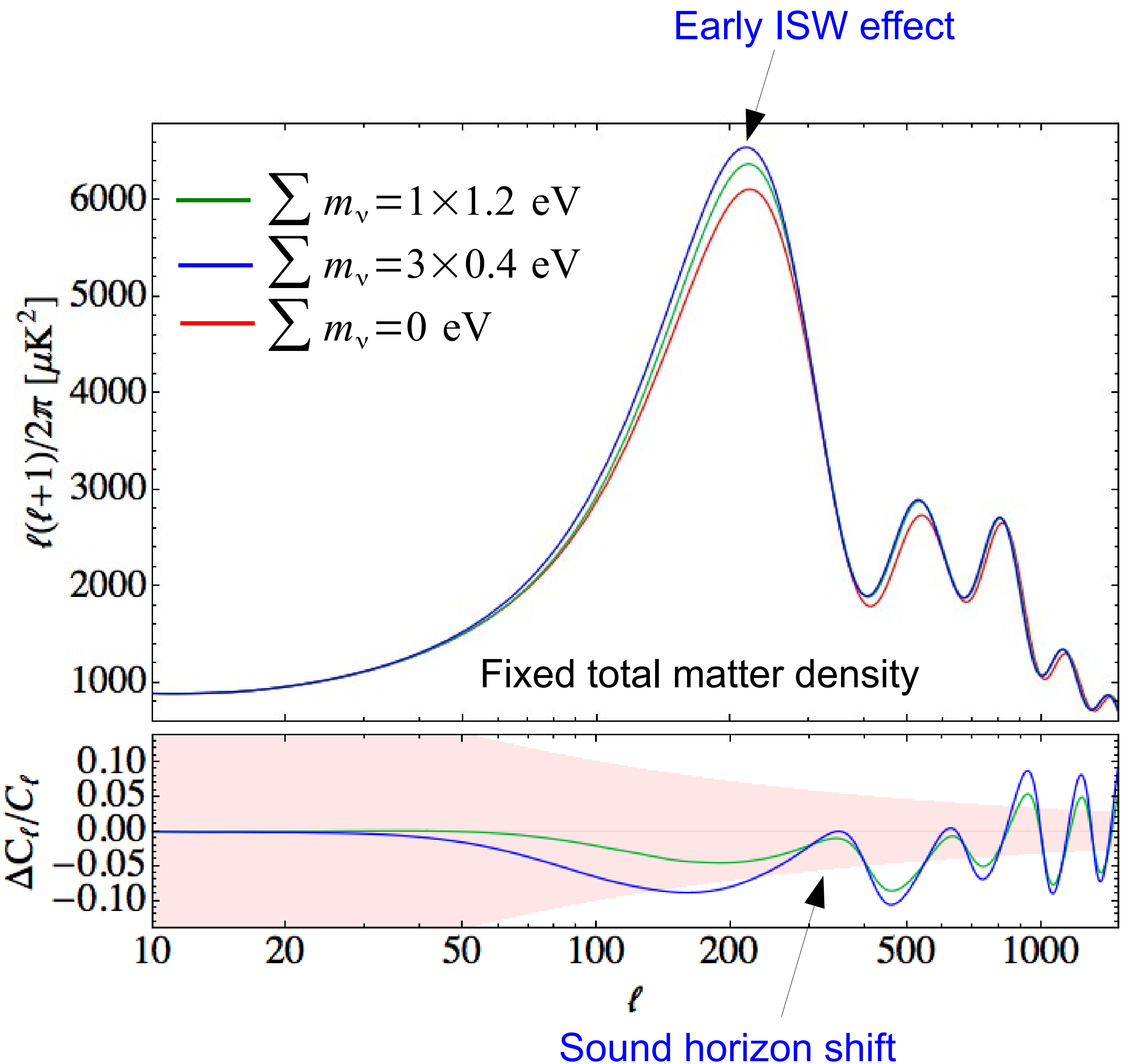


  - CMB photons suffer less redshift than in the case of a constant Ψ.
  - **Larger** observed temperature fluctuations:

time

$$\frac{\Delta T}{T}_{\mathrm{ISW}}(\hat{n})=\int_0^{\tau_0} d\tau\, e^{-\kappa(\tau)}\left[\dot{\Psi}(\tau,\hat{n}(\tau_0-\tau))+\dot{\Phi}(\tau,\hat{n}(\tau_0-\tau))\right]$$

Optical depth



Current constraints from CMB alone:

$$\sum m_\nu < 1.2 \text{ eV} \quad (95\%\text{C.L.})$$

ΛCDM + neutrino mass
(7 parameters)

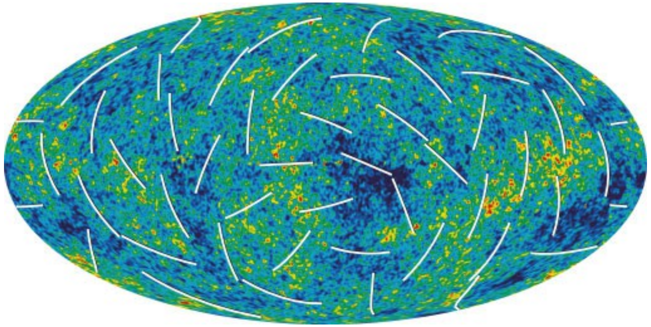
Komatsu et al. [WMAP7] 2010

$$\sum m_\nu < 1.3 \text{ eV} \quad (95\%\text{C.L.})$$

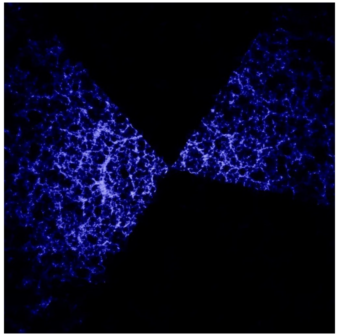
Hinshaw et al. [WMAP9] 2012

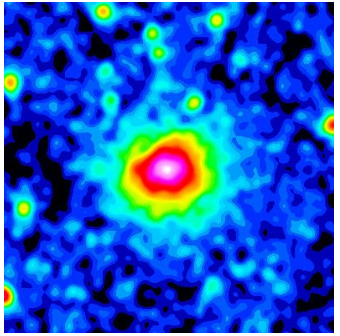
Indirect detection...

Exploit the effects of (subdominant) neutrino dark matter on precision cosmological observables:

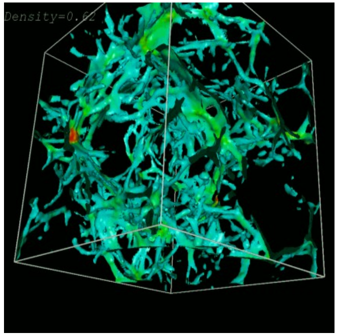


- **Cosmic microwave background anisotropies**
  - Effects on the evolution of the homogeneous background





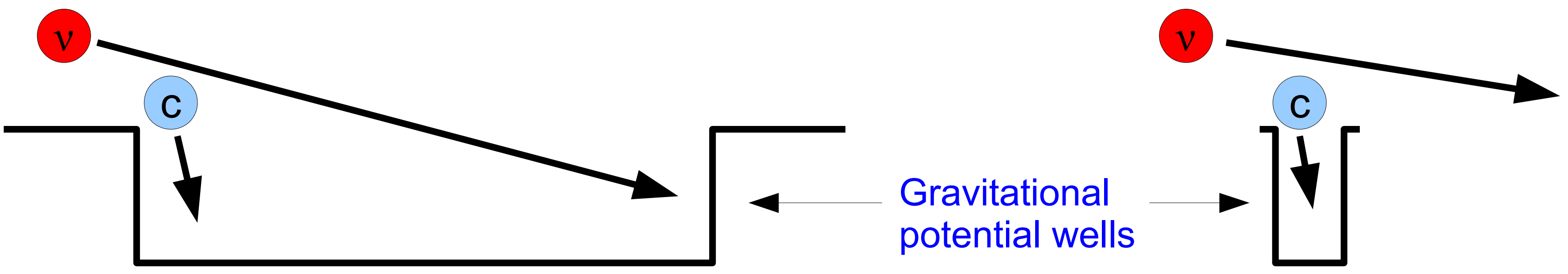
- **<u>Large-scale matter distribution</u>**
  - Effects on the level of the inhomegeneities



Subdominant neutrino DM and large-scale structure...

The presence of CDM acts as a source of density perturbations.

- No complete erasure of perturbations on small scales.
- But thermal motion of the relic neutrinos still makes neutrino clustering difficult.



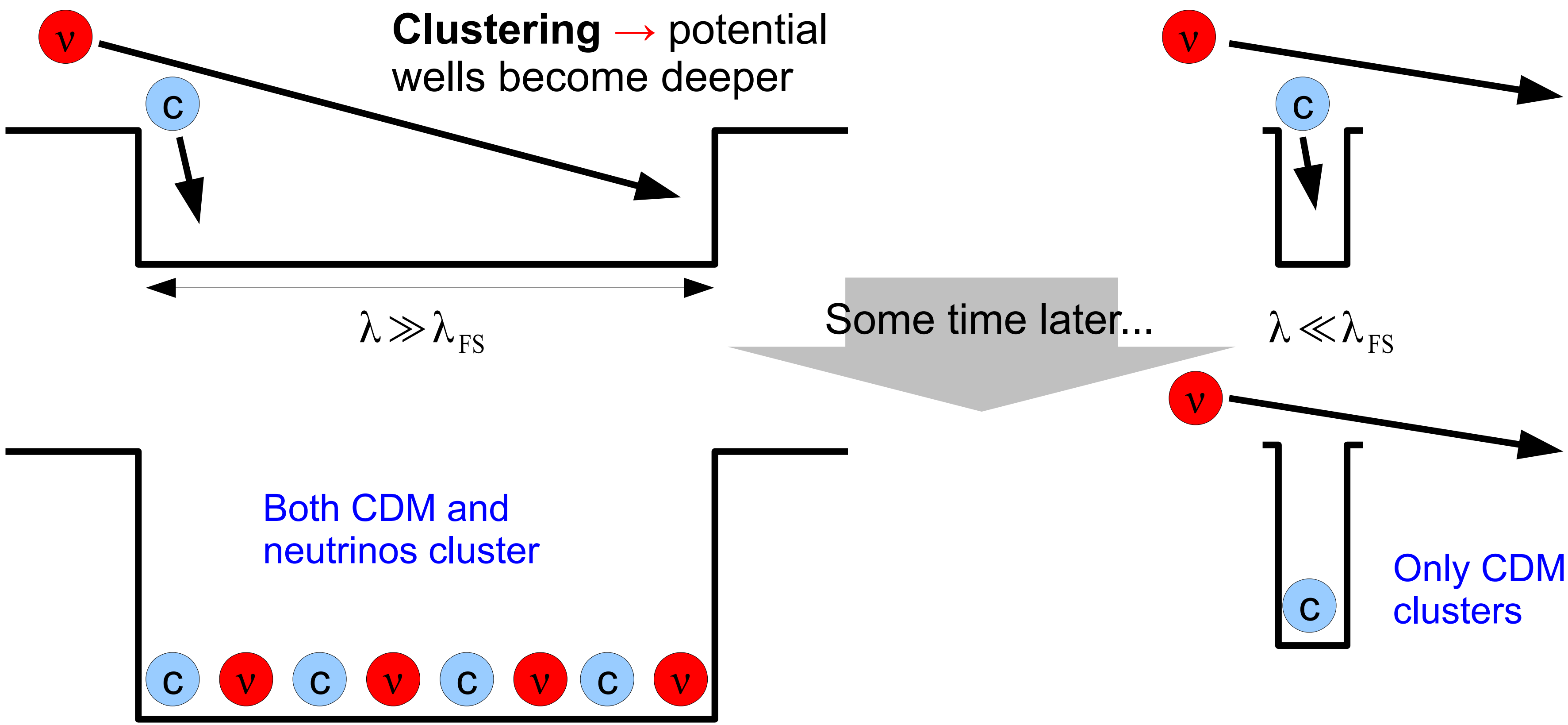
Free-streaming scale:

$$\lambda_{\rm FS} \equiv \sqrt{\frac{8\pi^2 v_{\rm thermal}^2}{3\Omega_m H^2}} \simeq 4.2 \sqrt{\frac{1+z}{\Omega_{m,0}}} \left(\frac{\rm eV}{m_\nu}\right) h^{-1}\,{\rm Mpc}\,; \quad k_{\rm FS} \equiv \frac{2\pi}{\lambda_{\rm FS}}$$

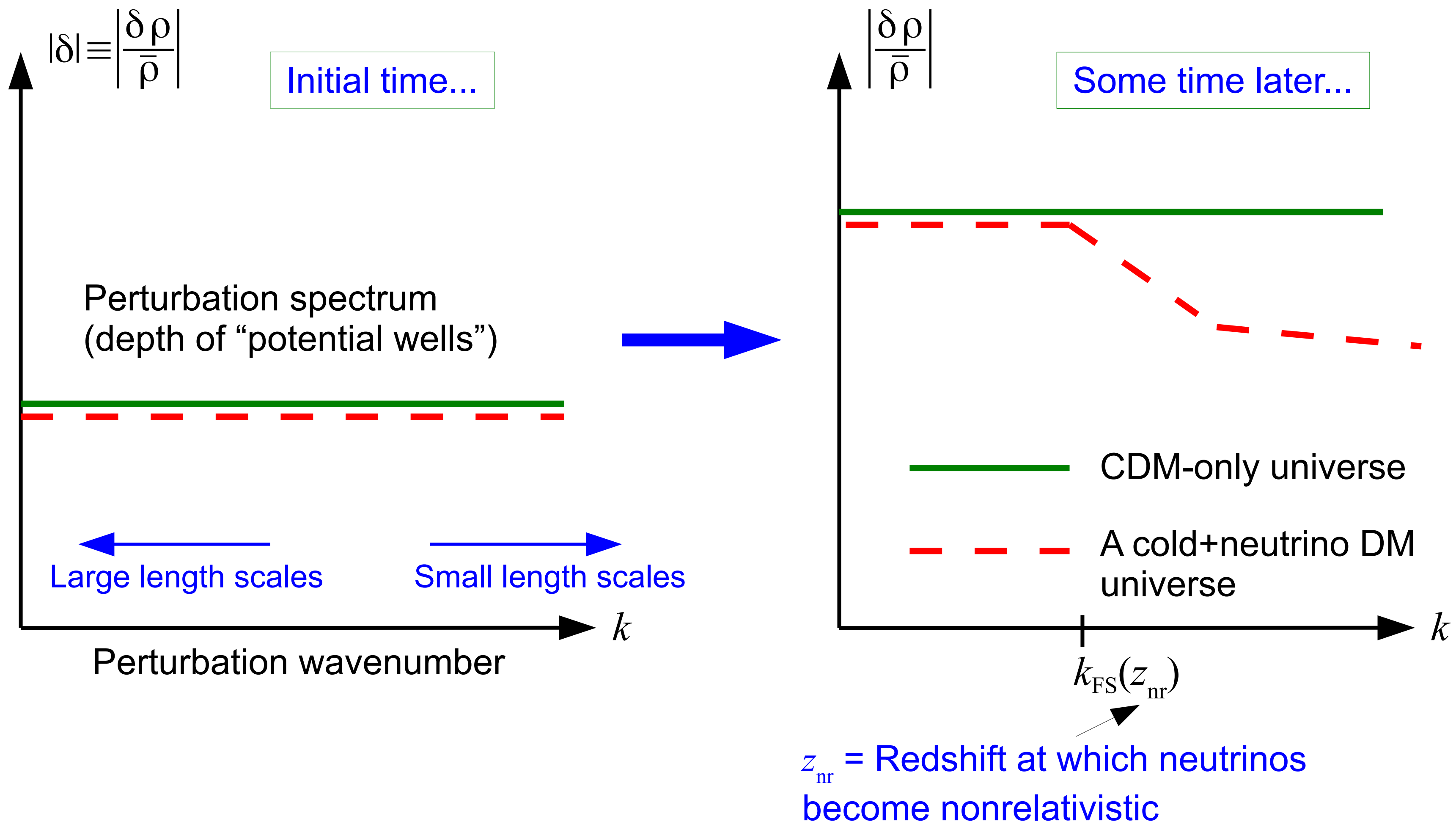
$\lambda \gg \lambda_{\rm FS}$, $k \ll k_{\rm FS}$ Clustering

$\lambda \ll \lambda_{\rm FS}$, $k \gg k_{\rm FS}$ Non-clustering

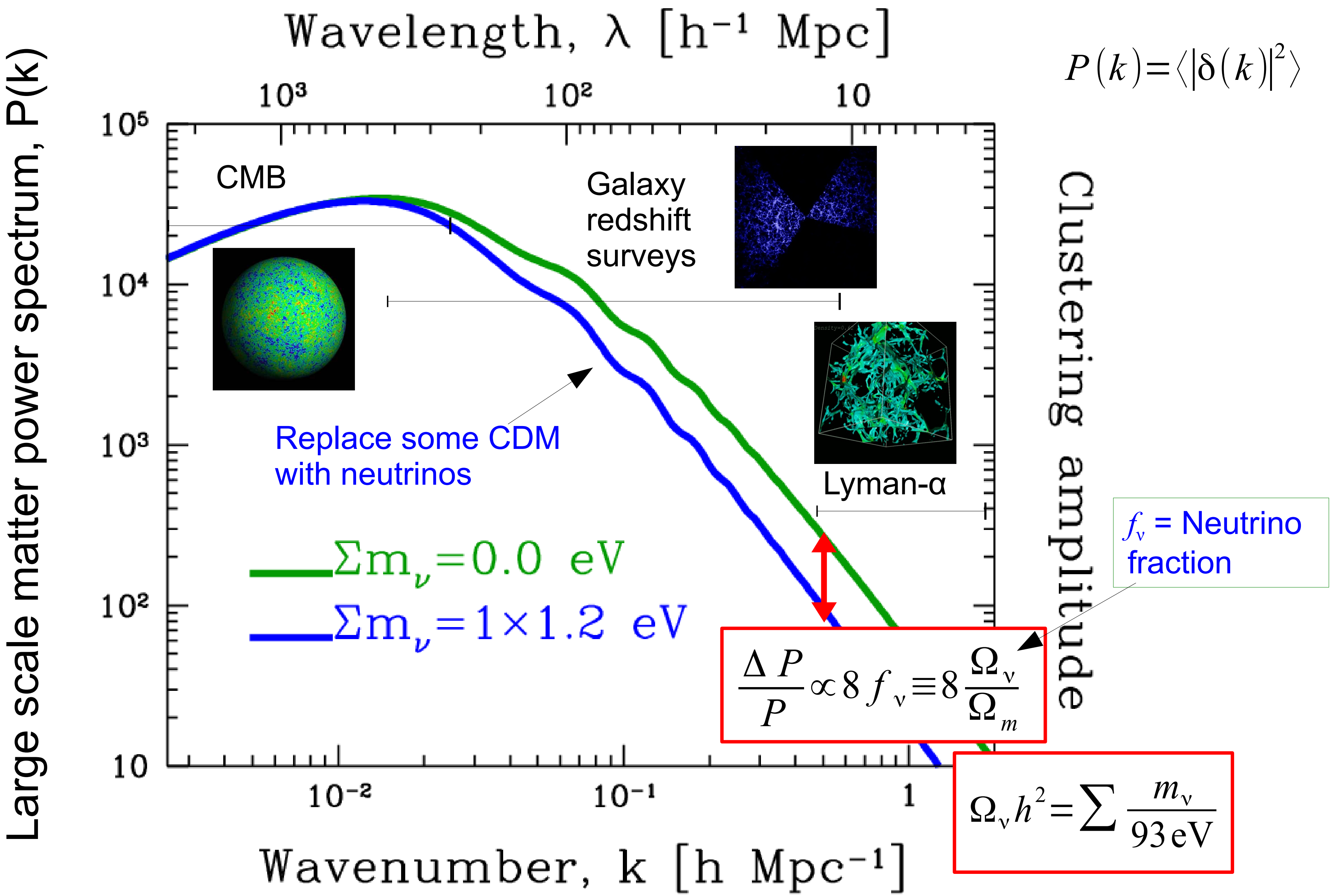
Consider a neutrino and a cold dark matter particle encountering two gravitational potential wells of different sizes:



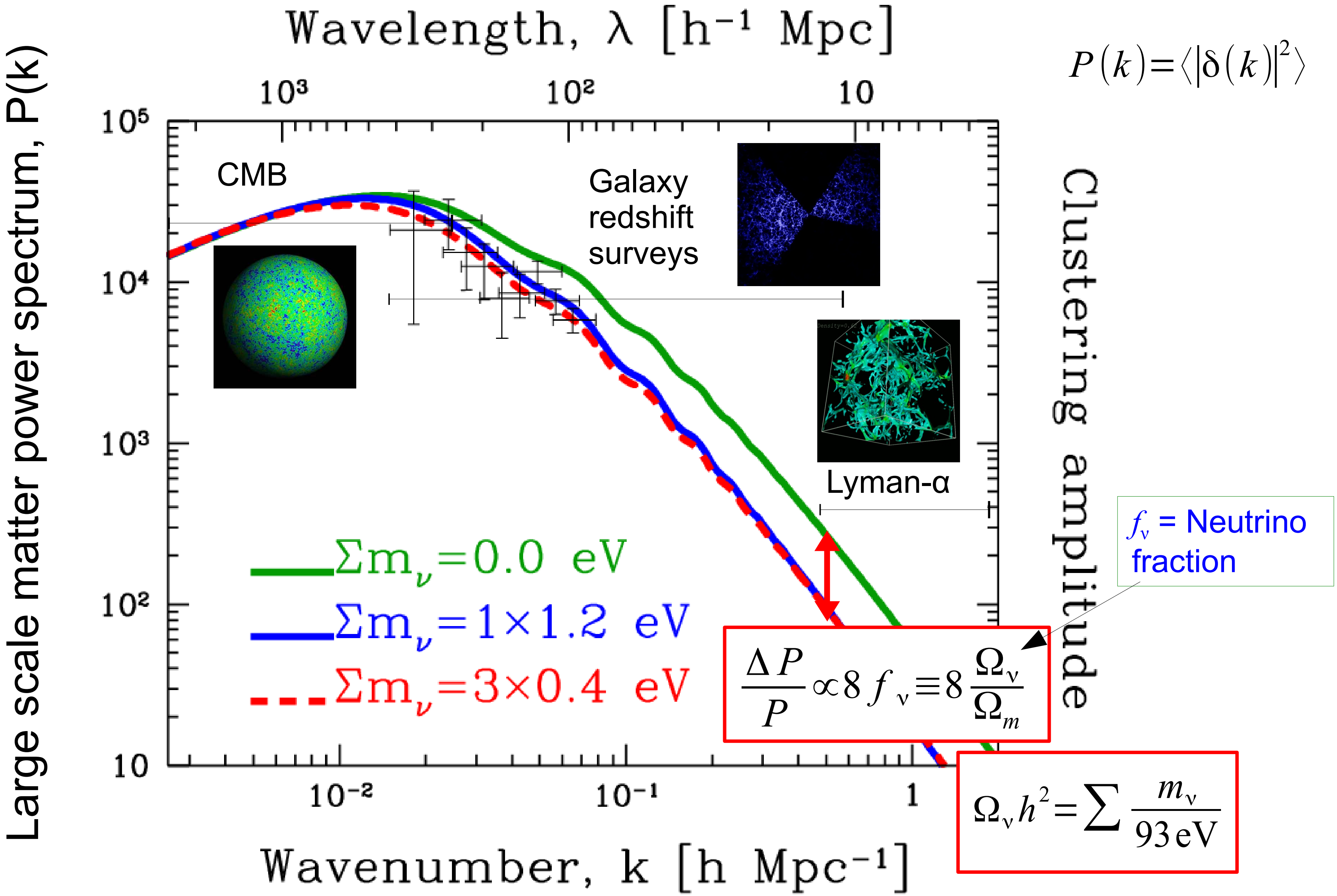
→ **Free-streaming** (non-clustering) neutrinos slows down the **growth** of density perturbations on scales $\lambda << \lambda_{FS}$.



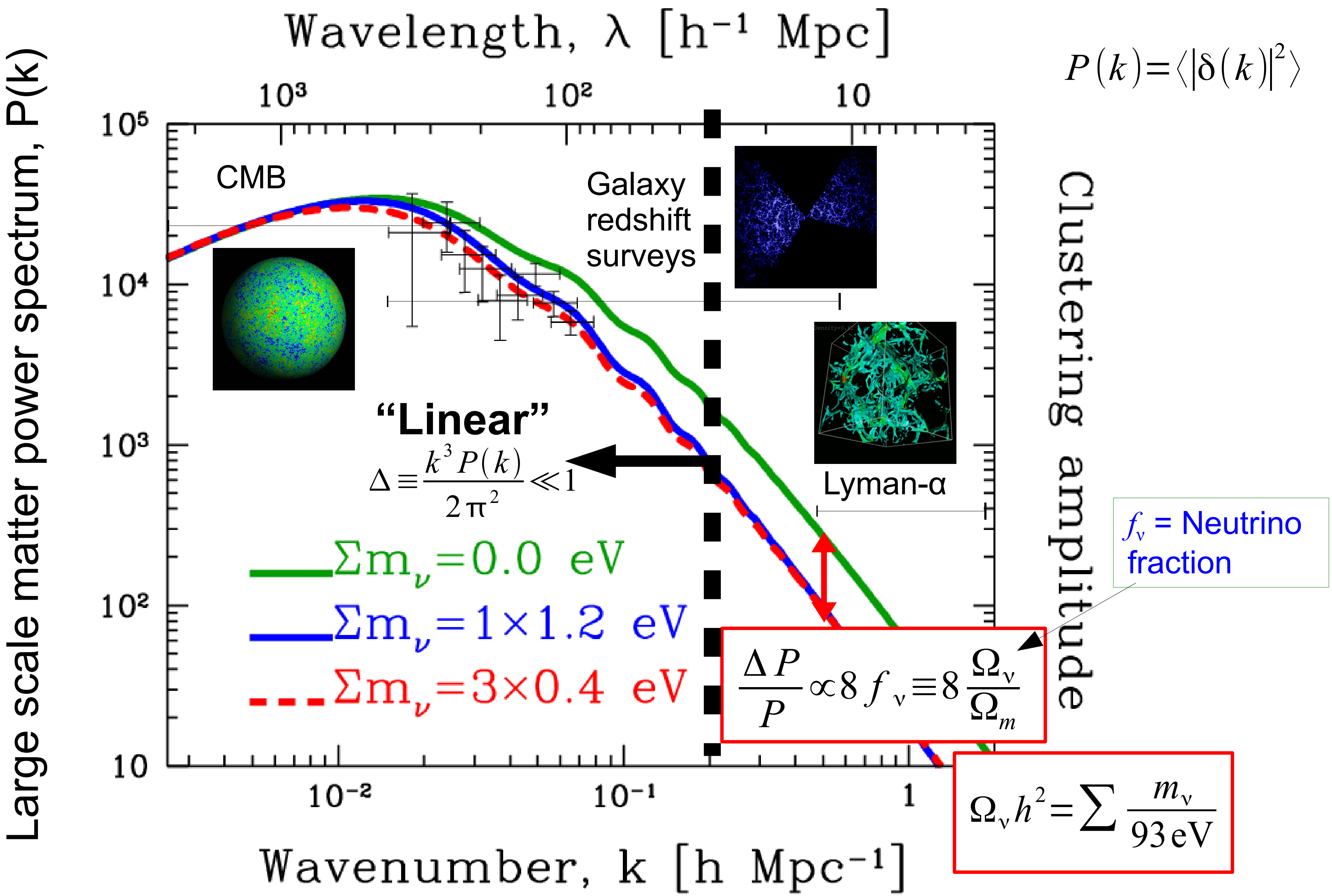
The presence of neutrino dark matter induces a step-like feature in the **spectrum** of density perturbations.



Wavelength, λ [h⁻¹ Mpc]
10³
10²
10
$P(k) = \langle |\delta(k)|^2 \rangle$
Large scale matter power spectrum, P(k)
Clustering amplitude
CMB
Galaxy redshift surveys
Lyman-α
Replace some CDM with neutrinos
$\Sigma m_\nu = 0.0$ eV
$\Sigma m_\nu = 1 \times 1.2$ eV
f_ν = Neutrino fraction
$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$
$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$
10⁵
10⁴
10³
10²
10
10⁻²
10⁻¹
1
Wavenumber, k [h Mpc⁻¹]



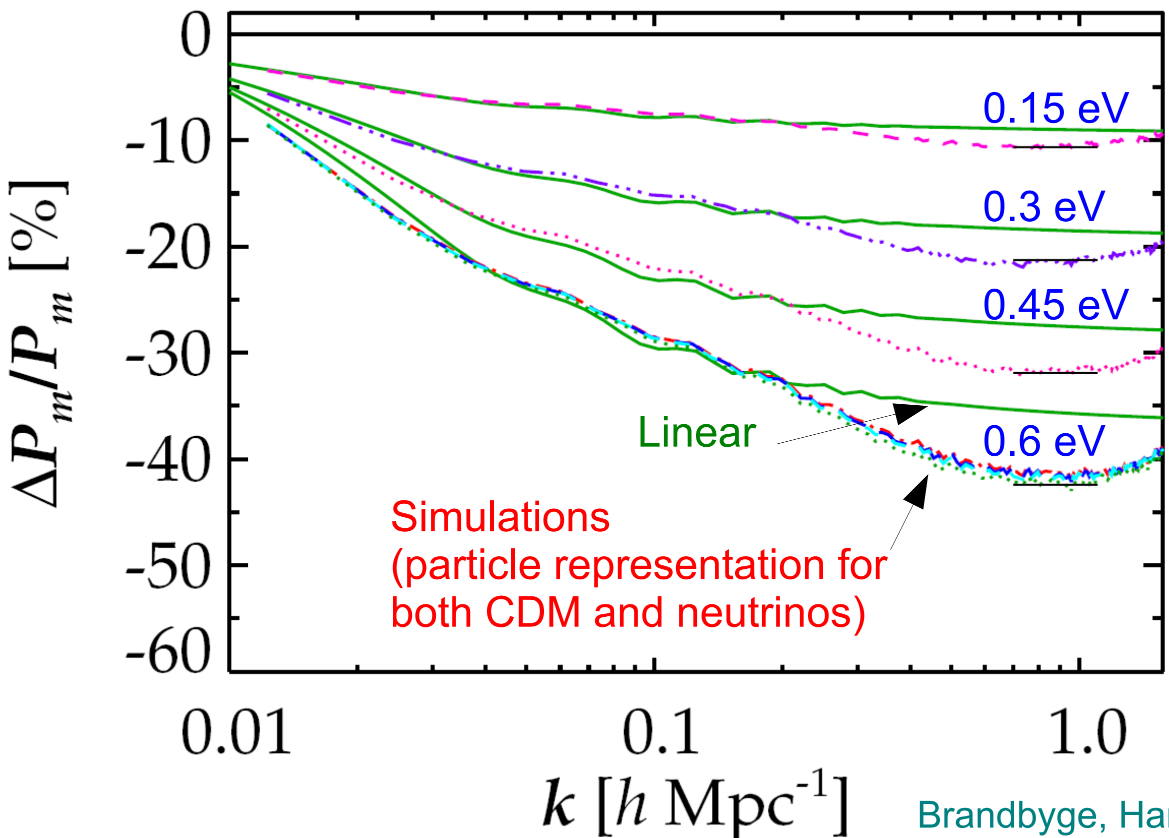
Wavelength, λ [h^{-1} Mpc]
10^3
10^2
10
$P(k) = \langle |\delta(k)|^2 \rangle$
Large scale matter power spectrum, P(k)
10^5
10^4
10^3
10^2
10
CMB
Galaxy redshift surveys
Lyman-α
Clustering amplitude
f_ν = Neutrino fraction
$\Sigma m_\nu = 0.0$ eV
$\Sigma m_\nu = 1 \times 1.2$ eV
$\Sigma m_\nu = 3 \times 0.4$ eV
$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$
$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$
10^{-2}
10^{-1}
1
Wavenumber, k [h Mpc^{-1}]



Wavelength, λ [h⁻¹ Mpc]
$P(k) = \langle |\delta(k)|^2 \rangle$
10³
10²
10
Large scale matter power spectrum, P(k)
10⁵
10⁴
10³
10²
10
CMB
Galaxy redshift surveys
Lyman-α
Clustering amplitude
"Linear"
$\Delta \equiv \frac{k^3 P(k)}{2\pi^2} \ll 1$
$\Sigma m_\nu = 0.0$ eV
$\Sigma m_\nu = 1 \times 1.2$ eV
$\Sigma m_\nu = 3 \times 0.4$ eV
f_ν = Neutrino fraction
$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$
$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\text{eV}}$
10⁻²
10⁻¹
1
Wavenumber, k [h Mpc⁻¹]

Change in the total matter power spectrum relative to the massless case:

$$\frac{\Delta P_m}{P_m} \equiv \frac{P_{f_\nu \neq 0}(k) - P_{f_\nu = 0}(k)}{P_{f_\nu = 0}(k)}$$



Linear perturbation theory:

$$\frac{\Delta P_m}{P_m} \sim 8 \frac{\Omega_\nu}{\Omega_m}$$

With nonlinear corrections:

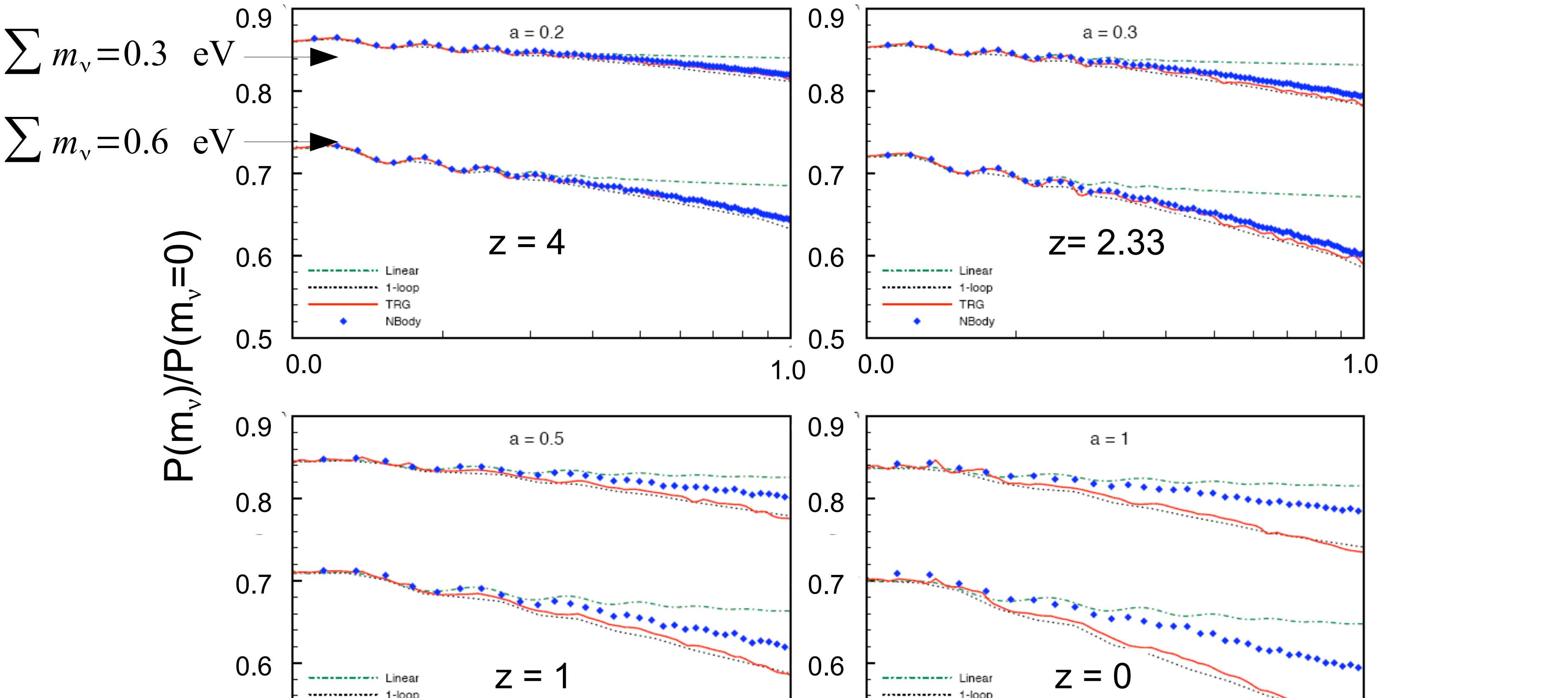
$$\frac{\Delta P_m}{P_m} \sim 9.8 \frac{\Omega_\nu}{\Omega_m}$$

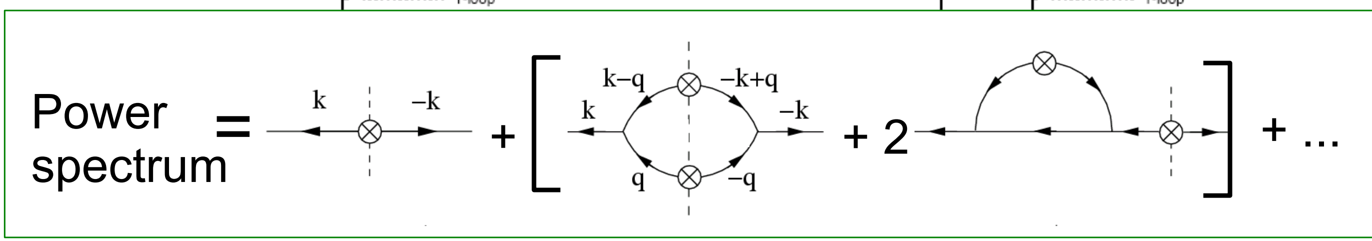
Brandbyge, Hannestad, Haugbolle & Thomsen 2008;
Viel, Haehnelt & Springel 2010; Bird, Viel & Haehnelt 2012

Approximation scheme (linear neutrino evolution) $\Big\{$ Brandbyge & Hannestad 2009, 2010; Ali-Haimoud & Bird 2012

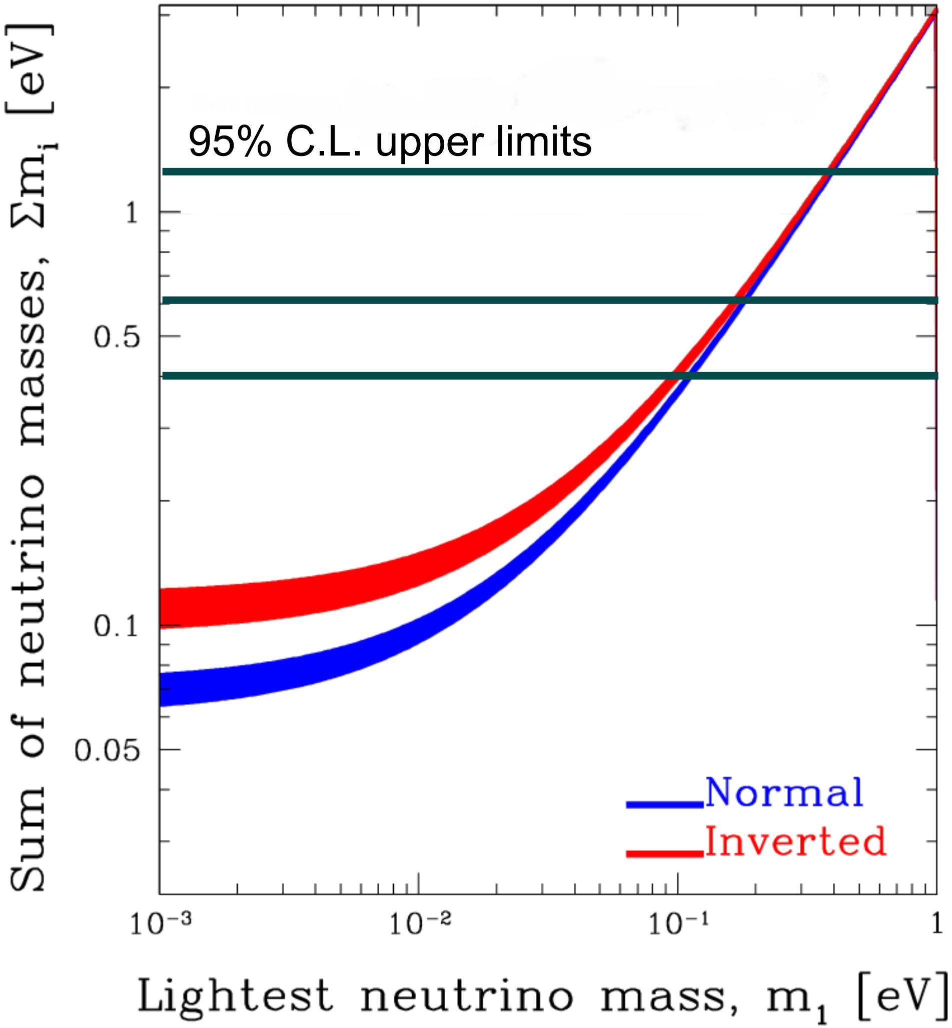
Semi-analytical: Loops and beyond...

Saito et al. 2008; Y³W 2008; Shoji & Komatsu 2009
Lesgourgues, Matarrese, Pietroni & Riotto 2009





Present constraints...



Hannestad, Mirizzi, Raffelt & Y^3W 2010

ΛCDM+neutrino mass (7 parameters)

CMB only (WMAP7+ACBAR+BICEP+QuaD)

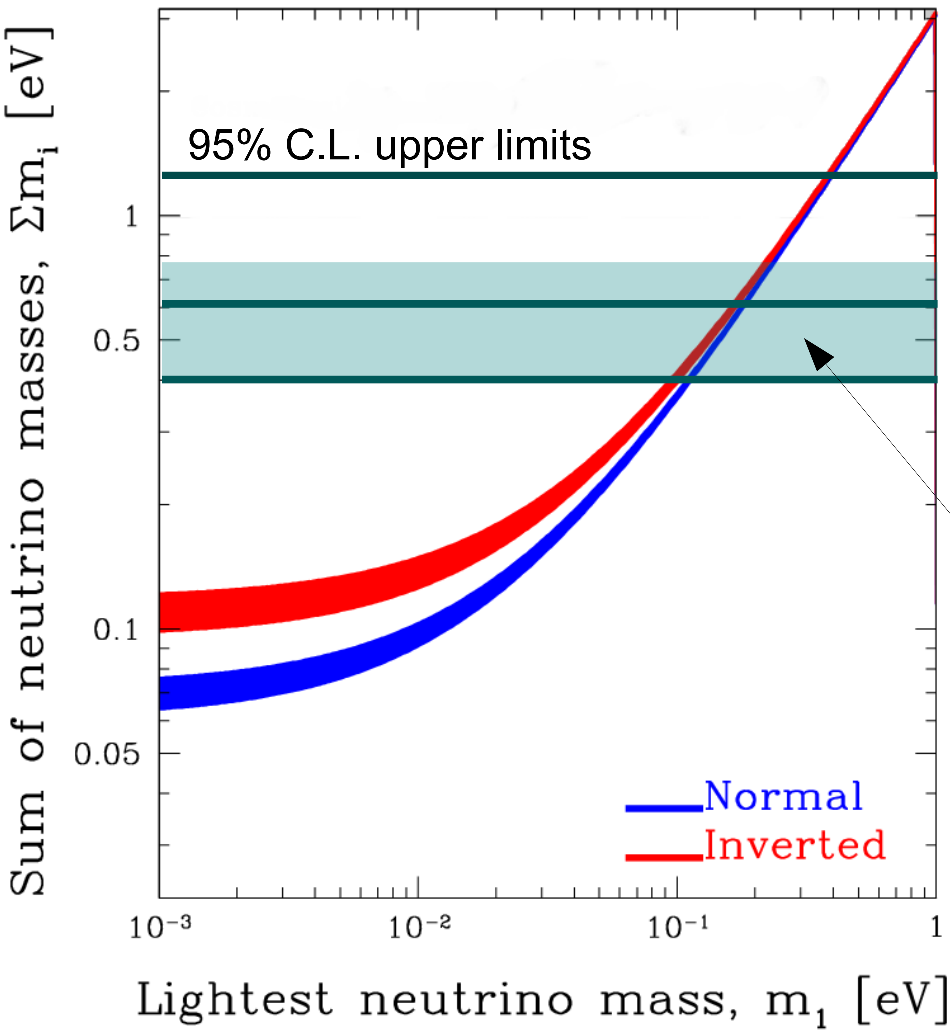
+ **LSS power spectrum** (SDSS7 LRG)

+ LSS + **HST determination of H_0**

WMAP9 numbers are very similar

Hinshaw et al. [WMAP9] 2012

Present constraints...



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ΛCDM+neutrino mass (7 parameters)

CMB only (WMAP7+ACBAR+BICEP+QuaD)

+ **LSS power spectrum** (SDSS7 LRG)

+ LSS + **HST determination of H_0**

More complex parameter space

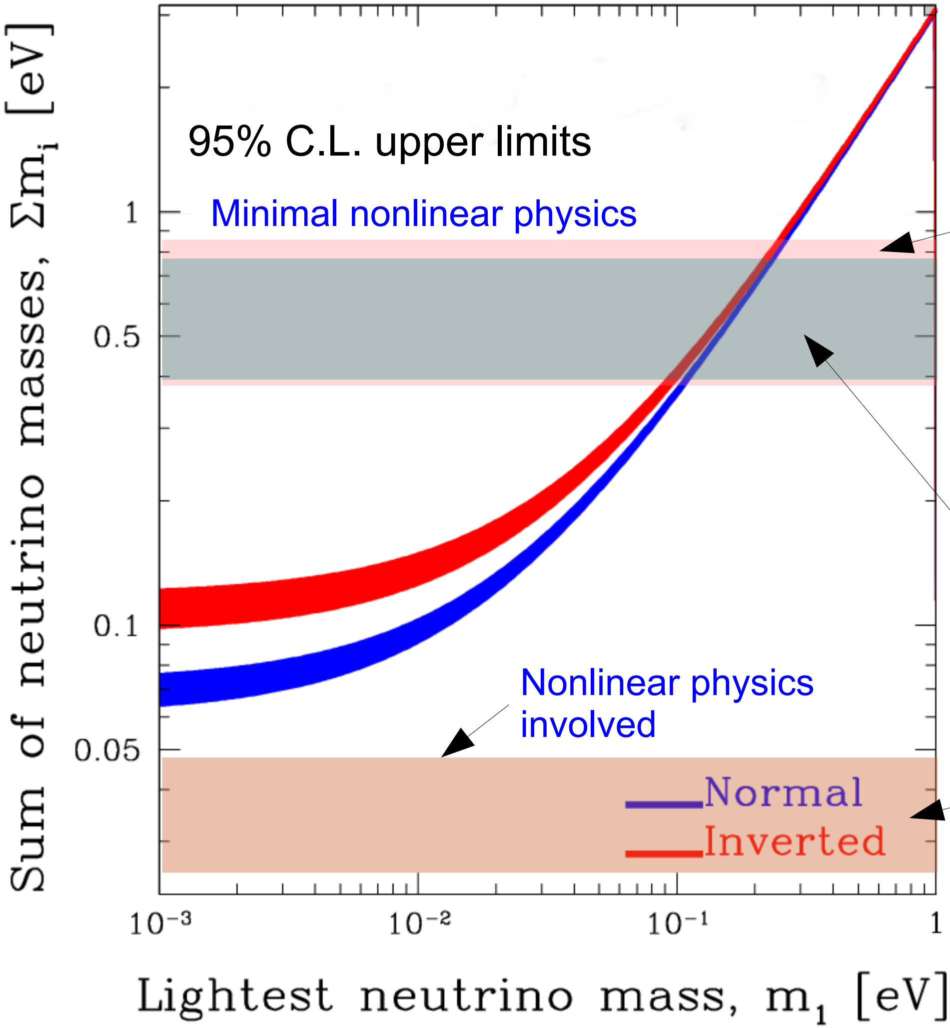
$$\sum m_\nu < 0.36 \rightarrow 0.76\,\mathrm{eV} \quad (95\%\,\mathrm{C.L.})$$

CMB+LSS+H_0+**SNIa**

Gonzalez-Garcia et al. 2010

Includes uncertainties in
- Number of neutrino species
- Dark energy equation of state
- Inflation physics (tensors, running)
- Spatial curvature

Future sensitivities...



Planck alone (1 year) 2013

$$\sum m_\nu < 0.34 \rightarrow 0.84\,\text{eV} \quad (95\%\,\text{C.L.})$$

Perotto et al. 2006

Present constraints

$$\sum m_\nu < 0.36 \rightarrow 0.76\,\text{eV} \quad (95\%\,\text{C.L.})$$

2020+

Planck+**Euclid photo-z galaxy survey**

$$\sum m_\nu < 0.022 \rightarrow 0.044 \quad (95\%\,\text{C.L.})$$

2-5σ detection possible!
(depending on treatment of galaxy bias)

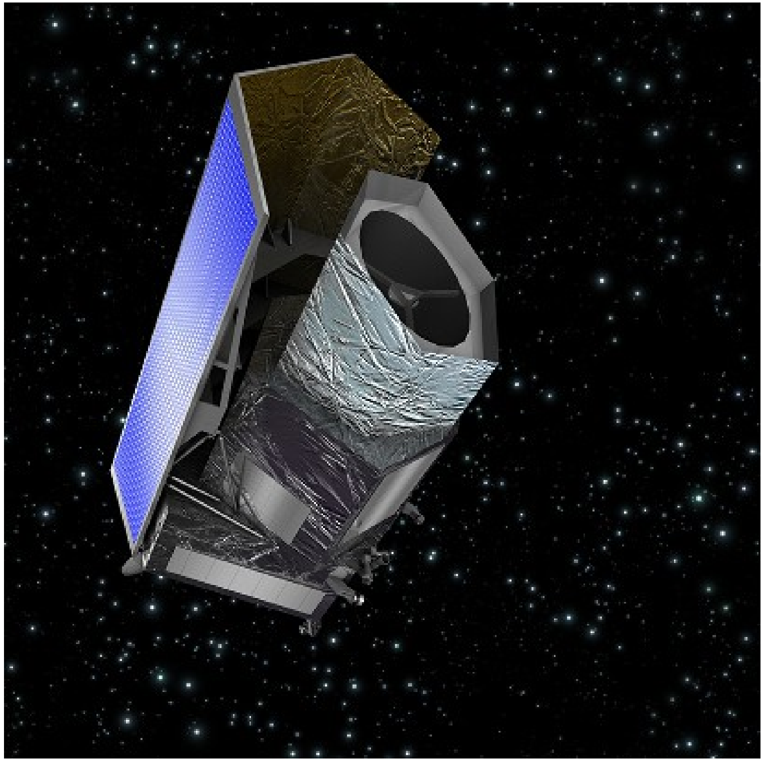
Hamann, Hannestad & Y[3]W 2012

2. Euclid sensitivity forecast...

ESA Euclid mission selected for implementation...

Launch planned for 2019.

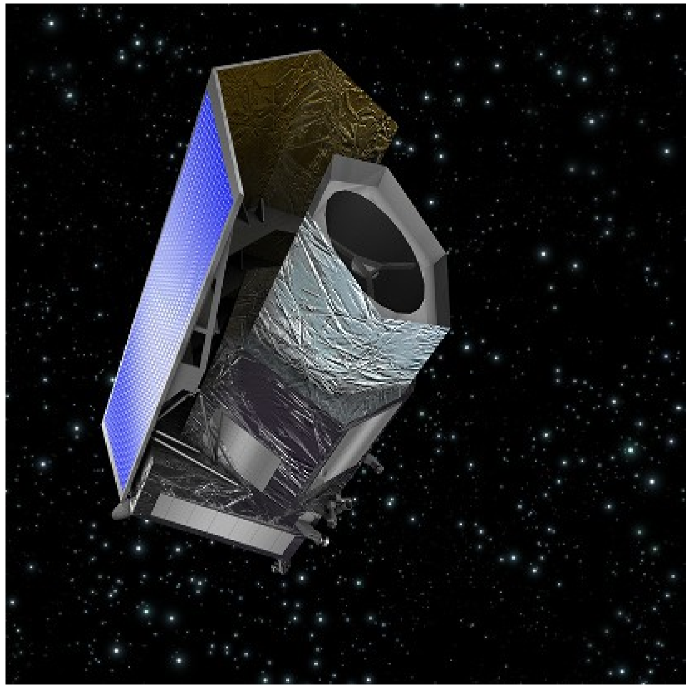
- 6-year lifetime
- 15000 deg^2 (>1/3 of the sky)
- Galaxies and clusters out to z~2
  - Photo-z for 1 billion galaxies
  - Spectro-z for 50 million galaxies
- Optimised for weak gravitational lensing (cosmic shear)



ESA Euclid mission selected for implementation...

Galaxy clusters
(cluster mass function)

Type Ia supernovae



Baryon acoustic oscillations (BAO)

Galaxy distribution
(<u>photo-z</u> and spectro-z)

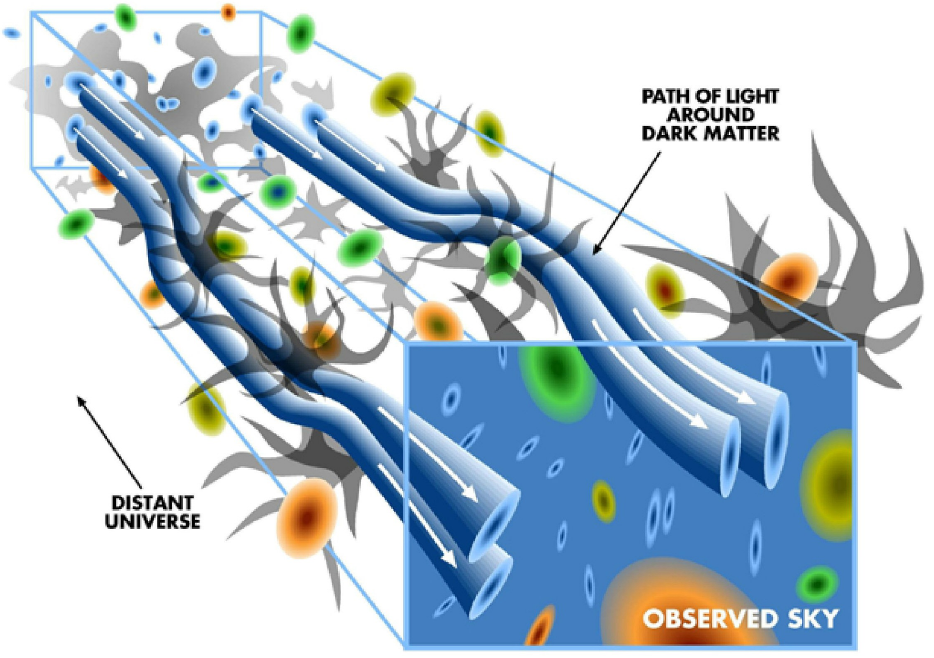
<u>Cosmic shear</u>
(weak gravitational lensing of galaxies)

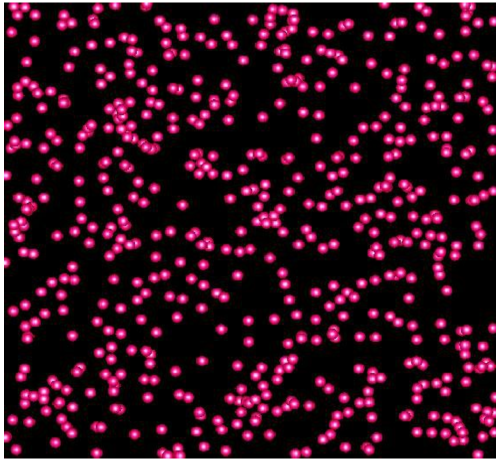
But everything I am about to say applies also to similar surveys such as LSST.

Weak lensing of galaxies/Cosmic shear...

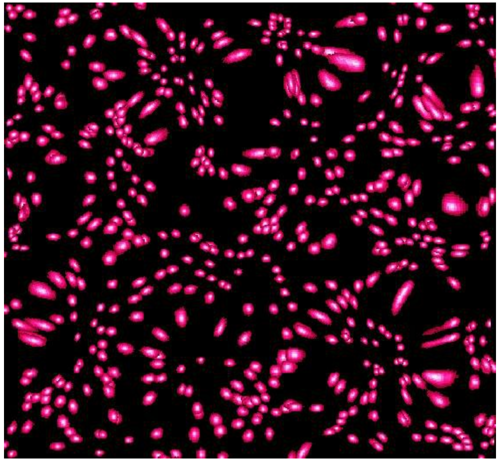
Distortion (magnification or stretching) of distant galaxy images by **foreground matter**.

- Sensitive to both luminous and dark matter (no bias problem).

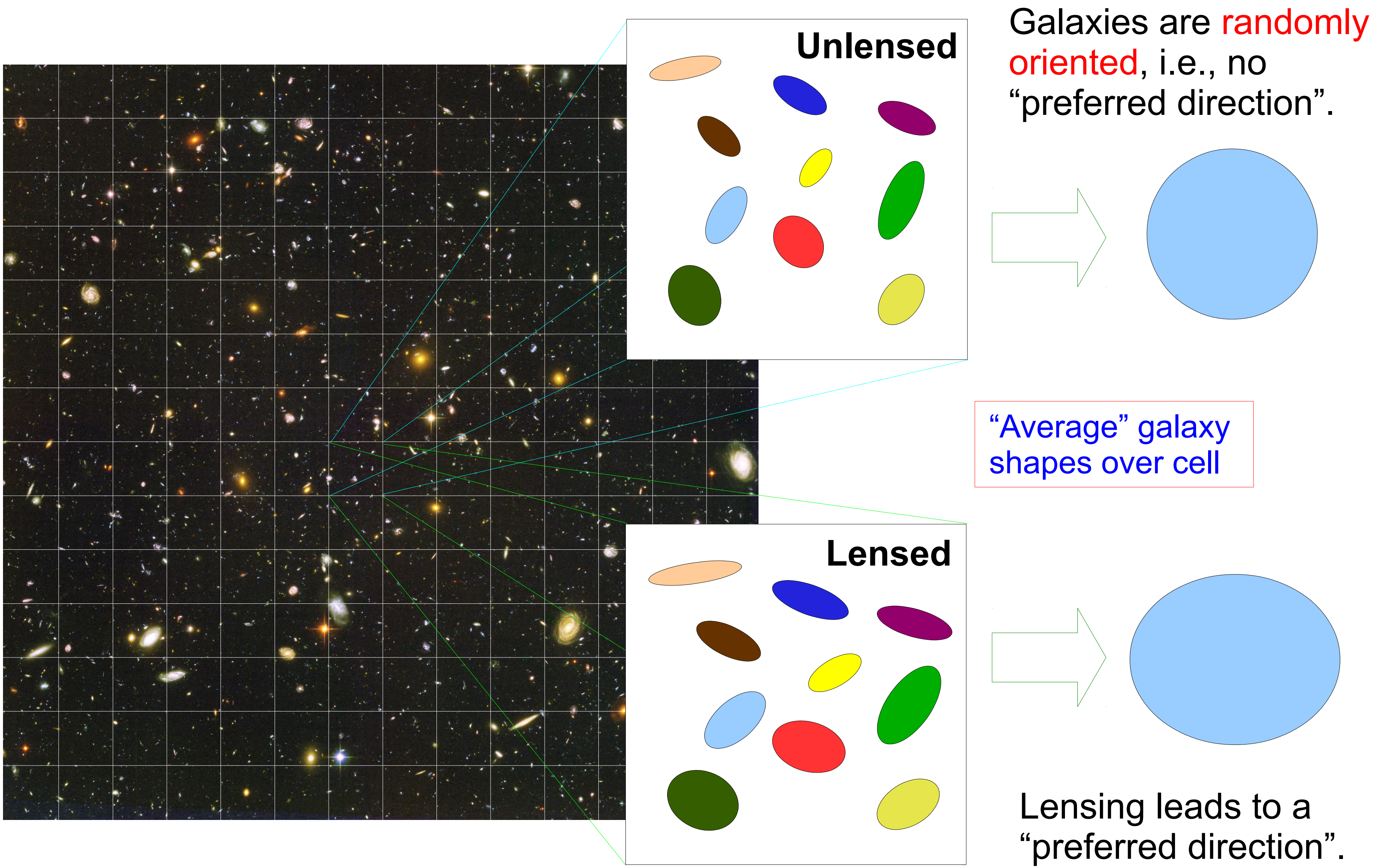




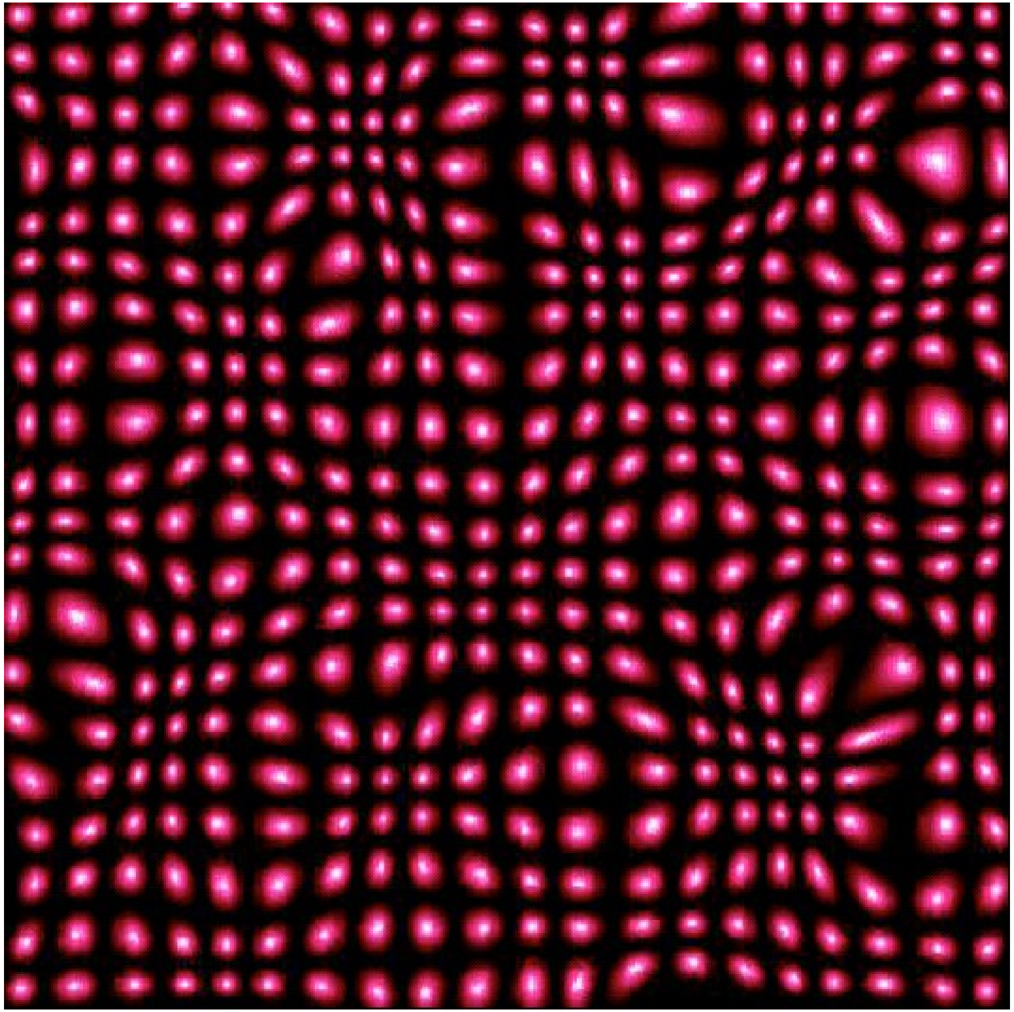
Unlensed



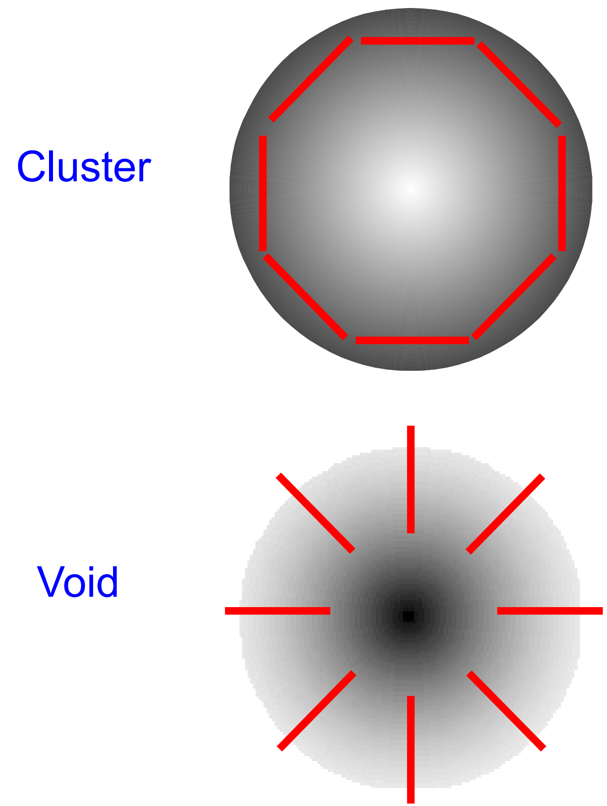
Lensed


Unlensed
Galaxies are randomly oriented, i.e., no "preferred direction".
"Average" galaxy shapes over cell
Lensed
Lensing leads to a "preferred direction".

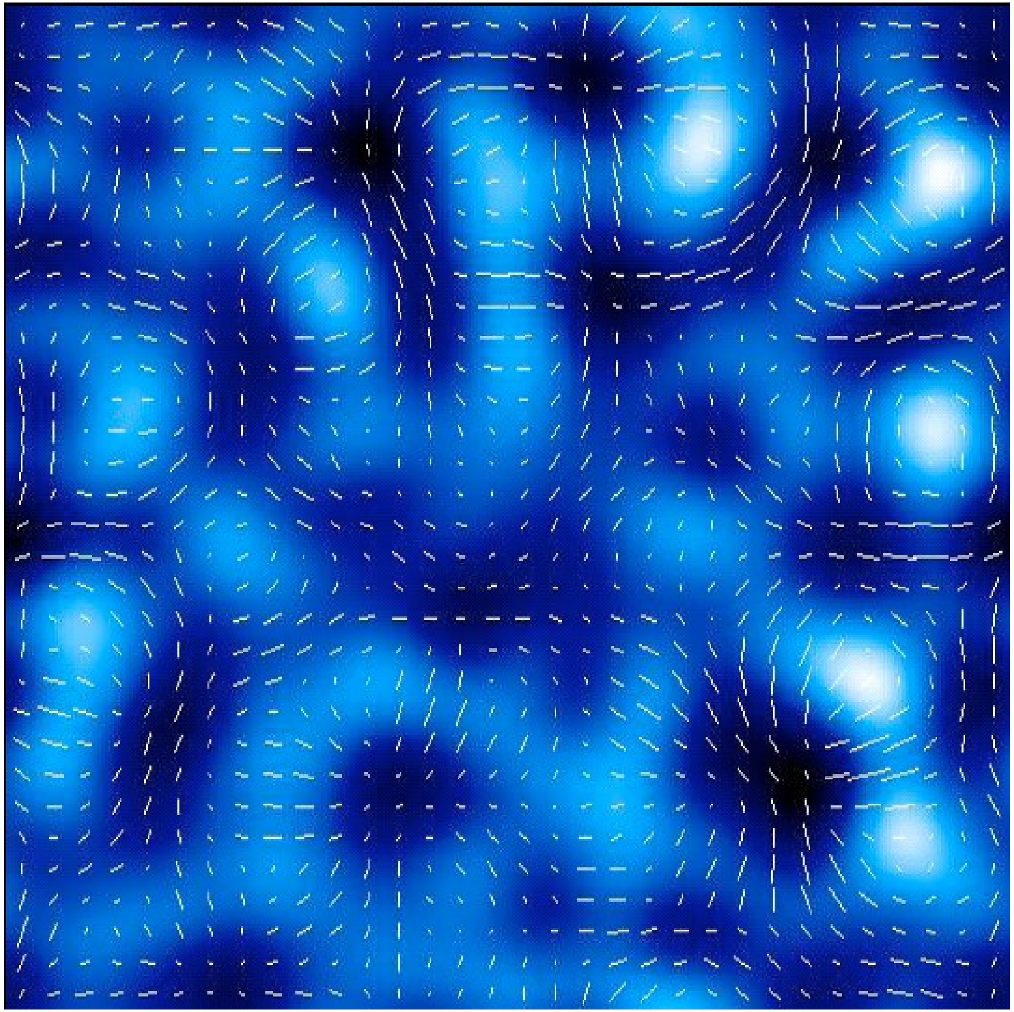
Shear map



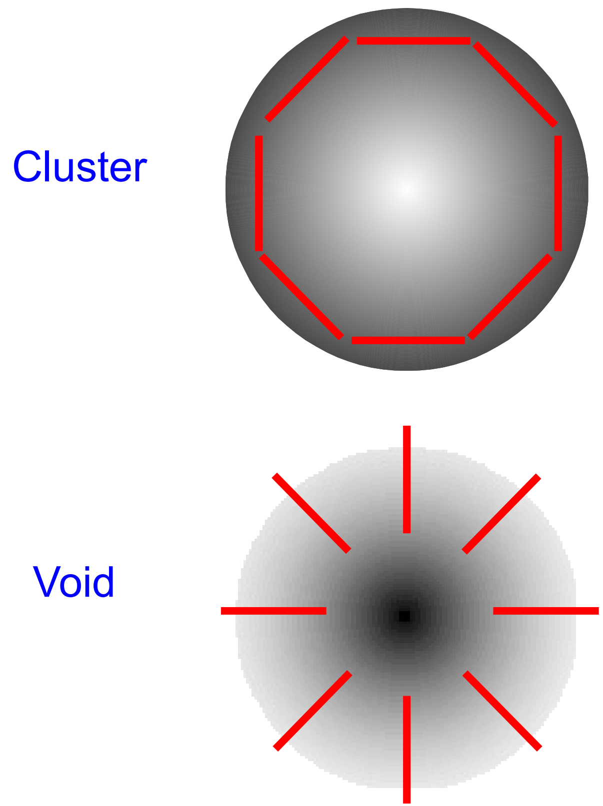
Weak lensing theory predicts:



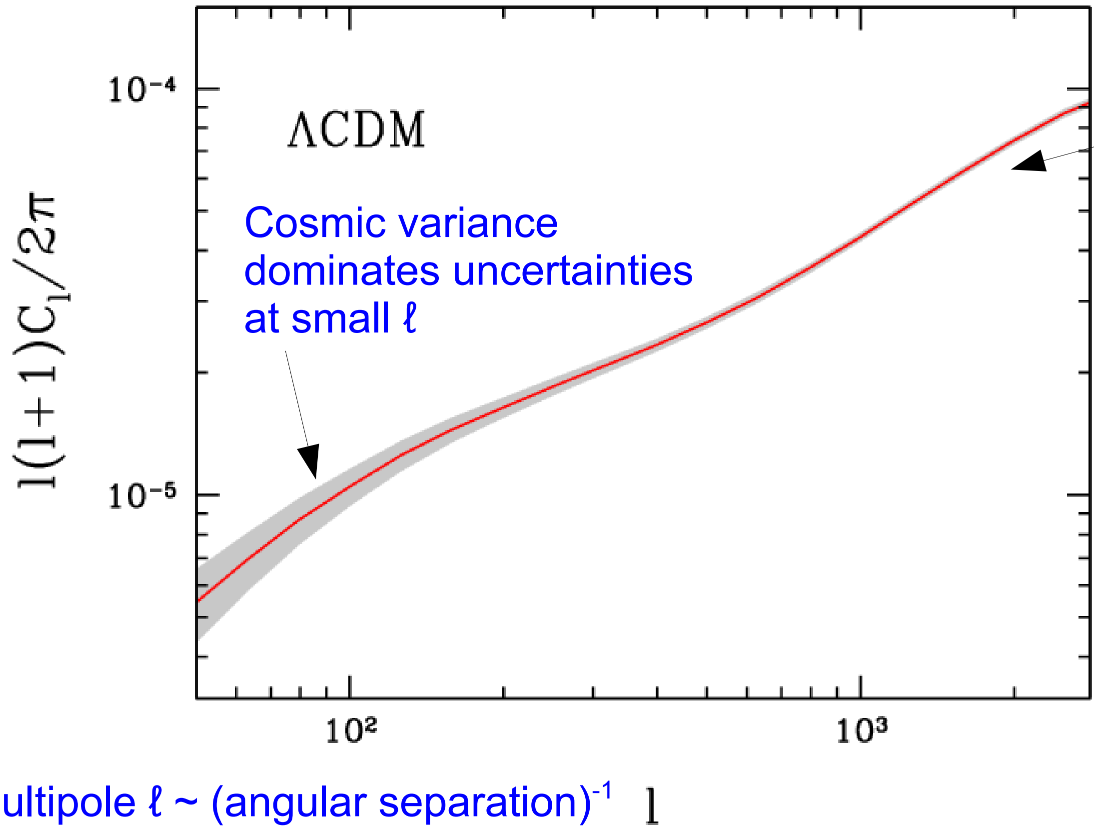
Shear map → Convergence map (projected mass)



Weak lensing theory predicts:



Convergence (or shear) power spectrum:



Shot noise
dominates at large ℓ

$$\Delta C_\ell = \frac{\langle \gamma^2 \rangle}{n^2}$$

γ = Intrinsic ellipticity
n = source galaxy
surface density

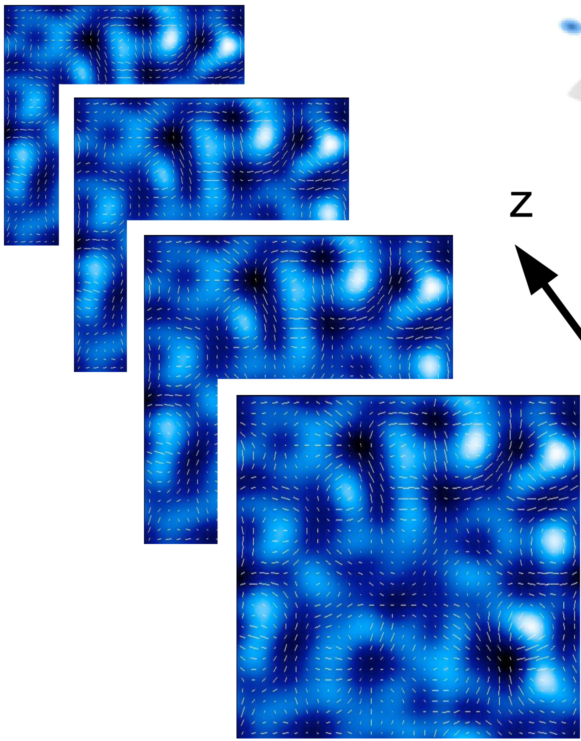
multipole ℓ ~ (angular separation)$^{-1}$

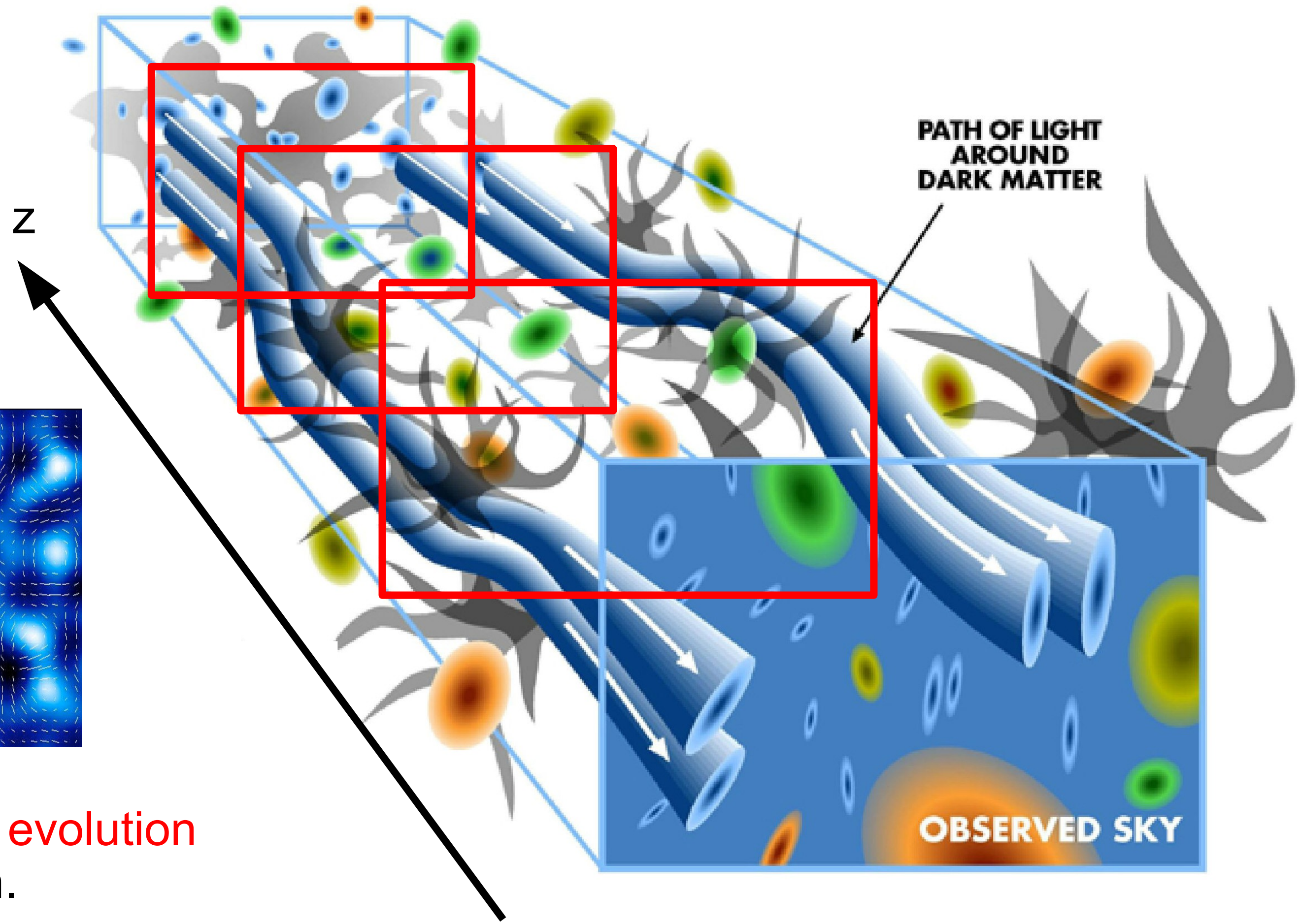
$$C_l \propto \int_0^\infty d\chi\, a^{-2} \left[\int_\chi^\infty d\chi'\, n_{\mathrm{gal}}(\chi') \frac{D(\chi'-\chi)}{D(\chi')} \right]^2 P_{\mathrm{matter}}(k = l/D(\chi))$$

(Limber limit)

Tomography = bin galaxy images by redshift

- Photometric redshifts for ~ 1 billion galaxies in Euclid survey.

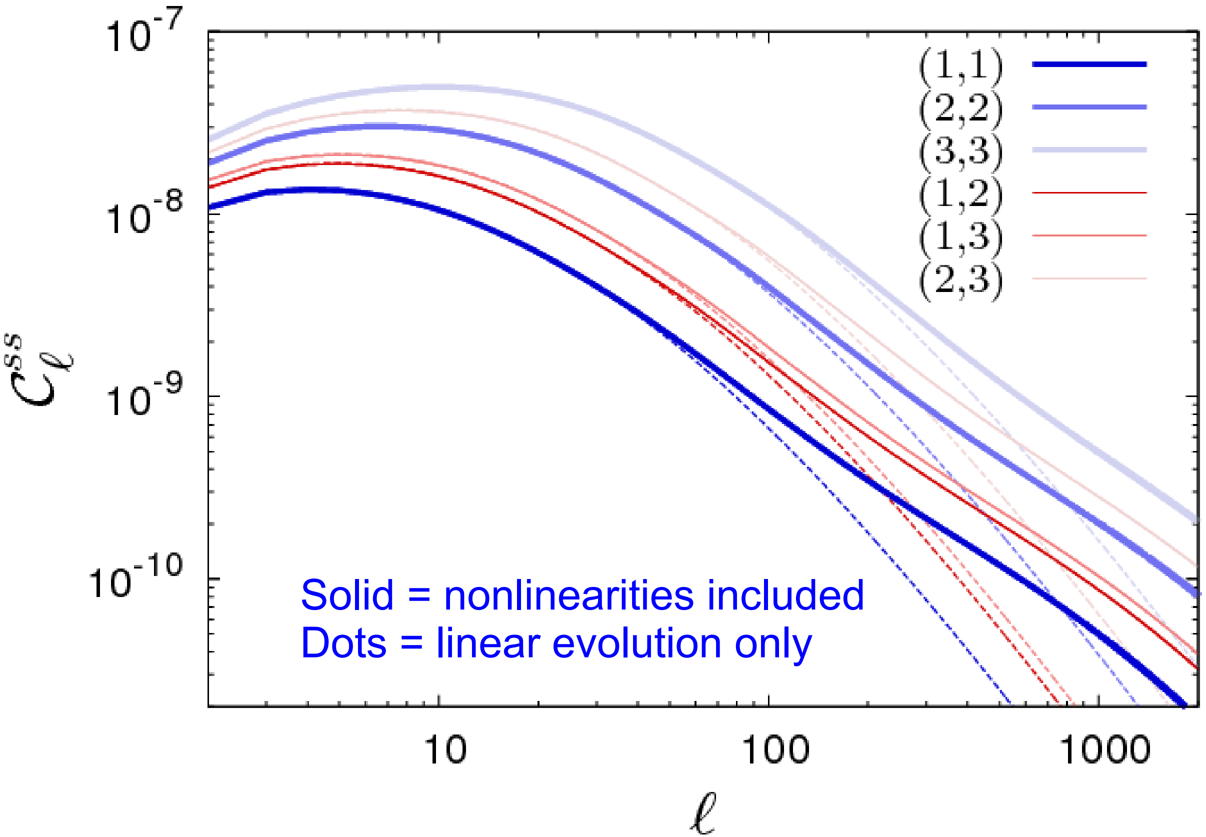




Tomography probes the evolution
of the matter distribution.

Shear power auto & cross-spectra for 3 redshift bins:

- High redshift images are lensed more.
- Large cross-correlation signal.



Signal dominated measurement expected up to $\ell \sim 2000$.

- Nonlinear corrections are important for the cosmic shear signal.

Our cosmic shear forecast...

We assume **nonlinear corrections** will be known to <1% accuracy up to $\ell = 2000$.

- Mock nonlinear corrections from HaloFit. Smith et al. 2003

HaloFit = A fitting function calibrated against a set of N-body simulations

Realistic assumption?

- Collisionless simulations are relatively easy to do.
- But beware of dissipative baryon physics at $\ell > 1000$ (believed to be a 1% effect, but who knows).

Tomography: 2 redshift bins (no gain with more bins).

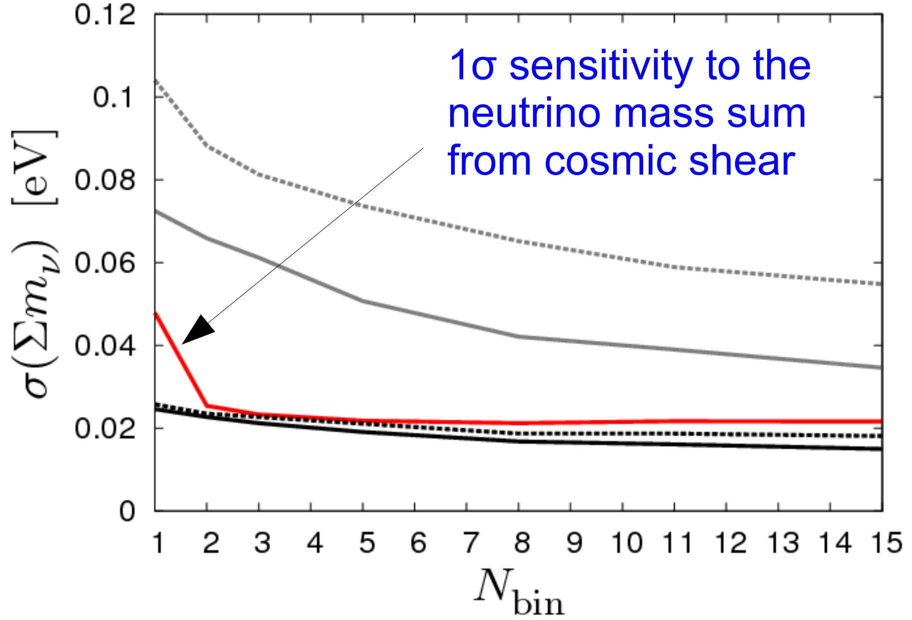


Photo-z galaxy survey...

The **same galaxy images** used to determine the shear power spectra can be analysed for their own clustering properties.

- **Photometric-z uncertainty**: $dz = 0.03\,(1+z)$ → Loss of small-scale information in the line-of-sight direction.

We account for this loss by considering 2D power angular spectra integrated over in a broad (> dz) redshift range:

W = window function
of the redshift bin

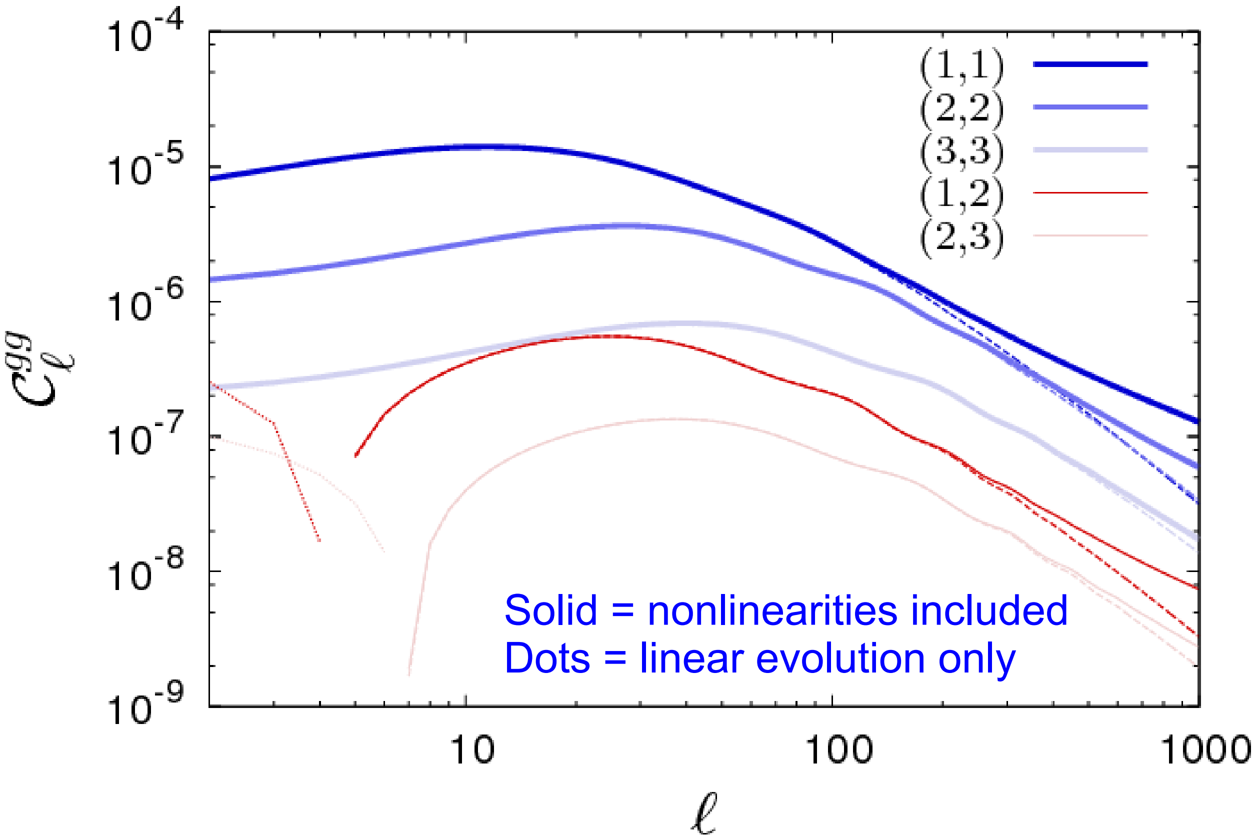
$$C_l \propto \int_0^\infty d\chi \frac{W^2(\chi)}{\chi^2} P_{\text{matter}}(k = l/\chi) \qquad \text{(Limber limit)}$$

- **For neutrino masses**, going 3D with spectro-z does not improve the sensitivity.
- But useful for dark energy/modified gravity/BAO.

Audren et al. 2012

Galaxy power auto & cross-spectra for 3 redshift bins:

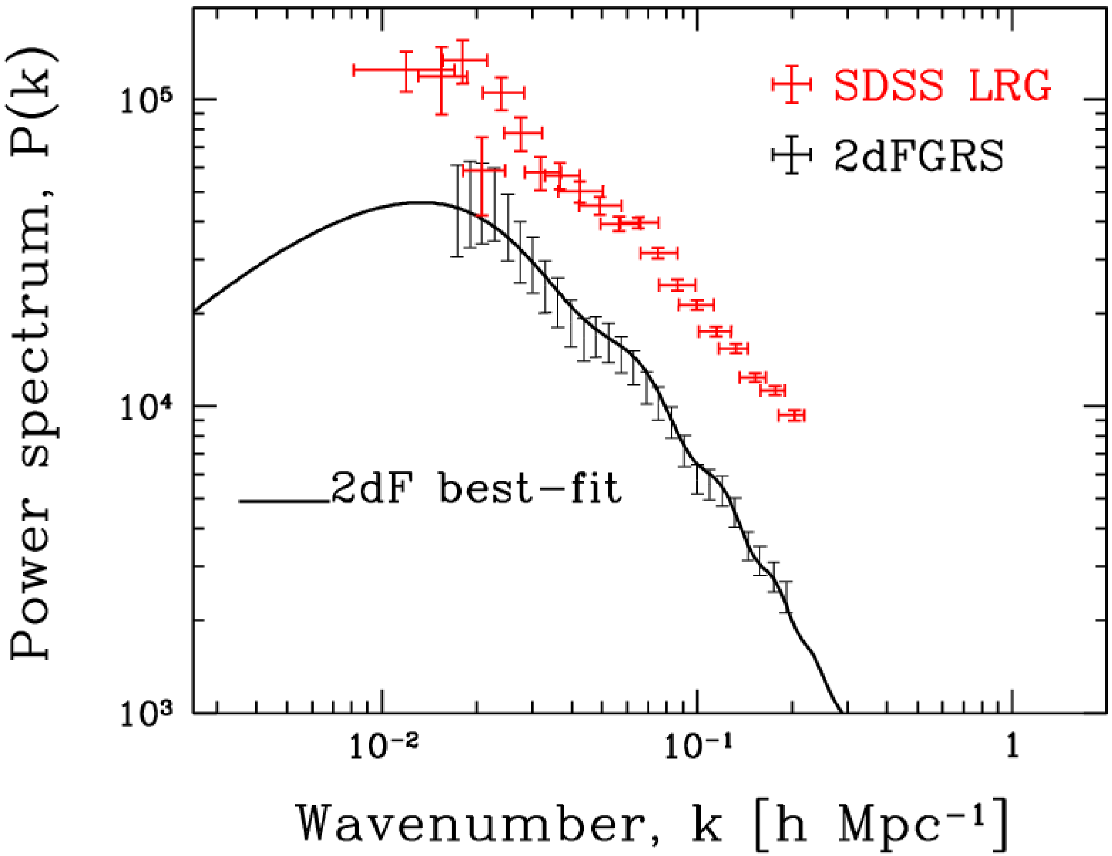
- Appreciable cross-correlation signal between adjacent bins because of photometric redshift uncertainties.
- Otherwise, no intrinsic correlation

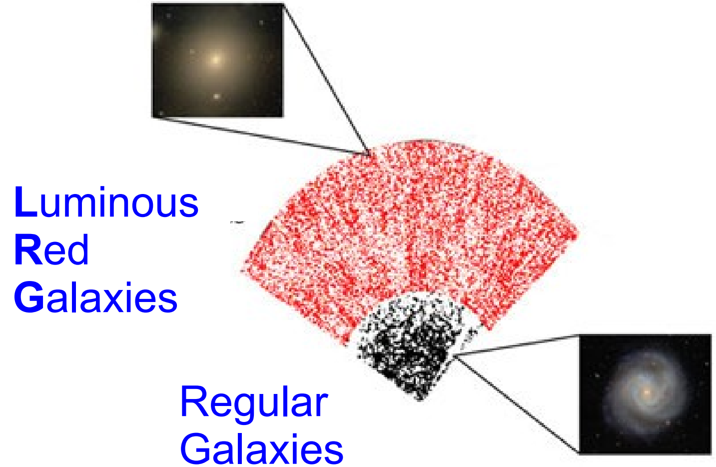


Nonlinear corrections

- Only nonlinearities in the matter density fluctuations has been accounted for in this figure.
- Other (not shown) sources include scale-dependent galaxy bias.

Linear galaxy bias:





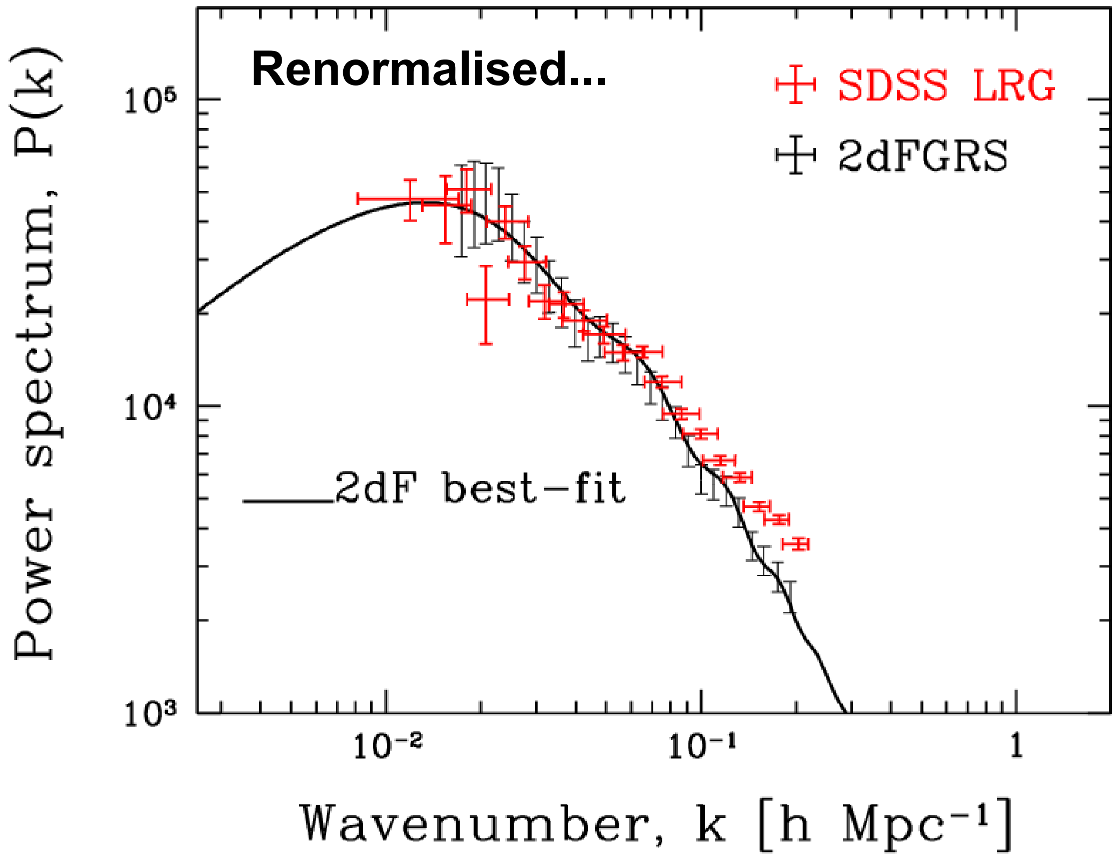
On large scales, we expect the clustering of galaxies to trace the underlying matter density field up to a constant factor:

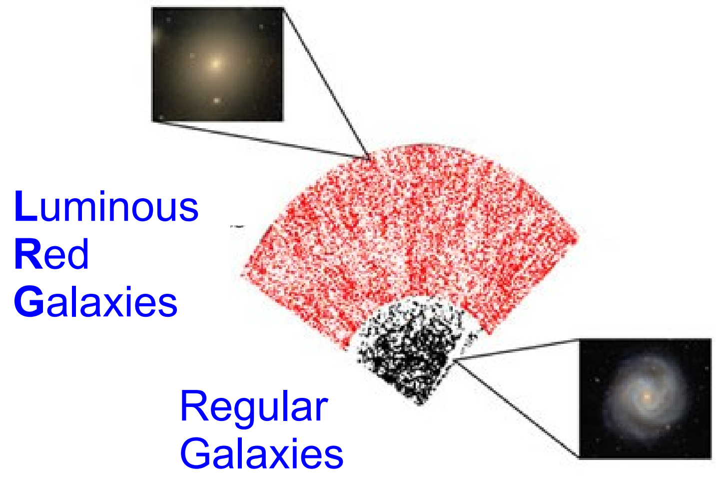
$$P_{\text{galaxy}}(k) = b^2 P_{\text{matter}}(k)$$

Depends on the tracer;
not predictable from first principles

* This is really old data, but illustrates the point anyway...

Scale-dependent galaxy bias:





In reality, the bias factor is k-dependent:

$$P_{\text{galaxy}}(k) = b^2(k)\, P_{\text{matter}}(k)$$

Also tracer-dependent;
even less predictable than
the linear bias factor...

* This is really old data, but illustrates the point anyway...

Our galaxy clustering forecast...

Modelling **galaxy bias** is the main problem here.

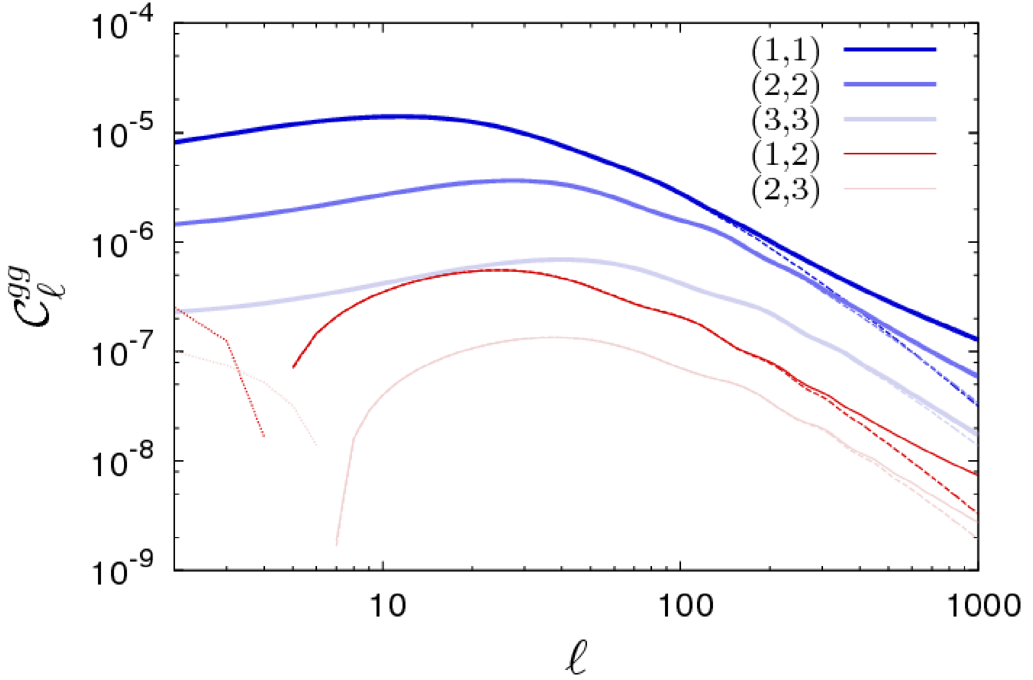
Scale-dependent bias:

- We discard mock data where departure from linearity exceeds cosmic variance:

$$\epsilon_{\rm nl}\left(1+\sqrt{\frac{2}{2\ell+1}}\right) \geq \left.\frac{\mathcal{P}_{\rm nl}(k,\bar{z}_i)}{\mathcal{P}_{\rm lin}(k,\bar{z}_i)}\right|_{k=\ell/\chi(\bar{z}_i)}$$

→ **Redshift-dependent ℓ_{max}**.

- Tolerance factor ε_{nl} = 1 by default (also considered ultra-conservative case ε_{nl} = 0.1).



Our galaxy clustering forecast...

Modelling **galaxy bias** is the main problem here.

Linear bias: two limiting cases

- Optimistic: Linear bias is exactly known.
- Pessimistic: No information at all.
  - N redshift bins $\rightarrow$ N linear bias parameters to marginalise.

The reality is somewhere in between.

Our galaxy clustering forecast...

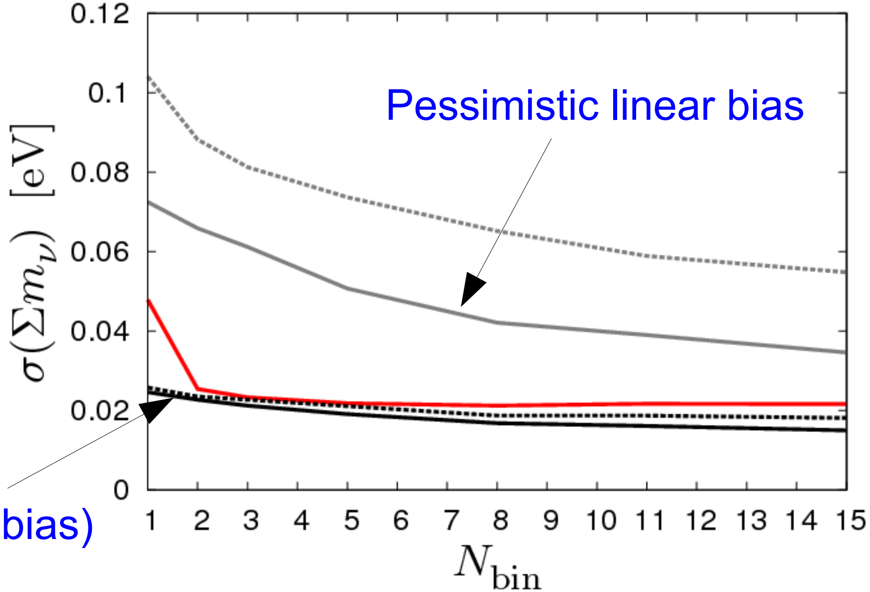
Modelling **galaxy bias** is the main problem here.

Linear bias: two limiting cases

- Optimistic: Linear bias is exactly known.
- Pessimistic: No information at all.
  - N redshift bins → N linear bias parameters to marginalise.

The reality is somewhere in between.

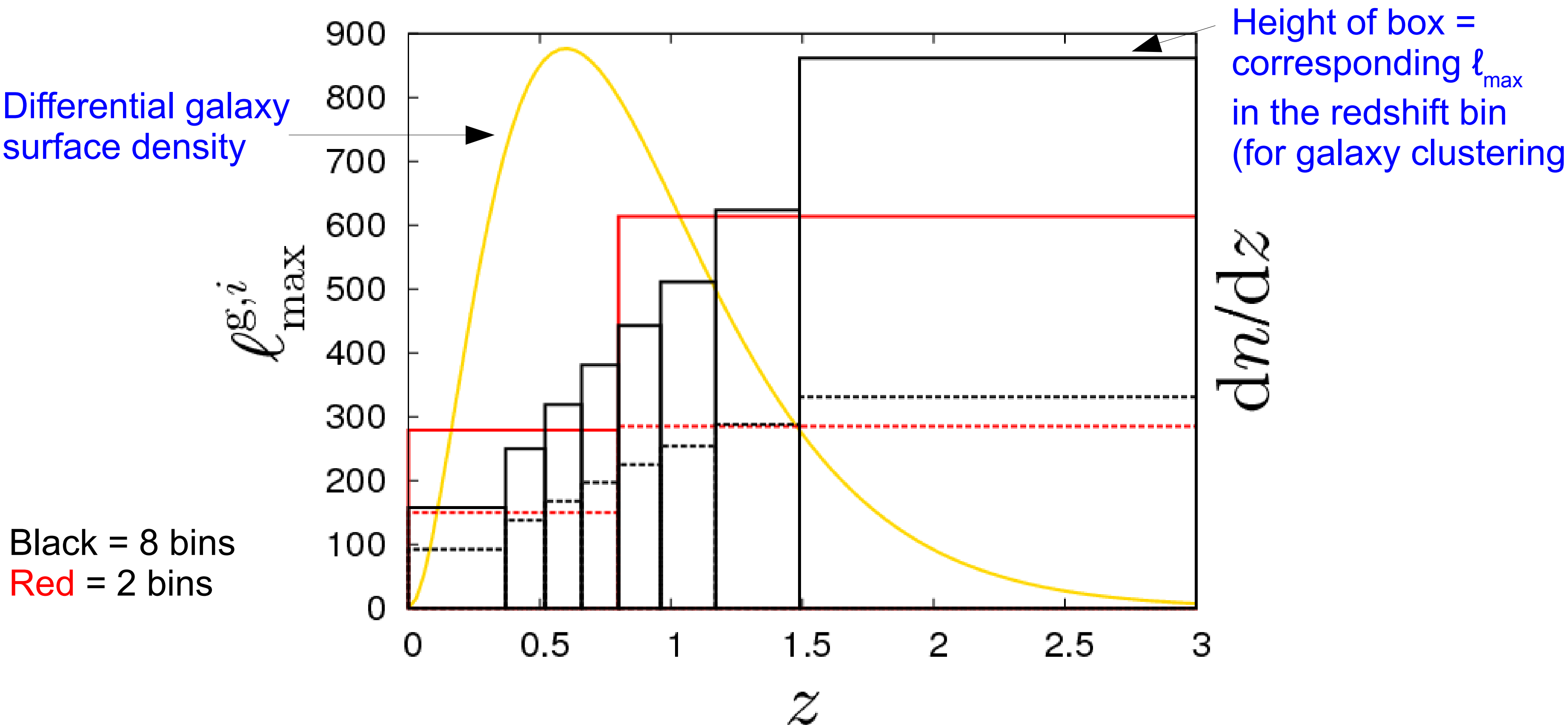
Tomography: 8 redshift bins (not much improvement with more bins).



1σ sensitivity to the neutrino mass sum from galaxy clustering (optimistic linear bias)

Redshift binning...

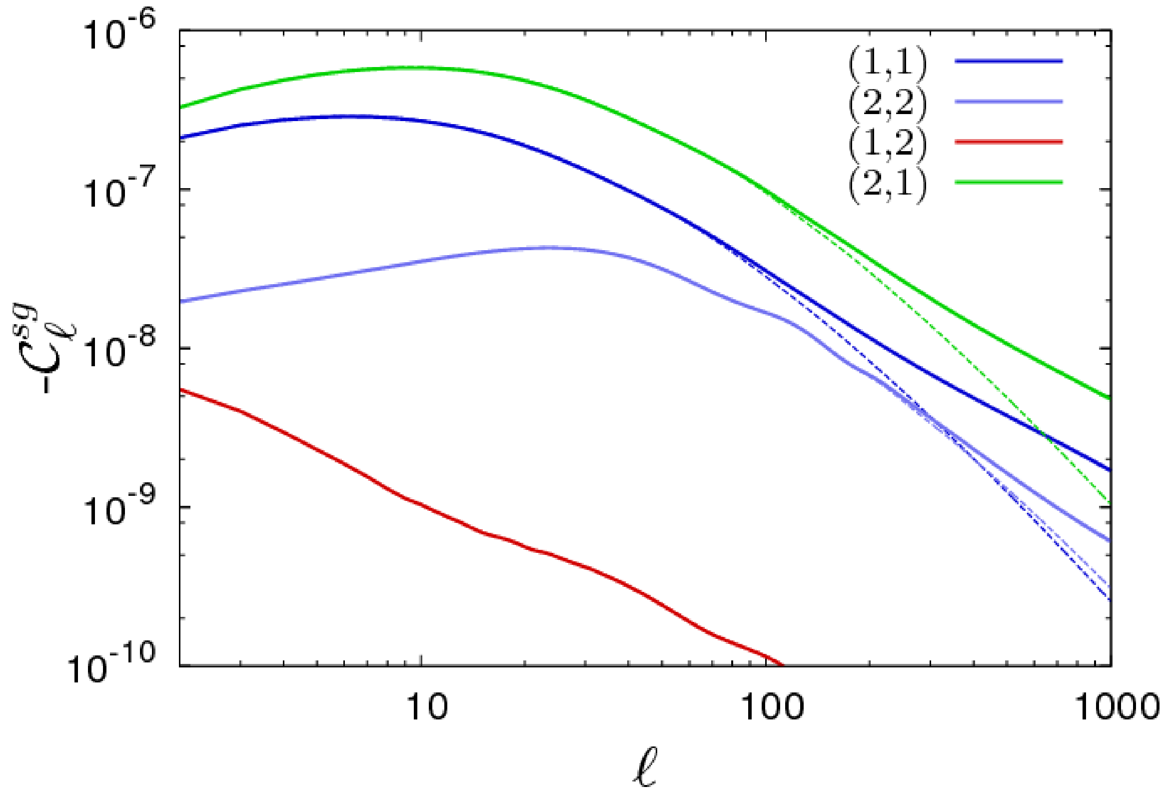
We choose our redshift bins by demanding the **surface density of galaxies** to be the same in all bins.



Shear-galaxy cross correlation...

We assume the shear and the galaxy samples cover the exact **same patch of the sky**.

- Significant shear-galaxy cross-correlation signal.
- Turns out to be not very useful for neutrino mass measurement.
- But can improve dark energy constraints somewhat (more later).



Shear vs galaxy clustering...

Besides the galaxy bias, there is one more subtle difference between the two probes:

- **Cosmic shear** = bending of light rays → sensitive to the **metric perturbations** Φ.
- **Galaxy clustering** (if bias is known) probes the **matter density perturbations** δ_m.

In **ΛCDM-type cosmologies** (in the subhorizon limit):

ω_m = physical matter density

Poisson equation

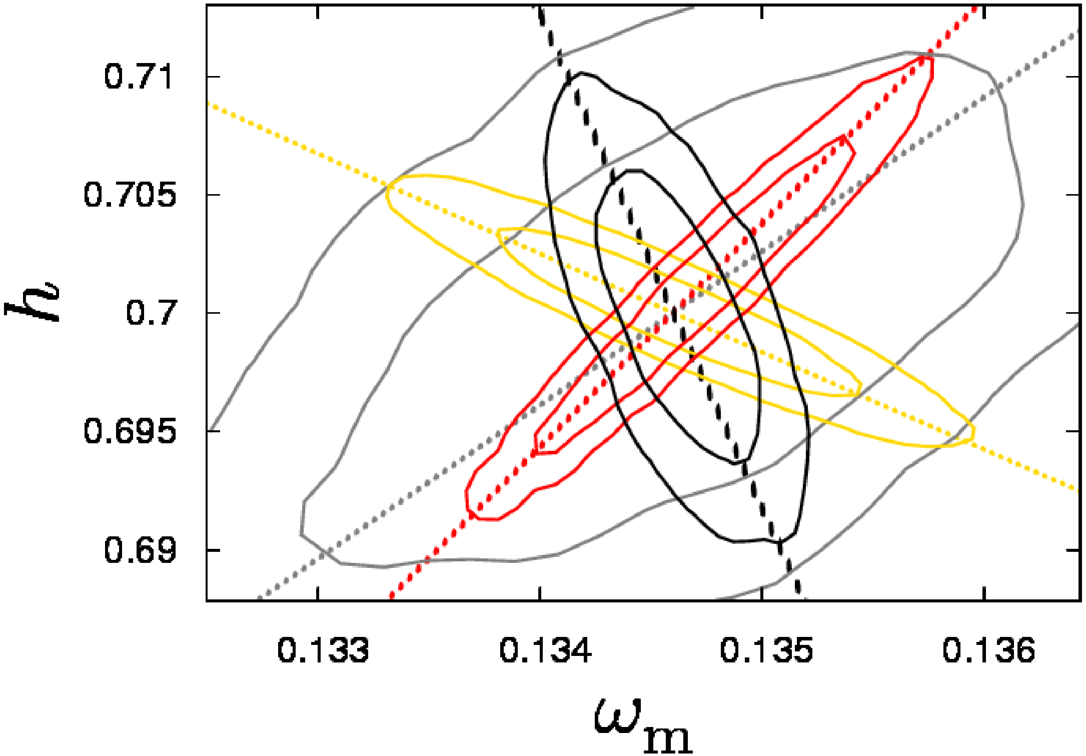
$$\boxed{k^2 \Phi \propto -\frac{3}{2}\omega_m \delta_m}$$

- The extra ω_m factor makes the parameter degeneracy directions of cosmic shear and galaxy clustering very different!

Shear vs galaxy clustering: degeneracy directions...

ω_m vs h degeneracy in a restricted 2-parameter analysis.

Black = galaxy only (optimistic bias)
Red = cosmic shear only
Gold = Planck CMB only
Grey = galaxy only (pessimistic bias)



- The ω_m-h degeneracy is completely broken when cosmic shear and galaxy clustering are **used in combination**.

  → Will also help to tighten the neutrino mass constraint.

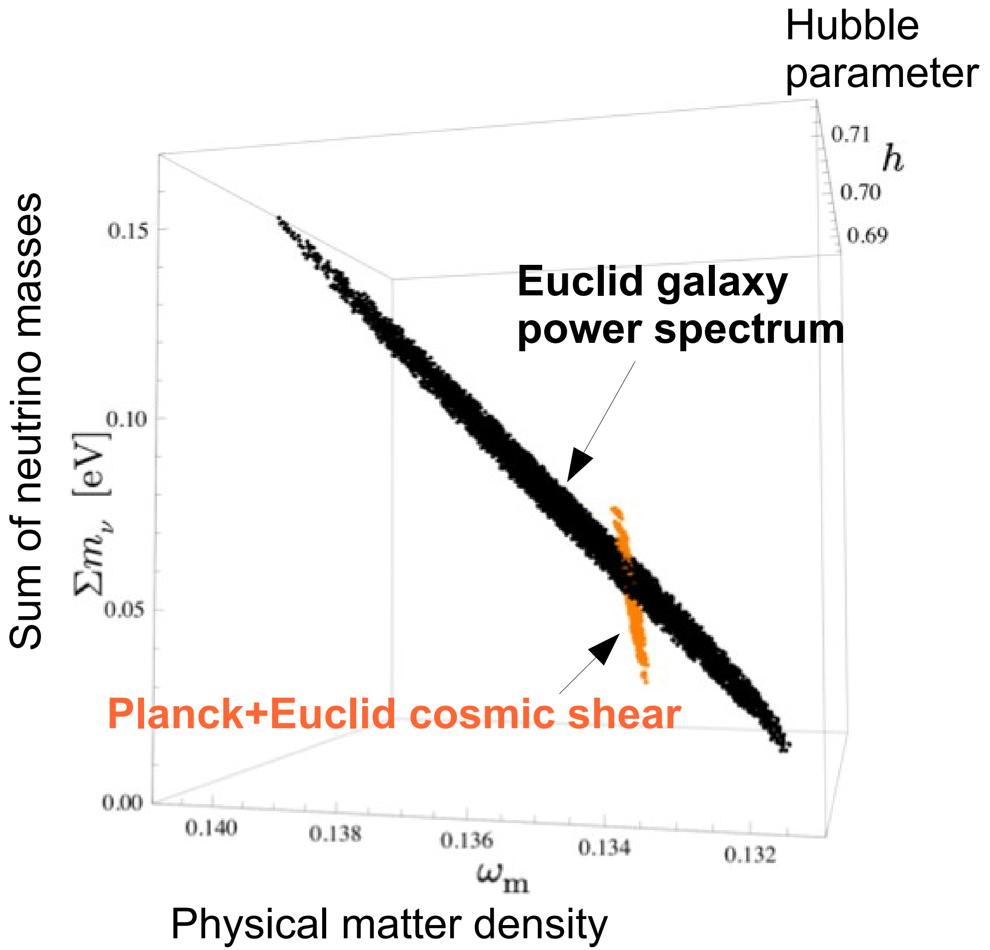
Add neutrino mass: three-way degeneracy...

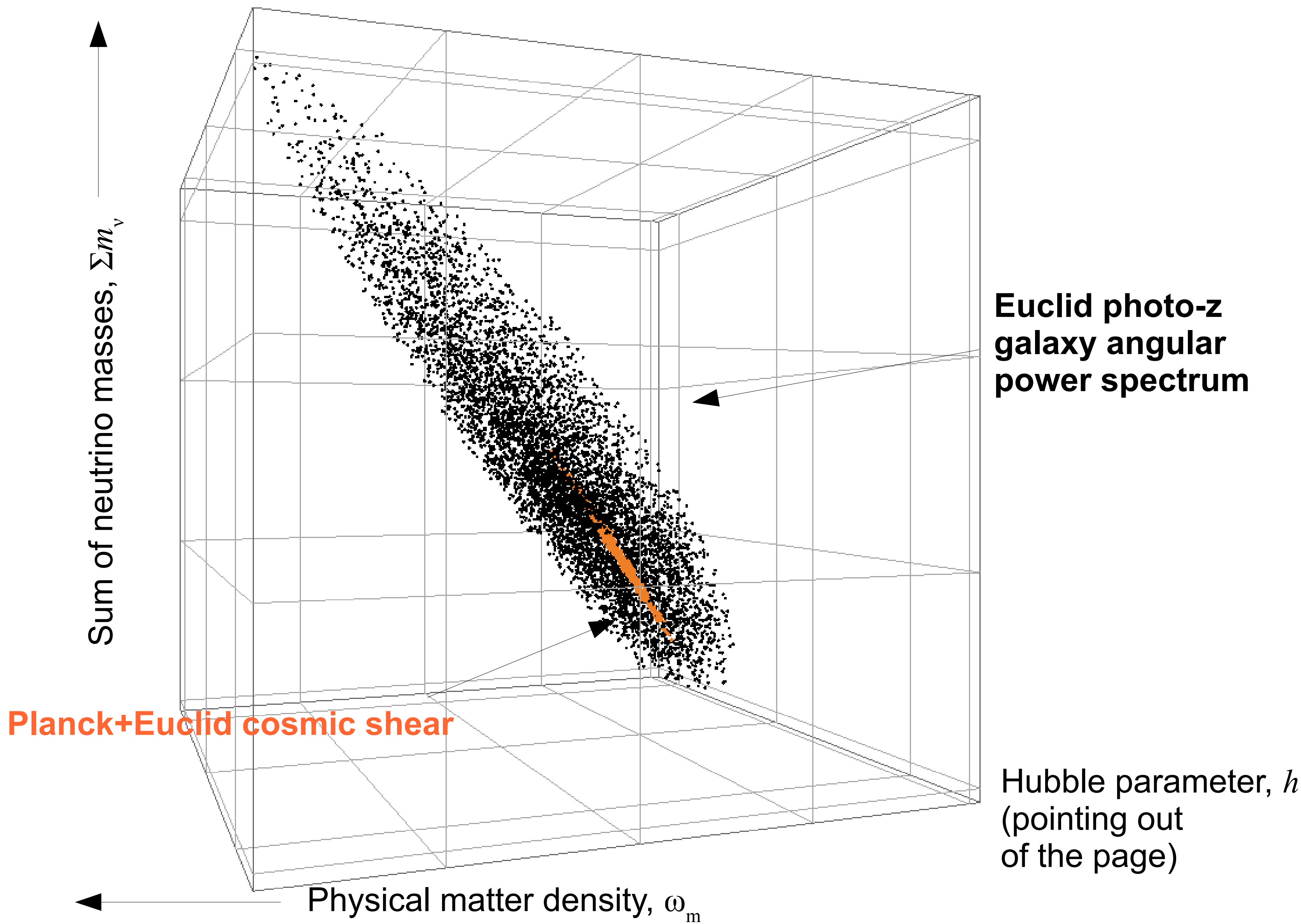
Including neutrino mass in the analysis creates a **three-way degeneracy** between (ω_m, h, Σm_ν).

- Different orientations of ellipsoids for cosmic shear and galaxy clustering.

- When combined, the three-way degeneracy can be broken very effectively.

This is our central message!





Sum of neutrino masses, Σm_ν
Euclid photo-z
galaxy angular
power spectrum
Planck+Euclid cosmic shear
Hubble parameter, h
(pointing out
of the page)
Physical matter density, ω_m

Some numbers...

A **7-parameter forecast**:

matter density, Initial conditions

$$\Theta = (\omega_b, \omega_m, h, A_s, n_s, \tau, \sum m_\nu)$$

Neutrino mass sum (modelled as 1 massive + 2 massless neutrinos)

baryon density

Hubble parameter

Optical depth (affects CMB only)

Data	$10^3 \times \sigma(\omega_{dm})$	$100 \times \sigma(h)$	$\sigma(\sum m_\nu)/\mathrm{eV}$
c	2.02	1.427	0.143
cs	0.423	0.295	0.025
cg	0.583	0.317	0.016
$\mathrm{cg_l}$	0.828	0.448	0.019
$\mathrm{cg_b}$	0.723	0.488	0.039
$\mathrm{cg_{bl}}$	1.165	0.780	0.059
csg	0.201	0.083	0.011
csgx	0.181	0.071	0.011
$\mathrm{csg_b}$	0.385	0.268	0.023
$\mathrm{csg_b x}$	0.354	0.244	0.022

- **Dramatic improvement** in sensitivities to (ω_m, h, Σm_ν) when shear and galaxy clustering are combined.
- Shear-galaxy cross-correlation is not so important.

c = CMB (Planck); g = galaxy clustering
s = cosmic shear; x = shear-galaxy cross

Some numbers...

A **7-parameter forecast**:

matter density   Initial conditions

$$\Theta = (\omega_b, \omega_m, h, A_s, n_s, \tau, \sum m_\nu)$$

Neutrino mass sum (modelled as 1 massive + 2 massless neutrinos)

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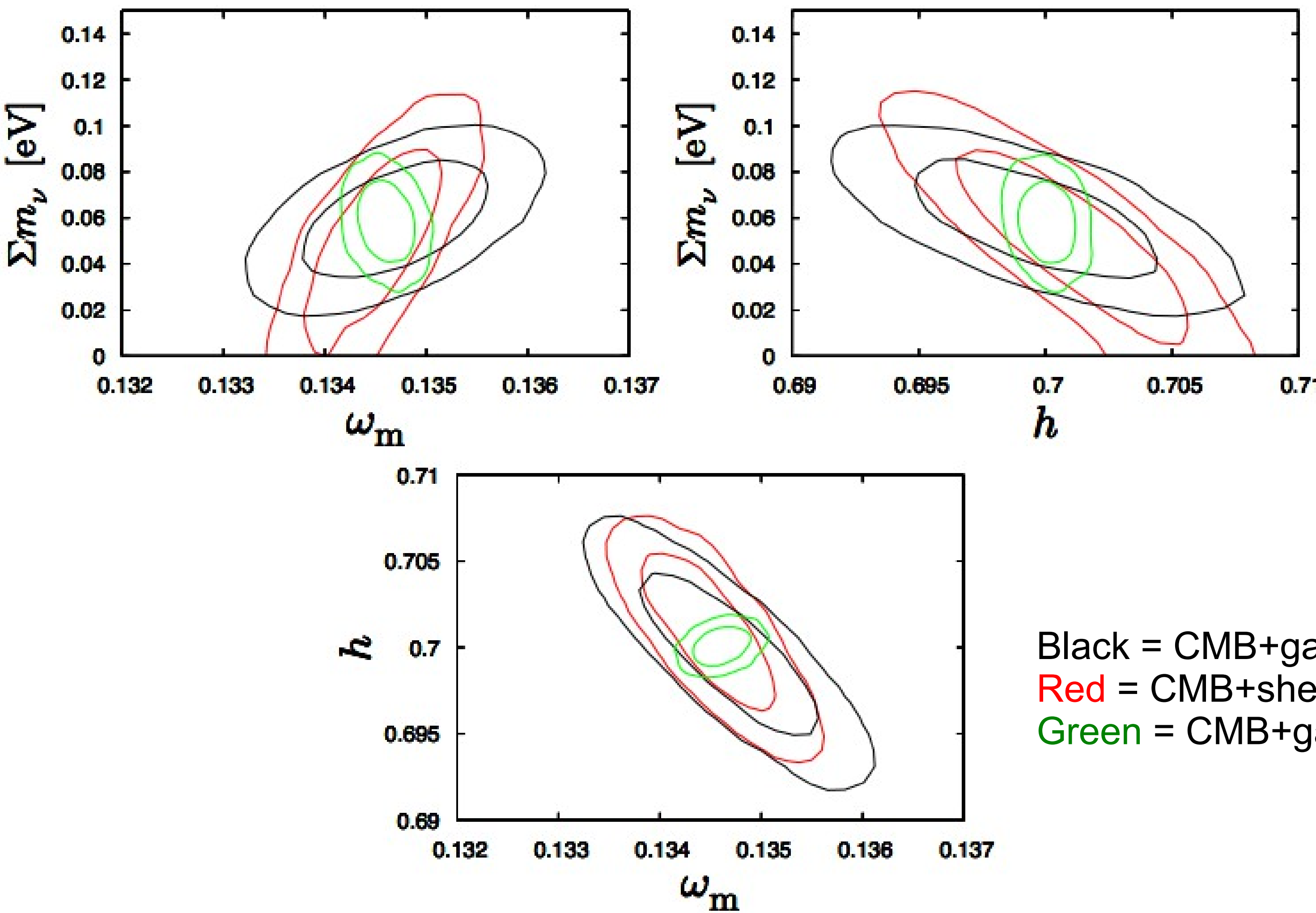
$\mathrm{csg_b}$	0.385	0.268	0.023
$\mathrm{csg_bx}$	0.354	0.244	0.022

- **Galaxy clustering** adds some marginal improvement on the constraint from CMB+cosmic shear even if the linear galaxy bias is completely unknown.

c = CMB (Planck); g = galaxy clustering
s = cosmic shear; x = shear-galaxy cross

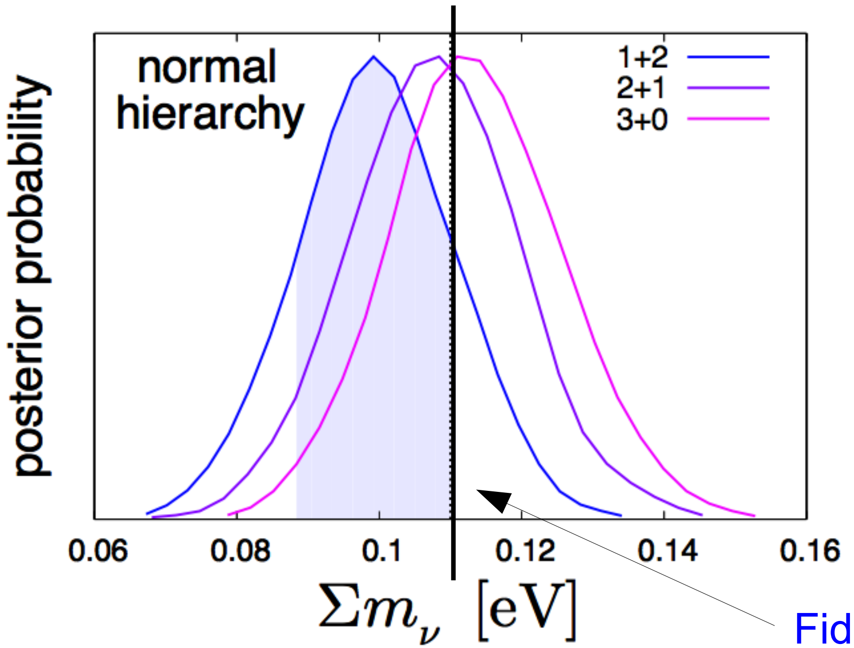


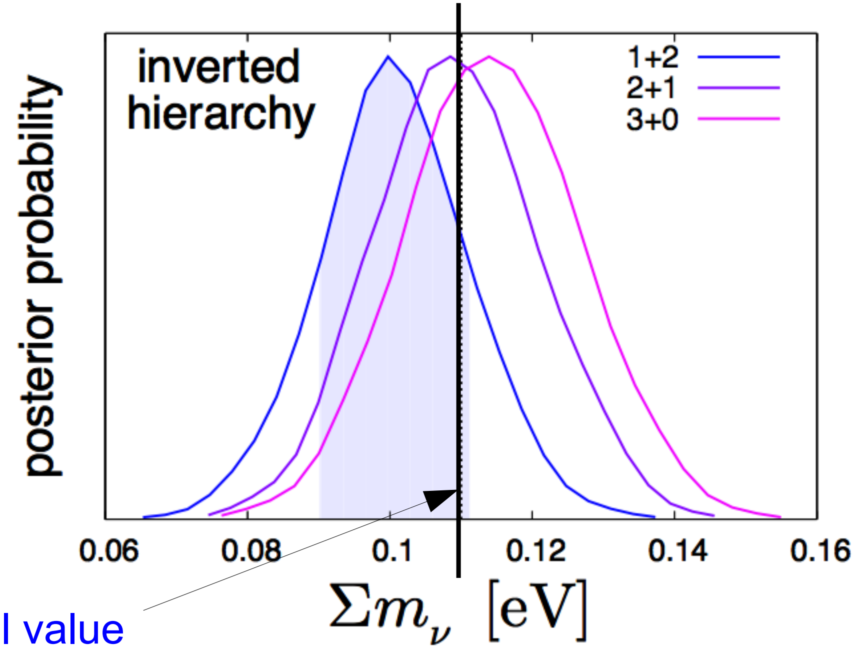
Black = CMB+galaxy (optim. bias)
Red = CMB+shear
Green = CMB+galaxy+shear

Good enough to measure the mass spectrum?

Unfortunately not.

- In fact we can model the mass spectrum any way we like and the data cannot tell.





Fiducial value

1+2 = 1 massive + 2 massless
2+1 = 2 (equally) massive + 1 massless
3+0 = 3 (equally) massive + 0 massless

We always recover the fiducial value within 1σ.

Extended models...

Besides the 7 vanilla parameters, some other cosmological parameters are known to be degenerate with the neutrino mass.

Extra radiation — Dark energy EoS

Data	$10^3 \times \sigma(\omega_{\rm dm})$	$100 \times \sigma(h)$	$\sigma(\sum m_\nu)/\text{eV}$	$\sigma(N_{\rm eff}^{\rm ml})$	$\sigma(w)$
cs	1.864	0.638	0.064	0.081	0.0310
cg	1.121	0.655	0.020	0.086	0.0163
csg	0.885	0.324	0.012	0.056	0.0083
csgx	0.874	0.292	0.012	0.055	0.0065
csg$_{\rm b}$	1.400	0.529	0.042	0.068	0.0207
csg$_{\rm b}$x	1.390	0.482	0.042	0.068	0.0186
csgx (7-parameter)	0.181	0.071	0.011	-	-
csg$_{\rm b}$x (7-parameter)	0.354	0.244	0.022	-	-

c=CMB (Planck); g=galaxy power spectrum; s=cosmic shear; x=shear-galaxy cross-correlation

- **Optimistic linear bias**: No deterioration of sensitivity to Σm_ν; still 5σ+.
- **Pessimistic linear bias**: Factor of 2 deterioration in sensitivity.

Summary...

- The existence of neutrino dark matter is a fundamental prediction of SM+FLRW cosmology+neutrino oscillation experiments.

- **Existing precision cosmological data** already place strong constraints on the abundance of neutrino dark matter and hence the neutrino mass.

- **Future observations** with Planck+Euclid will do much better, especially when cosmic shear and galaxy clustering data are analysed in combination.

  - A 2-5σ detection is possible even if the neutrino mass is the smallest allowed by oscillation experiments.

- **The challenge** (for theorists): get the nonlinear corrections right!