Beyond the Standard Model of Cosmology:

Dark Energy, Neutrinos, and Primordial Non-Gaussianity

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Agenda: two parts

- 1) Dark Energy and Neutrino Masses: CMB, SNe, WL, Galaxies, including cross-correlations
- 2) Primordial Non-Gaussianity from the Power Spectrum of 21 cm Emission during the Epoch of Reionization

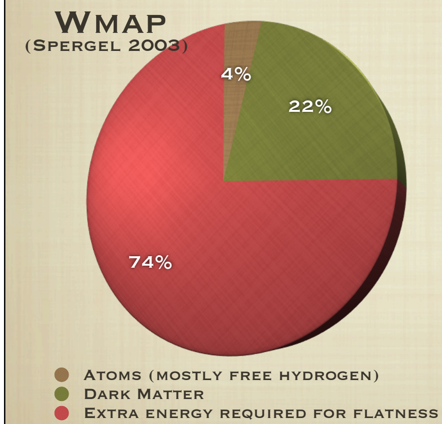
Agenda Part 1

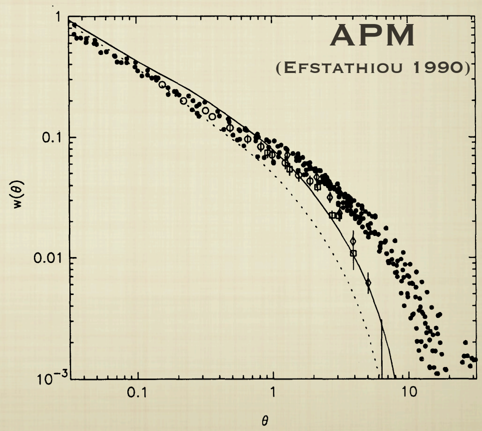
- Dark energy and neutrino masses: motivation and present constraints
- Dark energy and neutrino masses from Distances and Matter Power Spectrum
- Joint analysis including CMB, SNe, WL, Galaxies, including cross-correlations

Why dark energy?

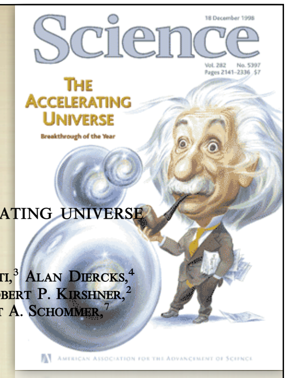
Universe is Flat (CMB)

Excess Large-scale power





Why dark energy?



The Astronomical Journal, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

Adam G. Riess,[1] Alexei V. Filippenko,[1] Peter Challis,[2] Alejandro Clocchiatti,[3] Alan Diercks,[4]
Peter M. Garnavich,[2] Ron L. Gilliland,[5] Craig J. Hogan,[4] Saurabh Jha,[2] Robert P. Kirshner,[2]
B. Leibundgut,[6] M. M. Phillips,[7] David Reiss,[4] Brian P. Schmidt,[8,9] Robert A. Schommer,[7]
R. Chris Smith,[7,10] J. Spyromilio,[6] Christopher Stubbs,[4]
Nicholas B. Suntzeff,[7] and John Tonry[11]
Received 1998 March 13; revised 1998 May 6

The Astrophysical Journal, 517:565–586, 1999 June 1

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. Perlmutter,[1] G. Aldering, G. Goldhaber,[1] R. A. Knop, P. Nugent, P. G. Castro,[2] S. Deustua, S. Fabbro,[3]
A. Goobar,[4] D. E. Groom, I. M. Hook,[5] A. G. Kim,[1,6] M. Y. Kim, J. C. Lee,[7] N. J. Nunes,[2] R. Pain,[3]
C. R. Pennypacker,[8] and R. Quimby
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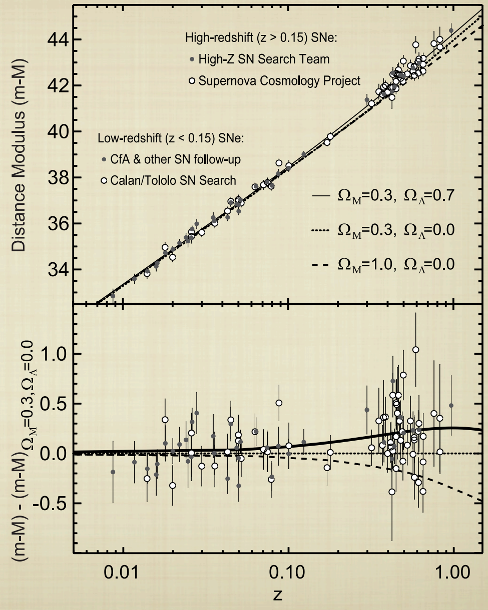
Why dark energy?

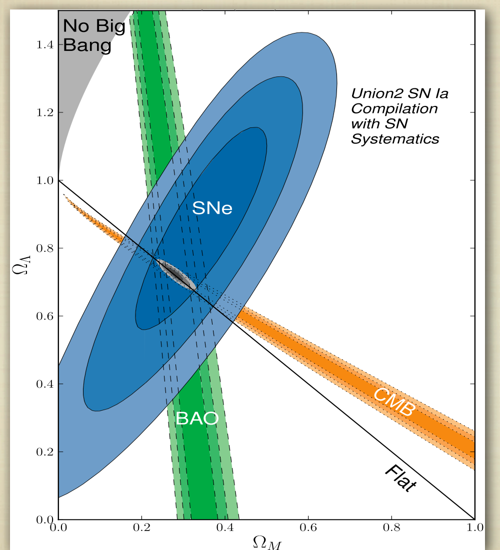
Universe accelerates (SNe)

$$w = p/\rho < -1/3$$

70% Dark Energy



Cosmic complementarity



Amanullah et al 2010
(Supernova Cosmology Project)

But why dark energy different from Λ?

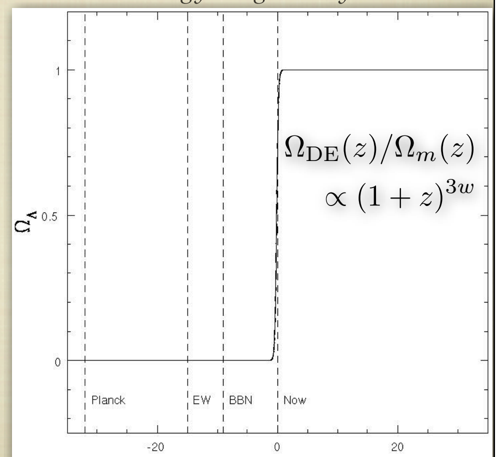
Fine tuning problem

Why is Λ 120 orders of magnitude smaller than expected?

Note: 2 separate problems that ***could*** be linked. Acceleration and V.E. Even if solve DE problem, need to solve V.E. problem (v.v.)

Coincidence problem

Why is dark energy starting to dominate the energy budget today?



Carroll et al (1992)

Two approaches in the DE game

- Create specific model for Dark Energy from a theoretically pleasing standpoint. Use observations to either rule out or constrain the model.

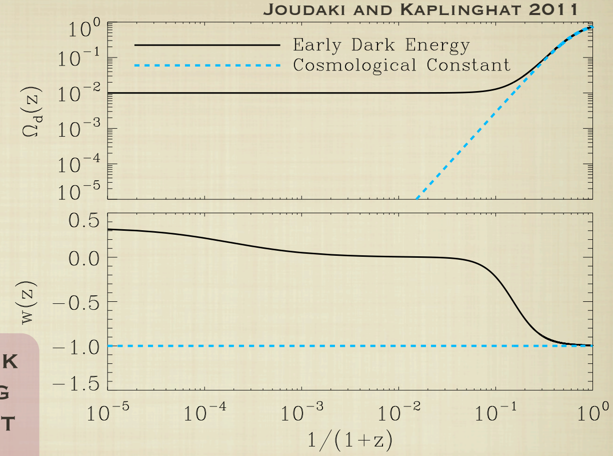
- Clump all of above models into non-V.E. class. Try to first rule out this cosmological constant scenario by searching for $w(z) \neq -1$. Use generalized parameterizations.

Early dark energy

Doran and Robbers 2006
Joudaki and Kaplinghat 2011

Why DE domination today?

$$\Omega_{\rm DE}(z)/\Omega_m(z) \propto (1+z)^{3w}$$



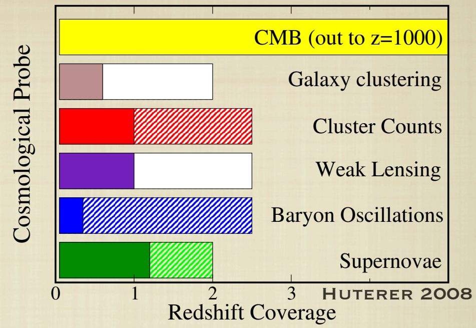
How does our lack of understanding DE in the redshift desert affect measurements of DE and neutrino mass at late times?

$$\Omega_{\rm DE}(z) = \Omega_w(z) + \Omega_e A(z)$$

E.g. DE from galaxy clustering measurements biased by 1-sigma (Linder & Robbers 2008).

Present status of DE measurements

Current and future constraints:
Redshift desert
SNe presently strongest probe of DE
WL most powerful future probe (DETF 2007), as both function of expansion history and growth of structure

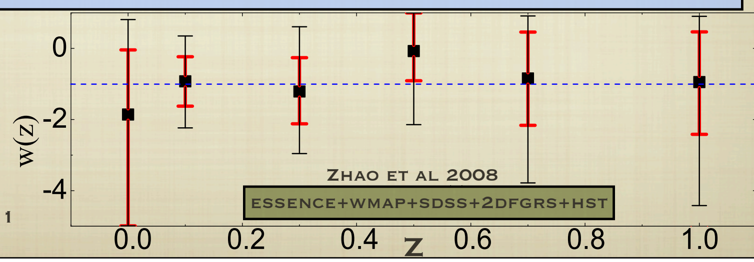


Huterer 2008

While current data fully consistent with ΛCDM, they do not exclude more exotic models of DE in which the density or EOS vary with time.

EDE at few percent

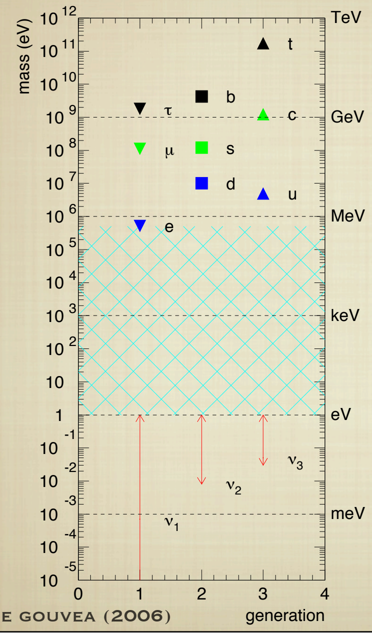
Doran 2007
Reichardt 2011



Zhao et al 2008

ESSENCE+WMAP+SDSS+2dFGRS+HST

Problems with neutrino mass



de Gouvea (2006)

Fermion masses in general one of major mysteries of SM. Measurement of neutrino masses could provide useful new perspective.

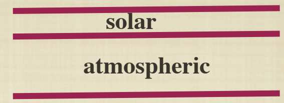
Why neutrino masses so much smaller than other fermions?

Neutrinos fundamentally different?

Neutrino masses generated by a distinct dynamical mechanism?

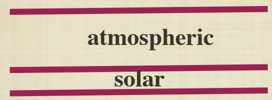
Allowed mass schemes

IH



Sum of neutrino masses greater than about 90 meV

NH



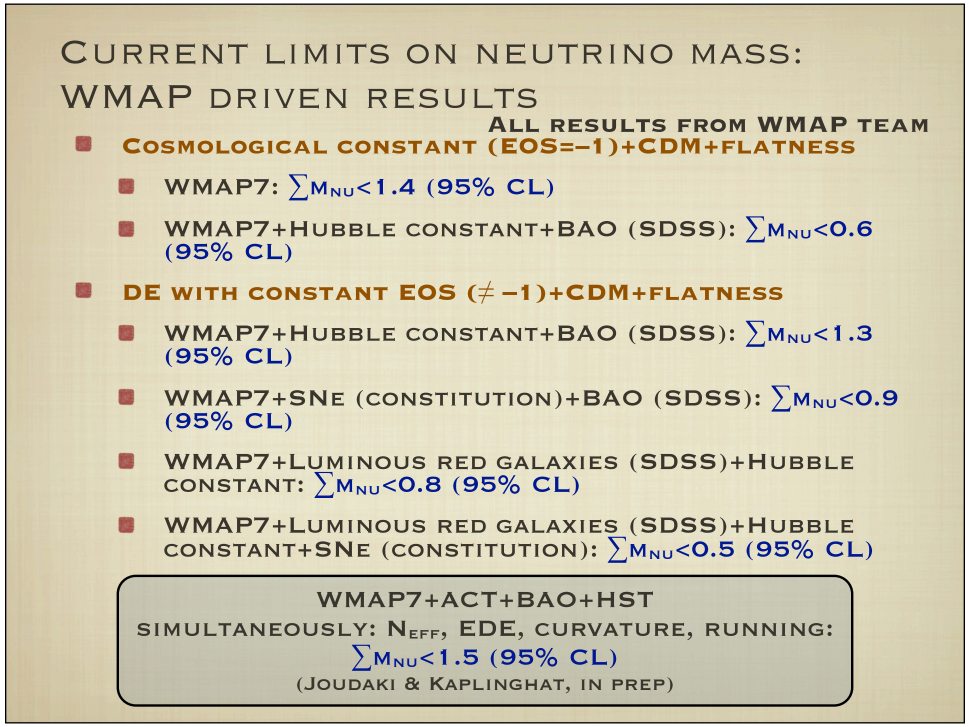
Sum of neutrino masses greater than about 60 meV

Atmospheric: $\delta m^2 = 3 \times 10^{-3}$ eV^2

Solar: $\delta m^2 = 5 \times 10^{-5}$ eV^2

see Particle data group for references

Laboratory experiments (such as double beta decay) and cosmology should be able to probe this regime.


Current limits on neutrino mass: WMAP driven results
All results from WMAP team
Cosmological constant (EOS=–1)+CDM+flatness
WMAP7: ∑mnu<1.4 (95% CL)
WMAP7+Hubble constant+BAO (SDSS): ∑mnu<0.6 (95% CL)
DE with constant EOS (≠ –1)+CDM+flatness
WMAP7+Hubble constant+BAO (SDSS): ∑mnu<1.3 (95% CL)
WMAP7+SNe (constitution)+BAO (SDSS): ∑mnu<0.9 (95% CL)
WMAP7+Luminous red galaxies (SDSS)+Hubble constant: ∑mnu<0.8 (95% CL)
WMAP7+Luminous red galaxies (SDSS)+Hubble constant+SNe (constitution): ∑mnu<0.5 (95% CL)
WMAP7+ACT+BAO+HST
simultaneously: Neff, EDE, curvature, running:
∑mnu<1.5 (95% CL)
(Joudaki & Kaplinghat, in prep)

Current limits on neutrino mass: WMAP driven results

All results from WMAP team

- **Cosmological constant (EOS=−1)+CDM+flatness**
  - WMAP7: $\sum m_{\nu} < 1.4$ (95% CL)
  - WMAP7+Hubble constant+BAO (SDSS): $\sum m_{\nu} < 0.6$ (95% CL)
- **DE with constant EOS ($\neq -1$)+CDM+flatness**
  - WMAP7+Hubble constant+BAO (SDSS): $\sum m_{\nu} < 1.3$ (95% CL)
  - WMAP7+SNe (constitution)+BAO (SDSS): $\sum m_{\nu} < 0.9$ (95% CL)
  - WMAP7+Luminous red galaxies (SDSS)+Hubble constant: $\sum m_{\nu} < 0.8$ (95% CL)
  - WMAP7+Luminous red galaxies (SDSS)+Hubble constant+SNe (constitution): $\sum m_{\nu} < 0.5$ (95% CL)

For comparison, tritium decay

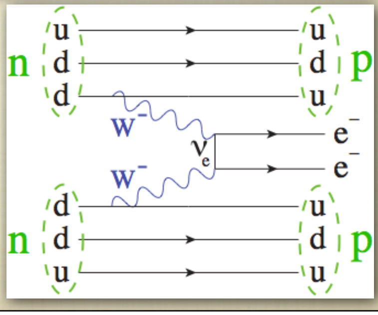
(Kraus et al 2004):

$m_{\nu e} < 2$ eV (95% CL)

Future of Laboratory Constraints

- Kinematic: KATRIN (tritium β decay) $(p + 2n \rightarrow 2p + n + e^- + \bar{\nu}_e)$
  - Aim: $m_{\nu e}$ < 0.2 eV at 95% CL.

- Neutrinoless double beta decay: (e.g. GERDA, SNO+, Majorana, DUSEL, INO)
  - test if neutrinos are Majorana particles
  - Next gen ~ 100 milli-eV to 10 milli-eV in double beta decay mass



Agenda Part 1

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- Dark energy and neutrino masses from Distances and Matter Power Spectrum
- Joint analysis including CMB, SNe, WL, Galaxies, including cross-correlations

arXiv:1106.0299

Dark Energy and Neutrino Masses from Future Measurements of the Expansion History and Growth of Structure

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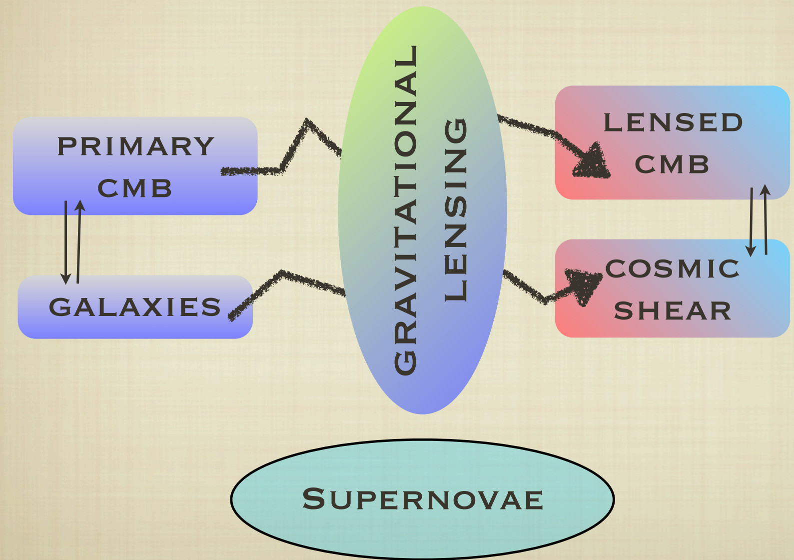
(Dated: June 3, 2011)

We forecast the expected cosmological constraints from a combination of probes of both the universal expansion rate and matter perturbation growth, in the form of weak lensing tomography, galaxy tomography, supernovae, and the cosmic microwave background incorporating all cross-correlations between the observables for an extensive cosmological parameter set. We allow for non-zero curvature and parameterize our ignorance of the early universe by allowing for a non-negligible fraction of dark energy (DE) at high redshifts. We find that early DE density can be constrained to 0.2% of the critical density of the universe with Planck combined with a ground-based LSST-like survey, while curvature can be constrained to 0.06%. However, these additional degrees of freedom degrade our ability to measure late-time dark energy and the sum of neutrino masses. We find that the combination of cosmological probes can break degeneracies and constrain the sum of neutrino masses to 40 meV, present DE density also to 0.2% of the critical density, and the equation of state to 0.01 – roughly a factor of two degradation in the constraints overall compared to the case without allowing for early DE. The constraints for a space-based mission are similar. Even a modest 1% dark energy fraction of the critical density at high redshift, if not accounted for in future analyses, biases the cosmological parameters by up to 2σ. Our analysis suggests that throwing out nonlinear scales (multipoles > 1000) may not result in significant degradation in future parameter measurements when multiple cosmological probes are combined. We also find that including cross-correlations between the different probes should result in better constraints by up to a factor of about 2 for the sum of neutrino masses and early dark energy density.

Cosmological probes of dark energy and neutrino mass



Covariance matrix

w_0	Ω_{d0}	Ω_e	$\sum m_\nu(\mathrm{eV})$	n_s	$\frac{dn_s}{d\ln k}$
$10^{10}\Delta_R^2$	$\Omega_c h^2$	$10^3\Omega_b h^2$	$N_{\rm eff}$	τ	Ω_k

Aim: break degeneracies by wide combination of high-z and low-z probes. Functions of P(k) and distances.

First time such a comprehensive future dataset including both auto and cross correlations analyzed. Tough, but kind of cosmological data we will have.

2000 x 13 x 13

$$\mathbf{C}_\ell = \begin{pmatrix} C_\ell^{\{\kappa\}\{\kappa\}} & C_\ell^{\{\kappa\}\kappa_c} & C_\ell^{\{\kappa\}T} & 0 & C_\ell^{\{\kappa\}\{g\}} \\ C_\ell^{\kappa_c\{\kappa\}} & C_\ell^{\kappa_c\kappa_c} & C_\ell^{\kappa_c T} & 0 & C_\ell^{\kappa_c\{g\}} \\ C_\ell^{T\{\kappa\}} & C_\ell^{T\kappa_c} & C_\ell^{TT} & C_\ell^{TE} & C_\ell^{T\{g\}} \\ 0 & 0 & C_\ell^{ET} & C_\ell^{EE} & 0 \\ C_\ell^{\{g\}\{\kappa\}} & C_\ell^{\{g\}\kappa_c} & C_\ell^{\{g\}T} & 0 & C_\ell^{\{g\}\{g\}} \end{pmatrix}$$

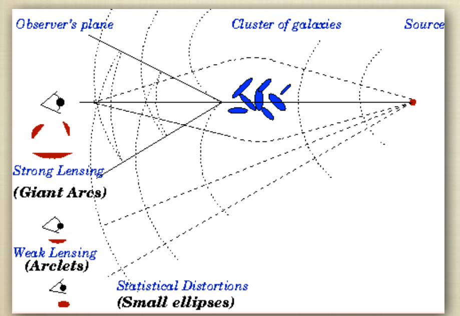
Joudaki and Kaplinghat (2011)

Closer look: Weak Lensing tomography

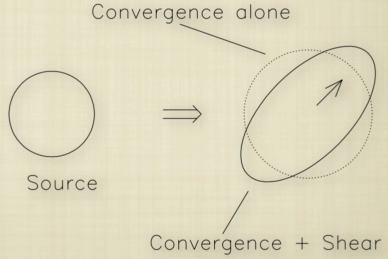
Most potential to constrain dark energy: DETF 2006

Gravitational lensing magnifies (convergence=κ) and distorts the shape (shear=γ) of galaxies. In the weak lensing limit: $|\gamma|, |\kappa| << 1$.

In the weak lensing regime these percent-level magnifications and shape distortions of galaxies need to be analyzed statistically.



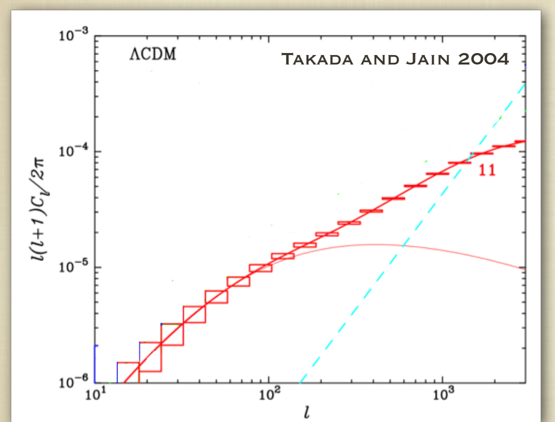
B. Jain (www.hep.upenn.edu/~bjain/lensing.html)



Bartelmann & Narayan (1996)

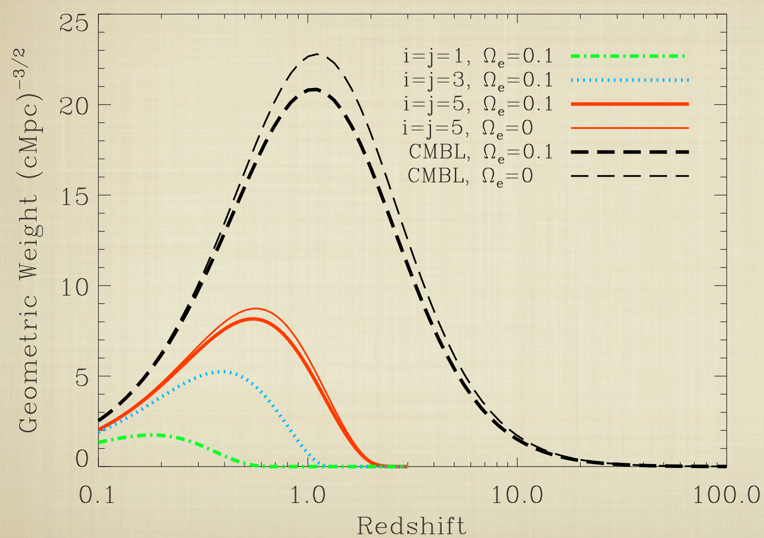
Weak lensing power spectrum

Measure shear on the sky. Plot shows Fourier transform of correlations in shear, against angular scale.



$$C_{ij}(l) = \int_0^{\chi_H} d\chi \underbrace{W_i(\chi)W_j(\chi)\chi^{-2}}_{\surd} \underbrace{P_\delta(k = l/\chi; \chi)}_{?}$$

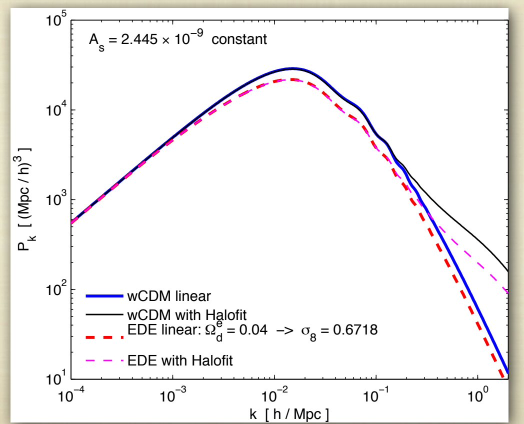
From where are we getting the info?



Joudaki and Kaplinghat (2011)

Impact of DE and Neutrinos on distances and matter power spectrum

Dark energy increases distances between objects. Neutrinos cannot be disentangled from baryons and CDM in distance measurements (e.g. SNe).

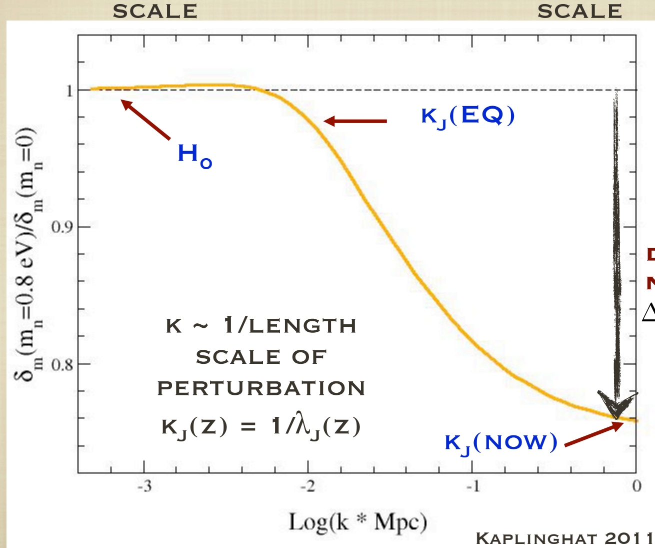


Hollenstein 2009

Overdensities w/ Massive Neutrinos

Horizon scale

Galaxy scale



~ energy density in neutrinos

$\Delta P_m(k)/P_m(k)$

$\propto -8\ \Omega_\nu/\Omega_m$

Systematic uncertainties in WL

Optimism with lensing predicated on overcoming vast systematic uncertainties in measurement and theory.

- Nonlinear matter power spectrum -- DE (McDonald 2006), neutrinos (Saito et al 2009), baryons (Rudd 2007, Dalen 2011)
  → SN feedback, radiative heating/cooling, star formation, AGN feedback
- Reduced shear (Dodelson 2005, Shapiro 2009: 1-sigma biases)
  $$g = \gamma/(1-\kappa)$$
- Photometric redshift uncertainties (Ma 2005, Huterer 2006)
  → Spectroscopic sample 10^4-10^5 galaxies (Amara & Refregier 2006)
- Shear calibration errors & PSF anisotropies (Huterer et al 2006), Higher order correction terms to lensing integral (e.g. Born approx: Cooray & Hu 2004), intrinsic alignments (Hirata & Seljak 2004)

Joint analyses may self-calibrate systematics
(e.g., Jain & Hu 2004, Zentner et al 2007)

Additional information may be extracted from WL maps (e.g. 3pt fcn (Takada & Jain 2004))

Agenda Part 1

- Dark energy and neutrino masses: motivation and present constraints
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- Joint analysis including CMB, SNe, WL, Galaxies, including cross-correlations

Explored survey properties: WL and SNe

Large-Scale Structure Survey Properties

Probe	$f_{\rm sky}$	$\bar{n}_{\rm g}$ (arcmin^{-2})	$z_{\rm peak}$	$\sqrt{\langle\gamma^2\rangle}$	$\ell_{\rm max}$	No. bins
LSST	0.5	50	1.0	0.22	3000	5
JDEM	0.1	100	1.0	0.22	3000	5
LSST_{1000}	0.5	50	1.0	0.22	1000	5
JDEM_{1000}	0.1	100	1.0	0.22	1000	5

300 SNe for z<0.1
JDEM: 2000 SNe 0.1<z<1.7
LSST: 300,000 SNe 0.1<z<0.8
intrinsic noise: 0.1
Systematic floor α 0.01(1+z)/2.7

Explored survey properties: Galaxies and CMB

Nonlinear Cutoffs in Galaxy Surveys

Bin	1	2	3	4	5
z_{median}	0.38	0.93	1.3	1.7	2.5
$k_{\max}$	0.11	0.14	0.17	0.21	0.29
$\ell_{\max}$	120	320	490	720	1200

CMB Survey Properties

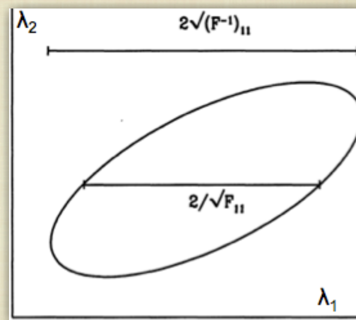
Experiment	Channel	FWHM	$\Delta T/T \times 10^6$	$\Delta P/T \times 10^6$
Planck	100	10	25	40
	143	7.1	16	30
	217	5.0	24	49
EPIC-2m	100	8.0	0.84	1.19
	150	5.0	0.81	1.15
	220	3.5	1.24	1.75

Fisher matrix

How accurately can we estimate model parameters from given data set?

Basic building block: likelihood function, defined as probability that given experiment would get the data it did given a theory.

$$\ln L(\lambda) = \ln L(\bar{\lambda}) + \frac{1}{2}\frac{\partial^2 \ln L}{\partial \lambda^2}|_{\lambda=\bar{\lambda}}(\lambda - \bar{\lambda})^2$$



$$F_{\alpha\beta}^{\rm total} = \sum_\ell \Delta\ell \times {\rm Tr}\left[\tilde{\mathbf{C}}_\ell^{-1}\frac{\partial \mathbf{C}_\ell}{\partial p_\alpha}\tilde{\mathbf{C}}_\ell^{-1}\frac{\partial \mathbf{C}_\ell}{\partial p_\beta}\right] + F_{\alpha\beta}^{\rm SN}$$

Fisher (1935); Tegmark et al (1997); Dodelson (2003)

Fisher matrix

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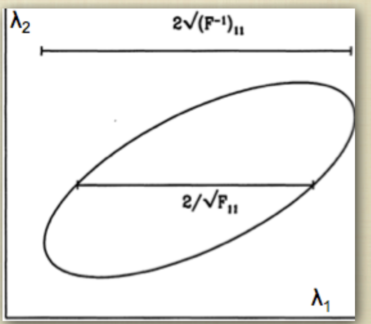
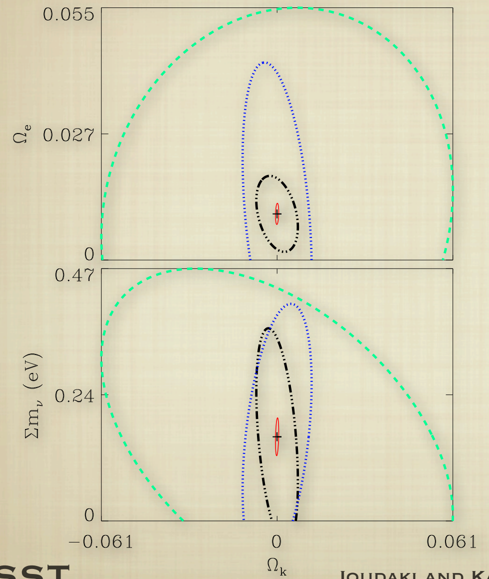


$$\mathbf{C}_\ell = \begin{pmatrix} C_\ell^{\{\kappa\}\{\kappa\}} & C_\ell^{\{\kappa\}\kappa_c} & C_\ell^{\{\kappa\}T} & 0 & C_\ell^{\{\kappa\}\{g\}} \\ C_\ell^{\kappa_c\{\kappa\}} & C_\ell^{\kappa_c\kappa_c} & C_\ell^{\kappa_c T} & 0 & C_\ell^{\kappa_c\{g\}} \\ C_\ell^{T\{\kappa\}} & C_\ell^{T\kappa_c} & C_\ell^{TT} & C_\ell^{TE} & C_\ell^{T\{g\}} \\ 0 & 0 & C_\ell^{ET} & C_\ell^{EE} & 0 \\ C_\ell^{\{g\}\{\kappa\}} & C_\ell^{\{g\}\kappa_c} & C_\ell^{\{g\}T} & 0 & C_\ell^{\{g\}\{g\}} \end{pmatrix}$$

$$F_{\alpha\beta}^{\rm total} = \sum_\ell \Delta\ell \times {\rm Tr}\left[\tilde{\mathbf{C}}_\ell^{-1}\frac{\partial \mathbf{C}_\ell}{\partial p_\alpha}\tilde{\mathbf{C}}_\ell^{-1}\frac{\partial \mathbf{C}_\ell}{\partial p_\beta}\right] + F_{\alpha\beta}^{\rm SN}$$

Fisher (1935); Tegmark et al (1997); Dodelson (2003)

Joint analysis with future measures of structure formation and expansion rate



$$\sigma(\Omega_k) \simeq 6 \times 10^{-4}$$

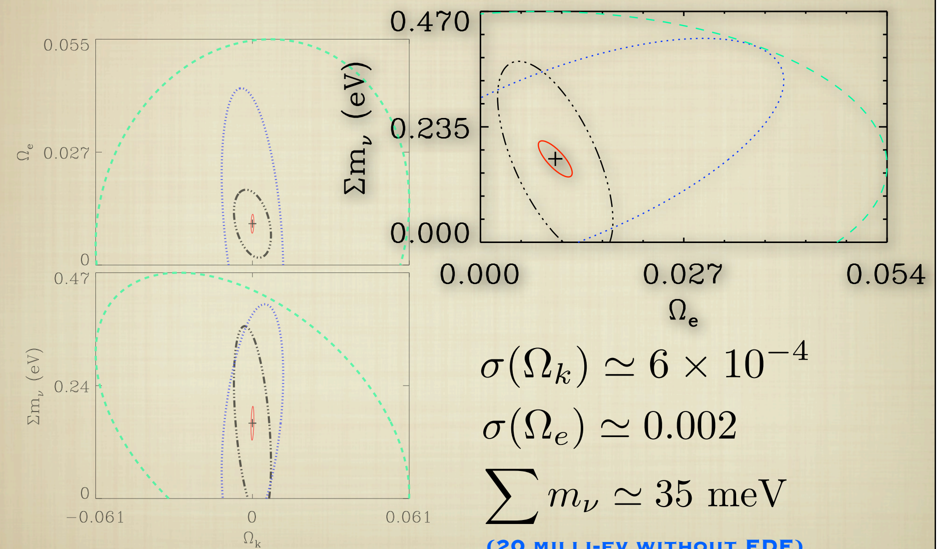
$$\sigma(\Omega_e) \simeq 0.002$$

$$\sum m_\nu \simeq 35 \text{ meV}$$

LSST

Joudaki and Kaplinghat (2011)

Joint analysis with future measures of structure formation and expansion rate



$$\sigma(\Omega_k) \simeq 6 \times 10^{-4}$$

$$\sigma(\Omega_e) \simeq 0.002$$

$$\sum m_\nu \simeq 35 \text{ meV}$$

(20 milli-eV without EDE)

LSST

Joudaki and Kaplinghat (2011)

Joint analysis: Early dark energy

- Dominant constraint from CMB: within 1% from Planck

- Constraint improves by factor 4 in joint analysis (all probes + all cross-corrs)

- Late-time DE degraded by additional DOF from EDE: 0.002 in density and 1% in eos. Factors 2 and 3 worse than w/ EDE fixed.

- Throwing out nonlinear scales (ℓ>1000) may not result in significant degradation. Including cross-corrs improves DE density and sum of neutrino masses by factor of 2.

- Even modest 1% EDE, if not accounted for, may shift DE estimates by 1 - 2 sigma.

Joint analysis: Massive Neutrinos

- Dominant constraint from CMB lensing: 0.2 eV from Planck
- Constraint improves by factor 5 in joint analysis with Planck
- The joint constraints improve by factor <2 when EDE is not allowed to vary.
- These constraints unaffected by our ignorance of curvature, which can be constrained to 6×10^{-3} by CMB T+lensing alone, and improved by order of magnitude in the joint analysis.
- Even modest 1% EDE, if not accounted for, may shift estimates of neutrino mass sum and number by 20-40%.

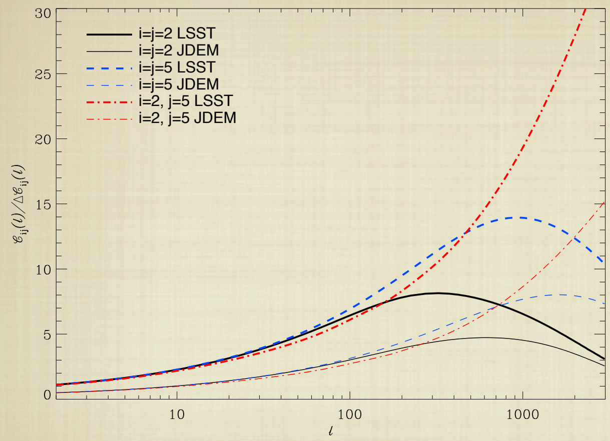
Epic-2m

- Proposed future CMB mission. With up to 40% increased resolution and factor of 30 lower noise in an individual band than Planck, the epic-2m survey shows improved CMB constraints across the board.

- Sum of neutrino masses and dark energy constraints improved by factor >2 from cmb temperature+lensing compared to Planck.

- Joint analysis constraints also show substantial gains compared to Planck - about 30% in DE, 40% in sum of neutrino masses, and up to factor 2 in other parameters.

Wide or Deep?



LSST better at weak lensing, while JDEM better at SNe. Combined constraints effectively the same.

How many DE EOS parameters (no EDE)?

For exploring physics behind acceleration, crucial question is how much can we learn about dynamics through next-generation experiments.

Linder & Huterer (2005): 2 at <10% (CMB+SNe+WL)

Sarkar, SJ, et al (2007): 4 at 5-10% (CMB+SNe+BAO)

Joudaki & Kaplinghat (2011): 1 at 0.3% or 10 at 1% (CMB+SNe+galaxies+WL +cross-correlations). Including neutrino mass and curvature.

How many neutrinos?

Present Data

- WMAP7+ACT+BAO+HST: N_{EFF} = 4.56 +/- 0.75

Dunkley et al (2011)

However, we know neutrinos have mass. Moreover, including constant w, running, curvature:

- WMAP7+ACT+BAO+HST: N_{EFF} = 3.84 +/- 1.09

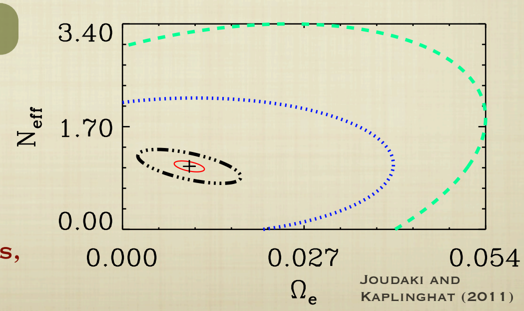
Joudaki & Kaplinghat (in prep)

Future Data

CMB:
N_{EFF} = +/- 0.28

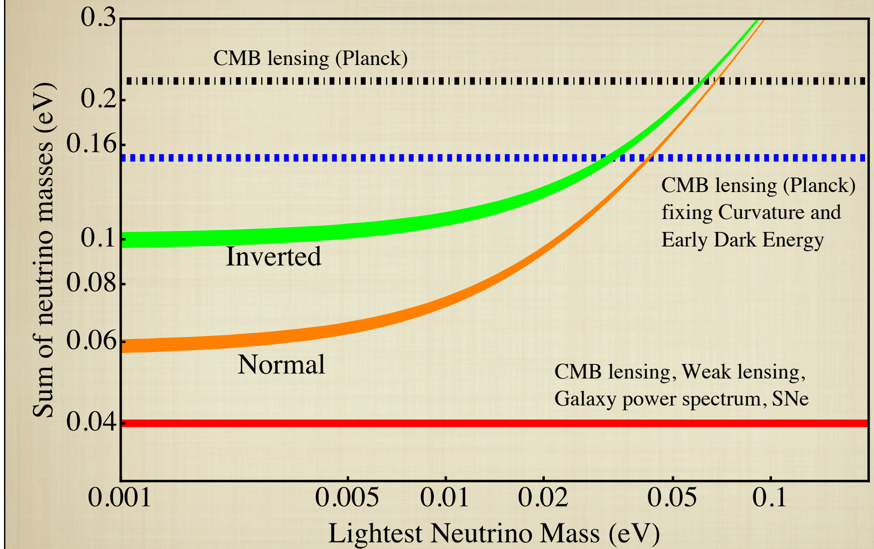
ALL:
N_{EFF} = +/- 0.09

Includes neutrino mass, EDE, curvature, etc



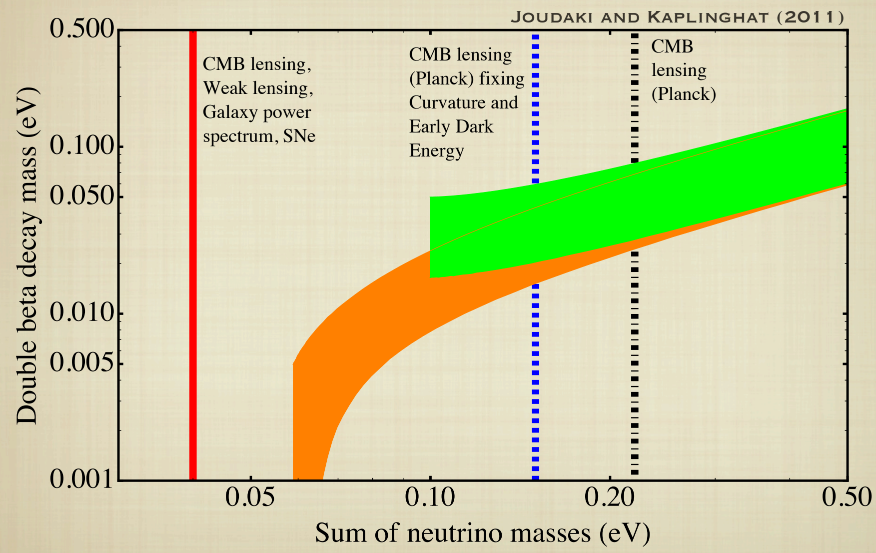
Joudaki and Kaplinghat (2011)

Neutrino mass forecasts

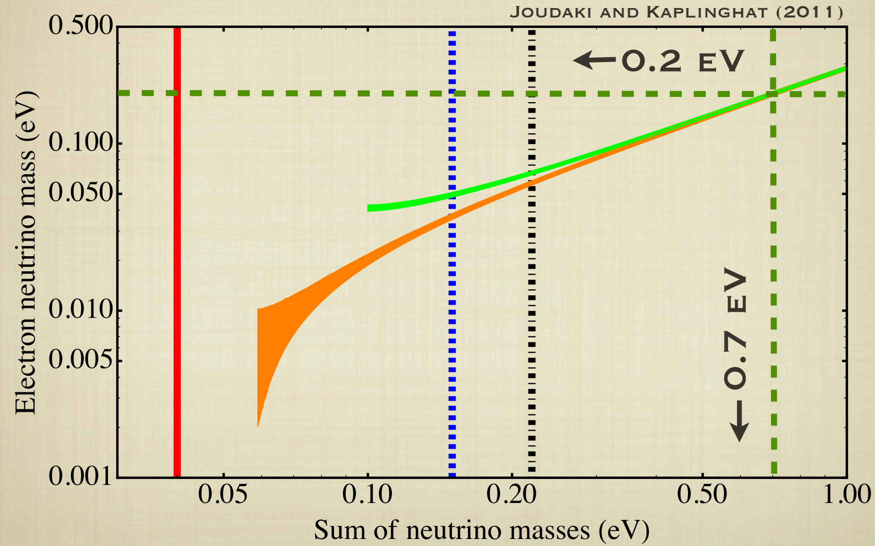


Joudaki and Kaplinghat (2011)

Complementarity with Double beta decay experiments



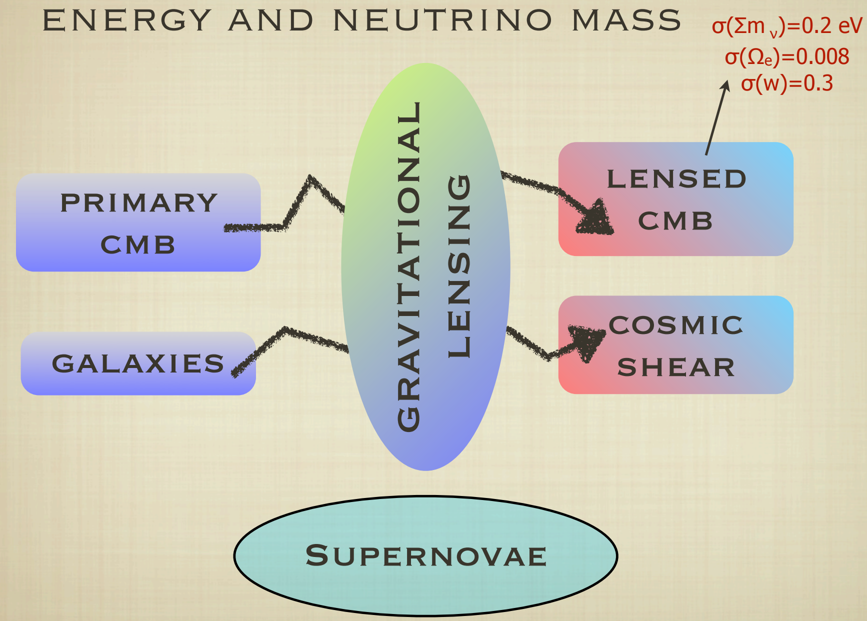
Complementarity with beta decay experiments

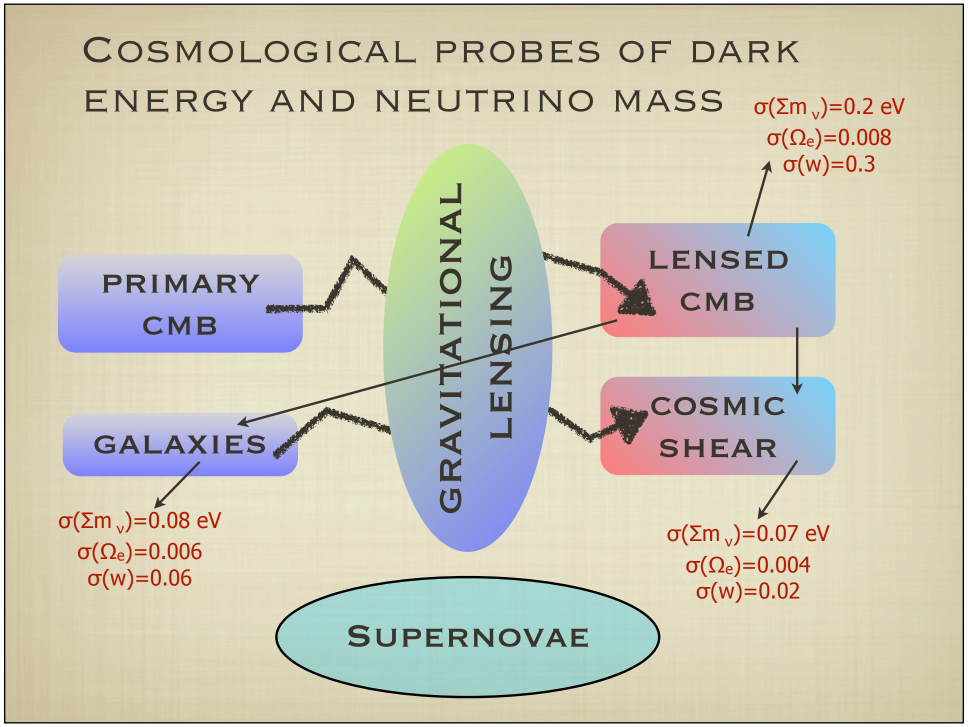


Conclusions and Notes

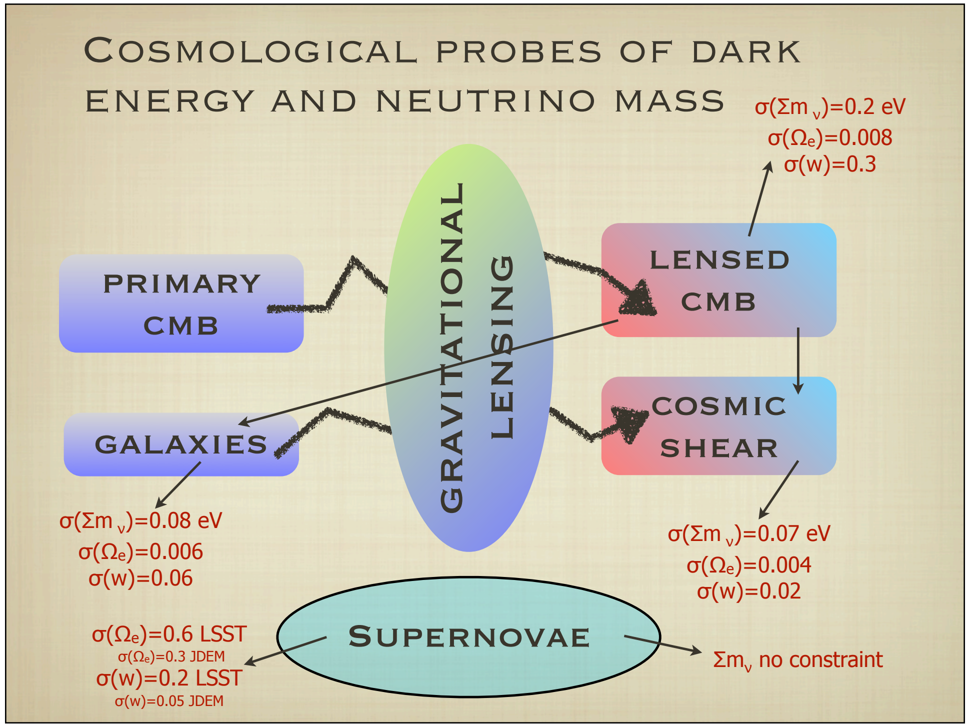
- Present data is consistent with a cosmological constant, albeit with large error bars.
- Cosmology can constrain dark energy at both high and low redshift to part in thousand level precision.
- not accounting for DE at high redshift may bias low redshift dark energy constraints by 1-2 sigma.
- Present data suggest sum of neutrino masses less than about 1 eV.
- Cosmology can probe sum of neutrino masses down to an exquisite 0.04 eV even when allowing for non-flat geometry and unknown high redshift universe. Complementarity with laboratory experiments will be very interesting.

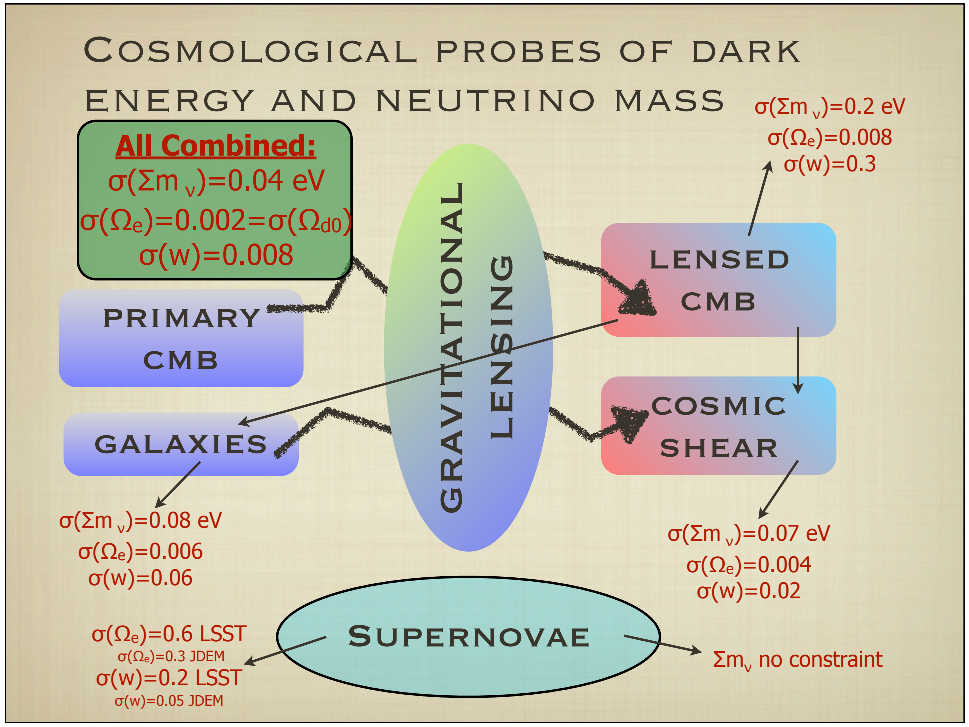
Cosmological probes of dark energy and neutrino mass





Cosmological probes of dark energy and neutrino mass
$\sigma(\Sigma m_{\nu})=0.2$ eV
$\sigma(\Omega_e)=0.008$
$\sigma(w)=0.3$
Primary CMB
Gravitational lensing
Lensed CMB
Galaxies
Cosmic shear
$\sigma(\Sigma m_{\nu})=0.08$ eV
$\sigma(\Omega_e)=0.006$
$\sigma(w)=0.06$
$\sigma(\Sigma m_{\nu})=0.07$ eV
$\sigma(\Omega_e)=0.004$
$\sigma(w)=0.02$
Supernovae


Cosmological probes of dark energy and neutrino mass
σ(Σm ν)=0.2 eV
σ(Ωe)=0.008
σ(w)=0.3
Gravitational Lensing
Primary CMB
Lensed CMB
Galaxies
Cosmic Shear
σ(Σm ν)=0.08 eV
σ(Ωe)=0.006
σ(w)=0.06
σ(Σm ν)=0.07 eV
σ(Ωe)=0.004
σ(w)=0.02
Supernovae
σ(Ωe)=0.6 LSST
σ(Ωe)=0.3 JDEM
σ(w)=0.2 LSST
σ(w)=0.05 JDEM
Σmν no constraint


Cosmological probes of dark energy and neutrino mass
All Combined:
σ(Σm ν)=0.04 eV
σ(Ωe)=0.002=σ(Ωd0)
σ(w)=0.008
Primary CMB
Galaxies
Gravitational Lensing
Lensed CMB
Cosmic Shear
σ(Σm ν)=0.2 eV
σ(Ωe)=0.008
σ(w)=0.3
σ(Σm ν)=0.08 eV
σ(Ωe)=0.006
σ(w)=0.06
σ(Σm ν)=0.07 eV
σ(Ωe)=0.004
σ(w)=0.02
Supernovae
σ(Ωe)=0.6 LSST
σ(Ωe)=0.3 JDEM
σ(w)=0.2 LSST
σ(w)=0.05 JDEM
Σmν no constraint

Agenda: two parts

- 1) Dark Energy and Neutrino Masses: CMB, SNe, WL, Galaxies, including cross-correlations
- 2) Primordial Non-Gaussianity from the Power Spectrum of 21 cm Emission during the Epoch of Reionization

Agenda Part 2

- PRIMORDIAL NON-GAUSSIANITY AND CONNECTION TO 21 CM PHYSICS
- EXPECTED CONSTRAINTS ON F_{NL} RELATIVE TO DESIGN OF 21 CM EXPERIMENTS

arXiv:1105.1773

Primordial non-Gaussianity from the 21 cm Power Spectrum during the Epoch of Reionization

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(Dated: August 12, 2011)

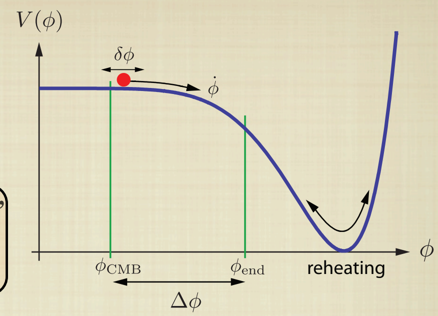
Primordial non-Gaussianity is a crucial test of inflationary cosmology. We consider the impact of non-Gaussianity on the ionization power spectrum from 21 cm emission at the epoch of reionization. We focus on the power spectrum on large scales at redshifts of 7 to 8 and explore the expected constraint on the local non-Gaussianity parameter $f_{\rm NL}$ for current and next-generation 21 cm experiments. We show that experiments such as SKA and MWA could measure $f_{\rm NL}$ values of order 10. This can be improved by an order of magnitude with a fast-Fourier transform telescope like Omniscope.

PRL 107, 131304 (2011)

Inflation

Inflationary epoch in early universe as solution to horizon and flatness problems.

Lasting at least 60 e-folds, resulting in almost Gaussian scale-invariant density perturbations.



Powerful mechanism to distinguish between inflationary models is amplitude and scale dependence of mild NG in perturbations of primordial density.

Canonical single field inflation predicts $|f_{NL}| \ll 1$, while evolution after inflation generates $f_{NL} \sim 1$.

Guth 1981
Linde 1982
Maldacena 2003
Liguori et al 2006

Scale-dependent bias from primordial NG

$$\Phi_{\rm NG}(\mathbf{x}) = \phi(\mathbf{x}) + f_{\rm NL}\left(\phi^2(\mathbf{x}) - \langle\phi^2\rangle\right)$$

(dominant for squeezed triangles: $k_3 \ll k_2 \approx k_1$)

$$\delta_{\rm NG} \;=\; -(3\Omega_m/2ar_H^2)\nabla^2\Phi_{\rm NG}$$

$$\nabla^2\Phi_{\rm NG} = \nabla^2\phi + 2f_{\rm NL}[\phi\nabla^2\phi + |\nabla\phi|^2]$$

$$\delta_{\rm NG} \approx \delta[1 + 2f_{\rm NL}\phi]$$

$$\Delta b_h(k,z) = 3(b_h - 1)f_{\rm NL}\Omega_m H_0^2\bar{\delta}_c/\left(D(z)k^2T(k)\right)$$

Dalal et al 2008
Matarrese & Verde 2008

Present f_{NL} constraints

f_{NL} = 32 ± 21 (WMAP7: Komatsu et al 2011)

f_{NL} = 28 ± 23 (SDSS: Slosar et al 2008)

Future f_{NL} constraints

Planck TTT: $\sigma(f_{NL}) \sim 5$ (Bluebook 2006)

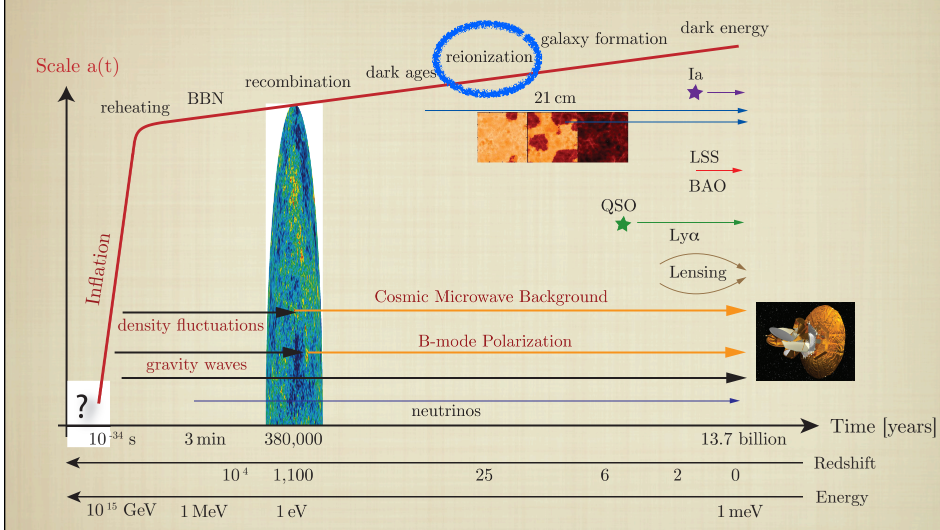
gg+gT: Carbone & Verde (2008)

survey	z range	sq deg	mean galaxy density $(h/Mpc)^3$	Δf_{NL}
SDSS LRG's	$0.16 < z < 0.47$	7.6×10^3	1.36×10^{-4}	40
BOSS	$0 < z < 0.7$	10^4	2.66×10^{-4}	18
WFMOS low z	$0.5 < z < 1.3$	2×10^3	4.88×10^{-4}	15
WFMOS high z	$2.3 < z < 3.3$	3×10^2	4.55×10^{-4}	17
ADEPT	$1 < z < 2$	2.8×10^4	9.37×10^{-4}	1.5
EUCLID	$0 < z < 2$	2×10^4	1.56×10^{-3}	1.7
DES	$0.2 < z < 1.3$	5×10^3	1.85×10^{-3}	8
PanSTARRS	$0 < z < 1.2$	3×10^4	1.72×10^{-3}	3.5
LSST	$0.3 < z < 3.6$	3×10^4	2.77×10^{-3}	0.7

cluster counts: $\sigma(f_{NL}) \sim 5$ (Cunha et al 2010)

21 cm bispectrum: $\sigma(f_{NL}) \lesssim 1$ (Pillepich et al 2007)

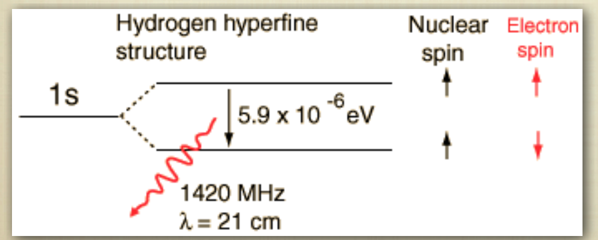
Universal History



21 cm line

Main Observable: Fluctuations in 21 cm brightness temperature from variations in hydrogen density and neutral fraction

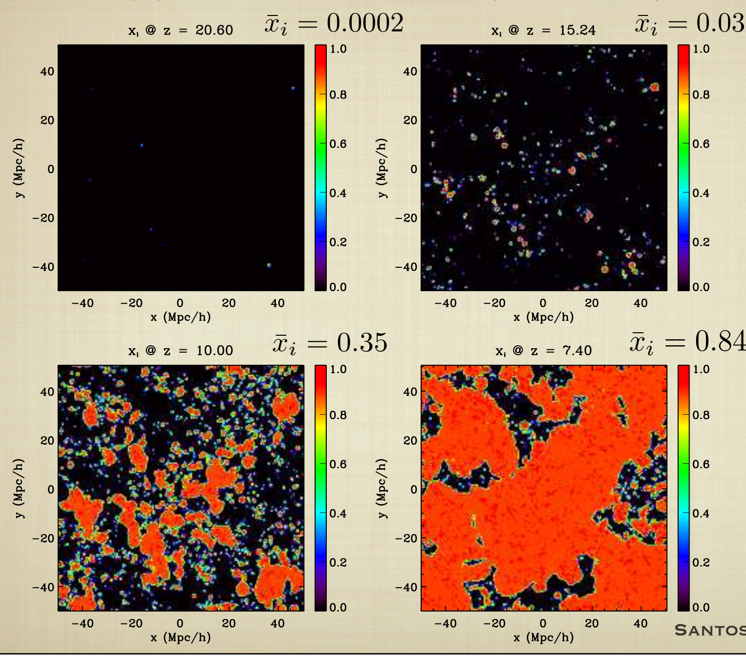
$$P_{\Delta T}(\mathbf{k}, z) = \mathscr{P}_{\delta\delta}(k,z) - 2\mathscr{P}_{x\delta}(k,z) + \mathscr{P}_{xx}(k,z) + 2\left[\mathscr{P}_{\delta\delta}(k,z) - \mathscr{P}_{x\delta}(k,z)\right]\mu^2 + \mathscr{P}_{\delta\delta}(k,z)\mu^4.$$



Unique signature on how neutral hydrogen evolved from LSS to complete reionization

Furlanetto et al 2006

Bubble Growth - biased tracers



Santos et al 2008

Scale-dependent bias from primordial NG

Dalal et al (2008)

$$\Delta b_h(k,z) = 3(b_h - 1) f_{\rm NL} \Omega_m H_0^2 \bar{\delta}_c / \left(D(z) k^2 T(k)\right)$$

Joudaki et al (2011)

$$\Delta b_x(k,z) = 3(b_x - 1) f_{\rm NL} \Omega_m H_0^2 \bar{\delta}_B / \left(D(z) k^2 T(k)\right)$$

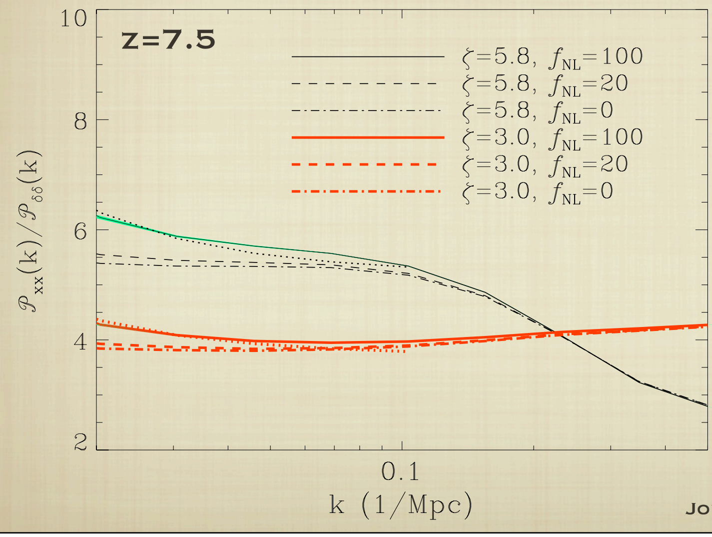
$$\mathscr{P}_{x\delta}/\mathscr{P}_{\delta\delta} = b_x + \Delta b_x, \; \mathscr{P}_{xx}/\mathscr{P}_{\delta\delta} = (b_x + \Delta b_x)^2$$

- Bias increases linearly with $f_{\rm NL}$.
- Bias increases with scale as $1/k^2$.
- Bias increases with redshift as $(1+z)$.

Dalal et al 2008
Matarrese & Verde 2008

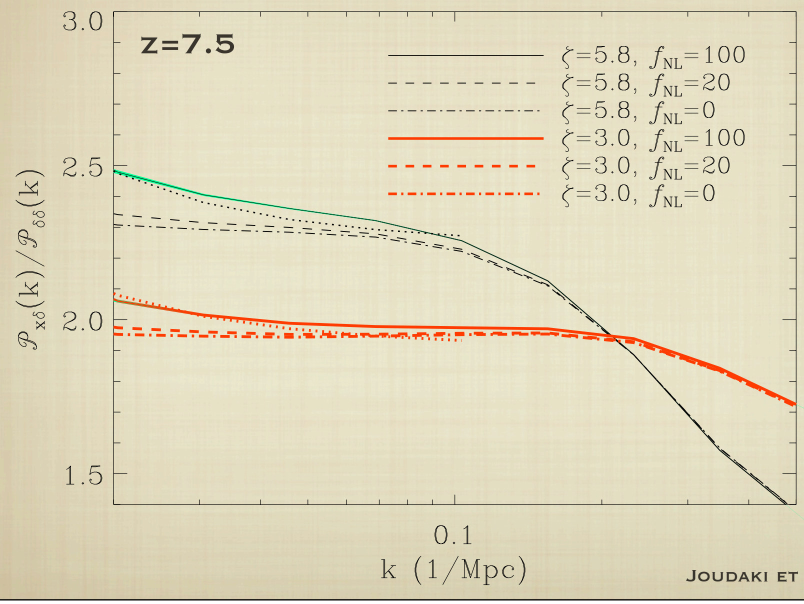
Bias in the Ionization Spectrum

Simulations of the ionization distribution during EoR.
Box of comoving length 3000 Mpc.
Initial matter density field from NG potential.



Joudaki et al 2011

Bias in Ionization-Density Spectrum



Joudaki et al 2011

Agenda Part 2

- Primordial non-Gaussianity and connection to 21 cm Physics
- Expected Constraints on f_{NL} relative to Design of 21 cm Experiments

LOw Frequency ARray (LOFAR)

Primarily in Netherlands.
77 large (diameter ~ 100 m) stations,
each with thousands of antennae. Signal
from stations correlated to form image.
Presently at calibration stage.

Lofar.org

Murchison Widefield Array (MWA)

Built in Western Australia. 500 4mx4m stations, each with 16 correlated antennae. At least 3 years until data collection.

mwatelescope.org

Square Kilometer Array (SKA)

Built either in Western Australia or South Africa. 7000 small antennae. First light around 2020.

skatelescope.org

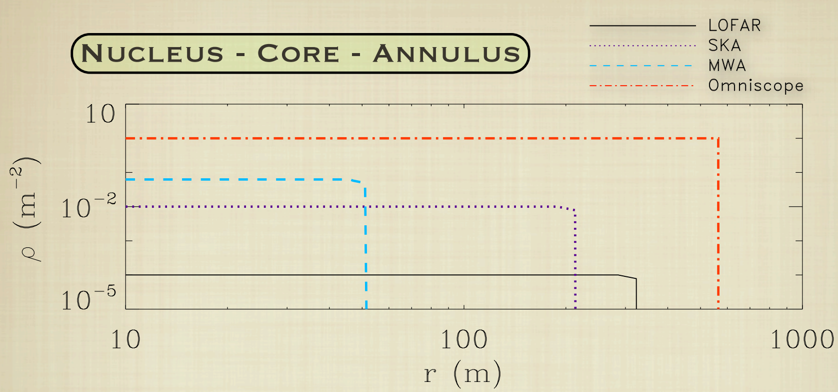
Omniscope

Fast-fourier transform telescope, which correlates all of its antennae. One million 1Mx1M antennae in contiguous nucleus. Prototype stage.

Tegmark & Zaldarriaga 2010

Current and Future Experiments

Nucleus - Core - Annulus



Experiment	$N_{\rm ant}$	$L_{\rm min}$ (m)	$L_{\rm max}$ (m)	FOV ($\deg^2$)	$A_e (m^2)$
LOFAR	32	100	650	$2 \times \pi 2.4^2$	590
MWA	500	4.0	100	$\pi 16^2$	13
SKA	1400	10	430	$\pi 8.6^2$	45
Omniscope	10^6	1.0	1100	2.1×10^4	1.0

Joudaki et al 2011

Foregrounds and considered scales

- The limiting factor for 21 cm observations is cleaning of foregrounds, which are 10^4 times larger than the signal (e.g. galactic synchotron (~70%), galactic bremsstrahlung, and extragalactic point sources).
- By subtracting a cubic polynomial from the foregrounds (McQuinn 2006), they are lowered well below the signal for $k_{LOS} > 2\pi/yB = 0.063$/Mpc for 6 MHz bandwidth. We also consider more optimistic scenario.
- Perpendicular $k_{\perp}$-modes set by the min/max baselines. LOFAR: [0.039,0.25]/Mpc, MWA: [0.0016, 0.040]/Mpc, SKA: [0.0039, 0.17]/Mpc, Omniscope: [3.9e-4, 0.44]/Mpc.
- Single redshift bin at z=7.5, with bias b_x=2.3 and mean neutral fraction x_H=0.5. Nonlinearities force $k < 2$/Mpc, but we impose an even earlier cutoff at 0.15/Mpc.

McQuinn et al 2006
Joudaki et al 2011

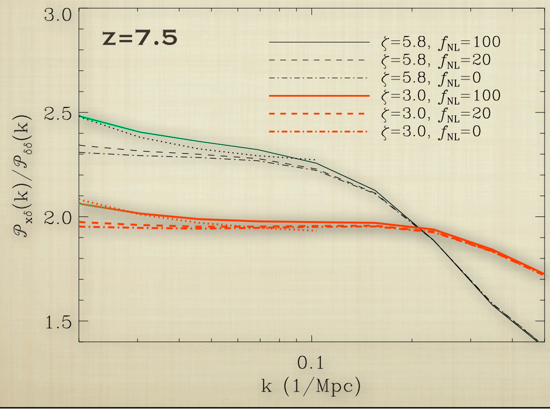
P_{21}(k) revisited: Modes considered

$f_{\rm NL}, b_x, \bar{x}_{\rm H}$

Neglecting other parameters good to 10% level

$[\Omega_c h^2,\ \Delta_R^2,\ n_s,\ {\rm d}n_s/{\rm d}\ln k]$

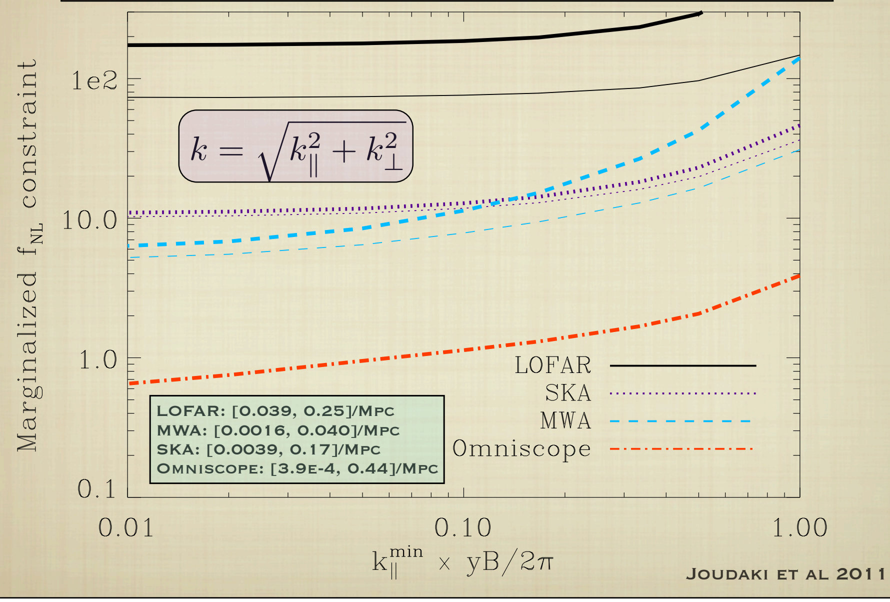
+ Planck



Joudaki et al 2011

Future Constraints vs. Foregrounds

Thick lines: with noise | Thin lines: w/o noise | Bandwidth 6 MHz



What is f_{NL} sensitivity to Exp. Design?

Sensitivity enters via two quantities: Antenna Number and Bandwidth

Bandwidth limits number of modes (i) and largest scales probed along LOS (ii)

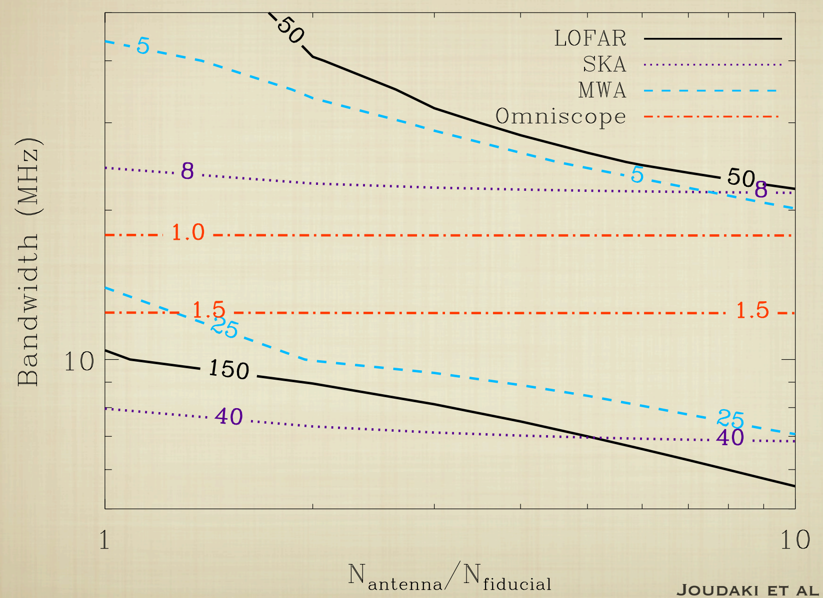
i) $V \propto B$ ii) $k_{\parallel}^{\rm min} \propto 1/B$

Larger number of antennae for fixed array density lowers the noise (i) and number of perpendicular modes (ii)

i) $n(k_{\perp}) \propto N_{\rm ant}$ ii) $k_{\perp}^{\rm max} \propto L_{\rm max} \propto \sqrt{N_{\rm ant}}$

Joudaki et al 2011

Future Constraints vs. Exp. Design



Joudaki et al 2011

Special considerations

- Extending the considered modes to scales $k = 2/\mathrm{Mpc}$ (with strong prior on exponential tail) improves the constraints by up to a factor of 2 for the different experimental configurations.

- When only information from scales $k < 0.10/\mathrm{Mpc}$ (as opposed to $0.15/\mathrm{Mpc}$) is available, the constraint on f_{NL} degrades by up to factor of 2 when marginalizing over $[b_x, x_H]$, and by up to 30% when $[b_x, x_H]$ are fixed.

- Fixing the ionization fraction and bias improves the f_{NL} constraints by factor of 1.5 up to factor of 10, for different cases and experiments considered.

- For fiducial configurations alone, the f_{NL} constraints improve by factors of 2 (MWA) to 3 (LOFAR, SKA, Omniscope) when fixing bias to be function of ionization fraction.

Conclusions

- The search for signature of primordial NG is a key test of inflationary theories. Large values for NG parameter $f_{NL} \gg 1$ will rule out standard single field inflationary models.

- The ionization power spectrum from 21 cm emission during the EoR provides an alternative approach to constrain f_{NL} relative to the CMB and LSS.

- Future 21 cm telescopes like MWA and SKA will be able to measure f_{NL} to accuracy of order 10, which improves by an order of magnitude for Omniscope.

- Increased bandwidth is more powerful than boosting antenna number in the search for f_{NL}, especially for CVL probes like SKA and Omniscope.

Thanks for listening.