Mocking the LIM LAM *with PeakPatches++*

Bond & Stein @ JHU IM17

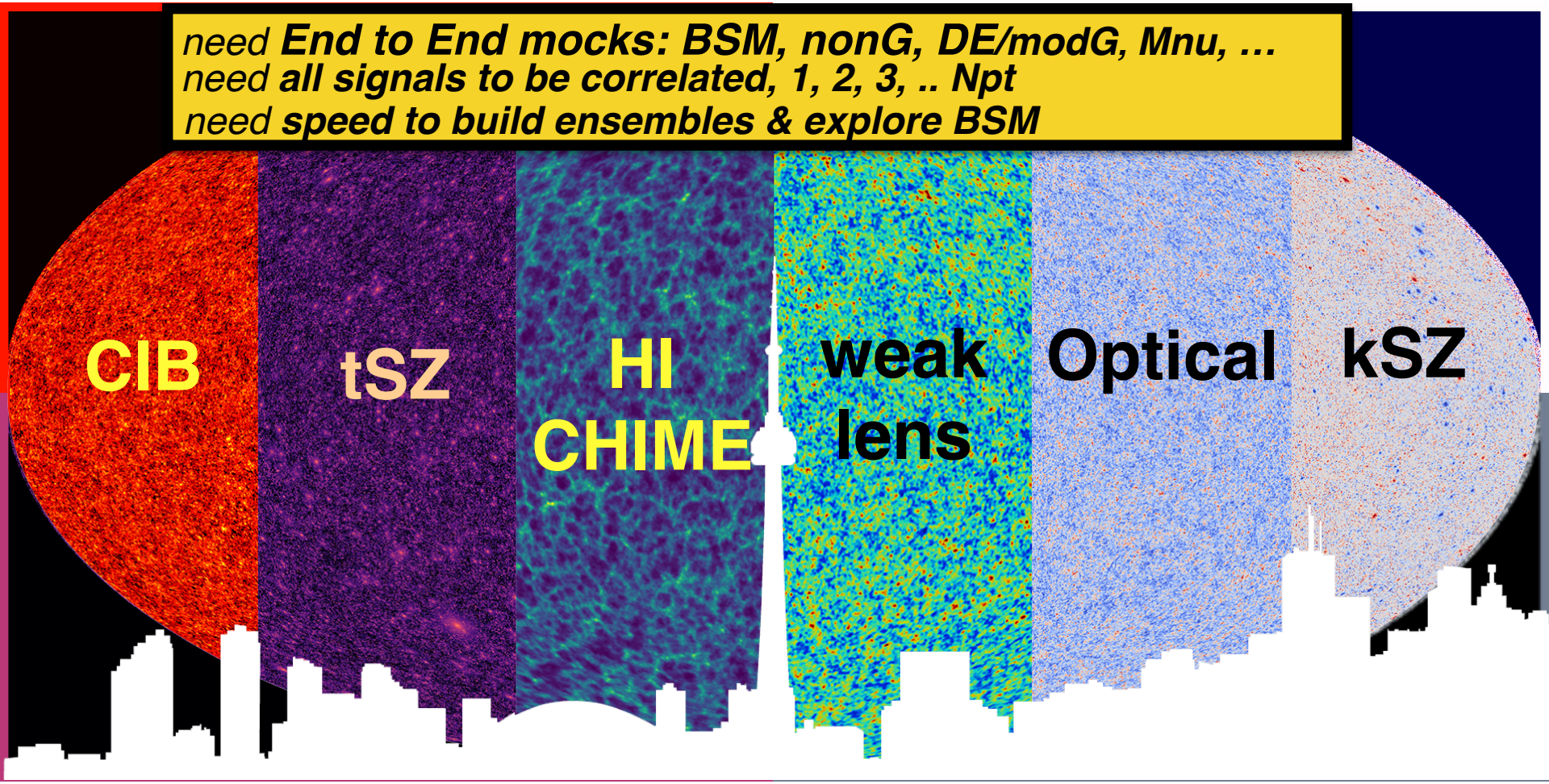
Line Intensity Mapping and Line Absorption Mapping *fLIMfLAM*

radio: HI CO CII, … + optical Ly a, …

z=.8-2.5 z=2.4-3.4 z=6-8

Marcelo Alvarez, Dick Bond, George Stein + FIRE: Lakhlani + Murray + Hopkins +

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



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)*

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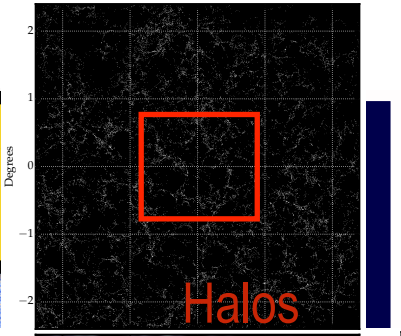
Survey Area



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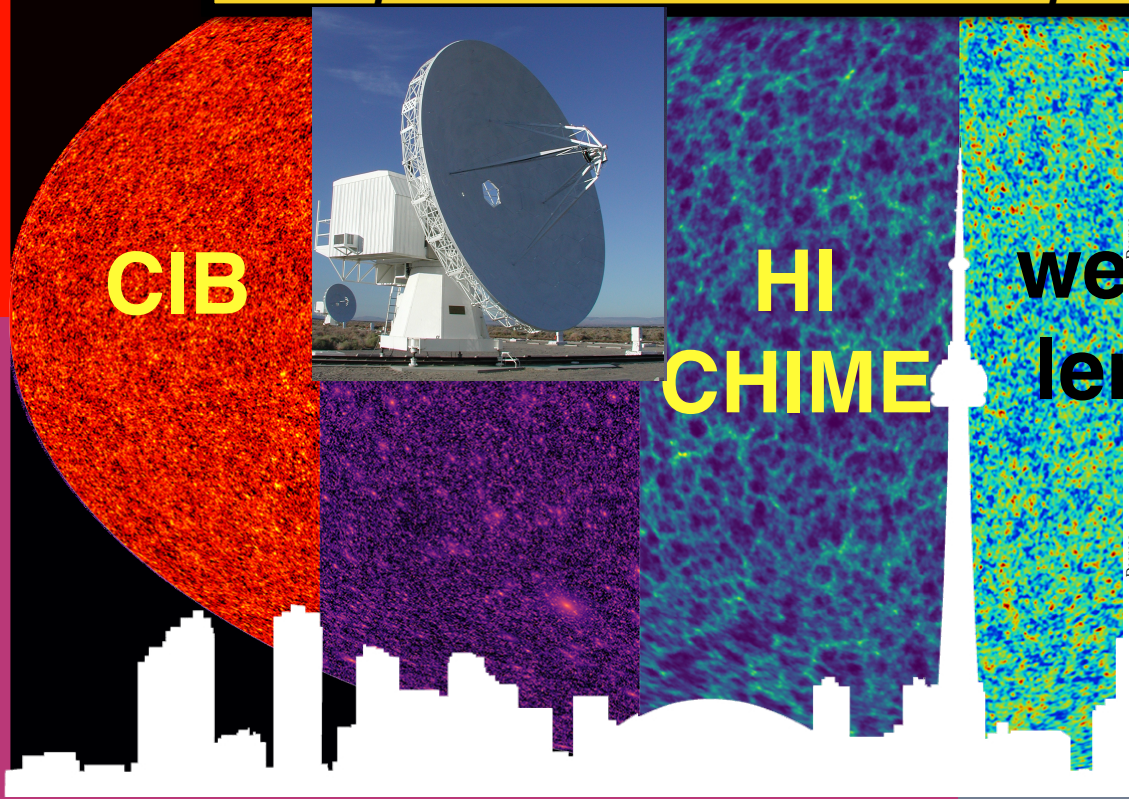
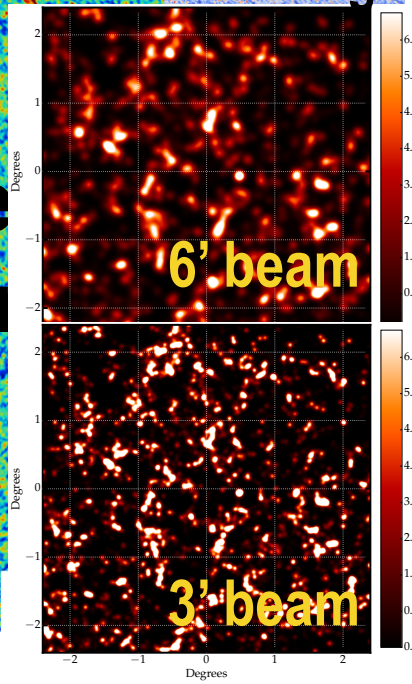
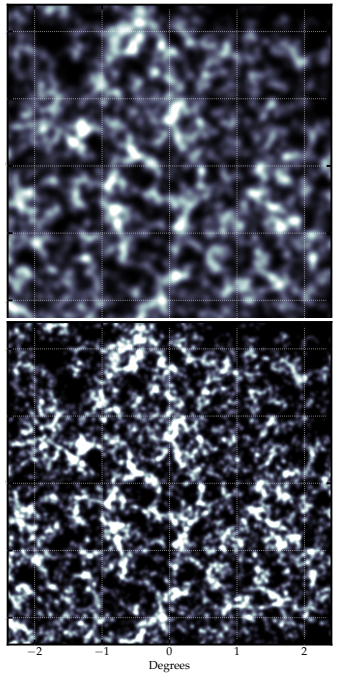


40 MHz slicing





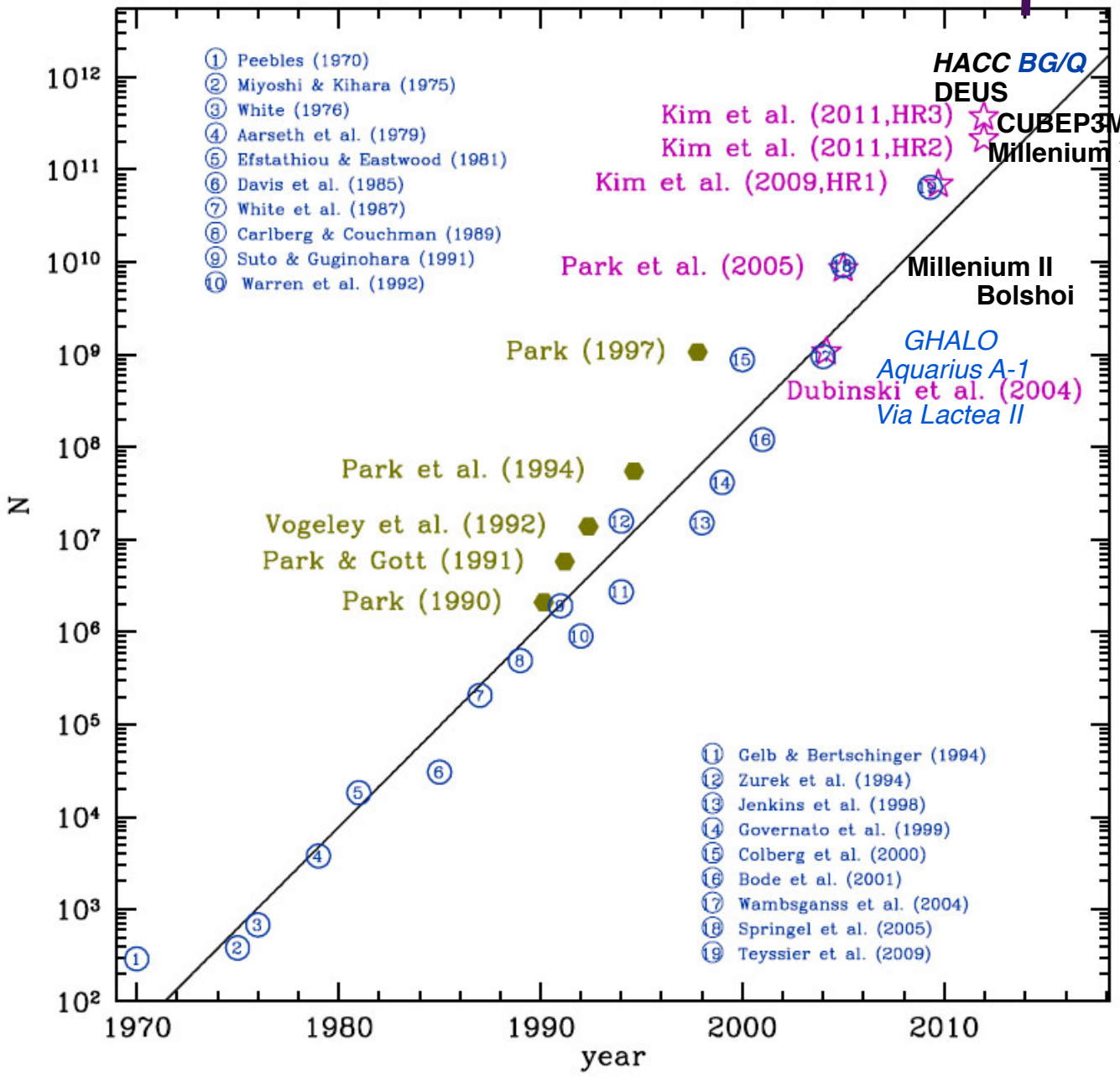
Planck, AdvACT, SO, CMB-S4, CCATp, EUCLID, LSST, CHIME, HIRAX, SKA, COMAP, …

NBody History

CUBEP3M HCDM in China

Euclid Flagship 2

OuterRim LSST 1.1



Juhan Kim etal 2011 +

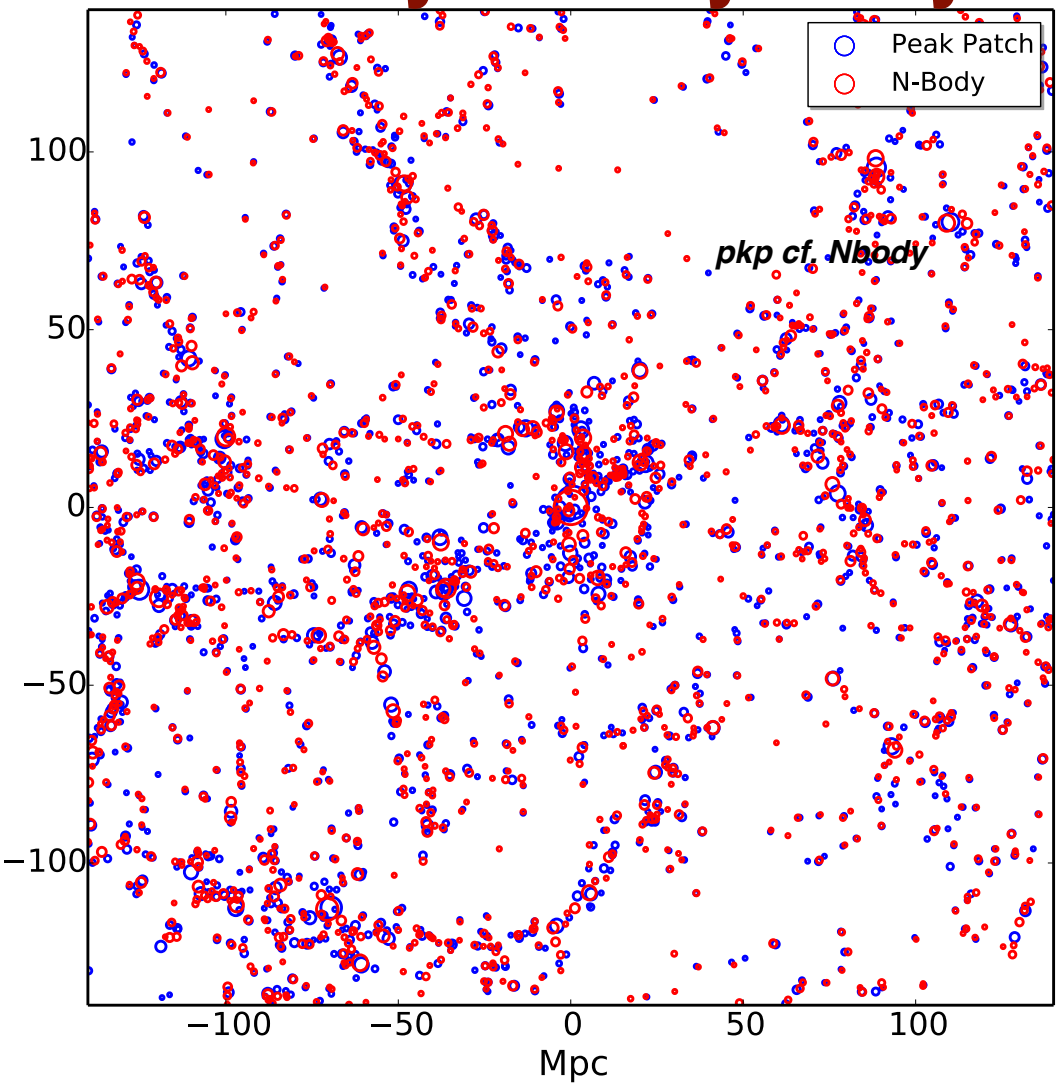
Euclid Flagship simulation, *Stadel, Tessyier, .. all official Euclid estimates will be done with this sim:*
$(12600)^3$ lightcone to z=2.3, 3780 h^{-1}Mpc PKDgrav… *need deeper to cf. Spitzer*
10 trillion particles, 50 billion halos, 125 Mpc tiling, Planck13 parameters

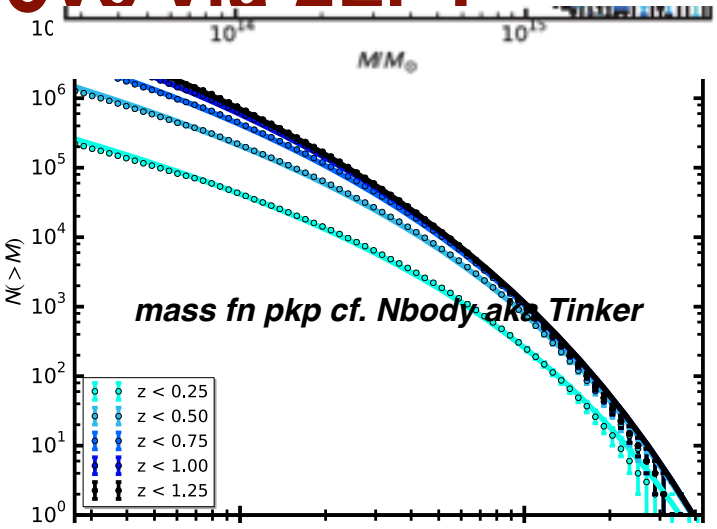
LSST: Argonne Outer Rim simulation $(10300)^3$ aka 1.1 trillion 4200 Mpc, 7 kpc force res, Ntile=64Mpc, 64^3 cores, *Heitmann, Habib,*

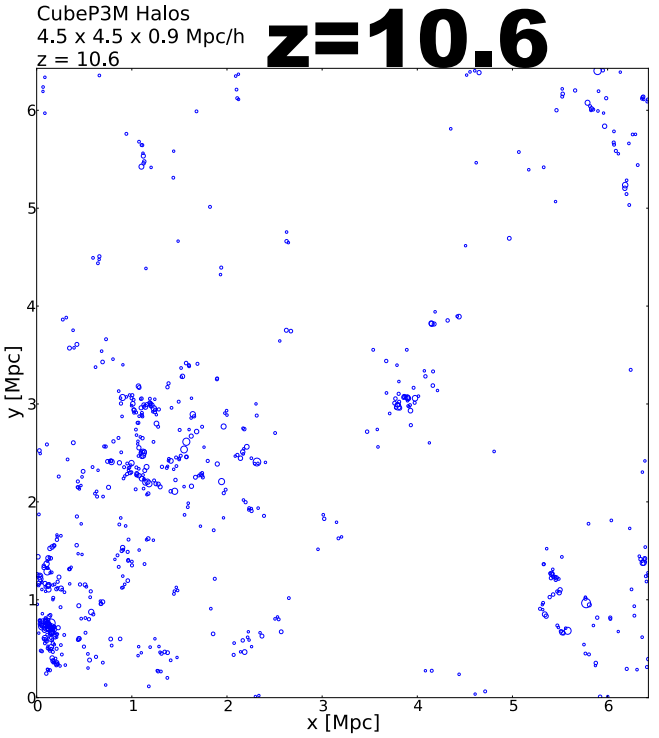
- ***Approximate Rapid Halo Finders/Movers***
- **speed for fast Monte Carlo mocks, statistics and BSMc physics cf. accuracy**
- ***we are agnostic about best rapid halo finder:***
- **PeakPatches 1993.96 *Bond, Myers, lightcone naturally comes out, halo by halo***
- **PThalos 2001 - *Scoccimarro, Sheth,***
- **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+ 17
speed~1000 X Nbody

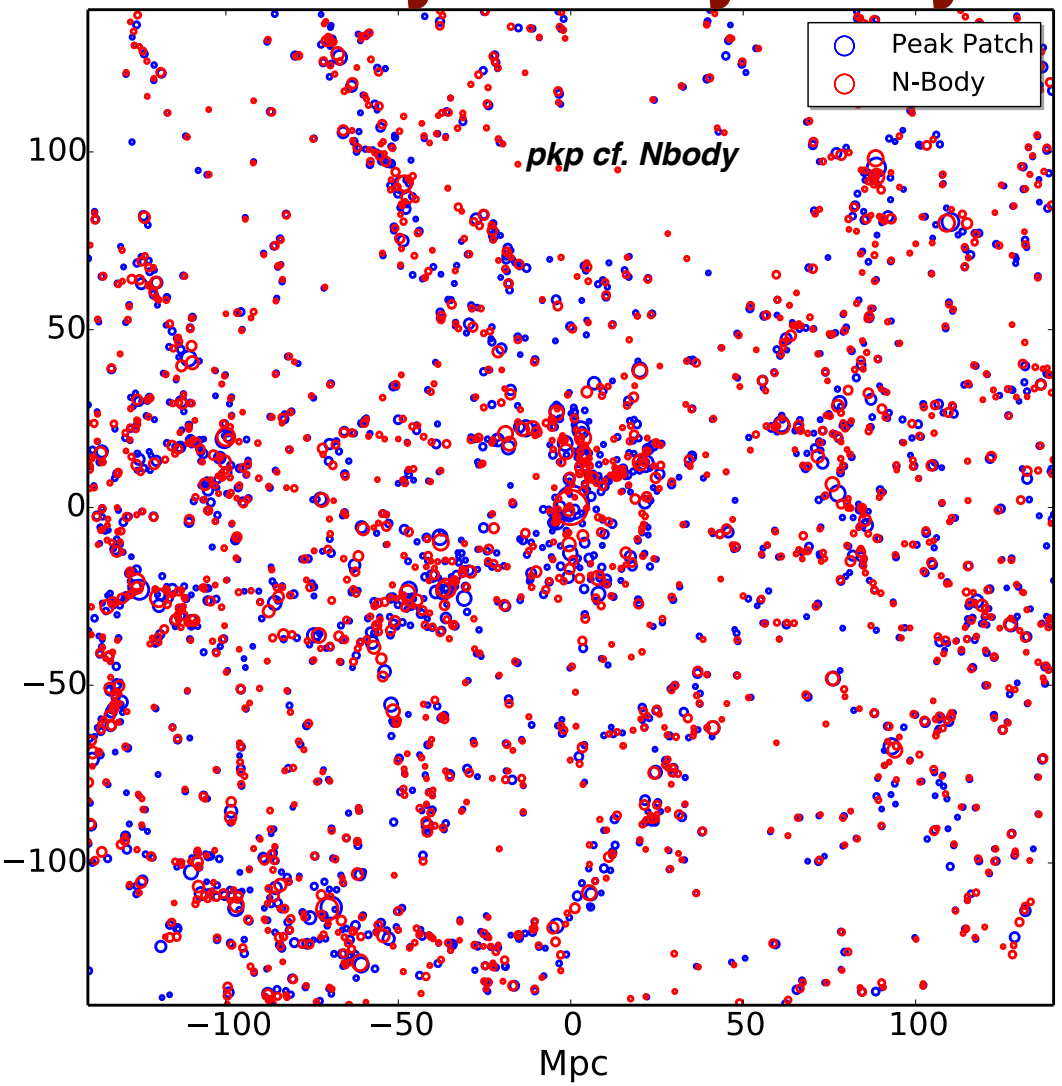
BIAS & 2-point clustering of halos is understood numerically & analytically: move via 2LPT

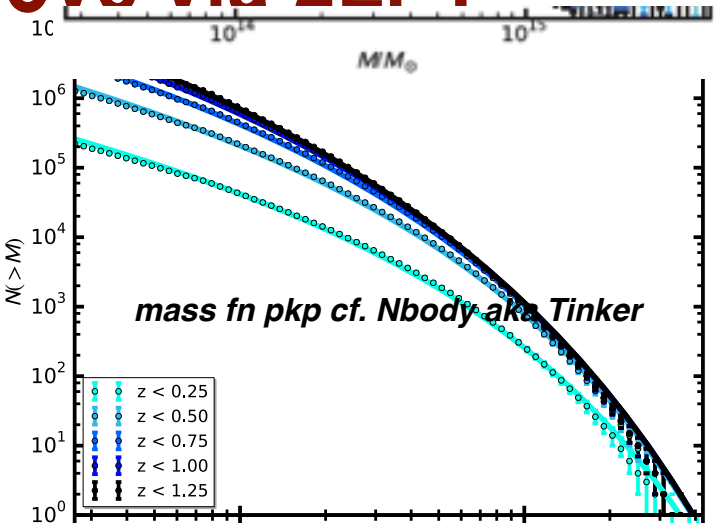


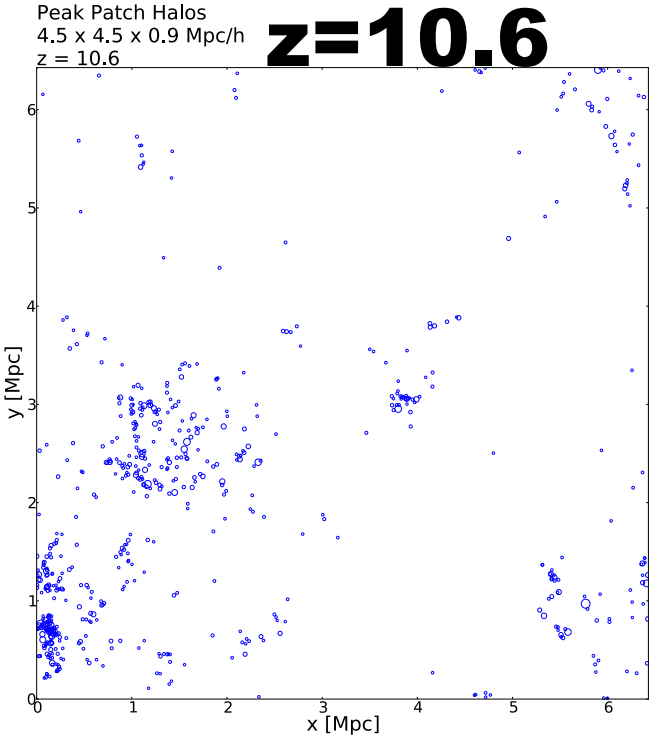




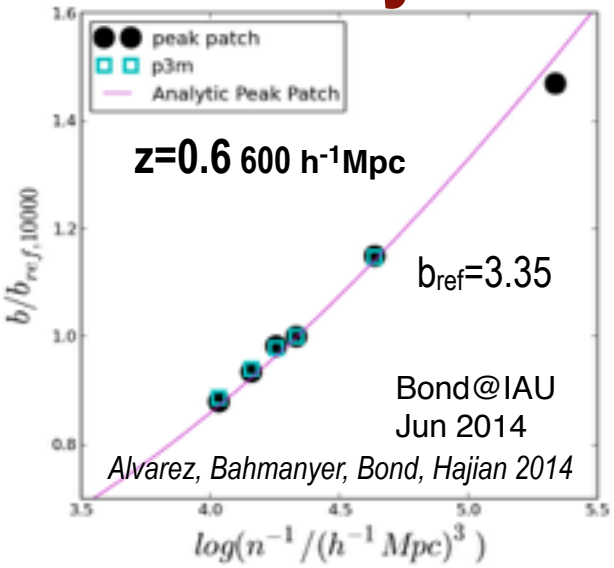
BIAS & 2-point clustering of halos is understood numerically & analytically: move via 2LPT

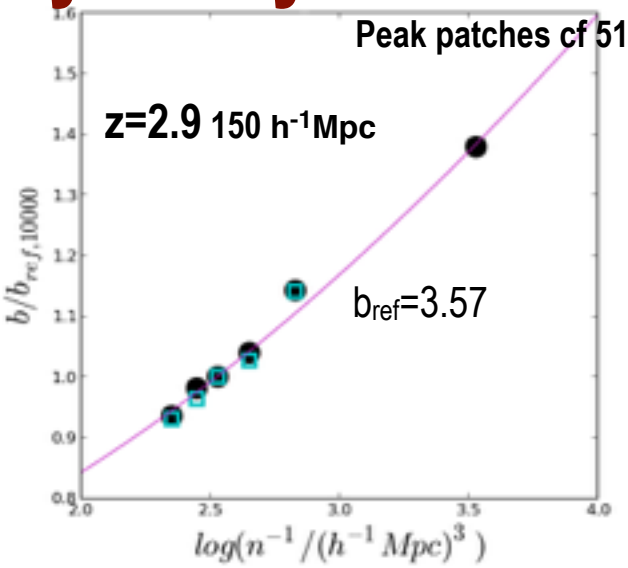


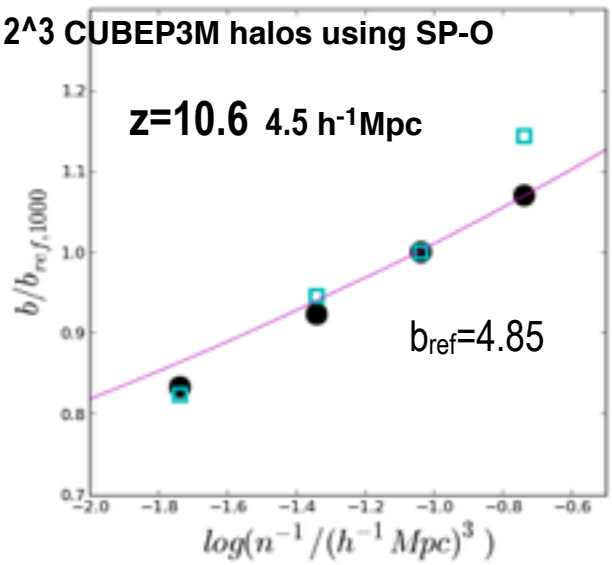


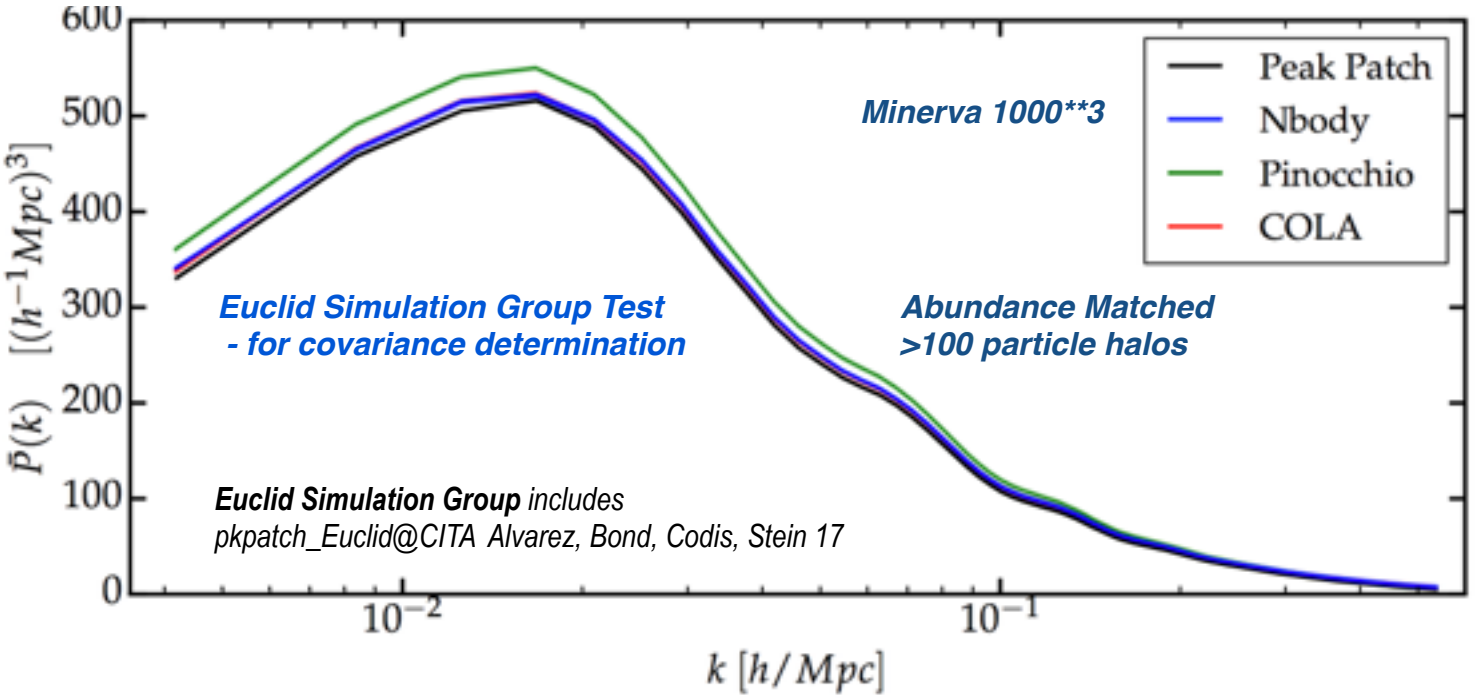


BIAS & 2-point clustering of halos is understood numerically & analytically: move via 1LPT or 2LPT









the Peak Patch Picture of Halos

generalized random field 'cluster-decomposition' aka halo expansion

THEN BBKS, BCEK, B+Myers91,93,96, BKP web, BW

NOW: CITA mini-industry Alvarez, Bond, Stein 2017 **Battaglia, Berger, Codis, van Engelen, Huang, Bahmanyer,** *undergrads*

the ***true Effective Field Theory*** *of Large Scale Structure* $R_c(x)$
adaptive in Scale space: resolution = a 5th dimension

Entangled **Hot halos => Warm Cosmic Web** *Structure* **=> Cool Linear Dynamics of 2LPT+**

"couplings" are the susceptibilities/ response functions/ form factors of fine grained high entropy phenomena => approach to targeted measures via observations, hi res sims

$$u_q(x)=\sum_c \chi_{qc}(x-x_c,R_{Ec})q_c\delta N_c(x_c,R_{Ec})+u_{qf}(x)\Theta_{VE}+u_{qf}(x)(1-\Theta_{VE})$$

inside = $\Theta_{VE}(x)$, *1 or 0 outside =*$1-\Theta_{VE}(x)$=*complement*

χ_{qc} ***susceptibility*** *of* u_q *to the "charge"* q_c *the art of halo models*

$q=M_{tot},\sim Vol_L\ M_{dm},\ M_{gas},\ PV,\ Vol_E,\ K_{dm},\ BE,\ S,\ S_{config},\ S_{dm}\ldots$
$N_{HI}\ L_{CO}\ L_{opt}\ L_{IR}\ L_X\ Y_X\ Y_{SZ}$ ..

via measurement: hi res ***gas sims*** *BBPS, n-body sims,* ***observations***
$M_c\sim R_{Lc}^3$, $Vol_E\sim R_{Ec}^3$, BE_c ,*orientation from the peak patch algorithm*

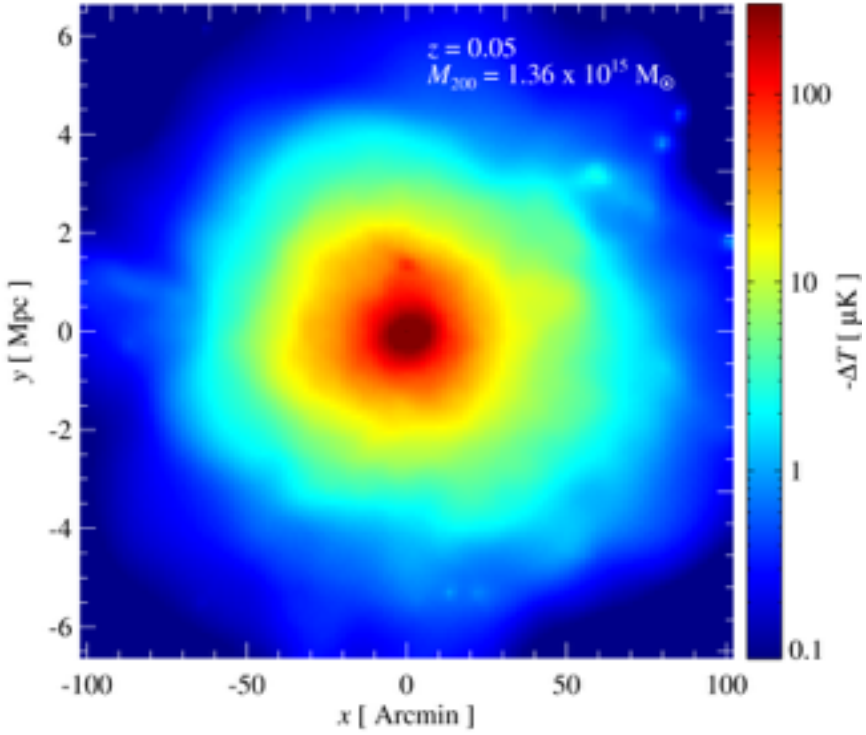
importance sampling to organize the susceptibility measurements?
Prob(u_q) = int Prob(u_q | control parameters) dProb (control parameters)

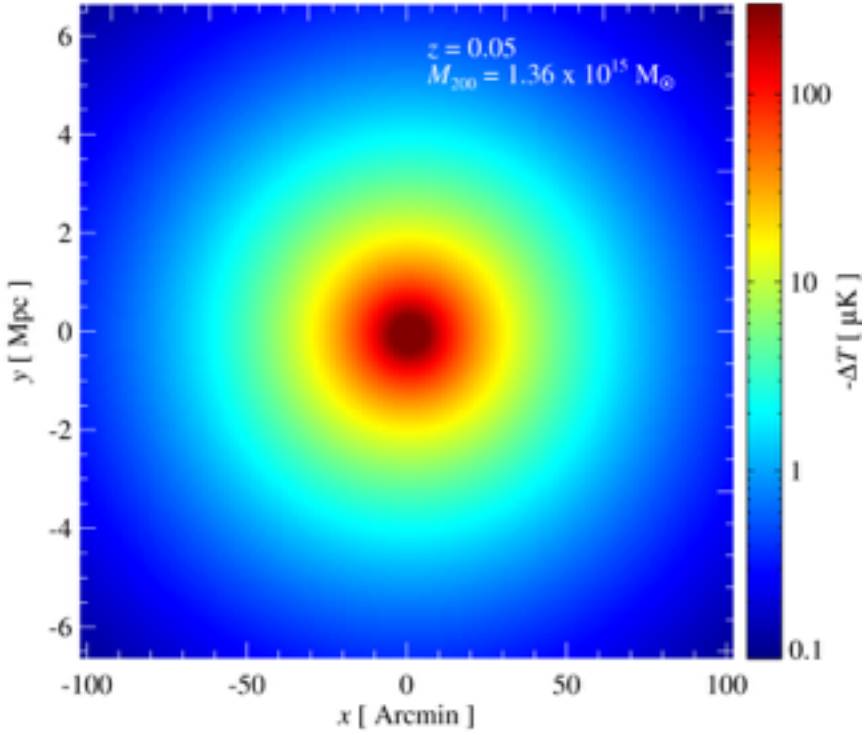
2D pressure exact vs. fit ➪ pressure sub-structure

BBPS 2011 gas sims with feedback for tSZ, kSZ

scaled stacked pressure profiles = pressure susceptibilities (M_h,z)

Planck universal pressure profile for y = Puppy, agrees



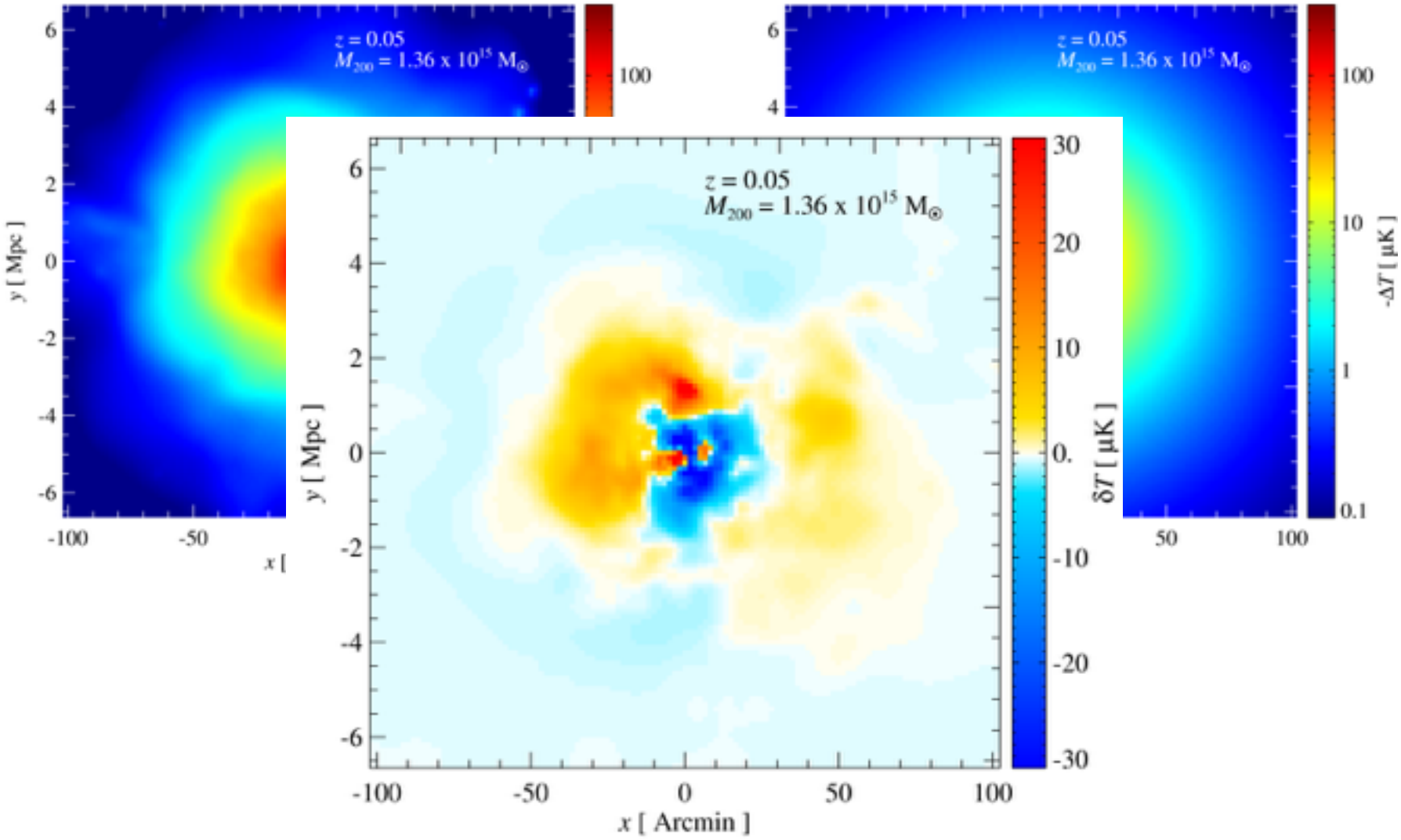


Same cluster (pasted on GNFW according to mass)
@ 30 GHz, z = 0.05 Mass ~10^{15} M_{sun}

2D pressure exact vs. fit ⇨ pressure sub-structure

BBPS 2011 gas sims with feedback for tSZ, kSZ

p_f (residual "noise")



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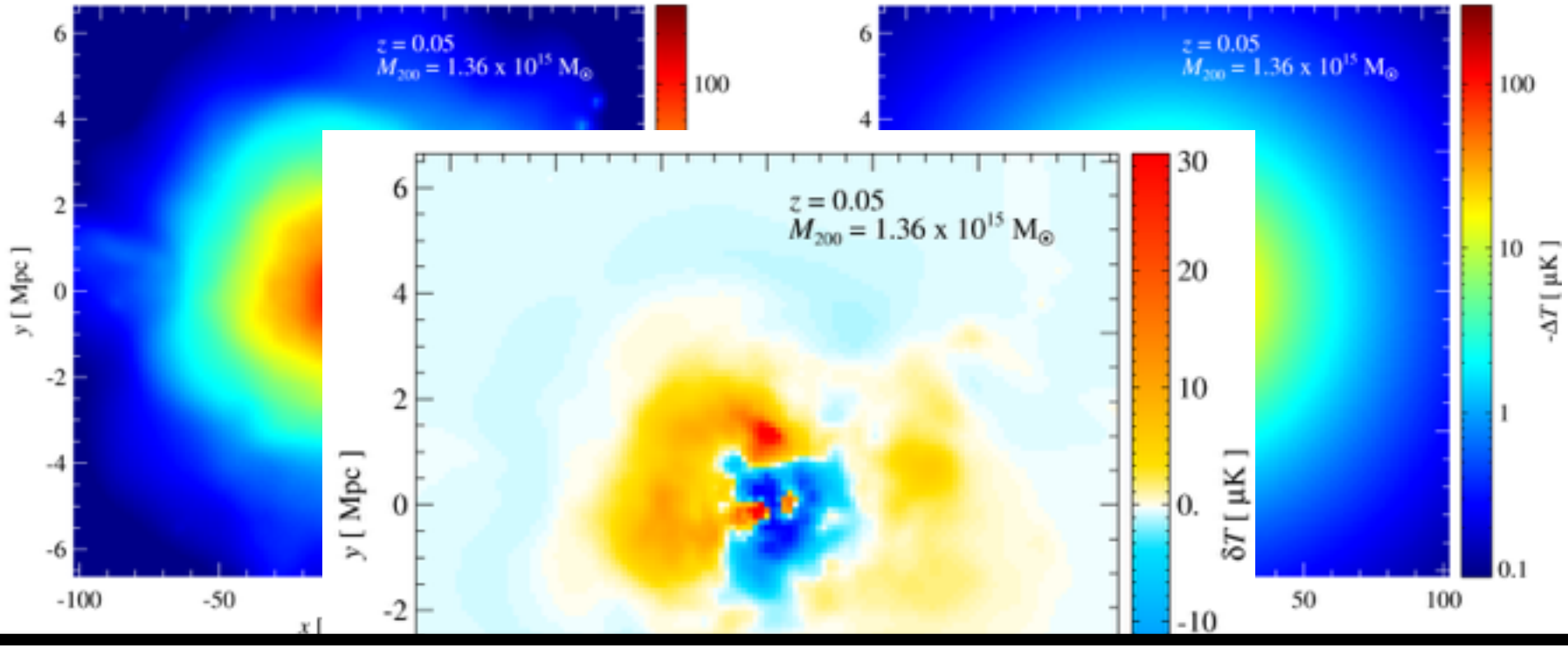


modelling the fluctuations about mean pressure fields from BBPS gasdynamical sims => complex but not overwhelming

measuring the mean CO susceptibilities

- subject to constraints? SFR, at high res disk orientation, …

fluctuations about the mean: overwhelming at high res

saved by the beam?

LIM transverse line blending

=> coarse-grained CO

=> integrated LCO (SFR(z), .., Mhalo)

=> many galaxies, less burst sensitive

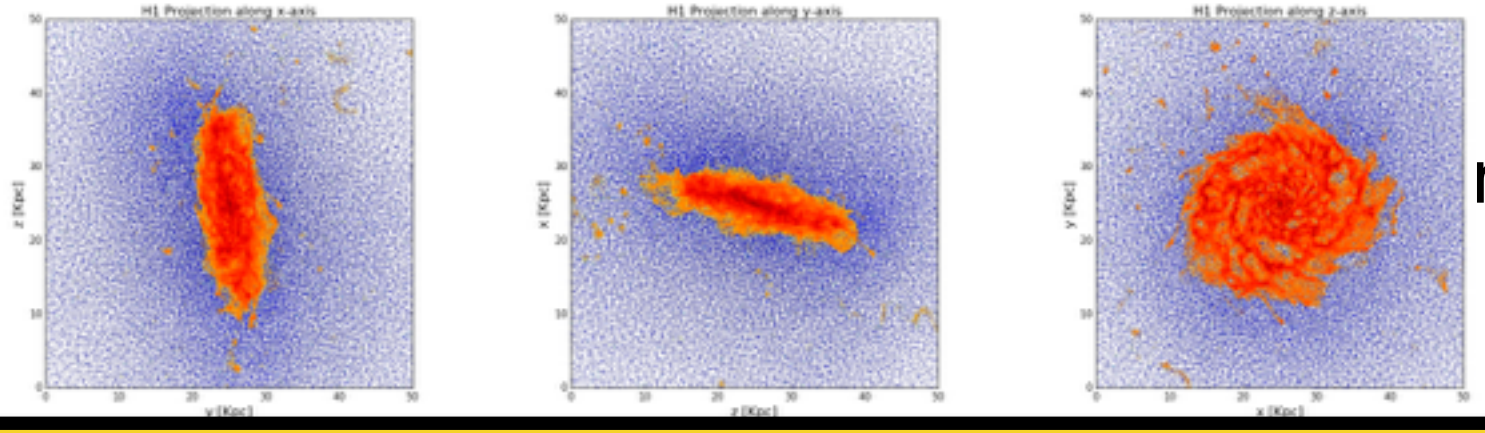
fluctuations ~ measurable uncorrelated stochasticity about the mean?

importance sampling:

Prob(CO etaI) = int Prob(CO etaI| control parameters) dProb (control parameters)

galaxy assembly = out of control?

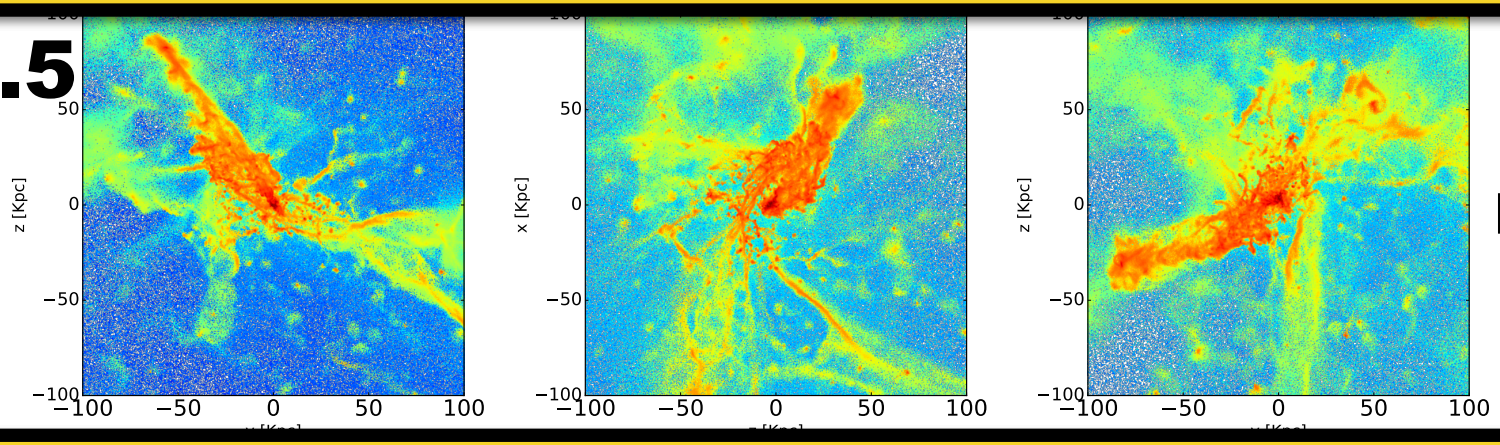
z=0



n_HI

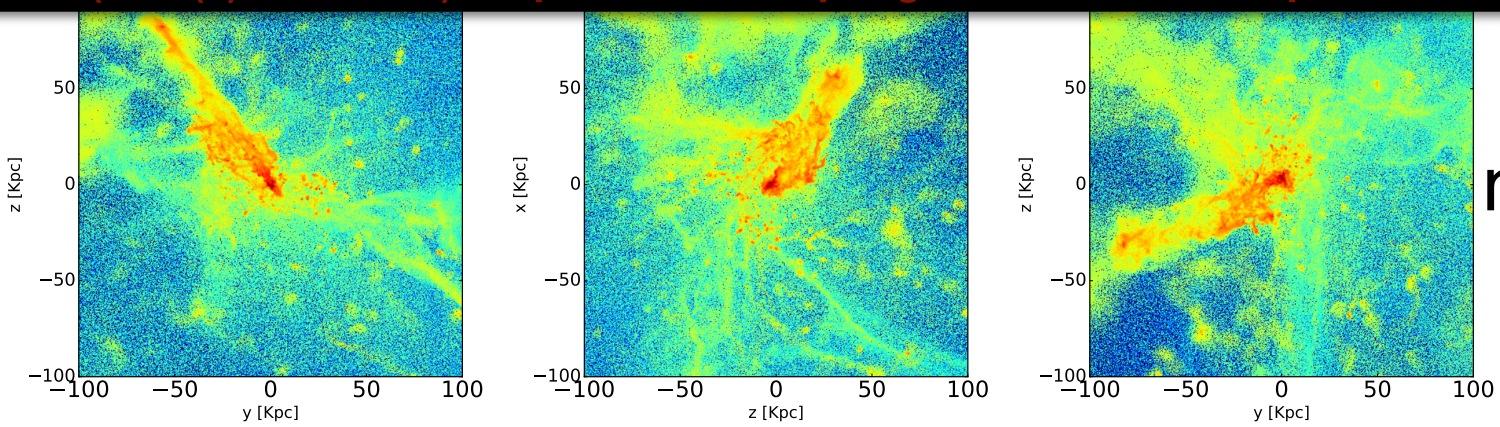
hi res FIRE hydro (Hopkins+) z=2.5 => 10(12) Msun galaxy at z=0 Gunjan Lakhlani, Murray +ABS

z=2.5



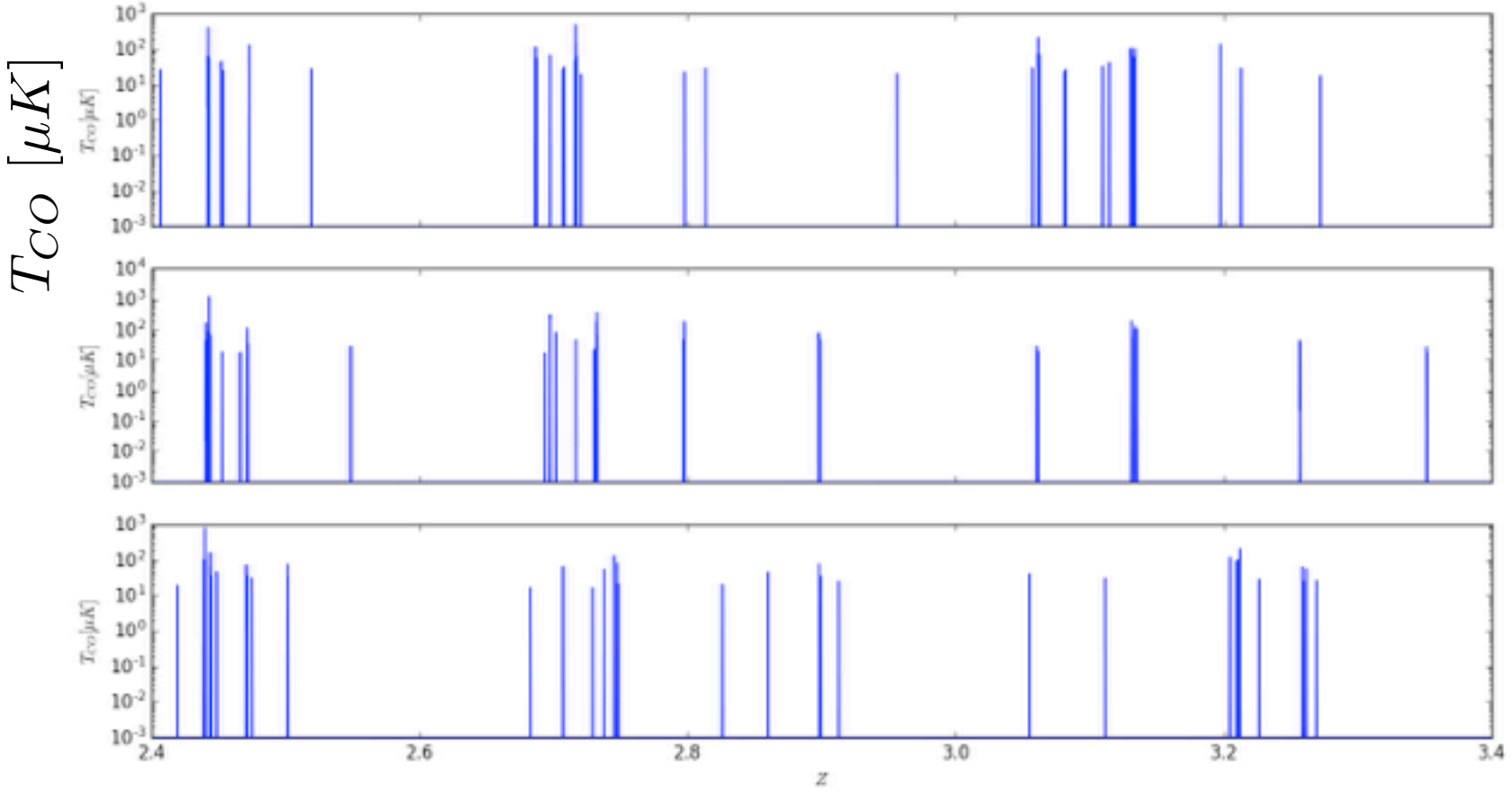
n_HI

LCO (SFR(z), .., Mhalo): importance sampling for relevant halo parameters for SFR?!



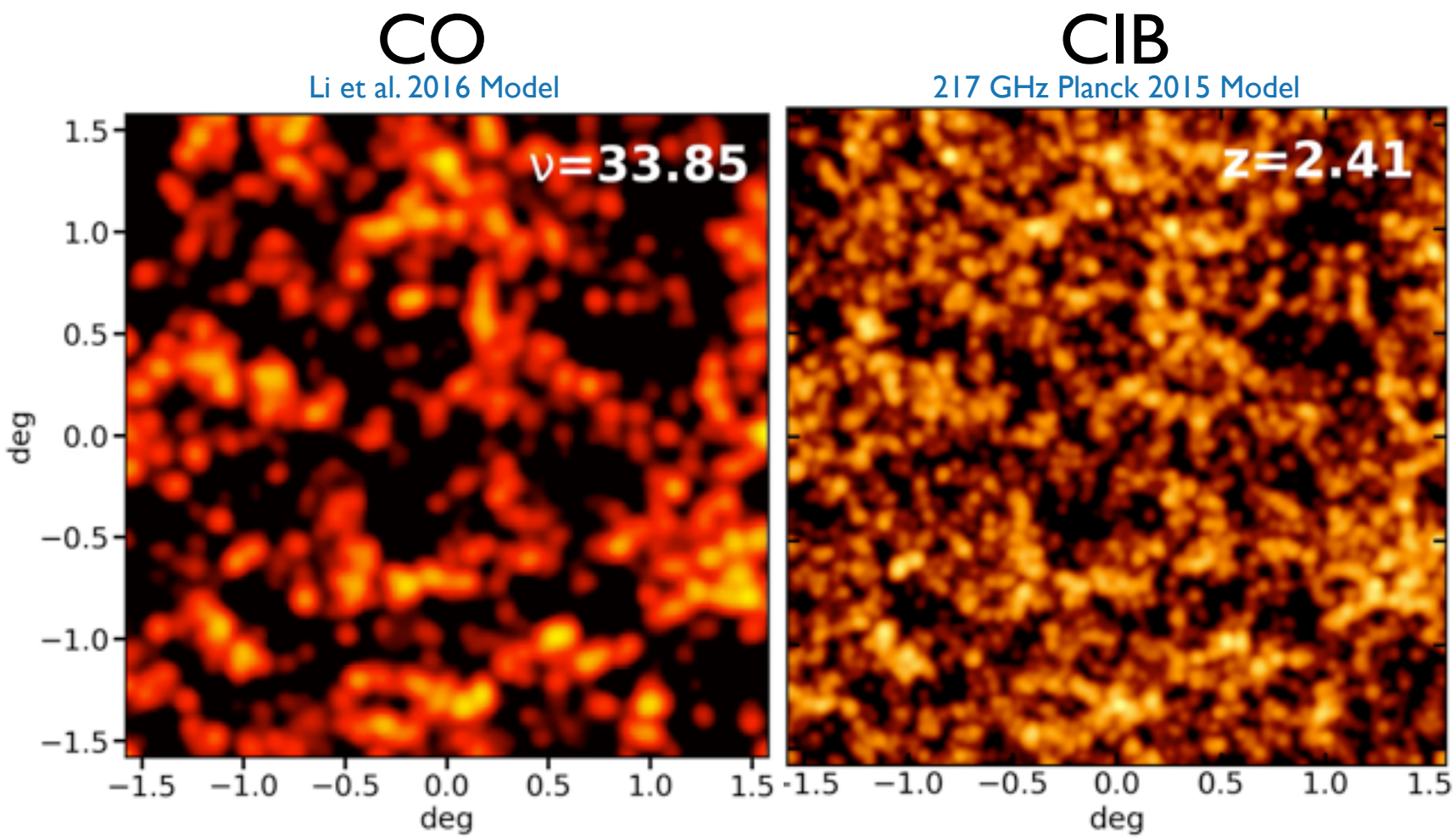
n_O

simulated CO lines 30” apart through halos
with galaxies distributed according to a Halo Occupation distribution
includes internal velocities, but no internal galaxy fluctuation/orientation effects
single object complexity is somewhat mitigated by the ~ 3 arcmin COMAP beam

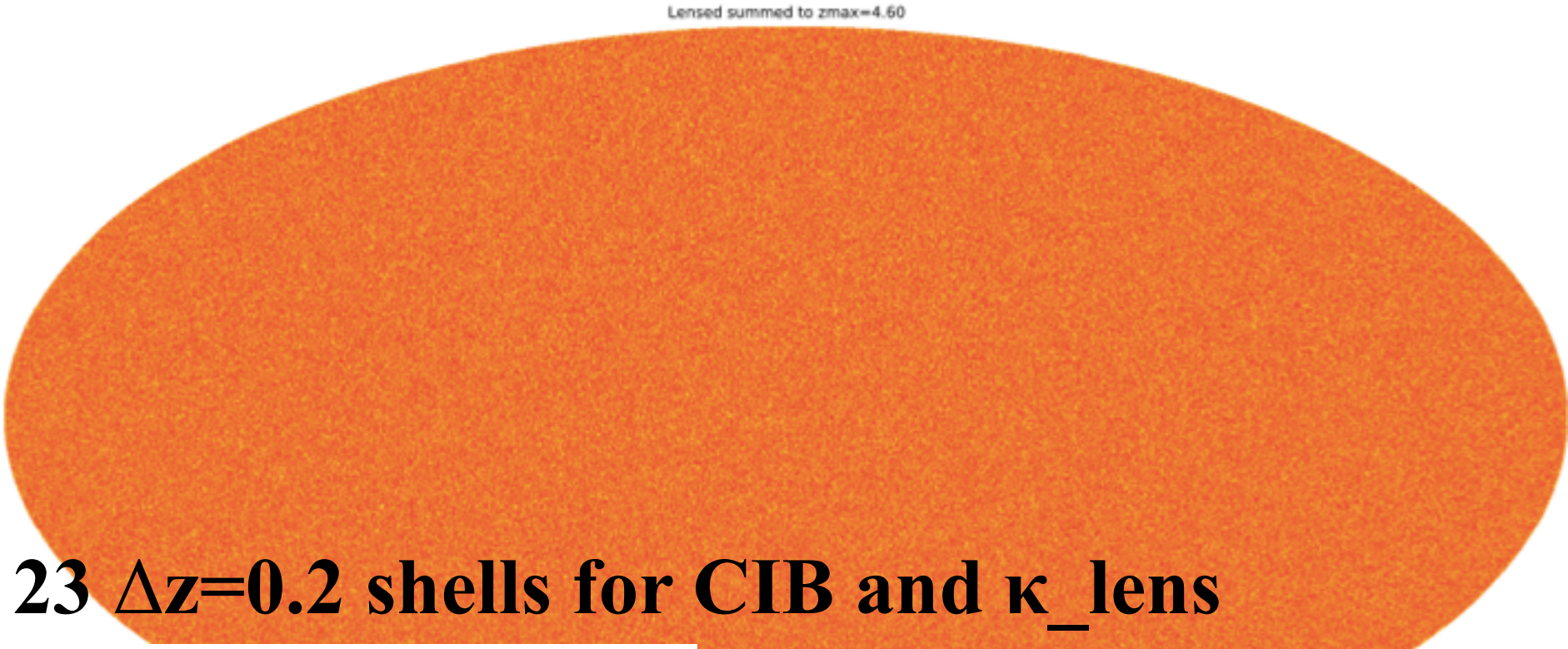


Ronan Kerr + ABS

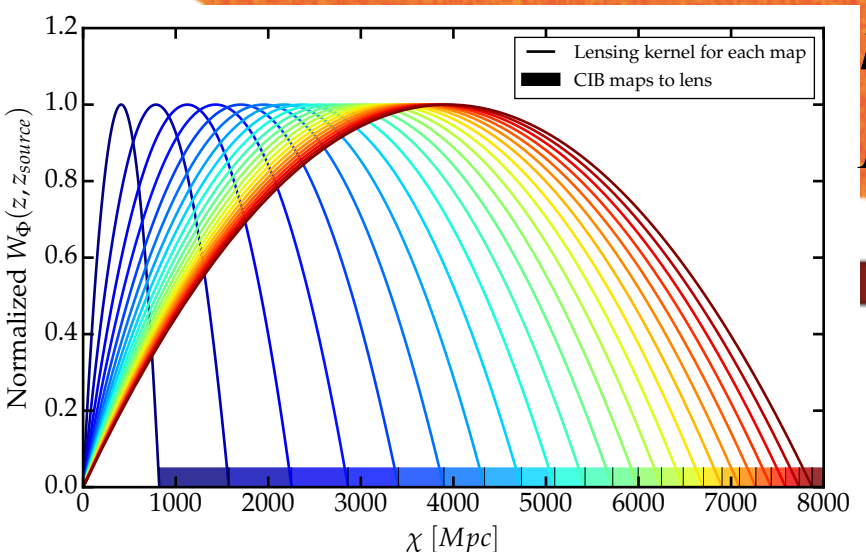
Lensing of the CIB & COmap & HImap &..



Lensing of the CIB & COmap & HImap &..

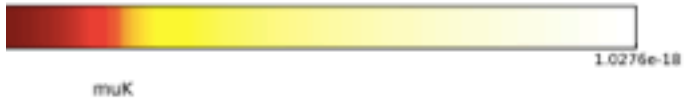


23 Δz=0.2 shells for CIB and κ_lens



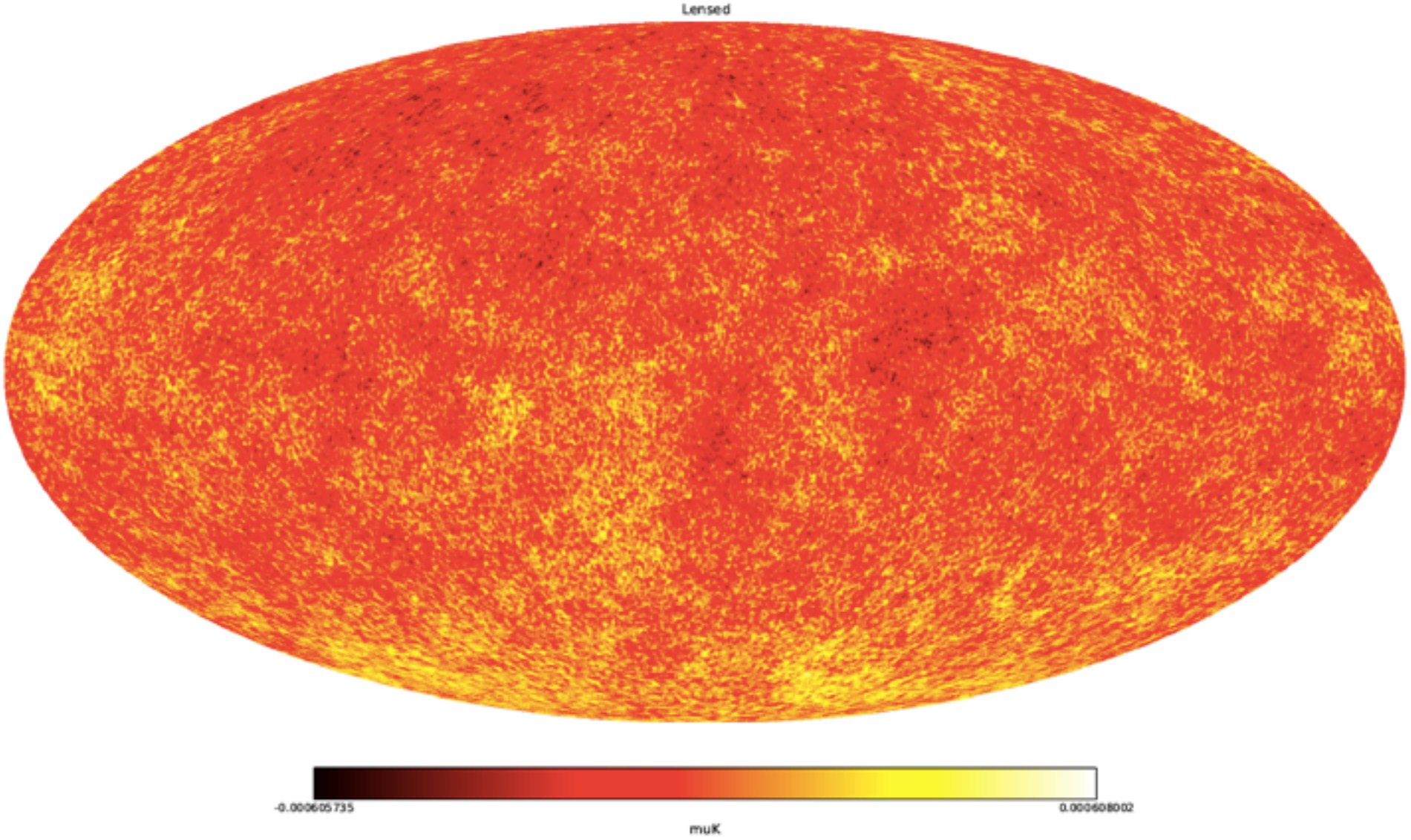
κ_lens from peak patch halos

DM+gas+stars inside +2LPT outside



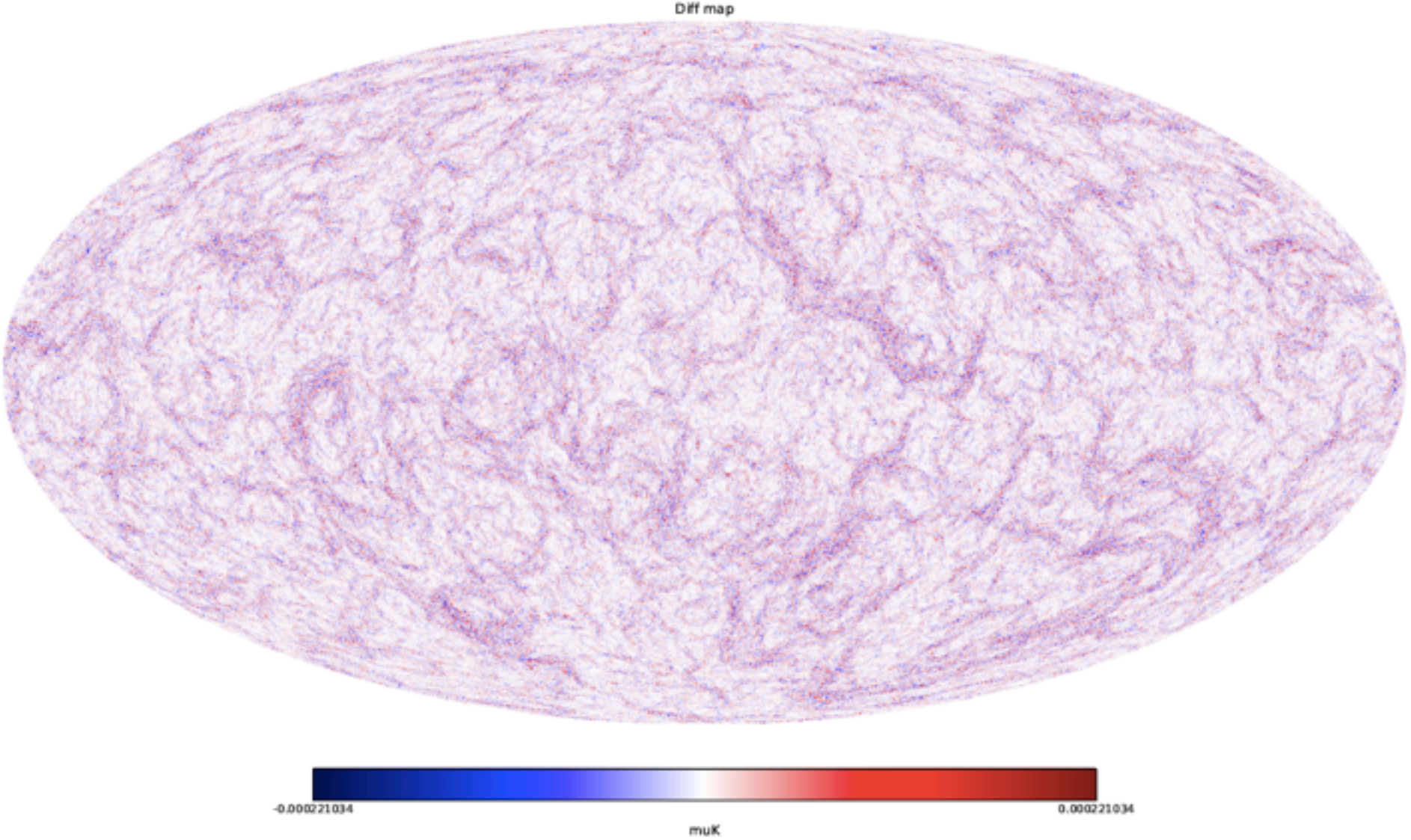
Lensing of the CMB

CMB*lensed*



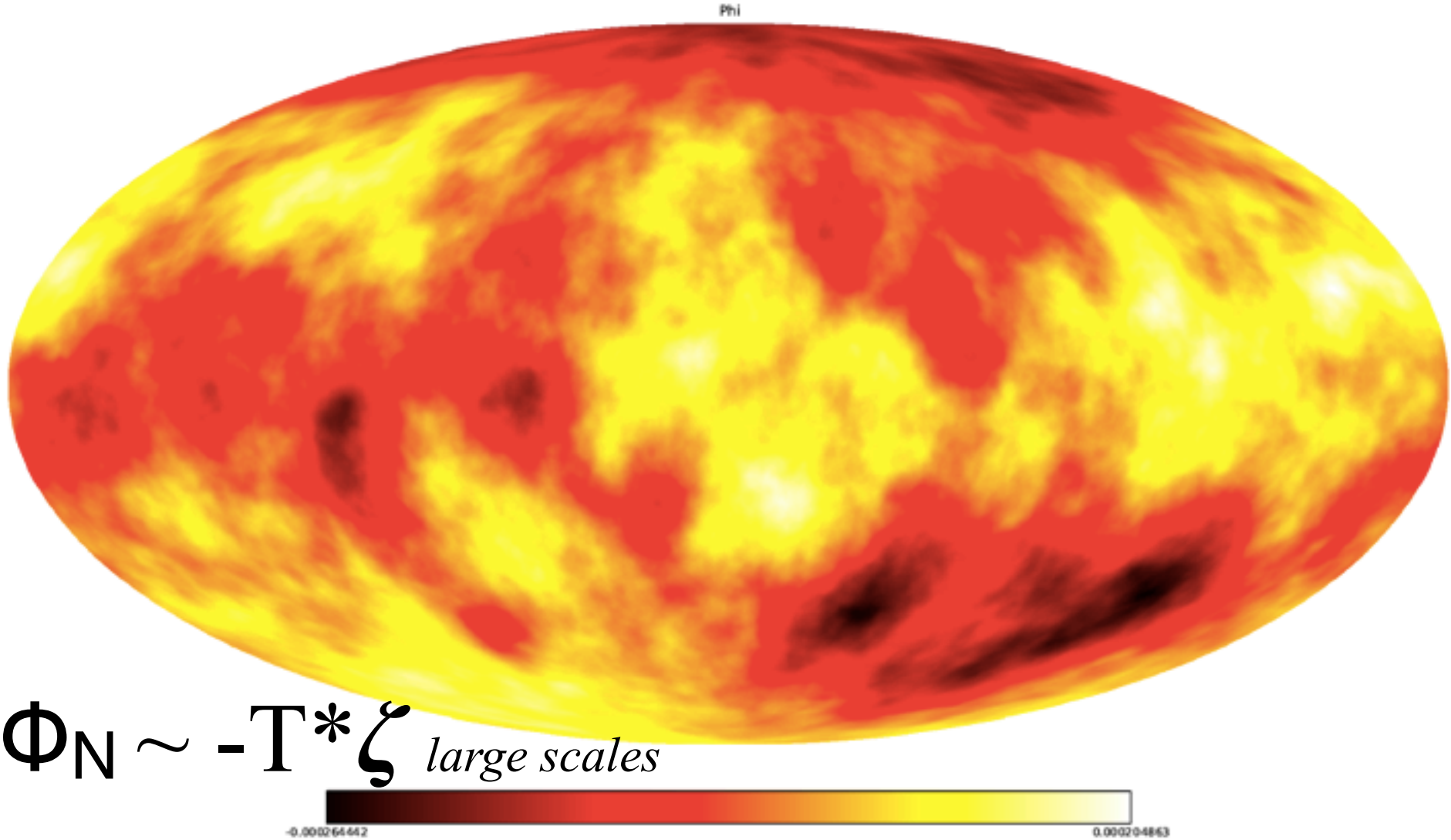
Lensing of the CMB

CMB*lensed* - CMB*unlensed*



CMB Lensing Gravitational Potential:

peak patch halos DM+gas+stars inside, 2LPT outside



$\Phi_N \sim -T*\zeta$ *large scales*

BSMc from LIMLAM?

reconstructing ζ ~ ***early Universe ln a(x,t)***

modes 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

ζ- TOPOGRAPHY & CARTOGRAPHY

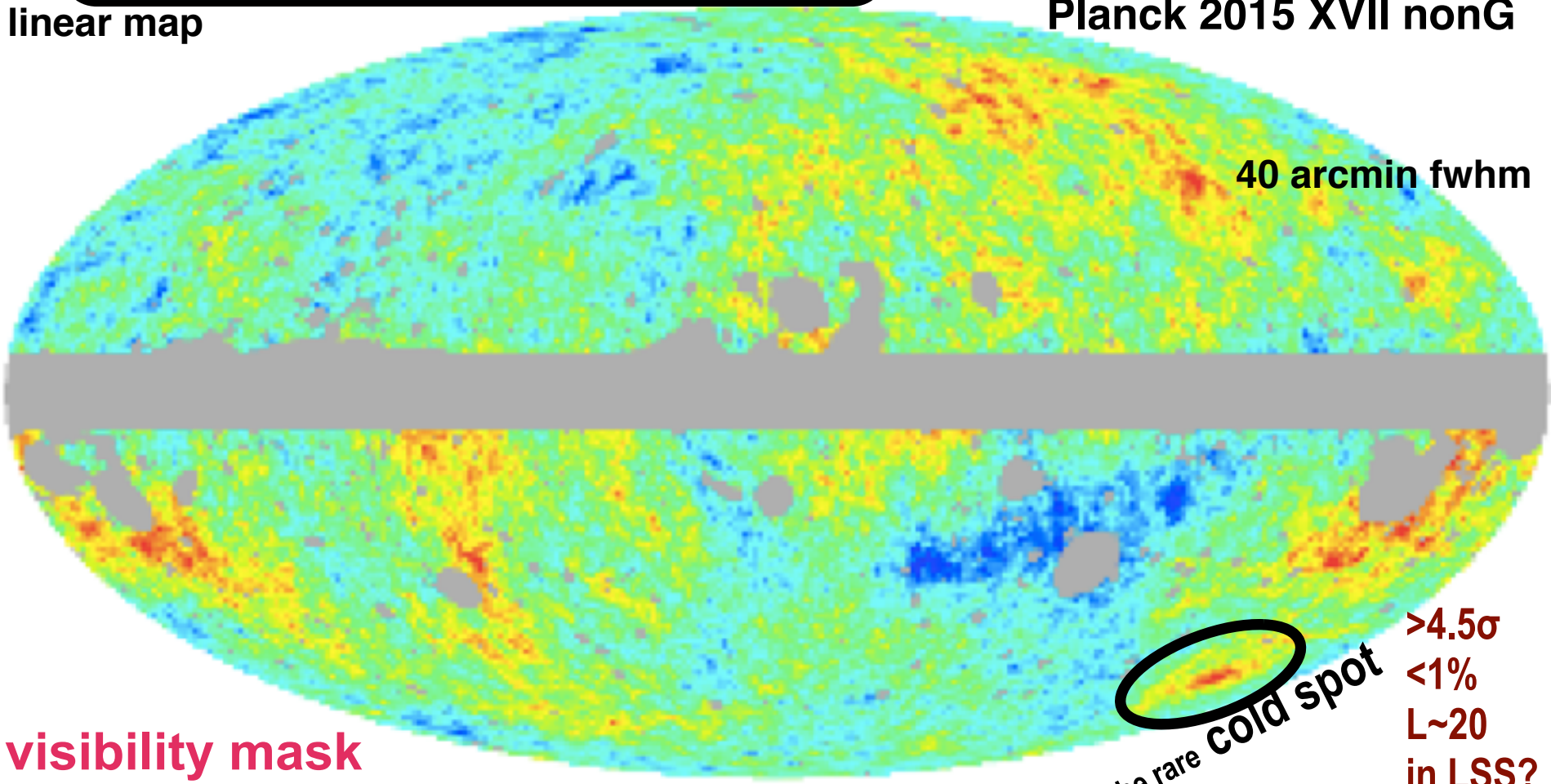
of our Hubble-patch bit of the early universe: RECONSTRUCT

<ζ | Temp, E pol>

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

linear map

Planck 2015 XVII nonG



BSMc varieties of nonGaussianity:

conventional correlated perturbative *Planck2015-constrained* f_{NL} *SphereX target, SKA X surveys*

caustics from preheating (1cm scale horizon) **modulated** by light non-inflaton fields fluctuating **on large scales** & super-horizon scales ζ **uncorrelated** with conventional inflaton-ζ

=> **3D intermittency** cf. 2D WMAP cold spot

unconventional but generic?

a nonlinear (large scale) bias response to the nearly scale invariant light field
cf. LSS bias of clusters/galaxies via a threshold function on the linear density field

or remnants of bubbles during inflation

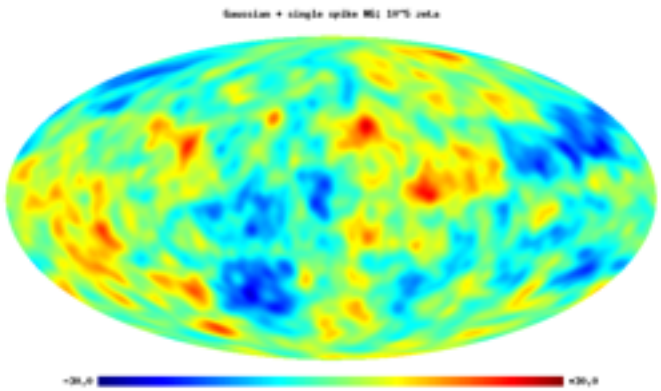
or …

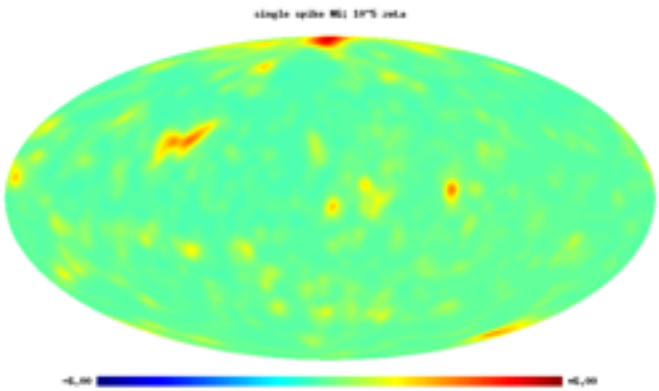
apparent breakdown of LSS homogeneity

2D intermittency WMAP cold spot

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

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

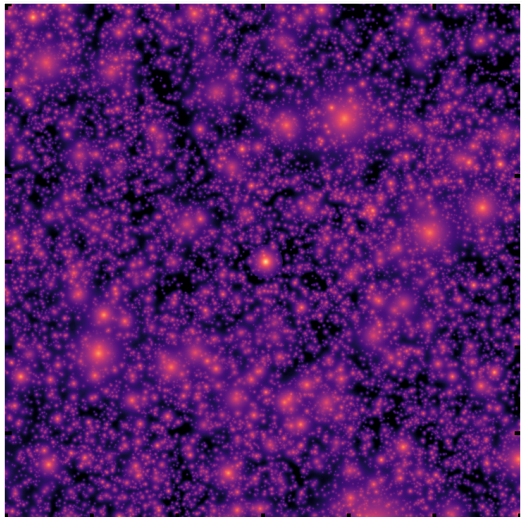




3D intermittency

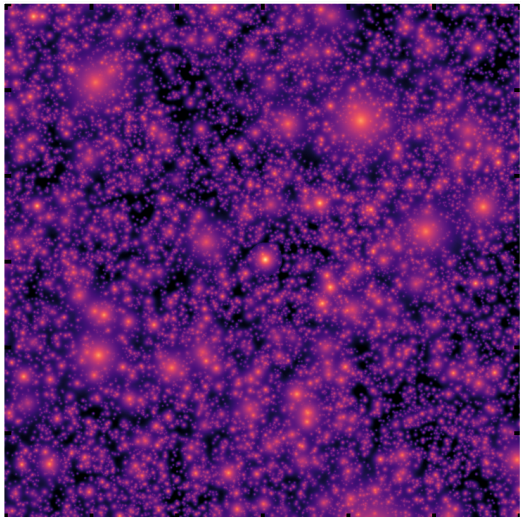
uncorrelated nonG 'wide open' cf. usual correlated highly constrained nonG

LSS tSZ: Gaussian std



B2FH, b+braden+frolov+huang

LSS tSZ: Gaussian std + subdominant uncorrelated ζ

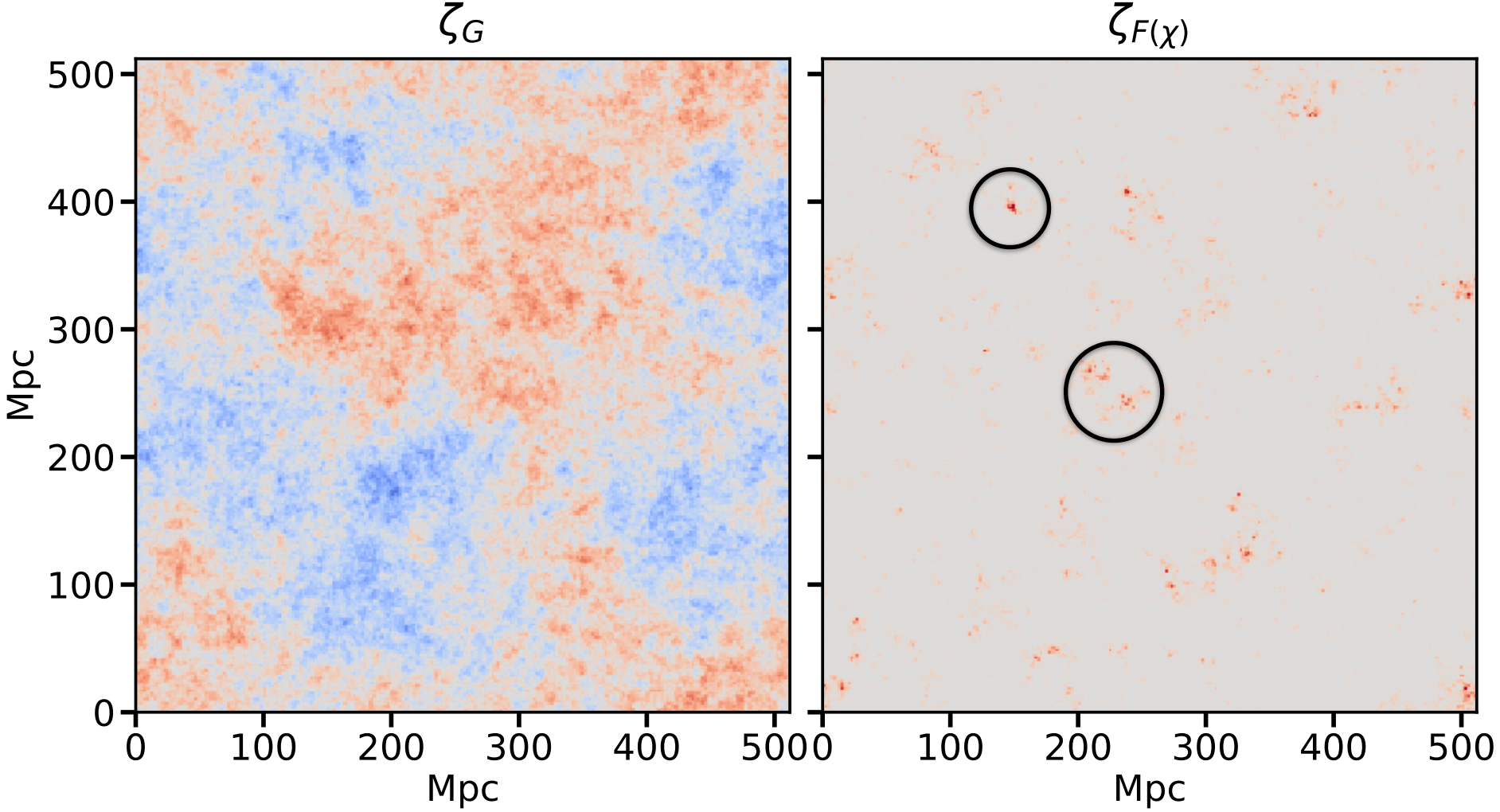


ABSB+FH, alvarez+b+stein+frolov+huang

Primordial Non-Gaussianity in the Peak Patch method:

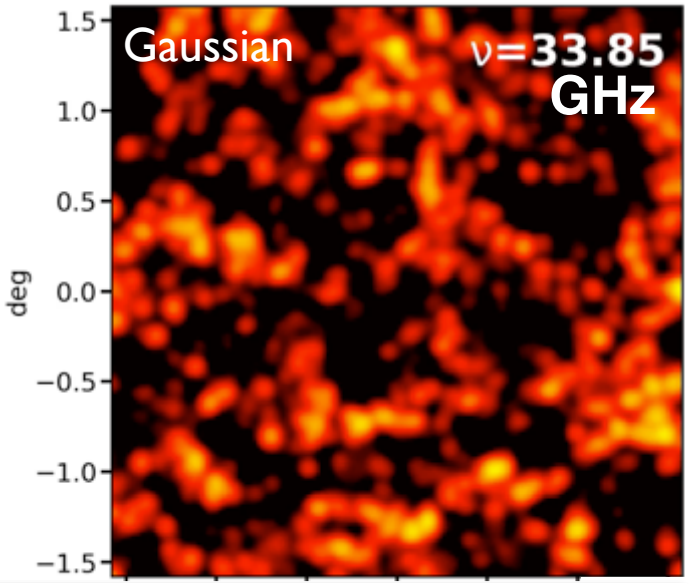
Intermittent Non-Gaussian case

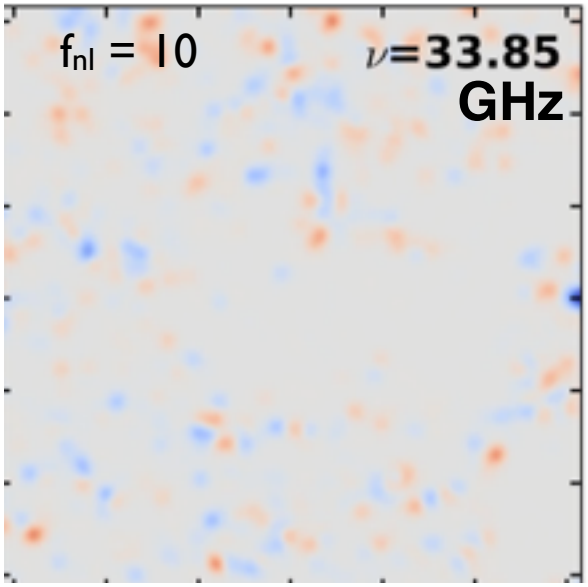
***uncorrelated* ζ[GRF]**

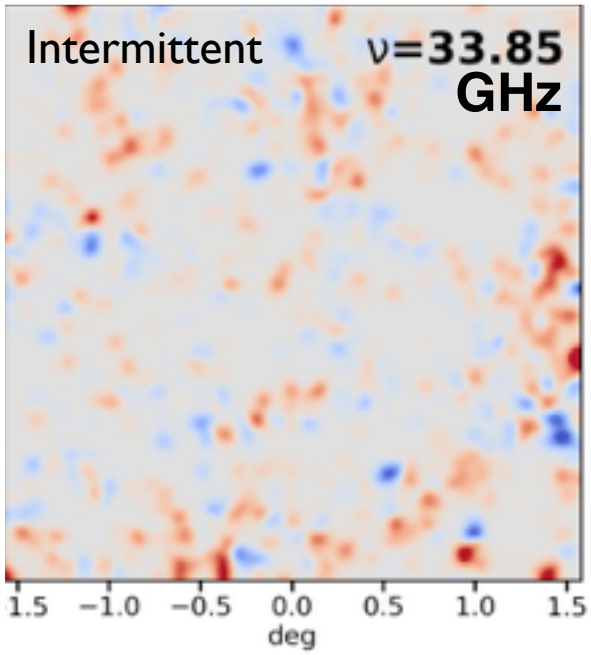


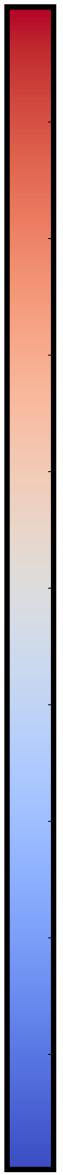
Primordial Non-Gaussianity in CO

$\sigma_8 = 0.82$
In all cases









pp *summary:* fast halo finding for ensembles & BSMc works well (enough)

"mocking heaven" apps: **tSZ, CIB** *original motivation => tSZxCIB*, **kSZ, Lens**
optical galaxies **via HOD for CMASS, Euclid, LSST, .. DES, HSC, sphereX**
"intensity mapping" **of HI (CHIME, HIREX, ..,SKA) of CO COmap, CII**
well suited: **to cross-correlation studies of all sorts**
well suited: **to characterize correlated/non-Gaussian errors**
well suited: **light cones** *automatic, no interpolation*
Physics: *beyond Lambda:* dynamical DarkEnergy, modified gravity
LSS *non-Gaussianity:* perturbative, intermittent, scale-dependent bias

response functions to stimuli= mean susceptibilities

fluctuations inside controlled? outside 2LPT and subgrid halos adequate?
tSZ in pp control; CO out of pp control?
work on Lensing of the CIB and LIM is underway
why do LIMLAM? just understand galactic weather / storms
a theorist's hope: component-separate gastrophysics to reveal
fundamental BSMc physics
e.g., using LIM to further develop the ζ map of the early universe - stacked ζ
primordial nonG of all sorts in 3D. intermittent modulated heating with caustics
caustics are ubiquitous: **LSS/cosmic web & preheating**
large volume is better HI cf. CO - bubbly reionization hard to disentangle

END