SU The Entropic Matter(s) of an Ordered Universe: CITA@CITA Cosmic Information Theory & Analysis

Dick Bond@SU18 the nonlinear COSMIC WEB

dSG/dt

INFLATION

ν decoupling ~ms

recombination

primary anisotropies

- linear perturbations: scalar/density, tensor/ gravity wave dS/dt>0
- tightly-coupled photon-baryon fluid: oscillations δγ vγ πγ
- viscously damped
- polarization πγ DarkM
- gravitational redshift Φ SW dΦ/dt

Decoupling LSS

17 kpc (19 Mpc)

dS/dt>0

secondary anisotropies

- nonlinear evolution
- weak lensing
- thermal SZ+kinetic SZ
- dΦ /dt
- dusty/radio galaxies dG

Lsound/ ksound

DarkE

MILKY WAY

z=0

Bayesian flow prior to posterior via likelihood

dSastro <0

reionization

z ~ 1100

redshift z

z ~ 10

dS/dt>0

13.8-10^-50 Gyrs

13.8-10^-3.4 Gyrs

time t

10Gyrs

today

ν decoupling ~ms

recombination

the **nonlinear COSMIC WEB**

dS_G/dt

INFLATION

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- linear perturbations: scalar/density, tensor/ gravity wave $dS/dt>0$
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oscillations $\delta\gamma$ $v\gamma$ $\pi\gamma$

- viscously damped
- polarization $\pi\gamma$ **DarkM**
- gravitational redshift Φ SW $d\Phi/dt$

67

Decoupling LSS

17 kpc (19 Mpc)

BAO 7

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- nonlinear evolution
- weak lensing
- thermal SZ+kinetic SZ
- $d\Phi/dt$
- dusty/radio galaxies, dGs

3

Lsound/ ksound

CMB LENS

SNa LENS

H0

BAO (z)

2⇓1

cls ISW

DarkE

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Prob (system I order) | **entropy =<information-content>** Quantity Shannon 1948

"Now I am in the grip of a new vision, that Everything Is Information. The more I have pondered the mystery of the quantum and our strange ability to comprehend this world in which we live, the more I see possible fundamental roles for logic and information as the bedrock of physical theory. ... I continue to search."

IQ=information quality

IT from BIT
from BITs in IT

*the **medium** is the **message***
McLuhan 1964 UofT

$S_{fi} = \int dq\, P_f\, ln[P_f^{-1} P_i] = < s_{fi} | f > = < s_K s_{fi} - Tr \varepsilon_{fi} | f > = d\mathcal{F}_{s,fi}/d\alpha_s |_{\alpha s=1}$

generalized parameter space {q} ~phase space

*relative **Shannon** entropy= - KullbackLeibler divergence cf. **KolmogorovSinai** entropy*

$P_f(q) = \rho_f \sqrt{G_f}$ probability density functional **distribution function**

⇐ ***quantum*** (von Neumann) $S = -Tr\, \rho\, ln\, \rho = < s_{op} | \rho >$ **density matrix**

QITA Quantum Information Theory & Analysis

relative RENYI entropy of order α_S

$exp[-\mathcal{F}_{S,fi}(\alpha_S)] = < exp[-\alpha_S s_{fi}] >_i = exp[-(\alpha_S - 1) S_{\alpha S,fi}]$

concentration/clumping measure $ln <\rho^{\alpha S}>_V / <\rho>_V^{\alpha S}$

(1 is Shannon)

Statistical Paths in Cosmic Theory & Data via the* Bayesian chain = *Cosmoticians' Agenda

$P_f(q|D,\alpha T) = P(D|q,\alpha,T)\, P_i(q|\alpha,T) / P(D|\alpha T)$ ***Evidence aka Partition Function*** $exp[-\mathcal{F}(\alpha D|T)]$

D=CMB,LSS, SN,.., ***complexity****, life* *experimental sequence*

$P_f(q|D,T) = \int P_f(q|\alpha,D,T)\, P_i(\alpha|T)\, d\alpha$ ***T~thermostat=theory prior***

$\prod_e P(D_e|q,\alpha,T) \Rightarrow s_{fi} = \sum_e \delta s_e$

$d<s_{fi}>/dt<0$ parameter volume ⬇

α_A = ***control parameters*** *aka* ***order parameters*** *conjugate to* $<\Delta Q^A(q)$ *operators*

$S(<\Delta Q>) = \alpha_A <\Delta Q^A|\alpha> - \mathcal{F}(\alpha)$ ***LTE*** $\alpha_A(x)$ ***~Lagrange multipliers*** $-\beta\mu_J$ ***&*** $\beta=1/T$ ***&*** β****pressure, ..***

non-eq thermodynamics: ***flux*** $J_{heat}^i(x)$ $J_n^{Ji}(x)$ ***conjugate thermodynamical forces*** $\mathbf{B}_{Ai}$ $(\sim \partial_i \alpha_A)$ J_s^i

more control $C^{-1}{}_{ij}\, \delta q^i \delta q^j\, 2$ = ***GaussianRF,***

$S_{fi} = Tr\{ln\, C_f\, C_i^{-1} + 1 - C_f\, C_i^{-1}\}/2$

...N order correlations limit dof freedom = reduce entropy

to IQ filter, compress, reduce, marginalize

IQ~{minimal length messages/codes | error tolerance}

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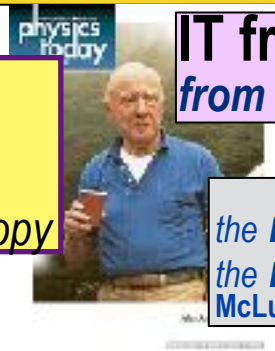

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Coherent Inflation with Quantum Jitter to Hot Big Bang, an Incoherent Particle Soup

how (most of) the entropy in matter

=> *GUT plasma/quark soup* => $S(\gamma,\nu)$ was generated *(through a shock-in-time)*

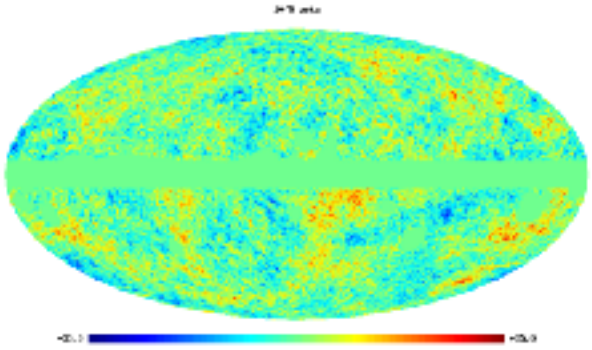
pre-shock KS dynamical entropy creates conditions for Shannon entropy controlled chaos

via nonlinear coupling of the inflaton to new interaction channels g,χ_a *ultimately to standard model degrees of freedom*

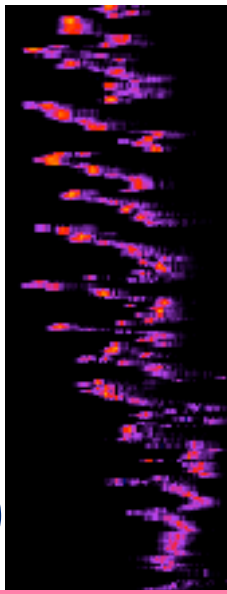
∃ a role for *decaying particles, 1st order phase transitions?*

exactly who, what, where, when, why?

we search for fossil "non-Gaussian" structures from this period with CMB +LSS



$a_{Shock}(g)$



non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating

Studying the
Cosmic Tango

Prob (Webskys I order) Prob (order)

some non-early U applications of "CITA" to cosmic-complexity

- information in **nearly-Gaussian** density/potential random **fields** of U, & in weakly and strongly non-linear fields. *ergodic theorem* & ***constrained fields***
- spatial coarse-grained **CMB entropy** & how we capture it
- **dark matter entropy, cluster &** ***protocluster*** **&** ***cosmic web*** **entropy**

MHD turbulence entropy with cooling & grain polarized emission - CMB fgnd **DUST**

- ***How Shannon info-entropy flows from CMB bolometer timestreams to marginalized cosmic parameters via Bayesian chains from prior to posterior. 1D & 2D & ... $\Delta S(q,DT)$*** *(cf. ACT10),* ***q=r, w, n_s, ...***

dS/dt 2

Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)

how most of the entropy in baryons & dark matter was generated

strain waves break => clusters/groups (galaxies/dwarfs) in the cosmic web collapse => shocked gas & extreme nonlinear phase space entanglement of dark matter / stars

KS dynamical entropy creates conditions for coarse-grained Shannon entropy - ps wrapping

then the baryons feed back entropy: exploding stars, accreting black holes => dusty CIB radiation

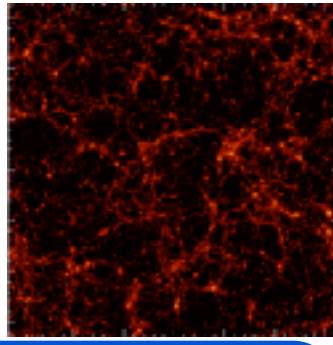
Learning the Cluster Tango

$S_{th,cl} \sim 10^{76}$

cf. $S_{U,m+r} \sim 10^{88.6}$

***Cosmic Hydro Sims** include all effects - except of course those not included Thou Shalt Mock*

(create a mini-ensemble of SPH gas+DM sims for SMc)



nr Sackur-Tetrode: $\Delta s = 1/2 \mathrm{Tr}\, ln\, G_{ij} + ln\, \rho^{-1} + 1$ *(includes clumping+anisotropy+..)*

fine-*macro-small*-grain 10^6 baryons in cubic metres cf. **sph--*macro-large*- grain 10^{65} baryons. ~26 dims per sph-grain, huge dimensional reduction, scaled-radial-*resolution*-grain further dim reduction. entanglement of fine & coarse & EFT. feedback.**

A Figure of Merit: Lyman Cooling flows in Parameter Space

By the mid to late 80s, the inflation-based theoretical control-parameter space was defined, including the basic 6 +r+Ω_k+Λ (even dynamical DE via Peebles & Ratra). & beginnings of non-Gaussianity.

basic 6 includes (n_s A_s) cdm, B, Compton depth tau_C, H0 derived

story since: the incremental Bayesian flow from theory prior to eye-of-the-needle constraints. Continuous process, with many contractions.

figure of merit for experiments, $\langle \ln VOLUME_{ps} \rangle$ = posterior Shannon entropy: *how the (radically compressed) one-dimensional entropy of cosmic parameters, the high quality bits we quest, did/will change as the experiments became/become more & more precise.*

Shannon entropy difference $\Delta S_{fi}(q,DT)=\int dq\, P_f \ln P_f^{-1} - \int dq\, P_i \ln P_i^{-1}$

figure of merit for anomalies & tensions are the observed entropy fluctuations δs_obs compatible with $P_i(\delta s \mid D1$ fiducial ~SMc) e.g., D1=Planck2018 best-fit SMc; P(q|D1,D2) bimodality

we compress the Petabit++ observed cosmic info into a precious few IQ bits encoding 6+ parameters of the Minimal Cosmic Standard model (tilted ΛCDM) - and anomaly/tension characterizations

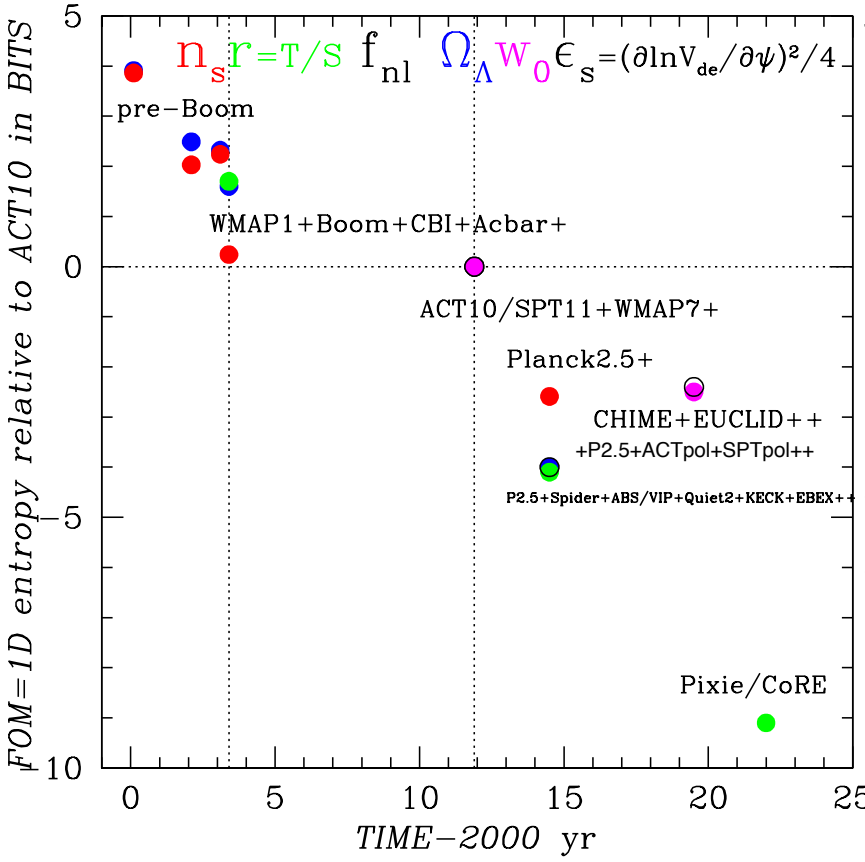
WMAP: 1.15 Tbits in 9yrs, cf. MyLifeBits, Gordon Bell, 1.28 Tbits in 9yrs, Planck 36 Tbits, ACT 304 Tbits. Radically Compress to high quality Bits. Terabit=10^{12}bits=125 GigaBytes.

vintage 2012 *snapshot of the past & forecasted future* $\Delta S_{1D,fi}$

a figure of merit for experiments, <ln VOLUME$_{ps}$> = posterior Shannon entropy: ***how the (radically compressed) one-dimensional entropy of cosmic parameters, the high quality bits we quest, did/will change as the experiments became/become more & more precise:***

$\Delta S_{fi}(q,DT)$
i=ACT10

⬇ IQ



the **entropic flow** measured relative to **ACT10+WMAP7**

cosmic parameters are **entangled.** 1D is the system, other parameters, cosmic +**nuissance** = reservoir

measured in **bits**, each lowered bit is a very big deal

in many measure parameters, **Planck15 close to forecast (& Planck18 moreso)** - but not for r!

Calibrese+13 **ACT+SPT+WMAP9 parameters (***updated 17***) cf. Planck13,15..18 ~ params close**

shows how optimistic our timelines were cf. now
Spider still analyzing 2018 paper, maybe late 2018 second launch; no EBEX, Quiet2, ABS trail blaze but ..
Planck 2.5yr about right, fully bona fide pol Planck 2018
KECK is there (aka Bicep/Keck)
Euclid first data ~2023+
ambition of **AdvACT, SPT3g not envisaged (stage 3) & Simns Observatory, CMB Stage 4, LiteBird + ..**

forecasting is alive and healthy, SO, CMB Stage 4, etal. - the future is cooler still

2D ΔS_{2f} for DarkE improves by ~5 bits

early & late Universe theory issues

new physics lurking in real webskys

anomalies?

all expts agree ∃ large entropy fluctuation δs_obs from the SMc equilibrium

δs_obs cf. P(δs|D1) outlier. are systematics under control?; have nonG tails in P(δs) been taken into account?; or can the anomaly rise to a solid > 18 bit fluctuation aka 5sigma => new theory control parameter But <(δs)^2|D1> at lowL

tensions?

2 expts have a large-ish entropy fluctuation in an SMc control variable,

δs_obs cf. -lnP(δs)|D1> -lnP(δs)|D2> are systematics under control?; have nonG tails in P(δs) been taken into account?; or can the anomaly rise to a solid > 18 bit fluctuation => 2 wells emerge, symmetry breaking, new order parameter e.g., low z H0 cf higher z H0

what are the **degrees of freedom / parameters** *of the* **ultra early Universe?** *TBD*
what is the **theory prior** *of the* **ultra early Universe?** *TBD wide open landscape?*

Quantum Inflation - if quantum energy then quantum gravity (entangled) then gravitons
Phonons *density fluctuations = Trace strain = spatial 3-volume fluctuations*

=> *combined* **entropy-like measure** ζ =inflaton

$\zeta(x,t) = \int_{\text{field-path}} (dE+pdV)/3(E+pV)$

Gravitons *tensor perturbations transverse traceless strain* $P_{GW} = r\,P_\zeta$ *grail* $r < .07$ *now, to* $< .001$
Isocons *when multiple particle-species - orthogonal scalar degrees of freedom to inflaton/phonon*
Dilatons *4-volume fluctuations - Higgs inflation* $L_G(R)$ *gravity - conformally-flatten potentials*
moduli, axions *connection to particle physics models "fundamental scalars" .. string theory*
fermions, vector gauge fields, *Standard model of particle physics* **.. vector perturbations**

begin-inflate => inflate => end-inflate => preheat => non-equlibrium heat+entropy
=> *Standard Model particle physics* **QuarkGluon plasma radiation dominated**
=> dark matter dominated *structure via gravitational instability* **=> dark energy now**

order **parameters** *from the* **ultra early U?** *so far* $\zeta \approx GRF,\ \mathcal{P}_{\zeta\zeta}(k)$ *2* ζ*-params*

random sound **loudness** $P_\zeta(k_p)$**+ bass/treble** $n_s = 0.968 \pm 0.006$ *5.6σ from 1*

coarse-grained *stochastic inflation k~Ha resolution/dynamics relation*

$d\zeta(x,Ha) = [\mathcal{P}_{\zeta\zeta}(k)]^{1/2}\ [d\ln Ha]^{1/2}\eta_{GRD}(x,Ha)$ *quantum fluctuations & no drift*

cf. $dS_{fi} = dS_{KSfi} - dTr\mathcal{E}_{fi} = \delta S_{fi}$ *(fg-> cg) FokkerPlanck for Prob(*δS_{fi}*| control)*

the **true quadratic ζ-Websky** of the **ζ-scape**

Planck 2015 XX inflation => Planck 2018 inflation: TTTEEE lowL Epol + BK15 BB

CMB TT power L~ 20-30 dip => ζ-Spectrum k-dip; *includes CMB lensing, parameter marginalization*

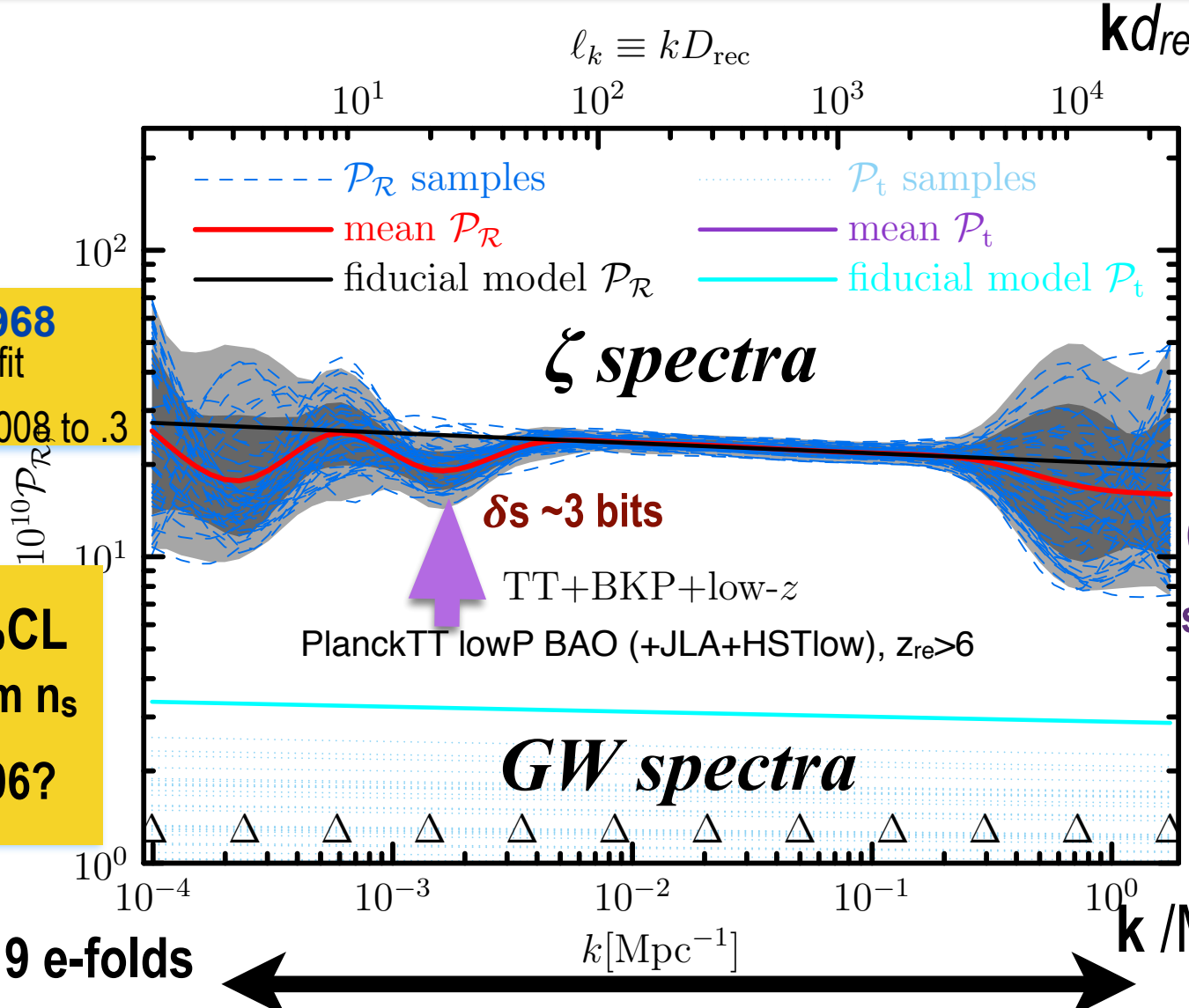
kd_{rec} ≳L

uniform n_s=0.968
P15+LSS best fit

superb 12-knot fit k~ .008 to .3

GW: r<.11 95%CL
cf. **r<0.09 uniform n_s**

r<0.07 BK, <0.06?



EE (L>30) looks similar

=> V(ϕ)

9 e-folds

k /Mpc

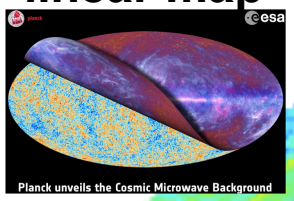
$\langle\zeta|$*Temp, E pol*$\rangle$-*WebSky* reveals *early universe phonons*

ζ- TOPOGRAPHY & CARTOGRAPHY

=> @a ~$1/10^{55}$ only 2 numbers
more: r? $n_s(k)$? nonGaussian; isocons

caution: not de-lensed, but the Wiener filter does partially de-lens

linear map



Planck 2015 XVII nonG

40 arcmin fwhm

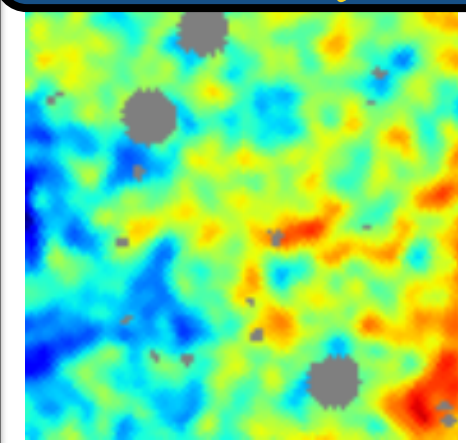
random sound loudness $P_\zeta(k_p)$+ bass/treble n_s =0.968±0.006 *5.6σ from 1*

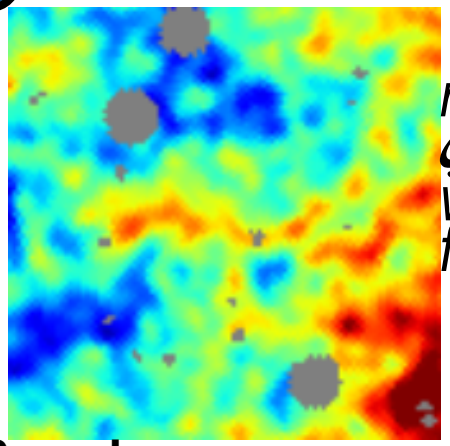
visibility mask

$\int$d ***visibility***(*distance*) $\langle\zeta|$*Temp, E pol*$\rangle$ (*angles, distance*)

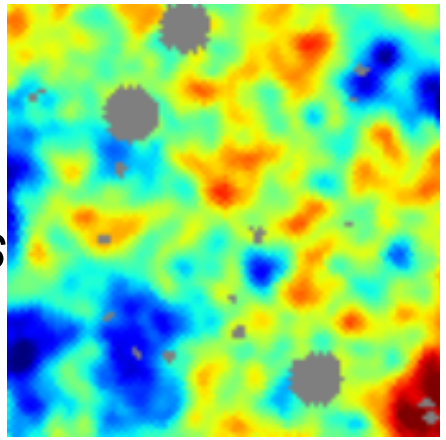
real ζ -WebSky mean field

visibility mask





real ζ-WebSkys with fluctuations

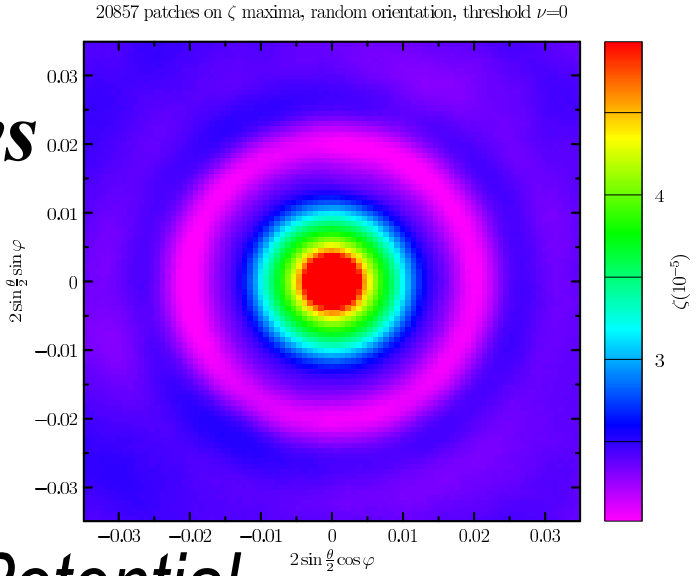


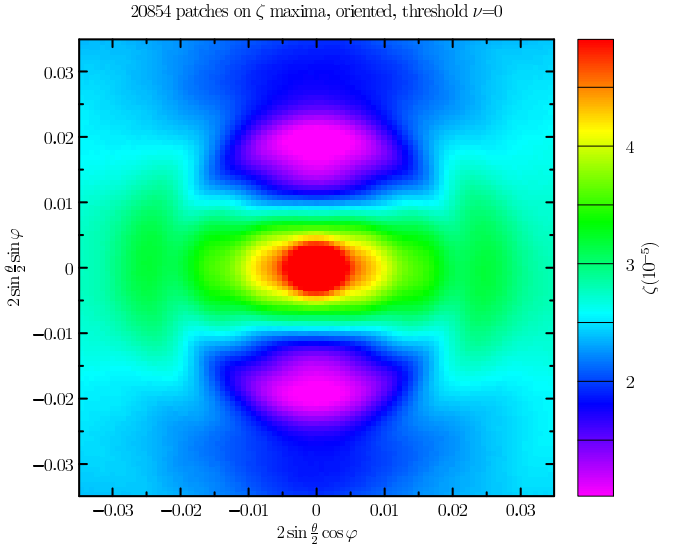
20x20 sq deg

zoom in, higher res: 20 arcmin fwhm

real ζ-WebSkys stacked to damp fluctuations

$\langle \zeta | \zeta_{pk} \rangle |_{dv}$





similar to -Gravitational Potential WebSkys

oriented stacks, etc.

Beyond the Standard Model of cosmology? SMc = *tilted*ΛCDM +r aka (ζ, h_{+x})

BSMc = SMc + primordial anomalies in the true ζ -WebSky

f_{NL^*} =-0.52 ± 3.0 for ζ

std **nonG** $\zeta = \zeta_G + f_{NL^*}(\zeta_G^2 - \langle\zeta_G^2\rangle)$ local & equilateral pattern & orthogonal

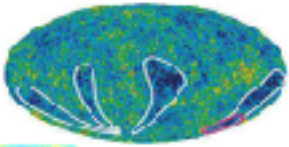
non-std nonG $\zeta = \zeta_{inflaton}$ + ***uncorrelated*** $\zeta_{[GRF}\}$ modulated heating intermittent?

CMB TT correlation C(θ) ~0 @ >60°
hemisphere difference ~7% at low resolution

$\langle\zeta\,|T,E\text{-pol}\rangle$

octupole/quadrupole alignment

dipole modulation/ asymmetry direction

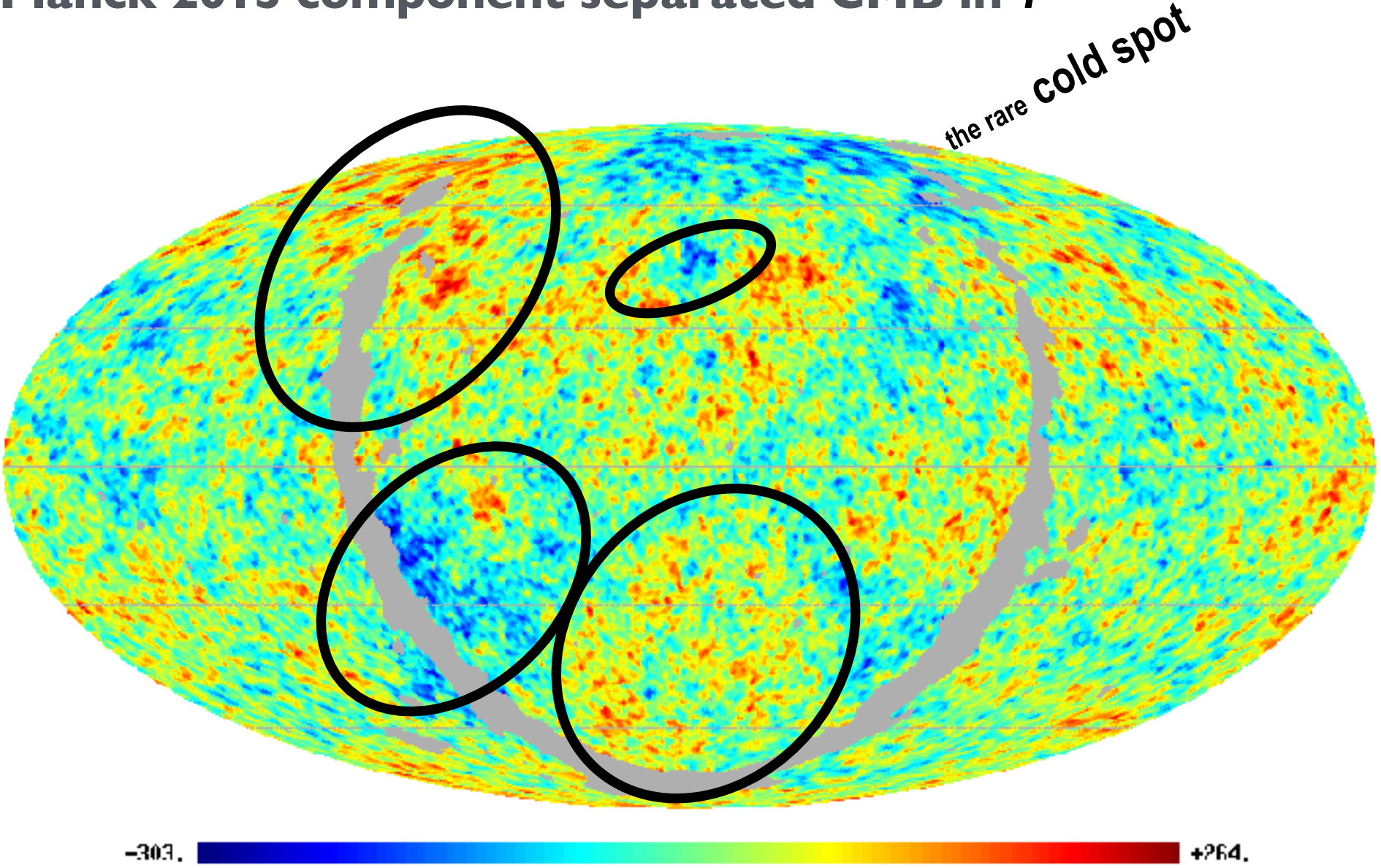


CMB TT power L~ 20-30 dip => ζ-Spectrum k-dip

rotated true T-WebSky

BFH, b+frolov+huang

Planck 2015 component separated CMB in *T*



CMB *~10,000,000 T/E modes of SMc aka tΛCDM*

≲500 modes of anomaly ….. ≲100 modes reionization history

creating probe-ensembles given control parameters for statistical analyses of cosmic BigData

nonlinear LSS WebSkys &

Secondary CMB WebSkysb

primary CMB = linear response Websky to $\zeta(x)$ via $\mathcal{P}_{\zeta\zeta}(k)$

Simulation of the 7+ numbers
begets the **Cosmic Web** of clusters
now a~1 & galaxies then a~1/4

~ billion light years

state of the art simulations
a~1 to 1/1.1

SIMPLICITY to COMPLEXITY under Gravity

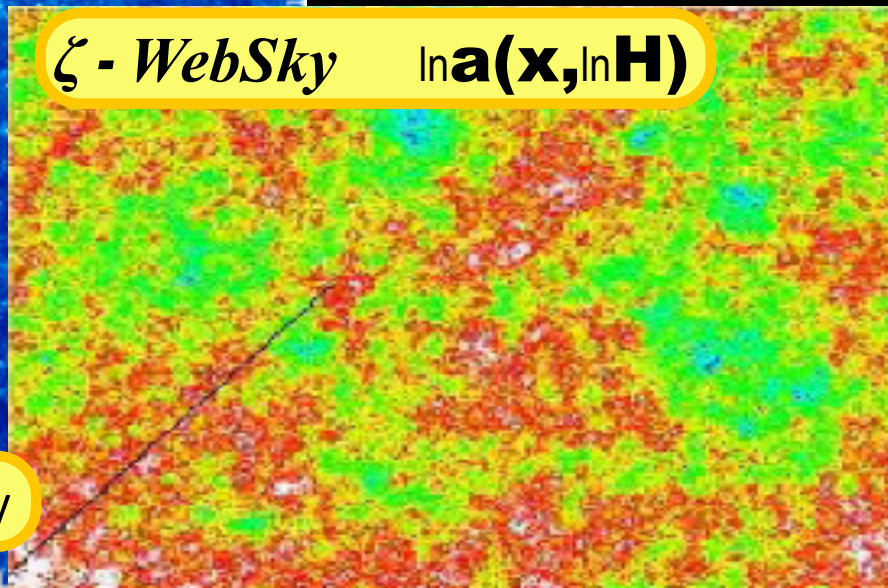
filament

void

cluster

supercluster

baryonic matter *+gas; dark matter; dark energy



Surveys of the Web(z)

the LSS data bases for fundamental physics &/or cosmic weather

optical z-surveys / weak lensing surveys (CFHT,SDSSx,KIDS,HSC,DES, DESI,LSST,Euclid,WFIRST), hi-z galaxy surveys (LyBreak SphereX...), sub-mm/Cosmic Infrared Background surveys (SCUBA, Blast, Herschel, Planck, ACT, SPT .. CCATp), radio (NVSS, FIRST, CHIME,HIRAX,MeerKAT.., SKA, Paper..), thermal/kinetic Sunyaev-Zeldovich surveys (Planck, ACT, SPT CCATp), HI intensity mapping (CHIME, .. SKA), CO intensity mapping (COMAP),..

+ Primary CMB surveys Pol r & hi res

Cosmic Observables for Fundamental Physics: ***mock WebSkys*** *vs. the* ***real Webskys***

Entanglement & Entropy

U=R∪S ruled by (information) entropy in bits, entangled. ***the fine grains in the coarse grains***

fit into a UV-complete theory (ultra-high energy to the Planck scale) strings, landscape, ..
& IR-complete theory (post-inflation heating -> quark/gluon plasma)??? TBD

Early Universe generates a coarse-grained $\zeta(x,t) = \int_{\text{field-path}} (dE+pdV)/3(E+pV) = \ln a(x,\ln H)$

all Webskys are entangled thru $\zeta(x,t)$***; Theory & Data entangled; all cosmic parameters entangled***

the real $\langle\zeta(x,t)|TE\rangle$ ***Websky + fluctuations*** Planck 2015 XVII nonG

cf. mock $\zeta(x,t)$ ***Webskys with subdominant non-Gaussianity <=> the Reconstruction game***

Primary CMB Webskys are gravitationally lensed; all Secondary CMB Webskys are lensed

weakly and strongly nonlinear Webskys: Secondaries & galaxies /halos & LineIntensityMaps/LAMs

entanglement of WebSkys of all large fsky CMB experiments

& WebSkys of all large sky LSS experiments optical CIB tSZ kSZ lens HI CO Halpha Lyalpha CII

Webskys in CMB Planck/AdvACT/SO/S4 in LSS Euclid in LIM/LAM CHIME/HIRAX; COMAP; CII@CCATp

BSMc *Webskys;* ***primordial (nonstd) nonG****; dynamical DE; coupled DE; massive nu HCDM;* ***FuzzyDM***

the ***WebSky*** Suite of Sky Simulations

being used for EUCLID, ACT, SO, CMB-S4, COMAP, CHIME, CCAT-p, …

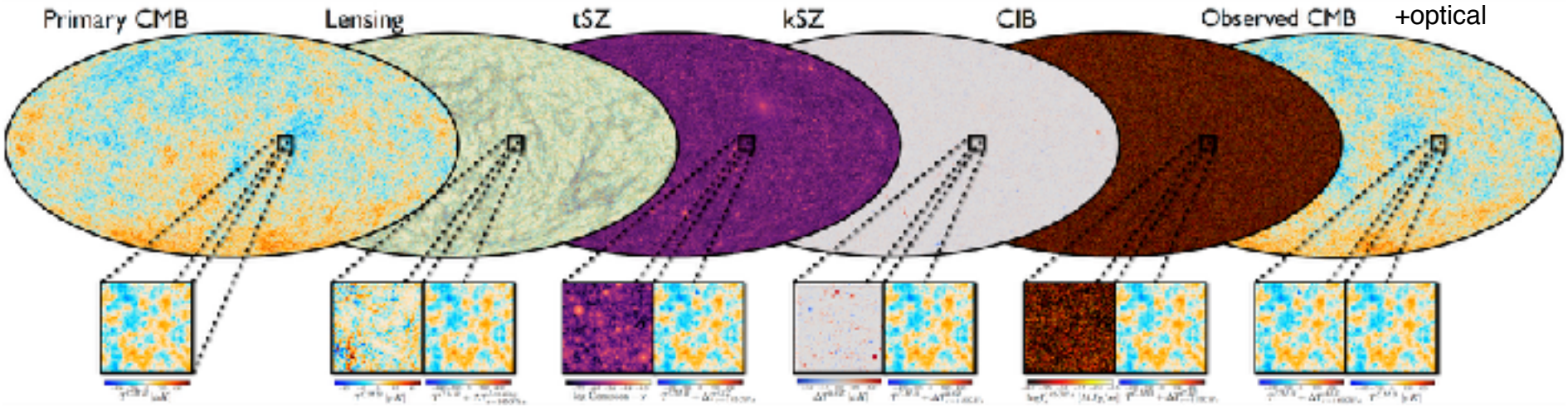
`mocks.cita.utoronto.ca` `@NERSC: /project/projectdirs/cmb`

Fast Halo Catalogs for WebSky Sims via Peak Patches + 2LPT

16^3 Gpc^3 Volume @8192^3 Resolution Halo Mass Resolution ~ 1e13 M_{sun}/h Memory Footprint: 2 TB

Full Sky for 0 < z < 4.5 **~5000 CPU Hours**

+LIM HI CO CII
+optical



CITA mini-industry **Alvarez, Bond, Stein + apps:** *Codis + Huang + van Engelen + Battaglia+ Connor Bevington, Bruno Régaldo-Saint Blancard + Louis Pham & to HI & LIM Phil Berger, Ronan Kerr + FIRE: Lakhlani + Murray + Hopkins +*

need ***all signals to be correlated, 1, 2, 3, .. Npt*** *… through* ***ζ(x,t)***
need ***End to End mocks: BSM, nonG, DE/modG, Mnu, xDM, …***
need ***speed to build ensembles & explore BSM***

cf. Planck 2015 XII: *Full Focal Plane Sims: FFP8 ensemble of 10K* ***End****to****End*** *mission realizations in 1M maps. instrument noise + CMB + PSkyModel + .. (25M NERSC CPU hrs)*

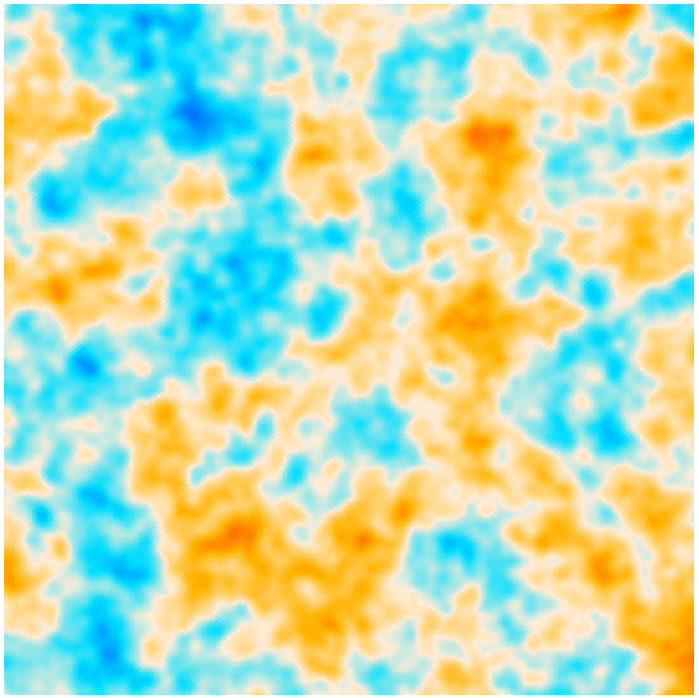
Extragalactic Sky Model

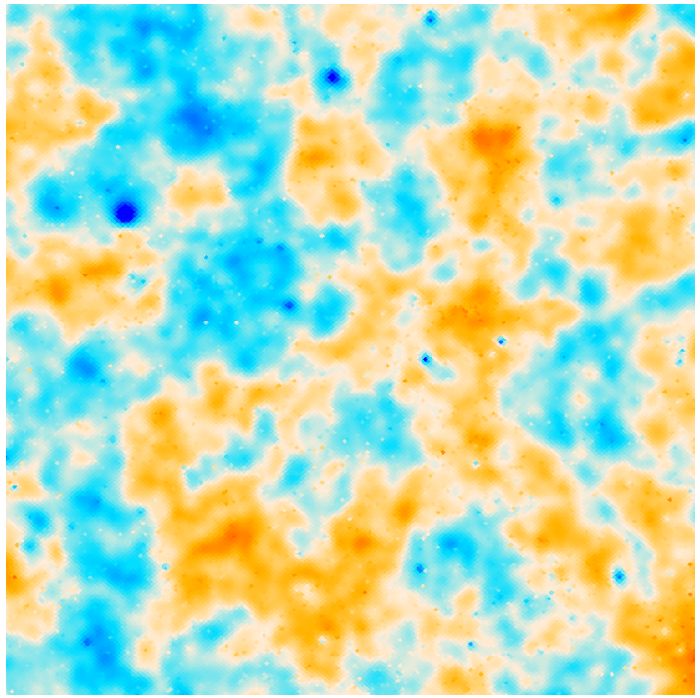
CMB without Extragalactic Foregrounds

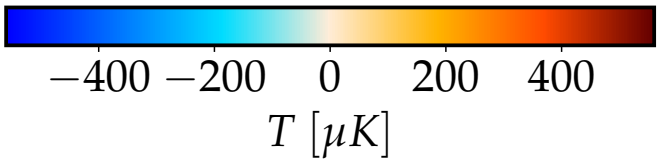
CMB with Extragalactic Foregrounds

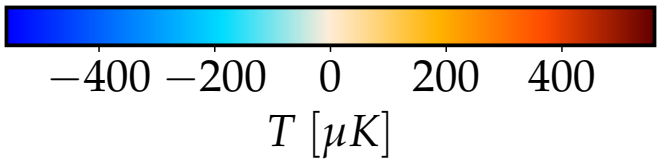
lensing + tSZ + kSZ + CIB

6 deg









$\nu = 148GHz$

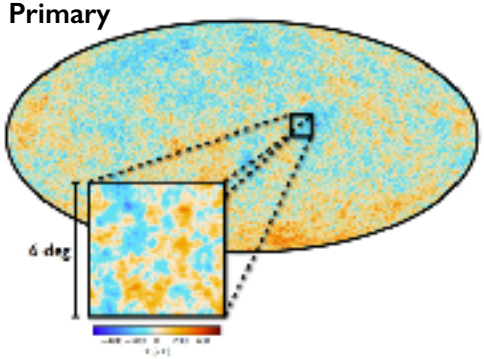
\+ Galactic Sky Model

\+ generalized noises

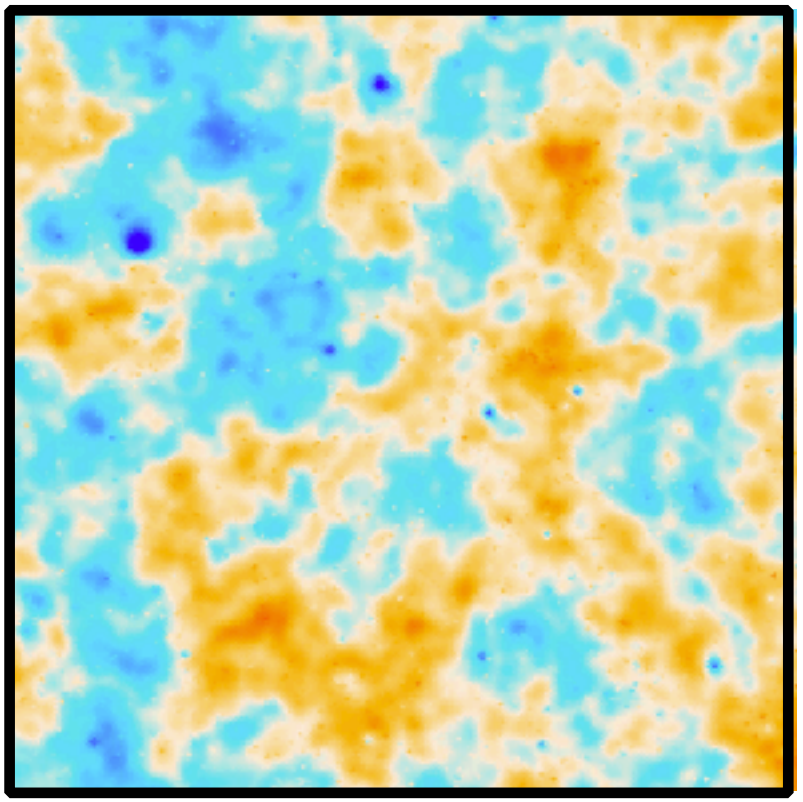
BPSM Beyond the Planck Sky Model

WebSky **Multi-Component WebSkys aka Maps**

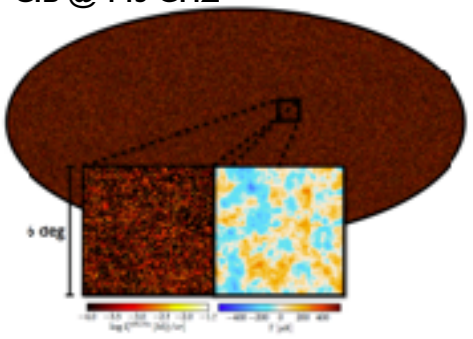
Primary



+

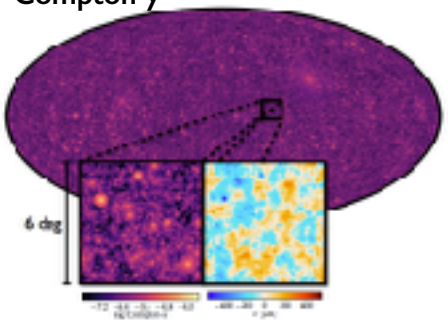


CIB @ 143 GHZ



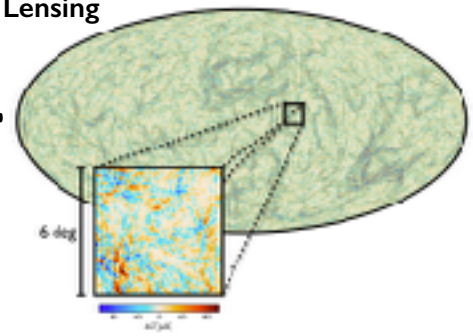
+

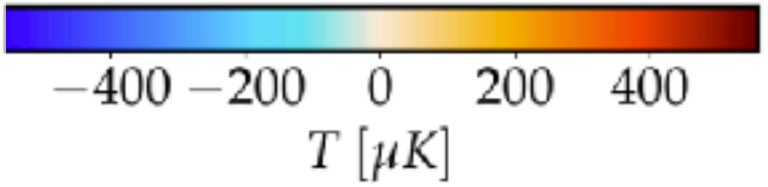
Compton-y



+

Lensing





recent peak-patch tests:

mass function cf. N-body

tSZ power cf. **Planck2015 y-map**

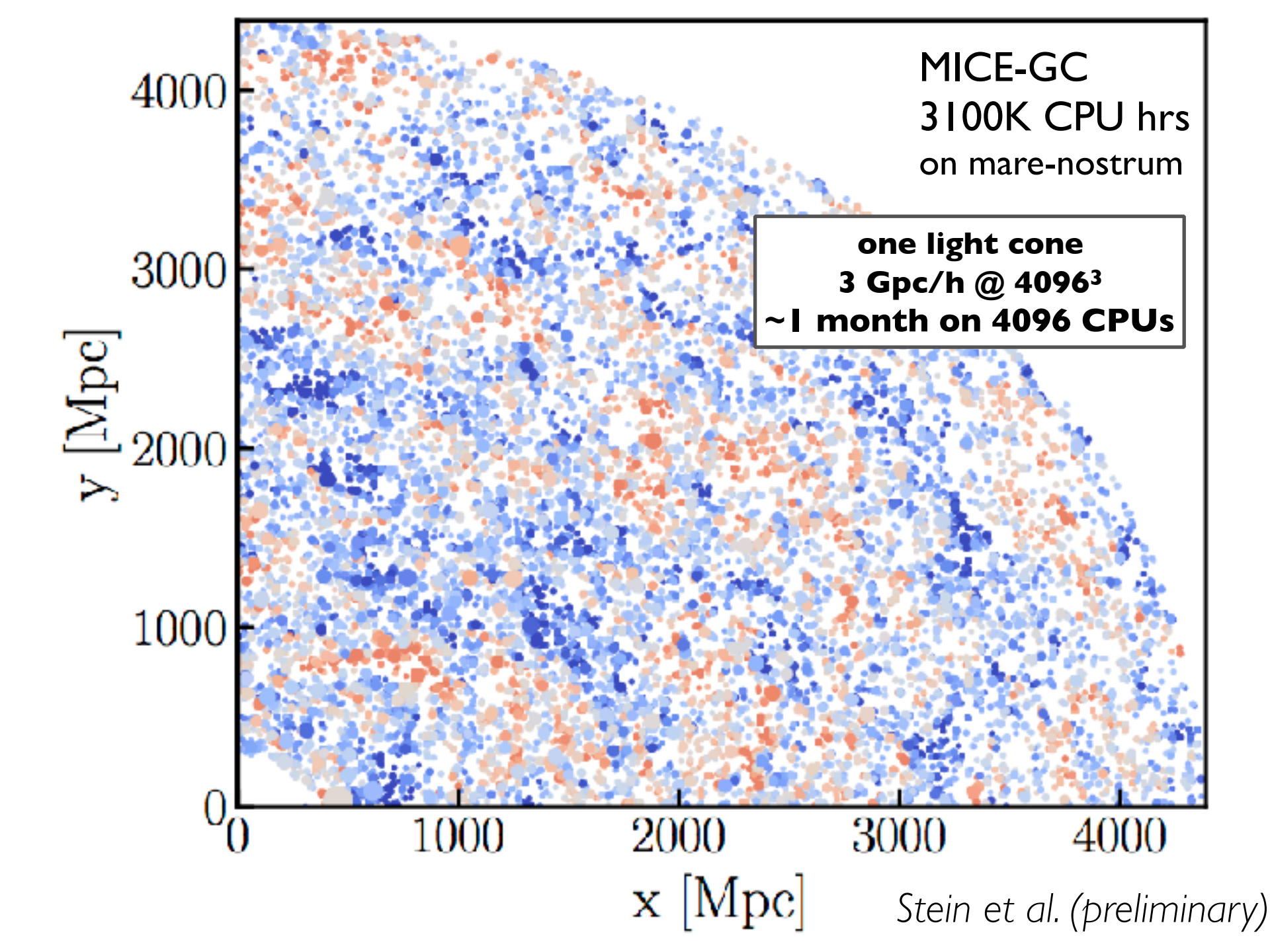
WebSky tSZ x CIB cf. Planck 2015

Euclid clustering vs. MICE-GC

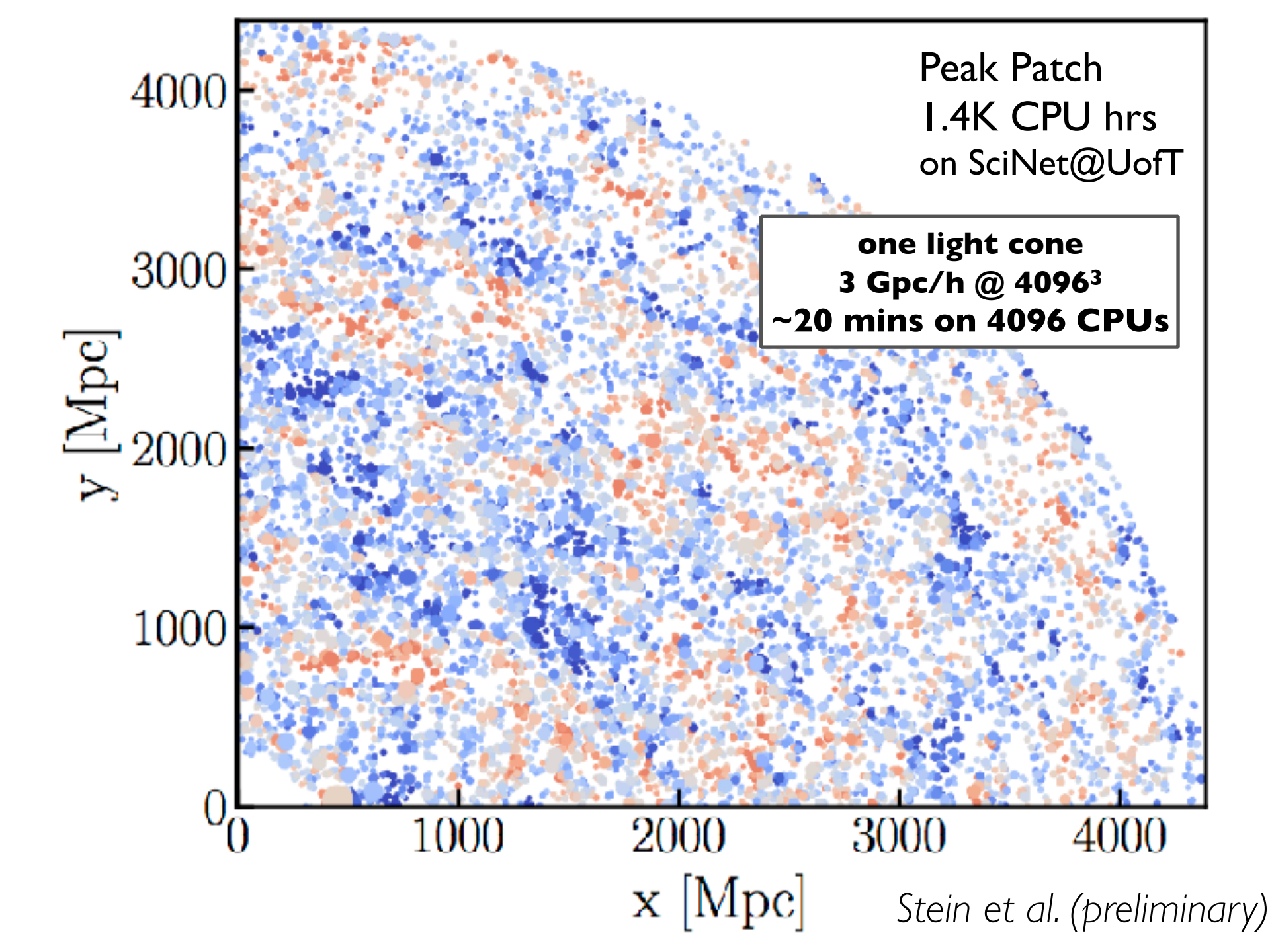
Euclid power spectrum/bias vs. Minerva

WebSky CMB Lensing cf. Lewis' Lenspix

++

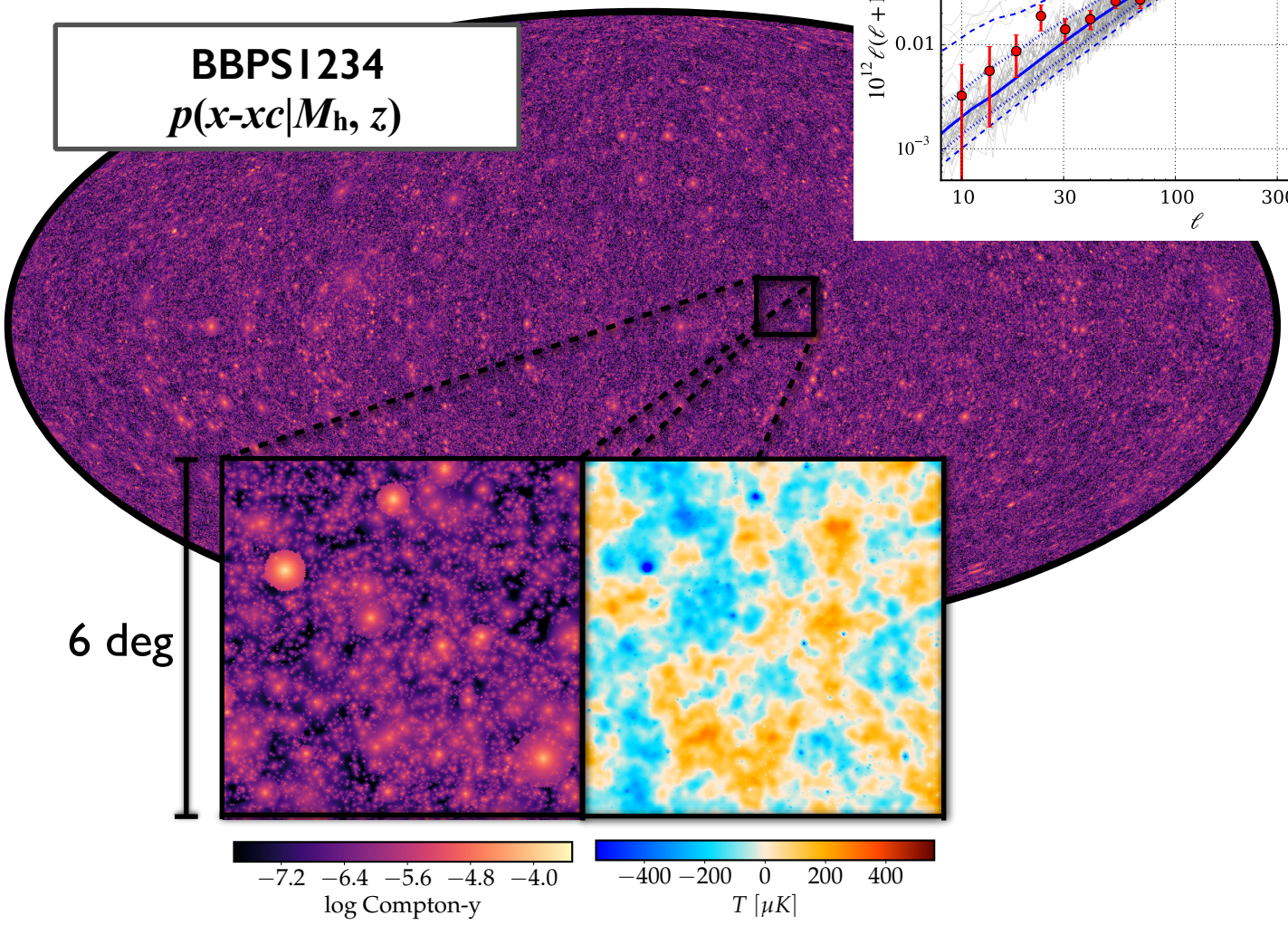


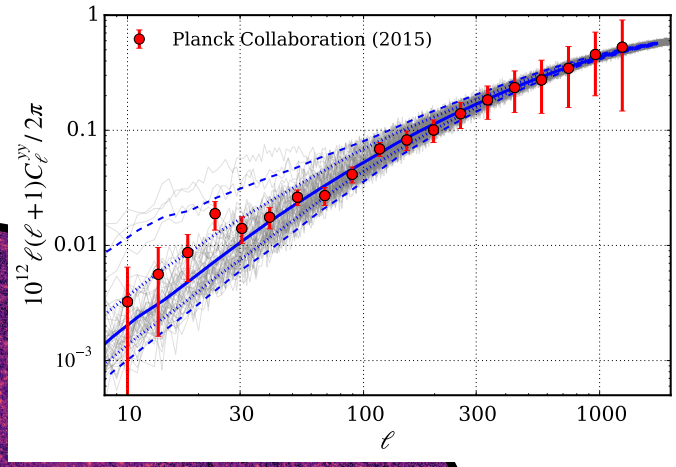
Stein et al. (preliminary)

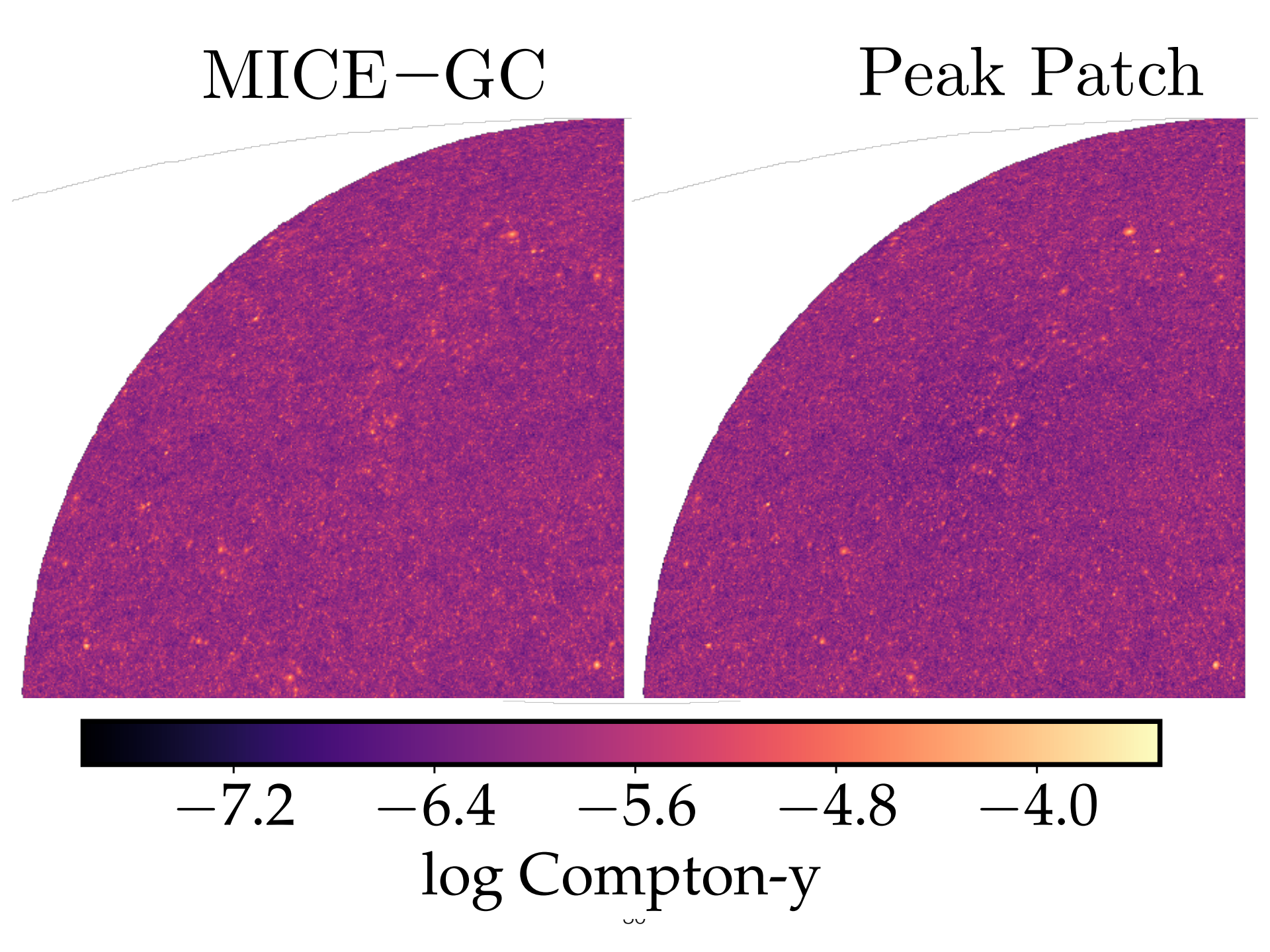


Stein et al. (preliminary)

Compton-y / tSZ WebSkys

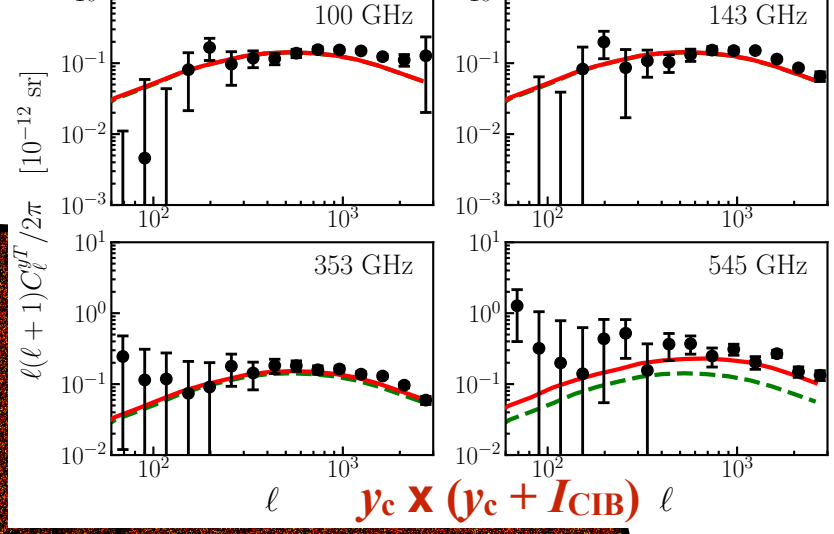


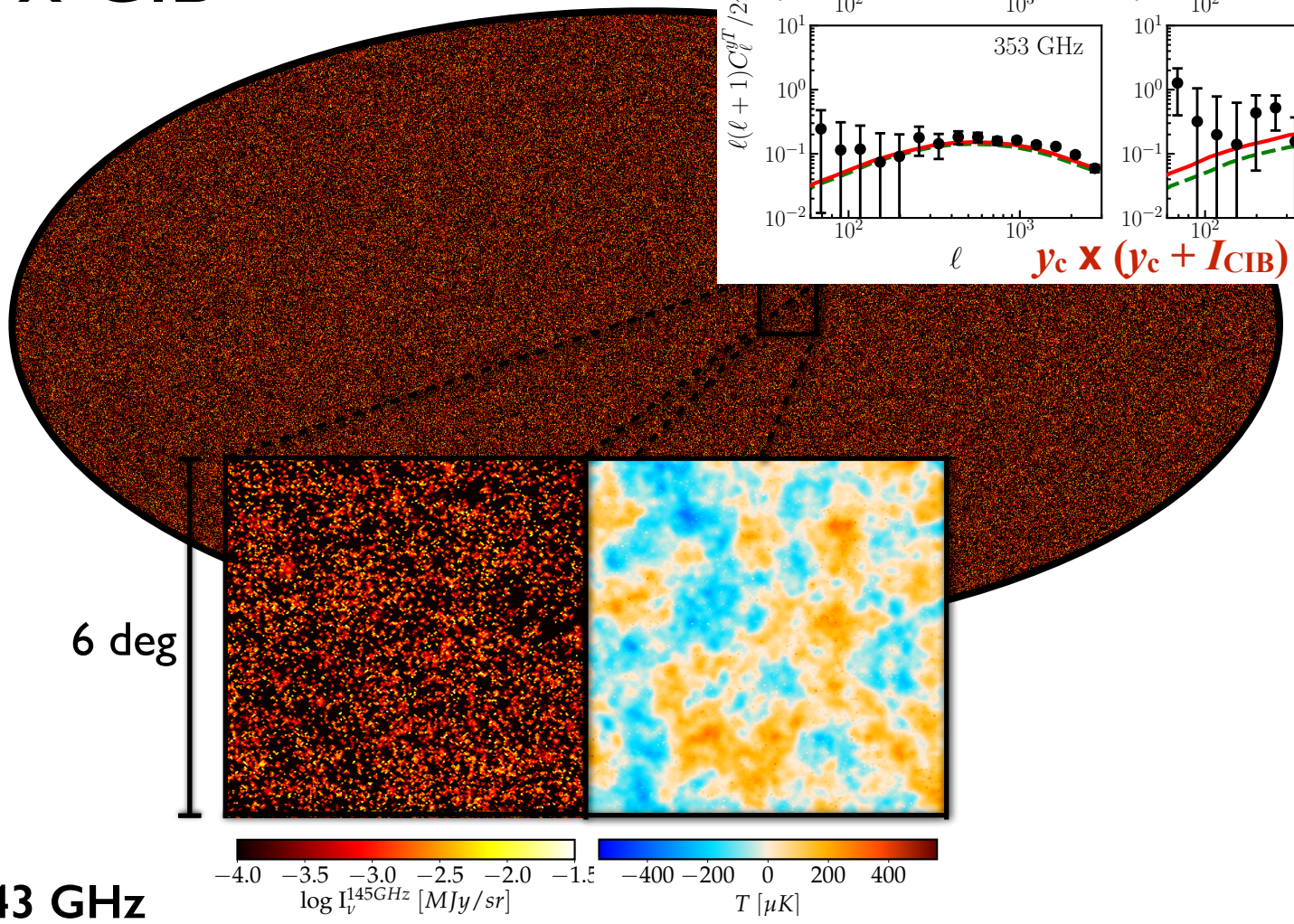



MICE−GC
Peak Patch
−7.2
−6.4
−5.6
−4.8
−4.0
log Compton-y

CIB near & far

& tSZ x CIB



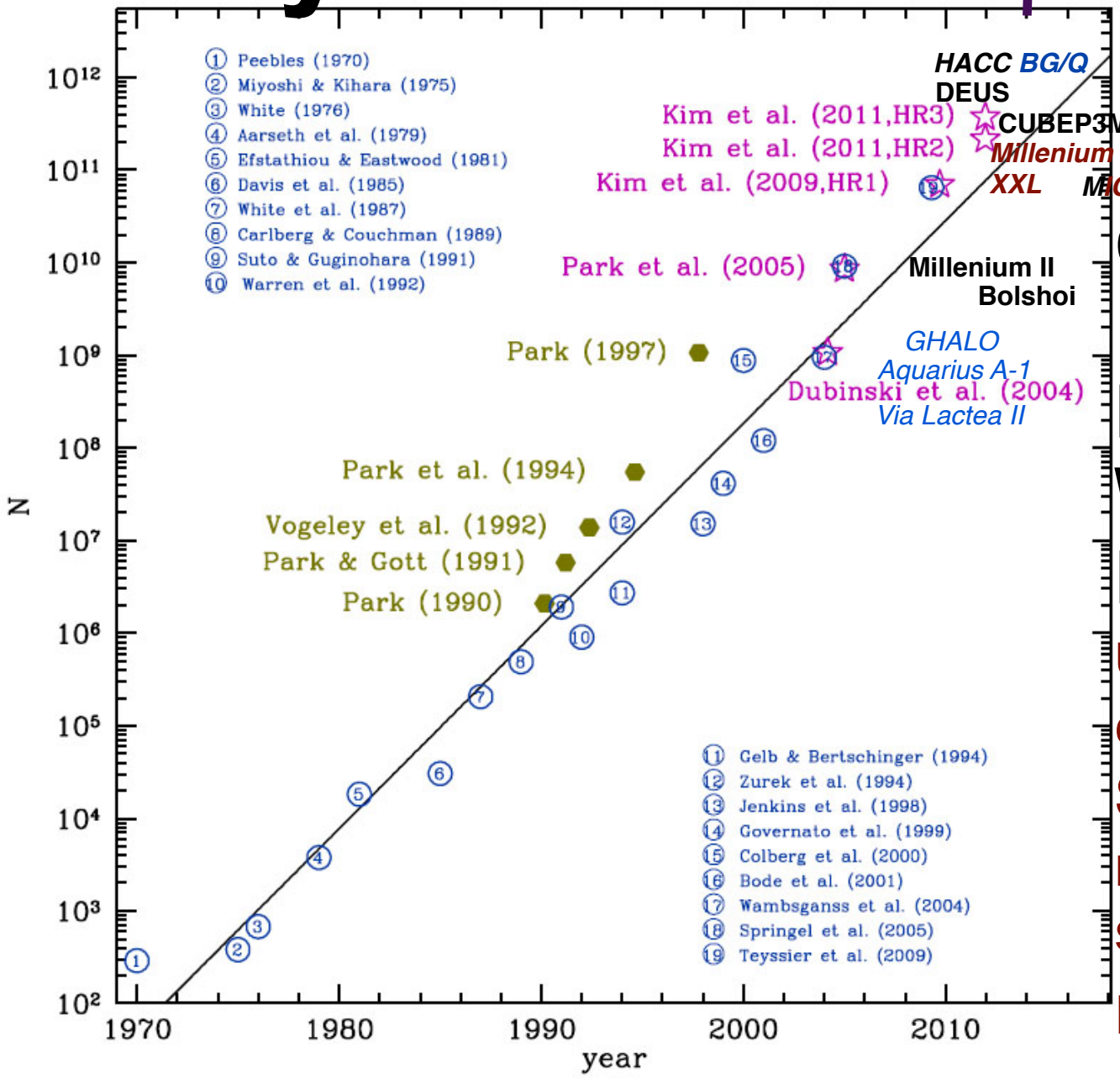


CIB @ 143 GHz

Planck (2015) CIB Model
HOD + subgrid 2LPT

N-body then & now

CUBEP3M HCDM in China



Juhan Kim etal 2011 +

Creating Dark Matter Websky Patches under controls SMc/BSMc resolution/ size no gas

Euclid Flagship simulation, *Stadel, Tessyier, .. all official Euclid estimates will be done with this sim:*
$(12600)^3$ lightcone to z=2.3, 5558 Mpc PKDgrav… *need deeper to cf. Spitzer*
10 trillion particles, 50 billion halos, 125 Mpc tiling, Planck13 parameters
LSST: Argonne Outer Rim simulation $(10300)^3$ aka 1.1 trillion 4200 Mpc, 7 kpc force res, Ntile=64Mpc, 64^3 cores, *Heitmann, Habib,*
MICE Grand Challenge: Marenostrum $(4096)^3$ 4388 Mpc 71 kpc force res, Fosalba+13 Gadget2
Minerva: 300 $(1000)^3$ sims 2143 Mpc

- ***cf. Approximate Rapid Halo Finders/Movers***

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- ***Approximate Rapid Halo Finders/Movers***
- **speed for fast Monte Carlo mocks, statistics and BSMc physics cf. accuracy**
- ***we are agnostic about best rapid halo finder:***
- **PeakPatches 1993.96 *Bond, Myers, lightcone naturally comes out, halo by halo***
- **PThalos 2001 - *Scoccimarro, Sheth,***
- **PINOCCHIO 2002 - *Monaco et,* PINpointing Orbit Crossing-Collapsed Hierarchical Objects,**
- **Millenium 2006 N-Body + artful painting *Volker +, Simon White, Alex Szalay,***
- **COmoving Lagrangian Acceleration COLA, 2013 *Tassev, Zaldarriaga, Eisenstein,***
- **sCOLA 2015,**
- **Augmented LPT APT 2013 - *Kitaura, Hess,***
- **PATCHY 2013 - *Kitaura, Yepes,* Prada PerturbAtion Theory Catalog generator of Halo and galaxY distributions,**
- **FastPM 2016 - *Feng, Chu, Seljak,***
- **cf. Minerva N-body 300 sims 1000^3 1.5 h^{-1}Gpc to cf. ICE-COLA, Pinocchio, PeakPatches**
- **cf. 512 suite of N-body Gadget 2016 *Szalay +***

Alvarez Bond Stein+ 18
speed~1000 X Nbody

early U applications of *CITA*@CITA to cosmic-complexity

- ☆ ***the superhorizon measure problem & the Lambda-scape***

- ☆ ***the emergence of the collective from the random!***
  coherence from driven zero-point vacuum fluctuations ⇨ V
  inflaton, gravity waves; decohere

- ☆ ***let there be heat:*** entropy generation in **preheating** from the coherent inflaton (origin of all "matter")

$S_{U,m+r} \sim 10^{88.6}$

cf. $S_G \sim 10^{121.9}$

udying the

osmic Tango

BSMc $\zeta(x)$ nonGaussianity in nonlinear LSS WebSkys

CMB modes
~ f_{sky} L_{max}^2

LSS tomography
X k_{max} d_{max}

std nonG $\zeta = \zeta_G + \mathbf{f_{NL}}^{*} (\zeta_G^2 - \langle\zeta_G^2\rangle)$ local & equilateral pattern & orthogonal

non-std nonG $\zeta = \zeta_{inflaton}$ + ***uncorrelated*** $\zeta_{[GRF]}$ modulated heating intermittent?

uncorrelated nonG 'wide open' cf. usual correlated highly constrained nonG

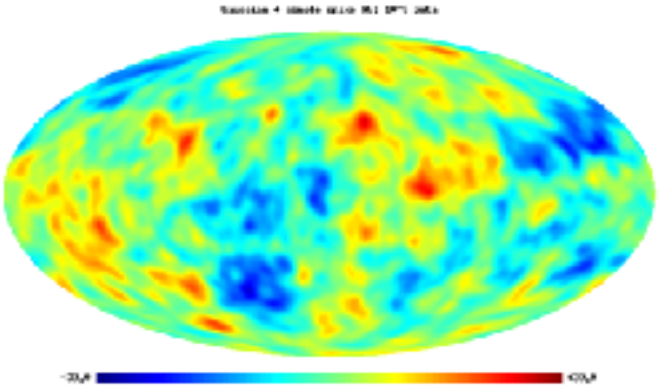
=> ***quest for*** unconventional primordial nonGaussian

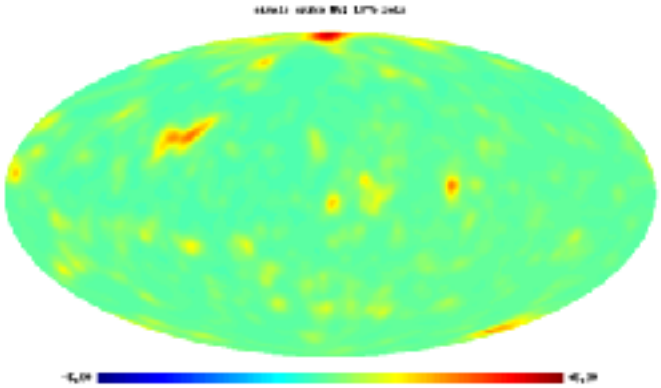
Mock WebSky of Primary CMB with subdominant non-Gaussianity giving coldspot

uncorrelated nonG 'wide open' cf. usual correlated highly constrained nonG f_{nl}

CMB+LSS mocks to test: standard Gaussian inflaton ζ_{inf}+ subdominant uncorrelated ζ_{isoc}

e.g., ***from modulated preheating by isocons***

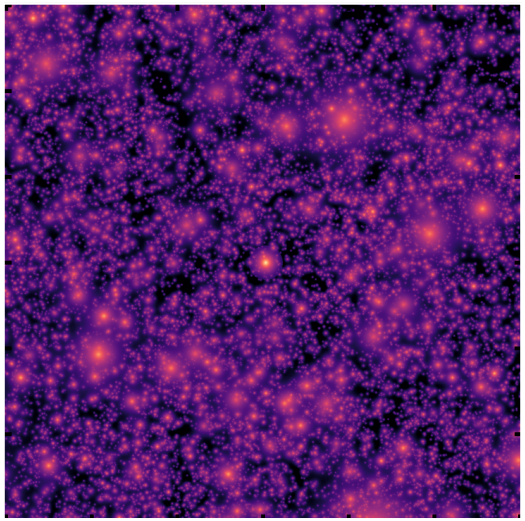




BSMc nonG

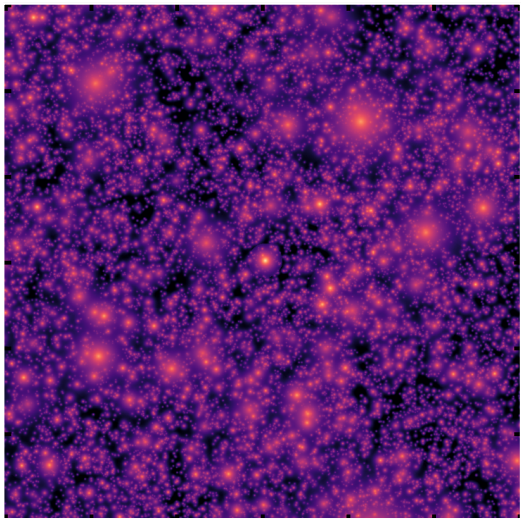
Mock WebSky of tSZ Secondary CMB with subdominant non-Gaussianity

LSS tSZ: Gaussian std **Gaussian ζ_{inf}**



B2FH, b+braden+frolov+huang

LSS tSZ: Gaussian std + subdominant uncorrelated ζ



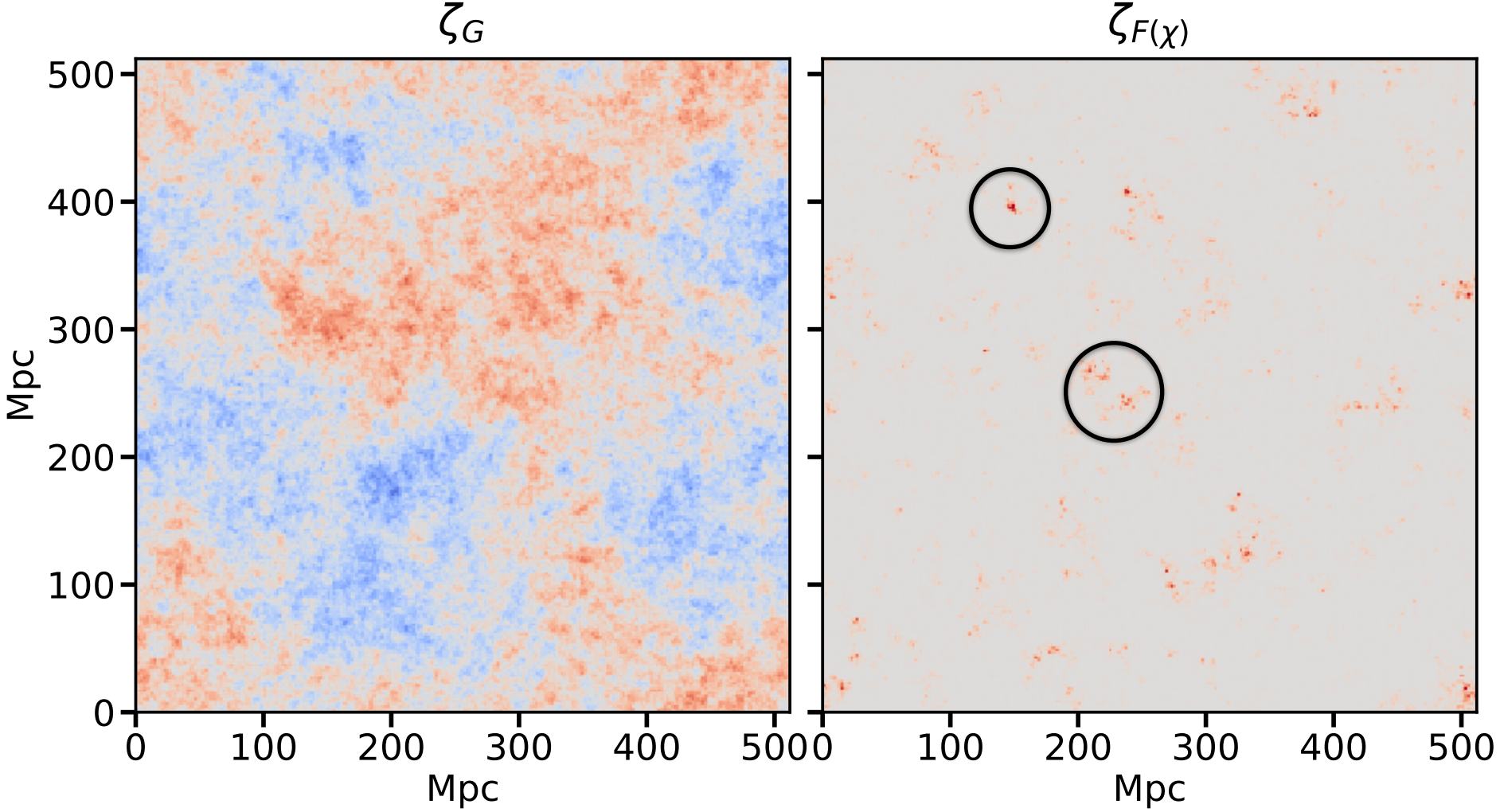
ABSB+FH, alvarez+b+stein+frolov+huang

Gaussian ζ_{inf} + uncorrelated intermittent nonG ζ_{isoc}

Primordial Non-Gaussianity in the Peak Patch method:

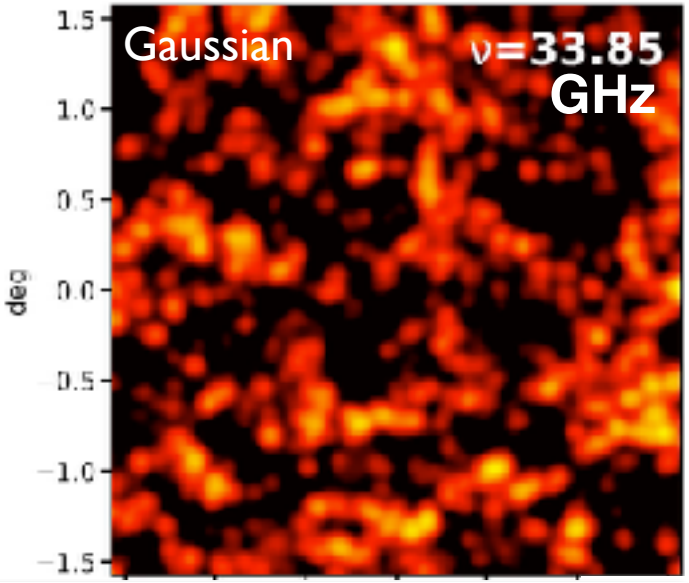
Intermittent Non-Gaussian case

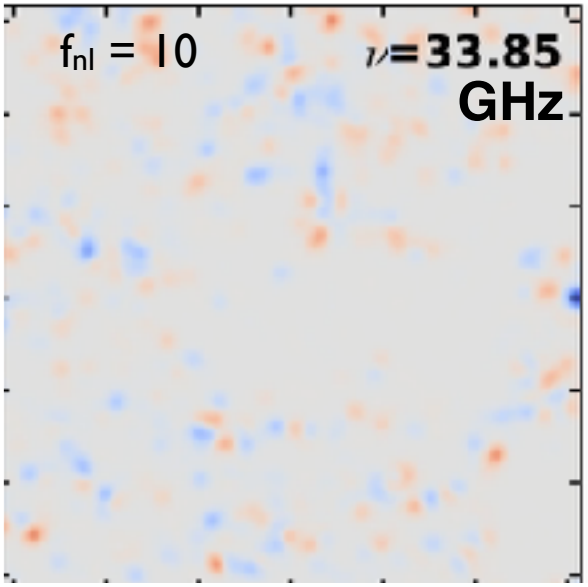
***uncorrelated* ζ[GRF]**

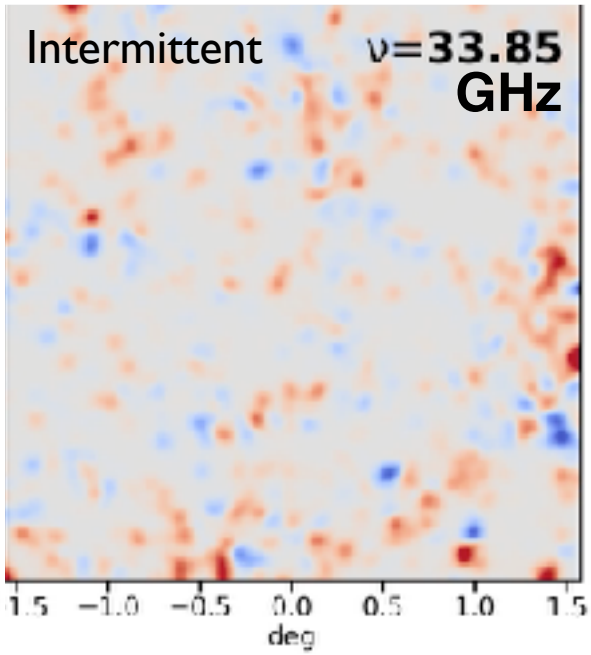


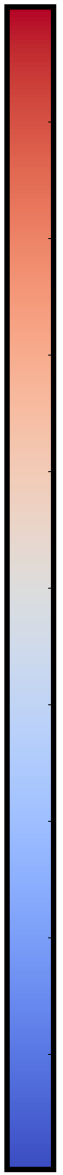
Primordial Non-Gaussianity in CO

$\sigma_8 = 0.82$
In all cases









relic1: ζ *from* ***inflaton*** *- observable = all cosmic structure CMB&LSS & stars/humans etal*
amplitude & slope <-> acceleration history & Veff simple over observable range

relic2: ***entropy*** *cooled remnant of particle/field plasma post-inflation* $S_{tot} = S_{CMB} + S_{CnuB}$

$10^{88.6}$ *cf.* $S_G \sim 10^{121.9}$ *asymptotic DE*

relic3: ***baryon asymmetry*** *of matter over antimatter* N_{baryon}/S_{tot}

$10^{-10.06}$

relic4: ***dark matter*** *from quark/gluon plasma - only seen gravitationally WIMPS, axions,..*

26.8 ± 0.9%

relic5: big bang nucleosynthesis products ***H, He, D, Li*** *(influenced by CnuB)*

relic 6: ***CMB*** *with all its fluctuations & polarization*

relic 7: galaxies & large scale clustering, flows, gravitational lensing

relic 8: ***dark energy*** *does it have kinetic energy density? is it coupled?*

68.8 ± 0.9%

what are the degrees of freedom / parameters of the ultra early Universe? TBD

relics not yet seen: in quest of what lies Beyond *the Standard Model of cosmology* SMc

from inflation

- **non-Gaussian features in ζ from weak nonlinearities** *(very nearly)* **Gaussian random field**
  local nonG for $\Phi_N = G + f_{nl} G^2$ $f_{nl} = 0.8 \pm 5.0$
- **gravity waves (not so far - obscured by dust)**
  P15+BKP r<0.09 uniform n_s
  cf. *0<r<.11 95% CL P15+BKP 12 knots*
- **isocon relic (not so far) - Planck on CDM isocurvature, neutrino, correlated**
  < 2% isocurvature role

bubble remnants of tunneling during inflation

from heating

- **isocon memories (not so far)**
- **strong subdominant but intermittent nonlinearities in ζ (spikes via chaotic billiards)**
- **curvatons oscillons strings domain walls - short lived**
- **rare WIMPzillas as dark matter**

from later quark gluon plasma

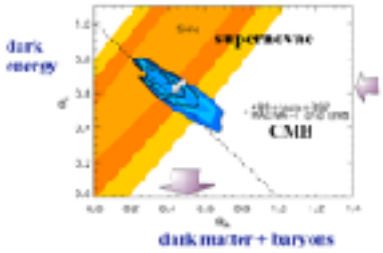
- **late phase transitions**

anomalies in CMB & LSS

could be ***primordial. large-scale, intermittent? statistics of just a few (modes, spatial rare events)?***

tensions in CMB & LSS

could be systematic error underestimates ***BSMc matter, coupled DE? statistical homogeneity. fuzzy dark matter.***



future fate of

the cold-death of the Universe (cf. ~1800s heat-death)

coherence (dark energy $\rho_{de}(t,x) \Rightarrow V_{de} \sim \Lambda$)

beats incoherence (Υ,ν,h_{+x},..p,n,e)

but entropy/particle remains *(for surviving particles)* e.g.,5.2 bits/photon

the **gravo-thermal catastrophe** = negative specific heat - goal to localize all mass into black holes & make accelerating voids ***to straighten U*** *out, radiating entropy along the way*

although $S_G = M_{bh}^2/2M_P^2$ decays into radiation, $S_G = M_P^2/2(H/2\pi)^2 \sim 10^{121.9}$ remains (until tunnel)

END