Title: Cosmological probes of inflation and the 21 cm line

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Abstract: Inflation is one of the foundational paradigms of our picture of the Universe. Yet distinguishing between the multitude of different inflationary models presents major observational challenges. In this talk, I will discuss a number of inflationary observables, specifically the tilt and running of the primordial power spectrum, compensated isocurvature modes, and non-Gaussianity, and the extent to which they might be constrained by future galaxy surveys and 21 cm experiments.

# Cosmological probes of inflation and the 21 cm line

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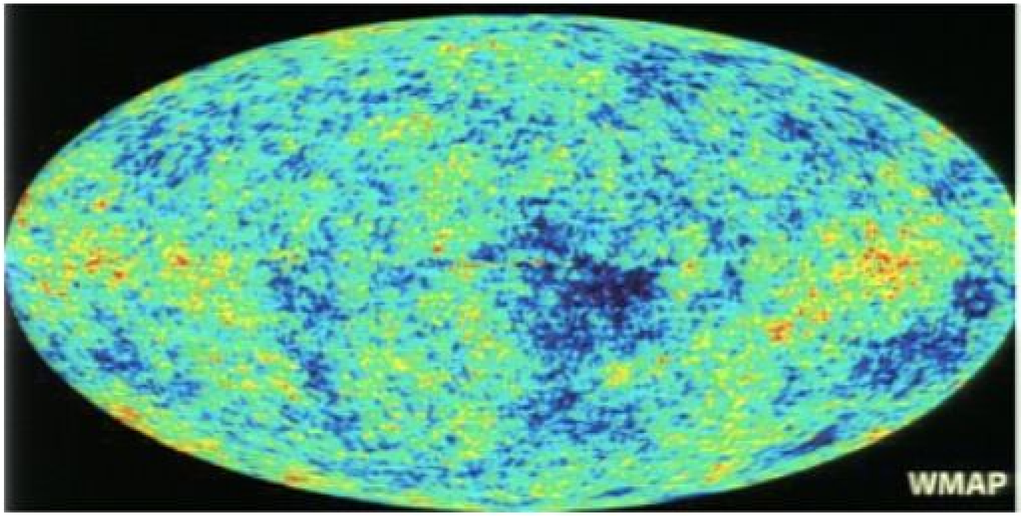
# the Golden Age of Cosmology




| Class | Parameter | *WMAP* 5 Year Mean[b] | *WMAP*+BAO+SN Mean |
|---|---|---|---|
| Primary | $100\Omega_b h^2$ | $2.273 \pm 0.062$ | $2.267^{+0.058}_{-0.059}$ |
| | $\Omega_c h^2$ | $0.1099 \pm 0.0062$ | $0.1131 \pm 0.0034$ |
| | $\Omega_\Lambda$ | $0.742 \pm 0.030$ | $0.726 \pm 0.015$ |
| | $n_s$ | $0.963^{+0.014}_{-0.015}$ | $0.960 \pm 0.013$ |
| | $\tau$ | $0.087 \pm 0.017$ | $0.084 \pm 0.016$ |
| | $\Delta^2_{\mathcal{R}}(k_0^c)$ | $(2.41 \pm 0.11) \times 10^{-9}$ | $(2.445 \pm 0.096) \times 10^{-9}$ |

Komatsu+ 2009

Six numbers to accurately model most of cosmology

# Where next?

• Each of those six numbers belies an unsolved problem in cosmology

| | |
|---|---|
| $100\Omega_b h^2$ | Baryogenesis |
| $\Omega_c h^2$ | Dark matter |
| $\Omega_\Lambda$ | Dark energy |
| $n_s$ | Inflation |
| $\Delta^2_{\mathcal{R}}(k_0^{\rm c})$ | |
| $\tau$ | Reionization |

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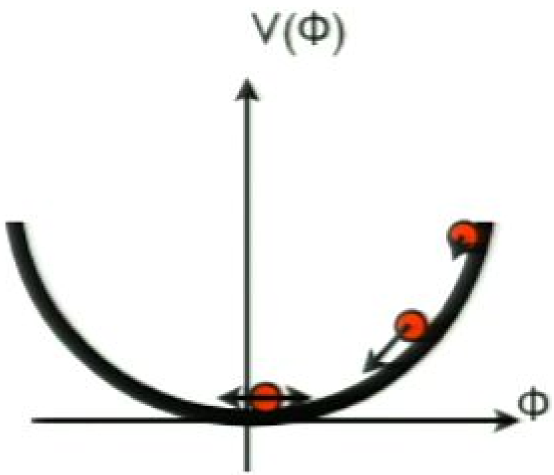
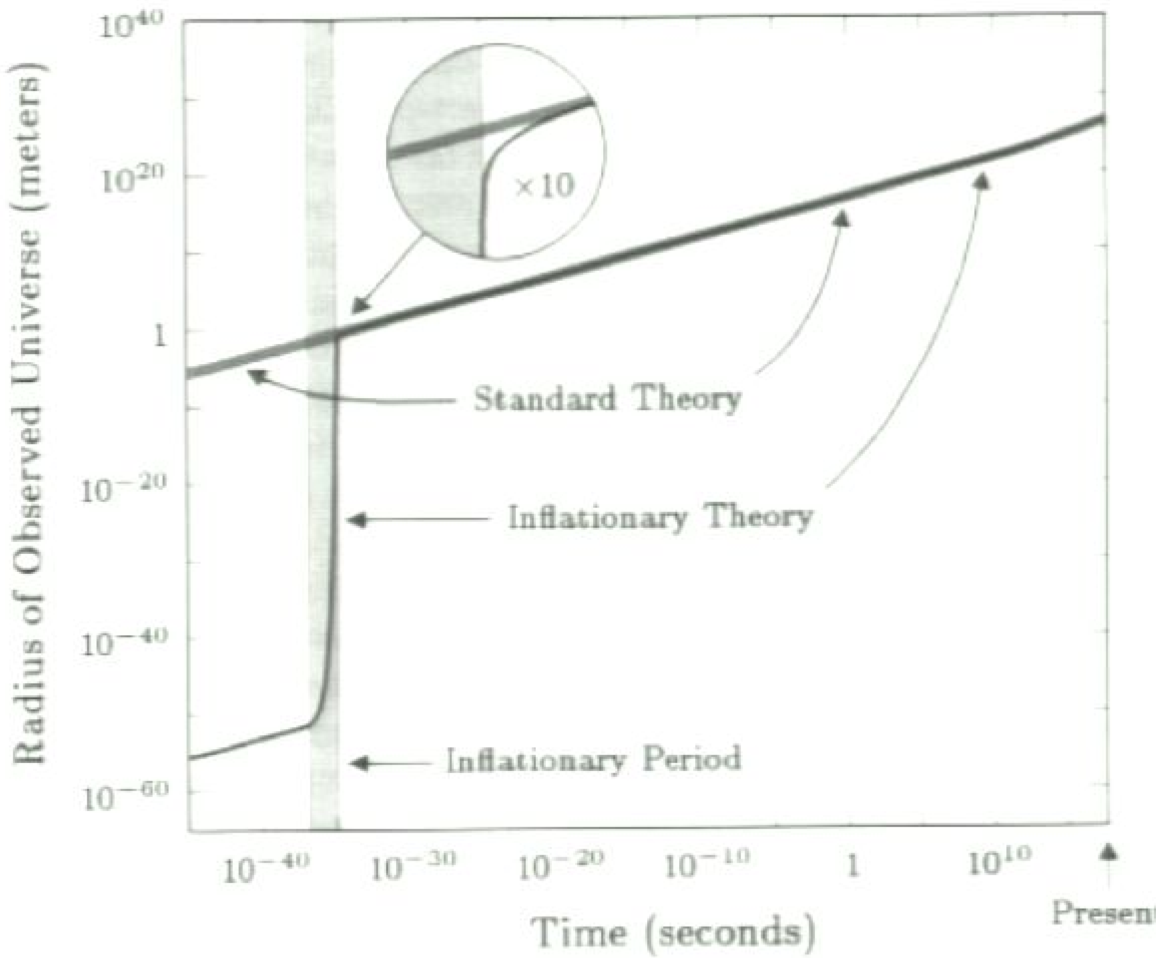
| $n_s$, $\Delta^2_{\mathcal{R}}(k_0^{\mathrm{c}})$ | Inflation |
| $\tau$ | Reionization |

# Inflation




Potential energy dominated phase leads to accelerated expansion

# Fingerprints of Inflation

- Tilt/running
- B-modes
- Isocurvature
- Non-Gaussianity
- Topological defects
- Gravitational waves
- ...

Constrain inflationary potential

Help determine class of model

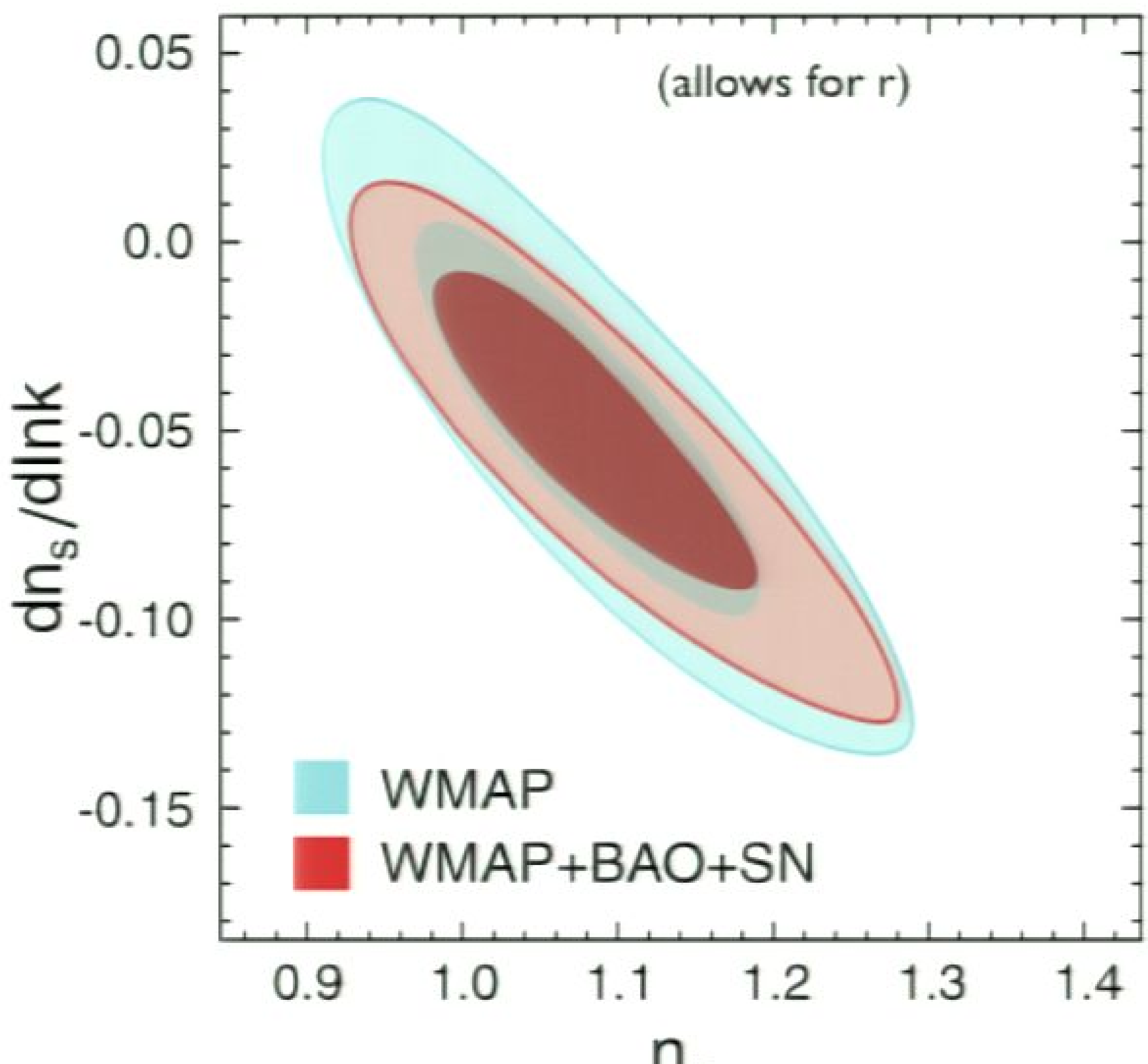
Constraining inflationary parameter space observationally is highly challenging

# Overview

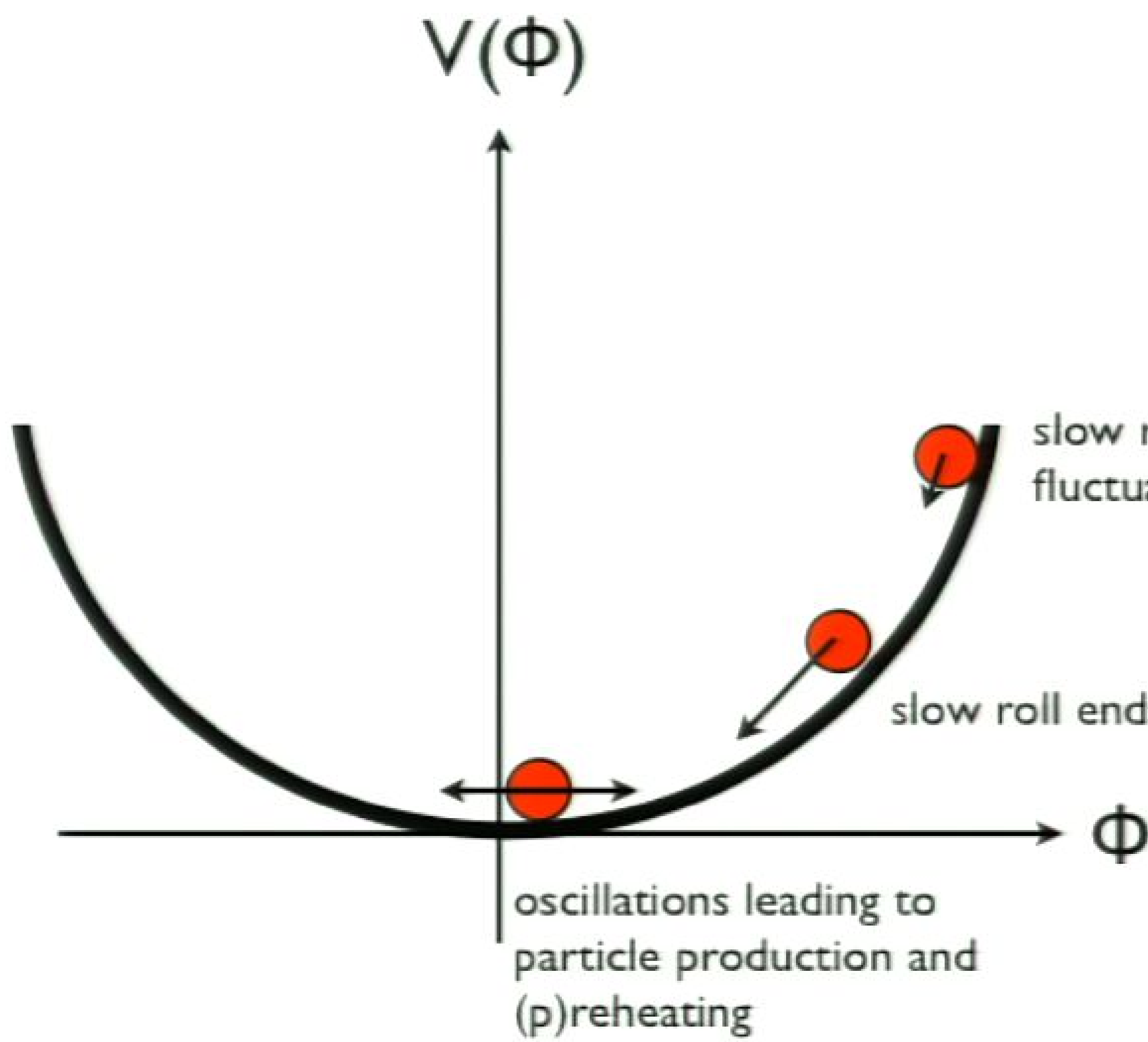
- Tilt and running of the inflationary power spectrum
- Compensated Isocurvature Mode
- Non-Gaussianity

# Tilt and running

Adshead, Easther, Pritchard, Loeb 2010



# Slow roll inflation






Fluctuations only probe part of the potential

# Inflationary power spectrum

Shape of primordial power spectrum gives constraints on inflationary potential

$$\mathcal{P}_\zeta(k) = A_s(k_\star)\left(\frac{k}{k_\star}\right)^{n_s(k)-1},$$

$$\mathcal{P}_h(k) = A_t(k_\star)\left(\frac{k}{k_\star}\right)^{n_t(k)},$$

Potential ⟶ Slow roll parameters ⟶ Observables

$$\epsilon(\phi) = \frac{M_{\rm Pl}^2}{2}\left[\frac{V'}{V}\right]^2,$$

$$\eta(\phi) = M_{\rm Pl}^2\frac{V''}{V},$$

$$\xi(\phi) = M_{\rm Pl}^4\frac{V'V'''}{V^2}.$$

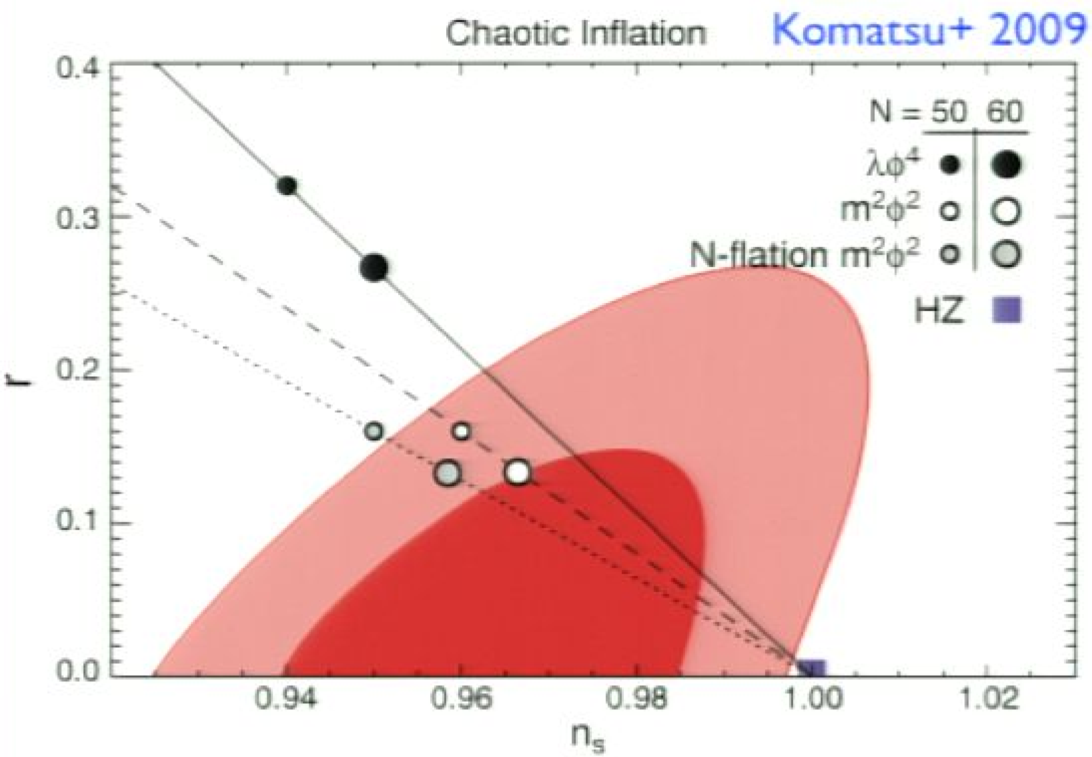
$$\frac{1}{2}(n_s-1) = -3\epsilon+\eta-\left(\frac{5}{3}+12C\right)\epsilon^2+(8C-1)\epsilon\eta+\frac{1}{3}\eta^2 -\left(C-\frac{1}{3}\right)\xi+\cdots.$$

$$\frac{\mathrm{d}n_s}{\mathrm{d}\log k} = 16\epsilon\eta-24\epsilon^2-2\xi+\cdots.$$

$$r = 16\epsilon\left[1-\frac{2}{3}\epsilon+\frac{1}{3}\eta+2C(2\epsilon-\eta)\right]+\cdots.$$

# Current constraints

Existing constraints already give interesting constraints on some inflationary models



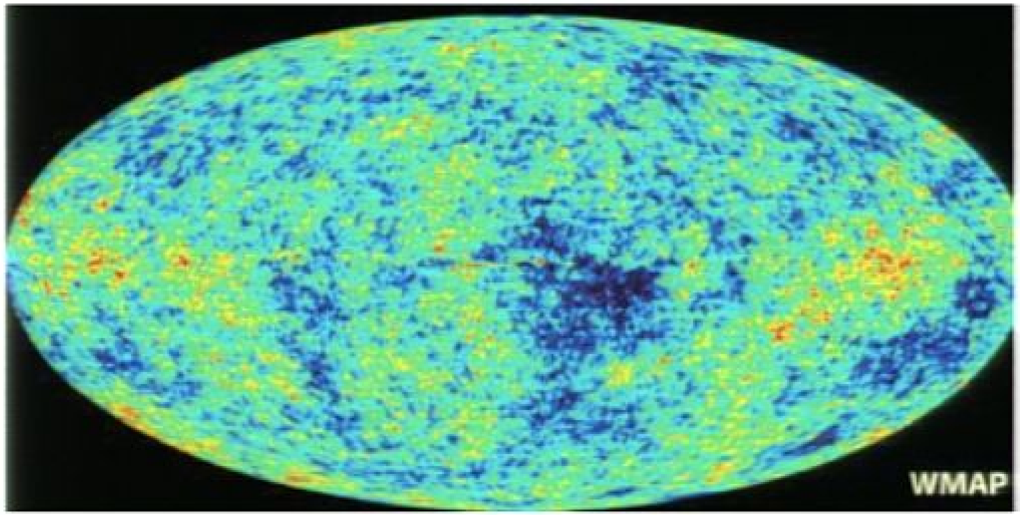

Baumann+ 2009

| Parameter | 5-year *WMAP* | *WMAP*+BAO+SN |
|---|---|---|
| $n_s$ | $0.963^{+0.014}_{-0.015}$ | $0.960^{+0.013}_{-0.013}$ |
| $n_s$ | $0.986 \pm 0.022$ | $0.970 \pm 0.015$ |
| $r$ | $< 0.43$ | $< 0.22$ |
| $n_s$ | $1.031^{+0.054}_{-0.055}$ | $1.017^{+0.042}_{-0.043}$ |
| $\alpha_s$ | $-0.037 \pm 0.028$ | $-0.028^{+0.020}_{-0.020}$ |
| $n_s$ | $1.087^{+0.072}_{-0.073}$ | $1.089^{+0.070}_{-0.068}$ |
| $r$ | $< 0.58$ | $< 0.55$ |
| $\alpha_s$ | $-0.050 \pm 0.034$ | $-0.058 \pm 0.028$ |

Deviation from scale invariance only if running is fixed

Running essentially unconstrained with current data

# CMB




Planck basically cosmic variance limited in TT $n_s \sim 4*10^{-3}$ $\alpha_s = 5*10^{-3}$

CMBpol a little better $n_s \sim 2*10^{-3}$ $\alpha_s = 4*10^{-3}$

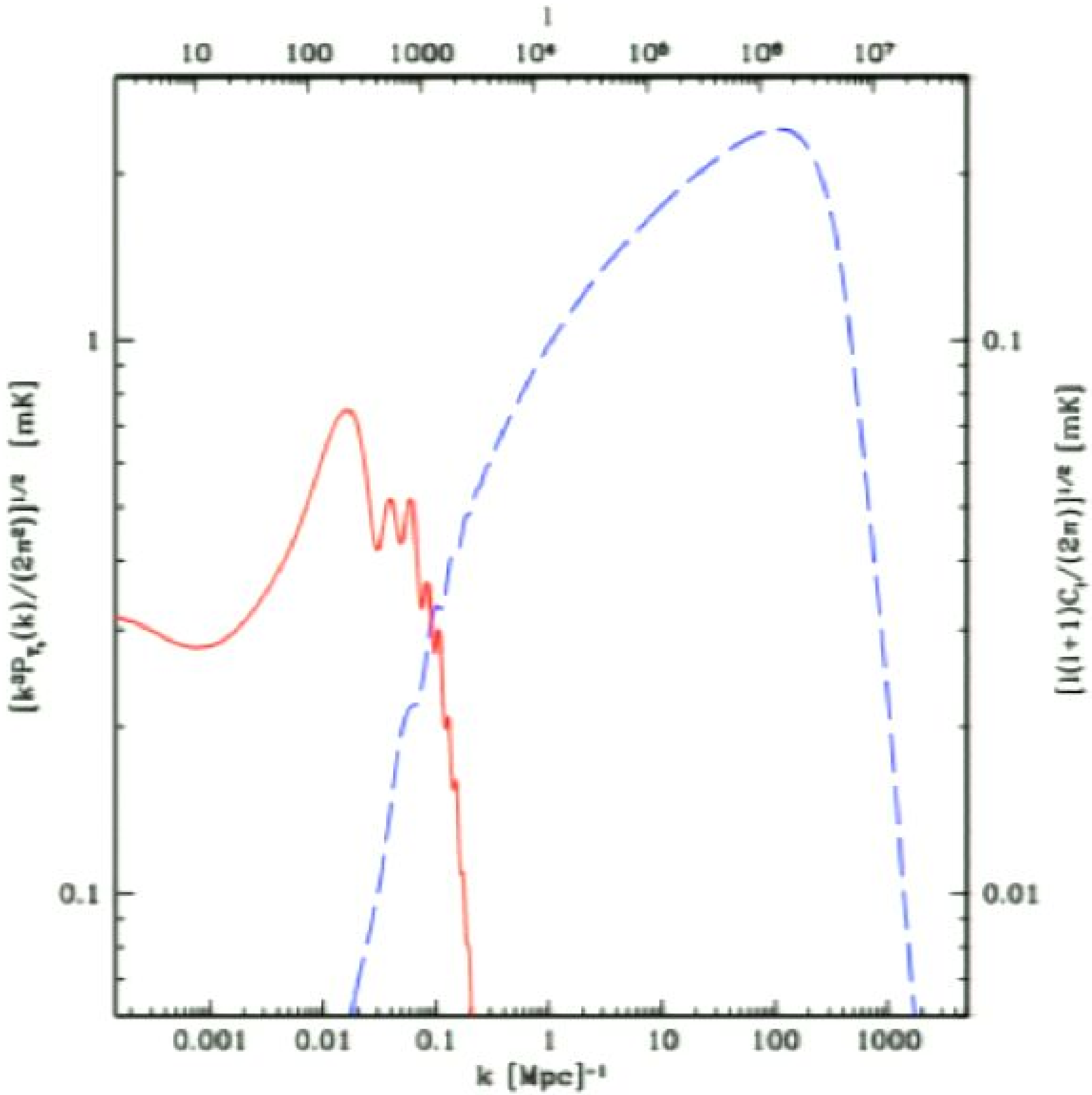
| Errors | *WMAP* | *Planck* | EPIC-LC | | EPIC-2m | |
|---|---|---|---|---|---|---|
| | no FGs | no FGs | no FGs | with Pess FGs | no FGs | with Opt FGs |
| $\Delta n_s$ | 0.031 | 0.0036 | – | – | 0.0016 | 0.0016 |
| $\Delta \alpha_s$ | 0.023 | 0.0052 | – | – | 0.0036 | 0.0036 |
| $\Delta r$ | 0.31 | 0.011 | $5.4 \times 10^{-4}$ | $9.2 \times 10^{-4}$ | $4.8 \times 10^{-4}$ | $5.4 \times 10^{-4}$ |

Baumann+ 2009



Future improvements really from combining with other data sets

# More scales...

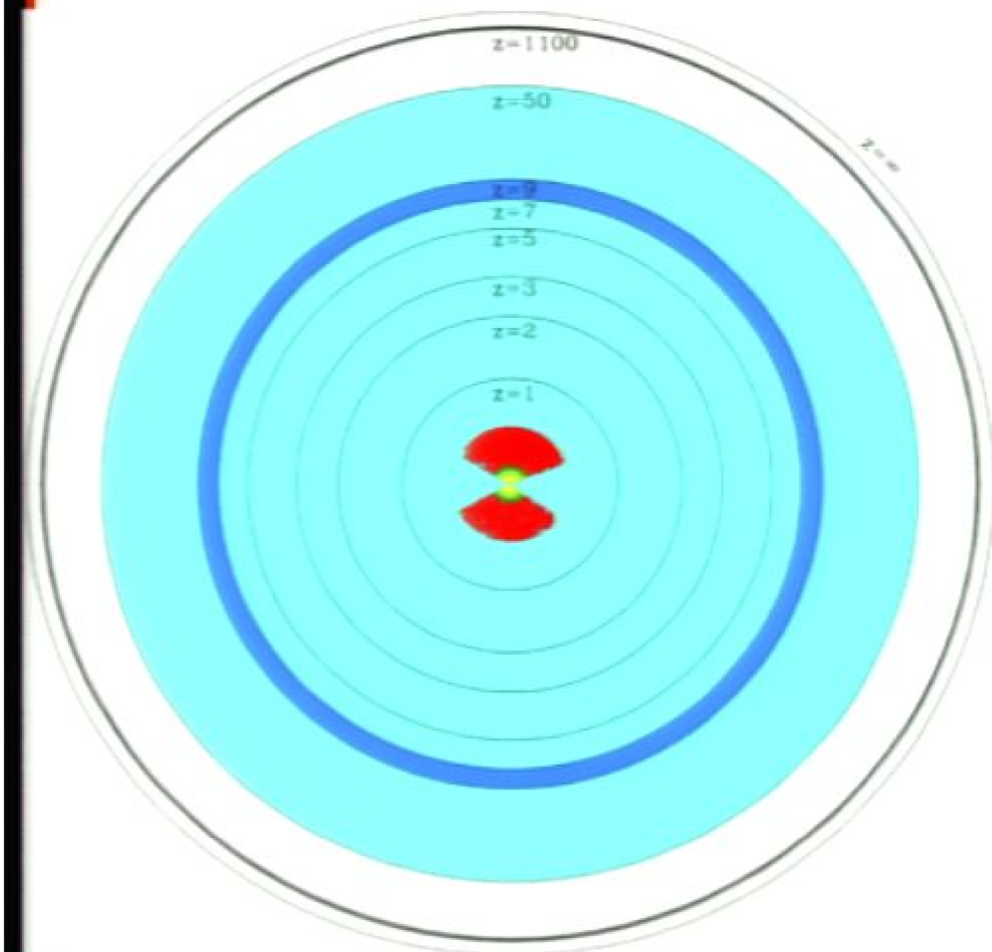


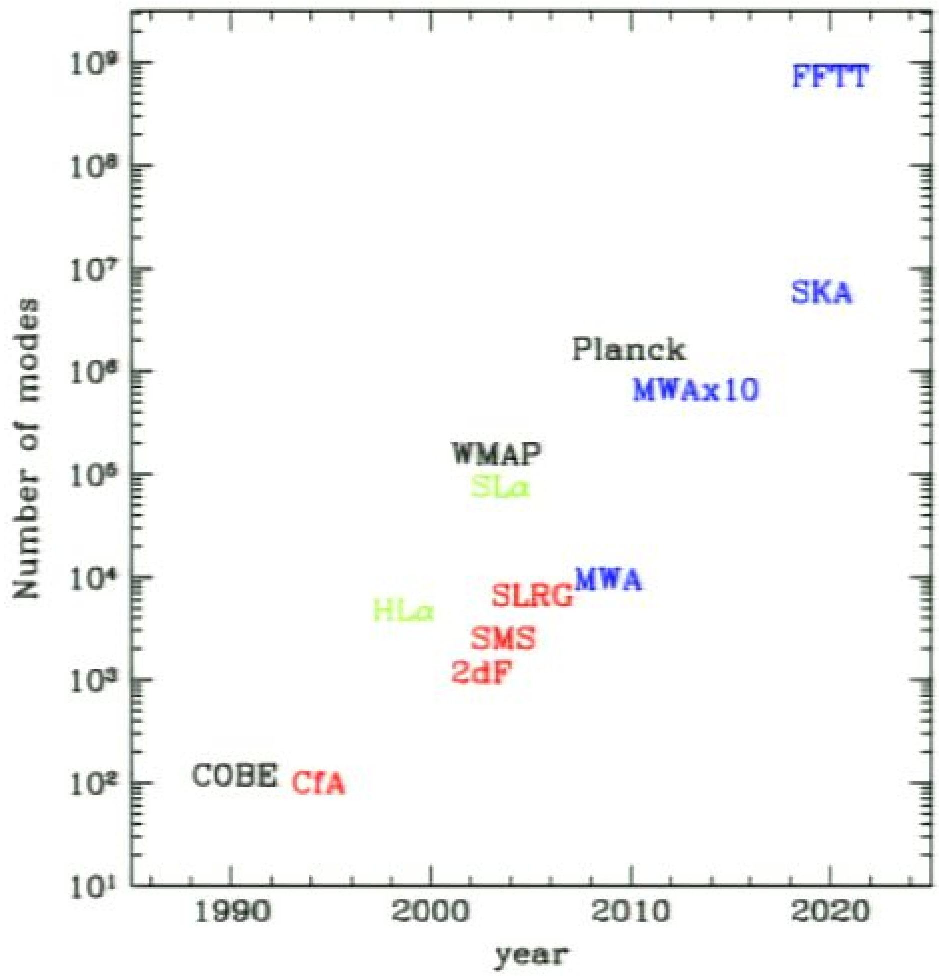





Kleban+ 2007

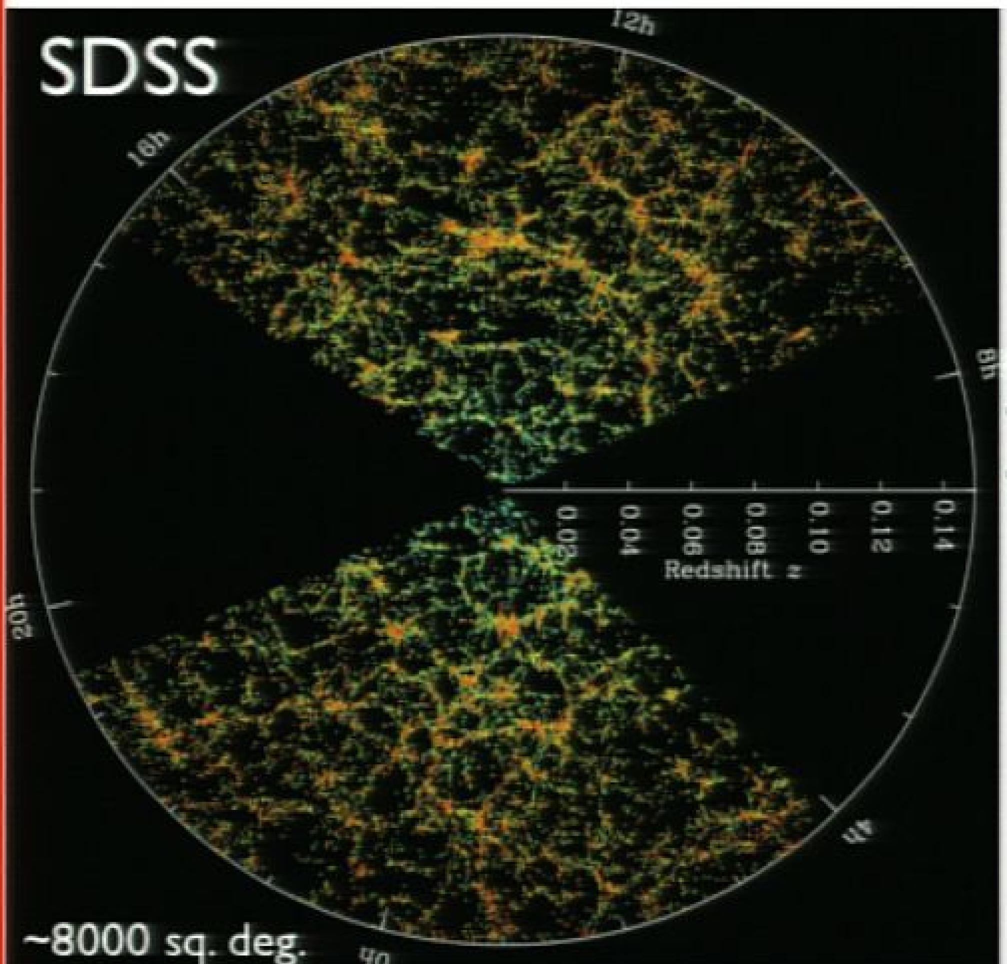
# More volume...

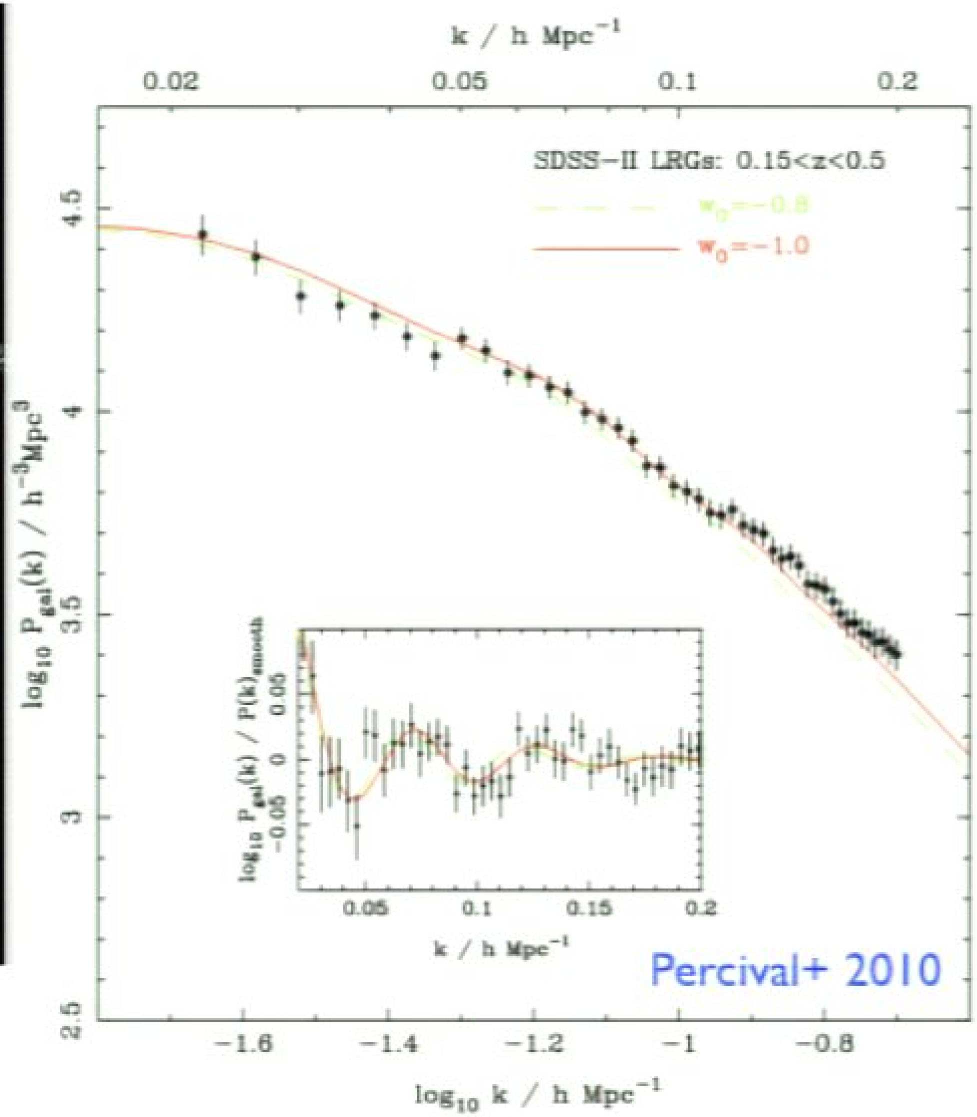



Tegmark & Zaldarriaga 2009

# Galaxy surveys



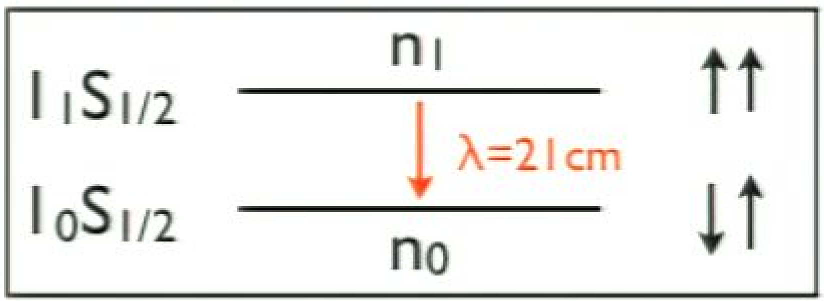




Galaxies provide biased tracer of density field

Many large surveys being planned: BOSS, HETDEX, DES, LSST, EUCLID, WFIRST

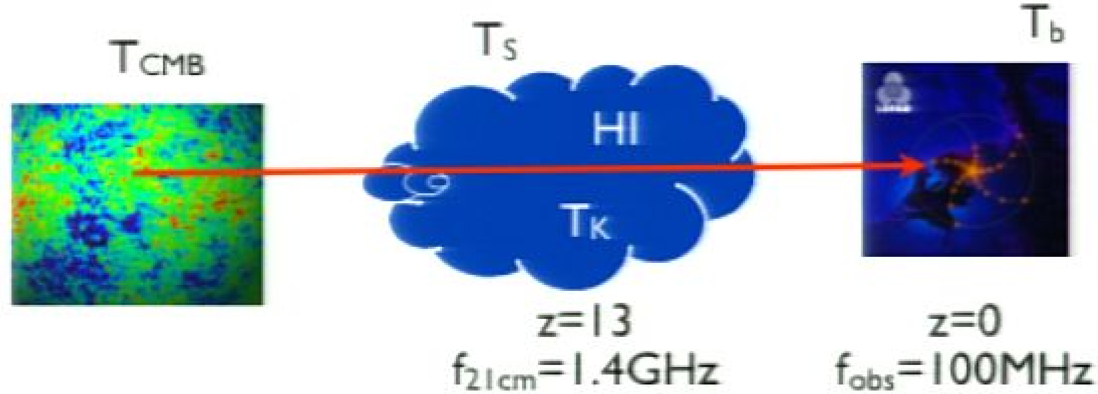
# 21 cm experiments

- HI hyperfine structure




$$n_1/n_0 = 3\exp(-h\nu_{21\mathrm{cm}}/kT_s)$$

- Use CMB to backlight structure




- 3D mapping of HI possible - angles & frequency
- 21 cm brightness temperature

$$T_b = 27x_{\rm HI}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\,\mathrm{mK}$$

- 21 cm spin temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

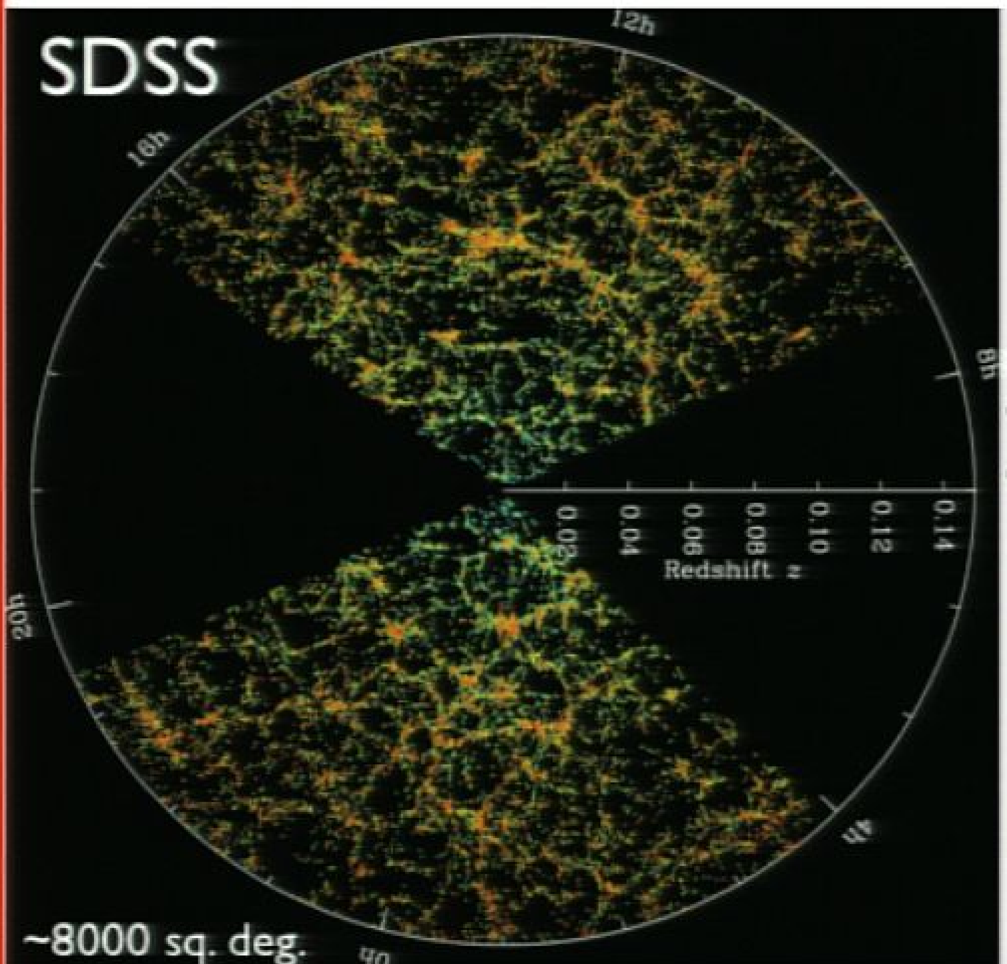
Coupling mechanisms:

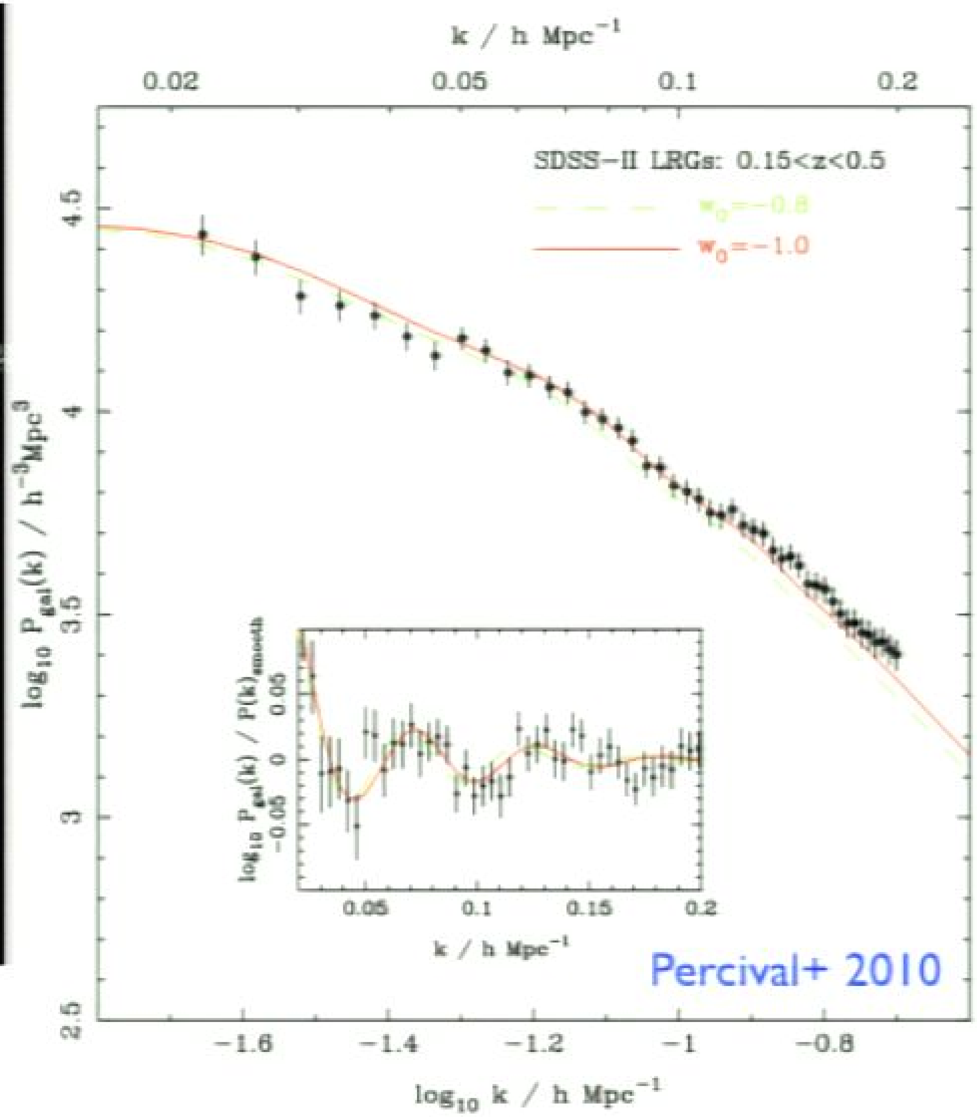
Radiative transitions (CMB)

Collisions

Wouthysen-Field Effect

# Galaxy surveys

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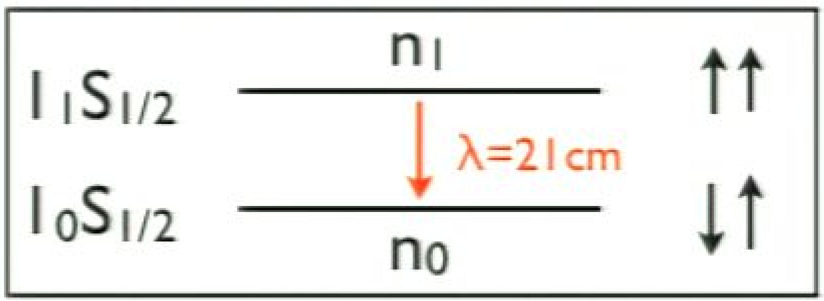


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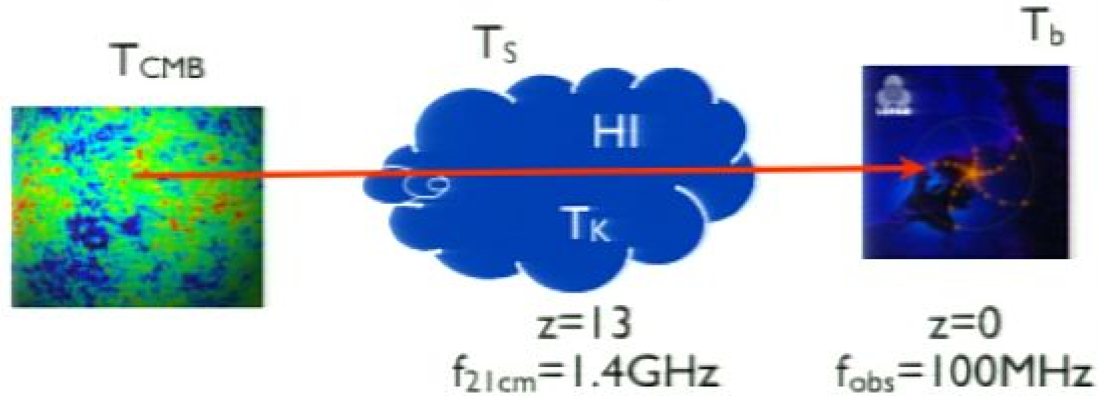


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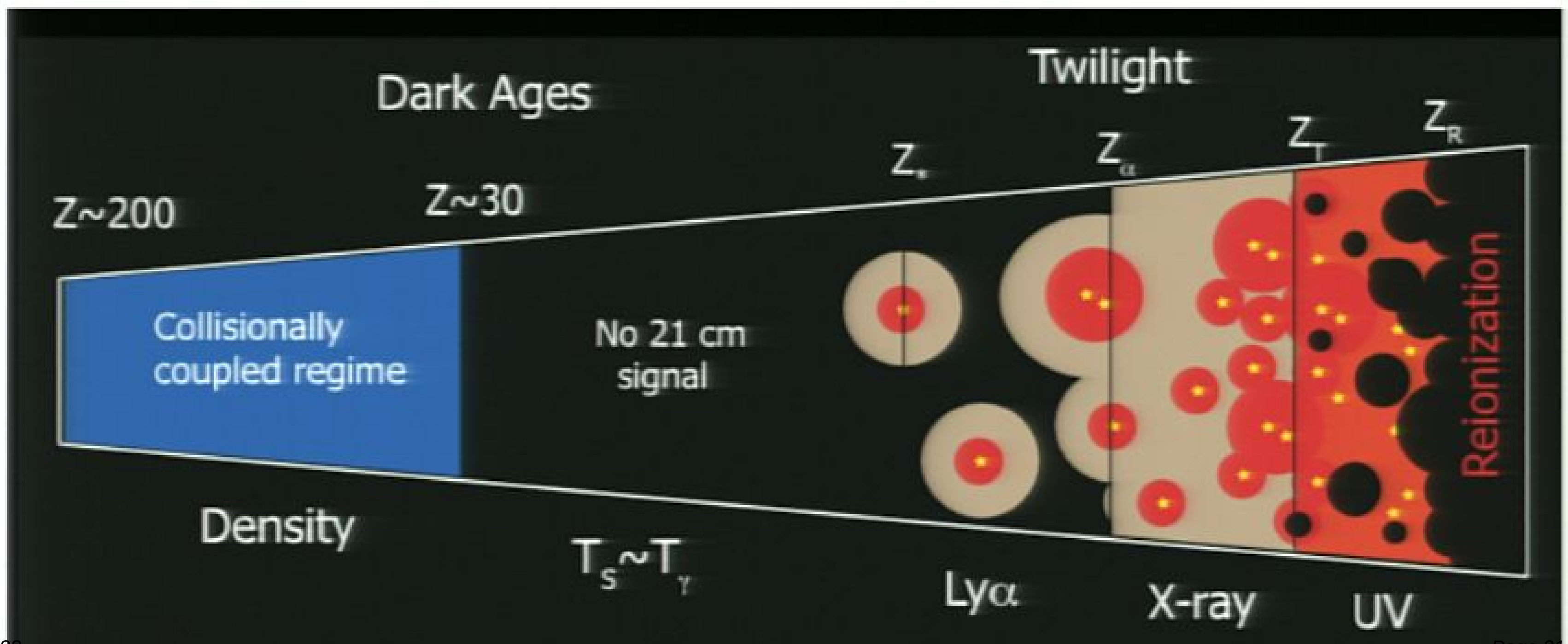
# 21 cm signal evolution

| Brightness temperature | baryon density | neutral fraction | IGM temperature | Lya flux | velocity gradient |
|---|---|---|---|---|---|

$$\delta_{T_b} = \beta\delta_b + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$

| cosmology | reionization | X-ray sources | Lya sources | cosmology |
|---|---|---|---|---|






for 21 cm review see Furlanetto, Oh & Briggs (2006)

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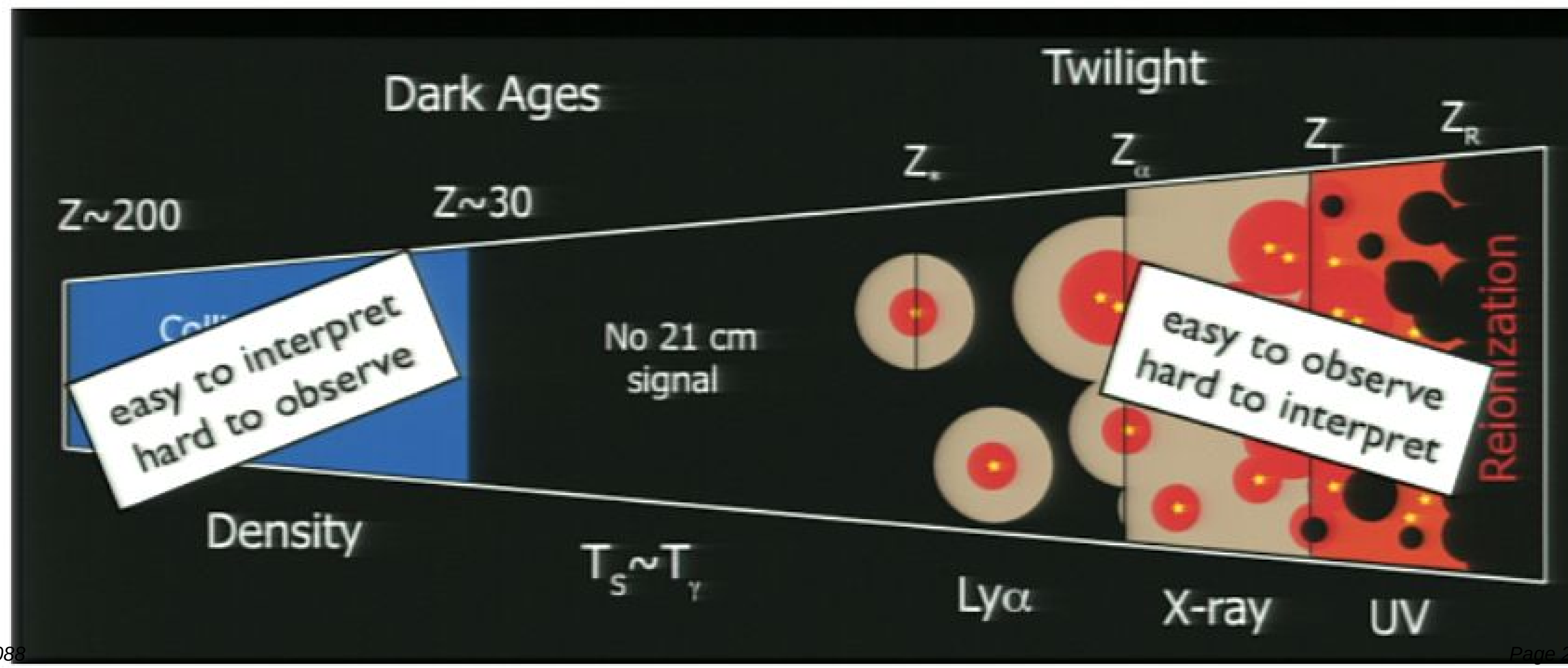




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# Planned experiments

## Current


## Soon
(next few years)




z~8-12

## Future
(~2022)


## further future


Tegmark & Zaldarriaga (2008)

# Inflationary power spectrum

Shape of primordial power spectrum gives constraints on inflationary potential

$$\mathcal{P}_\zeta(k) = A_s(k_\star)\left(\frac{k}{k_\star}\right)^{n_s(k)-1},$$

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$z \sim 8\text{-}12$

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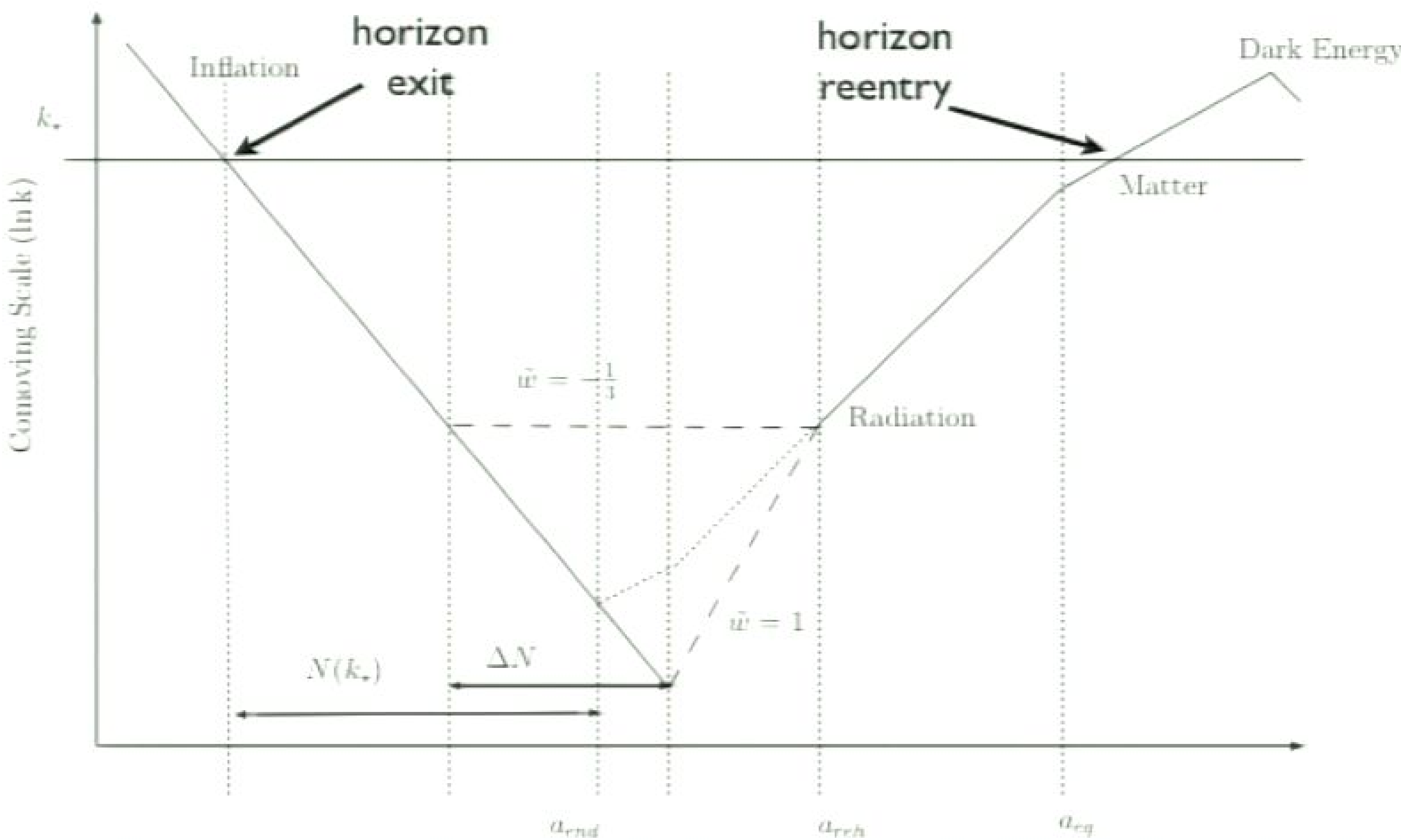
# Post-inflationary equation of state

Matching observables to theory requires knowledge of number of e-foldings to connect observed scale to corresponding field value during inflation

$$N(k) \equiv \log\left(\frac{a(t_{end})}{a(t_k)}\right) = \int_{t_k}^{t_{end}} H(t)\mathrm{d}t \simeq \frac{1}{M_{\rm Pl}^2}\int_{\phi_{end}}^{\phi_k} \frac{V}{V'}\mathrm{d}\phi\,.$$



# Matching equation

Easy for post-inflationary equation of state to differ from radiation (w=1/3):

- matter dominated phase w=0
- kination w=1
- thermal inflation w<-1/3

Post-inflationary equation of state unknown, but can define effective equation of state

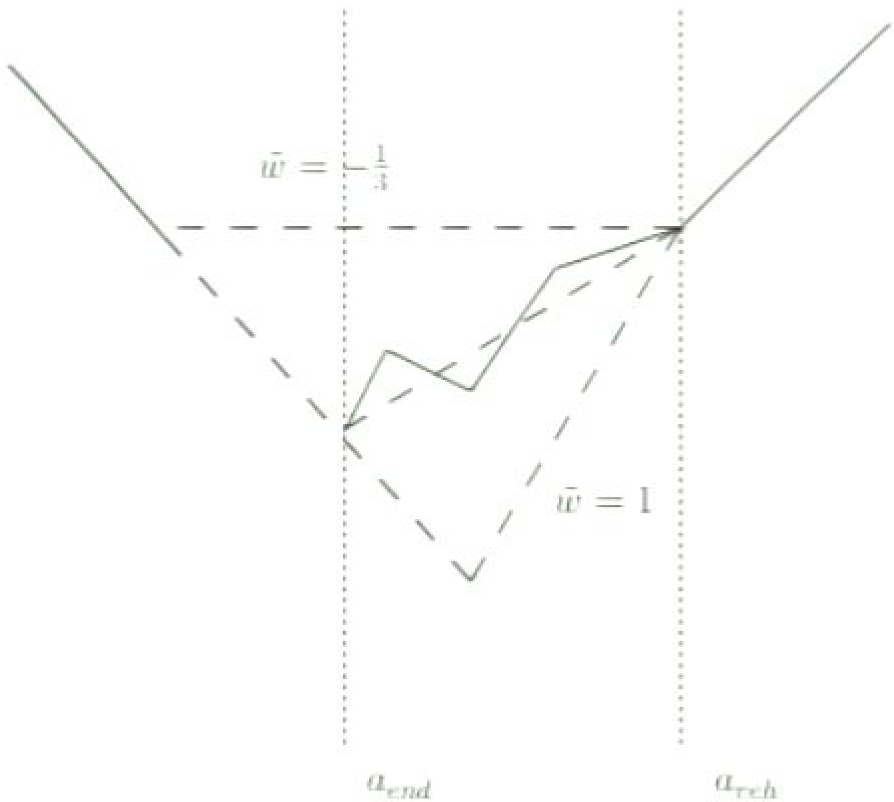
$$\tilde{w} = \frac{1}{\Delta \log a} \int w(a) \mathrm{d} \log a. \qquad \log\left(\frac{a_{end} H_{end}}{a_{reh} H_{reh}}\right) = -\frac{(1+3\tilde{w})}{6(1+\tilde{w})} \log\left(\frac{2}{3} \frac{\rho_{reh}}{V_{end}}\right)$$

$$N(k) = 56.12 - \log\left(\frac{k}{k_\star}\right) + \frac{1}{3(1+\tilde{w})} \log\left(\frac{2}{3}\right) + \log\left(\frac{V_k^{\frac{1}{4}}}{V_{end}^{\frac{1}{4}}}\right) + \frac{(1-3\tilde{w})}{3(1+\tilde{w})} \log\left(\frac{\rho_{reh}^{\frac{1}{4}}}{V_{end}^{\frac{1}{4}}}\right) + \log\left(\frac{V_k^{\frac{1}{4}}}{10^{16}\mathrm{GeV}}\right),$$

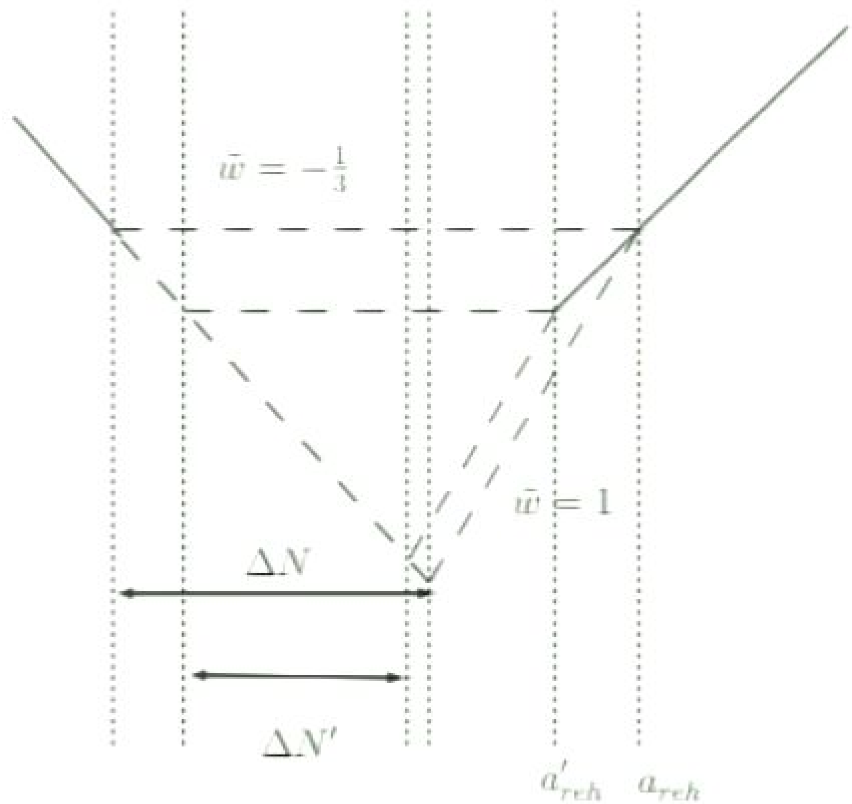
# Effective equation of state

One number to average over details

$$\bar{w} = \frac{1}{\Delta \log a} \int w(a) \mathrm{d} \log a.$$




Definition depends on specifying a temperature at which definitely radiation dominated



# Post-inflationary equation of state

Running couples to uncertainty in N to generate uncertainty in tilt

$$\Delta n_s \sim \alpha_s \Delta N.$$

Uncertainty can be comparable to statistical uncertainty e.g. for Planck

$$10^{-4} \lesssim |\alpha_s| \lesssim 10^{-3}. \quad + \quad \Delta N \sim 10 \quad \longrightarrow \quad \Delta n_s \sim 0.005$$

# Classes of inflationary model

*Single term potentials:* $\phi^n$

$$V = \lambda M_{Pl}^{4-n} \frac{\phi^n}{n},$$

*Natural Inflation*

$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right].$$

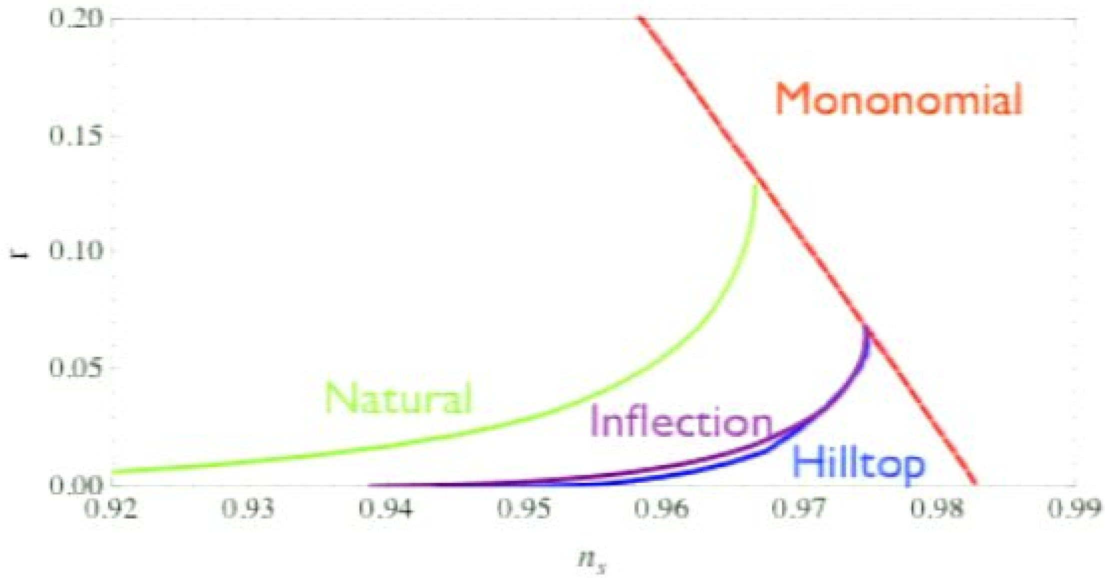
*Hilltop and Inflection Point Inflation*

$$V(\phi) = \Lambda^4 - \lambda M_{\rm Pl}^{4-n} \frac{\phi^n}{n},$$

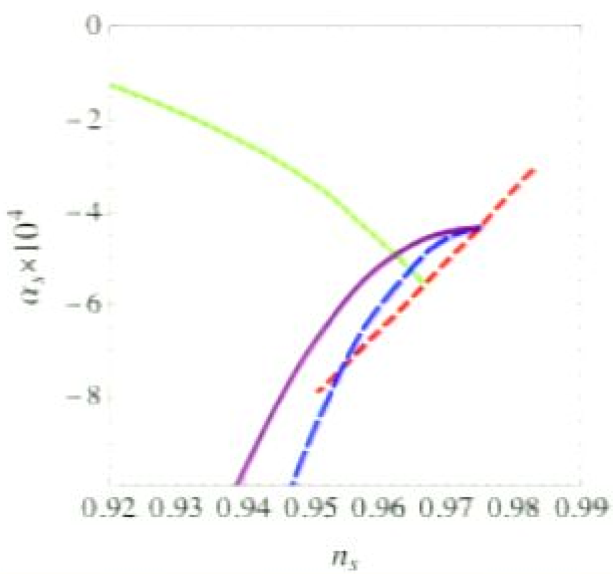
Simple slow roll inflation candidates with potential descirbed by single parameter

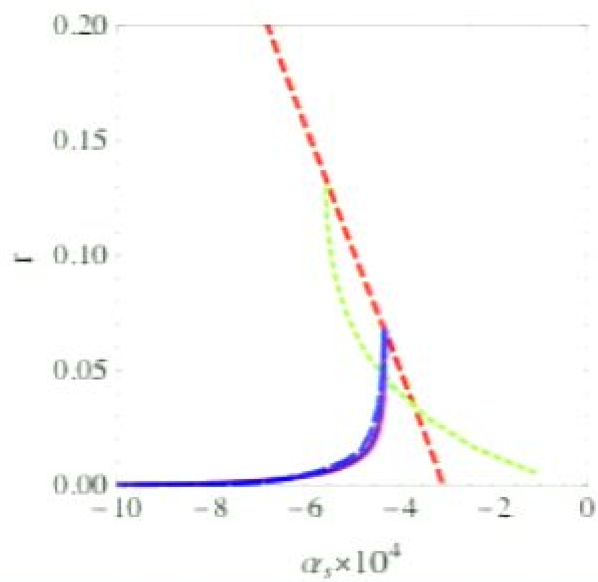
Well defined end of inflation in each scenario

# Inflationary Zooplots



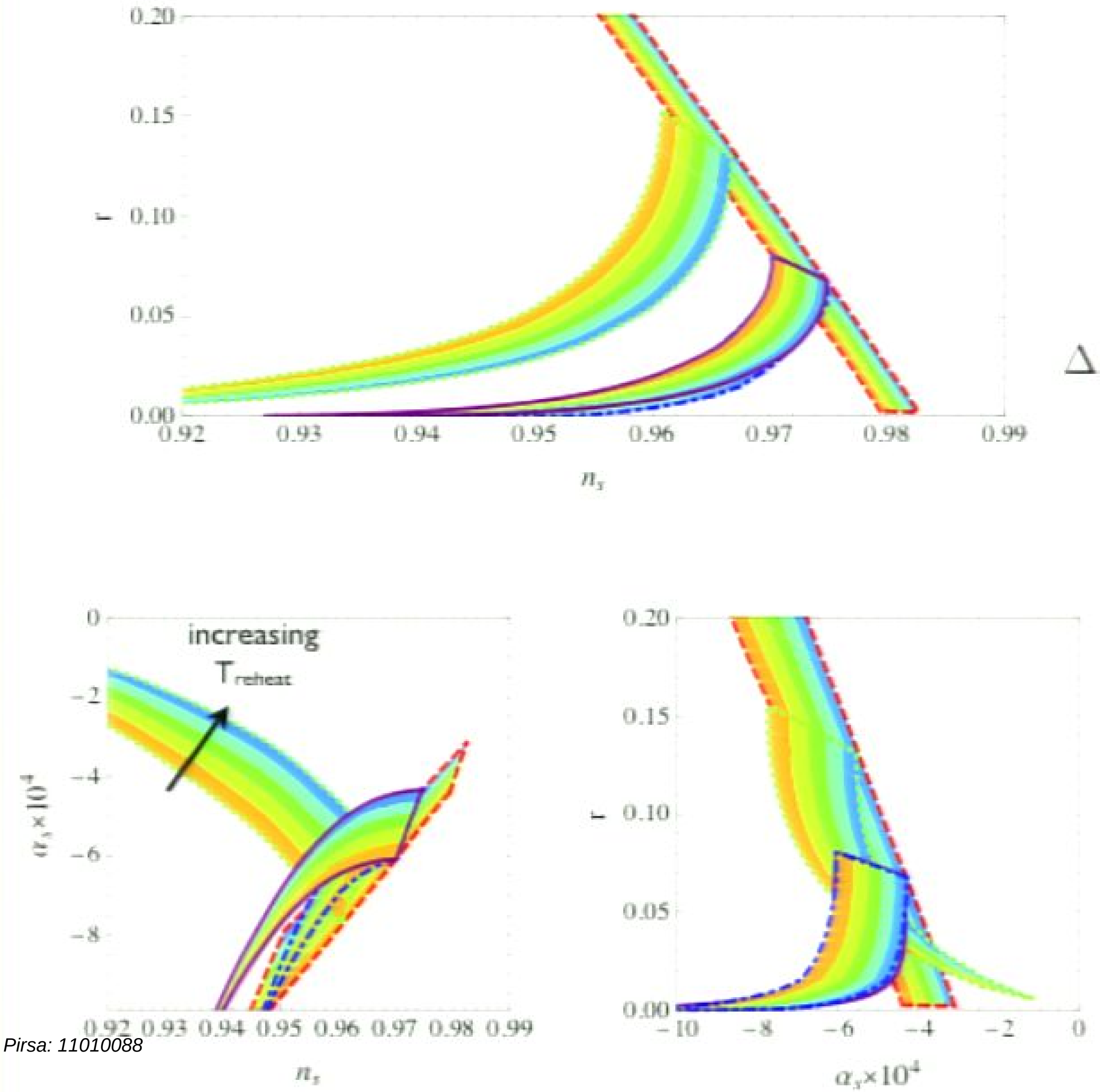

Lines represent different values of single parameter describing the potential




For fixed N, uniqe mapping from ($n_s$,r,α) to model

# Matter dominated period

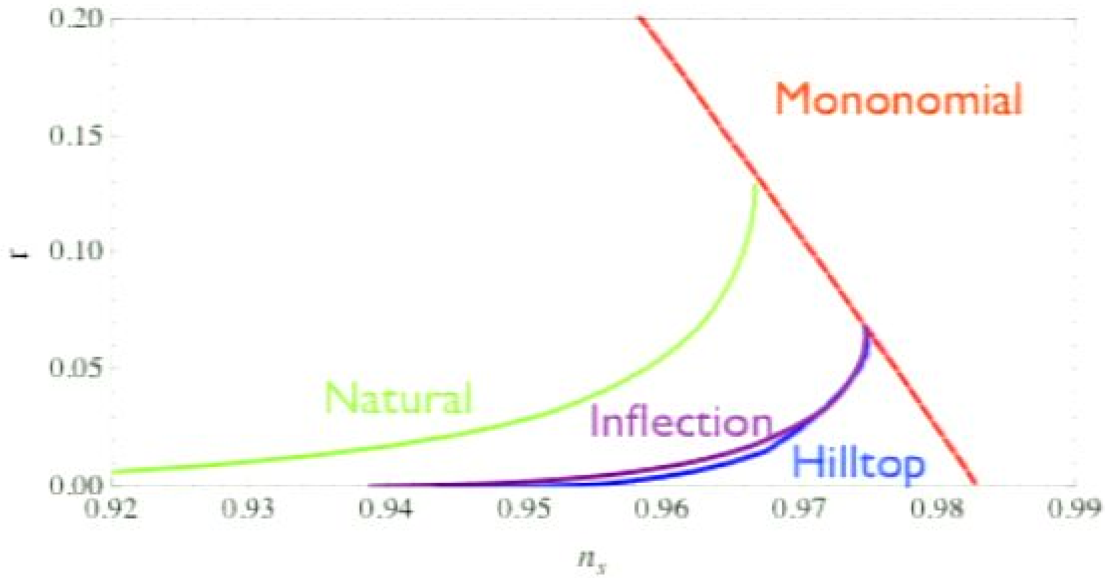



Assume matter domination followed by thermalisation $T_{reheat} > 10^3$GeV

$$\Delta N(k) \sim -9 \text{ if } (\rho_{end}/\rho_{reh})^{1/4} \sim 10^{12}.$$

broadening of prediction complicates interpretation of observations

# Inflationary Zooplots

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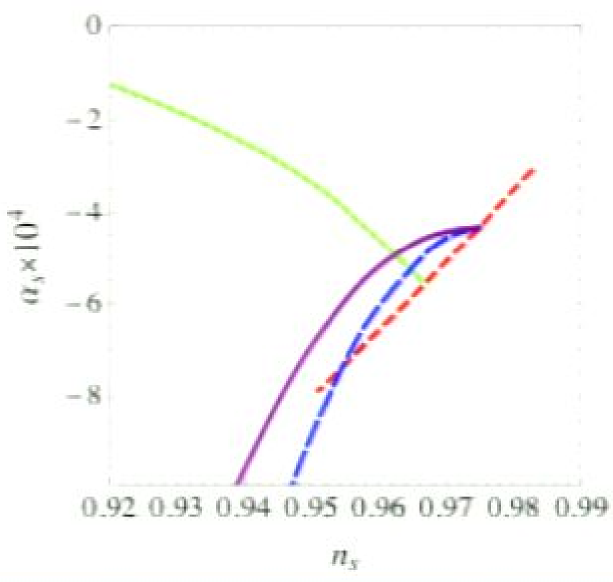


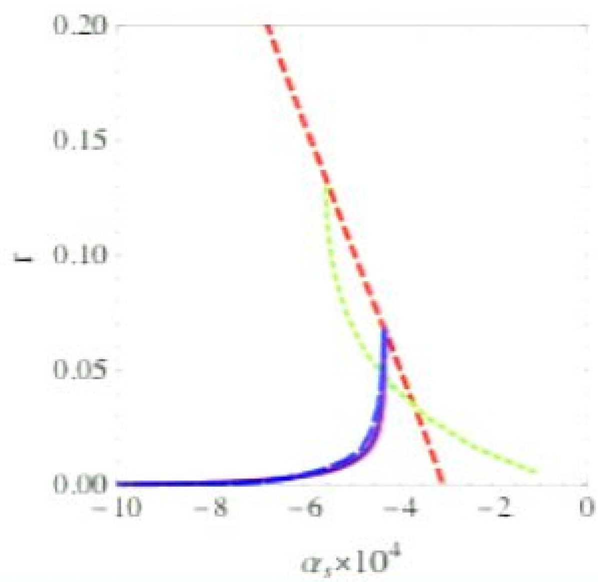


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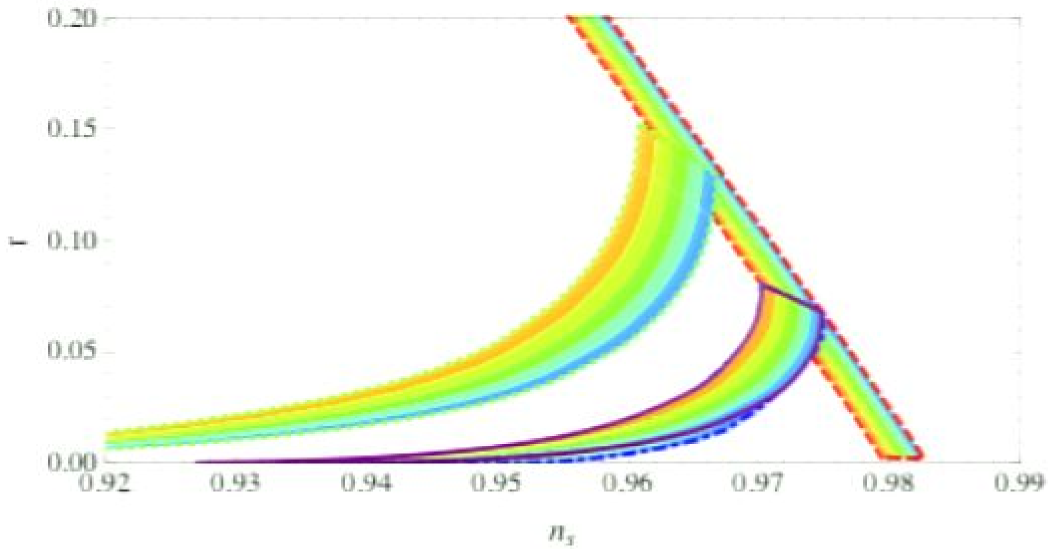


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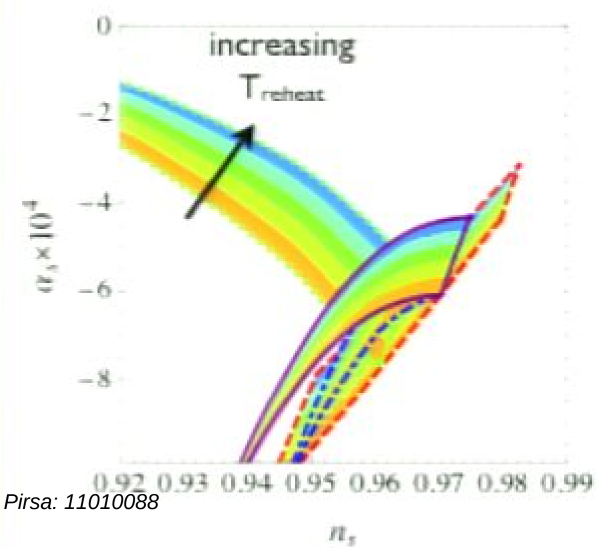
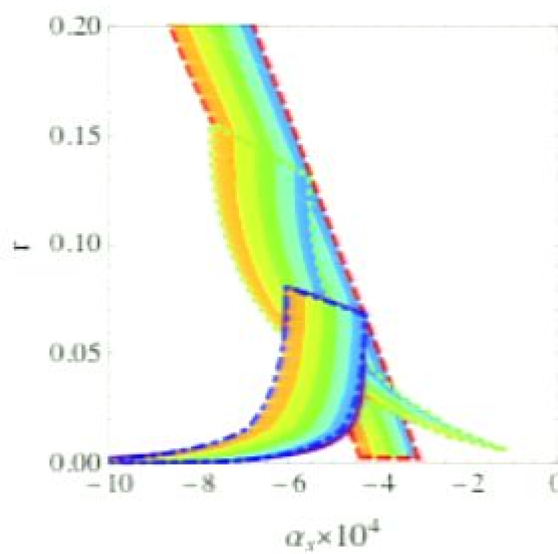
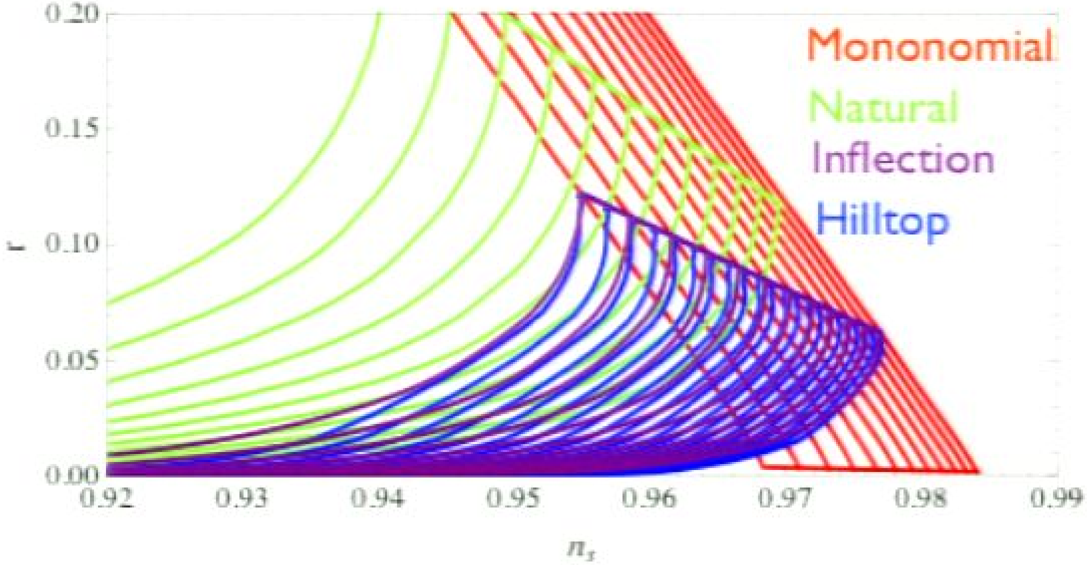



broadening of prediction complicates interpretation of observations

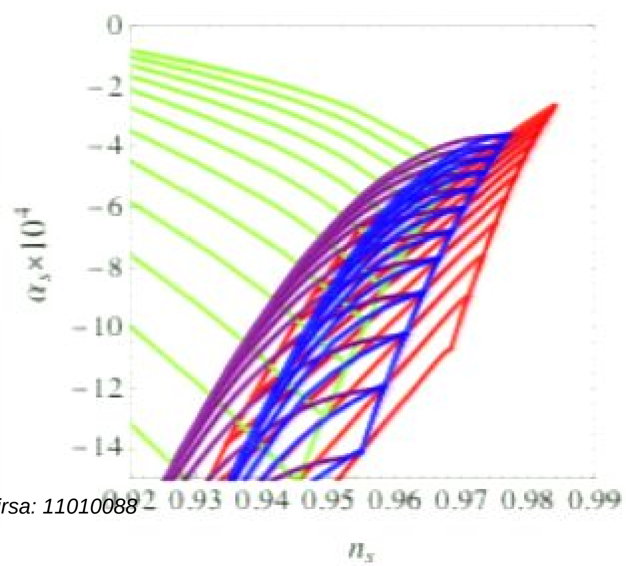
# Full uncertainty

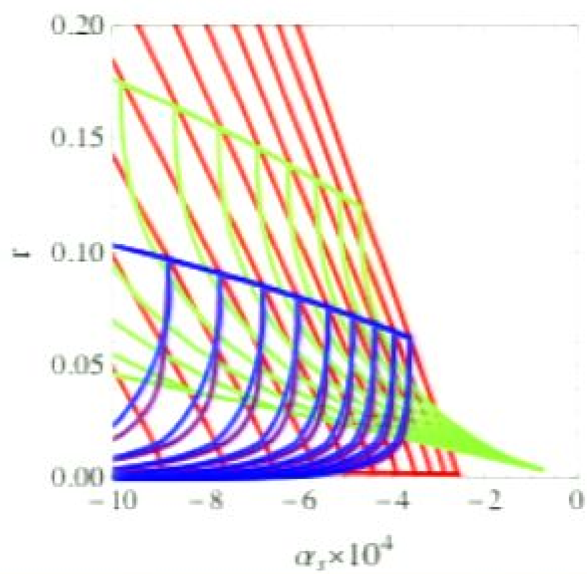



Really should allow for full range of uncertainty

$-1/3<w<1$
$T_{reheat}=1\,\text{TeV}$

$$-25 < \Delta N < 8.4$$



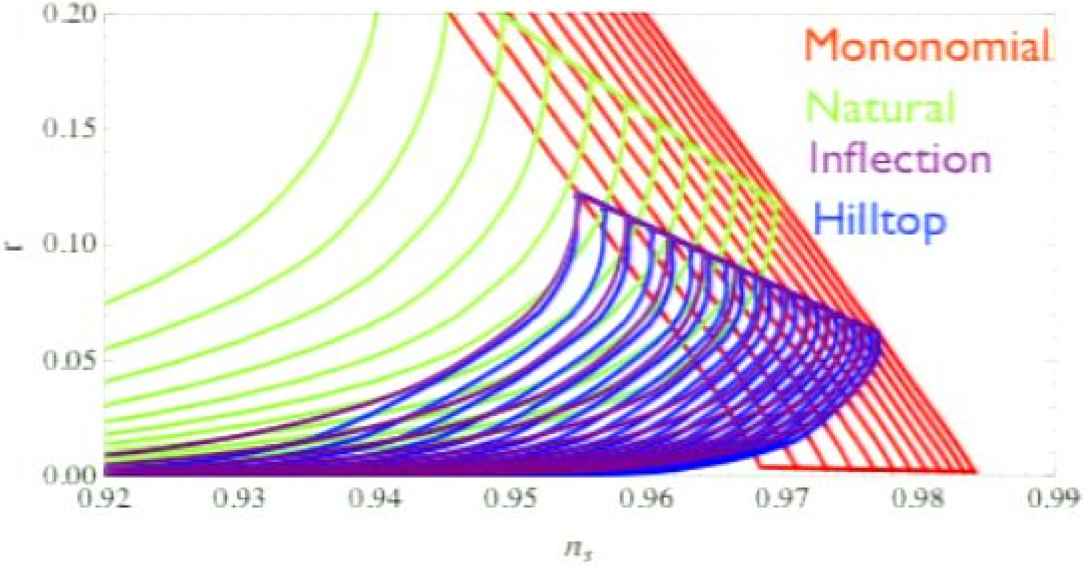




Measurement of tilt, running does not unique identify inflationary model

# How can you break degeneracy?

- Fundamental limitation in mapping observables to inflationary potential due to post-inflation equation of state
- Can more precise measurements help?
- Measure B-modes
- Target running $10^{-4} \lesssim |\alpha_s| \lesssim 10^{-3}$.

# Full uncertainty

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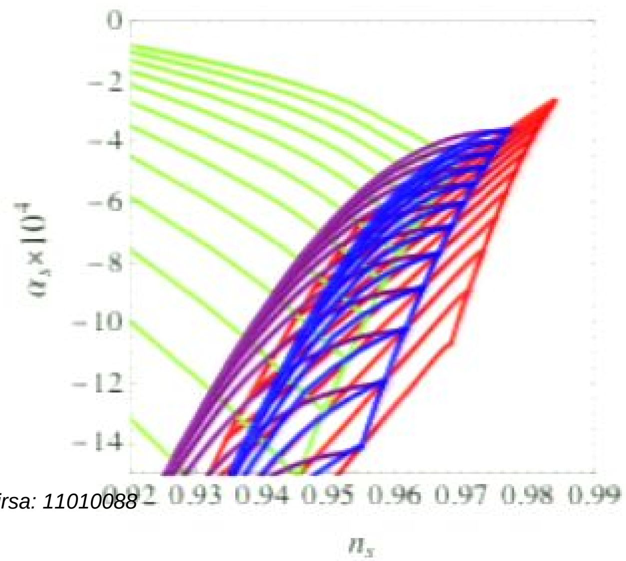


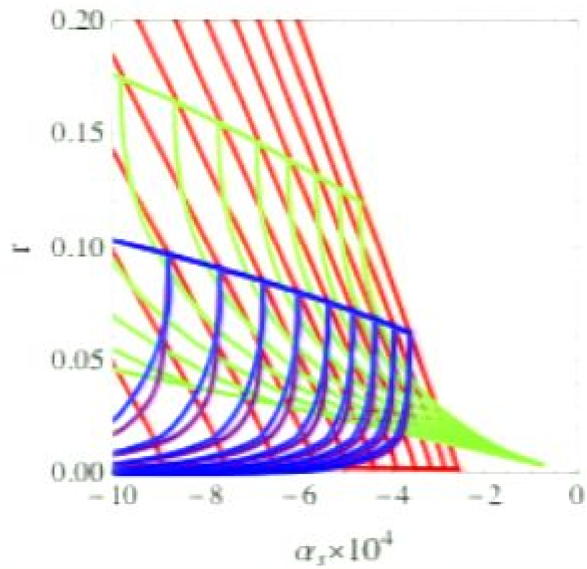


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# Galaxy surveys

Galaxy survey sensitivity set by:

1. Survey volume
2. Number density of galaxies
3. Non-linear scale

$$F_{ij} = \int_0^{k_{\max}} \frac{\mathrm{d}^3\mathbf{k}}{2(2\pi)^3} \frac{\partial \log P(\mathbf{k})}{\partial p_i} \frac{\partial \log P(\mathbf{k})}{\partial p_j} \left[ \frac{n_{\rm gal} P(k,\mu)}{n_{\rm gal} P(k,\mu) + 1} \right]^2 V_{\rm survey},$$

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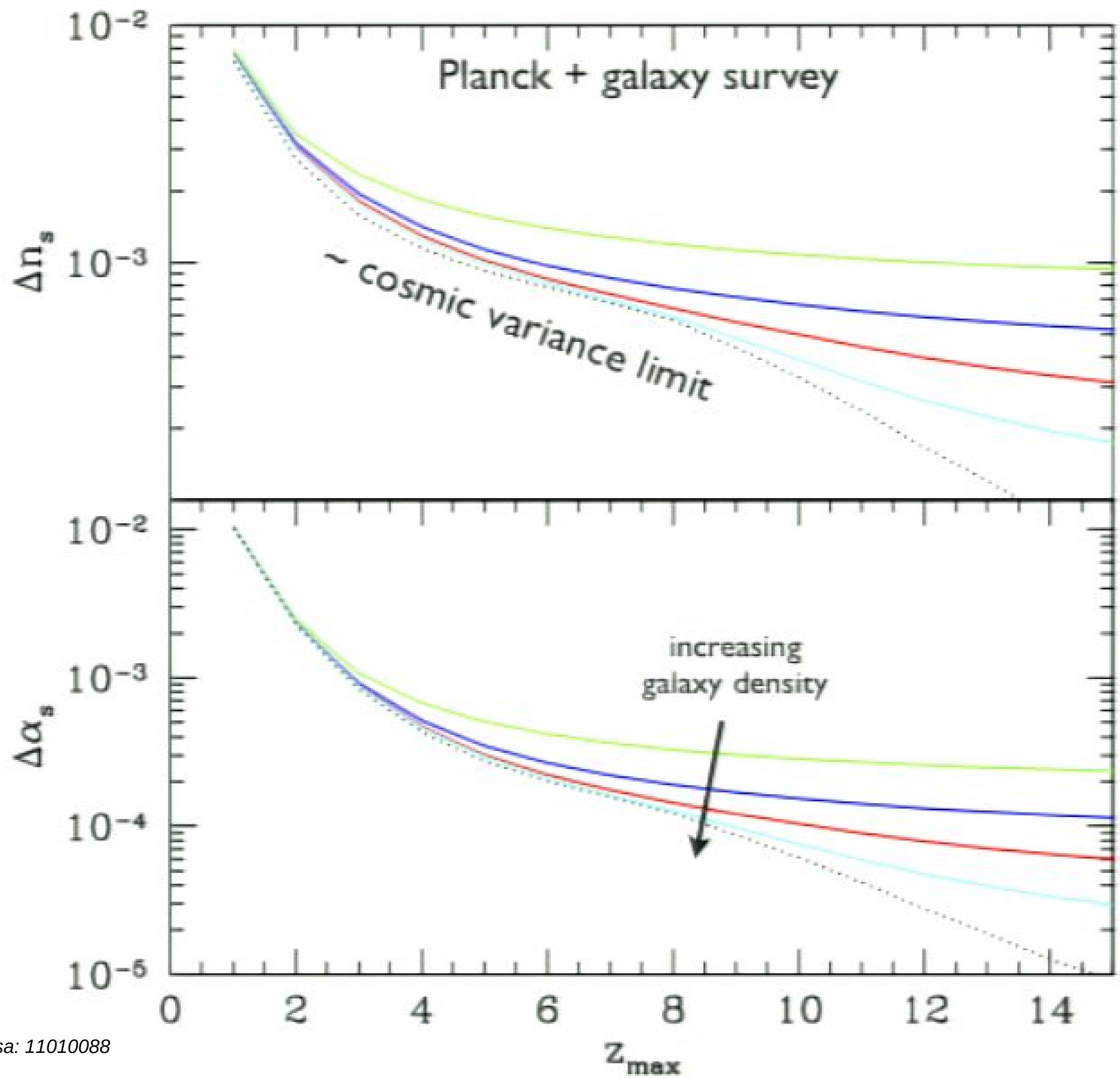
# Large scale structure




Higher in redshift one goes the more volume is available

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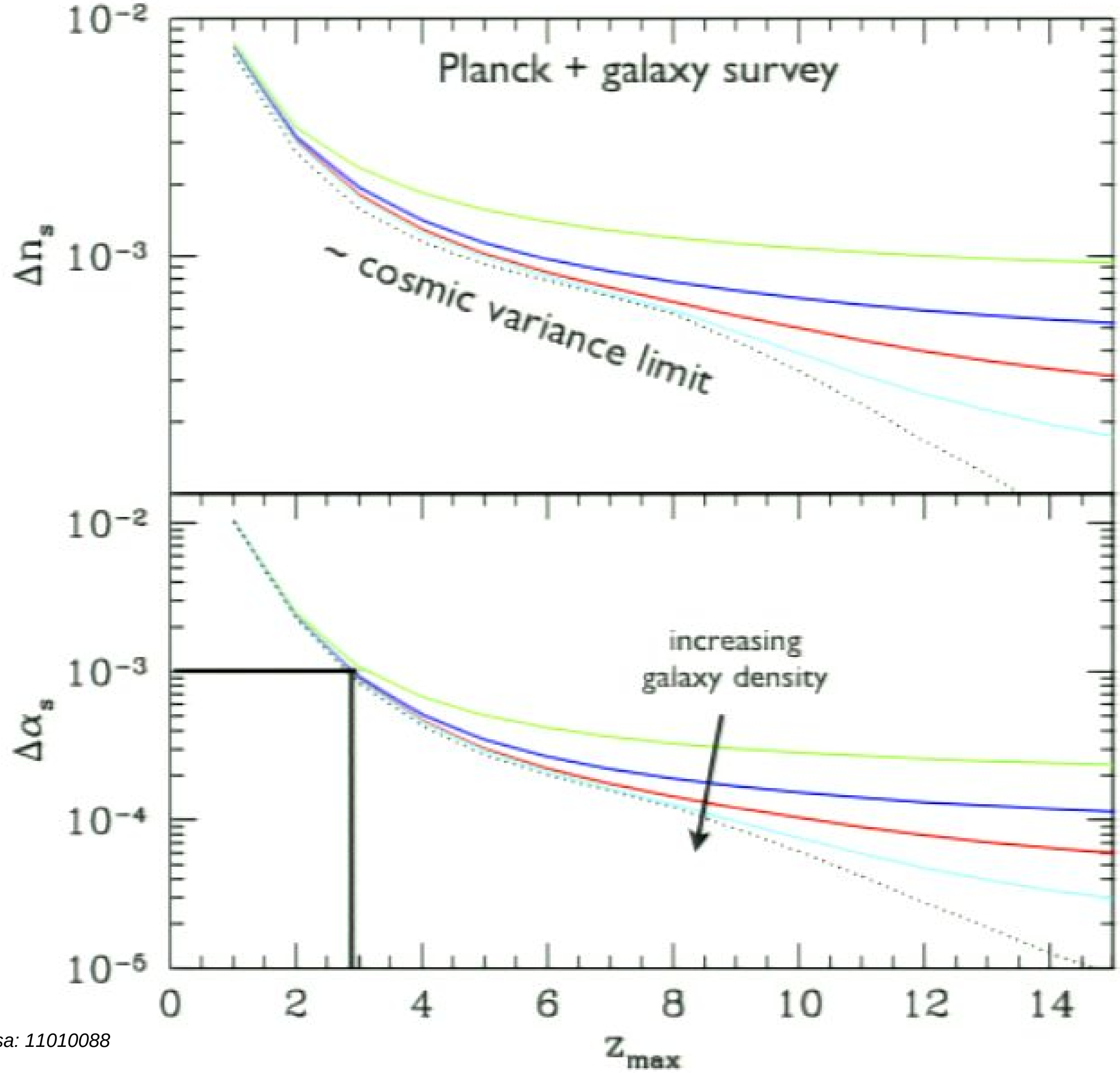


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galaxy surveys out to z~3 provide $10^{-3}$ constraint

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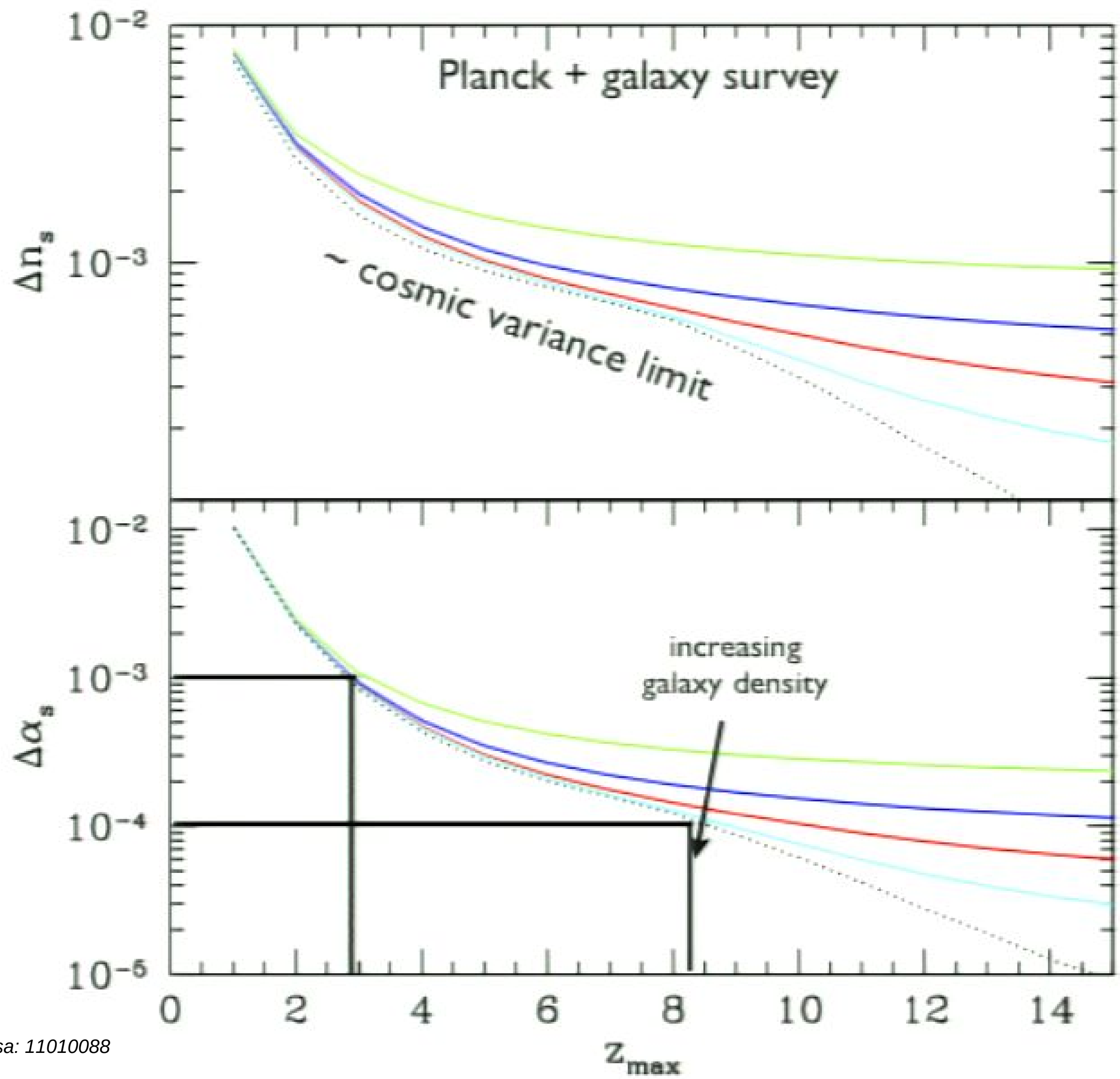


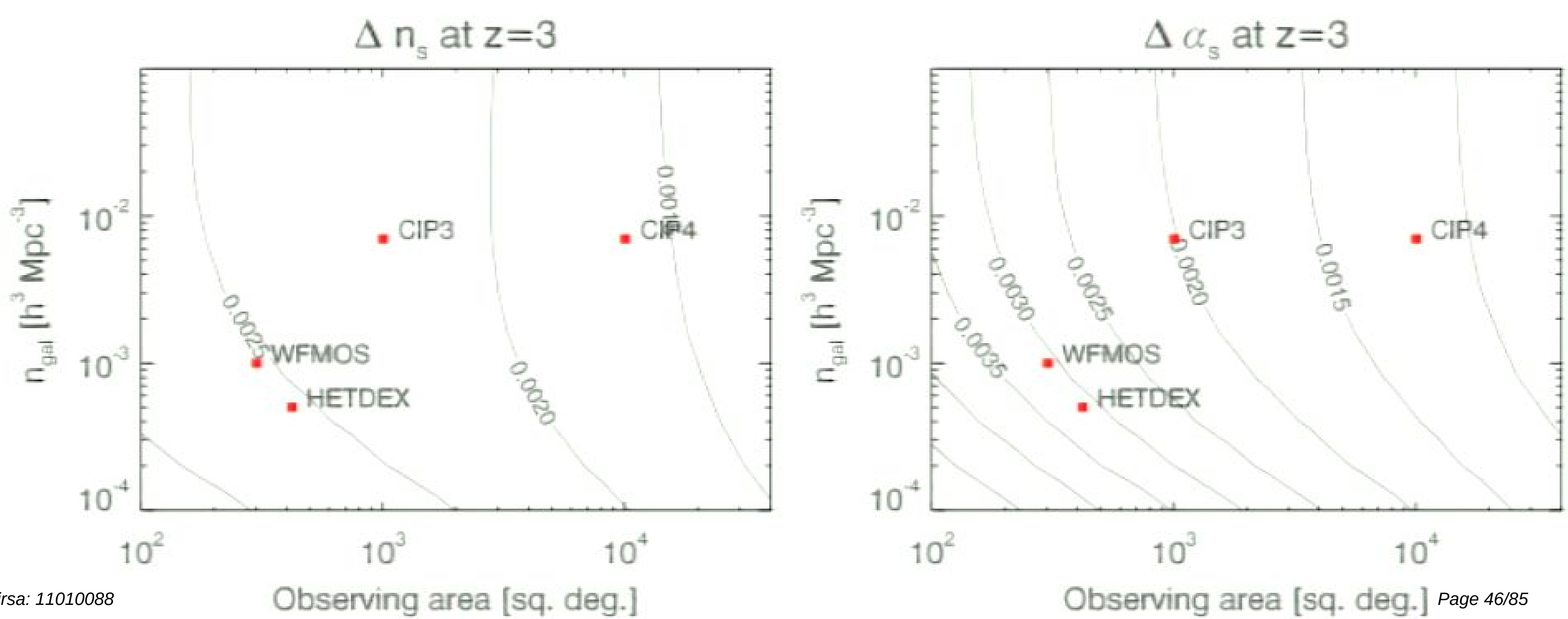

Higher in redshift one goes the more volume is available

galaxy surveys out to z~3 provide $10^{-3}$ constraint

21 cm experiment at z~8 provide $10^{-4}$ constraint

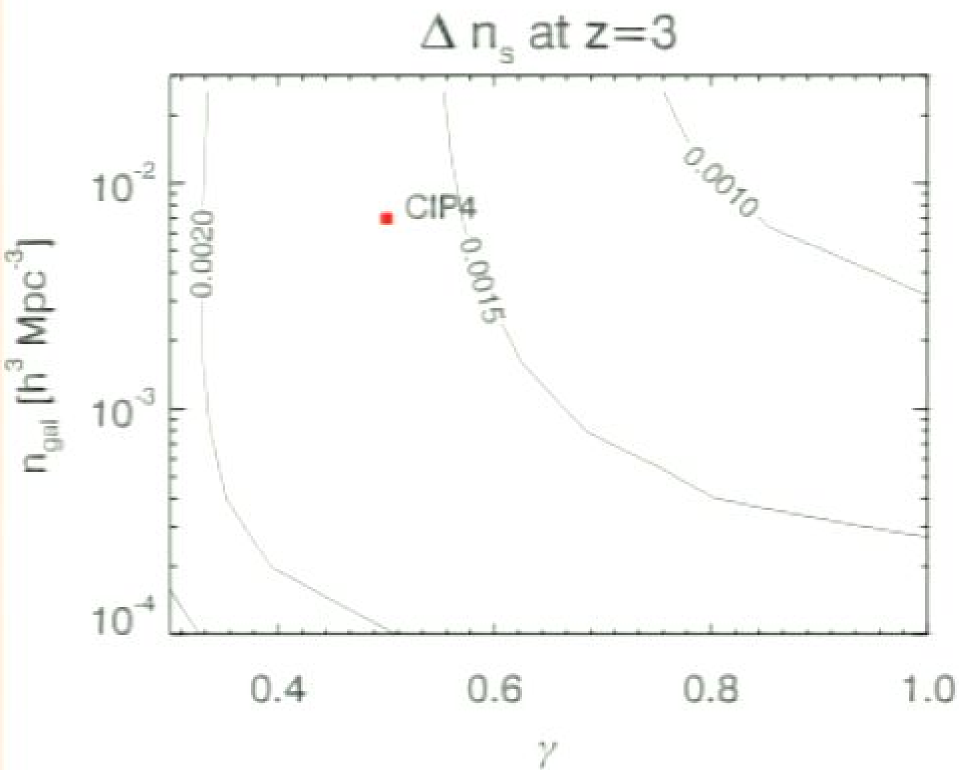
# Galaxy surveys

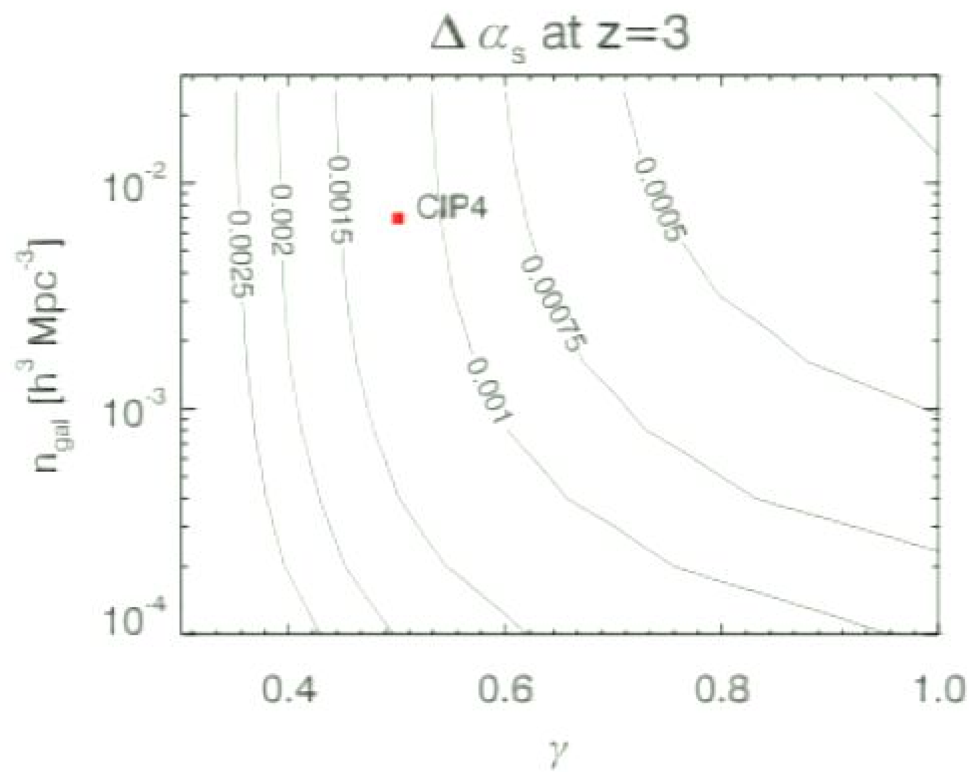
- Extra information in galaxy surveys can significantly improve constraints on running
- Really need large sky area survey to beat down statistical uncertainties
- Match galaxy density to survey area to optimise inflationary constraints



# Non-linearities

- Non-linearities on small scales will ultimately defeat attempts to measure scale-dependence
- To some extent these can be modelled to extend the number of usable scales
- Factor of ~2 improvement possible for typical galaxy surveys




$k > k_{nl} = \pi/(2R_{nl})$ $\qquad \sigma(R_{nl}) = \gamma.$

# 21 cm experiments

Radio interferometers power spectrum sensitivity set by:

1. Sky temperature
2. Integration time
3. Bandwidth <=> depth of survey volume
4. Number of correlated stations
5. Total collecting area
6. Effective tile size <=> instantaneous field of view <=> survey volume

uncertainty per mode

$$\sigma_P^2(k,\mu) = \frac{1}{N_{\rm field}}\left[\bar{T}_b^2 P_{21}(k,\mu) + T_{\rm sys}^2 \frac{1}{Bt_{\rm int}} \frac{D^2 \Delta D}{n(k_\perp)} \left(\frac{\lambda^2}{A_e}\right)^2\right]^2$$

sample variance

thermal noise

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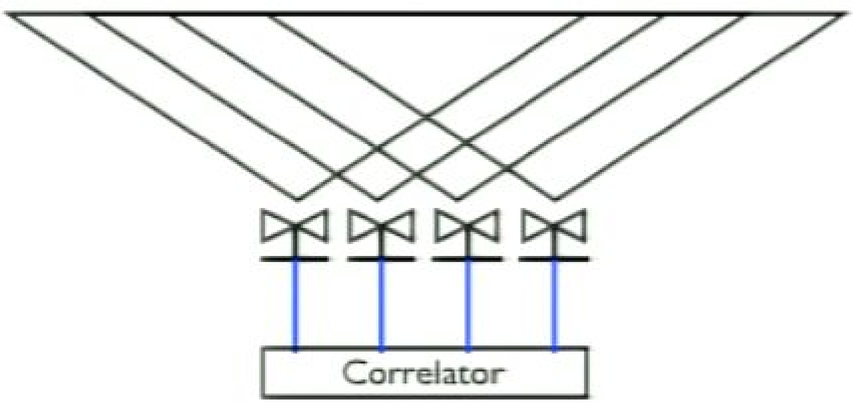
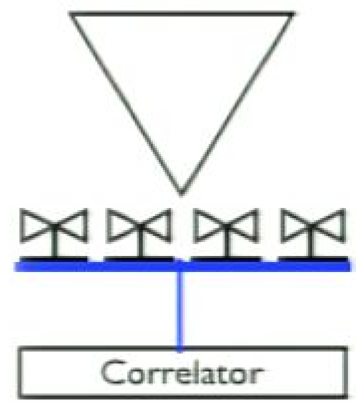



Correlating individual dipoles leads to higher sensitivity and larger instanteous field of view




beam~λ/D

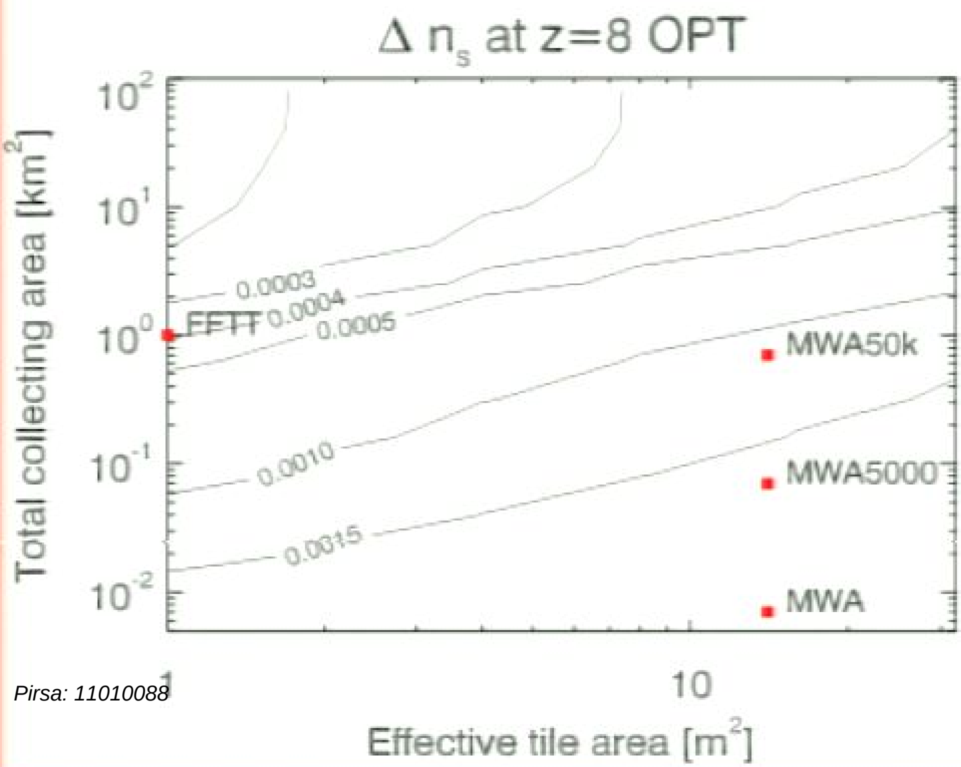
Summing signal from dipoles before correlating reduces computational cost

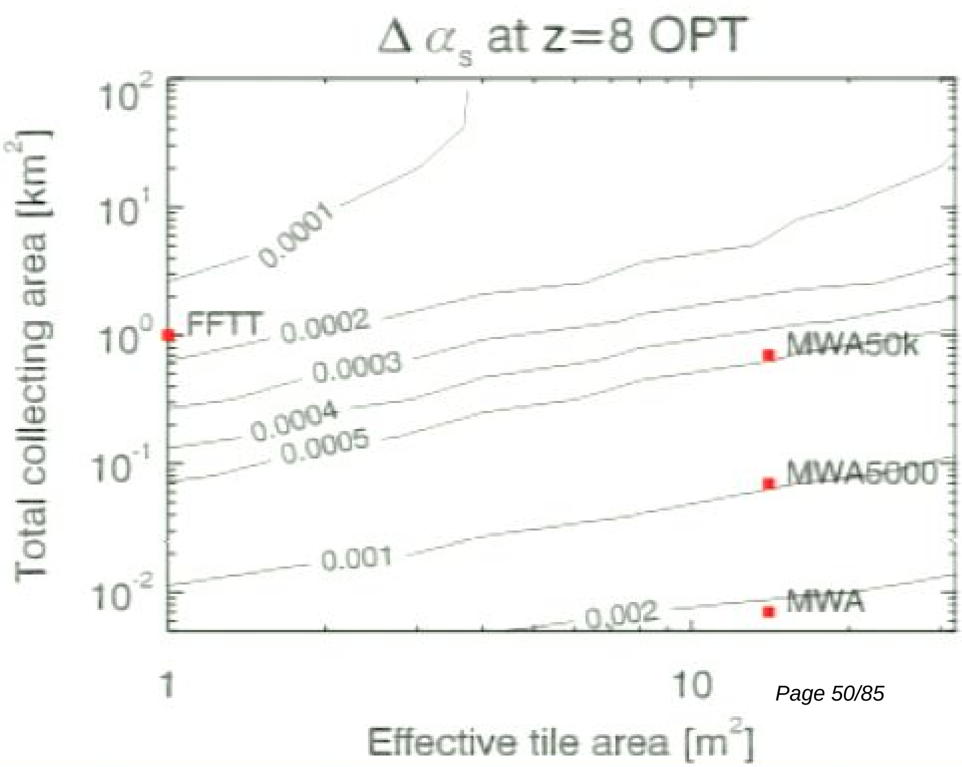
# 21 cm experiments

- More volume at high redshifts => 21 cm experiments potentially very useful
- Caveats relate to the challenge of separating cosmology from astrophysics
  => optimistic estimates of modelling astrophysics degrade sensitivity by ~2

Mao+2008

- Pathfinders lack the sensitivity to provide major improvements
  => Next generation arrays and technological improvements needed to realise potential
- z>30 observations require ~1000 times more collecting area to achieve similar sensitivity



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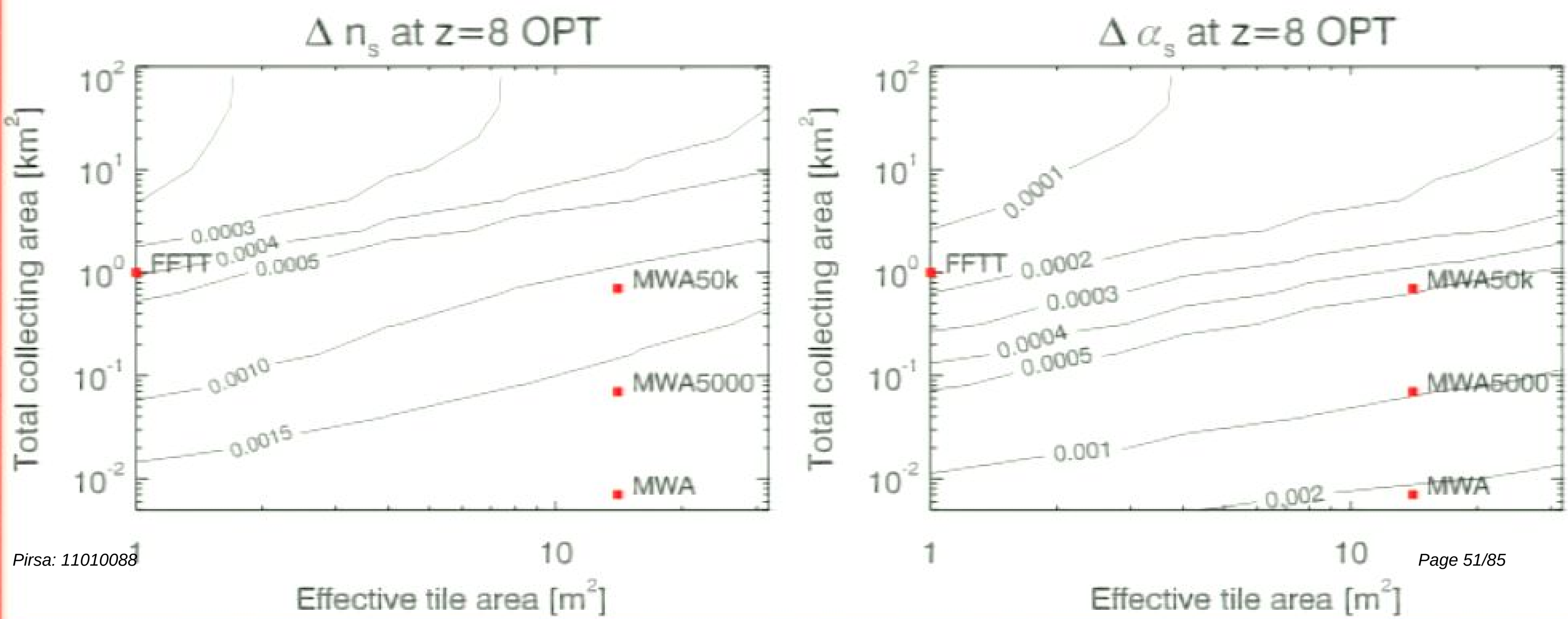

# Possible constraints

| Experiment | | $\Delta n_s$ | $\Delta \alpha_s$ | $\Delta r$ | |
|---|---|---|---|---|---|
| CIP3 | | 0.0089 | 0.0028 | - | |
| CIP4 | | 0.0028 | 0.0009 | - | |
| FFTT | OPT | 0.0011 | 0.00023 | - | |
| | MID | 0.00082 | 0.00032 | - | |
| Planck | | 0.0032 | 0.005 | 0.058 | |
| +CIP3 | | 0.0019 | 0.0011 | 0.05 | |
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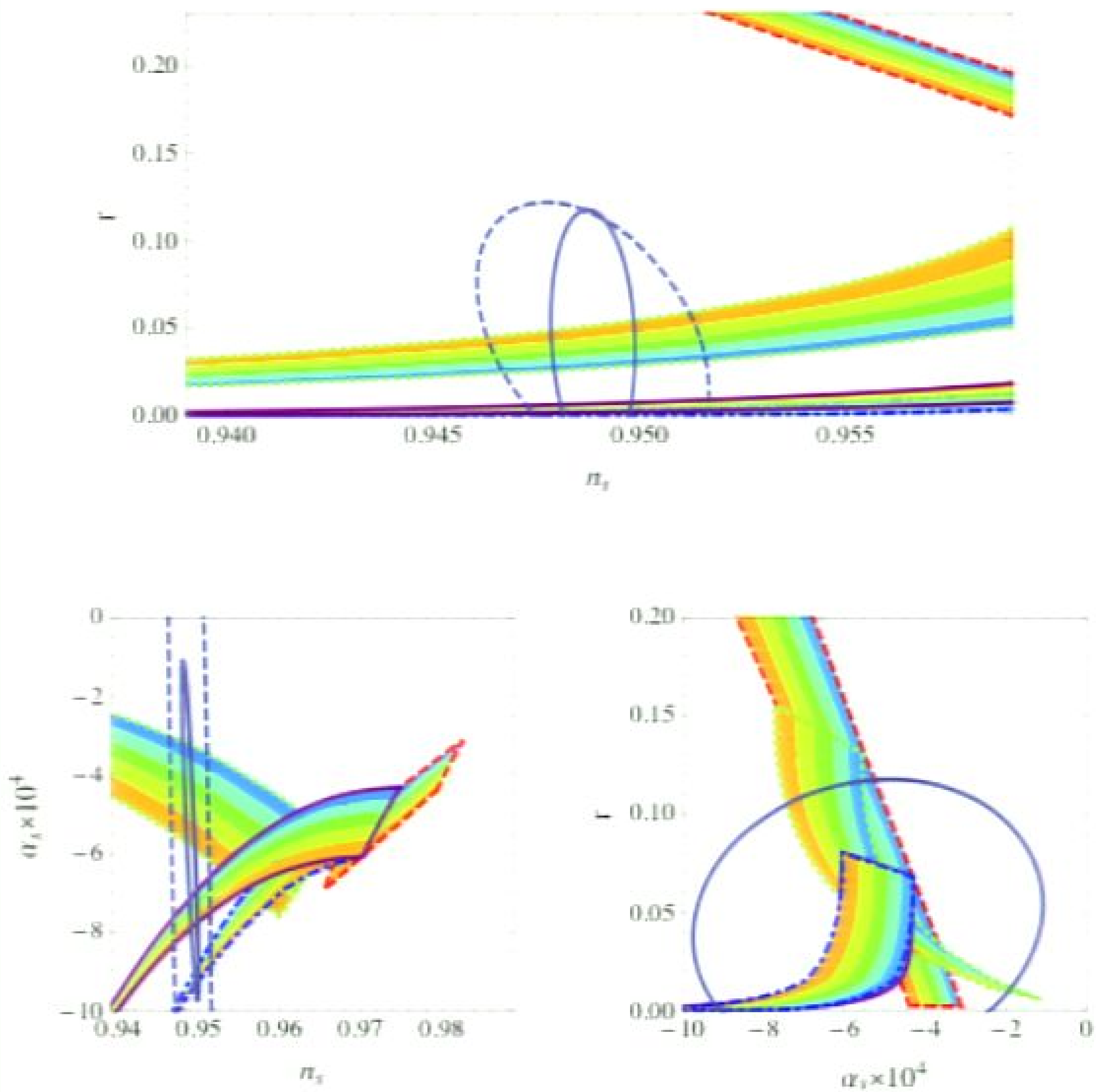
| +FFTT | OPT | 0.00034 | 0.000095 | 0.048 | no astrophysics |
| | MID | 0.00067 | 0.00028 | 0.048 | astrophysics modelled |

# Equation of state constraints




| | Natural | | $\phi^n$ | |
|---|---|---|---|---|
| | $N$ | $f$ | $N$ | $n$ |
| fiducial values | 51 | $\sqrt{8\pi}$ | 51 | 2 |
| Planck | 5.1 | - | 3.6 | - |
| | - | 0.33 | - | 0.25 |
| | 14.5 | 0.93 | 19.7 | 1.4 |
| $+\ \sigma_r = 0.01$ | 3.5 | 0.26 | 8.6 | 0.41 |
| CIP+Planck | 1.69 | - | 1.2 | - |
| | - | 0.11 | - | 0.09 |
| | 13.7 | 0.87 | 14.5 | 1.14 |
| $+\ \sigma_r = 0.01$ | 2.8 | 0.18 | 3.96 | 0.27 |
| FFTT+Planck | 0.41 | - | 0.29 | - |
| | - | 0.027 | - | 0.024 |
| | 7.0 | 0.45 | 11.0 | 0.91 |
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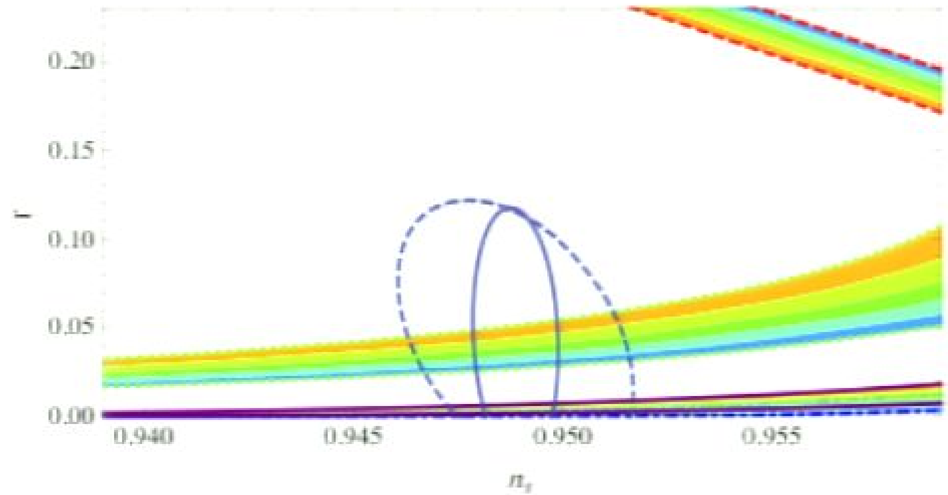


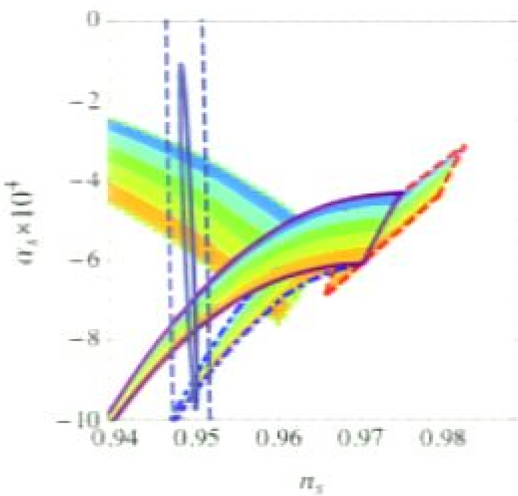


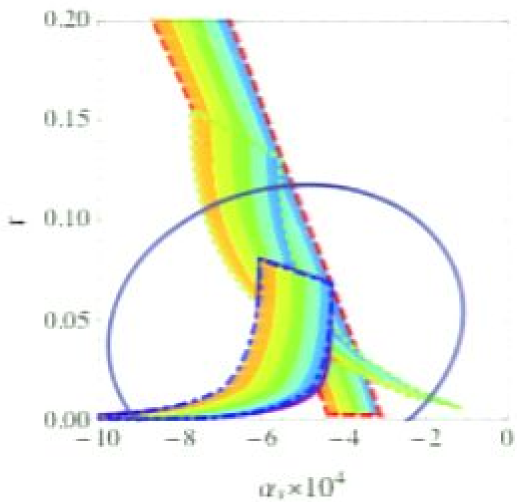


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# Summary

- Running couples with post-inflationary equation of state to produce uncertainty in tilt
- Leads to degeneracy between different inflationary potentials
- Measuring running at level predicted by slow roll inflation models is challenging
- Galaxy surveys reach ~ $10^{-3}$ level
- 21 cm experiments reach $10^{-4}$ level
- Purely statistical argument: control of systematics is the limiting factor

# Isocurvature

Gordon & Pritchard 2009

# Inflation and isocurvature

- Single field inflation predicts adiabatic perturbations

$$\frac{\delta\rho_i}{(1+w_i)\rho_i} - \frac{\delta\rho_j}{(1+w_j)\rho_j} = 0$$

- Multi-field inflation e.g. curvaton allows for isocurvature

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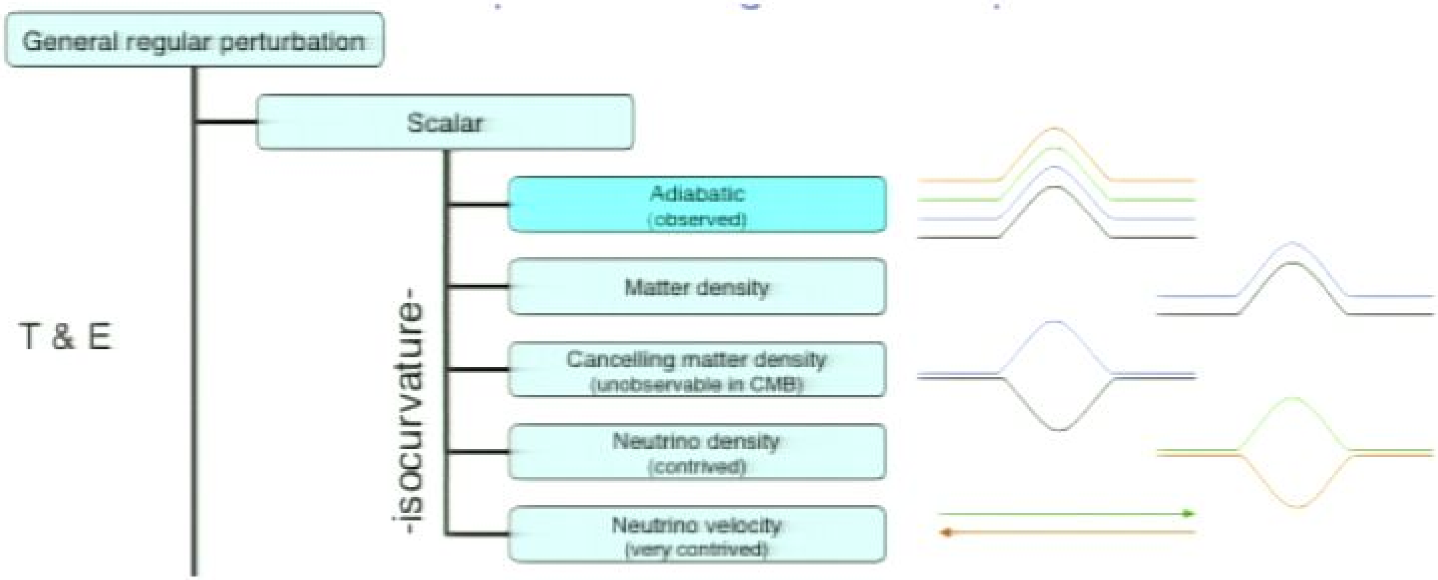


Credit: Anthony Lewis




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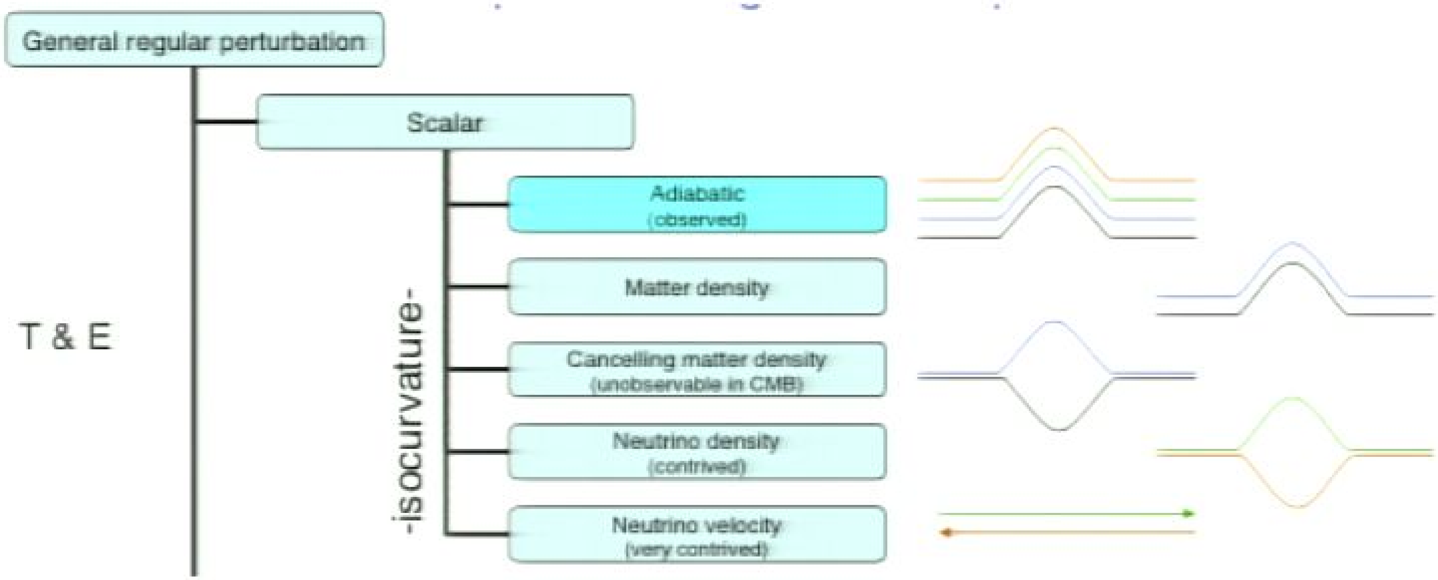


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# Compensated isocurvature mode

- Can decompose density into adiabatic and isocurvature

$$\delta\rho_i = \delta\rho_i|_{\rm adiab} + \delta\rho_i|_{\rm isoc}$$

- There exists a compensated mode

$$S_{{\rm CDM},\gamma} = \mathcal{I}\zeta, \qquad S_{b,\gamma} = -\frac{\Omega_{\rm CDM}}{\Omega_b}\mathcal{I}\zeta$$

such that

$$\delta\rho_{\rm CDM}|_{\rm isoc} = -\,\delta\rho_b|_{\rm isoc} \qquad \delta\rho_\gamma|_{\rm isoc} = \delta\rho_\nu|_{\rm isoc} = 0$$

- Looks like a spatial variation in the baryon fraction

$$r \approx \Omega_b/(\Omega_b + \Omega_{\rm CDM})$$

- No effect on CMB, except at second order at $l>10^6$

where produces perturbation to sound speed

Gordon & Lewis 2003

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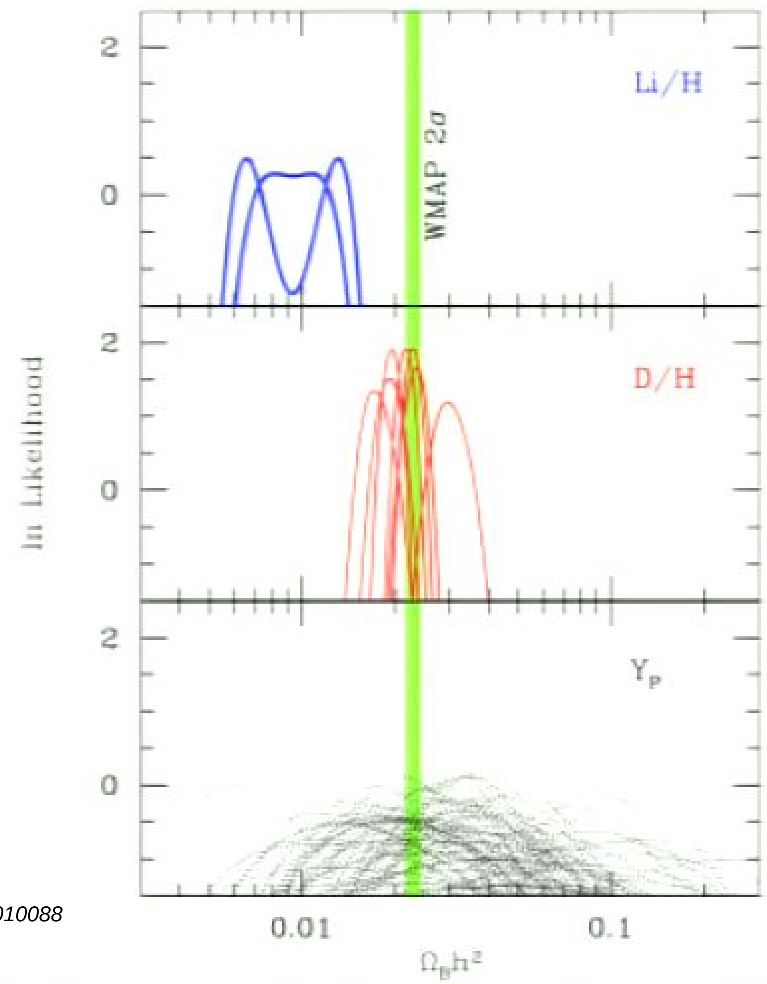
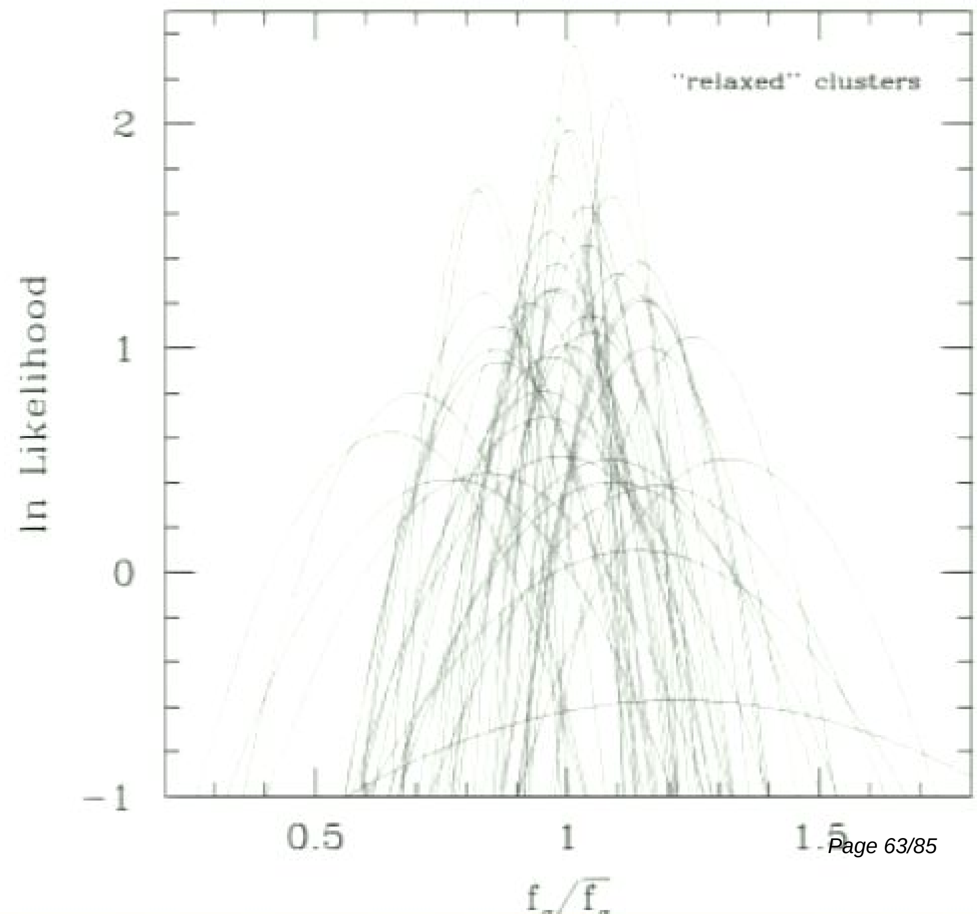
# Baryon fraction variation?

- BBN: abundances of Deutrium, $^4$He, $^3$He, Li give direct probe of local baryon fraction

- Clusters: X-ray emissivity probes baryonic mass while radial profiles constrain total mass => measure of $f_{gas}$

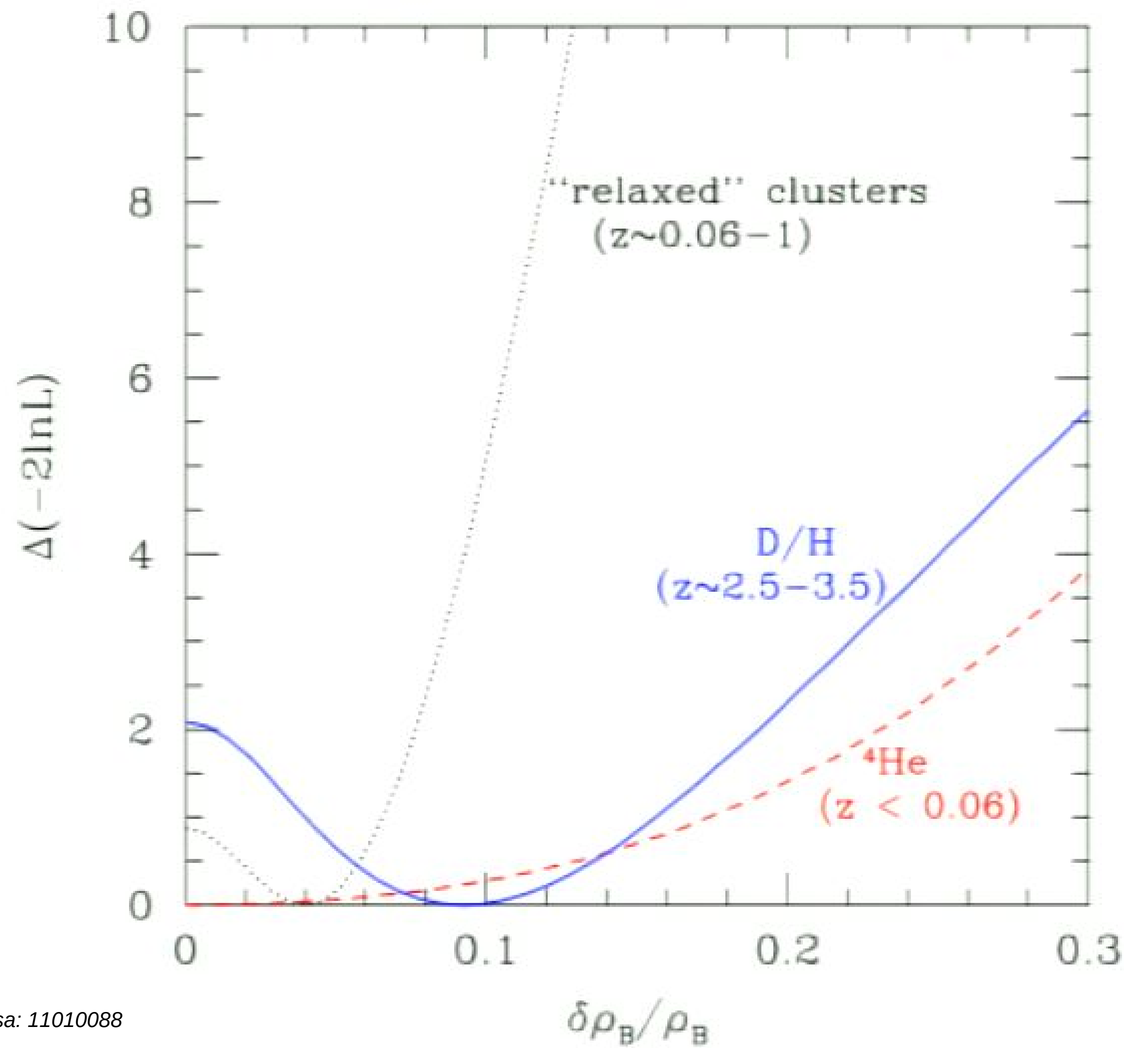
Holder, Nollett, van Engelen 2010



# Larger spatial variation?

What do we currently know about spatial variation in the baryon fraction?




$\delta\rho_B/\rho_B < 0.27$ $\quad$ $^4$He

$\delta\rho_B/\rho_B < 0.26,$ $\quad$ D/H

$\delta\rho_B/\rho_B <$ 0.08 $\quad$ Clusters

No existing evidence for spatial variation in the baryon fraction

Systematics dominate

Holder, Nollett, van Engelen 2010

# Curvaton model

- Introduce light curvaton field negligible energy density during inflation

Lyth & Wands 2002

- After inflation ends: inflaton decays into radiation curvaton oscillates and eventually decays

- If CDM generated before curvaton decay (e.g. wimpzilla)

$$S_{\mathrm{CDM},\gamma} = -3\zeta$$

- If baryon number created by curvaton decay (e.g. sneutrino curvaton), while inflaton energy density relevant

$$S_{b,\gamma} = 3\frac{1-r}{r}\zeta \qquad r \approx \rho_{\mathrm{curvaton}}/\rho_{\mathrm{total}}$$ at time of curvaton decay

- In this scenario, we get a compensated mode with

$$\mathcal{I} = -3. \qquad r \approx \Omega_b/(\Omega_b + \Omega_{\mathrm{CDM}}) \approx 0.17$$

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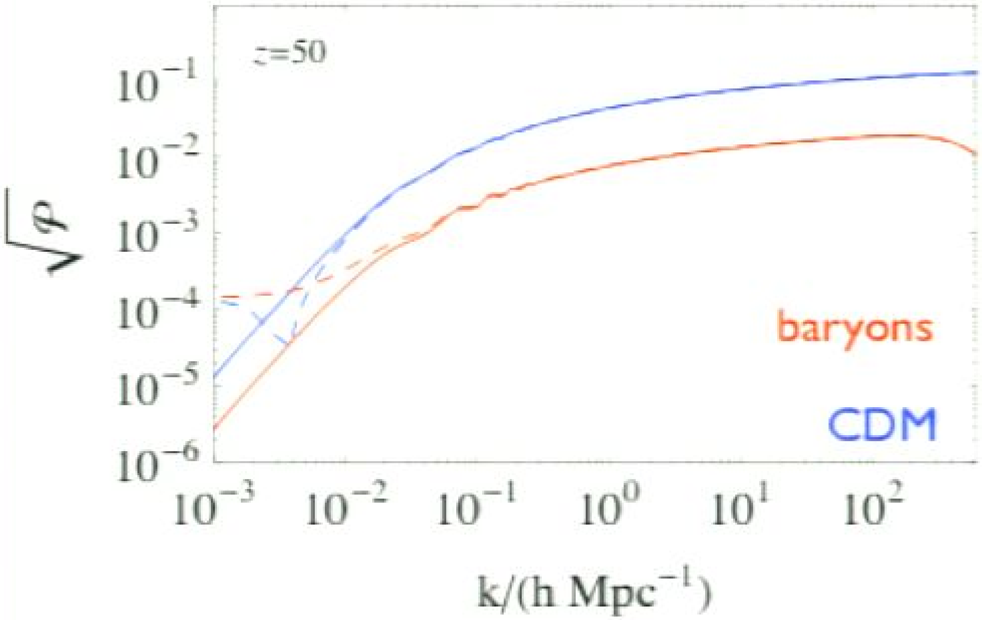
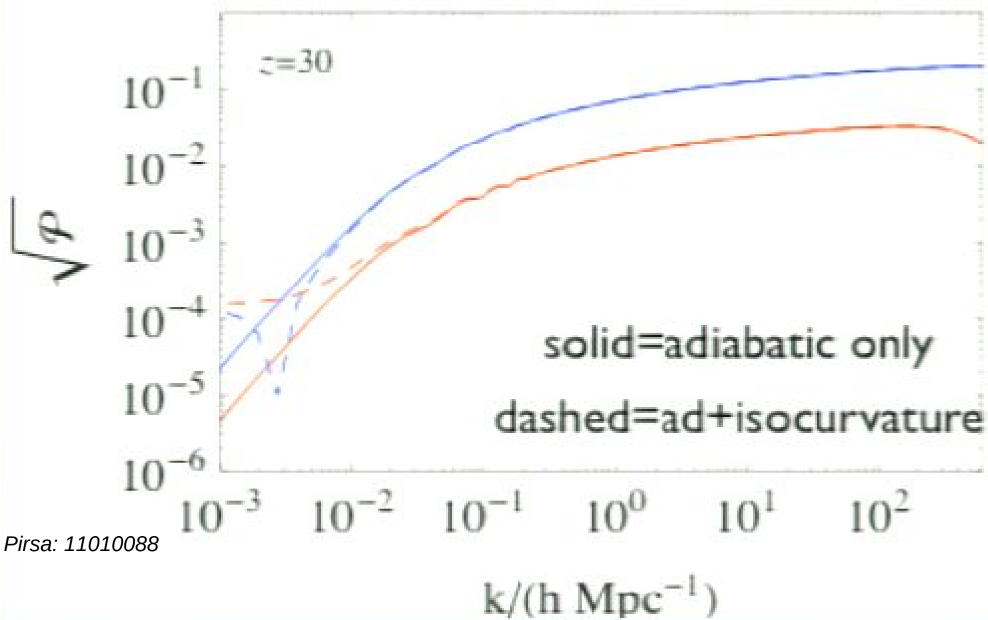
# Effect on power spectrum




Affects matter power spectrum on smallest scales in same way as CMB k>200 Mpc$^{-1}$

large scale effect in baryon and CDM power spectrum




21 cm experiments sensitive to baryon power spectrum
=> can see this mode

c.f. Barkana & Loeb 2005

Compensated mode doesn't evolve so becomes negligible at low redshift

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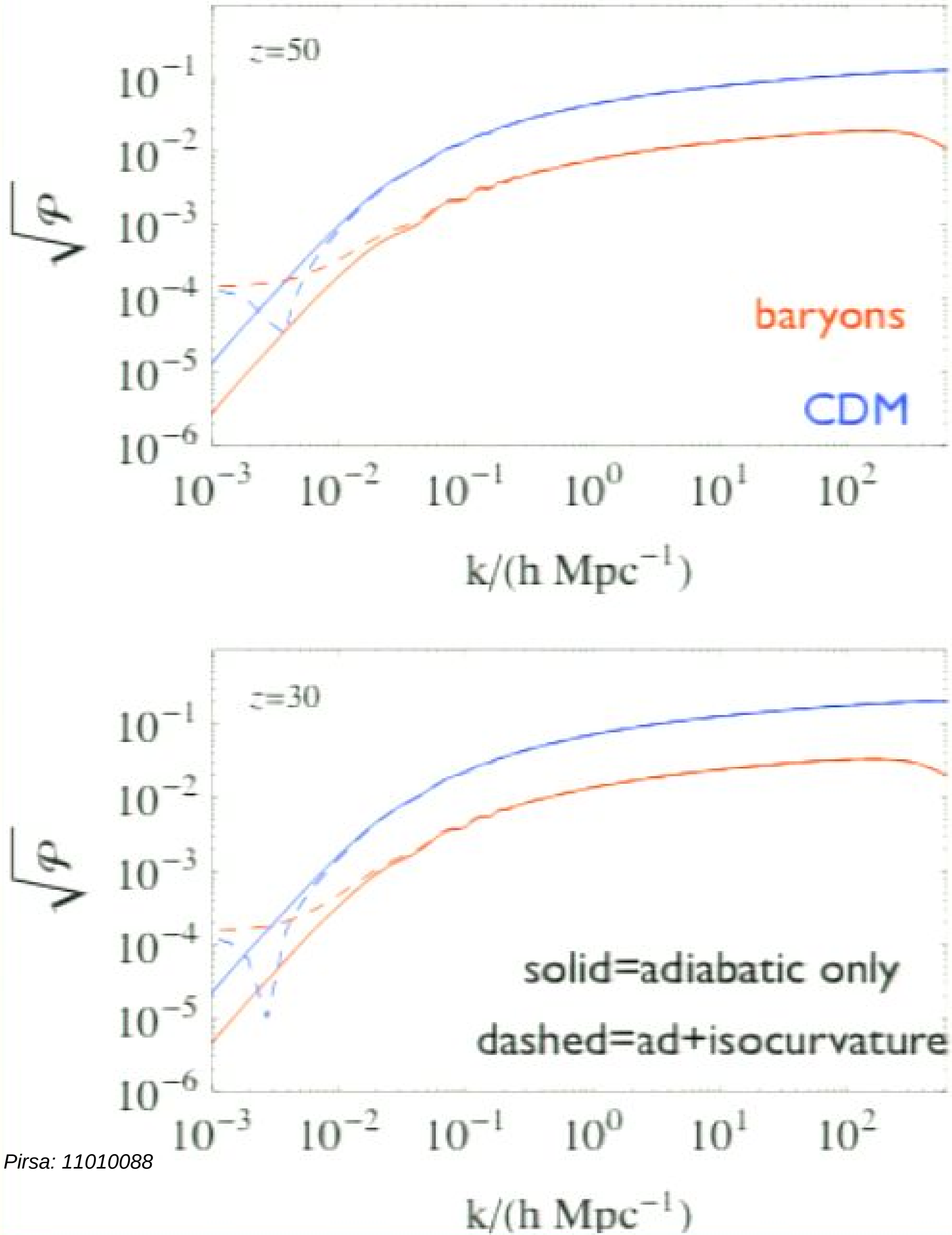


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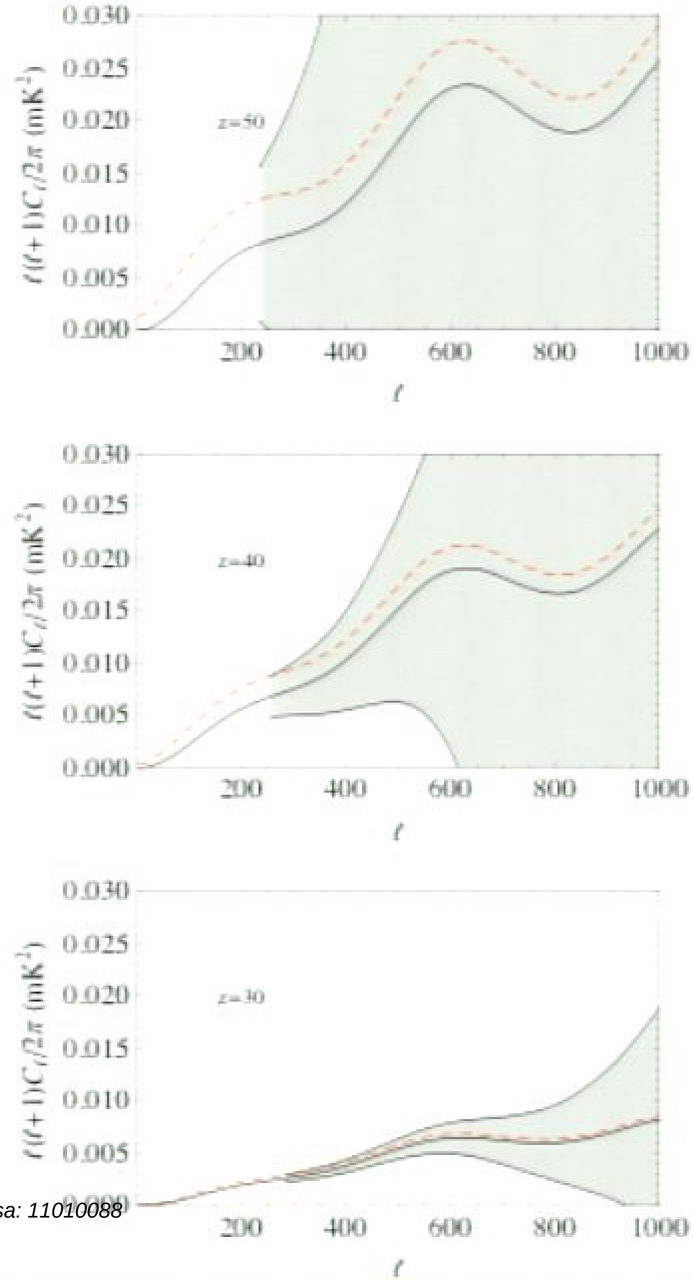
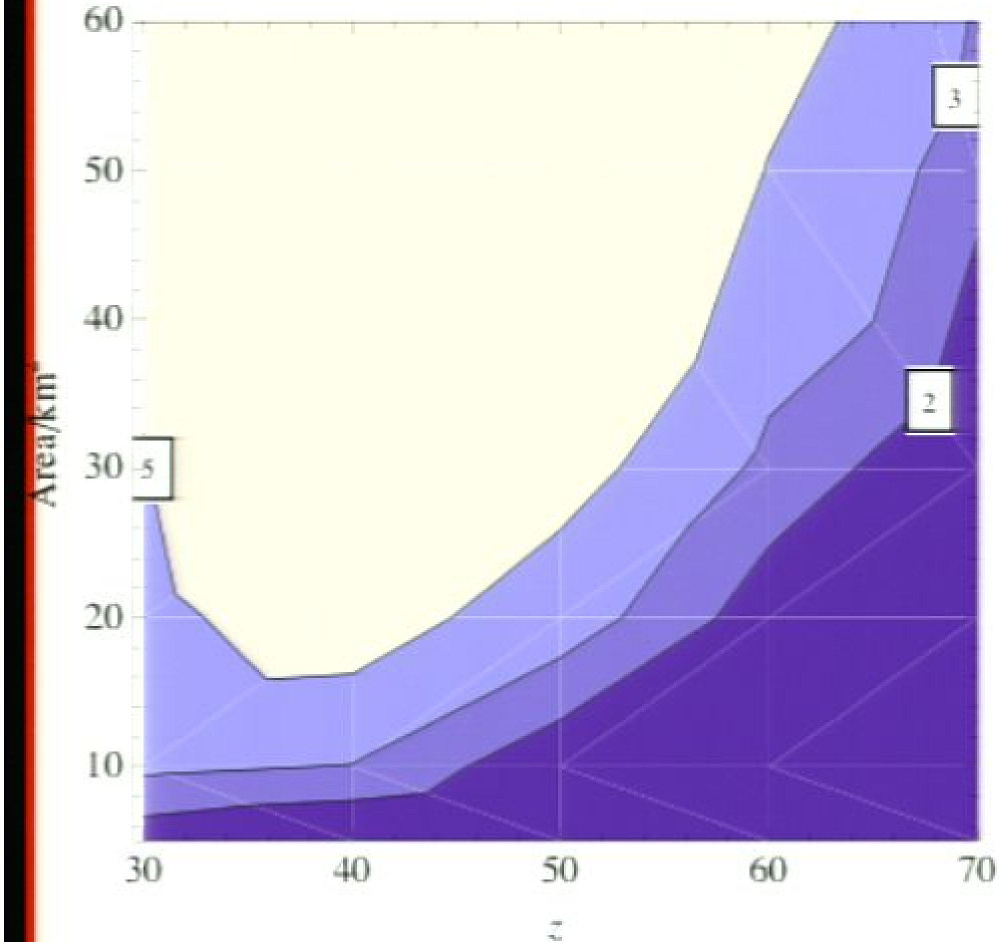
# 21 cm observations

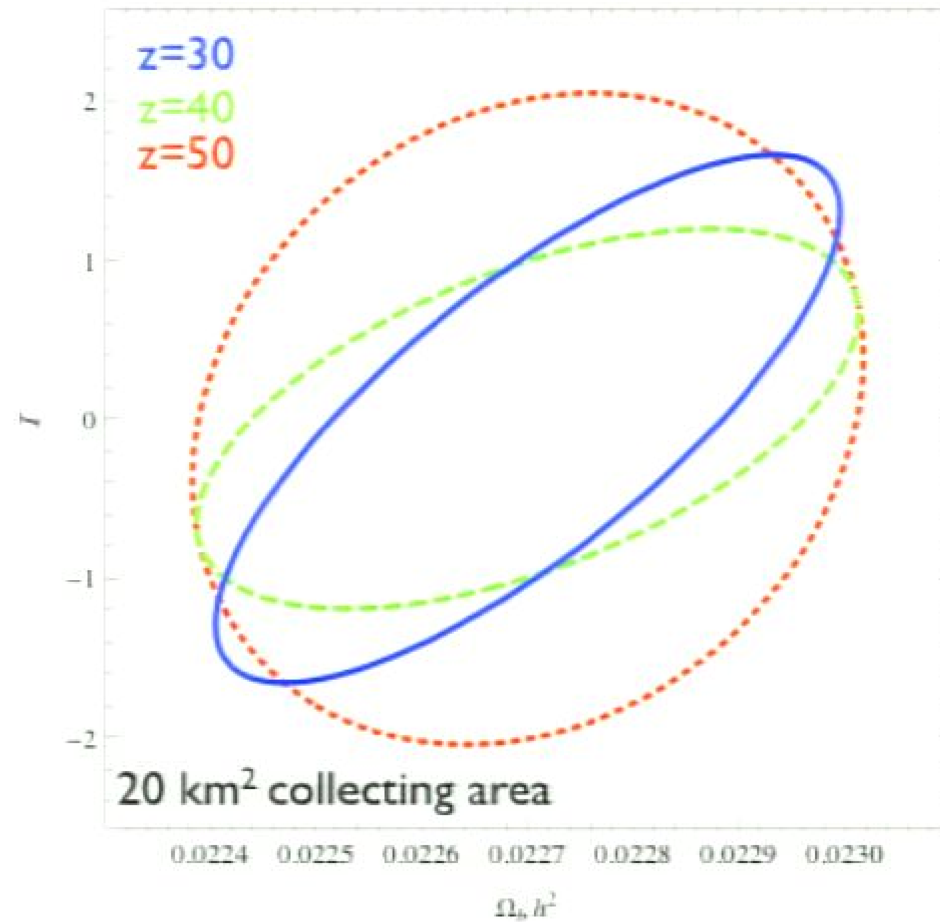



Need to operate at high z to see the effect

FFTT like instrument
(1km$^2$ area)

# Constraints and degeneracies




Need ~20 km$^2$ collecting area for 5 sigma detection

Somewhat degenerate with $\Omega_b h^2$

# Fine tuning caveats

- WMAP3 constrains baryon isocurvature (2 sig)

$$-0.42 \geq S_{b,\gamma}/\zeta \leq 0.25$$

- If compensation is not exact then residual gives

$$\frac{S_{b,\gamma}}{\zeta} = -3\frac{\Omega_{\rm CDM}}{\Omega_b} + 3\frac{1-r}{r}$$

- Requires r to be within 4% of

$$r \approx \Omega_b/(\Omega_b + \Omega_{\rm CDM}) \approx 0.17$$

- Curvaton model also predicts non-Gaussianity

$f_{nl} = 5/4r \qquad r \approx 0.17 \qquad f_{\rm nl} \approx 7.35$

# Isocurvature summary

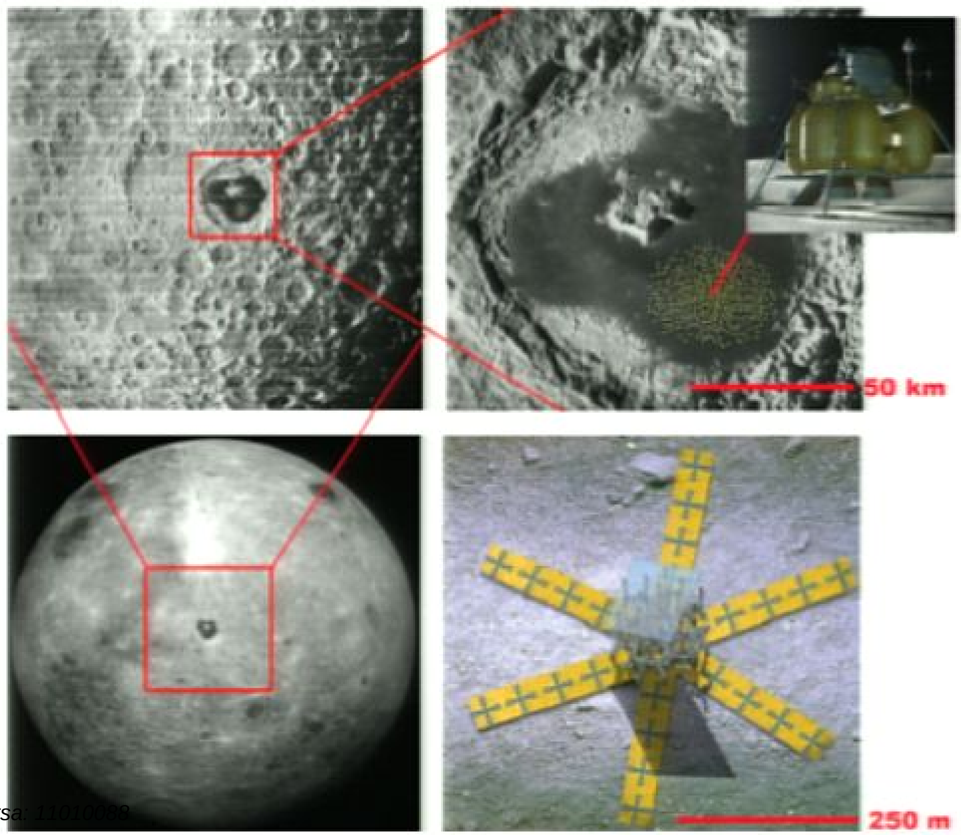
- baryon fraction variation only constrained at ~20% level
- Do mechanisms exist for producing this level?
- Curvaton scenario can produce $\sim 10^{-5}$ variation
- 21 cm offers opportunity to measure compensated isocurvature mode not seen elsewhere
- Need $\sim 10$ km$^2$ collecting area to do 21 cm cosmology at $z>30$
- For $z>30$ need to go to frequencies < 50 MHz. Ionospheric distortion becomes large

# Lunar arrays

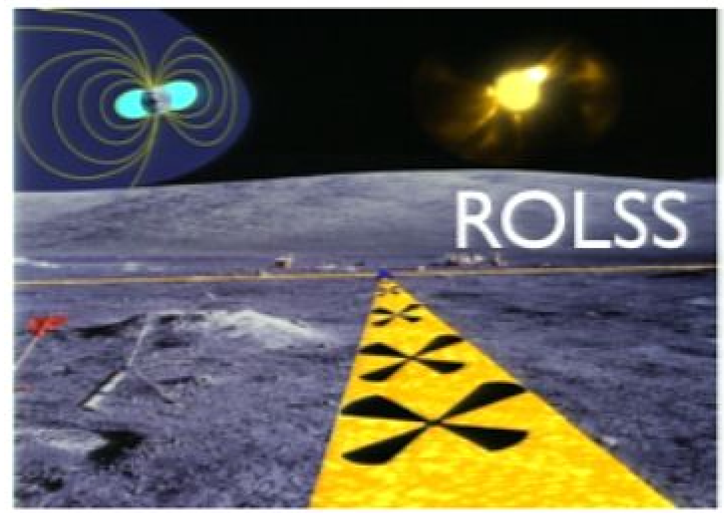
Go to moon to escape ionosphere?

Radio dipoles potentially simple, cheap, and light

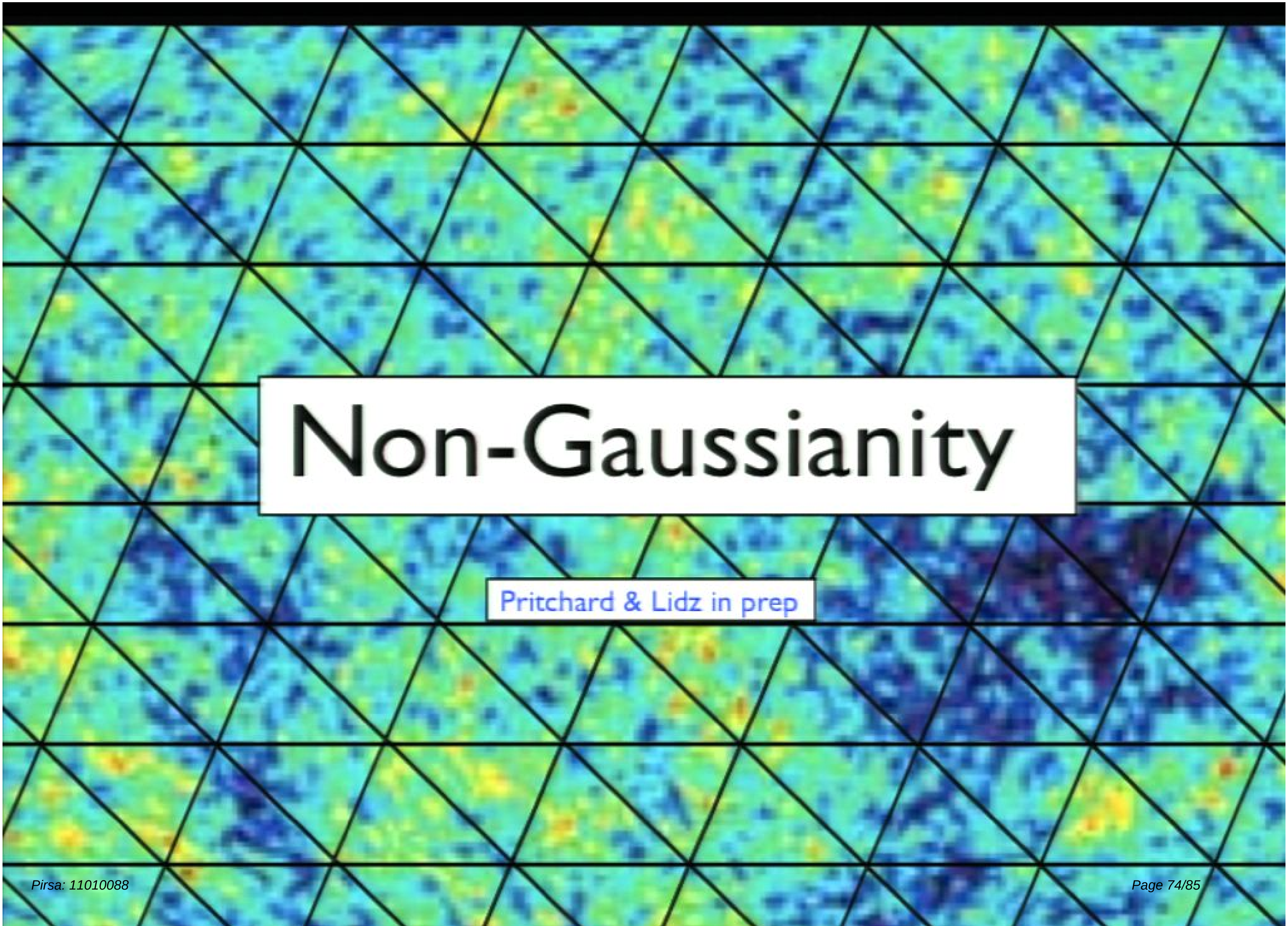
Power supply and data transmission are challenges




LARC/DALI




Need Ares V launcher
~1 $km^2$/launch


Non-Gaussianity
Pritchard & Lidz in prep

# Non-Gaussianity

- Expect primordial fluctuations to be almost Gaussian
- Often parametrized by fNL

$$\Phi(\mathbf{x}) = \Phi_G(\mathbf{x}) + f_{NL}^{\text{loc.}}[\Phi_G^2(\mathbf{x}) - \langle\Phi_G^2(\mathbf{x})\rangle],$$

- WMAP5 $-4<f_{NL}<80$

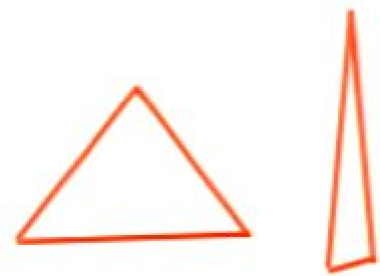
  Smith, Senatore, Zaldarriaga 2009

  Planck $f_{NL}\sim O(3)$

- In slow roll, $f_{NL}\sim(1-n_s)\sim0.05$
  Other models produce larger $f_{NL}$

# Non-Gaussianity and 21 cm

- Claims that ideal 21 cm experiments can detect $f_{NL}$ during dark ages
  O(1) Pillepich+ 2007
  O(0.01) Cooray 2006



- Measure via bispectrum

$$\langle\delta(\mathbf{k_1})\delta(\mathbf{k_2})\delta(\mathbf{k_3})\rangle = (2\pi)^3\delta^{(3)}(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})B(\mathbf{k_1},\mathbf{k_2},\mathbf{k_3})$$

- 21 cm bispectrum from density and neutral fraction fluctuations

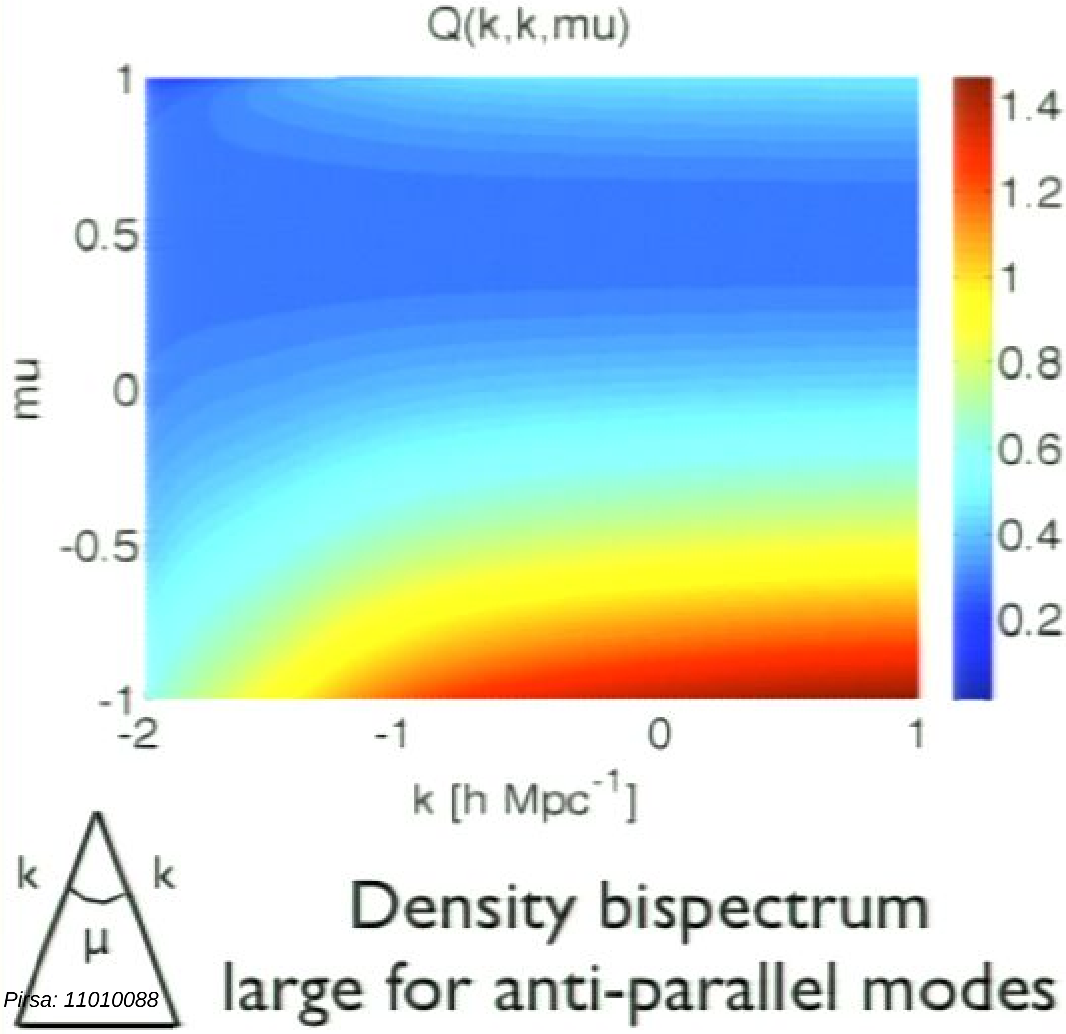
$$\delta_{T_b} = \delta + \delta_x \qquad B_{T_b} = B_{\delta\delta\delta} + 3B_{x\delta\delta} + 3B_{xx\delta} + B_{xxx}$$

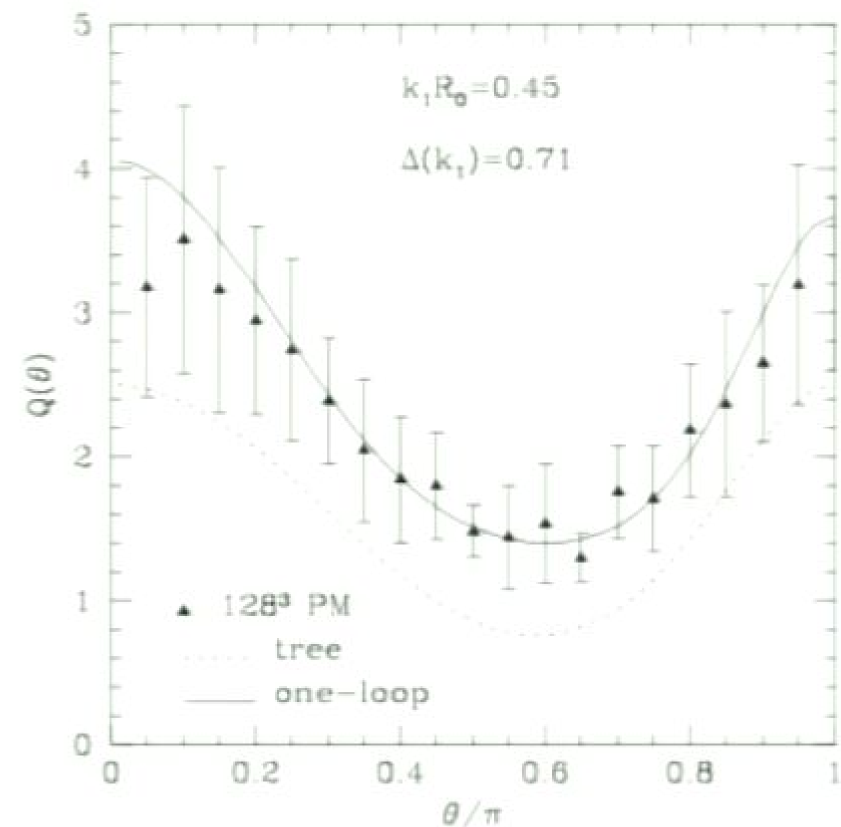
- Reduced bispectrum

$$Q(k_1, k_2, k_3) \equiv \frac{B(k_1, k_2, k_3)}{P(k_1)P(k_2) + \text{cyc.}}$$

# Density bispectrum

$$B_G(k_1, k_2, k_3) = 2F_2(\mathbf{k}_1, \mathbf{k}_2)P_L(k_1)P_L(k_2) + \text{cyc.}$$



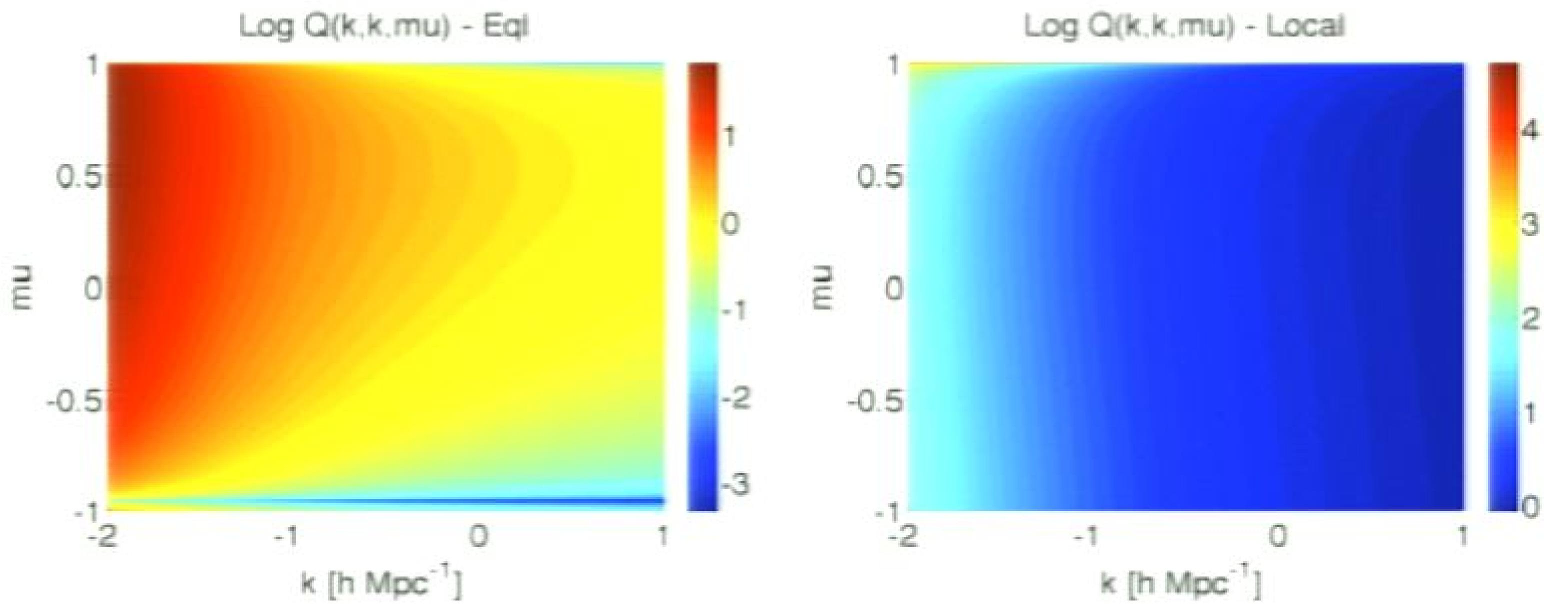




Density bispectrum
large for anti-parallel modes

Scoccimarro 1998

# Primordial bispectrum

Different inflation models produce different shape non-Gaussianity



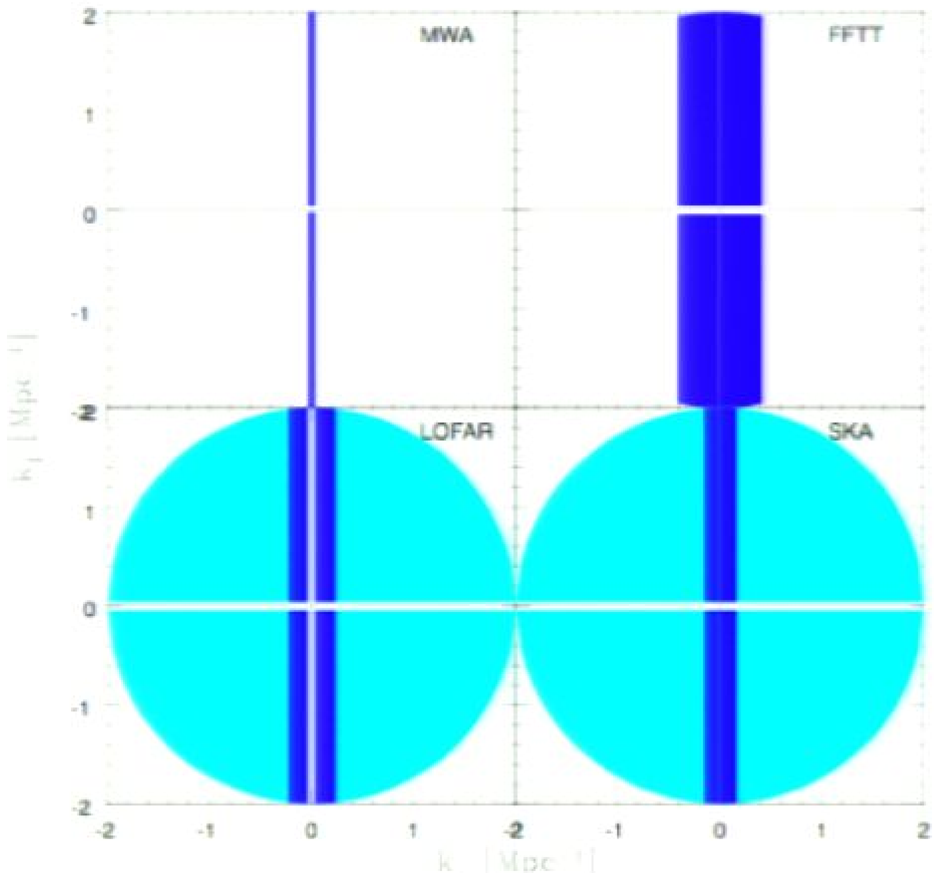
# Sensitivity calculations and geometry

variance per mode

$$\Delta Q_s^2(k_1, k_2, k_3) \simeq \frac{s_{123} k_f^3}{V_B} \frac{P_{\rm tot}(k_1) P_{\rm tot}(k_2) P_{\rm tot}(k_3)}{[P_s(k_1) P_s(k_2) + {\rm cyc.}]^2}.$$

Sefusatti & Komatsu 2007

Sum over modes that fit in experiment

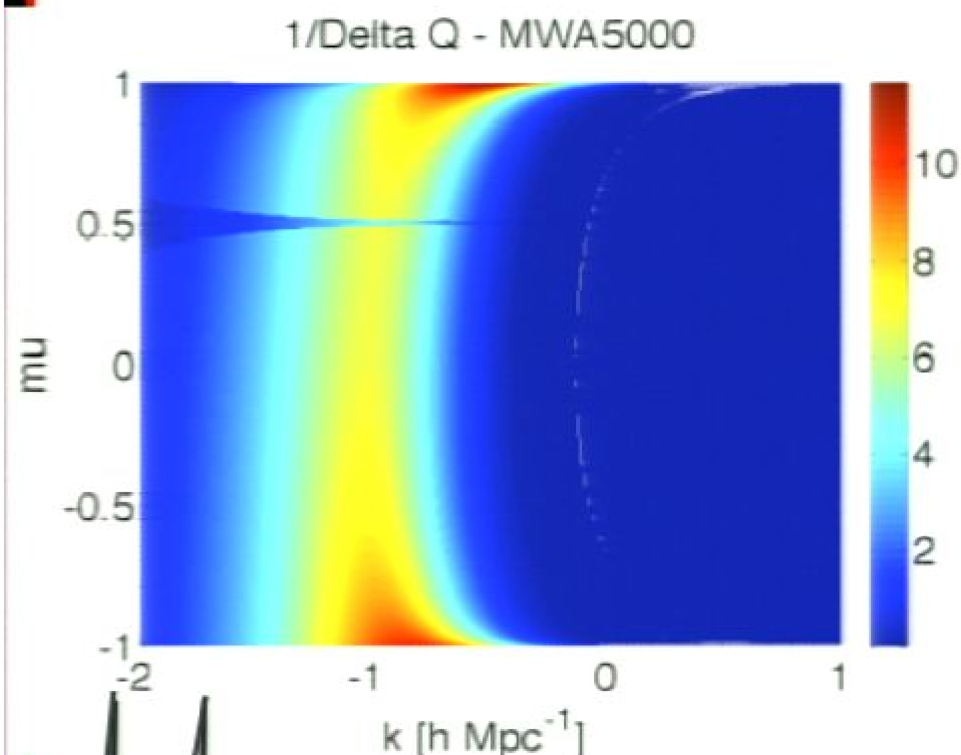



Experiments have cylindrical symmetry in k space

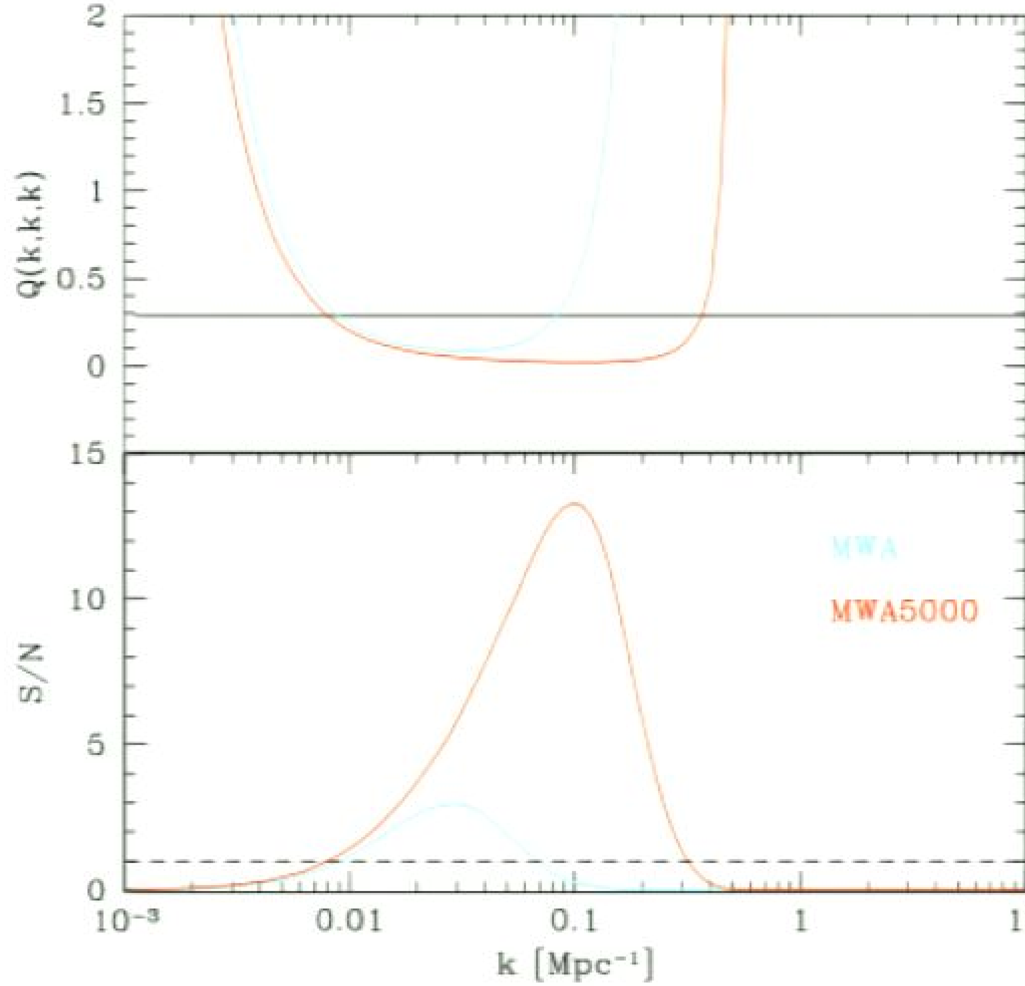
work in progress with Adam Lidz

# Sensitivity

Calculation for tree-level density bispectrum




Equilateral triangles




Moderate sensitivity to bispectrum

# fNL from bispectrum

Sefusatti & Komatsu 2007

SDSS-LRG: $f_{NL}$~113

ADEPT: $f_{NL}$~4

z=8

MWA: $f_{NL}$=100

SKA: $f_{NL}$=13

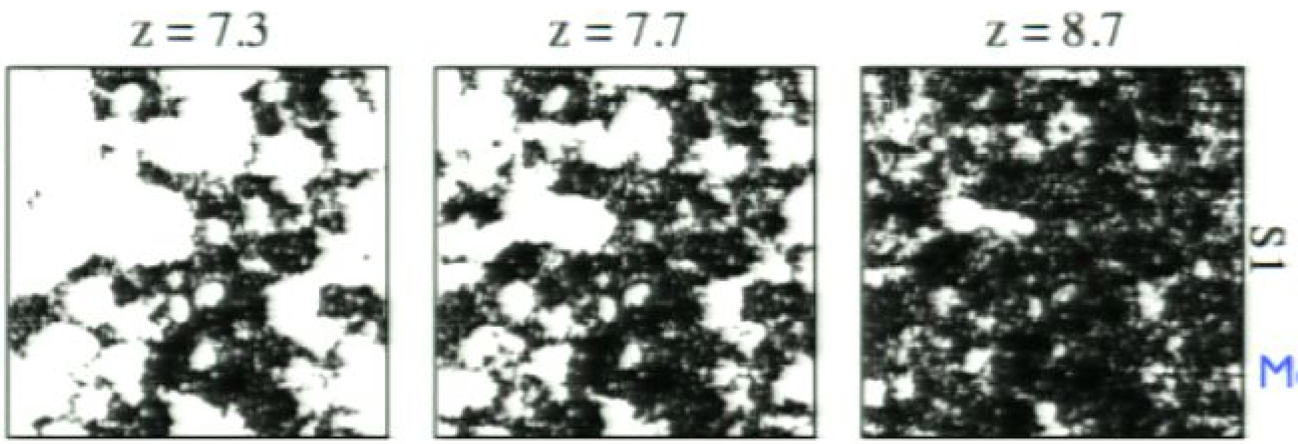
FFTT: $f_{NL}$=0.8

z=30

10 $km^2$ FFTT: $f_{NL}$=6

(hazard warning)

# Non-Gaussianity from reionization



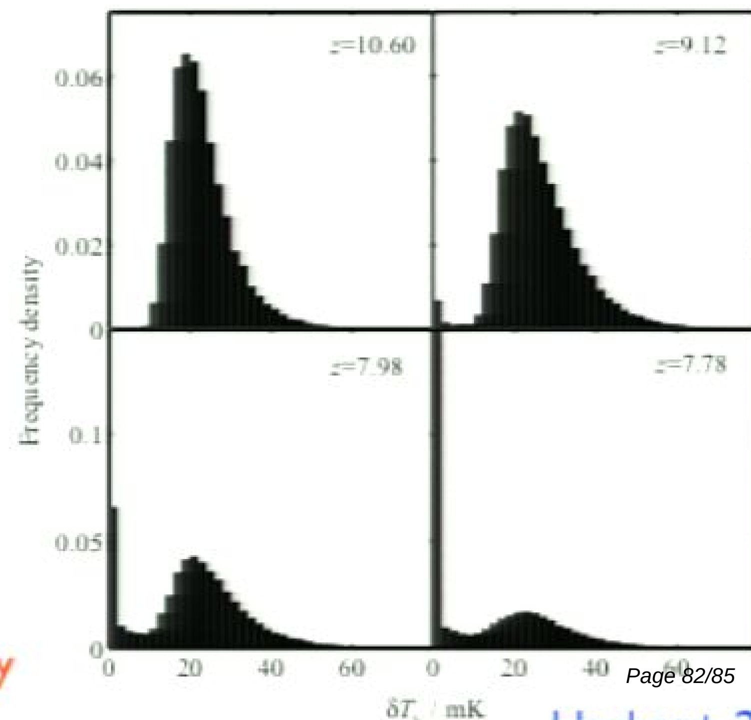

McQuinn+ 2007

Reionization is intrinsically non-Gaussian

Ionized bubbles leads to significant skewness in pdf

non-Gaussianity contains useful information about bubbles sizes and topology of reionization

What are the best statistics for using non-Gaussianity to learn about reionization?



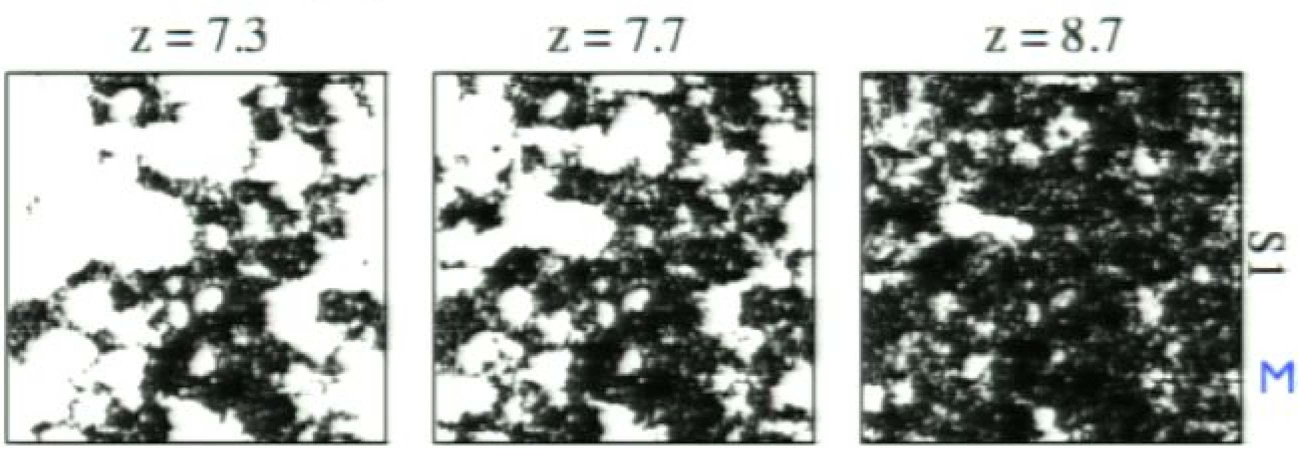

Harker+ 2009

# Bispectrum from reionization

Go with what you know...

Measure bispectrum by counting triangles in box

$$\hat{\bar{B}}_{\mathrm{d}} = \frac{V_\mu^2}{N_{\mathrm{tri}}} \sum_{\mathbf{n}_1,\mathbf{n}_2}^{N_{\mathrm{tri}}} \mathcal{R}e[\delta_{\mathrm{d}}(\mathbf{k}_{\mathbf{n}_1})\delta_{\mathrm{d}}(\mathbf{k}_{\mathbf{n}_2})\delta_{\mathrm{d}}(\mathbf{k}_{-\mathbf{n}_1-\mathbf{n}_2})],$$



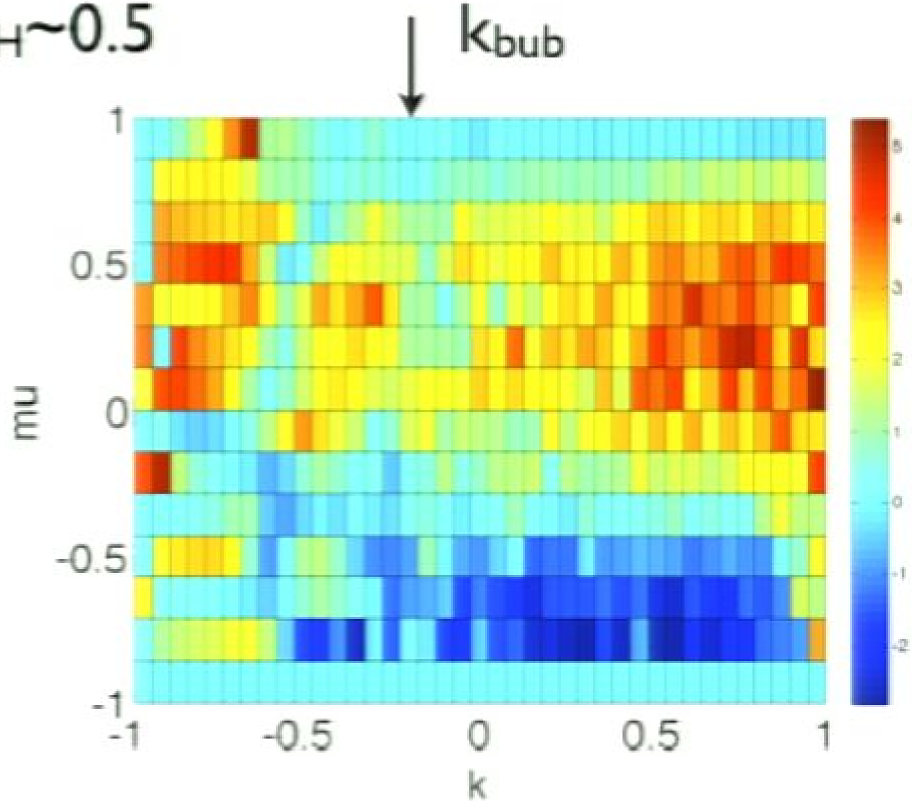

McQuinn+ 2007

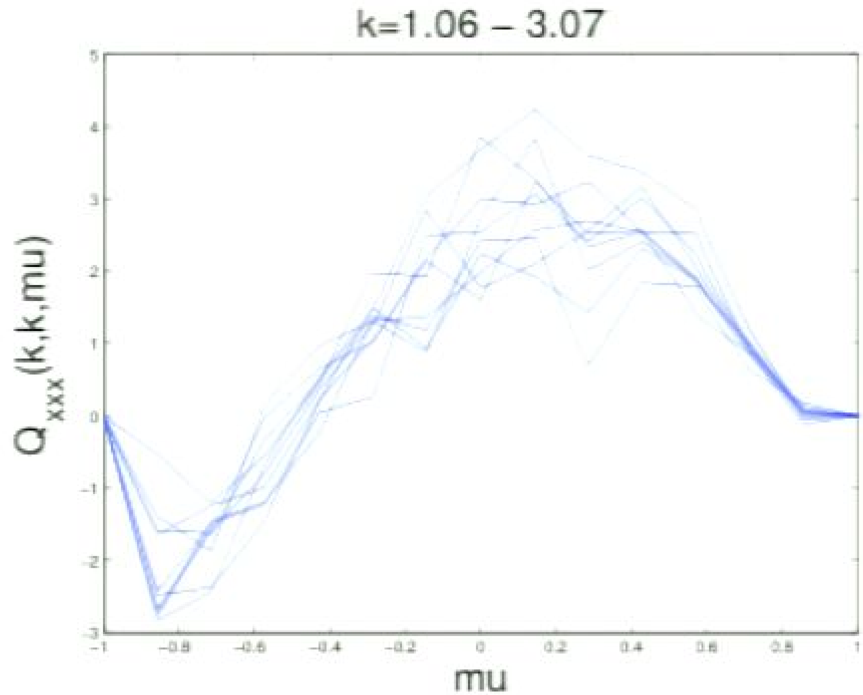


Use to build some intuition about physical effects

# Ionization bispectrum

$x_H \sim 0.5$




Similar amplitude but different shape to density bispectrum

Expect characteristic scale from bubble sizes

Currently building analytic model for this...

# Conclusions

- Moving to "diamond age" of cosmology requires pushing frontiers of precision, redshift, and scale
- Tilt and running can be improved significantly, but hard to get to slow roll level
- Post-inflationary equation of state is a significant source of degeneracy in interpretation
- Compensated isocurvature mode largely unconstrained - future 21 cm experiments might help
- 21 cm observations of non-Gaussianity comparable to galaxy surveys, but non-G of reionization poorly understood