Neutrinos and the observational cosmology

IPMU Neutrino Focus week, March 08

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Introduction

- Purpose: introduction to neutrinos/LyA limits from cosmology
- relativistic components in the universe
- comment on recent results from WMAP
- motivate matter power spectrum as crucial observable
- Lyman alpha forest and comparison to galaxy power spectrum
- challenges to Lyman-alpha

Neutrinos in cosmology

- Assuming massless, they are like photons but
  - fermions rather than bosons:
    - Contribute 7/8 of energy density at the same temperature
  - decouple before electron - positron annihilation:
    - Their temperature can be calculated assuming conservation of entropy, one gets

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

or 56/cm^3 <- cf 10^10/cm^3 for direct detection

Neutrinos in cosmology

- Next assume they are massive, but light enough so that they were still ultra-relativistic at the time of decoupling
- Their energy density today is

  number density x mass x c squared
- Hence, one can derive:

$$\omega_\nu = \Omega_\nu h^2 = \frac{\sum_i m_i}{92.4\,\mathrm{eV}}$$

- **Need 16 eV per neutrino species to close the Universe!**

Neutrinos in cosmology

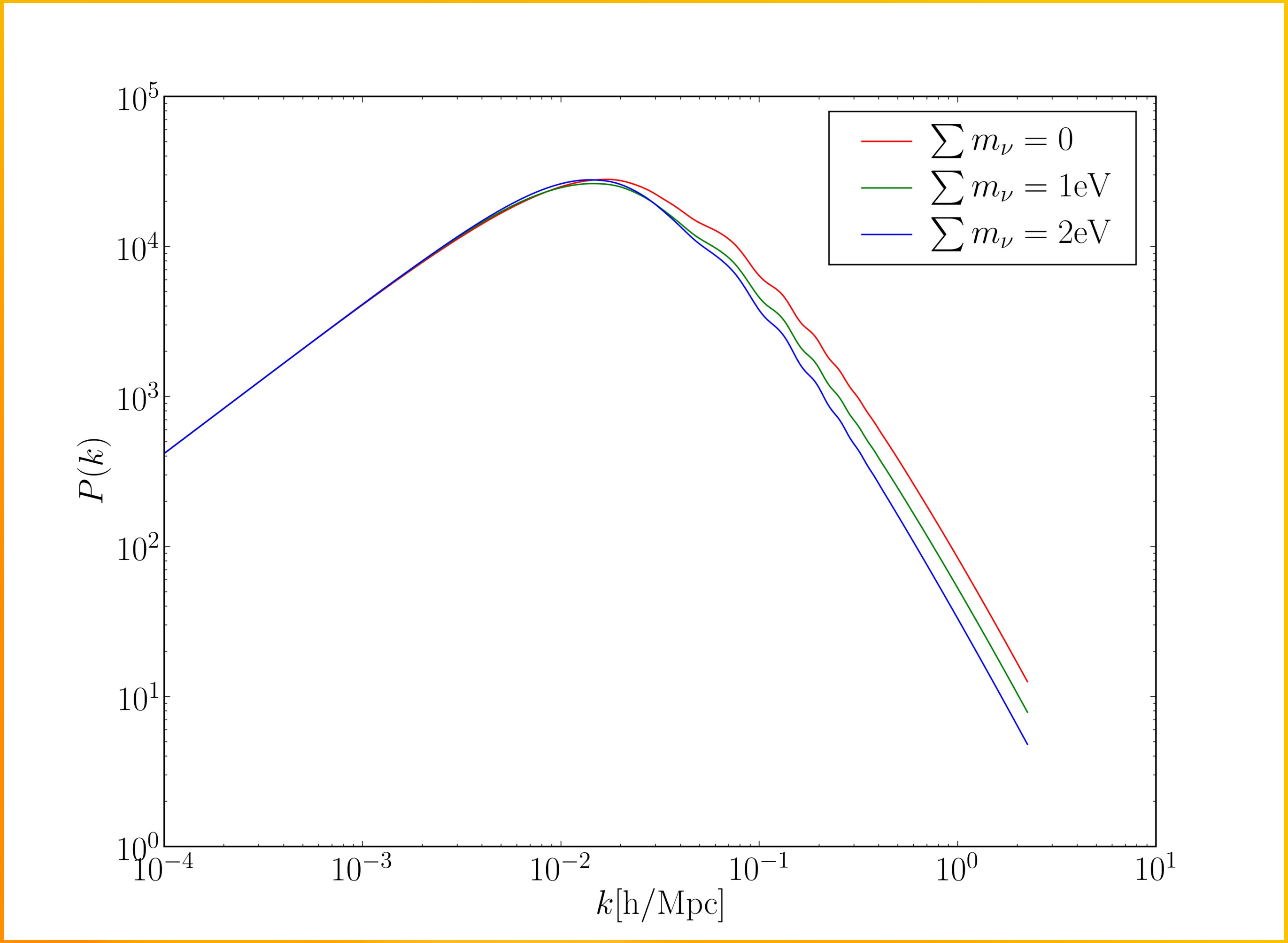
- Could neutrino be dark matter? **NO!**
  - Neutrino would be relativistic early on, erasing structure on scales smaller than free-streaming scale

$$k_{fs} \sim 10\, Mpc^{-1} \left(\frac{m_{nu}}{1\, keV} \right)$$

  - exponential supression characteristic of **HOT D.M.**
  - not observed, DM is cold as far as we can tell
- Standard model is therefore:

Perfectly cold dark matter + 3 essentially massless nu

Neutrinos in cosmology

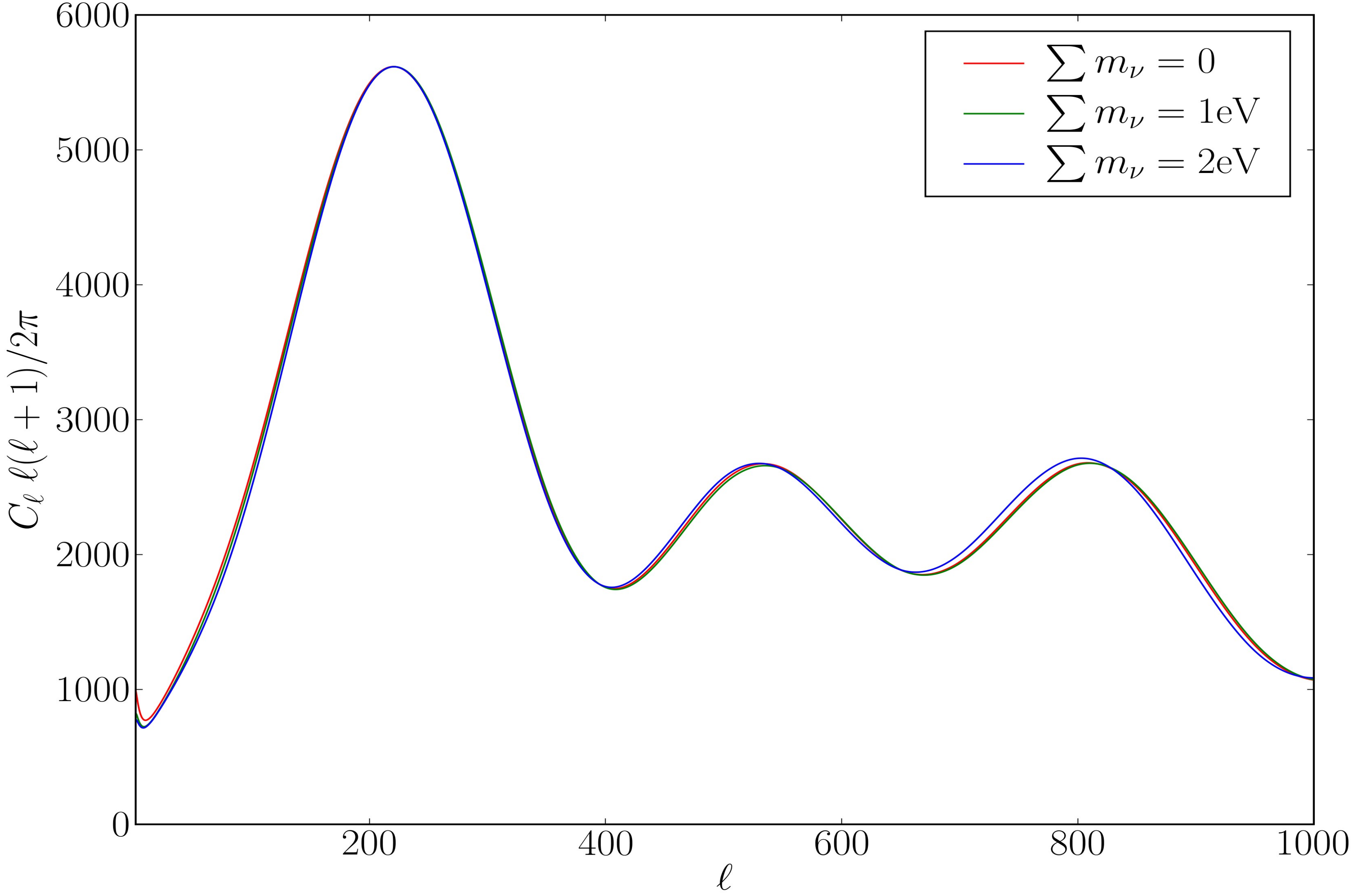


- Massive neutrinos + cold dark matter don't produce and exponential cut-off
- A suppression on small-scales still present
- Can put limits on neutrino mass!

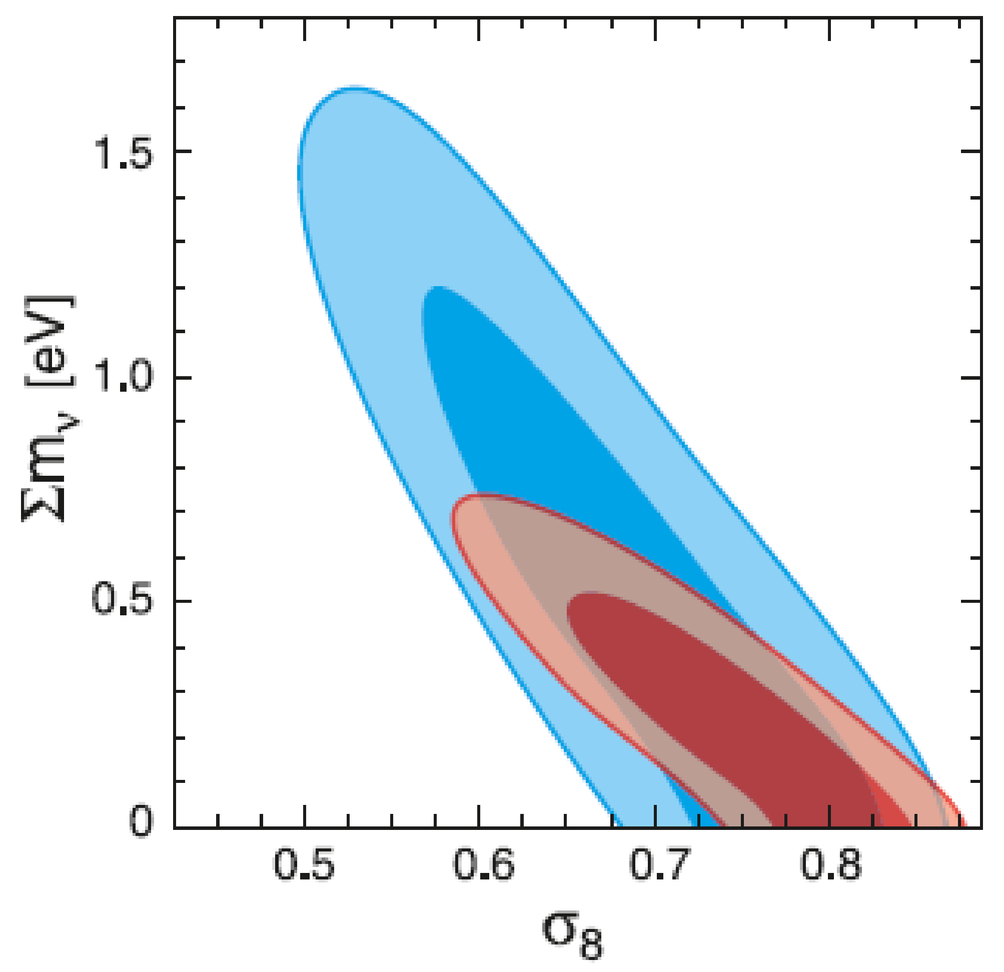
Mass limits

2dF + WMAP	Hannestad et al 03	<1.0 eV
SDSS +WMAP	Tegmark et al 04	<1.7 eV
WMAP + 2dF + SDSS	Crotty et al	<1.0 eV
WMAP + SDSS + Ly-α	Seljak et al 04	<0.43 eV
Clusters+WMAP	Allen et al 04	$0.56^{+0.3}_{-0.2}$ eV
WMAP3 + everything + Ly-α	Seljak, McDonald, AS	<0.17 eV
WMAP3 + SDSS, conservative	Zunckel & Ferreira	<2.2 eV
WMAP5	Dunkley	<1.3 eV
WMAP5+BAO+SN	Komatsu	<0.6 eV

WMAP 5 mass constraints

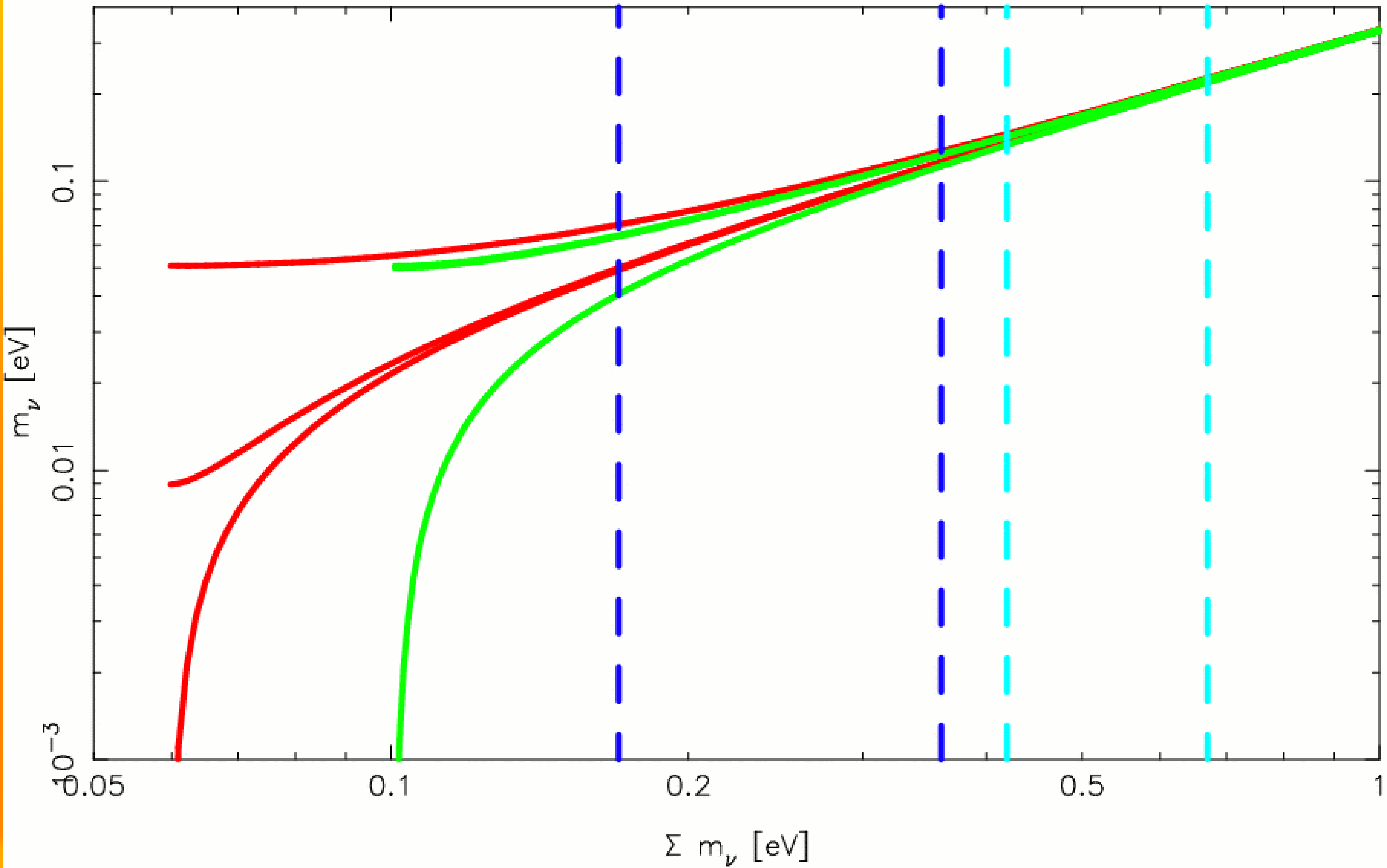


WMAP 5 mass constraints



- Surprising that they can do it so well...
- Constraint improved by factor of 2 upon BAO, SN
- BAO treatment could have been better

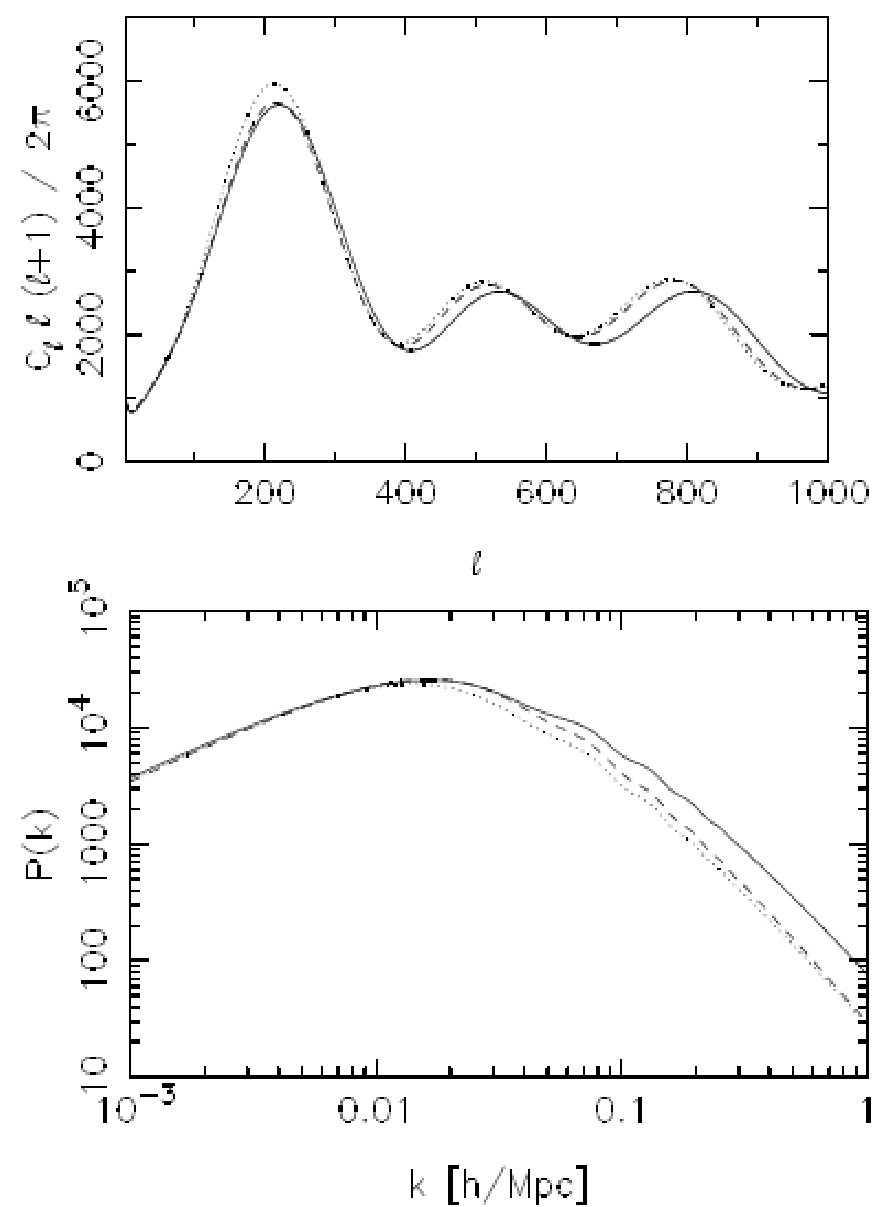
Mass hierarchies

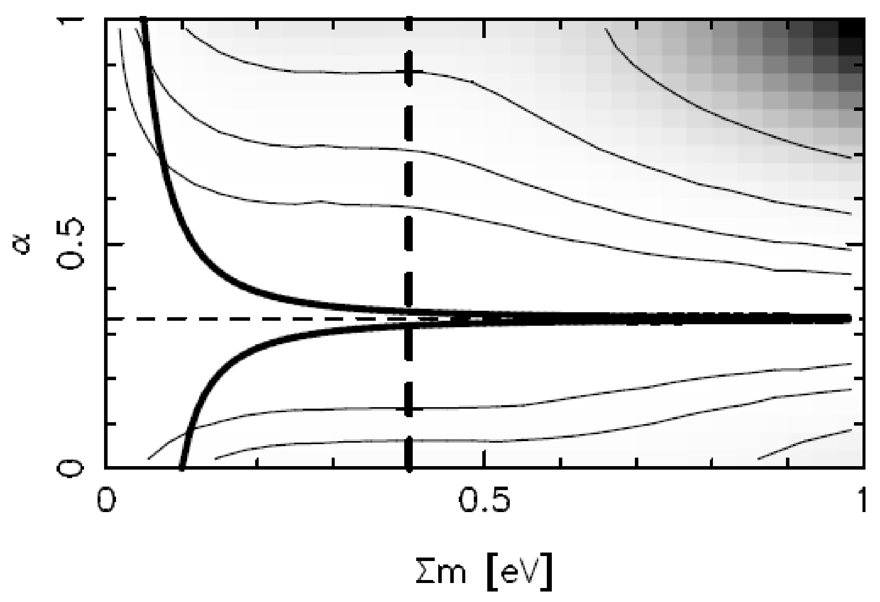


- Better than Fisher matrix!!

Neutrino mass difference

- Signal is there in principle (Lesgourgues 2003, Slosar 2006)
- Unless really lucky will be impossible to detect from cosmology





Other particles

- Light particles will always form ultra-relativistic gas early on
- **Flavour physics seems to be completely absent(?!)**
- Assuming Boltzman distribution have 3 parameters: mass, energy density today, temperature today
- only two independent
- Typically particle physics parameters enters only at determining abundance
- Typical examples: thermalised warm dark matter (cold and light), axions, sterile neutrinos, etc.

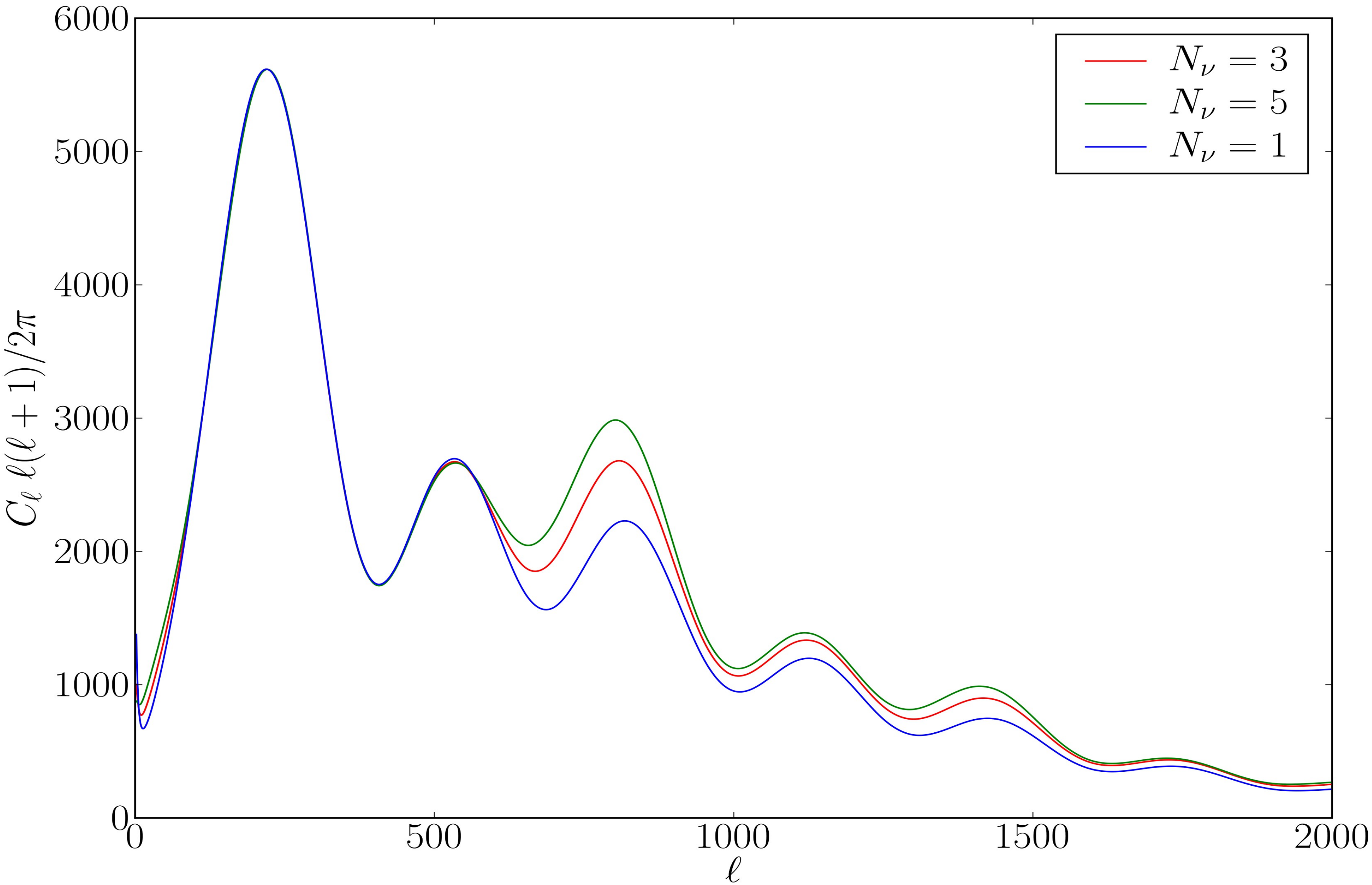
Relativistic energy density

- Special limit of mass going to zero
- Ultra-relativistic species, **parametrised** in terms of Nnu
- Canonical value Nnu=3.04
- change:
  - matter-radiation equality
  - sources of anisotropic stress
- Measure by BBN, CMB & co.

Relativistic energy density

- z decays want Nnu = 3(.04)
- BBN prefers smaller values, <4 at 95%
- CMB + other probes preferred much higher values! Used to be >3 at 95% c.l. **with WMAP3**
- Latest WMAP5:
  - >2.3 from CMB alone at 95%
  - Nnu = 4.4+−1.5 when one adds BAO, SN, HST
  - comparing Nnu=0 with 3.04 = delta chi2 = 8.2

WMAP5 needs third peak



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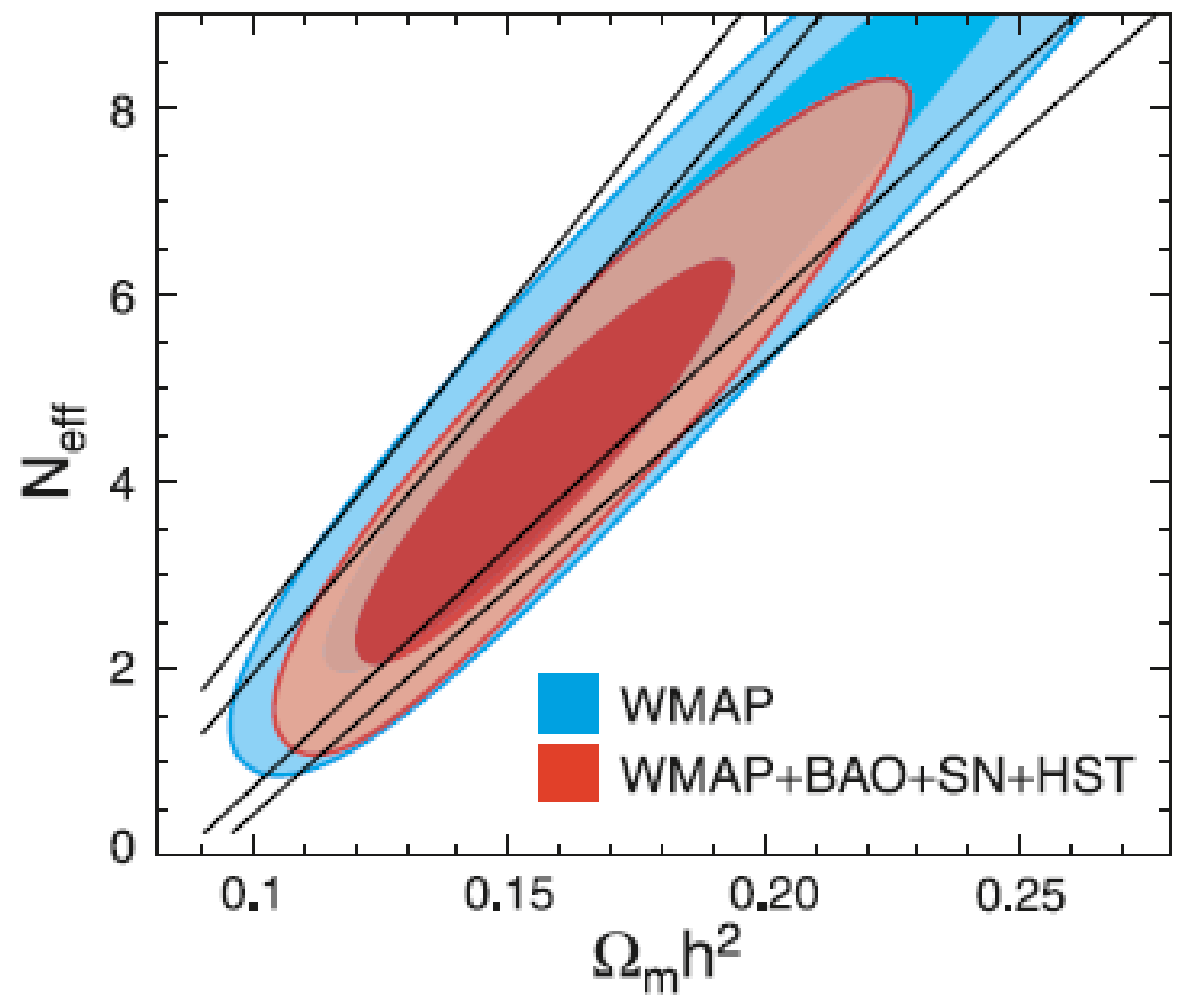


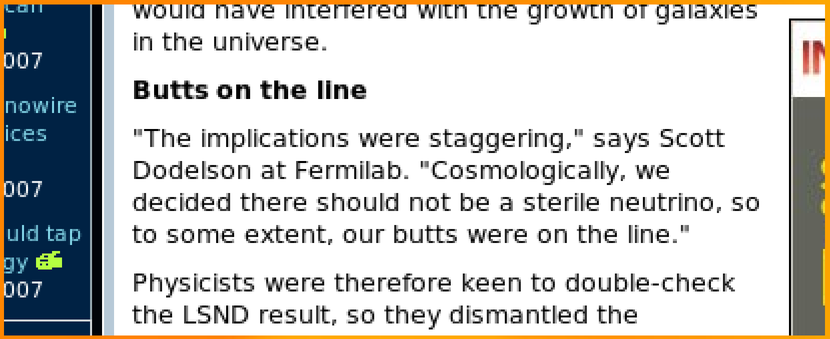
Sterile neutrinos

- Sterile neutrinos come in 2 kinds:
  - very light, usually thermalized species:
    - eV range
    - thermalized
    - kind of stuff that was used to explain LSND

  - dark matter candidate <= **TALK BY KUSENKO!!**
    - keV range
    - sub-thermal
    - more interesting, could explain a lot of tangential astrophysical observations
    - simplest models ruled out

Light steriles

- 4^{th} sterile state could explain LSND
- disfavoured by cosmology (mass < 0.23eV; Dodelson, Melchiorri, AS 2006)
- nonexistence confirmed by MiniBoone

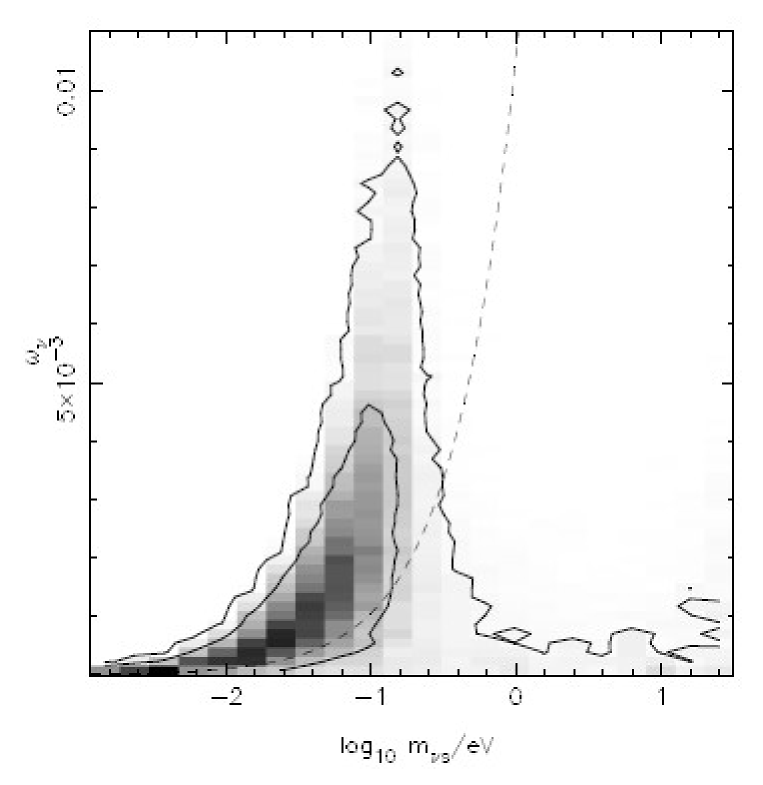


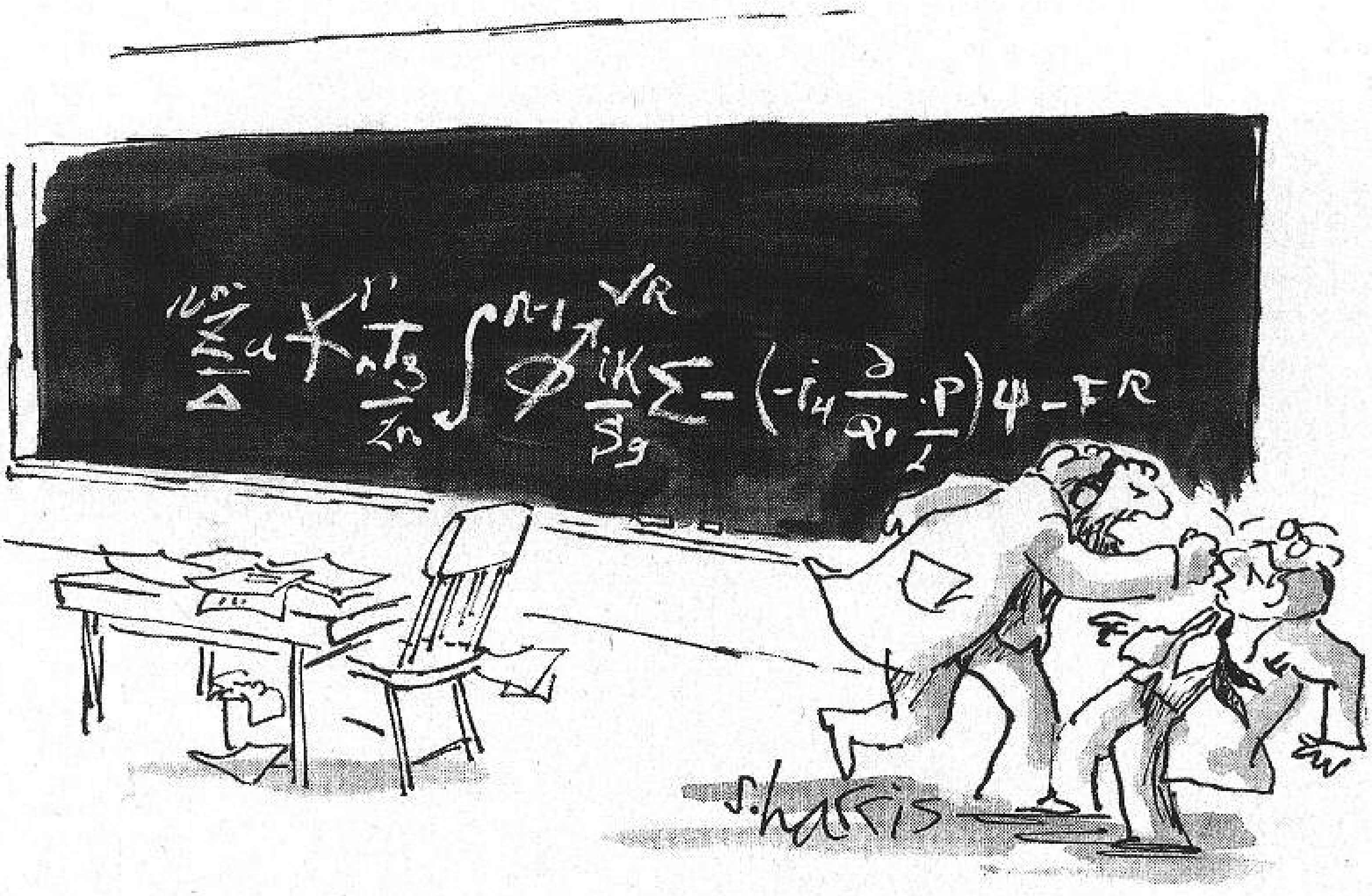
would have interfered with the growth of galaxies in the universe.

Butts on the line

"The implications were staggering," says Scott Dodelson at Fermilab. "Cosmologically, we decided there should not be a sterile neutrino, so to some extent, our butts were on the line."

Physicists were therefore keen to double-check the LSND result, so they dismantled the





"YOU WANT PROOF? I'LL GIVE YOU PROOF!"

Cosmologist convincing particle physicist about the validity of cosmological limits.

Measuring P(k)

- Matter power spectrum non-trivial to measure.
- Many methods on the market. Main ones are:
    - Cosmic Microwave Background
    - Clusters of galaxies
    - galaxy power spectrum
    - weak lensing
    - Lyman-alpha forest

Galaxy power spectrum

- Assume galaxies trace underlying mass density in a Poisson-like process:

$$\delta_g(\vec{x}) = b\,\delta_m(\vec{x})$$

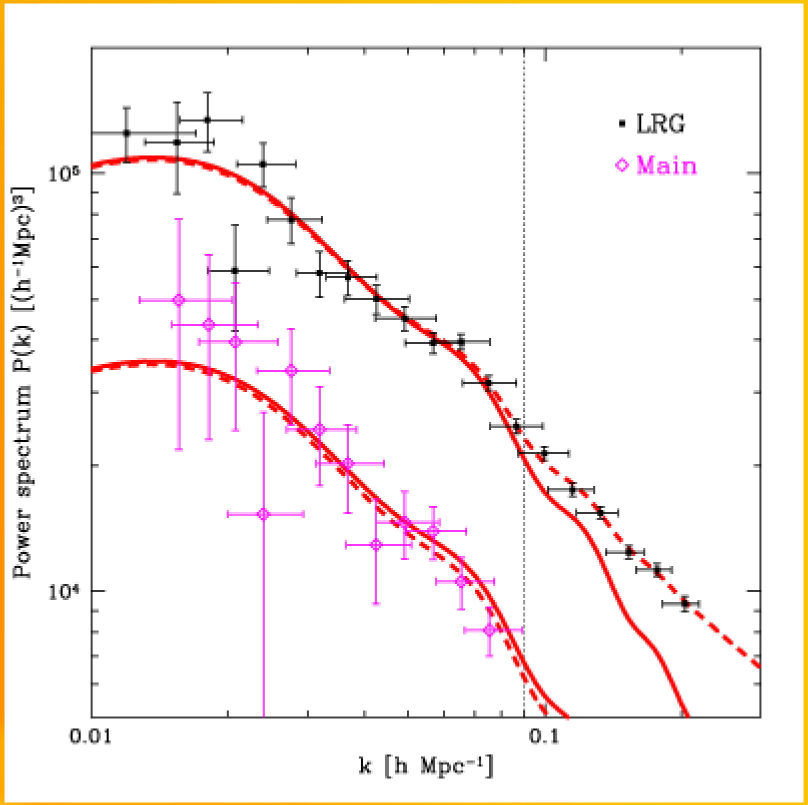
- On large scales (typically k<0.03 h/Mpc) any local process give you linear bias (!!):

$$\delta_g(\vec{x}) = f(\delta_m(\vec{x}), \nabla\delta_m(\vec{x}), \ldots) \Rightarrow \delta_g(\vec{k}) = b\,\delta_m(\vec{k})$$

- The power spectrum is then unknown to an overall amplitude: $P_g(k) = b^2 P_m(k)$

Galaxy power spectrum

- Galaxies offer an easy start - one large scales one is safe (from Tegmark at el):



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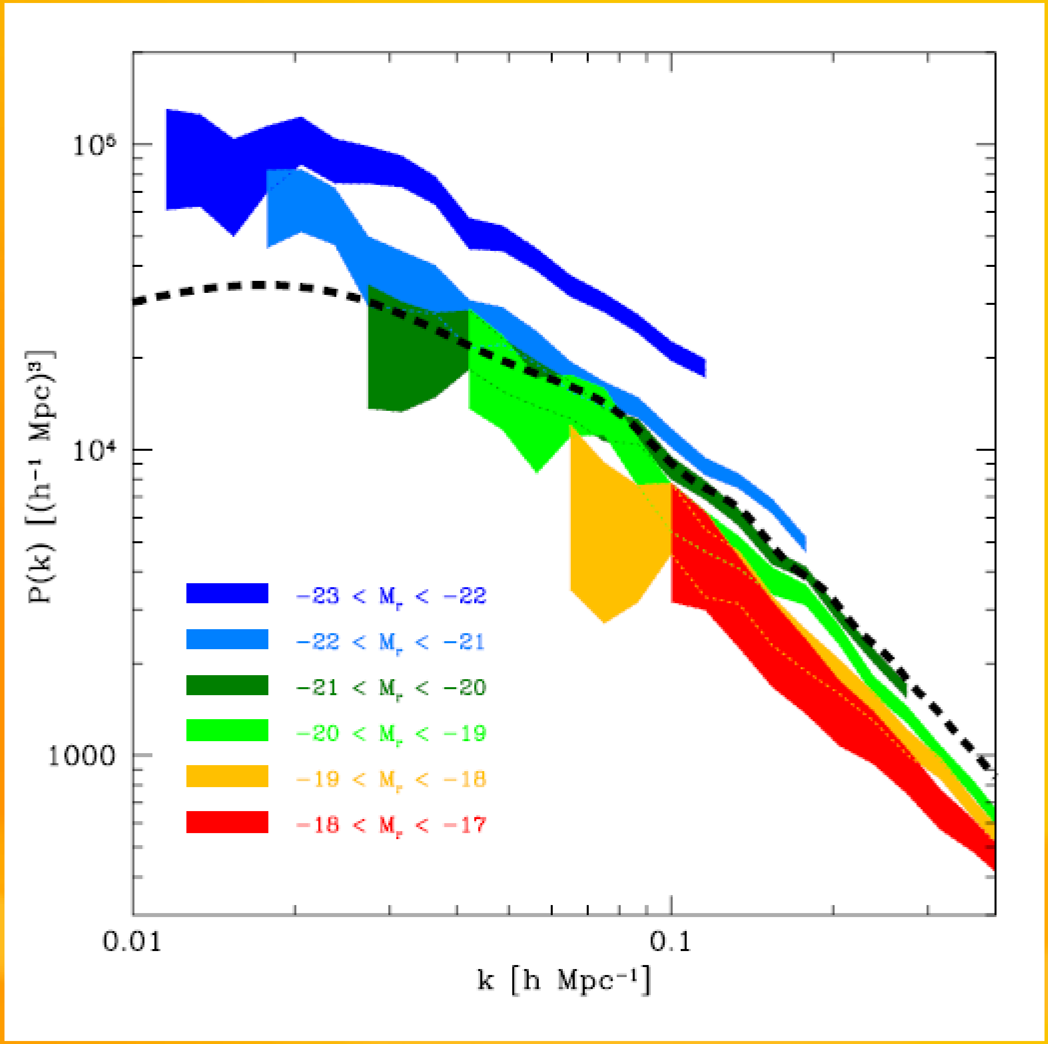
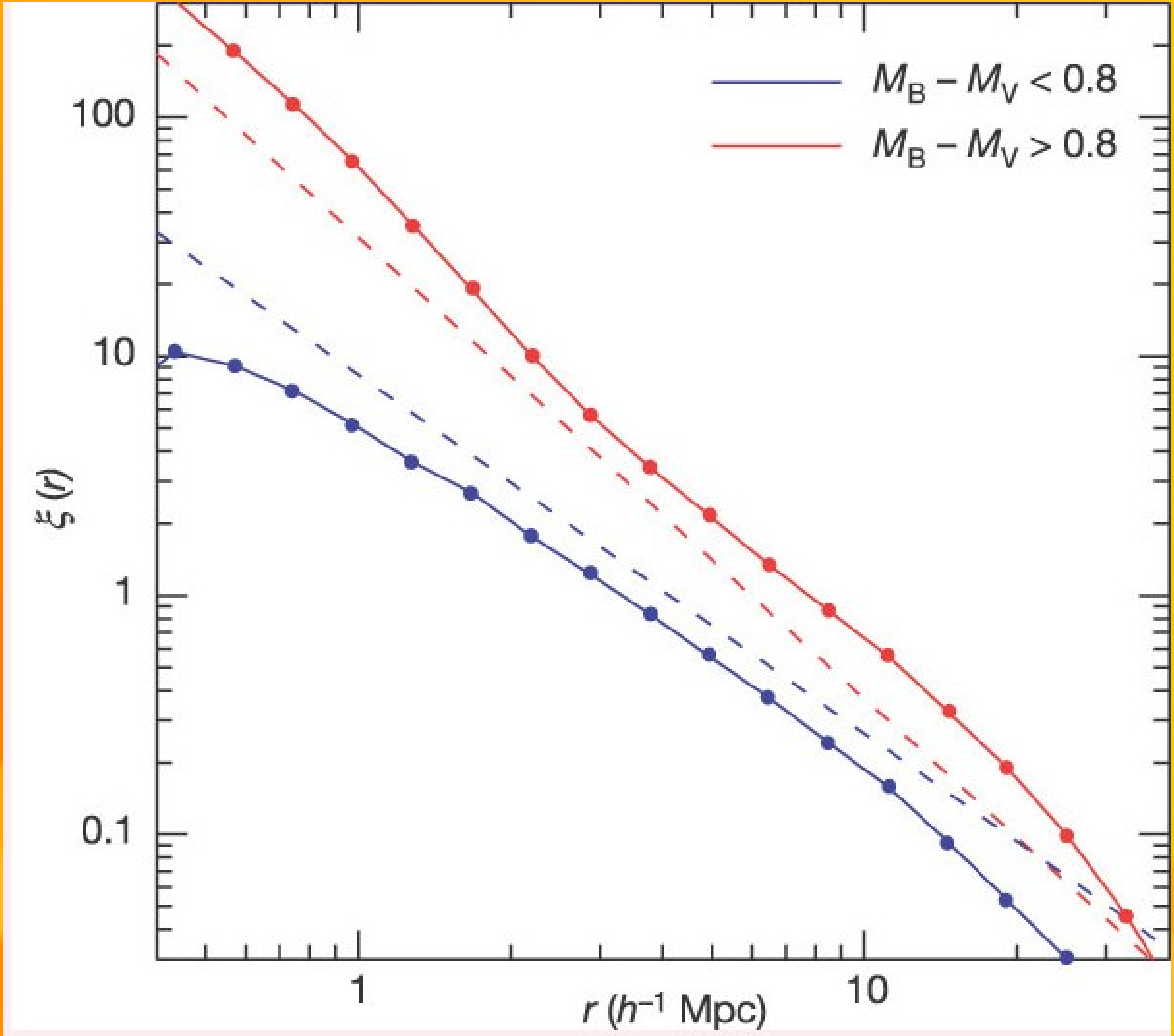


Galaxy power spectrum

- To some extend we understand what is going on (Springel et al):

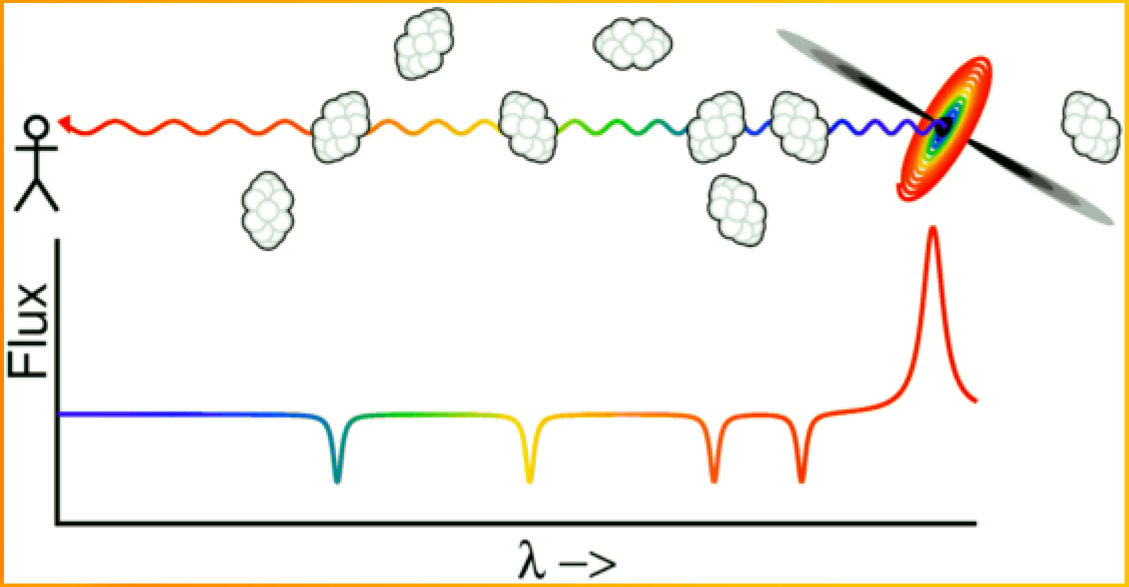


Galaxy power spectrum

- But do we understand things to few percent level required for the forthcoming surveys?
- Galaxies are formed at high-density peaks in the primordial density field.
- The galaxy formation process must be at least somewhat non-local and environment dependent
- One generically expects scale-dependent bias b(k) and the entire gastrophysics comes into play
- Gastrophysics is like meteorology. We understand something, but difficult to understand everything.

Lyman-alpha forest

- clouds of hydrogen absorb light from distant quasars, blueward of Lyman-alpha emission



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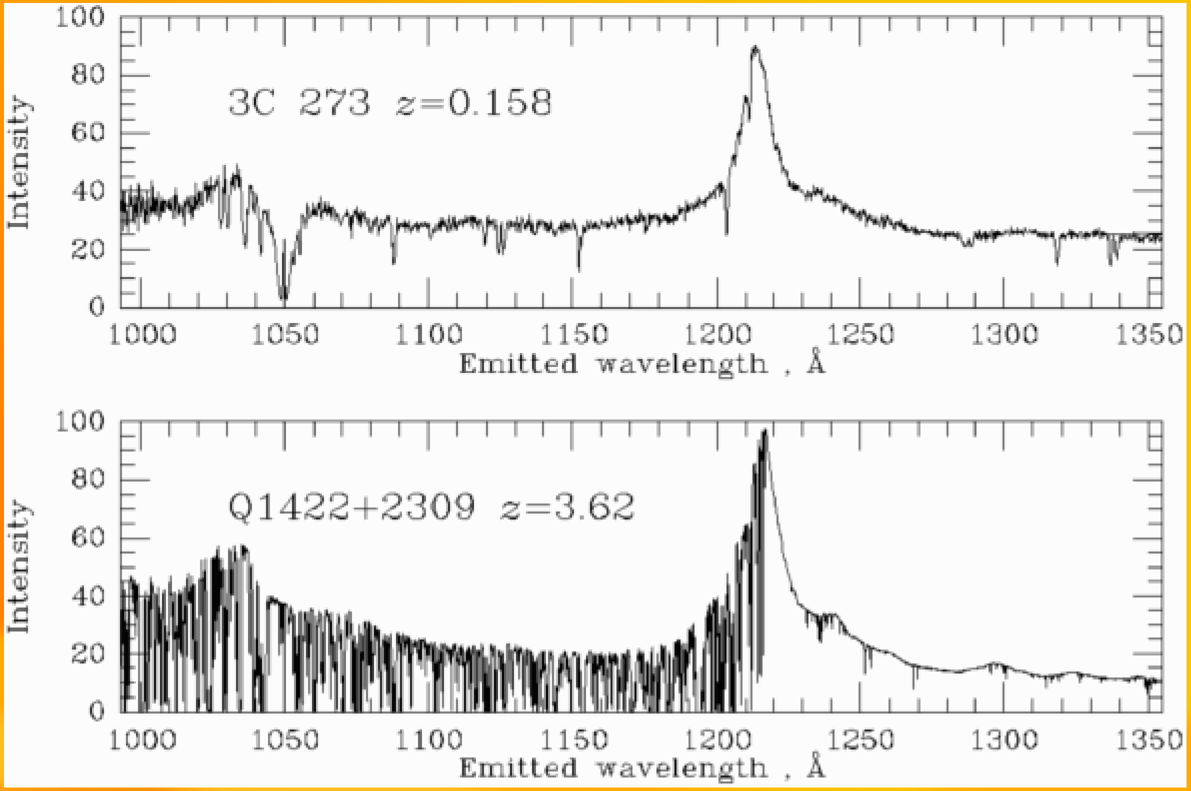
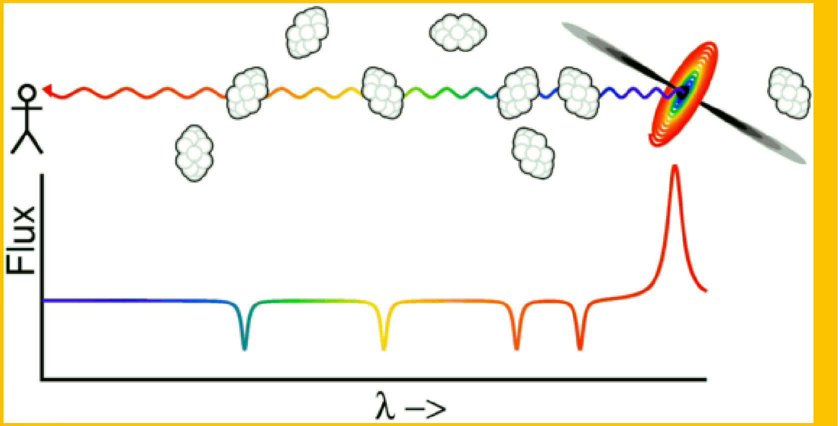


Lyman-alpha forest

- line of sight goes through typical parts of the universe
- systems are weakly non-linear and hence a-priori calculable



- much higher redshift than galaxies
- Astrophysics comes in only at second order and can be marginalised over.
- Small scale physics, shocks and cooling are not important and can be modelled roughly

Lyman-alpha forest

Scales probed by Lyman-alpha:

- 100 kpc scales: warm dark matter, dm decays, etc.
- 1 Mpc scales: netrino masses, running spectral index, etc
- >10 Mpc scales: dark energy, curvature baryonic oscillations (deep future!)

Evolution of baryons

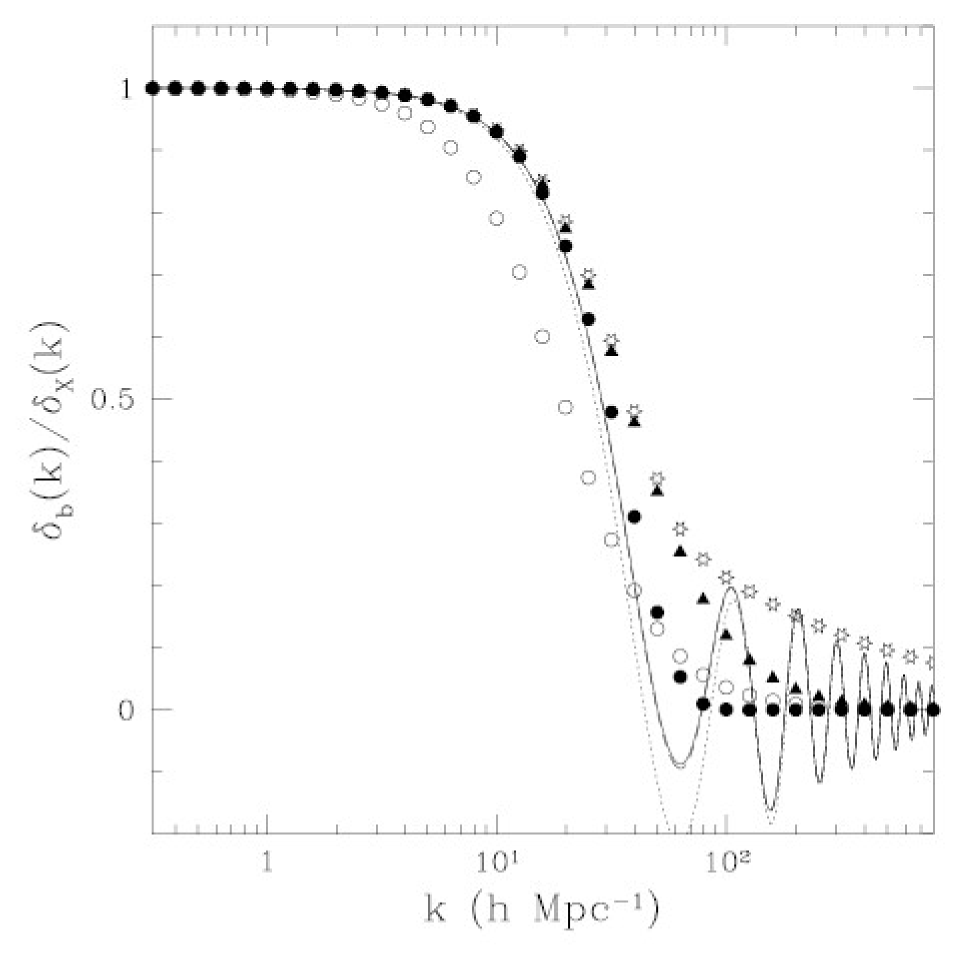
- Seminal papers by Gnedin and Hui
- At linear order

$$\frac{\partial^2 \delta_x}{\partial t^2} + 2H\frac{\partial \delta_x}{\partial t} = 4\pi G\bar{\rho}\left(f_x\delta_x + f_b\delta_b\right)$$

$$\frac{\partial^2 \delta_b}{\partial t^2} + 2H\frac{\partial \delta_b}{\partial t} = 4\pi G\bar{\rho}\left(f_x\delta_x + f_b\delta_b\right) - \frac{c_s^2}{a^2}k^2\delta_b$$

- On large scales baryons follow dark matter
- On small scales, pressure suppresses fluctuations

Pressure filtering



- Amount of filtering depends on the thermal history of the inter-galactic medium

From baryons to flux

- Absorption done by neutral hydrogen in photo-ionisation equilibrium:

$$\Gamma n_{HI} = \alpha(T) n_p n_e$$

$$n_{HI} \propto \frac{\alpha(T)\rho_b^2}{\Gamma} \ll 1$$

and so, optical depth:

$$\tau \sim A \frac{(1+\delta)^{1.7}}{\Gamma}$$

Dapmped systems:

- High density regions:
  - >2.0x10^20 atoms/cm^2 – DLAs ->CAN SEE THEM
  - >1.5x10^17 atoms/cm^2 – LLSs -> CANNOT SEE THEM
- LLS – self shielding means that optical depth increases dramatically with density:
  - n_HI increases by around 100
  - at the same time Pf changes by less than 0.1%

Simulating Ly-A:

- To really compare observations with theory need to simulate baryons numerically
  - analytical calculations suggest hydro-PM
    - rather than full hydrodynamic treatment, models baryons as particles that see extra "pressure" potential
    - Assume $T = T_0 \rho^{\gamma - 1}$
  - marginalise over different thermal histories

Basic IGM params:

- All in all have 4 parameters describing IGM:
  - γ-1 , $\gamma - 1$ are parameters of equation of state:

$$T = T_0 \rho^{\gamma - 1}$$

  - $\bar{F}$ is the mean flux
  - $T=T_0\rho^{\gamma-1}$ parametrises the thermal history of IGM

Ly-A: data & theory

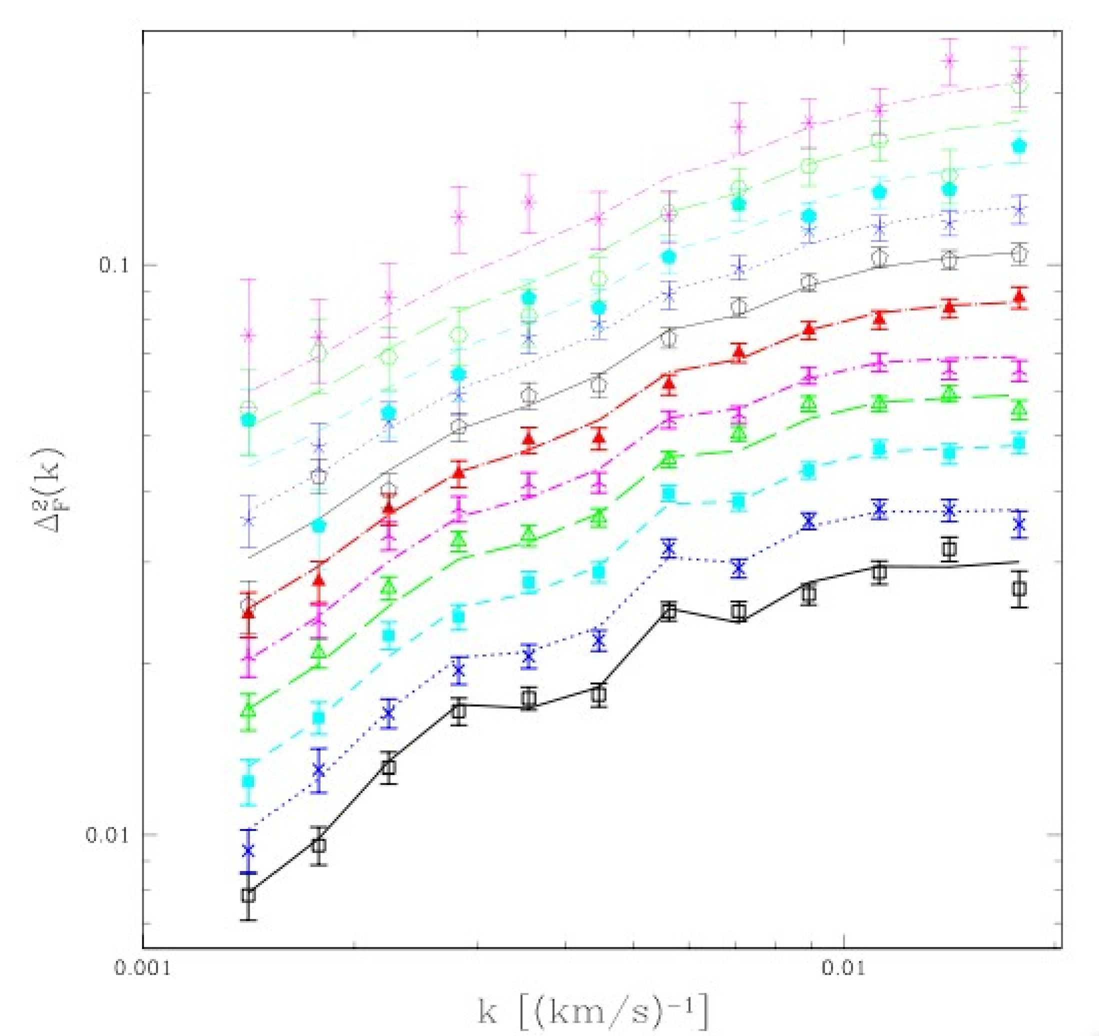
How to compare theory to observations?

Sensible data observables:

- one-point distribution function
- flux power spectrum
- (flux bispectrum)

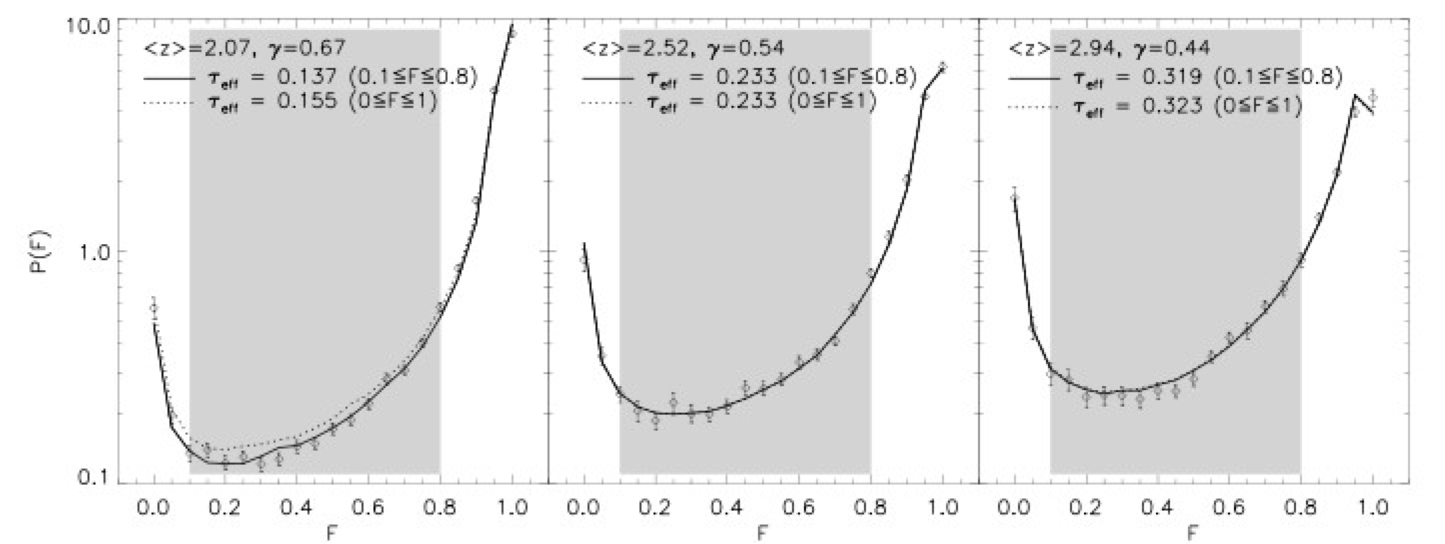
Run hydroPM N-body simulations and simulate observations.

Ly-A: Flux power spectrum



- McDonald et al, 2006

Ly-A: one-point PDF

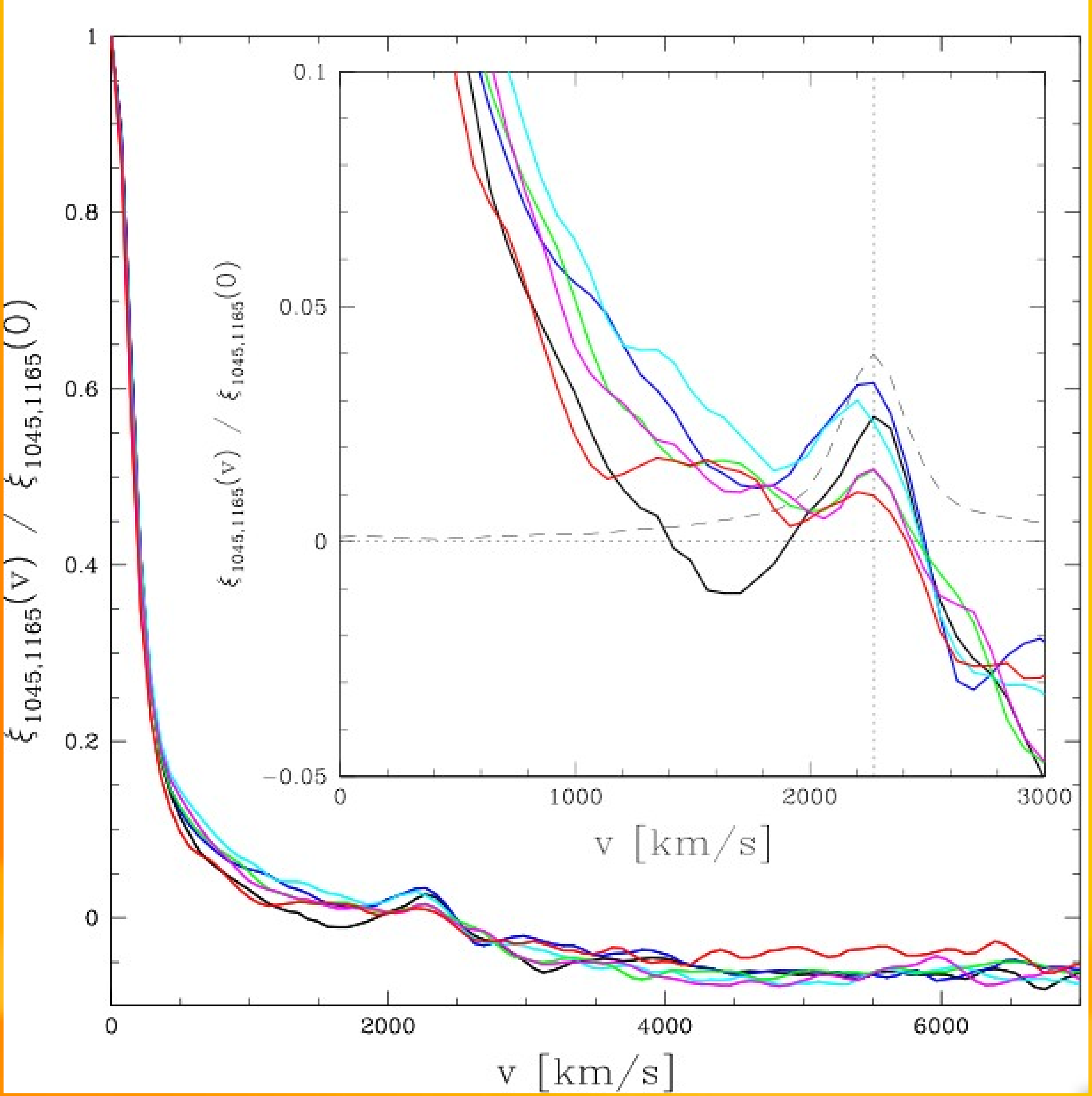


- Kim et al, 2007

Lyman-alpha challenges:

- Many challenges – but fixable in principle
- Nagging metal lines:
  - can subtract them manually (Tytler et al)
  - subtract them statistically by measuring their power spectrum outside LyA absorption
  - Si III absorbs at 1206 Angstrems (LyA at 1216!!) – take it out from correlation function

Si III absorption



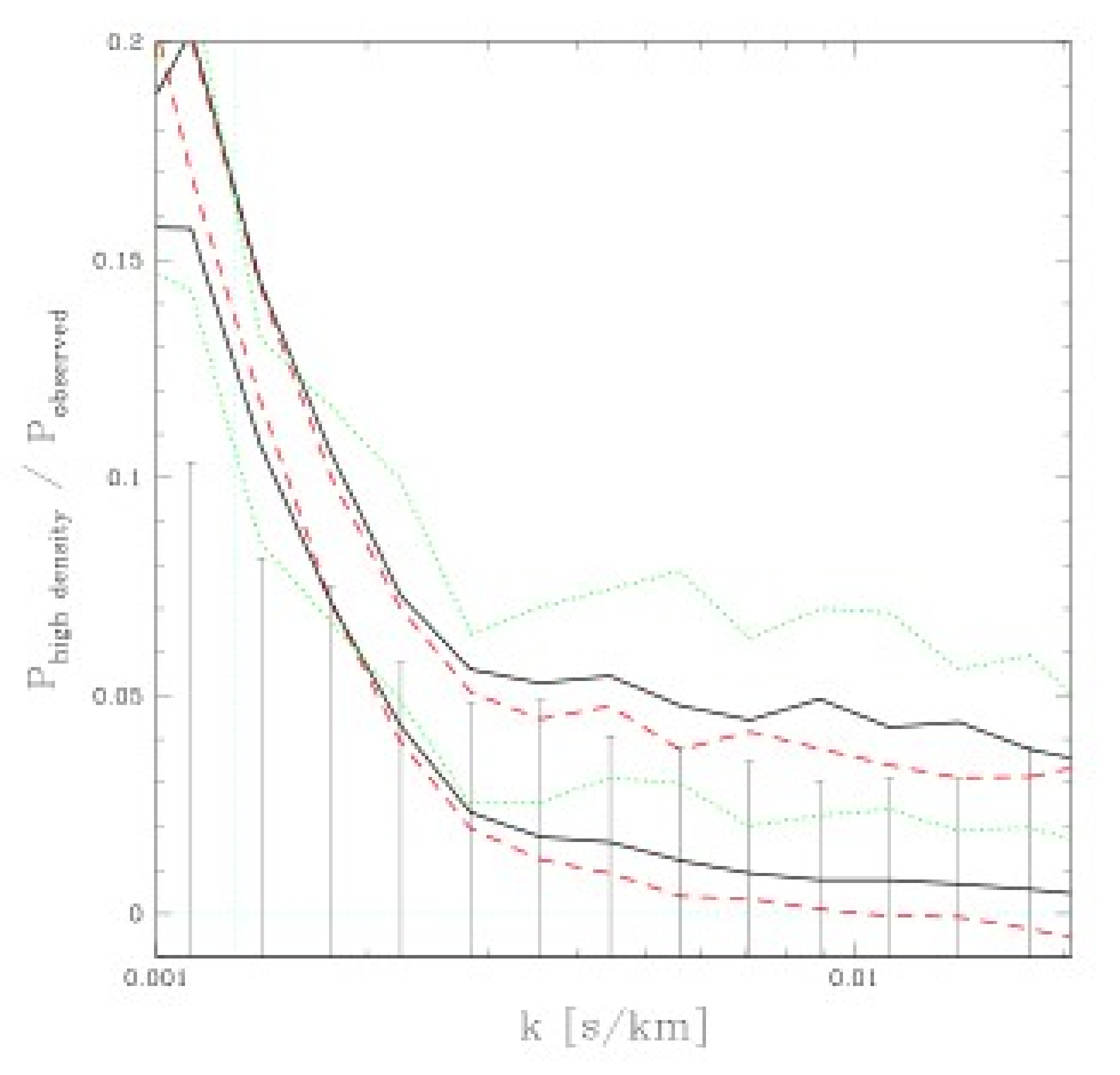
Lyman-alpha challenges

- Simulation sizes:
  - need many simulations
  - need big box sizes
  - need good resolution
- In practice we do resolution correction:

$$P(k) = P_{big\ box}(k) \times \left(\frac{P_{small\ box,\ high\ res}(k)}{P_{small\ box,\ big\ box\ res}(k)} \right)$$

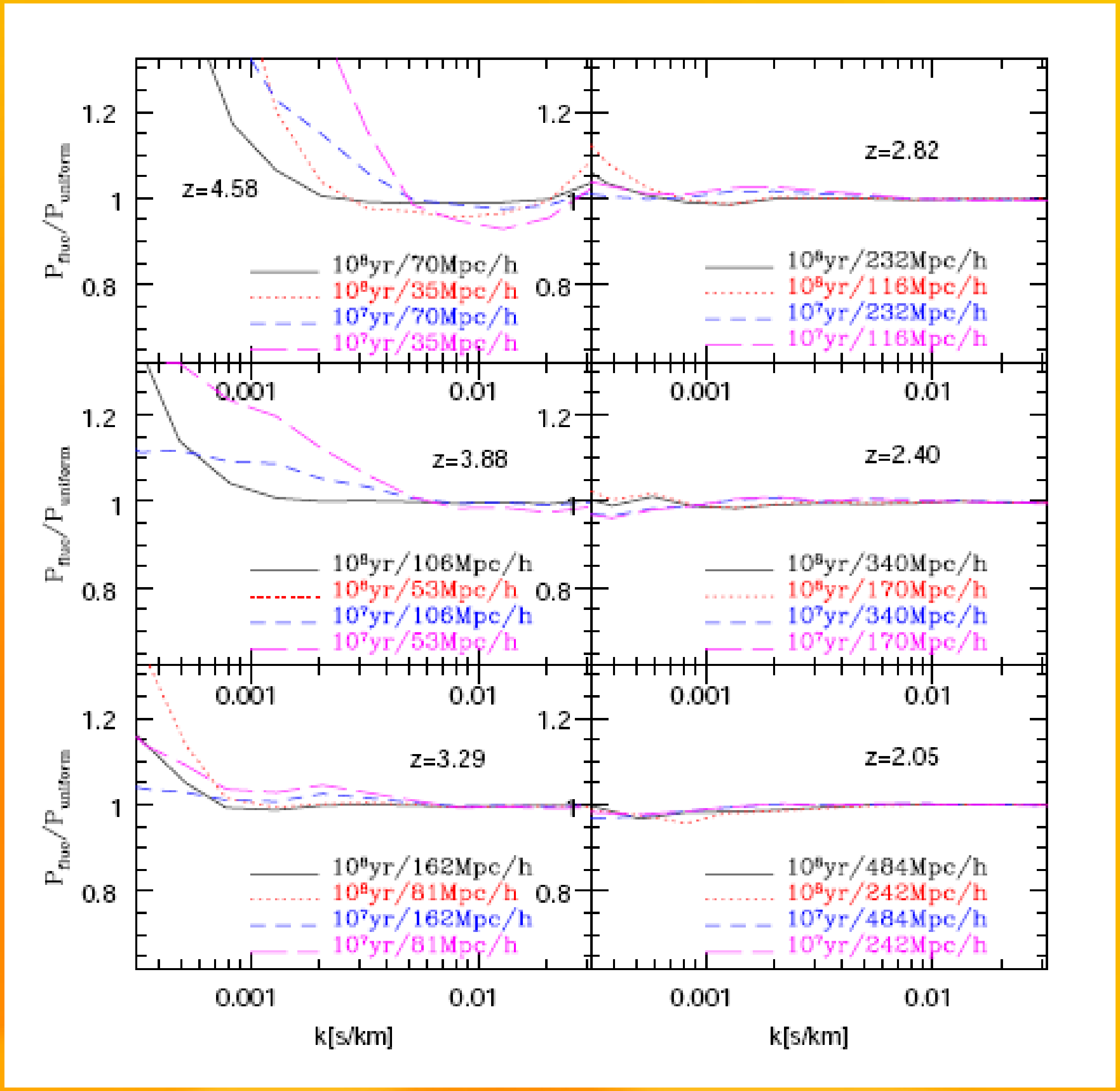
- a couple more years...

Damping wings of LLS



- Subtle but important systematics:
  - Damping wings of high-density absorbers – important and must be taken into account

Ionizing bckg fluctuations



- The ionizing background not uniform, what is its effect?
- Can be modelled very well: we know quasar lifetimes, halos they occupy, etc.
- Very clean observational signature - not seen

Galactic Superwinds

- Galaxies with lots of star-formation and SN activity spit stuff out into intergalactic medium
- Completely degenerated with IG parameters

State of the art today

- Two groups really:
  - McDonald and company
  - Viel and company
- Stringest limits on simplest sterile neutrino model (>28 keV)
- Stringest limits on sum of neutrino masses (<0.3eV at 99.7% but with WMAP3!!)
- killed LSND results before MiniBoone
- Stringest limits on spectral index running (<0.015)
- etc, etc.

Lyman-alpha future

- so far one spectrum at a time
- I am working on bi-spectrum of SDSS LYA
- efforts to do close pairs already under way (Hennawi, Pamanabhan, etc.)
- with sufficient density of quasars can do proper 3D everyone with everyone correlation
- BOSS: Baryon Oscillation Spectroscopic Survey:
  - SDSS extension
  - 20 $z>2.2$ quasars per square degree
  - 1.5% on D_A and H at $z=2.5$

Conclusions

- dark matter power spectrum contains a wealth of information about early universe, its contents, etc.
- Lyman-alpha data still not quite ready for prime-time:
  - not enough groups
  - not enough computers
- But ultimately it should do great stuff:
  - weakly non-linear physics
  - typical parts of the universe
  - no real show-stopper