Dick Bond CITA on behalf of the Planck collaboration

Quantum Inflation in the 2015 Planck Era & Beyond

phonon ~ $\zeta = \ln\rho|_a / 3(1+\langle w \rangle)$ = *energy-density quanta*

isotropic (volume) strain ~ $\zeta = \ln a|_\rho$ $\zeta_{NL} = \ln(\rho\, a^{3(1+w)})/3(1+w)$ <= $dE+pdV$

Cosmic_Probes[$\zeta(\mathbf{x})$, q_{cosmic}, isoc, ..] or $\zeta(\mathbf{k})$,

or looking out $\zeta_{LM}(\chi)$, $\chi=|\mathbf{x}|$ & $\zeta_{LM}(k)$, $k=|\mathbf{k}|$ **maps**

CMB_Probe no tomography:

projected-χ *few modes per LM* $\langle\zeta_{LM}(\chi)|T_{LM}\rangle$ $\langle\zeta_{LM}(\chi)|E_{LM}\rangle$

available modes: $f_{sky} L_{max}^2$ $-f_{sky} L_{min}^2$ $L_{max} \sim L_{damp}$

Planck near limit of nonG exploration with CMB (ACT/SPT) $f_{NL} \pm 5$

gravity waves ~Transverse_Traceless_Strain: *no tomography, limited L range* n_t

LSS_Probe tomography:

Large Scale Structure Galaxy Surveys

available modes ~ $f_{sky} L_{max}^2\, k_{max}\, d_{max}$

~ $f_{sky} (k_{max}^3\, d_{max}^3)$, $k_{min} \sim 2\pi/d_{max}$ $V_{com} \sim d_{max}^3$

How many high precision extra modes can we realize?

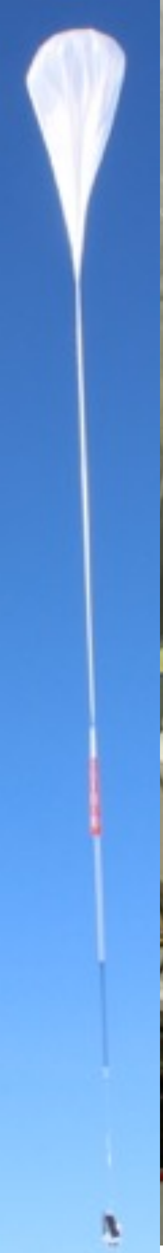
CMB stage II, III, IV

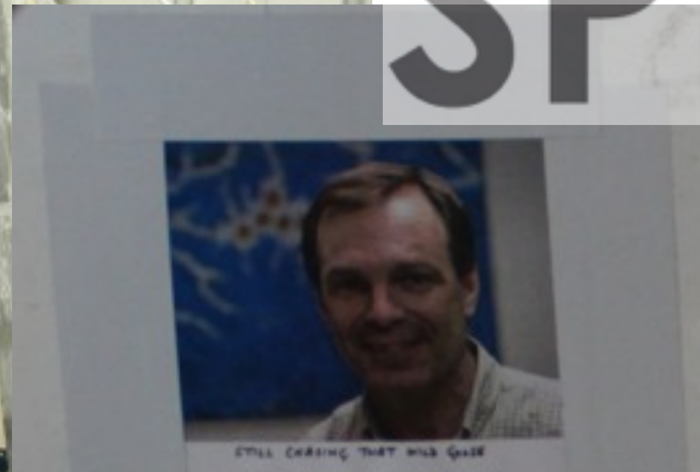
lyman page, ferrara 2014

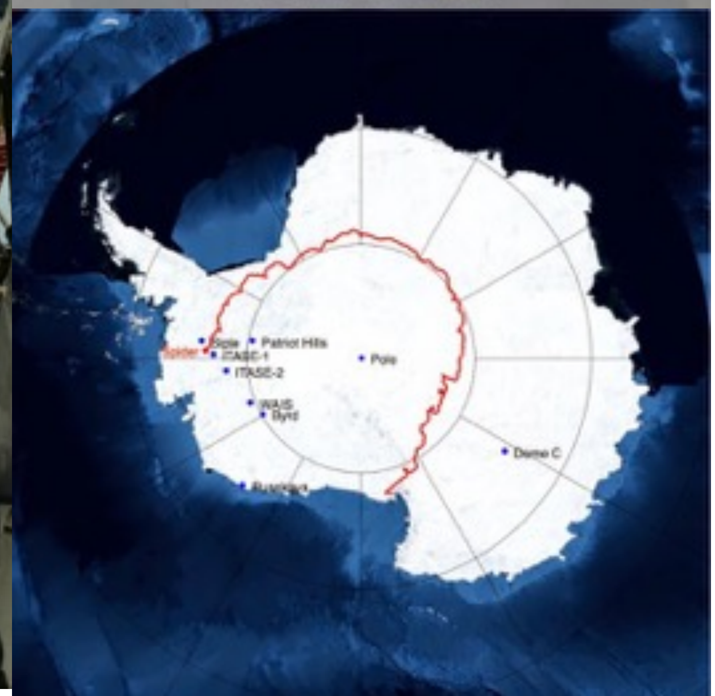
Ground Based

	Chile	Have data	Current or planned freqs
*	ABS		145 GHz
	ACTPol/AdvACt		30, 40, 90, 150, 230 GHz
	POLARBEAR		90, 150 GHz
*	CLASS		40, 90, 150 GHz
	Antarctica		
*	BICEP/KECK		90, 150, 220 GHz
	SPTPol		90, 150 GHz
	QUBIC-Bolo int.	2016	90, 150, 220 GHz
	Elsewhere (for now)		
	B-Machine –WMRS		40 GHz
*	GroundBIRD, LiteBIRD	2016	150 GHz
*	GLP – Greenland	TBD	150, 210, 270 GHz
*	MuSE-Multimoded	TBD	44, 95, 145, 225, 275 GHz
	QUIJOTE –Canaries, HEMPTS		11-20, 30 GHz

SPIDER







PRINCETON UNIVERSITY

SLAC NATIONAL ACCELERATOR LABORATORY

Imperial College London

UNIVERSITY OF TORONTO

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique théorique

STANFORD UNIVERSITY

CASE WESTERN RESERVE UNIVERSITY EST. 1826

NASA

NSF

NIST

NSERC CRSNG

CSA ASC

JPL

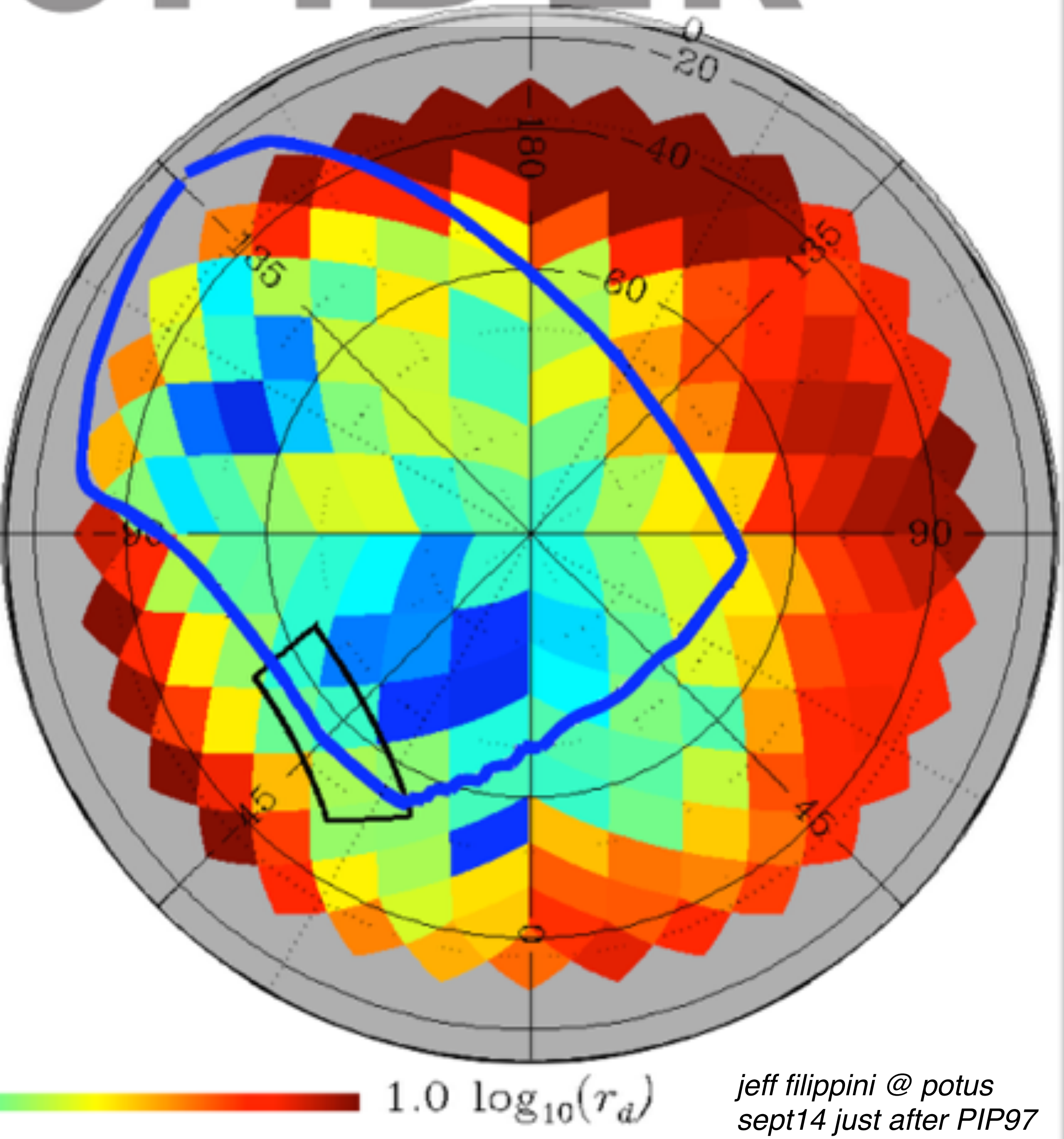
the David & Lucile Packard FOUNDATION

UNIVERSITY OF KWAZULU-NATAL

UBC

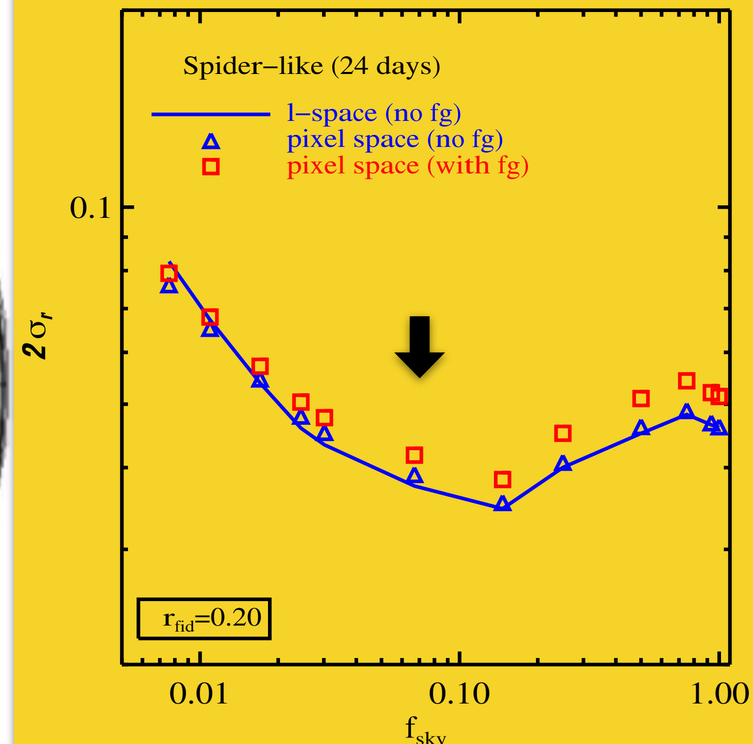
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

SPIDER



jeff filippini @ potus
sept14 just after PIP97

Jan 2015 flight ~ 16d
fsky,eff=0.65
3/3 @ 90/150 GHz
~2K detectors incl yield
L ~ 10-300
2016+ flight
2/2/2 @ 90/150/280 GHz

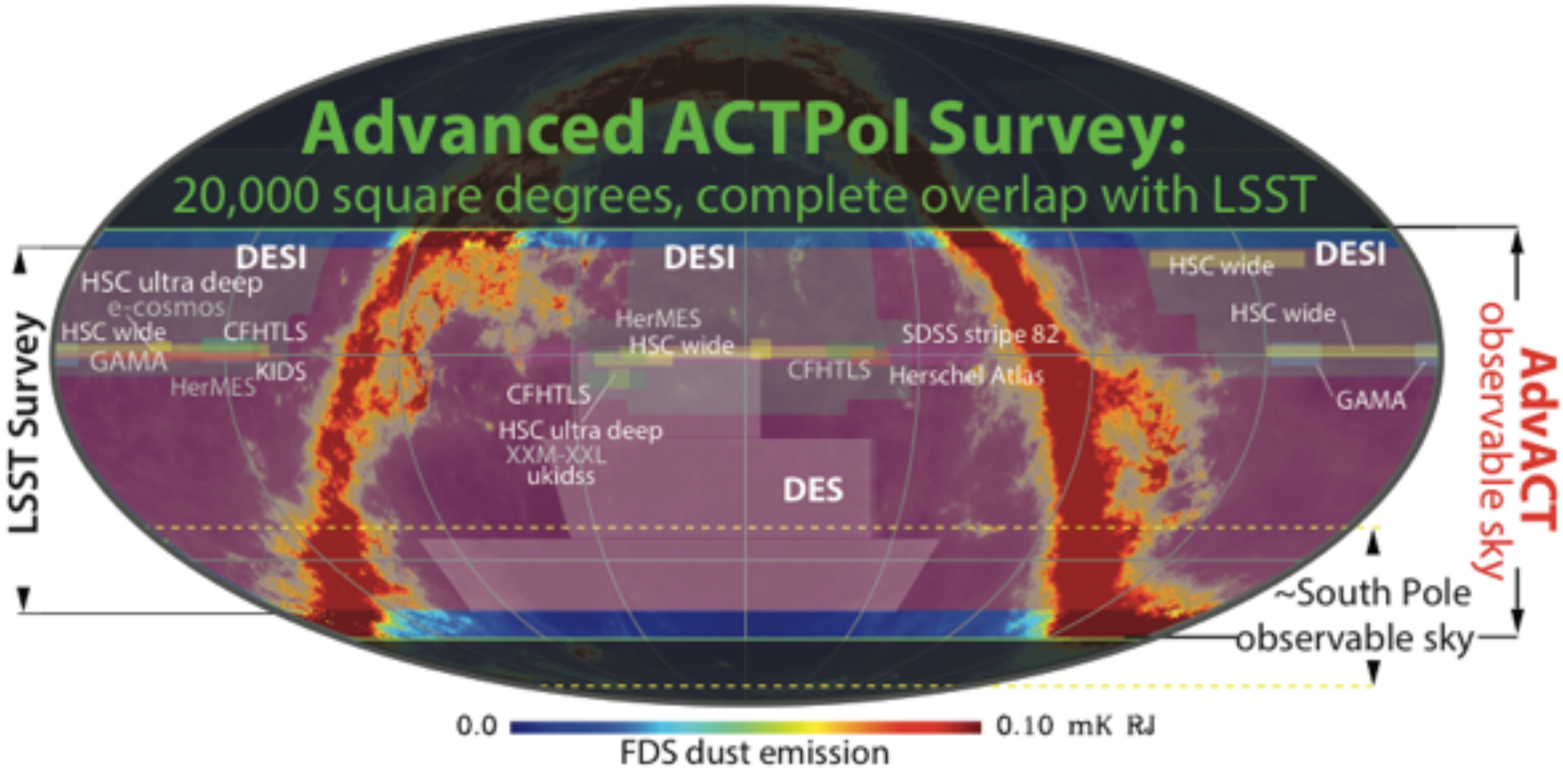


forecasts
0.03 2 sigma 1st flight no fgnd
0.02 2 sigma 2nd flight
0.03 2 sigma 2nd flight fgnd cleaned

The ACT Collaboration

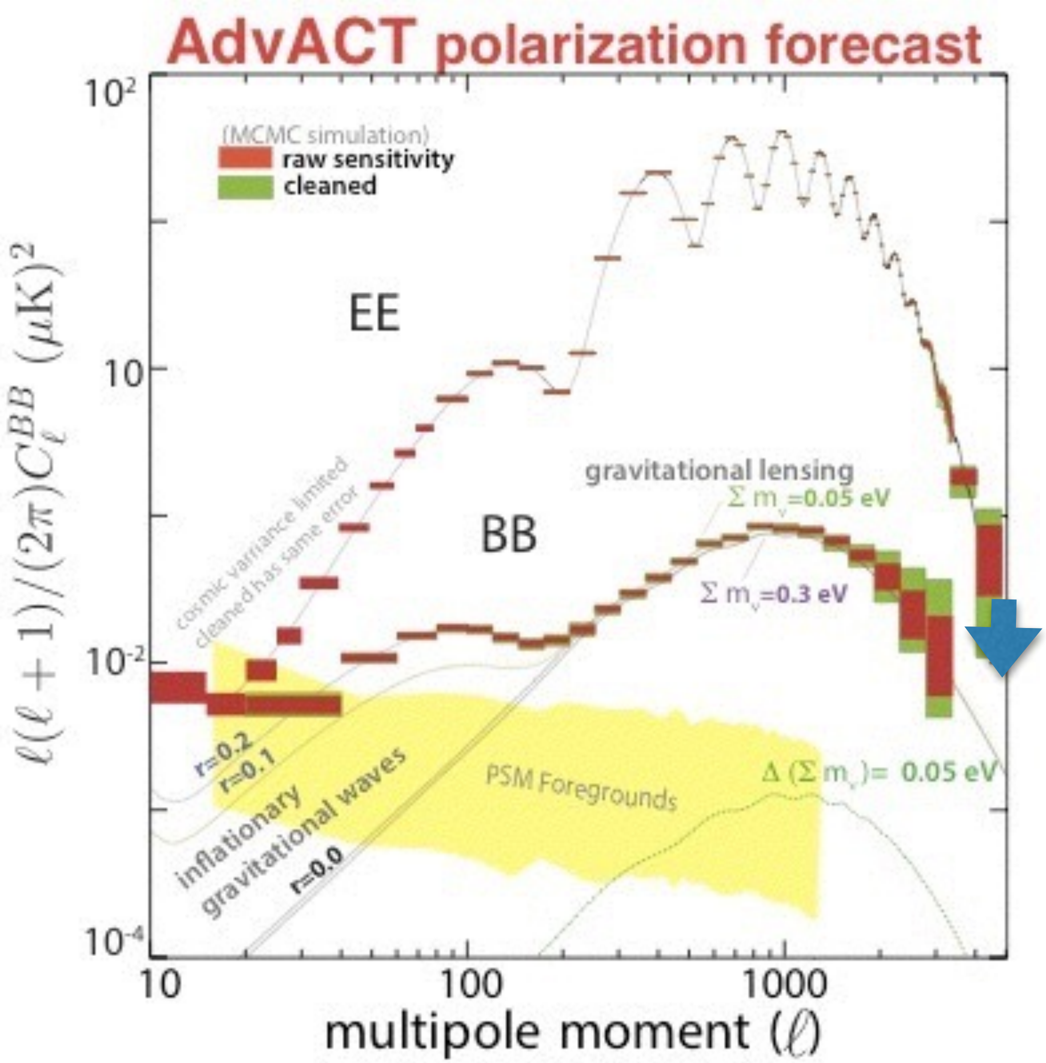
ACT, now ACTpol, => Advanced ACTpol

Advanced ACTPol (AdvACT) Observations



- ~20,000 deg^2 survey (f_{sky}~0.5) with complete LSST overlap as well as DES, ALMA, and other observatories located in Chile
- Substantial overlap with spectroscopic surveys (SDSS, PFS, DESI)

AdvACT: Power Spectra



Error bars above shown for r = 0.2

High S/N B-mode detections for r > 0.01 are measured in independent frequency bands (90 & 150 GHz) and on many patches across the sky.

This provides important cross-checks on any detected signal

Also shown:

- Error bars before and after foreground cleaning
- Varying amplitudes of the gravitational lensing signal for different values of the sum of the neutrino masses
- Planck forecasts

CMB stage IV
DOE funding, *grand unification of ground efforts*
200-500K detectors @ SP, Atacama, Greenland (GLP)?

Inflation Physics from the Cosmic Microwave Background and Large Scale Structure

Topical Conveners: J.E. Carlstrom, A.T. Lee

K.N. Abazajian, K. Arnold, J. Austermann, B.A. Benson, C. Bischoff, J. Bock, J.R. Bond, J. Borrill, I. Buder, D.L. Burke, E. Calabrese, J.E. Carlstrom, C.S. Carvalho, C.L. Chang, H.C. Chiang, S. Church, A. Cooray, T.M. Crawford*, B.P. Crill, K.S. Dawson, S. Das, M.J. Devlin, M. Dobbs, S. Dodelson, O. Doré, J. Dunkley, J.L. Feng, A. Fraisse, J. Gallicchio, S.B. Giddings, D. Green, N.W. Halverson, S. Hanany, D. Hanson, S.R. Hildebrandt, A. Hincks, R. Hlozek, G. Holder, W.L. Holzapfel, K. Honscheid, G. Horowitz, W. Hu, J. Hubmayr, K. Irwin, M. Jackson, W.C. Jones, R. Kallosh, M. Kamionkowski, B. Keating, R. Keisler, W. Kinney, L. Knox, E. Komatsu, J. Kovac, C.-L. Kuo, A. Kusaka, C. Lawrence, A.T. Lee, E. Leitch, A. Linde, E. Linder, P. Lubin, J. Maldacena, E. Martinec, J. McMahon, A. Miller, V. Mukhanov, L. Newburgh, M.D. Niemack, H. Nguyen, H.T. Nguyen, L. Page, C. Pryke, C.L. Reichardt, J.E. Ruhl, N. Sehgal, U. Seljak, L. Senatore, J. Sievers, E. Silverstein, A. Slosar, K.M. Smith, D. Spergel, S.T. Staggs, A. Stark, R. Stompor, A.G. Vieregg, G. Wang, S. Watson, E.J. Wollack, W.L.K. Wu, K.W. Yoon, O. Zahn, and M. Zaldarriaga

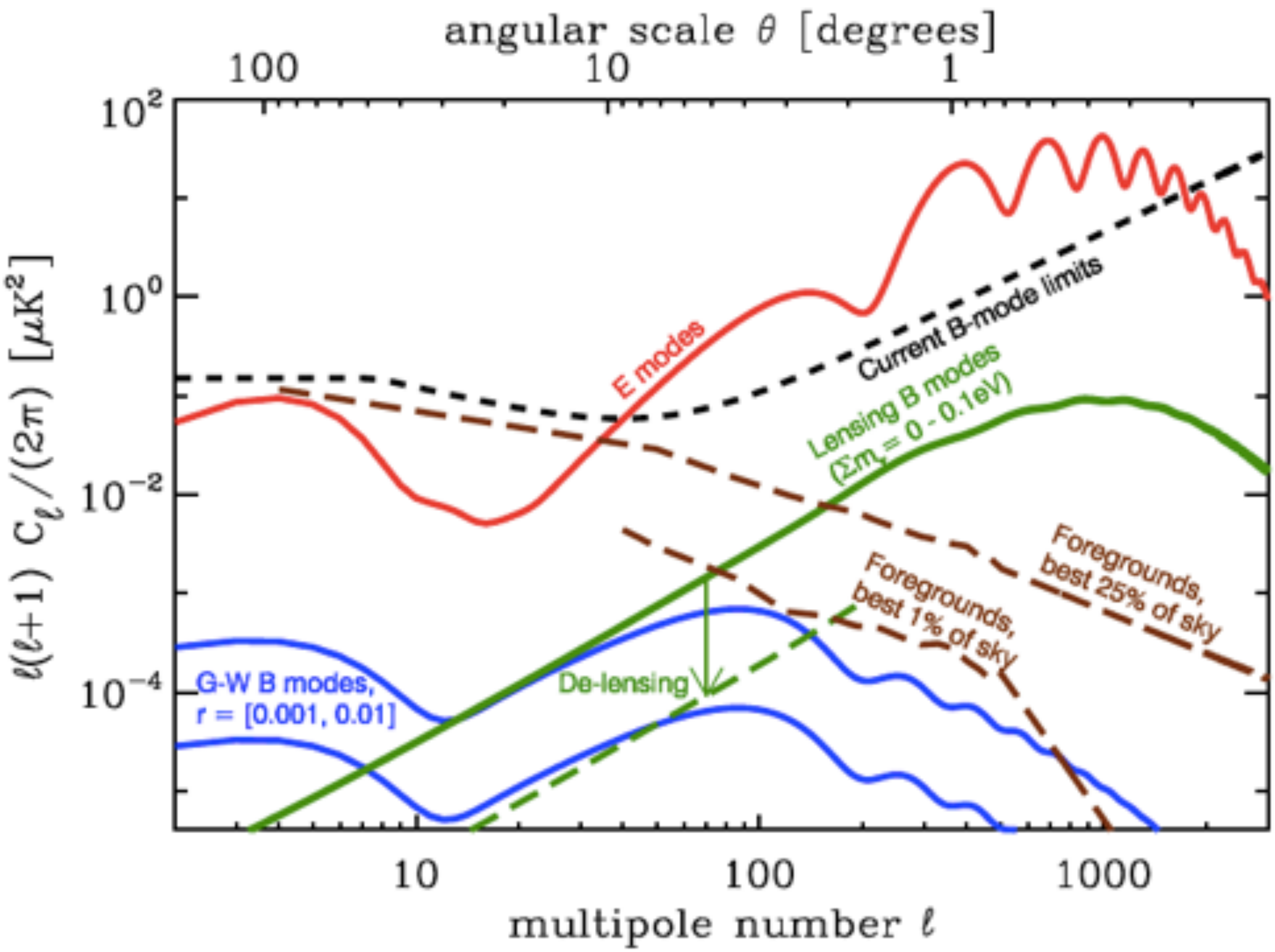
Cdns on the case; CMBpol satellites too?

SATELLITE MISSION OPPORTUNITIES FOR CMB POLARIZATION: WHITE PAPER FOR THE CANADIAN LRP MIDTERM REVIEW

Dick Bond[2,3], Scott Chapman[6], Matt Dobbs[1,*], Mark Halpern[4], Gary Hinshaw[4,*], Gil Holder[1], Peter Martin[2,3,5]
Barth Netterfield[2], Douglas Scott[4], Kendrick Smith[7], Keith Vanderlinde[2,5]

Draft version November 29, 2014

CMB stage IV

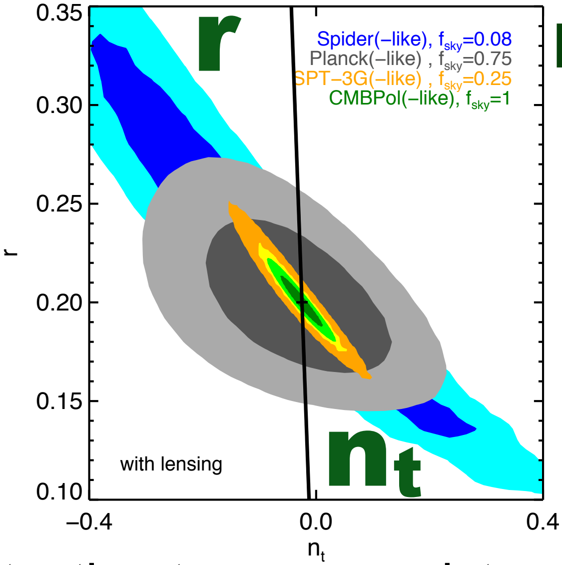


angular scale θ [degrees]
100
10
1
10^2
10^0
10^{-2}
10^{-4}
$\ell(\ell+1)\ C_\ell/(2\pi)\ [\mu K^2]$
E modes
Current B-mode limits
Lensing B modes
(Σm_ν = 0 - 0.1eV)
Foregrounds, best 25% of sky
Foregrounds, best 1% of sky
G-W B modes,
r = [0.001, 0.01]
De-lensing
10
100
1000
multipole number ℓ

future

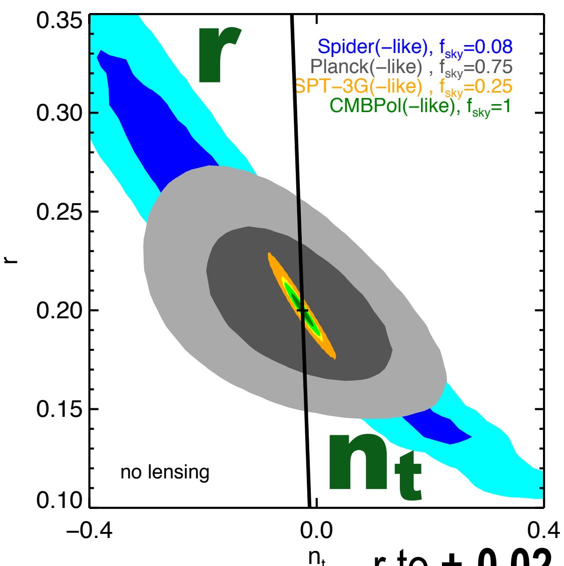
AdvACTpol (f_{sky}~50%): *Cosmological Forecasts*

Planck_f, Spider, SPT3g, .. CMBpol (CoRE+,Pixie,.)



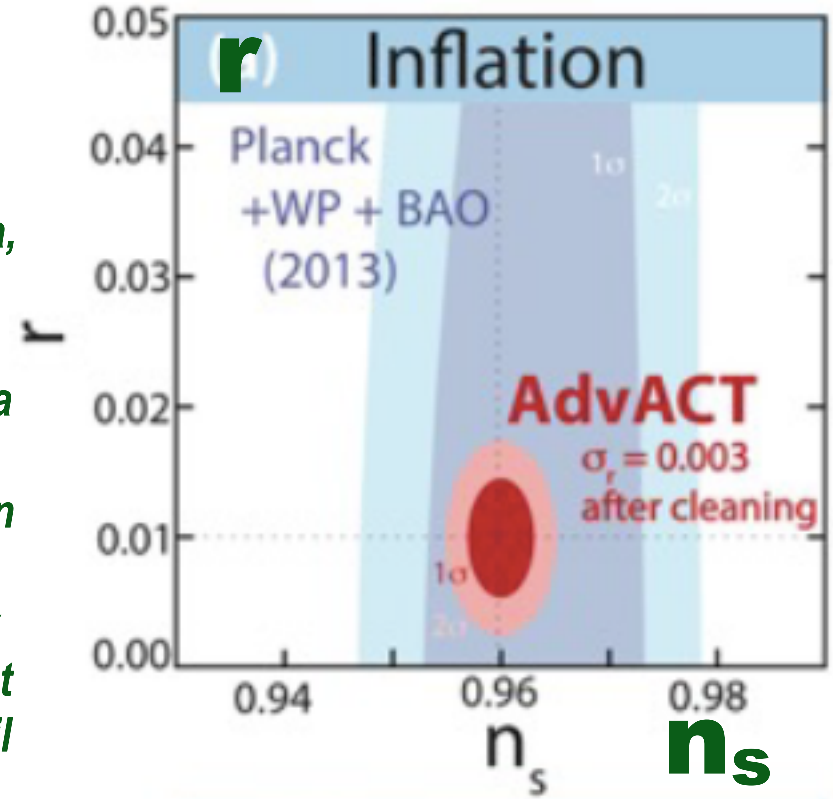
testing tensor consistency?

better f_{sky}=25% for spt3g/AdvACT-like than current 6% goal for spt3g



$n_t \approx -r/8$

nice BB spectra, hence a slope, but tensor consistency is a steep relation. how well we can do will depend upon the ability to de-lens to get to the high L tail

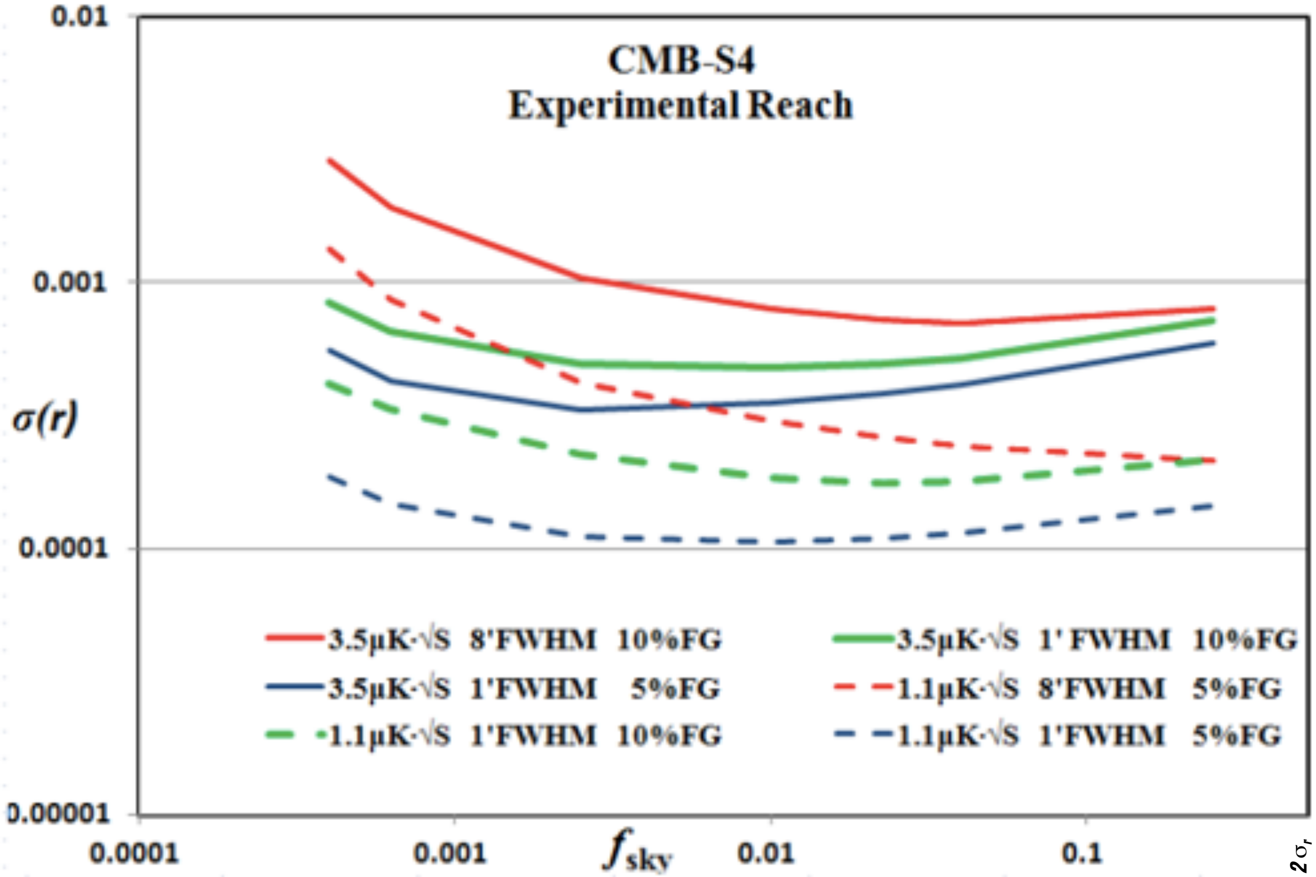


Planck_f uses pre-launch blue book forecast sensitivities

r to **+-0.02 Spider** forecast

r to **+-0.003 AdvACTpol** forecast w/ fgnds

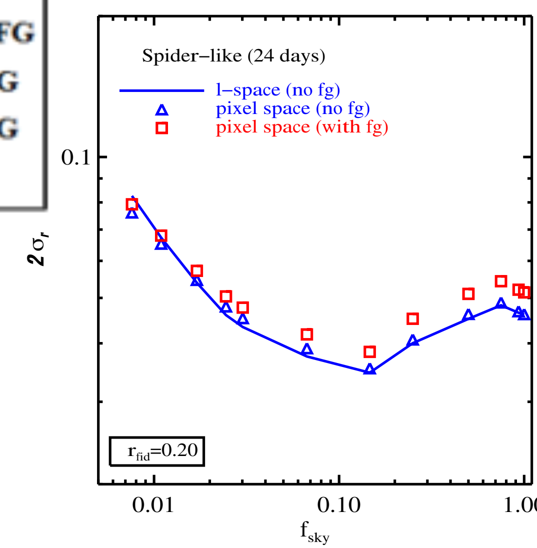
CMB stage IV
200-500K detectors @ SP, Atacama, Greenland (GLP)?



can we get such precision from the ground?
optimism informed by great technology
but to be shown

balloon future, higher frequency ULDB?

satellites?



Beyond Planck 2015 +LSS:
Inflation futures from CMB & LSS: LSS & nonG

≳10,000,000 T/E modes of tΛCDM
≲1000 modes of (slight) anomaly
≲200 modes T/E reionization history
the vast CMB-un-illuminated $\zeta_{LM}(d)$
LSS tomography f_{sky} L_{max}^2 k_{max} d_{max}
LSS ~ CMB x 1000?

New bispectrum constraints using full mission data including polarization

Shape and method	f_{NL}(KSW) Independent	ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	1.8 ± 5.6
Equilateral	−10 ± 69	−9.2 ± 69
Orthogonal	−43 ± 33	−20 ± 33
SMICA (T+E)		
Local	6.5 ± 5.1	0.71 ± 5.1
Equilateral	−8.9 ± 44	−9.5 ± 44
Orthogonal	−35 ± 22	−25 ± 22

ben wandelt, ferrara 2014
on behalf of Planck

Preliminary

2.3.1 Non-Gaussianity from the CMB

The current best limits on primordial non-Gaussianity are obtained using data from the *Planck* satellite [67]: $f_{NL}^{local} = 2.7 \pm 5.8$, $f_{NL}^{equilateral} = -42 \pm 75$ and $f_{NL}^{orthogonal} = -25 \pm 39$. At the angular scales that contribute most of the weight to the f_{NL} constraints, *Planck* has measured the CMB temperature fluctuations as well as they can be measured (i.e., the constraints on f_{NL} is now limited by cosmic variance, not noise). Adding CMB polarization information will improve this constraint, but at most by $\sqrt{3}$.

LSS & nonG

white paper on nonG+LSS on arXiv 1412.4671

outcome of CITA October 23-24 2014 meeting

DESI, LSST, Euclid .. CHIME .. SphereX proposal

the varieties of nonG f_{NL} … feature nG … preheating F_{NL} [χ,g]

scale-dependent bias & power spectrum on very large scales

bispectrum - more promising than scale-dependent bias it seems

nonG intermittent F_{NL}

=> search for large scale rare events, e.g., superduper superclusters

Testing Inflation with Large Scale Structure: Connecting Hopes with Reality

Conveners: Olivier Doré and Daniel Green

Marcelo Alvarez[1], Tobias Baldauf[2], J. Richard Bond[1,3], Neal Dalal[4], Roland de Putter[5,6], Olivier Doré[5,6], Daniel Green[1,3], Chris Hirata[7], Zhiqi Huang[1], Dragan Huterer[8], Donghui Jeong[9], Matthew C. Johnson[10,11], Elisabeth Krause[12], Marilena Loverde[13], Joel Meyers[1], P. Daniel Meerburg[1], Leonardo Senatore[12], Sarah Shandera[9], Eva Silverstein[12], Anže Slosar[14], Kendrick Smith[11], Matias Zaldarriaga[1], Valentin Assassi[15], Jonathan Braden[1], Amir Hajian[1], Takeshi Kobayashi[1,11], George Stein[1], Alexander van Engelen[1]

[1] *Canadian Institute for Theoretical Astrophysics, University of Toronto, ON*

LSS & nonG

	LSST	DESI	Euclid	SPHEREx	CHIME
Survey type	photo	spectro	photo+spectro	low-res spectro	21-cm
Ground or space	ground	ground	space	space	ground
Previous surveys	CFHTLS, DES, HSC	BOSS, eBOSS, PFS	no direct precursor	PRIMUS, COMBO-17, COSMOS	GBT HIM
Survey start	2020	2020	2018	2020	2016
Redshift-range	$z < 3$ (1% sources above 3)	$z < 1.4$, $2 < z < 3.5$ (Lya)	$z < 3$	$z < 1.5$	$0.75 < z < 2.5$
Survey area [deg^2]	20k	14k	15k	40k	20k
Approximate number of objects	2×10^9 (WL sources)	$22{\times}10^6$ gal., $\sim 2.4 \times 10^5$ QSOs	40×10^6 redshifts, 1.5×10^9 photo-zs	15×10^9 pixels	10^7 pixels
Galaxy clustering	✓✓$^\diamond$	✓	✓	✓	✓
Weak lensing	✓		✓		✓
RSD		✓	✓	✓✓	✓✓
Multi-tracer	✓✓	✓✓	✓✓	✓	

Table 2. A selection of currently funded or planned surveys. Other important surveys not included in the table are PFS, JPAS, PAU, EMU. Relevant survey links [LSST],[DESI],[Euclid], [UBC],[PFS], [JPAS],[PAU], [EMU]. $^\diamond$Galaxy clustering is possible, but very strong radial degradation.

LSS & nonG **SphereX** *is low-ish res, photo-z*

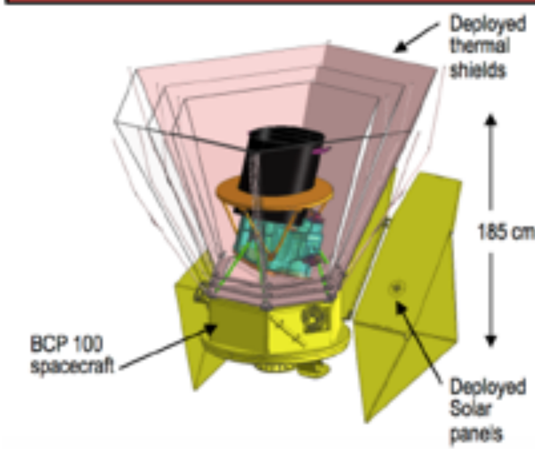
SPHEREx: An All-Sky Spectral Survey

A high throughput, low-resolution near-infrared spectrometer

Optical-IR imaging spectrometer
λ= 0.75-4.1 μm R=41.5
λ= 4.1-4.8 μm R=150
20cm telescope
Passively cooled
6.2"x6.2" pixels
2x(3.5x7) sq. deg. FOV

- ➡**Inflation Science**
  - ➡ Cosmology derived from 3-D galaxy large-scale structure.
  - ➡ Survey the $z < 1.5$ universe to fundamental limits to measure signatures of inflation, non-Gaussianity, the primordial power spectrum, and dark energy.
  - ➡ Complement Euclid and WFIRST which survey smaller areas at $z > 1$.
- ➡**Determine how interstellar ices bring water and organics into proto-planetary systems through absorption in ice spectra**
- ➡**Measure Extra-galactic Background Light to probe EOR**

SPHEREx data-set:
R=40 spectra spanning (0.75μm< λ <4.81μm) for every 6.2" pixel over the entire sky



SPHEREx Creates a High Legacy All-Sky Survey

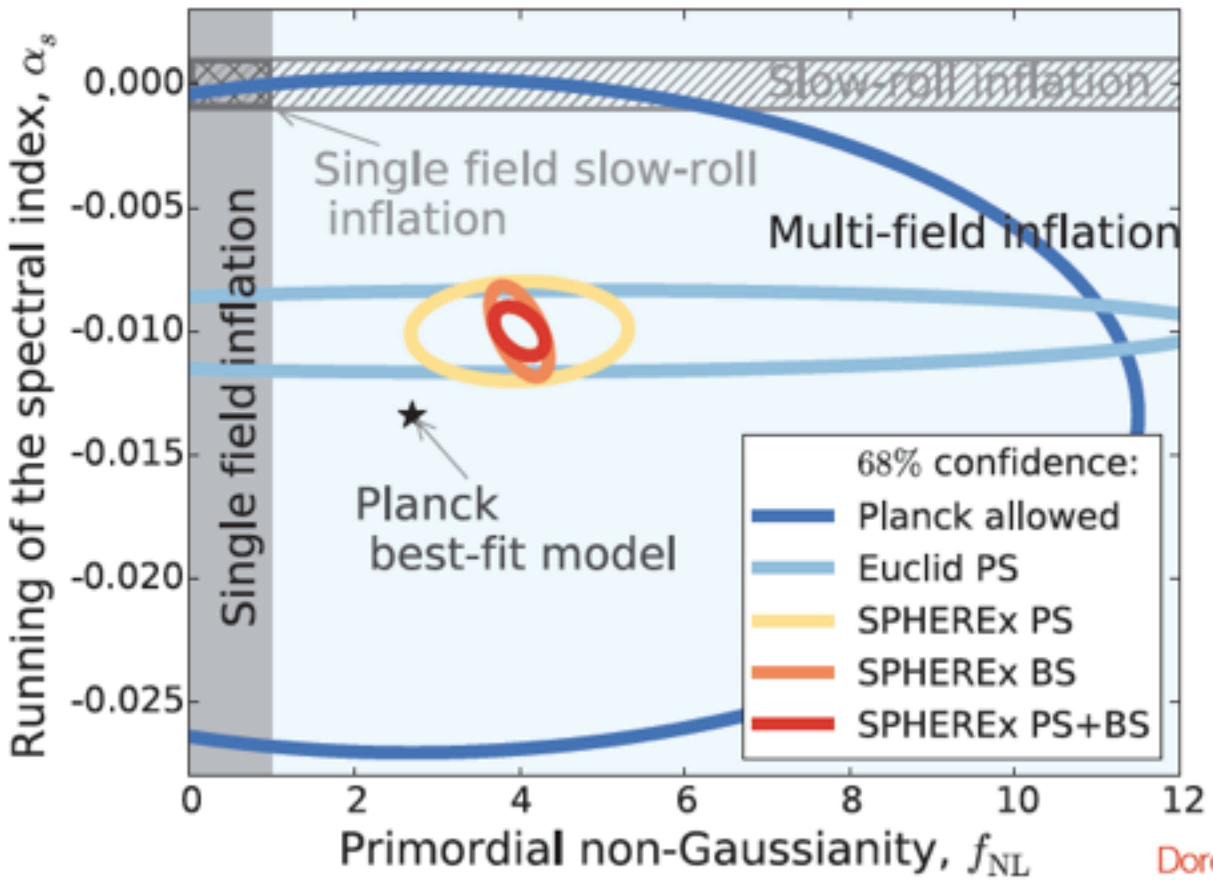
Extra-galatic sources	1.4 billion
	120M
	9.8M
	>1.5M QSOs with redshift
	0-300 QSOs with redshift > 7
	25,000 galaxy clusters with redshift
Galactic sources	>100M
	>10^4
	>400 brown dwarf spectra

SMEX Concept; PI: J. Bock, PS: O. Doré

LSS & nonG

SPHEREx as a Probe of non-Gaussianity

$\sigma(f_{NL}^{loc})$ ~ 0.8 (3-D Powerspectrum)
$\sigma(f_{NL}^{loc})$ ~ 0.2 (3-D Bispectrum)



Doré, Bock et al. 2014
Alvarez et al. 2014 1412.4671

bispectrum delivers more than scale dependent bias

CHIME Collaboration

THE UNIVERSITY OF BRITISH COLUMBIA

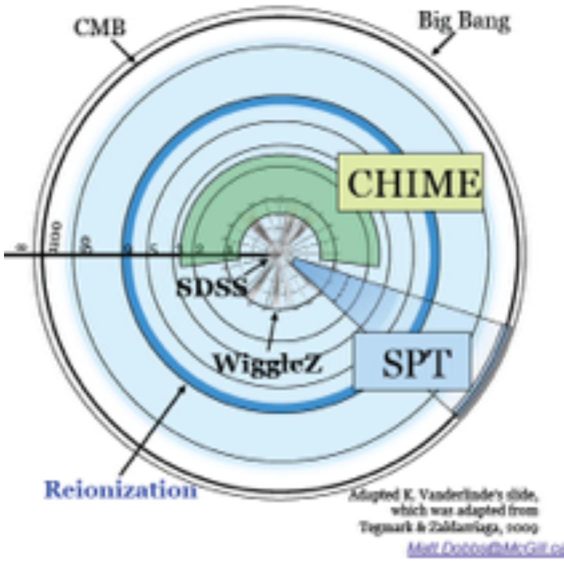
- Graeme Addison
- Mandana Amiri
- Meiling Deng
- Mateus Fandino
- Kenneth Gibbs
- Carolin Hofer
- Mark Halpern
- Adam Hincks
- Gary Hinshaw
- Kiyo Masui
- Kris Sigurdson
- Mike Sitwell
- Rick Smegal
- Don Wiebe

McGill

- Kevin Bandura
- J-F Cliché
- Matt Dobbs
- Adam Gilbert
- David Hanna
- Juan Mena Parra
- Graeme Smecher
- Amy Tang

UNIVERSITY OF TORONTO

- Dick Bond
- Liam Connor
- Nolan Denman
- Peter Klages
- Laura Newburgh
- Ue-Li Pen
- Andre Recnik
- Richard Shaw
- Keith Vanderlinde



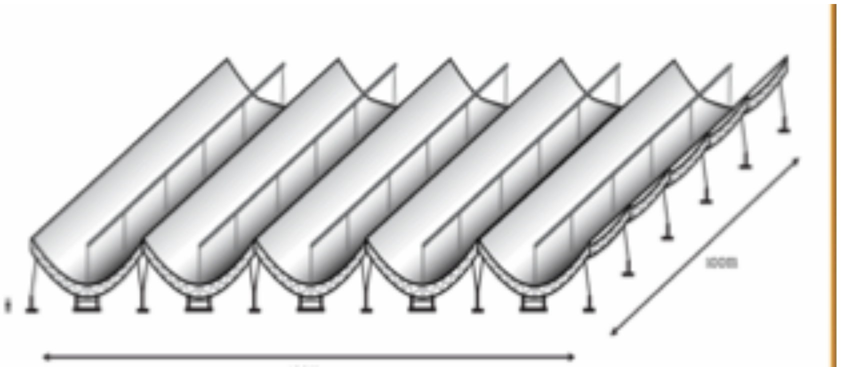
DRAO NRC · CNRC

- Tom Landecker

CMU Jeff Peterson
PI Kendrick Smith

will generate more data per second than the annual internet use of every smartphone in the world combined

the new radio astronomy, GPU-enabled



CHIME Collaboration

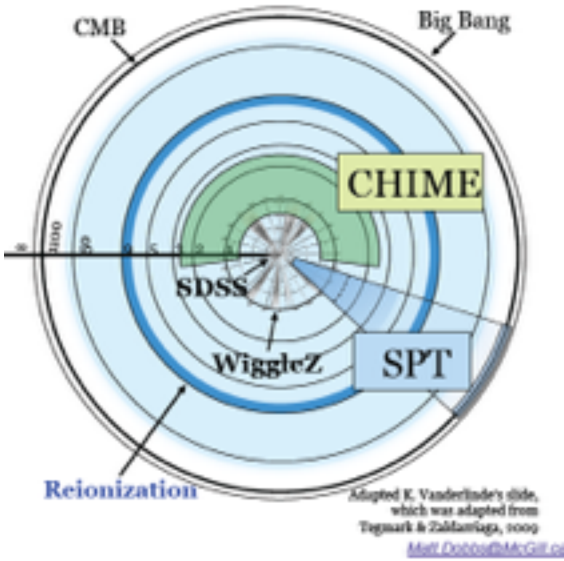
THE UNIVERSITY OF BRITISH COLUMBIA

McGill

UNIVERSITY OF TORONTO

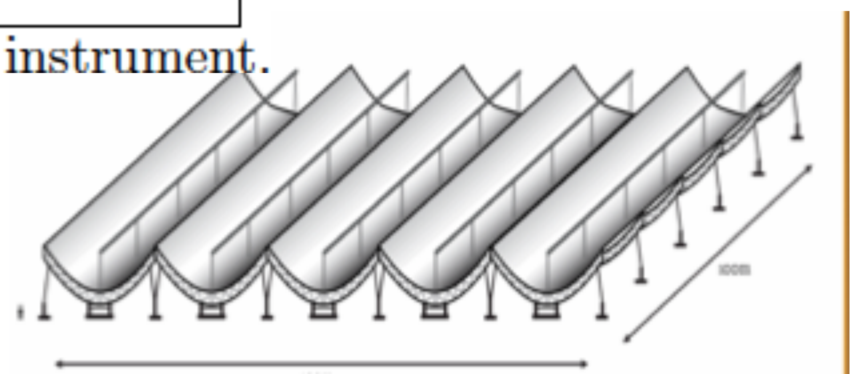
Location	DRAO (49°19′N, 119°37′W)
Number of inputs	2560
Frequency range	400 – 800 MHz
Frequency resolution	0.39 MHz
Wavelength range	75 – 37 cm
Redshift range	z = 2.5 – 0.8
Epoch	11 – 8 Gyr
E-W FOV	2.5° – 1.3°
N-S FOV	∼90° about zenith
Angular resolution	0.52° – 0.26°
Spatial resolution	10 – 50 Mpc

Table 1: The salient features of the CHIME instrument.



bandura+14, newburgh+14
spie proceedings, arXiv

the new radio astronomy, GPU-enabled



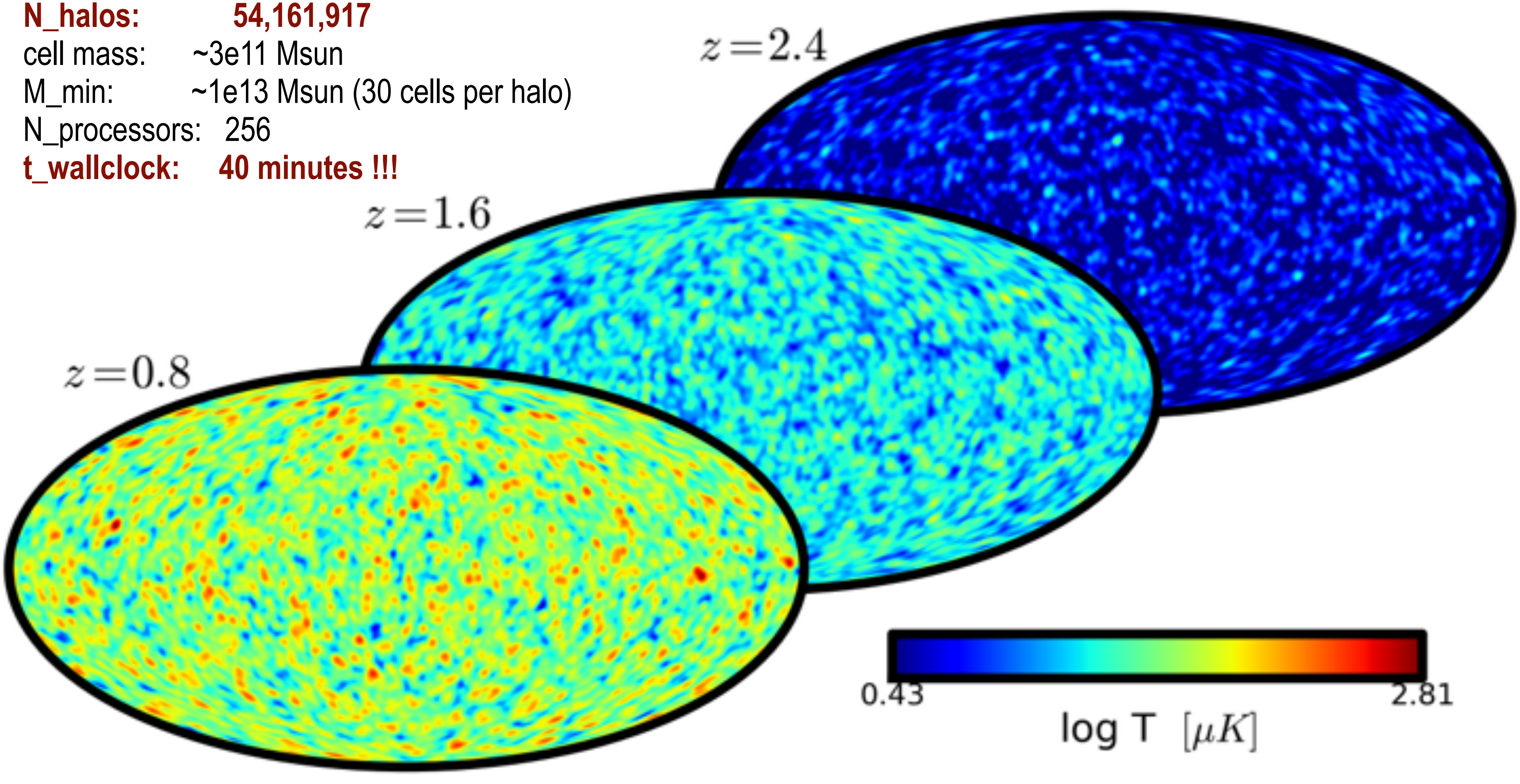
CHIME sample all-sky $\Delta\nu$ maps sim to 6 Gpc to cover z=0.8 to 2.5

$$\frac{L_{HI}}{M_H} = \frac{L_{HI}}{M_{HI}}\frac{M_{HI}}{M_H} = \frac{3hA_{10}\nu_0}{4m_{HI}}\left(\frac{\Omega_{HI}}{\Omega_m f_{col}}\right)$$

peak patch simulation details

periodic box: 12 Gpc
N_boxes: 9952
z_max: 2.5
N_res: 5860^3
N_halos: 54,161,917
cell mass: ~3e11 Msun
M_min: ~1e13 Msun (30 cells per halo)
N_processors: 256
t_wallclock: 40 minutes !!!

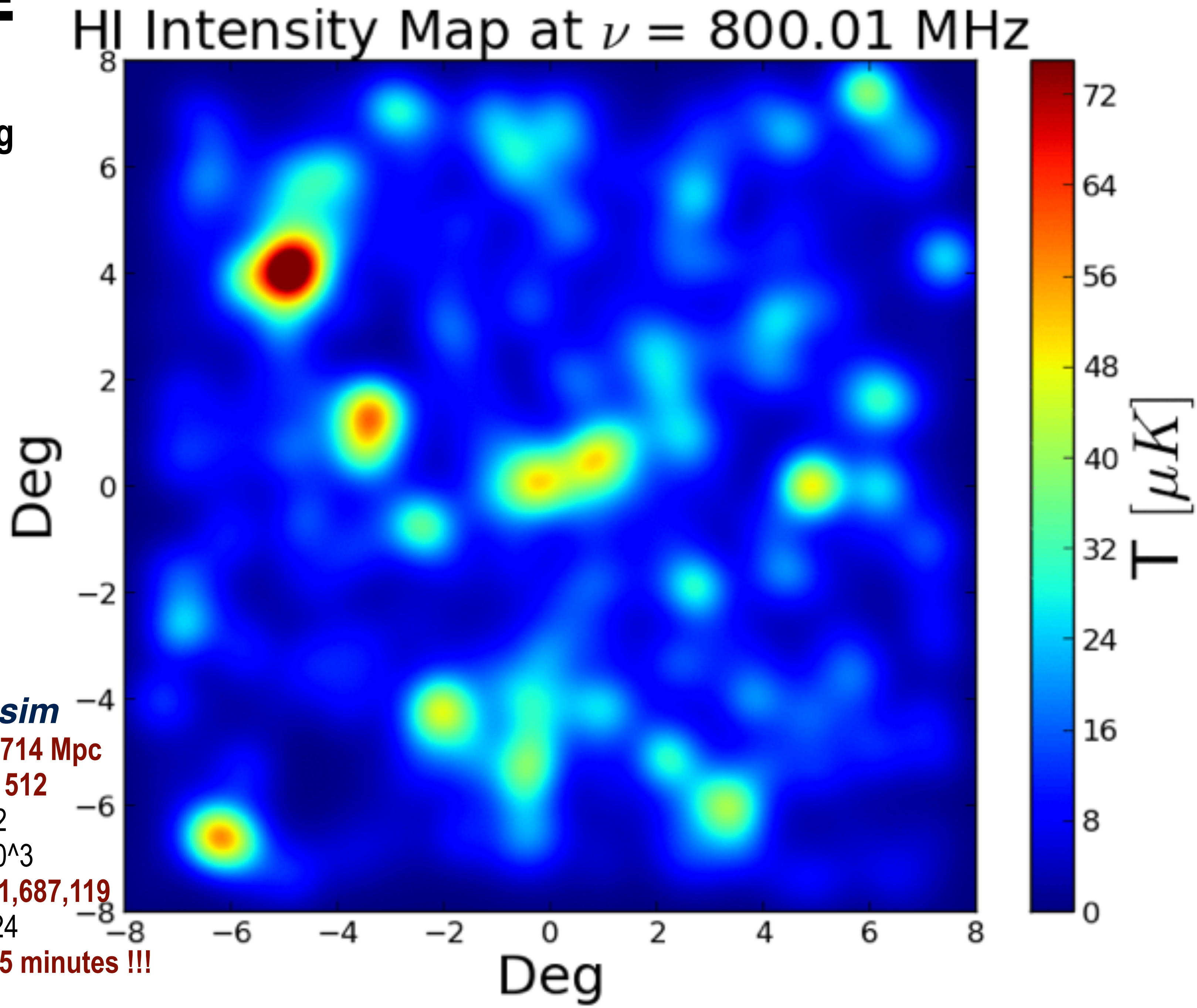
halo mass to total flux: Ω_{HI} = 0.5 x10^{-3}
from GBT X corr observations & f_{coll} = 0.2



CHIME

how the simulated HI sky changes with *ν aka z*

fwhm = 1deg



peak patch sim

periodic box: 714 Mpc

N_boxes: 512

z_max: 0.82

N_res: 1200^3

N_halos: 1,687,119

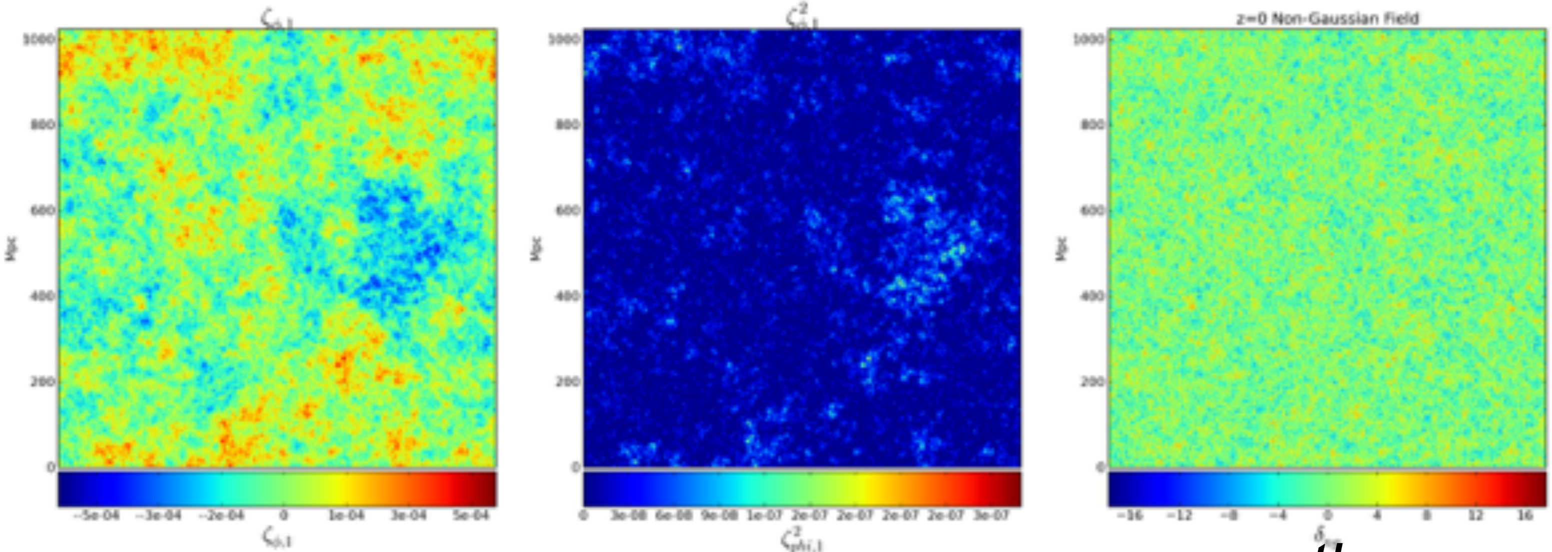
N_processors: 24

t_wallclock: 25 minutes !!!

alatt=1Mpc, N=1024

LSS & nonGaussian mocks

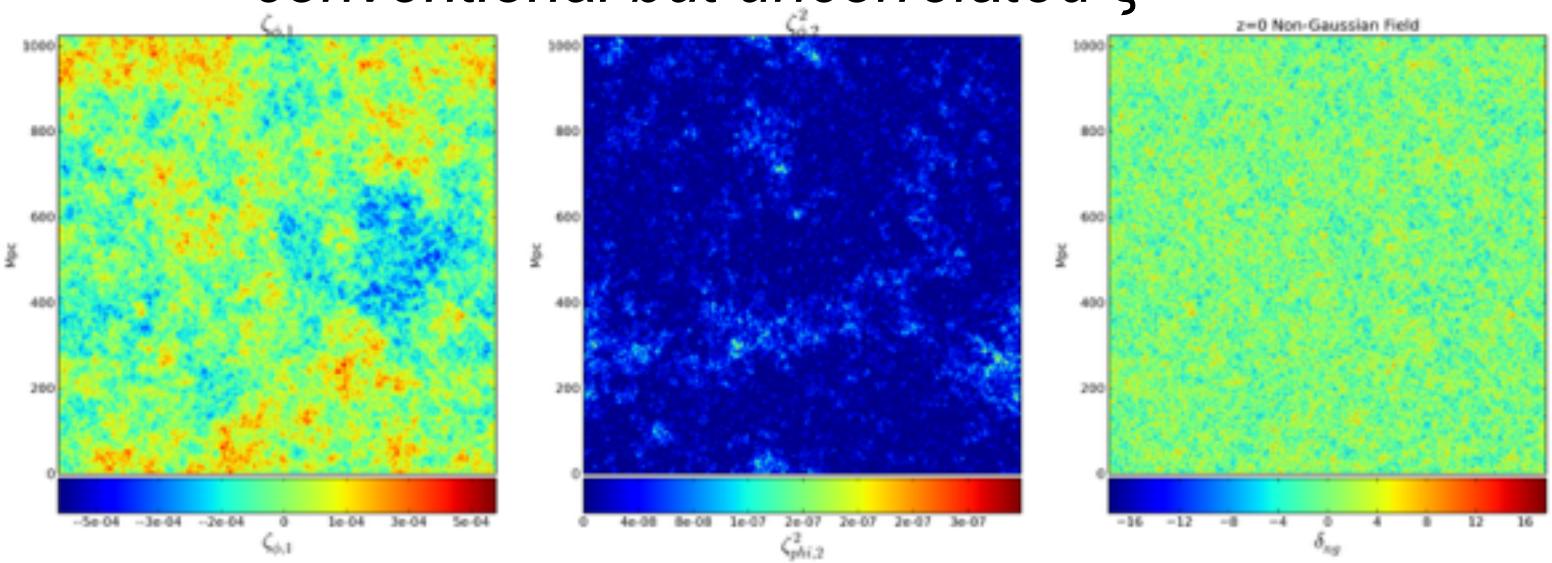
Alvarez,Bond,Huang,Stein,Braden,Frolov14



conventional inflaton-induced correlated ζ^2

the non-Gaussian initial density field

conventional but uncorrelated ζ^2

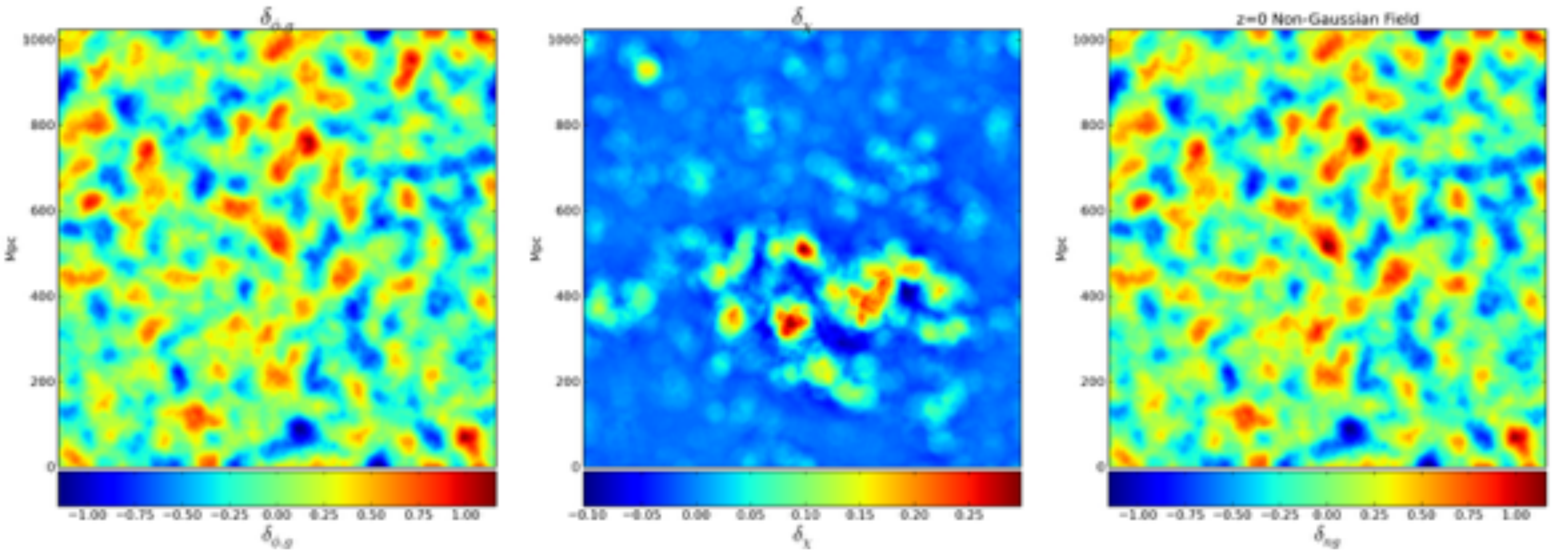


search with bispectrum & scale-dependent bias in power spectrum *alatt=1Mpc, N=1024*

LSS & nonGaussian mocks

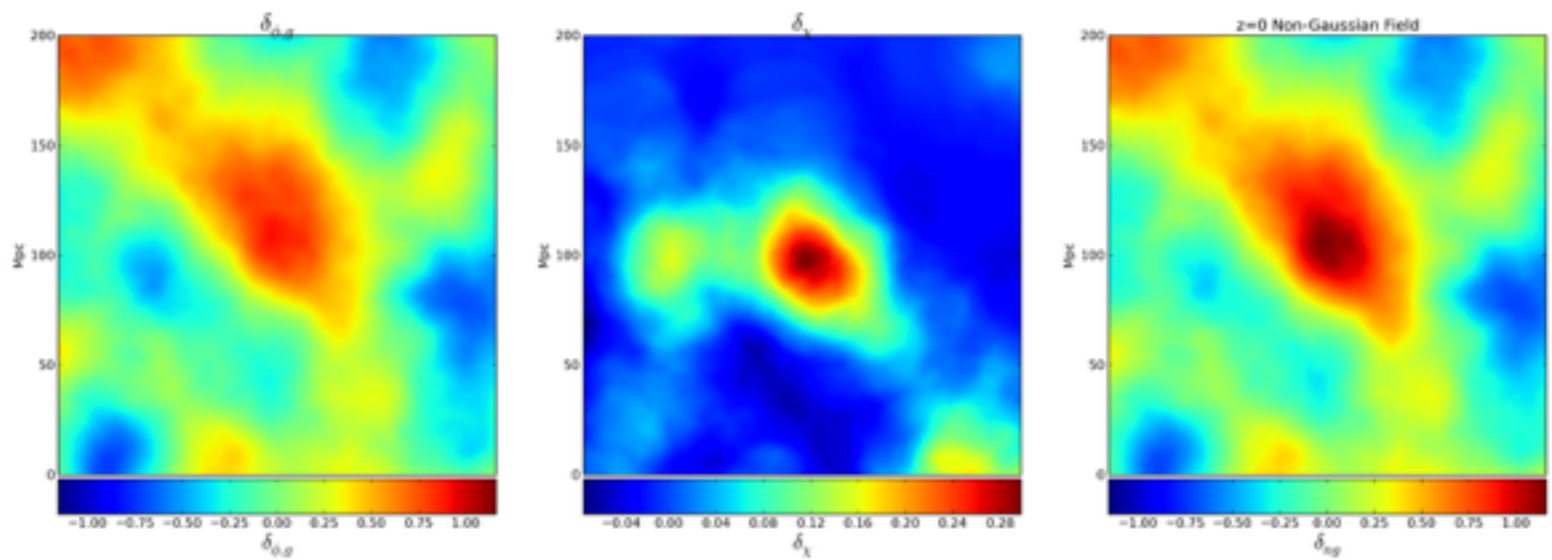
Gaussian Spike Model Smoothed on R=32Mpc

Alvarez,Bond,Huang,Stein,Braden,Frolov14



modulated intermittent preheating nonG

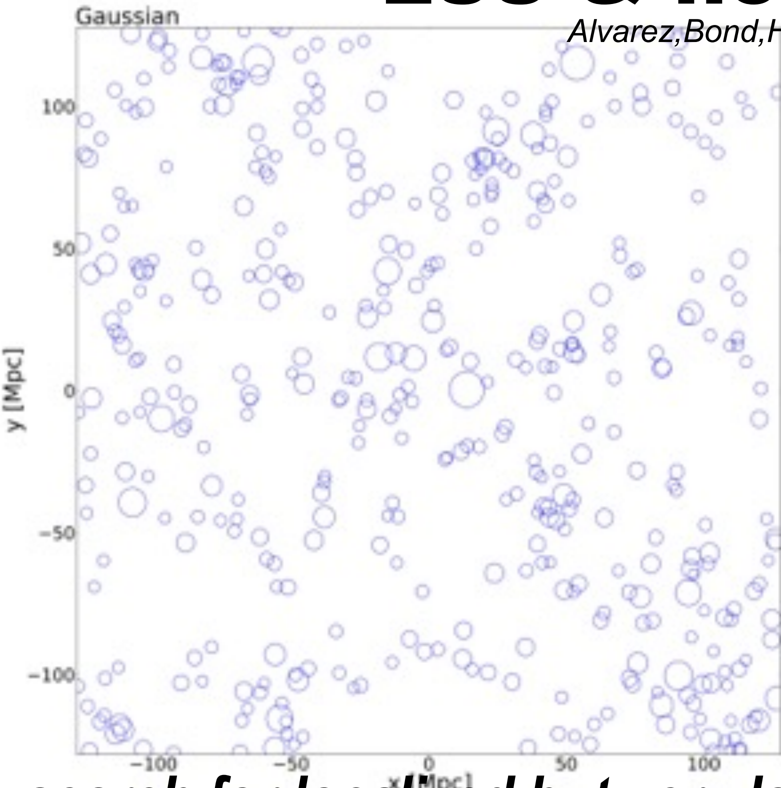
Gaussian Spike Model Smoothed on R=32Mpc



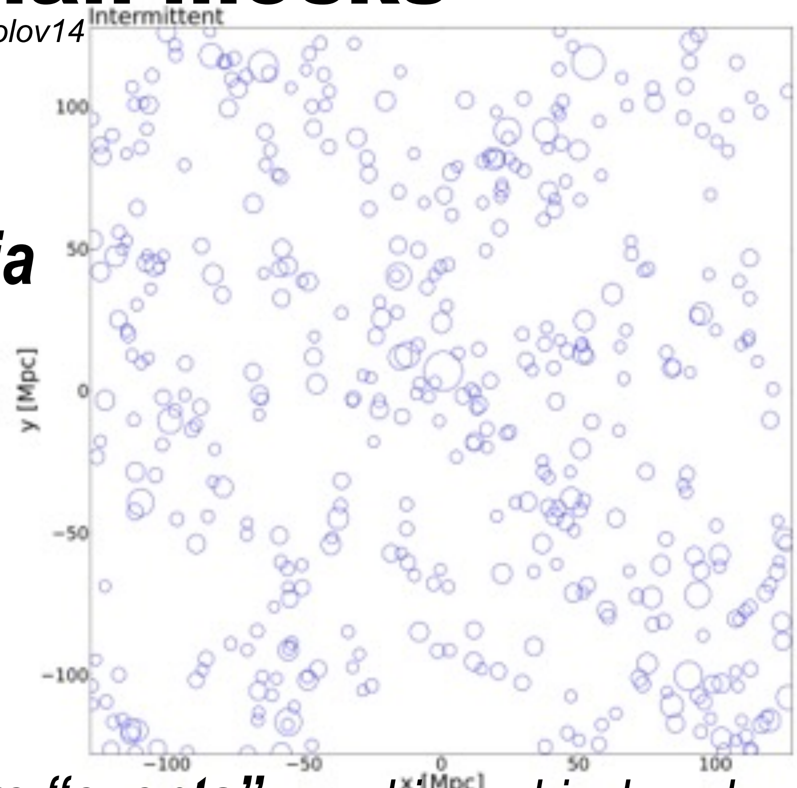
search for localized but very large scale rare "events" *e.g., hierarchical peaks*

LSS & nonGaussian mocks

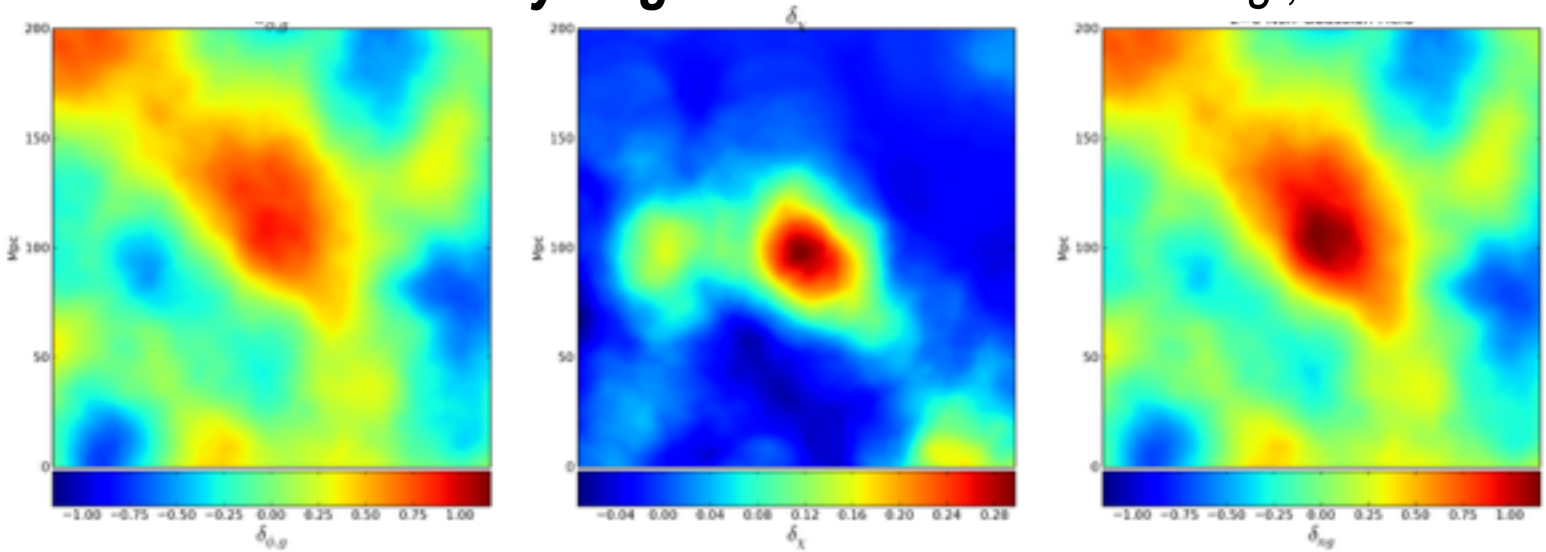
Alvarez,Bond,Huang,Stein,Braden,Frolov14



halo nonG patterns galaxies via HoD



search for localized but very large scale rare "events" *e.g., hierarchical peaks*



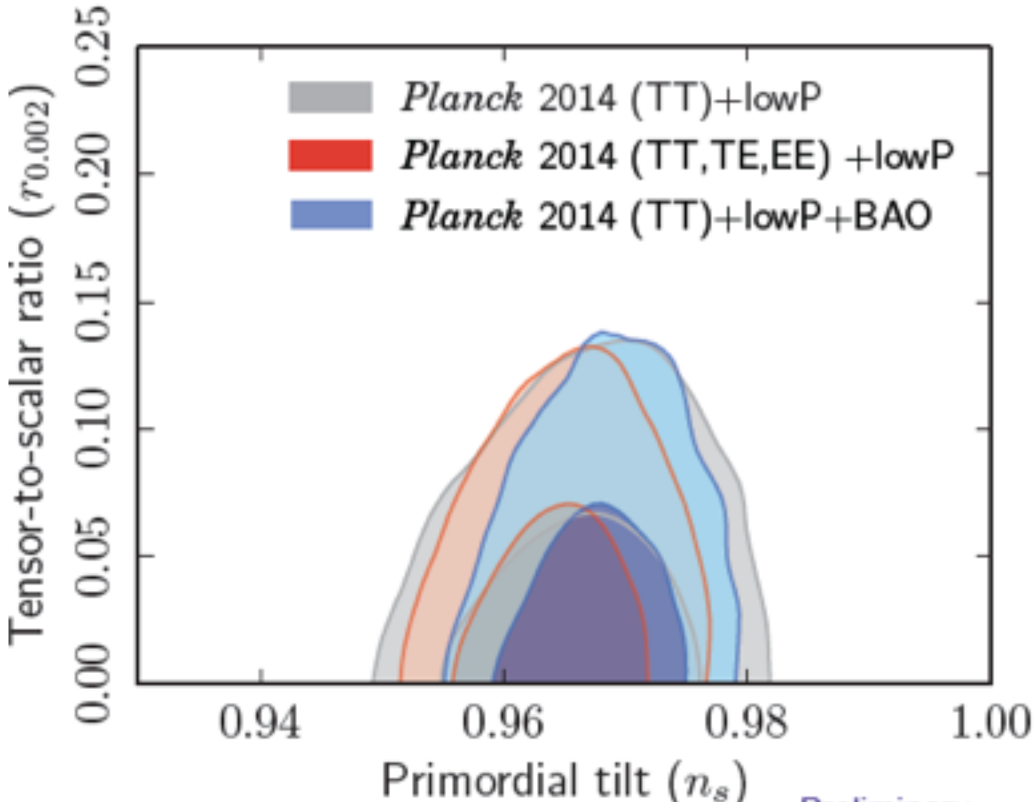
CMB restricts us to a projected 2D ζ-scape
we will reconstruct **phonon/isotropic strain** power,
but the future may look much the same as now (perhaps) => **V** => **ε**

r futures look bright modulo the dusty MW
we will reconstruct **graviton** power
de-lens for **consistency check** r-n_t **TBD**

thou shalt mock the LSS future *end-to-end*
to probe the 3D ζ-scape, modes abound
success modulo large scale mode control of systematics

the END

+ BAO



Preliminary

Constraints on tensors

$$r = \frac{\mathcal{P}_t(k_*)}{\mathcal{P}_\mathcal{R}(k_*)} \approx -8n_t$$

$r_{0.002} < 0.10$ (95 %CL, *Planck* TT + lowP) Preliminary

$r_{0.002} < 0.11$ (95 %CL, *Planck* TT + lensing + lowP)

$r_{0.002} < 0.10$ (95 %CL, *Planck* TT, TE, EE + lowP)

$r_{0.002} < 0.09$ (95 %CL, *Planck* TT + lowP/wWMAP)

WMAP 9 low resolution polarization data dust cleaned with Planck 353 GHz

0<r<.49 95%CL, .2±.15 1σ

cf. **r<0.11 uniform n_s**

*we don't need all LM+k modes to reconstruct L-independent $\mathcal{P}_\zeta$(**k**) in quadratic space*

$k^2 \sim L^2/d_{rec}^2 + k_{||}^2$

bonus: top-down ***de-lens***

Quadratic ln$\mathcal{P}_\zeta$(lnk) Maps

***aka* Radical Compressions**

=> ultra-early Universe sound/phonon spectrum

12 knots, cubic spline

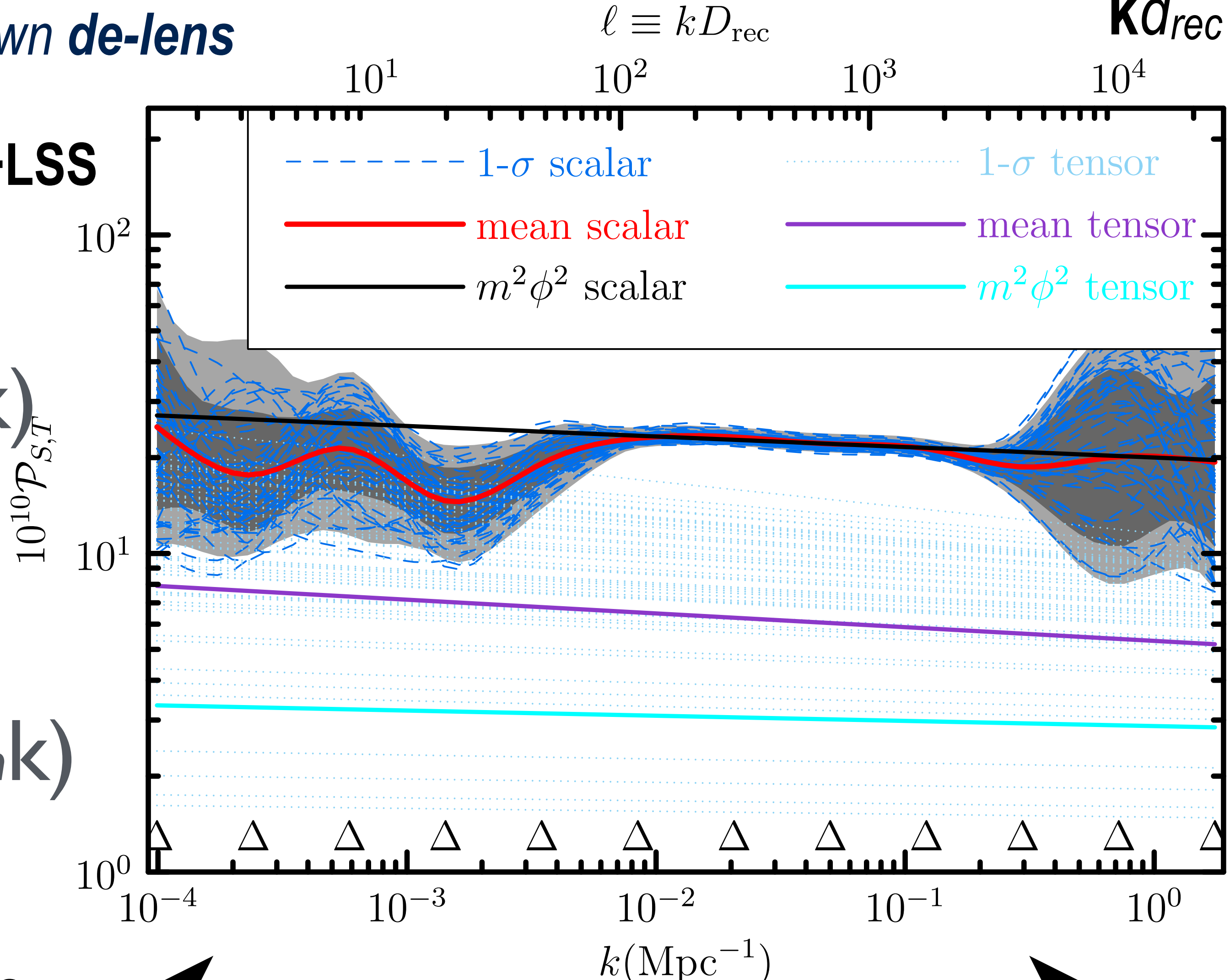
k*d$_{rec}$* ≳*L*

cf. **Planck13+LSS**

ln$\mathcal{P}_\zeta$(lnk)

Planck13 & WMAP => stable features

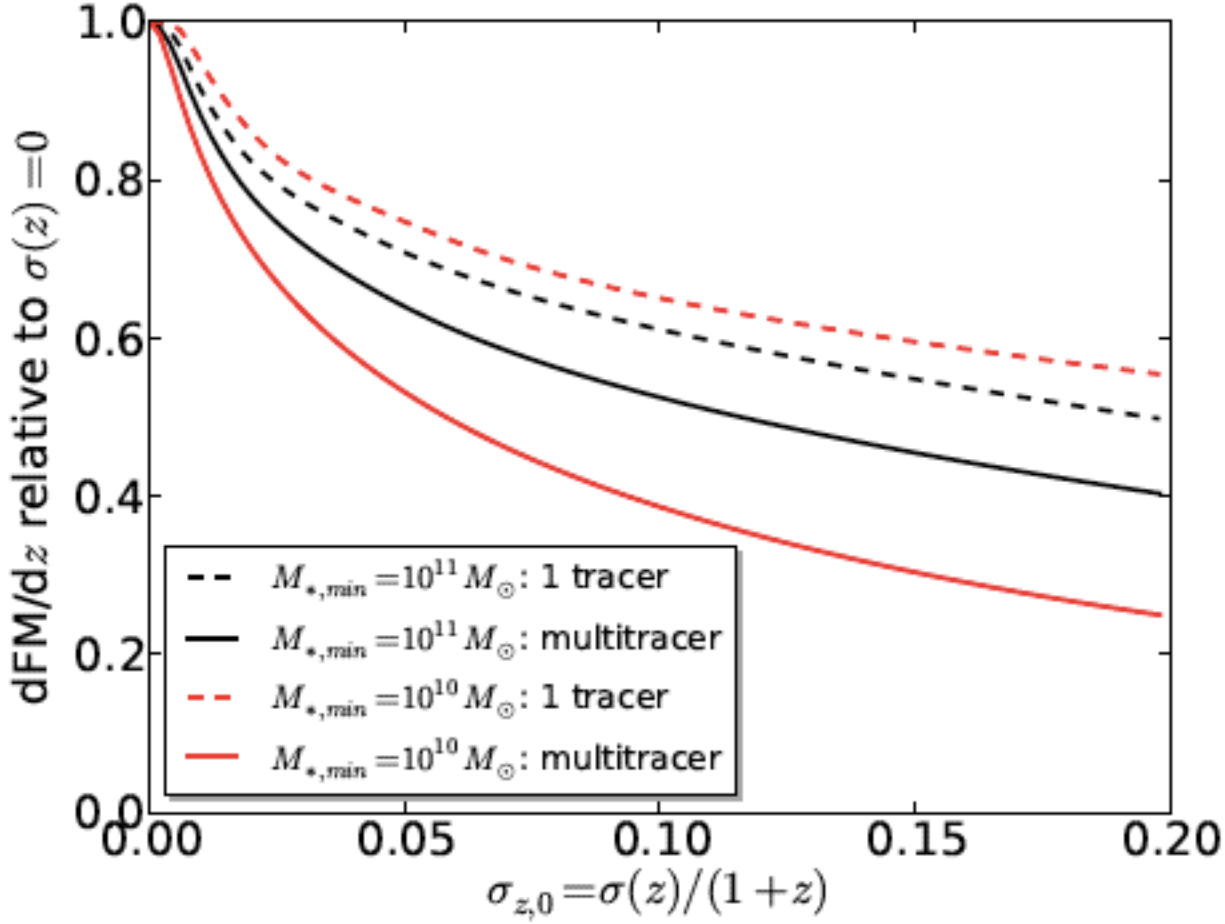
ln$\mathcal{P}_{GW}$(lnk)



9 e-folds

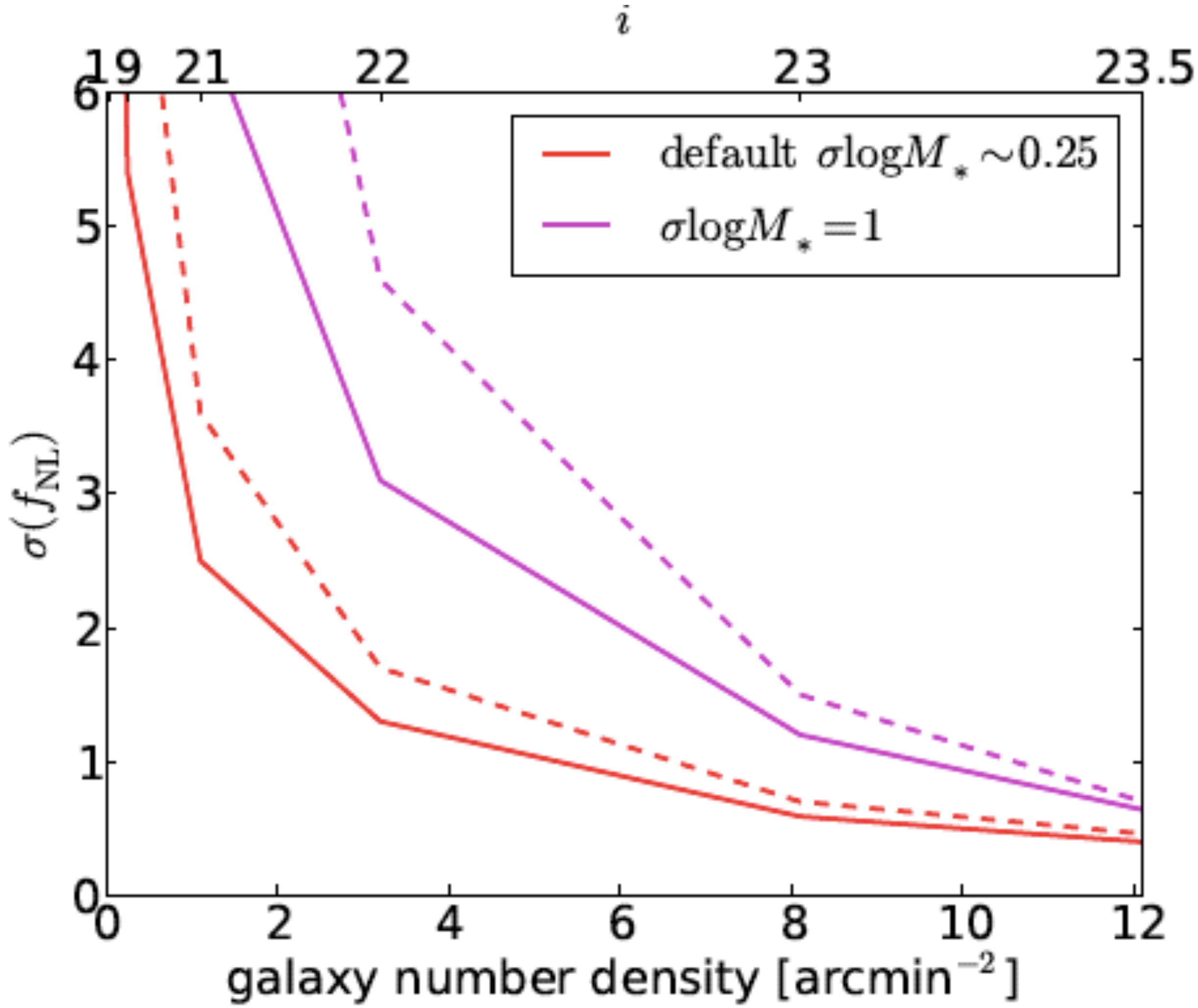
LSS & nonG

1412.4671



LSS & nonG

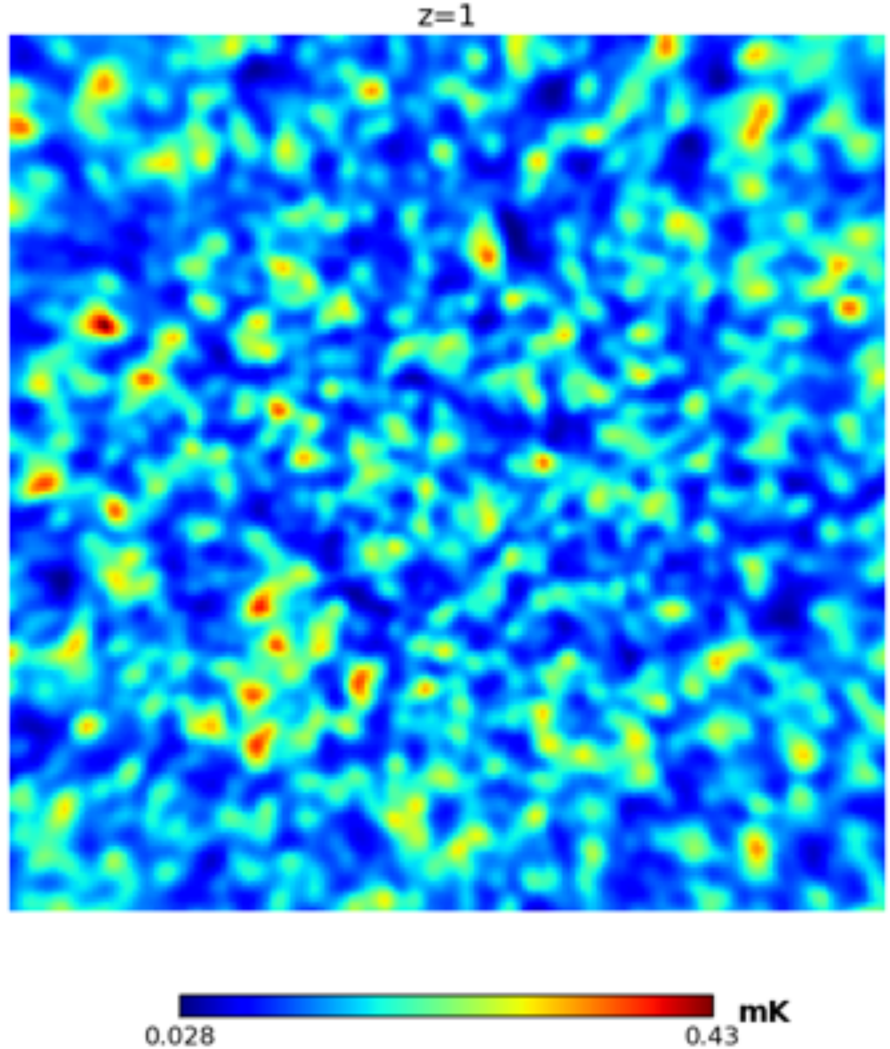
1412.4671



CHIME

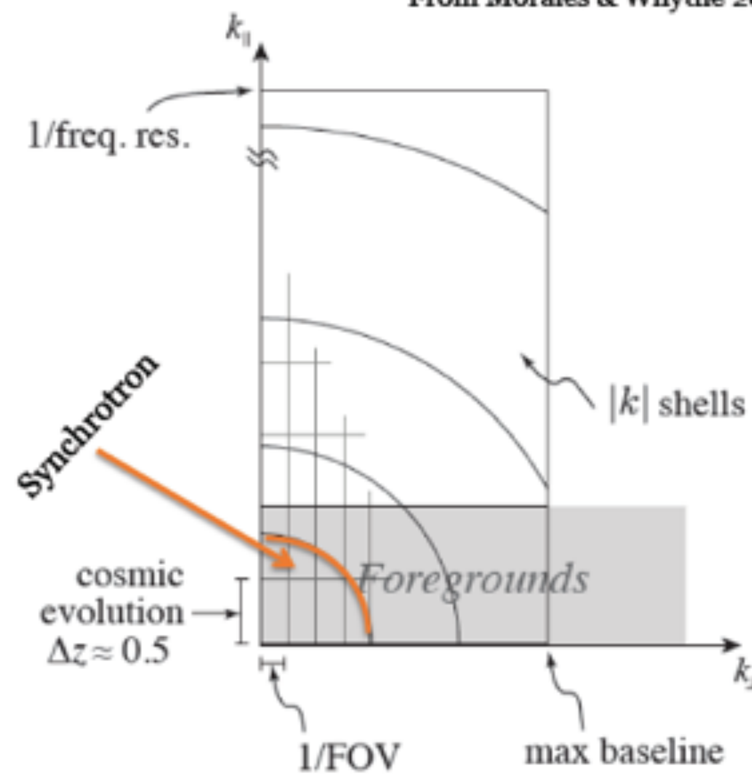
SphereX *is also low-ish res, photo-z*

z=1 zoom in brightness temperature zoom (with a stacked 20 MHz bandwidth)



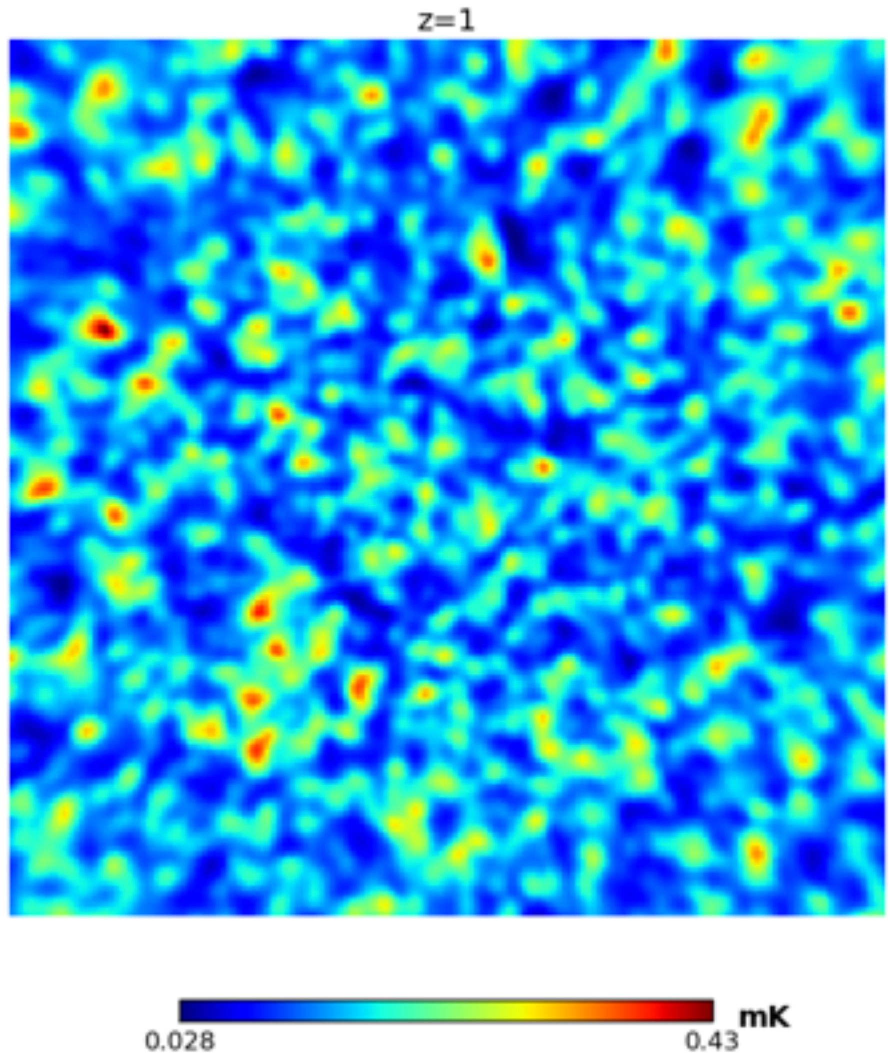
Galactic foregrounds (synchrotron) are smooth, but many many orders of magnitude cleaning is needed,
signal-to-noise eigenmode method Shaw+14
nontrivial processing is needed

From Morales & Whythe 2009



CHIME

z=1 zoom in brightness temperature zoom (with a stacked 20 MHz bandwidth)



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