Mocking Heaven's Web *with PeakPatches++*

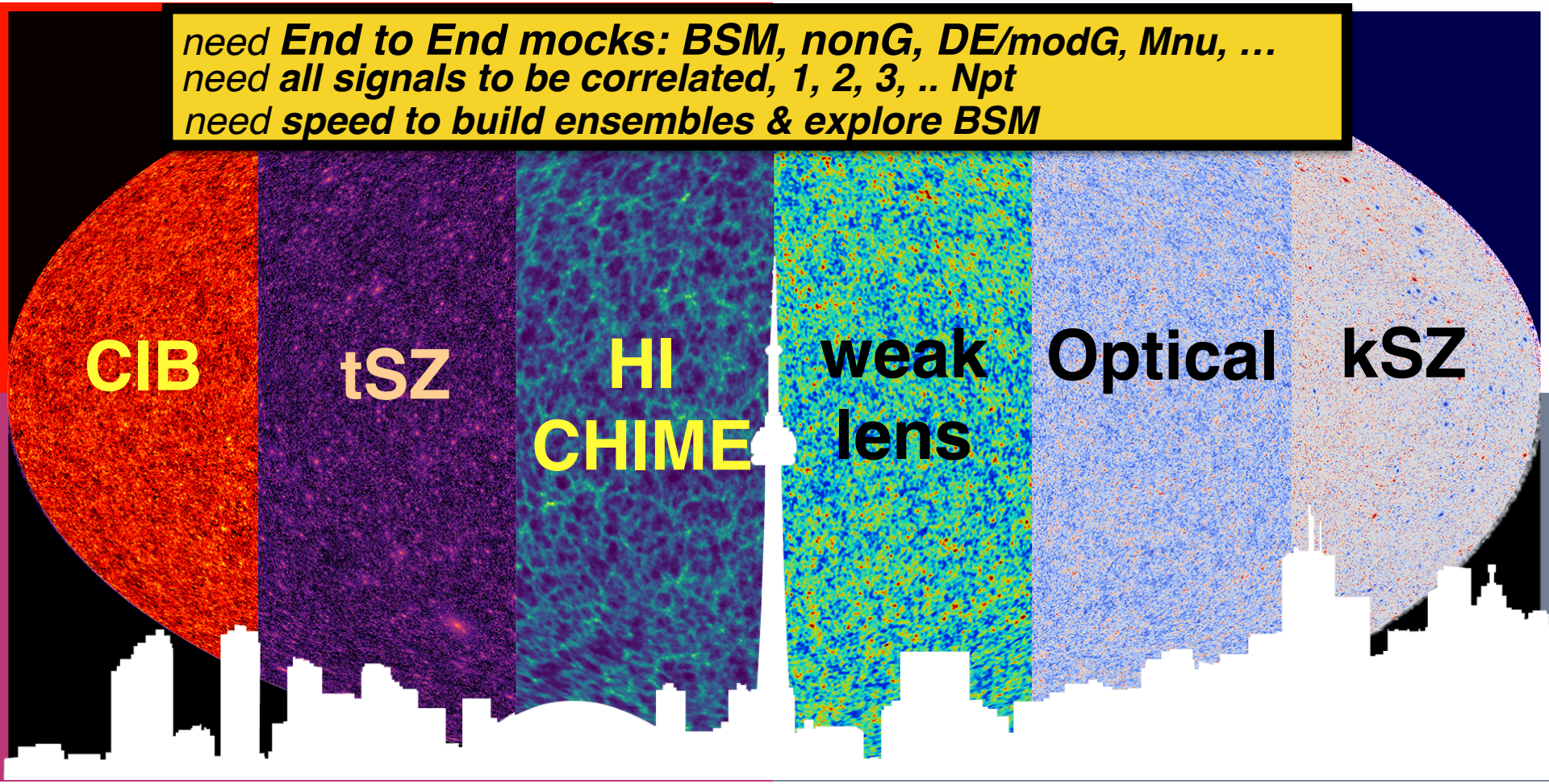
Dick Bond @ Slovenia17 Nonlinear Universe

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

Line Intensity Mapping and Line Absorption Mapping *fLIMfLAM*

CITA mini-industry: Marcelo Alvarez, Dick Bond, George Stein & Battaglia, Codis, van Engelen & FIRE: Lakhlani + Murray + Hopkins + Berger & Connor Bevington, Bruno Régaldo-Saint Blancard, Ronan Kerr, Louis Pham

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)*

Mocking Heaven *with PeakPatches++*

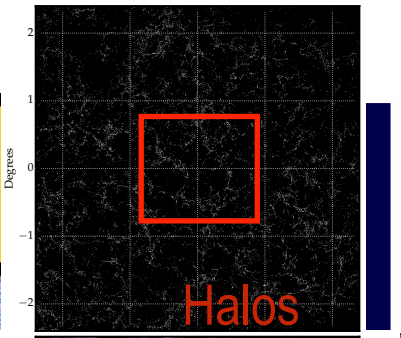
Line Intensity Mapping and Line Absorption Mapping

radio: HI CO CII, … + optical Ly a, …

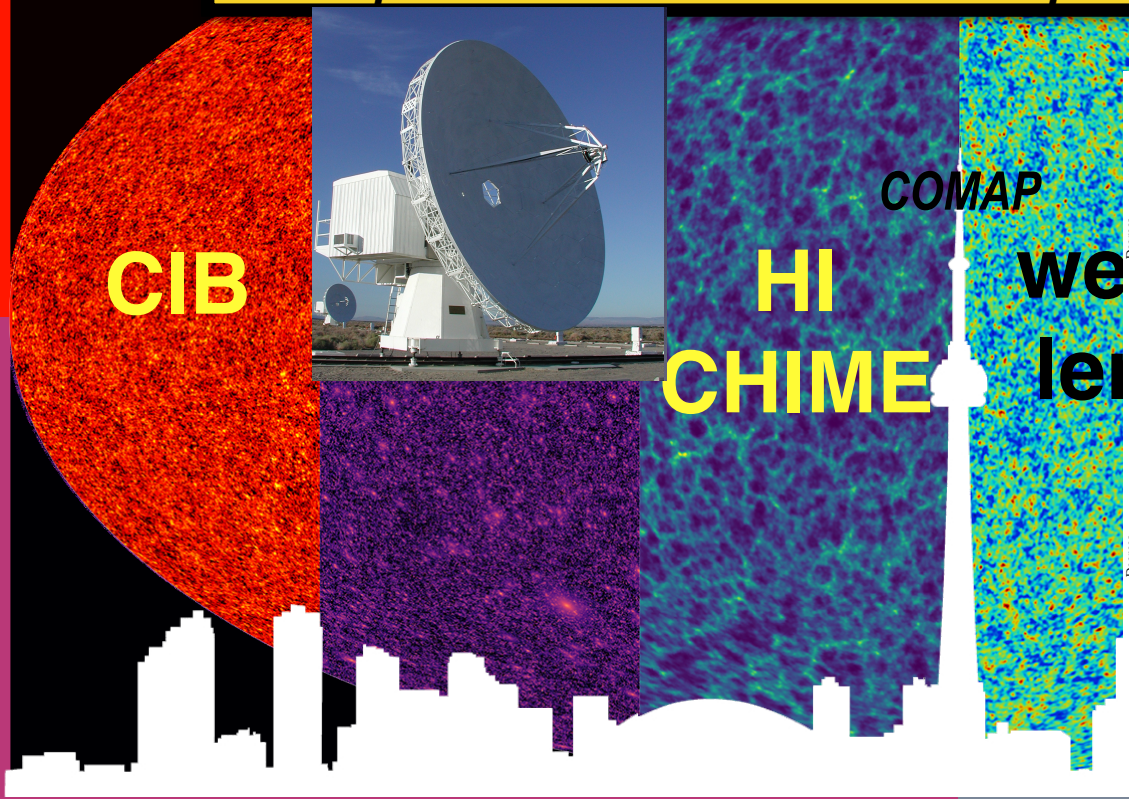
z=0.8-2.5 z=2.4-3.4 z=6-8

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

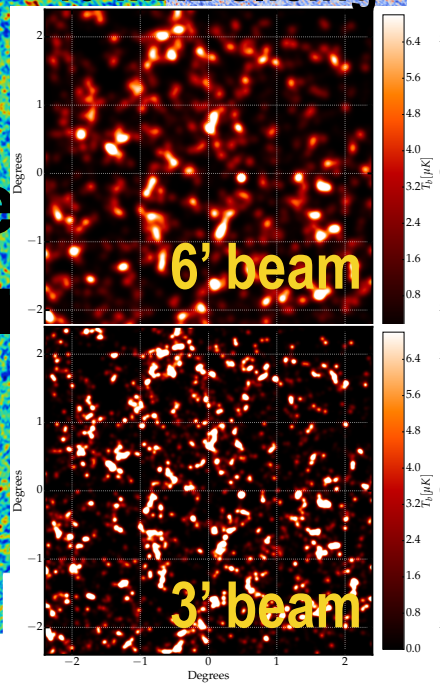
COMAP Survey Area

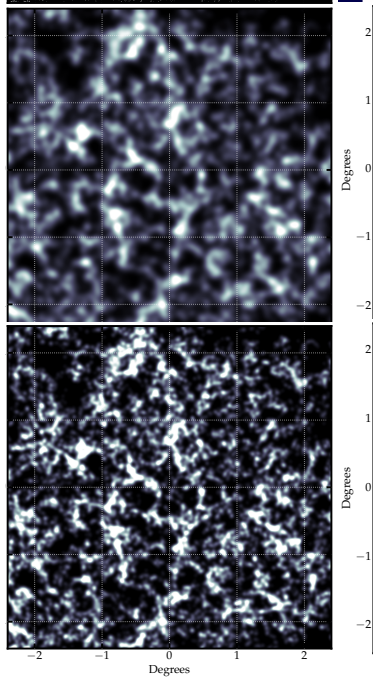


need ***End to End mocks: BSM, nonG, DE/modG, Mnu,***
need ***all signals to be correlated, 1, 2, 3, .. Npt***
need ***speed to build ensembles & explore BSM***



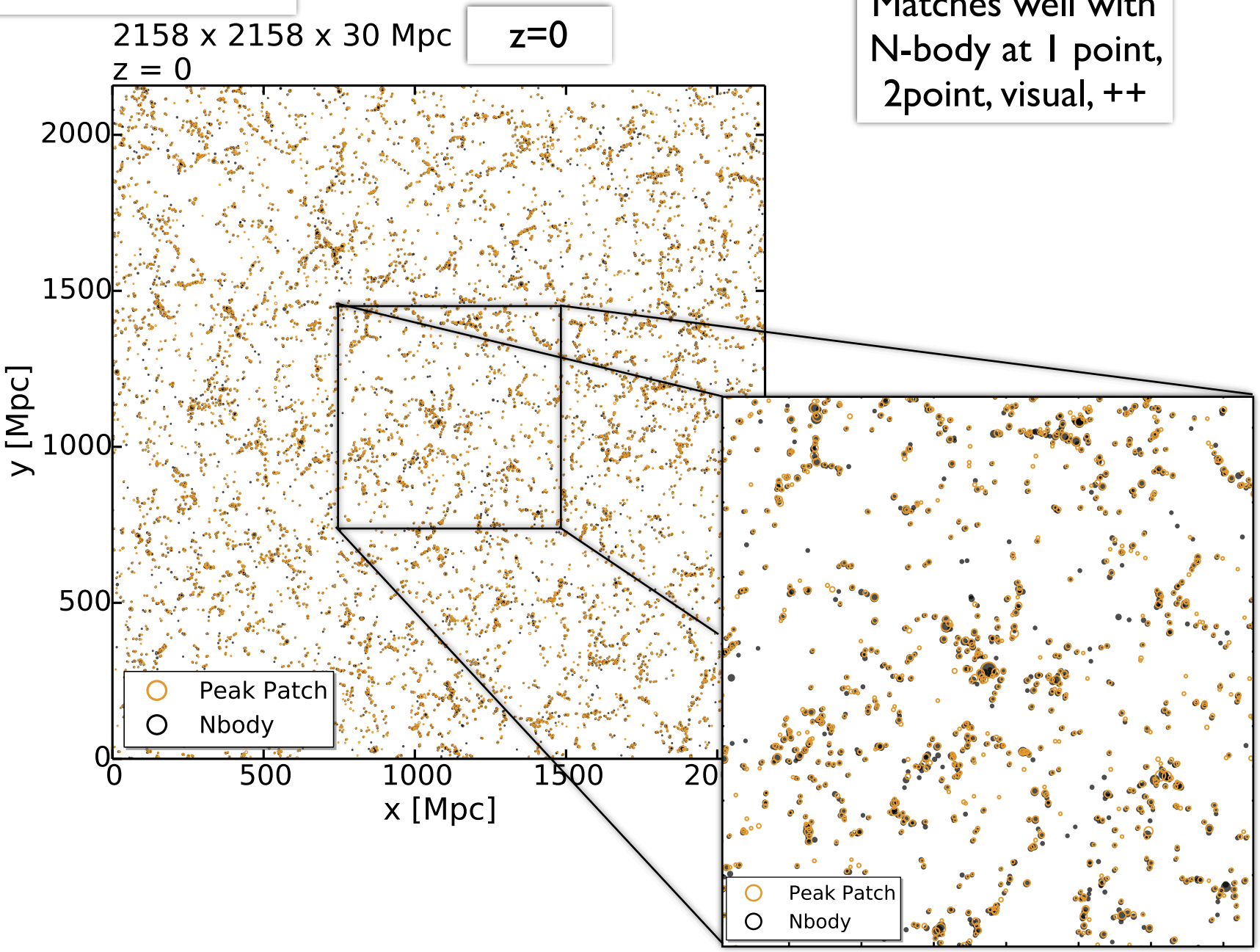
40 MHz slicing





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

Peak Patch Validation:



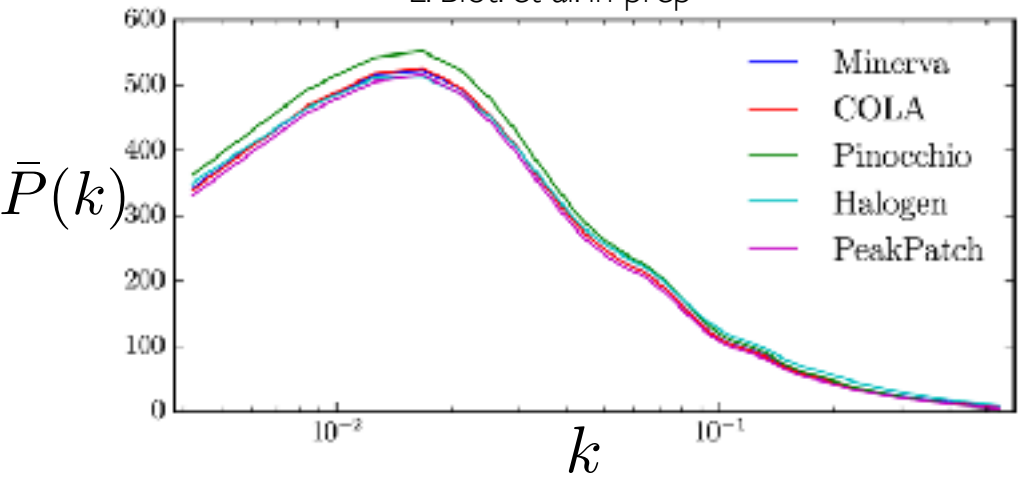
Matches well with N-body at 1 point, 2point, visual, ++

Fast Mocks with the Peak Patch Method: Validation

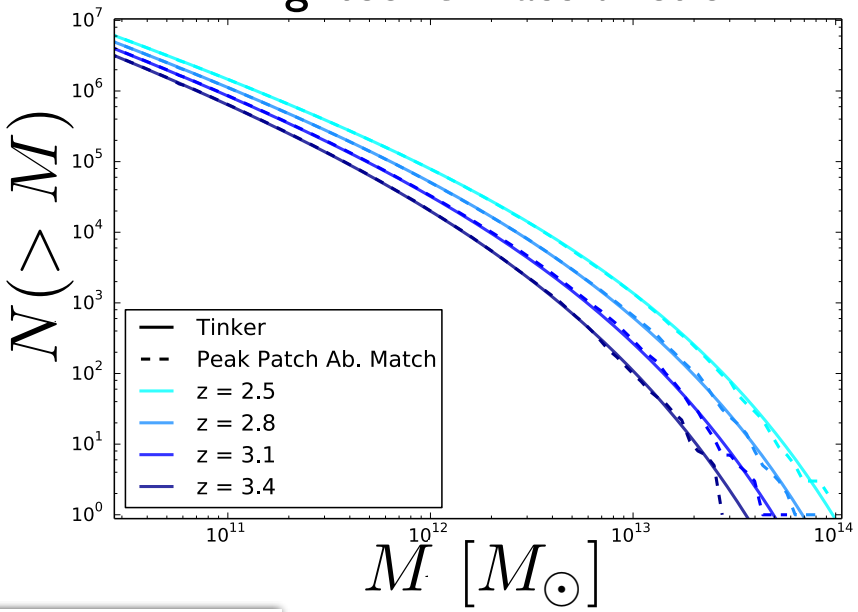
Matches well with N-body at 1 point, 2point, visual, ++

EUCLID comparison project

L. Blot. et al. in prep



Lightcone Massfunction



COMAP sim Stats:

Lbox = 1065 Mpc, 2.4 < z < 3.4

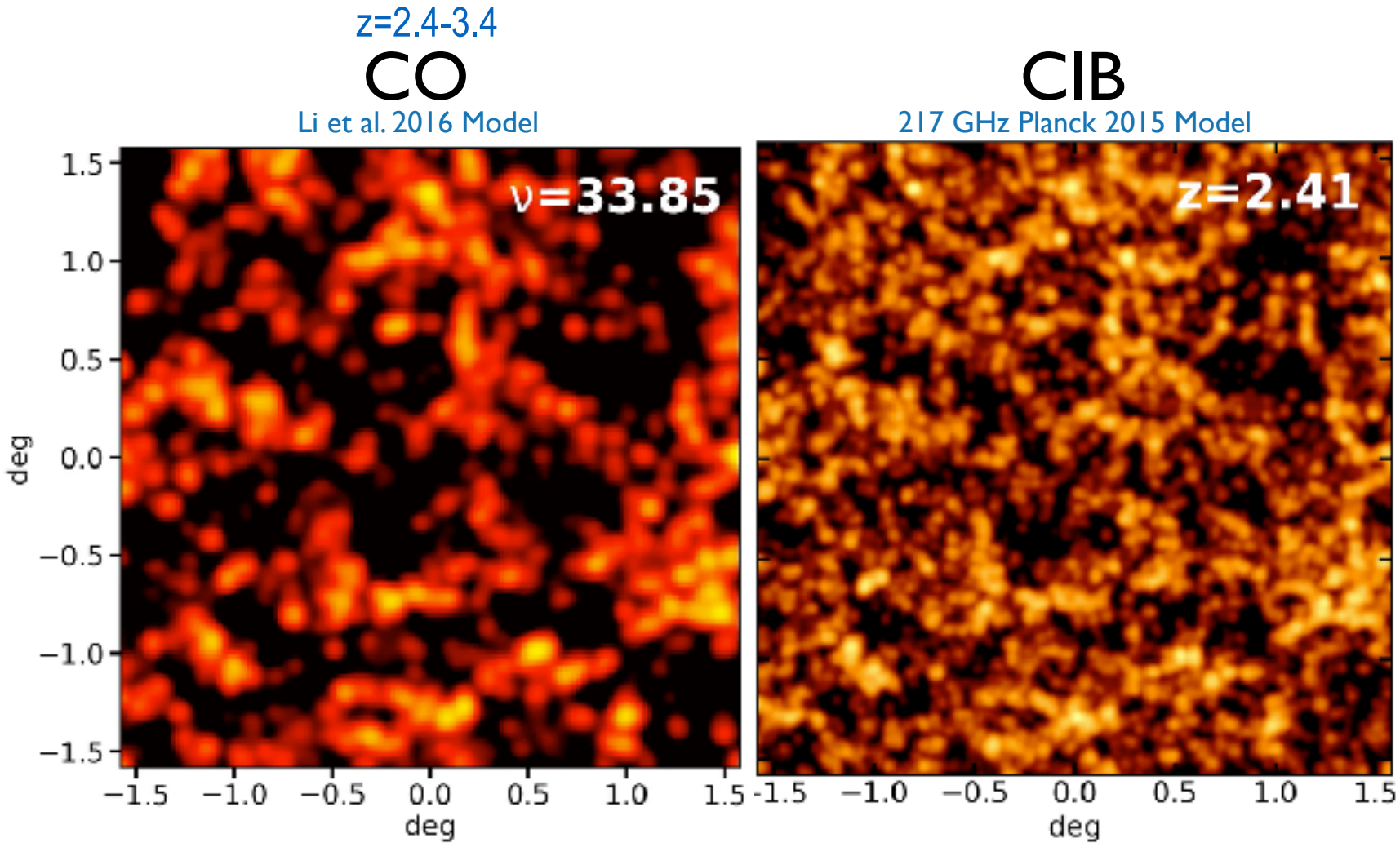
ncell = 4096^3

nproc = 2048, time = 20 minutes

M_{min} = 2.5 x 10^{10}

COmap sims using Li+ Mhalo -> LCO cf. CIB a la Planck13,15

Danger: correlated stochasticity of bursty star formation etc. @ end talk



underway: **Lensing of CIB & COmap & HImaps &..**

Peak-patches = "hot" halos

B+Myers 91-96; BBKS 83-86

physics compelled the few choices in BM;
no modification with massive parallelization in ABS+17

hot dynamics => $\mathbf{e}^{i}_{J}(r_c,t,R_c)$

homogeneous ellipsoid evolution:
coarse-grained treatment of fine-grained dynamics

cool coarse-grained halo-flow dynamics

=> $\mathbf{s}^{i}(r_c,t,R_c)$ 1LPT -> 2LPT

higher order approximate s_{NL}

a sum - formulated to be implemented

=> warm coarse-grained dynamics

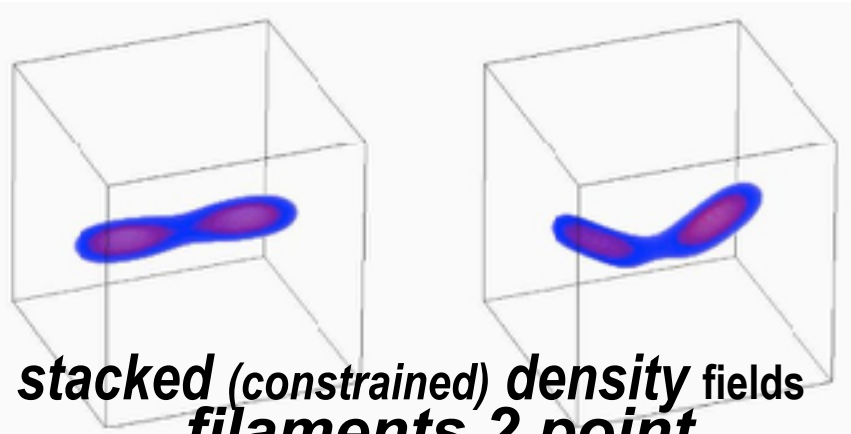
flow of fine-grained to inform coarse-grained
via constrained response functions aka susceptibilities

stacked ***correlations transformed to susceptibilities***
by removing halo-halo correlations
constraints are "charges". tensor orientations, assembly bias etal
importance sampling via control parameters
to measure susceptibilities. in fine-grained sims e.g., hydro
BUT complex gasdynamics with feedback - LIM issue

=> *The* ***Cosmic Web***
B+Kofman+Pogosyan 96-99

"molecular" bond Picture of LSS Filaments & Membranes

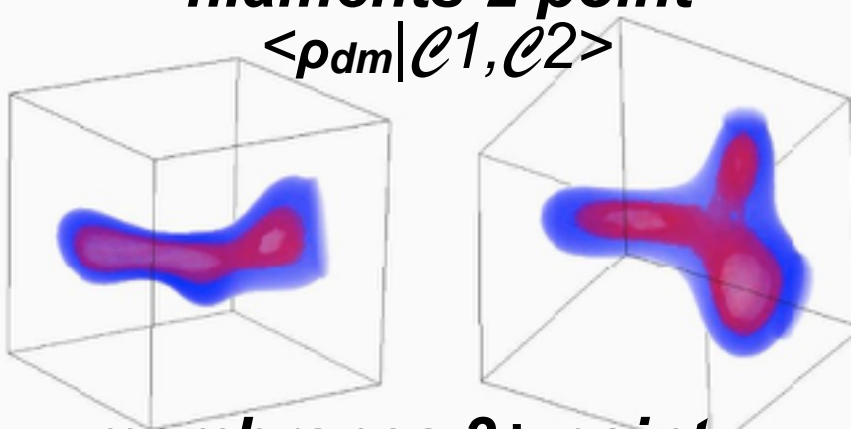
expansion in susceptibilities for GRF



stacked *(constrained)* ***density*** **fields**

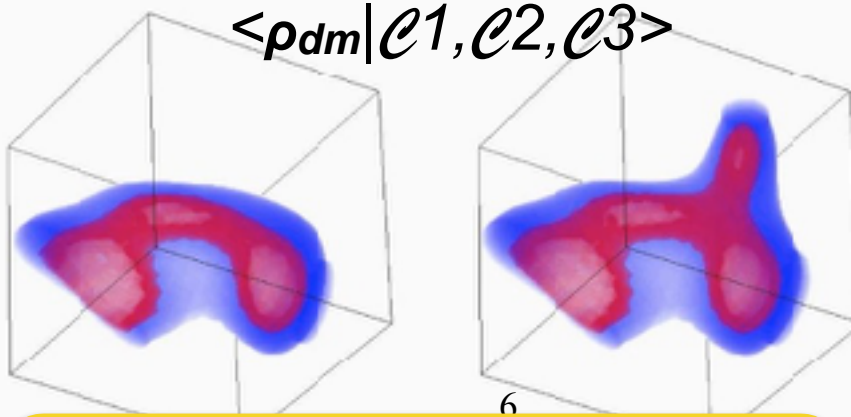
filaments 2 point

$\langle \rho_{dm} | \mathcal{C}1, \mathcal{C}2 \rangle$



membranes 3+ point

$\langle \rho_{dm} | \mathcal{C}1, \mathcal{C}2, \mathcal{C}3 \rangle$



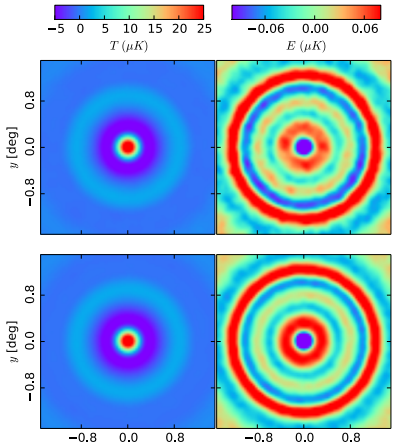
1-point stack has better stats $\langle \rho_{dm} | \mathcal{C}1 \rangle$

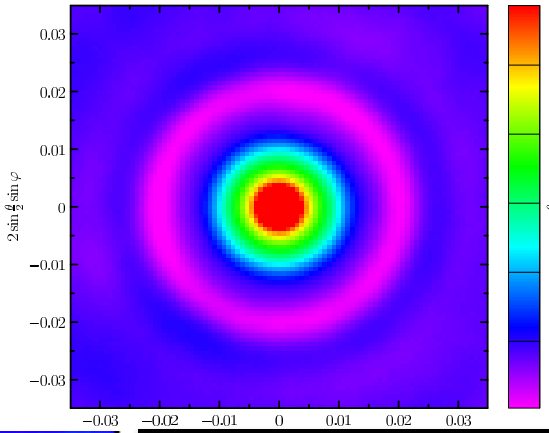
Stacking @ CITA - oriented asymmetric on extrema & other points

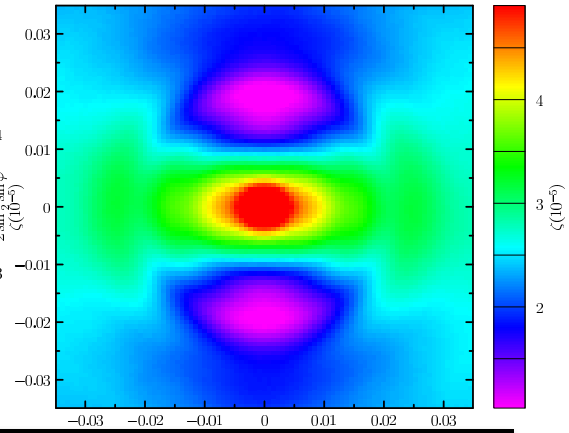
Topography of the CMB Web, ISM Web, y-web, IQU/ E B

oriented/symmetry-broken stacking on field points peaks saddles (cols, passes)

ACTPol *stack*
<T,E,B|T-field>
Louis+16

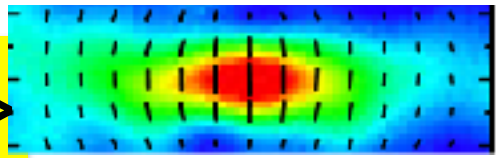






B+Frolov+Huang

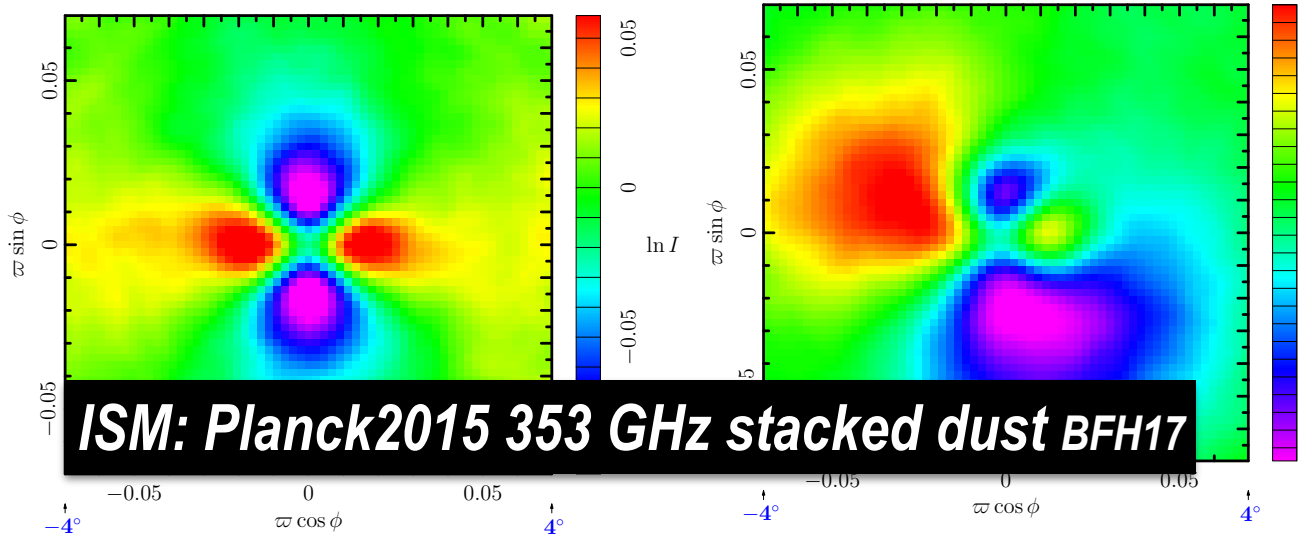
<Qr |oriented l-pk>



stacked on 7779 cols, Hessian oriented

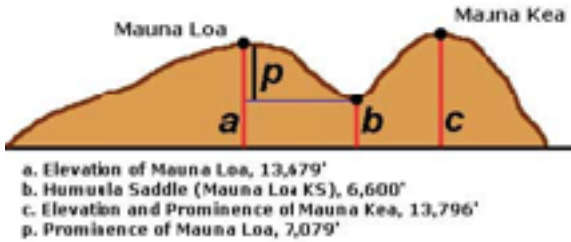
earlyU SuperWeb map Planck2015 XVII
stacked ζ-map | ζ-pk TQU> BFH17

stacked on 7779 cols, Hessian oriented



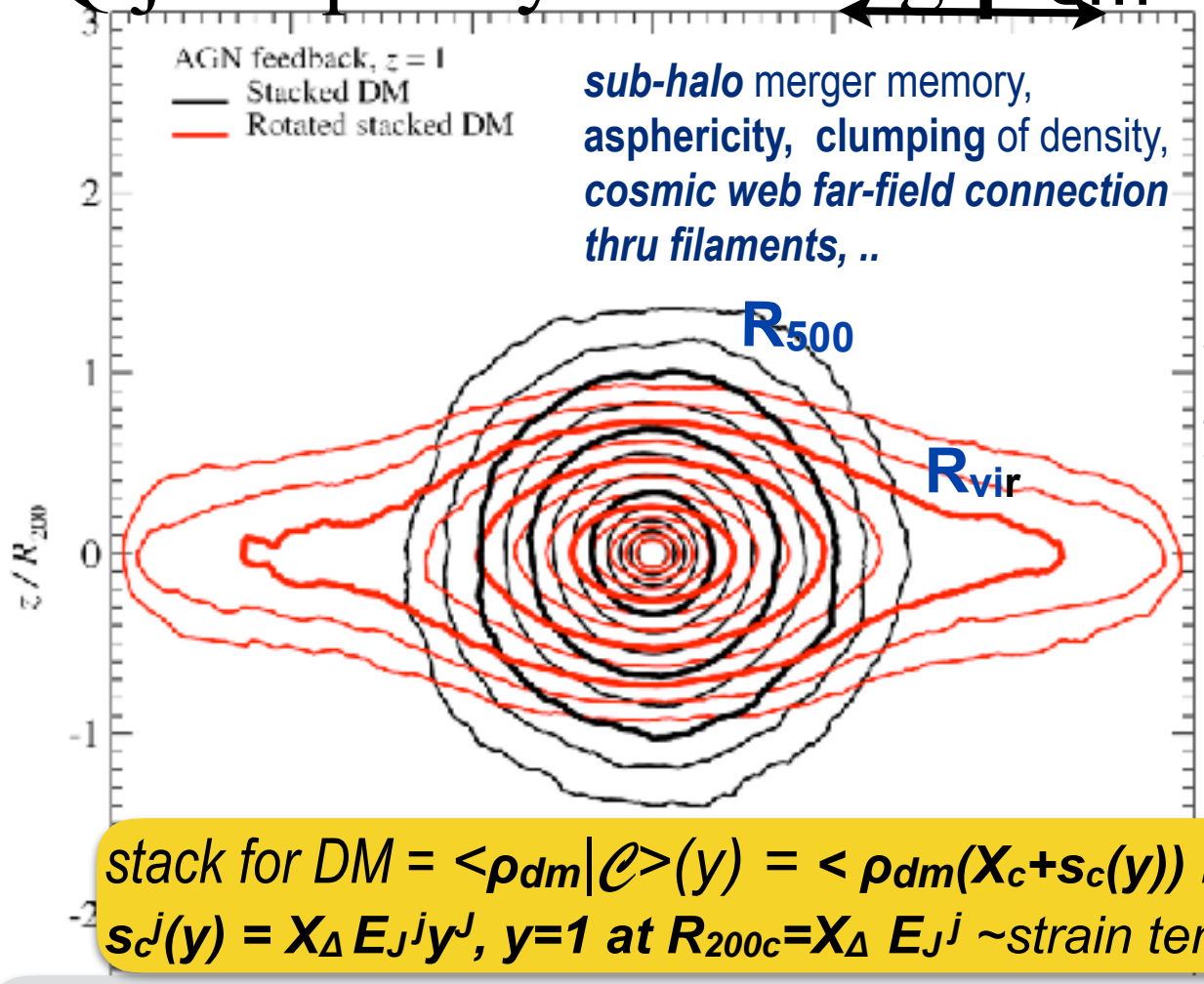
ISM: Planck2015 353 GHz stacked dust BFH17

stacked + Hessian
+ direction info
<ln I | I-saddle
broken symm>



Stack to get interior cluster susceptibilities

Qij Ellipticity Orienting ρ_{dm} z=1



sub-halo merger memory,
asphericity, clumping of density,
cosmic web far-field connection thru filaments, ..

R_{500}

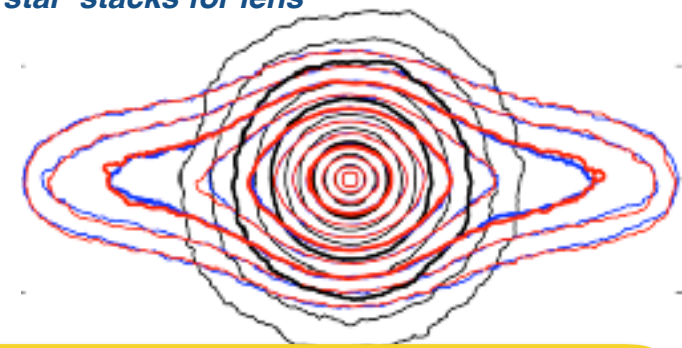
R_{vir}

DM in cluster-Y_{SZ} "far-field" is increasingly elongated: a little near-field filament penetration

e(gas) < e(DM) /2
z=1 extreme cf. z=0

Battaglia, Bond, Pfrommer, Sievers 1,2,3,4 gasdynamical simulations with AGN feedback

DM density stacks for lens
pressure stacks for tSZ
gas density stacks for kSZ & lens
'star' stacks for lens

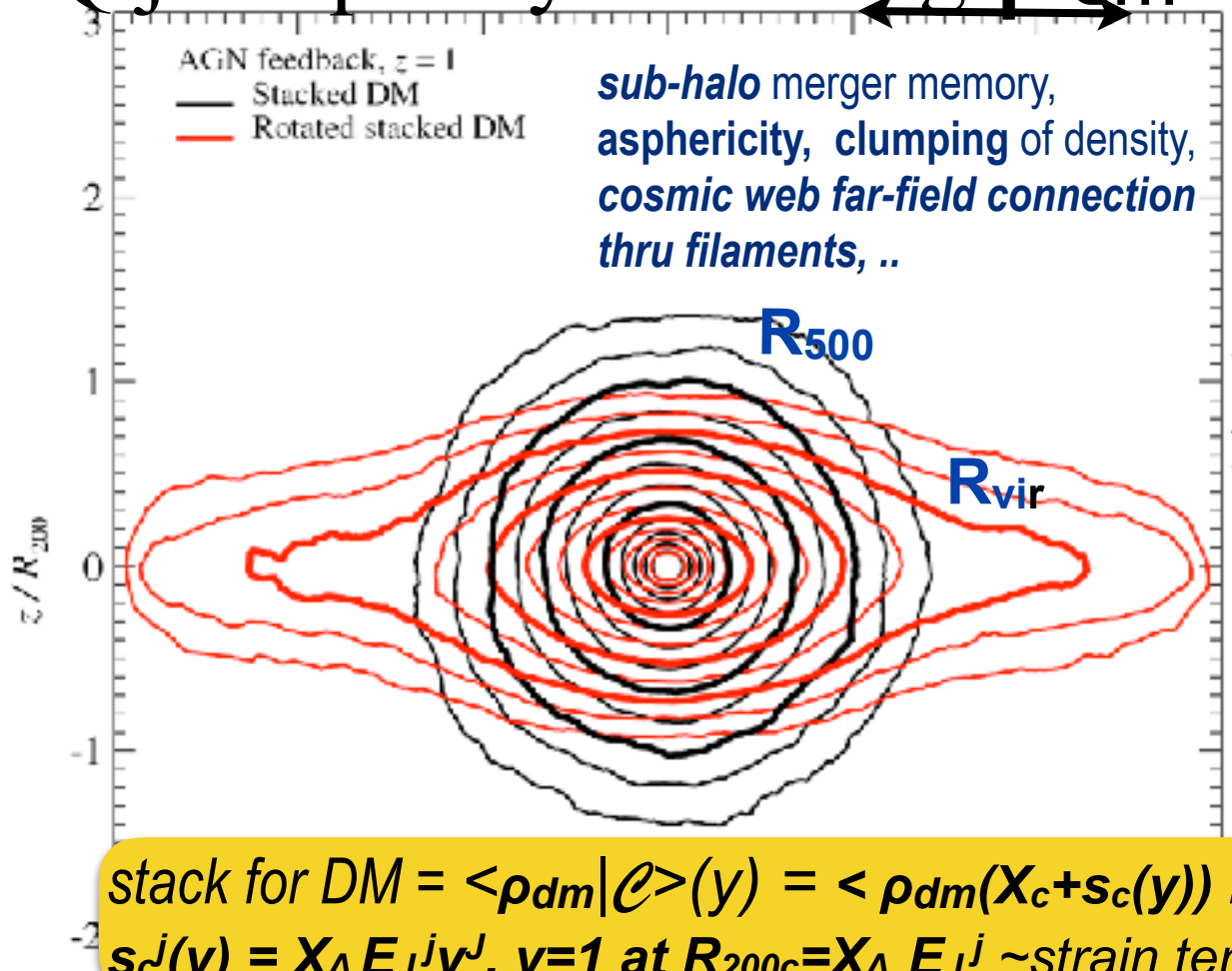


stack for DM = $\langle \rho_{dm}|\mathscr{C}\rangle(y) = \langle \rho_{dm}(X_c+s_c(y))\, n_{\mathscr{C}}(X_c)\rangle / \langle n_{\mathscr{C}}(X_c)\rangle$,

$s_c^j(y) = X_\Delta E_J{}^j y^J$, $y=1$ at $R_{200c}=X_\Delta E_J{}^j$ *~strain tensor ~(quadrupole tensor)*$^{-1/2}$

Stack to get interior cluster susceptibilities

Qij Ellipticity Orienting ρ_{dm} z=1



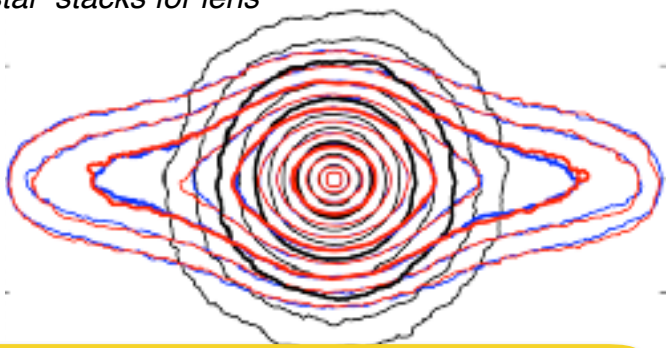
sub-halo merger memory,
asphericity, clumping of density,
cosmic web far-field connection thru filaments, ..

R_{500}

R_{vir}

DM in cluster-Y_{SZ} "far-field" is increasingly elongated: a little near-field filament penetration
e(gas) < e(DM) /2
z=1 extreme cf. z=0

Battaglia, Bond, Pfrommer, Sievers 1,2,3,4
gasdynamical simulations with AGN feedback
DM density stacks for lens
pressure stacks for tSZ
gas density stacks for kSZ & lens
'star' stacks for lens



stack for DM = $\langle \rho_{dm}|\mathcal{C}\rangle(y) = \langle \rho_{dm}(X_c+s_c(y))\, n_{\mathcal{C}}(X_c)\rangle / \langle n_{\mathcal{C}}(X_c)\rangle$,
$s_c^j(y) = X_\Delta E_J{}^j y^J$, $y=1$ at $R_{200c}=X_\Delta E_J{}^j$ ~*strain tensor* ~*(quadrupole tensor)*$^{-1/2}$

$\chi_{q,c}$ *susceptibility*$(q\ \mathcal{C}1)(y) = \langle [\rho_q(X_c+s_c(y)]/q_c\, n_{\mathcal{C}}(X_c)\rangle \langle n_{\mathcal{C}}(X_c) n_{\mathcal{C}1}(X_{c1})\rangle^{-1}$

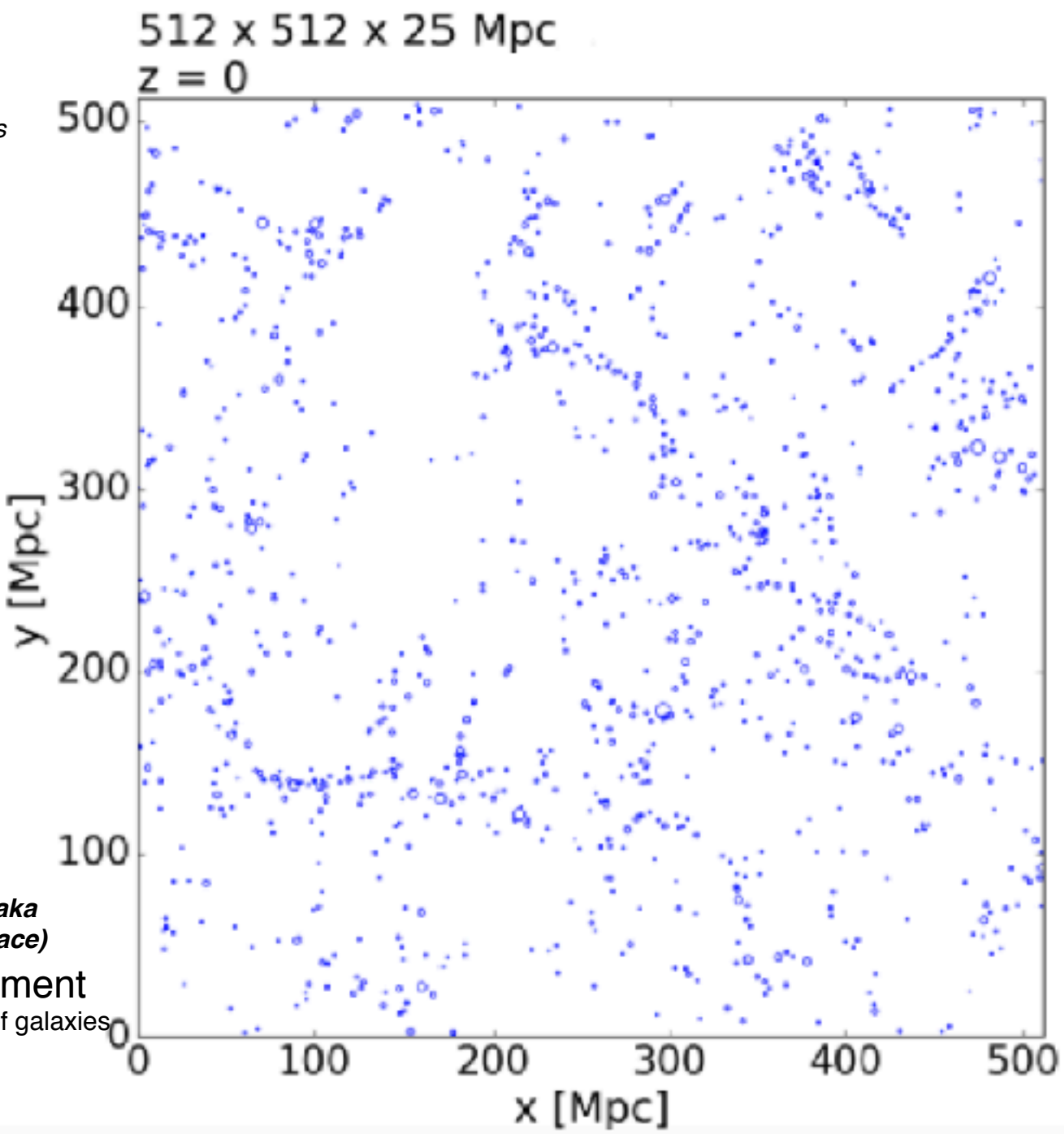
$\rho_q(x) = \sum_c \chi_{q,c}(x-x_c, R_{Ec}) q_c \delta N_c(x_c, R_{Ec})$ + ***inside & outside fluctuations***

Alvarez, Bond, Stein, Codis +
Connor Bevington,
Bruno Régaldo-Saint Blancard

the cluster class $\mathscr{C}$ *for the peak patches can orient according to the strain tensor (ellipsoidal symmetry) and can also have a direction (pk patch flow)*

simulation examples

$R_c\, e_J{}^j$



strain/linear-tide oriented pk-patches aka halos in final-state space (Eulerian space)

filament zoom intrinsic alignment

important noise source for weak lensing of galaxies

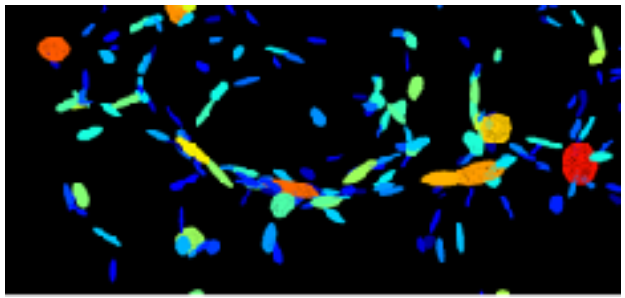
Alvarez, Bond, Stein, Codis +

Connor Bevington,
Bruno Régaldo-Saint Blancard

the cluster class $\mathscr{C}$ *for the peak patches*

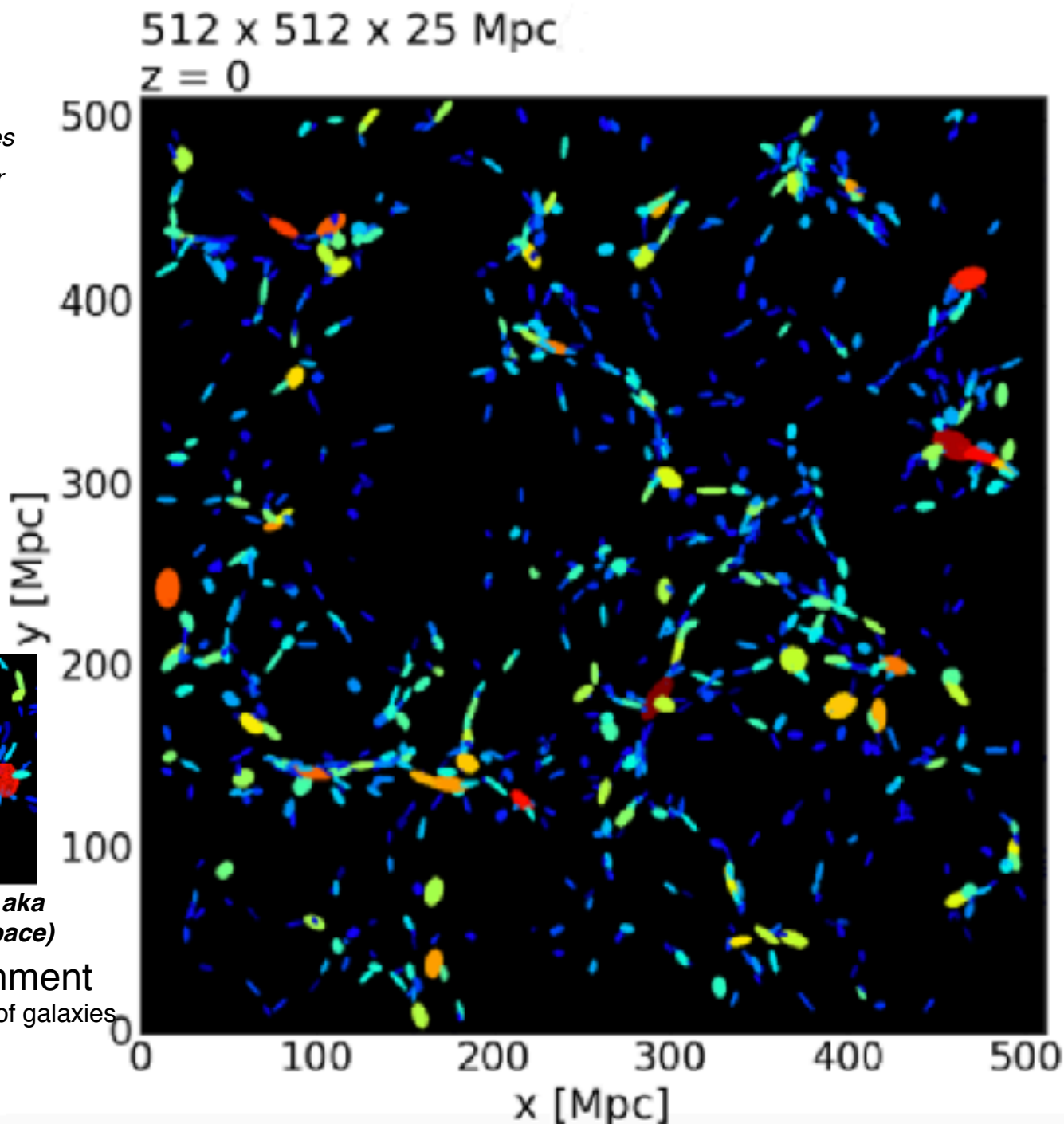
can orient according to the strain tensor (ellipsoidal symmetry) and can also have a direction (pk patch flow)

simulation examples



$R_c\, e_J{}^j$

strain/linear-tide oriented pk-patches aka halos in final-state space (Eulerian space)



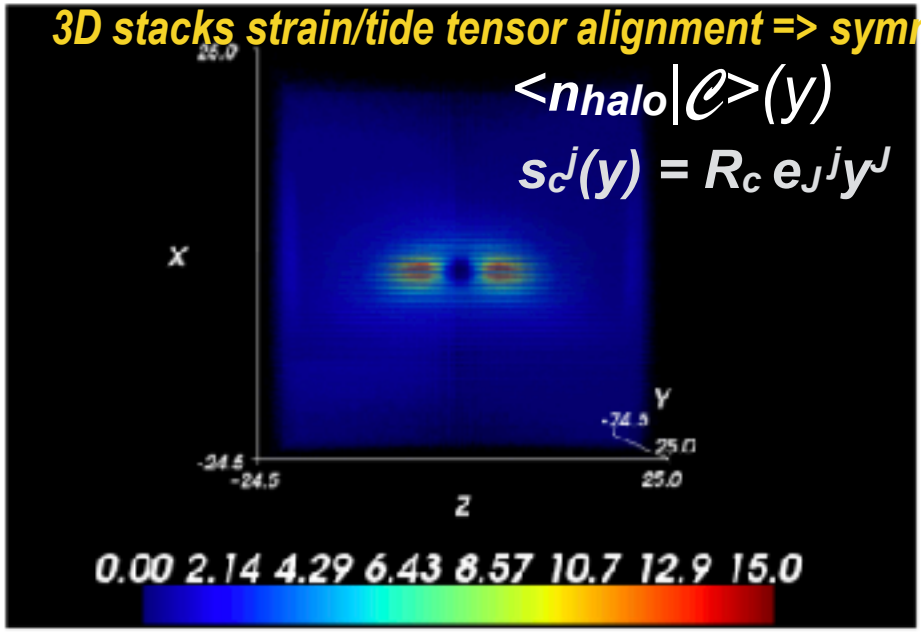
filament zoom intrinsic alignment

important noise source for weak lensing of galaxies

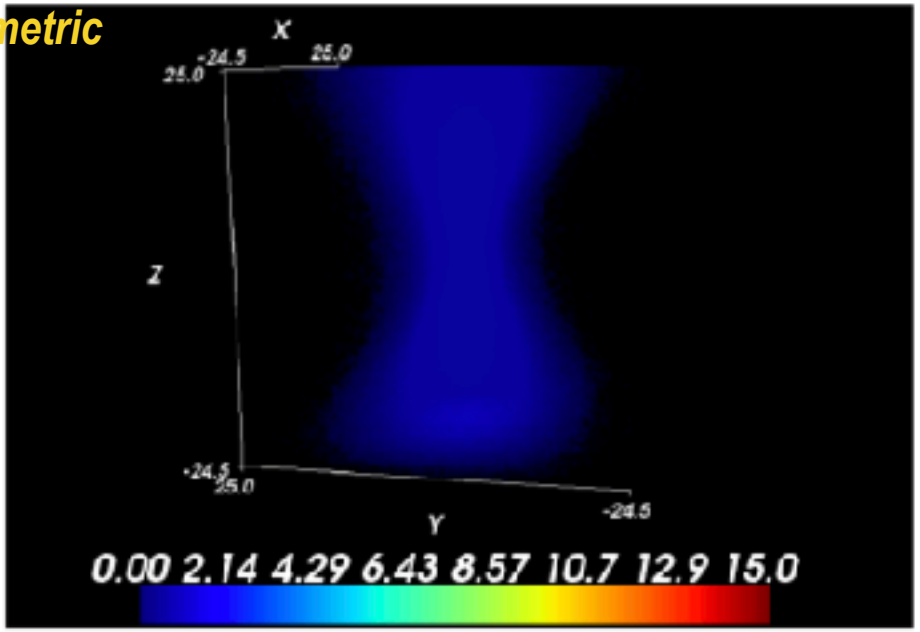
3D stacks strain/tide tensor alignment => symmetric

$\langle n_{halo} | \mathcal{C} \rangle (y)$

$s_c^j(y) = R_c \, e_J{}^j y^J$

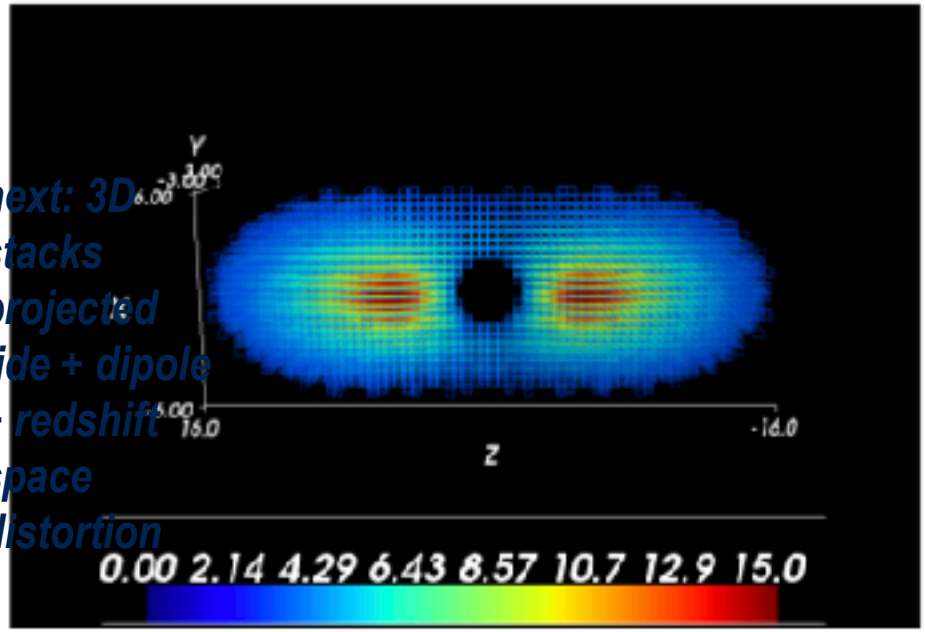


(a) $\xi^{\mathcal{E}}_{\delta\delta}(r) > 0$ display.

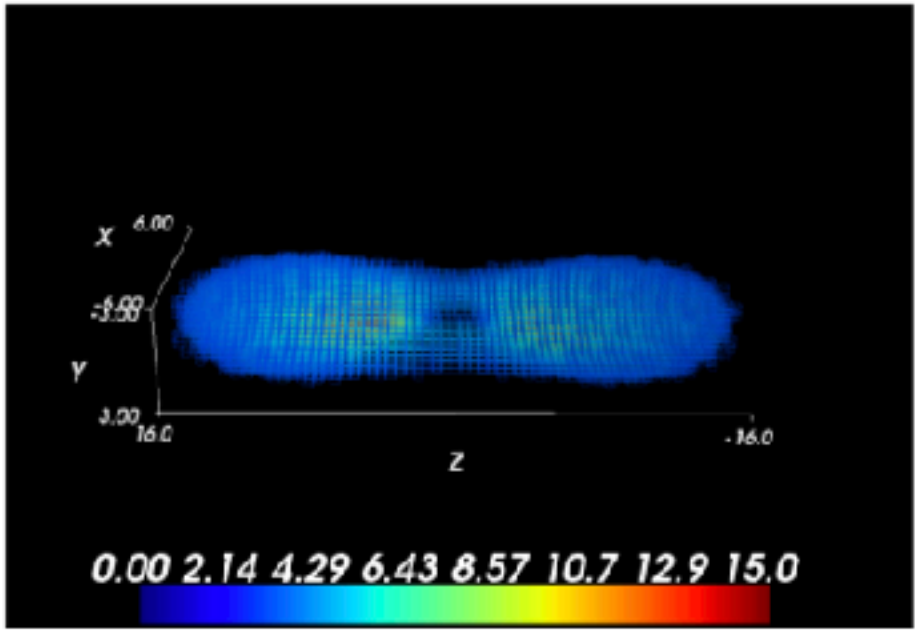


(b) $\xi^{\mathcal{E}}_{\delta\delta}(r) > 0$ display.

next: 3D stacks projected tide + dipole + redshift space distortion



(c) $\xi^{\mathcal{E}}_{\delta\delta}(r) > 3$ display.

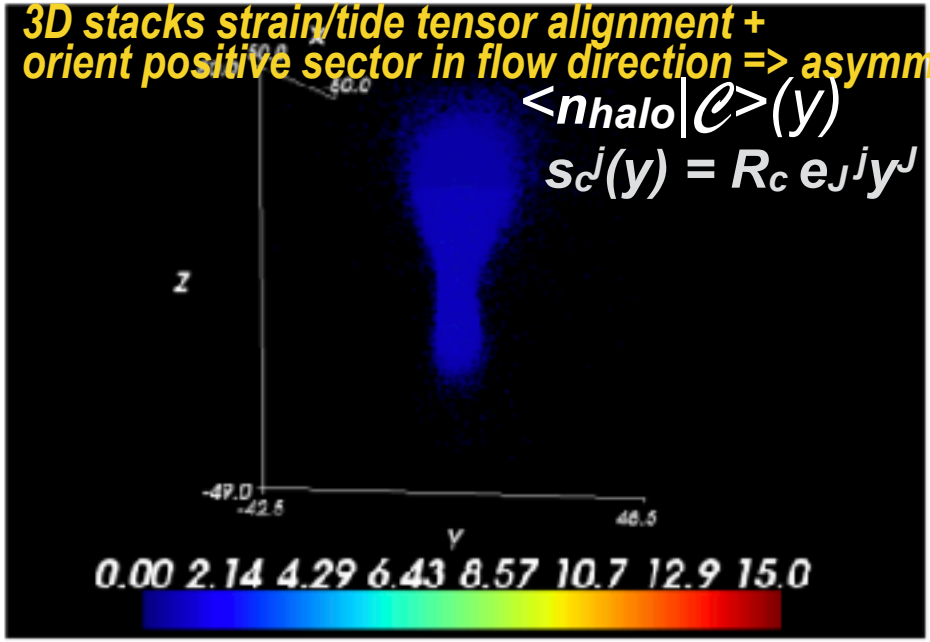


(d) $\xi^{\mathcal{E}}_{\delta\delta}(r) > 3$ display.

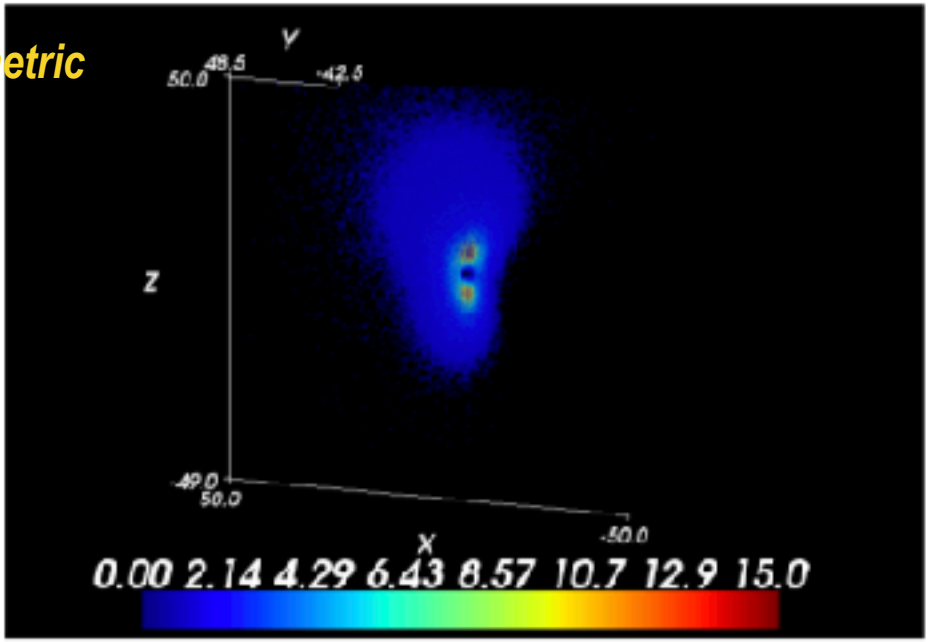
3D stacks strain/tide tensor alignment +
orient positive sector in flow direction => asymmetric

$\langle n_{halo} | \mathcal{E} \rangle (y)$

$s_c^j(y) = R_c \, e_J{}^j y^J$

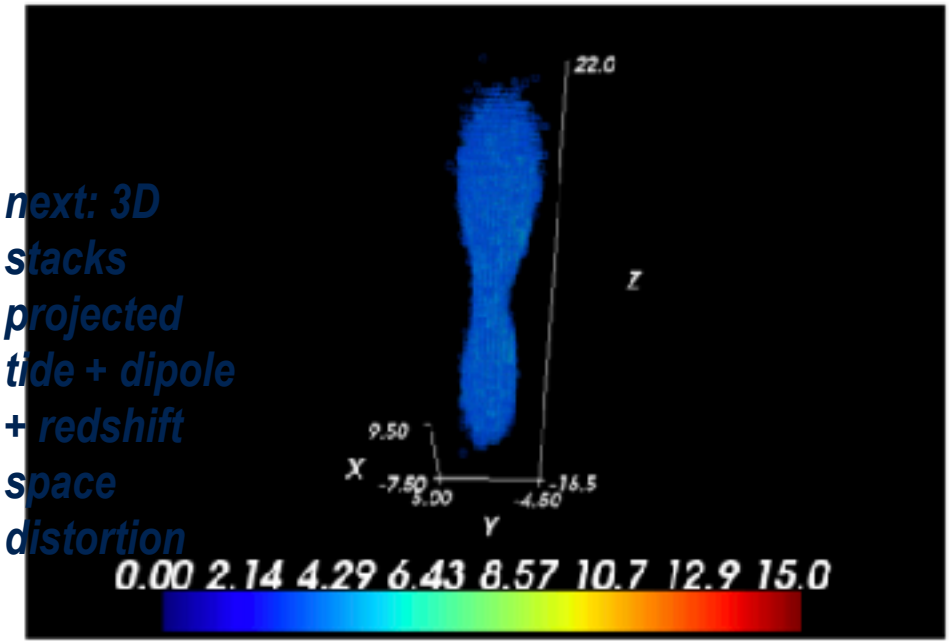


(a) $\xi^{\mathcal{E}}_{\delta\delta}(r) > 1$ display.

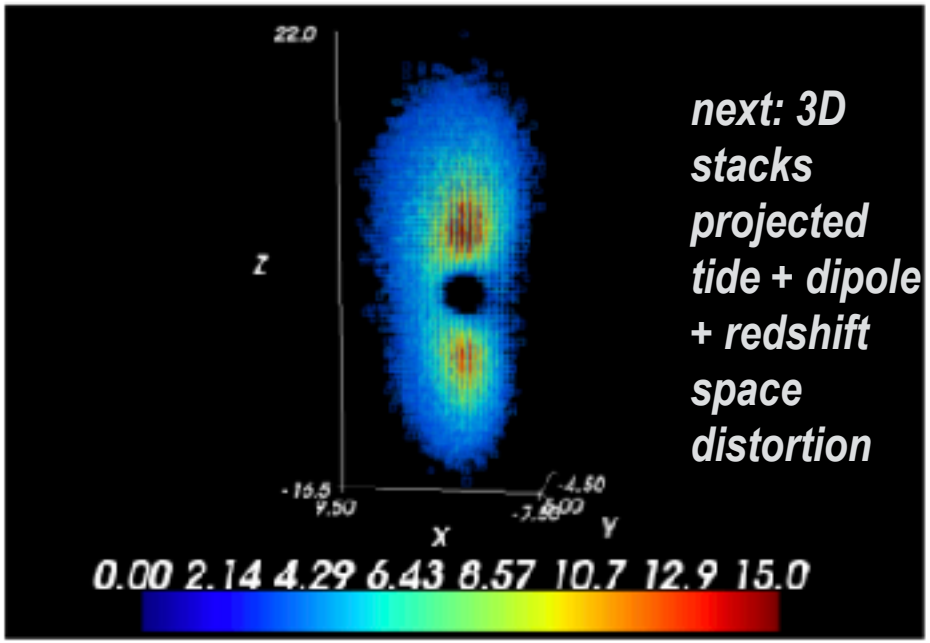


(b) $\xi^{\mathcal{E}}_{\delta\delta}(r) > 1$ display.

next: 3D stacks projected tide + dipole + redshift space distortion



(c) $\xi^{\mathcal{E}}_{\delta\delta}(r) > 3$ display.



(d) $\xi^{\mathcal{E}}_{\delta\delta}(r) > 3$ display.

next: 3D stacks projected tide + dipole + redshift space distortion

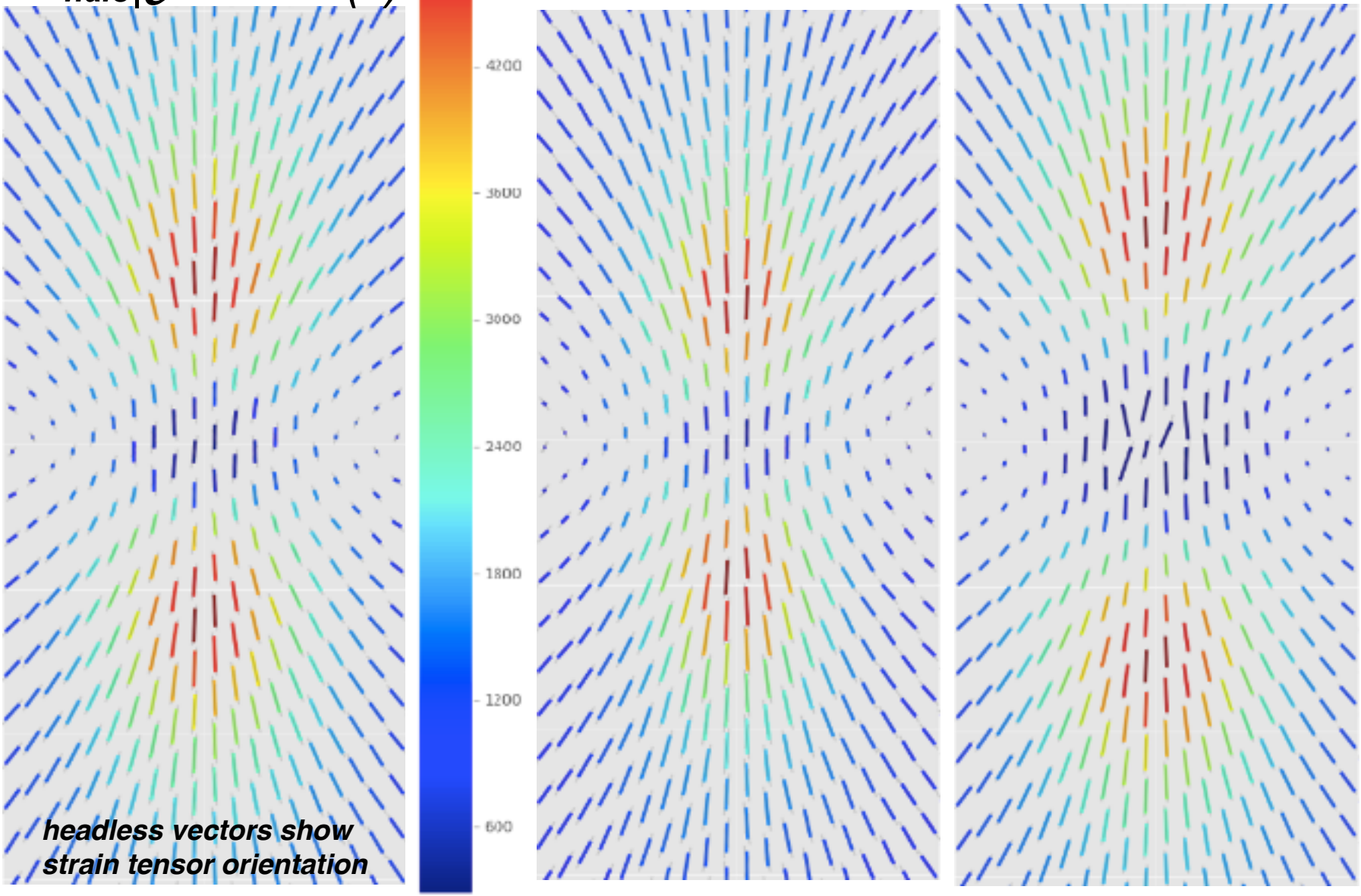
Projected-strain/tide 2D stacks

10Mpc X 30Mpc all masses

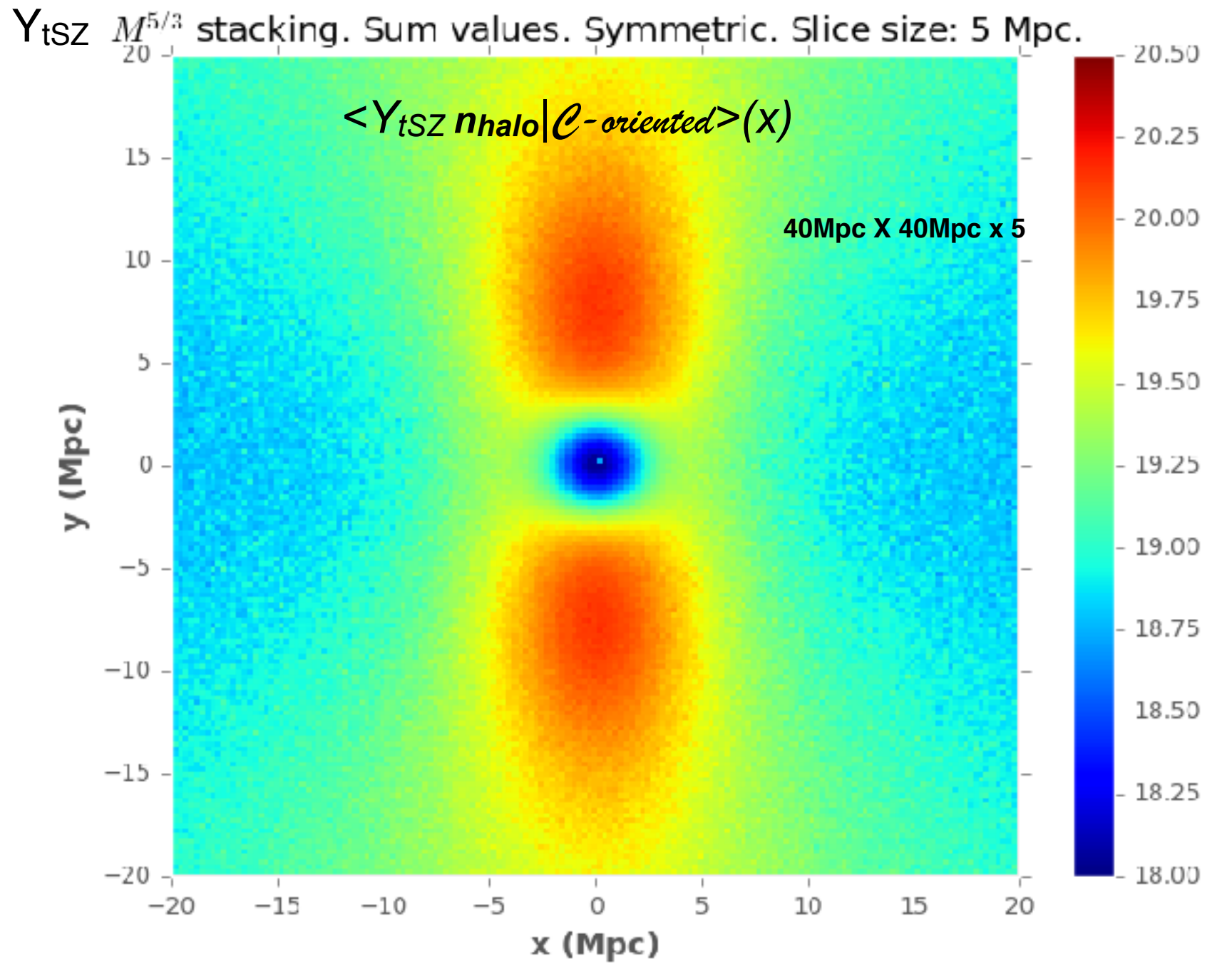
$\langle n_{halo} | \mathcal{C}\text{-oriented} \rangle (X)$

< 10^14 Msun

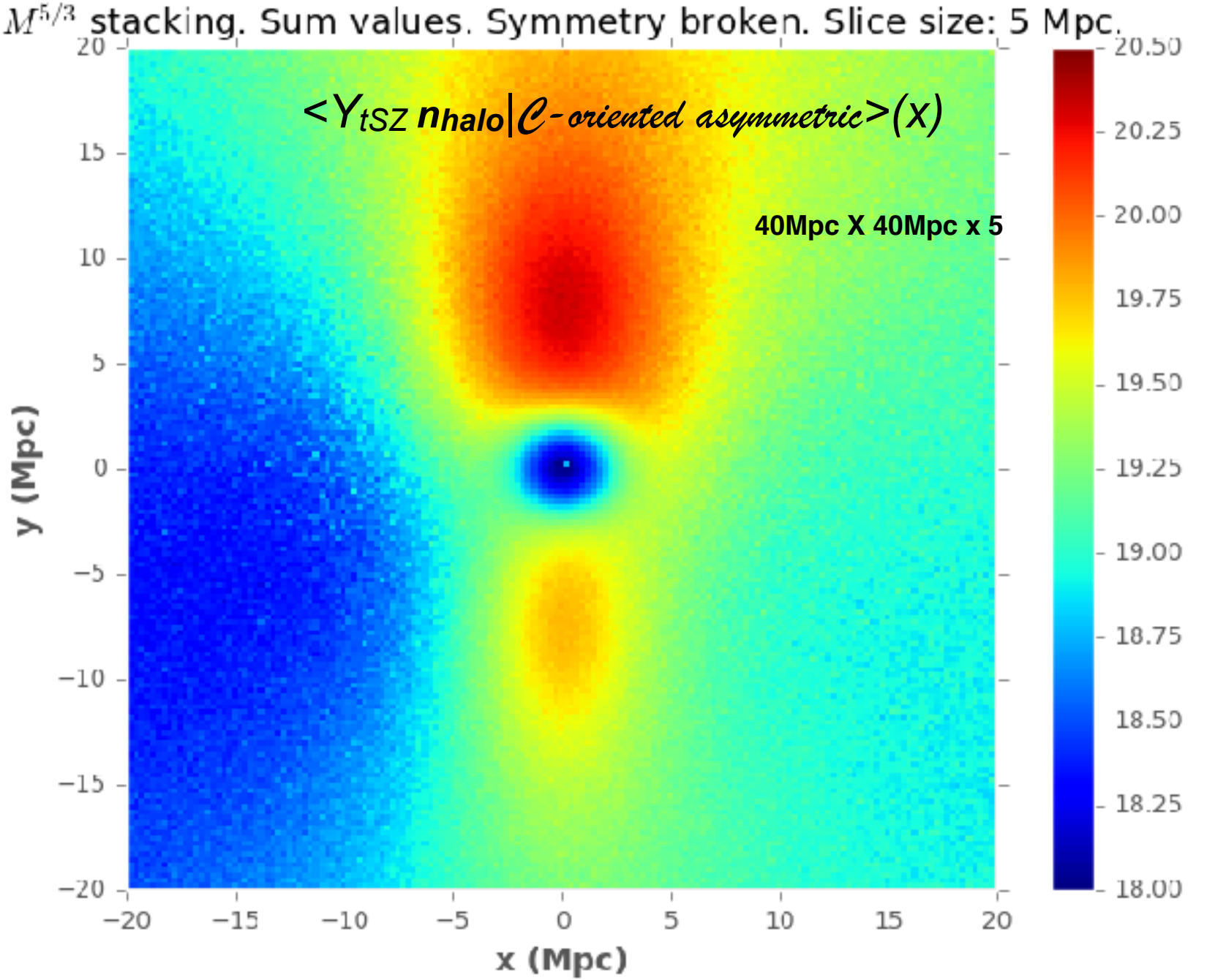
10^14 - 10^15 Msun



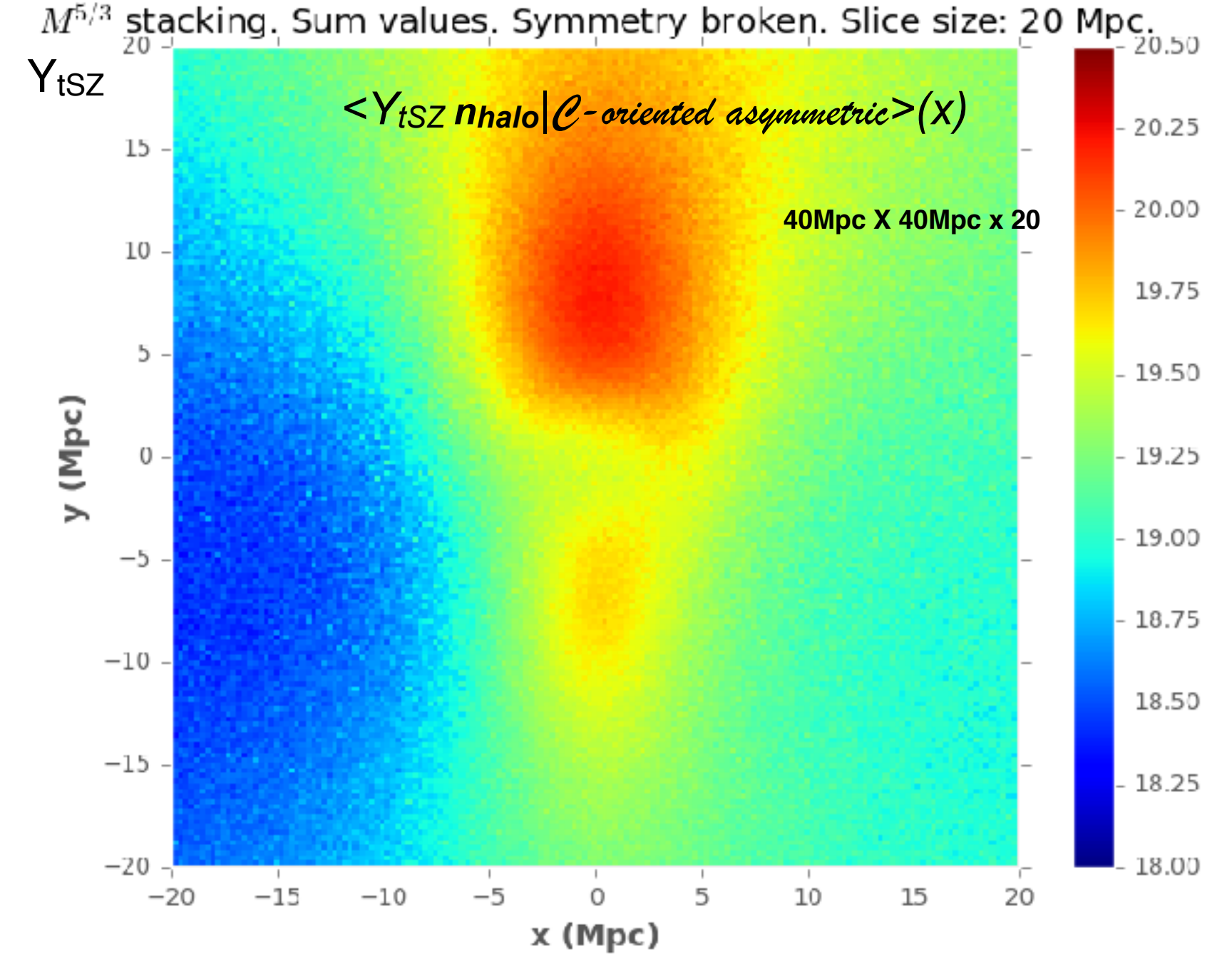
Projected-strain/tide 2D stacks, perfect resolution tSZ weighting



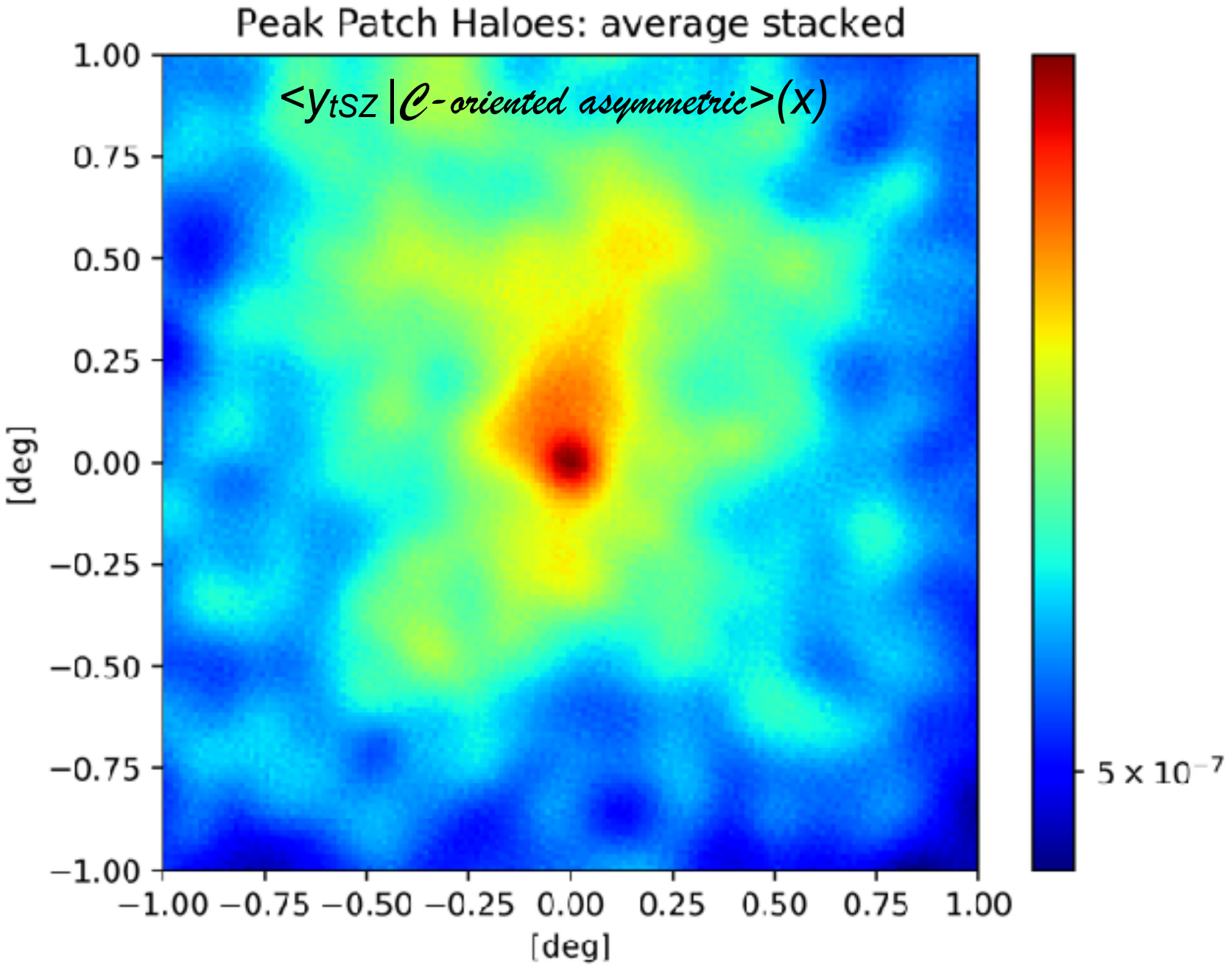
Projected-strain/tide 2D stacks, perfect resolution tSZ weighting



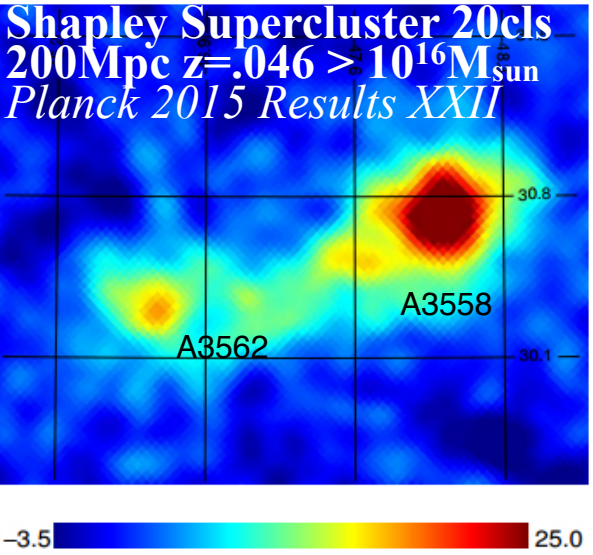
Projected-strain/tide 2D stacks, perfect resolution tSZ weighting



pp tSZ is 7 arcmin fwhm smoothed before stacking
100K redmapper cls mock, least massive



Shapley Supercluster 20cls
200Mpc z=.046 >$10^{16}M_{sun}$
Planck 2015 Results XXII

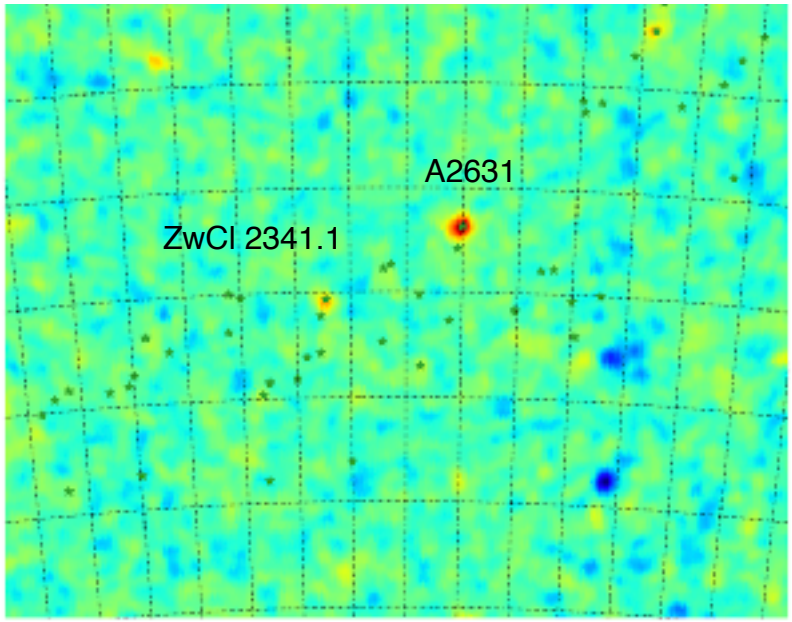


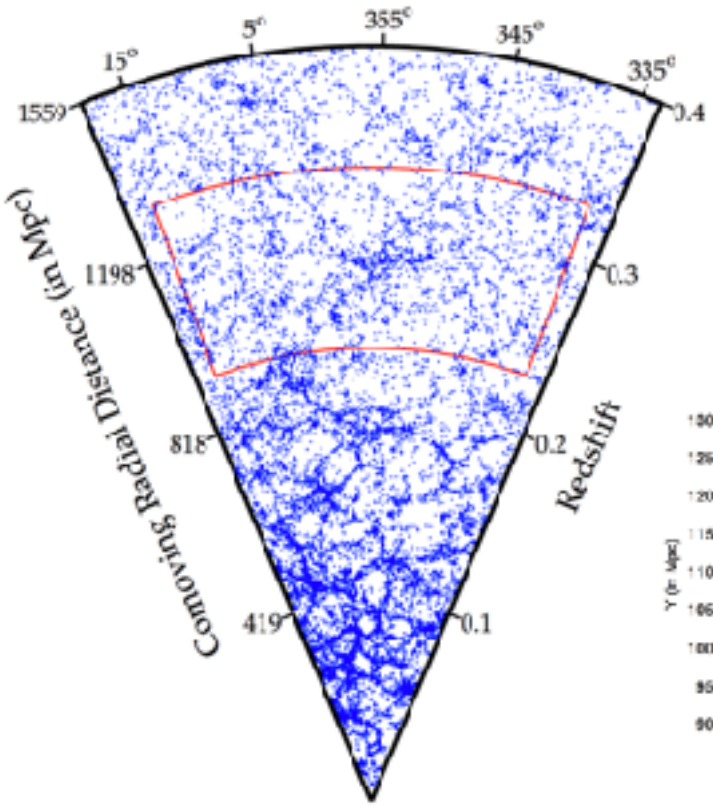
Mollweide view

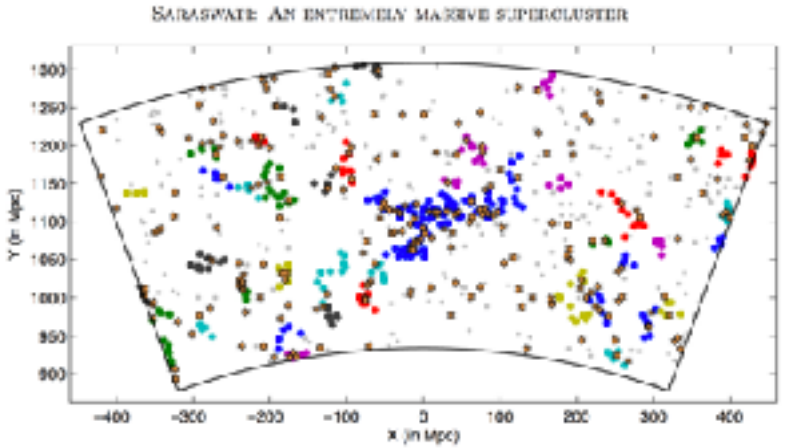
SARASWATI: AN EXTREMELY MASSIVE ~ 200 MEGAPARSEC SCALE SUPERCLUSTER

Saraswati supercluster z~.28, > Shapley?

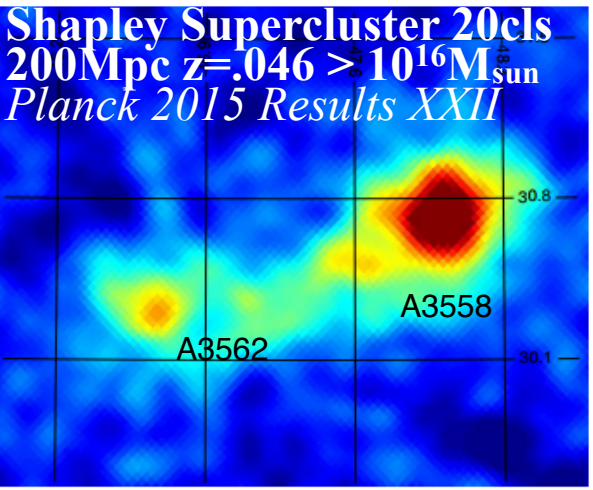
JOYDEEP BAGCHI,[1] SHISHIR SANKHYAYAN,[2] PRAKASH SARKAR,[3] SOMAK RAYCHAUDHURY,[1] JOE JACOB,[4] AND PRATIK DABHADE[1]

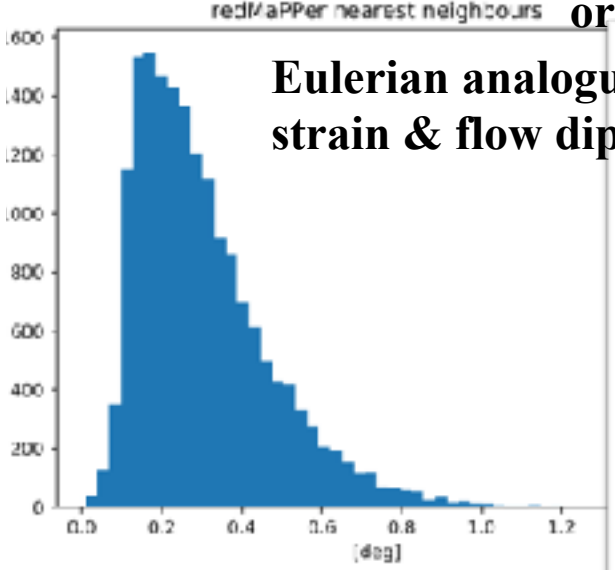






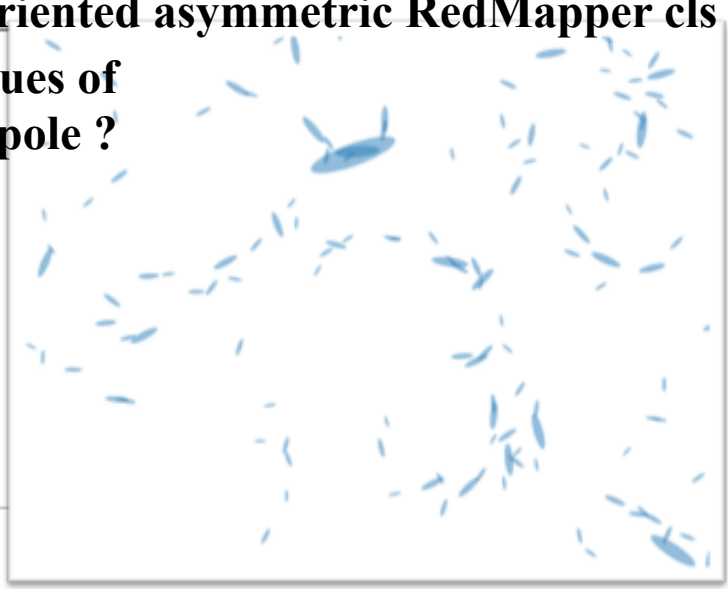
Shapley Supercluster 20cls
200Mpc z=.046 >$10^{16}M_{sun}$
Planck 2015 Results XXII

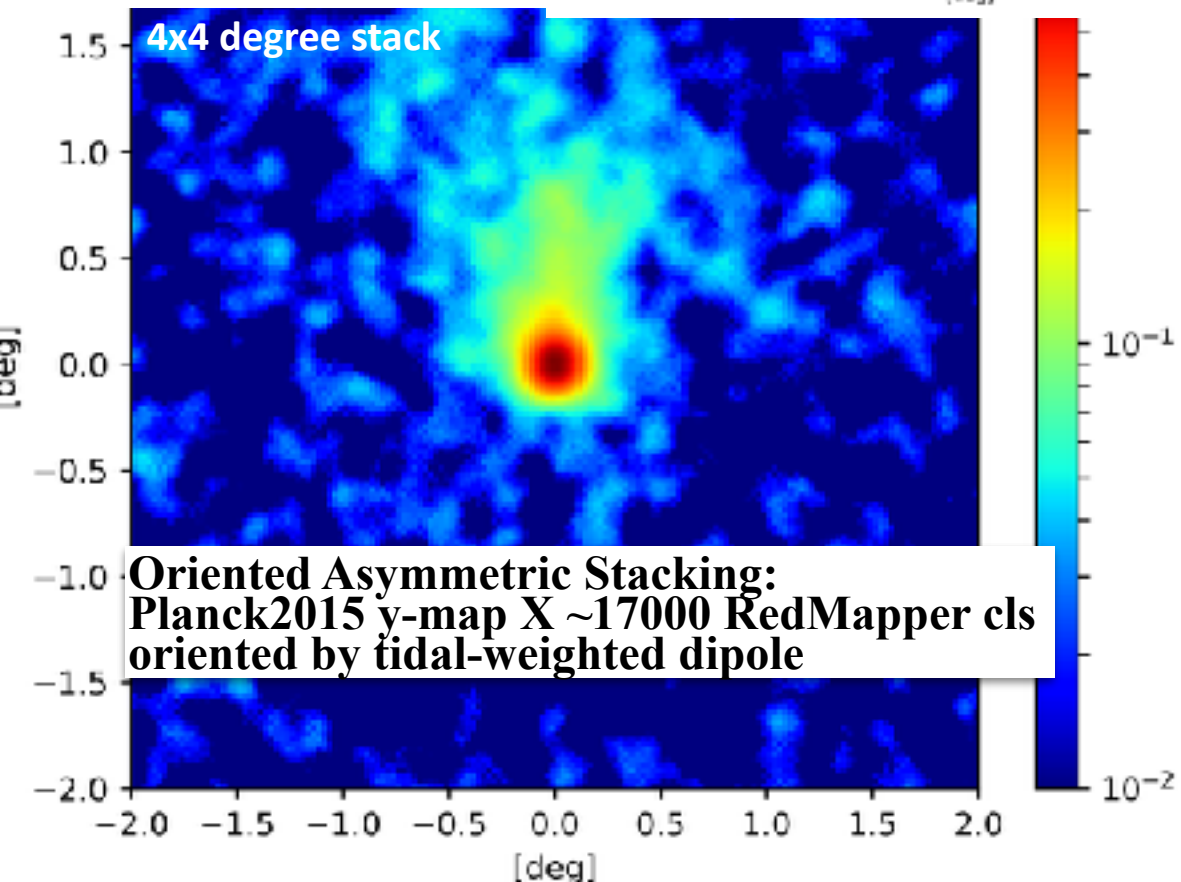




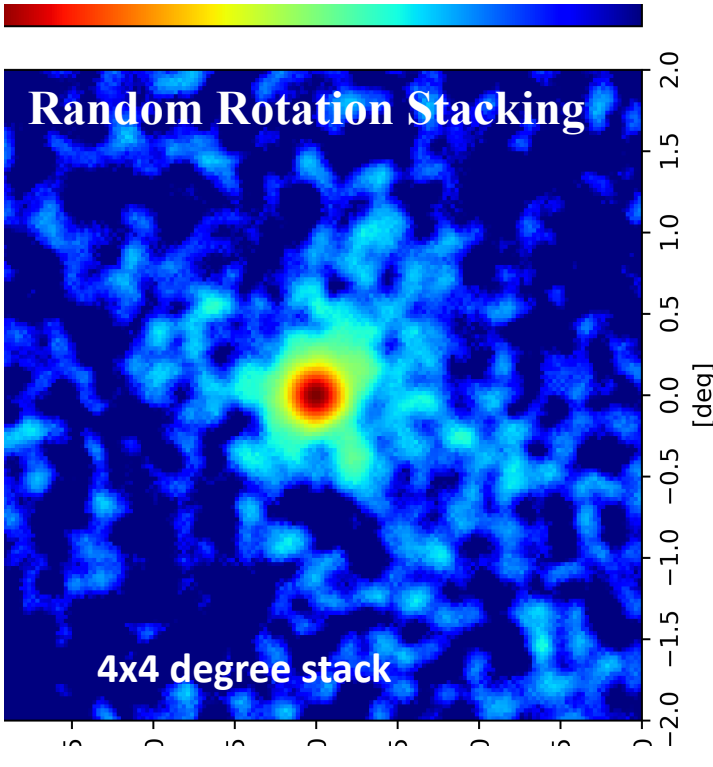
Eulerian analogues of strain & flow dipole ?

oriented asymmetric RedMapper cls

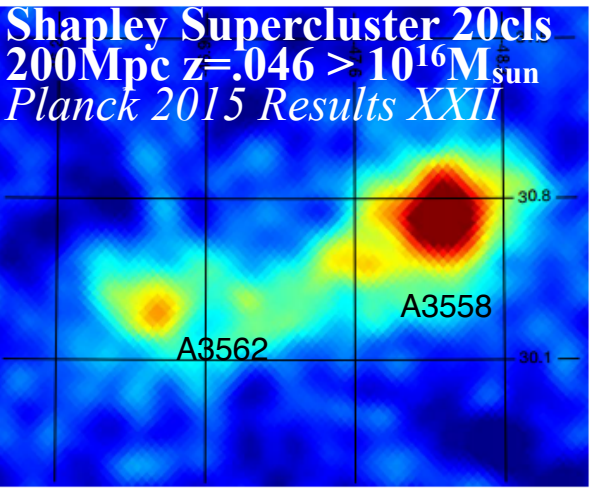


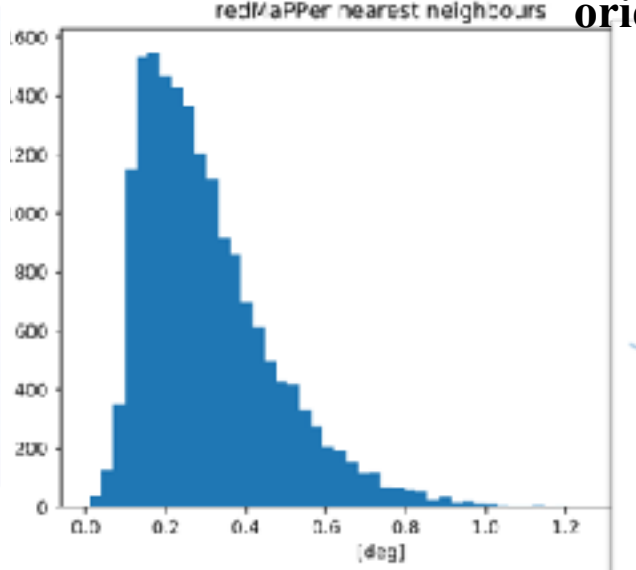


Oriented Asymmetric Stacking:
Planck2015 y-map X ~17000 RedMapper cls oriented by tidal-weighted dipole

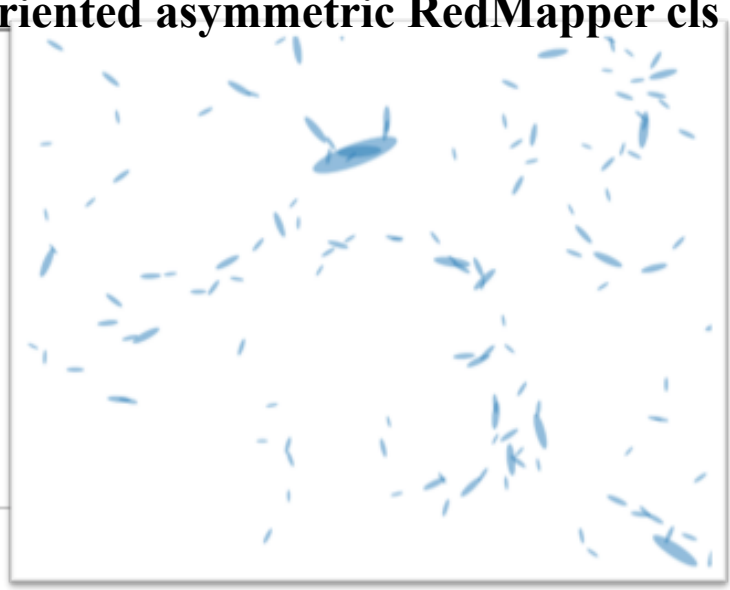


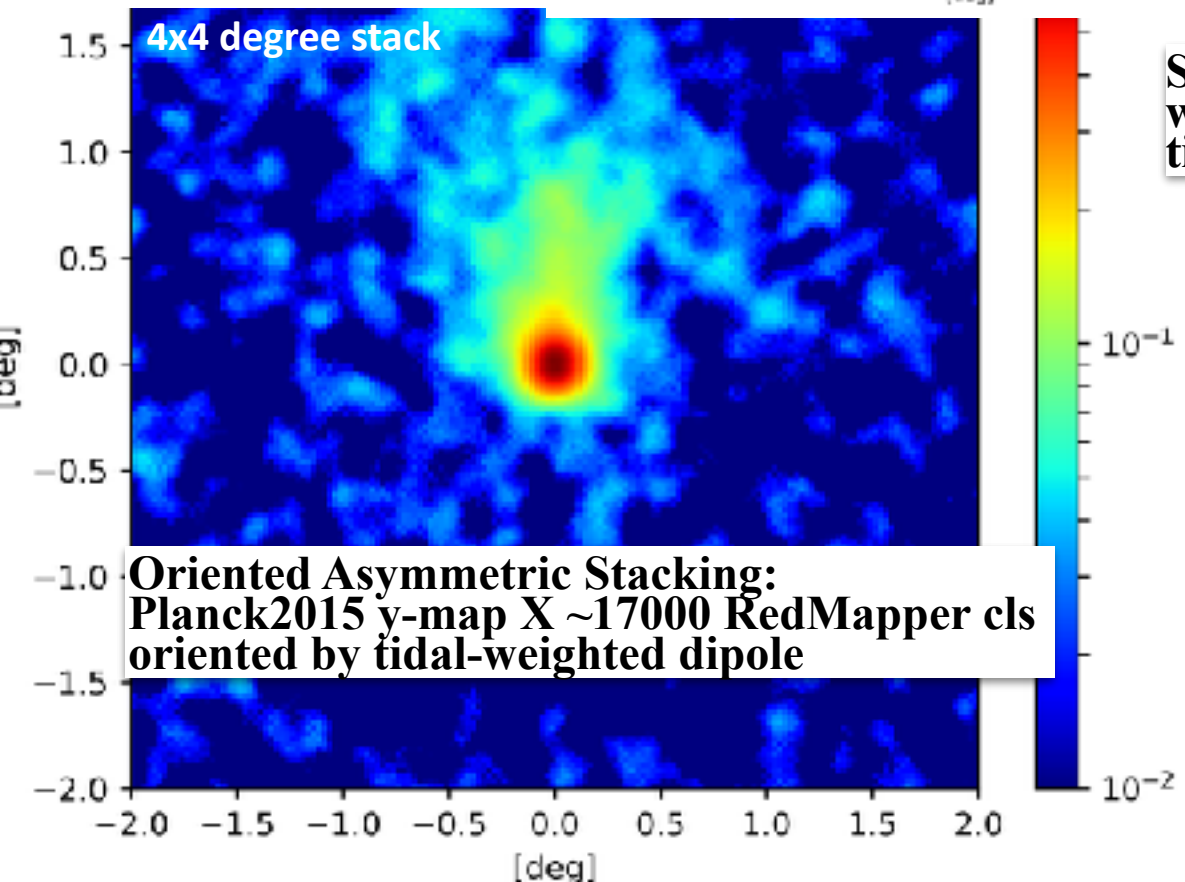
Shapley Supercluster 20cls
200Mpc z=.046 >$10^{16}M_{sun}$
Planck 2015 Results XXII





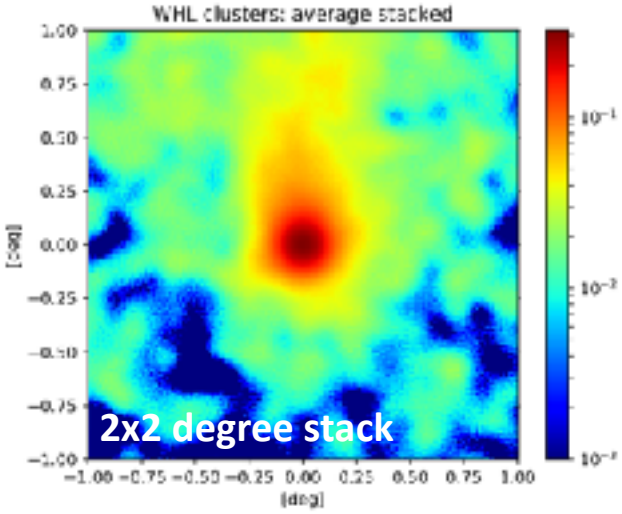
oriented asymmetric RedMapper cls





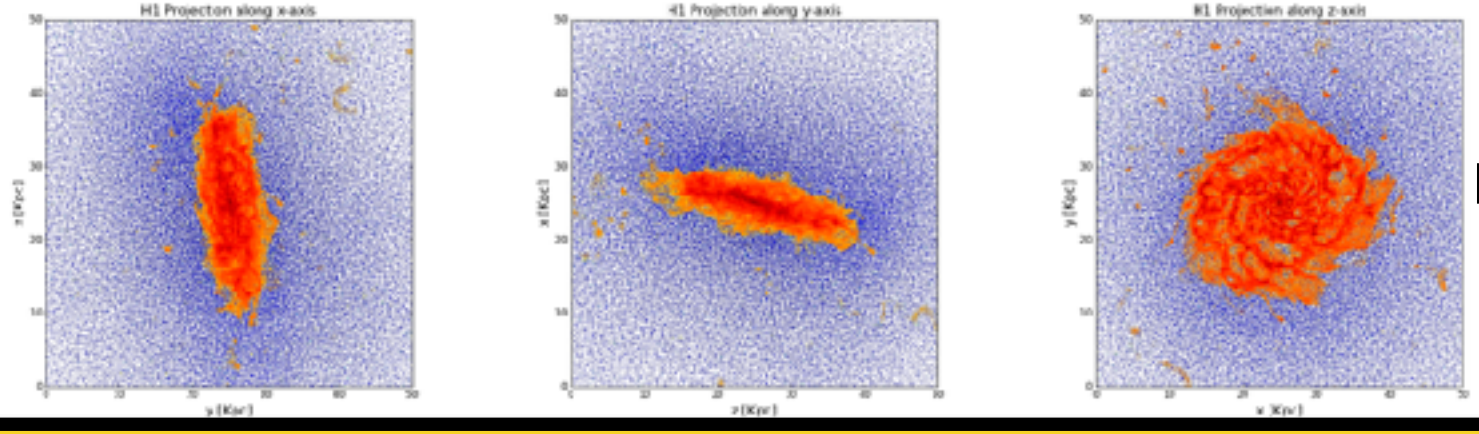
Oriented Asymmetric Stacking:
Planck2015 y-map X ~17000 RedMapper cls oriented by tidal-weighted dipole

Sloan WHL clusters Wen+12 with cuts 75000 cls oriented by tidal-weighted dipole



Data cf. pkpatch mocks of tSZ X ncl for redmapper selection function- in progress

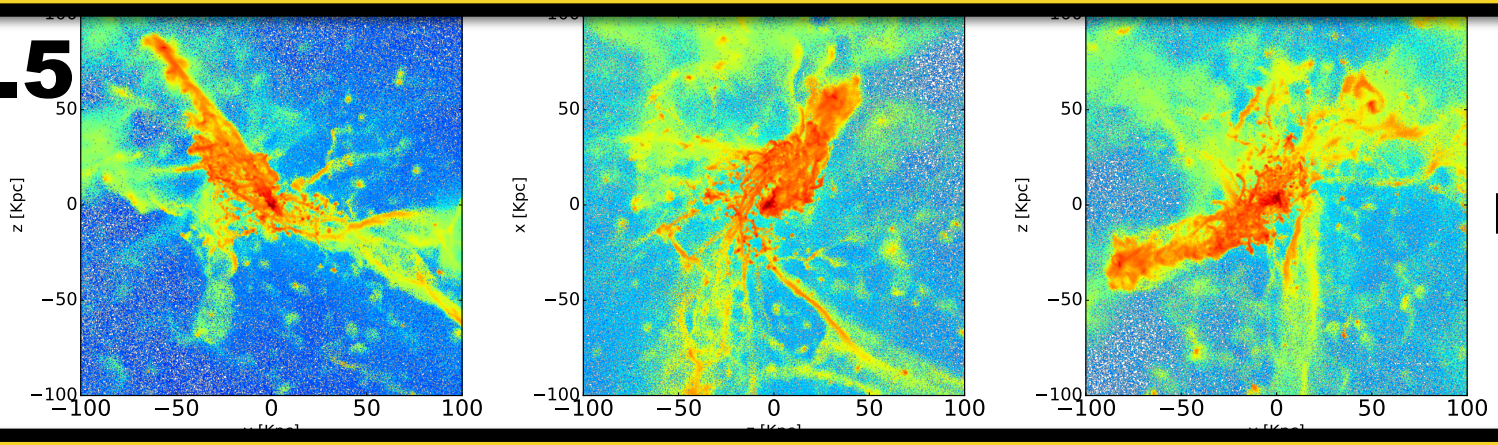
z=0



n_HI

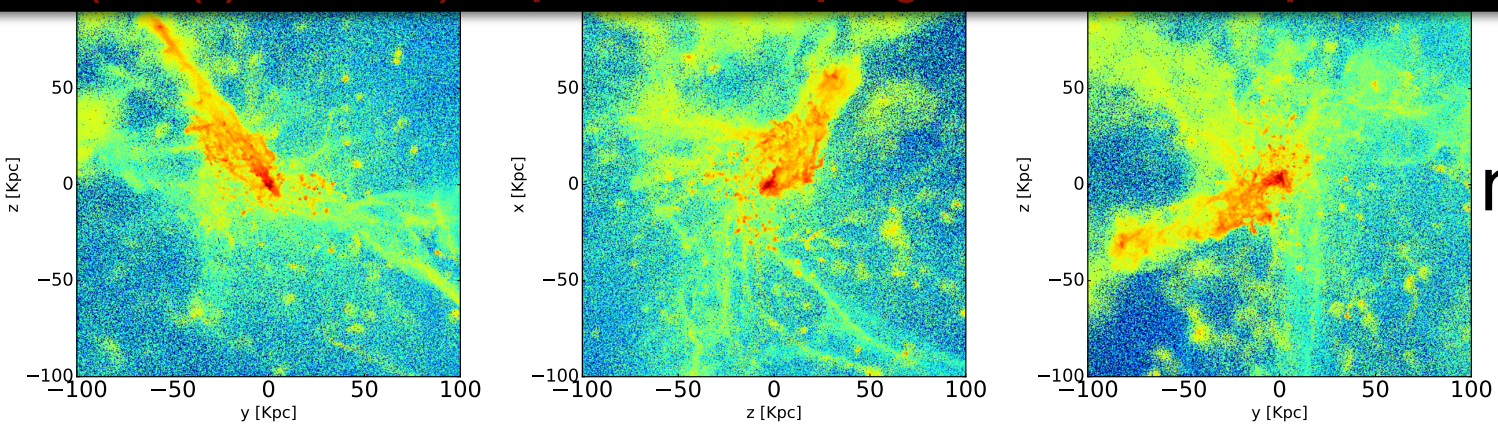
hi res FIRE hydro (Hopkins+) z=2.5 => 10(12) Msun galaxy at z=0 *Gunjan Lakhlani, Murray +ABS*

z=2.5



n_HI

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



n_O

pp modus-operandi measure response functions to stimuli= susceptibilities

fluctuations inside controlled? outside 2LPT and subgrid halos adequate?

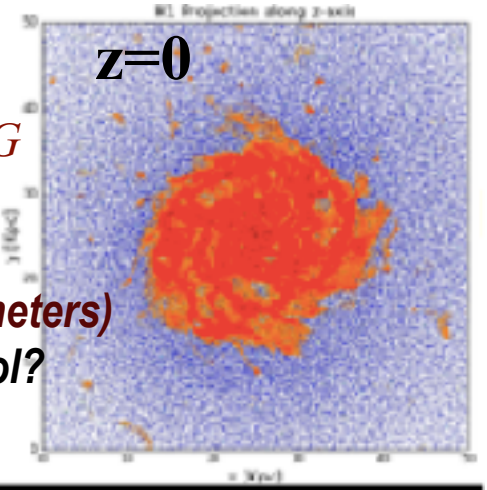
tSZ, kSZ ***in pp-control*** BBSP sims, PUPPY;

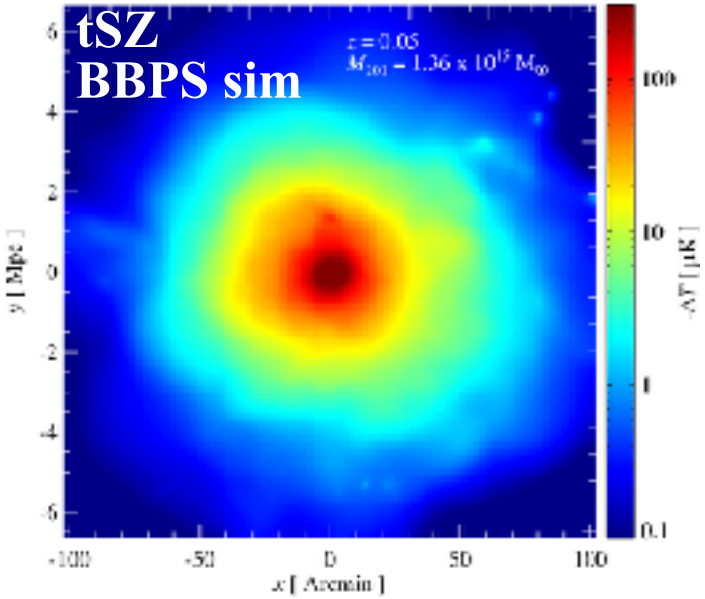
CO, HI, CIB via FIRE sims *ABS+Lakhkani+Murray+Ronan Kerr UG*

importance sampling: probabilistic control over an ensemble of sims constrained initial conditions via mean-fields + fluctuations or via zoom:

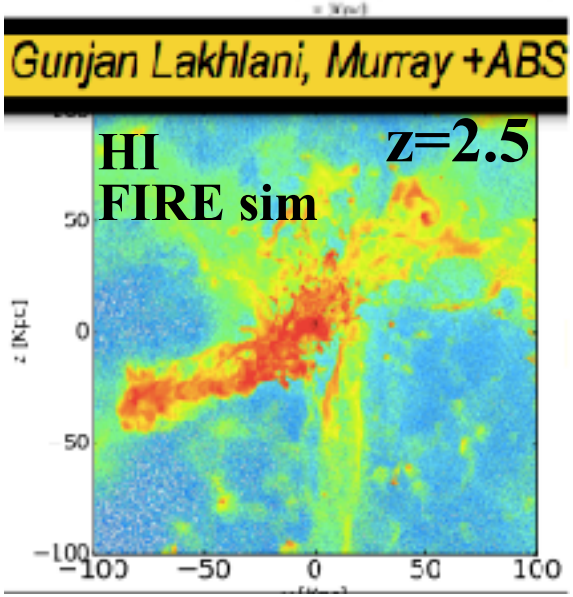
Prob(CO etal) = int Prob(CO etal| control parameters) dProb (control parameters)

galaxy assembly = out of control? e.g. CO ~ dM*/dt, how to FIRE-sim-control?





GIZMO P-SPH
(Hopkins 15)

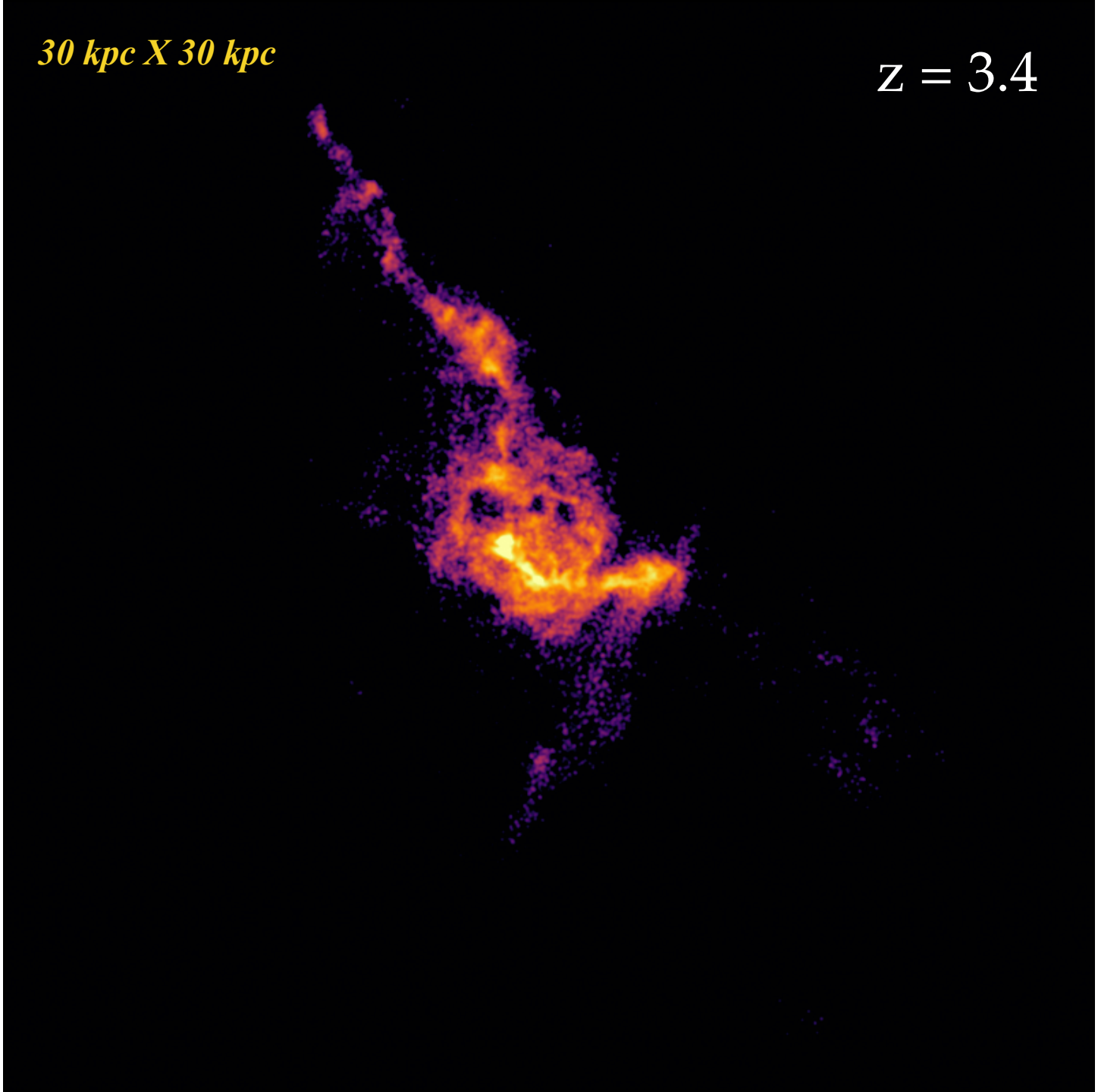


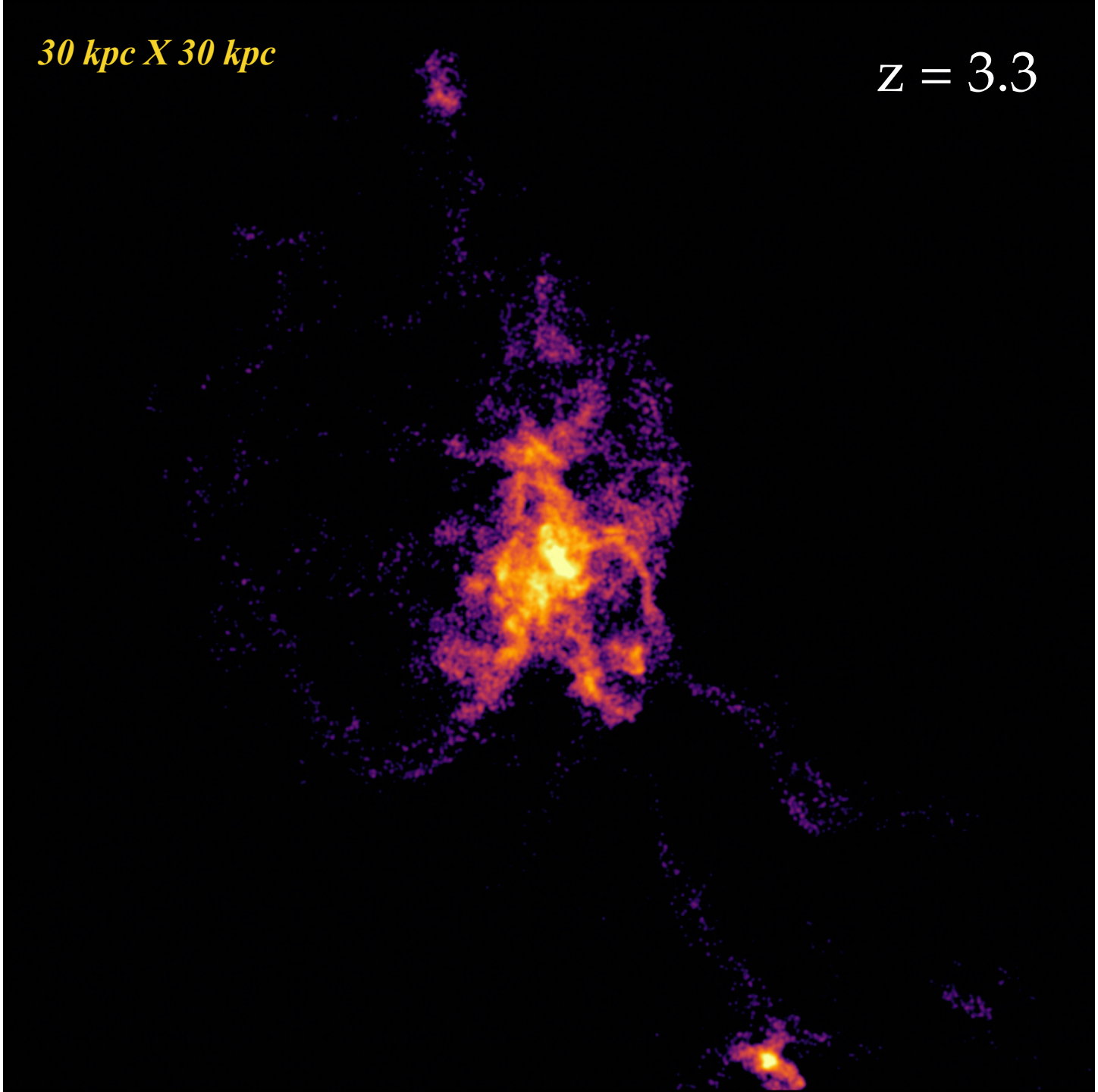
Lensing of CMB, CIB & LIM & cls underway *ABS+ LouisPham UG +van Engelen*

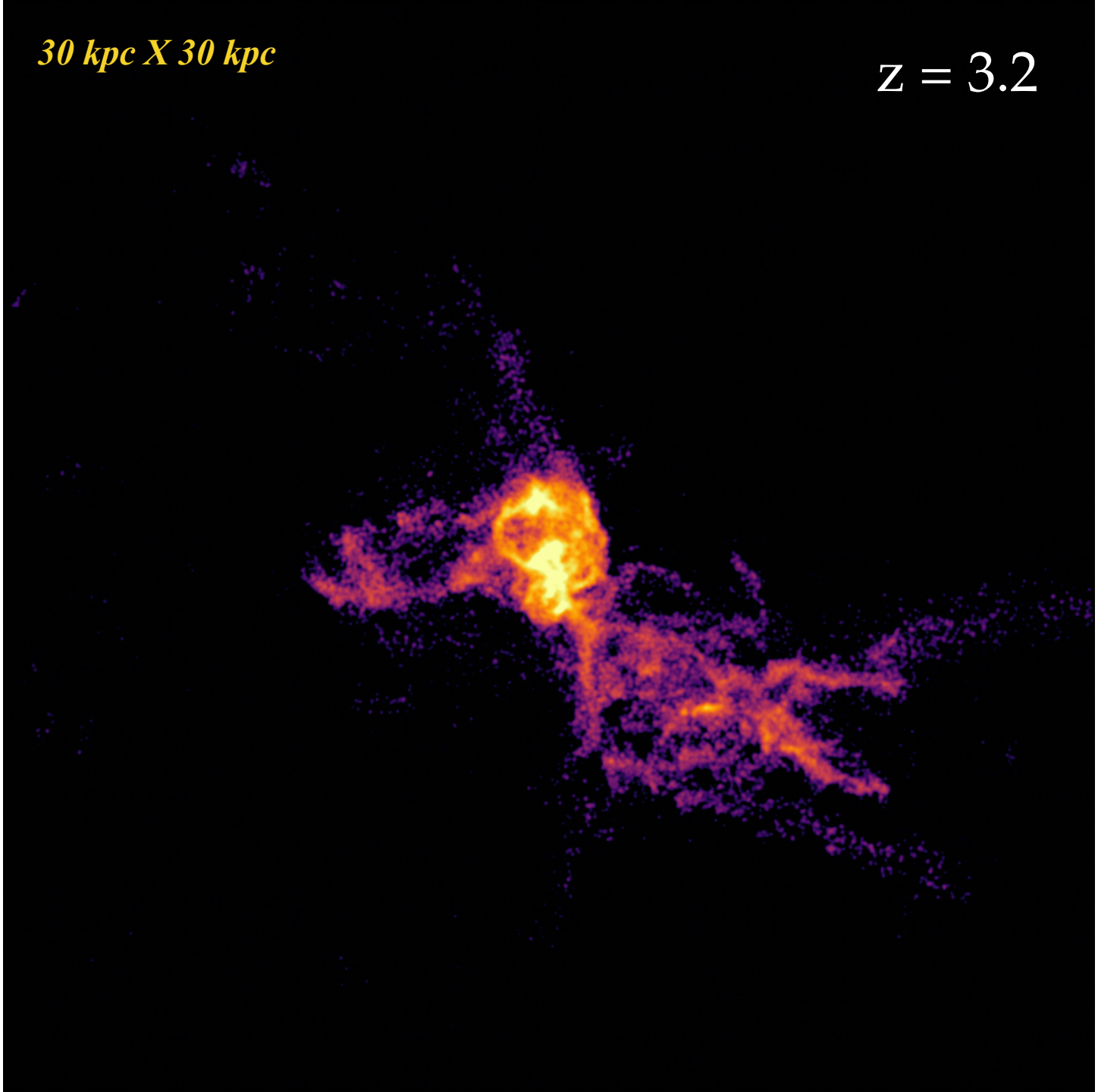
why do LIMLAM? just understand galactic weather / storms

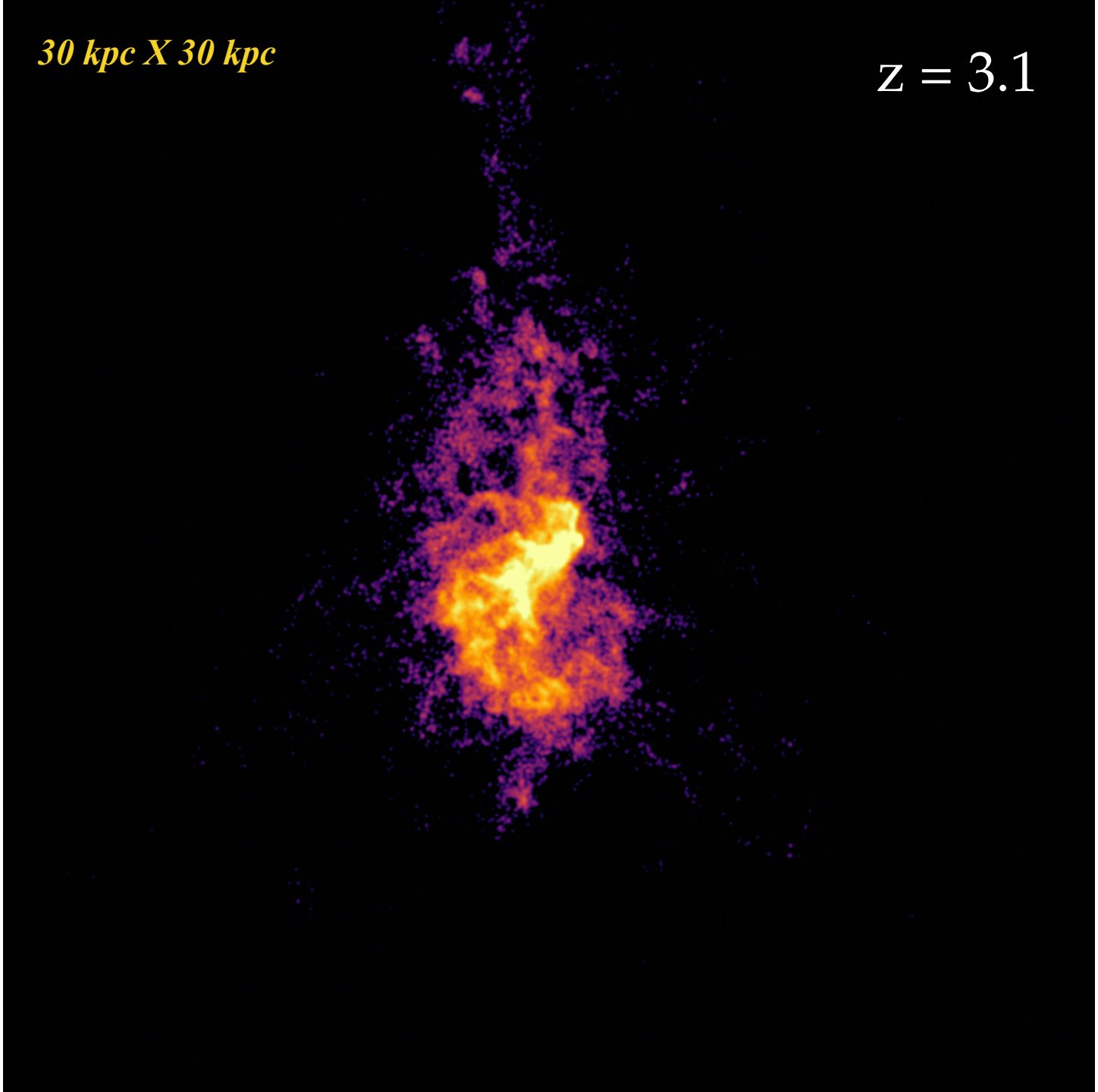
theorist hope: component-separate gastrophysics to reveal fundamental BSMc physics

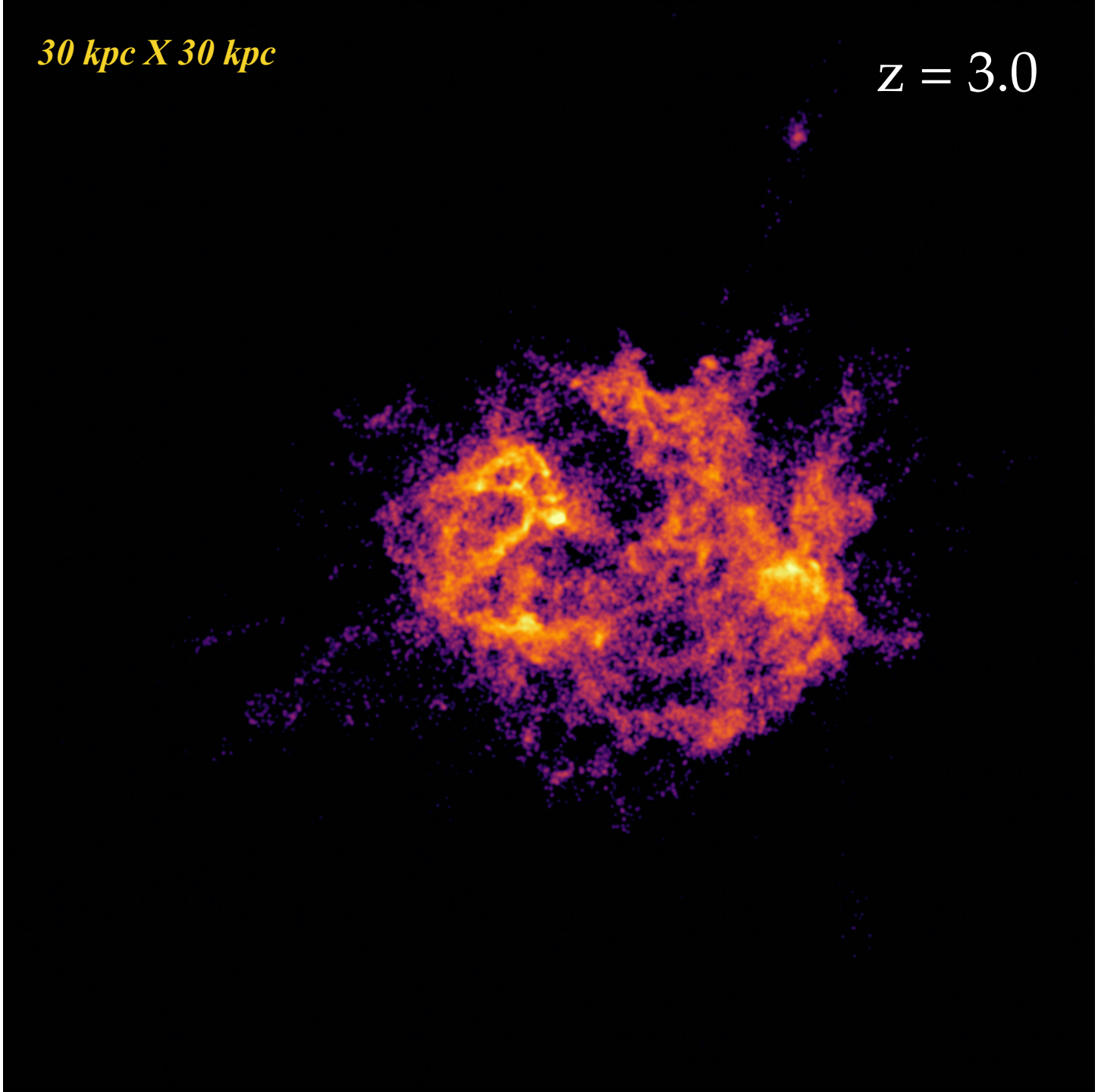
e.g., use LSS to further develop the map of the early universe from CMB ***(stacked)***

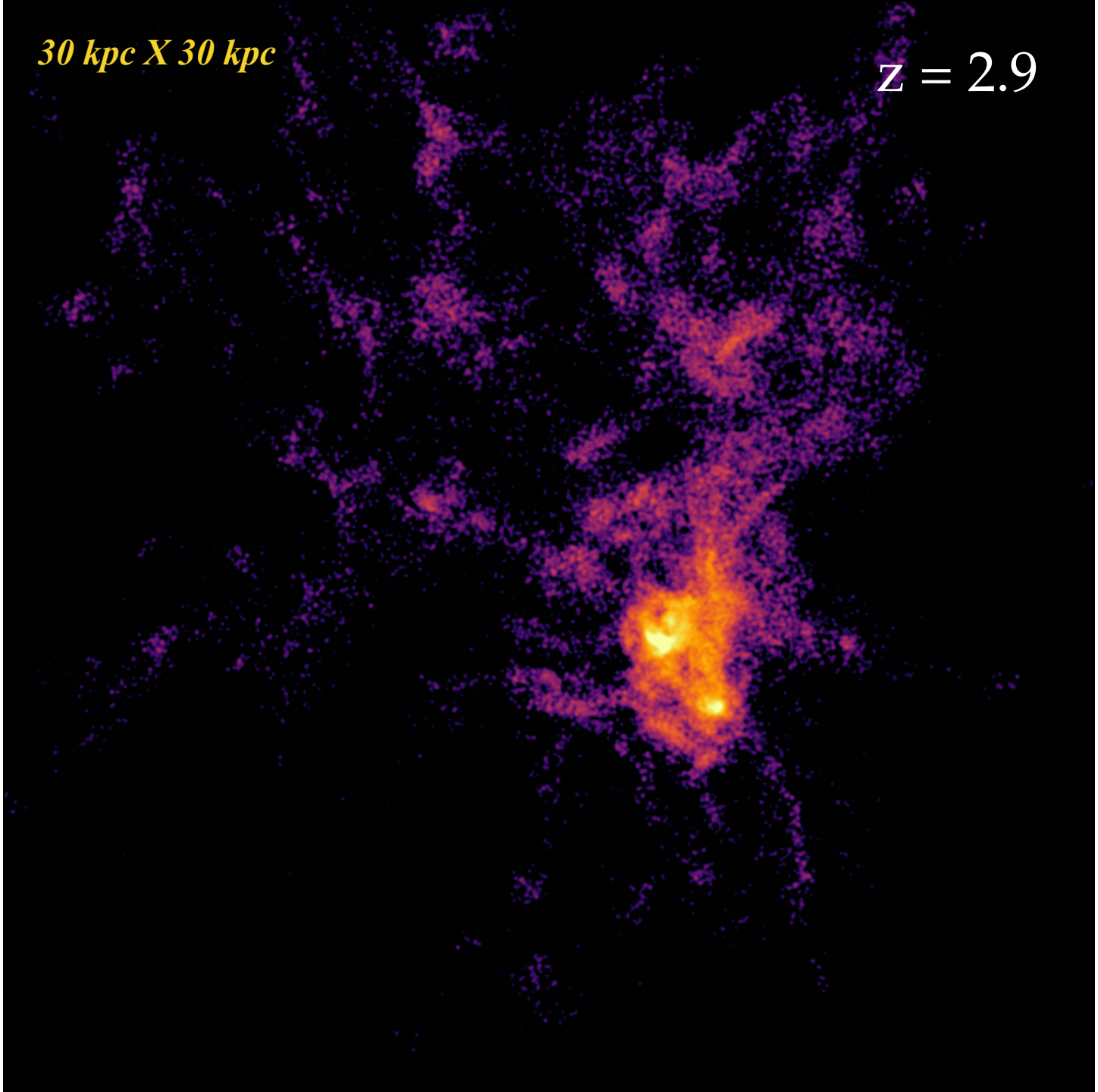

30 kpc X 30 kpc
z = 3.4

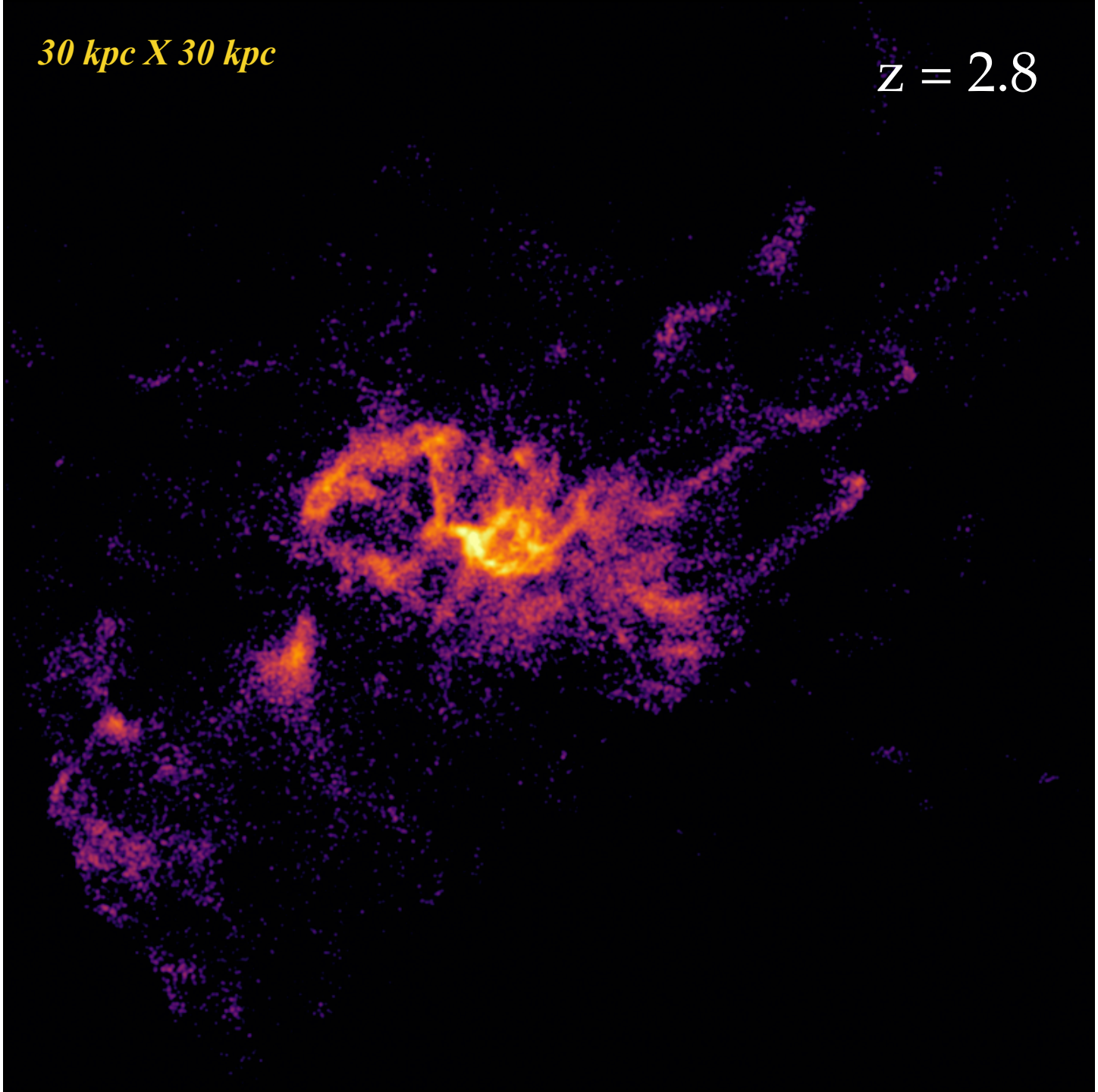

30 kpc X 30 kpc
z = 3.3

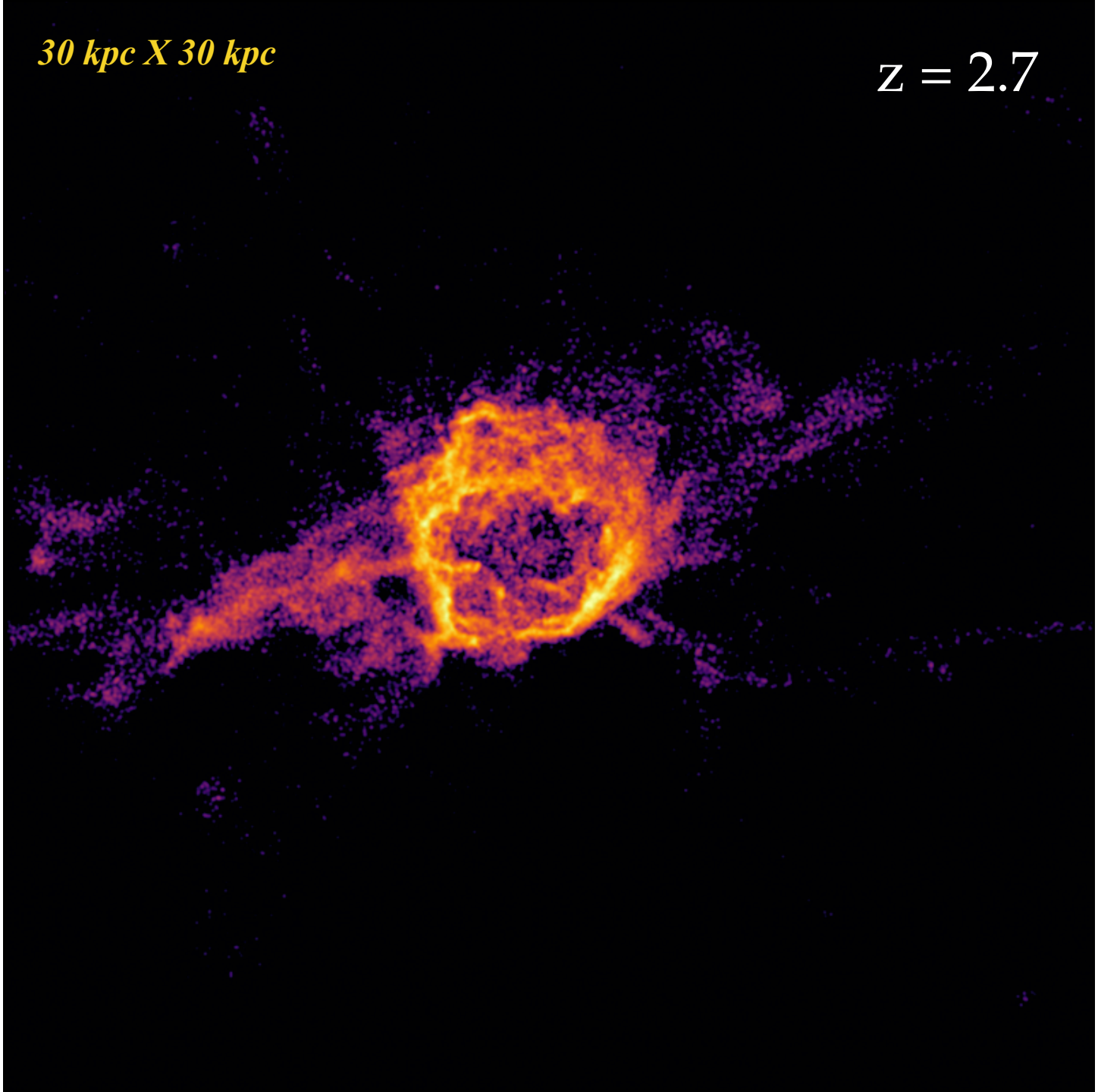

30 kpc X 30 kpc
z = 3.2

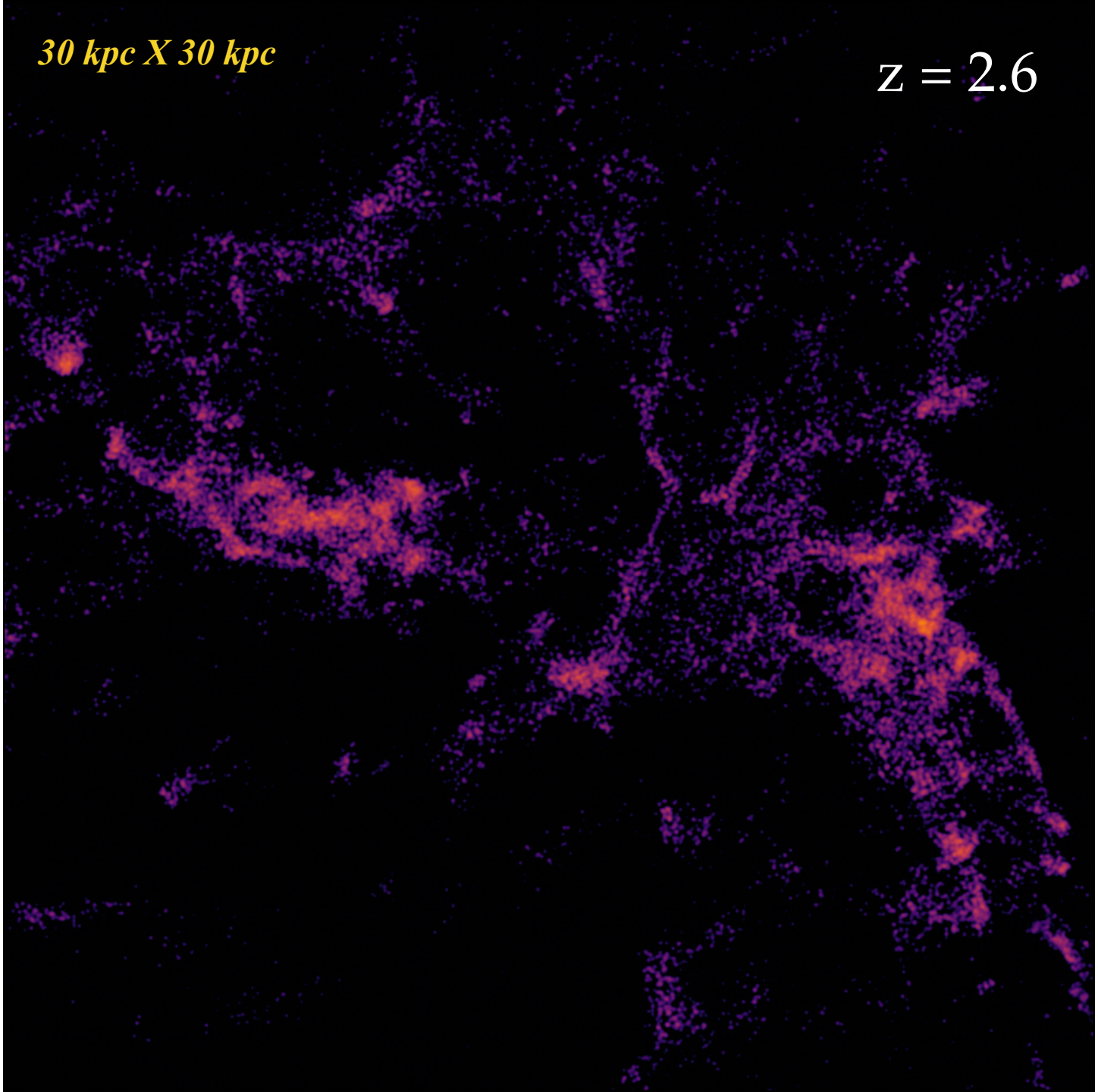

30 kpc X 30 kpc
z = 3.1

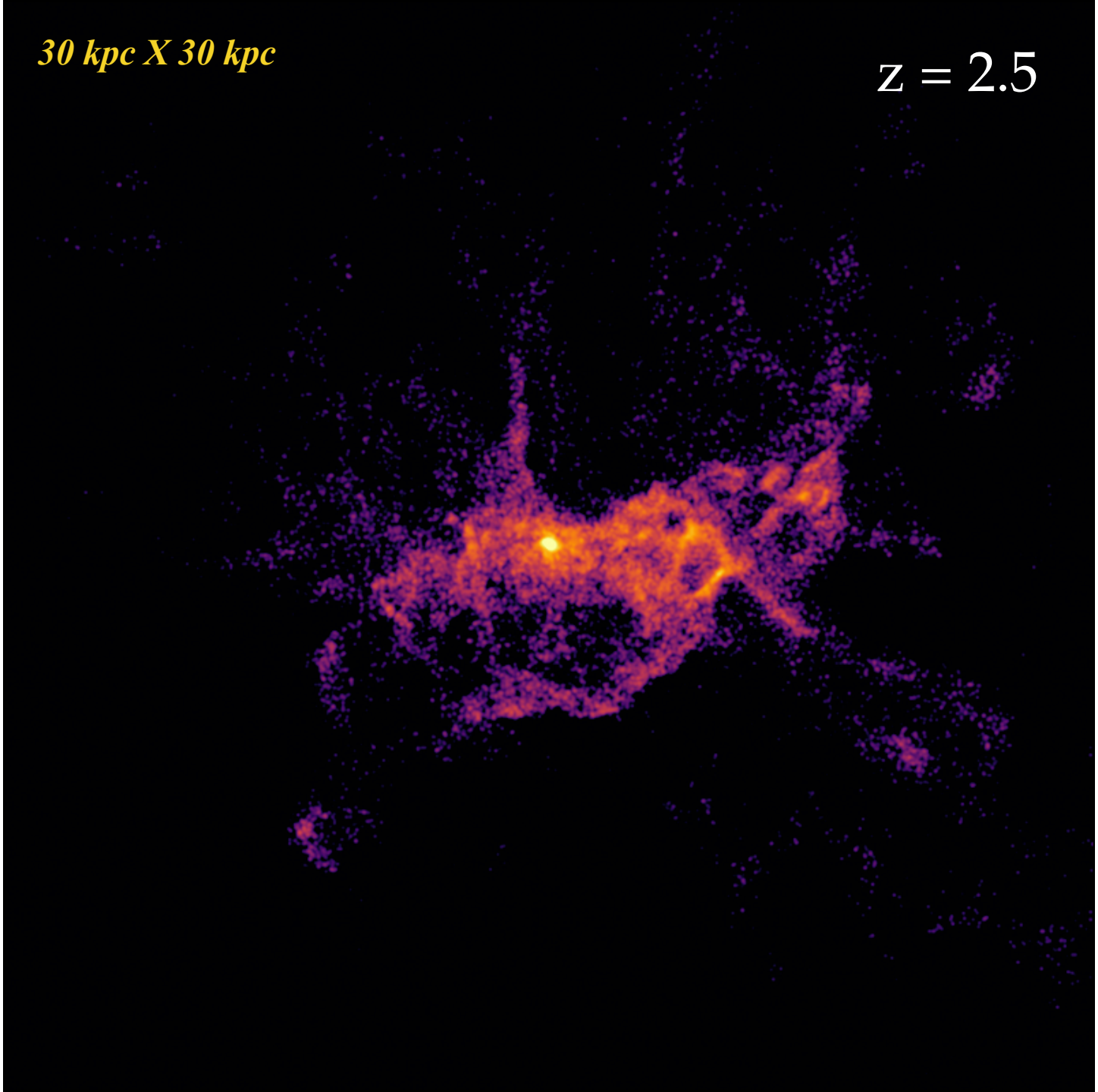

30 kpc X 30 kpc
z = 3.0

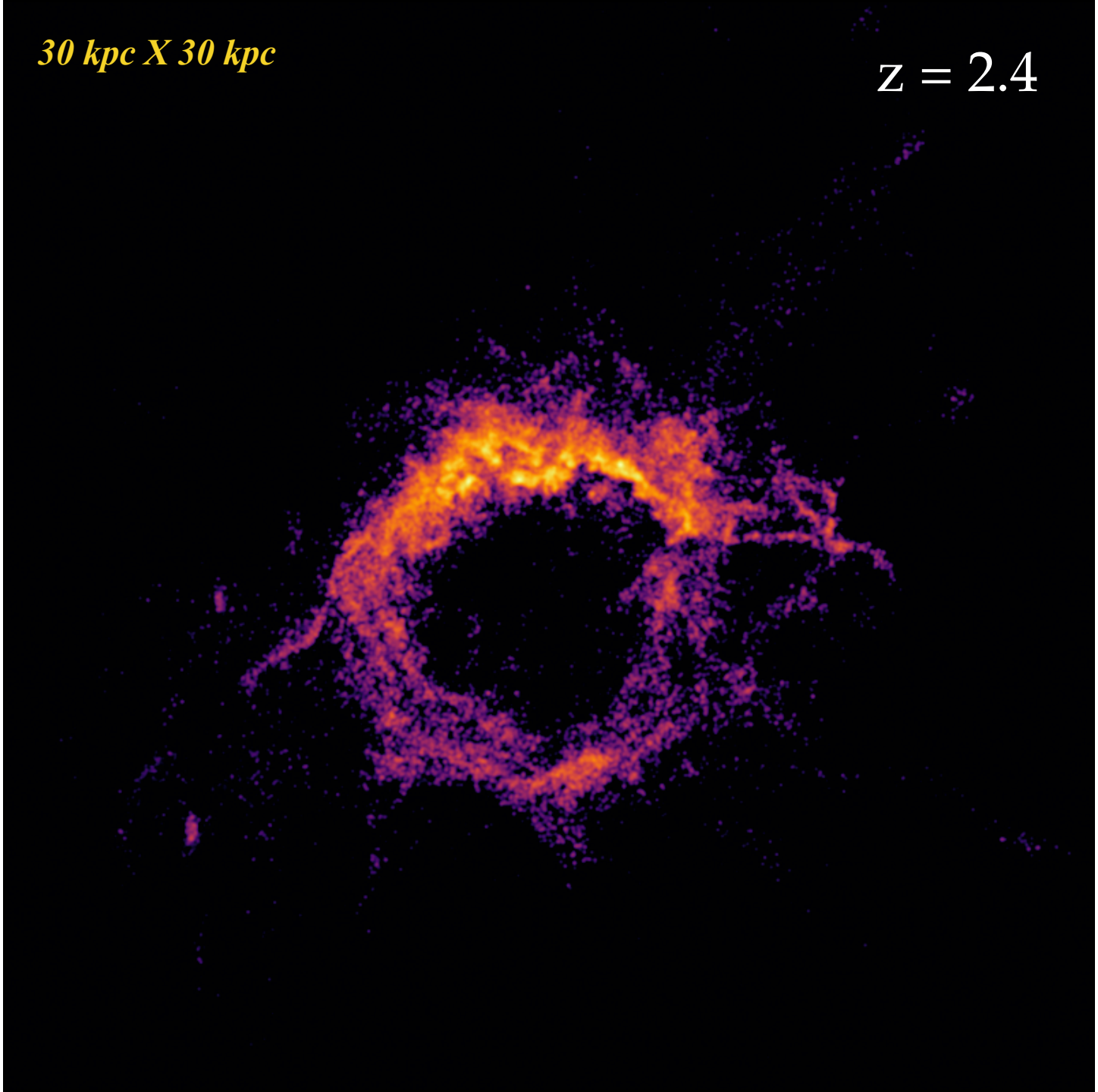

30 kpc X 30 kpc
z = 2.9

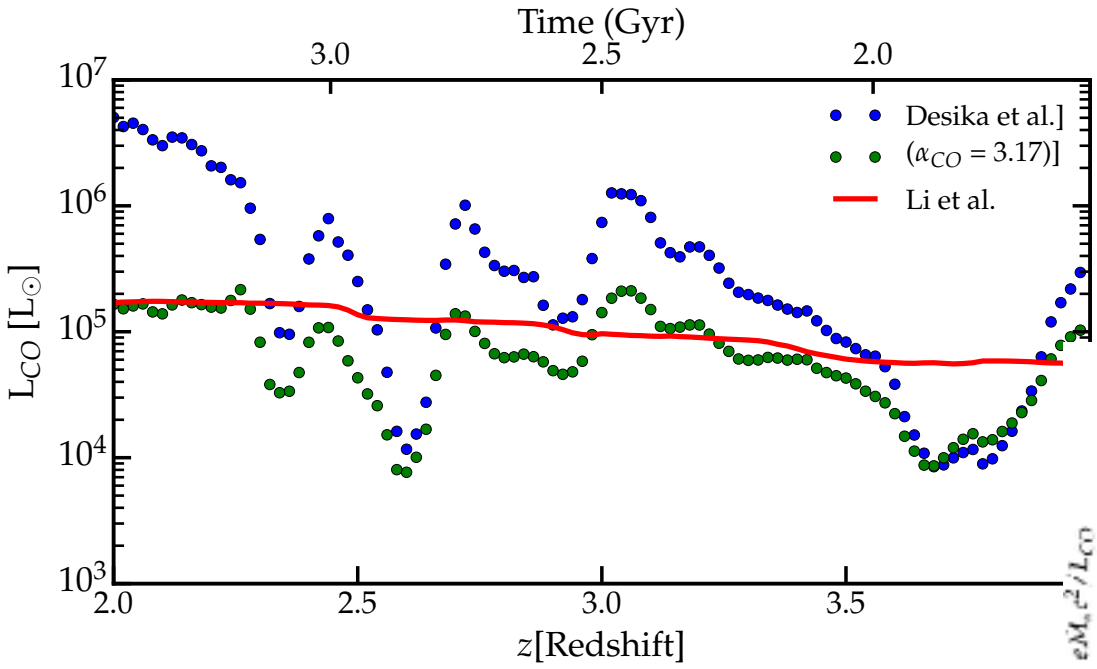

30 kpc X 30 kpc
z = 2.8

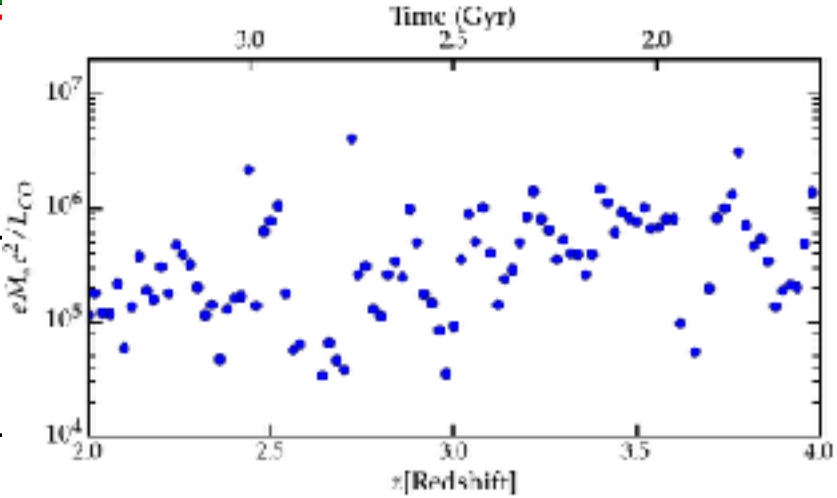

30 kpc X 30 kpc
z = 2.7

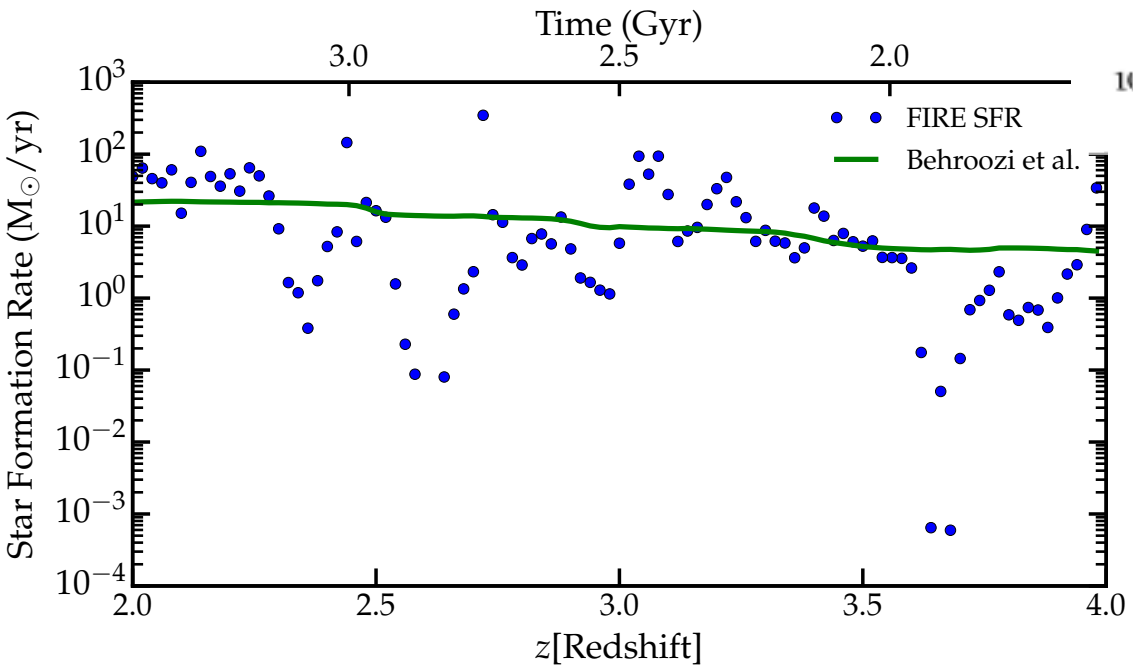

30 kpc X 30 kpc
z = 2.6


30 kpc X 30 kpc
z = 2.5


30 kpc X 30 kpc
z = 2.4


Time (Gyr)
3.0
2.5
2.0
10^7
10^6
10^5
10^4
10^3
L_{CO} [$L_\odot$]
Desika et al.]
(α_{CO} = 3.17)]
Li et al.
2.0
2.5
3.0
3.5
z[Redshift]


Time (Gyr)
3.0
2.5
2.0
10^7
10^6
10^5
10^4
eM_*c^2/L_{CO}
2.0
2.5
3.0
3.5
4.0
z[Redshift]


Time (Gyr)
3.0
2.5
2.0
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Star Formation Rate ($M_\odot$/yr)
FIRE SFR
Behroozi et al.
2.0
2.5
3.0
3.5
4.0
z[Redshift]

CO, HI, CII, FIR, SFR from hi res FIRE hydro ABS + Gunjan Lakhlani + Norm Murray + Hopkins +

measuring mean CO susceptibilities & HI & CII & ..

- 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 etal) = int Prob(CO etal| control parameters) dProb (control parameters)

galaxy assembly = out of control?

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

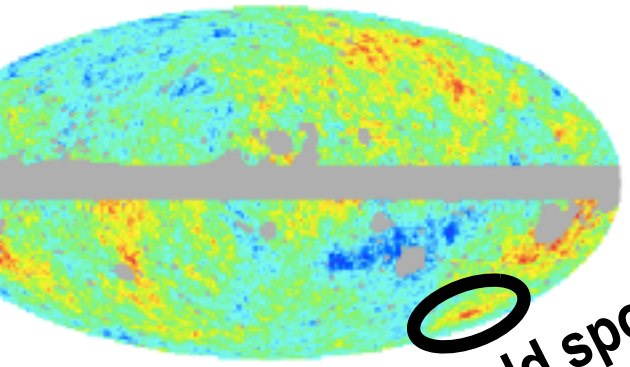
or remnants of bubbles during inflation

or …

apparent breakdown of LSS homogeneity

2D intermittency WMAP cold spot

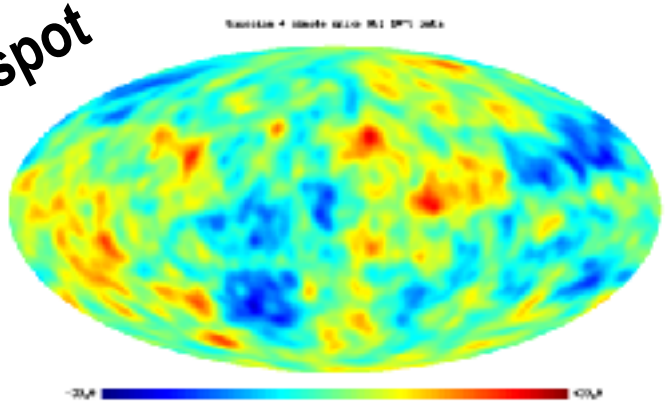
$\zeta|T,E$:

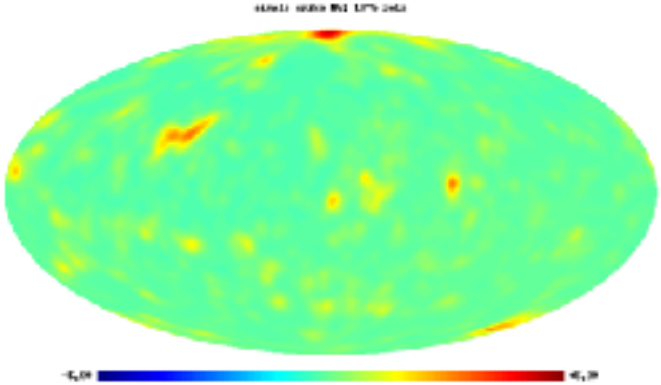


the rare cold spot

>4.5σ
<1%
L~20
in LSS?

CMB+LSS mocks to test: standard Gaussian inflaton ζ_{inf}+ subdominant uncorrelated ζ_{isoc} e.g., from modulated preheating

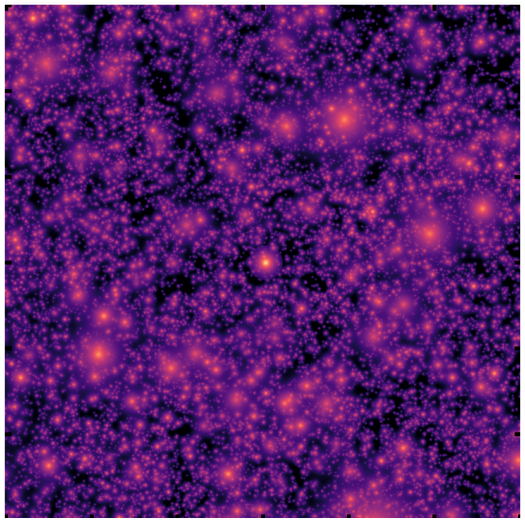




3D intermittency

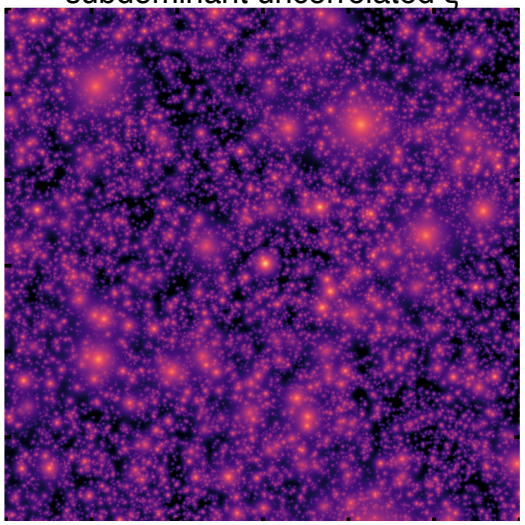
uncorrelated nonG 'wide open' cf. usual correlated highly constrained nonG

LSS tSZ: Gaussian std



B2FH, b+braden+frolov+huang

LSS tSZ: Gaussian std + subdominant uncorrelated ζ



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

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}

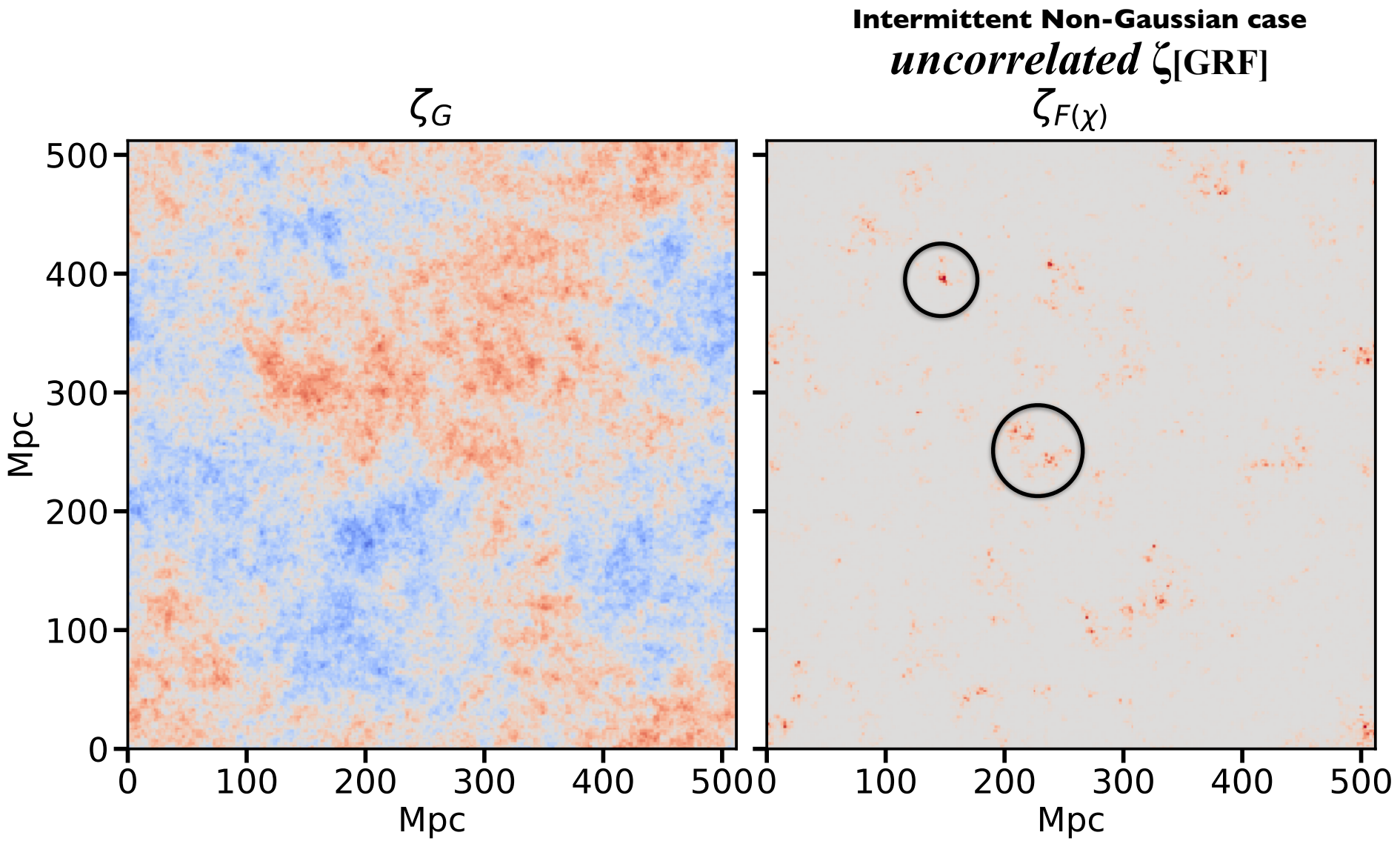
std nonG $\zeta = \zeta_G + \mathbf{f_{NL}}^{*} (\zeta_G^2 - \langle\zeta_G^2\rangle)$ local & equilateral pattern & orthogonal

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

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

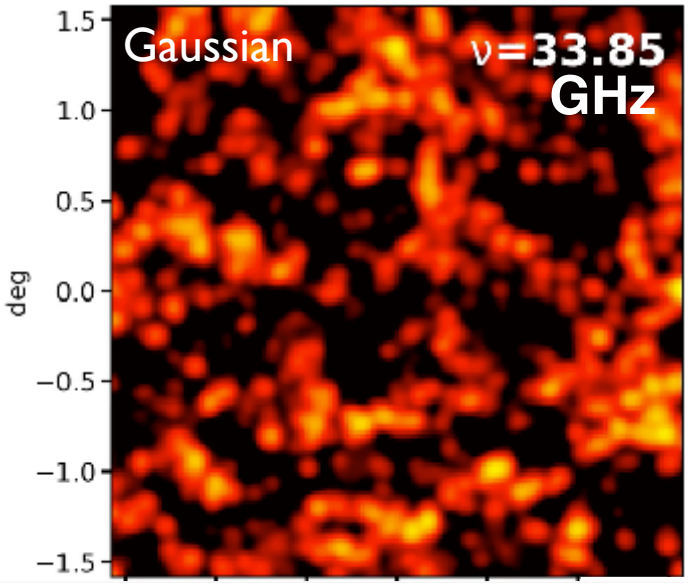
=> *quest for* unconventional primordial nonGaussian

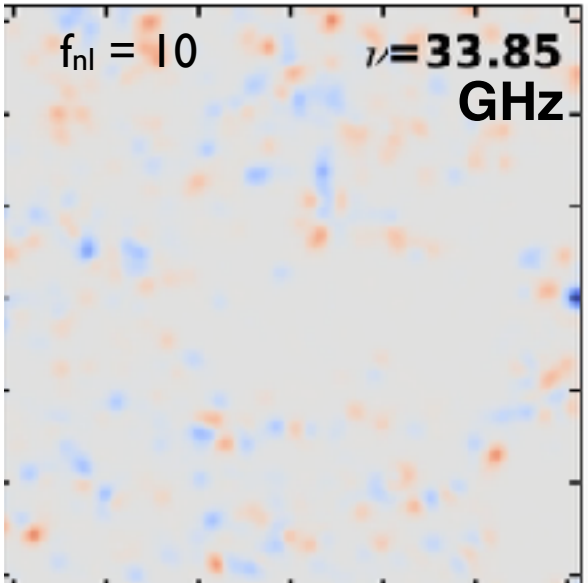
Primordial Non-Gaussianity in COMAP via Peak Patch sims:

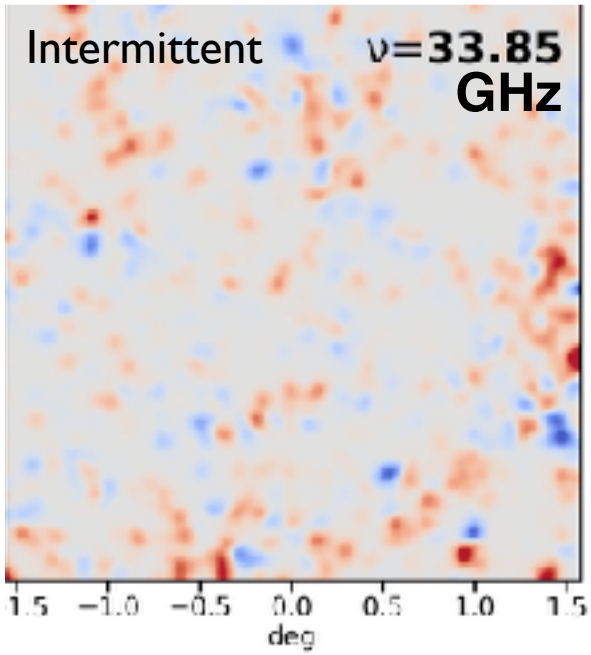


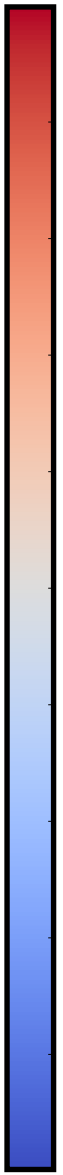
Primordial Non-Gaussianity in CO

$\sigma_8 = 0.82$
In all cases









pp+ ***for coarse-grained mapping of the cosmic web:***

fast halo finding for ensembles & BSMc - *works well BM, ABS+ tsts, Euclid tst*

halo interiors: measured mean-field stacked susceptibilities

2LPT for fluctuations external to halos (& unresolved biased halo-field)

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

"mocking heaven" apps: **tSZ, CIB, kSZ** *original CMB motivation => tSZxCIB*, **Lens**

optical galaxies **via HOD for CMASS, Euclid, LSST, .. DES, HSC, sphereX**

Line intensity mapping **of HI (CHIME, HIREX, ..,SKA) COmap, CII CCATp**

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**

CITA mini-industry: Marcelo Alvarez, Dick Bond, George Stein & Battaglia, Codis, van Engelen & FIRE: Lakhlani + Murray + Hopkins + Berger & Connor Bevington, Bruno Régaldo-Saint Blancard, Ronan Kerr, Louis Pham

END