Neutrinos and the large scale structure

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- **the role of neutrinos in the cosmic budget**
- **neutrinos and the formation of cosmic structures**
- **cosmological constraints on the neutrino mass**

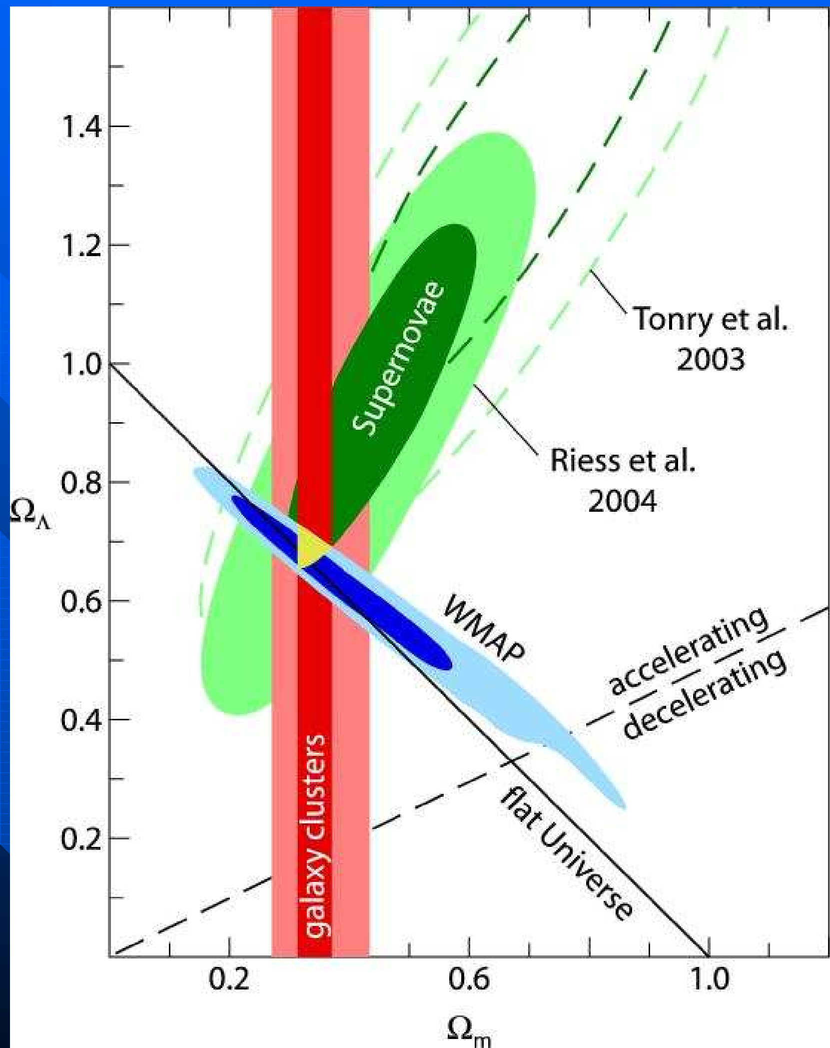
Perspectives in Neutrino Physics & Astrophysics
Bologna, 17th June 2005

The cosmic budget

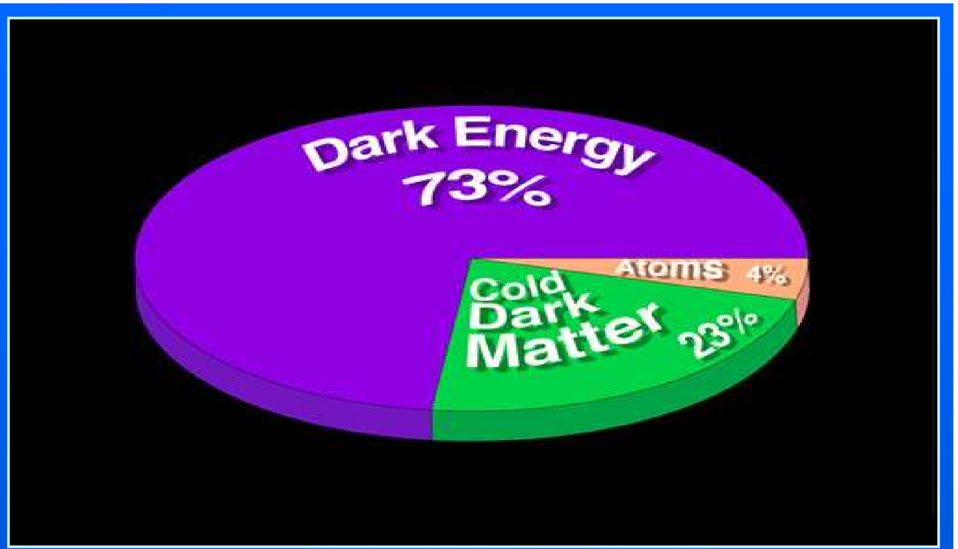
Independent data sets give a consistent determination of the amount of Dark Energy and Dark Matter in the Universe. The relative weights being measured by their density parameter

$$\Omega_i = \rho_i / \rho_c$$

where $\rho_c = \cong 10^{-29}$ g/cm^3 is the *critical density* i.e. the energy density which closes the Universe



The cosmic budget



- ✓ **About 73% of the energy content of our Universe is in the form of some exotic component, called <u>Dark Energy</u>, or "<u>Quintessence</u>", which causes a large-scale cosmic repulsion among celestial objects, thereby mimicking a sort of anti-gravity effect. The simplest dark energy candidate is the Cosmological Constant Λ.**

- ✓ **Only about 4% of the cosmic energy budget is in the form of ordinary "baryonic" matter, out of which only a small fraction shines in the galaxies (quite likely most of the baryon reside in filaments forming the <u>Warm-Hot Intergalactic Medium</u> (WHIM), a sort of cosmic web connecting the galaxies and clusters of galaxies*).***

- ✓ **About 23% of the cosmic budget is made of <u>Dark Matter,</u> a collisionless component whose presence we only perceive gravitationally.**

Cosmological neutrinos

Neutrinos are in equilibriun with the primeval plasma through weak interaction reactions. They **decouple** from the plasma at

$$\mathbf{T_{dec} \approx 1\ MeV}$$

Today we have a cosmological neutrino background at a **temperature**

$\mathbf{T_\nu = (4/11)^{1/3}\ T_\gamma \approx 1.945\ K,}$

corresponding to $kT_\nu \approx 1.68 \cdot 10^{-4}$ eV

The Neutrino density

This corresponds to a present neutrino number density of

$\mathbf{n_{0\nu} \approx 0.1827 \cdot T_\nu^{3} \approx 112\ cm^{-3}}$

That for a massive neutrino translates in

$\mathbf{\rho_{0\nu} \approx 1.9 \cdot N_\nu \langle m_\nu/10eV \rangle \cdot 10^{-30}\ g\ cm^{3}}$

or equivalently

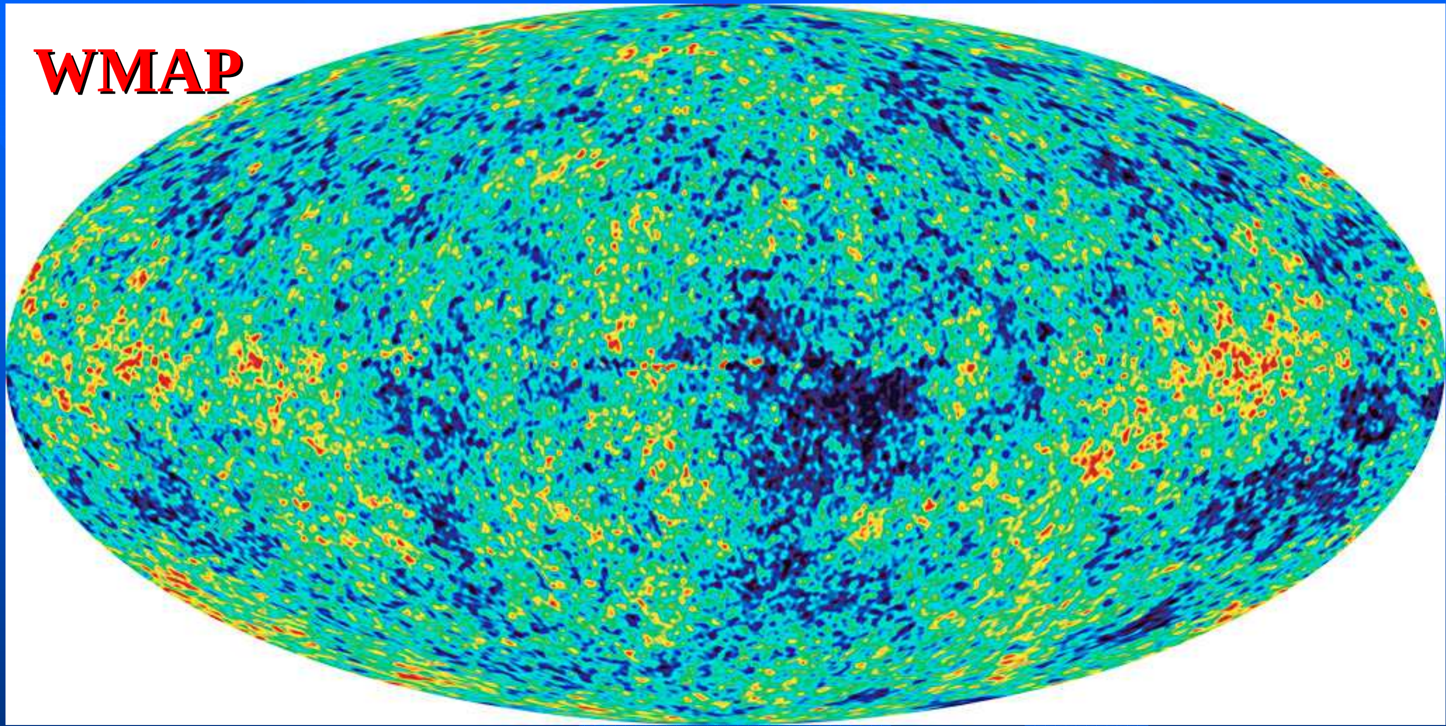
$\mathbf{\Omega_{0\nu}\ h^{2} \approx 0.1 \cdot N_\nu \langle m_\nu/10eV \rangle}$

i.e. in order to be a good candidate for the dark matter component of our universe ($\Omega_{0M}\ h^2 \approx 0.14$), neutrinos need to have a **mean mass of approximately 5 eV!**

A **direct detection is very difficult** but…

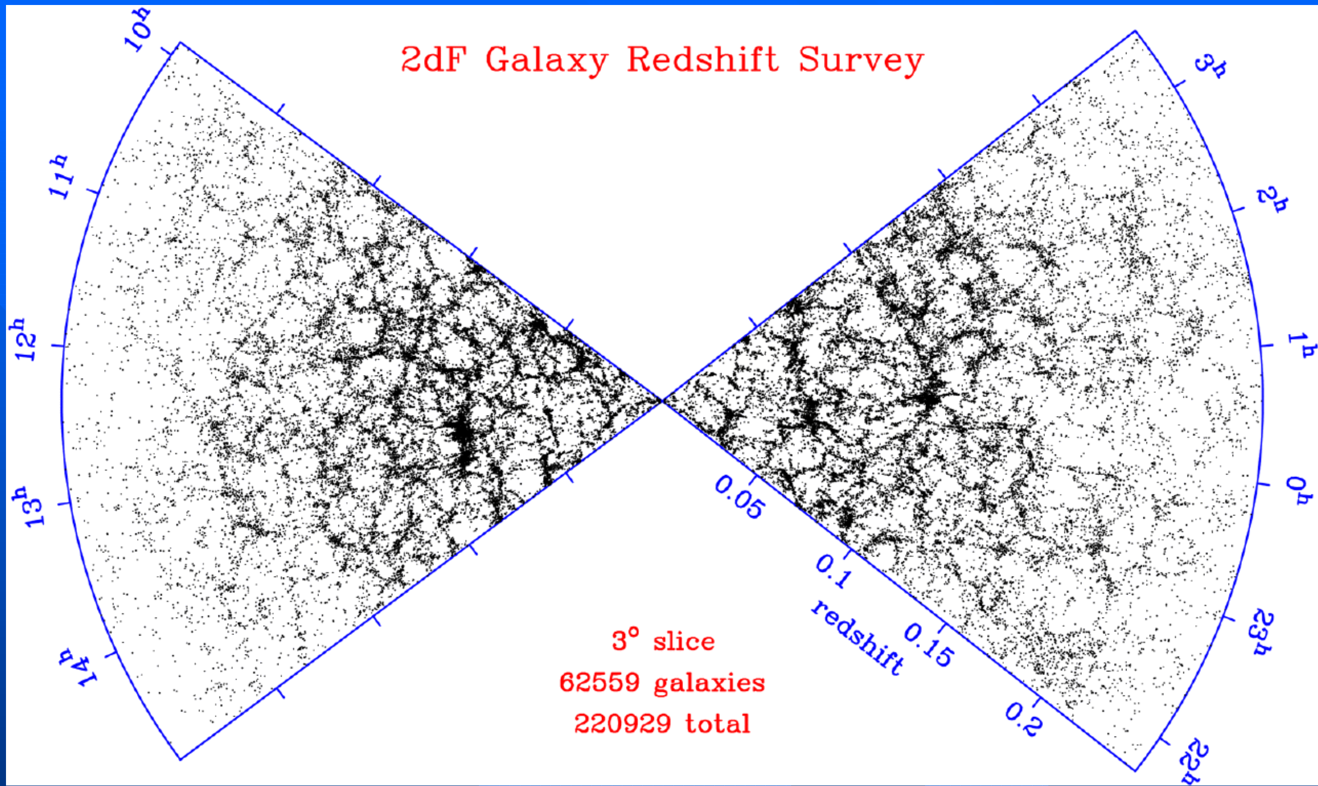
They have a strong impact on the **formation and evolution of cosmic structures,** the so-called **cosmic clustering,** which now can be accurately measured.

The Model for Structure formation



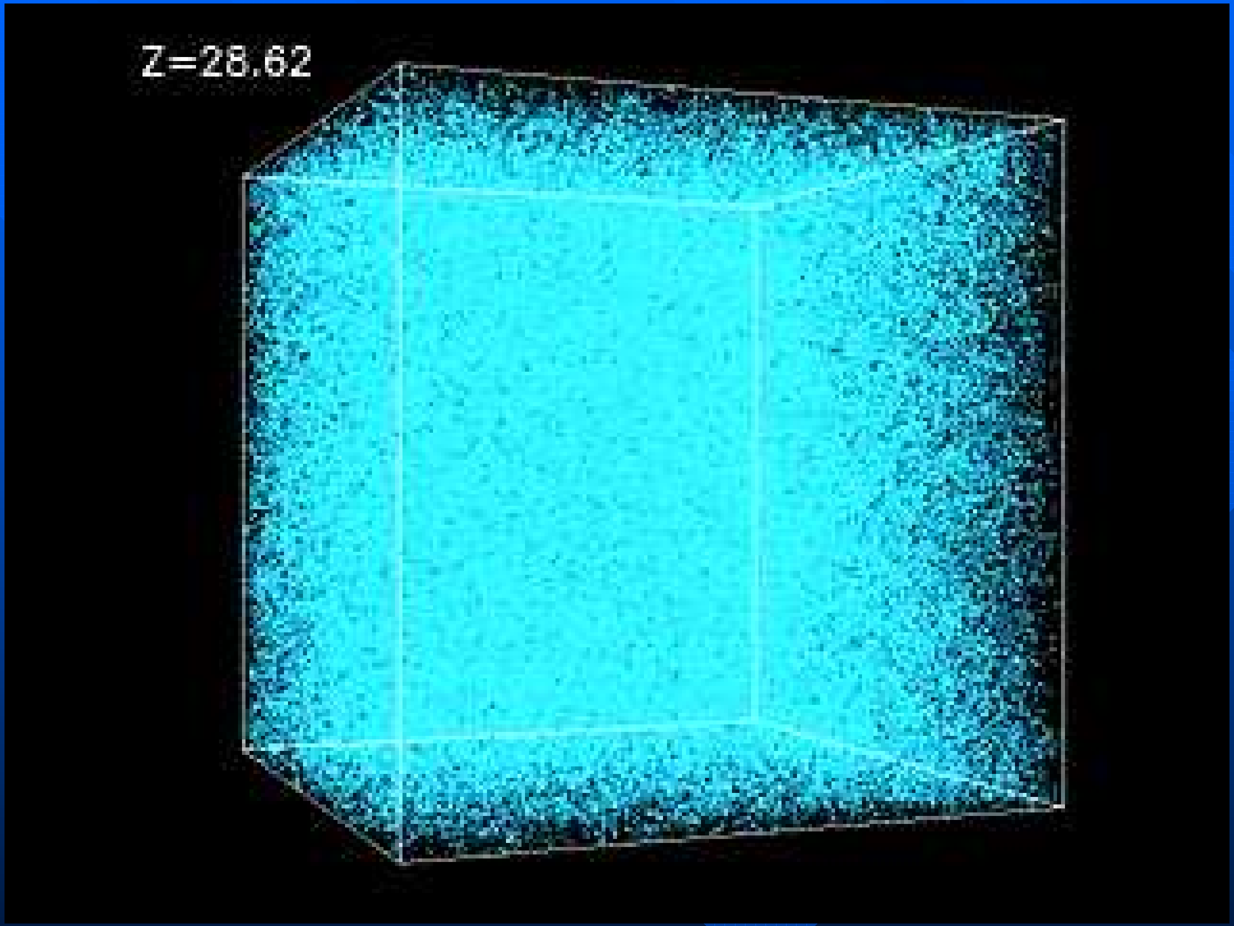
The **cosmic microwave background** (CMB) tells us that the universe is almost perfectly uniform spatially, with density variations from place to place only at the level of **10^{-5}**.

The Model for Structure formation



Gravitational instability caused these tiny fluctuations to grow in amplitude into the large scale structure we observe: gravity is an attactive force and tends to increase the overdensity over time

Redshift evolution of clustering



The linear solution

IF all the matter contributing to the cosmic density is able to cluster (like dark matter or ordinary matter with negligible pressure), then density fluctuations δ grow as the cosmic expansion factor $a \propto (1+z)^{-1}$, i.e.

$$\delta \propto a,$$

But, **IF** some fraction $(1-\Omega_*)$ is unable to cluster (i.e. it is gravitationally inert), then the growth will be **slower**

$$\delta \propto a^p,$$

where $p \approx \Omega_*^{0.6}$.

Note that the inert component can include dark energy if present and photons and neutrinos on sufficiently large scales.

Consequences

- <u>**At early times,**</u> the cosmic density is dominated by photons. This implies p≈0: fluctuations cannot start growing until the epoch of matter-domination (MD), starting at z ≈3700
- <u>**At recent times**</u> (z ≈0.3), the density is dominated by dark energy (DE), which gradually stops the growth of fluctuations after a net growth factor of about $(a_{DE}/a_{MD}) \approx 4700$

What about neutrinos?

Massive non-relativistic neutrinos cannot cluster on small scales because of their high velocities. In the period between matter and dark energy domination, neutrinos are a roughly constant fraction $f_\nu = (1-\Omega_*)$ of the matter density.

Then the net fluctuation growth factor is

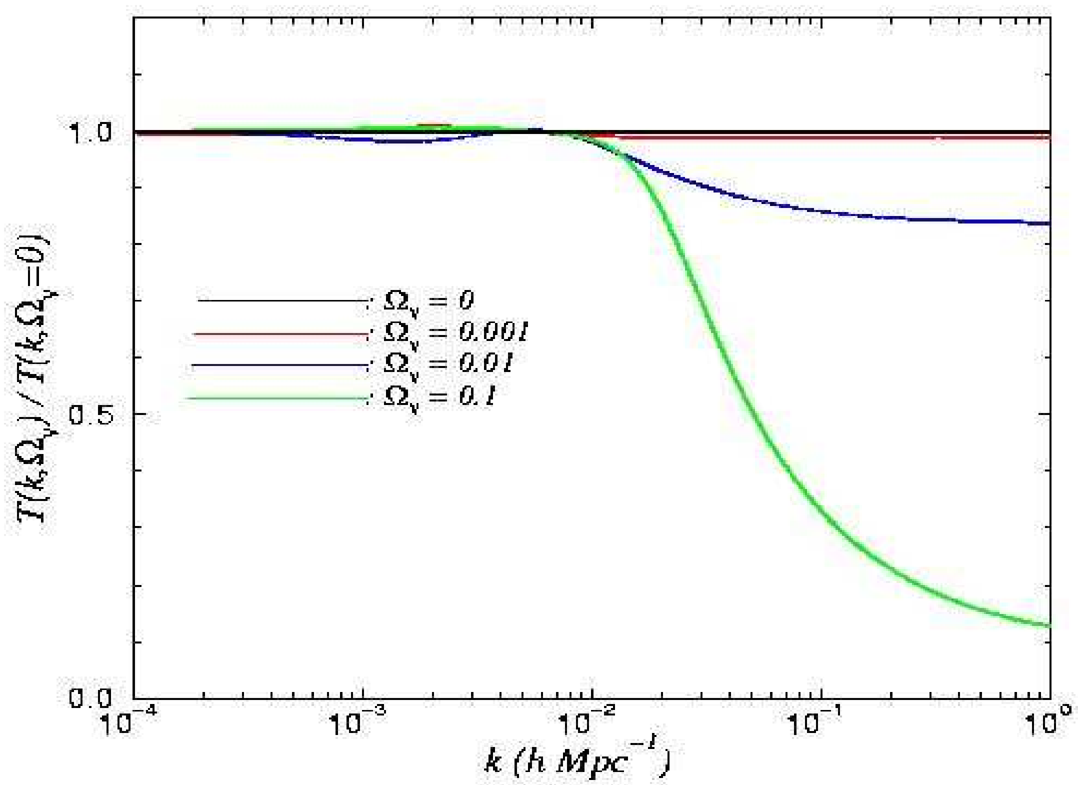
$$(a_{DE}/a_{MD})^p \approx 4700^p \approx 4700 \exp(-4 f_\nu)$$

Even a small neutrino fraction has a large effect!

The transfer function T(k)

In cosmology this effect can be quantify by using the **density power spectrum P(K)**, giving the variance of fluctuations δ in Fourier space. Usually this can be written as

$$P(k)=A\,k^n\,T^2(k)$$



Neutrino free streaming:
$\Delta P(k)/P(k)=-8f_\nu$

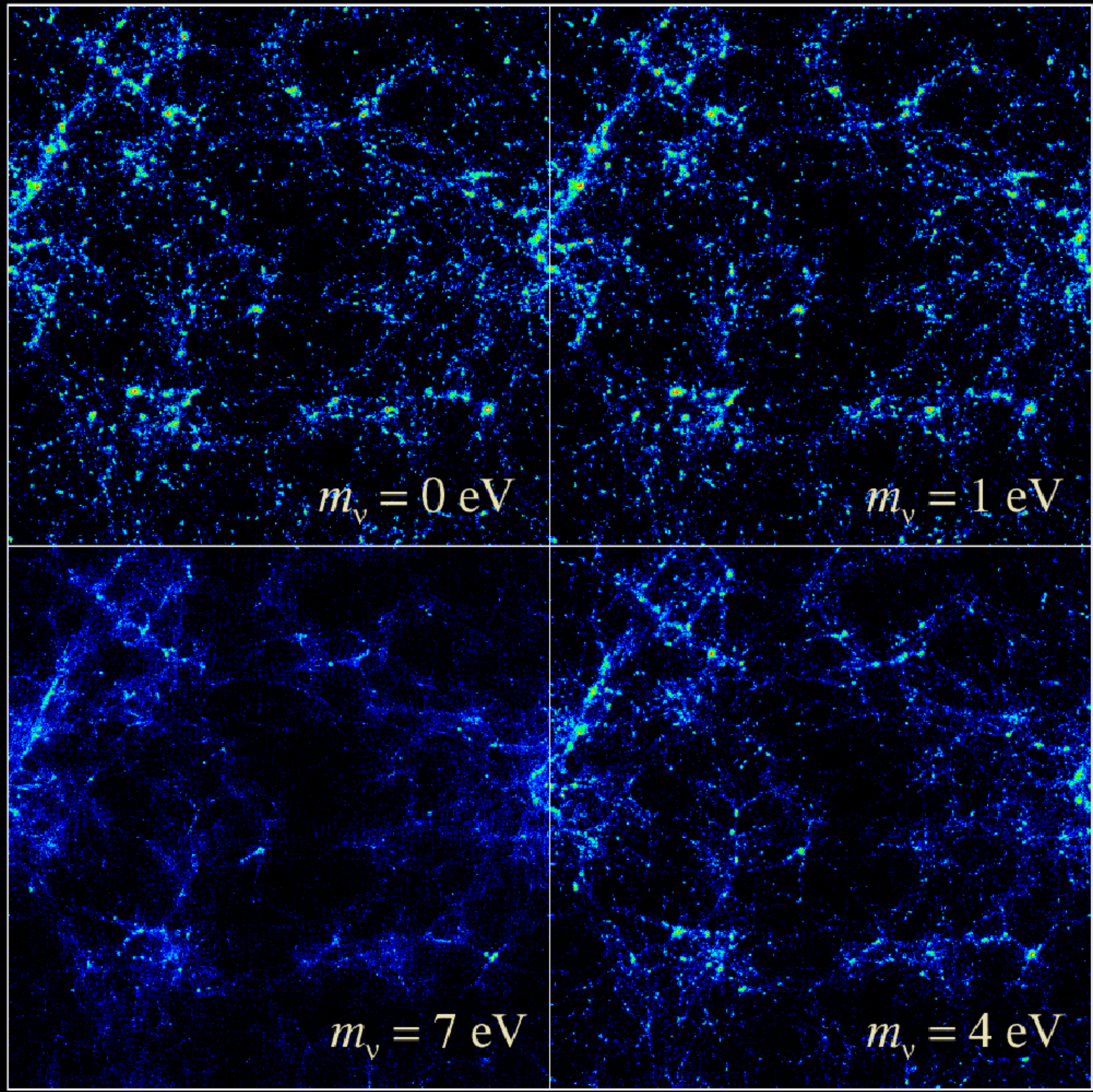
Practical consequences

- There is a scale, called **neutrino free-streaming scale,** below wich clustering is strongly suppressed.
- Neutrinos will not cluster in overdense clumps so small that their escape velocity is much smaller than the typical neutrino velocity.
- **On larger scales** neutrinos behave just as cold dark matter: Ω_* =1 and p=1

The power spectrum changes its shape in a characteristic way

N-body results

There is less clustering in models with massive neutrinos



Ma '96

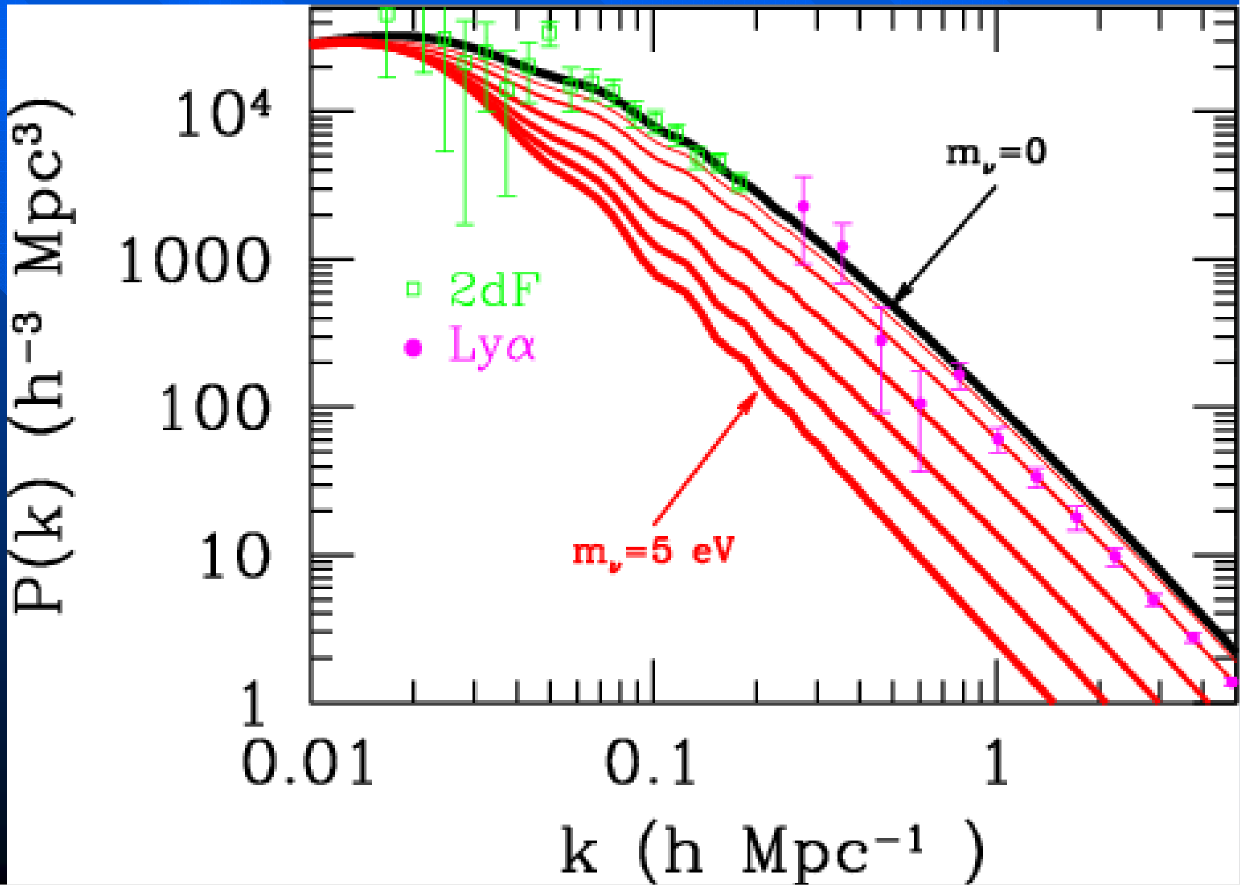
The top-down scenario

Now we know that $\Omega_{0m} \approx 0.3$.
If we assume that all dark matter is contributed by neutrinos, because of free-streaming there will be a strong suppression of power at small scales.
Consequently cosmic structures would have formed first at large scales (galaxy clusters), and smaller structures (like galaxies) would form later by fragmentation:
this is the so-called **top-down scenario**

But, starting from late ’80s, we have evidences in favour of a **bottom-up** structure formation (hierarchical) model, where objects formed first at small scale.

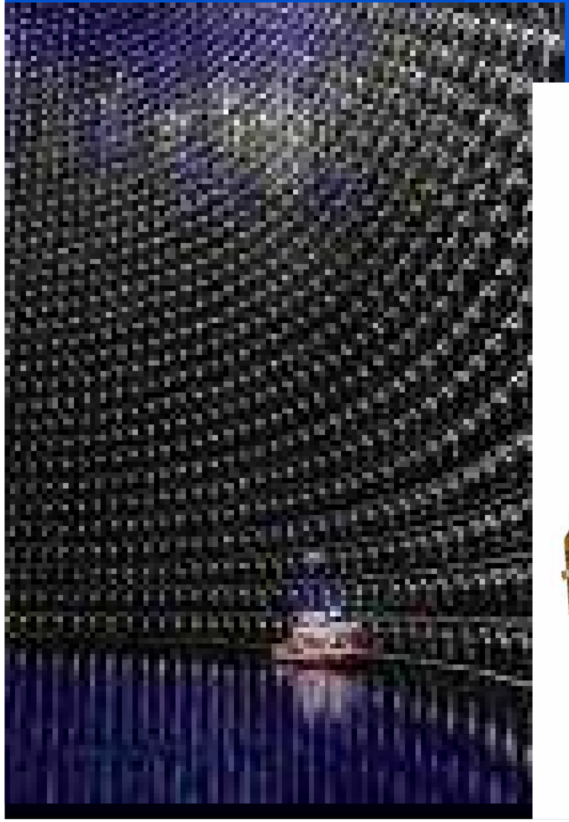
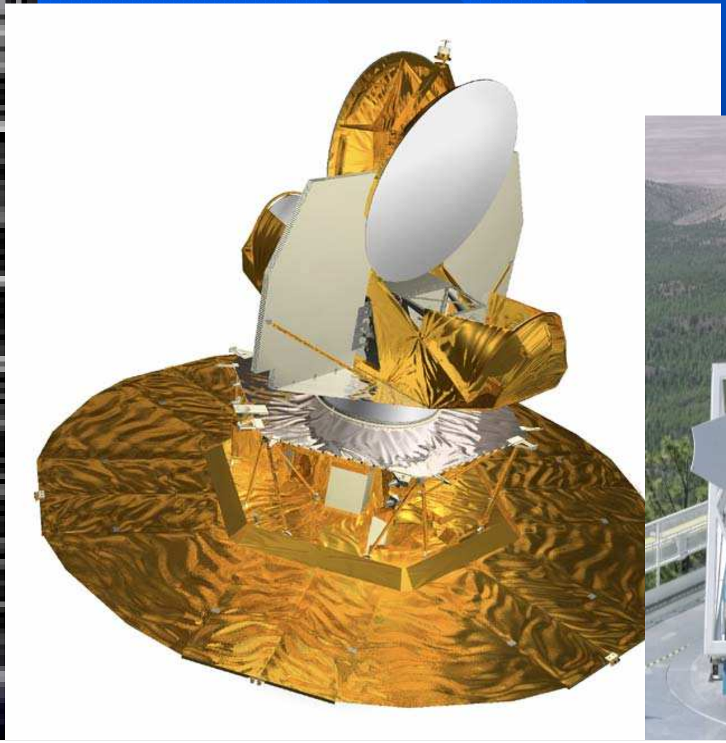
Now this is confirmed by observational data. A **cold** (i.e. non-relativistic when it decoupled from the thermal background) **dark matter** (CDM) component is strongly favoured

dark matter cannot be dominated by neutrinos!



Weighing neutrinos

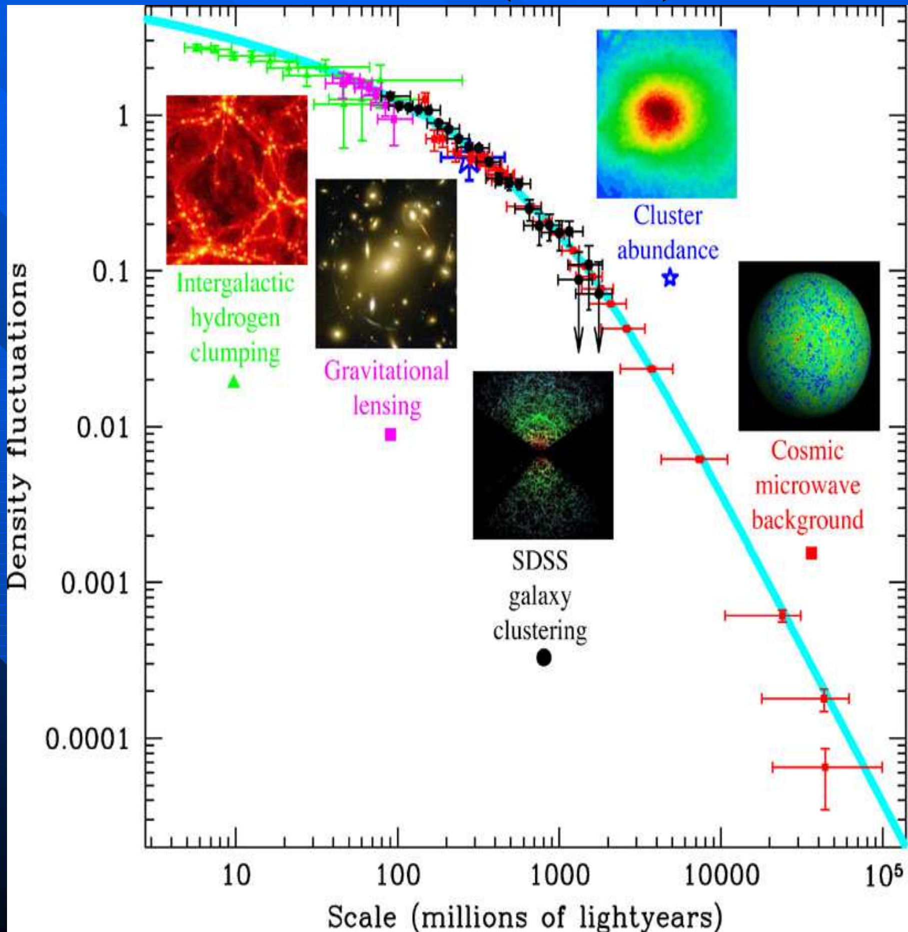
However, neutrinos, even if non-dominant, are **massive and abundant**. So, if we have accurate measuments of cosmic clustering (as we start to have now), we can hope to use cosmological observations to put constraints on the neutrino mass which can be combined with laboratory bounds

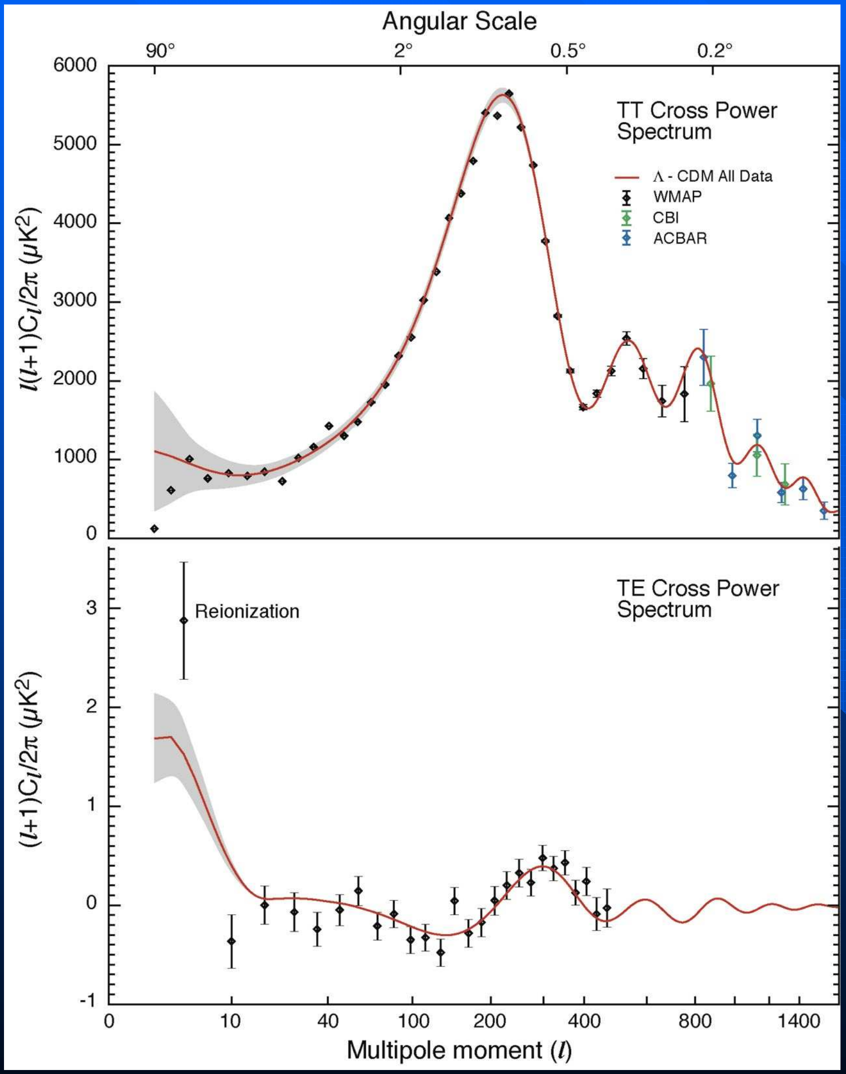

Cosmological observables

- Cosmic microwave background (CMB)
- Galaxy surveys & large scale structure (LSS)
- Lyman alpha forest
- Galaxy clusters
- Gravitational lensing
- …

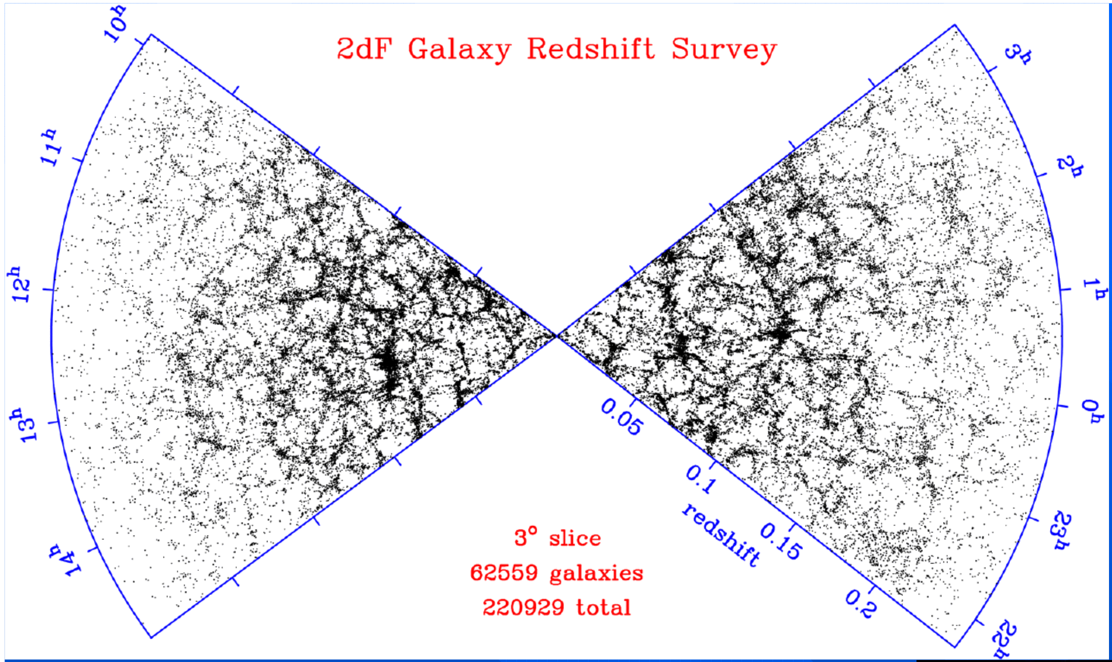
Tegmark



WMAP CMB anisotropies

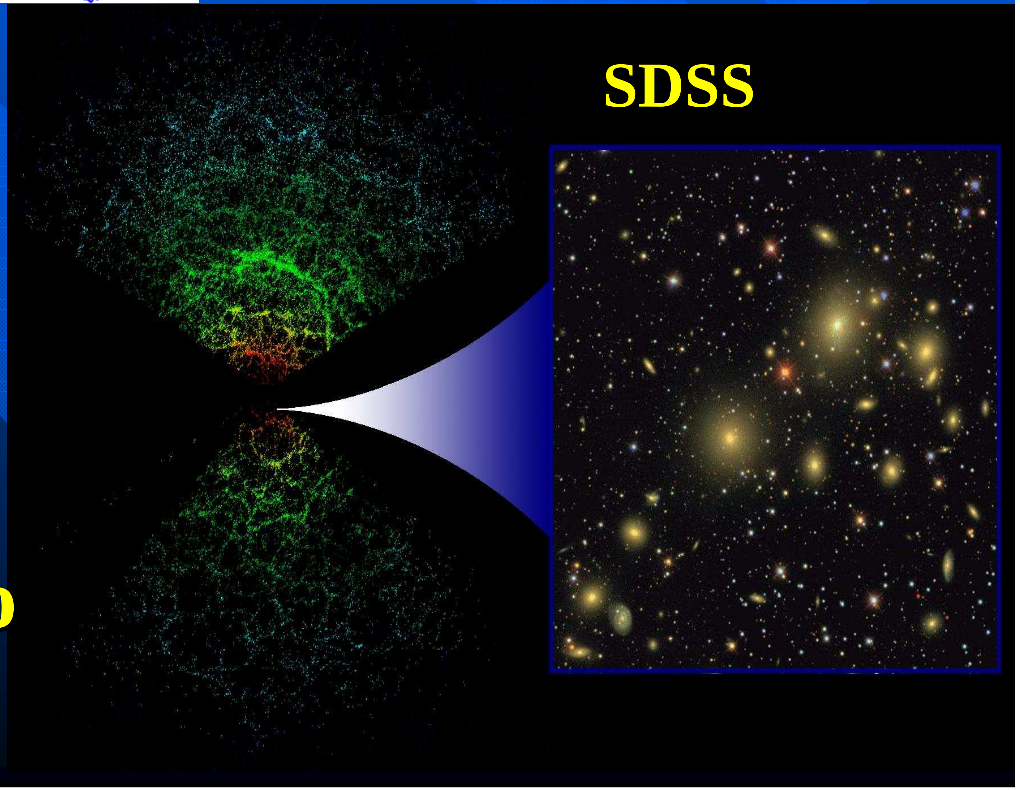


CMB alone is NOT sensitive to massive neutrinos: there is only a small enhancement of the acoustic peaks.
However, they are able to put strong constraints on the matter density and on other parameters: this allows, when combined with other data, to **break degeneracies**

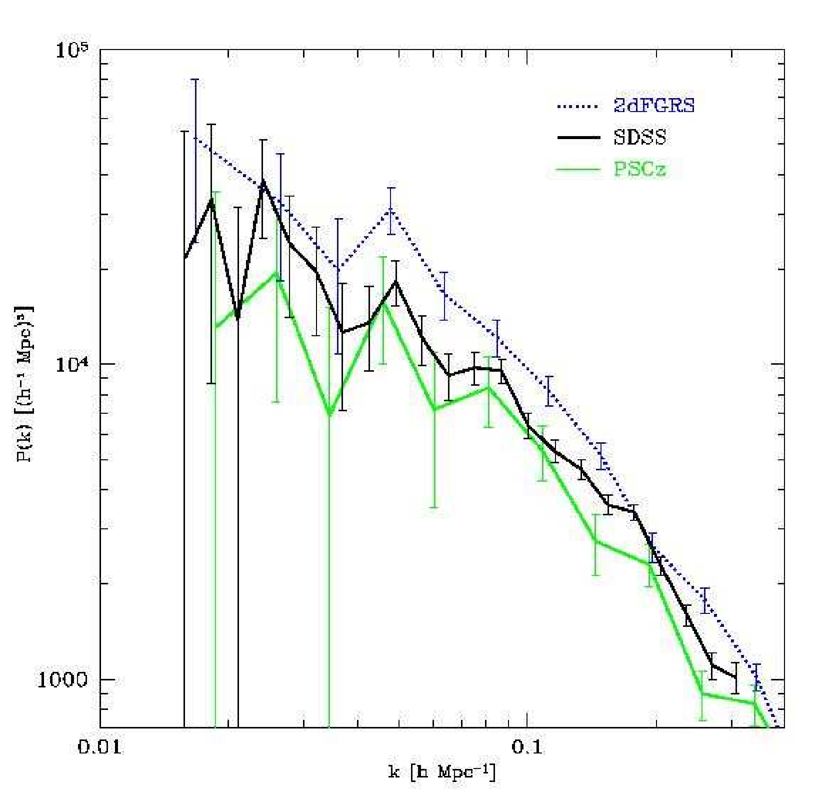


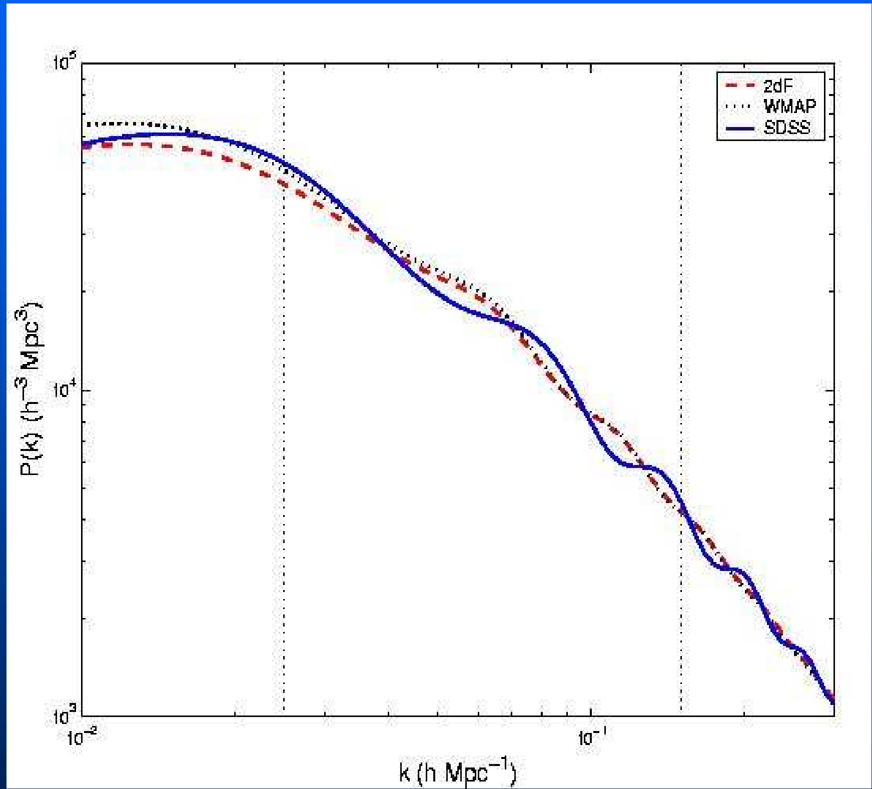
Galaxy surveys

- Large surveys with >200k galaxy redshifts: **2dF and SDSS**
- In linear regime, **sensitive to neutrino fraction $f_\nu=\Omega_\nu/\Omega_m$**



2dF vs SDSS Power spectra

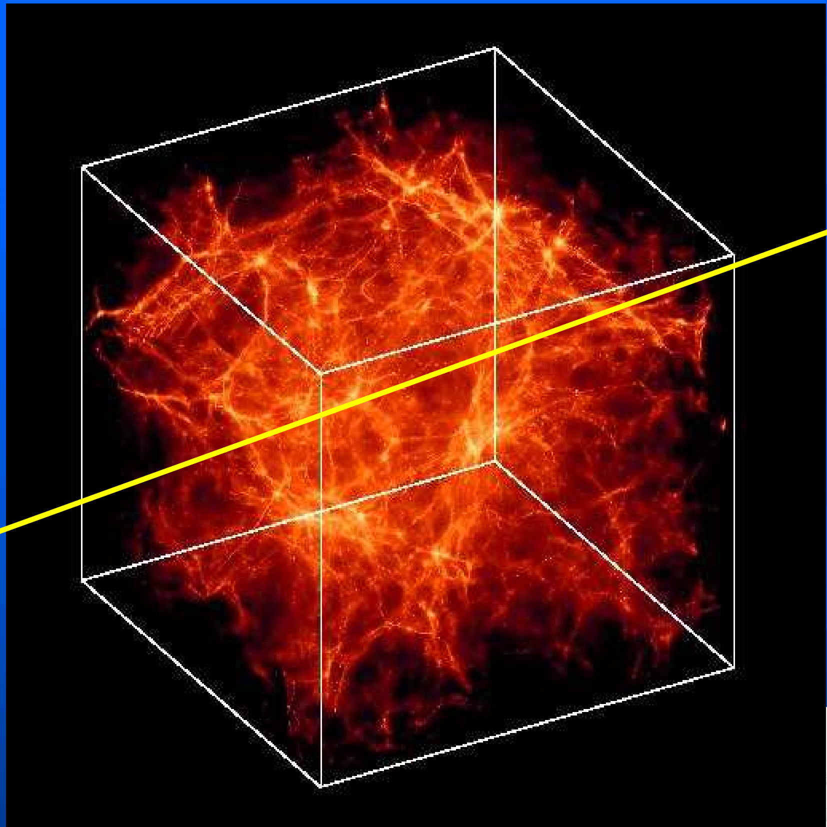




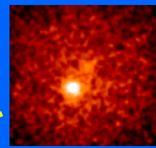
Tegmark et al. 2003

Pope et al. 2004

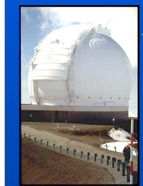
Lyman-α forest



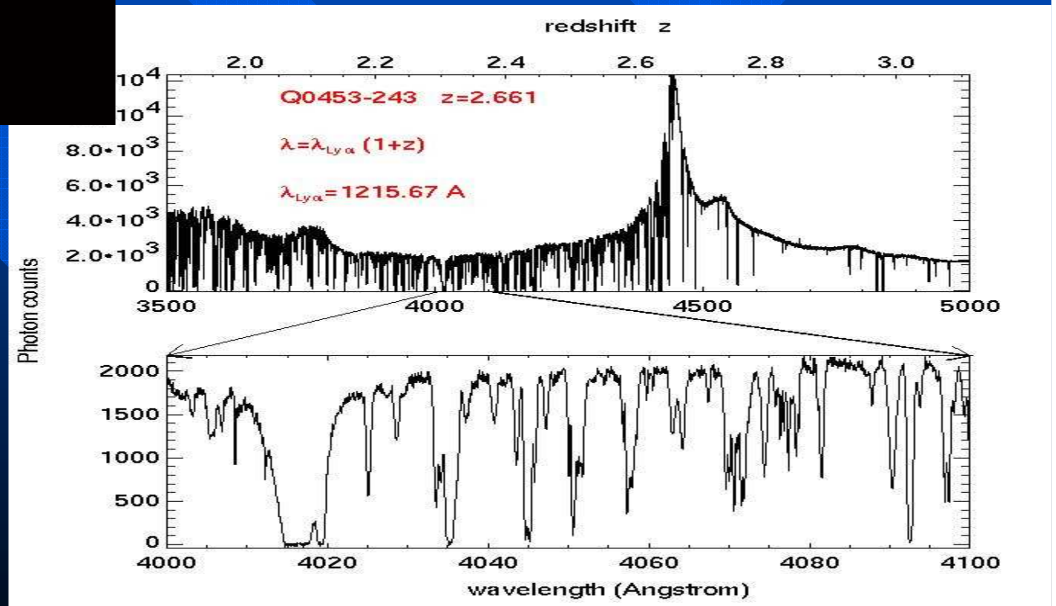
QSO



obs.



80 % of the baryons at z=3
are in the Lyman-α forest
(Rauch 1998)



baryons as tracer of the dark matter density field

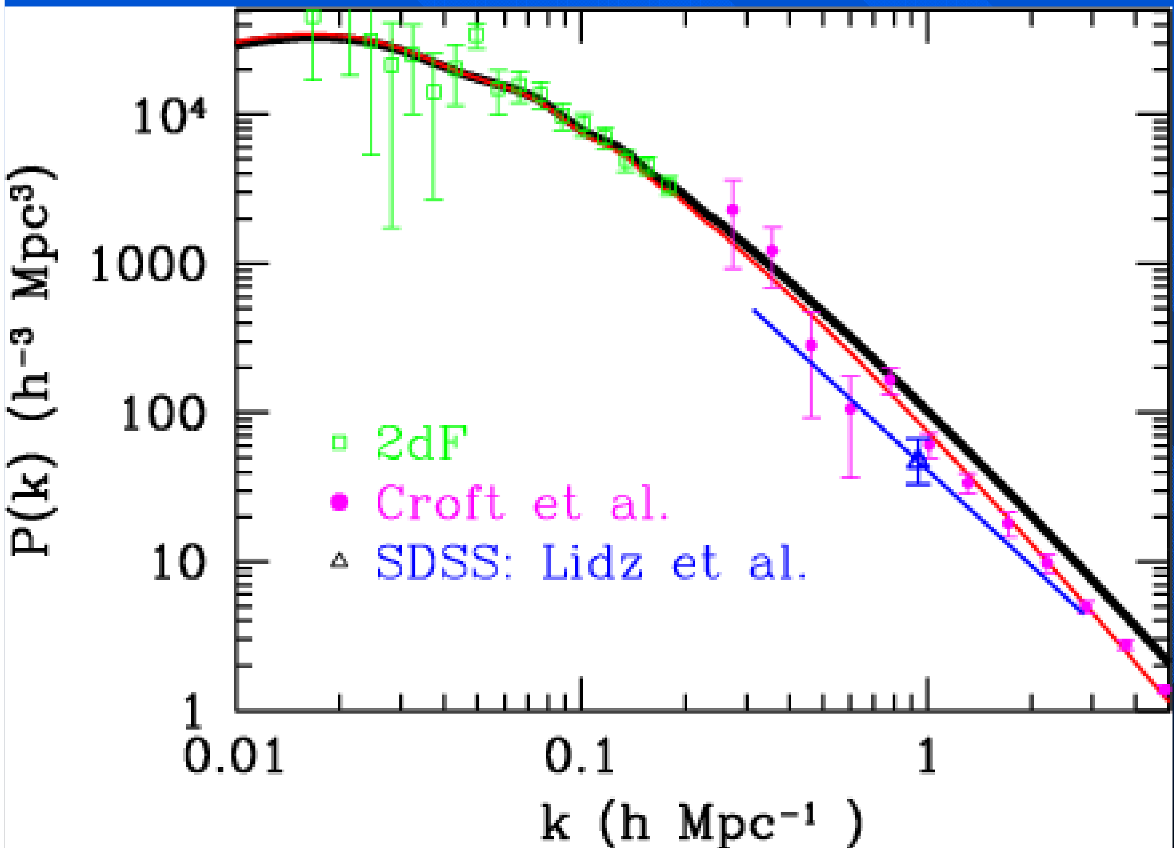
$\delta_{IGM} \sim \delta_{DM}$

at scales larger than the Jeans length ~ 1 com Mpc

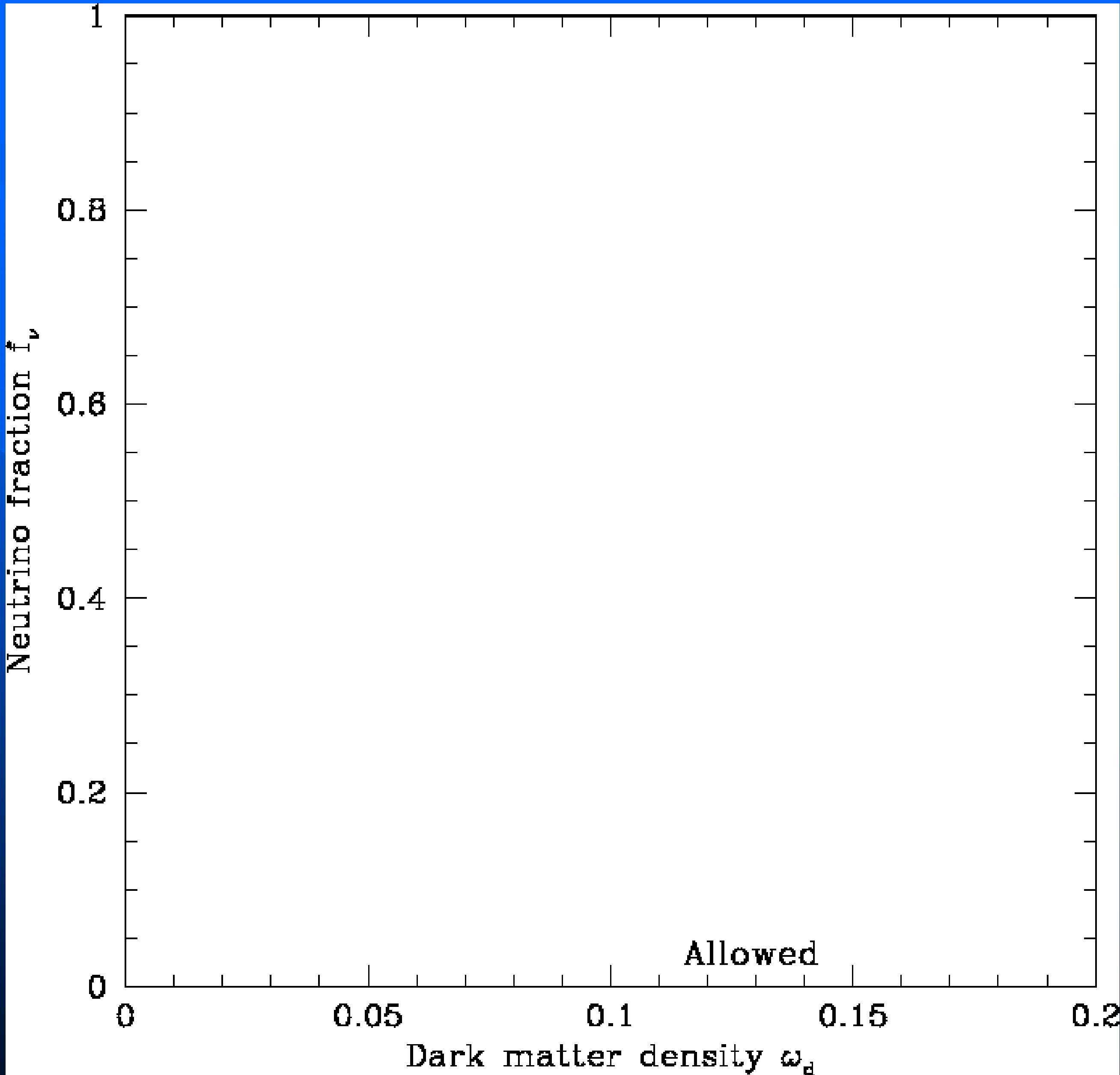
Viel et al. 2005

3D Lyman-alpha Power Spectrum

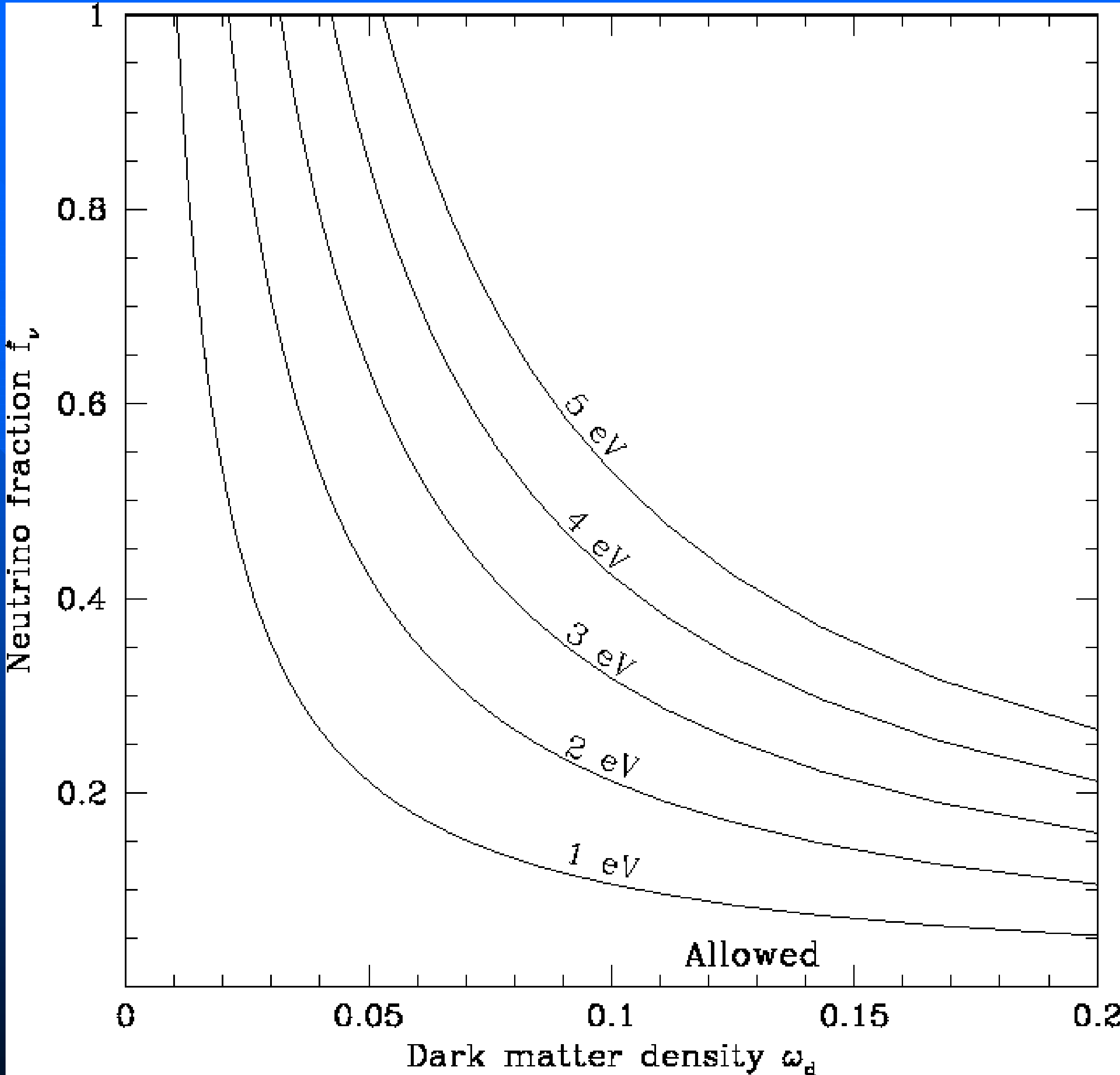
Very sensitive because at small scales, but quite model-dependent



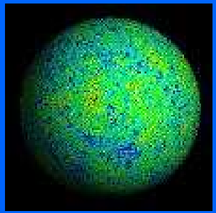
- Run many simulations with CDM-like 3D spectra
- Extract 1D Flux power spectra from each simulation
- Fit amplitude and slope of power at 1 Mpc



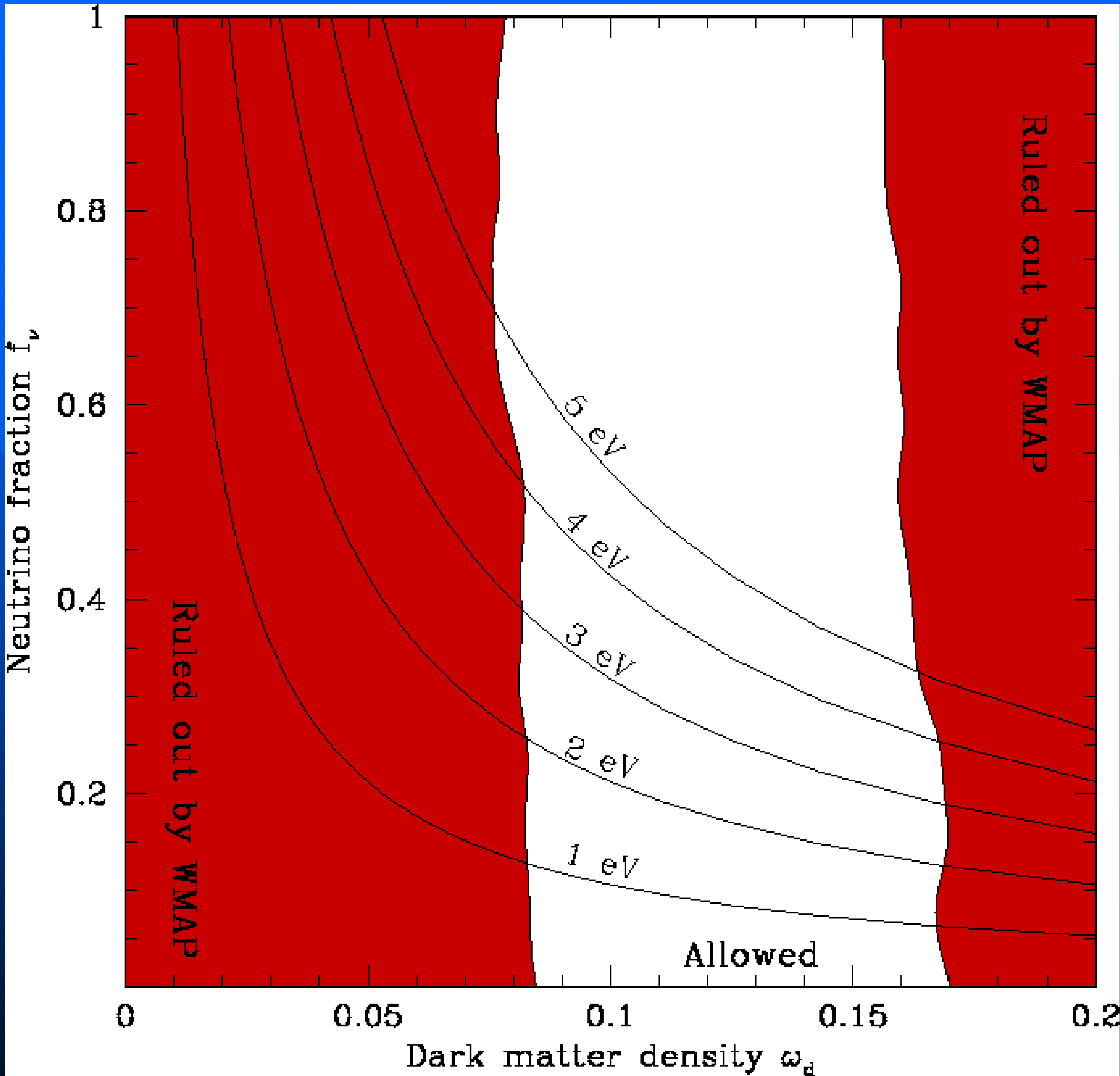
Neutrino fraction f_ν
1
0.8
0.6
0.4
0.2
0
0
0.05
0.1
0.15
0.2
Dark matter density ω_d
Allowed



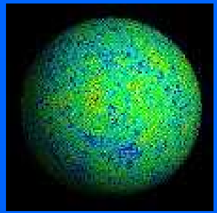
Neutrino fraction f_ν
Dark matter density ω_d
1
0.8
0.6
0.4
0.2
0
0.05
0.1
0.15
0.2
5 eV
4 eV
3 eV
2 eV
1 eV
Allowed



CMB

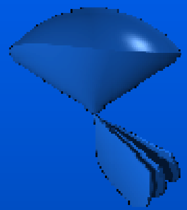


Ruled out by WMAP
Ruled out by WMAP
Allowed
5 eV
4 eV
3 eV
2 eV
1 eV
Neutrino fraction f_ν
Dark matter density ω_d
0
0.05
0.1
0.15
0.2
0.2
0.4
0.6
0.8
1

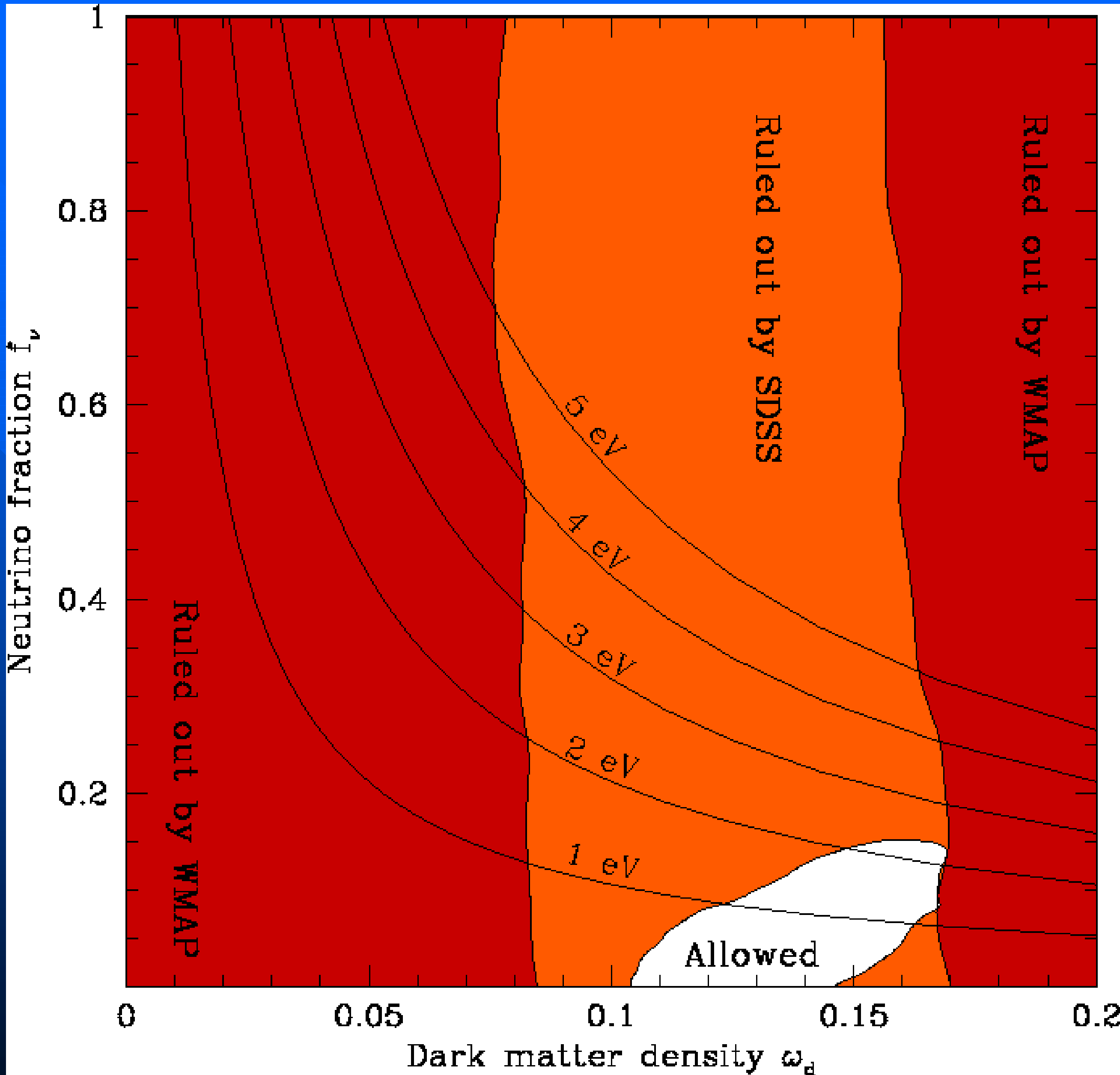


CMB

+



LSS



Neutrino fraction f_ν
Dark matter density ω_d
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Ruled out by SDSS
Ruled out by WMAP
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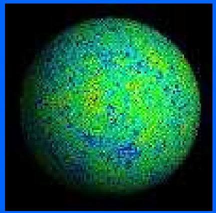
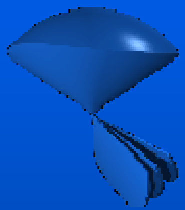
5 eV
4 eV
3 eV
2 eV
1 eV
Allowed

Tegmark 2005



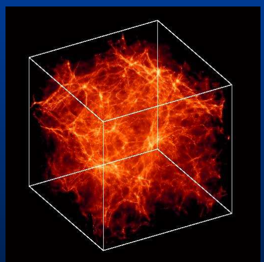
CMB

+

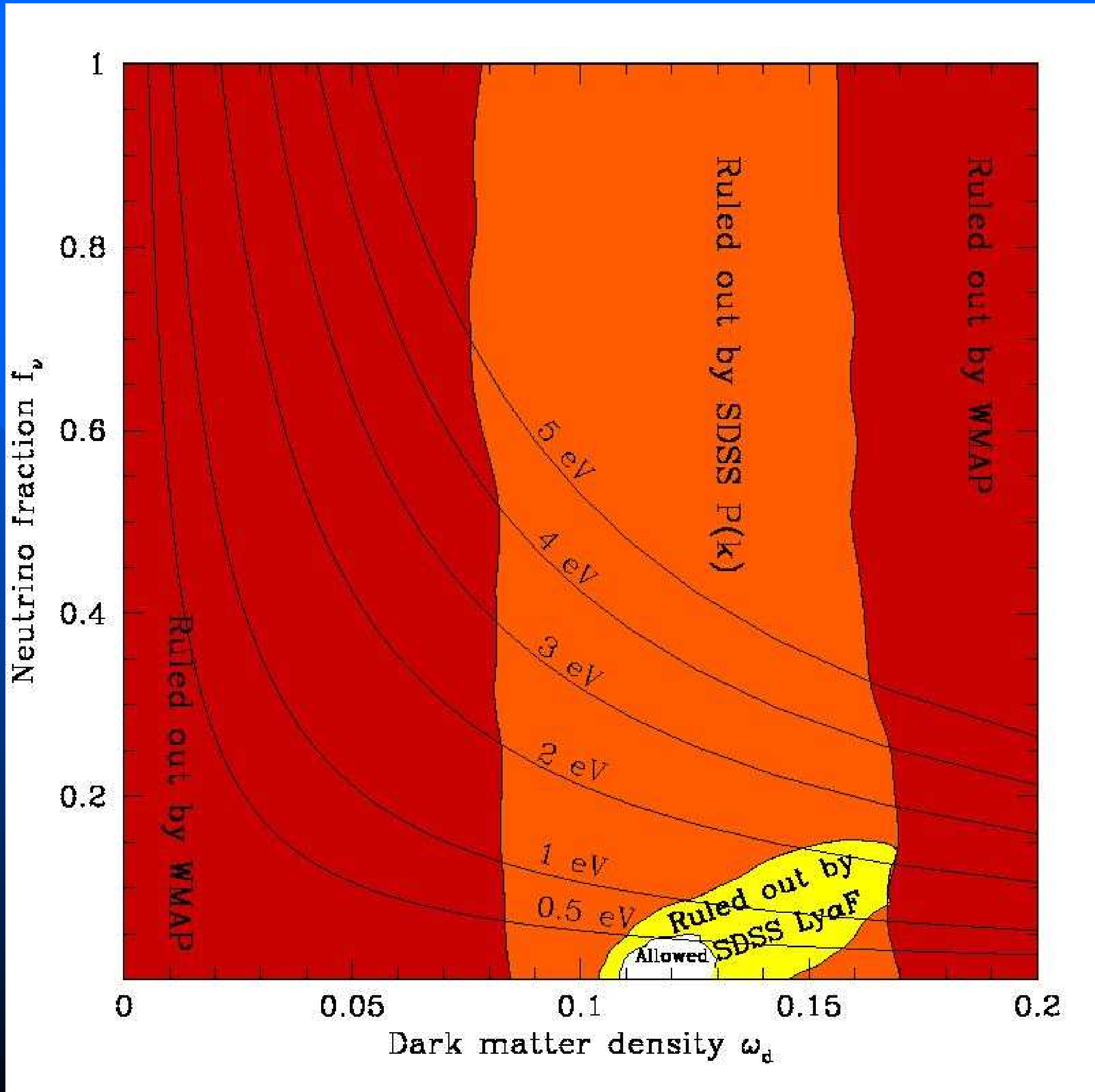


LSS

+



LyaF



A partial summary of neutrino mass from cosmology

Data	Authors	Σm_i
2dFGRS	Elgaroy et al 2002	<1.8 eV
WMAP+2dF+..	Spergel et al. 2003	<0.7 eV
WMAP+2dF	Hannestad 2003	<1.0 eV
SDSS+WMAP	Tegmark et al. 2004	<1.7 eV
WMAP+2dF	Crotty et al. 2004	<1.0 eV
WMAP+SDSS Lya	Seljak et al. 2004	**<0.43 eV**
Clusters+WMAP	Allen et al. 2004	$0.56^{+0.30}_{-0.26}$ eV

All upper limits 95%, but different assumed priors!

Conclusions

- Cosmological constraints on neutrino mass **(≤1eV total)** arise from ***power spectrum*** (but attention to priors)

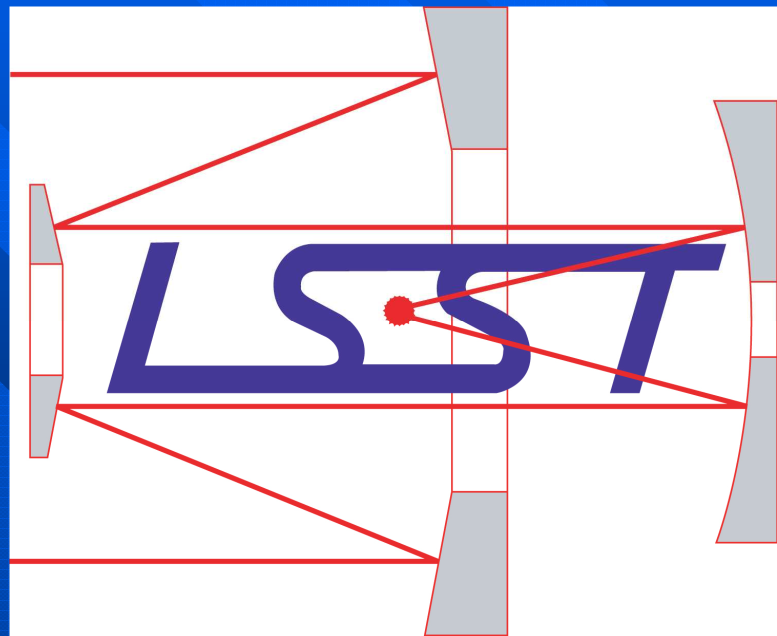
- Wide variety of techniques/experiments needed to eliminate **systematics/degeneracies**

- Physicists must become familiar with: inflation, CMB, LSS, dark energy, …

Future Galaxy Cluster Surveys

LSST (Large Synoptic Survey Telescope)

A proposed ground-based 8.4-meter telescope detecting galaxy clusters by their weak lensing signals.



Sky coverage: 18000 deg^2,
Number of clusters: 200,000;

($0.1 < z < 1.4$, $M_{min}=10^{13.7}h^{-1}M_{sun}$)

Future CMB Surveys

Planck Surveyor

Measurement of TT, EE and TE in three frequency bands.

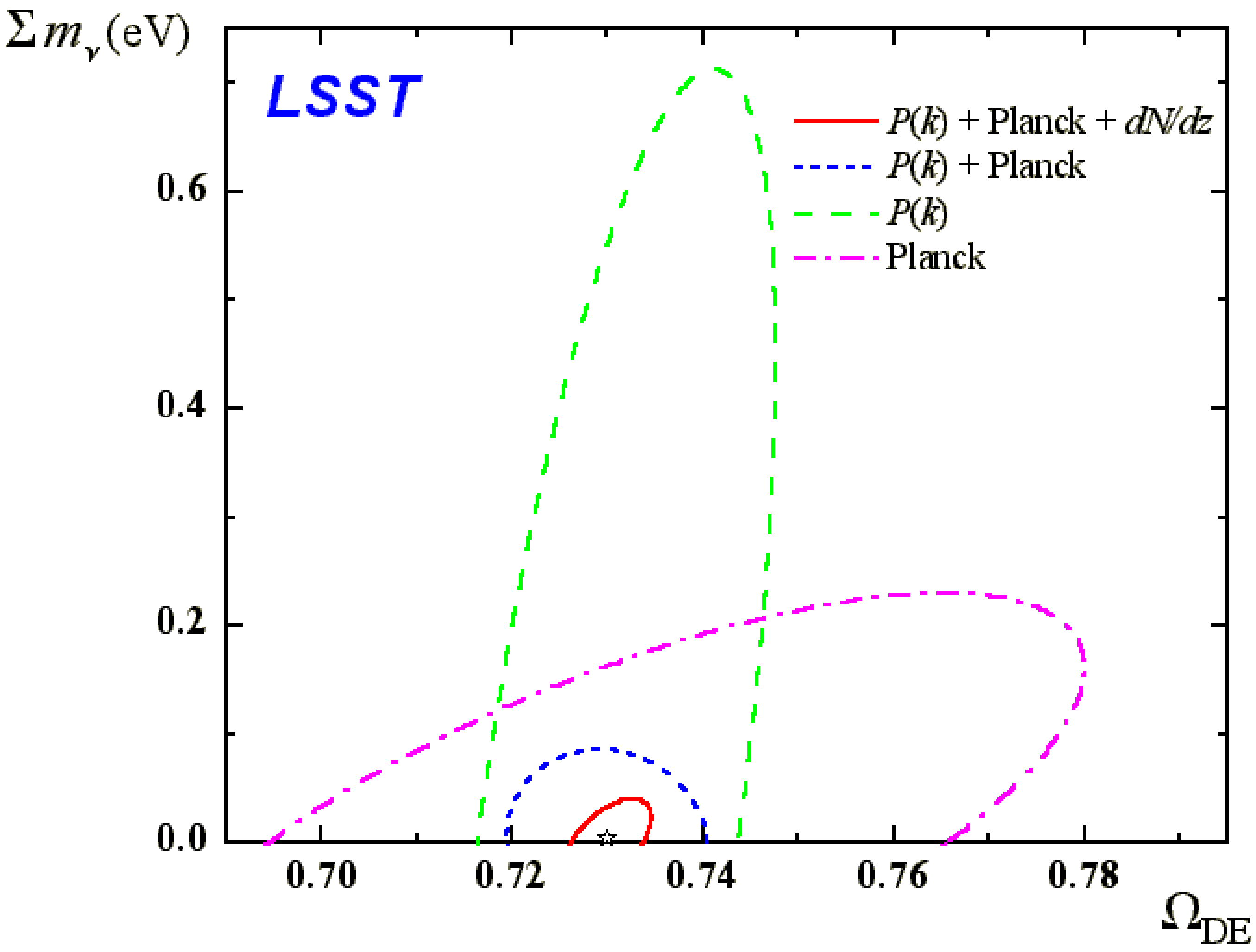
Constraints from CMB (unlensed) alone (1σ):

$$\Delta(w_a) \approx 1.0,$$

$$\Delta(\Sigma m_\nu) \approx 0.2\mathrm{eV};$$

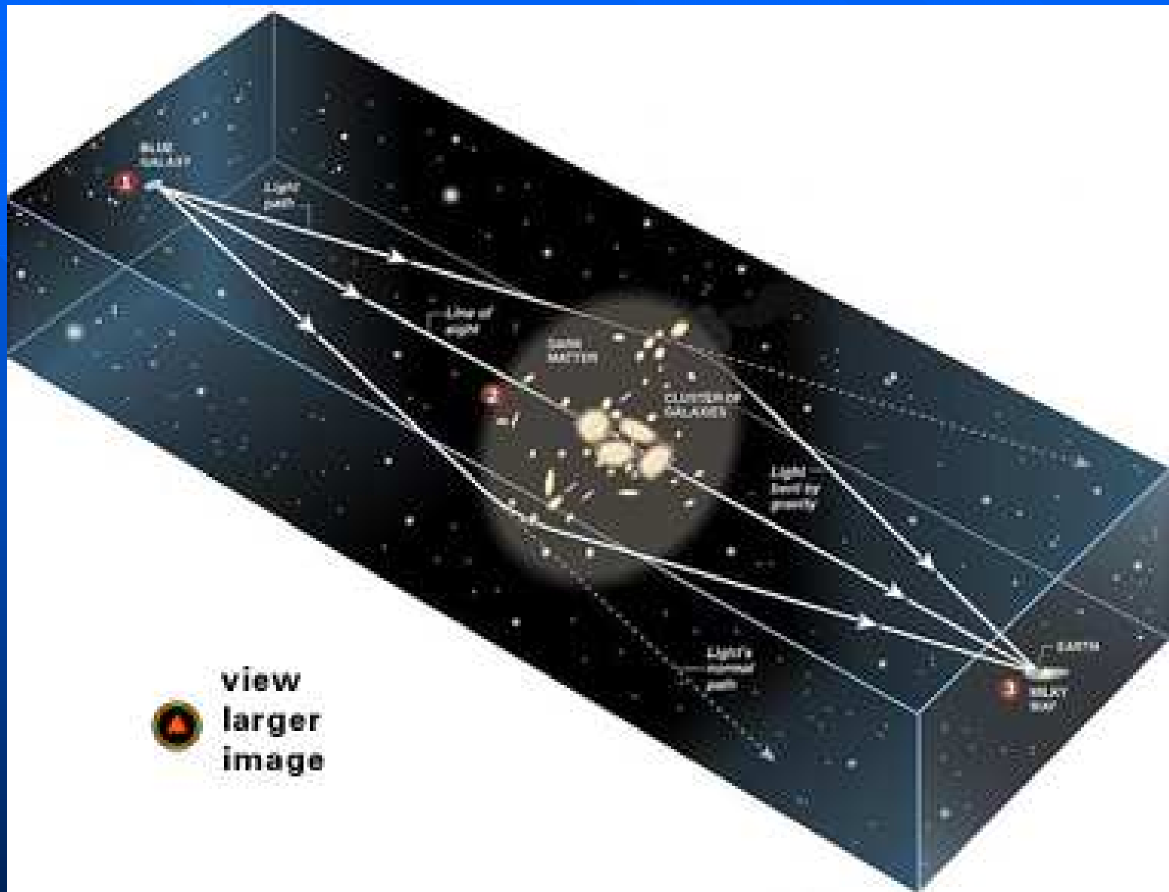
e.g. **Eisenstein, Hu & Tegmark (1999)**

Constraints from clusters will be complementary to those from cosmic microwave background (CMB) anisotropy measurement.



$\Delta(\Sigma m_\nu) \sim 0.04$ eV.   (LSST + Planck)

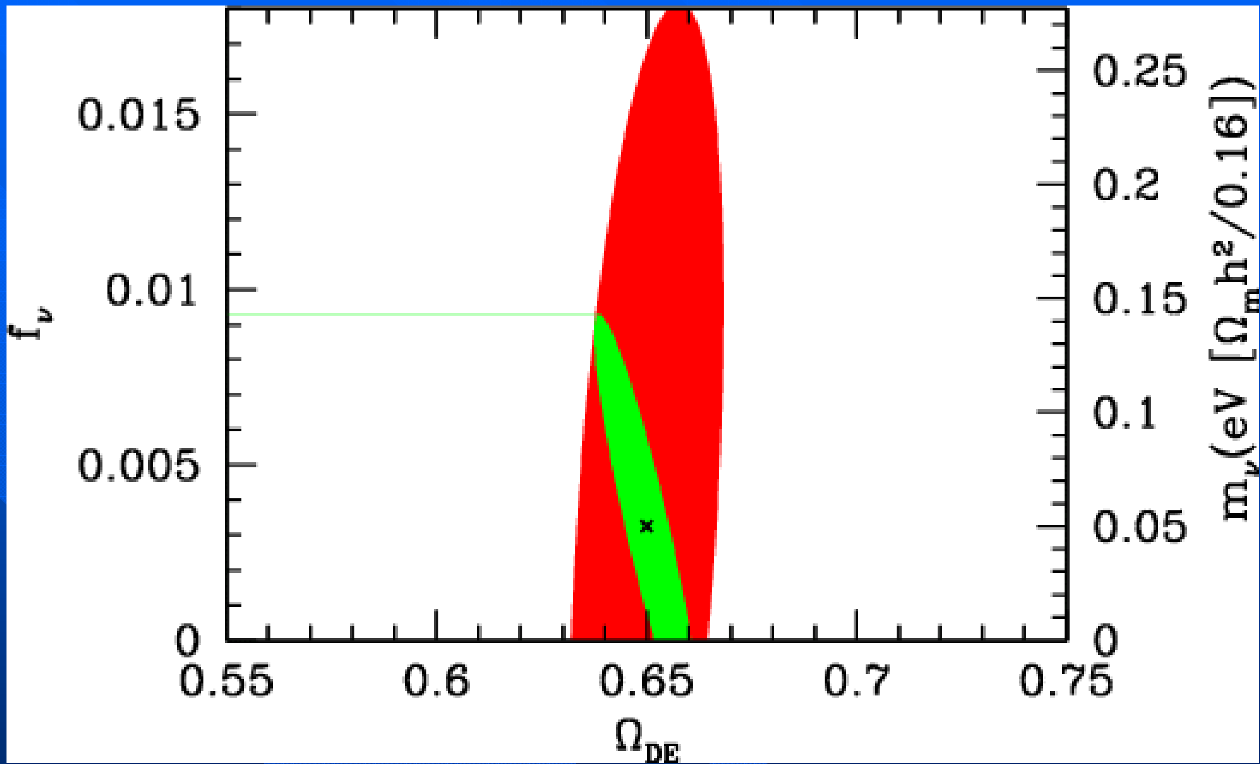
Weak Gravitational Lensing



Unlike galaxy surveys and Lyman alpha, lensing directly probes mass distribution!

Weak Lensing

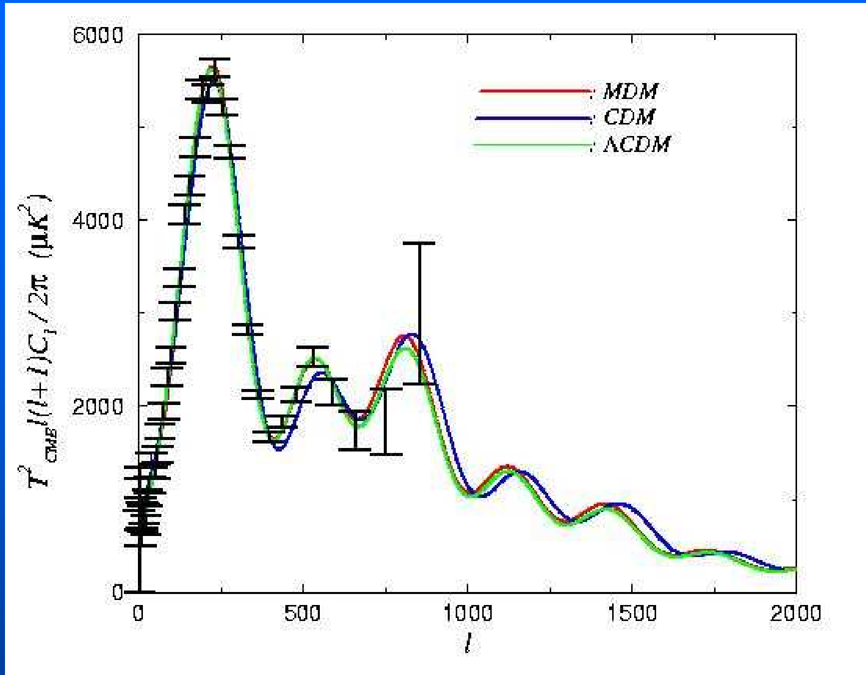
- Measure power spectrum AND/OR measure growth of spectrum at late time
- Sensitive to neutrino mass AND dark energy
- Ergo, accelerator neutrino experiments will teach us about dark energy!



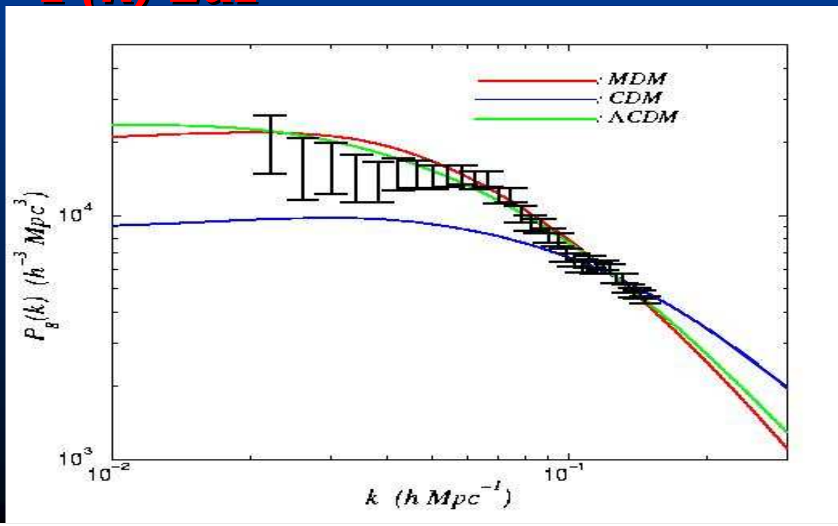
Abazajian & Dodelson (2002)

WMAP

Mixed Dark Matter?



P(k) 2dF

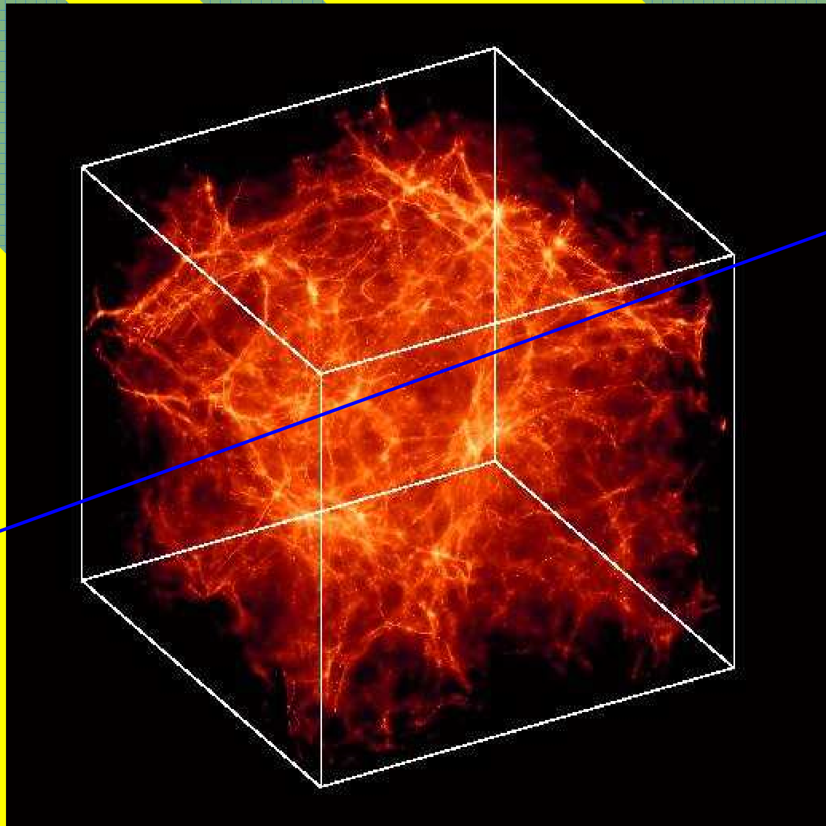


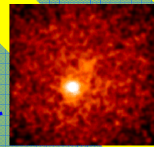
- Ω_m=1, Ω_ν=0.2, *h*=0.45

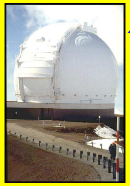
* Consistent with 2dF.
* To fit WMAP,
a **break** is required in the Primordial power-spectrum (e.g. Blanchard et al. 2003).

* Also at odds with HST's H_0, SNIa , cluster evolution and baryon fraction.

Elgaroy & Lahav, 2003



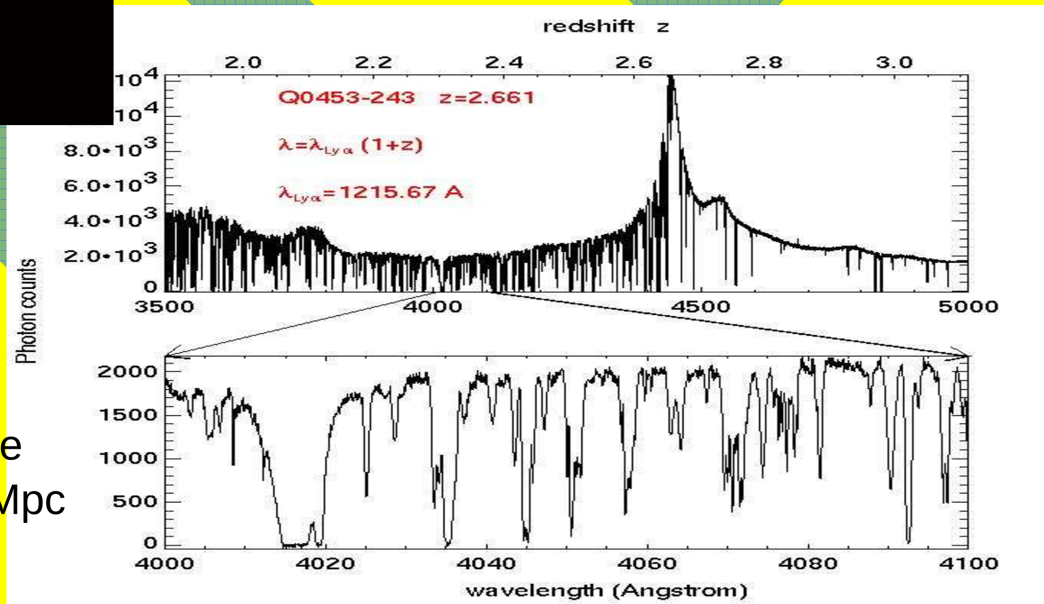




80 % of the baryons at z=3 are in the Lyman-α forest

(Rauch 1998)

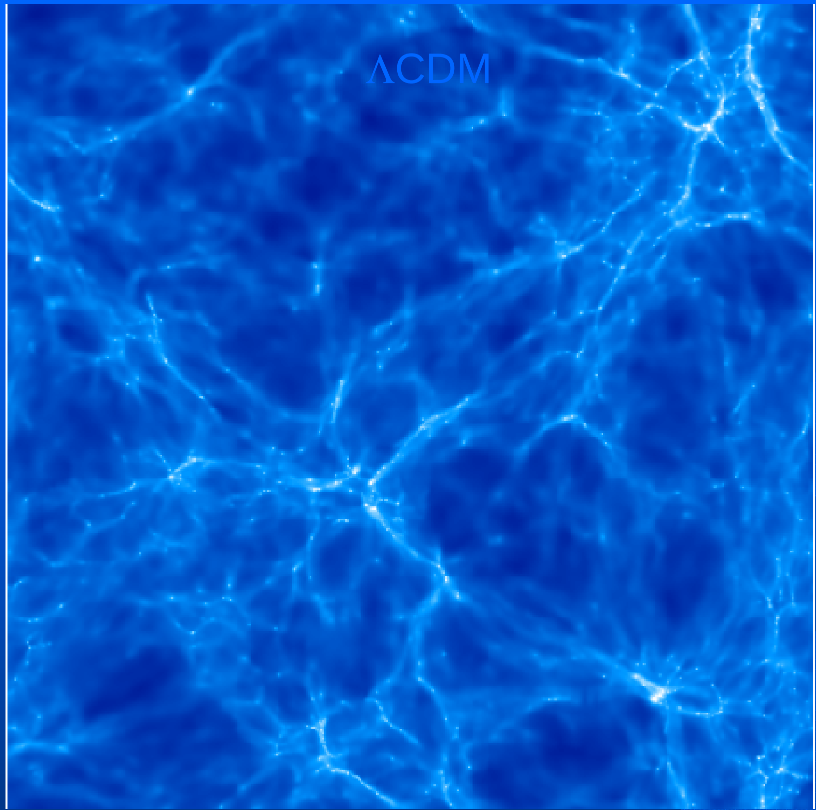
baryons as tracer of the dark matter density field

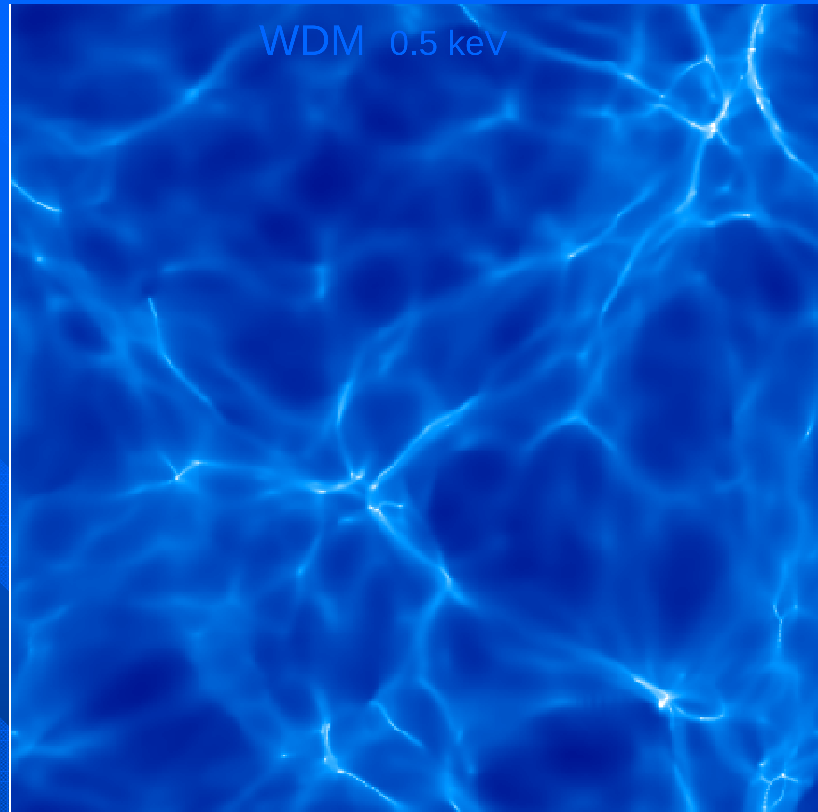


$\delta_{IGM} \sim \delta_{DM}$ at scales larger than the Jeans length ~ 1 com Mpc

$\tau \sim (\delta_{IGM})^{1.6}\, T^{-0.7} / \Gamma$

Cosmological implications: Warm Dark Matter particles-I





30 comoving Mpc/h z=3 gas distribution

In general

$k_{FS} \sim 5\, T_\nu/T_x\, (m_x/1\mathrm{keV})\, \mathrm{Mpc}^{-1}$

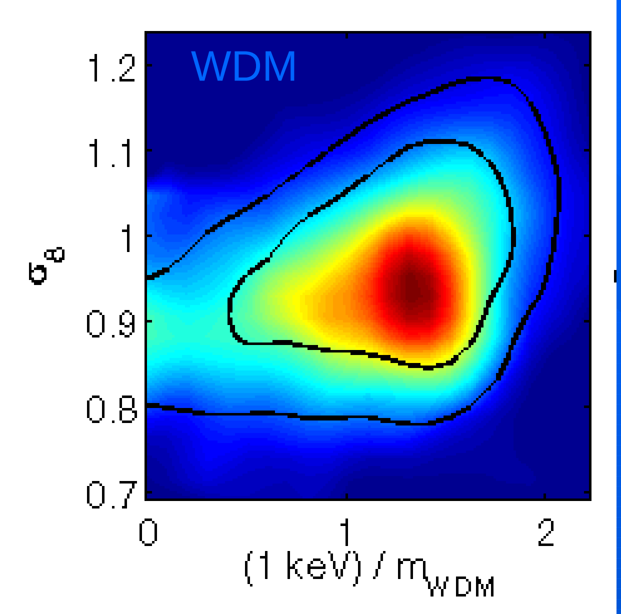
Set by relativistic degrees of freedom at decoupling

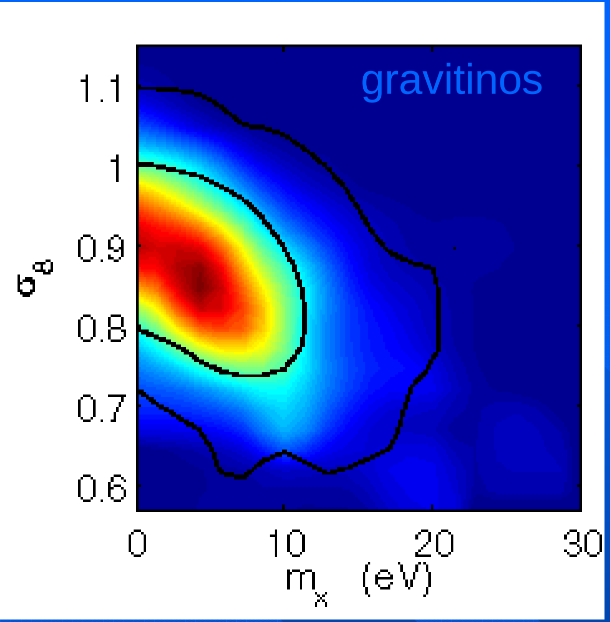
if light gravitinos

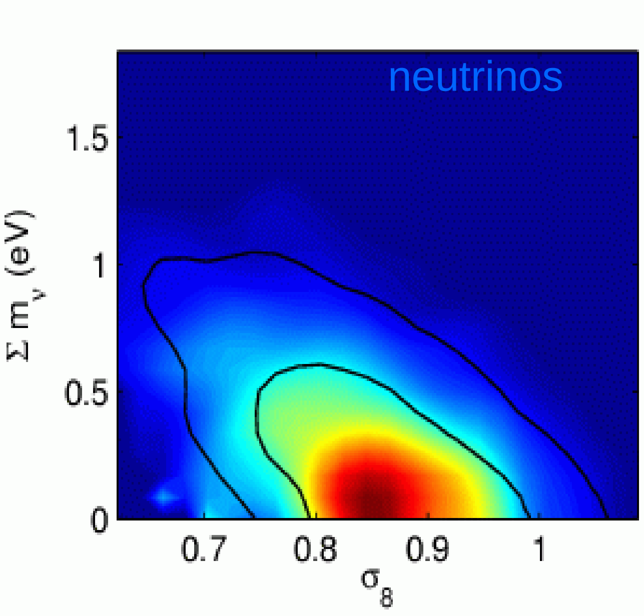
$k_{FS} \sim 1.5\ (m_x/100\mathrm{eV})\ h/\mathrm{Mpc}$

Viel, Lesgourgues, Haehnelt, Matarrese, Riotto, PRD, 2005, 71, 063534

Cosmological implications: WDM, gravitinos, neutrinos







m_{WDM} > 550 eV (2σ)

> 2keV sterile neutrino (2σ)

m_{grav} < 16 eV (2σ)

Σmν (eV) = 0.33 ± 0.27

WMAP + 2dF + LYα

	ΛWDM	ΛCWDM
$\Omega_x h^2$	0.124 ± 0.015	0.149 ± 0.019
$\Omega_B h^2$	0.024 ± 0.001	0.024 ± 0.001
h	0.72 ± 0.06	0.71 ± 0.06
τ	0.18 ± 0.09	0.17 ± 0.08
σ_8	0.96 ± 0.08	0.86 ± 0.09
n	1.01 ± 0.04	1.00 ± 0.04
α (Mpc/h)	0.06 ± 0.03	—
f_x	—	0.05 ± 0.04

Set limits on the scale of Supersymmetry breaking if gravitino is the LSP

Λ_{susy} < 260 TeV

SDSS gets < 0.45 at 95% C.L. (more observables)

Neutrinos and the large scale structure

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