Eichiro Komatsu ***Dick Bond:*** Synergy between Clusters & other cosmological probes

$n_{cluster}$

$(Y_{SZ}, M_{lens}, Y_X, L_X, T_X, L_{cl,opt}, R_{ich}, \ldots \mid z,$ gold-sample, thresholds)

$+ C_L^{SZ}$(cuts) $+\xi_{cc}(r|n_{cl})$ will deliver valuable cosmic gastrophysics for sure.

Will it deliver fundamental physics e.g., the dark energy EOS, primordial non-Gaussianity??? σ_8 even?

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valuable cosmic gastrophysics for sure.

Will it deliver fundamental physics

e.g., the dark energy EOS, primordial non-Gaussianity??? σ_8 even?

cluster/gp system used since 80s: Xtra power ξ_{cc} ξ_{cg} => xCDM

$P_{\rho\rho}$(.25h/Mpc) aka σ_8 via n_{cl} *are we really ready for prime time? mock-ing!!*

KITP congrats david

80 81 **84** 88 **95** 97 00 **02** 04

SN DM + CMB + precision CMB + weak lens

incl polarization SB cluster test

Bethe Bias / LSS (hydro – SZ)

etal + cosmic strings

theorists/phenomenologists/experimentalists/observers

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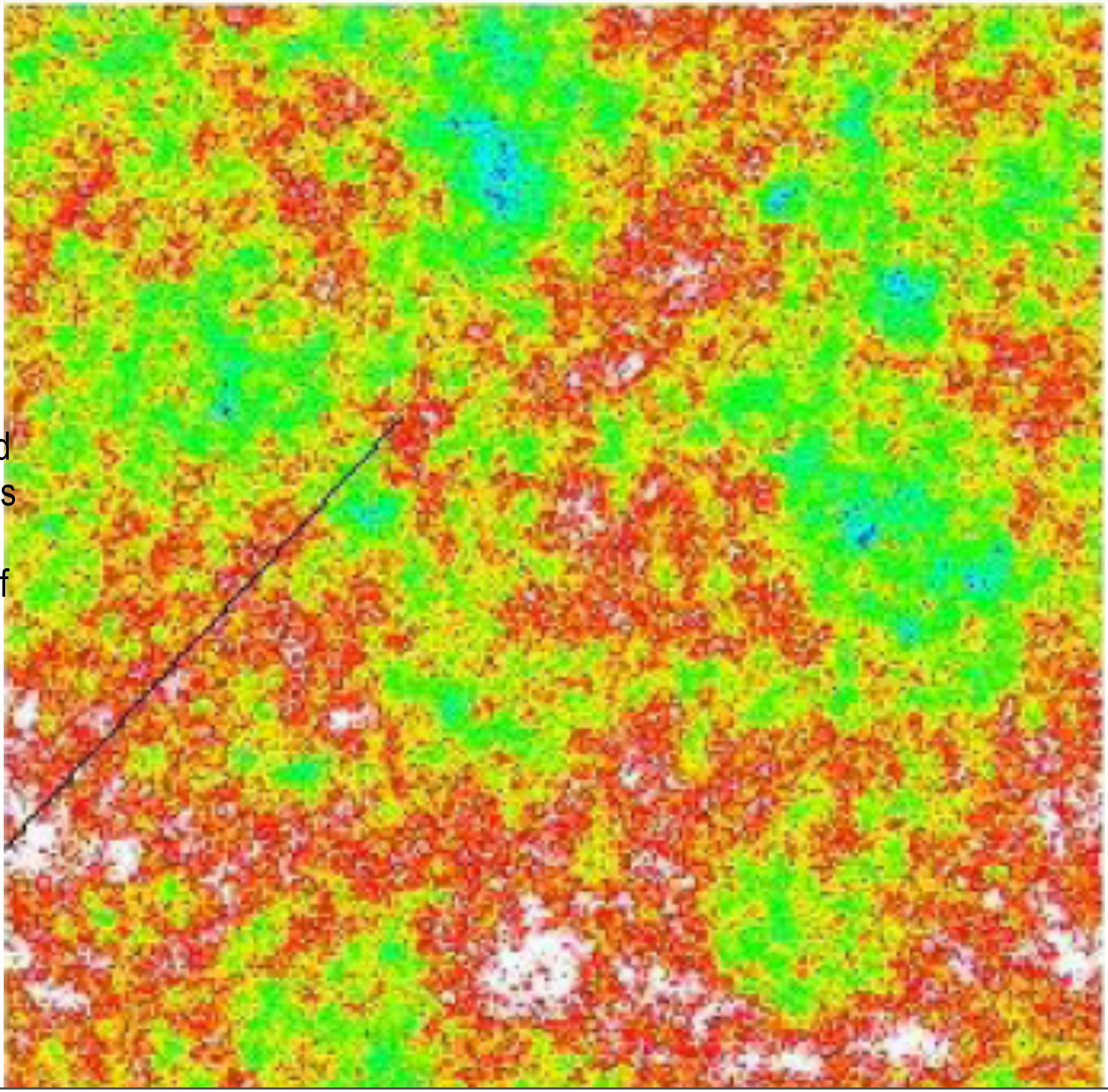
rare event bias: even in 84 it was recognized that there was another parameter beyond peak height (ν~ mass) to characterize bias (x shape ~ concentration). in 90s, cluster patches showed anisotropic $\xi_{cc}(r|n_{cl})$ arises with protocluster tidal field constraints, ie environment enforces constructive wave interference, and it is the longest waves interfering that give the bias. *not surprising that generalized bias is not trivial since this is what defines the structure of the cosmic web, superclusters, etc.*

$n_{\text{rare-events}}$ (M-sort-of, & other selection biases) *statistics of one or a few - care must be taken to make big claims*

"every cluster is a bullet cluster" - or was a bullet *, tis the nature of the hierarchy*

fluctuations in the **early universe "vacuum" grow** to *all* **structure**

scalar field fluctuations in the vacuum of the ultra-early Universe



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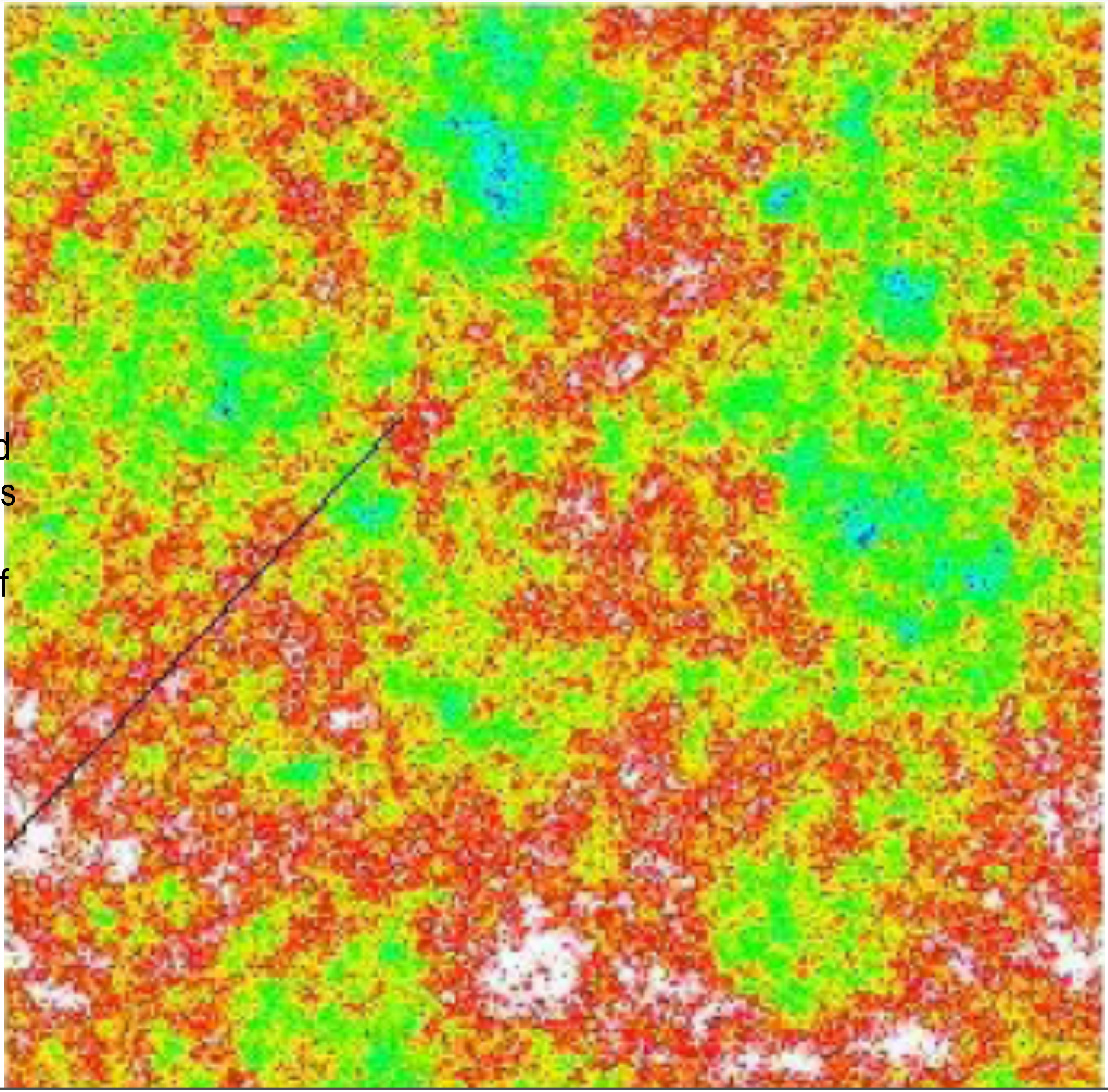
scalar field fluctuations in the vacuum of the ultra-early Universe



evolve from early U vacuum potential and vacuum noise

fluctuations in the **early universe "vacuum" grow** to *all* **structure**

400 Mpc

ΛCDM

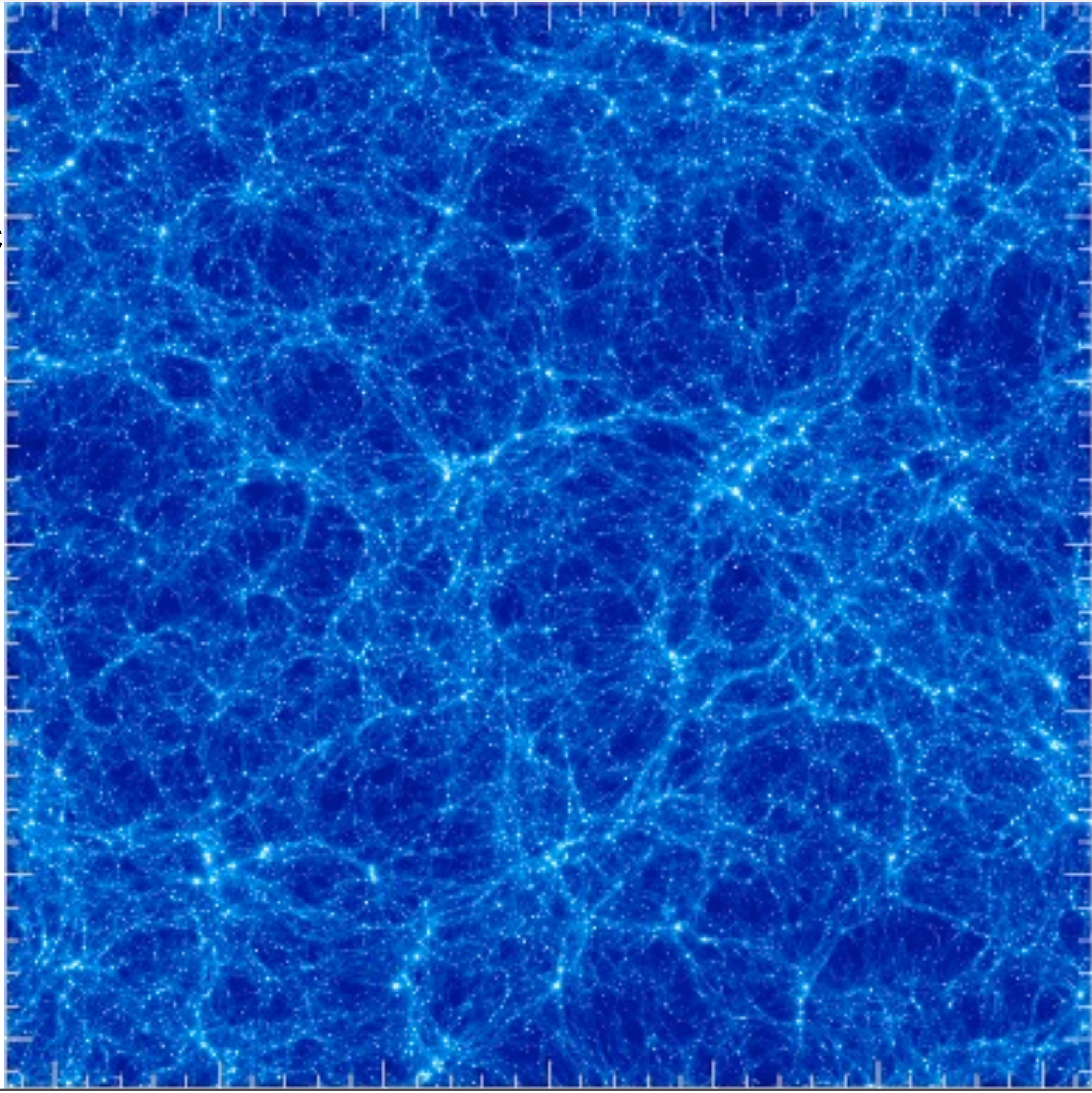
WMAP5

gas density

Gadget-3

SF+ SN E+ winds +CRs

512^3



all this can

evolve from early U vacuum potential and vacuum noise

in the presence of late U vacuum potential aka dark energy

pressure intermittency *in the cosmic web, in cluster-group concentrations probed by* **tSZ**

400 Mpc

ΛCDM

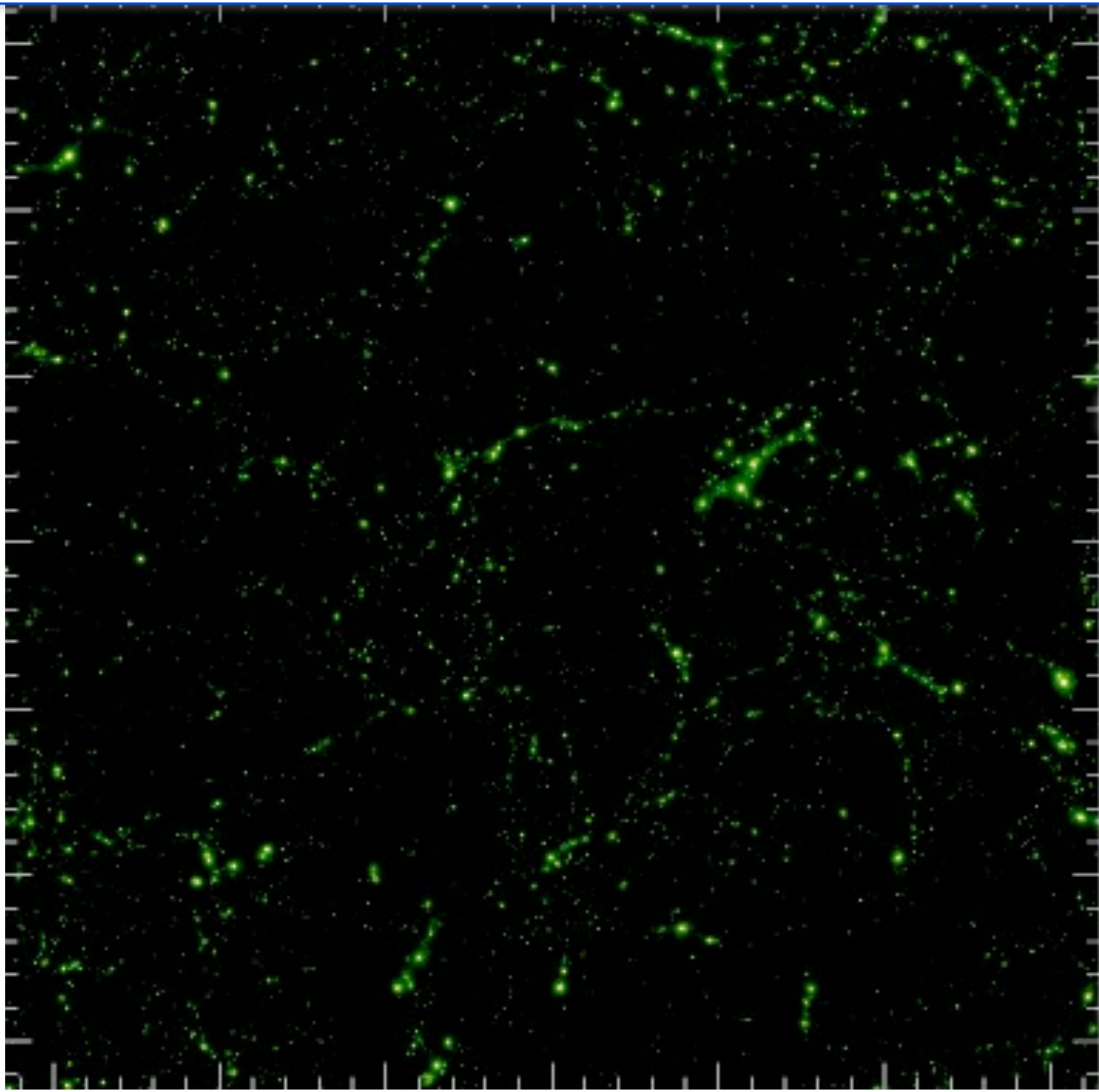
WMAP5

gas pressure

Gadget-3

SF+ SN E+ winds +CRs

512^3



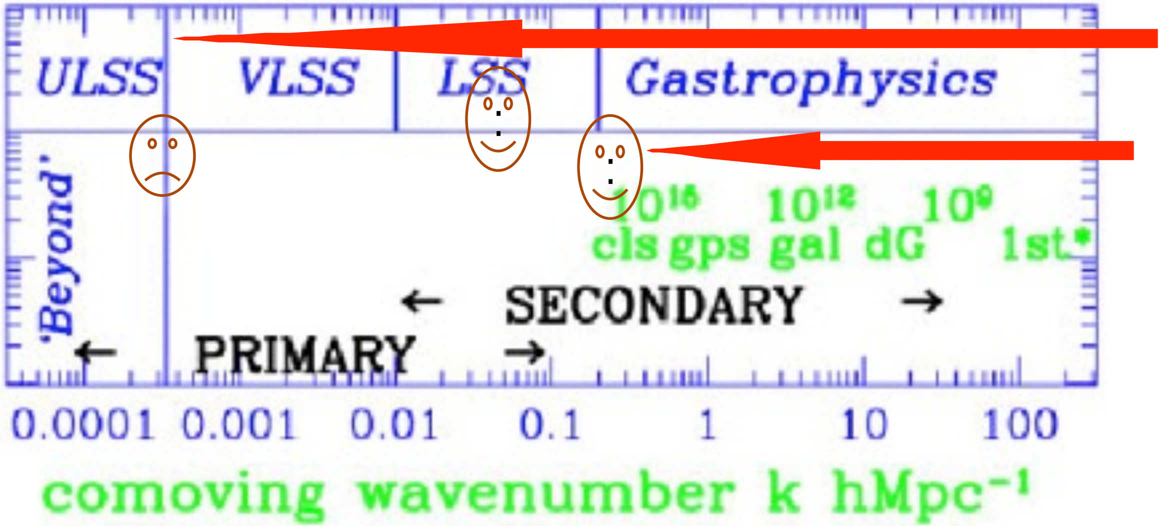
entangled in the cosmic web

descending into the real gastrophysics

of

cosmic weather

the energetic, turbulent, dissipative, compressive life of the IGM/ICM/ISM



K_{hor}(t)=Ha

K_{NL}(t)

$$\lambda_{phys} = 2\pi \bar{a}(t)/k, \quad \bar{a} = 1 \ \text{now}$$

Cosmic Spatial Length Scale (unwrinkled)

Momentum Space PROBES

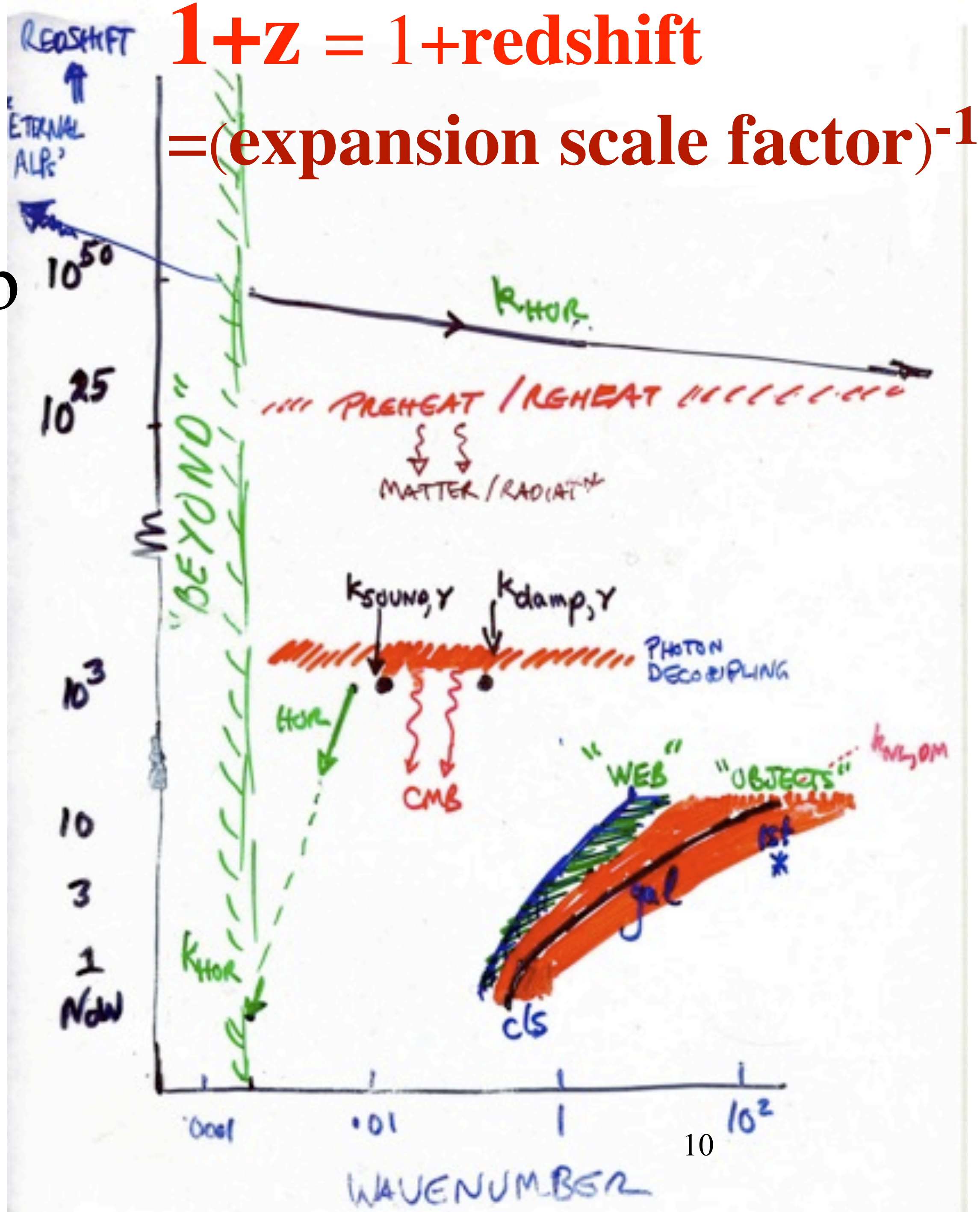
K_{hor}(t)=Ha

redshift *vs* wavenumber: k_{NL} & the cosmic web

"virialized" collapsed objects bridged by a network of filaments, membranes & voids

1+z = 1+redshift

=(expansion scale factor)$^{-1}$



redshift *vs* wavenumber: k_{NL} & the cosmic web

"virialized" collapsed objects bridged by a network of filaments, membranes & voids

=>"molecular" picture of LSS

initial density spectrum $d\sigma_{\rho L}^2/d\ln k$

~percolation of the web

$\sigma_{\rho L}$ **(k)~0.65** cf. $\sigma_{\rho L}$ **(k_{NL})=1**

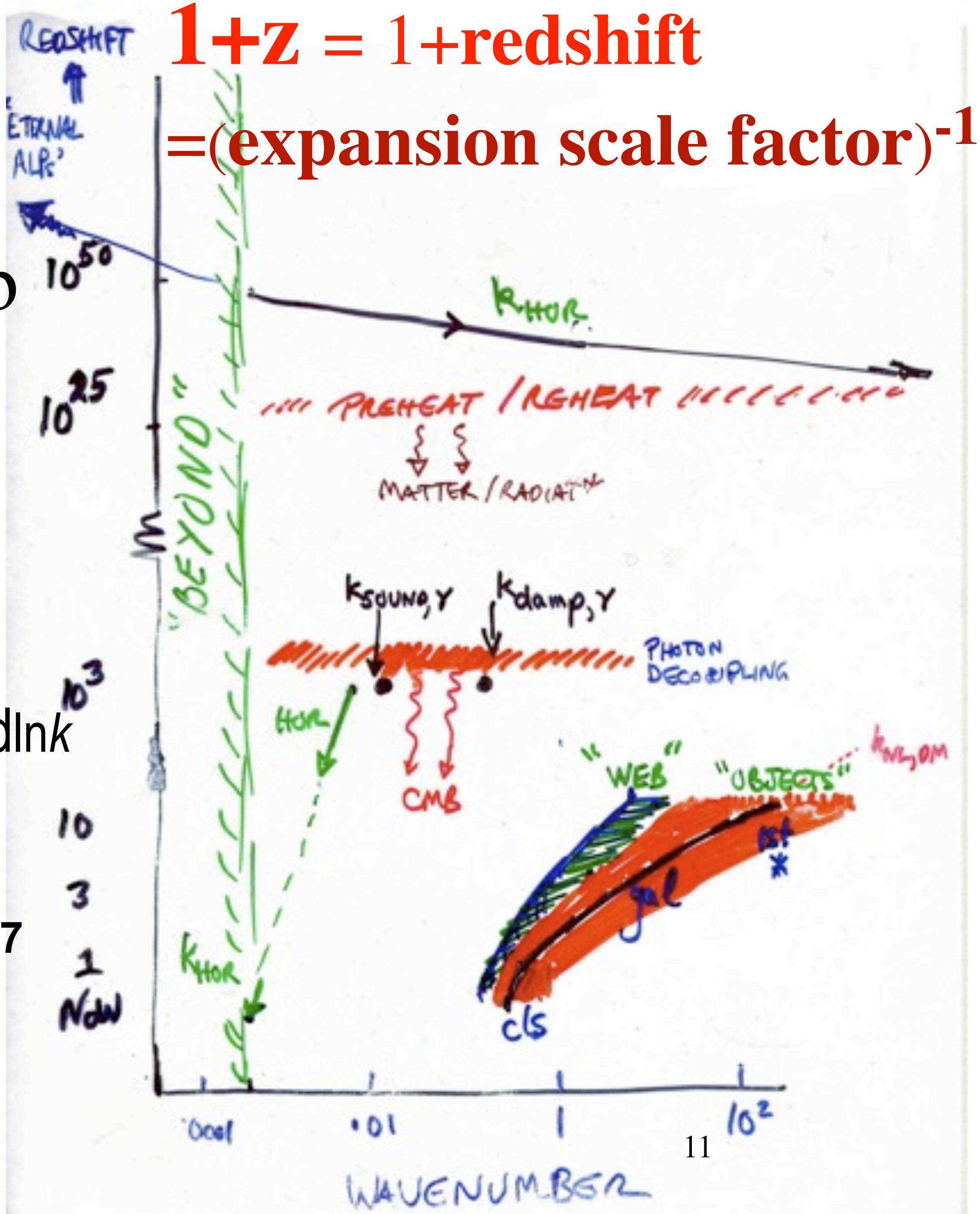
cf. halo $\delta_L \equiv \nu\sigma_{\rho L}$ **(k) ~1.6-2.7**

$n_{halo}(\sigma_{\rho L}^2, ...)$ ~ n_{halo} **(M,...)**

bias(M,...)~ $\delta n_{halo} / \delta\rho_m$

P(*subhalo|halo*)

1+z = 1+redshift =(expansion scale factor)$^{-1}$



Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c

$\ln A_s$ n_s $r = A_t/A_s$ $dn_s/d\ln k$ n_t

1+w0, wa

$\theta \sim \ell_s^{-1}$

ne(a)

$\sim \ln \sigma_8^2$

+ subdominant
isocurvature, cosmic string,
& fgnds, tSZ,kSZ, ...

Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c

$\ln A_s$ n_s $r = A_t / A_s$ $dn_s / d\ln k$ n_t

1+w0, wa

$\theta \sim \ell_s^{-1}$

ne(a)

$\sim \ln \sigma_8^2$

+ subdominant isocurvature, cosmic string,

& fgnds, tSZ,kSZ, ...

Neo-Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c

$\ln A_s$ n_s $r = A_t/A_s$ $dn_s/d\ln k$ n_t

$1+w_0, w_a$ $\theta \sim \ell_s^{-1}$ $n_e(a)$ $\sim \ln \sigma_8^2$

new parameters: **trajectory probabilities for early-inflatons & late-inflatons**

(partially) blind cf. informed "theory" priors

$\ln P_s(\ln k)$ & $r(k_p)$ & $\ln P_t(\ln k)$

$$\varepsilon_\phi \times 2/3 = 1 + w_{de}(a) = -\, d\ln \rho_\phi / d\ln \mathbf{a}^3$$

+ subdominant isocurvature, cosmic string,

& fgnds, tSZ,kSZ, ...

future of DARK ENERGY phenomenology: "equation of state"

CMB gives rulers at z=1100 angular-diameter-distance maps to T/E patterns now

CMB ISW effects and low L give limited sensitivity – cosmic variance

X-correlation with 5 density surveys, each ~2.5 sigma

SN standard candles luminosity-distance (comoving radial distance, i.e. conformal time)

number densities & counts comoving volume

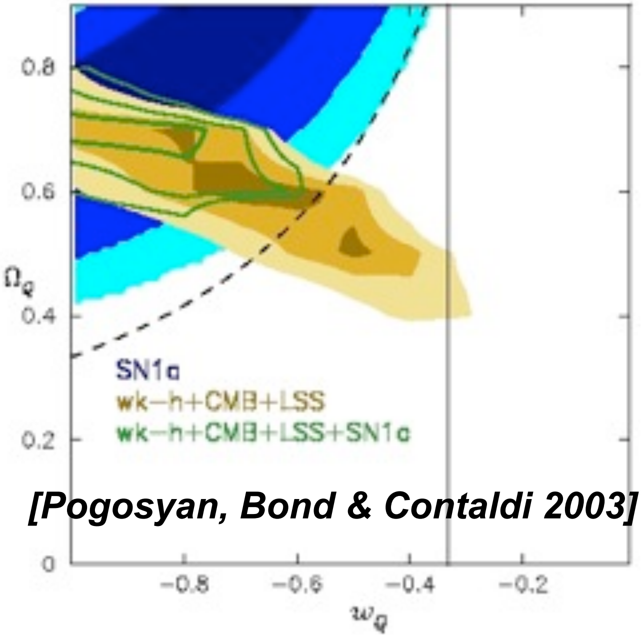
Cluster/gp system: SZ (Compton scattering off hot gas) + optical + X "tomography"

+ hope (gas)

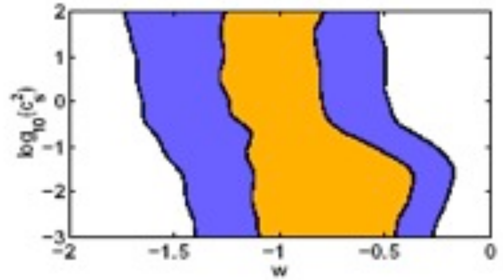
Dependence on linear perturbation evolution

d ln D / d ln a (counts, weak clustering) i.e. d ln σ_8/ d ln a

& its nonlinear memory (in **weak lensing**, galaxy & cluster clustering, ...)



[Pogosyan, Bond & Contaldi 2003]



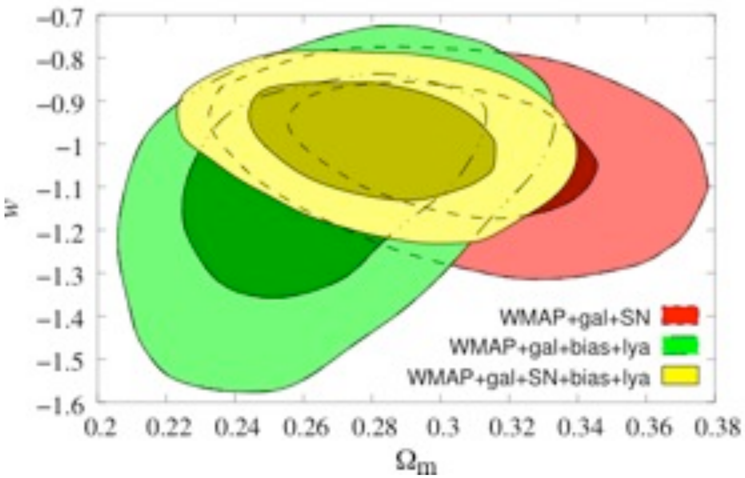
[Weller & Lewis 2003]

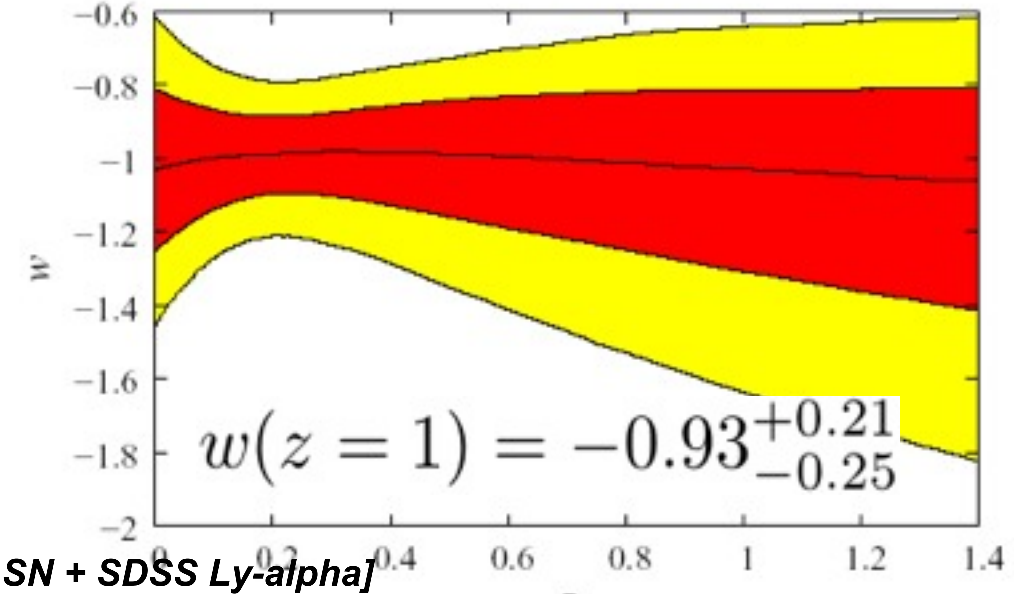
acceleration trajectories: evolution of Dark Energy equation of state **w(ln a)** to cf. **q(ln a)** in redshift bands

constant w, contributes a uniform acceleration

now **SN+CMB+LSS w < -0.7** & -**1** aka Λ OK

$$w = w_0 + (a-1)w_1 + (a-1)^2 w_2$$



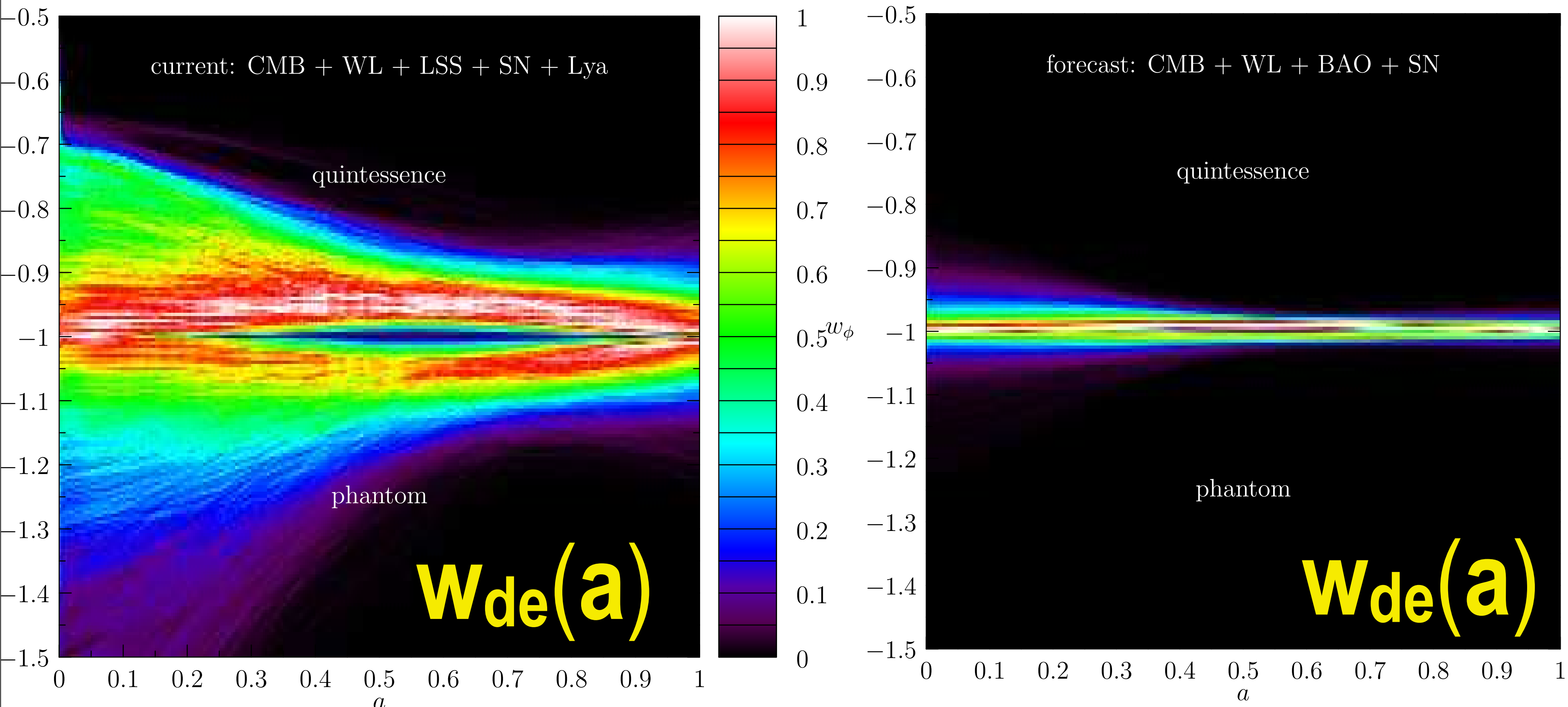


[Seljak, McDonald, ..., SDSS et al. 2004, CMB + SN + SDSS Ly-alpha]

October 2004, The Future of Physics, KITP, UC Santa Barbara, The Phenomenology of Dark Energy and Cosmic Acceleration

future DE equation of state trajectories NOW

$(1+w_{de}) = -\, d\ln\rho_{de} / d\ln a^3 = 2/3\ \varepsilon_\psi$ & $\varepsilon = \Omega_\psi \varepsilon_\psi + \Omega_m \varepsilon_m$ & $\varepsilon_m = 3/2$



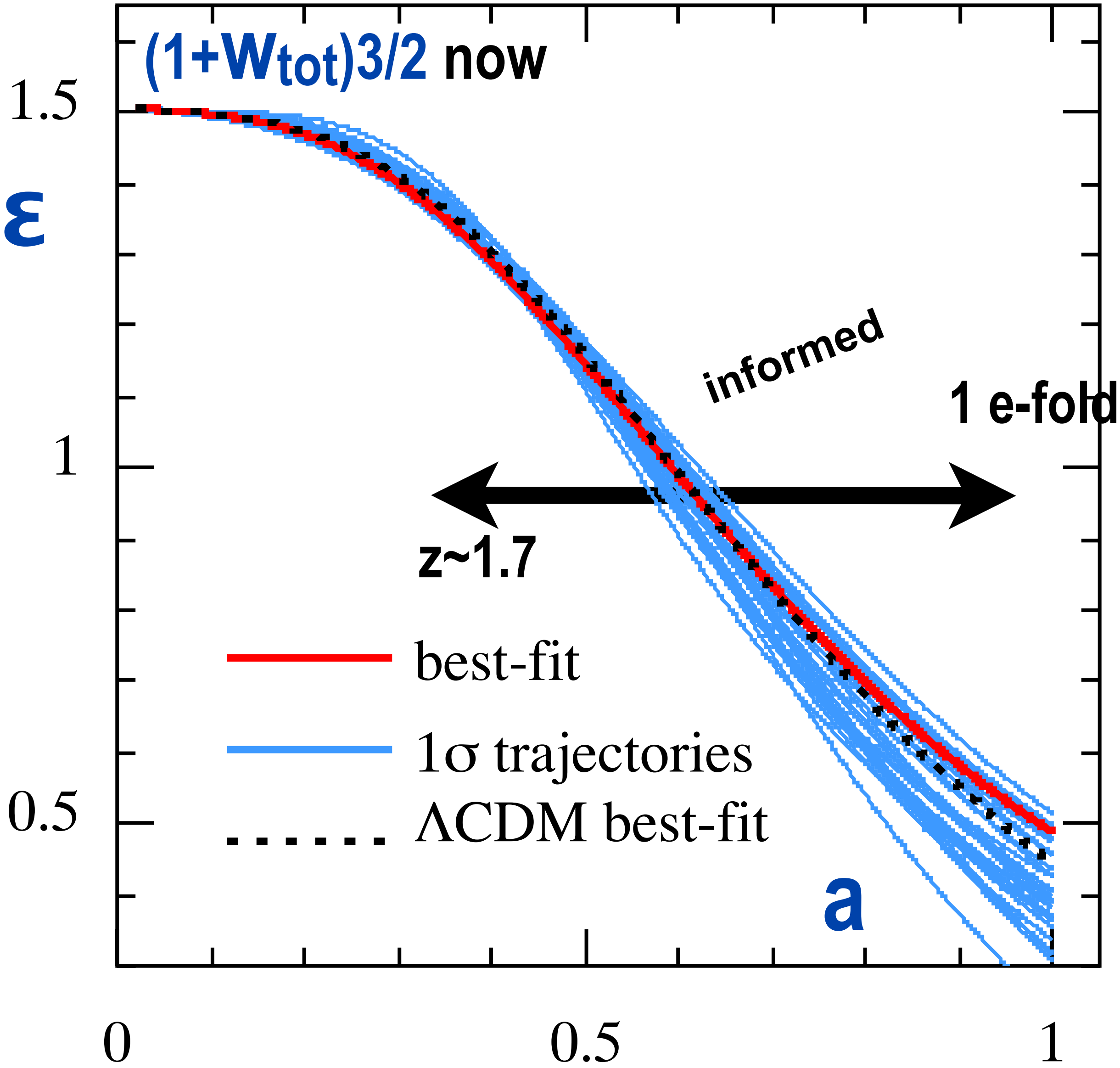
future = Planck2.5+CHIME-BOSS-BAO+"JDEM-SN+Euclid-WL"

3-parameter w_{de} $(z|V(\psi),IC)$ paves even wild late-inflaton trajectories

semi-blind w_{de} (z) in many z-bands determines only ~2 eigenvalues

current acceleration trajectories NOW

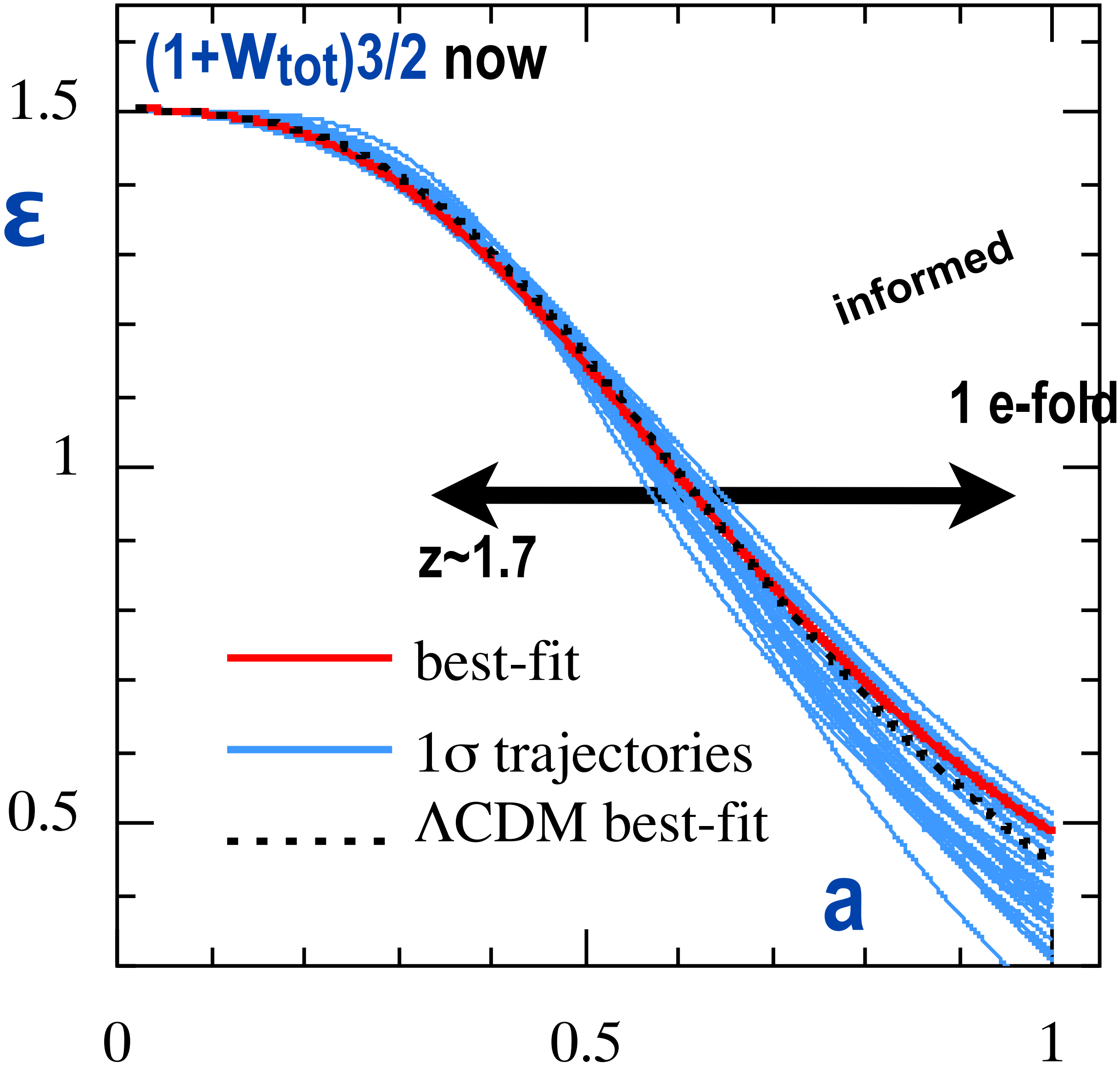
$(1+w_{tot}) = - d\ln\rho_{tot} / d\ln a^3 = 2/3\ \epsilon = - 2/3\ d\ln H / d\ln a$

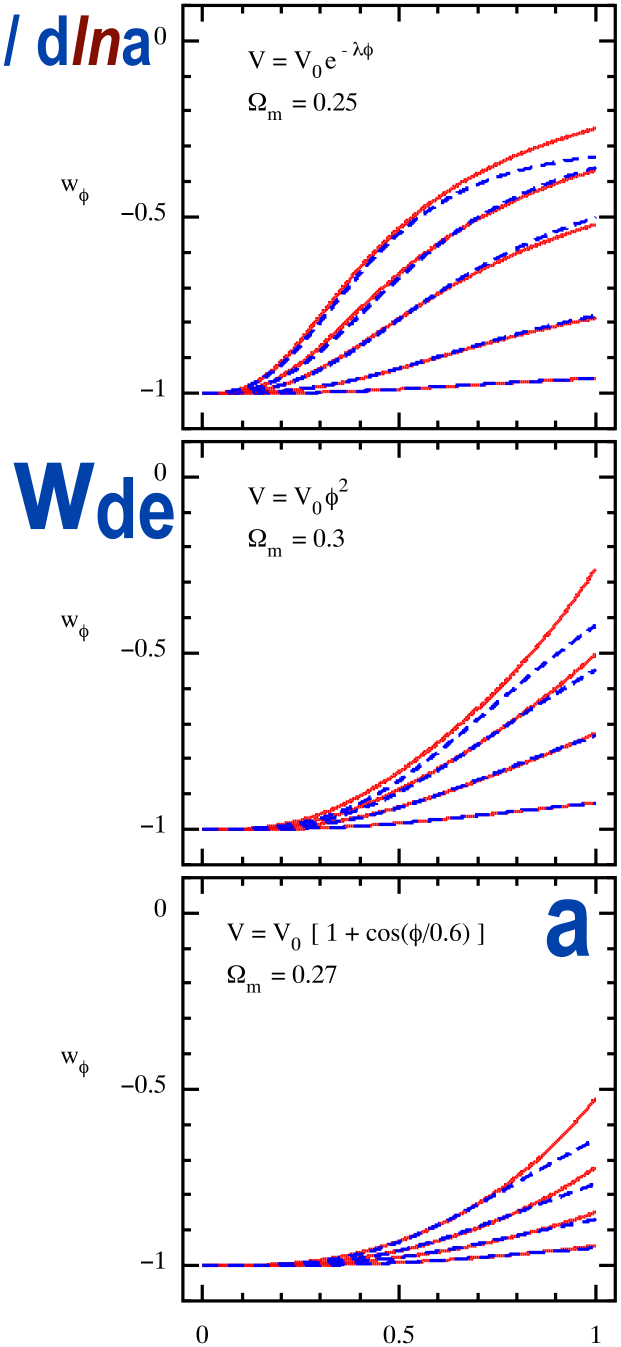


informed = 3-parameter $w_{de}(z|V(\psi),IC)$

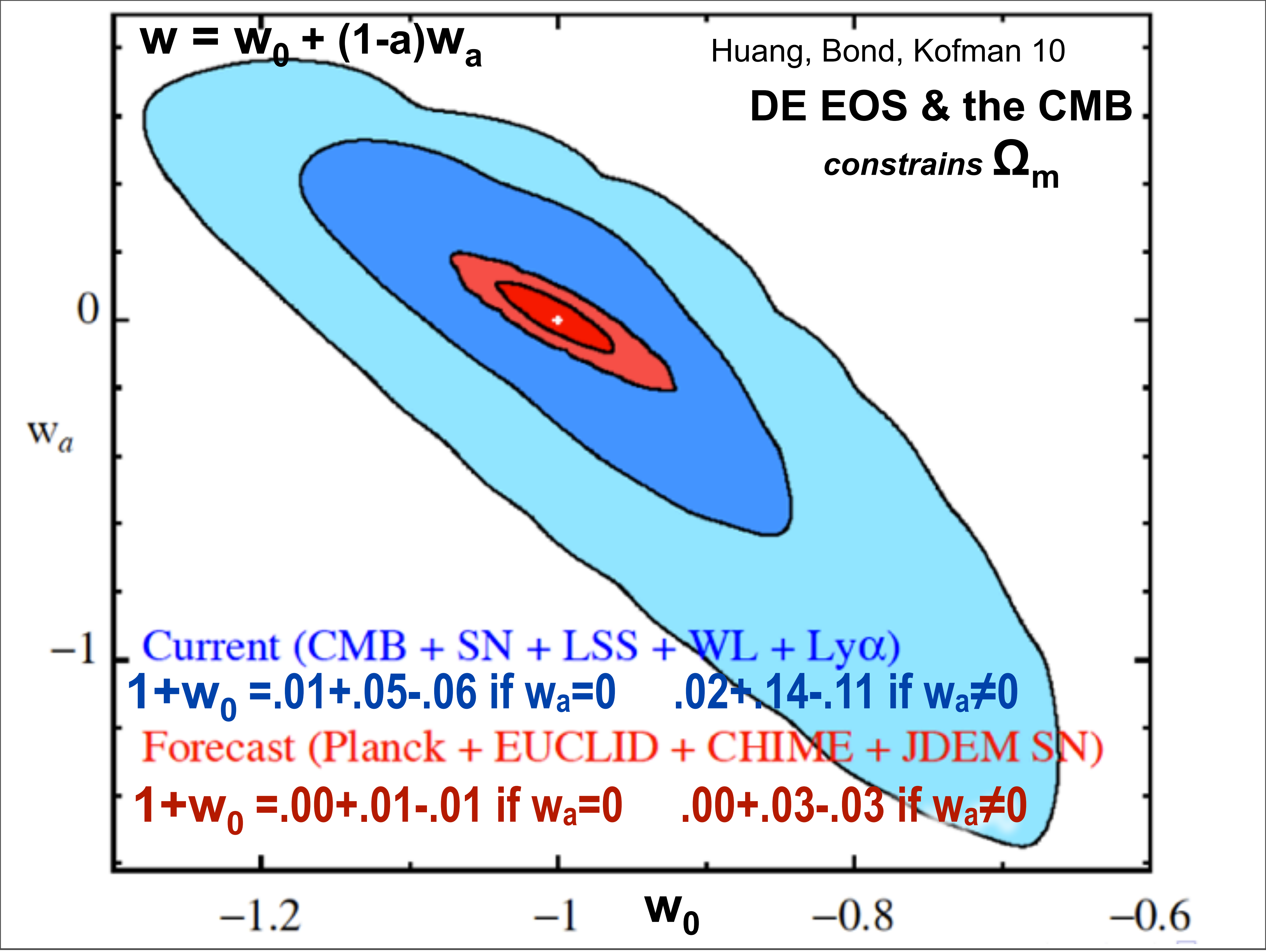
current acceleration trajectories NOW

$(1+w_{tot}) = - d\ln\rho_{tot} / d\ln a^3 = 2/3\ \epsilon = - 2/3\ d\ln H / d\ln a$



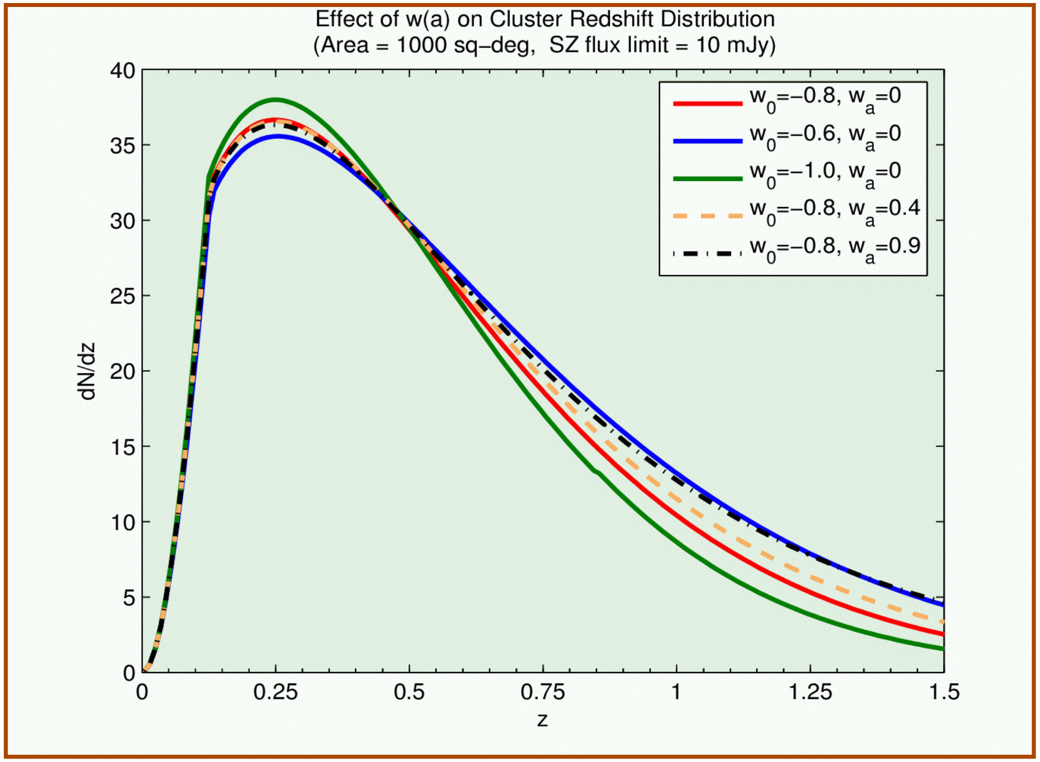


informed = 3-parameter $w_{de}(z|V(\psi),IC)$



w = w0 + (1-a)wa
Huang, Bond, Kofman 10
DE EOS & the CMB
constrains Ωm
Current (CMB + SN + LSS + WL + Lyα)
1+w0 =.01+.05-.06 if wa=0   .02+.14-.11 if wa≠0
Forecast (Planck + EUCLID + CHIME + JDEM SN)
1+w0 =.00+.01-.01 if wa=0   .00+.03-.03 if wa≠0
0
−1
wa
−1.2
−1
w0
−0.8
−0.6

2004 forecasted SPT counts σ_8~0.9 days



Subha Majumdar & Graham Cox CITA04

4000 sq deg with SPT, 22000 clusters

$1+w_0$ =.01+.05-.06 if w_a=0 .02+.14-.11 if $w_a \neq 0$

$1+w_0$ =.00+.01-.01 if w_a=0 .00+.03-.03 if $w_a \neq 0$

w_0

ACT counts, calibrate y => M => n(M) with sims - need more MC sims

$$y^{\rm true} = A\left(\frac{M^{\rm true}}{M_0}\right)^B \left(\frac{1+z}{1+z_0}\right)^C$$

8 Sehgal et al.

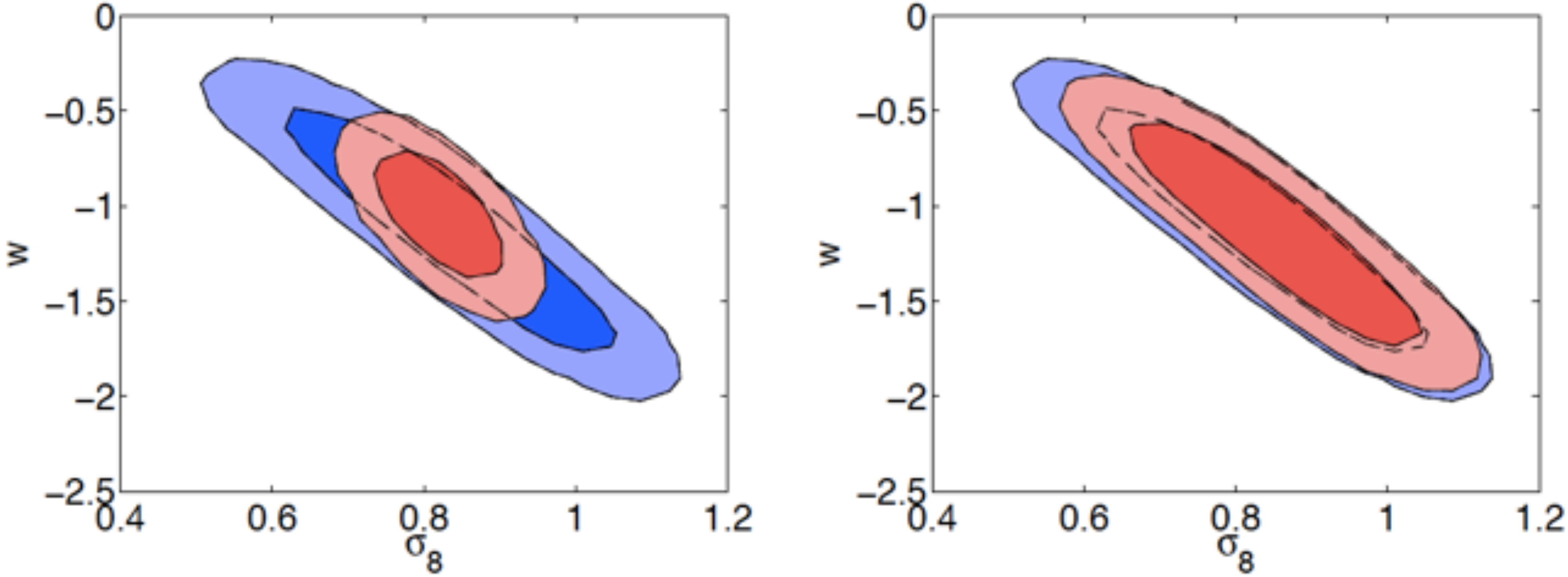


FIG. 6.— Likelihood contour plots of w versus σ_8 showing 1σ and 2σ marginalized contours. *Left*: Blue contours are for WMAP7 alone, and red contours are for WMAP7 plus ACT SZ detected clusters, fixing the mass-observable relation to the fiducial relation given in Section 4.2. *Right:* Contours are the same as in the left panel, except that the uncertainty in the mass-observable relation has been marginalized over within priors discussed in Section 4.3.

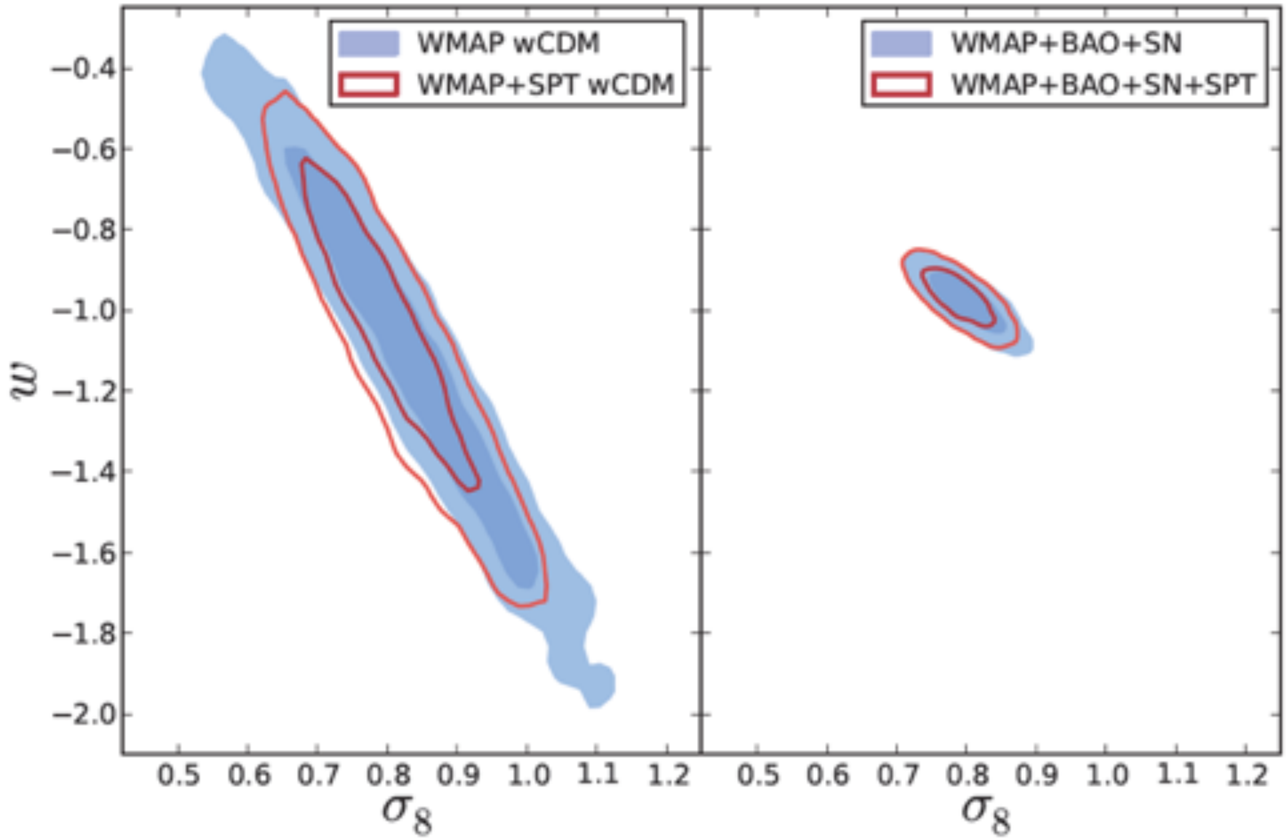
$1+w_0$ =.01+.05-.06 if w_a=0 .02+.14-.11 if $w_a \neq 0$

$1+w_0$ =.00+.01-.01 if w_a=0 .00+.03-.03 if $w_a \neq 0$

w_0

SPT counts Vanderlinde et 2010

$$y^{\mathrm{true}} = A\left(\frac{M^{\mathrm{true}}}{M_0}\right)^B\left(\frac{1+z}{1+z_0}\right)^C$$



$1+w_0 = .01 +.05 -.06$ if $w_a=0$ $\quad .02 +.14 -.11$ if $w_a \neq 0$

$1+w_0 = .00 +.01 -.01$ if $w_a=0$ $\quad .00 +.03 -.03$ if $w_a \neq 0$

w_0

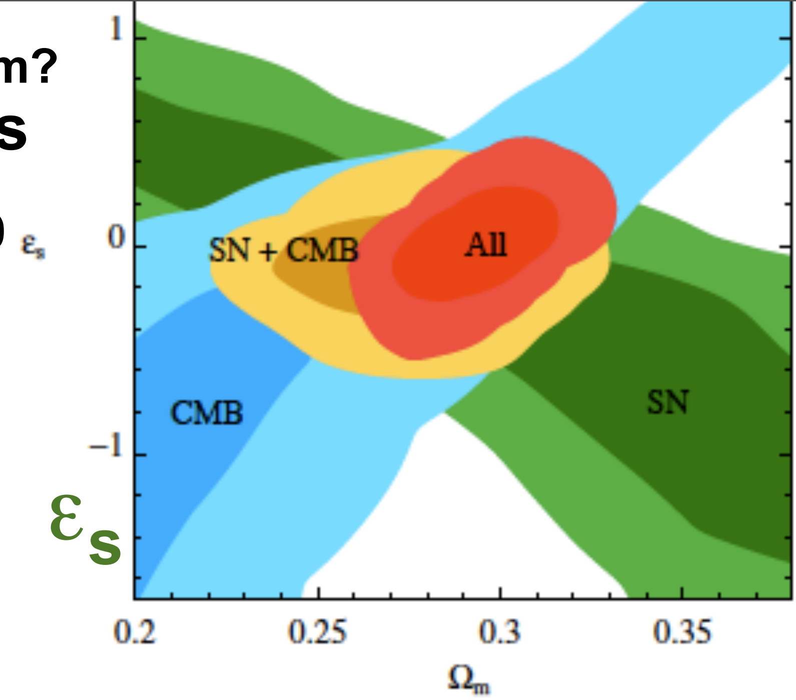
Quintessence $V(\psi)$ & KE<0 Phantom?
3-parameter paving of trajectories

$w(z|\varepsilon_s\ \alpha_t\ \varsigma_s)$ Huang, Bond, Kofman 10

$\varepsilon_s = (d\ln V/d\psi)^2/4$ @pivot a_{eq}

=.00 + .18 -.17 current

to =.005 + .031 -.025 future

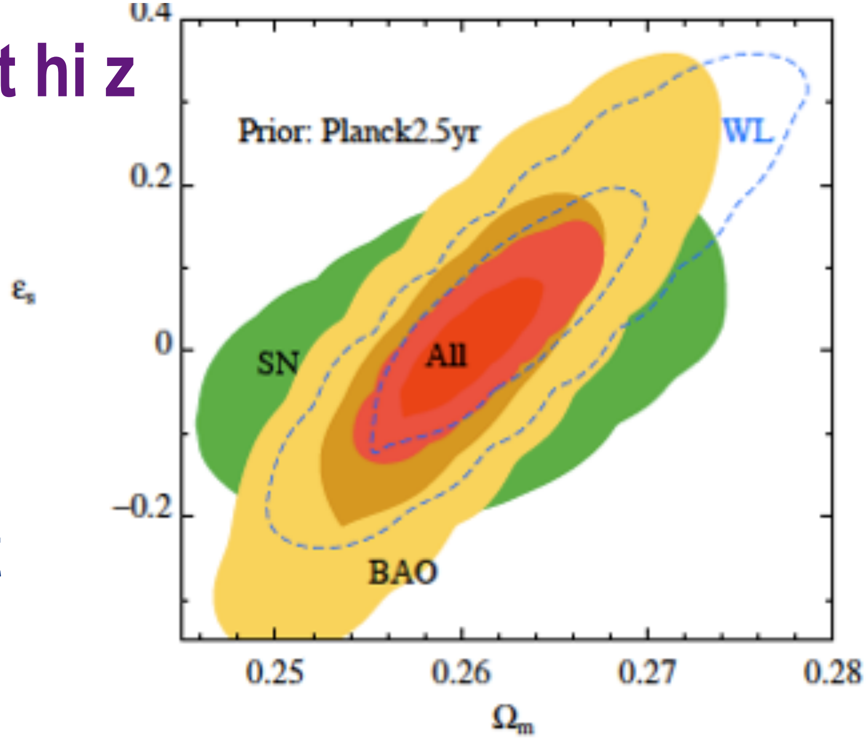


α_t ~tracking parameter ~$(1+w_{de})$ at hi z

=.00 + .21 +.58 current

to =.00 + .034 +.093 future

ς_s ~$d^2\ln V/d\psi^2$ ~ not constrained



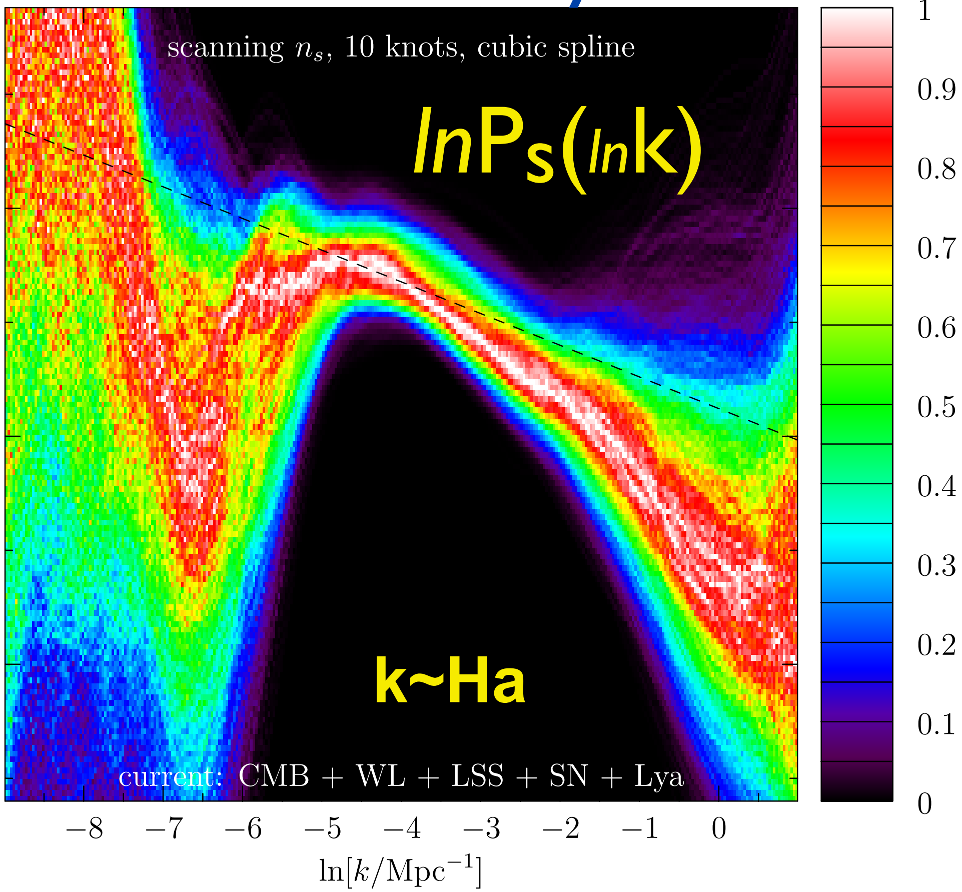
$1+w_0$ =.01+.05-.06 if w_a=0 current

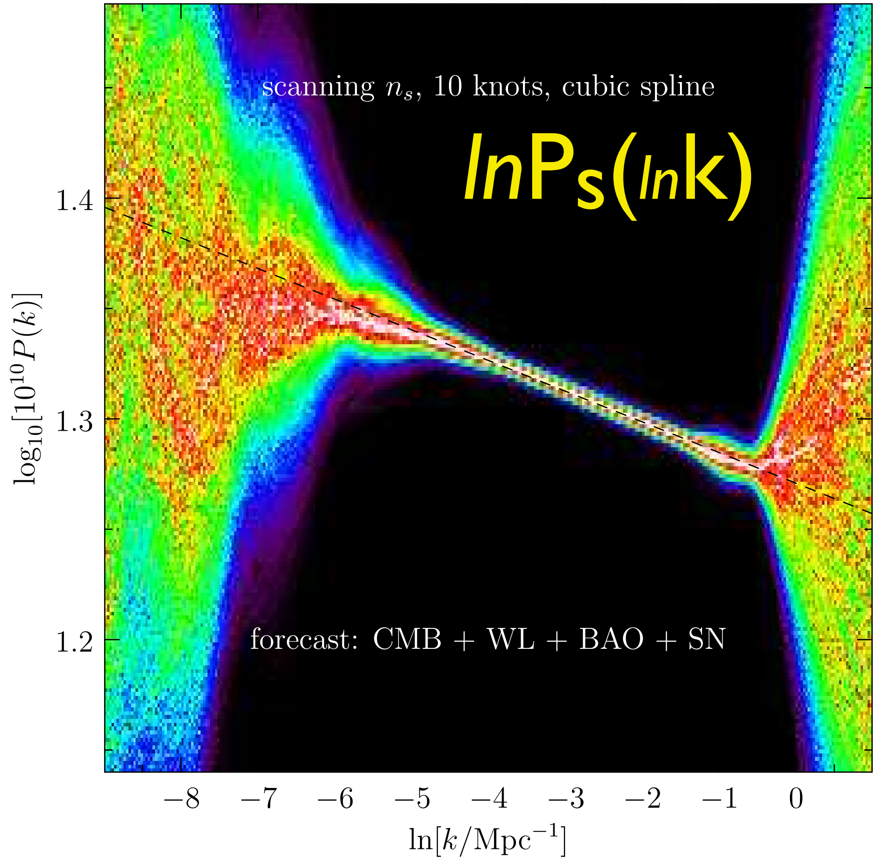
$1+w_0$ =.00+.01-.01 if w_a=0 future

future scalar power spectrum trajectories

scan **n_s**(*ln*k), *ln***A_s**=*ln*$P_s(k_{pivot,s})$, ***r***$(k_{pivot,t})$;

consistency => reconstruct **ε(*ln*Ha), V(ψ)**





$\varepsilon_\psi \approx \varepsilon$ = - d*ln*H / d*ln*a ; $V(\psi) \approx 3M_P^2H^2(1-\varepsilon/3)$; dψ/ d*ln*a = ±√ε

GW/S≡r ≈16ε

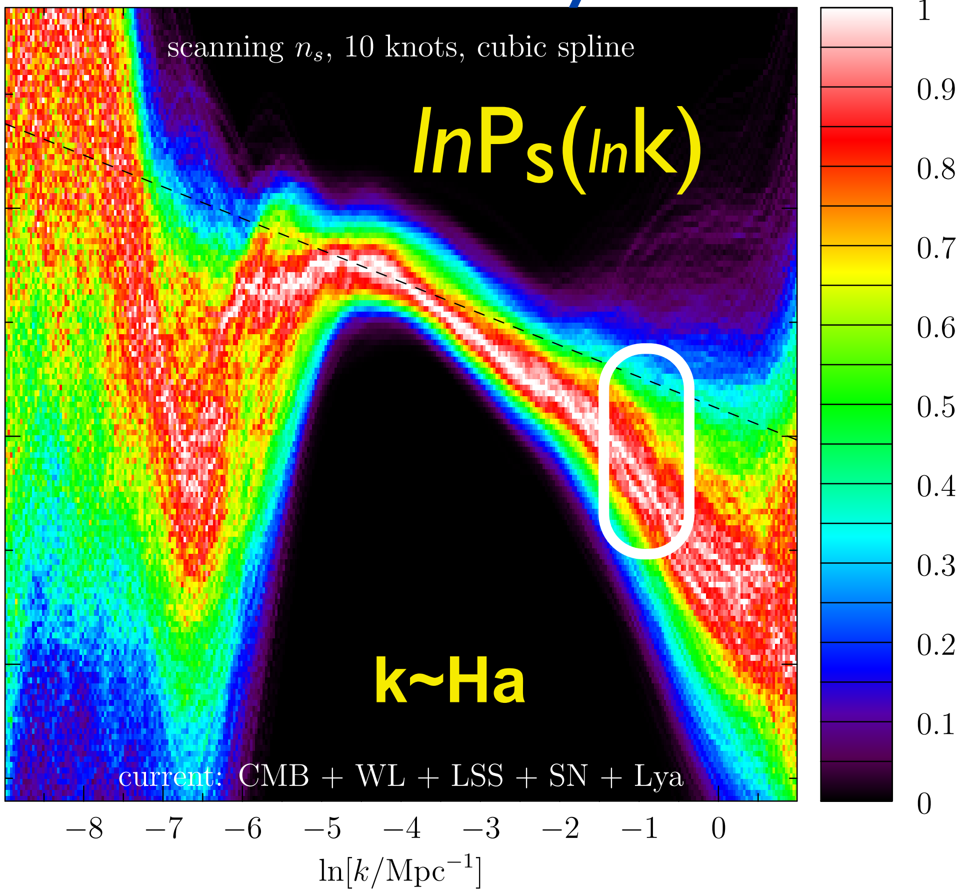
Bond, Contaldi, Huang, Kofman, Vaudrevange 2011

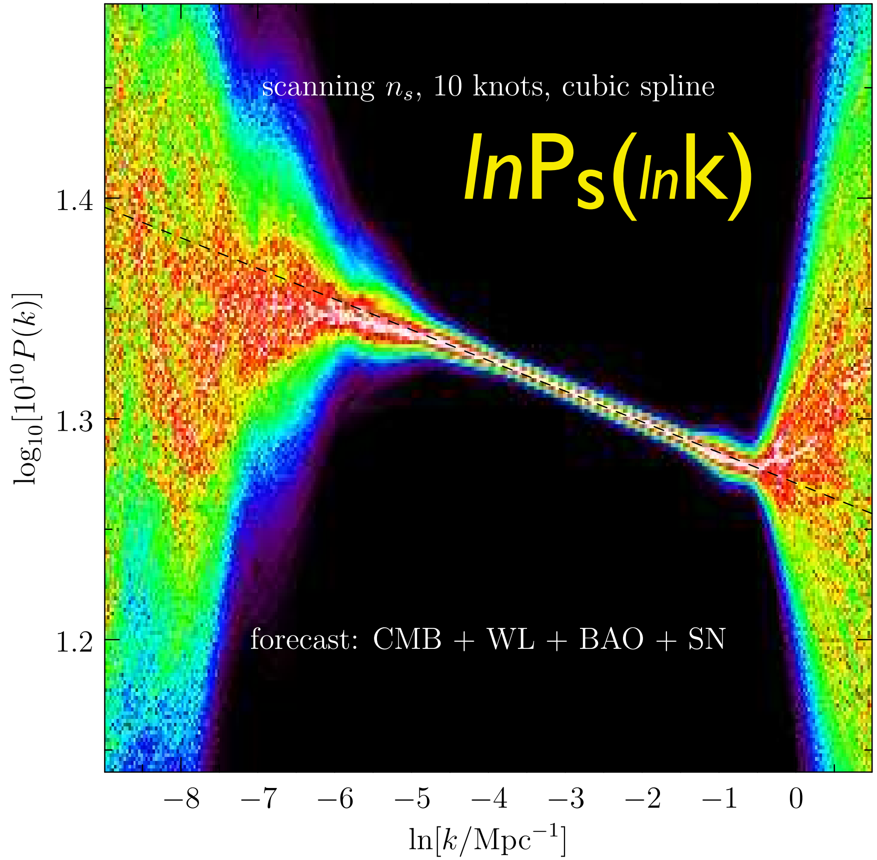
$r \approx 0.1 V / (10^{16} Gev)^4$

future scalar power spectrum trajectories

scan $\mathbf{n_s}(\ln k)$, $\ln \mathbf{A_s} = \ln P_s(k_{pivot,s})$, $\mathbf{r}(k_{pivot,t})$;

consistency => reconstruct $\varepsilon(\ln Ha)$, $V(\psi)$





$\varepsilon_\psi \approx \varepsilon = -\, d\ln H / d\ln a$; $V(\psi) \approx 3M_P^2 H^2 (1-\varepsilon/3)$; $d\psi / d\ln a = \pm\sqrt{\varepsilon}$

GW/S≡r ≈16ε

Bond, Contaldi, Huang, Kofman, Vaudrevange 2011

$r \approx 0.1 V / (10^{16} \mathrm{Gev})^4$

Standard Parameters of Cosmic Structure Formation

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$1+w_0, w_a$ $\theta \sim \ell_s^{-1}$ $n_e(a)$ $\sim \ln \sigma_8^2$

primordial non-Gaussianity

$\Phi(x) = \Phi_G(x) + f_{NL} (\Phi_G^2(x) - \langle \Phi_G^2 \rangle)$

local smooth

$-4 < f_{NL} < 80$ (+- 5 Planck)

+ subdominant

isocurvature, cosmic string,

& fgnds, tSZ,kSZ, ...

Standard Parameters of Cosmic Structure Formation

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bias modulation with a nearly scale invariant Φ_G out to R_{hor}

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$$\Phi(x) = \Phi_G(x) + f_{NL}\,(\Phi_G^2(x) - \langle \Phi_G^2 \rangle)$$

local smooth. use optimal pattern estimator

DBI inflation: non-quadratic kinetic energy

cosmic/fundamental strings/defects

from end-of-inflation & preheating

$$\Phi(x) = \Phi_G(x) + F_{NL}(\chi_b) - \langle F_{NL} \rangle$$

resonant preheating f_{NLeff} + cold spots

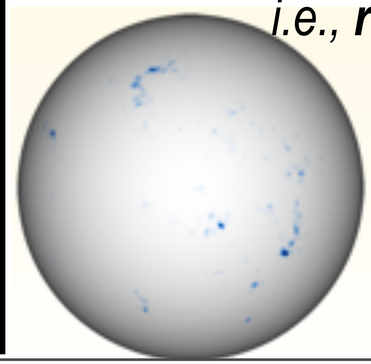
$-4 < f_{NL} < 80$ (+- 5 Planck)

CMB peaks (hot&cold)

=> the WMAP Cold Spot

clusters are frequency-matched cold/hot spots

i.e., ***rare event nonG tails***



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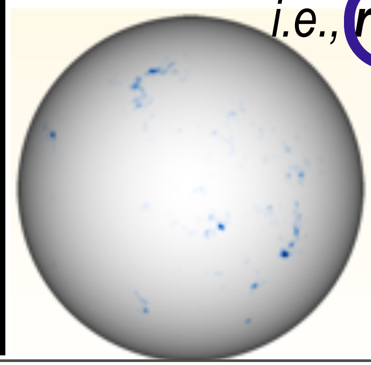


CBI ongoing to Sept'05

Acbar ongoing to Sept'06+

Bicep

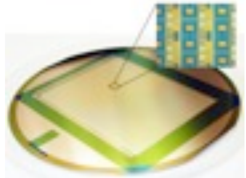
QUaD

Quiet1

Quiet2
(1000 HEMTs)
Chile

APEX
(~400 bolometers)
Chile

SCUBA
(12000 bolometers)



SZA
(Interferometer)
Owens Valley

ACT
(3000 bolometers)
Chile

2015
CMBpol

2003 2005 2007

2004 2006 2008

WMAP ongoing to 2007+

Polarbear
(300 bolometers)
California

POLARBEAR

SPT
(1000 bolometers)
South Pole

ALMA
(Interferometer)
Chile

Planck
(50 bolometers)
L2

October 2004, The Future of Physics, KITP, UC Santa Barbara, The Phenomenology of Dark Energy and Cosmic Acceleration

CBI pol to Apr'05 @Chile **CBI2**

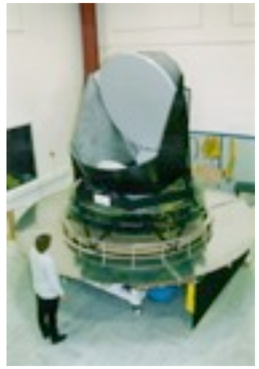
53+35 cls **(>=40)**

QUaD @SP

189 +10 **cls (>=1000)**

Planck09.4

52+ bolometers
+ HEMTs @L2
9 frequencies



WMAP @L2 **to 2010**

2004 2006 2008 **LHC** 2011

Bpol @L2

2005 2007 **21+26~50 (>=750)** 2009

Acbar@SP
~1 blind

>96

OVRO /BIMA array

38 cls

SZA@Cal

3 cls (z>1), x?

AMIBA

6 cls

AMI

7+1 cls >=50+25

APEX
~400 bolos@Chile

~25 cls

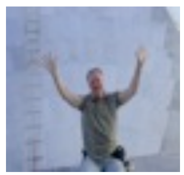
GBT

4 cls (~25 CLASH)

SPT
1000 bolos
@SPole

ACT **23+27~50 cls**

3000 bolos
3 freqs @Chile



SCUBA2
12000 bolos
JCMT @Hawaii

80s-90s
Ryle
OVRO

SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico

in praise of ***mocking the cluster/gp system*** *with increasing sophistication: Monte Carlo selections, contamination of probes,* $\boldsymbol{n_{cl}}$ *(what's happening, Mass++), & ... MC mock-observations & systematics*

cluster near, intermediate (> r500) & far (>r200) field

internal bulk flows aka turbulence

ratty edges from filament inflow

anisotropy ≠ spherical

line of sight contaminants for cylindrical measures

clumping, subhalos, ...

radio galaxies / AGN / BCG inside

other galaxies inside

background galaxies

short distance complexities in a coarse-grained world

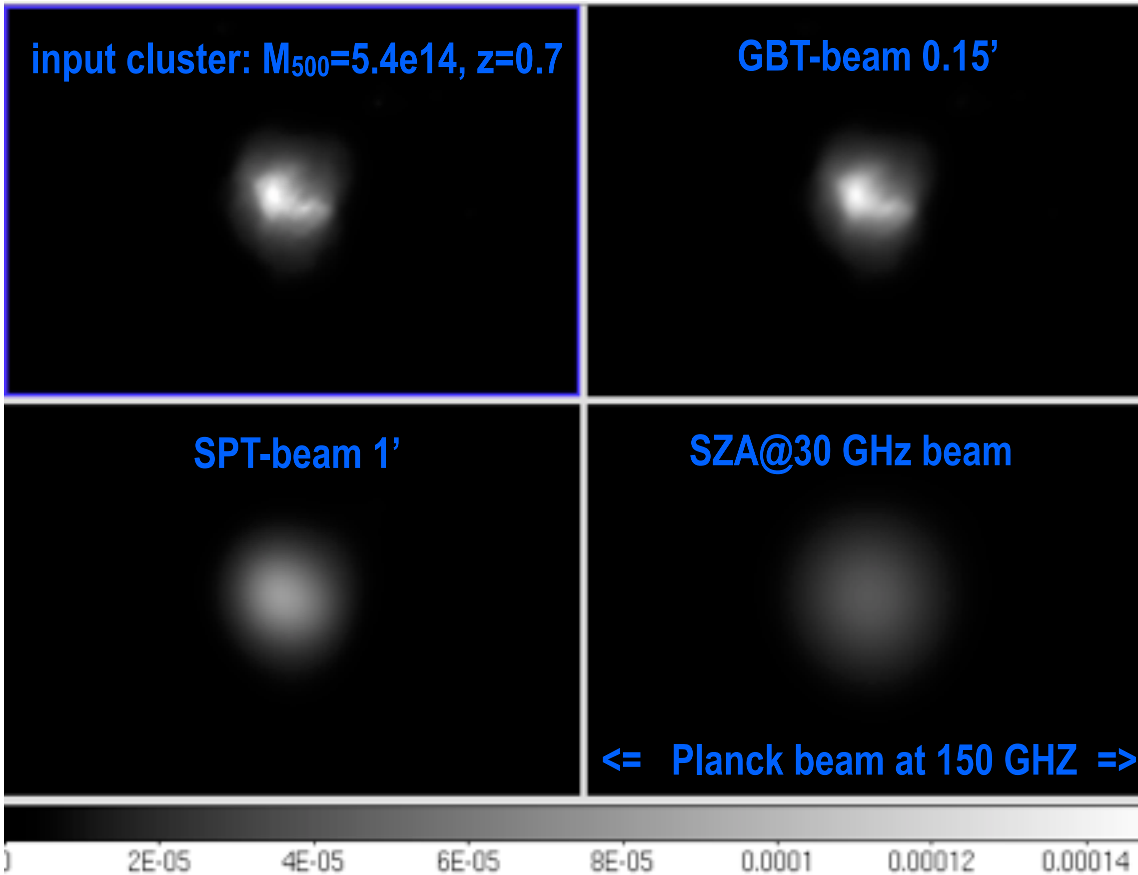
@Monsters Inc: good movement in this direction, e.g., ACT, Planck, SPT, DES, X..., an industry arises, Mockers Inc.

need: fast + numerous MC, but informed by high res full simulations

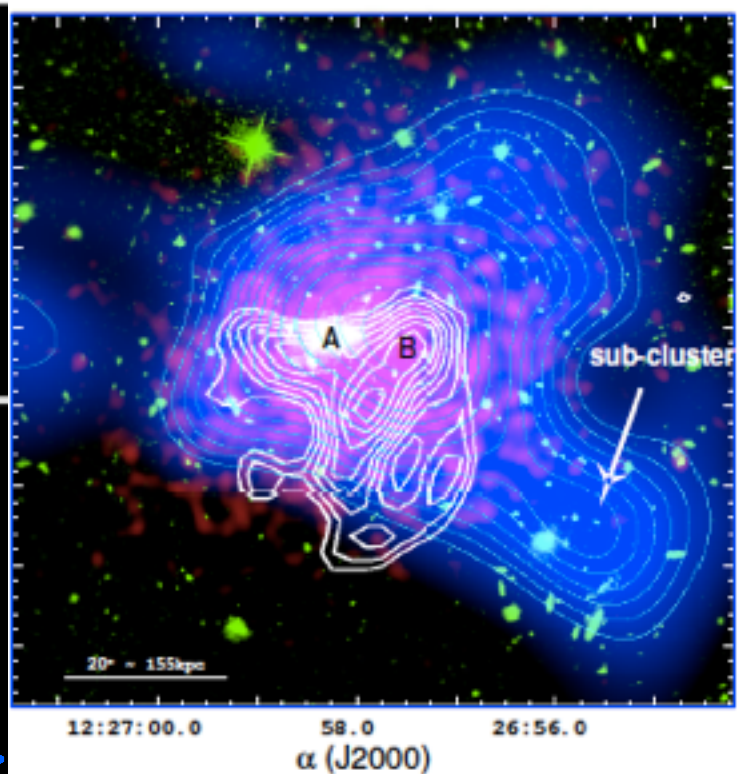
beware, although DM-dominated the gas/stars are - of course - highly biased inside the clusters, painting/splattering dark matter halo potential wells (e.g., $\mathbf{p_e}(\Phi_N(x))$ can never be accurate; e.g., DM ellipticity >> gas ellipticity

Mustang on GBT 90 GHz 64 bolometer array Imaging SZ @~10” res 4 cls 2010, ~25 Hubble CLASH cls to come Devlin, Mason, ...

future: High-Res SZ sim for MUSTANG2



now: CL1226 z=0.89



Red Chandra

Blue/cyan weak lens Σ

Green optical

White MUSTANG SZ >3σ

A BCG ~ X-ray peak

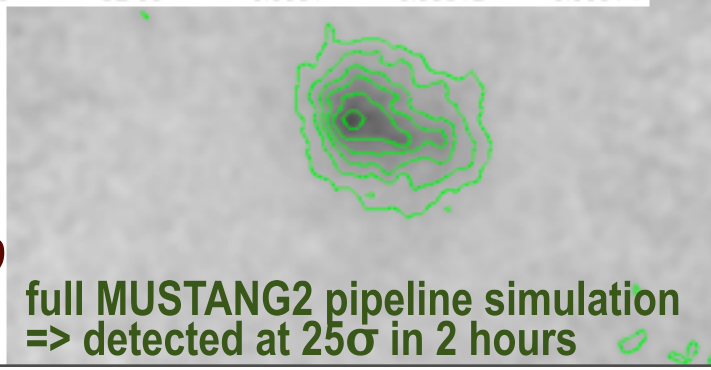
B Dark Matter peak

~ lobe of SZ ridge

100x mapping speed!

160 cf. 64 pixels, over larger area (5’ vs. 40”)

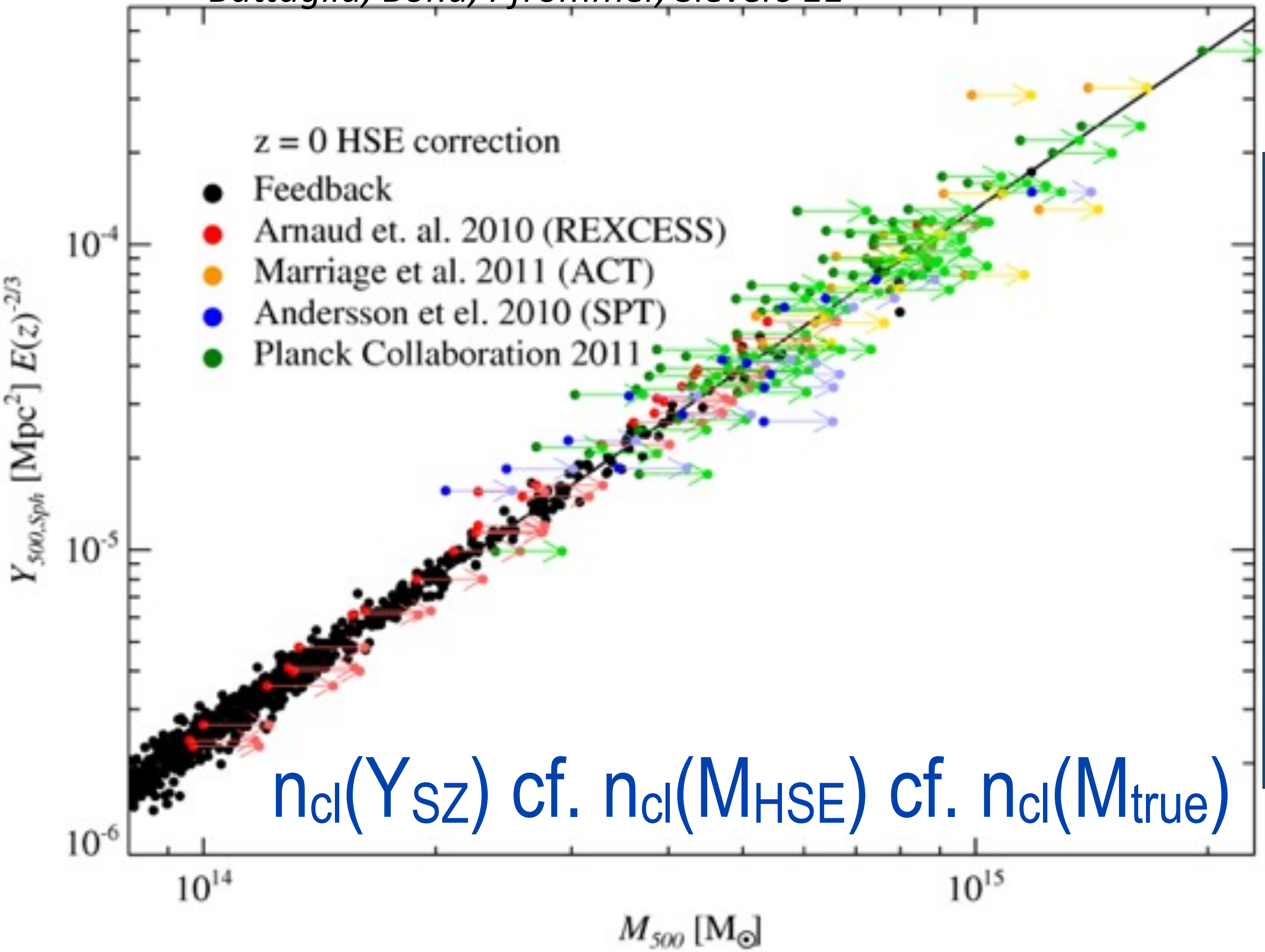
=> Planck followup to 35σ in 1hr



$Y(<r_\Delta)$-$M(<r_\Delta)$ relation, *where*

$M(<R_\Delta)/V(<R_\Delta)=\Delta\,\rho_{crit}$, Δ=2500, 500, 200

Battaglia, Bond, Pfrommer, Sievers 11



$n_{cl}(Y_{SZ})$ cf. $n_{cl}(M_{HSE})$ cf. $n_{cl}(M_{true})$

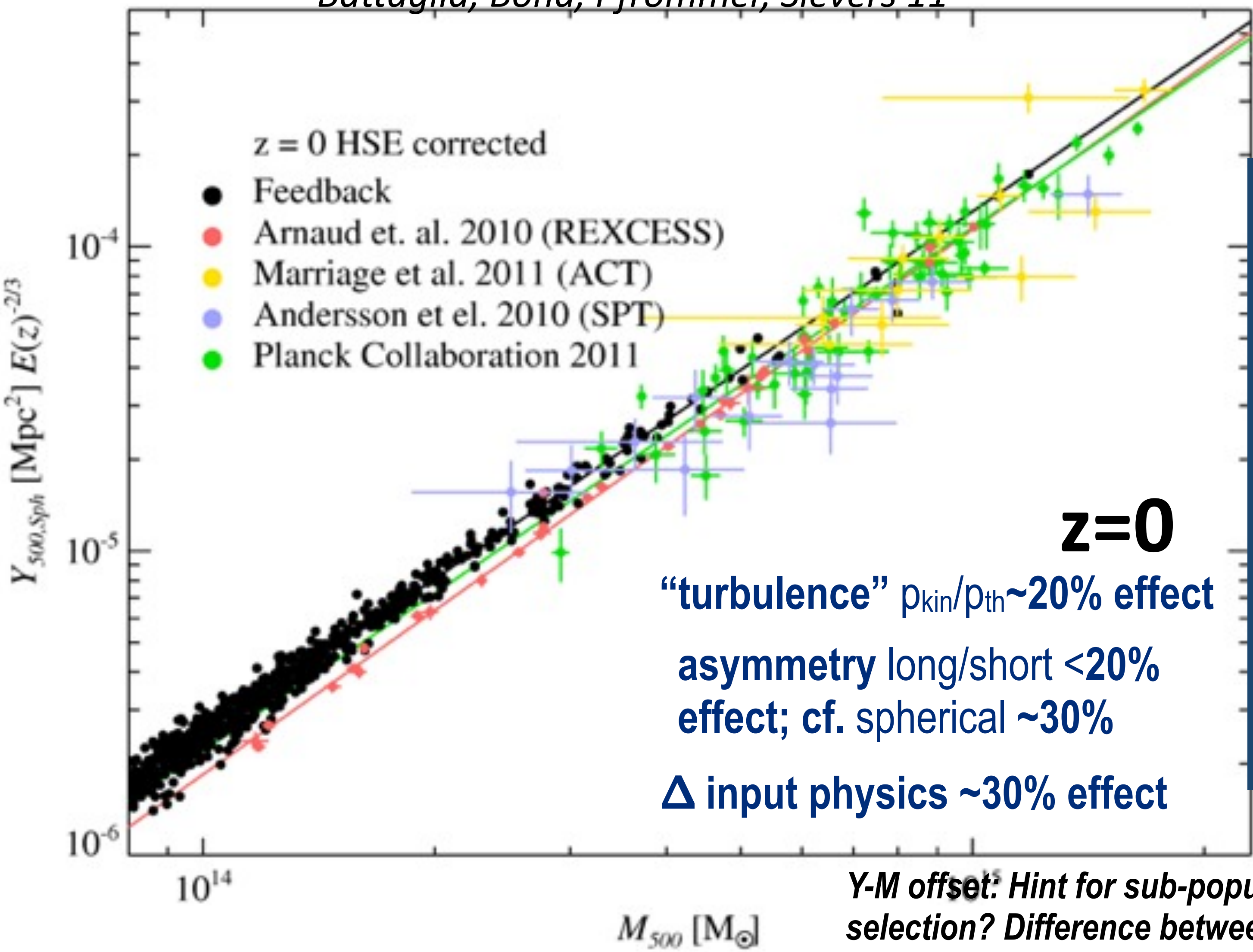
Planck-ESZ gives $\mathbf{Y_{5R500}}$

is Y_{SZ} a good mass proxy in $n_{cl}(M, z)$?
even though virial theorem $Y(e,K/U,\ldots|M)$
=> $n_{cl}(Y, z)$

$Y(<r_\Delta)$-$M(<r_\Delta)$ relation, *where*

$M(<R_\Delta)/V(<R_\Delta)=\Delta\,\rho_{crit}$, Δ=2500, 500, 200

Battaglia, Bond, Pfrommer, Sievers 11



z=0

"turbulence" p_{kin}/p_{th}**~20% effect**

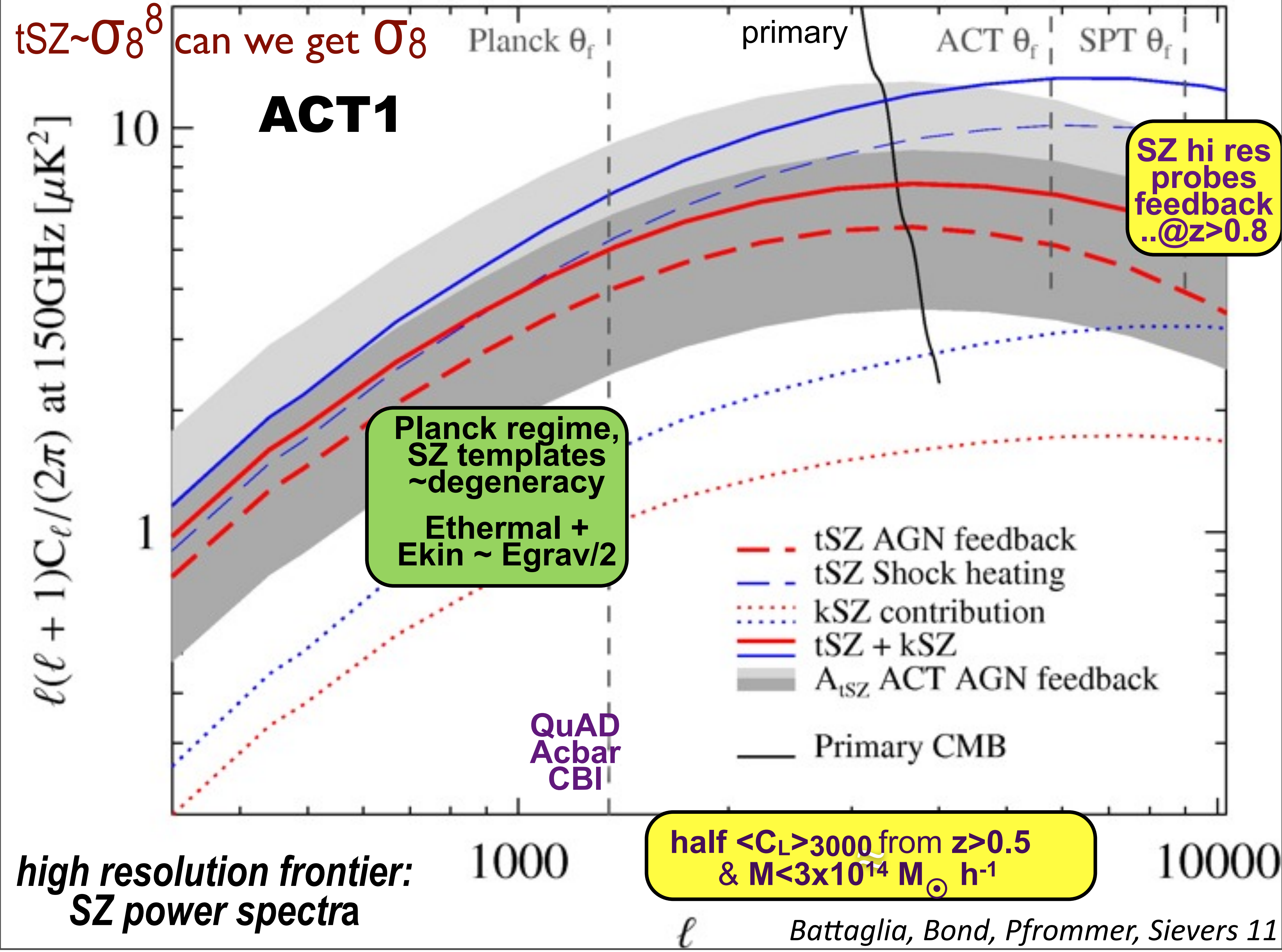
asymmetry long/short **<20% effect; cf.** spherical **~30%**

Δ input physics ~30% effect

Planck-ESZ gives $\mathbf{Y_{5R500}}$

is Y_{SZ} a good mass proxy in $n_{cl}(M, z)$? even though virial theorem Y(e,K/U,...|M) => $n_{cl}(Y, z)$

Y-M offset: Hint for sub-populations? Optical selection? Difference between Mx & MLens & Mbias?...


tSZ~σ8^8 can we get σ8
ACT1
Planck θf
primary
ACT θf
SPT θf
SZ hi res probes feedback ..@z>0.8
10
1
ℓ(ℓ + 1)Cℓ/(2π) at 150GHz [μK²]
Planck regime, SZ templates ~degeneracy
Ethermal + Ekin ~ Egrav/2
tSZ AGN feedback
tSZ Shock heating
kSZ contribution
tSZ + kSZ
AtSZ ACT AGN feedback
Primary CMB
QuAD
Acbar
CBI
1000
10000
ℓ
half <CL>3000 from z>0.5 & M<3x10^14 M⊙ h^-1
high resolution frontier: SZ power spectra
Battaglia, Bond, Pfrommer, Sievers 11

$n_s(k)$, GW $r(k)$, nonG f_{NL}++, $\rho_{de}(t)$, m_ν, strings, isocurvature, ...

near-future cosmology => PlanckEXT

EXT=many observatories & expts enabling the cosmology/astro

XMM Herschel Fermi WMAP GBT BLAST ACT SPT AMI CBI CBASS QUIET SDSS IRAS CO/HI-maps, ...

ACTpol, SPTpol, eRosita, PanStarrs, DES, LSST, Mustang2, CCAT, *ABS, Spider, EBEX, Keck, ...* $\subset$ **EXT**