4th Patras Workshop on Axions, WIMPs and WISPs
18–21 June 2008, DESY, Hamburg

Axion Hot Dark Matter Bounds

Georg Raffelt, Max-Planck-Institut für Physik, München

Motivation

Observations of the mass-density distribution in the universe provides very restrictive limits on a possible hot dark matter component

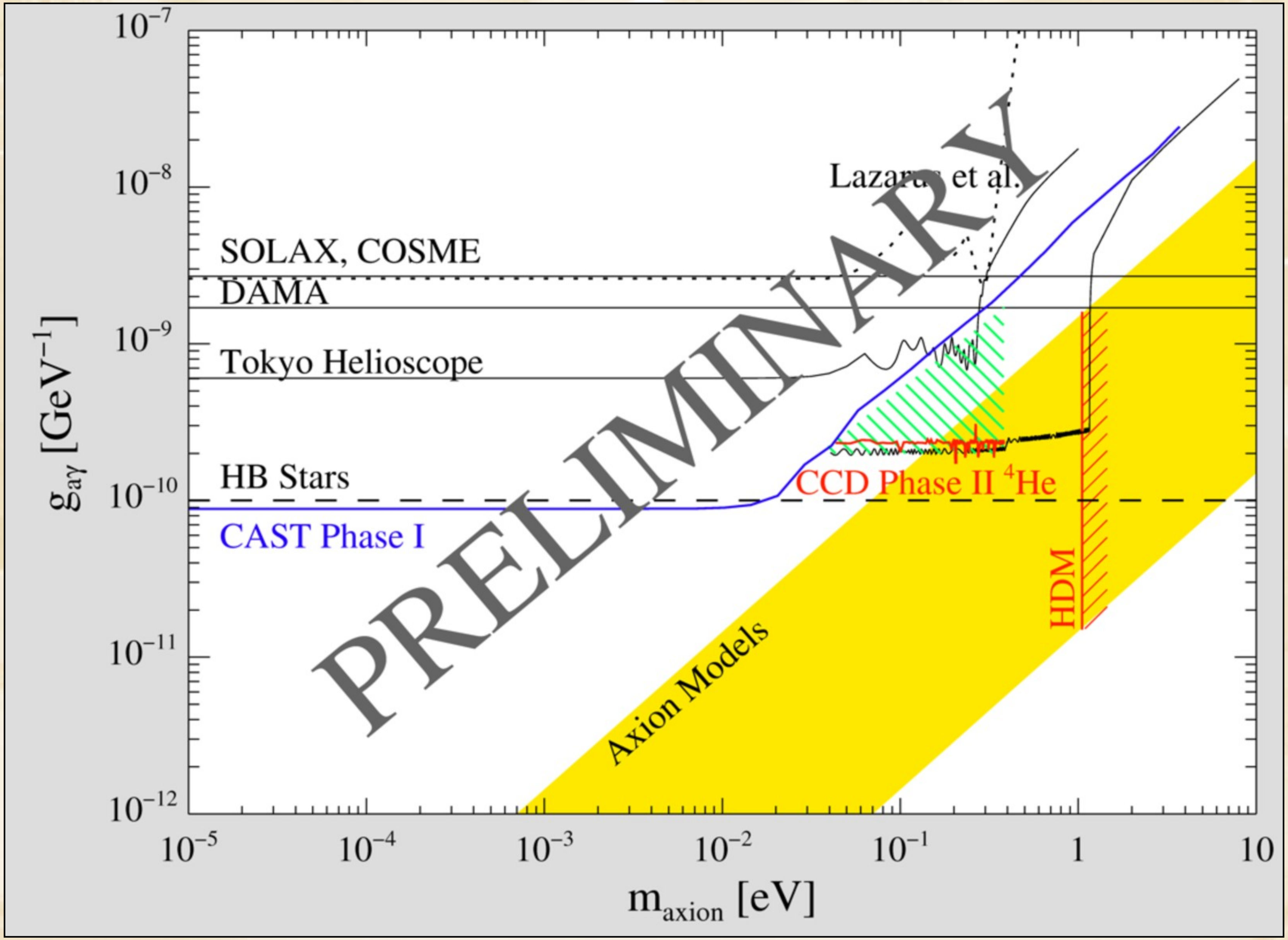
Restrictive limits exist on neutrino masses (in the sub-eV range)

- Analogous arguments for hypothetical particles (e.g. axions)
- In principle relevant for CAST and Tokyo searches (sub-eV to eV range)

What are the particle-physics assumptions entering such limits?

How reliable are the cosmological limits?

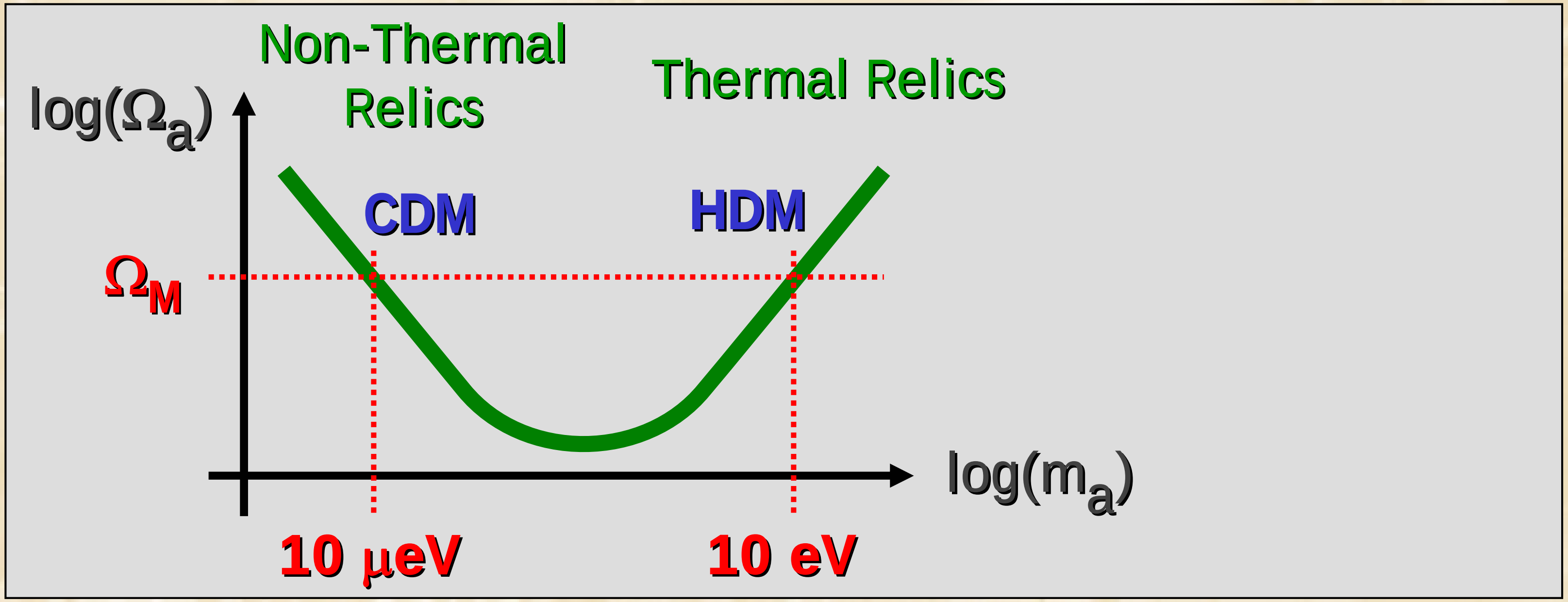
Limits from CAST-I and CAST-II



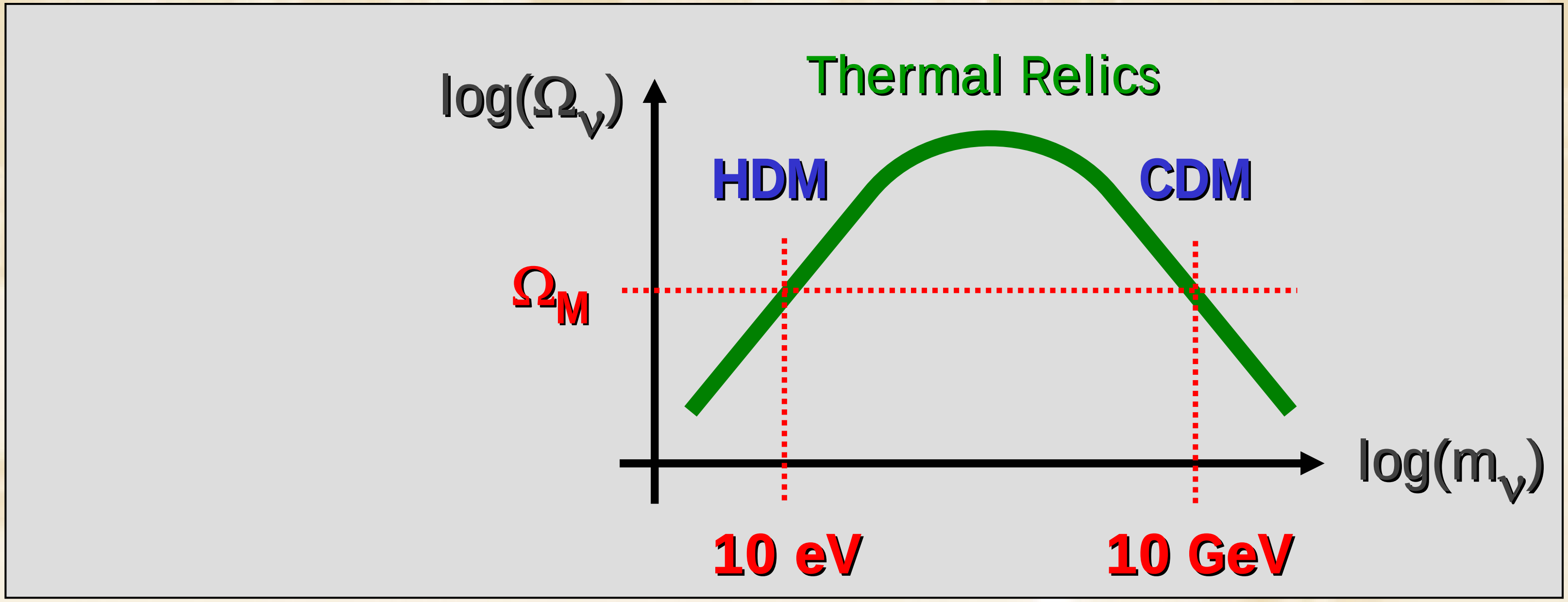
CAST-I results: PRL 94:121301 (2005) and JCAP 0704 (2007) 010
CAST-II results (He-4 filling): preliminary

Lee-Weinberg Curve for Neutrinos and Axions

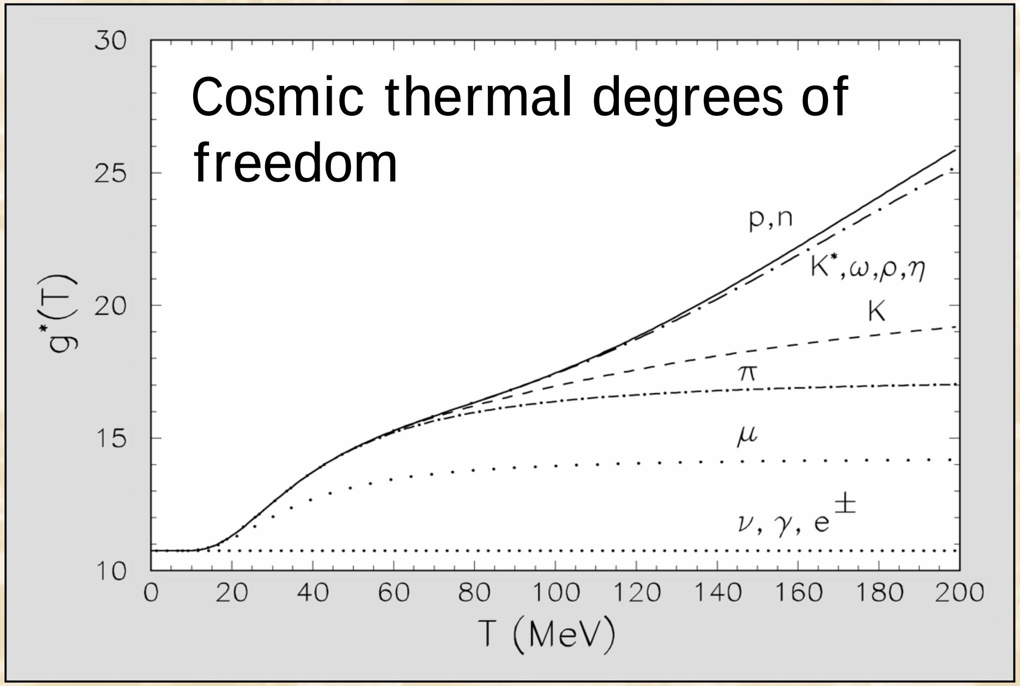
Axions

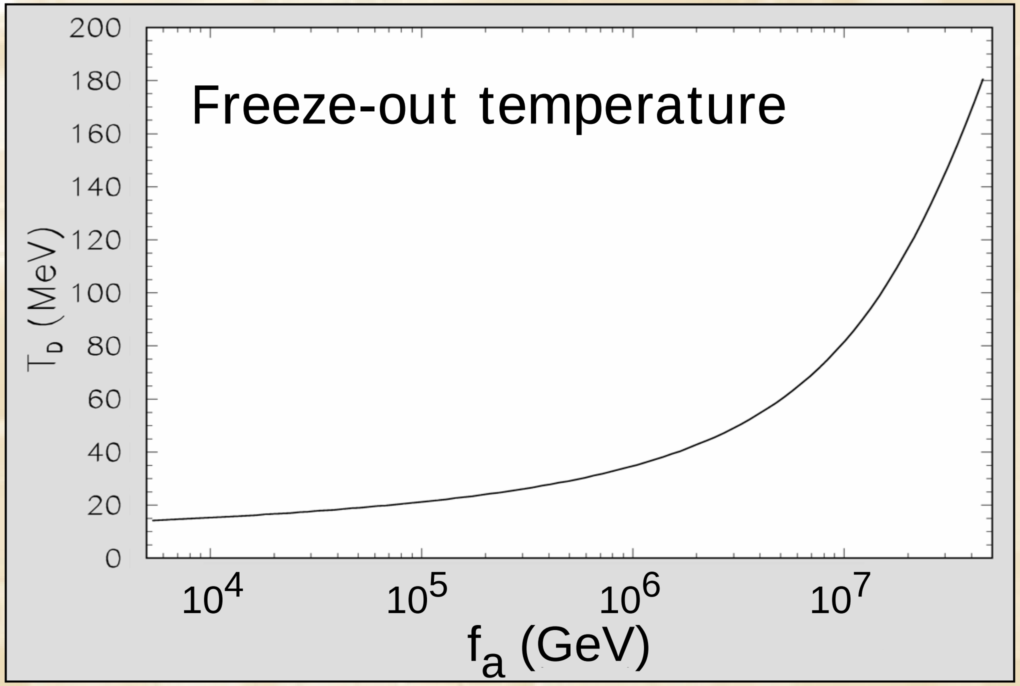


Neutrinos & WIMPs

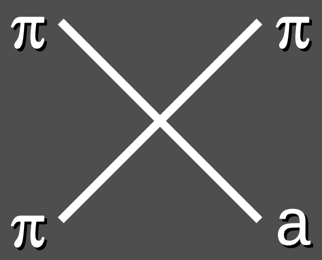


Axion Hot Dark Matter from Thermalization after Λ_{QCD}





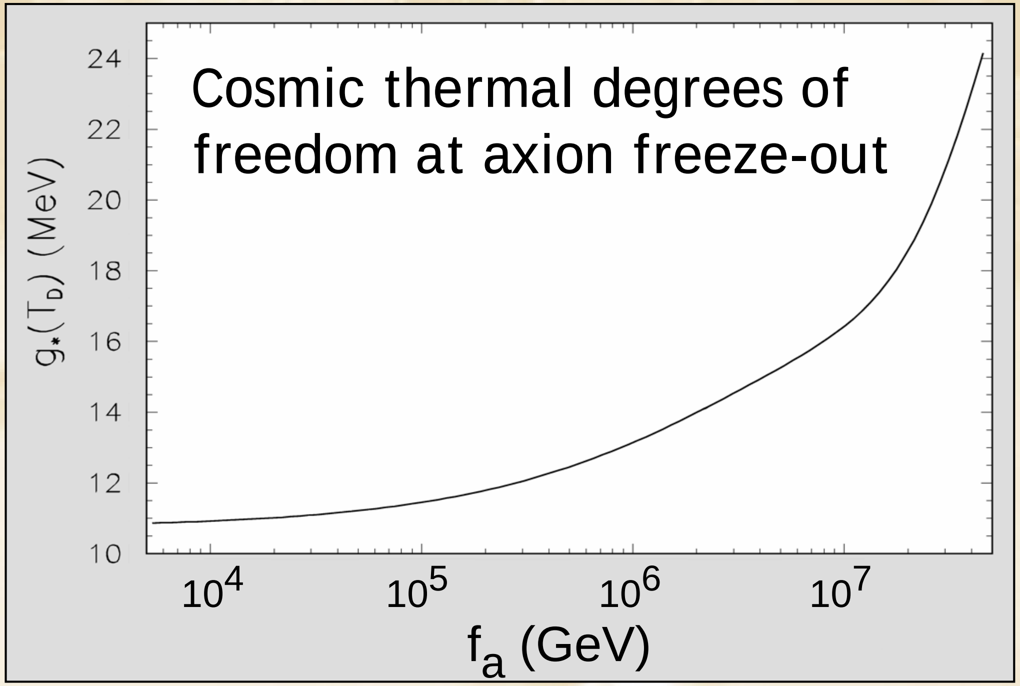
$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}\left(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0\right)\partial^\mu a$$



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

Chang & Choi, PLB 316 (1993) 51

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



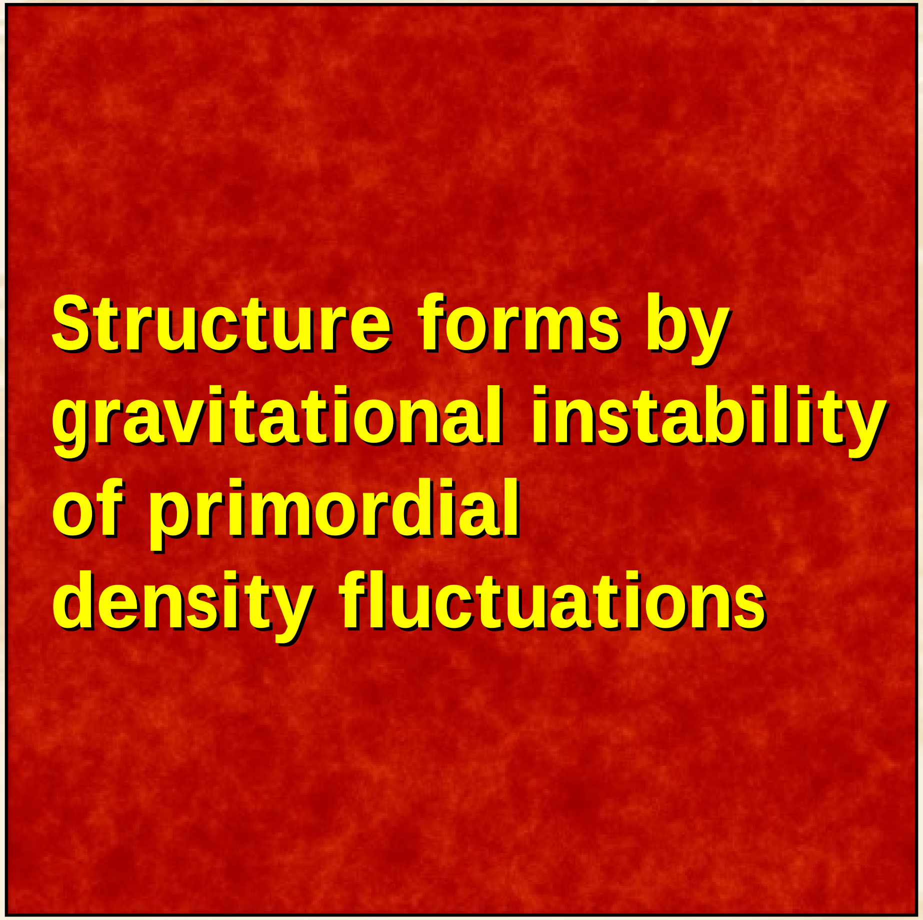
Low-Mass Particle Densities in the Universe

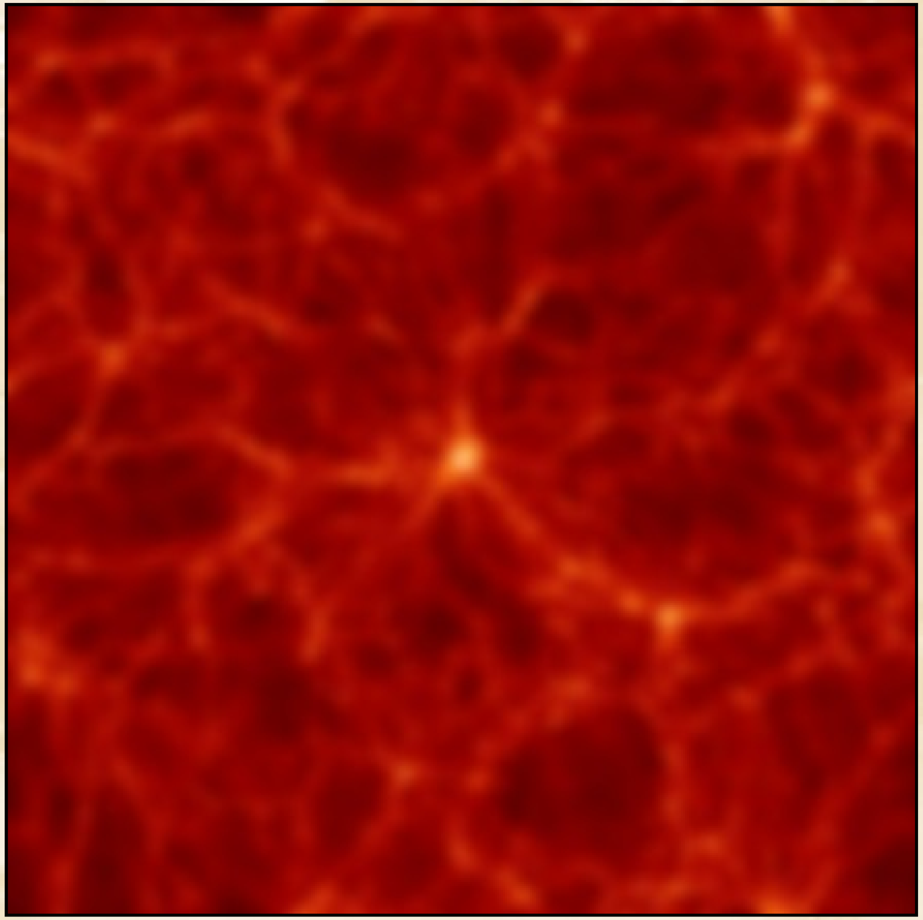
Photons	Cosmic microwave background radiation $T = 2.725$ K	$410\ cm^{-3}$
Neutrinos	Freeze out at $T \sim 2$ MeV before e^-e^+ annihilation $n_{\nu\bar{\nu}} = \frac{3}{11} n_\gamma$	$112\ cm^{-3}$ ($\nu\bar{\nu}$ in one flavor)
Axions (QCD)	For $f_a \sim 10^7$ GeV ($m_a \sim 1$ eV) Freeze out at $T \sim 80$ MeV ($\pi\pi\pi a$ interaction)	$\sim 50\ cm^{-3}$
ALPs (two photon vertex)	Primakoff freeze out ($g_{a\gamma\gamma} \sim 10^{-10}\ GeV^{-1}$) $T \gg T_{QCD} \sim 200$ MeV	$< 10\ cm^{-3}$

- No useful hot dark matter limit on ALPs in the CAST search range (too few of them today if they couple only by two-photon vertex)
- Axion mass limit comparable to limit on Σm_ν (Axion number density comparable to one neutrino flavor)

Structure Formation in the Universe

Smooth → **Structured**





A fraction of hot dark matter suppresses small-scale structure

What is wrong with neutrino dark matter?

Galactic Phase Space ("Tremaine-Gunn-Limit")

Maximum mass density of a degenerate Fermi gas

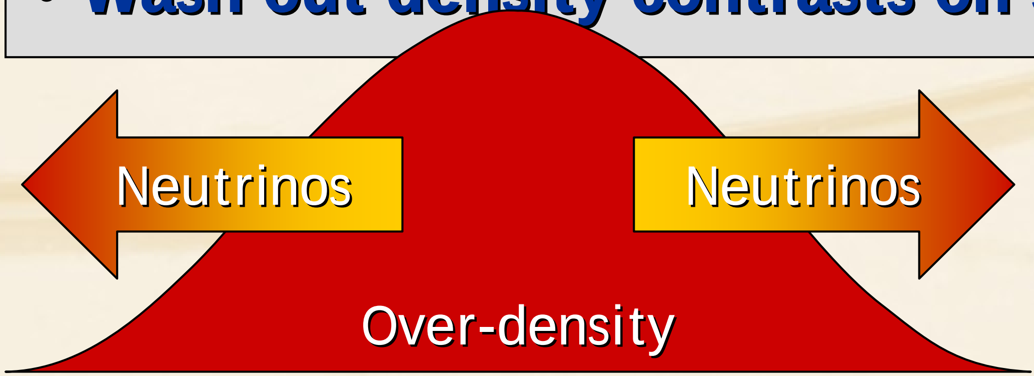
$$\rho_{max} = m_\nu \underbrace{\frac{p_{max}^3}{3\pi^2}}_{n_{max}} = \frac{m_\nu (m_\nu v_{escape})^3}{3\pi^2}$$

$m_\nu > 20 - 40$ eV — Spiral galaxies

$m_\nu > 100 - 200$ eV — Dwarf galaxies

Neutrino Free Streaming (Collisionless Phase Mixing)

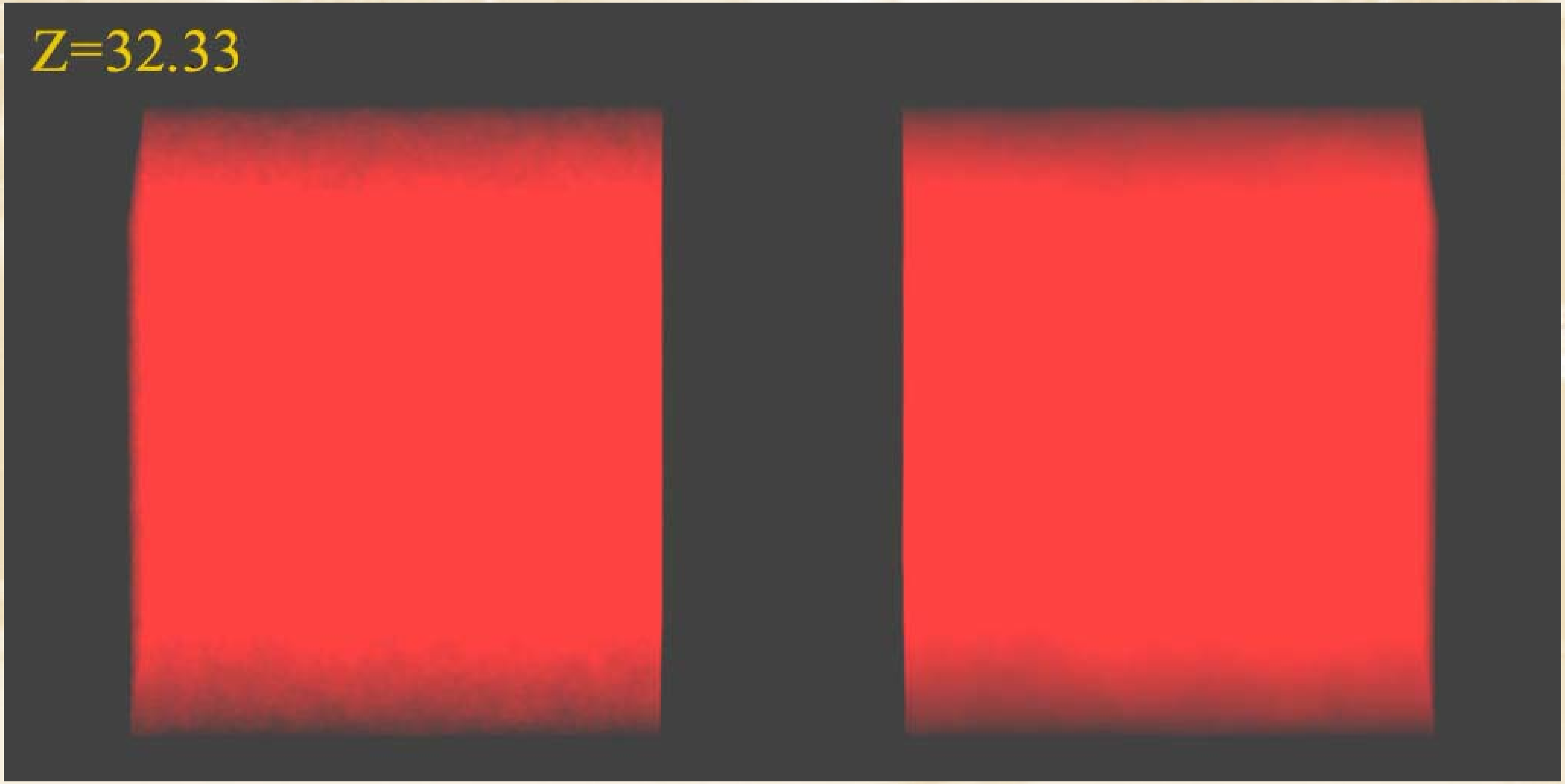
- **At T < 1 MeV neutrino scattering in early universe ineffective**
- **Stream freely until non-relativistic**
- **Wash out density contrasts on small scales**



- **Nus are "Hot Dark Matter"**
- **Ruled out by structure formation**

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

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 ($x = x_2 - x_1$)

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

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

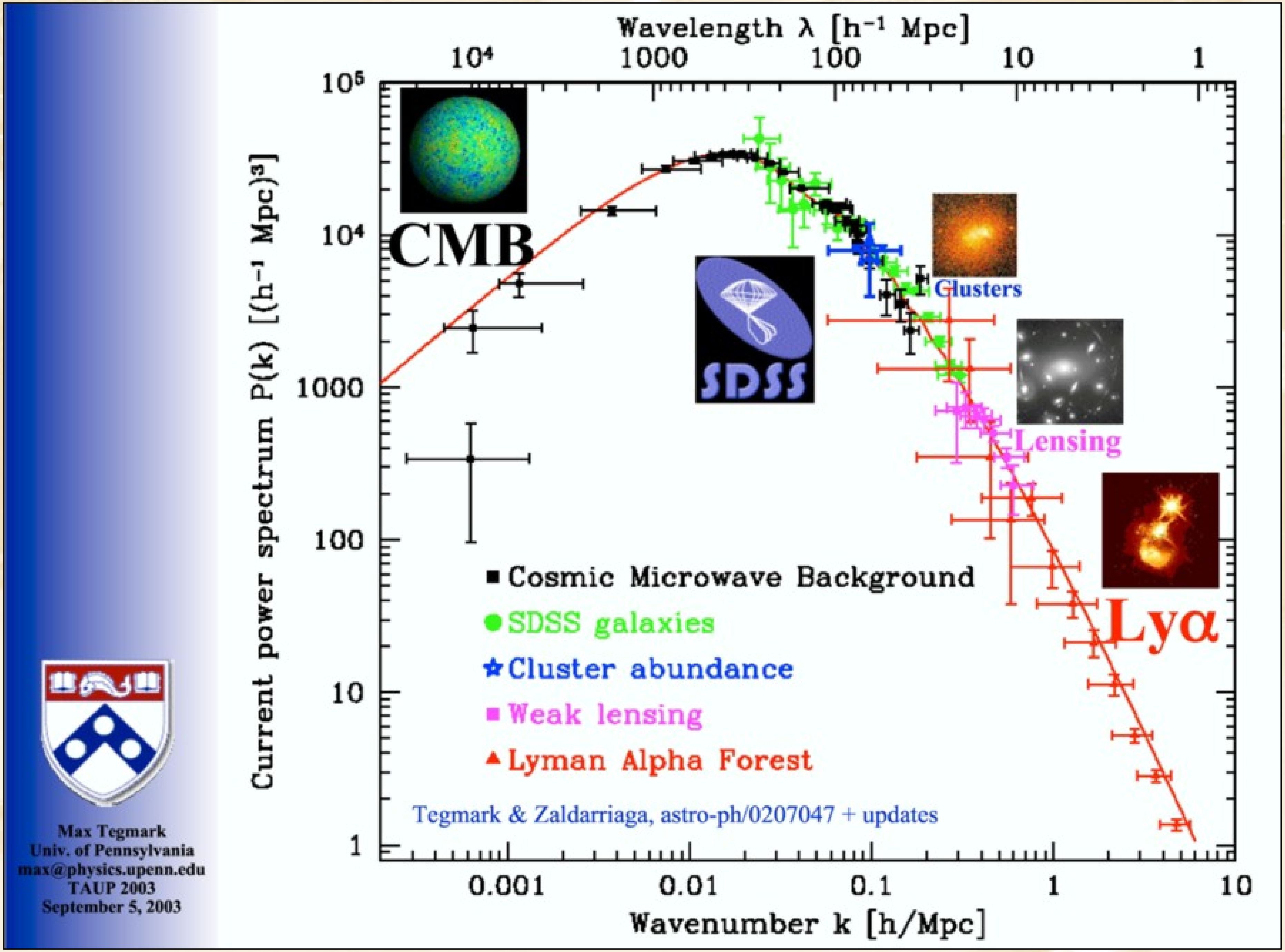
Gaussian random field (phases of Fourier modes δ_k uncorrelated) is fully characterized by the power spectrum

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

or equivalently by

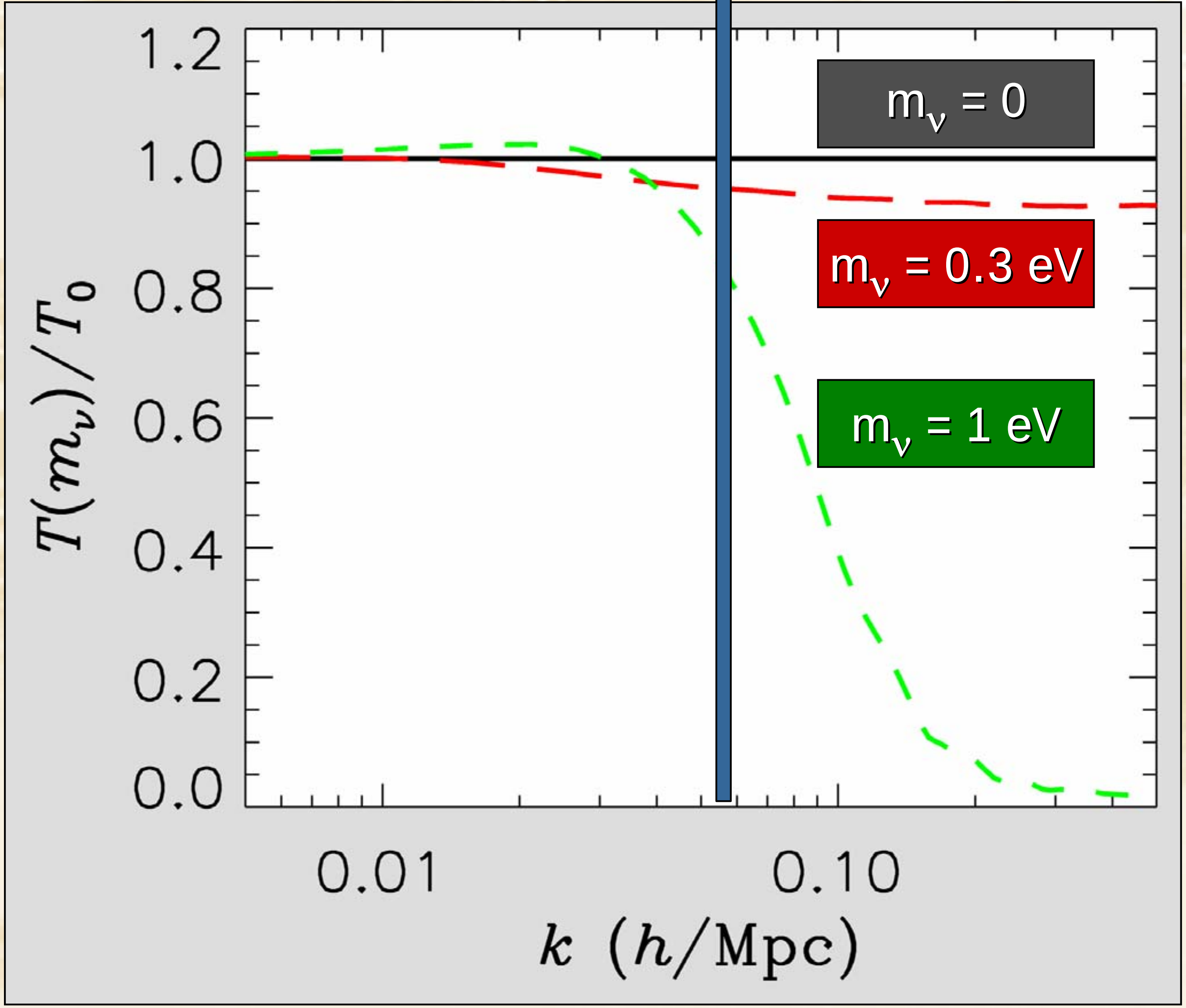
$$\Delta(k) = \left(\frac{k^3 P(k)}{2\pi^2}\right)^{1/2} = \frac{k^{3/2} |\delta_k|}{\sqrt{2}\,\pi}$$

Power Spectrum of Cosmic Density Fluctuations



Neutrino Free Streaming – Transfer Function

Power suppression for $\lambda_{FS} \gtrsim 100$ Mpc/h



Transfer function

$P(k) = T(k)\, P_0(k)$

Effect of neutrino free streaming on small scales

$T(k) = 1 - 8\Omega_\nu/\Omega_M$

valid for

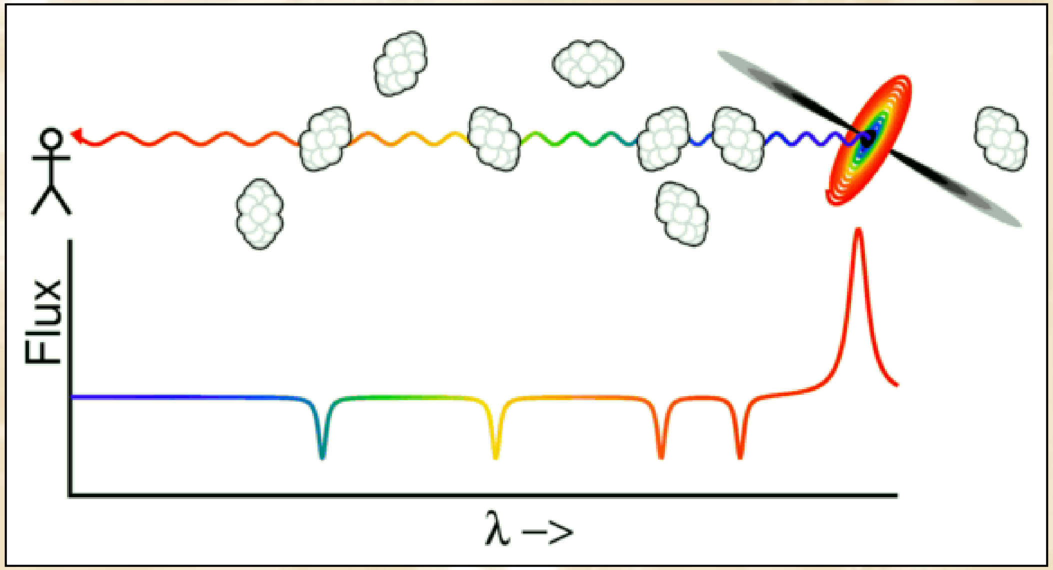
$8\Omega_\nu/\Omega_M \ll 1$

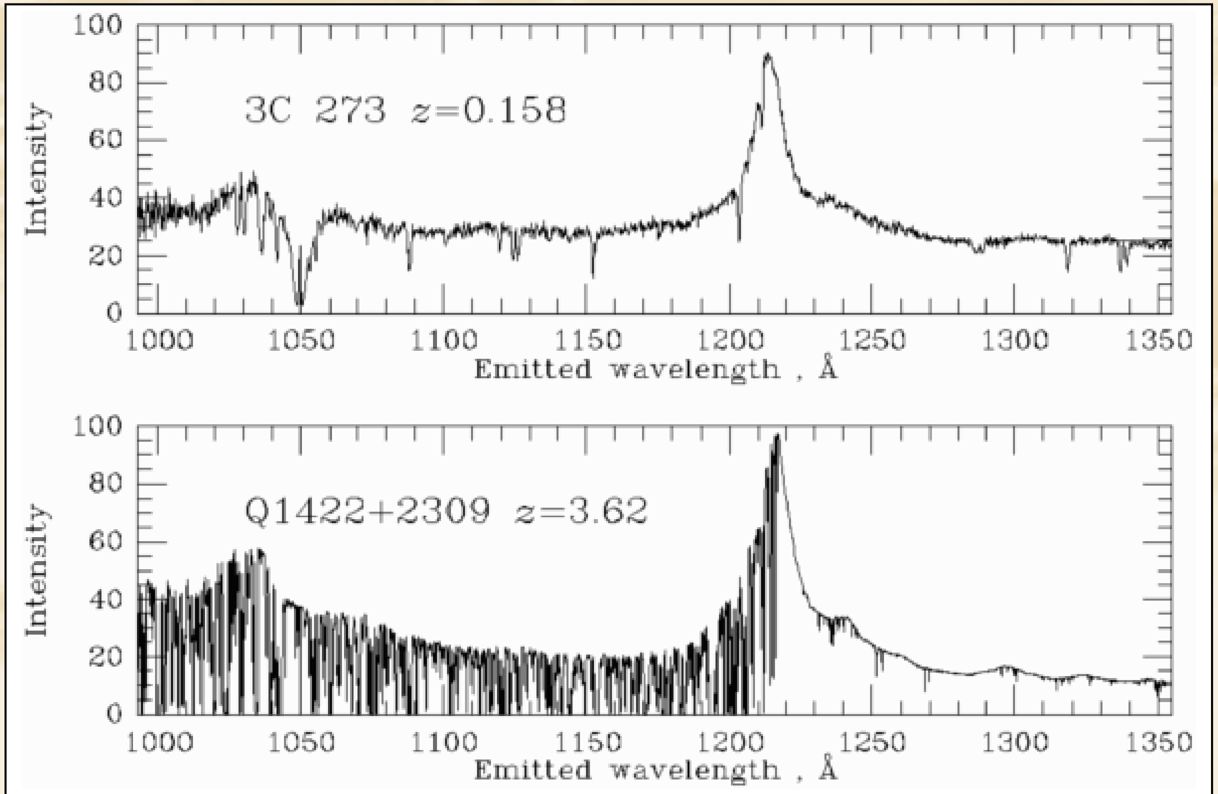
Hannestad, Neutrinos in Cosmology, hep-ph/0404239

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





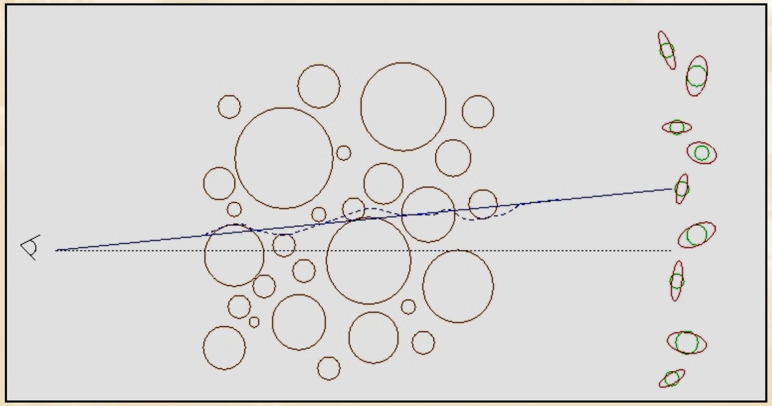
Examples for Lyman-α forest in low- and high-redshift quasars

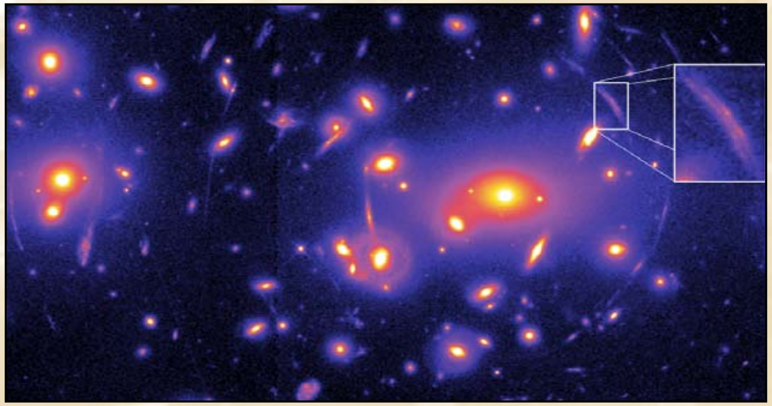
http://www.astr.ua.edu/keel/agn/forest.gif

Some Recent Cosmological Limits on Neutrino Masses

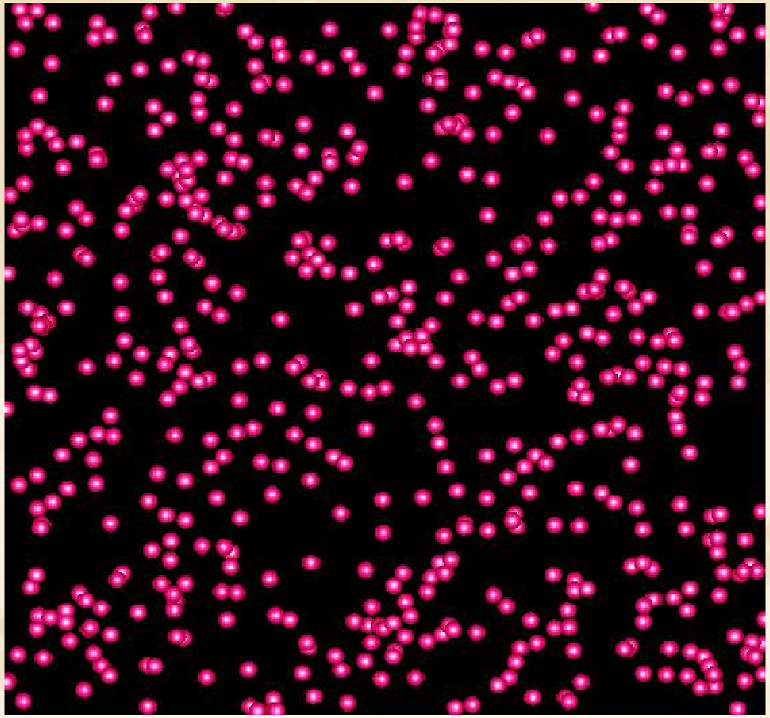
	Σm_ν/eV (limit 95%CL)	Data / Priors
Hannestad 2003 [astro-ph/0303076]	1.01	WMAP-1, CMB, 2dF, HST
Spergel et al. (WMAP) 2003 [astro-ph/0302209]	0.69	WMAP-1, 2dF, HST, σ_8
Crotty et al. 2004 [hep-ph/0402049]	1.0 0.6	WMAP-1, CMB, 2dF, SDSS & HST, SN
Hannestad 2004 [hep-ph/0409108]	0.65	WMAP-1, SDSS, SN 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 [hep-ph/0409108]	0.30	WMAP-1, CMB-small, SDSS, 2dF, SN Ia, BAO (SDSS), Ly-α (SDSS)
Spergel et al. 2006 [hep-ph/0409108]	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)

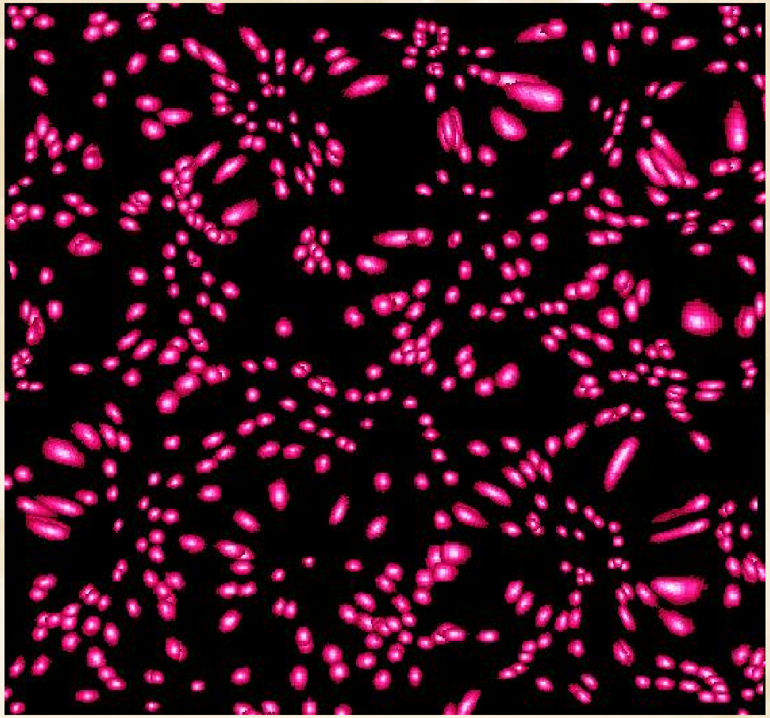
Weak Lensing – A Powerful Probe for the Future





Distortion of background images by foreground matter





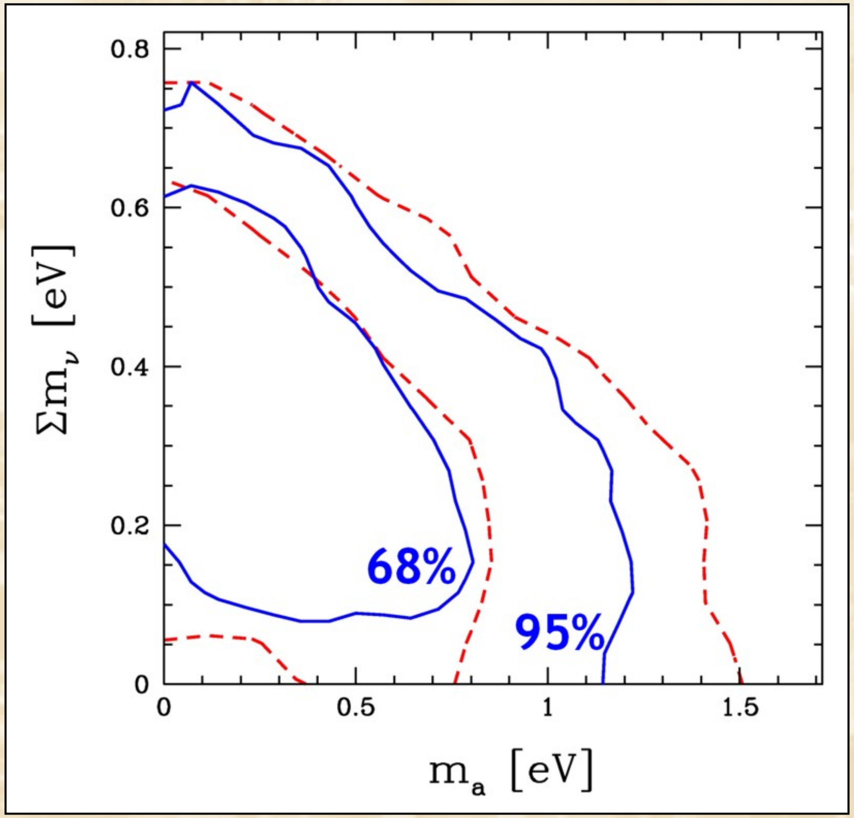
Unlensed

Lensed

Sensitivity Forecasts for Future LSS Observations

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

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]

Dashed (red) curves: Same with WMAP-3
From HMRW [arXiv:0706.4198]

Marginalizing over unknown neutrino hot dark matter component

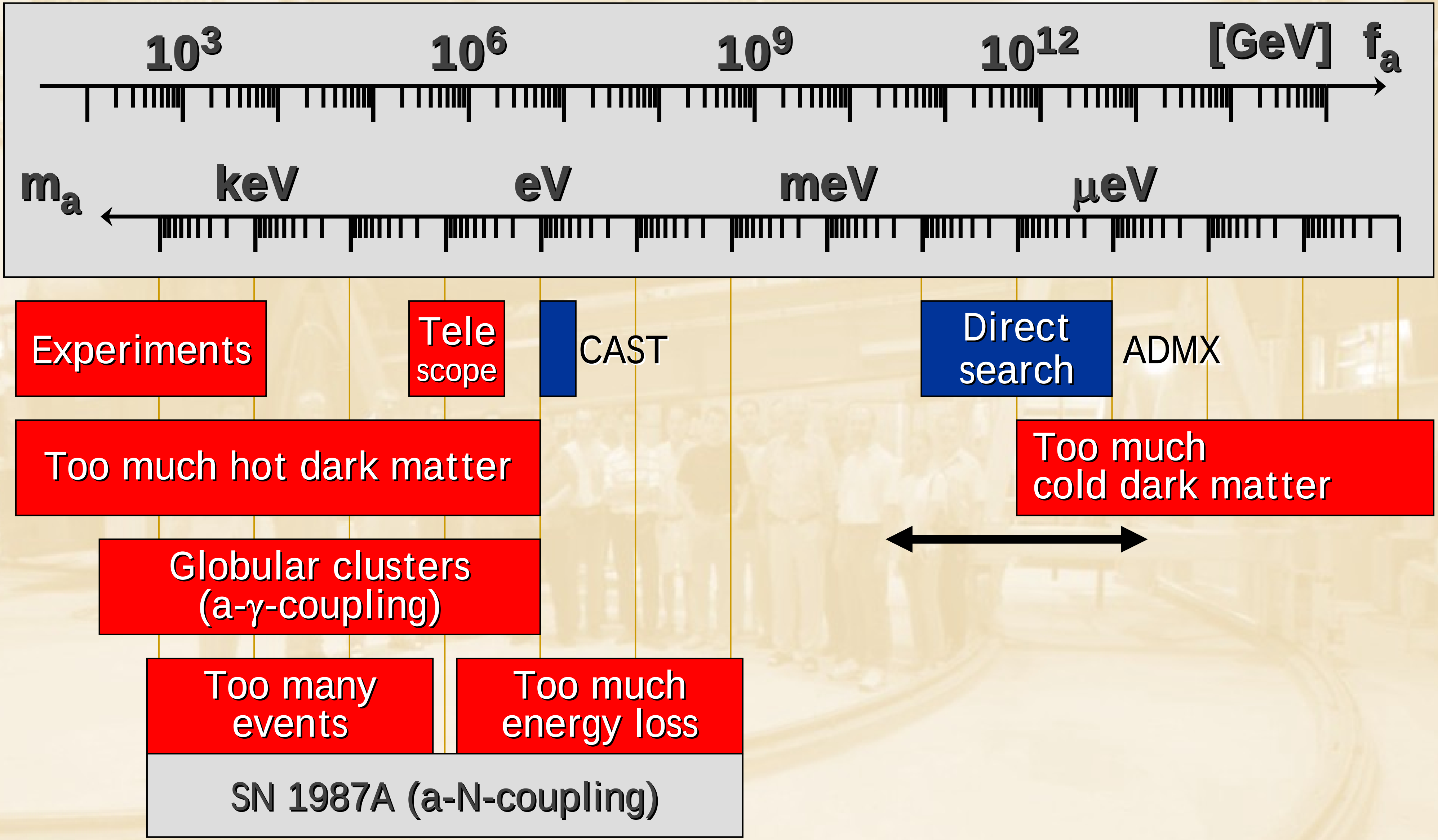
$m_a < 1.0$ eV (95% CL)	WMAP-5, LSS, BAO, SNIa	Hannestad, Mirizzi, Raffelt & Wong [arXiv:0803.1585]
$m_a < 0.4$ eV (95% CL)	WMAP-3, small-scale CMB, HST, BBN, LSS, Ly-α	Melchiorri, Mena & Slosar [arXiv:0705.2695]

Evolution of Axion Hot Dark Matter Limits

Hannestad, Mirizzi & Raffelt [hep-ph/0504059]	WMAP-1, LSS, HST, SNIa, Ly-α, $\Sigma m_\nu = 0$, χ^2 statistics	m_a < 1.05 eV (95% CL)
Melchiorri, Mena & Slosar [arXiv:0705.2695]	WMAP-3, small-scale CMB, HST, BBN, LSS, Ly-α, Σm_ν marginalized	m_a < 0.4 eV (95% CL)
Hannestad, Mirizzi, Raffelt & Wong [arXiv:0706.4198]	WMAP-3, LSS, BAO, SNIa, no Ly-α, Σm_ν marginalized	m_a < 1.2 eV (95% CL)
Hannestad, Mirizzi, Raffelt & Wong [arXiv:0803.1585]	WMAP-5, LSS, BAO, SNIa, no Ly-α, Σm_ν marginalized	m_a < 1.0 eV (95% CL)

- Including Ly-a together with WMAP-5 will likely worsen the limit of 0.4 eV from WMAP-3 + Ly-α
- Has not been done, but for neutrinos this is expected
- WMAP-5 and Ly-α more consistent with each other
- More consensus now that Ly-α is dangerous

Axion Bounds



Conclusion

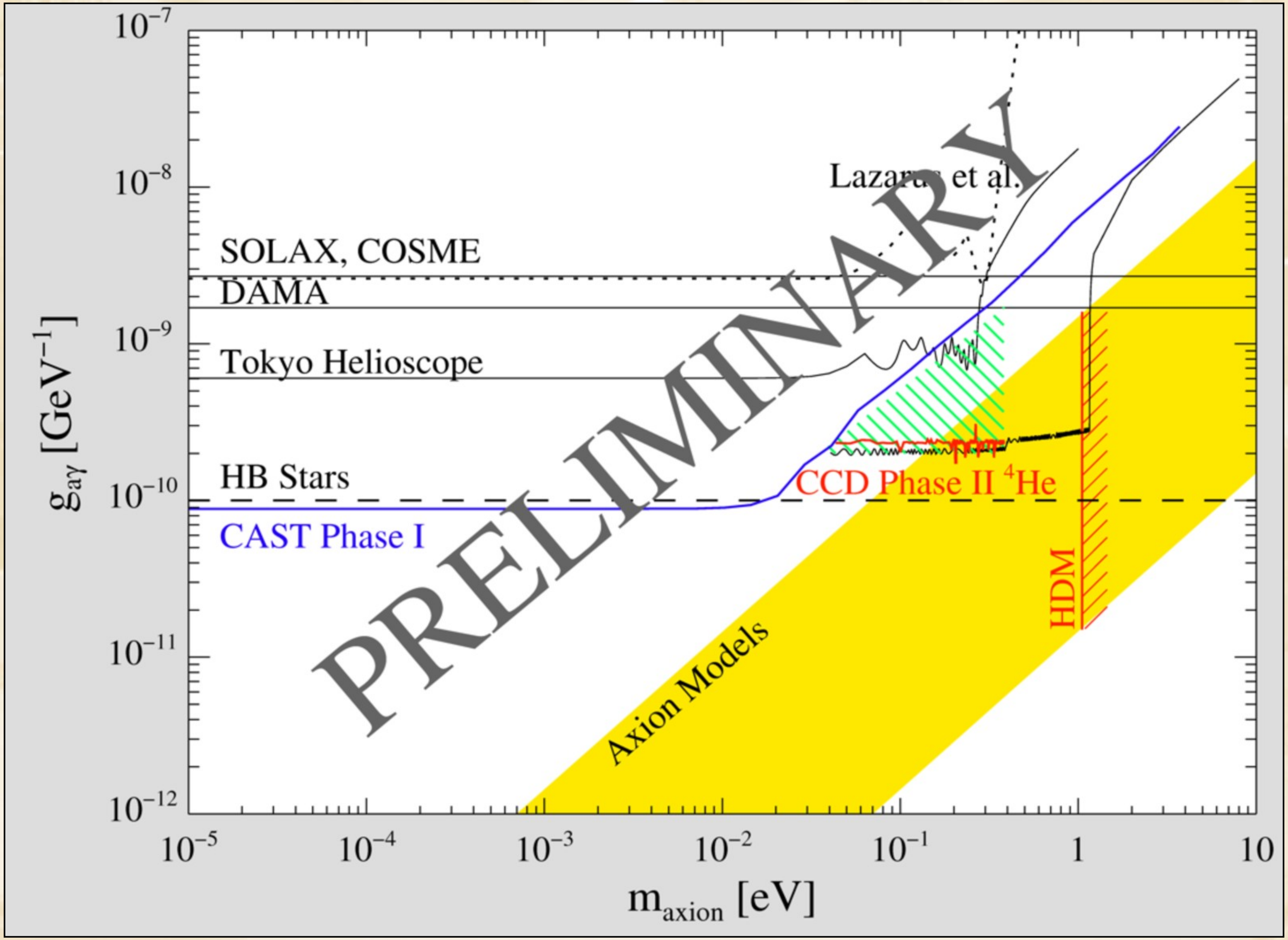
For general ALPs (only two-photon coupling)
no “hot dark matter competition” with helioscope searches

Most “aggressive” limits (using Ly-a) at ~ 0.4 eV (95% CL)
Probably large systematic uncertainties
DO NOT STOP CAST NOW !!!

Constraints can improve by better data (weak lensing)
Eventual detection of hot dark matter component ?
(neutrinos guaranteed at ~ 0.05 eV)

If neutrino masses are detected in the laboratory ($0\nu 2\beta$, KATRIN)
$\rightarrow$ Less room for axions in the hot dark matter inventory

Limits from CAST-I and CAST-II



CAST-I results: PRL 94:121301 (2005) and JCAP 0704 (2007) 010
CAST-II results (He-4 filling): preliminary

Helioscope searches and cosmological limits are nicely complementary!