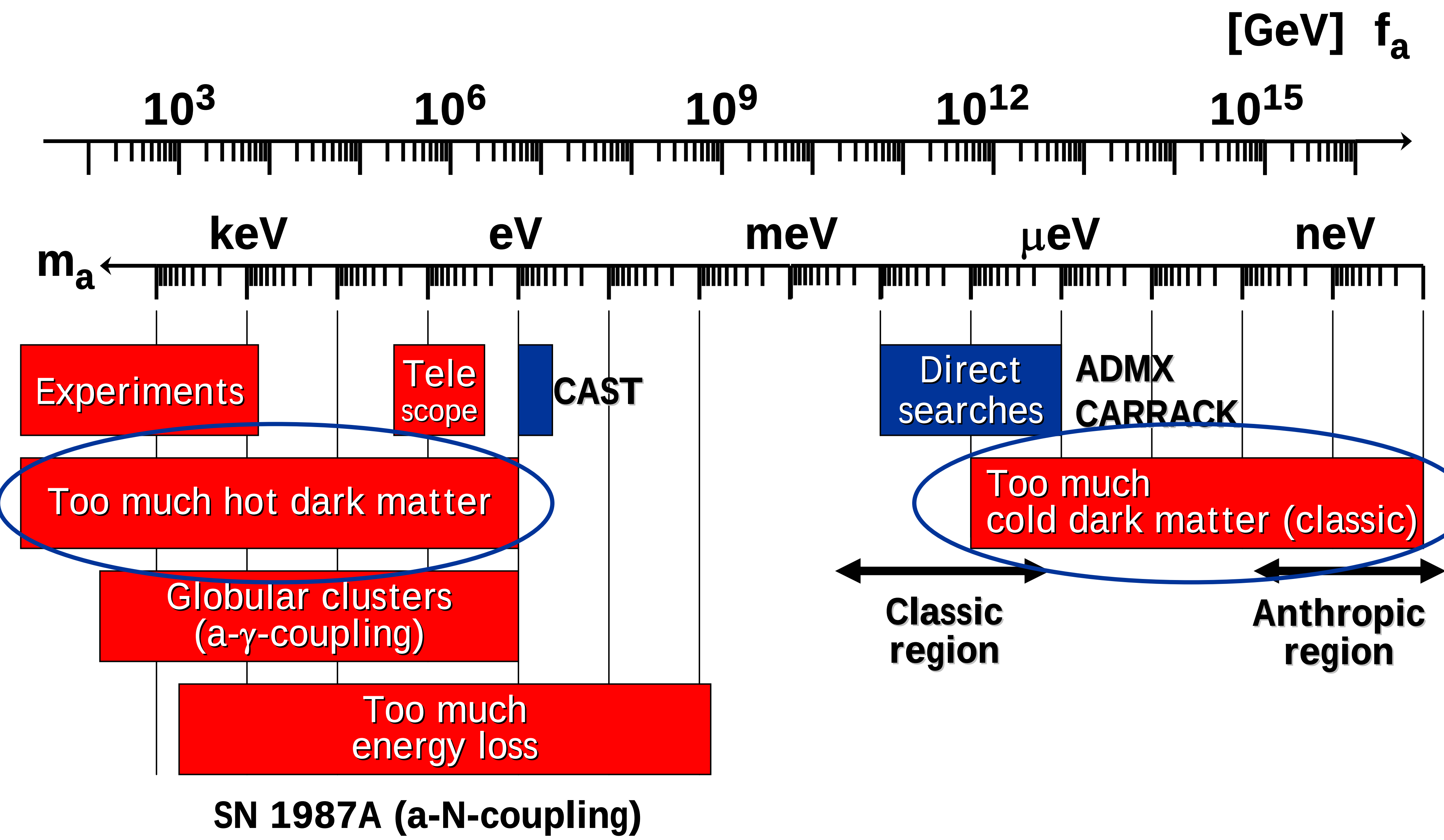
ASTROPHYSICAL AND COSMOLOGICAL BOUNDS ON AXIONS

STEEN HANNESTAD
DURHAM, 17 JULY 2009

Axion Bounds



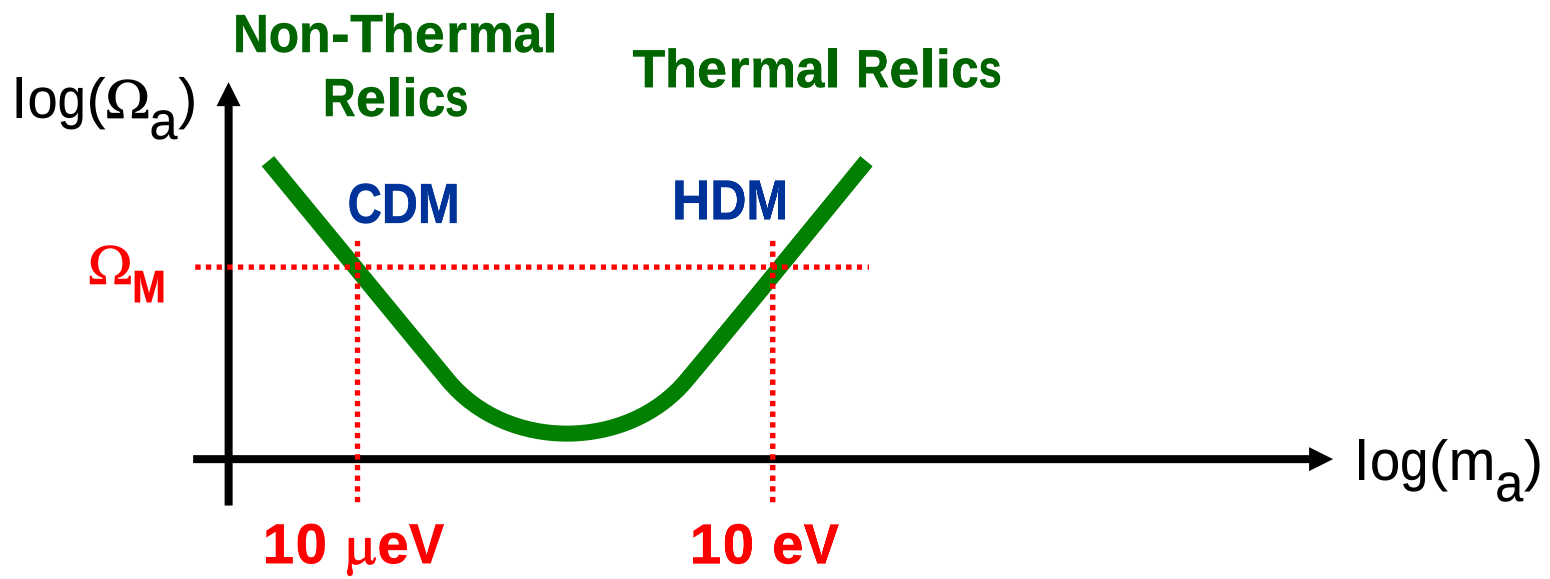
How are axions created cosmologically

- High mass axions are thermalised at temperatures of order ~ MeV – GeV and act as hot dark matter

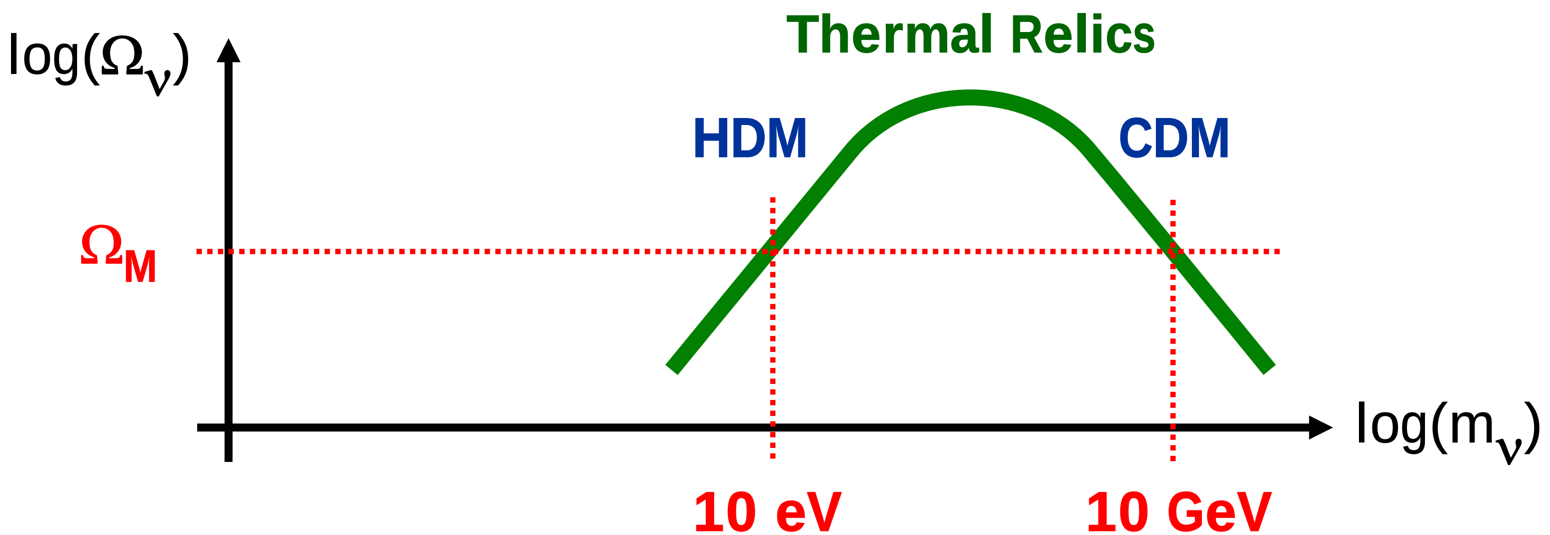
- Low mass axions are created non-thermally at high temperature and act as cold dark matter

Lee-Weinberg Curve for Neutrinos and Axions

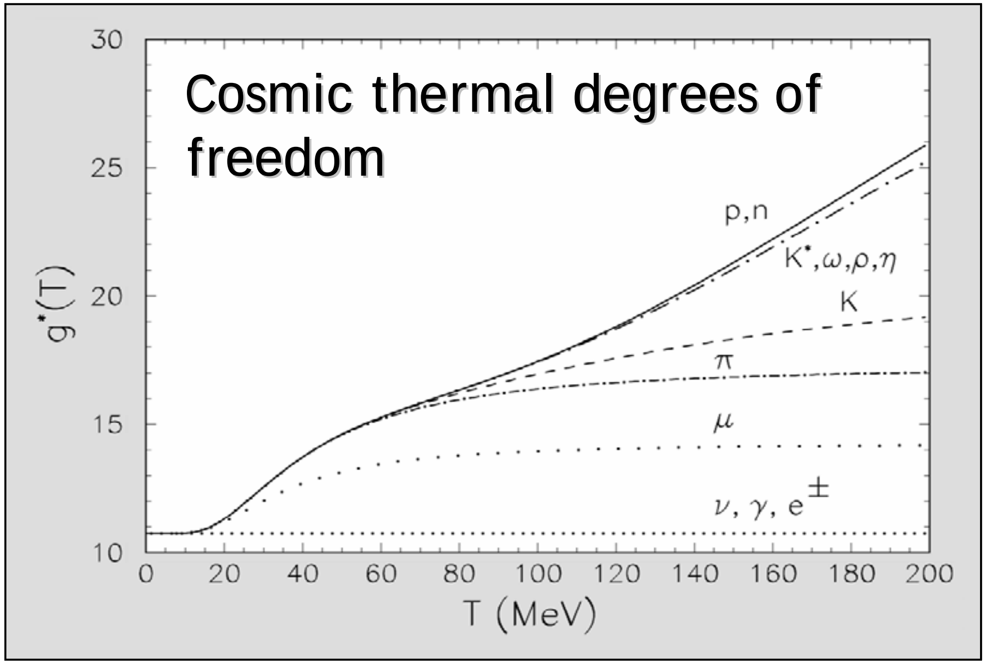
Axions

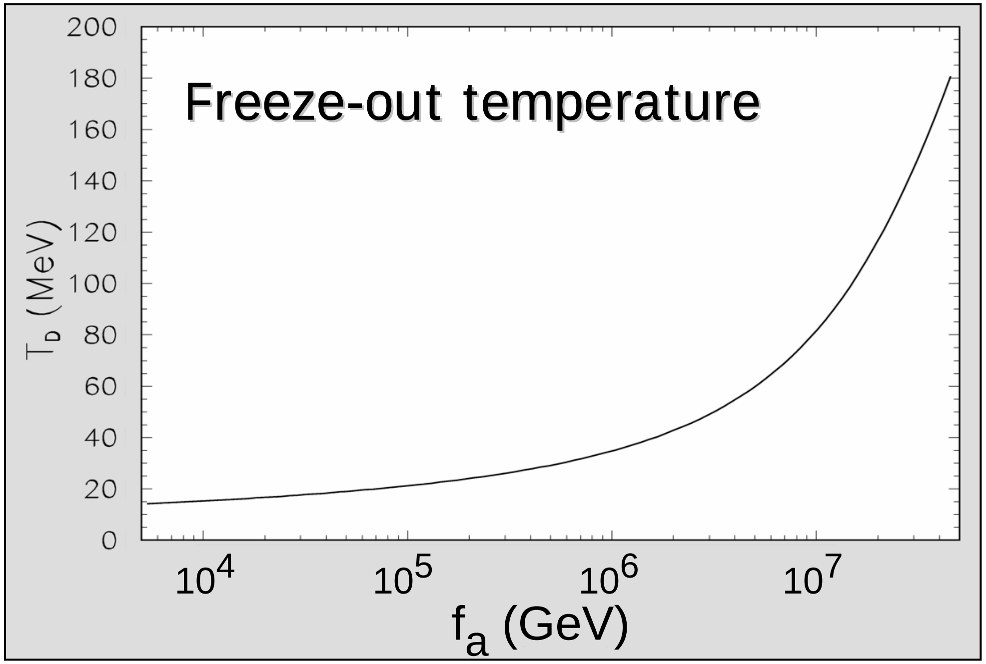


Neutrinos & WIMPs

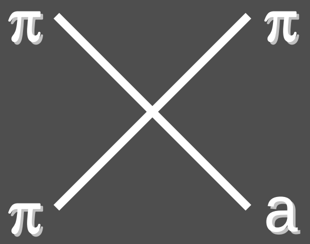


Axion Hot Dark Matter from Thermalization after Λ_{QCD}





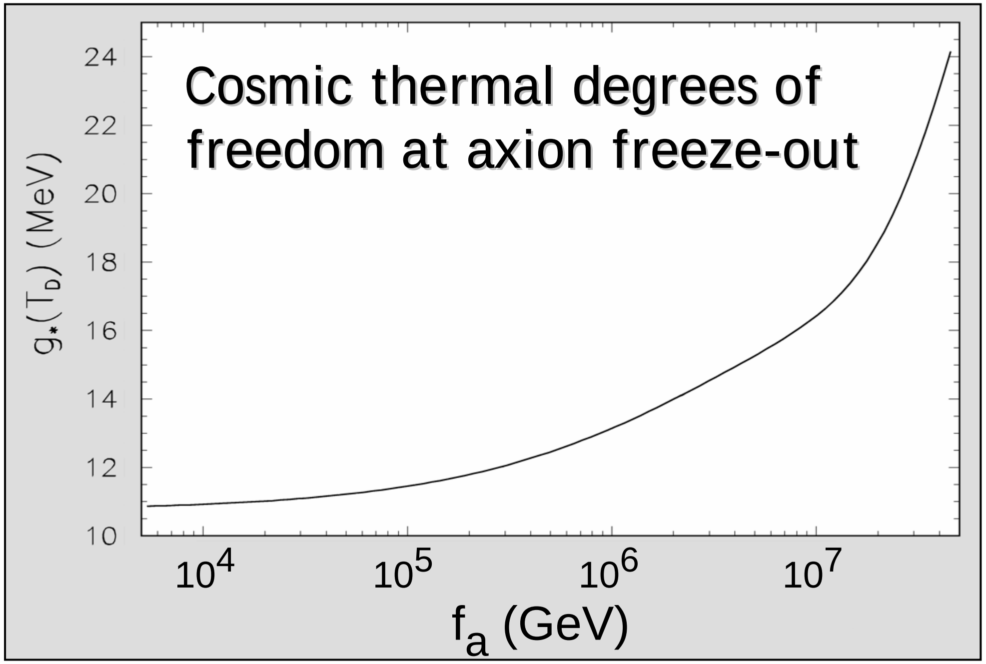
$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0)\partial^\mu a$$



$$C_{a\pi} = \frac{1-z}{3(1+z)} \approx 0.094$$

Chang & Choi, PLB 316 (1993) 51

STH, Mirizzi & Raffelt, JCAP 07 (2005) 02



Axion HDM properties

AXIONS AFFECT STRUCTURE FORMATION
BECAUSE THEY ARE A SOURCE OF DARK MATTER

HOWEVER, eV AXIONS ARE DIFFERENT FROM CDM
BECAUSE THEY FREE STREAM

SCALES SMALLER THAN d_{FS} DAMPED AWAY, LEADS TO
SUPPRESSION OF POWER ON SMALL SCALES

CONTRIBUTION TO DENSITY

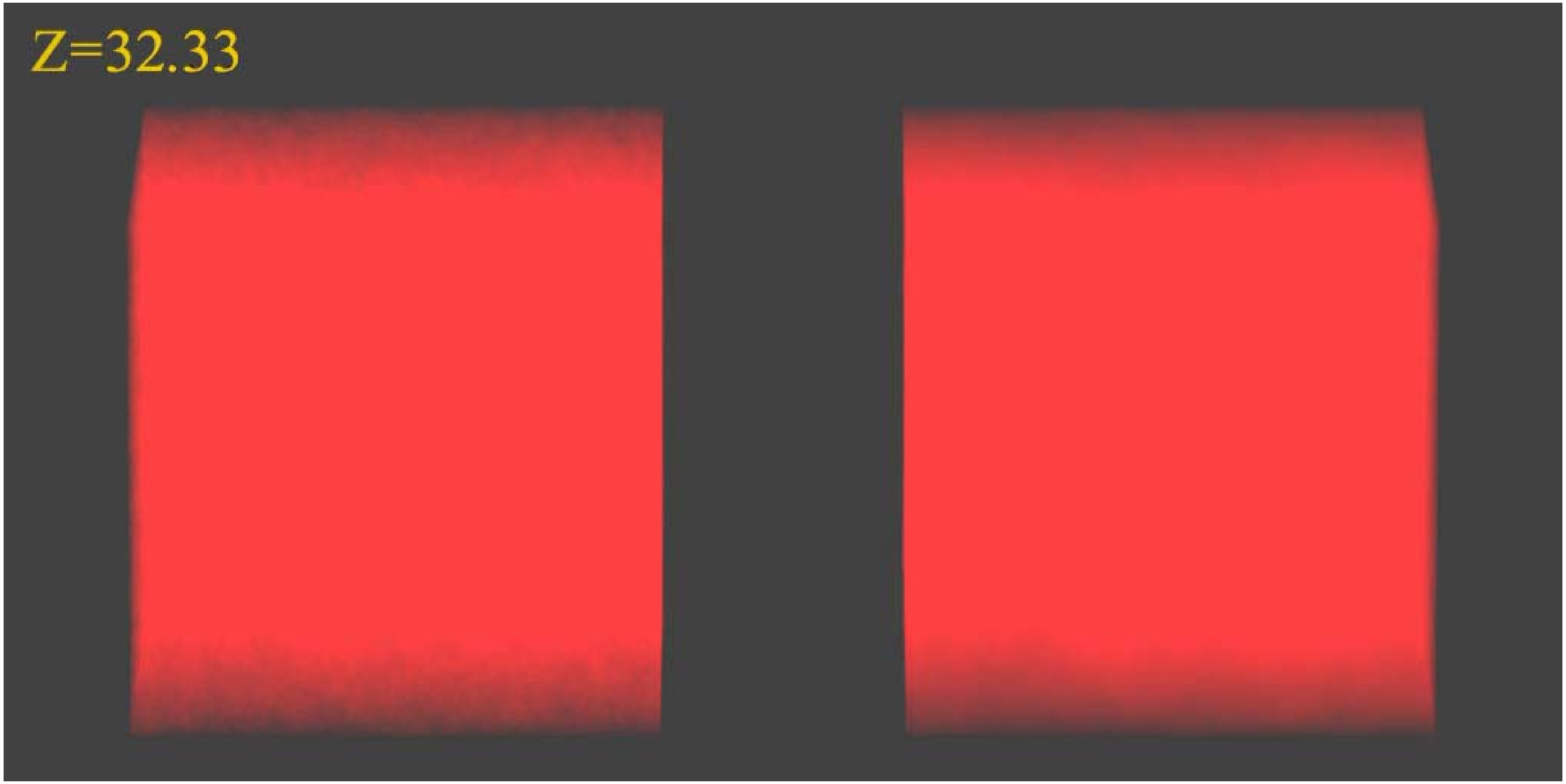
$$\Omega_X h^2 = \frac{m_X g_X}{183\,\mathrm{eV}} \frac{10.75}{g_{*X}} \times \begin{cases} 1 & \text{for fermions} \\ 4/3 & \text{for bosons} \end{cases}$$

FREE-STREAMING LENGTH

$$\lambda_{\mathrm{FS}} \sim \frac{20\,\mathrm{Mpc}}{\Omega_X h^2} \left(\frac{T_X}{T_\nu}\right)^4 \left[1 + \log\left(3.9 \frac{\Omega_X}{\Omega_m} \frac{T_\nu^2}{T_X^2}\right)\right]$$

Structure Formation with Hot Dark Matter

Standard ΛCDM Model	Neutrinos with Σm_ν = 6.9 eV



Structure fromation simulated with Gadget code
Cube size 256 Mpc at zero redshift

Troels Haugbølle, http://whome.phys.au.dk/~haugboel

Available cosmological data

The cosmic microwave background

Large scale structure of galaxies

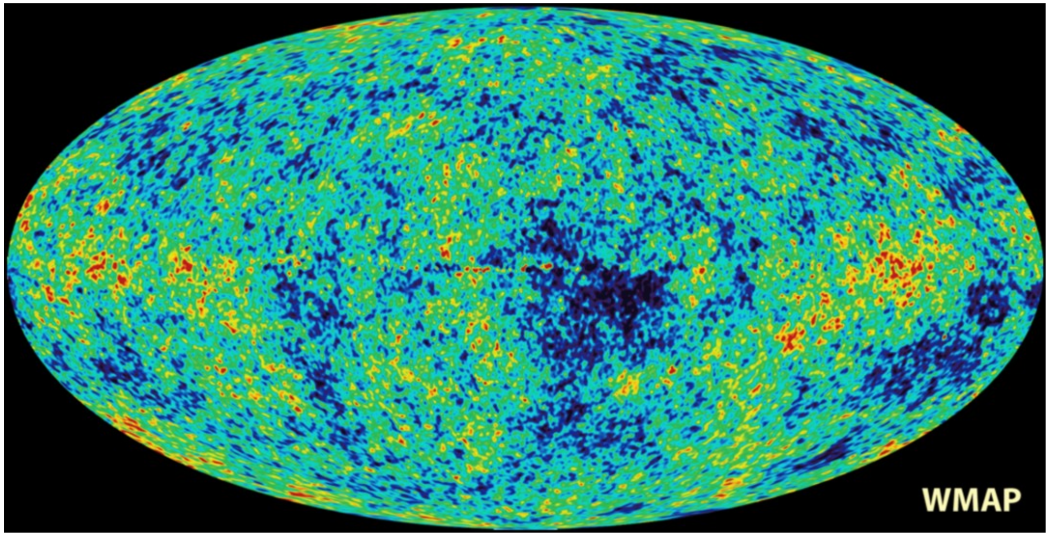
The Lyman-alpha forest

.....

Power Spectrum of CMB Temperature Fluctuations

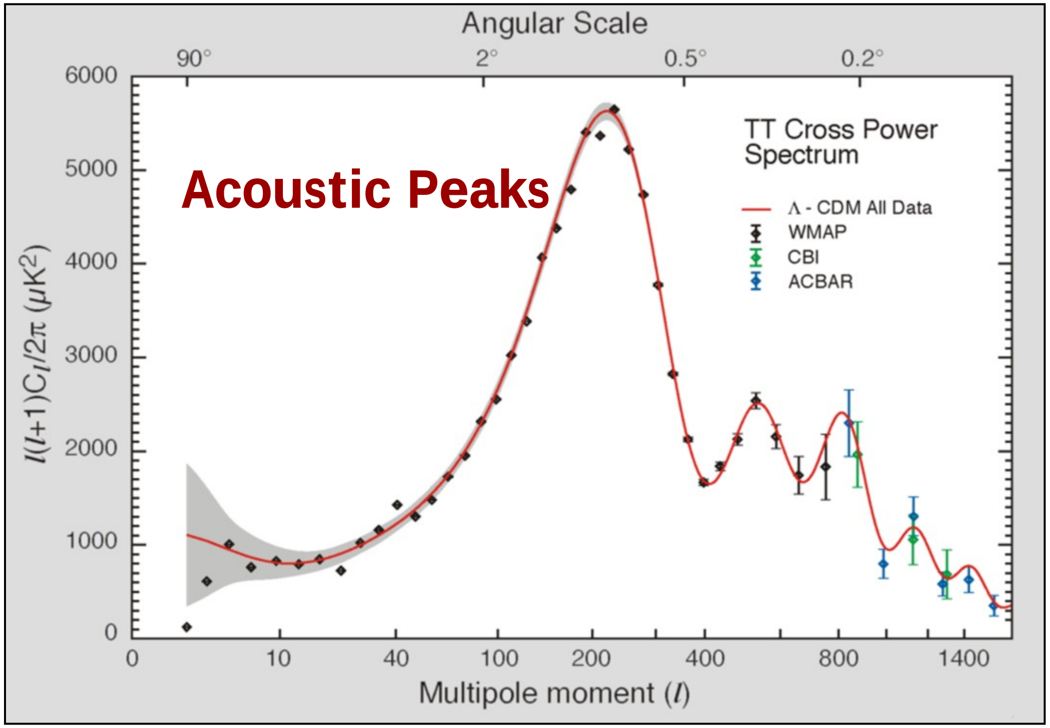
Sky map of CMBR temperature fluctuations

$$\Delta(\theta,\varphi) = \frac{T(\theta,\varphi) - \langle T \rangle}{\langle T \rangle}$$



Multipole expansion

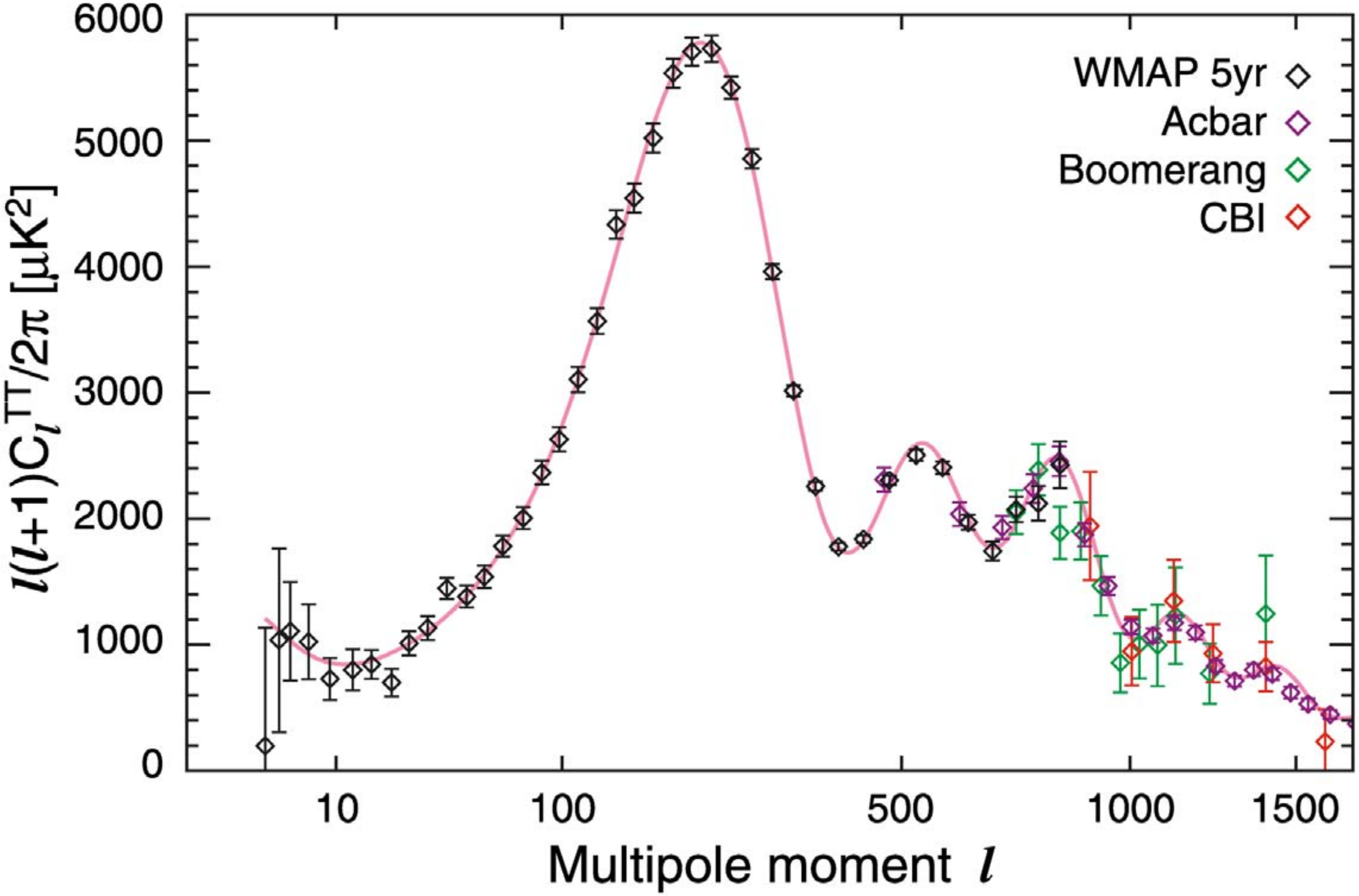
$$\Delta(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$



Angular power spectrum

$$C_\ell = \langle a_{\ell m}^{*} a_{\ell m} \rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m}^{*} a_{\ell m}$$

WMAP-5 TEMPERATURE POWER SPECTRUM



M NOLTA ET AL., arXiv:0803.0593

Power Spectrum of Density Fluctuations

Field of density fluctuations

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$

Fourier transform

$$\delta_k = \int d^3x \, e^{-ik\cdot x} \, \delta(x)$$

Power spectrum essentially square of Fourier transformation

$$\langle \delta_k \delta_{k'} \rangle = (2\pi)^3 \hat{\delta}(k - k') \, P(k)$$

with $\hat{\delta}$ the δ-function

Power spectrum is Fourier transform of two-point correlation function ($x=x_2-x_1$)

$$\xi(x) = \langle \delta(x_2)\delta(x_1) \rangle = \int \frac{d^3k}{(2\pi)^3} e^{ik\cdot x} P(k)$$

$$= \int \frac{d\Omega}{4\pi} \frac{dk}{k} e^{ik\cdot x} \underbrace{\frac{k^3 P(k)}{2\pi^2}}_{\Delta^2(k)}$$

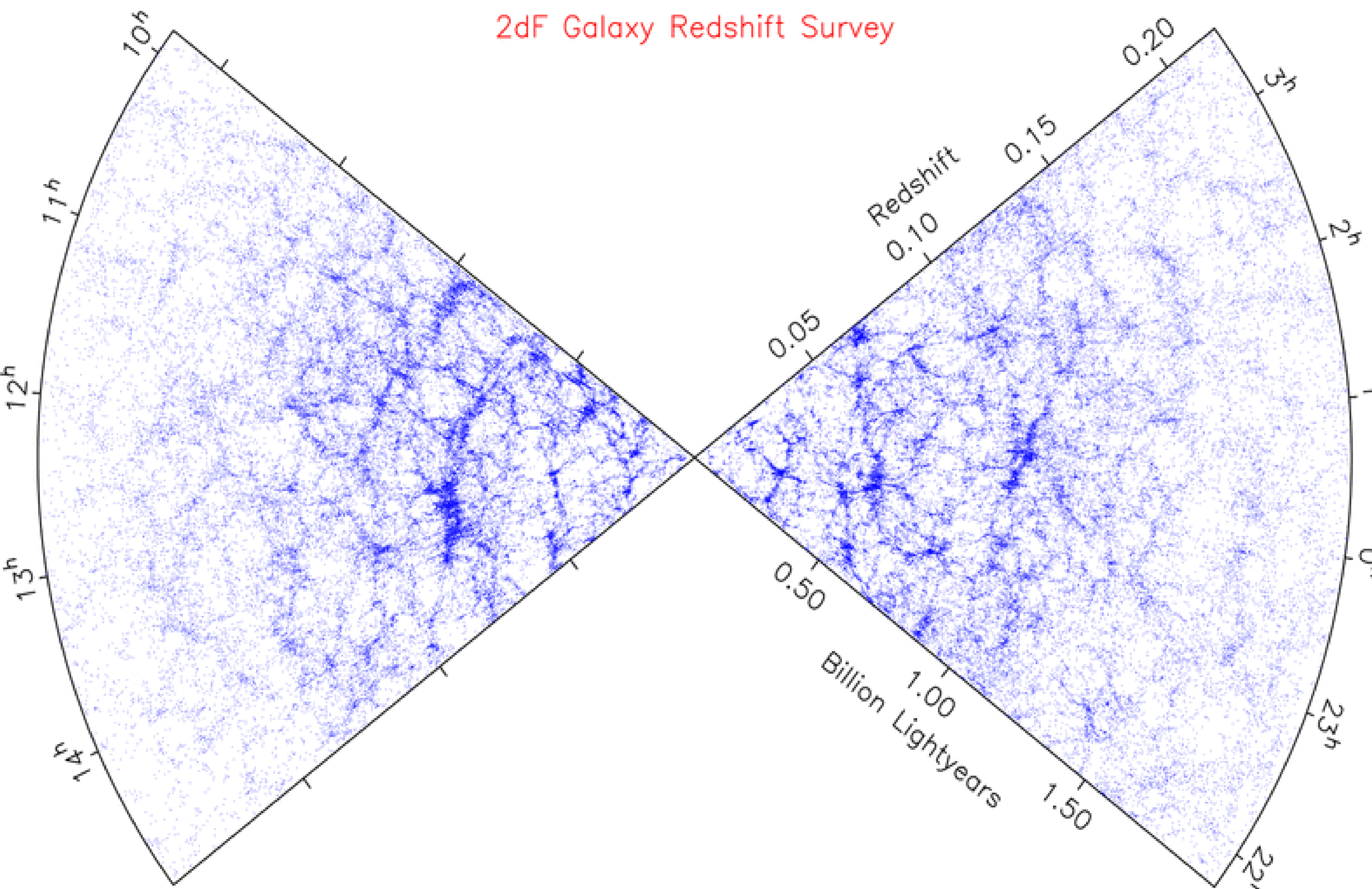
Gaussian random field (phases of Fourier modes δ_k uncorrelated) is fully characterized by the power spectrum

$$P(k) = |\delta_k|^2$$

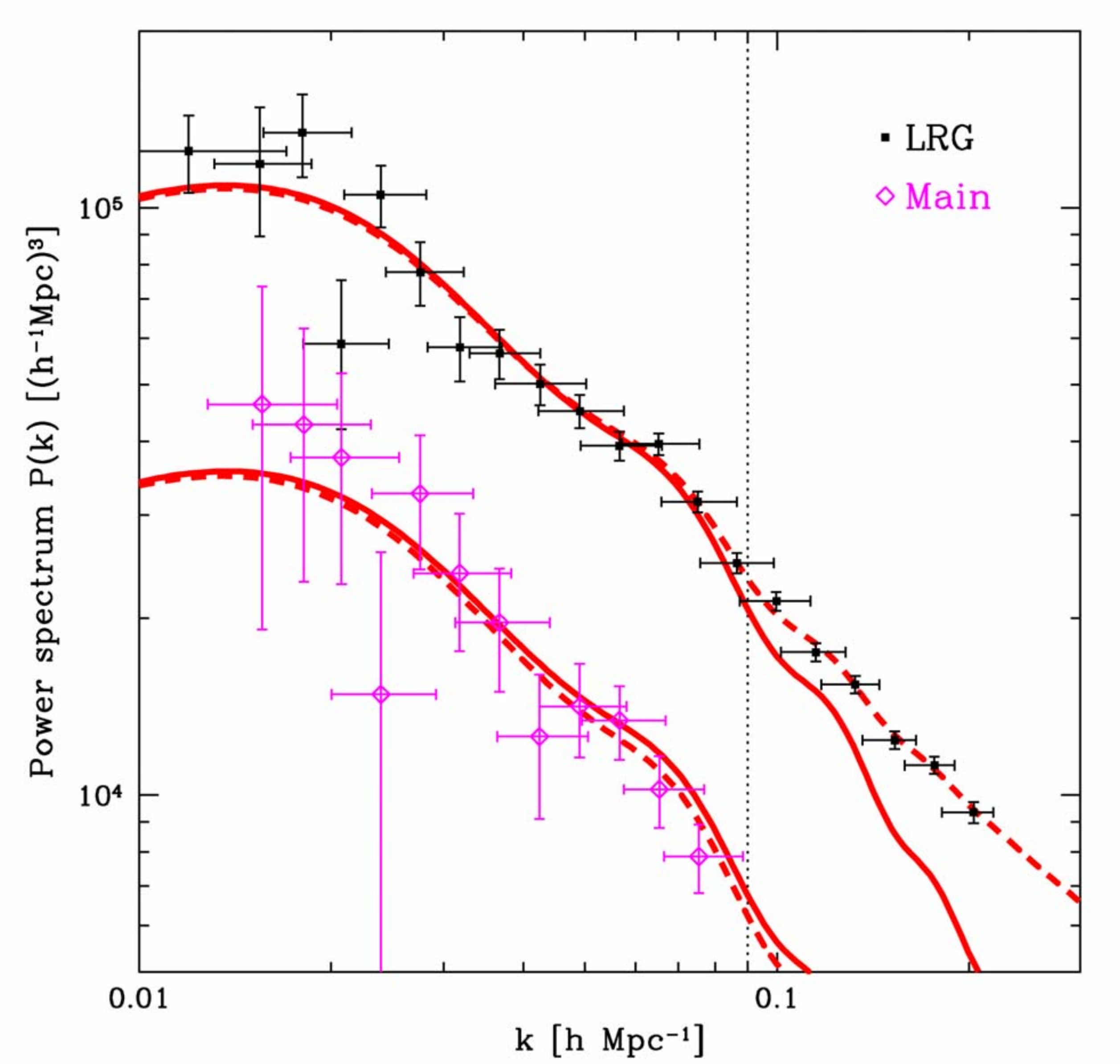
or equivalently by

$$\Delta(k) = \left(\frac{k^3 P(k)}{2\pi^2} \right)^{1/2} = \frac{k^{3/2} |\delta_k|}{\sqrt{2}\pi}$$

LARGE SCALE STRUCTURE SURVEYS - 2dF AND SDSS



SDSS SPECTRUM
TEGMARK ET AL. 2006

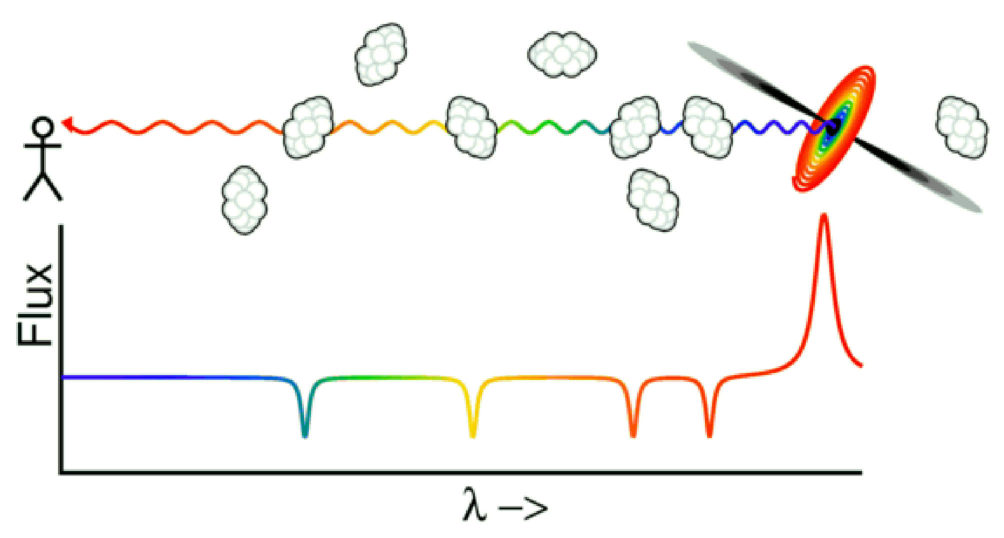


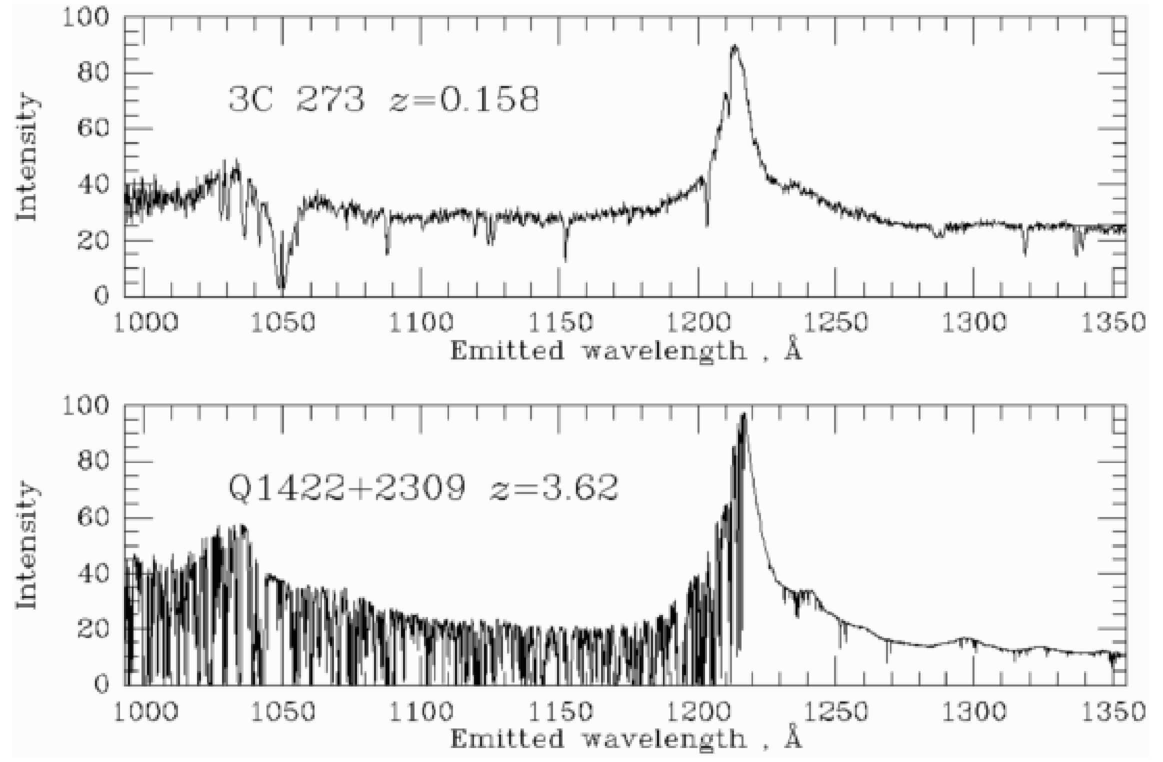
astro-ph/0608632

Lyman-alpha Forest

- Hydrogen clouds absorb from QSO continuum emission spectrum
- Absorption dips at Ly-α wavelengh corresponding to redshift

www.astro.ucla.edu/~wright/Lyman-alpha-forest.html

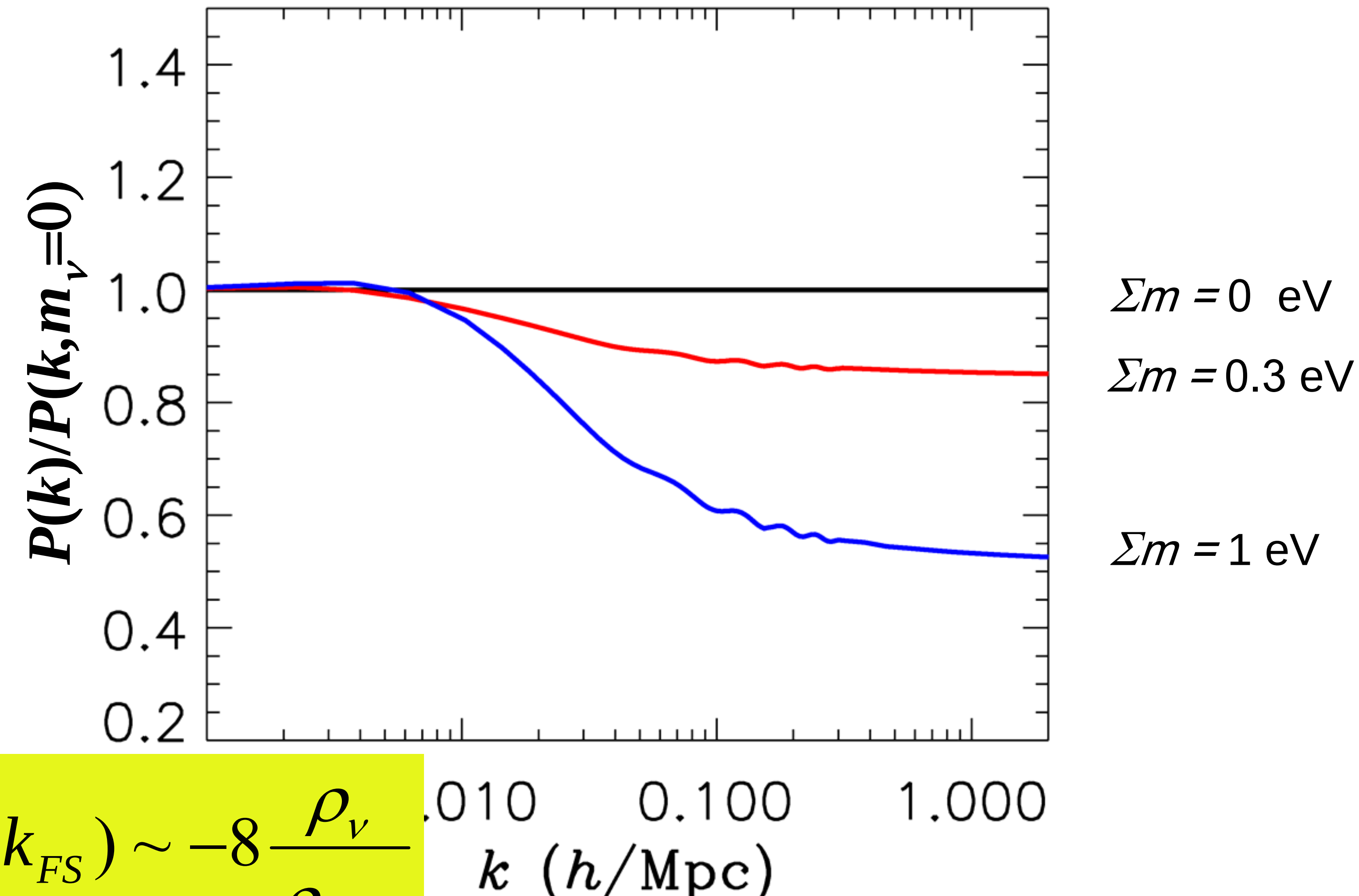




Examples for Lyman-α forest in low- and high-redshift quasars

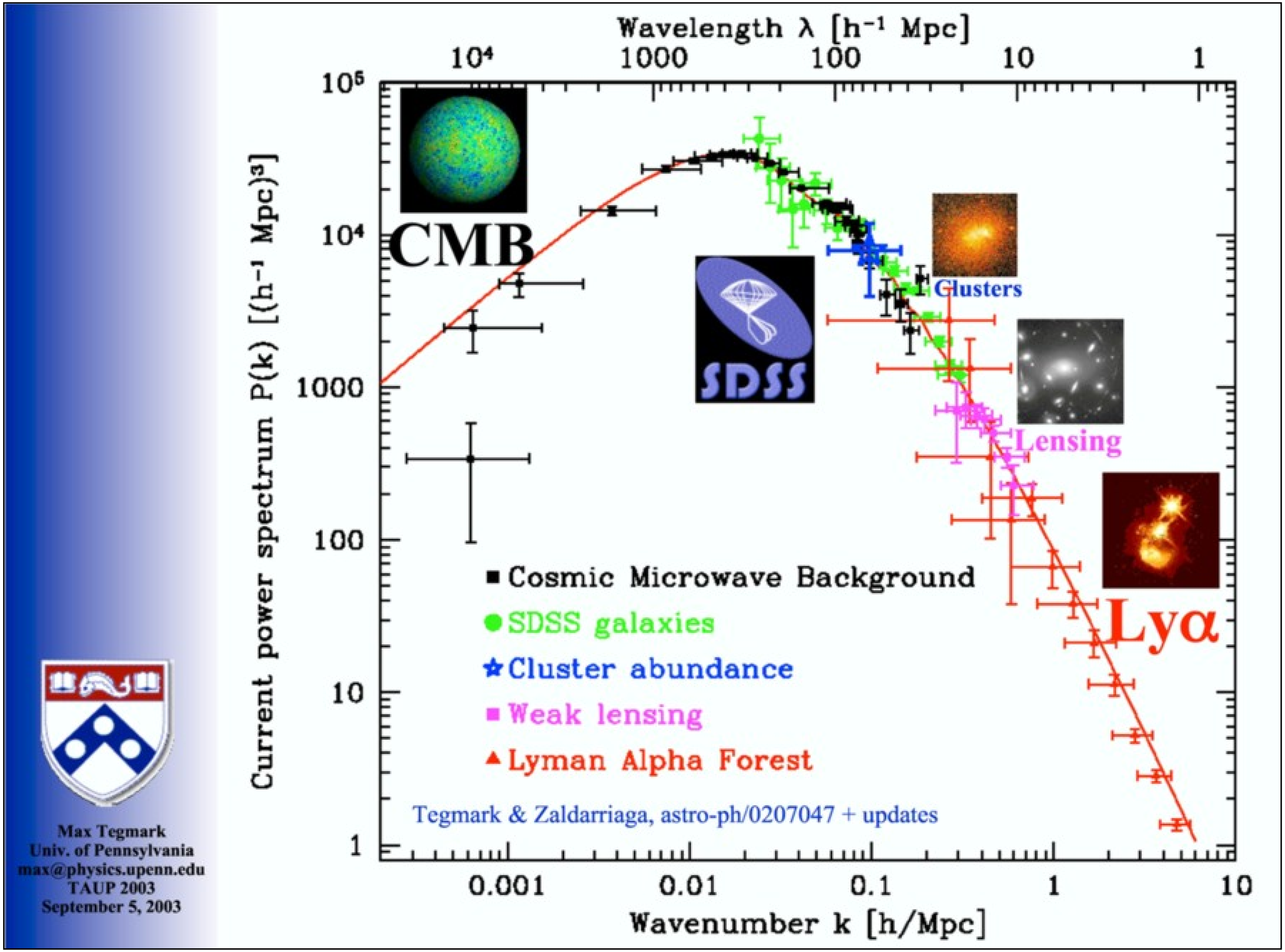
http://www.astr.ua.edu/keel/agn/forest.gif

FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH, THE SAME IS TRUE FOR AXIONS



$$\frac{P}{P_{m=0}}(k >> k_{FS}) \sim -8\frac{\rho_\nu}{\rho_{TOT}}$$

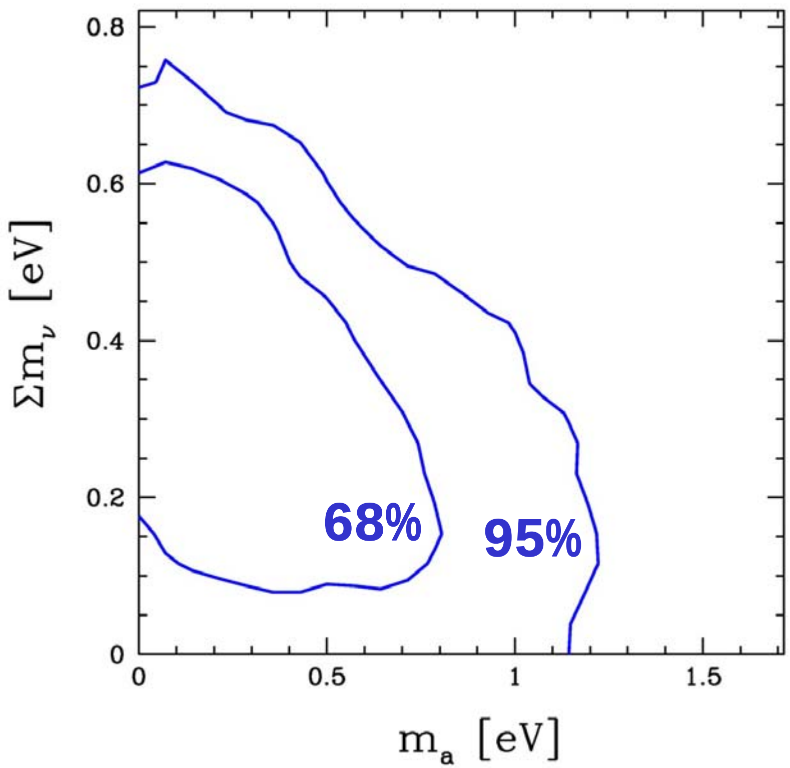
Power Spectrum of Cosmic Density Fluctuations



Some Recent Cosmological Limits on Neutrino Masses

	Σm_ν/eV (limit 95%CL)	Data / Priors
Hannestad 2003 [astro-ph/0303076]	1.01	WMAP-1, CMB, 2dF, HST
Spergel et al. (WMAP) 2003 [astro-ph/0302209]	0.69	WMAP-1, 2dF, HST, σ_8
Crotty et al. 2004 [hep-ph/0402049]	1.0 0.6	WMAP-1, CMB, 2dF, SDSS & HST, SN
Hannestad 2004 [hep-ph/0409108]	0.65	WMAP-1, SDSS, SN Ia gold sample, Ly-α data from Keck sample
Seljak et al. 2004 [astro-ph/0407372]	0.42	WMAP-1, SDSS, Bias, Ly-α data from SDSS sample
Hannestad et al. 2006 [astro-ph/0602155]	0.30	WMAP-1, CMB-small, SDSS, 2dF, SN Ia, BAO (SDSS), Ly-α (SDSS)
Spergel et al. 2006 [astro-ph/0603499]	0.68	WMAP-3, SDSS, 2dF, SN Ia, σ_8
Seljak et al. 2006 [astro-ph/0604335]	0.14	WMAP-3, CMB-small, SDSS, 2dF, SN Ia, BAO (SDSS), Ly-α (SDSS)

Axion Hot Dark Matter Limits from Precision Data



Credible regions for neutrino plus axion hot dark matter (WMAP-5, LSS, BAO, SNIa) Hannestad, Mirizzi, Raffelt & Wong [arXiv:0803.1585]

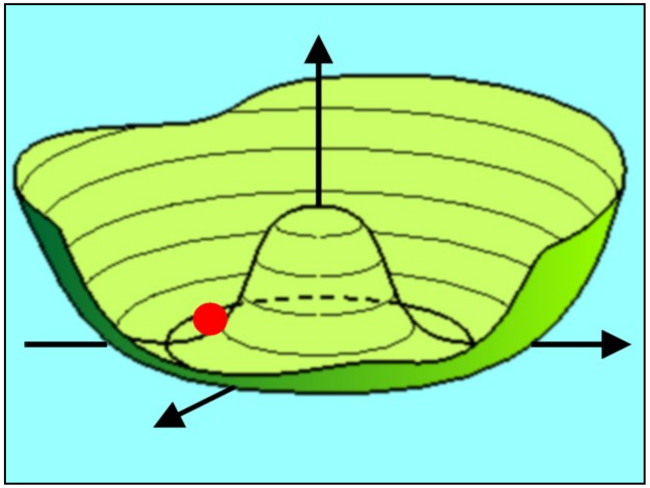
Marginalizing over unknown neutrino hot dark matter component

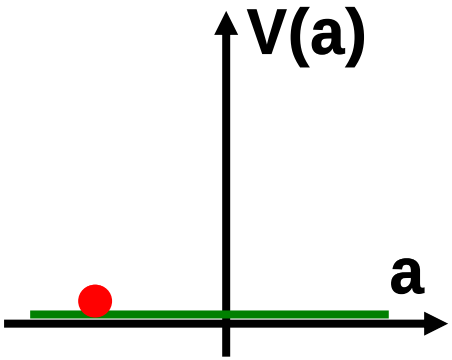
m_a < 1.0 eV (95% CL)	**WMAP-5, LSS, BAO, SNIa**	**Hannestad, Mirizzi, Raffelt & Wong [arXiv:0803.1585]**
m_a < 0.4 eV (95% CL)	**WMAP-3, small-scale CMB, HST, BBN, LSS, Ly-α**	**Melchiorri, Mena & Slosar [arXiv:0705.2695]**

Creation of Cold Cosmological Axions

$T \sim f_a$ (very early universe)

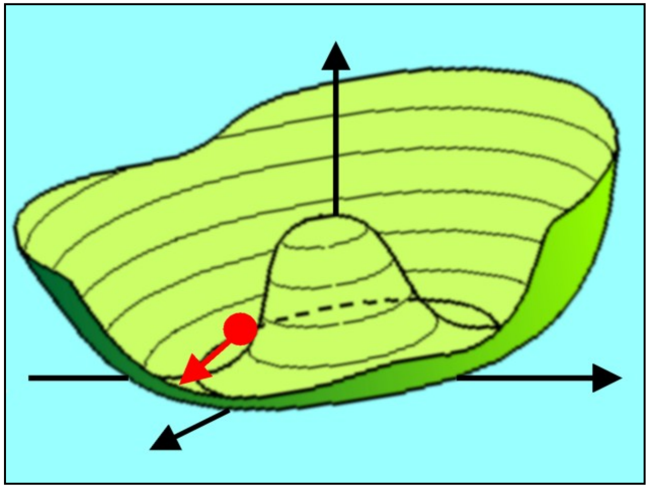
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"
- Axion field sits fixed at $a_1 = \Theta_1 f_a$

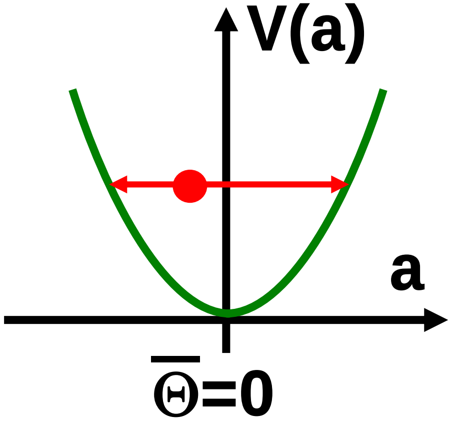




$T \sim 1$ GeV ($H \sim 10^{-9}$ eV)

- Axion mass turns on quickly by thermal instanton gas
- Field starts oscillating when $m_a \gtrsim 3H$
- Classical field oscillations (axions at rest)





- Axion number density in comoving volume conserved

$$n_a R^3 = m_a(T_1)\, a_1^2 R_1^3 \sim 3H_1 R_1^3 \Theta_1^2 f_a^2$$

- Axion mass density today: $\rho_a = m_a n_a \propto \Theta_1^2 m_a f_a^2 \propto \Theta_1^2 \frac{m_a^2 f_a^2}{m_a} \propto \Theta_1^2 \frac{m_\pi^2 f_\pi^2}{m_a}$

Cosmic Axion Density

Modern values for QCD parameters and temperature-dependent axion mass imply (Bae, Huh & Kim, arXiv:0806.0497)

$$\Omega_a h^2 = 0.195\,\Theta_i^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1.184} = 0.105\,\Theta_i^2 \left(\frac{10\ \mu\mathrm{eV}}{m_a}\right)^{1.184}$$

If axions provide the cold dark matter: $\Omega_a h^2 = 0.11$

$$\Theta_i = 0.75 \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)^{0.592} = 1.0 \left(\frac{m_a}{10\ \mu\mathrm{eV}}\right)^{0.592}$$

- $\Theta_i \sim 1$ implies $f_a \sim 10^{12}$ GeV and $m_a \sim 10\ \mu$eV ("classic window")
- $f_a \sim 10^{16}$ GeV (GUT scale) or larger (string inspired) requires $\Theta_i \lesssim 0.003$ ("anthropic window")

Cold Axion Populations

Case 1:
Inflation after PQ symmetry breaking

Homogeneous mode oscillates after

$$T \lesssim \Lambda_{QCD}$$

Dependence on initial misalignment angle

$$\Omega_a \propto \Theta_i^2$$

Dark matter density a cosmic random number ("environmental parameter")

- Isocurvature fluctuations from large quantum fluctuations of massless axion field created during inflation
- Strong CMB bounds on isocurvature fluctuations
- Scale of inflation required to be small

Case 2:
Reheating restores PQ symmetry

- Cosmic strings of broken $U_{PQ}(1)$ form by Kibble mechanism
- Radiate long-wavelength axions
- Ω_a independent of initial conditions

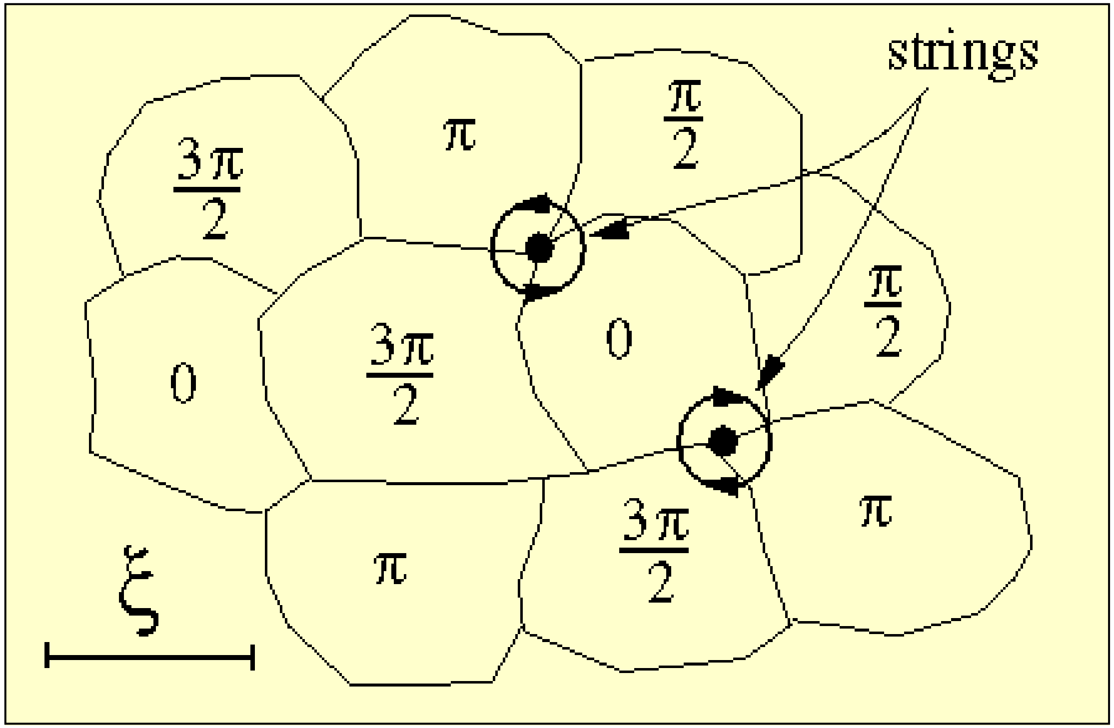
Inhomogeneities of axion field large, self-couplings lead to formation of mini-clusters

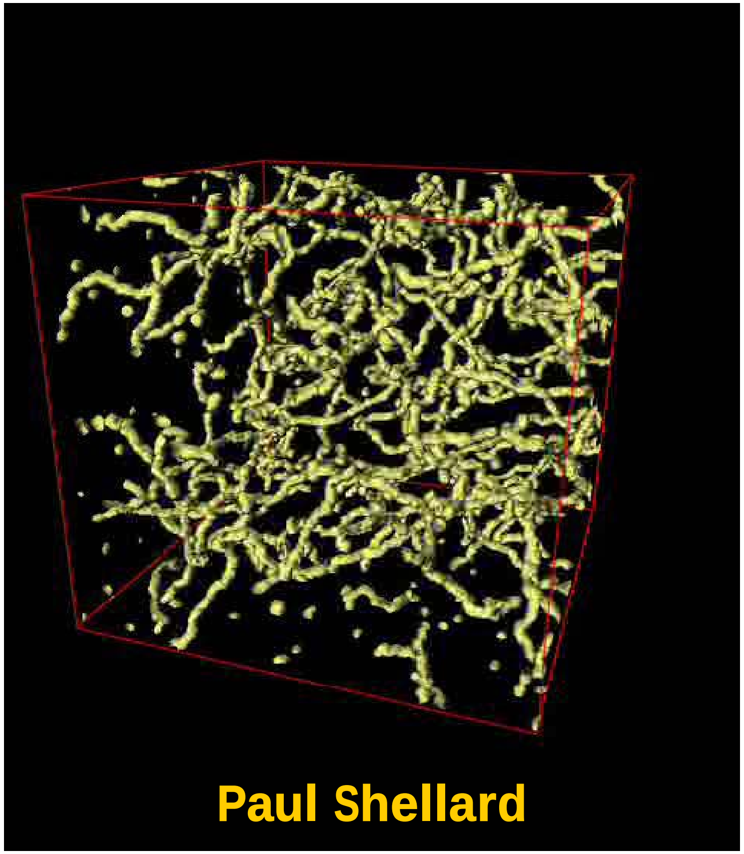
Typical properties

- Mass ~ 10^{-12} M_{sun}
- Radius ~ 10^{10} cm
- Mass fraction up to several 10%

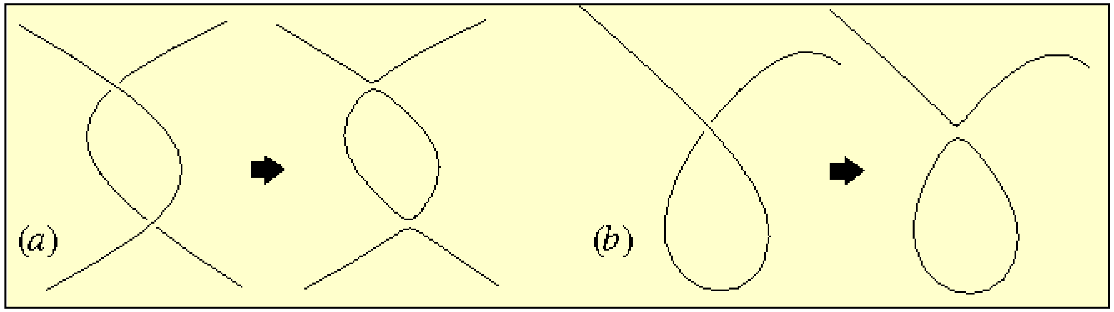
Axions from Cosmic Strings

Strings form by Kibble mechanism after break-down of $U_{PQ}(1)$





Small loops form by self-intersection



Inflation, Axions, and Anthropic Selection

If PQ symmetry is not restored after inflation

- Axion density determined by initial random number $-\pi < \Theta_i < +\pi$
- Different in different patches of the universe
- Our visible universe, after inflation, from a single patch
- Axion/photon ratio a cosmic random number, chosen by spontaneous symmetry breaking process

Allows for small $\Theta_i \lesssim 0.003$ and thus for f_a at GUT or string scale

- Is this "unlikely" or "unnatural" or "fine tuning"?
- Should one design experiments for very small-mass axion dark matter?

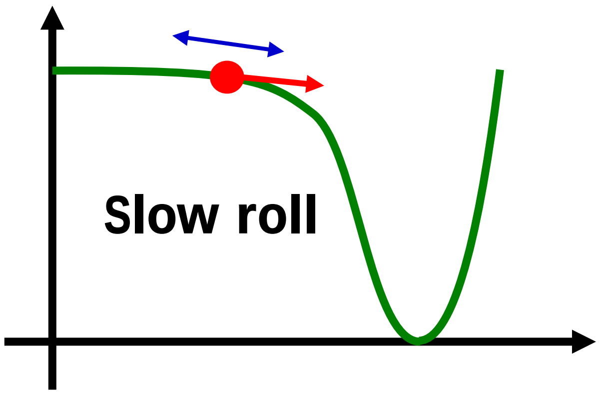
Difficult to form baryonic structures if baryon/dark matter density too low, posterior probability for small Θ_i not necessarily small

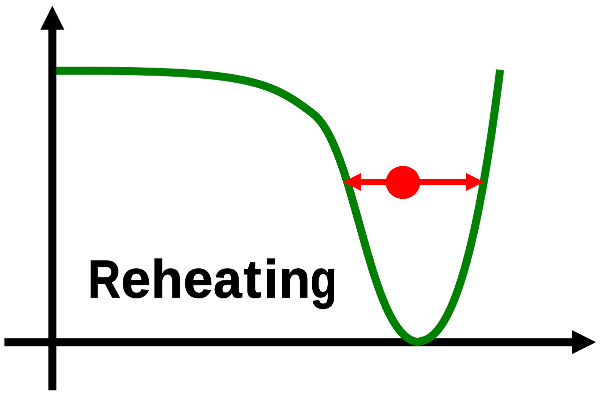
- Linde, "Inflation and axion cosmology," PLB 201:437, 1988
- Tegmark, Aguirre, Rees & Wilczek, "Dimensionless constants, cosmology and other dark matters," PRD 73:023505, 2006 [astro-ph/0511774]

Creation of Adiabatic vs. Isocurvature Perturbations

Inflaton field:

De Sitter expansion imprints scale invariant fluctuations

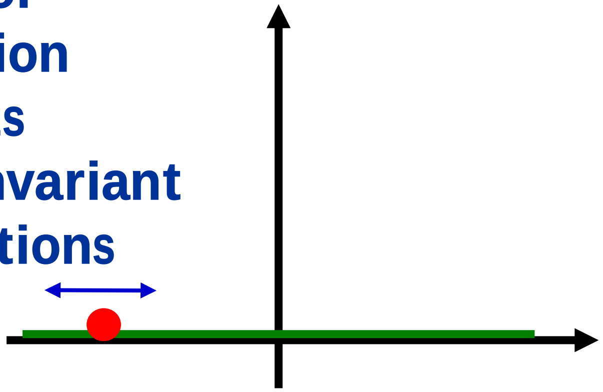


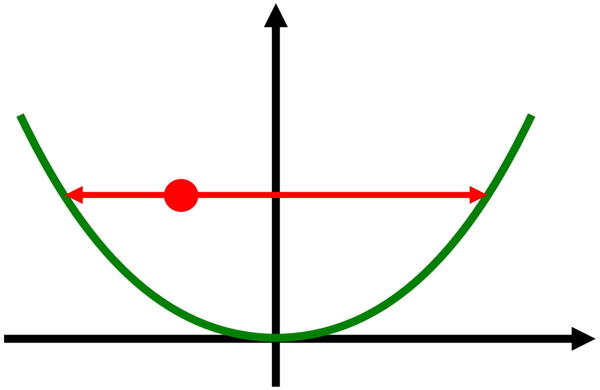


Inflaton decay → matter & radiation
Fluctuations in both (adiabatic)

Axion field:

De Sitter expansion imprints scale invariant fluctuations





Inflaton decay → radiation
Axion field oscillates late → matter
Fluctuations of matter relative to radiation: Entropy fluctuations

Amplitudes of Adiabatic and Isocurvature Perturbations

Entropy fluctuations induced by de Sitter expansion on axion field

$$S(k) = \frac{\Theta^2 - \langle \Theta^2 \rangle}{\langle \Theta^2 \rangle}$$

Isocurvature power spectrum, assuming Gaussian fluctuations ($n_{iso} = 1 - 2\varepsilon$, slow-roll parameter ε)

$$\langle |S(k)|^2 \rangle \sim \sigma_\Theta^2 \sim \frac{H_I^2}{\pi^2 f_a^2 \Theta_i^2} \propto \left(\frac{k}{k_0}\right)^{n_{iso}-1}$$

Usual curvature power spectrum

$$\langle |R(k)^2| \rangle \sim \frac{H_I^2}{\pi M_{Pl}^2 \varepsilon} \propto \left(\frac{k}{k_0}\right)^{n_{ad}-1}$$

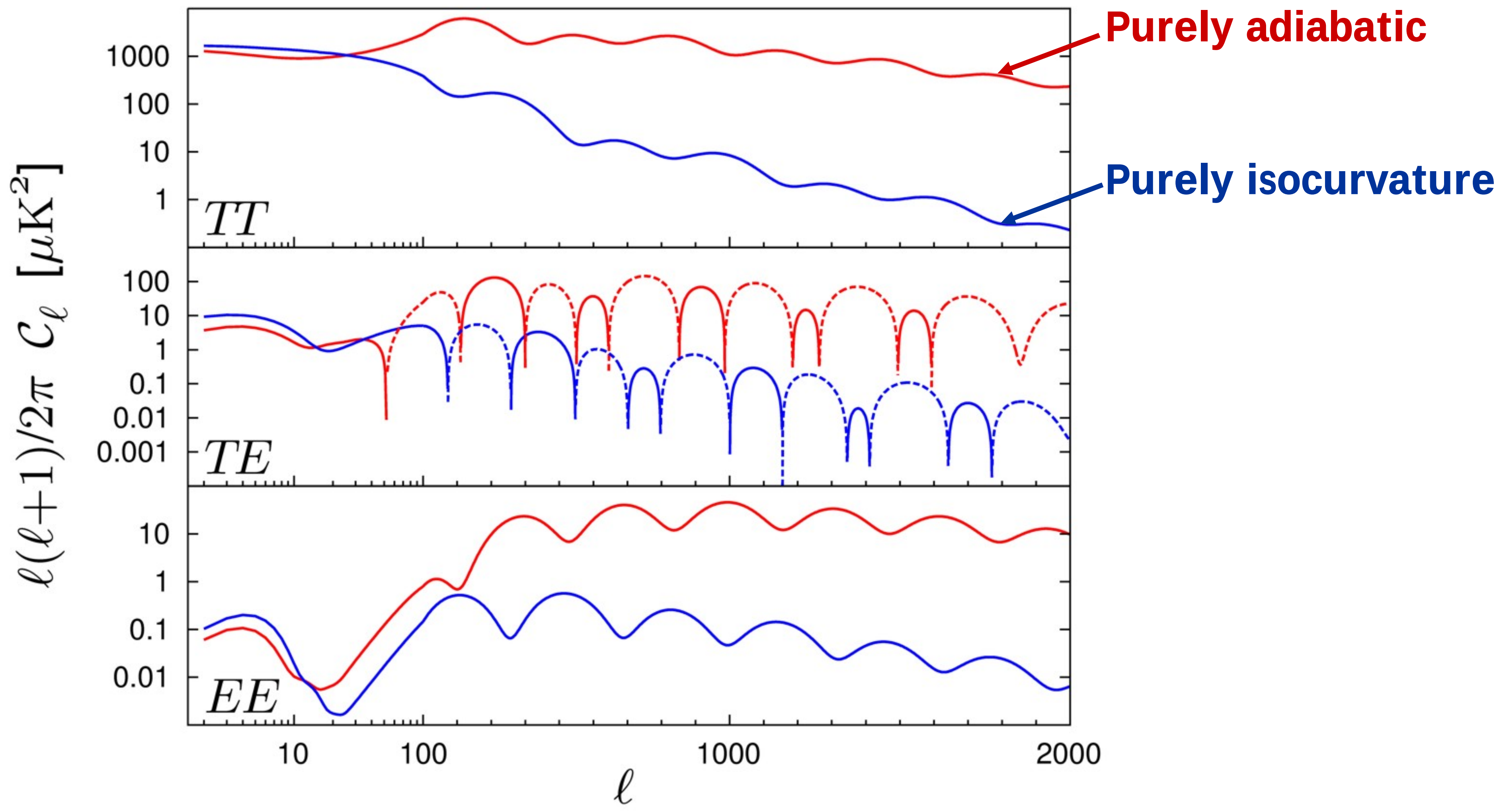
Total power spectrum uncorrelated sum

$$P(k) = \langle |R(k)^2| \rangle + \langle |S(k)^2| \rangle$$

Isocurvature fraction at pivot scale $k_0 = 0.002\ \mathrm{Mpc}^{-1}$

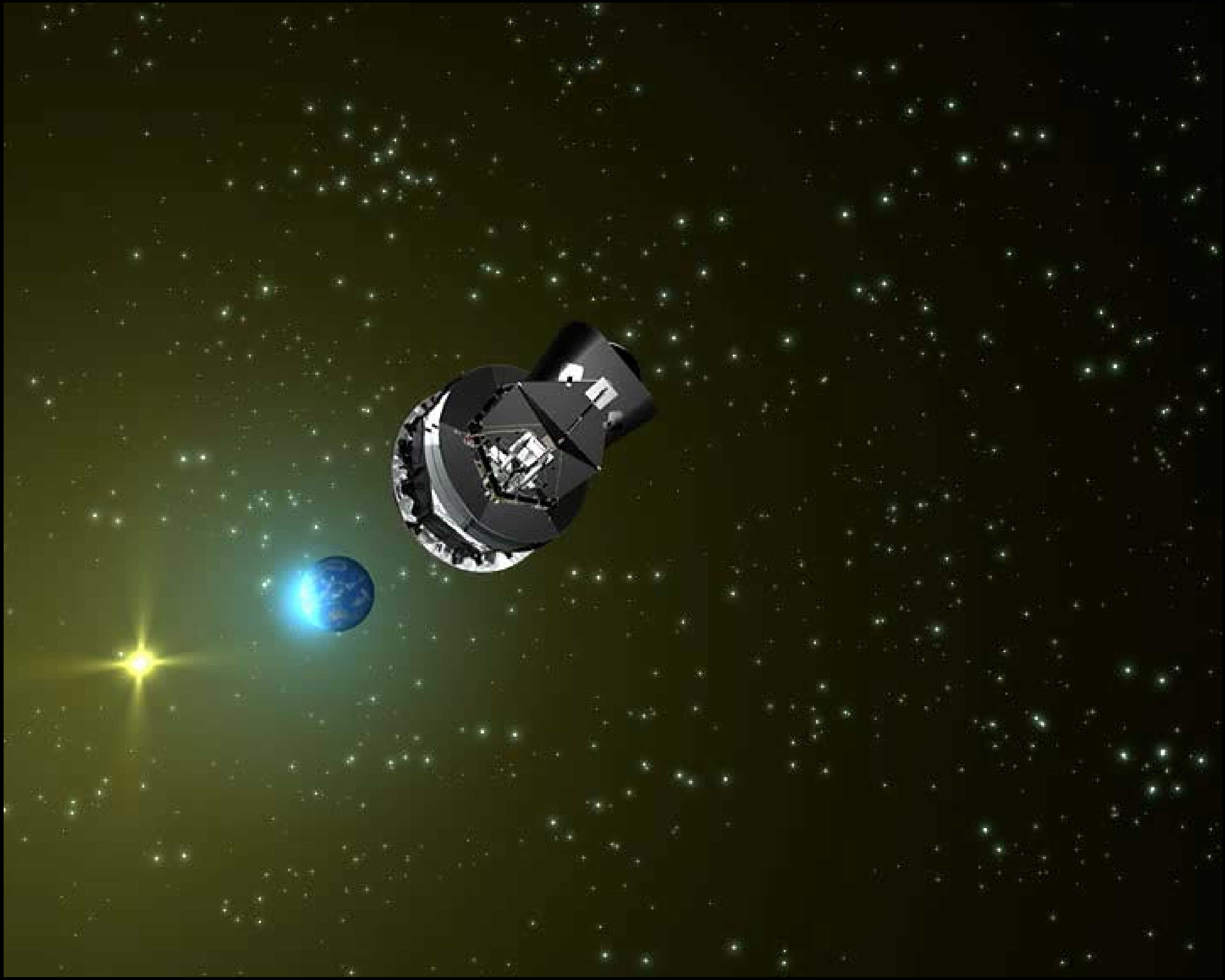
$$\alpha = \left. \frac{\langle |S(k)^2| \rangle}{\langle |R(k)^2| \rangle + \langle |S(k)^2| \rangle} \right|_{k=k_0} \sim \frac{H_I^2}{A_S \pi^2 f_a^2 \Theta_i^2}$$

CMB Angular Power Spectrum

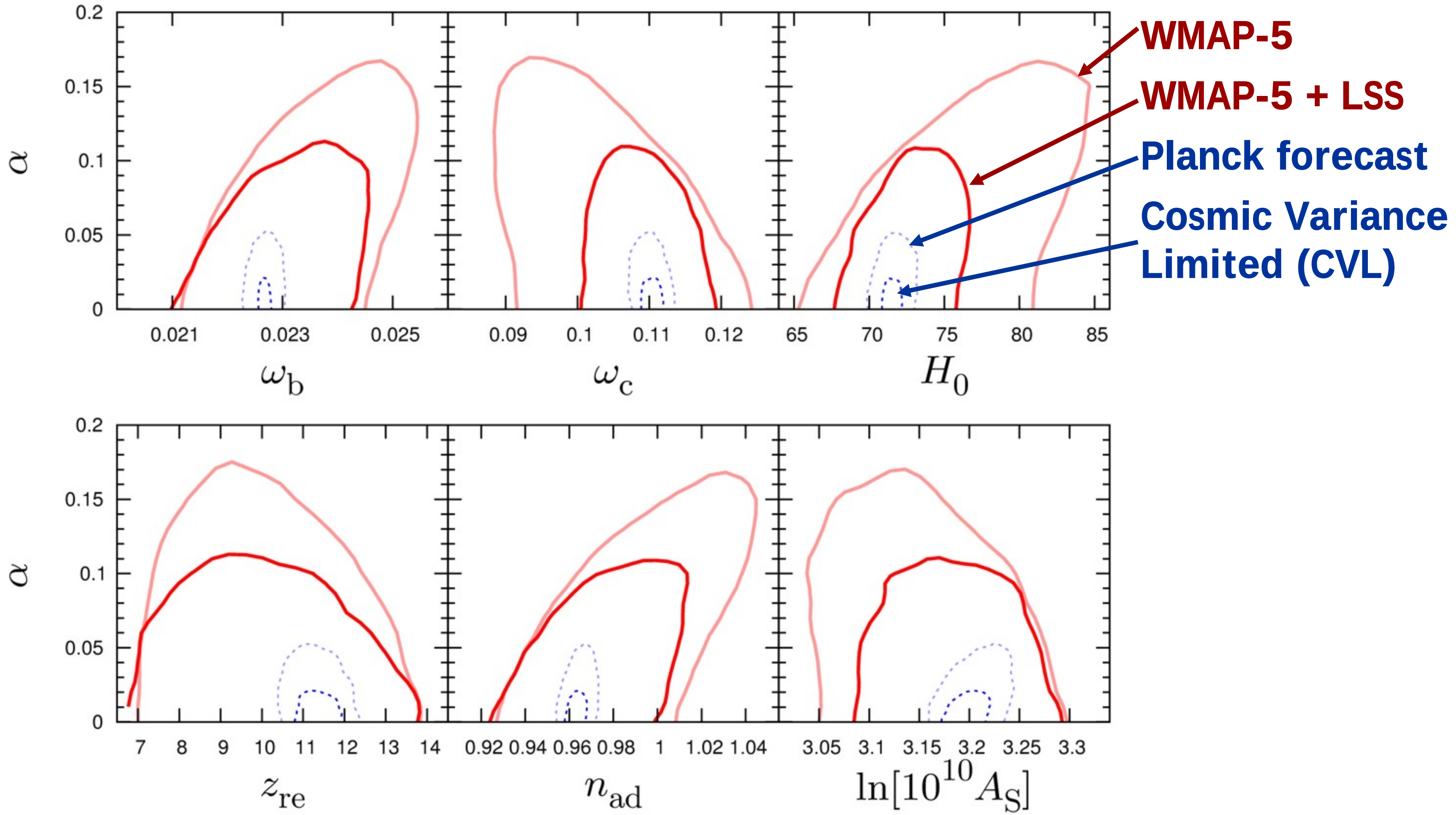


Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647

PLANCK Satellite – Successful Launch on 14 May 2009



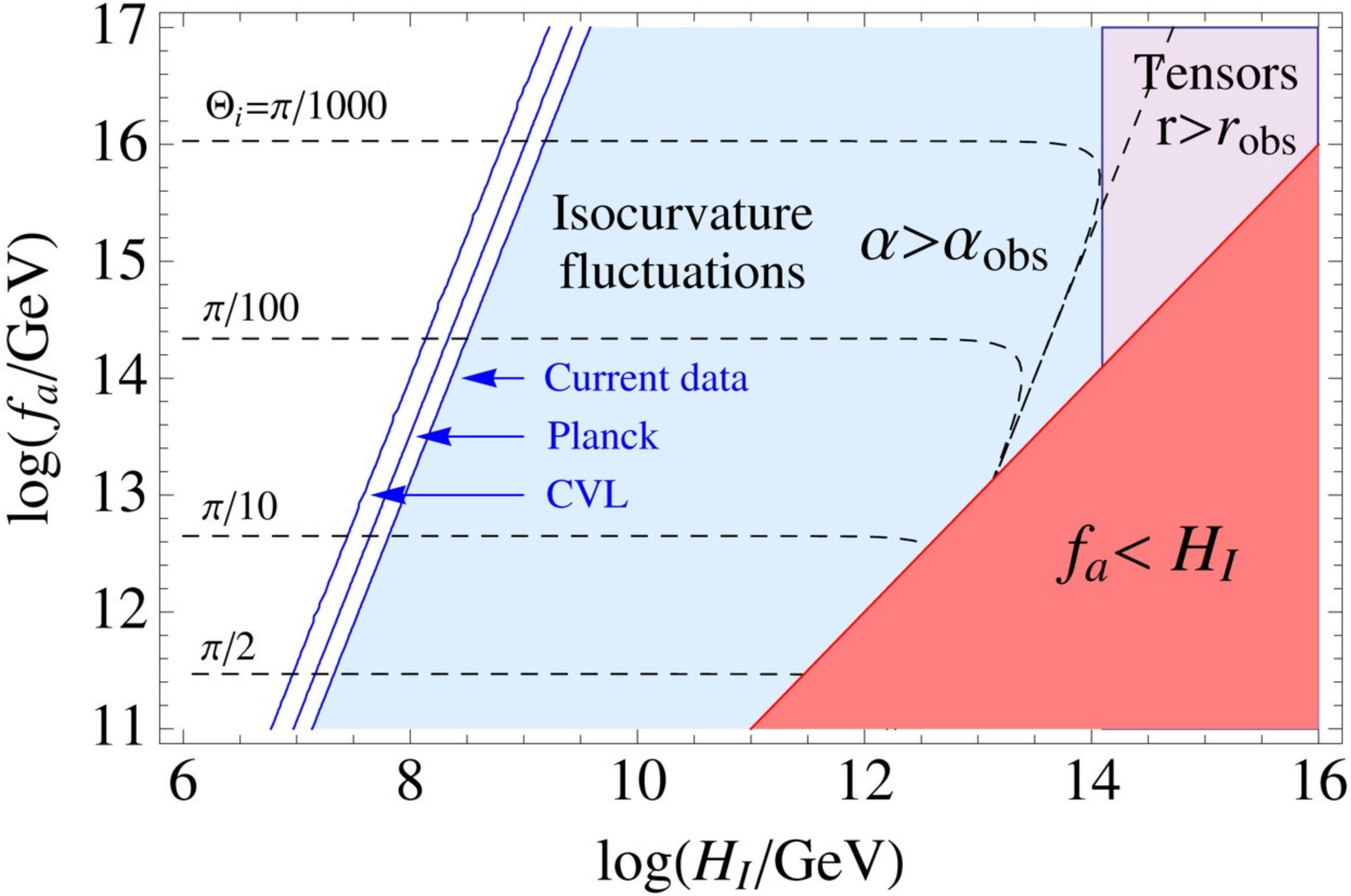
Parameter Degeneracies



Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647

Isocurvature Forecast

Hubble scale during inflation



Axion decay constant

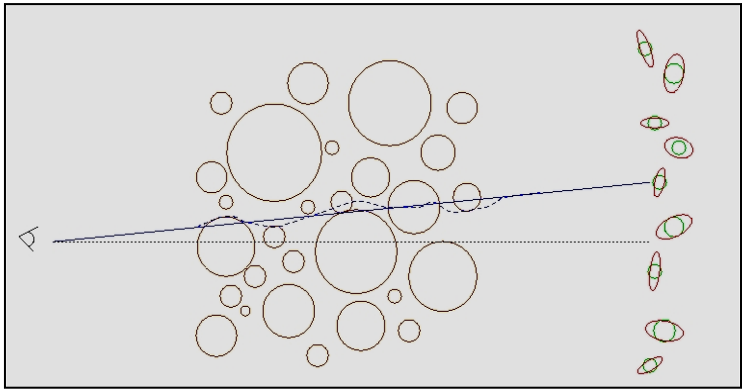
Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647

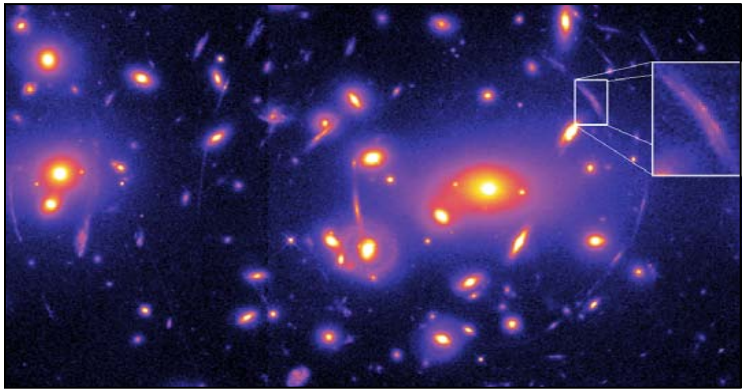
What will happen wrt axion HDM in the future

A large amount of new precision data will become available in the next decade

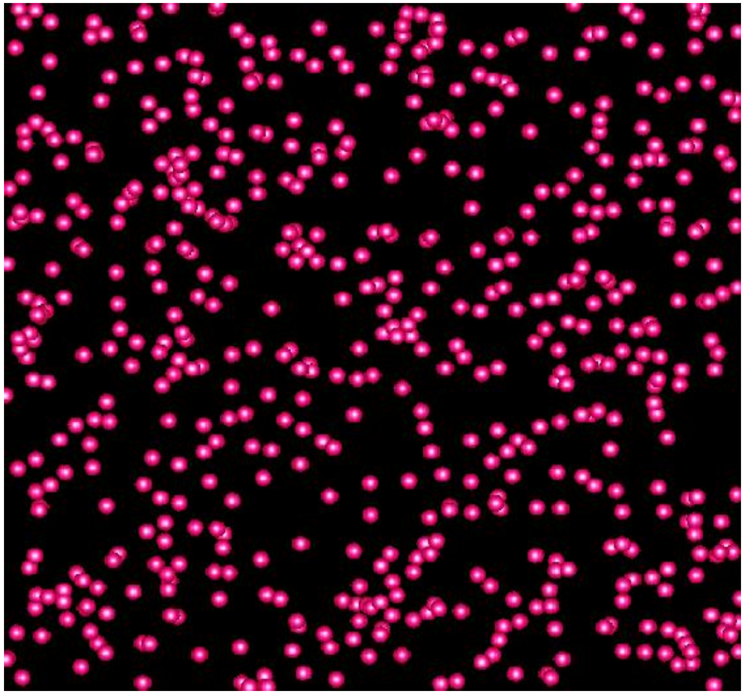
- New CMB data
- Weak lensing
- Baryon acoustic oscillation surveys
- 21-cm surveys

Weak Lensing – A Powerful Probe for the Future

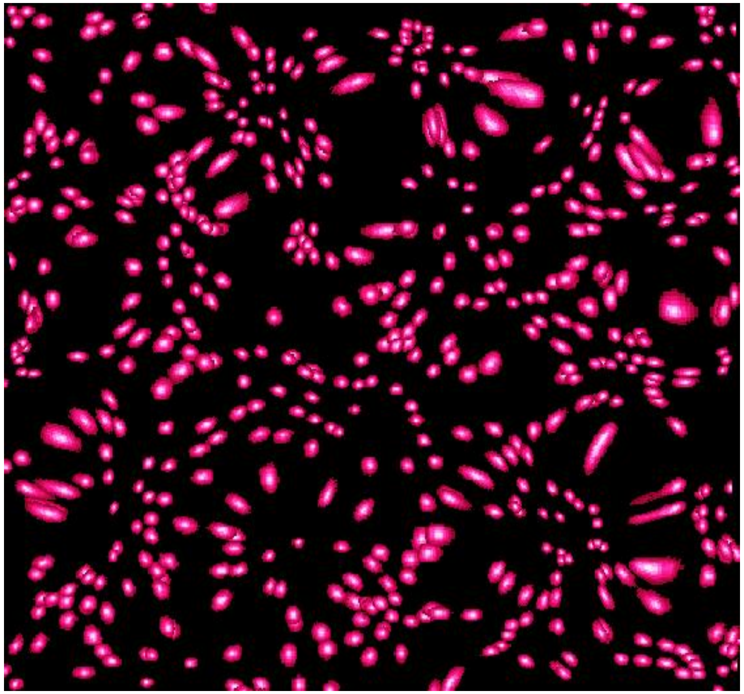




Distortion of background images by foreground matter



Unlensed



Lensed

FROM A WEAK LENSING SURVEY THE ANGULAR POWER SPECTRUM CAN BE CONSTRUCTED, JUST LIKE IN THE CASE OF CMB

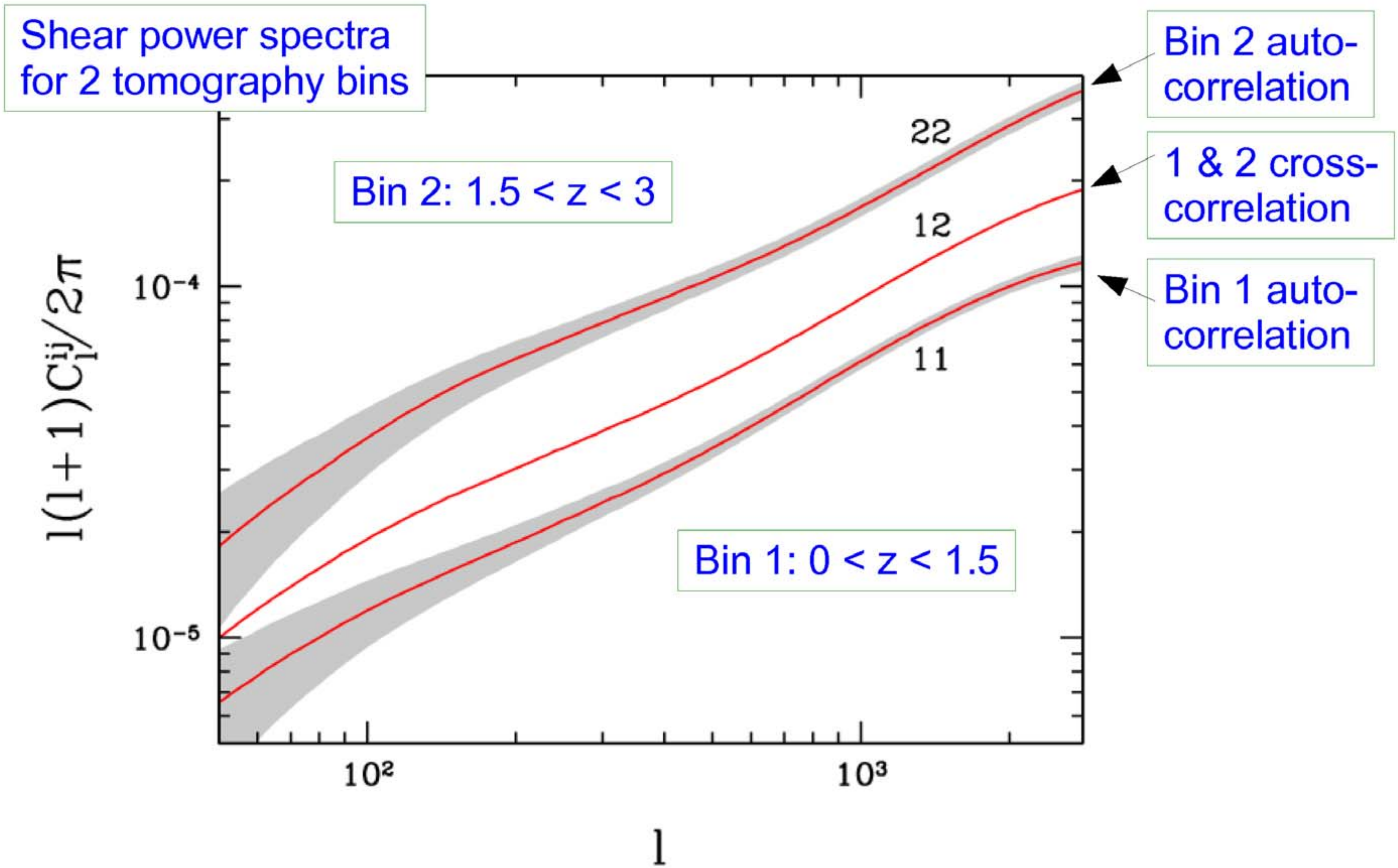
$$C_\ell = \frac{9}{16} H_0^4 \Omega_m^2 \int_0^{\chi_H} \left[\frac{g(\chi)}{a\chi} \right]^2 P(\ell / r, \chi) d\chi$$

$P(\ell / r, \chi)$ MATTER POWER SPECTRUM (NON-LINEAR)

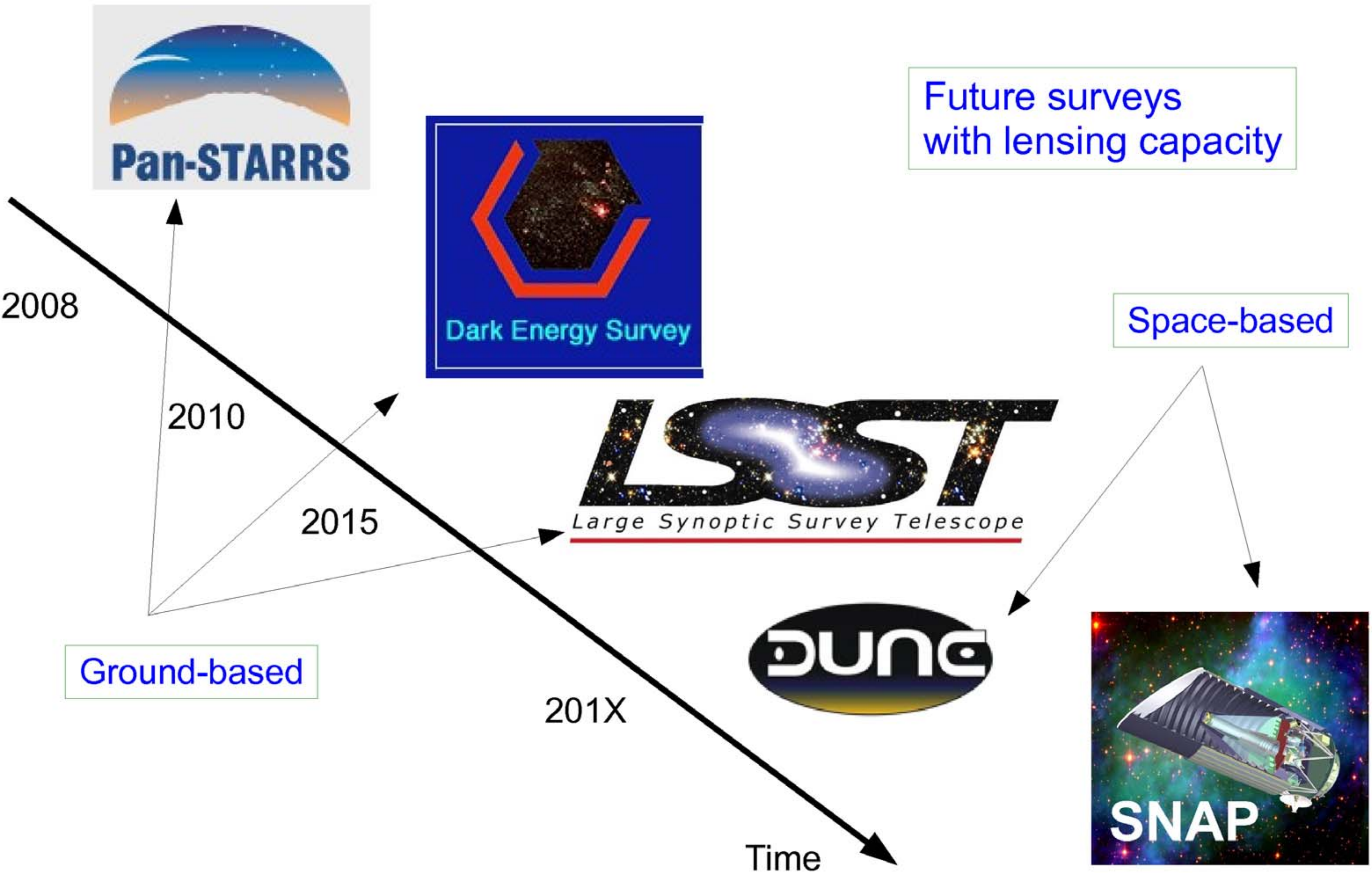
$$g(\chi) = 2 \int_0^{\chi_H} n(\chi') \frac{\chi(\chi' - \chi)}{\chi'} d\chi'$$

WEIGHT FUNCTION DESCRIBING LENSING PROBABILITY

(SEE FOR INSTANCE JAIN & SELJAK ’96, ABAZAJIAN & DODELSON ’03, SIMPSON & BRIDLE ’04)



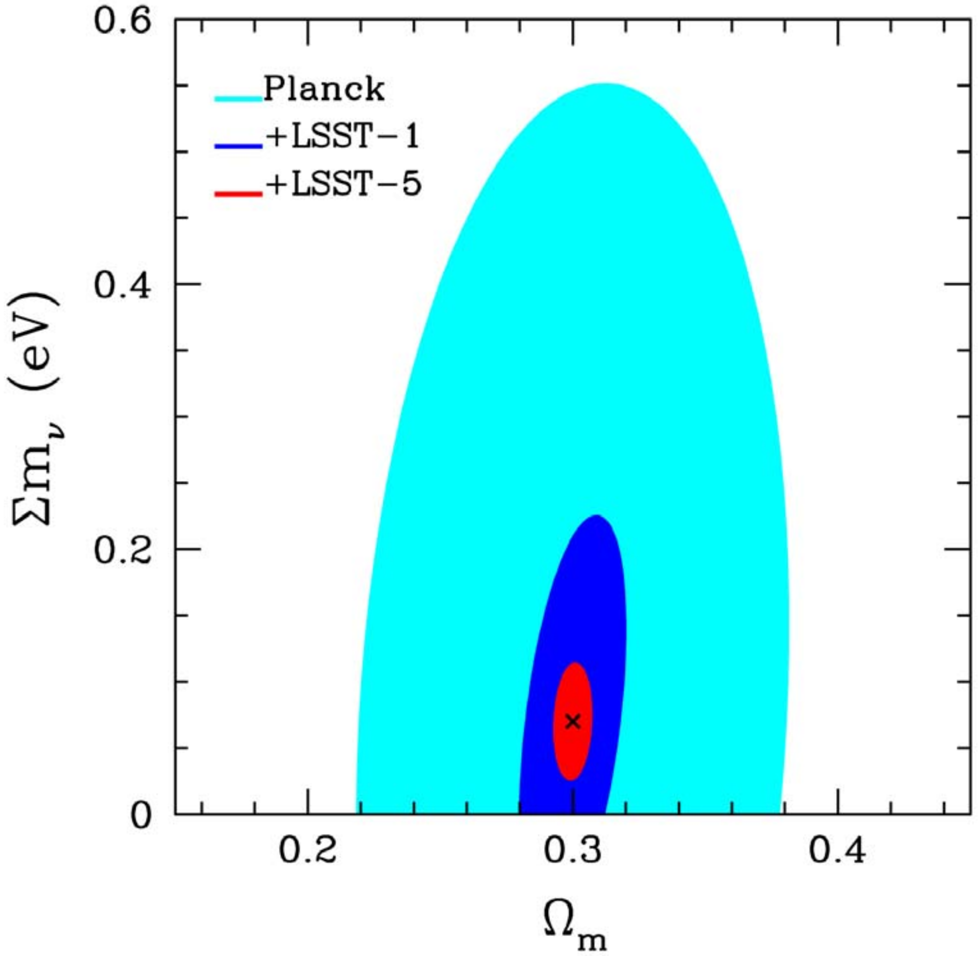
STH, TU, WONG 2006



Future surveys
with lensing capacity
Pan-STARRS
Dark Energy Survey
LSST
Large Synoptic Survey Telescope
DUNE
SNAP
2008
2010
2015
201X
Time
Ground-based
Space-based

THE SENSITIVITY TO NEUTRINO MASS WILL IMPROVE TO < 0.1 eV AT 95% C.L. USING WEAK LENSING

COULD POSSIBLY BE IMPROVED EVEN FURTHER USING FUTURE LARGE SCALE STRUCTURE SURVEYS



STH, TU & WONG 2006 (ASTRO-PH/0603019, JCAP)

Sensitivity Forecasts for Future LSS Observations

Lesgourgues, Pastor & Perotto, hep-ph/0403296	Planck & SDSS	Σm_ν > 0.21 eV detectable at 2σ
	Ideal CMB & 40 x SDSS	Σm_ν > 0.13 eV detectable at 2σ
Abazajian & Dodelson astro-ph/0212216	Future weak lensing survey 4000 deg^2	$\sigma(m_\nu)$ ~ 0.1 eV
Kaplinghat, Knox & Song, astro-ph/0303344	CMB lensing	$\sigma(m_\nu)$ ~ 0.15 eV (Planck) $\sigma(m_\nu)$ ~ 0.044 eV (CMBpol)
Wang, Haiman, Hu, Khoury & May, astro-ph/0505390	Weak-lensing selected sample of > 10^5 clusters	$\sigma(m_\nu)$ ~ 0.03 eV
Hannestad, Tu & Wong astro-ph/0603019	Weak-lensing tomography (LSST plus Planck)	$\sigma(m_\nu)$ ~ 0.05 eV

WHY IS WEAK LENSING TOMOGRAPHY SO GOOD?

IF MEASURED AT ONLY ONE REDSHIFT THE HOT DARK MATTER SIGNAL IS DEGENERATE WITH OTHER PARAMETERS

- CHANGING DARK ENERGY EQUATION OF STATE
- INITIAL CONDITIONS WITH BROKEN SCALE INVARIANCE

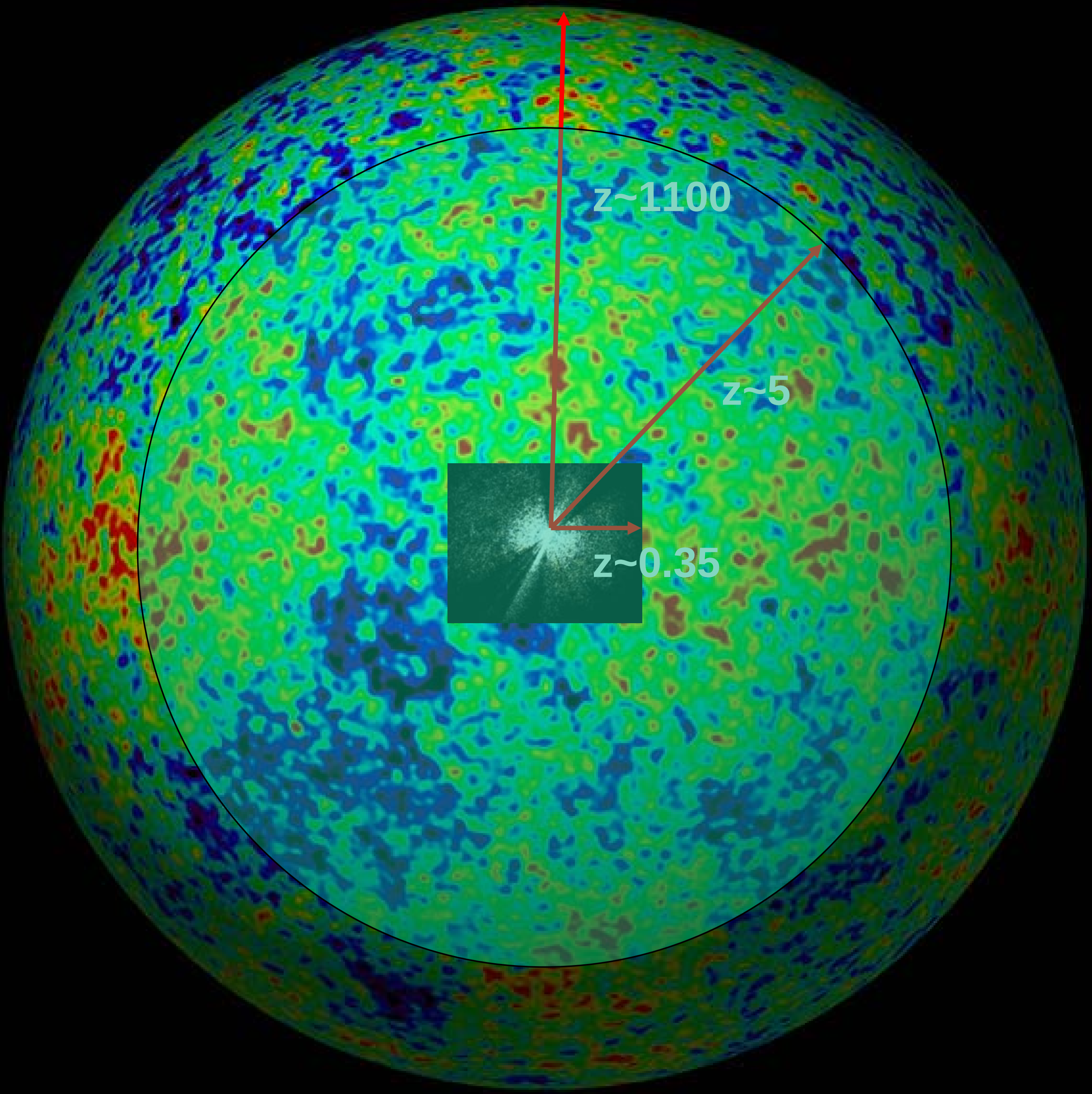
HOWEVER, BY MEASURING AT DIFFERENT REDSHIFTS THIS DEGENERACY CAN BE BROKEN

ADVANTAGES OF PROBING STRUCTURE AT HIGH REDSHIFT

- STRUCTURES ARE MORE LINEAR
- VOLUME IS LARGER (THE HORIZON VOLUME IS ~ 1000 TIMES LARGER THAN THE SDSS-LRG VOLUME)

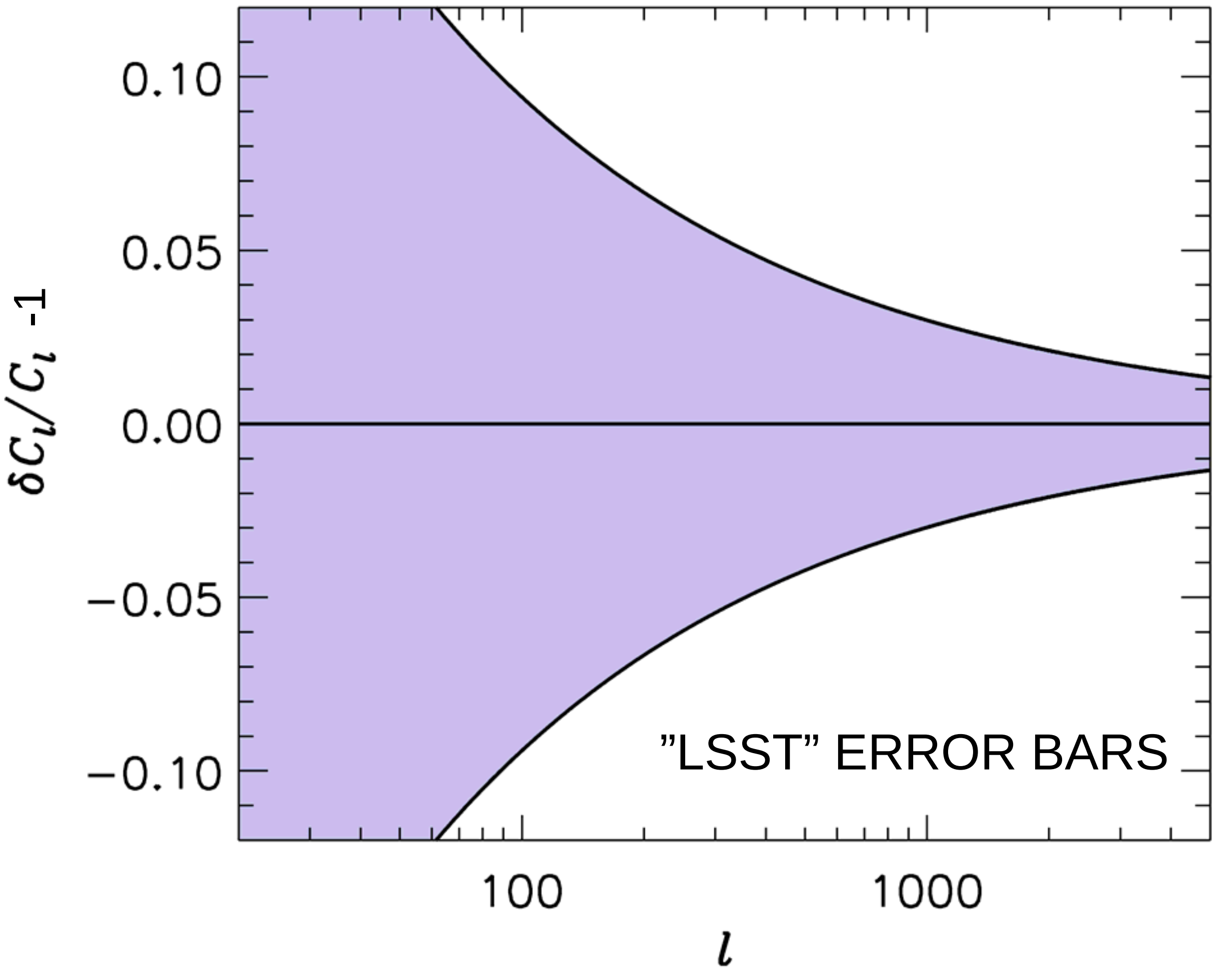
HOW TO DO IT?

- LYMAN-ALPHA?
- BAO? (WFMOS)
- GALAXIES? (LSST)
- 21-CM? (SKA)


z~1100
z~5
z~0.35

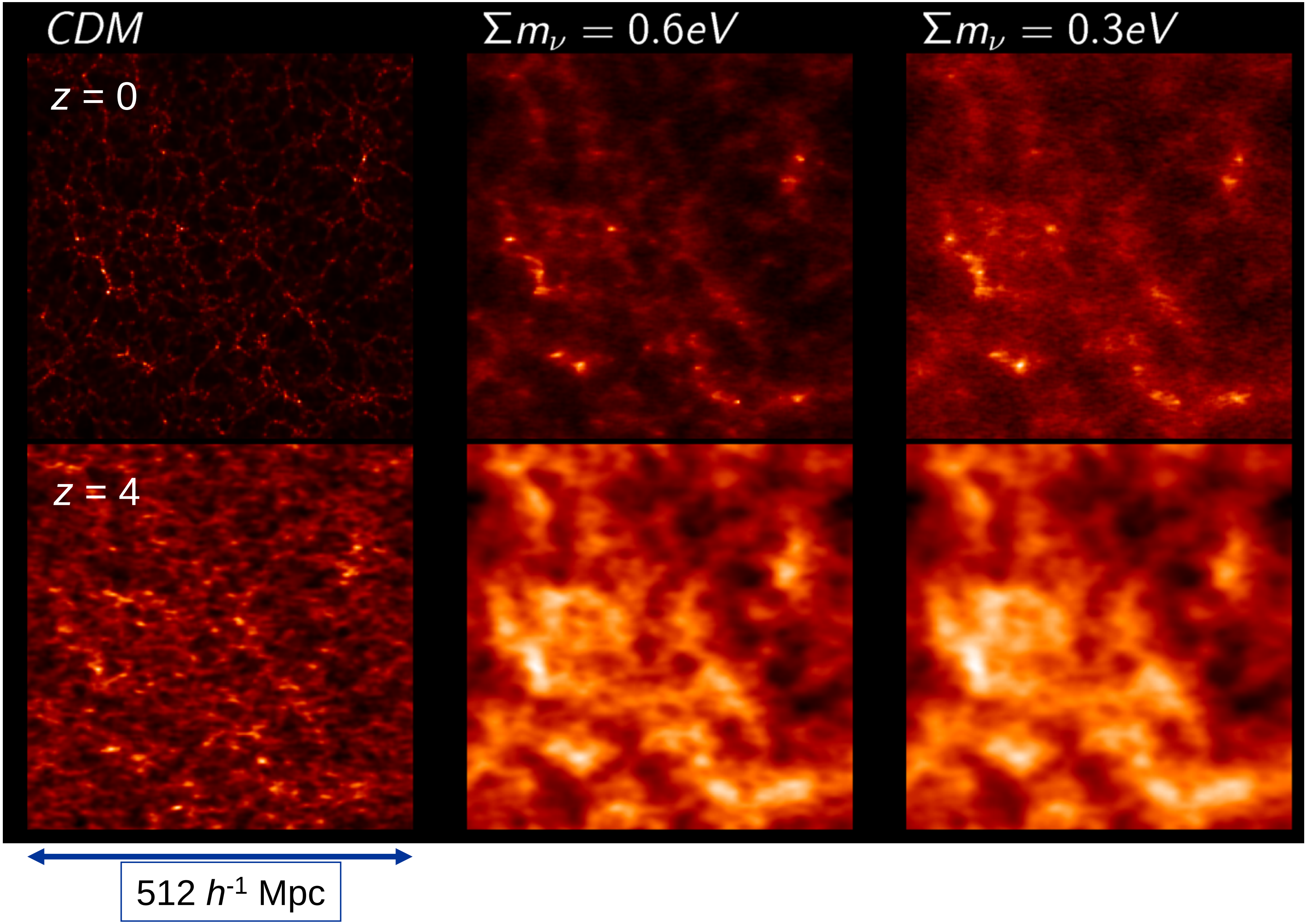
THIS SOUNDS GREAT, BUT UNFORTUNATELY THEORY MUST BE AT THE SAME LEVEL OF PRECISION BY THE TIME DATA-TAKING STARTS

FUTURE SURVEYS LIKE LSST WILL PROBE THE POWER SPECTRUM TO ~ 1-2 PERCENT PRECISION

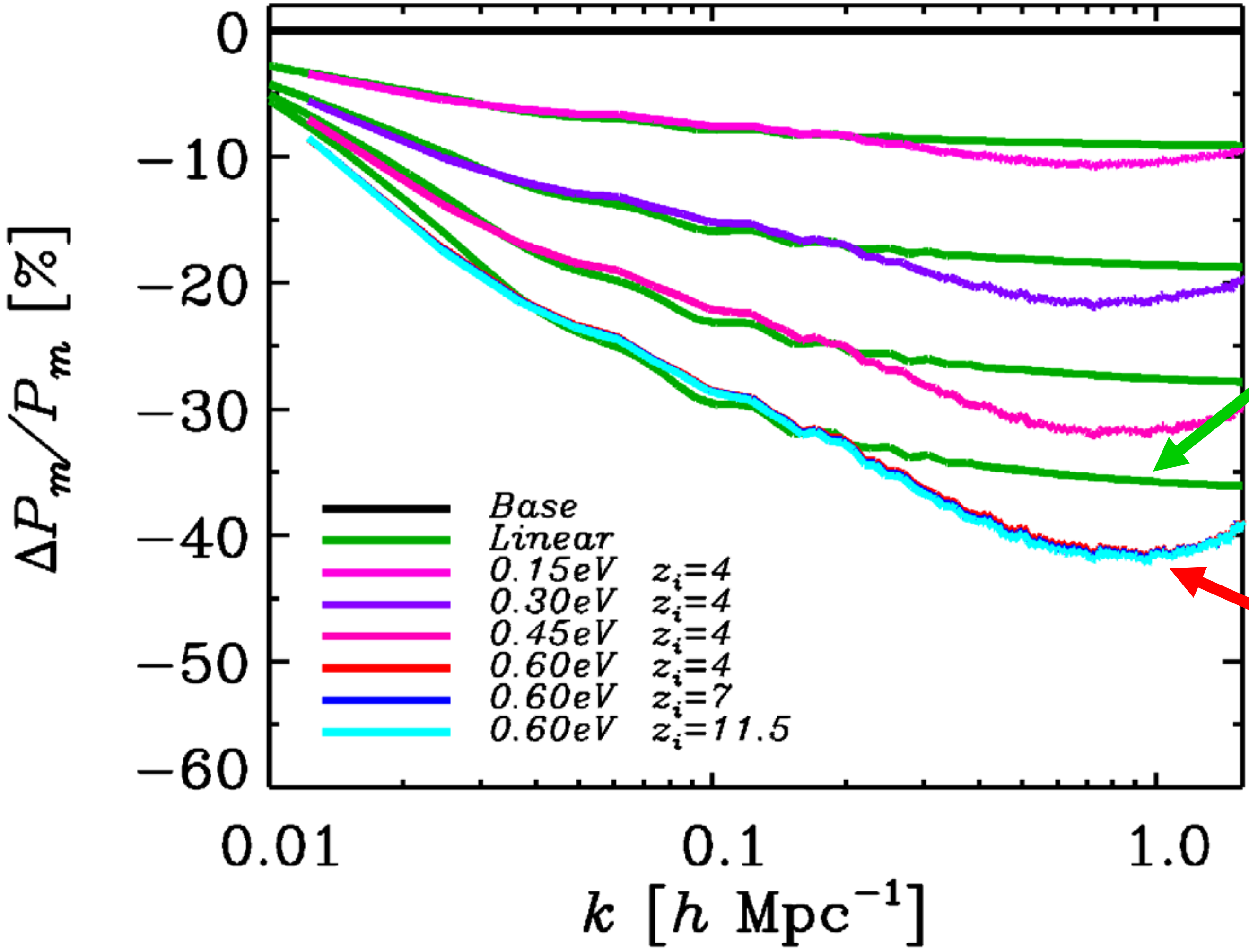


WE SHOULD BE ABLE TO CALCULATE THE POWER SPECTRUM TO AT LEAST THE SAME PRECISION!

Example: Evolution of neutrino density field



NON-LINEAR EVOLUTION PROVIDES AN ADDITIONAL AND VERY CHARACTERISTIC SUPPRESSION OF FLUCTUATION POWER DUE TO HDM (COULD BE USED AS A SMOKING GUN SIGNATURE)



LINEAR THEORY

$$\frac{\Delta P}{P} \sim -8\frac{\Omega_\nu}{\Omega_m}$$

FULL NON-LINEAR

$$\frac{\Delta P}{P} \sim -9.6\frac{\Omega_\nu}{\Omega_m}$$

Brandbyge, STH, Haugbølle, Thomsen, arXiv:0802.3700 (ApJ)

Summary

Cosmology provide very competitive laboratory for testing axion physics

Measurements of the large scale structure of the universe can potentially probe both very low and very high mass axions

In the coming years there will be a large amount of new and very precise cosmological data which will push the axion bounds