Dick Bond CITA

CMB@50 THEN & NOW & THEN

a celebration

early theory for the **CMB**

60s / 70s of PJEP, SZ, Silk of CMB damping, CMB polarizing Rees, ++,

who lived in a baryonic world

modulo Peebles & Ostriker ++

DM emergence *- to full blossom in the 80s*

HZP n=1 'natural' curvature spectrum early Universe quanta

- Starobinsky GW, Mukhanov phonons general equations of state, including inflation

…. then scalars

1980-82 hot, warm, cold

the **CDM miracle**:

West hierarchical galaxy clustering => isocurvature

East => natural adiabatic => superclustering

'pancake theory'

CDM turns HSZ n~1 adiabatic into the West's hierarchical picture, with superclustering => interconnected Cosmic Web

ΔT/T drops by > 10, experimentalists persevere

Delta T over Tea Toronto May 1987: first dedicated CMB conference, exptalists+theorists, primary+secondary ΔT/T

A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

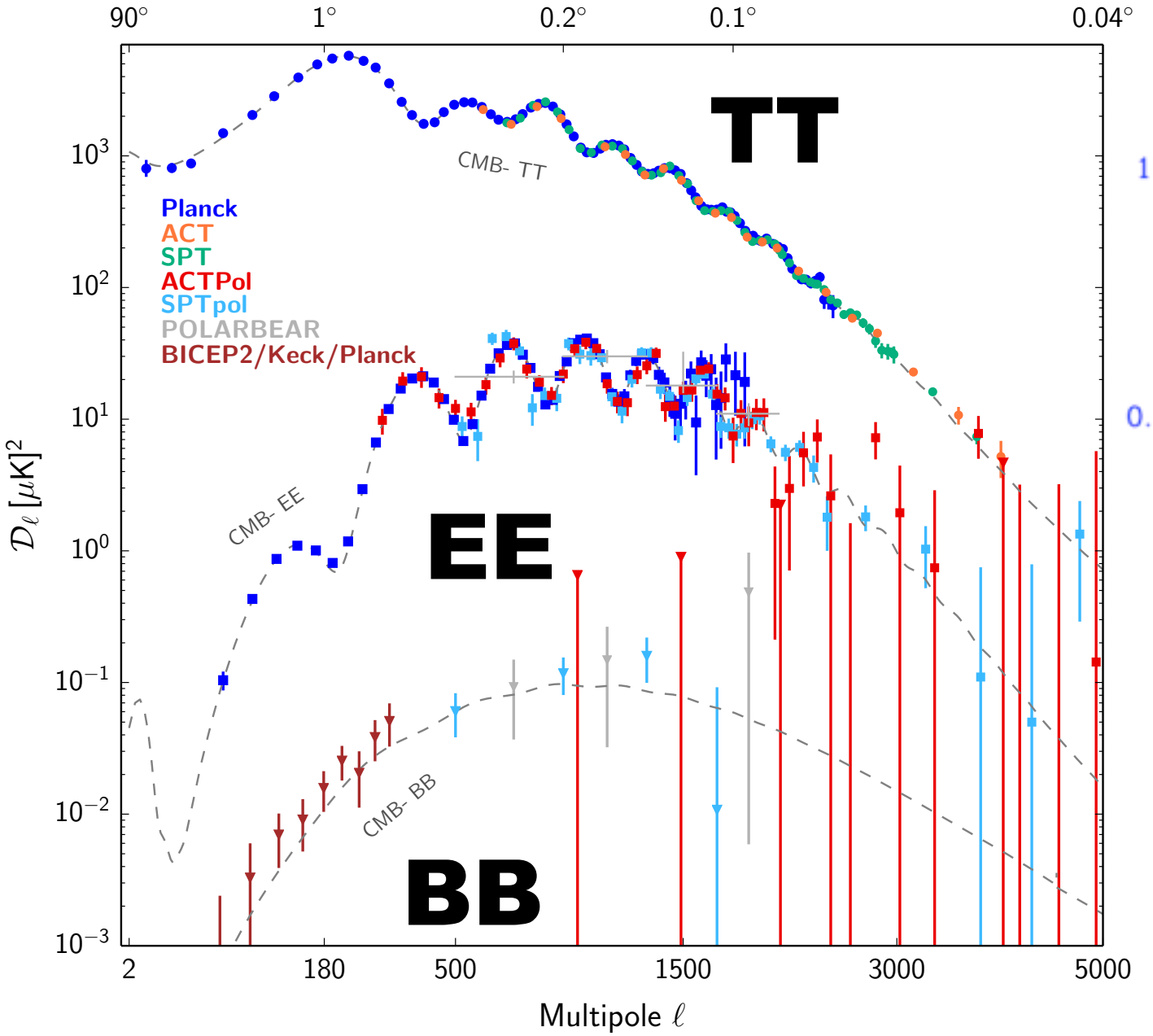
- very small angle anisotropies - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources
- small angle anisotropies - current results, optimal measuring strategies, statistical methods for small signals in larger noise, which universes can we rule out, the reheating issue, future detectors and techniques, CMB map statistics, polarization
- intermediate and large angle anisotropies - $5^o - 10^o$ results, future experiments at $\sim 1^o$, COBE and other large angle analyses, theoretical $C(\theta)'s$ and their angular power spectra, Sachs-Wolfe effect in open Universes, the isocurvature CDM and baryon stories, $\Delta T/T$ from gravitational waves, the cosmic string story.

1997 Princeton @ 250 cobe, heterogeneous CMB + LSS, but before SNe Lambda

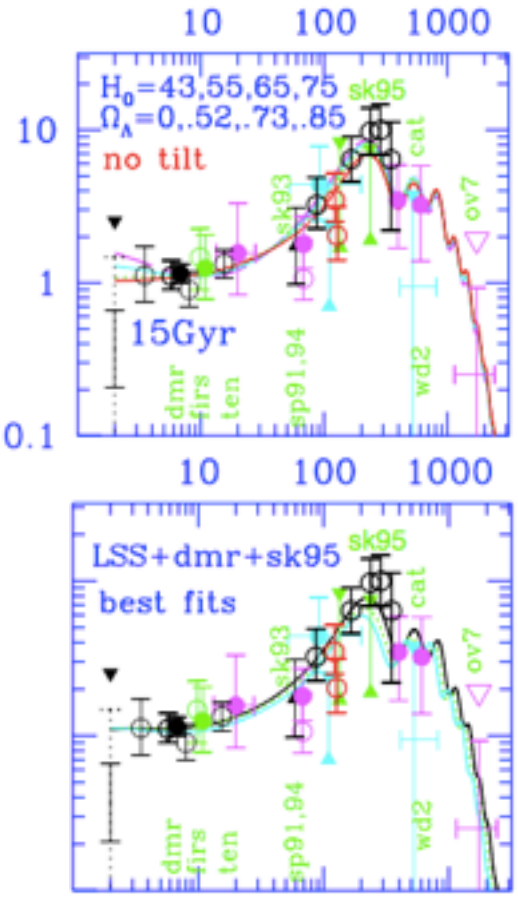
"We rightly celebrate Princeton's pivotal role in all this, over a full eighth of its venerable age, from background detection through tight distortion constraints, from the downward march in $\Delta T/T$ limits to discovery at large angles, then small, punctuated by decades of seminal theory, a MAP in the near-future and undoubtedly much beyond."

early 00's: the 7 pillars of the CMB, pre-WMAP1 .. all but GW; then WMAPext, then … Planck, ACT, SPT, Bicep/Keck, ..

Grand Unified CMB Spectra



cf. Princeton@250 1997



Erminia Calabrese for Planck

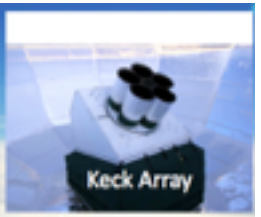
Atacama

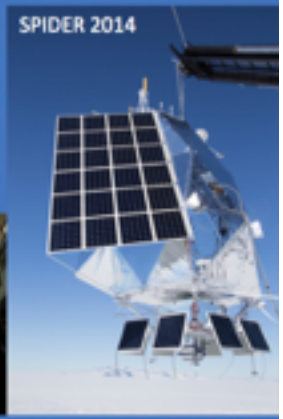
California+
South Africa
C-BASS 5 GHz

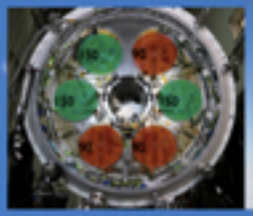
Tenerife (+South Africa?)
QUIJOTE 11, 13, 17, 19 GHz
(2015/16 - 30, 40 GHz)

California
B-Machine 40 GHz

South Pole







Antarctic balloons

& futures S4, more ballooning, back into space

managing the CMB

on to Stage IV CMB

Advanced ACTPol

boomerang ~40/paper

planck

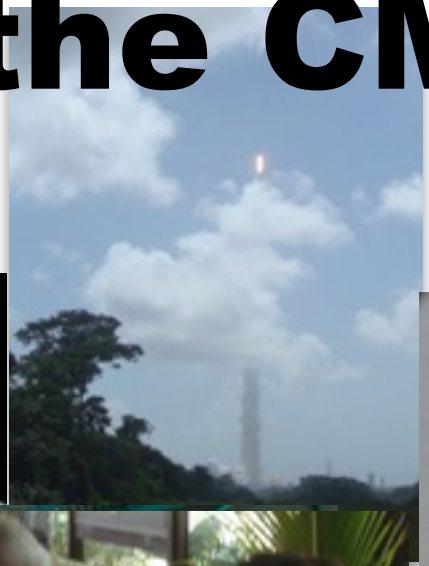
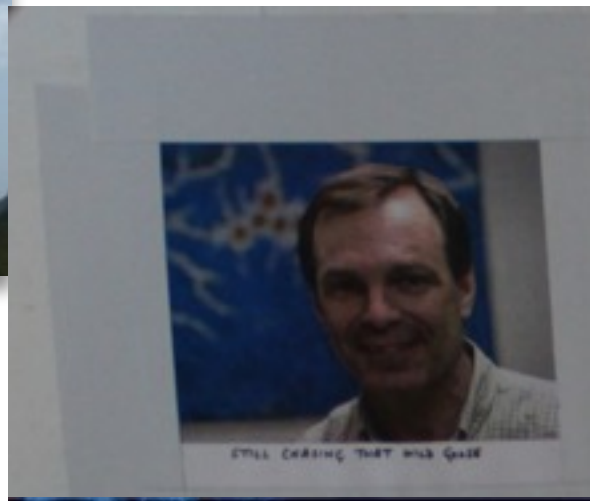
~250/paper, ~100 institutions

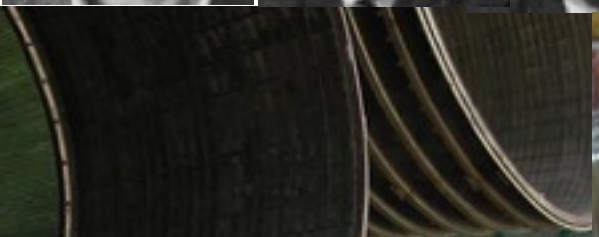
SPIDER

emotion in the CMB

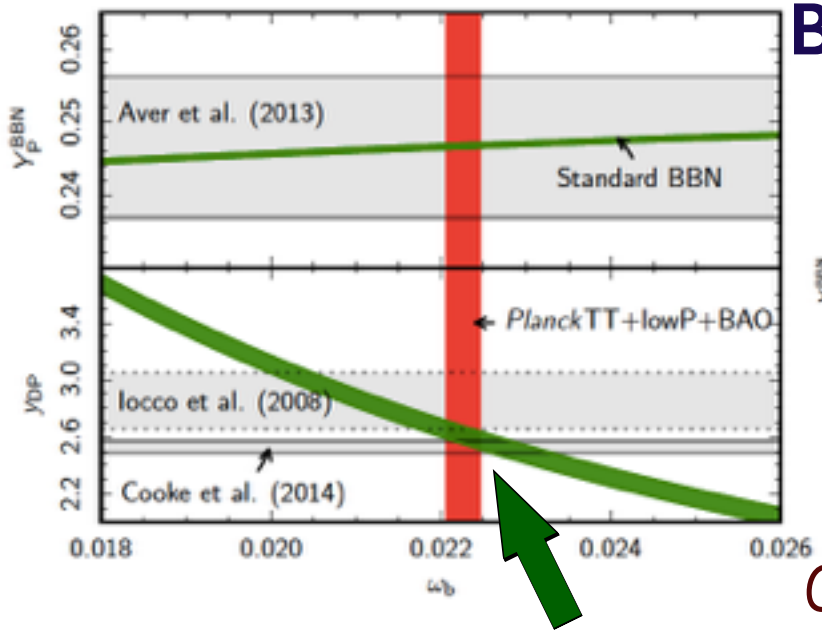






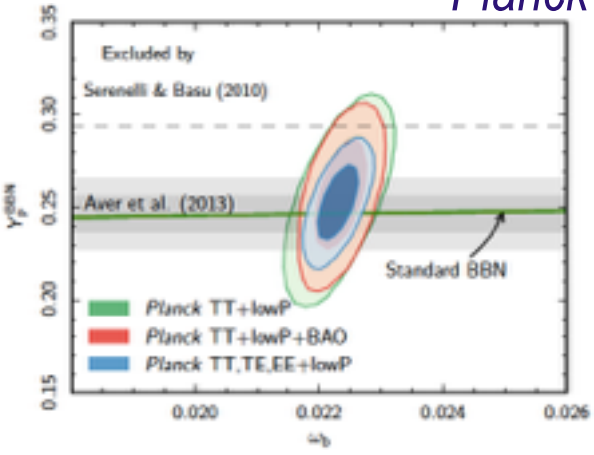
the **accuracy of CMB precision** - priceless



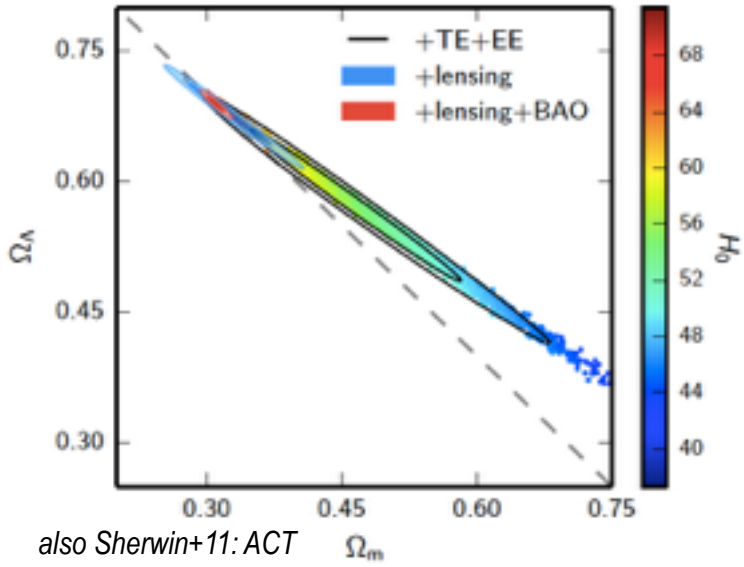
Baryometers

0.02229 +- 0.00033

Planck15 TT,TE,EE +loP+BAO



*CMB **lensing breaks "geometrical degeneracy":***
Planck alone cf. Planck+BAO



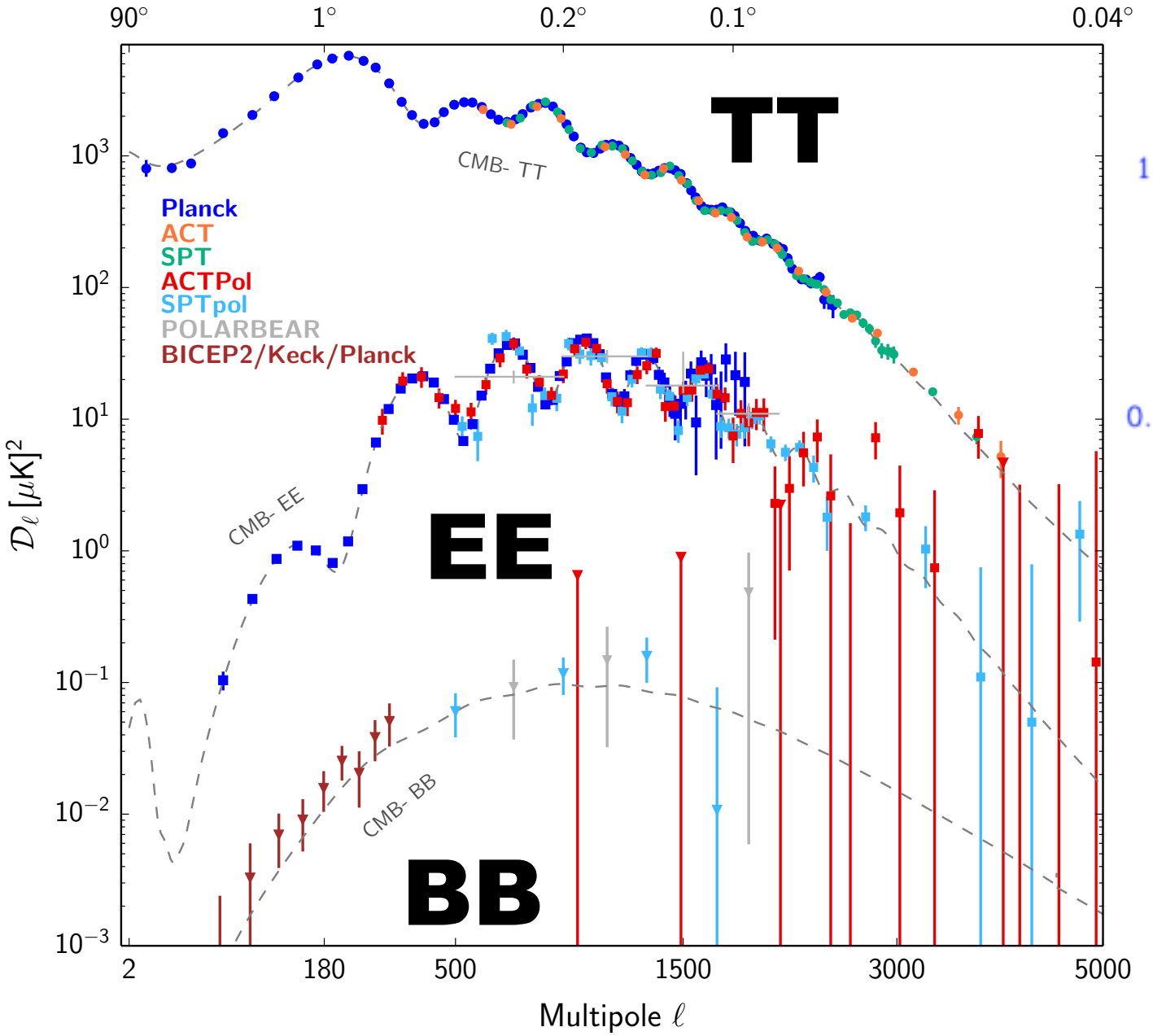
also Sherwin+11: ACT

we celebrate
baryonic matter from the CMB alone
dark matter from the CMB alone *SDMW 80σ, & EE alone*
dark energy from the "CMB alone"
& the emergence/successes of CMB lensing 40σ
Jo Dunkley: 'Lensing shows great potential'

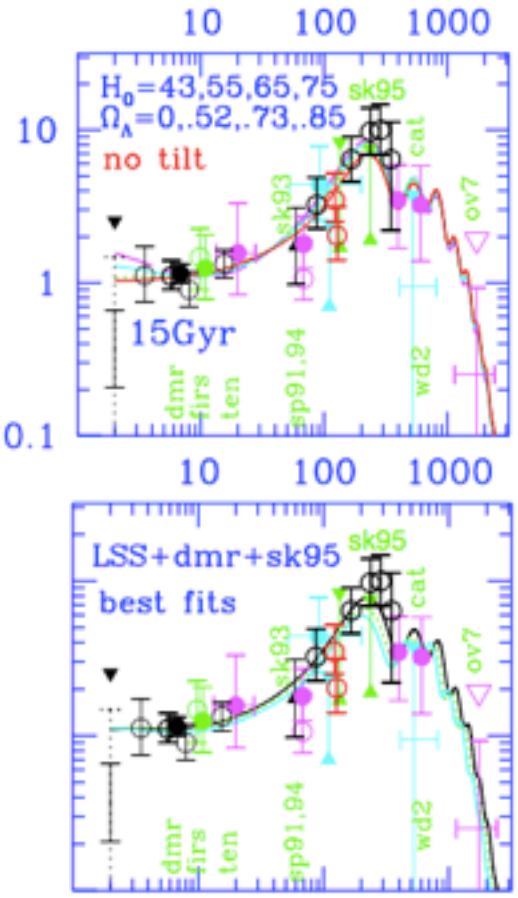
George Efstathiou: 'We were Spergeled'
to be spergeled is a positive verb, e.g., for ACTers ++

Bond to Efstathiou re the Parameter Paucity of the Universe:
'It's not nice to tell Mother Nature what to do'

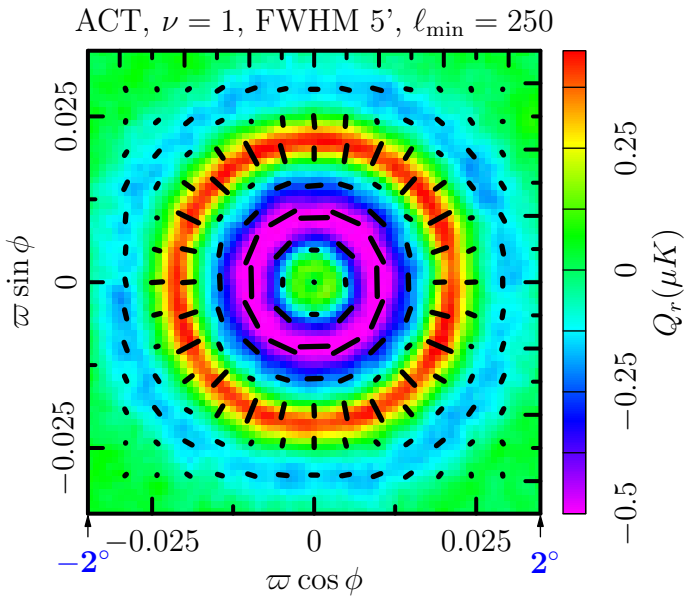
Grand Unified CMB Spectra

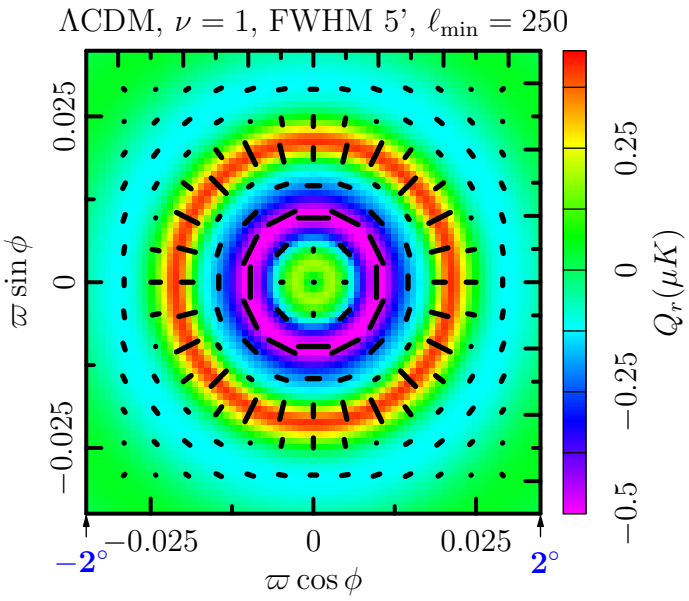


cf. Princeton@250 1997



Erminia Calabrese for Planck

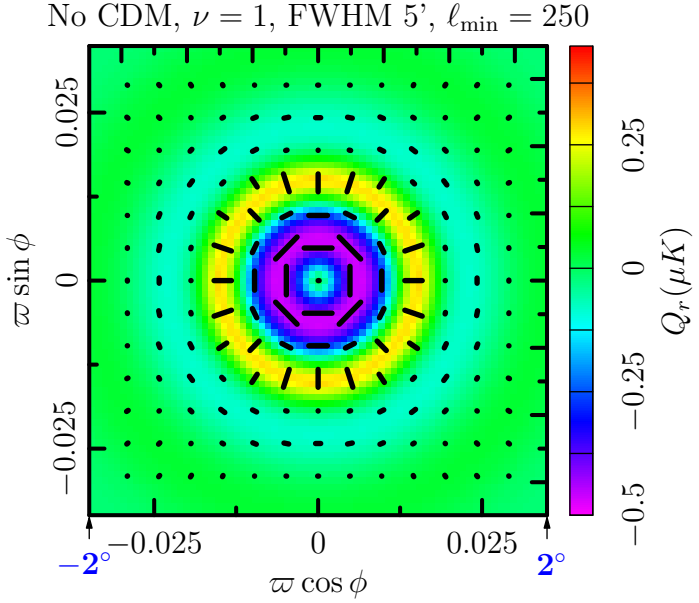


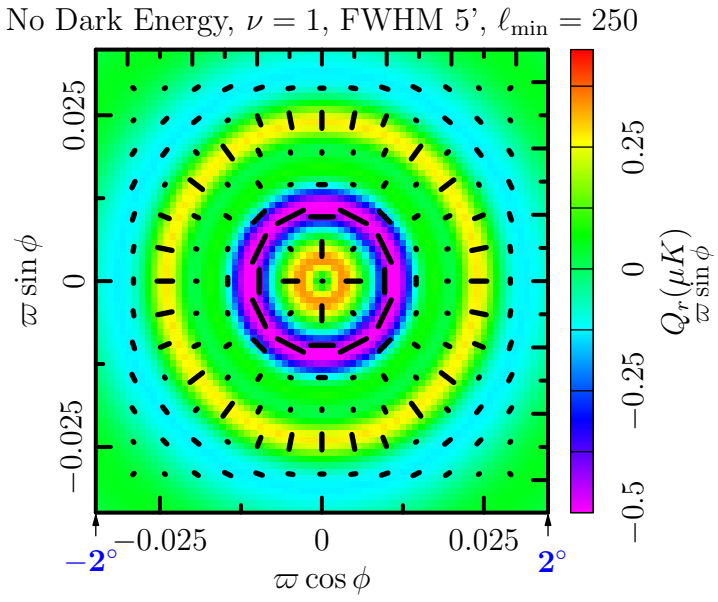


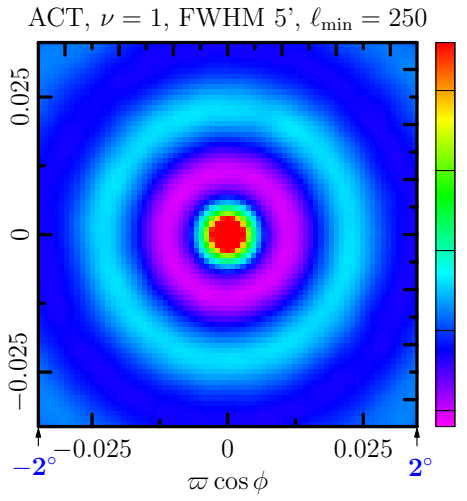
Stacking rotated polarization on field points (ACTpol data)

complementary view to 2D power spectrum,

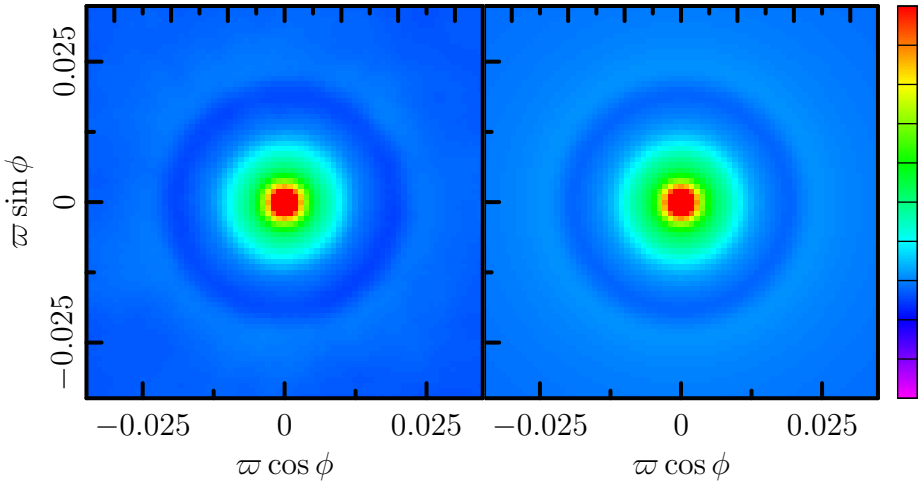
you select the points to stack on



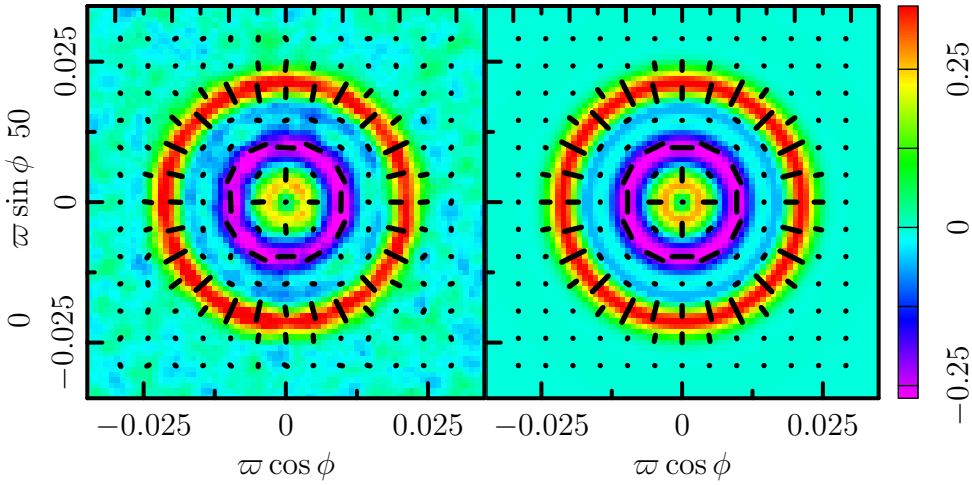




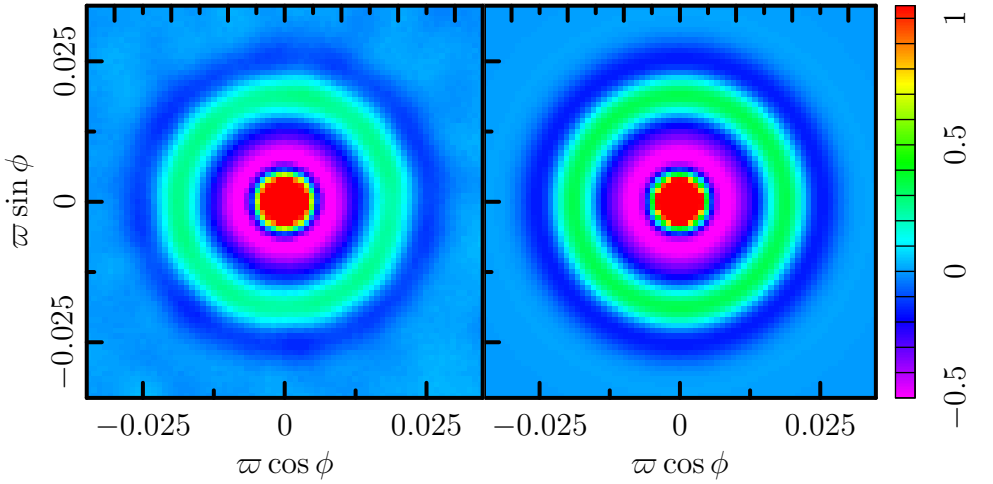
P15 T on T peaks



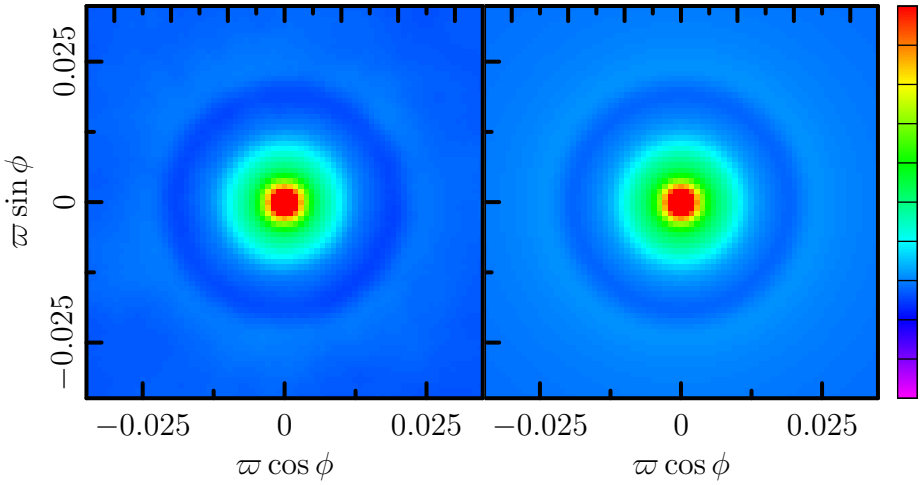
P15 Q_r on T peaks



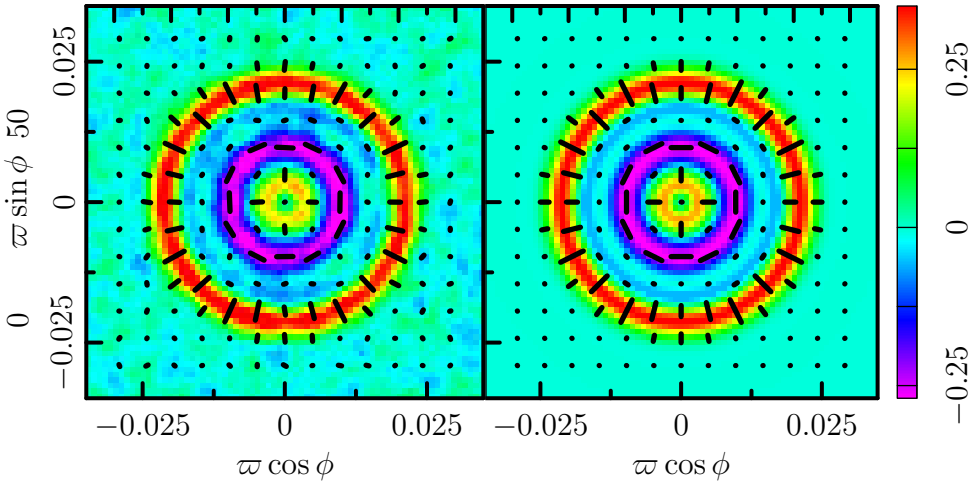
P15 E on E peaks!



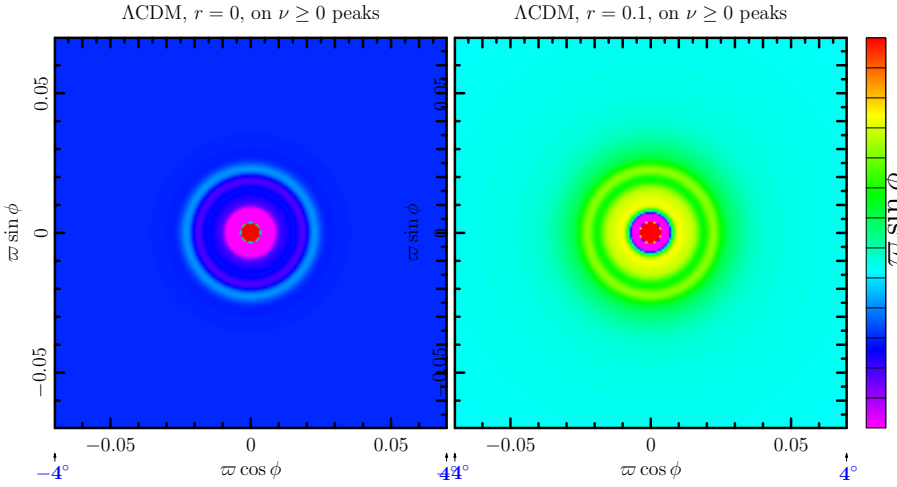
P15 T on T peaks



P15 Q_r on T peaks

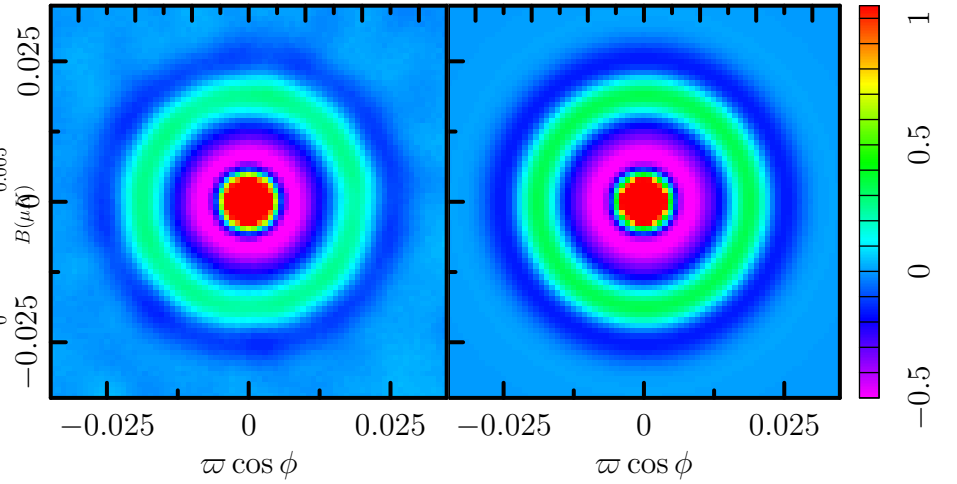


near + far future? B on B peaks noise-free dust-free sim



r=0 r=0.1

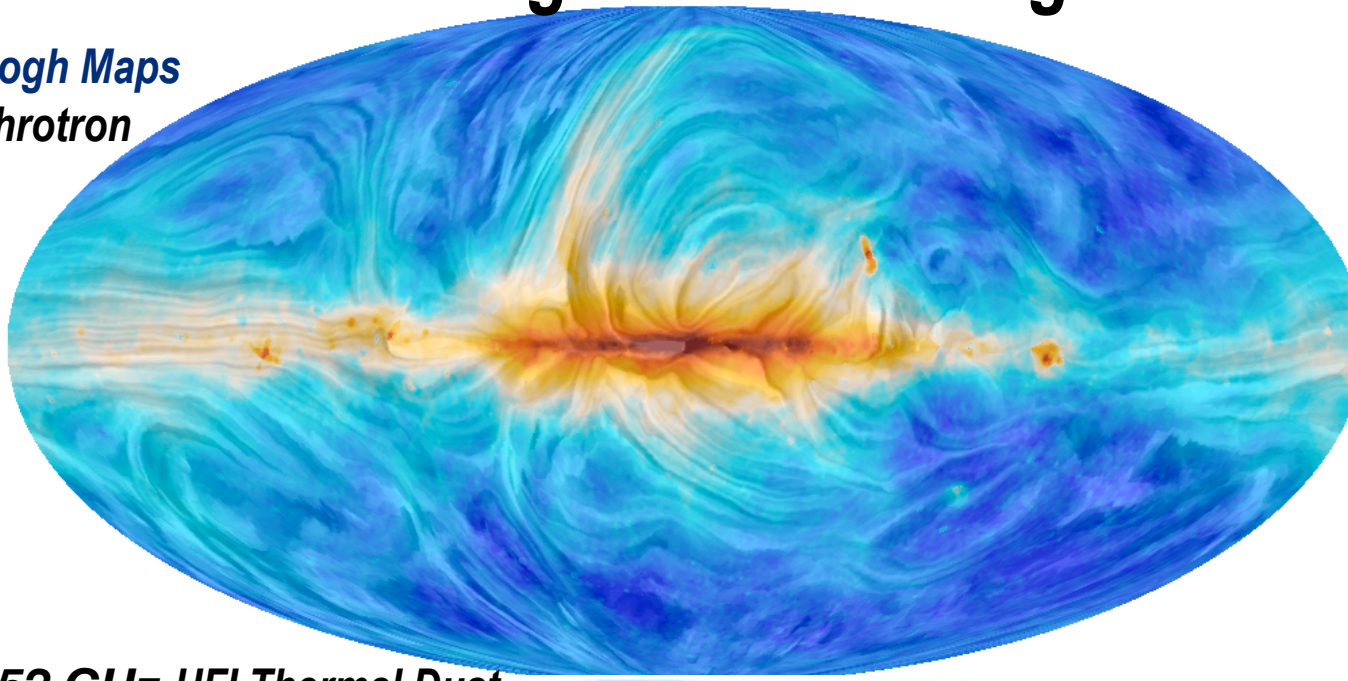
P15 E on E peaks!

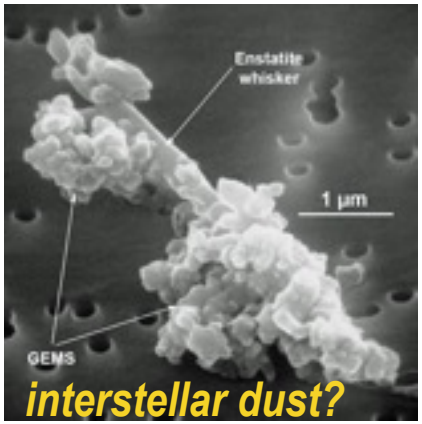


the gritty face of the CMB - foreground challenges

Planck T/P Combined van Gogh Maps

30 GHz LFI Synchrotron





interstellar dust?

our dusty pol dilemma

353 GHz HFI Thermal Dust

dust is complex, will be multi-Temp

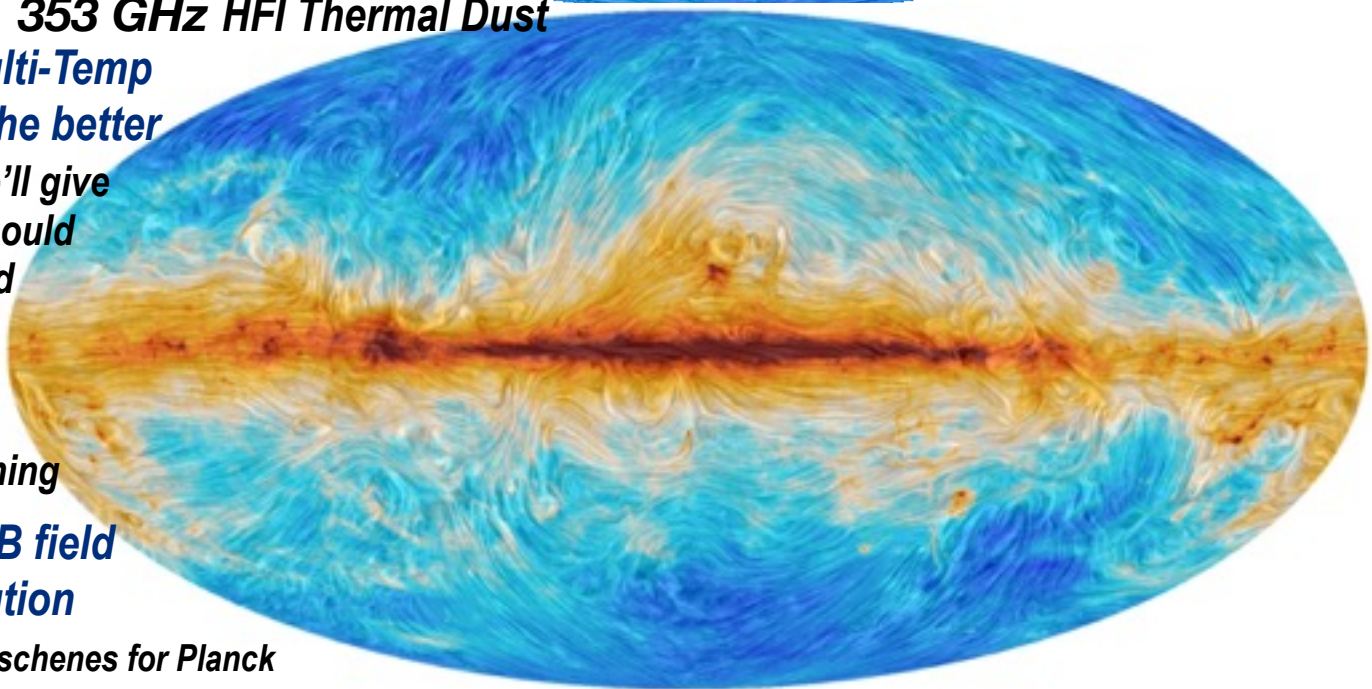
& .. => the more channels the better

PIXIE: *Fixsen paraphrase "we'll give you 400 dust channels, you should be able to come up with a good dust model over a weekend"*

=> PIXIE as/is an ISM machine

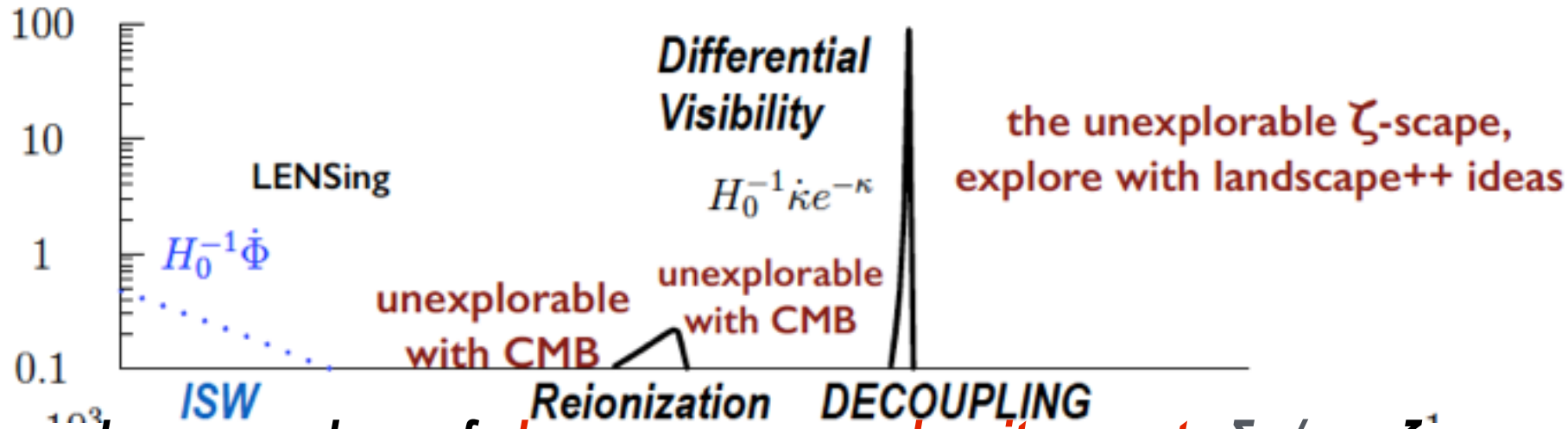
Planck was/is an ISM machine

=>CORE+++, LiteBIRD, ballooning



Polarization used to follow B field using Line Integral Convolution a directional "flow" *miville deschenes for Planck*

the ζ-LAND-**scape** from the **CMB**



a phenomenology of phonons = energy-density quanta δρ/ρ ~ ζ
<=> quanta of isotropic volume δVol / Vol ~ ζ

relativistic negative-pressure Equation of State (1+w)

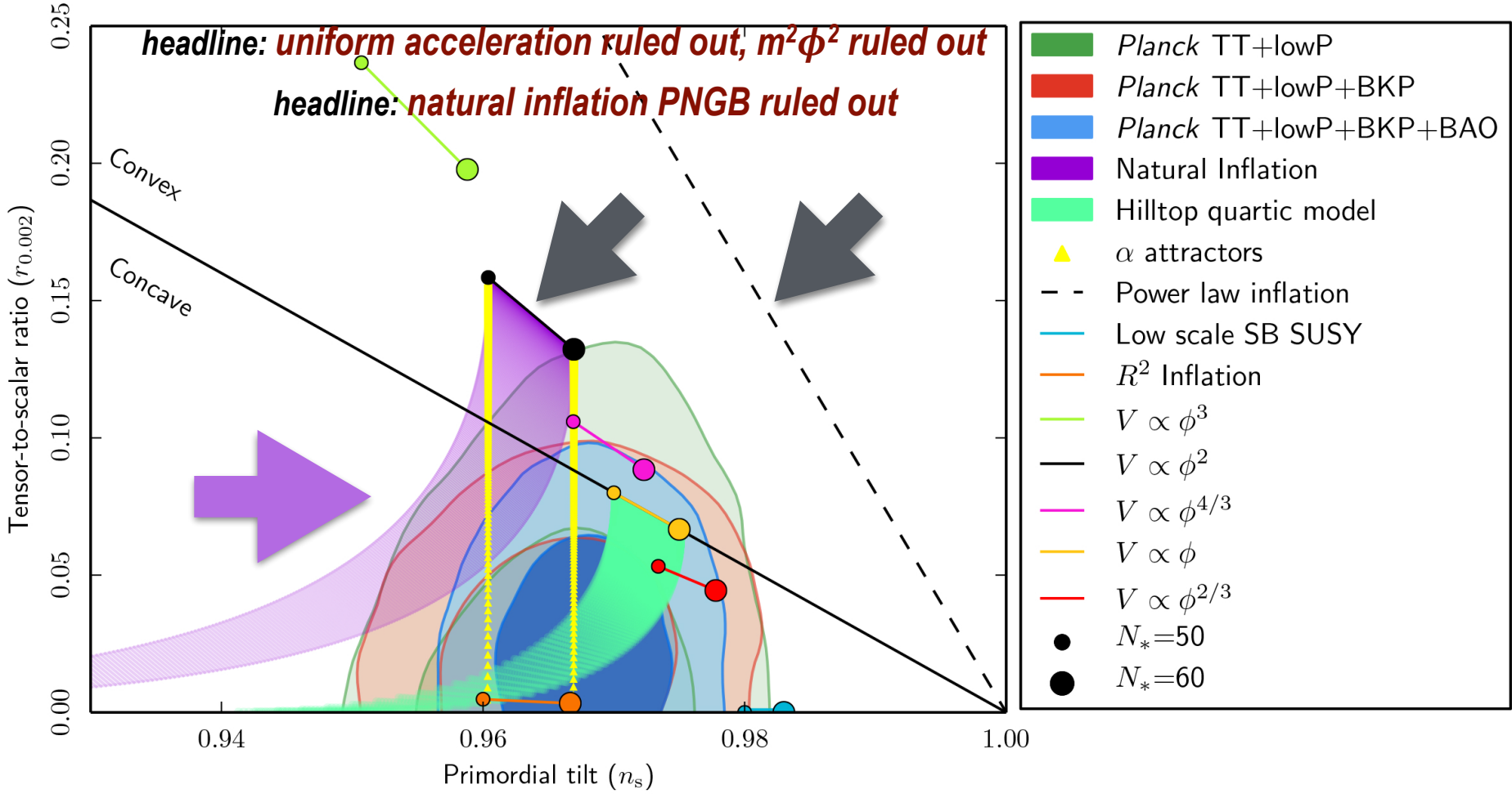
phonon = collective mode composed of fundamental scalar fields? w <=> V

comments re Fri AM discussion: U seems to be inflating now, Higgs seems to be a fundamental scalar => Mother Nature likes the ingredients. nonlinear feedback of fluctuations <=> "background". do we need a Landscape? genie is out of the bottle

phenomenology of gravitons = Transverse_Traceless_Strain quanta Prior on r ~ flat now

phenomenology of isocons = quanta ⊥ phonons (curvatons ...), entangled ... => HEAT

all that CMB+LSS can deliver is this phonon+ /strain+ Phenomenology. accelerate <=> inflate
how does it 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 if ever



key figure in WMAPn, Planck 2013, Planck 2015, …

P15+BKP r<0.09 uniform n_s

cf. **0<r<.11 95%CL P15+BKP 12 knots**

near-degeneracy broken by BB

cf. **P15+TT,TE,EE loP r<0.10 uniform n_s**

cf. **P15+loP+WMAP r<0.09 uniform n_s**

WMAP9 cleaned with 353 pol data

headline: conformally flattened potentials OK, includes R^2 inflation & Higgs inflation, α-attractors

Will any

Anomalies in the CMB

or Tensions with the CMB

turn into Subdominant Physics?

Planck2015+LSS some tension released. still Ho tension but not bad agreement+a bright future

Galaxy Lensing tension persists, systematics?

Cluster σ_{8SZ} cf $\sigma_{8primary}$ tension relaxing, with large $KE_{bulk}/KE_{thermal}$ corrections, hydro expected tho

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

BSMc = SMc + primordial anomalies

~10,000,000 T/E modes = *t*ΛCDM, ≲500 modes of anomaly

vast unexplored parts of the *ζ-scape* CMB is 2D

hope to use 3D **LSS tomography** f_{sky} L_{max}^2 k_{max} d_{max}

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

10^5 zeta

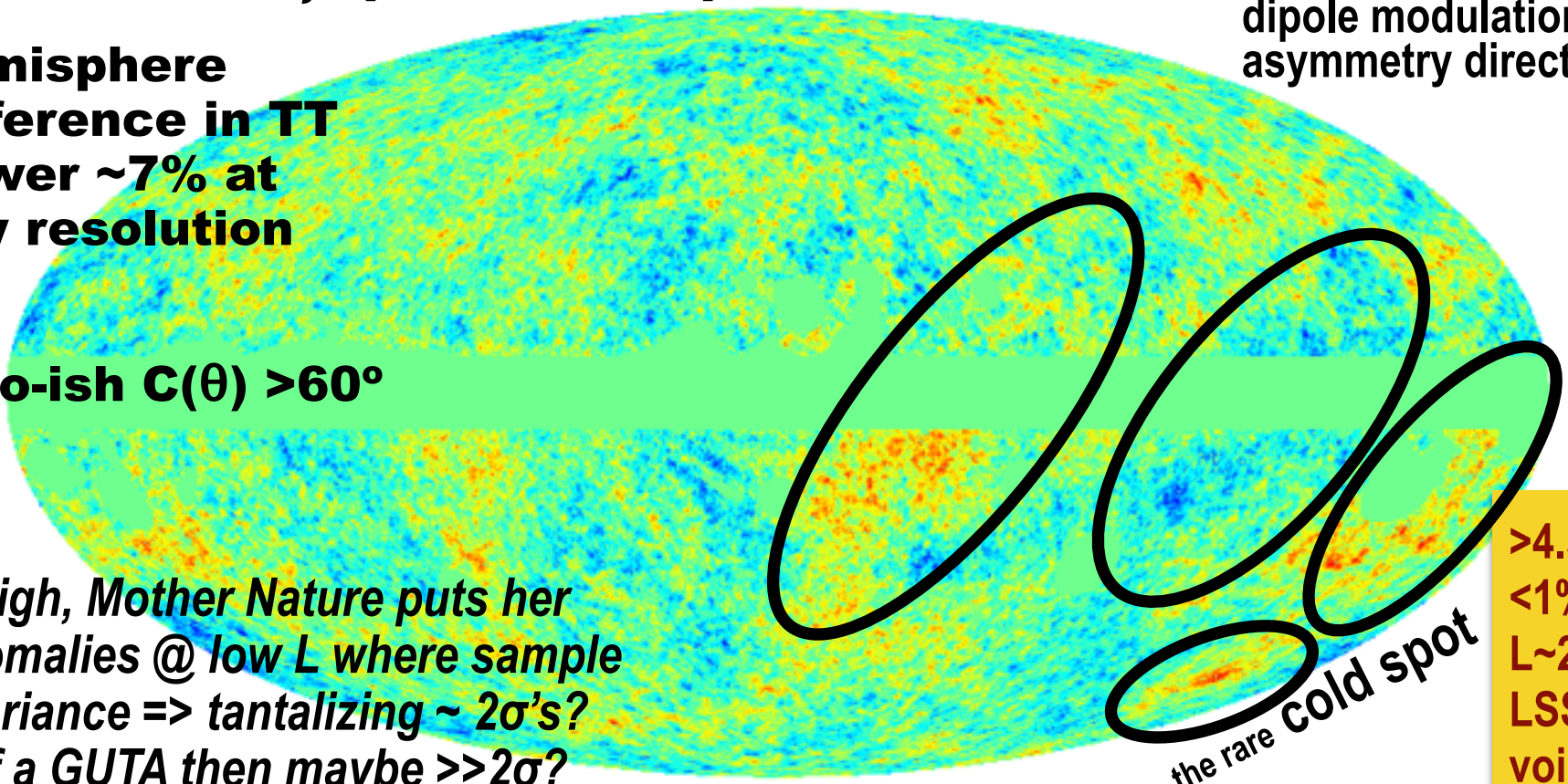
<ζ|*T,E*>

octupole/quadrupole alignment

dipole modulation/ asymmetry direction

hemisphere difference in TT power ~7% at low resolution

zero-ish C(θ) >60°



sigh, Mother Nature puts her Anomalies @ low L where sample variance => tantalizing ~ 2σ's? if a GUTA then maybe >>2σ?

>4.5σ
<1%
L~20
LSS
void?

-35.0 +35.0

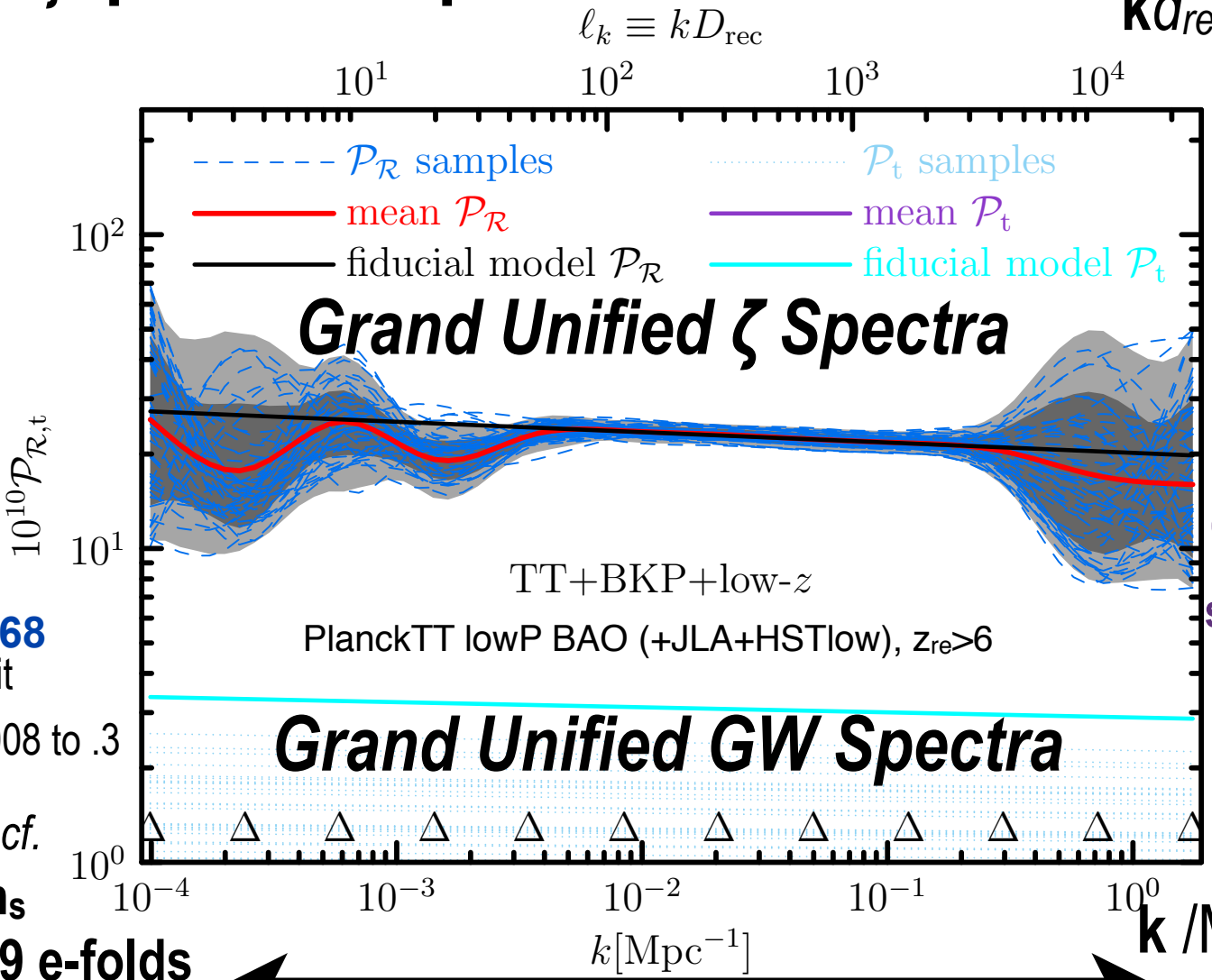
GUTA = Grand Unified Theory of Anomalies? TBD **intermittent?**

the ζ-**scape** & the **CMB**

aka mapping early U sound/phonons

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

kd_{rec} ≳L



EE (L>30) looks similar

=> V(ϕ)

uniform **n_s=0.968**
P15+LSS best fit

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

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

9 e-folds

k /Mpc

alas **a 2-number A_s-n_s early universe so far, simplest outcome but we want more, we are in quest of the subdominant**

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

r futures look bright (balloon, Stage 4, space) modulo the dirty MW
we will reconstruct graviton power
we will de-lens for consistency check: r-n_t ***optimistism TBD***

we mock the LSS future *end-to-end*
we hope to probe the **3D ζ-scape** *where* **modes abound & success is possible** *modulo large scale mode control of systematics* => **non-Gaussianity at a much deeper level, to what must be there f_{NL} < 1? yes, maybe**

entropy in the CMB & CνB

5.2 bits/photon $S_{U,m+r} \sim 10^{88.6}$ *cf.* $S_G \sim 10^{121.9}$ *asymptotic DE*

let there be heat: entropy generation in ***preheating*** from the coherent inflaton to incoherent high k modes (***origin of all "matter"***)
=> ***quark soup*** of SMpp (how?) => entropy in photons & neutrinos and a bit of other
do any observable relics ∃ from this epoch? a hope, *e.g.,* non-Gaussianity, *e.g.,* GW

subsequent early universe S-generation: phase transitions, out-of-equilibrium decay

∃ BBN constraints on S/B

but prior to the cosmic photosphere $z_{Planck} = 10^{6.8}$ ***only one number***

then μ *to* $z_{BE} = 10^{5.4}$, *then intermediate* $\mu(\nu,t)$, *then* y *below* $z_{Compton\ cool} = 10^{4.8}$, *now* $\delta E/E_\gamma < 10^{-4.2}$

viscous damping (small but ∃s), decaying dark matter, lines are hard but rewarding

we want to know all δS. ***PIXIE CORE+++ to TINY*** $<10^{-8.1}$ *for* $\delta E/E_\gamma = (4/3)\delta S/S_\gamma = 0.71\ (-\mu/T)_\gamma$ *or 4y*

after CMB+CνB, most δ**S in CIB =** *waste heat from dust re-emission of starlight & BH accretion energy*

distortion anomalies stimulated theory, then COBE/COBRA

fabulous CIB progress JCMT/Planck/Herschel .. ALMA theory uncertainties: Mother Nature must guide

the shocking Universe tSZ $S_{th,cl} \sim 10^{76}$ ***spectacular progress over past few yrs in tSZ, 100K SZ cluster future, cross with LSS catalogues (LBG, X, ..), and kSZ x galaxies future***

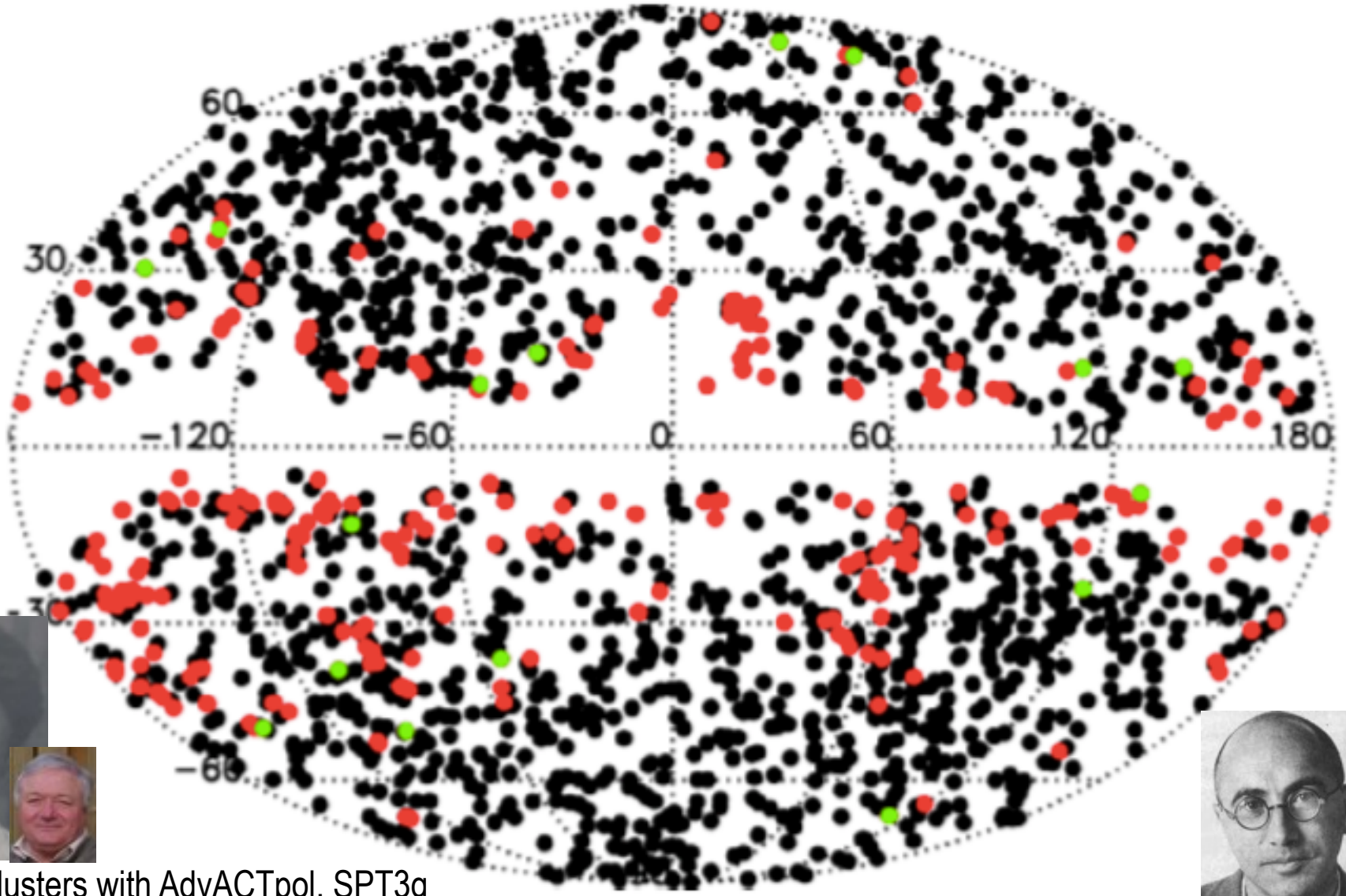
thermal SZ effect

Compton cooling of high pressure / entropy electrons by the CMB

Planck2015 PSZ2: 1652 clusters, 1203 confirmed, SPT 224 =>747cls, ACT 91 cls

cf. X-ray sample from ROSAT+ All-sky distribution of MCXC clusters ~1600 *(Piffaretti et 10)*

REFLEX, BCS, SGP, NEP, MACS, CIZA, 400SD, 160SD, SHARC, WARPS, EMSS



~ 100K clusters with AdvACTpol, SPT3g

history: CMB+LSS
CMBext, ext=LSS
LSSext => ext=CMB
future: LSS+CMB

large optical surveys DES, DESI, HSC, LSST, Euclid, WFIRST, novel radio surveys *CHIME, ..*

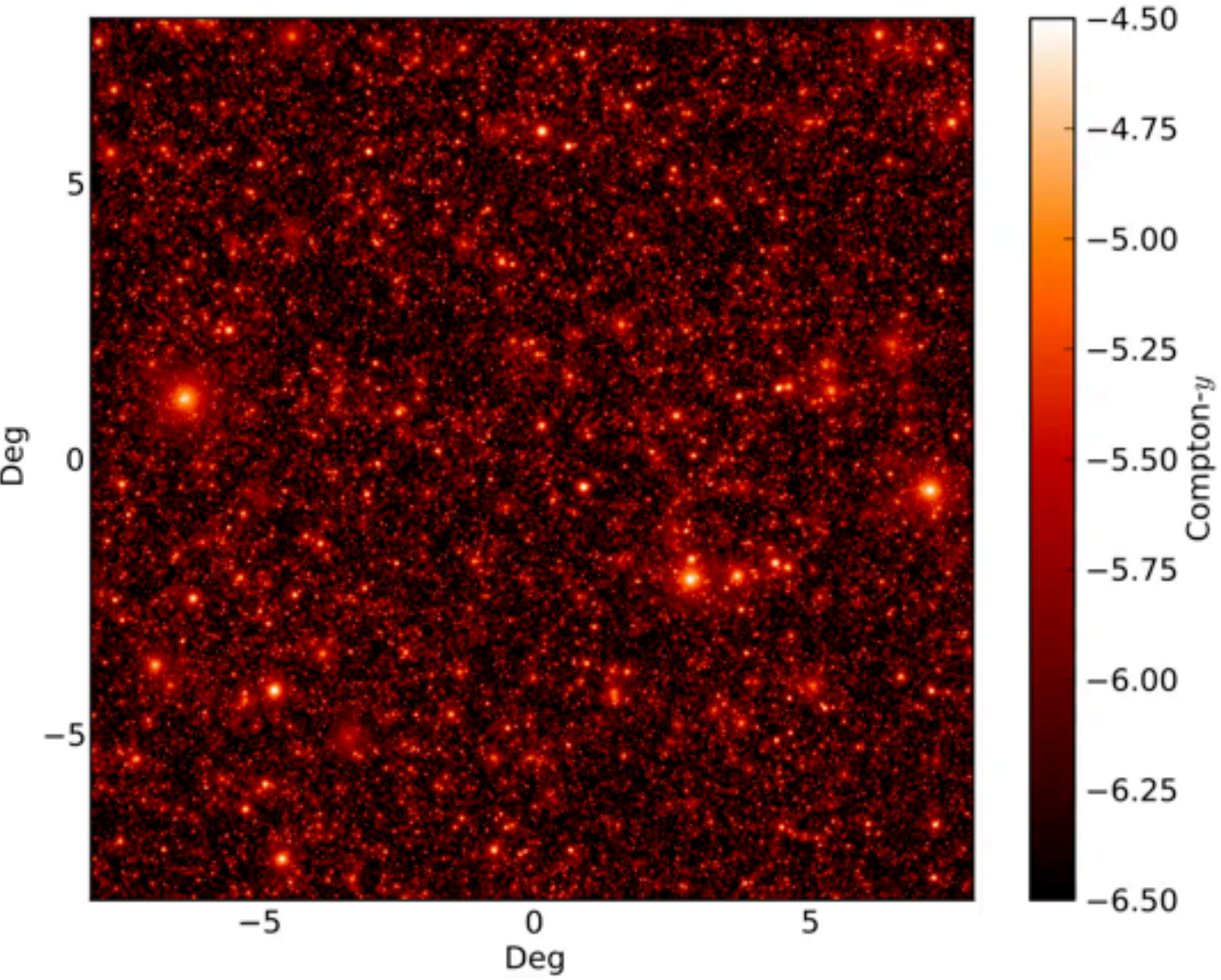
Large Teams of Theorist - Analyst - Observer - Experimentalist as for CMB

PJEP 'there was data and I could analyze it', *and we follow*

Mocking Heaven: ***forecast => mock => end-to-end pipeline***

Mocking Heaven: sample lightcone simulation for tΛCDM all-sky tSZ mock to z=2.5 => *much rich structure to find*

Planck, ACTpol, AdvACT, ***GBT, eRosita.. COMA,.. CHIME***



ABHSBB+15: <10 minutes on 128 cores on SciNet, 30000 core IBM GPC => ~400 sims for survey correlations

mock CIB => CIB*X*tSZ correlation, kSZ, X-ray, HI, CO intensity mapping

…

large z-surveys HOD DES, DESI, HSC, LSST, Euclid WFIRST

lensing

kSZ Peak-Patch maps use cluster/group dominance =moving cluster effect of Sunyaev + *Zeldovich*

Dick Bond CITA

CMB@50 THEN & NOW & THEN

a celebration

thanks to the organizers for this extended CMB family reunion

& we celebrate tonight in earnest, happy birthday Jim