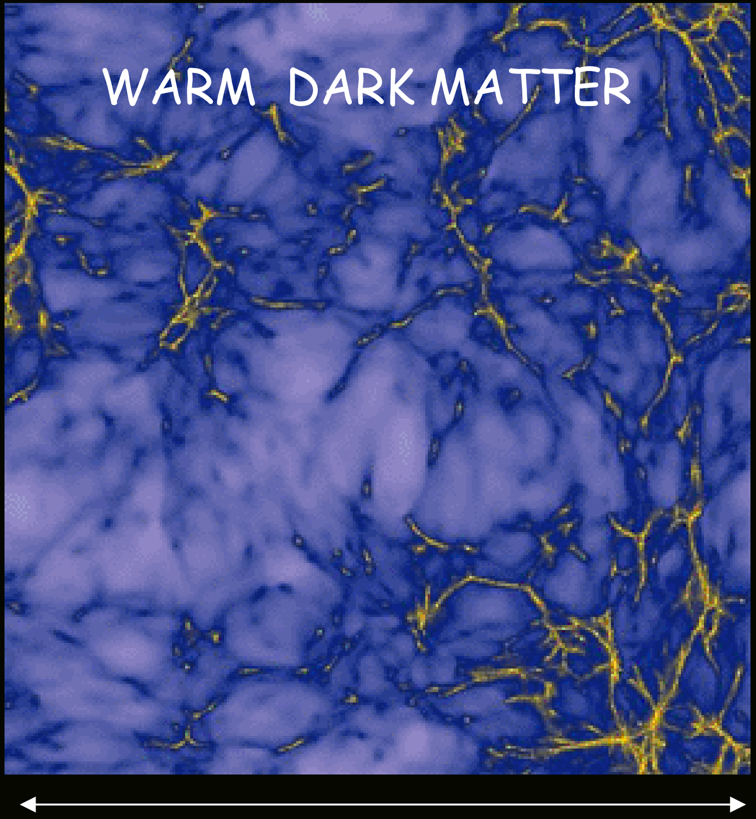
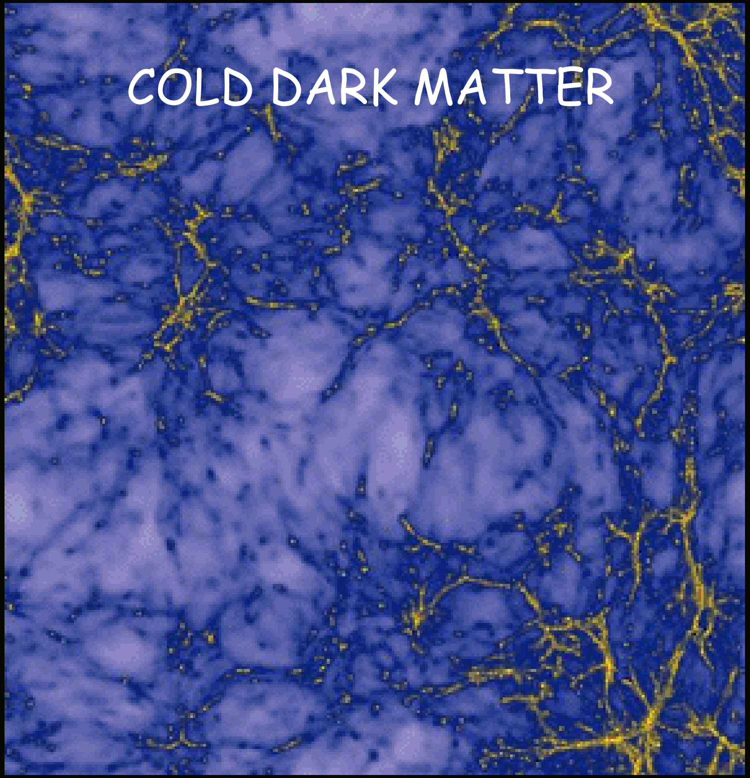
COSMOLOGY AND FUNDAMENTAL PHYSICS WITH THE INTERGALACTIC MEDIUM

MATTEO VIEL

INAF-OATS
and INFN-TS





IFAE – Naples (Italy) – 12th April 2007

PLAN OF THE TALK

- Introduction to the Lyman-α forest

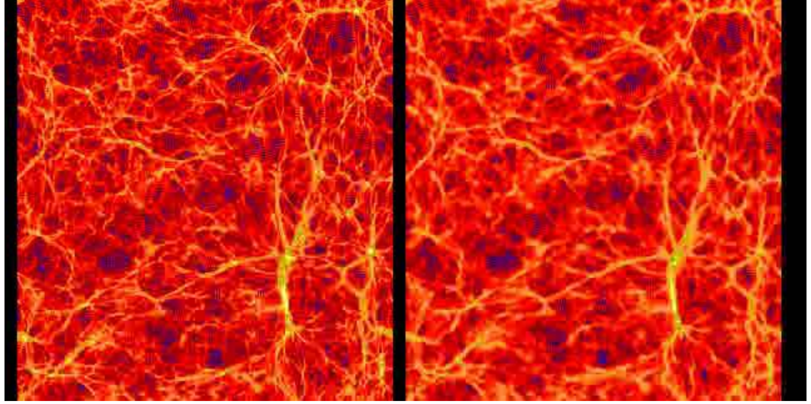
- Lyman-α forest and cosmological parameters

  σ_8 – n (amplitude and slope of the power spectrum)
  WMAP and large scale structure (Weak Lensing)

- Lyman-α forest and fundamental physics

  active neutrinos (hot dark matter – radiation)
  sterile neutrinos (warm dark matter)

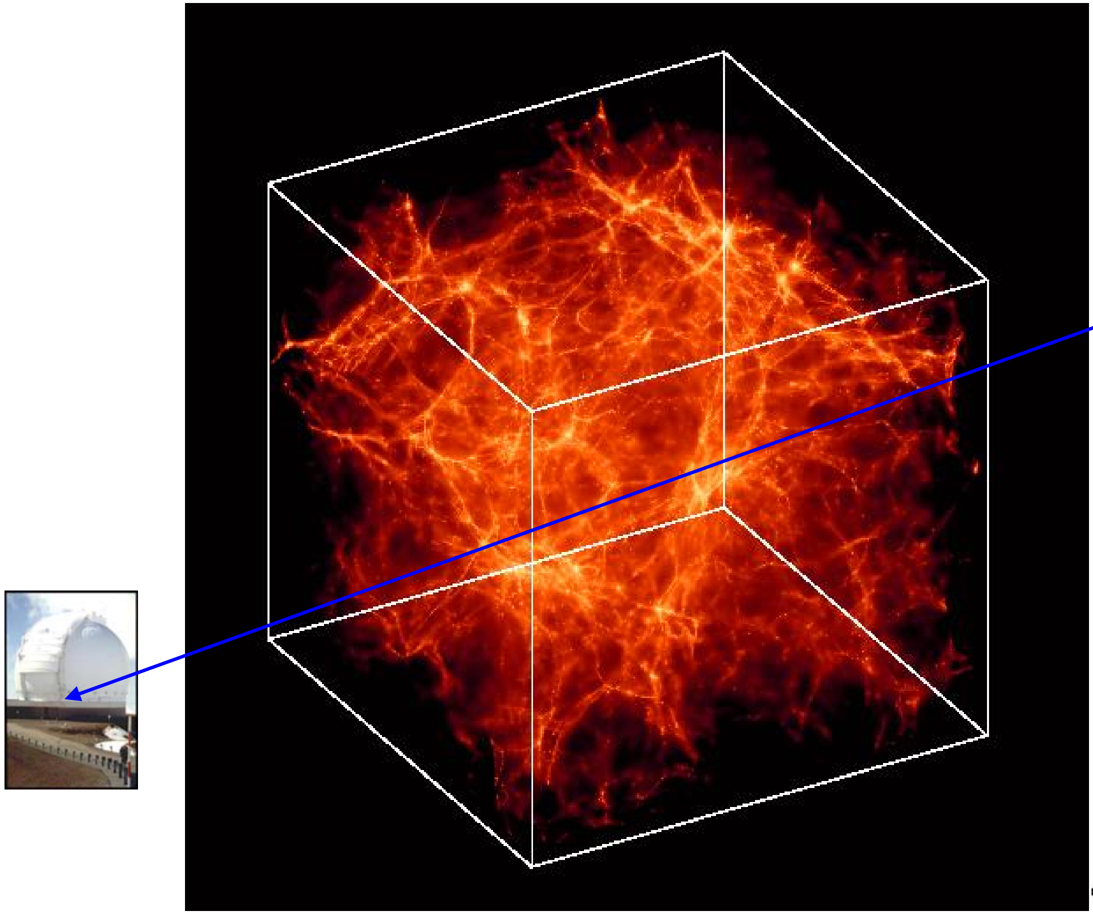
INTRO

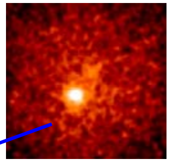


Physics of the simulations is simple: dark matter,
Gas cooling, photoionization heating, star formation

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

Bi & Davidsen (1997), Rauch (1998)

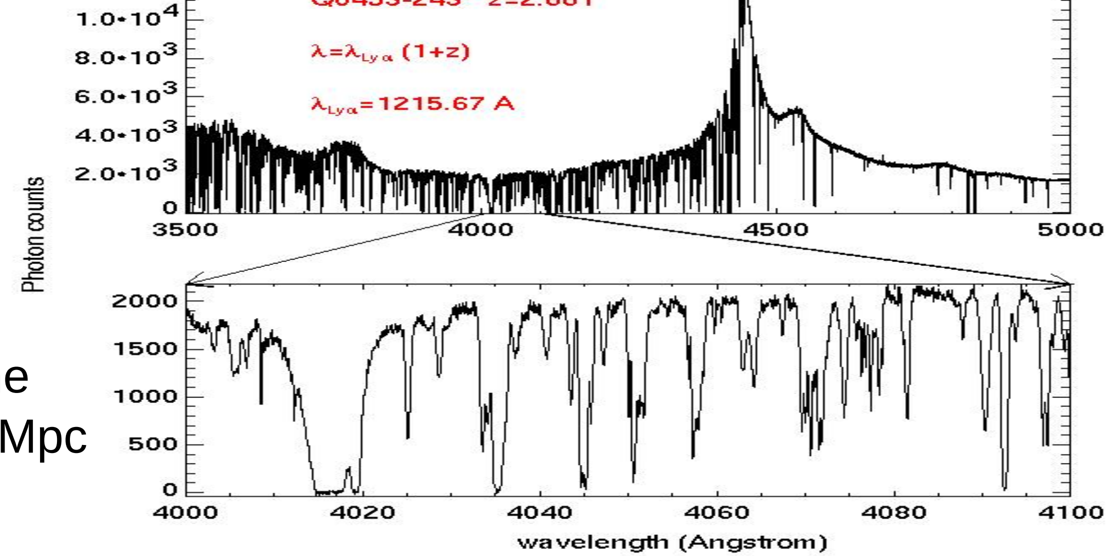




baryons as tracer of the dark matter density field

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

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



Modelling Lyman-α absorptions:

Dark matter evolution: linear theory of density perturbation +
Jeans length $L_J \sim \mathrm{sqrt}(T/\rho)$ + mildly non linear evolution

Hydrodynamical processes: mainly gas cooling
cooling by adiabatic expansion of the universe
heating of gaseous structures (reionization)

- photoionization by a uniform Ultraviolet Background
- Hydrostatic equilibrium of gas clouds

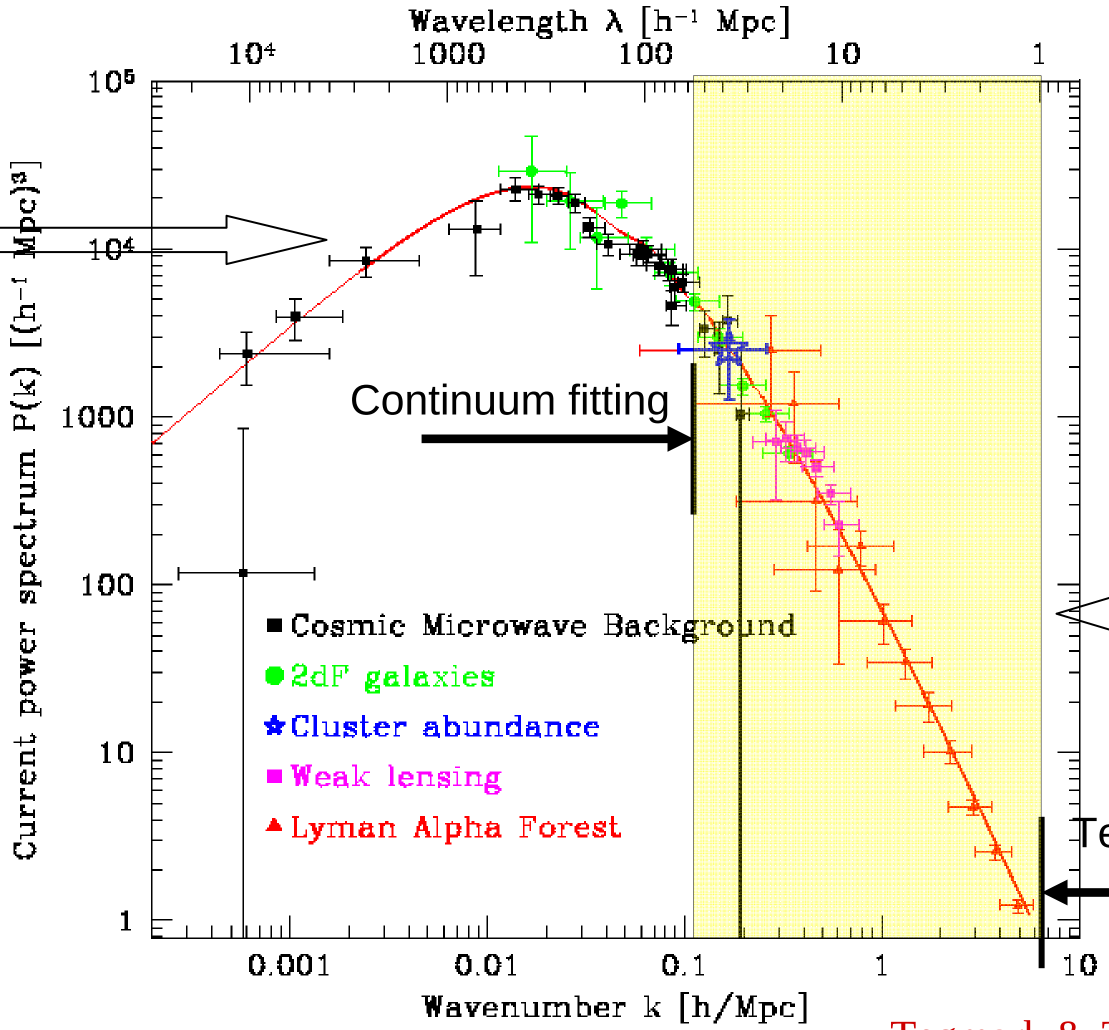
dynamical time = $1/\mathrm{sqrt}(G\,\rho) \sim$ sound crossing time= size /gas sound speed

Size of the cloud: > 100 kpc
Temperature: ~ 10^4 K
Mass in the cloud: ~ 10^9 M sun
Neutral hydrogen fraction: 10^{-5}

In practice, since the process is mildly non linear you need numerical simulations
To get convergence of the simulated flux at the percent level (observed)

GOAL: the primordial dark matter power spectrum from the observed flux spectrum

CMB physics
z = 1100
dynamics



Continuum fitting

Temperature, metals, noise

Lyα physics
z < 6
dynamics
+
termodynamics

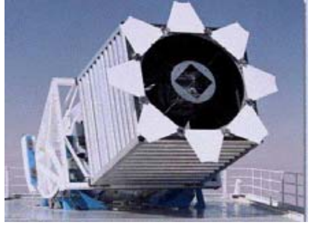
Tegmark & Zaldarriaga 2002

CMB + Lyman α ⟹ Long lever arm

Constrain spectral index and shape

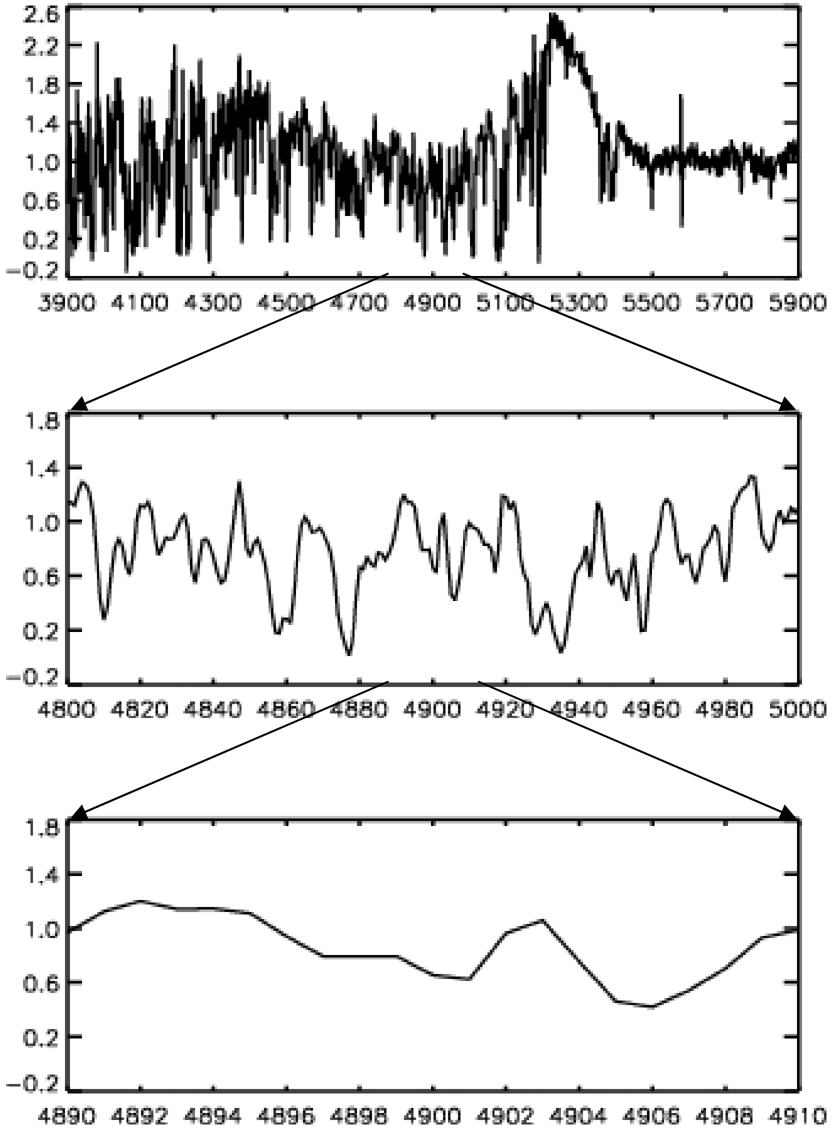
Relation: $P_{FLUX}(k)$ - $P_{MATTER}(k)$??

DATA



SDSS vs LUQAS

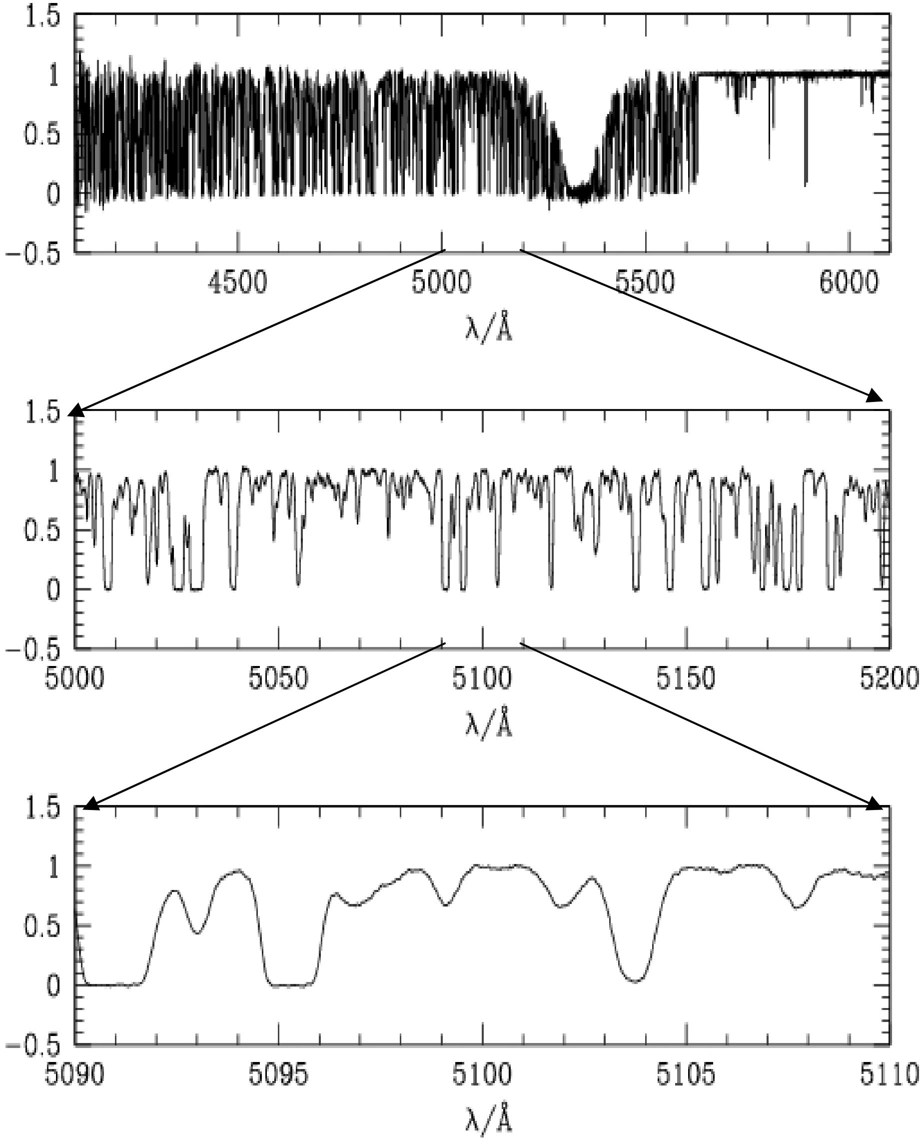
McDonald et al. 2006



SDSS

3000 LOW RESOLUTION LOW S/N

Kim, MV et al. 2004, MNRAS, 347, 355



LUQAS

30 HIGH RESOLUTION HIGH S/N

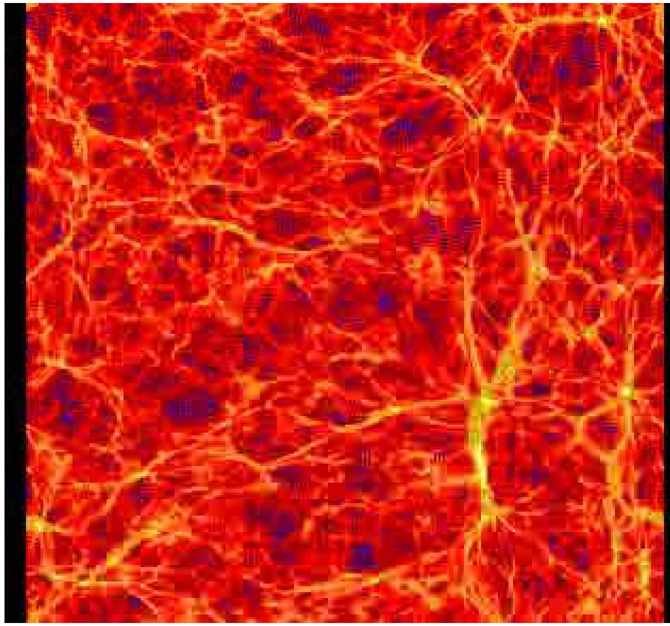
THEORY

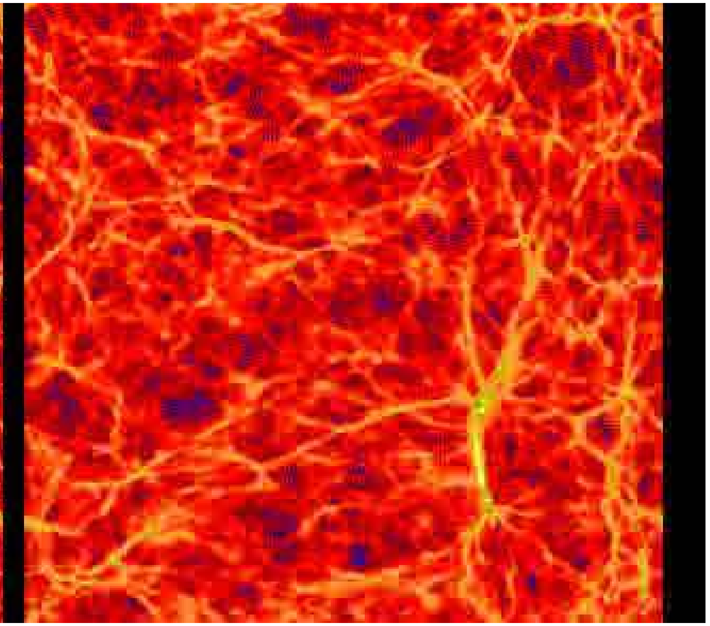
$\Omega_m = 0.26$ $\Omega_\Lambda = 0.74$ $\Omega_b = 0.0463$ $H_0 = 72$ km/sec/Mpc - 60 Mpc/h $2\text{x}400^3$ GAS+DM

2.5 com. kpc/h softening length

GADGET –II code COSMOS computer – DAMTP (Cambridge)

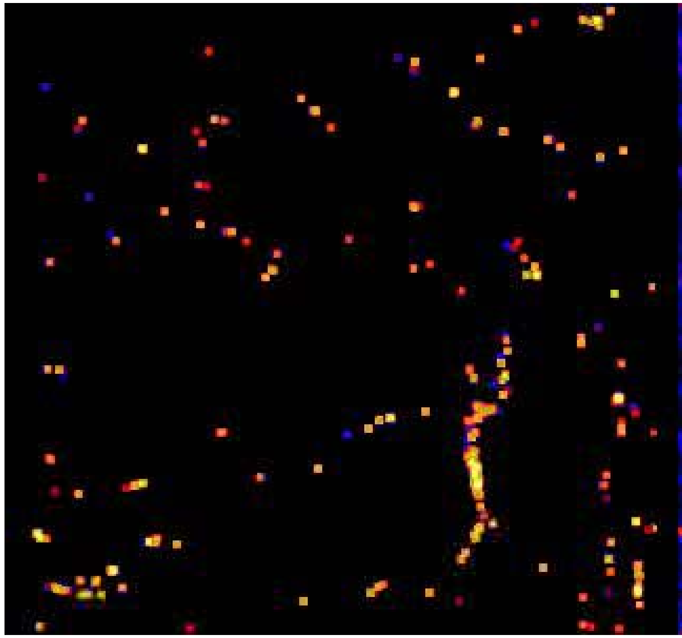
DM

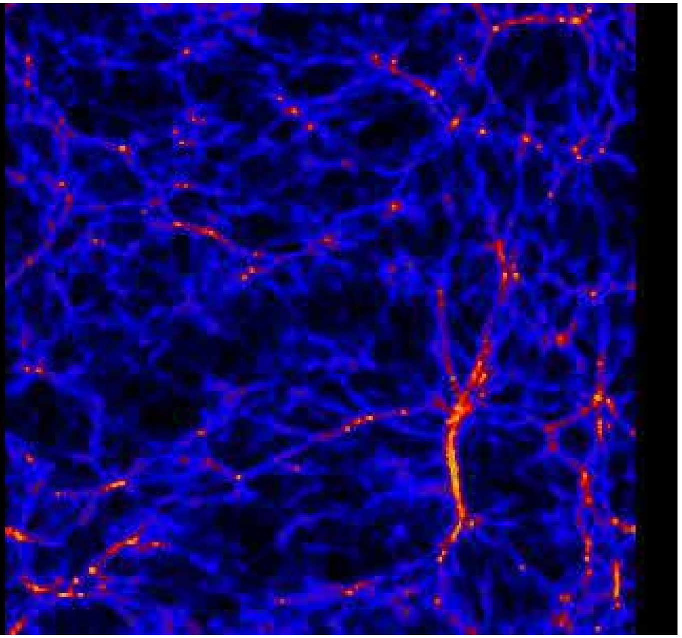




GAS

STARS



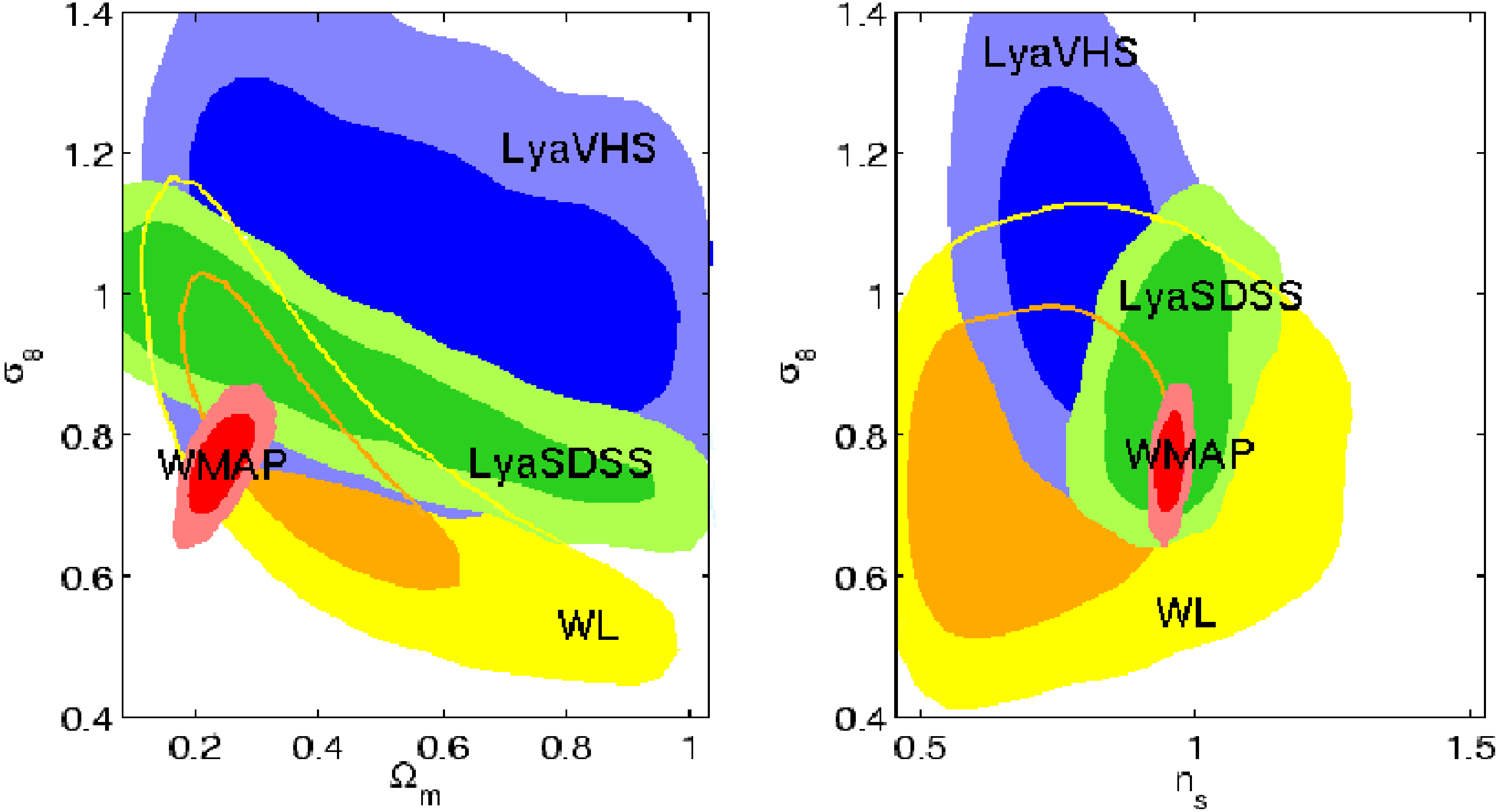


NEUTRAL
HYDROGEN

COSMOLOGICAL PARAMETERS

Lyman-α forest + Weak Lensing + WMAP3

VHS: high res Ly-a from Viel, Haehnelt, Springel 2004
SDSS: low res Ly-a from McDonald, Seljak et al. 2006
WL: COSMOS survey Weak Lensing (Massey et al. 2007)



AMPLITUDE

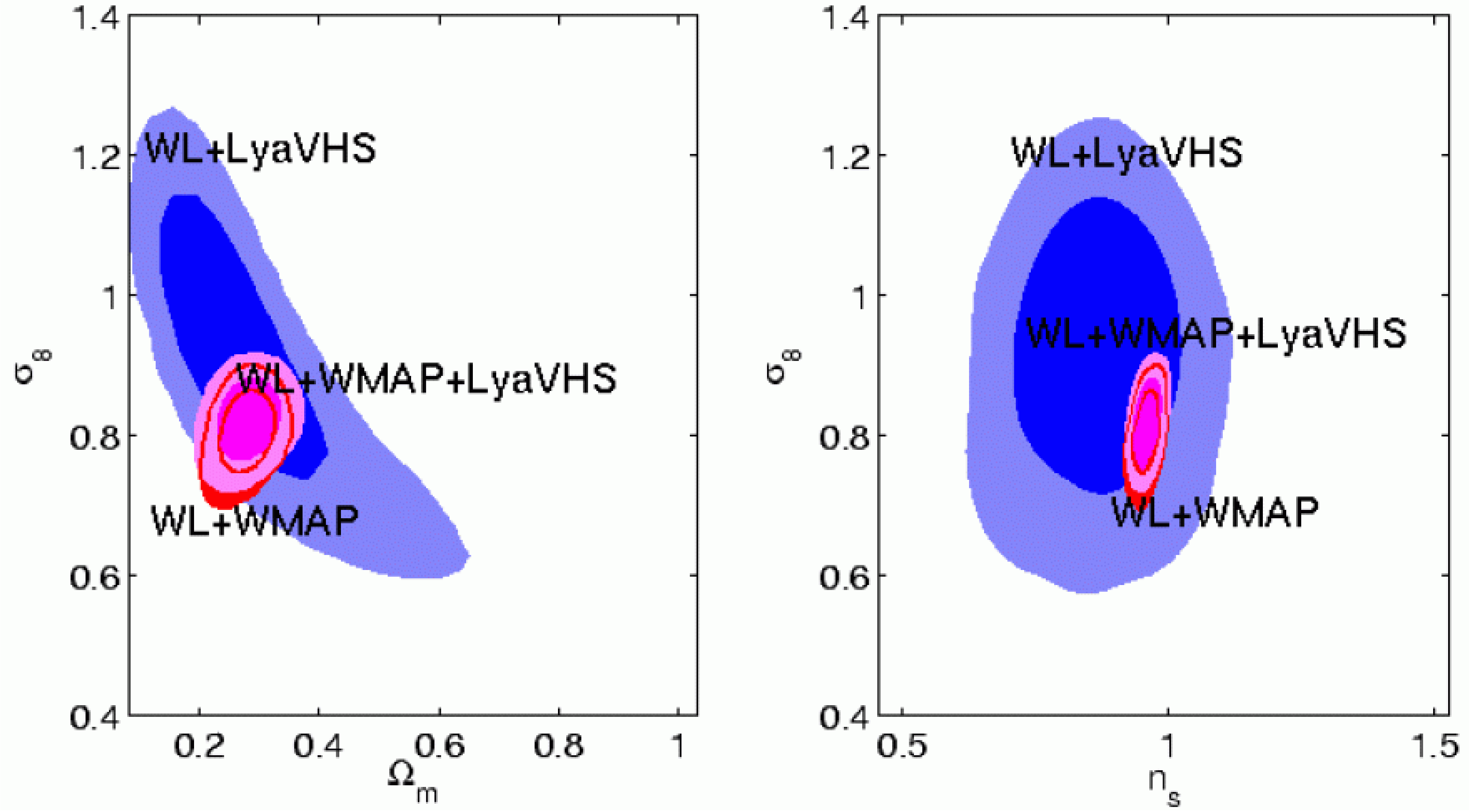
MATTER DENSITY

SPECTRAL INDEX

Viel , Haehnelt, Lewis, 2006, MNRAS, 370, 51L
Lesgourgues, MV, et al. 2007, in preparation

Lyman-α forest + Weak Lensing + WMAP3-II

VHS: high res Ly-a from Viel, Haehnelt, Springel 2004
WL: COSMOS survey Weak Lensing (Massey et al. 2007)



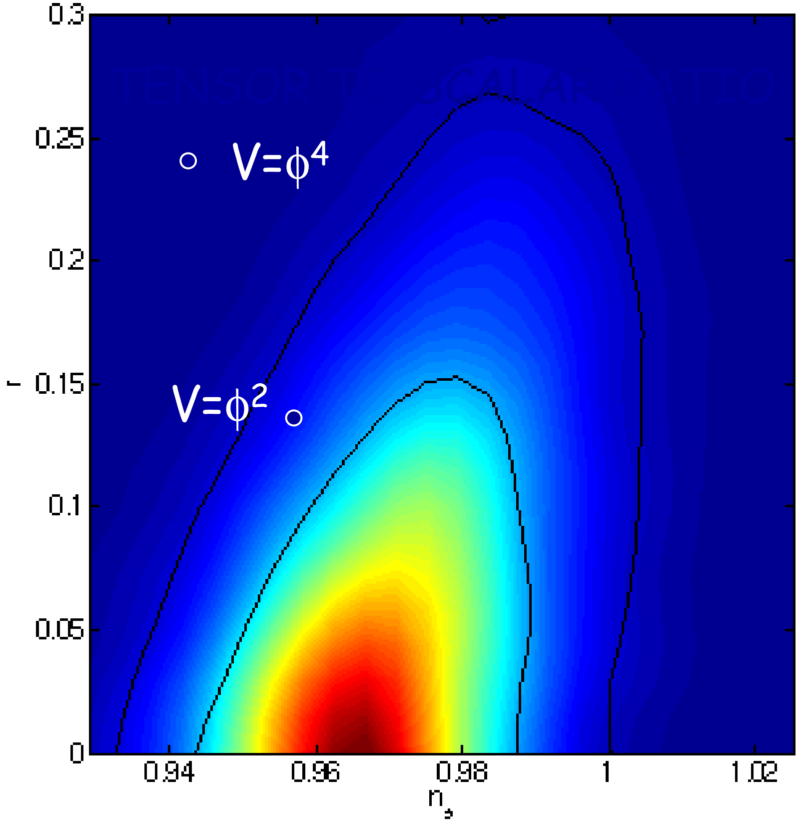
AMPLITUDE

MATTER DENSITY

SPECTRAL INDEX

Viel , Haehnelt, Lewis, 2006, MNRAS, 370, 51L
Lesgourgues, MV, et al. 2007, in preparation

Lyman-α forest + CMB - II



Signature of gravitational waves (tensors)
And inflation

n, r and dn/dlnk are related to the inflaton potential and its derivatives

$\Sigma m\nu$ (eV) < 0.68 (95 %C.L.)
r < 0.55 (95 % C.L.)
running = -0.055 ± 0.03

WMAP3 only

Seljak, Slosar. McDonald, 2006, JCAP, 0610, 014

WARM DARK MATTER

(Some) Motivations

- Some problems for cold dark matter at the small scales: 1- too **cuspy cores**,
  2- too **many satellites**, 3- **dwarf galaxies** less clustered than bright ones
  (e.g. Bode, Ostriker, Turok 2001)

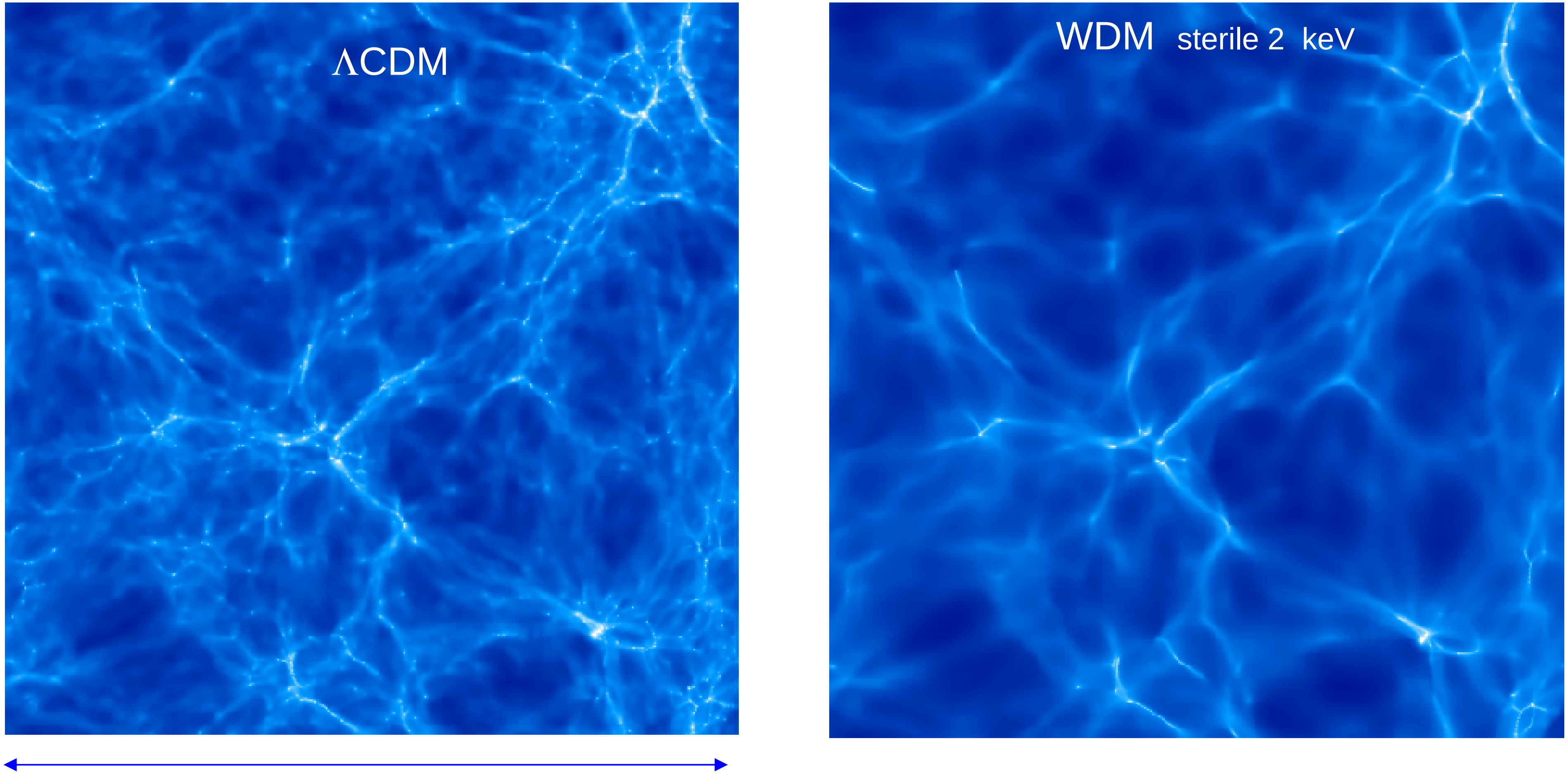
Although be aware that 1- **astrophysical processes** can act as well to alleviate these problems (feedback); 2- number of **observed satellites** is increasing (SDSS data); 3- galaxies along filaments in warm dark matter sims is probably a **numerical artifact**

- **Minimal extension of the Standard Model** for particle physics that accommodates neutrino oscillations naturally

Hints of a ster?le sector: LSND experiment prefers a sterile neutrino $m_{\nu} < 1$ eV
but Lyman-α data $m_{\nu} < 0.26$ eV
and best fit N eff (active) = 5.3

Although be aware that LSND results are controversial and that Lyman-α data that wish to probe the subeV limits are prone to systematic effects

Lyman-α and Warm Dark Matter



30 comoving Mpc/h z=3

See Bode, Ostriker, Turok 2001
Abazajian, Fuller, Patel 2001

In general

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

Set by relativistic degrees of freedom at decoupling

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

METHOD

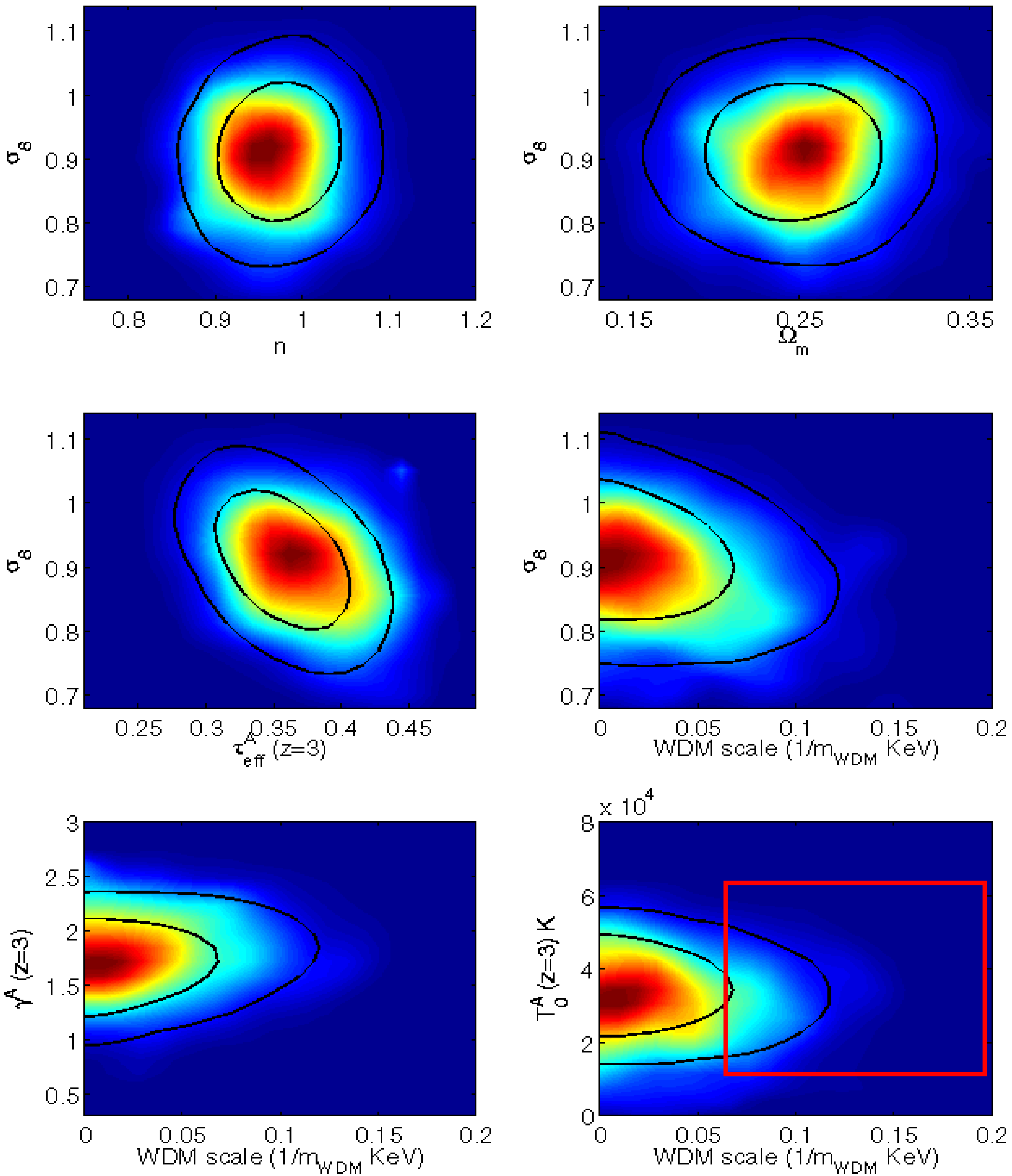
Lyman-α forest

Flux power

$$P_F(k, z; \mathbf{p}) = \underbrace{P_F(k, z; \mathbf{p}^0)}_{\text{Best fit}} + \sum_{i=1,N} \left. \frac{\partial P_F(k, z; p_i)}{\partial p_i} \right|_{\mathbf{p} = \mathbf{p}^0} (p_i - p_i^0)$$

p: astrophysical and cosmological parameters

but even resolution and/or box size effects if you want to save CPU time



Fitting SDSS data with
GADGET-2
this is SDSS Ly-α
only !!

M sterile neutrino > 10 KeV
95 % C.L.

SDSS data only

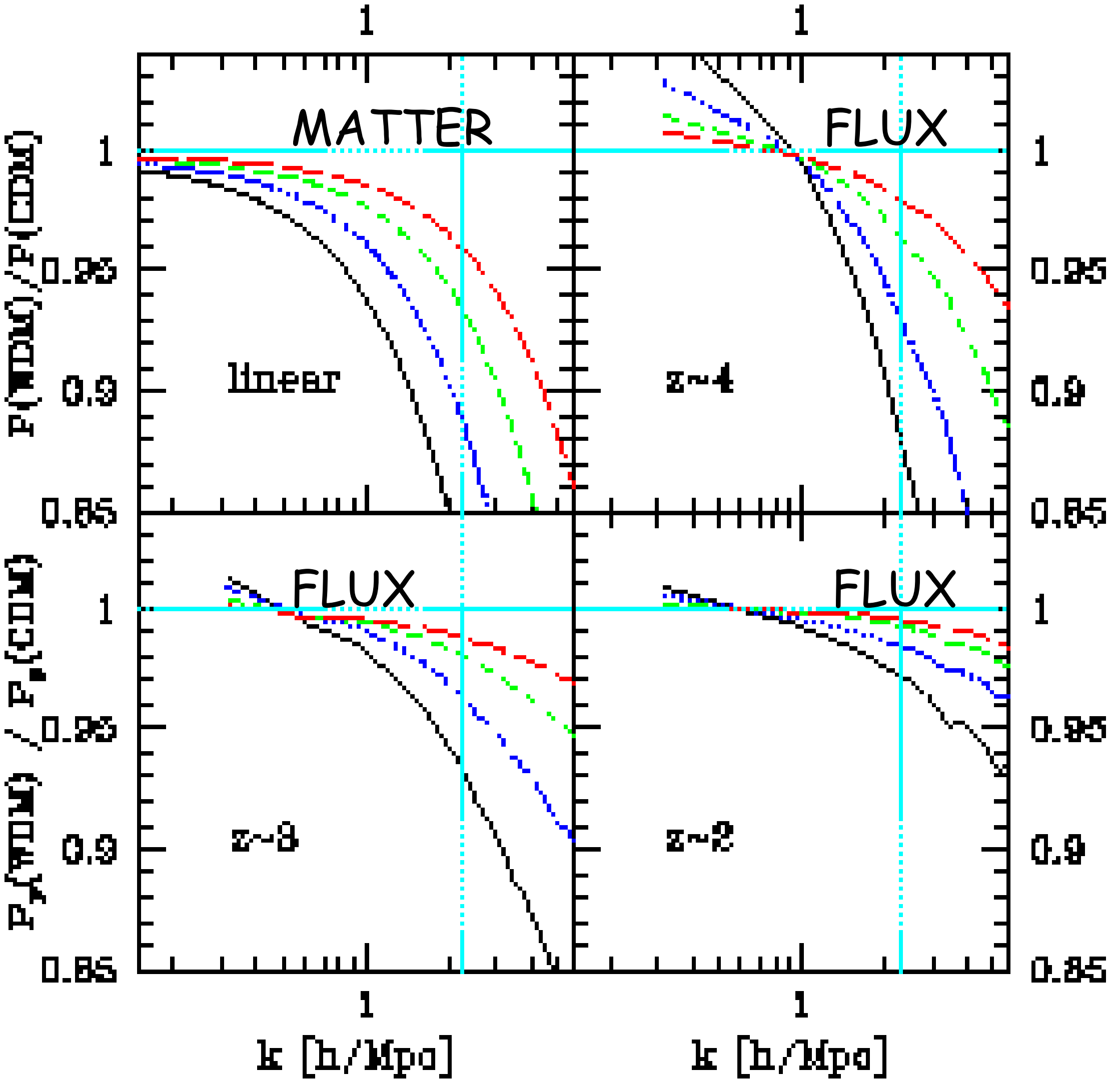
σ_8 = 0.91 ± 0.07
n = 0.97 ± 0.04

RESULTS

STERILES

Warm dark matter

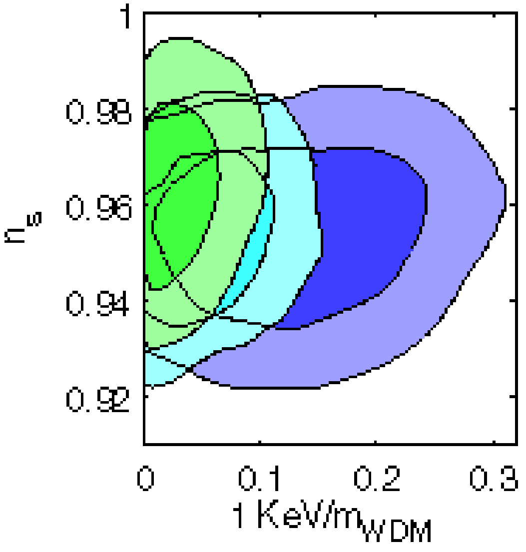
Lyman-α and Warm Dark Matter

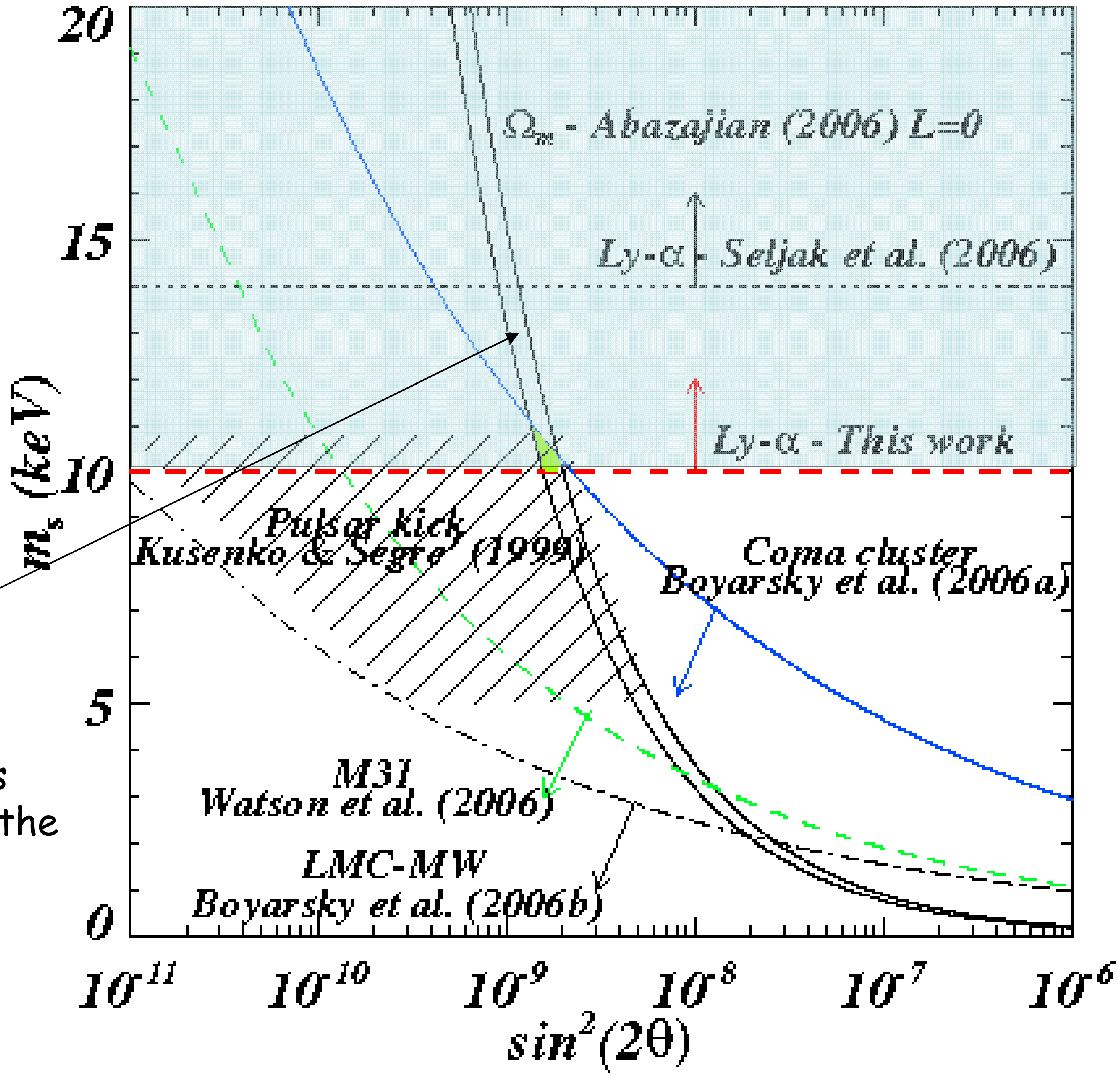


Seljak et al. 2006

m_{WDM} > 2 keV thermal
> 14 keV sterile neutrino

Lyα-WDM: new analysis of the SDSS data





$L_\nu = 0$

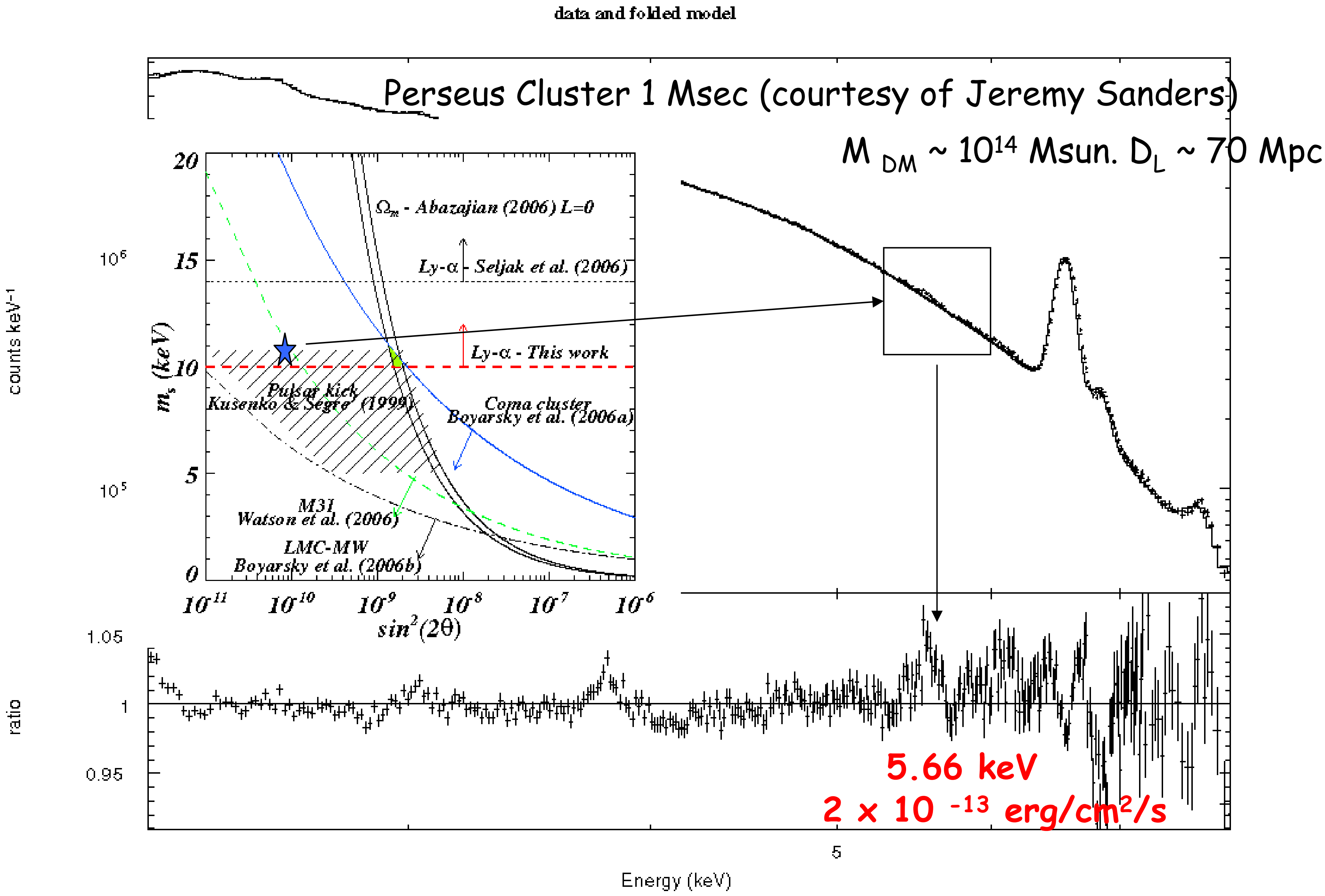
Leptonic number is conserved: this is the standard case

Viel, Lesgourgues, Haehnelt, Matarrese, Riotto, Phys.Rev.Lett., 2006, 97, 071301

X-RAY DETECTABILITY

Fabian, Sanders and coworkers.....

Decaying channel into photons and active neutrinos line with $E=m_s/2$ (X-band)



Perseus Cluster 1 Msec (courtesy of Jeremy Sanders)

$M_{DM} \sim 10^{14}$ Msun. $D_L \sim 70$ Mpc

5.66 keV

2×10^{-13} erg/cm²/s

Line flux ~ 5×10^{-18} erg cm $^{-2}$ s $^{-1}$ $(D_L/1\mathrm{Mpc})^{-2}$ $(M_{DM}/10^{11}\ M_{sun})$ $(\sin^2 2\theta/10^{-10})$ $(m_s/1\mathrm{kev})^5$

$\Delta E_{line} = v_{virial} E/c$ ~ 50 eV for a galaxy cluster 5 eV for a galaxy for E=5keV

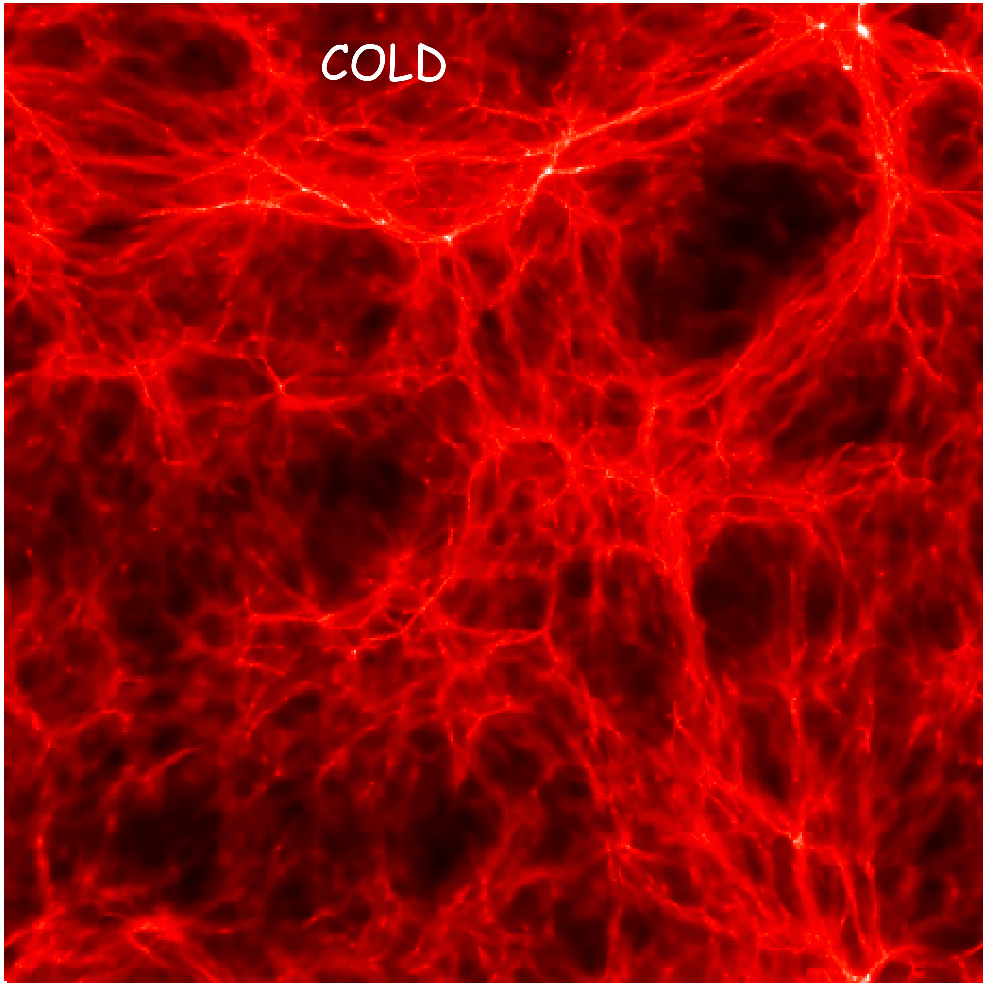
Note that the **EDGE (NASA proposal)** Low Energy Telescope will be at < 3(1.6) keV with a resolution of 1 eV So if the sterile neutrino is more massive than 10 keV it might not be seen by EDGE

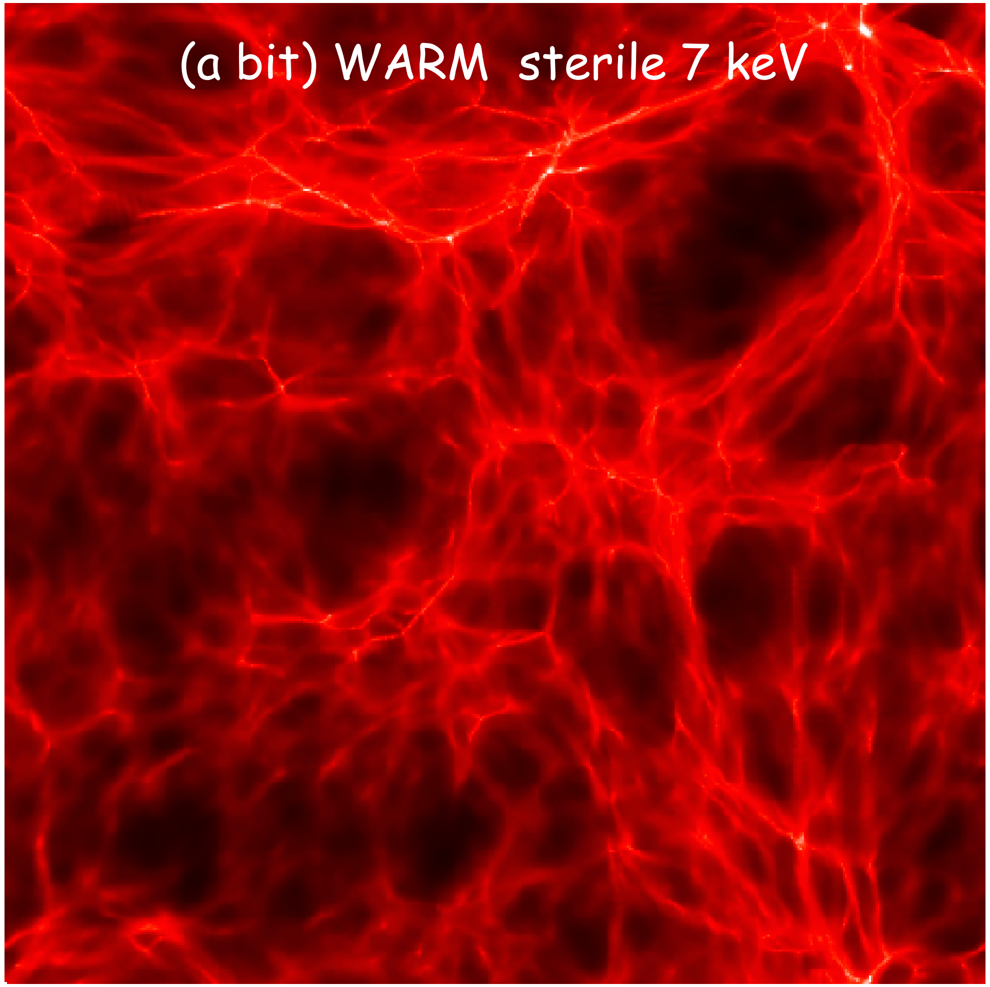
$\Delta E_{Xraybackground} \sim E$

SENSITIVITY of DETECTION ~ $1/\sqrt{(\Delta E)}$, $\sqrt{(A\ eff)}$, $\sqrt{FOV}$,

Note that both clusters and dwarf galaxies are about 1deg^2 in the sky having a larger field of view will not improve things dramatically

See Boyarsky, den Herder, Neronov, Ruchayskiy, 2006, astro-ph/0612219

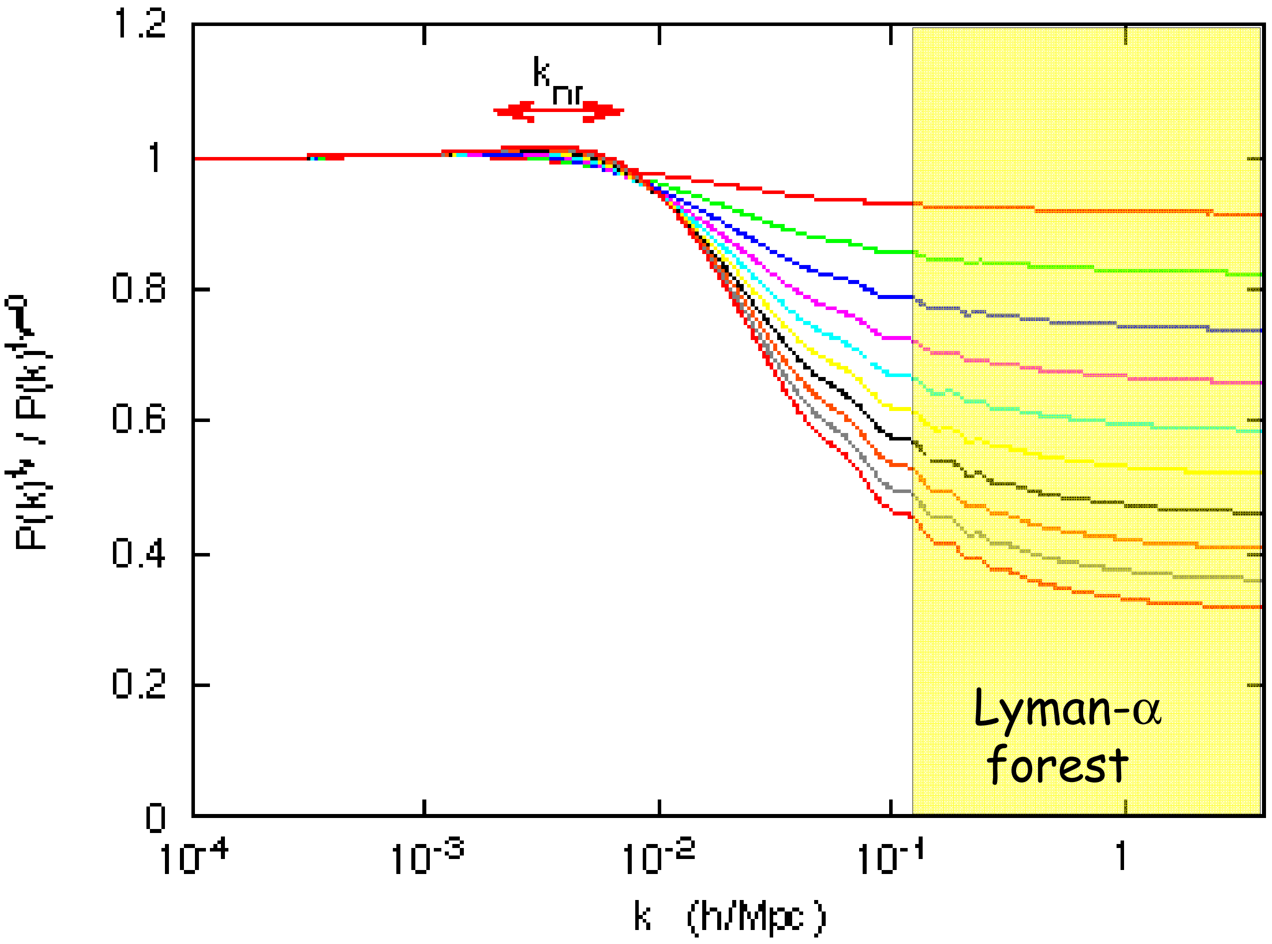

COLD


(a bit) WARM sterile 7 keV

RESULTS

ACTIVE

Active neutrinos - I

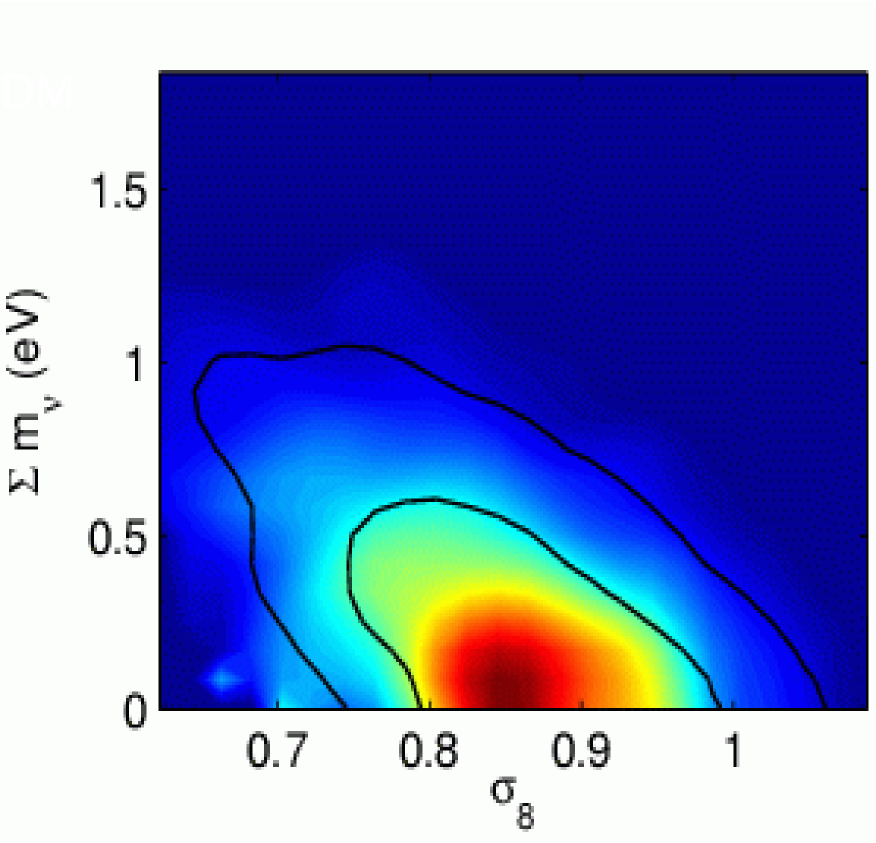


$\Sigma m_\nu = 0.138$ eV

$\Sigma m_\nu = 1.38$ eV

Lesgourgues & Pastor 2006

Active neutrinos and Lyman-α VHS

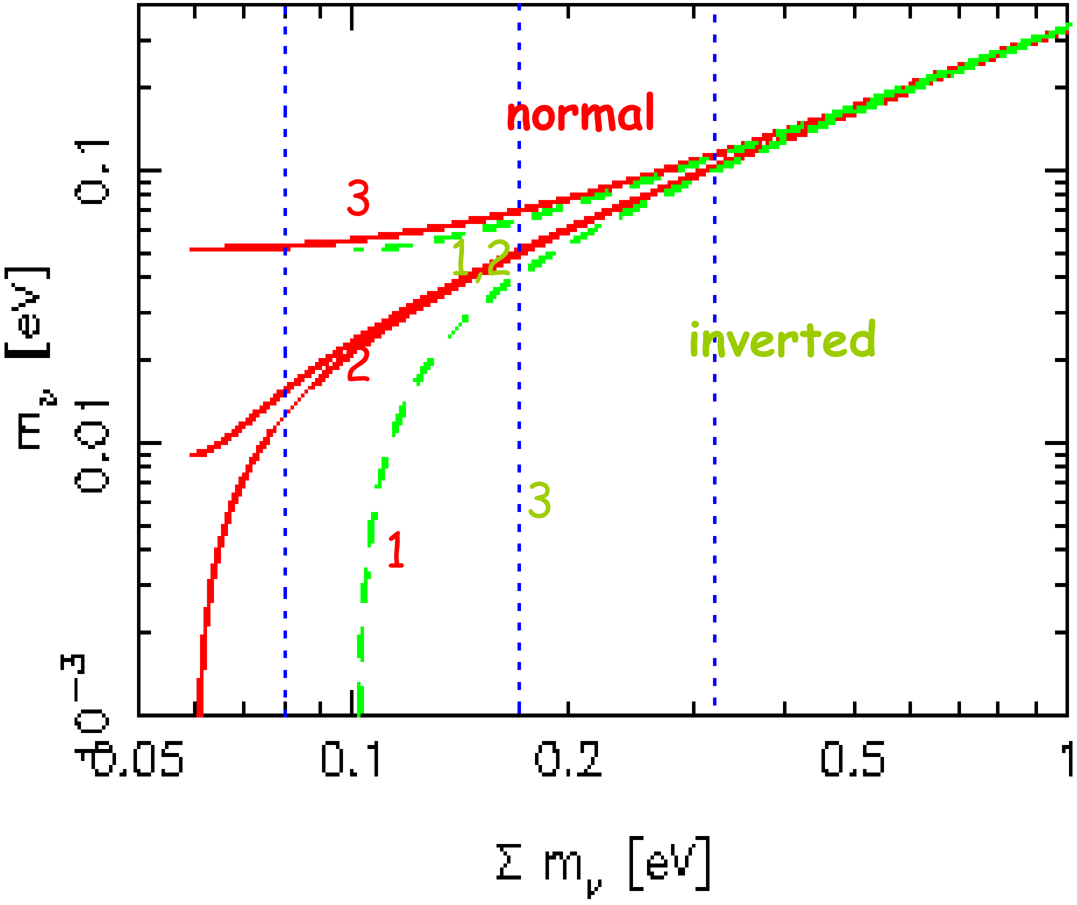


Σmν (eV) < 1 eV (95 % C.L.)
WMAP1 + 2dF + LYα

Good agreement with the latest Tegmark et al. results…..

Active neutrinos and Lyman-α SDSS - III

Seljak, Slosar. McDonald, 2006, JCAP, 0610, 014



Tight constraints because data
Are marginally compatible

$\Sigma m\nu$ (eV) < 0.17 (95 %C.L.)

r < 0.22 (95 % C.L.)

running = -0.020 ± 0.12

CMB + SN + SDSS gal+ SDSS Ly-α

Goobar et al. (aph/0602155) get upper limits 2-3 times larger……

SUMMARY

- Lyman-α forest is a complementary measurement of the matter power spectrum and can be use to constrain cosmology together with the CMB
There are no other observables at the forest scales and redshifts

- Sterile neutrino probably ruled out in the standard production mechanism
Tight constraints on active neutrinos

- All(?) the possible systematics are under control: there is really significant Power at these scales and redshifts (Weak lensing data support this)