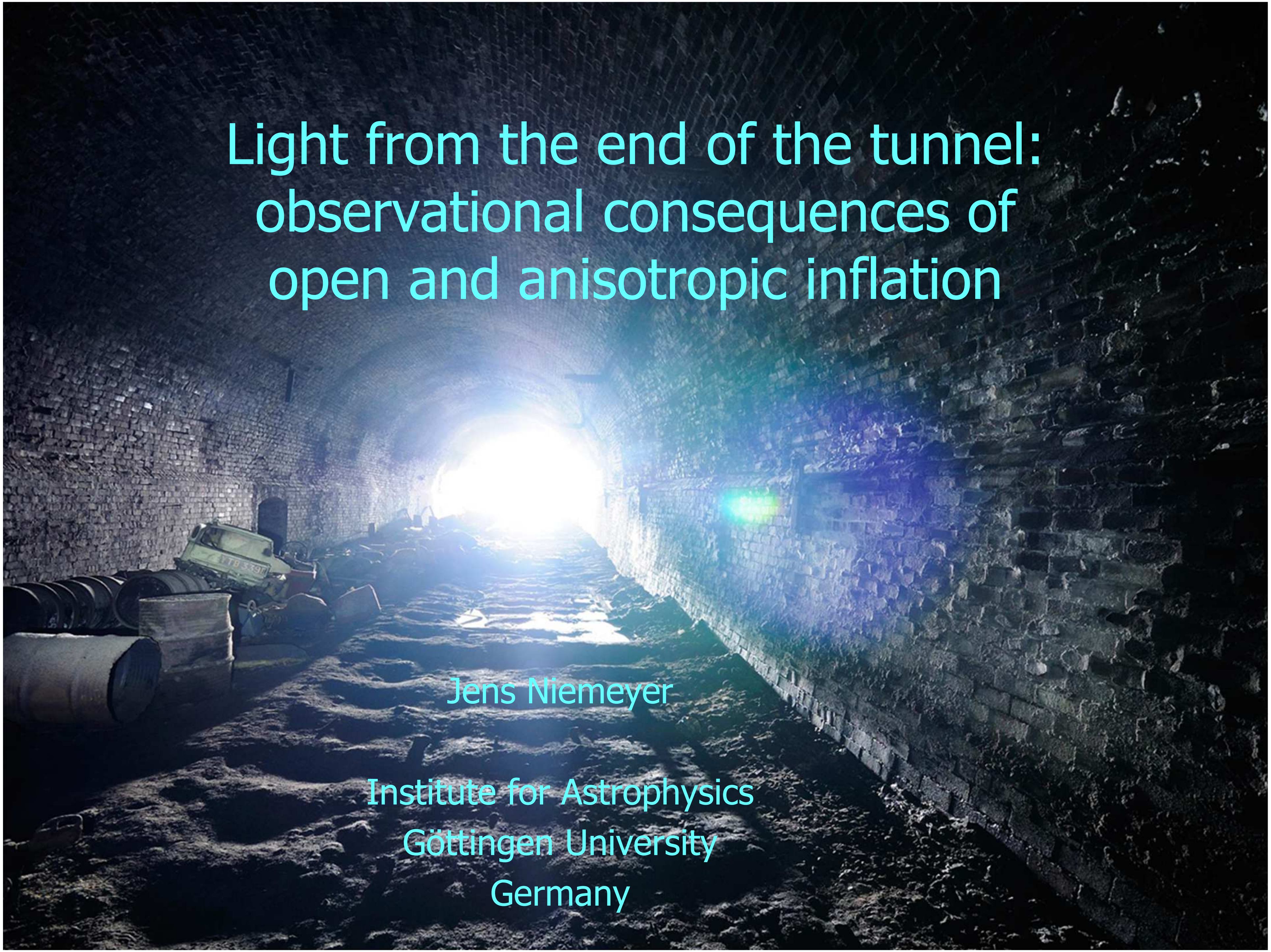

Light from the end of the tunnel: observational consequences of open and anisotropic inflation

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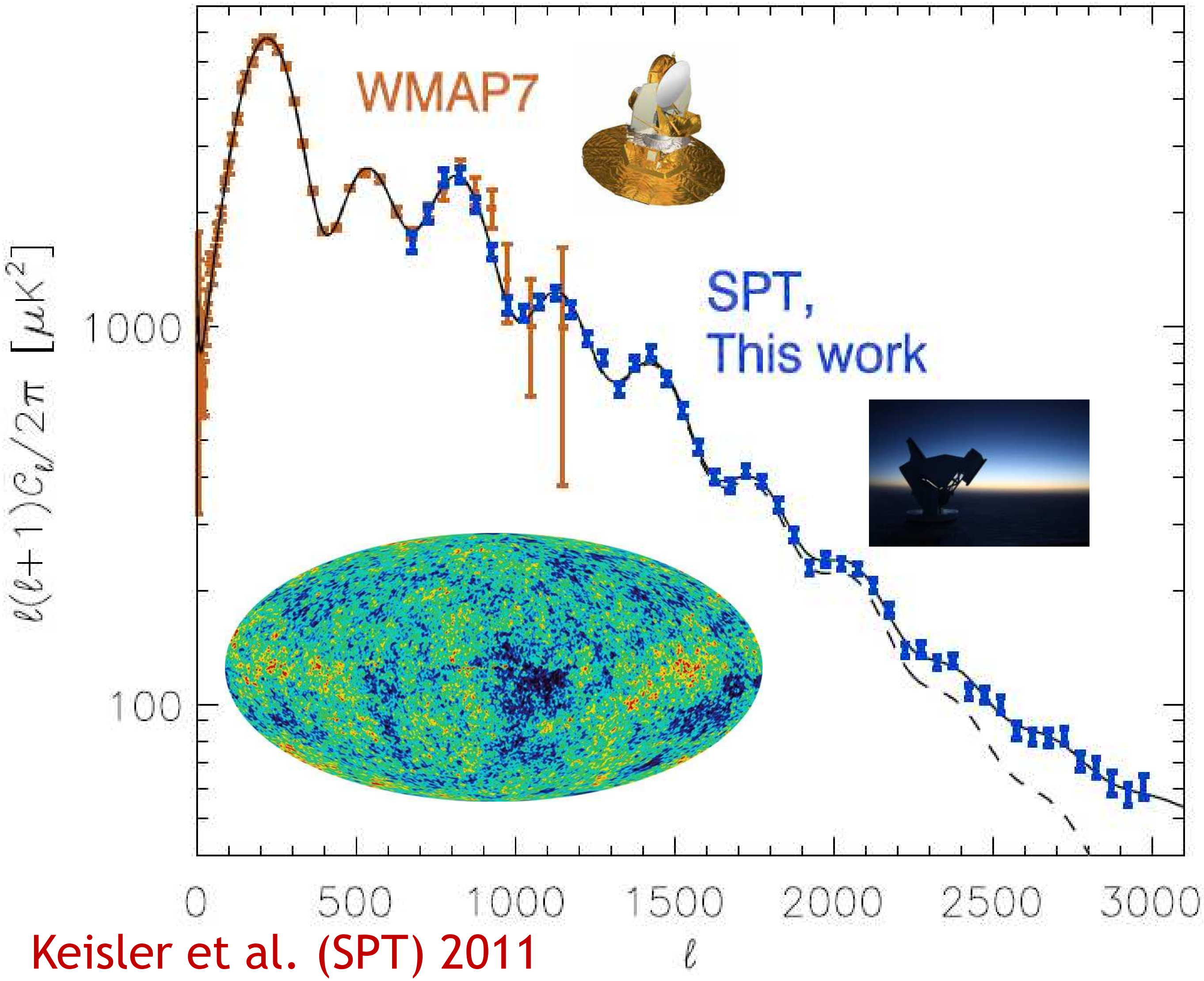
The Cosmic Microwave Background (CMB):
Things will never be this easy (linear, thermal, unbiased…) again



Keisler et al. (SPT) 2011

Shape:

$\Omega_M h^2$, $\Omega_B h^2$

n_s, $dn_s/d \ln k$

l-dependence:

$r_s(z_{rec}) \rightarrow D_A(z_{rec})$,
depends on h, Ω_Λ, Ω_{curv}
→ h for flat universe

Amplitude:

$A_{primordial}$ (with τ_{reion} from polarization)

Planck (early 2013):

„near-perfect“ measurements

From surface to volume

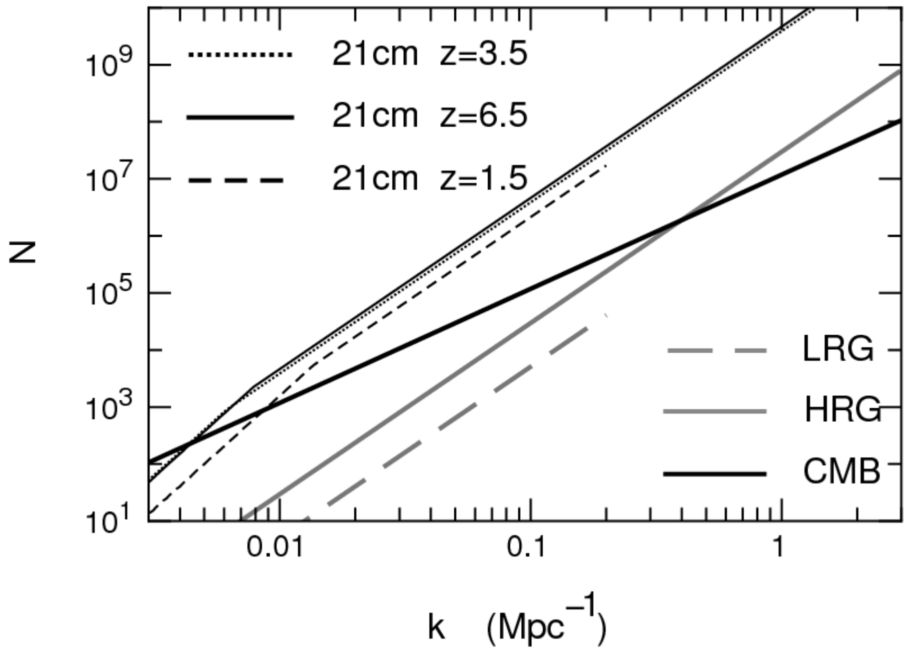
Sampling variance gives fundamental limitation from observed number of modes:

→ 3D (galaxies, hydrogen 21cm) superior to 2D (CMB)

$$\frac{\delta P}{P} = \frac{1}{N_{\rm modes}^{1/2}}$$

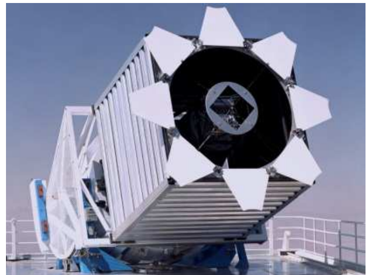
Range in z	Ω(sr)	$N_{\rm modes}$	$\delta P/P$	Surveys
$0.0 - 0.2$	3.0	3×10^4	6×10^{-3}	SDSS, SKA_0
$0.2 - 0.7$	3.0	8×10^5	1×10^{-3}	BOSS
$0.2 - 2.0$	0.06	1×10^5	3×10^{-3}	SKA_1
$0.2 - 2.0$	6.0	1×10^7	$\mathbf{3 \times 10^{-4}}$	SKA_2, BigBOSS,
$2.0 - 3.0$	0.3	6×10^5	1×10^{-3}	HETDEX
$2.0 - 6.0$	0.01	7×10^4	[a]	SKA_1
$2.0 - 6.0$	6.0	4×10^7	$\mathbf{2 \times 10^{-4}}$	SKA_2
$6.0 - 13.0$	0.03	2×10^5	[b]	SKA_0
$6.0 - 13.0$	0.03	2×10^5	2×10^{-3}	SKA_1
$6.0 - 13.0$	3.0	2×10^7	$\mathbf{2 \times 10^{-4}}$	SKA_2
$13.0 - 30.0$	0.03	2×10^5	[b]	SKA_1
$13.0 - 30.0$	3.0	2×10^7	$\mathbf{2 \times 10^{-4}}$	SKA_2
CMB	11.0[c]	2×10^5		WMAP, Planck

Rawlings 2011



Loeb & Wyithe 2008

Current and future galaxy surveys (selection)





SDSS III / BOSS (2009 – 2014):

$0.3 < z < 0.6$; ~1.5 million luminous red galaxies

$2.2 < z < 3$; ~160,000 Lyman alpha forest quasar spectra

WiggleZ (done):

$0.2 < z < 1$; ~240,000 blue emission-line galaxies

HETDEX (2013 – 2015):

$1.9 < z < 3.5$; ~0.8 million Lyman alpha emitters

Pan-STARRS, DES, HSC, LSST, BigBOSS . . .

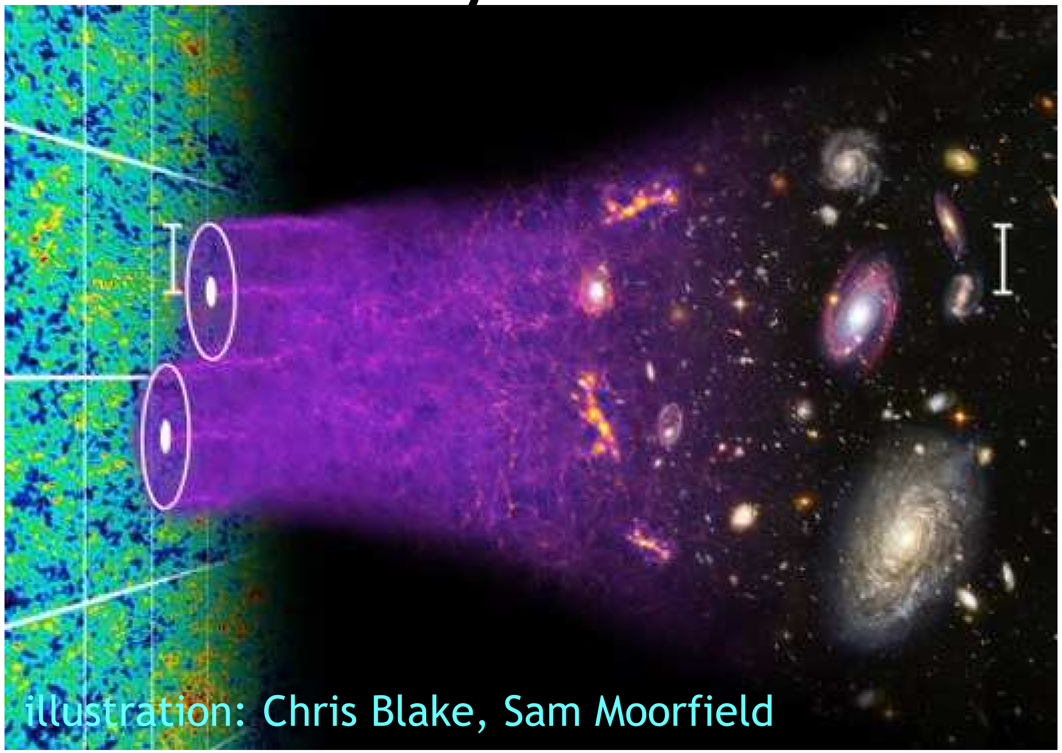
Euclid (~2019):

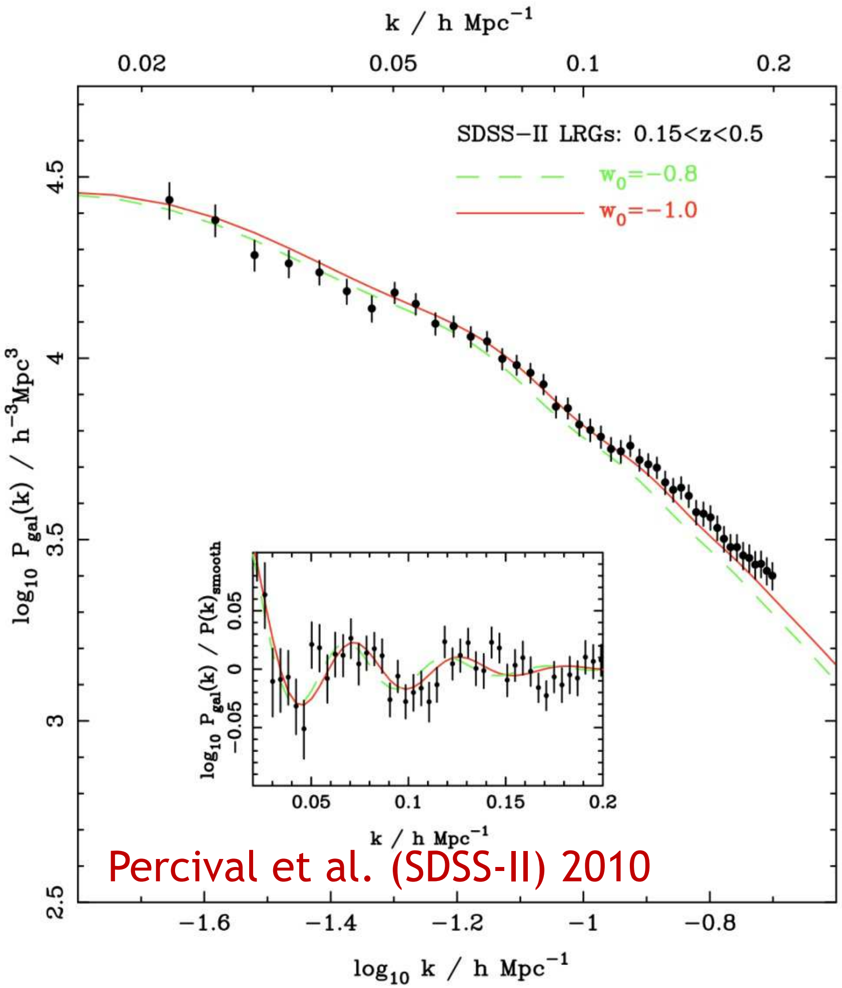
$0.8 < z < 2$; ~1.5 billion galaxies

Square Kilometer Array (~2020):

HI-intensity mapping ; ~ 1 billion HI-galaxies at $z < 6$

Baryon acoustic oscillations (BAO)





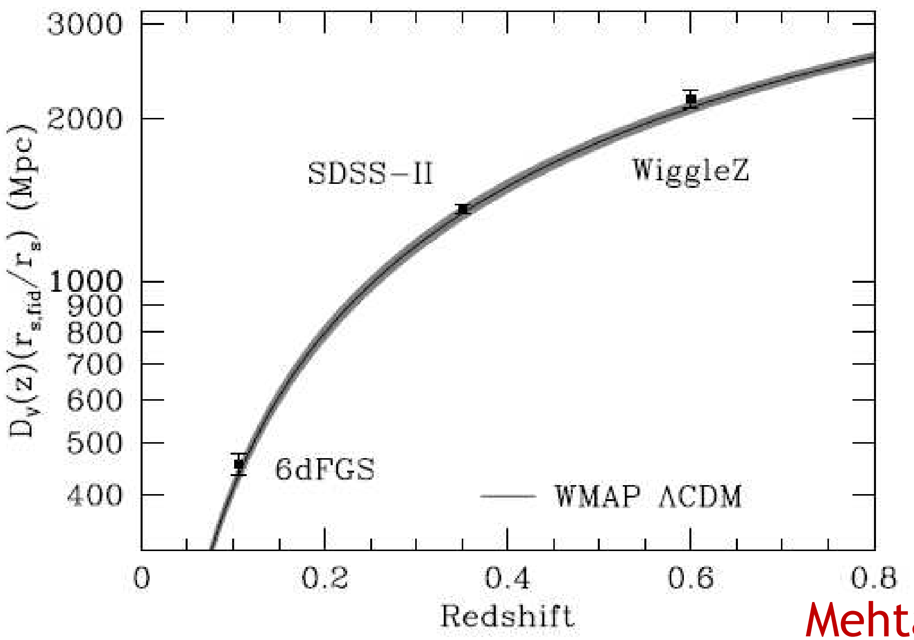
- acoustic structure imprinted at r_s ~150 Mpc
- so far detected in 6 different samples

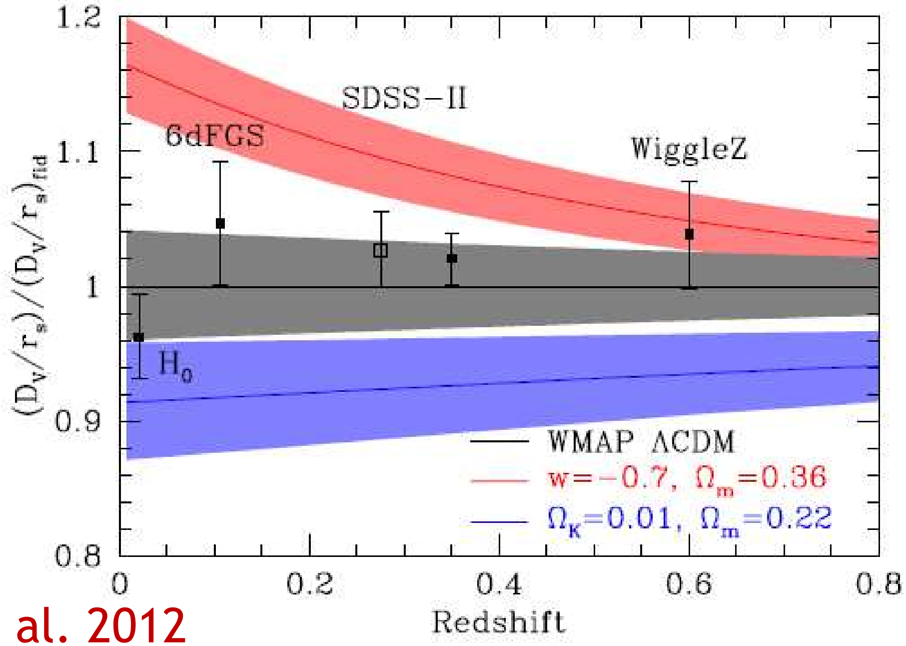
  best precision ~ 3 % (cf. Weinberg et al. 2012)
- $D_A(z)/r_s$ from angular direction, $H(z)r_s$ from line-of-sight direction

  in Mpc, not Mpc h^{-1} as supernovae
- only spherically averaged distance D_V ~ $D_A^{2/3}\,H^{-1/3}$ used so far

  in the future, use full 2-D power spectrum (Shoji, Jeong & Komatsu 2008)

Consistency of sound horizon distances from CMB and BAO

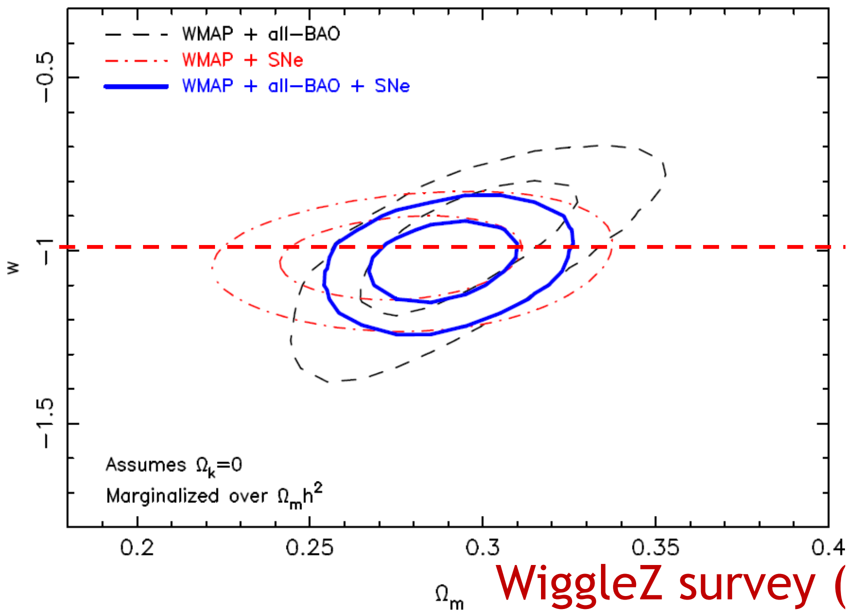


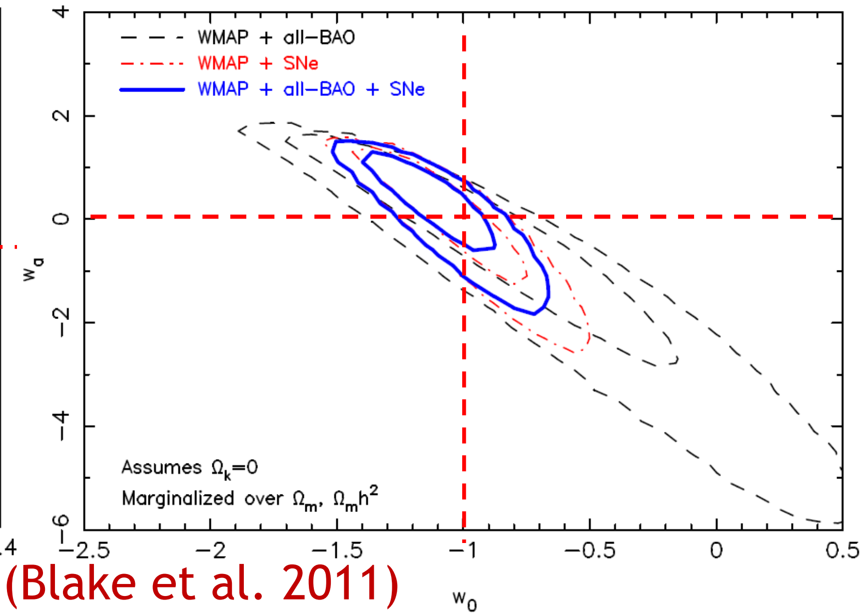


Mehta et al. 2012

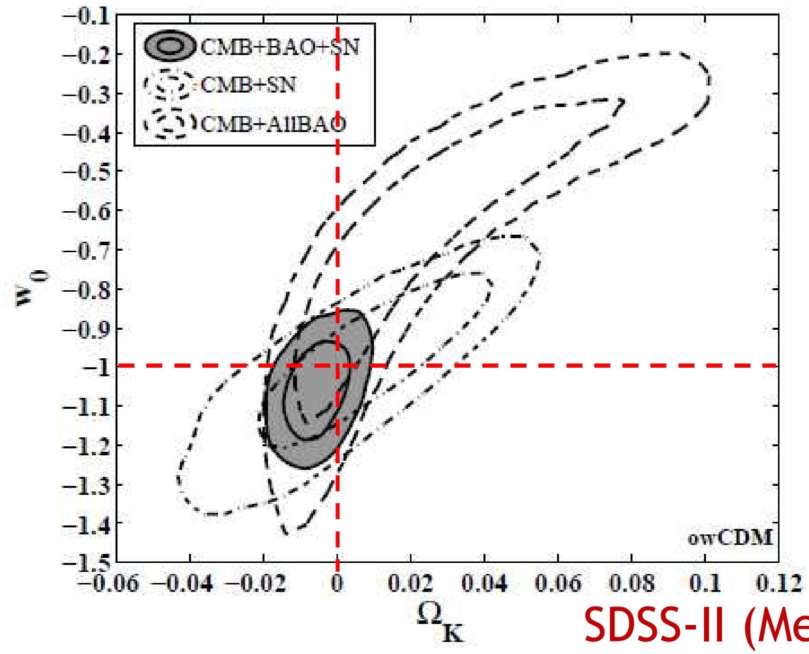
Shaded regions are 1-sigma uncertainties in $\Omega_M h^2$ around WMAP ΛCDM measurements.

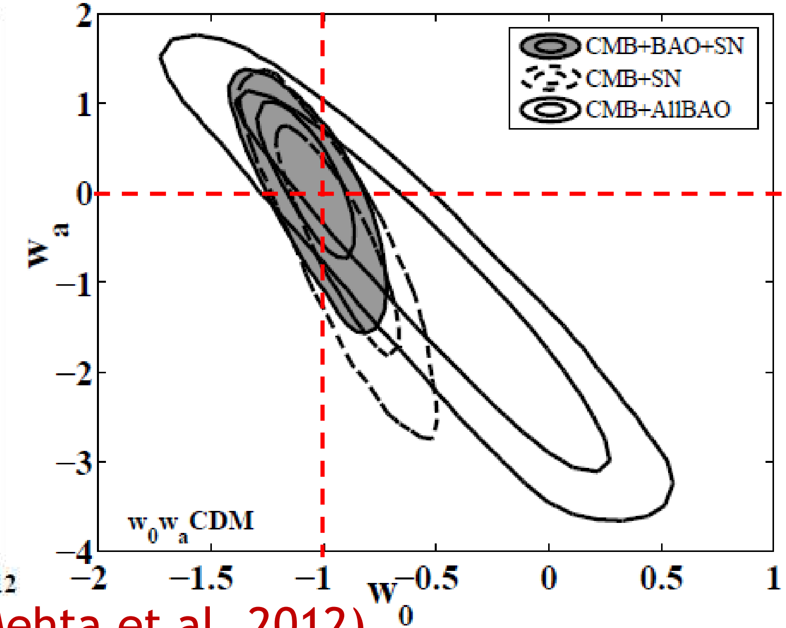
Current dark energy constraints from BAOs





WiggleZ survey (Blake et al. 2011)





SDSS-II (Mehta et al. 2012)

What can we expect to learn?

„Prediction is very difficult,
especially about the future."
(Niels Bohr)

Cosmological constant vs. something else:

- so far, Λ fits all the data
- even if $w_a \neq 0$ etc. should be detected, there is no good reason to assume Λ=0, so Λ must still be included in the fits
- additional probe of modified gravity: linear growth factor G(a). GR predicts:

$$f_{\rm GR}(z) \equiv \frac{d \ln G}{d \ln a} \approx \Omega_M(z)^\gamma \quad , \quad \gamma \approx 0.55$$

- important to use many independent observables and redshifts
- is backreaction an issue?

Other interesting physics from large-scale structure:

- neutrino masses, warm dark matter constraints
- non-vanilla inflation (primordial non-Gaussianities)
- …

Inflation and QG phenomenology

Inflationary phenomenology is well protected against QG effects.

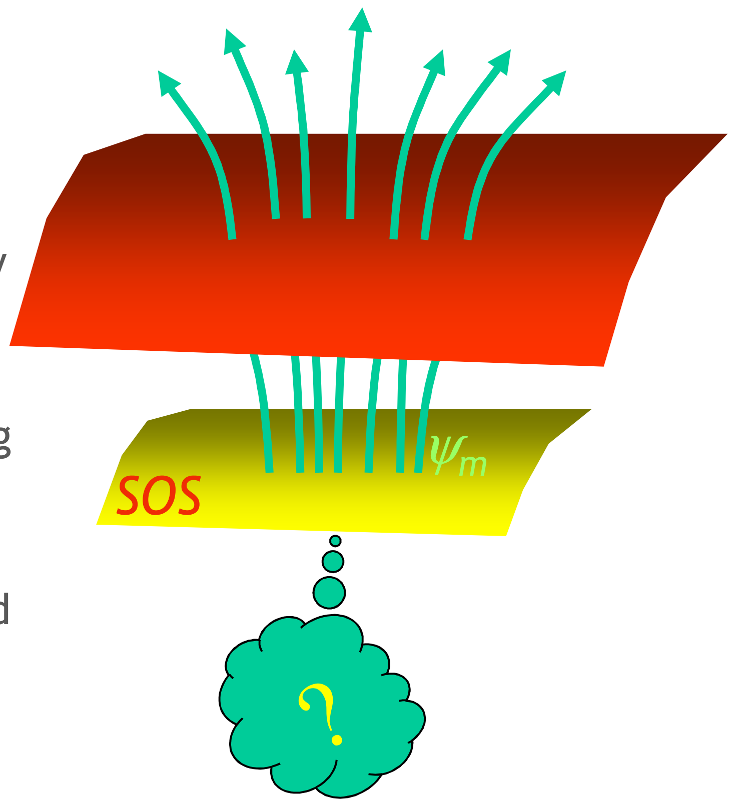
1. Initial state effects hidden beyond the horizon for N >> 60. Examples:
   - non-BD I: high-k excitations → non-Gaussianities and/or oscillatory corrections to power spectrum
   - non-BD II: low-k effects from bubble geometry → supercurvature perturbations
   - anisotropic initial conditions
   - a convincing case for detection will require non-zero curvature (i.e., N ~ 60) plus a unique combination of some of the above
     → need precise theory of initial conditions. Tunneling scenarios provide an example.

2. "trans-Planckian" effects. Popular classes of models:
   - boundary theories, either as initial state effect (see above) or on "new physics hypersurface"
   - nonlinear dispersion, modified uncertainty relations etc.
     strongly constrained by backreaction and adiabaticity (JN, Parentani '01)

Initial conditions in dynamical spacetimes

QFT in curved spacetimes: valid below cutoff $M < M_p$, lives on smooth manifold

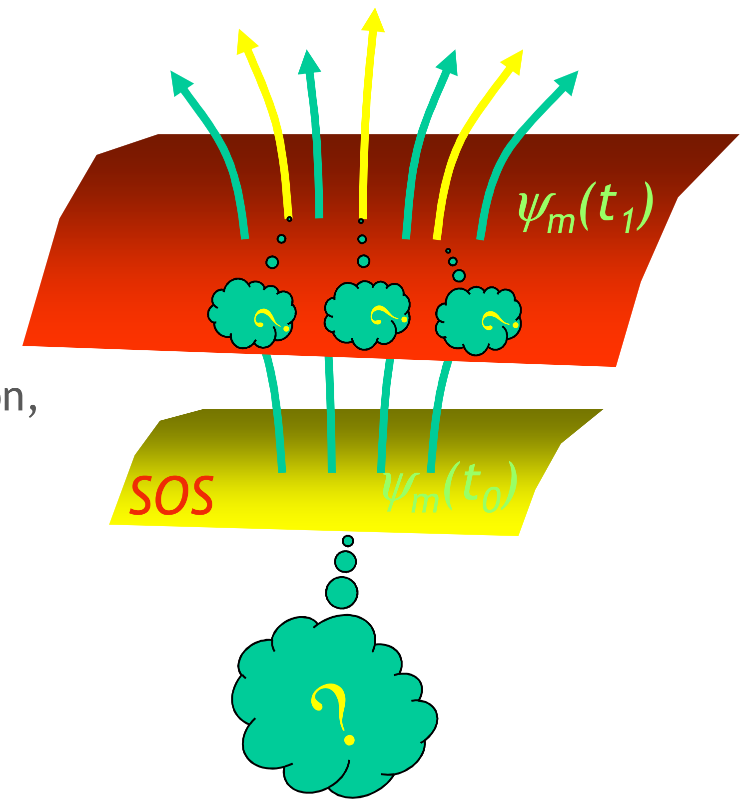
- initial cond.s for matter ψ_m assigned on "surface of semiclassicality (SOS)":
- gravity $\rightarrow$ initial data needs to be arbitrarily densely spaced (density of d.o.f. infinite)
- Lorentz invariance for arbitrary boosts $\rightarrow$ decoupling constrains choice of ψ_m (vacuum)
- Q: Can selection of SOS (and hence ψ_m) be described dynamically?



Initial conditions in dynamical spacetimes

What if LI is broken (or simply meaningless) for $l < M^{-1}$?

- SOS only well-defined for proper distances > M^{-1}
- gravity → modes must be depleted or created (density of d.o.f. finite)
- $\psi_m(t)$ constrained by phenomenology (backreaction, particle production)
- Q: Can selection of SOS *and* $\psi_m(t)$ be described dynamically ("mode creation")?



Boundary theories

Replace mode creation with boundary condition

1. <u>boundary cond. at $k/a(\eta_M) = M$</u>

   Danielsson; JN, Campo, Parentani; Easther, Greene, Kinney, Shi

   $\Rightarrow$ characteristic signature in power spectrum:

$$\Delta P(k) \propto \left(\frac{H(k)}{M}\right)^n \sin\left(2\frac{M}{H(k)} + \Theta\right)$$

where *n* depends on degree of non-adiabaticity;

but: signal strongly damped if cutoff fluctuates

   Campo, JN, Parentani

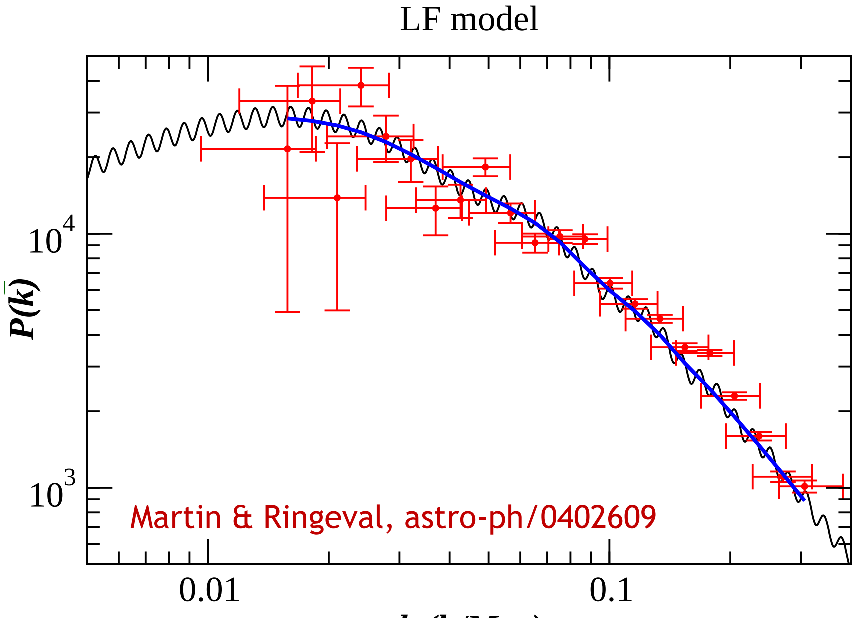
2. <u>boundary cond. at $\eta = \eta_0$</u>

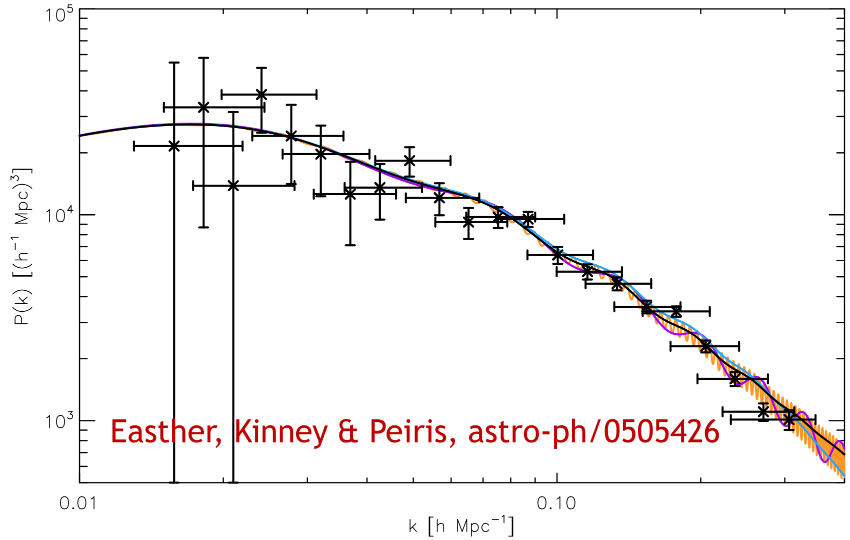
   „Boundary EFT"

   Schalm, Shiu, van der Schaar, Greene

   $\Rightarrow$ characteristic signature in power spectrum :

$$\Delta P(k) \propto \frac{k}{k^*} \sin\left(2\frac{k}{k^*}\frac{M}{H(k)}\right)$$





Open Inflation

Introduced in the 90s to make inflation compatible with $\Omega_m \sim 0.3$

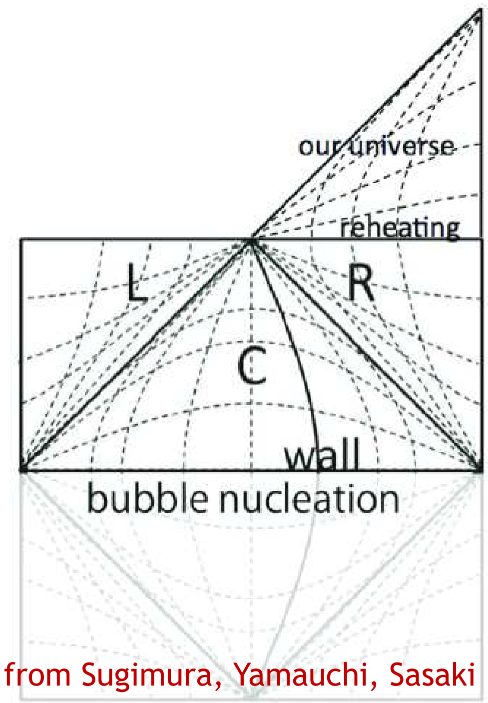
Linde, Sasaki, Tanaka, Yamamoto, Garcia-Bellido, Garriga, Montes, Lyth, Liddle,…

- false vacuum tunneling transitions produce bubbles of true vacuum with open homogeneous slices
- many models contain new, discrete "supercurvature modes" in their spectrum that originate from Cauchy data on the complete spacetime → amplitude sensitive to false vacuum scale:

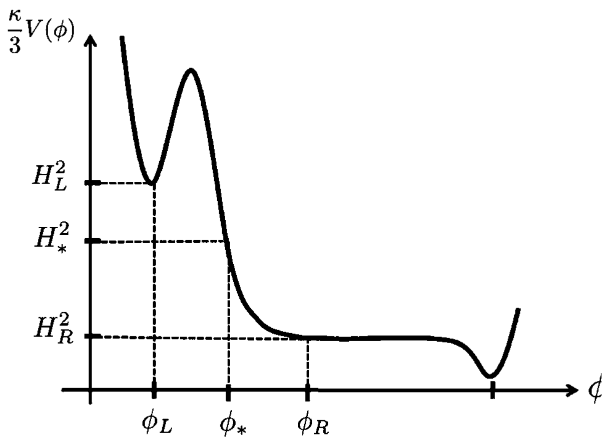
$$l(l+1)\, C_l^{\rm sc} \propto H_F^2\, \Omega_k^l$$

- single field models possible but need to be fine-tuned

  recently revisited by Vaudrevange, Westphal; Yamauchi, Linde, Naruko, Sasaki, Tanaka



from Sugimura, Yamauchi, Sasaki '12



from Yamauchi et al. '11

Open Inflation

Two-field open inflation: a natural arena for oscillatory corrections in the power- and bispectrum

Battefeld, JN, Vlaykov ’12; building on work by Xingang Chen

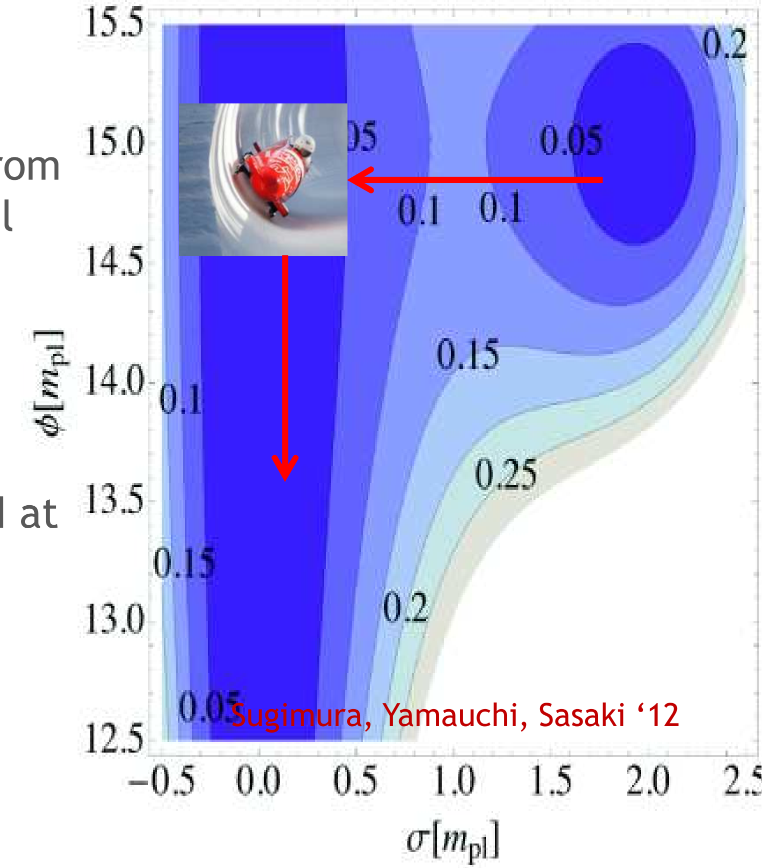
- basic physics: (massive) tunneling field displaced from minimum after tunneling, oscillates around minimal inflaton trajectory

- this produces oscillations in 2 and 3pt functions

- unique feature: background is curvature dominated at first → bispectrum amplitude has local maximum

- for (computationally) allowed parameters only marginally observable: $\frac{\Delta P_\zeta}{P_\zeta} \lesssim 0.1$

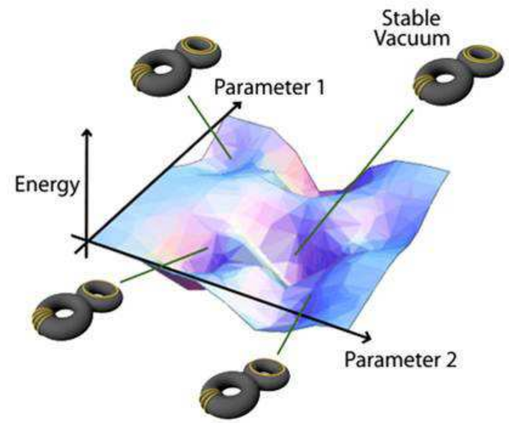
- combination with supercurvature modes?



Beyond the 4D Landscape

The standard string landscape is purely 4-dimensional

Transitions between vacua by means of Coleman-de Lucia type bubble nucleation + ensuing (“open“) inflation



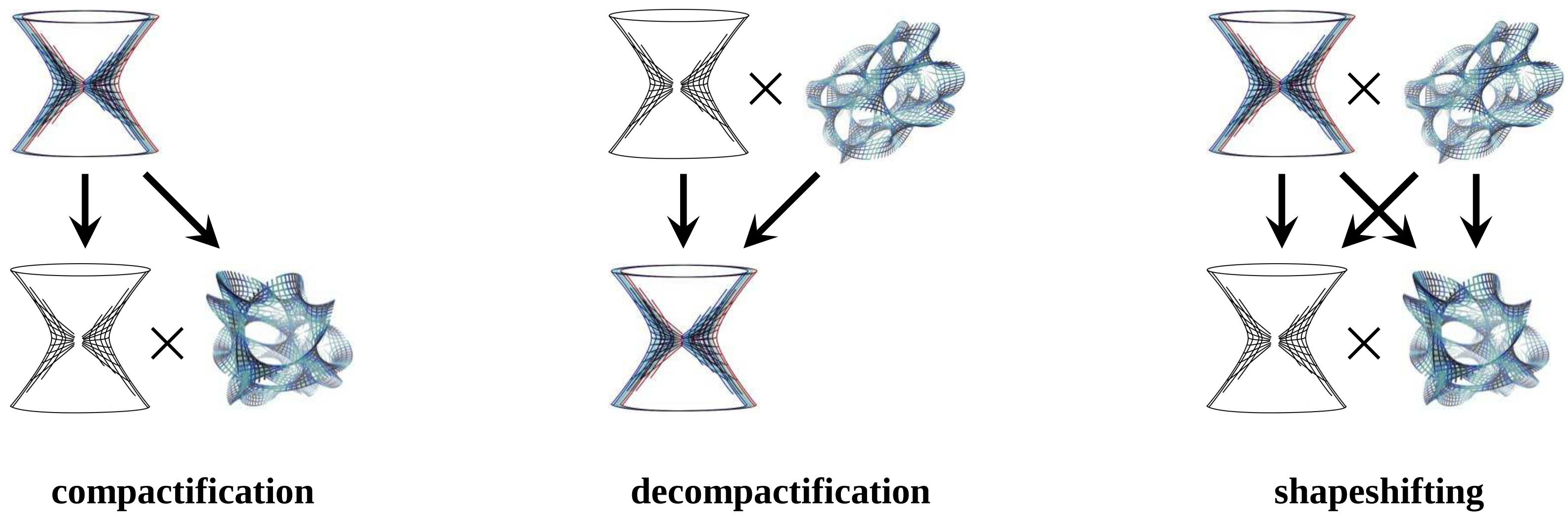
Cosmological transitions between vacua with different numbers of large dimensions:

- dynamical compactification
  Carroll, Johnson, Randall ’09
- dynamical decompactification
  Graham, Harnik, Rajendran ’10; Blanco-Pillado, Salem ’10; Adamek, Campo, JN ’10
- close relationship with pair creation of charged black holes
  Carroll, Johnson, Randall ’09; Blanco-Pillado, Schwartz-Perlov, Vilenkin ’10

The Shapeshifting Universe

More generally, large and small dimensions can exchange roles in tunneling vacuum transitions (“shapeshifting“)

i.e., several of our large/small dimensions could have been small/large in our parent vacuum



The Shapeshifting Universe

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Example: creation of anisotropic Kantowski-Sachs spacetime

Adamek, Campo, JN ’10

schematically: $\mathrm{dS}_D \times S_2 \times \mathcal{M}_d \longrightarrow \mathrm{KS}_{(4)} \times \mathcal{M}'_{d+D-2}$

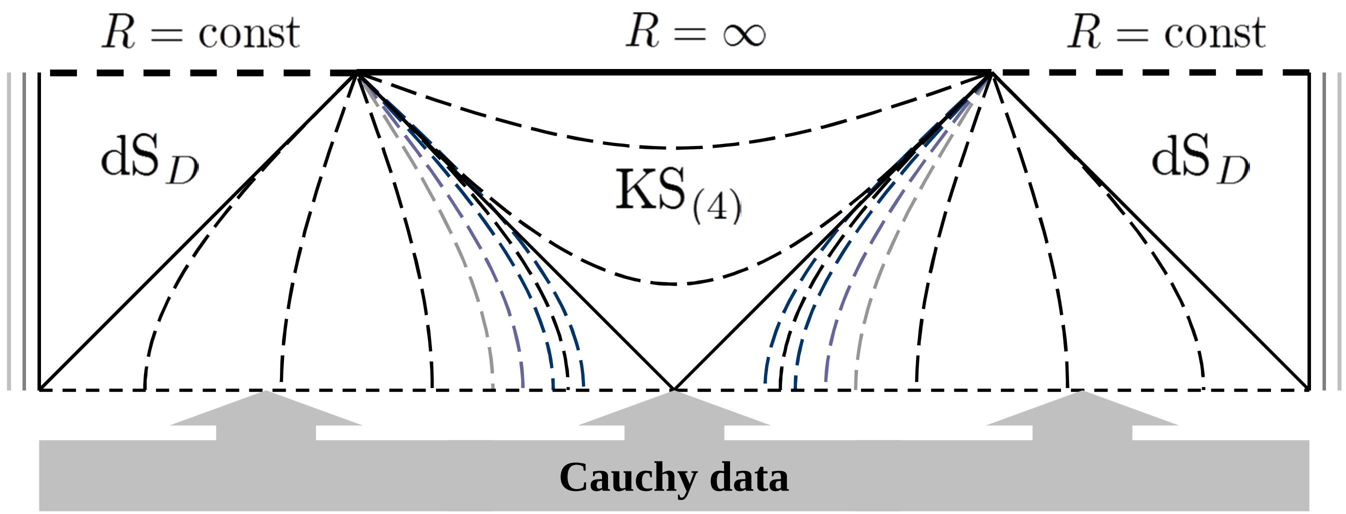
spatial topology of KS: $\mathbb{R} \times S_2$

alternative: decompactify 1 dimension → Bianchi III ($H_2 \times S_1$)

Blanco-Pillado, Salem ’10

→ fully specified anisotropic cosmology, look for signatures!

Primordial power spectrum in $KS_{(4)}$



Consider test scalar field on $KS_{(4)}$ background:

- extend static region of dS_4 beyond horizon → $KS_{(4)}$ foliation
- quantize, get positive frequency mode from regularity of Cauchy data
- compute power spectrum:

$$\mathcal{P} = \frac{H^2 \left|\Gamma\left(\frac{l+ik}{2}\right)\right|^2}{2\left(k^2 + (l+1)^2\right)\left|\Gamma\left(\frac{l+1+ik}{2}\right)\right|^2}$$

$(l > 0)$

CMB signatures

Main effect: quadrupolar distortion

Corrections to correlation between multipole coefficients

$$\langle a_{lm} a^*_{l'm'} \rangle \propto \frac{H^2}{2\pi} \delta_{mm'} (\delta_{ll'} + \delta C_{ll'mm})$$

scale as

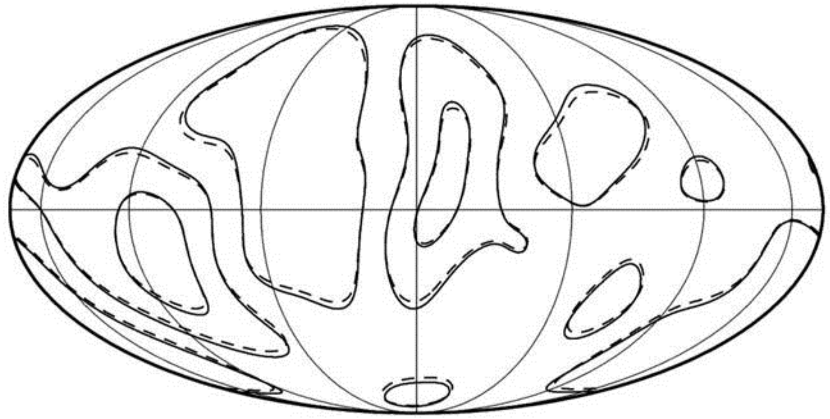
$$\delta C_{ll'mm} \propto \Omega_{k\perp}$$

with the anisotropic curvature parameter

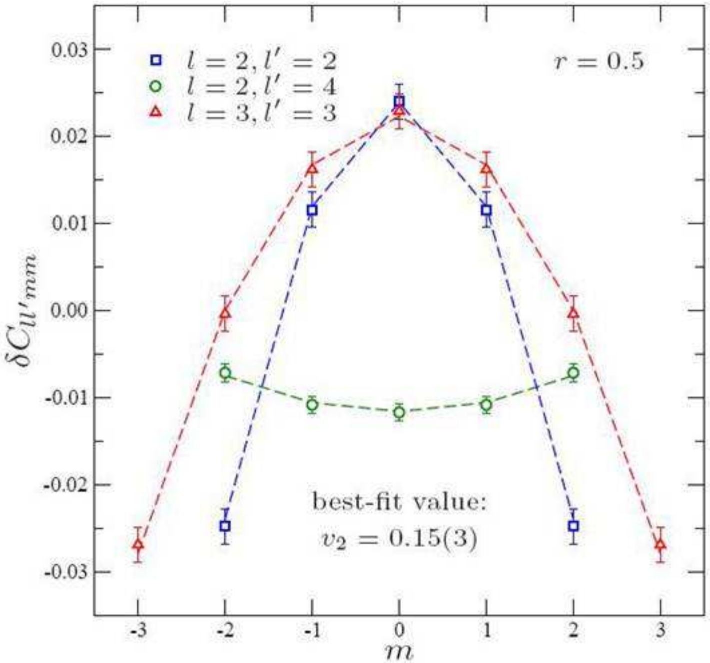
$$\Omega_{k\perp} = \frac{k_\perp}{a_\perp^2 H_\perp^2}$$

and

$$ds^2 = -dt^2 + a_\perp^2 \left(\frac{dr^2}{1 - k_\perp r^2} + r^2 \, d\phi^2 \right) + a_\parallel^2(t) \, dz^2$$



from J. Adamek's PhD thesis



However, anisotropic curvature would also produce an (unobserved) CMB quadrupole contribution of similar magnitude.

The weakest link in the CMB?

Scales larger than ~60 degrees look somewhat funny:

see Copi, Huterer, Schwartz, Starkman '10 for review and original references

- alignment of quadrupole and octopole with each other and perpendicular to the ecliptic and to the dipole
- 2-pt angular correlation function practically zero at angles > 60 degrees
- hemispherical and quadrupolar power asymmetry

The significance of these effects is disputed, but at the very least we do not live in a typical realization of the standard inflationary model.

The $KS_{(4)}$ model can account for the quadrupolar asymmetry if we ignore the quadrupole constraint on anisotropic curvature…

(to be continued)