Dick Bond CIFAR@CITA with CITA aka *Cosmic Information Theory & Analysis*

Probing the Cosmic Theory of Early & Late Universe Physics: from Simplicity to Complexity

IT from BIT *from BITs in IT*

information quantity = entropy *Shannon 1948*

information quality = IQ *essence*

info& *primarily-****earlyU***

=Bond@IAP 12.09.28

info& *primarily-****clusters/SZ***

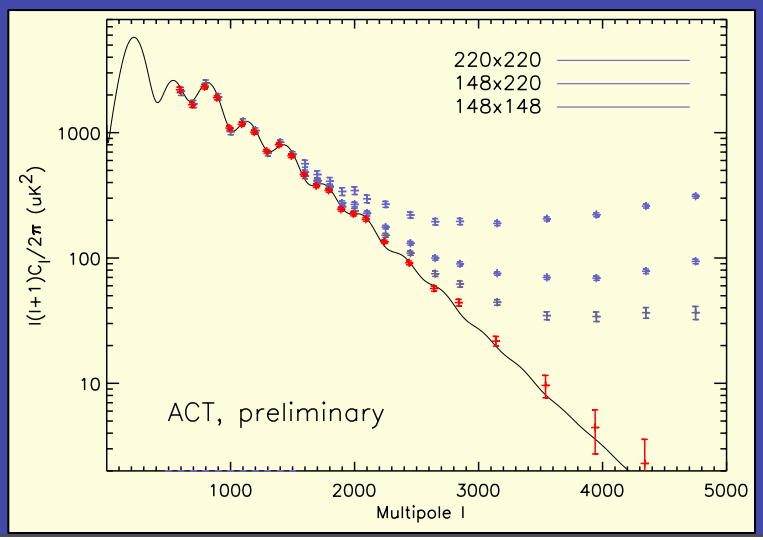
=Bond@IAS 12.10.04

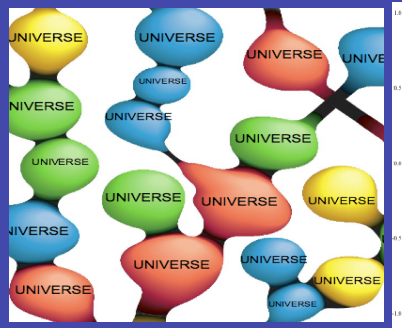
info& *primarily-****primaryCMB***

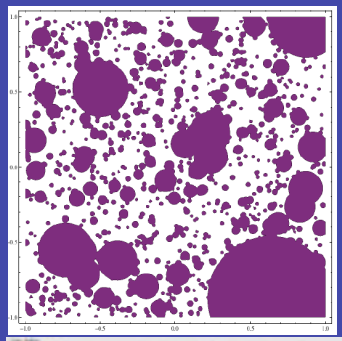
=Bond@APC 12.10.30

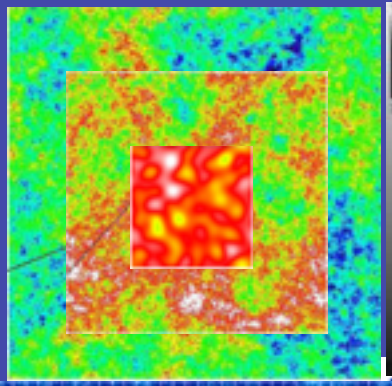
Damping Tail & Recombination History

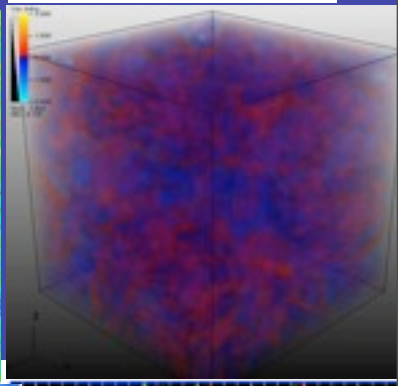
new ACT12+SPT12 *+ Planck13 to come*

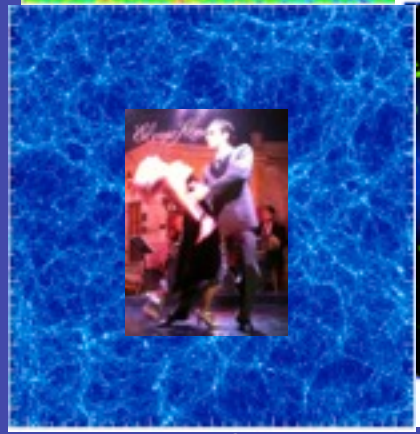


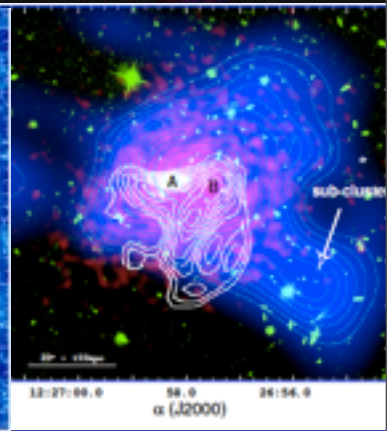






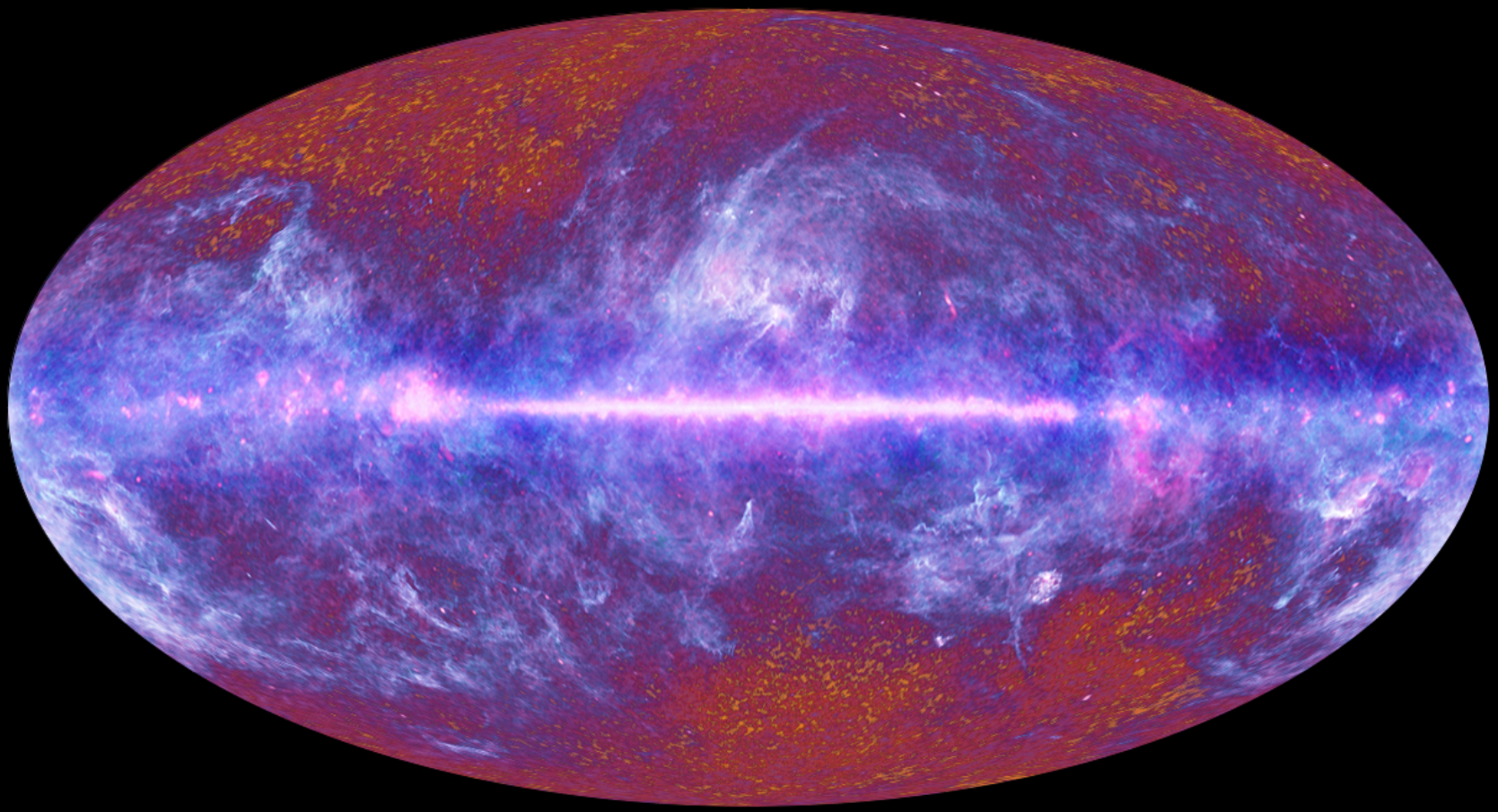






the coherent & the entropic, in all its forms,
from the ultra-early-U to Now to the ultra-late-U

*Prob (**cosmic parameters & trajectories** | CMB+LSS data, theory-framework)*



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gastrophysical simulations with feedback from AGN / starbursts / SN .. confront CMB+LSS data

The Planck one-year all-sky survey esa

Beyond the standard model: tilted ΛCDM + x

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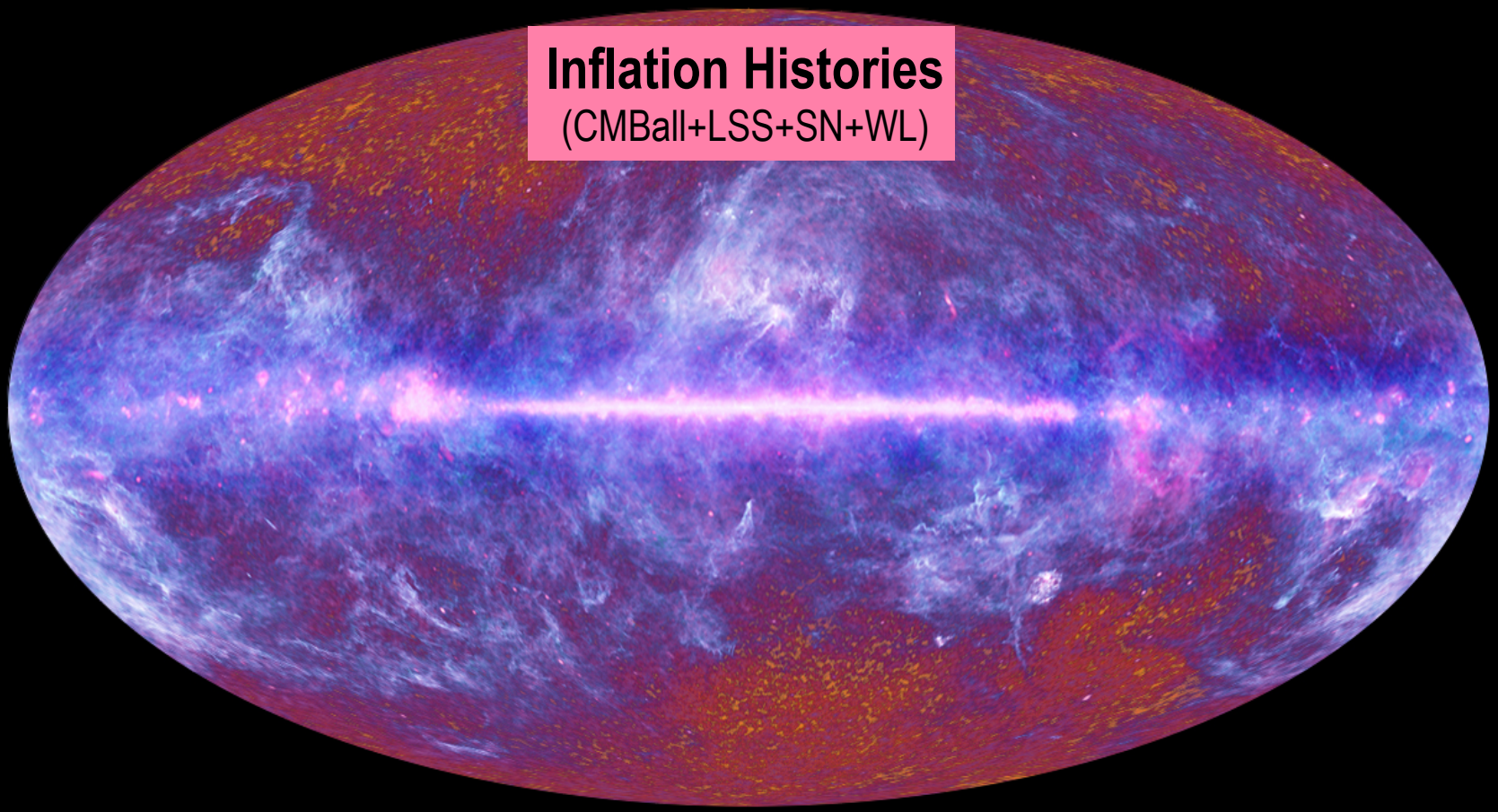

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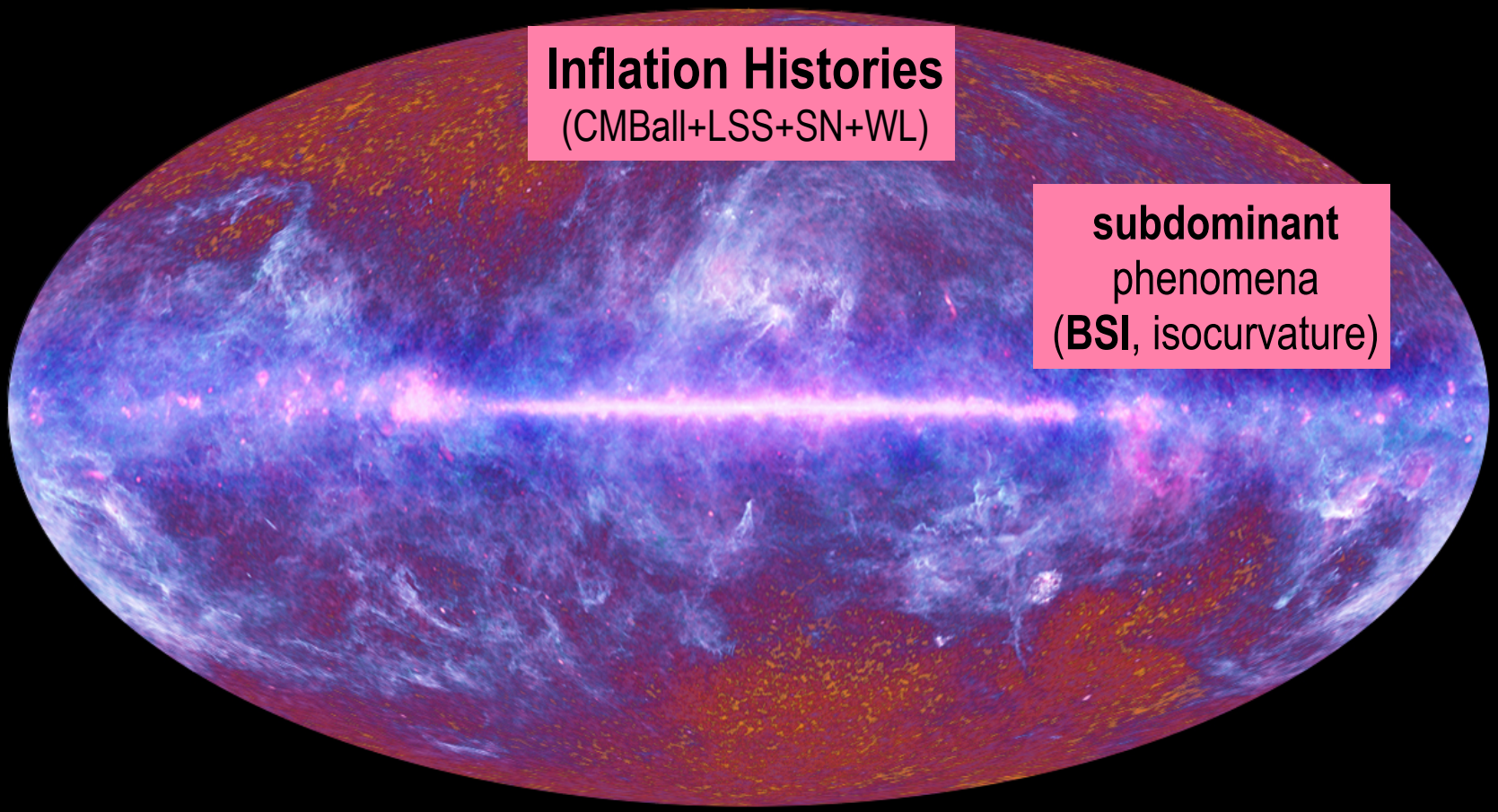

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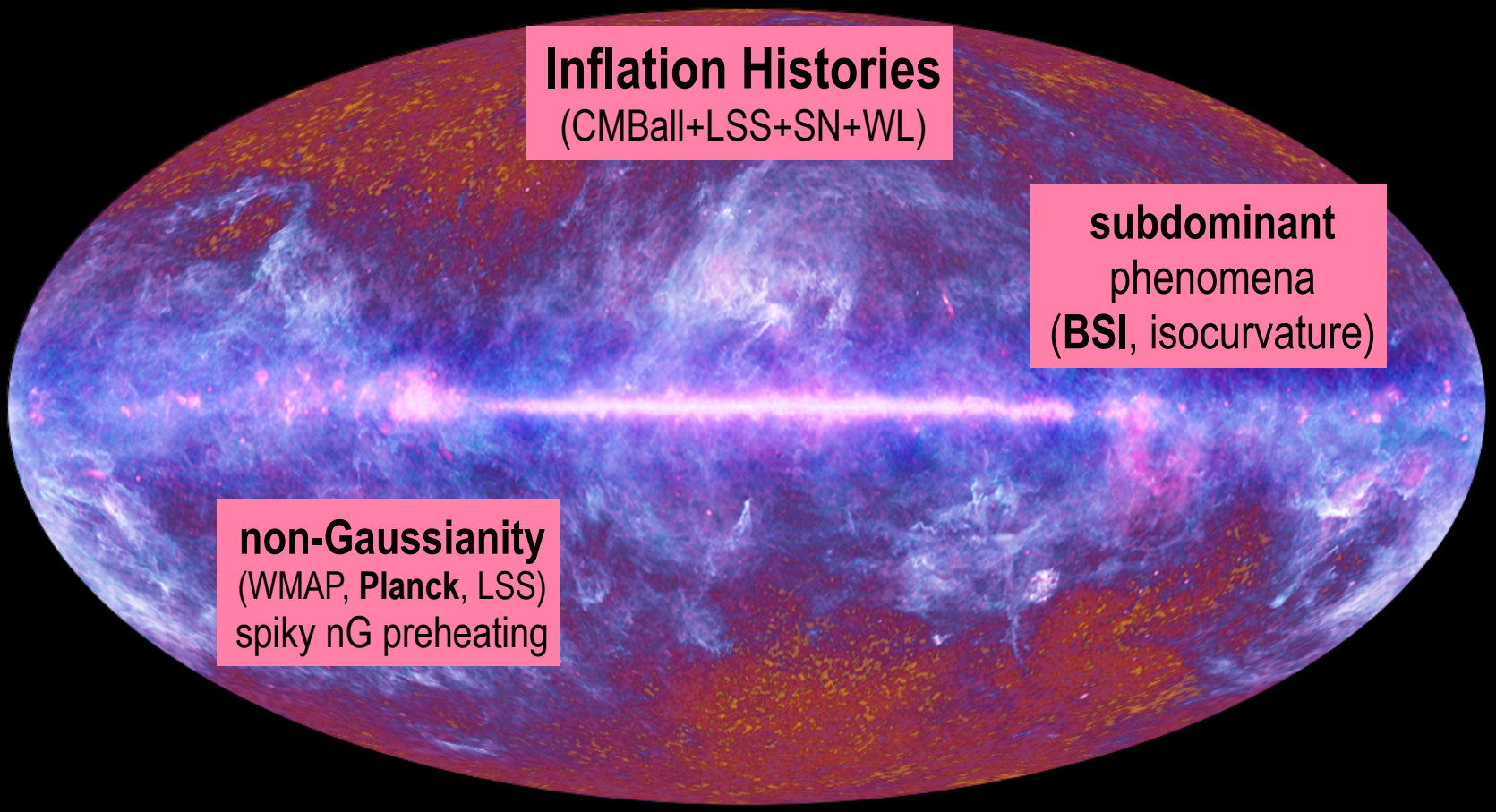

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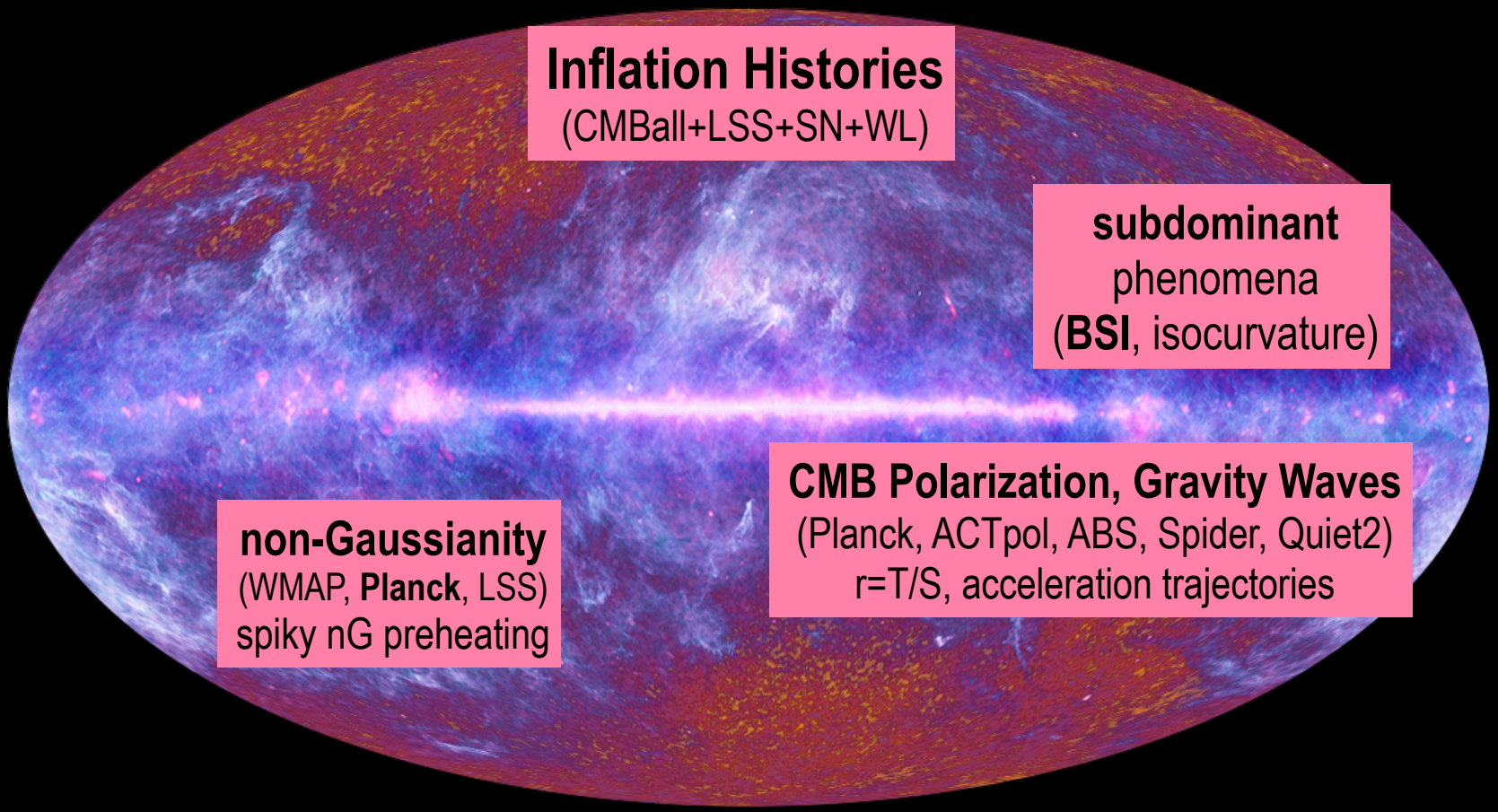

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(RecFast => CosmoRec, HyRec
(Planck+ACTpol+SPTpol)

Inflation Histories
(CMBall+LSS+SN+WL)

subdominant
phenomena
(**BSI**, isocurvature)

CMB Polarization, Gravity Waves
(Planck, ACTpol, ABS, Spider, Quiet2)
r=T/S, acceleration trajectories

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

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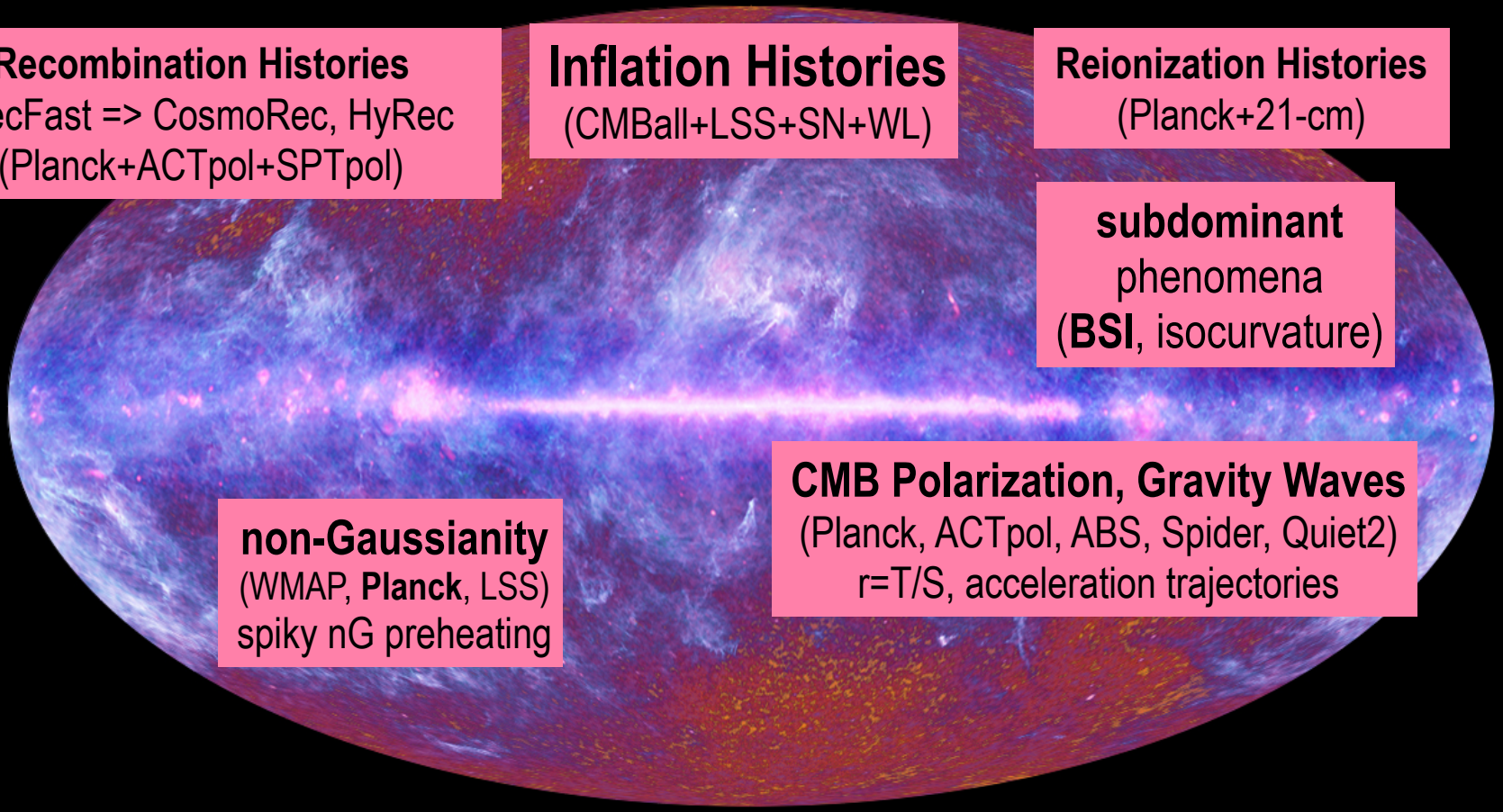

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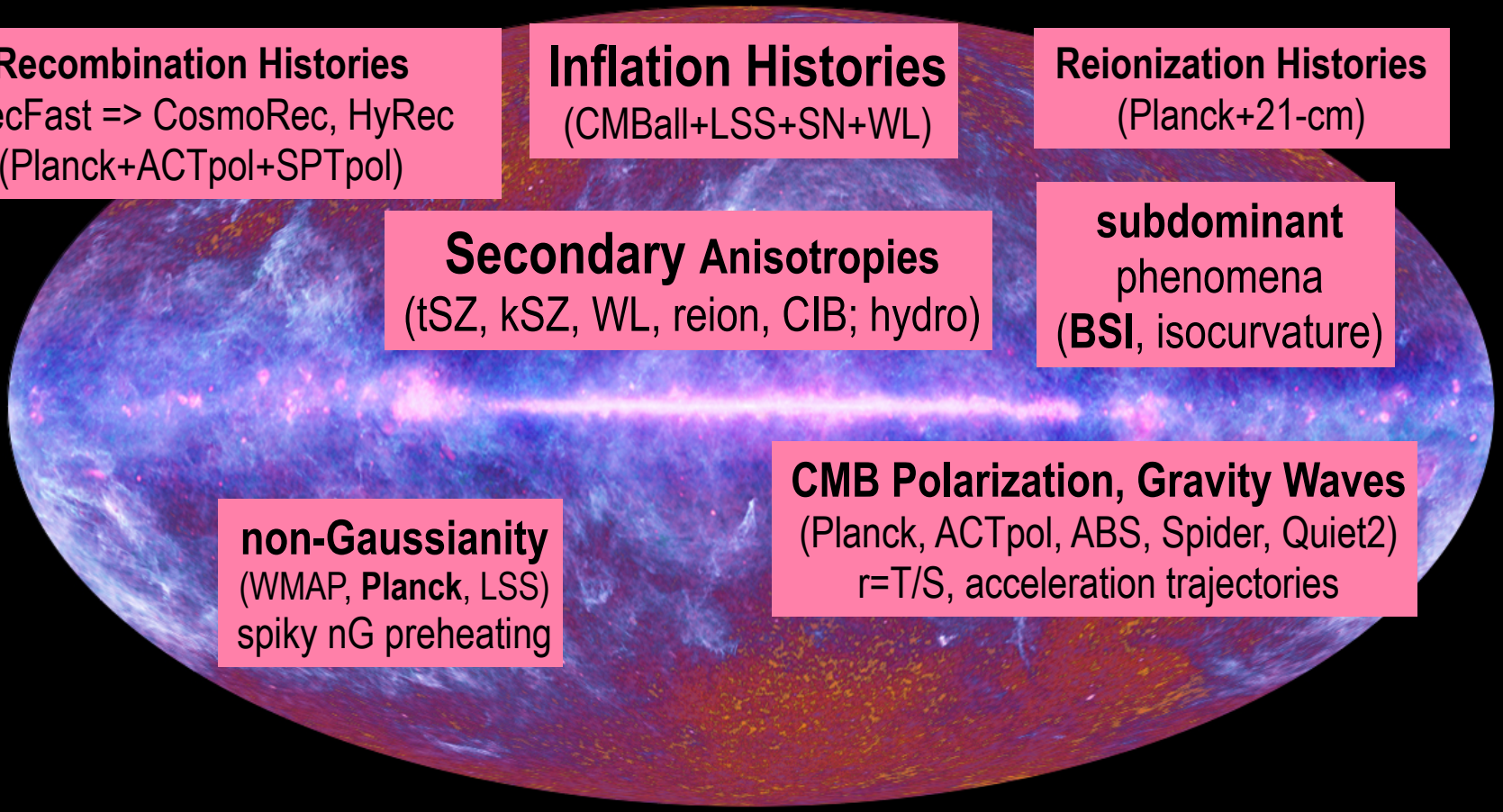

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Dark Energy Histories
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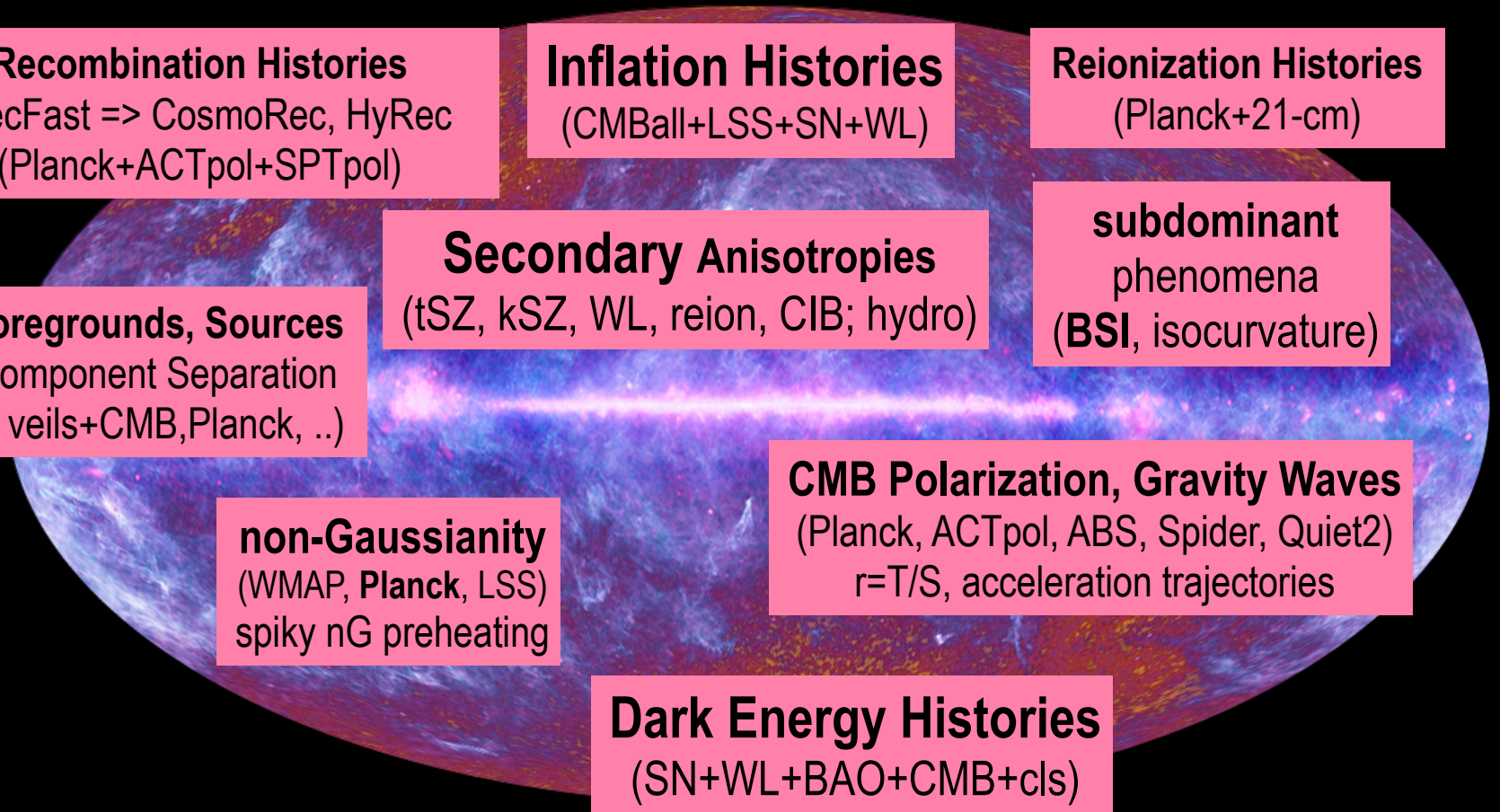

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Foregrounds, Sources
Component Separation
(7 veils+CMB,Planck, ..)

CMB Polarization, Gravity Waves
(Planck, ACTpol, ABS, Spider, Quiet2)
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the **nonlinear COSMIC WEB**

dS$_G$/dt

INFLATION

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- linear perturbations: scalar/density, tensor/ gravity wave **dS/dt>0**
- tightly-coupled photon-baryon fluid:

oscillations $\delta\gamma$ $v\gamma$ $\pi\gamma$

- viscously damped
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Φ SW $d\Phi/dt$

DarkM

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17 kpc (19 Mpc)

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DarkE

Lsound/ ksound

MILKY WAY

z=0

Bayesian flow prior to posterior via likelihood

reionization

dS$_{astro}$ <0

dS/dt>0

z ~ 1100 redshift z z ~ 10

time t

13.7-10^{-50}Gyrs **13.7Gyrs** **10Gyrs** today

IT from BIT from BITs in IT

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

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

the coherent and the entropic, in all its forms, from ultra-early-U to ultra-late-U

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

Studying the **Cosmic Tango**

en-TANGO-ment the dance of U=R∪S

Universe =System(s)+Reservoir =Signal(s)+Residual noise =Effective Theory+Hidden variables, =Data+Theory, **observer(s)+observed**

U=R∪S ruled by (information) entropy in bits, entangled.

the fine grains in the coarse grains

entropy =<information-content> Quantity Shannon 1948

generalized parameter space {q} ~phase space

$$S_f(D,T)=\int dq\, P_f\, ln[P_f^{-1}]$$

Boltzmann

$S=k_B ln W,$

$W=N_{states}$

$dS/dt > 0$

equal a priori probability

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A Long View of Particle Physics Frank Wilczek 2012, 25th Solvay:

Information as Foundation? *There are, I think, significant hints that it should be.*

QITA Quantum Information Theory & Analysis

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$P(q|D,T) = P(D|q,T)P(q|T)P(T)/P(D|T)$ *D=CMB,LSS,SN,..,* **complexity,** *life*

T=baryon, dark matter, vacuum mass-energy densities,..., early & late inflation as low energy flows/trajectories on a** (string) **landscape

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relative Shannon entropy = - Kullback Leibler divergence

$P_f(q)$ probability density functional **distribution function**

⇐ *quantum* **(von Neumann)** $S = -Tr\, \rho \ln \rho$ **density matrix**

Boltzmann

$S = k_B \ln W$, $W = N_{states}$

$dS/dt > 0$

Bayes measure

=>"$dS_f/dt < 0$"

as System knowledge ⬆

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relative RENYI entropy of order n *a concentration measure (1 is Shannon)*

$$\exp[-(n-1)S_{n,fi}(D,T)] = \langle \exp[-(n-1)\sigma_{fi}] \rangle_f \sim -\ln \langle \rho^n \rangle_V / \langle \rho \rangle_V^n$$

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IQ=information quality

IQ~{minimal length messages/codes | error tolerance} *Planck(E/T), genetic code, recipes, axioms, algorithms, IC/BC/evolution eq^n's*

cat information_overload.txt | grep fundamental | grep physics > exec_summary.tex

filter, compress, reduce, marginalize

early U applications of "CITA" to cosmic-complexity

$S_{U,m+r} \sim 10^{88.6}$ *cf.* $S_G \sim 10^{121.9}$

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

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

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

Studying the Cosmic Tango

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☛ information in **nearly-Gaussian** density/potential random **fields** of U, & in weakly and strongly non-linear fields. *ergodic theorem & constrained fields*

☛ spatial coarse-grained **CMB entropy** & how we capture it

☛ **dark matter entropy, cluster & *protocluster* & *cosmic web* entropy**

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

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

info& *primarily-***earlyU=Bond@IAP 12.09.28**

info& *primarily-***clusters/SZ=Bond@IAS 12.10.04**

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new ACT12+SPT12 *+ Planck13 to come*

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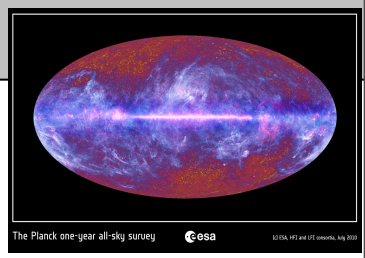
the gatherers of cosmic information

Cosmic **M**icrowave **B**ackground +

Large **S**cale **S**tructure experimental probes

then & now & then



2012 cosmology => *WMAP9*EXT

2013+ cosmology => *Planck*EXT

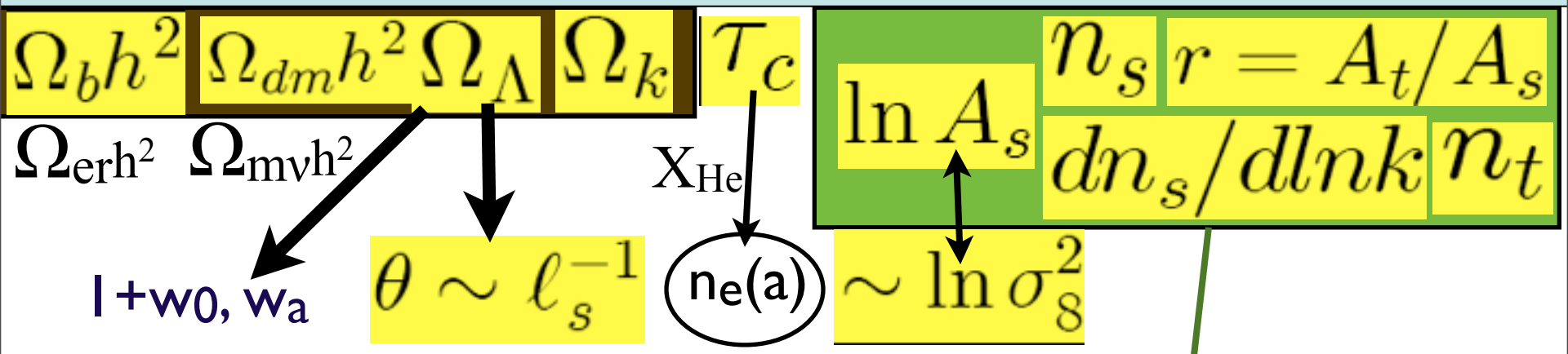
EXT=many observatories & expts enabling the cosmology/astro

ACT, SPT, ***Quiet,*** **GBT**, SSDS/BOSS, PanStarrs, ... ⊂ **EXTi**

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

ACTpol, SPTpol, ***ABS, Spider, Quiet-90,*** *EBEX, Keck,* **GBT**, PanStarrs, DES, HSC, ***CHIME,*** eRosita, **CCAT**, LSST, ***EUCLID,*** ... ⊂ **EXTf**

Standard Parameters of Cosmic Structure Formation



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

& for recombination: (partially) blind cf. informed "theory" priors

standard inflation space: n_s $dn_s/d\ln k$ r =T/S @k-pivots

Dunkley+ 2010 ACT+WMAP7

Keissler+ 2011 SPT+WMAP7

Inflation Histories
(CMBall+LSS+SN+WL)

$\ln$**Power$_s$~$\ln$25x10^{-10}** ± 0.036

n_s = 0.963 ± 0.011 (ACT10+WMAP+BAO+H0)

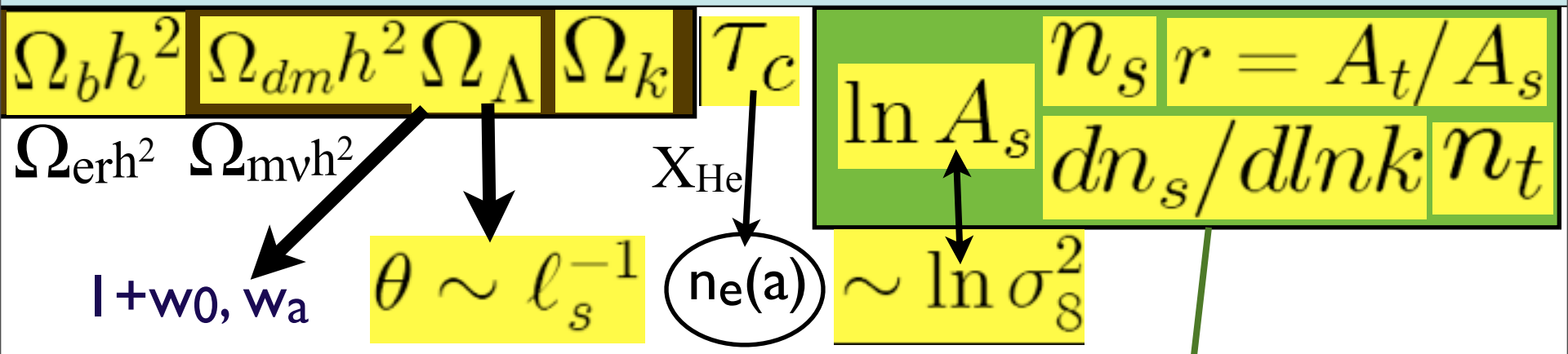
$dn_s/d\ln k$ = -0.024 ± 0.015 (ACT10+WMAP+BAO+H0)

r < 0.19, 0.17 (95% CL, ACT10+WMAP+BAO+H0, SPT11+...)

Hlozek+11 **Primordial power spectra(k);** Bond, Contaldi, Huang, Kofman, Vaudrevange 2011 ***w/o & with T-S consistency***

ACT12 final spectra now, final params in ~weeks, 1500 sq deg, ~1000 for params

Standard Parameters of Cosmic Structure Formation



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

& for recombination: (partially) blind cf. informed "theory" priors

standard inflation space: n_s $dn_s/d\ln k$ r =T/S @k-pivots

Dunkley+ 2010 ACT+WMAP7

Keissler+ 2011 SPT+WMAP7

Story+ 2012 SPT+WMAP7

Inflation Histories
(CMBall+LSS+SN+WL)

*ln***Power$_s$~***ln***22x10^{-10}** ± 0.028

n_s = 0.952 ± 0.0082 (SPT12+WMAP+BAO+H0, 0.962 ± 0.01)

$dn_s/d\ln k$ = -0.024 ± 0.015 (ACT10+WMAP+BAO+H0)

r < 0.11 (95% CL, SPT12+WMAP+BAO+H0, < 0.18 SPT12+WMAP7)

Hlozek+11 **Primordial power spectra(k);** Bond, Contaldi, Huang, Kofman, Vaudrevange 2011 ***w/o & with T-S consistency***

ACT12 final spectra now, final params in ~weeks, 1500 sq deg, ~1000 for params

CITA = Cosmic Information Theory & Analysis: *IT from BIT, from BITs in IT,*

Studying the Cosmic Tango *en-TANGO-ment* ***Universe=System+Res=Data+Theory*** =Signal(s)+*noise*=EFT+*Hidden variables*

we compress the Petabit++ observed cosmic info into a precious few bits encoding 6+ parameters of the Minimal Cosmic Standard model (tilted ΛCDM)

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

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

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

CMB@CITA: Boomerang, Acbar, CBI1,2, WMAP, Planck, ACT, Spider, Blast, & ACTpol, ABS, QUIET2;
GBT-Mustang2, CARMA/SZA, SCUBA2, ALMA, CCAT. CMB@CIFAR: these + APEX , SPT, SPTpol, EBEX

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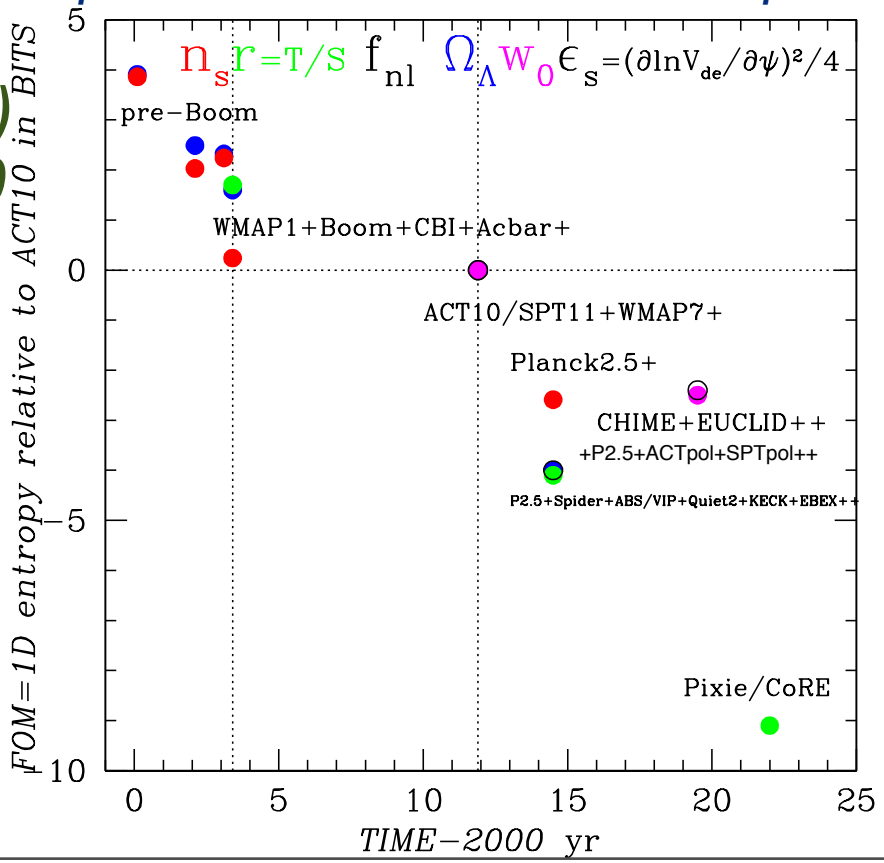
ΔS(q,DT)
i=ACT10



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

CITA = Cosmic Information Theory & Analysis: *IT from BIT, from BITs in IT,*

Studying the Cosmic Tango *en-TANGO-ment* ***Universe=System+Res=Data+Theory =Signal(s)+noise=EFT+Hidden variables***

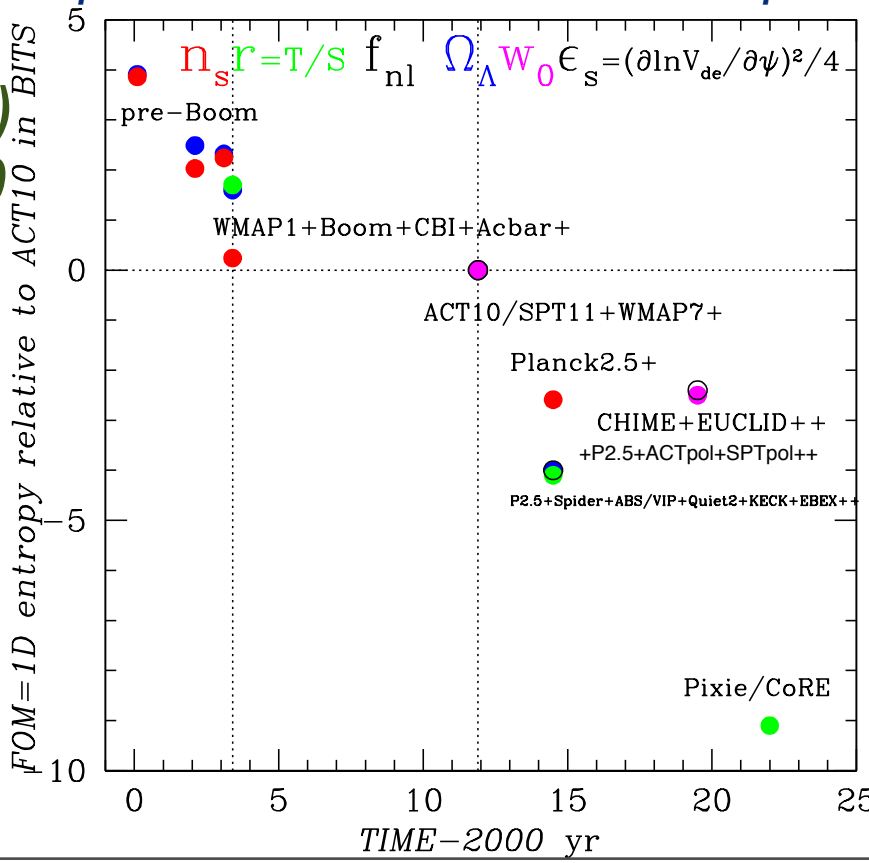
we compress the Petabit++ observed cosmic info into a precious few bits encoding 6+ parameters of the Minimal Cosmic Standard model (tilted ΛCDM)

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

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

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

$\Delta S(q,DT)$ *i=ACT10*



inflation

n_s: 0.963± 0.011 *0.952 ± 0.0082* **=>± 0.002 (Pext)**

r: < 0.17 *0.11* **=> < 0.007-0.013 (Pext)**

f_{nl}: -10< f_{NL} <74 => ± 5 (Pext)

dark energy

Ω_Λ: ± 0.012 =>± 0.001 (Pext)

w_0: ± 0.06 =>± 0.01 (Pext) **(± 0.14 =>± 0.03 if w_a)**

ln **V-slope^2/4 0.0± 0.18 =>± 0.03 (Pext)**

+2 other w-trajectory parameters BHK11,BH12

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

Dick Bond CIFAR@CITA with CITA aka *Cosmic Information Theory & Analysis*

Cosmic Information from the Microwave Background Radiation

the **nonlinear COSMIC WEB**

dS$_G$/dt

INFLATION

primary anisotropies

- linear perturbations: scalar/density, tensor/ gravity wave **dS/dt>0**
- tightly-coupled photon-baryon fluid:

oscillations $\delta\gamma$ $v\gamma$ $\pi\gamma$

- viscously damped
- polarization $\pi\gamma$
- gravitational redshift

Φ SW $d\Phi/dt$

DarkM

Decoupling LSS

17 kpc (19 Mpc)

secondary anisotropies **dS/dt>0**

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

DarkE

Lsound/ ksound

MILKY WAY

z=0

Bayesian flow prior to posterior via likelihood

reionization

dS$_{astro}$ <0

dS/dt>0

z ~ 1100 redshift z z ~ 10

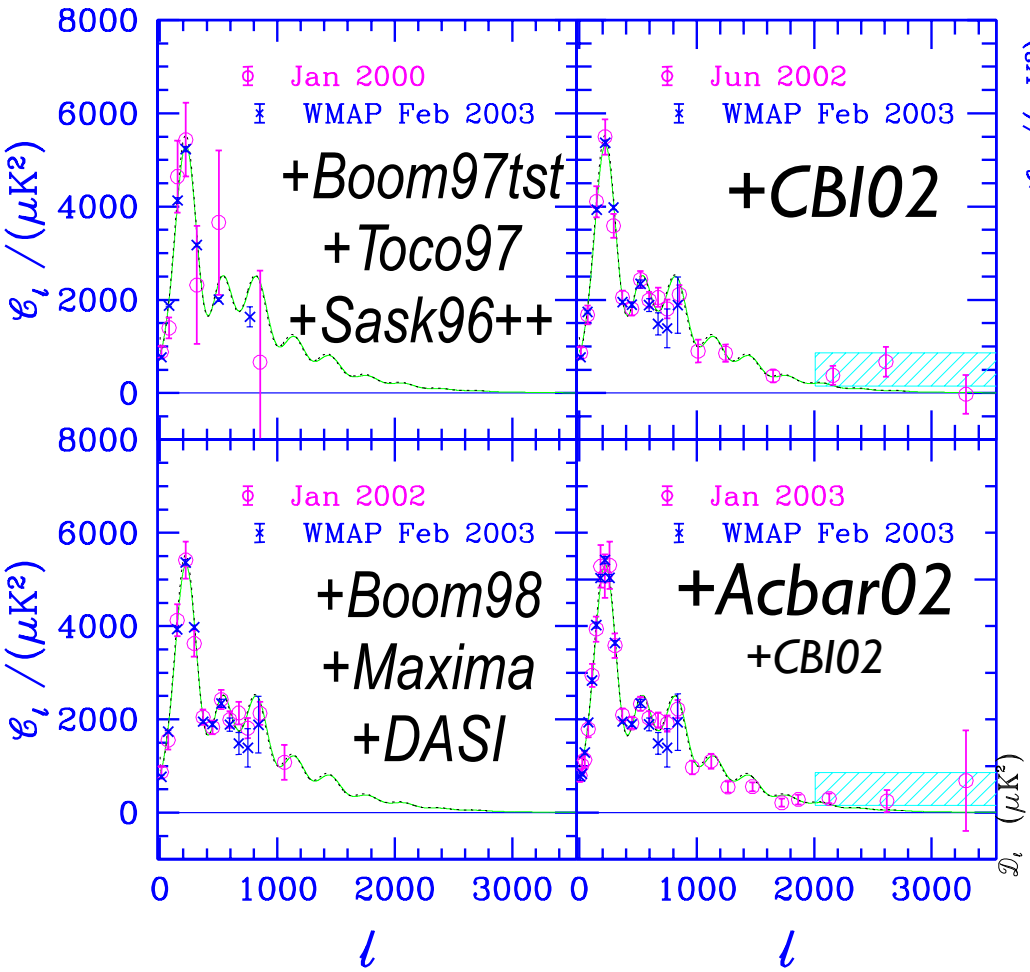
time t

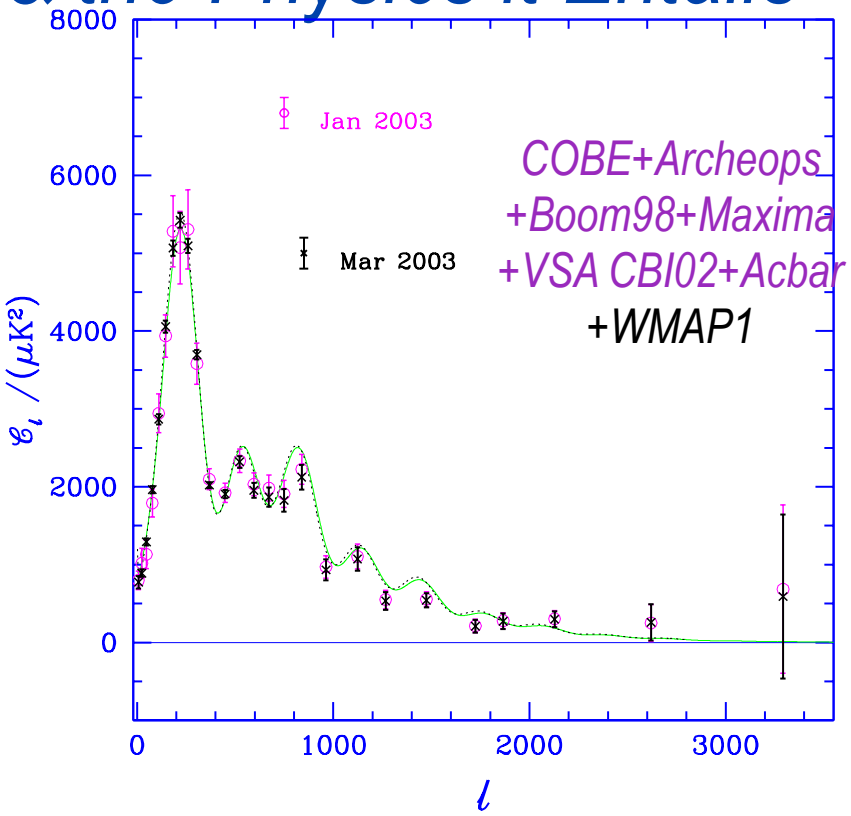
13.7-10^{-50}Gyrs **13.7Gyrs** **10Gyrs** today

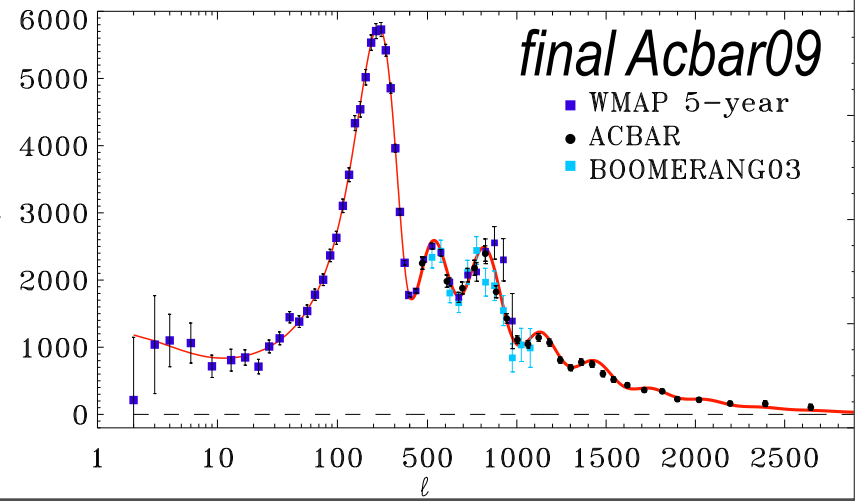
in Quest of the Damping Tail & the Physics it Entails

Grand Unified Spectra *aka* **GUS**

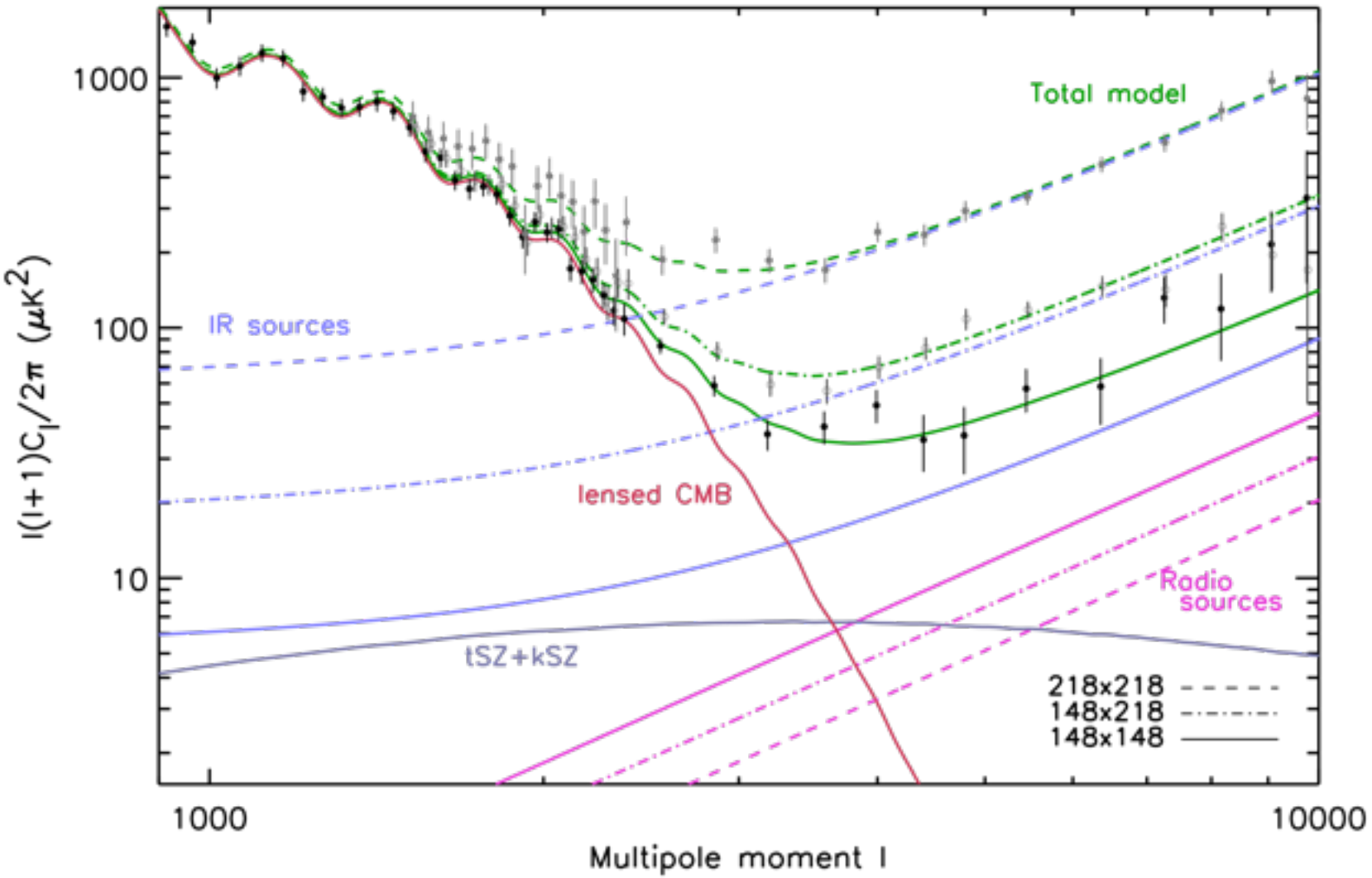
*COBE***EXT**





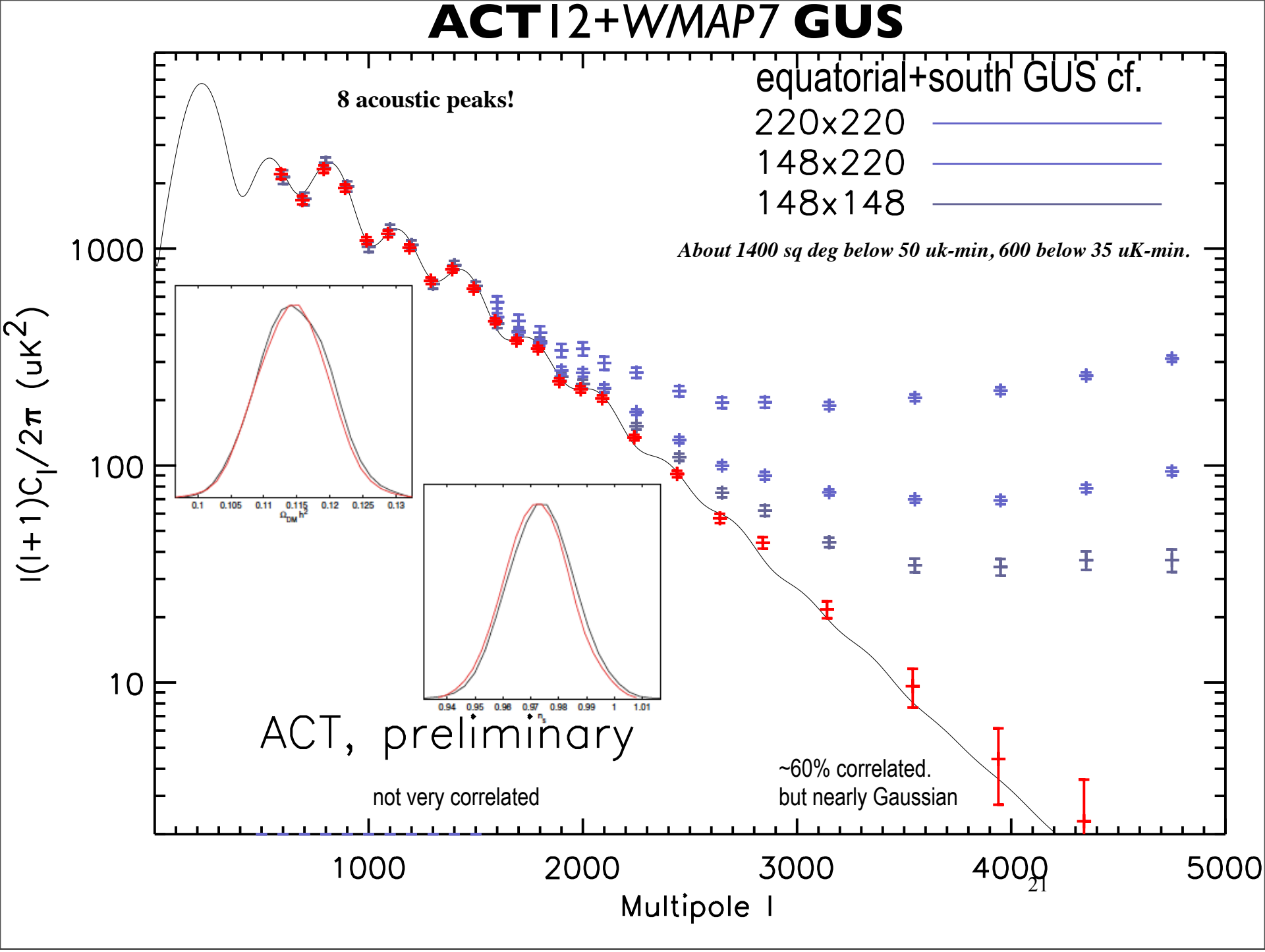


primordial (lensed) CMB + veils, *the veils = radio sources, the CIB, tSZ and kSZ (& Milky Way dust and synchrotron at lower multipoles)*



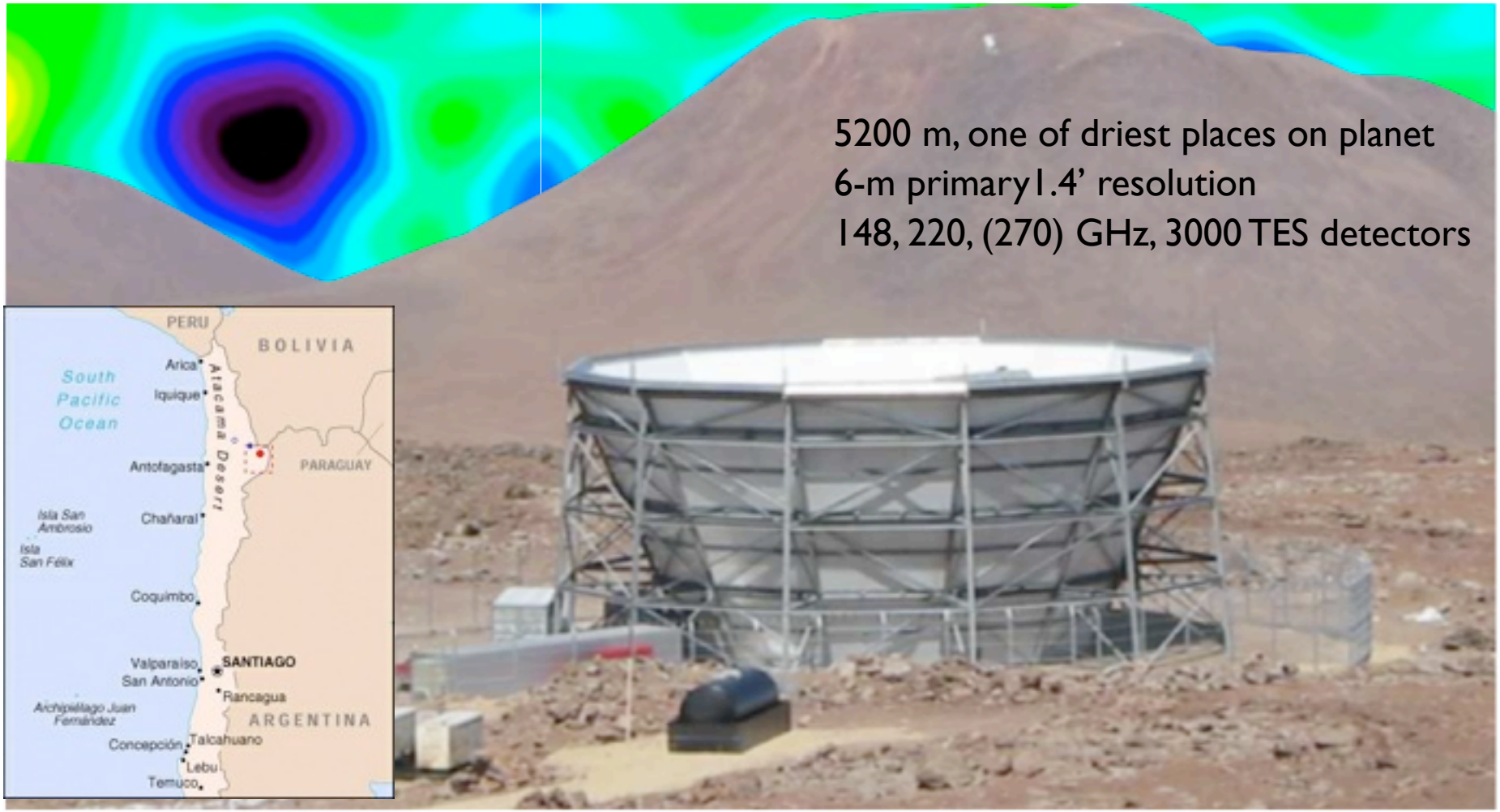
Dunkley+. 2010

ACT12+*WMAP7* GUS



Cosmology From 17,000 Feet:

Results From the Atacama Cosmology Telescope



CMB@CITA: Boomerang, Acbar, CBI1,2, WMAP, Planck, ACT, Spider, Blast, & ACTpol, ABS, QUIET2;
GBT-Mustang2, CARMA/SZA, SCUBA2, ALMA, CCAT. CMB@CIFAR: these + APEX , SPT, SPTpol, EBEX

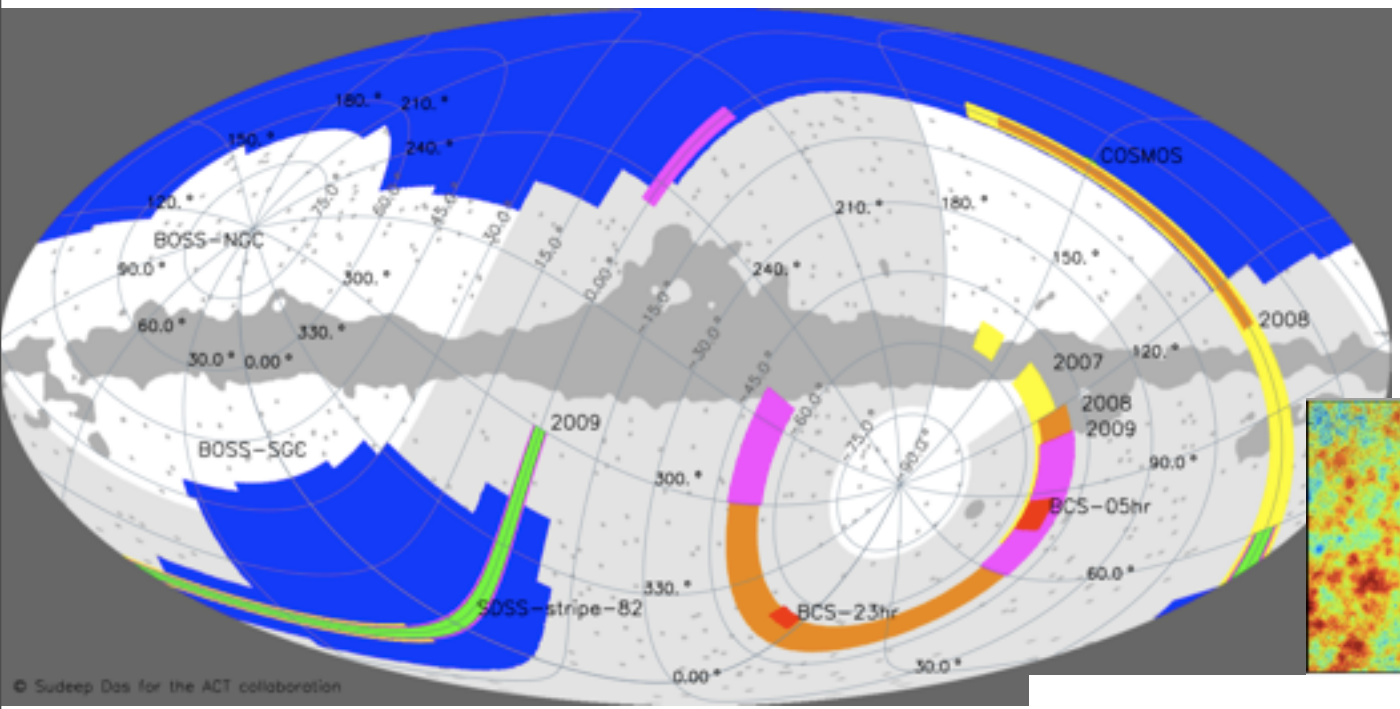
V. Acquaviva [1,2]
P. Ade [3]
P. Aguirre [4]
M. Amiri [5]
J. Appel [6]
E. Battistelli [7,5]
* N. Battaglia [8]
* J. R. Bond [8]
B. Brown [9]
B. Burger [5]
J. Chervenak [10]
S. Das [29,6,1]
M. Devlin [2]
S. Dicker [2]
W. B. Doriese [11]
J. Dunkley [12,6,1]
R. Dunner [4]
T. Essinger-Hileman [6]
R.P. Fisher [6]
J.W. Fowler [6]
* A. Hajian [6,8]
M. Halpern [5]
M. Hasselfield [5]
C. Hernandez-Monteagudo [13,2]
G. Hilton [11]
M. Hilton [14, 15]
* A. D. Hincks [6,8]
R. Hlozek [12, 1]
K. Huffenberger [16,6]
D. Hughes [17]
J. P. Hughes [18]
L. Infante [4]
K.D. Irwin [11]
N. Jarosik [6]
R. Jimenez [19]
J.B. Juin [4]
M. Kaul [2]
J. Klein [2]
A. Kosowsky [9]
J.M. Lau [20,6]
M. Limon [21]
Y.T. Lin [22,1,4]
R. Lupton [1]
T.A. Marriage [1,6]
D. Marsden [2]
K. Martocci [23,6]
P. Mauskopf [3]
F. Menanteau [18]
K. Moodley [14]
H. Moseley [10]
* B. Netterfield [24]
M.D. Niemack [11,6]
* M.R. Nolta [8]
L.A. Page (PI) [6]
L. Parker [6]
B. Partridge [25]
H. Quintana [4]
B. Reid [19,1]
N. Sehgal [20,18]
* J. Sievers [8,6]
D. Spergel [1]
S.T. Staggs [6]
O. Stryzak [6]
D. Swetz [2]
* E. Switzer [23,6,8]
R. Thornton [26,2]
H. Trac [27,1]
C. Tucker [3]
L. Verde [19]
R. Warne [14]
G. Wilson [28]
E. Wollack [10]
Y. Zhao [6]

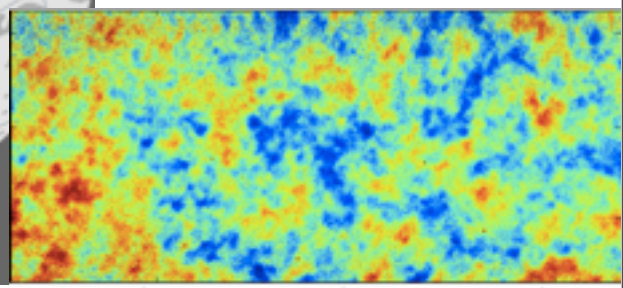
[1] Princeton University Astrophysics (USA)
[2] University of Pennsylvania (USA)
[3] Cardiff University (UK)
[4] Pontifica Universidad Catolica de Chile (Chile)
[5] University of British Columbia (Canada)
[6] Princeton University Physics (USA)
[7] University of Rome "La Sapienza" (Italy)
* [8] CITA, University of Toronto (Canada)
[9] University of Pittsburgh (USA)
[10] NASA Goddard Space Flight Center (USA)
[11] NIST Boulder (USA)
[12] Oxford University (UK)
[13] Max Planck Institut fur Astrophysik (Germany)
[14] University of KwaZulu-Natal (South Africa)
[15] South African Astronomical Observatory
[16] University of Miami (USA)
[17] INAOE (Mexico)
[18] Rutgers (USA)
[19] Institute de Ciencies de L'Espai (Spain)
[20] KIPAC, Stanford (USA)
[21] Columbia University (USA)
[22] IPMU (Japan)
[23] KICP, Chicago (USA)
* [24] University of Toronto (Canada)
[25] Haverford College (USA)
[26] West Chester University of Pennsylvania (USA)
[27] Harvard-Smithsonian CfA (USA)
[28] University of Massachusetts, Amherst (USA)
[29] BCCP UC Berkeley and LBL (USA)

end observing 2011: ACT completed 3 full seasons, over ~1300 deg^2, maps@CITA.

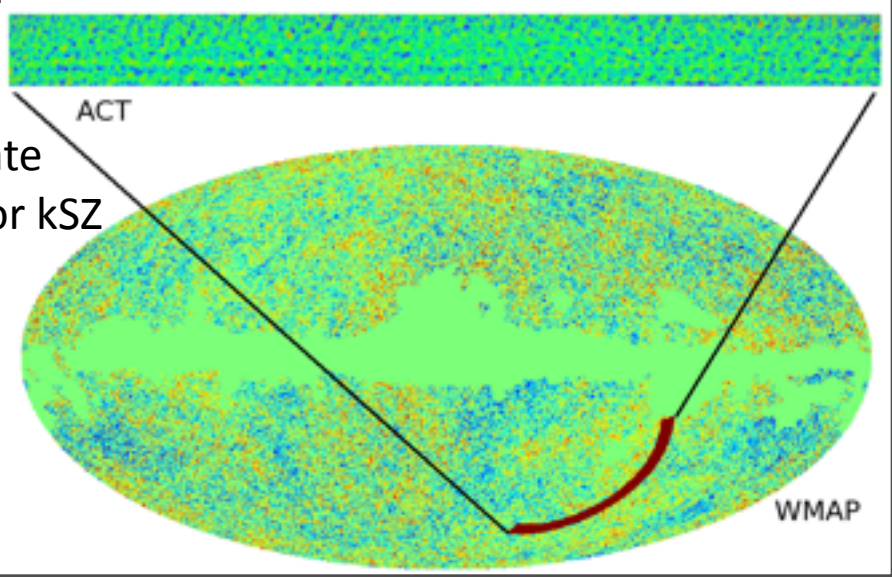
next step is ACTpol

About 1400 sq deg below 50 uk-min, 600 below 35 uK-min.





Hajian et al (2010)

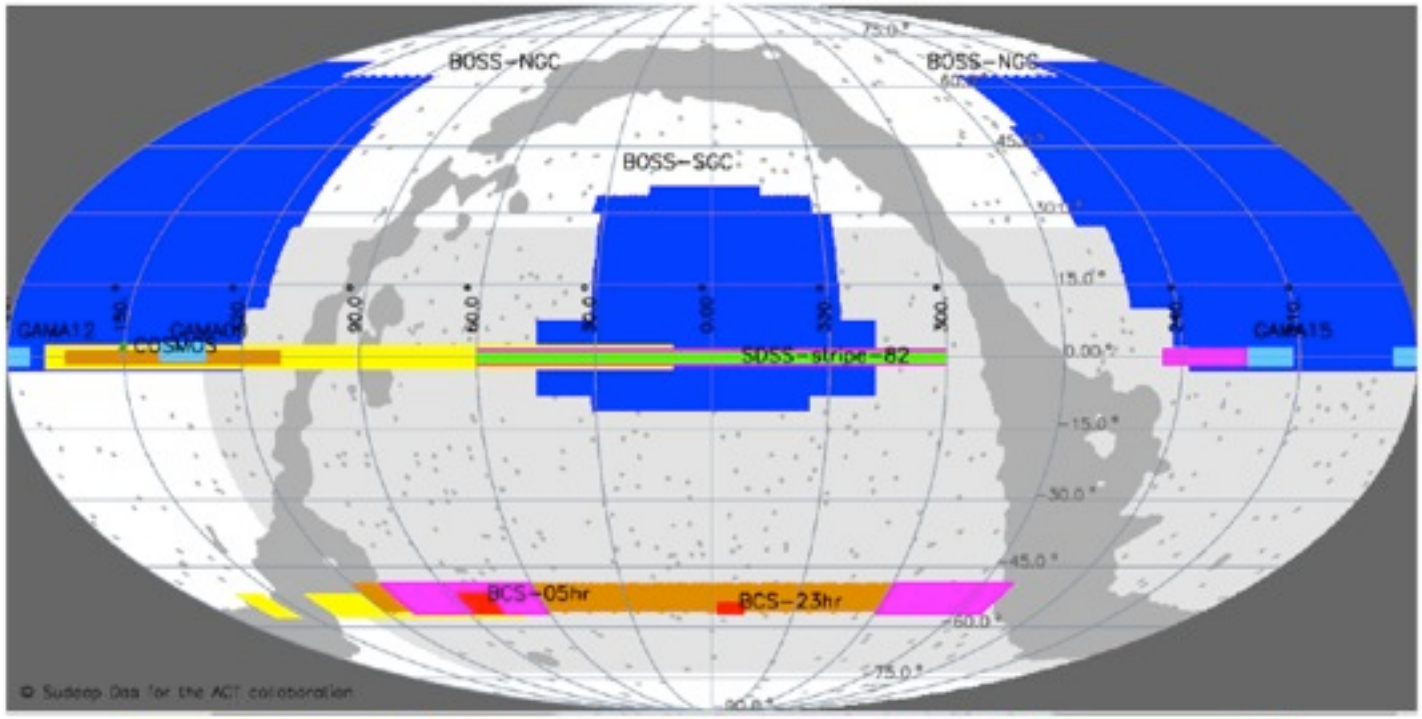


<ACT SZ x other data (opt, X, submm)>, ... X correlate overlaps SDSS III BOSS in the ACT equatorial strip, for kSZ

end observing 2011: ACT completed 3 full seasons, over ~1400 deg^2, maps@CITA.

next step is ACTpol >= 2013

About 1400 sq deg below 50 uk-min, 600 below 35 uK-min.

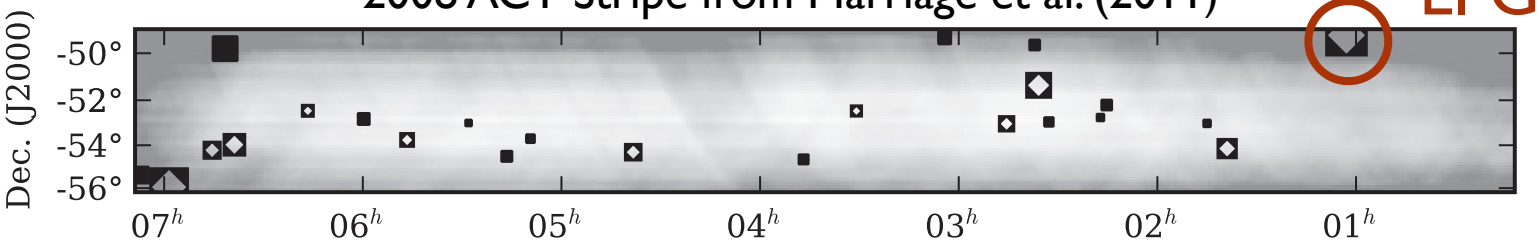


2007 | 2008 | 2009+2010 | Stripe 82

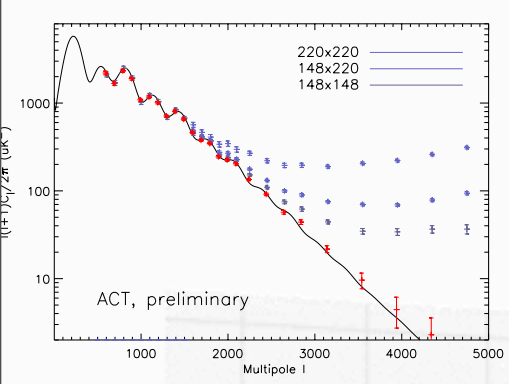
BCS | BOSS | GAMA | ACT Range | Mask

2008 ACT Stripe from Marriage et al. (2011)

El Gordo



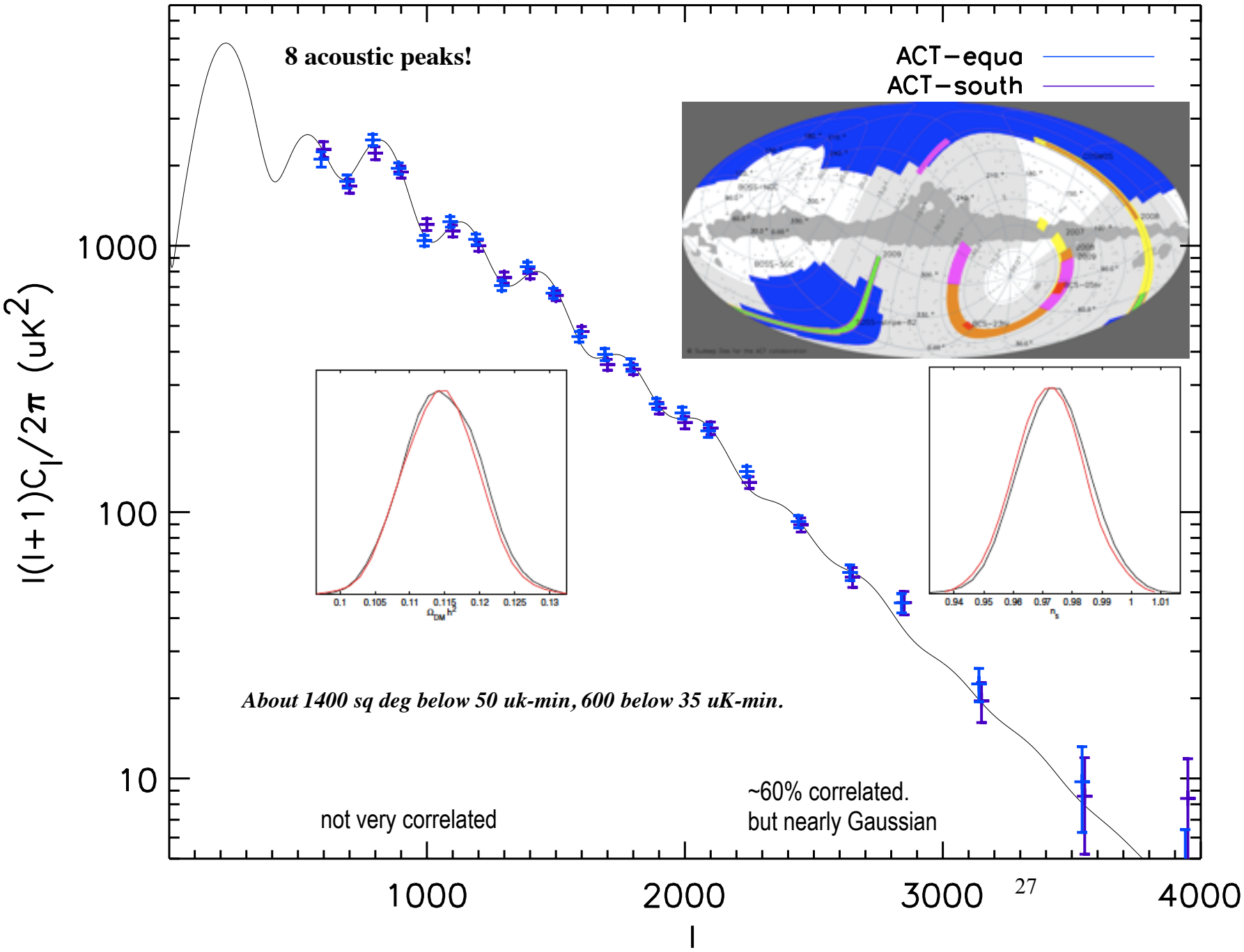
in Quest of the Damping Tail & the Physics it Entails



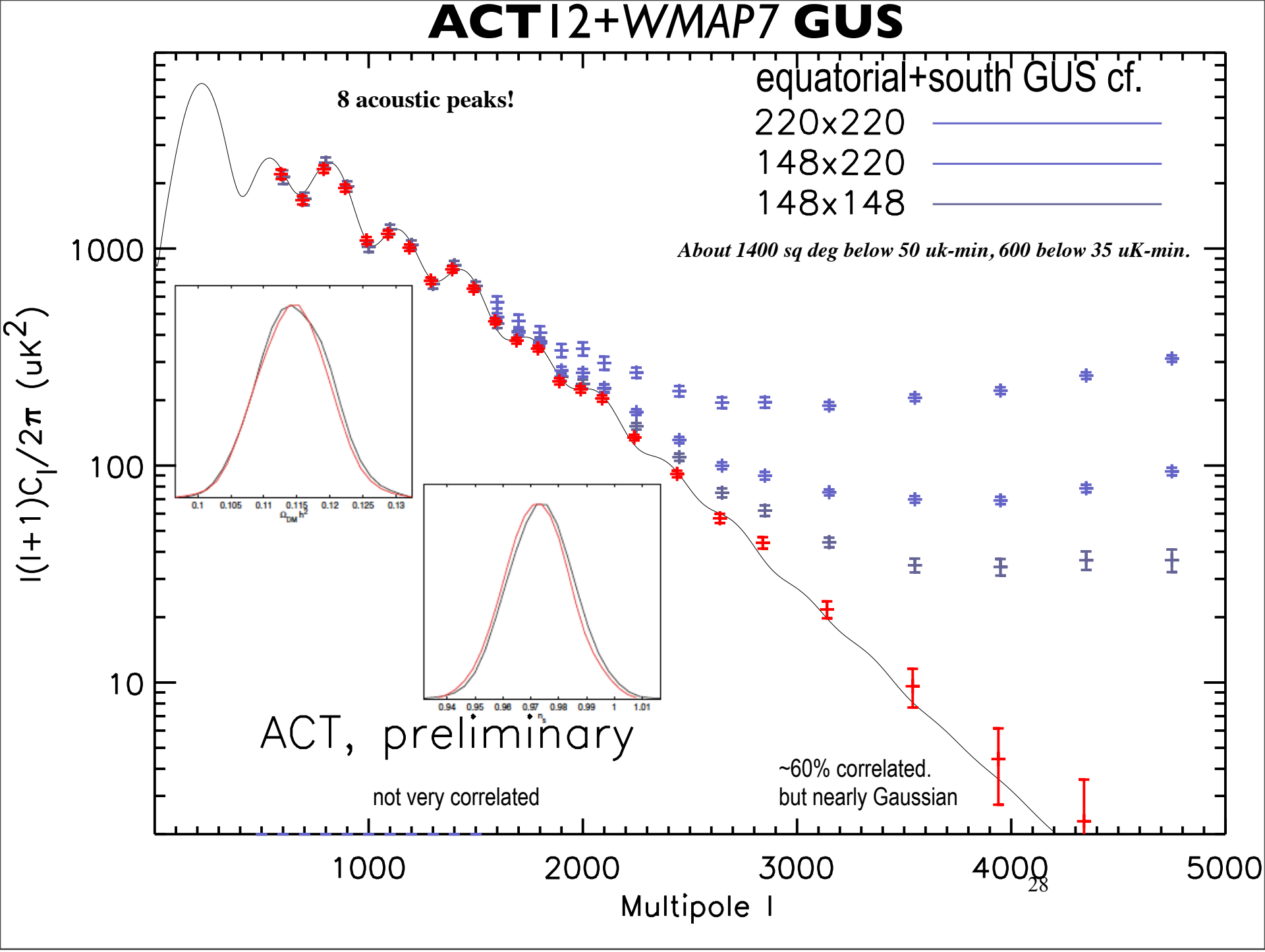
ACT 2D Power Spectrum

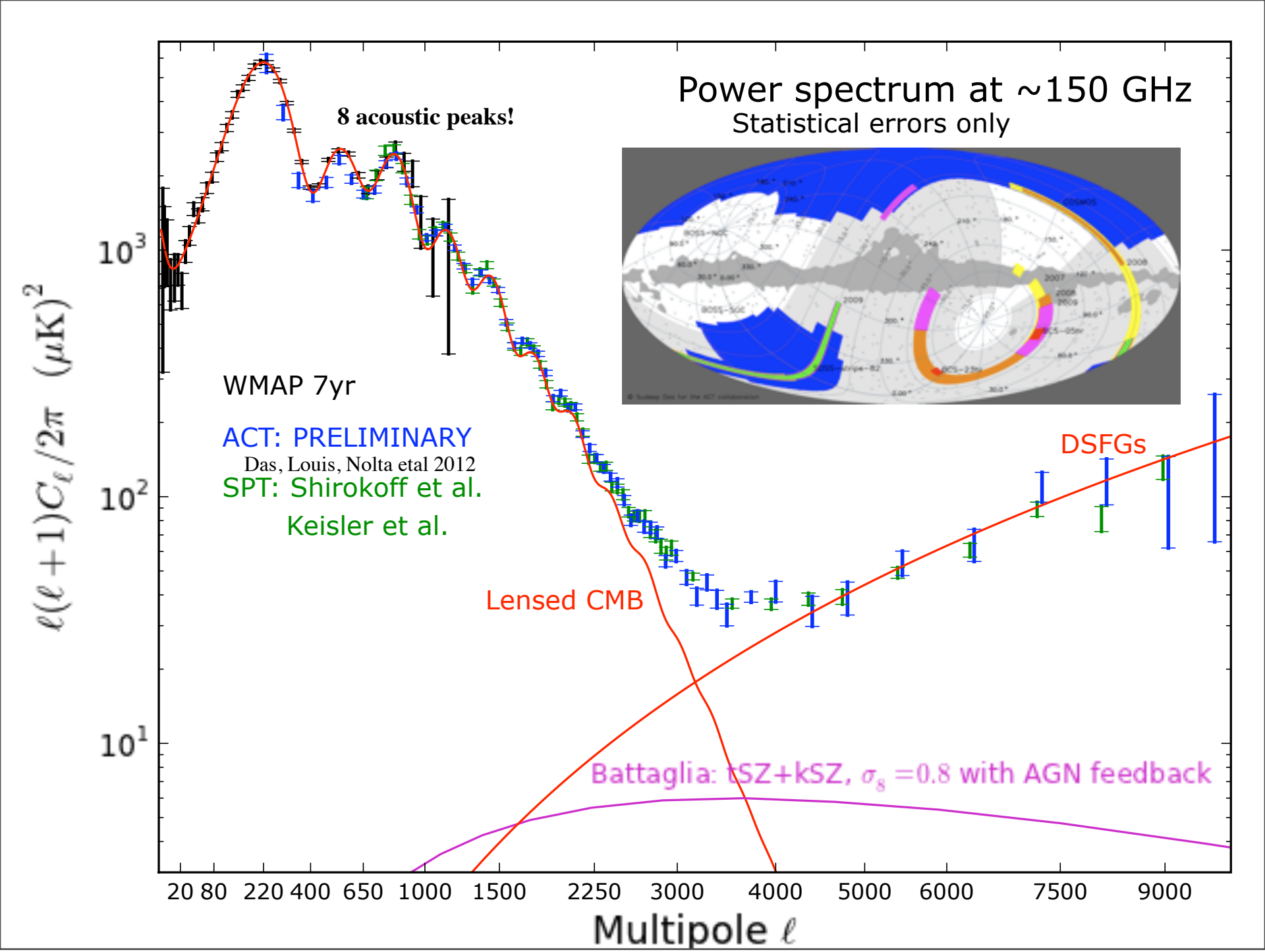
T. Louis and S. Das for the ACT Collab.

ACT+*WMAP7* GUS

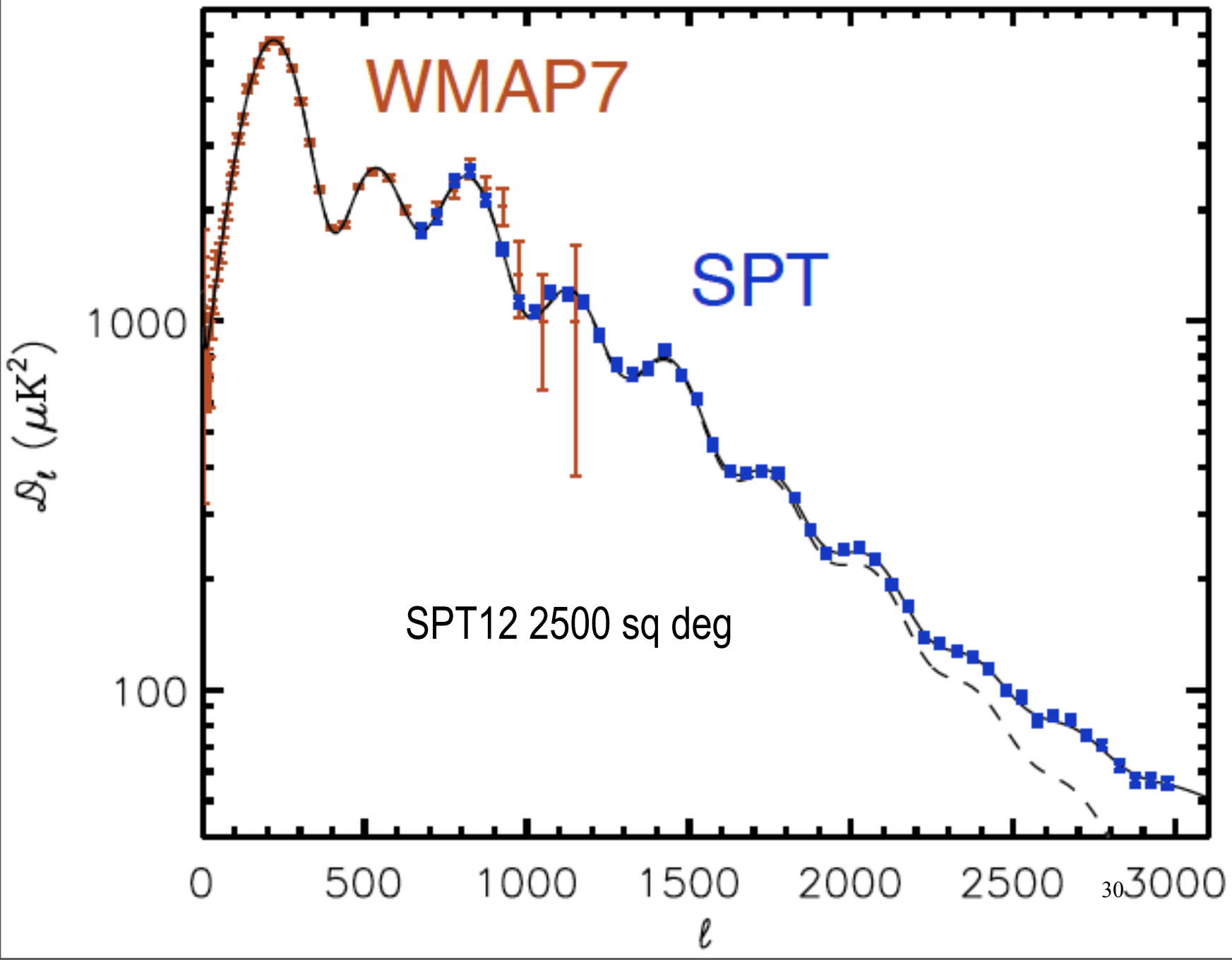


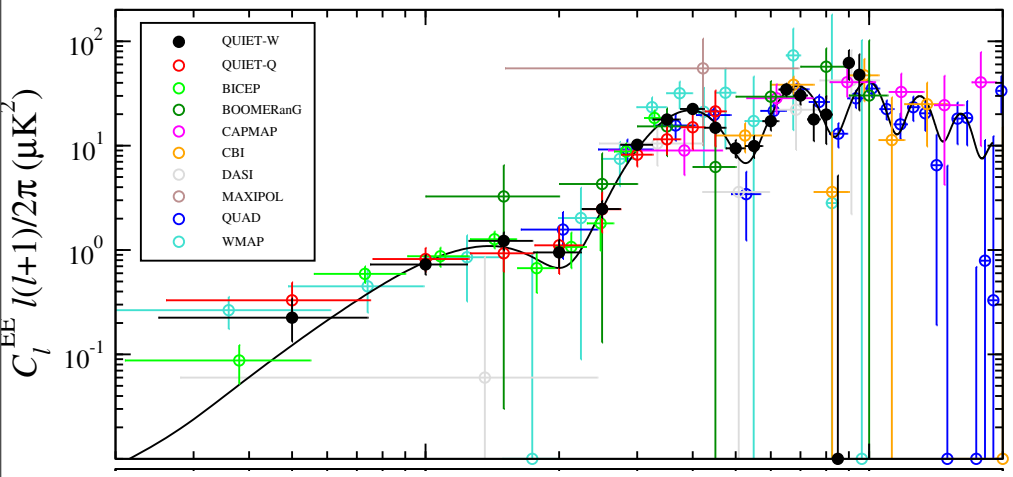
ACT12+*WMAP7* GUS




Power spectrum at ~150 GHz
Statistical errors only
8 acoustic peaks!
WMAP 7yr
ACT: PRELIMINARY
Das, Louis, Nolta etal 2012
SPT: Shirokoff et al.
Keisler et al.
DSFGs
Lensed CMB
Battaglia: tSZ+kSZ, $\sigma_8 = 0.8$ with AGN feedback
$\ell(\ell+1)C_\ell/2\pi \quad (\mu K)^2$
10^3
10^2
10^1
20 80 220 400 650 1000 1500 2250 3000 4000 5000 6000 7500 9000
Multipole ℓ

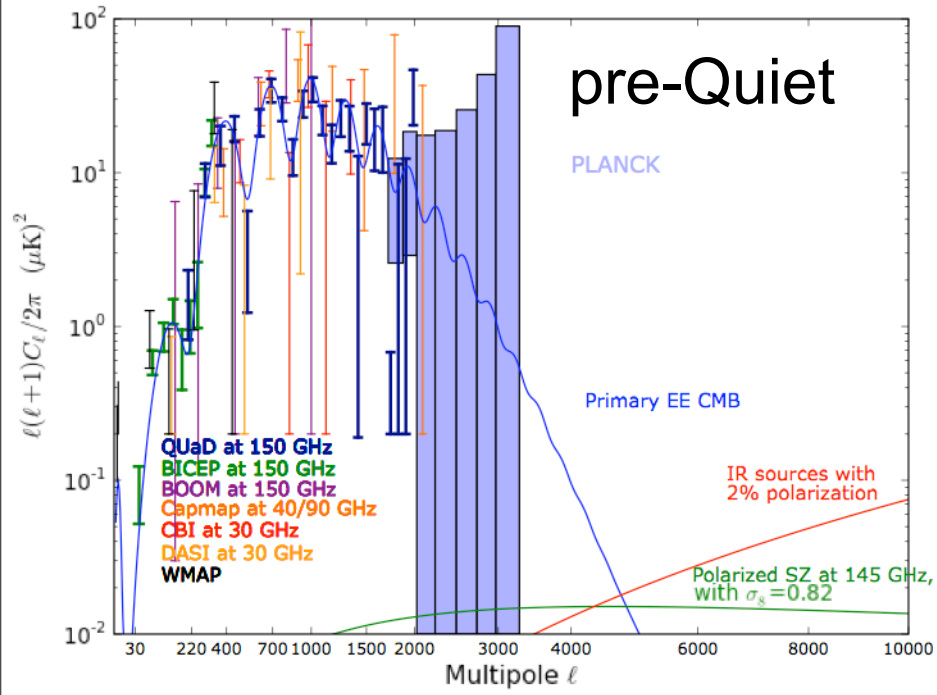
SPT12 1210.7231 Story+12 out Monday **Oct 29!**

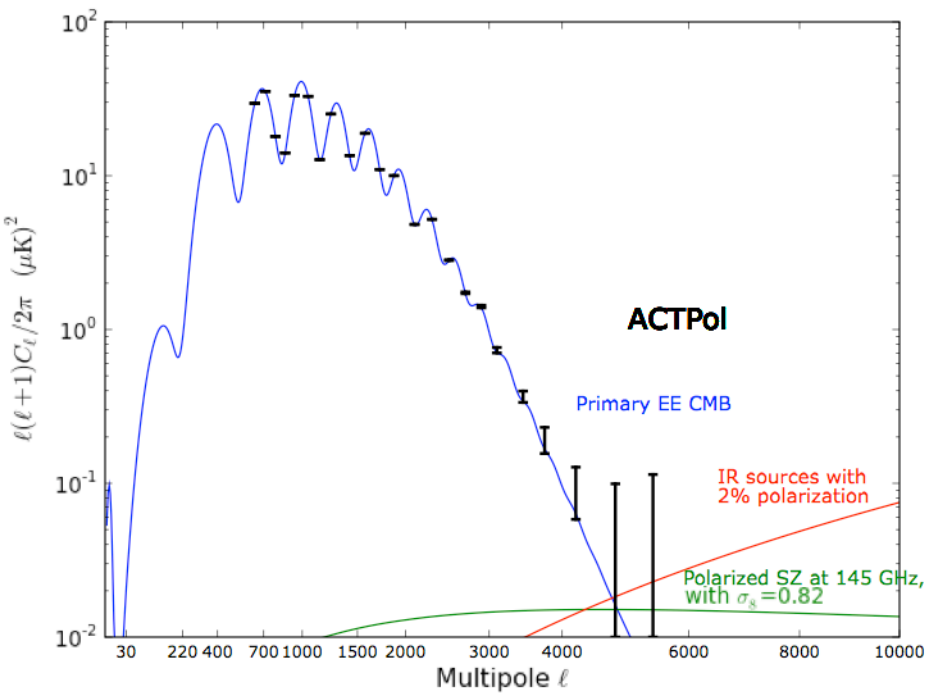




current EE polarization state, including July 2012 Quiet-90 results

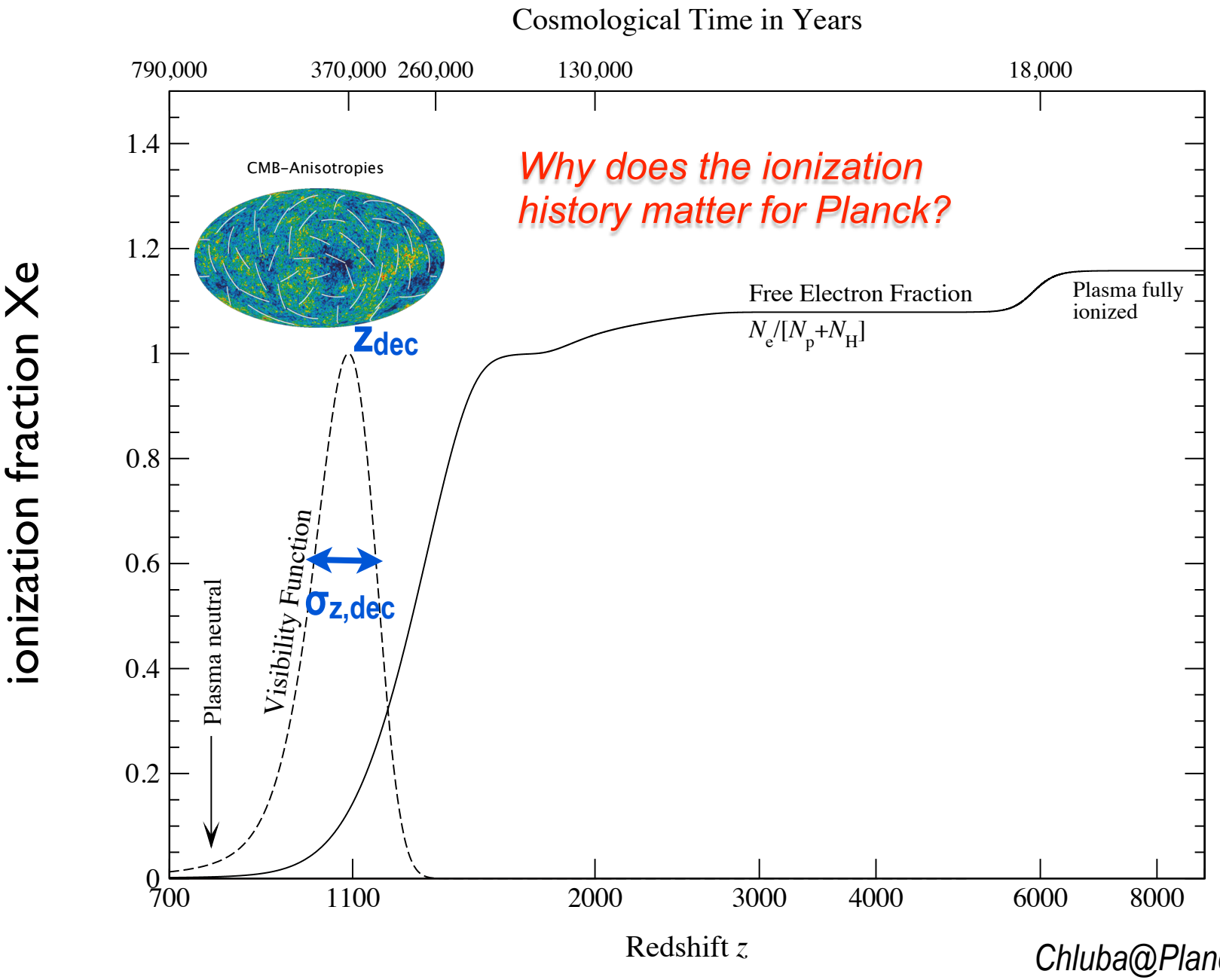
ACTpol forecast. SPTpol similar





CMB is clean in EE polarization to much higher L than TT => ACTpol + SPTpol nicely complement Planck

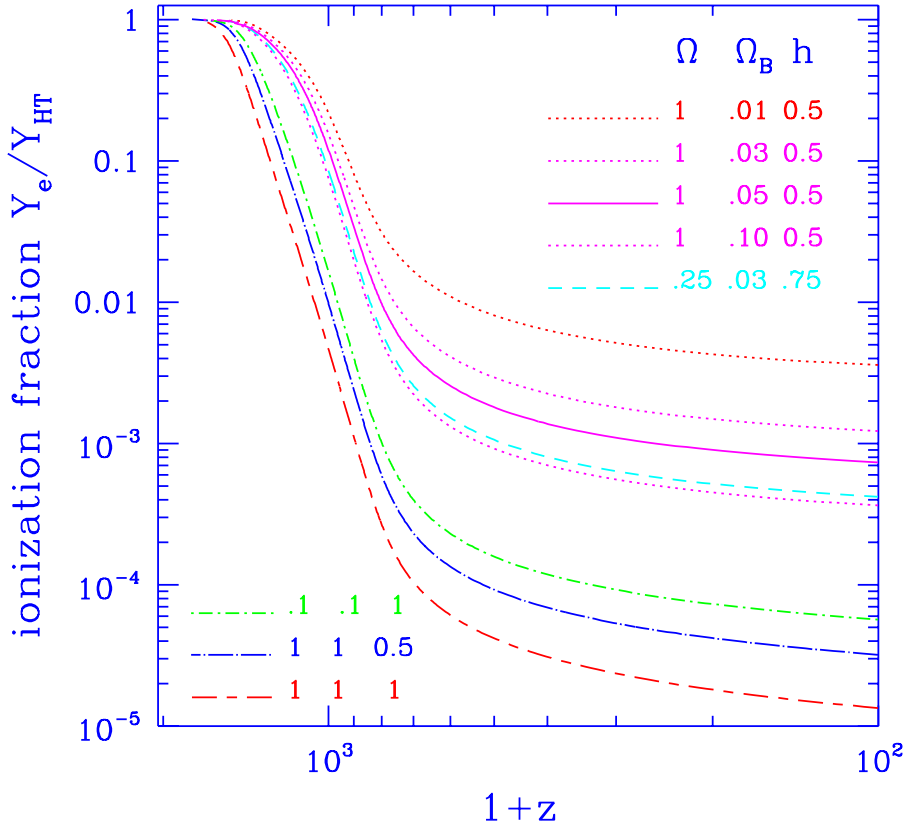
Standard Recombination History

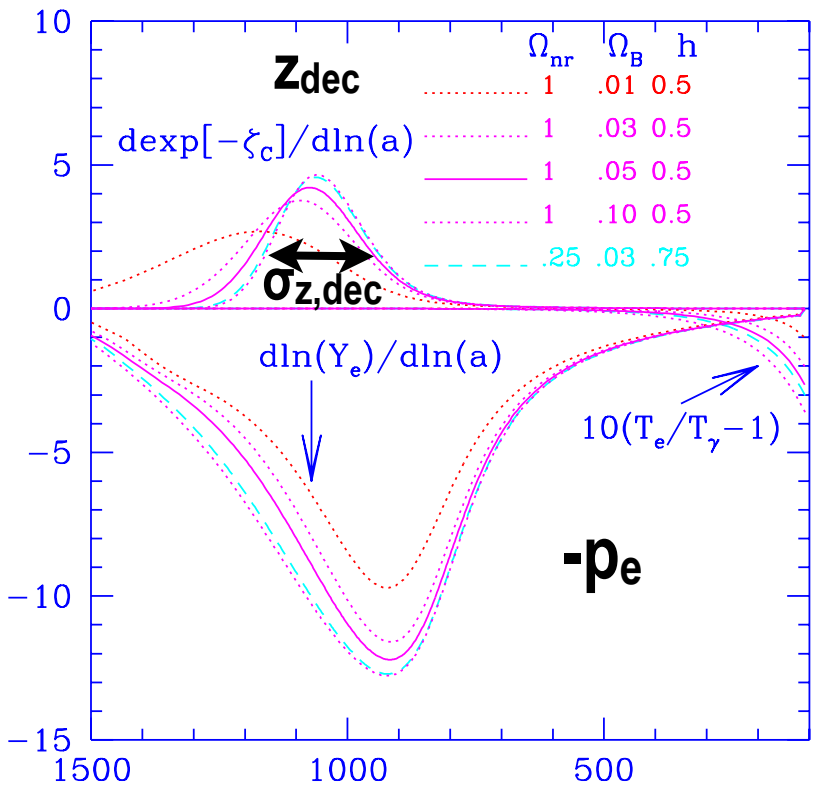


Chluba@Planck2011

Standard Recombination History

KSZ68,P68 => BE84,B96 => SSS99,00





running of the free electrons-per-baryon $Y_e = n_e/n_b$: $p_e = 3d\ln(n_e/n_b)/d\ln n_b$

p_e *from 0 to 9@dec to max 12 to 0*

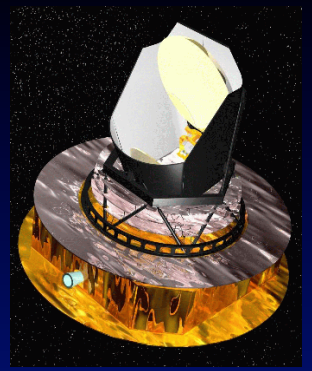
differential visibility = running of the visibility $n_e\sigma_T/H\ exp[-\int n_e\sigma_T/H\ d\ln a]$

kinematic shear viscosity $4/15 C_s^2/n_e\sigma_T$ thermal diffusion $n_b S_\gamma/n_e\sigma_T$

$C_L \sim exp[-(L/L_D)^{m_D}]$ damping envelope $m_D \sim 1.26$, $L_D \sim 1350$ *(6' fwhm)*

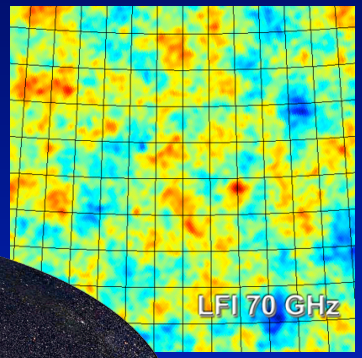
WKB baryon-photon tight coupling $L_D \sim (p_e + 2)(1+z_{dec})^{1/2} \sim (1+z_{dec})^{1/2}/\sigma_{z,dec}$

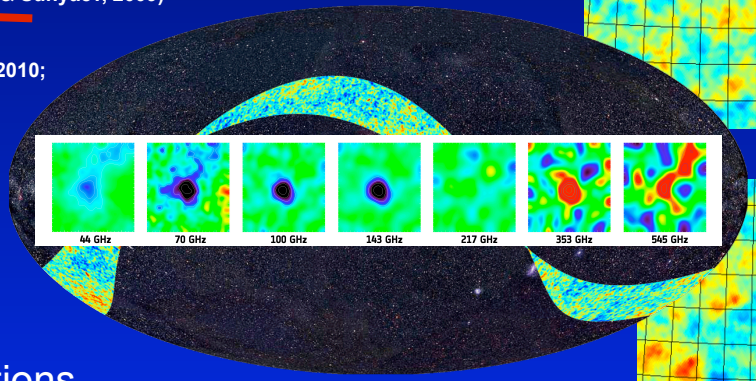
Getting Ready for Planck

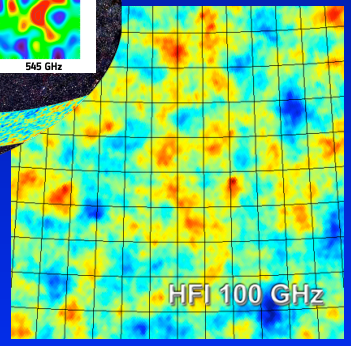


Hydrogen recombination

- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the 1s-2s two-photon absorption rate
  (Kholupenko & Ivanchik, 2006, Astr. Lett.; Fendt et al. 2008; Hirata 2008)
- Non-equilibrium effects in the angular momentum sub-states
  (Rubiño-Martín, JC & Sunyaev, 2006, MNRAS; JC, Rubiño-Martín & Sunyaev, 2007, MNRAS; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010)
- Feedback of Lyman-series photons (Ly[n] → Ly[n-1])
  (JC & Sunyaev, 2007, A&A; Kholupenko et al. 2010; Haimoud, Grin & Hirata, 2010)
- Lyman-α escape problem (*atomic recoil, time-dependence, partial redistribution*)
  (Dubrovich & Grachev, 2008; JC & Sunyaev, 2008; Forbes & Hirata, 2009; JC & Sunyaev, 2009)
- Collisions and Quadrupole lines
  (JC, Rubiño-Martín & Sunyaev, 2007; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010; JC, Fung & Switzer, in prep.)
- Raman scattering
  (Hirata 2008; JC & Thomas , 2010; Haimoud & Hirata, 2010)







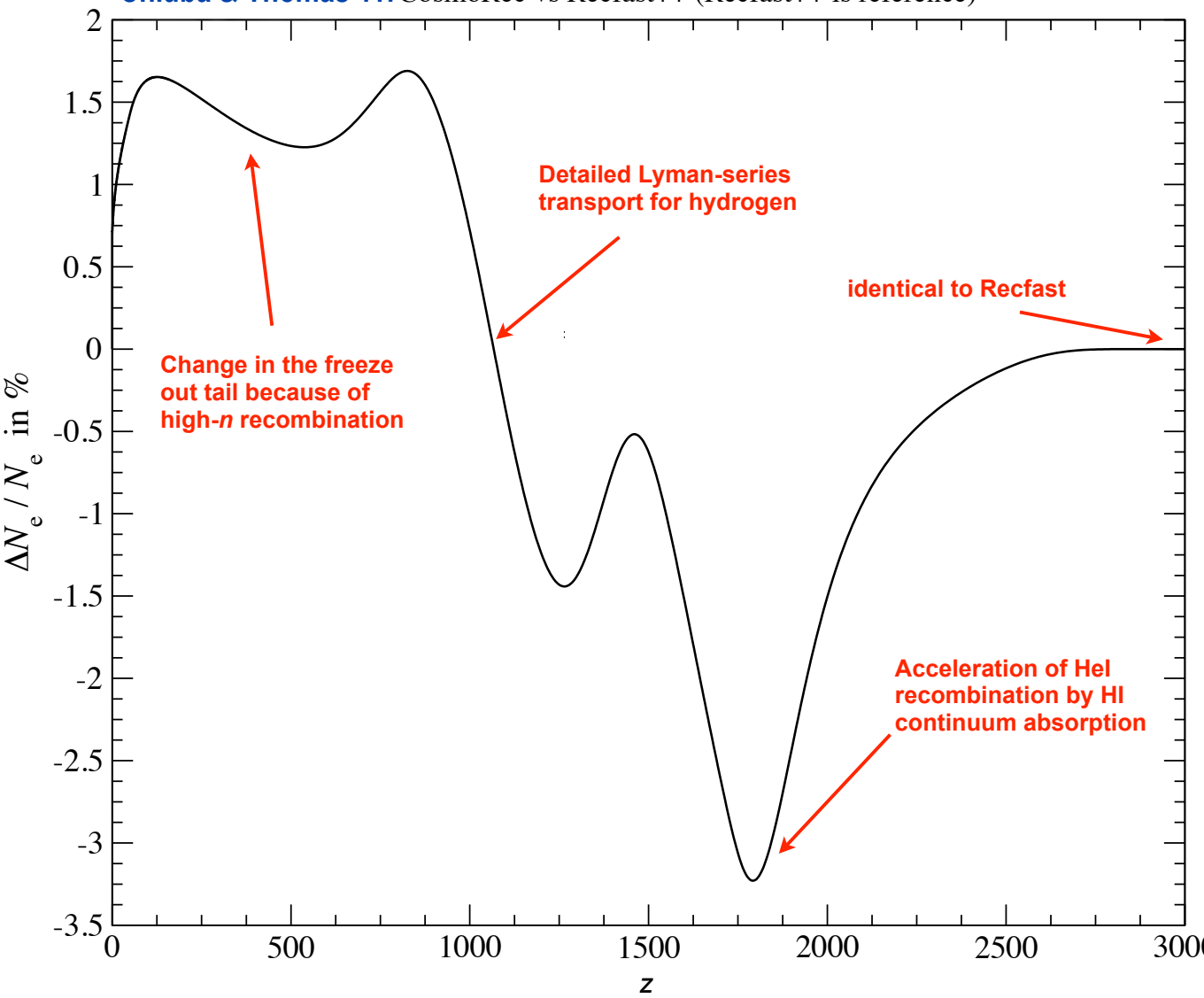
Helium recombination

- Similar list of processes as for hydrogen
  (Switzer & Hirata, 2007a&b; Hirata & Switzer, 2007)
- Spin forbidden 2p-1s triplet-singlet transitions
  (Dubrovich & Grachev, 2005, Astr. Lett.; Wong & Scott, 2007; Switzer & Hirata, 2007; Kholupenko, Ivanchik&Varshalovich, 2007)
- Hydrogen continuum opacity during He I recombination
  (Switzer & Hirata, 2007; Kholupenko, Ivanchik & Varshalovich, 2007; Rubiño-Martín, JC & Sunyaev, 2007)
- Detailed feedback of helium photons
  (Switzer & Hirata, 2007a; JC & Sunyaev, 2009, MNRAS)

$\Delta N_e \,/\, N_e \sim 0.1\,\%$

exhaustive study of the recombination physics has been done: *Rubino-Martin, Chluba, Switzer, Grin, Ali-Haimoud, Hirata,Dubrovich, Kholupenko, Grachev, Scott, Wong, Moss, cf. Seager, Sasselov, Scott (Recfast) cf. Zeldovich, Sunyaev, Kurt, Peebles, Bond, Efstathiou,*

Chluba & Thomas 11: CosmoRec vs Recfast++ (Recfast++ is reference)



accurate modeling for PlanckExt

to get 0.1-1% in parameter accuracy

=> 0.1-1% accuracy in $x_e(z\sim1100)$ needed

Planck (Chluba & Thomas 11):
-3.2σ bias in n_S
-2.1σ in $\Omega_b h^2$
CV-limited expt l ≤ 2000:
-7.4σ bias in n_S
-5.2 σ in $\Omega_b h^2$

CAMB now has an approximation to COSMOrec & HyRec

BUT what if there are: ***more recomb-corrections*** or **dark matter annihilation** or ***variation of fundamental constants*** or ***collision-corrections*** or ***?***

=> perturbative semi-blind eigen-analysis ***fbc11,fbsc12***

Fisher information matrix, a weight matrix, the *'PRECISION'*:

$F_{ij} = \langle \partial s_f/\partial q^i \; \partial s_f/\partial q^j \rangle_f = \langle \partial ln p_f/\partial q^i \; \partial ln p_f/\partial q^j \rangle_f$

= average entropy-content fluctuations $s = ln p^{-1}$ entropy= $\langle s \rangle_f$

Fisher $^{-1}$ = correlation matrix if Gaussian

Principal Component Analysis (PCA) of x_e-perturbations

$F_{ij} = \sum q^a \, XeM_{ai} \, XeM_{aj}$ ordered by decreasing weight, increasing error. q^a now=amplitude of eigenmode XeM_a

only low order high IQ ones are measurable

decide which ones by relative entropy criteria

saturate redshift space thru recombination with modes (100s)

(***M4 B-splines***, *Chebyshev, triangles, Fourier, Gaussians - doesn't matter which). modes of ln* x_e *uniform in z.*

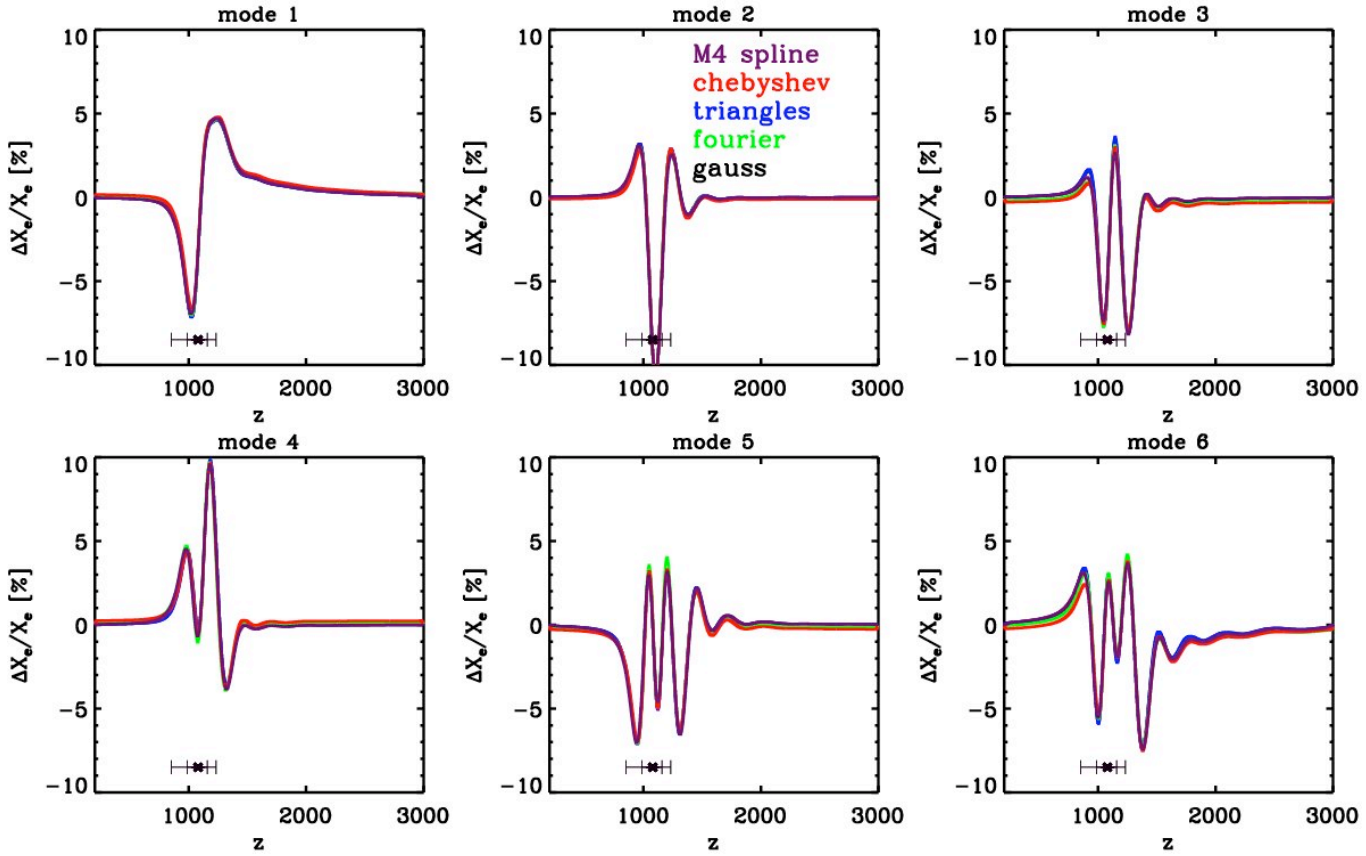
eXeM x_e*-perturbations marginalized over other cosmological parameters*

modify modes to focus on hi-z (Helium) or lo-z (freeze-out tail) recombination region,

e.g., $ln\,(x_e + \sigma_e)$ *fahrang+bond+chluba11,f+b+switzer+c12*

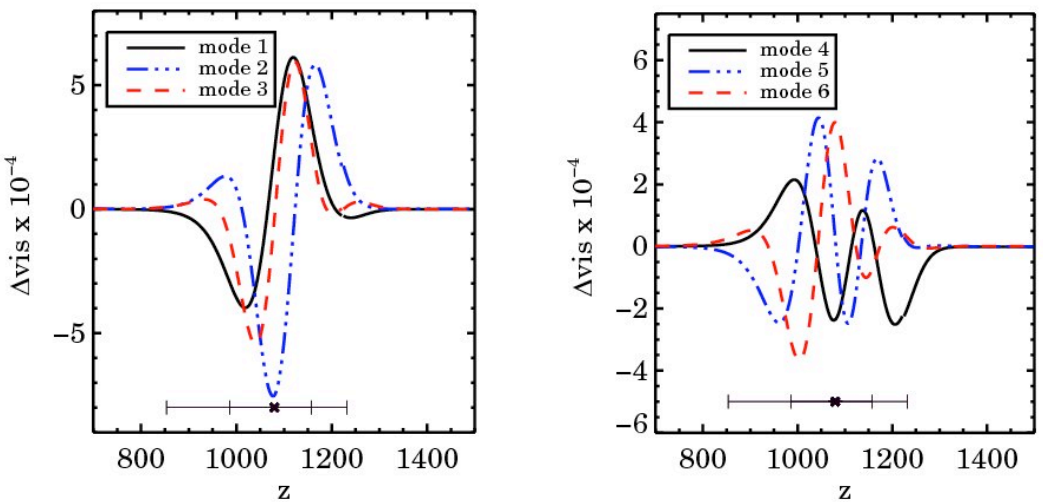
XeMs

$\Delta x_e/x_e$



XeMs in visibility

$\Delta visibility$

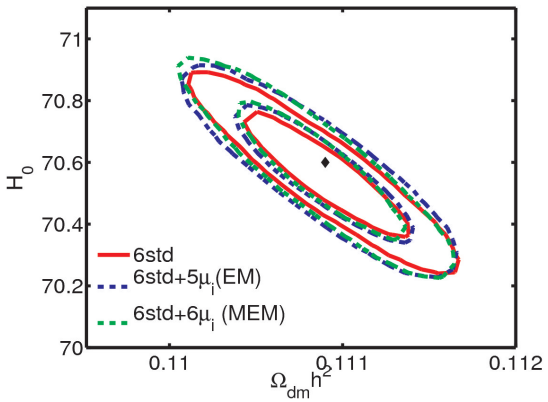


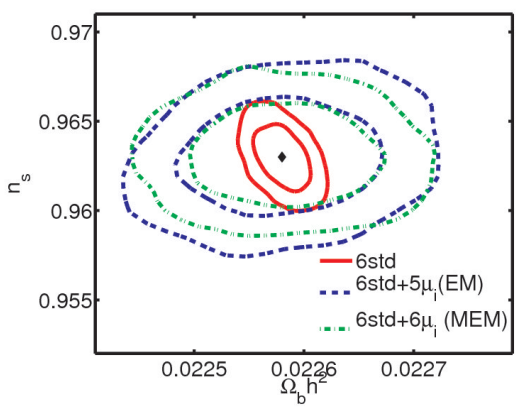
fahrang,bond,chluba*11*

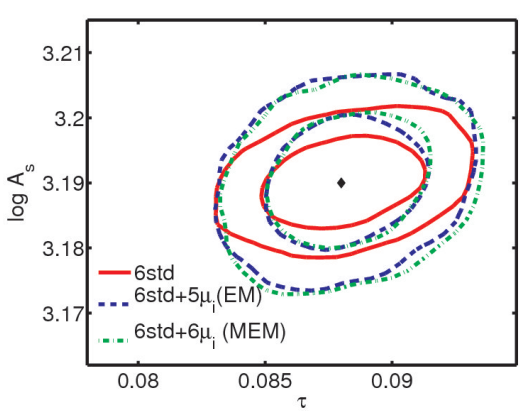
XeM's confirm a correct recombination model

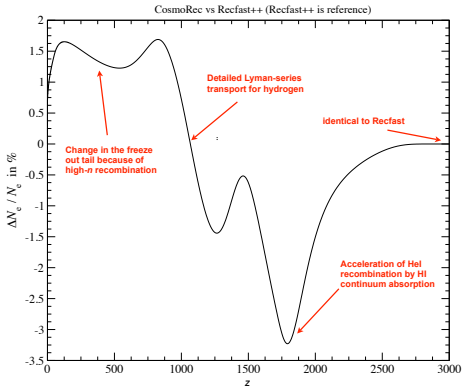
XeM's detect recfast is wrong => cosmorec change

ideal CVL expt.





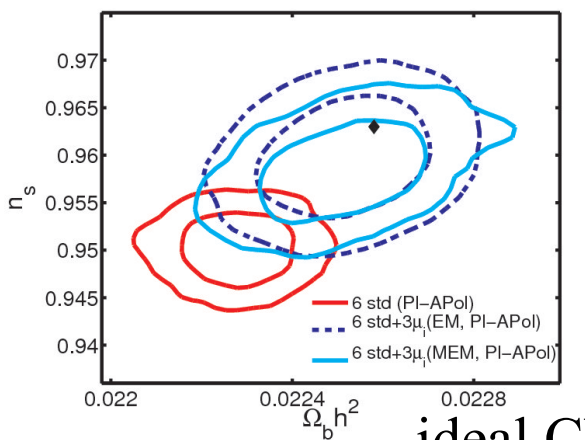


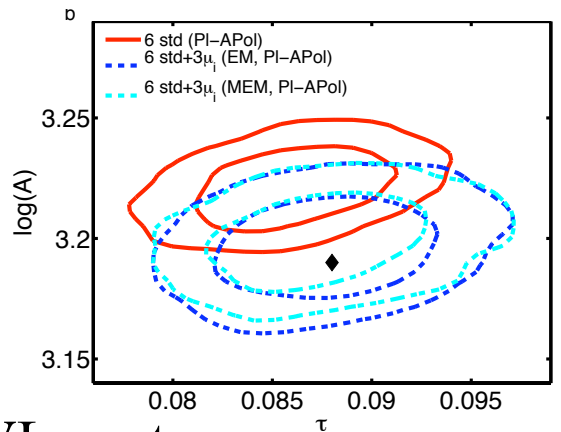


Chluba & Thomas, 2011

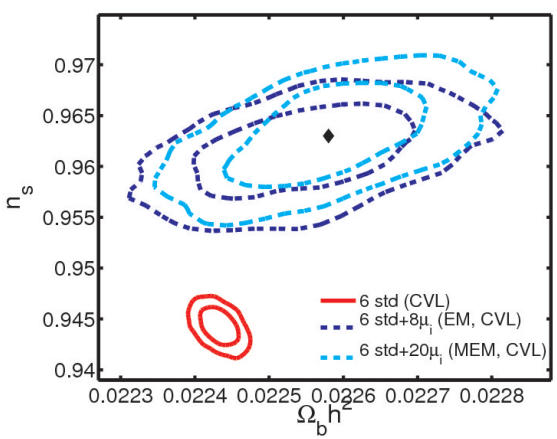
Planck+ACTPol-like

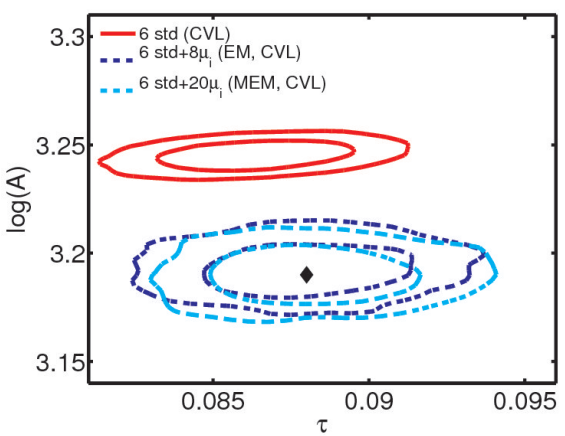
fahrang**,bond,chluba**11





ideal CVL expt.





Reconstructed x_e-perturbations

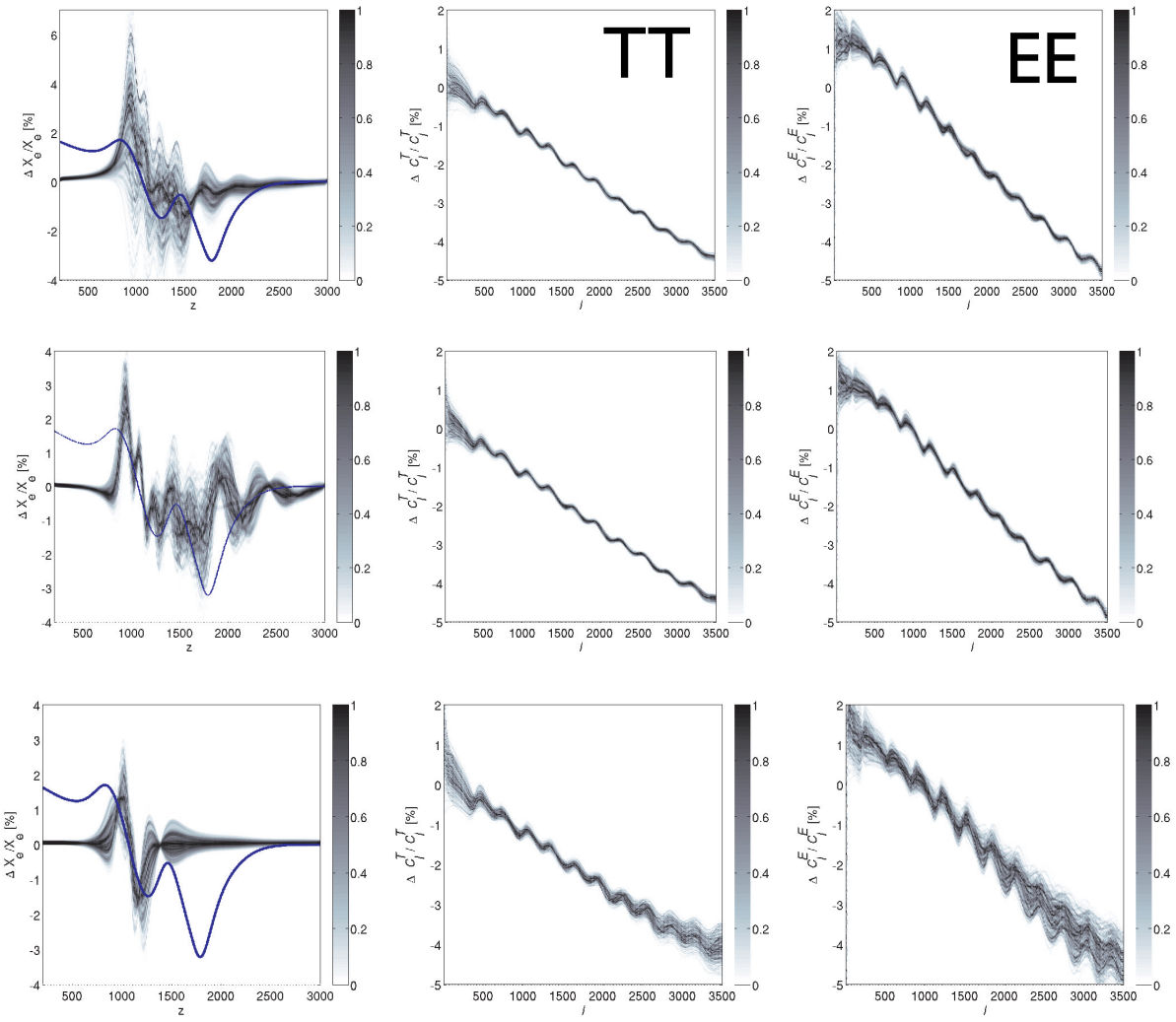
Helium recombination correction is not visible

Recombination correction is 'recovered

ideal expt
6 XeMs

ideal expt
10 eXeMs

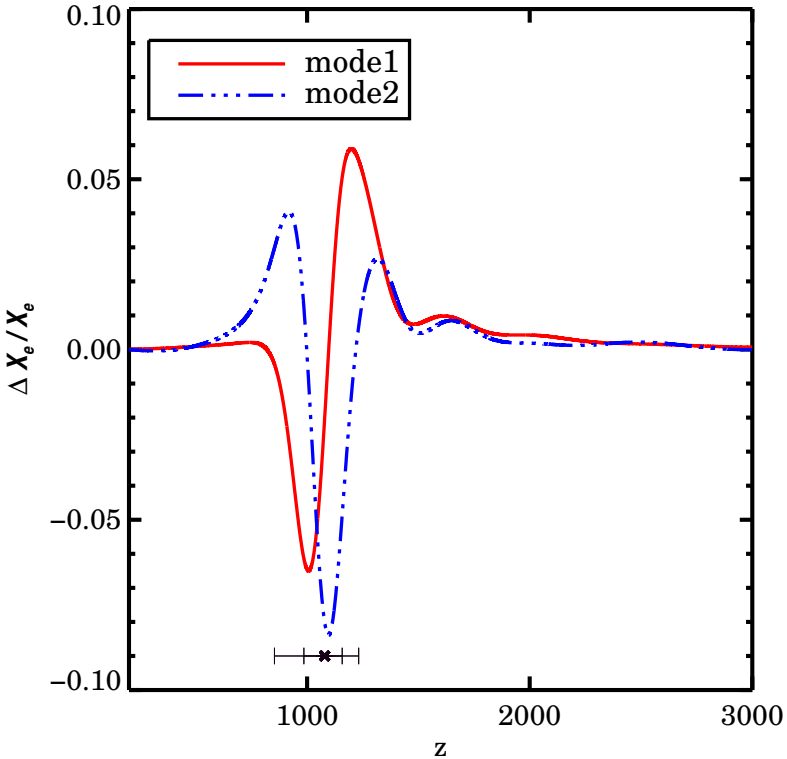
Planck+ACT/SPTPol-like
3 eXeMs

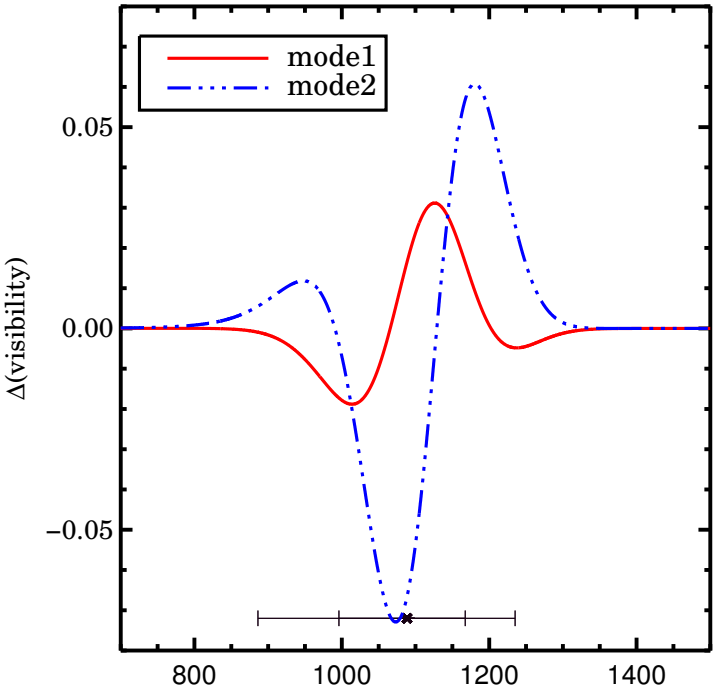


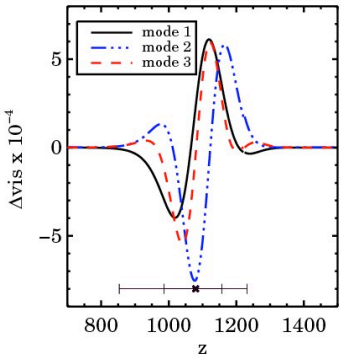
characteristic $\Delta C_L/C_L$ shape = perturbed damping tail

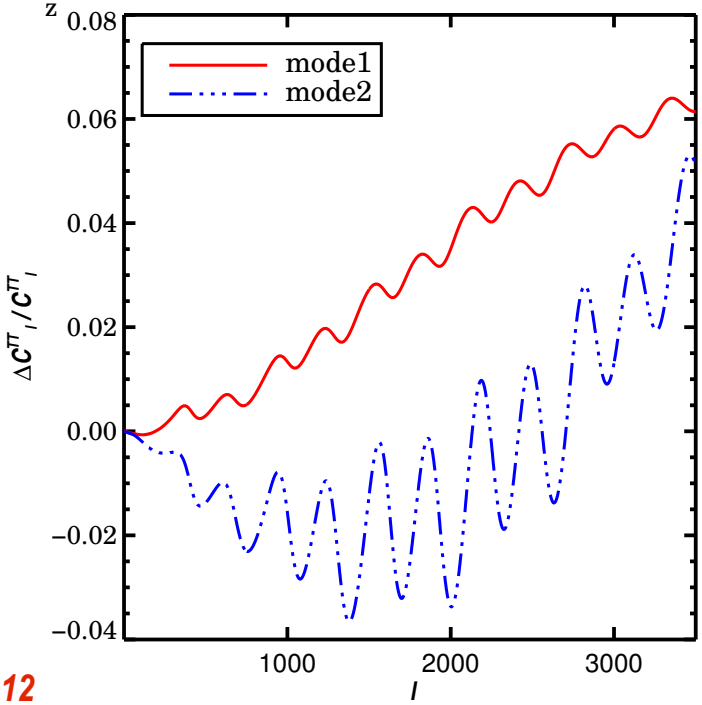
fahrang,bond,chluba*11*

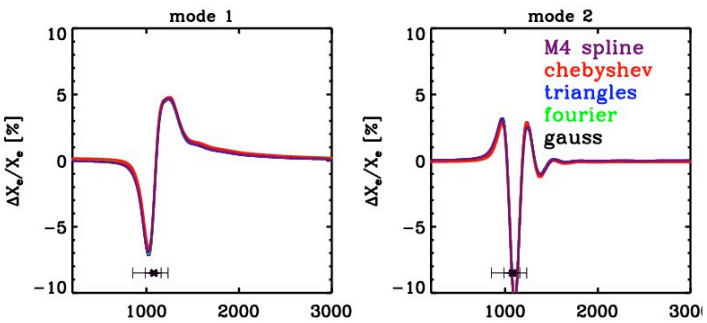
WMAP7+SPT11 2 XeMs



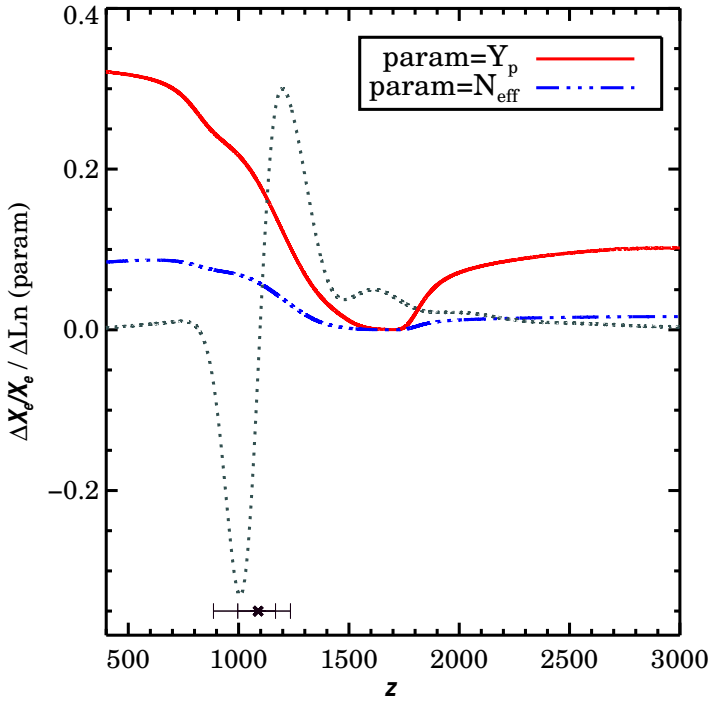


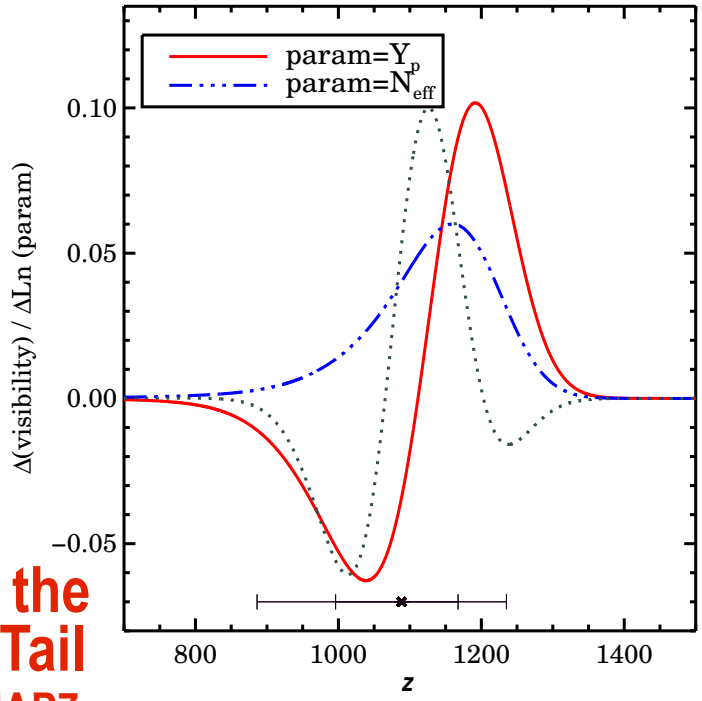






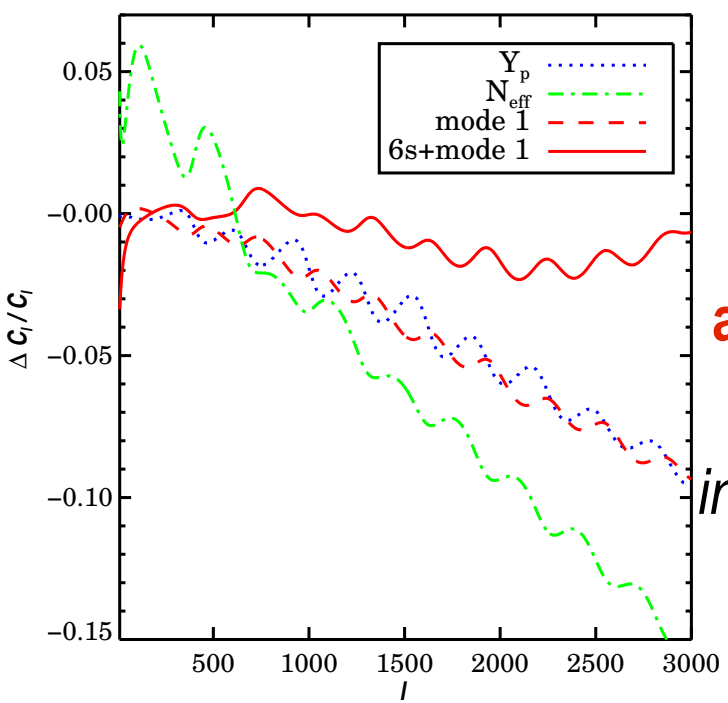
fahrang, *bond,* ***switzer,*** *chluba* ***12***

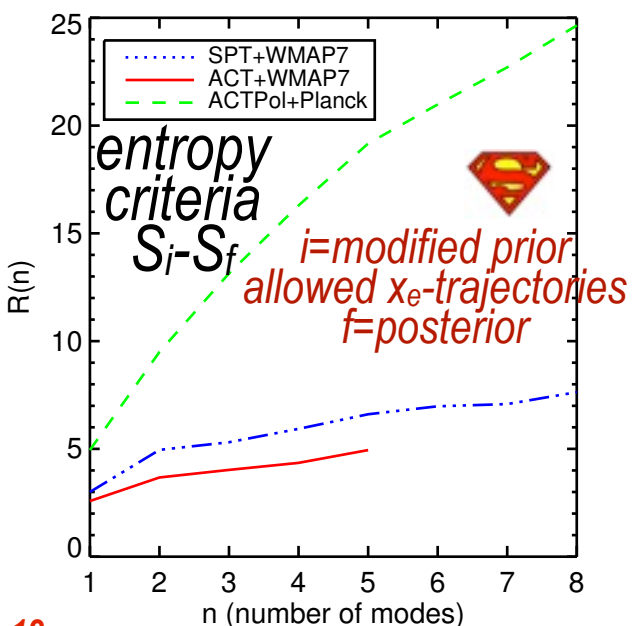




Probes of the Damping Tail
SPT11+WMAP7:
Y_P=.30 *cf.* **.25**
N_{eff}=4 *cf.* **3.06**

1st XeM also shows the damping tail anomaly *in ACT12,SPT12, Planck?*





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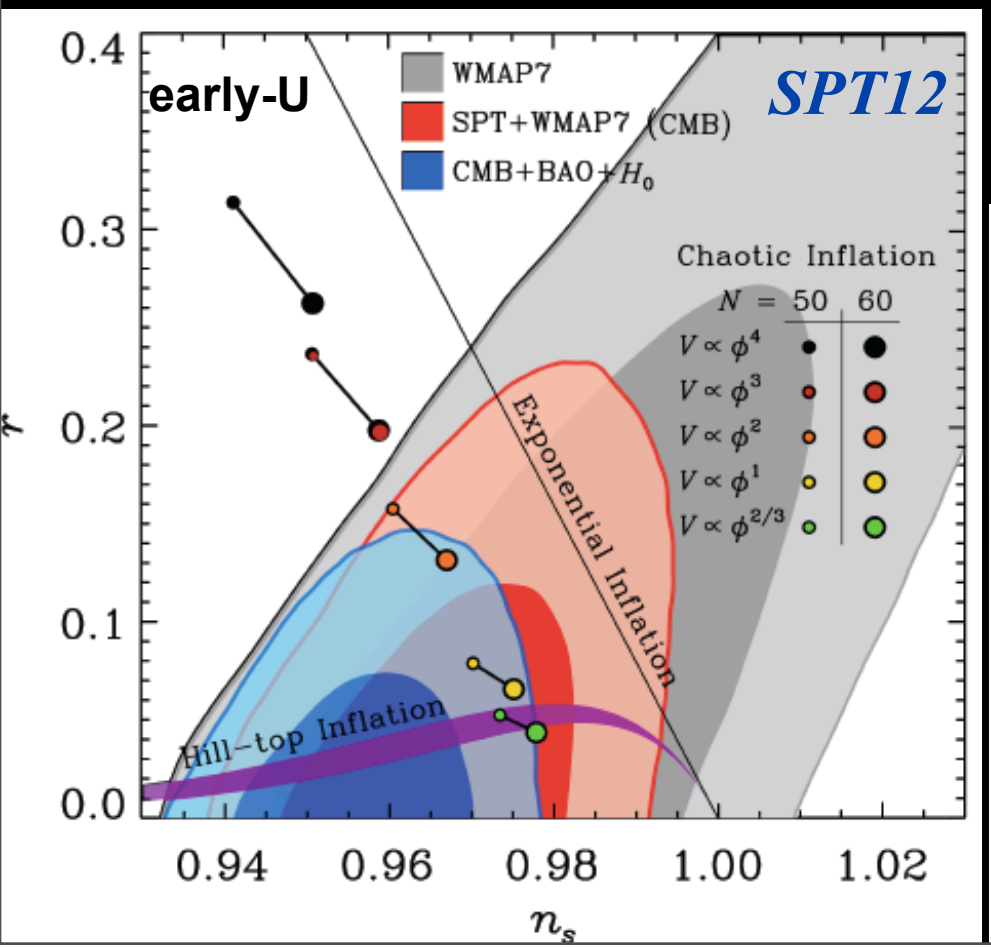
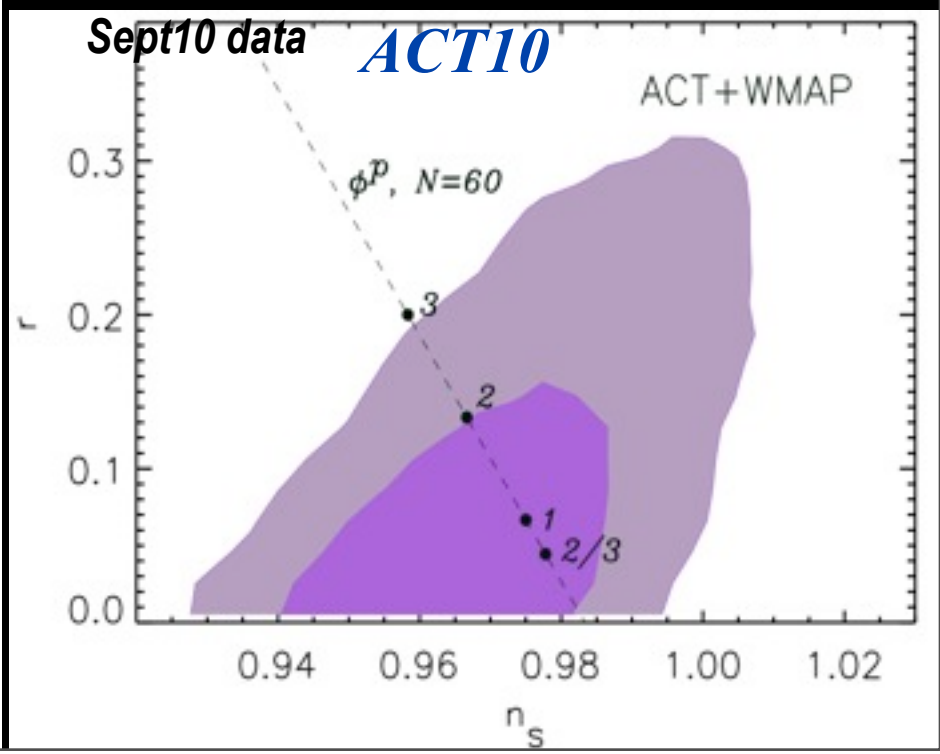
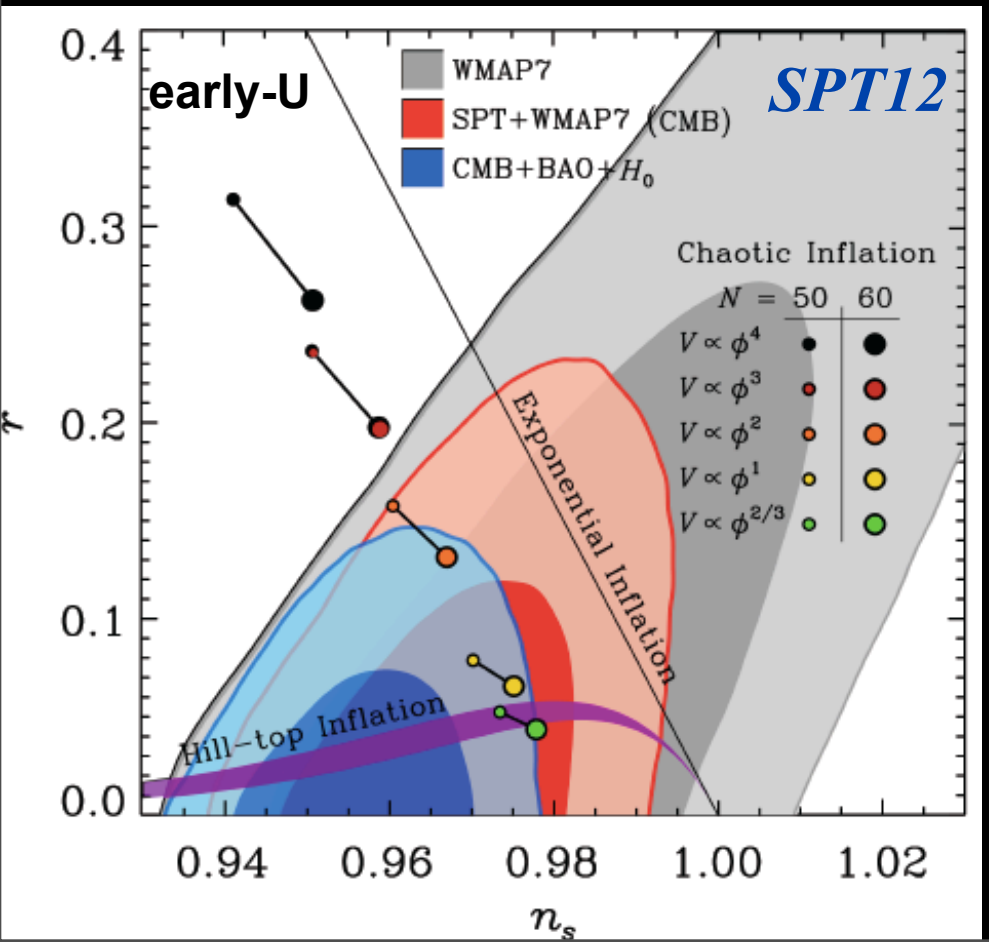
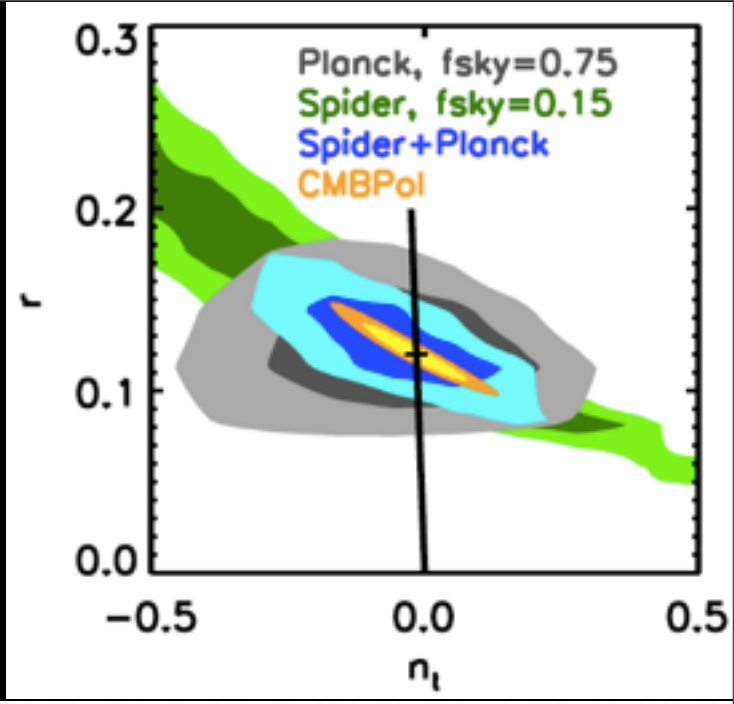
13.7-10^{-50}Gyrs **13.7Gyrs** **10Gyrs** today

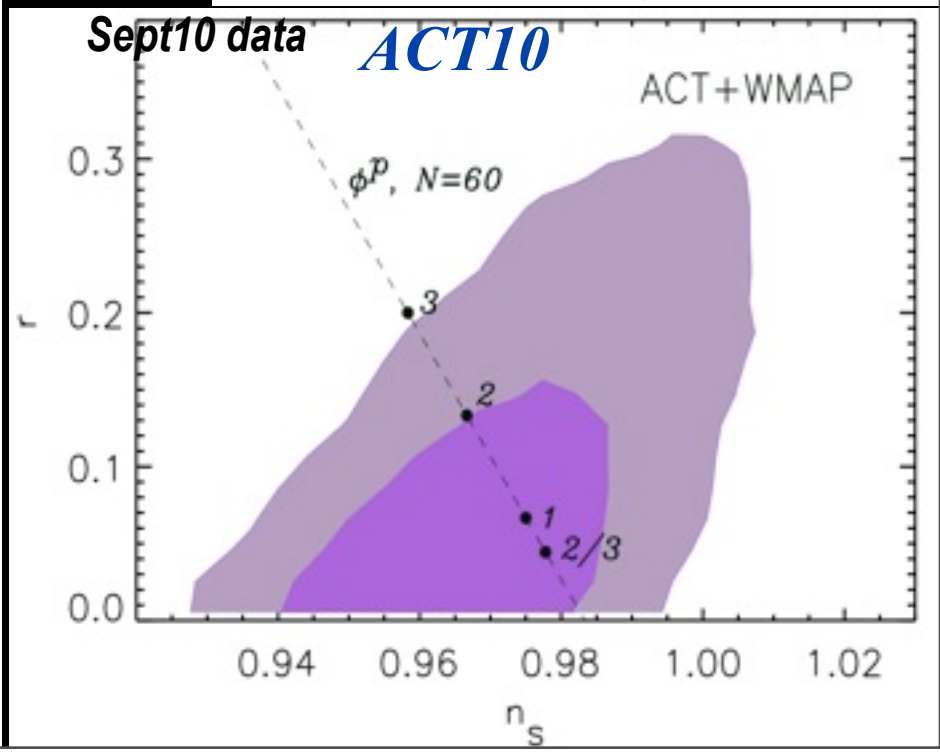

early-U
WMAP7
SPT+WMAP7 (CMB)
CMB+BAO+H_0
SPT12
Chaotic Inflation
N = 50 60
$V \propto \phi^4$
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^1$
$V \propto \phi^{2/3}$
Exponential Inflation
Hill-top Inflation
0.4
0.3
0.2
0.1
0.0
r
0.94
0.96
0.98
1.00
1.02
n_s


Sept10 data
ACT10
ACT+WMAP
ϕ^p, N=60
3
2
1
2/3
0.3
0.2
0.1
0.0
r
0.94
0.96
0.98
1.00
1.02
n_s

Farhang, Bond, Dore, Netterfield 11/12





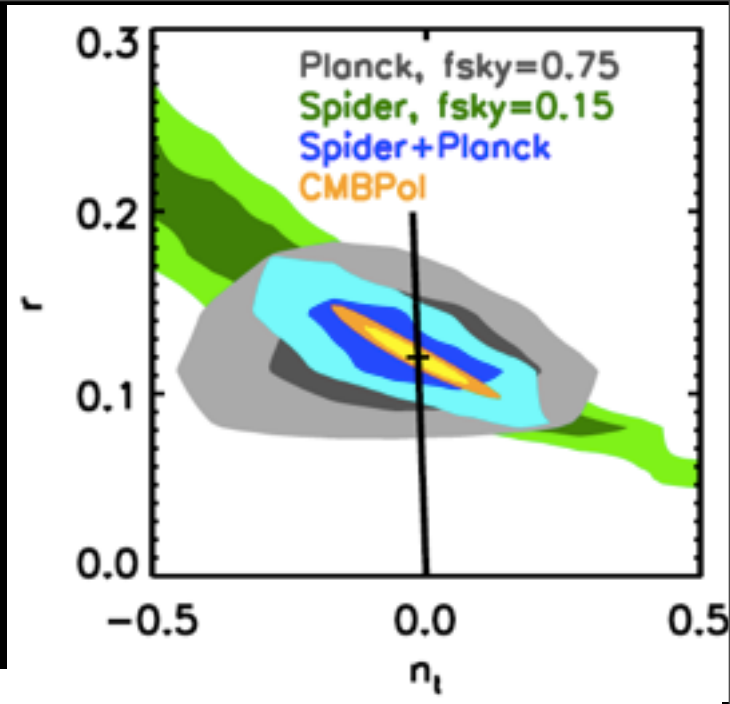


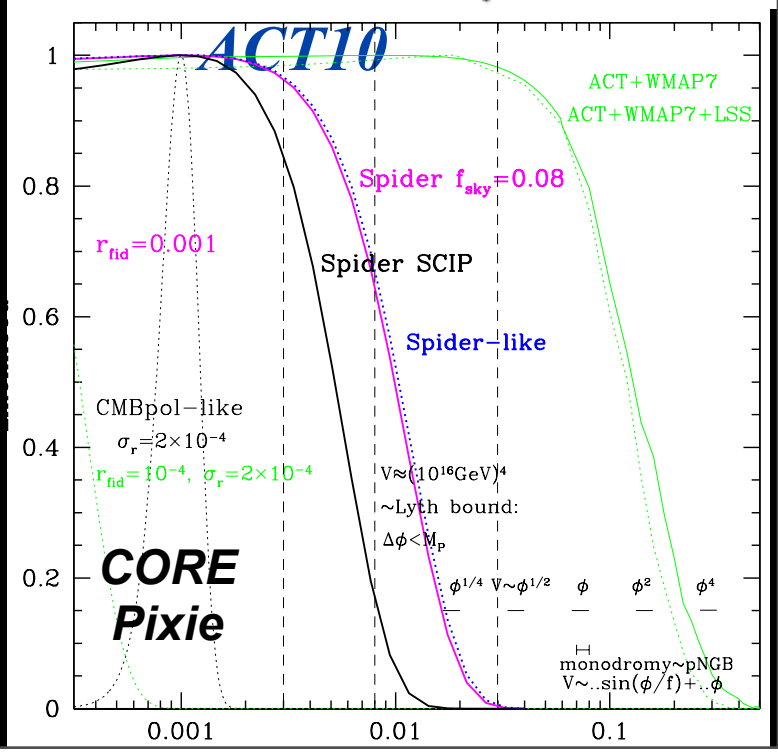
Farhang, Bond, Dore, Netterfield 11/12

Spider24days+Planck2.5yr:
r-n_t *matrix*-forecast
for r=0.12 input for $m^2\varphi^2$
($2\sigma_r$ ~0.02 including fgnds)

*similar r-forecasts for **ABS+/VIP, Quiet***

inflation consistency
$$-n_t \approx r/8 \approx 2\varepsilon(k)$$
$$1-n_s \approx 2\varepsilon + d\ln\varepsilon/d\ln Ha$$





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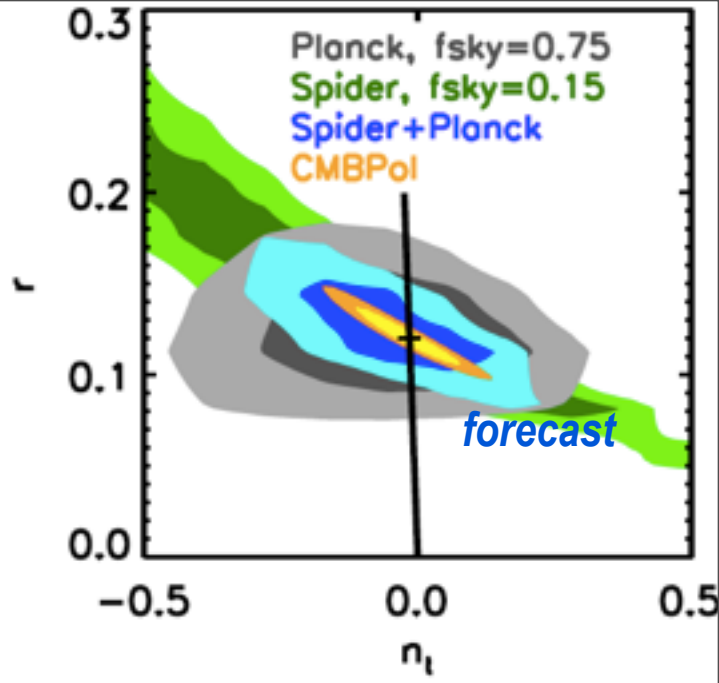

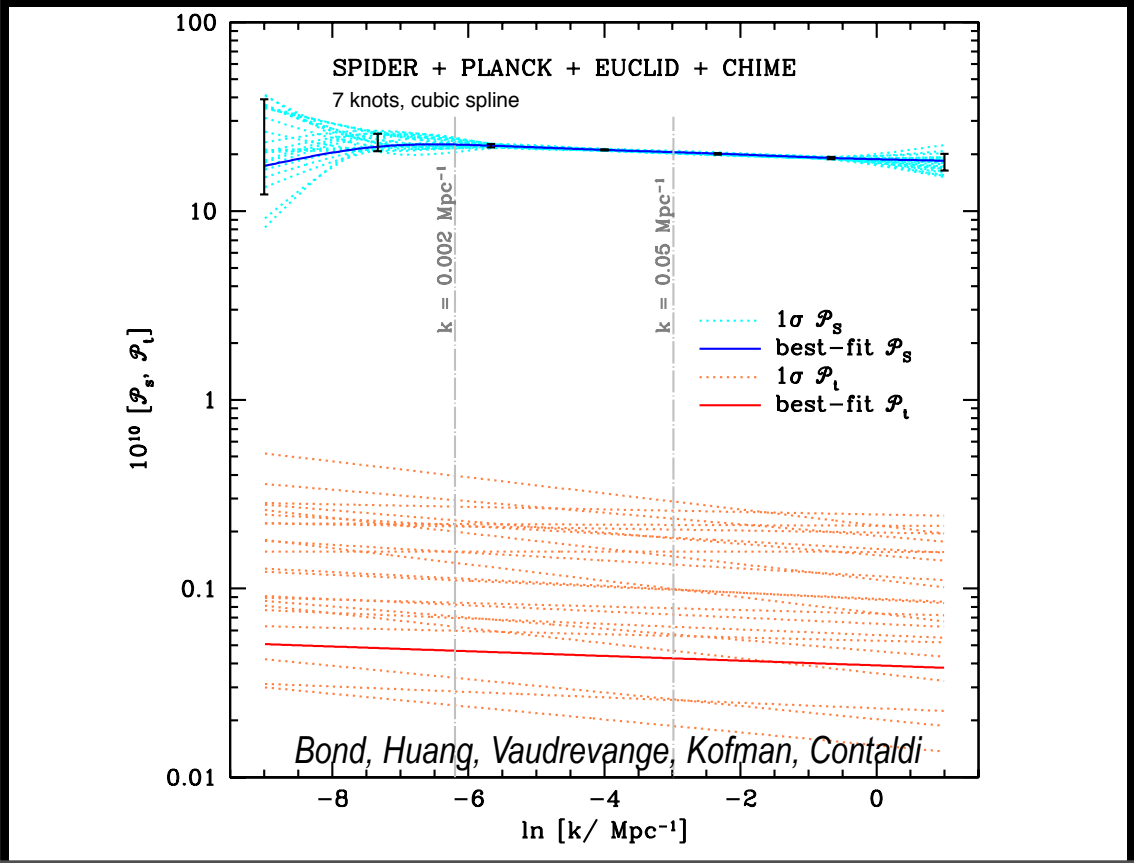

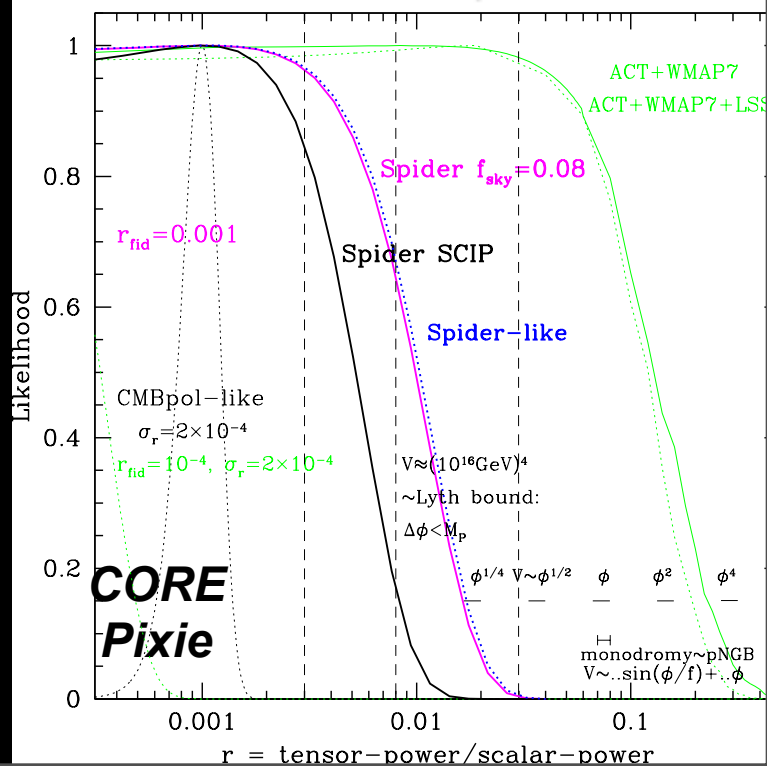

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- polarization $\pi\gamma$
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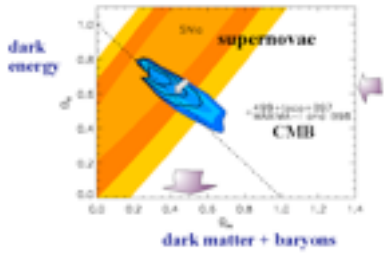


future fate of

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

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

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

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

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

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

late-inflaton DE trajectories $(1+w_{de}) = -\, d\ln p_{de} / d\ln a^3$

Ω_Λ: ± 0.012 =>± 0.001 (Pext)

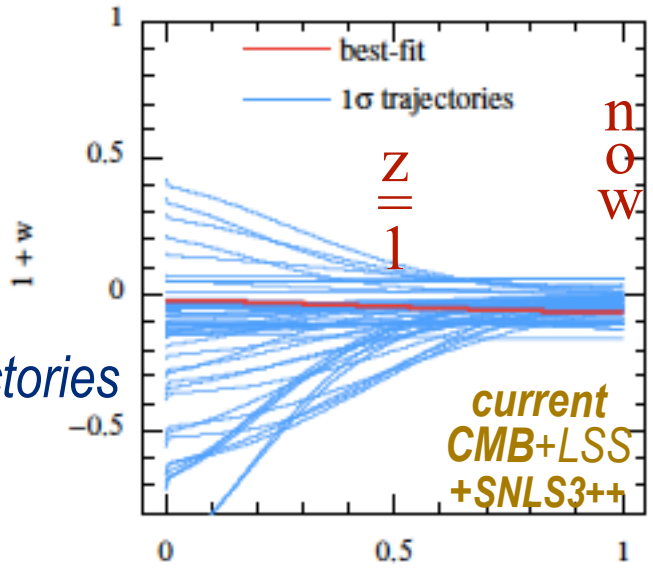
w_0: ± 0.06 =>± 0.01 (Pext) (± 0.14 =>± 0.03 if w_a)

$\varepsilon_s = \ln V\text{-slope}^2/4$ 0.0± 0.18 =>± 0.03 (Pext)

+2 other w-trajectory parameters BHK11,BH12

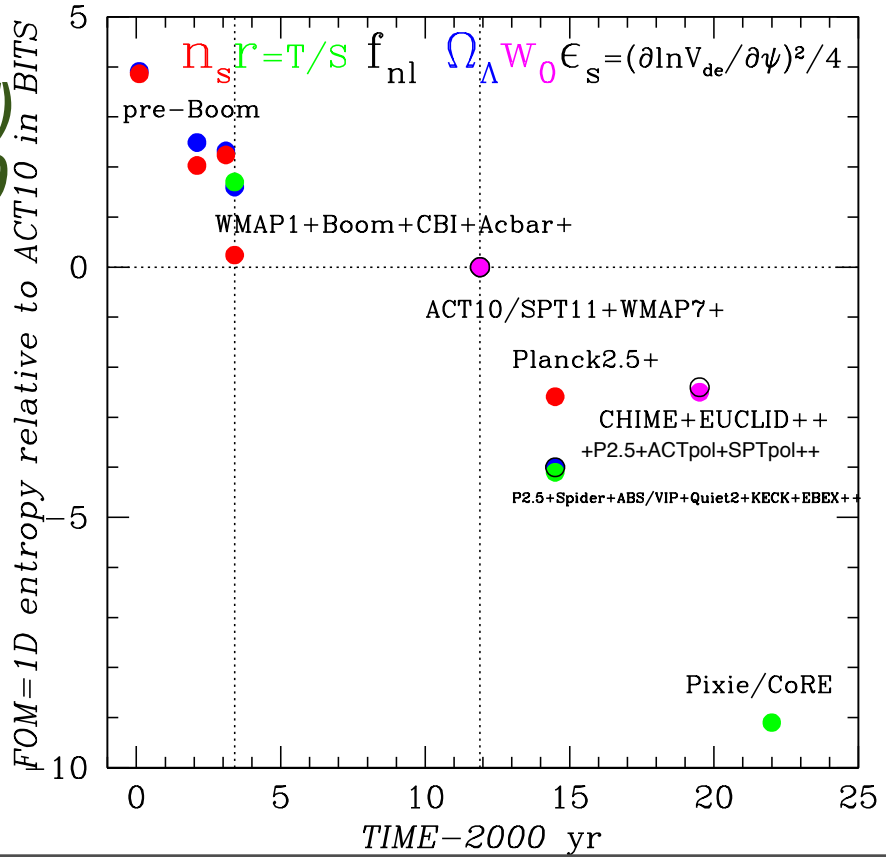
2D ΔS_{2f} for DarkE ($\varepsilon_s \varepsilon_{de\infty}$ or w_0 w_a) improves by ~5 bits

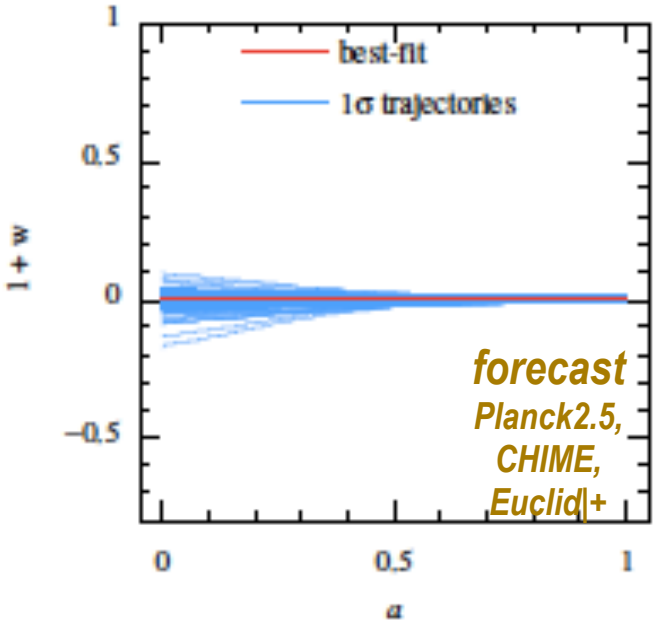
informed $\mathbf{w(a|\varepsilon_s \varepsilon_{de\infty} \varsigma_s)}$ *fits even wild late-inflaton trajectories*



Bond, Huang 2012

ΔS(q,DT)
***i*=ACT10**





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13.7-10^{-50}Gyrs | **13.7Gyrs** | time t | **10Gyrs** | today

early U applications of "CITA" to cosmic-complexity

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

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

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

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

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

P(q|D,T) =P(D|q,T)P(q|T)P(T)/P(D|T) D=CMB,LSS,SN,..,complexity, life
T=baryon, dark matter, vacuum mass-energy densities,...,
early & late inflation as low energy flows/trajectories on a (string) landscape

Old: Theory prior = delta function of THE correct one&only

New: Theory prior = probability distribution of **late-*ish*-flows** on a **LANDSCAPE**

Studying the Cosmic Tango

modulating post-inflation entropy generation shocks *via* long range fields

isocon

$\chi(\mathbf{x})$

or

$\mathbf{g}(\sigma(\mathbf{x}))$

or..

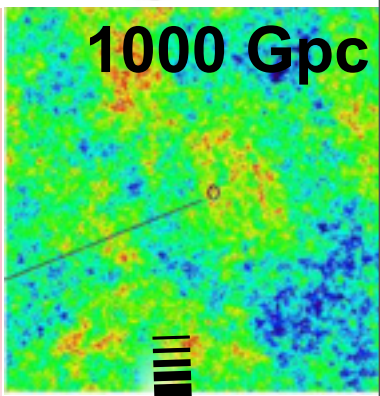
ϕ

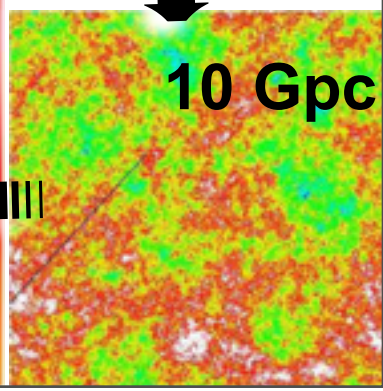
inflaton

pre-heating patch (~1cm)

Parametric Resonance

$g^2/\lambda \sim 1$





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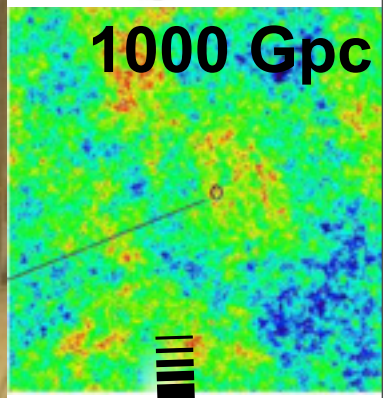
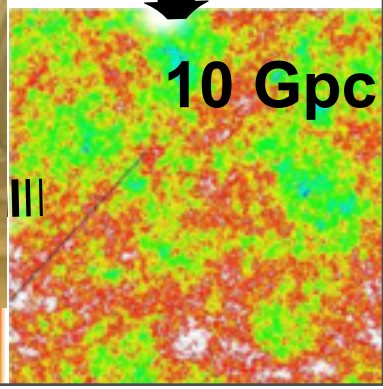




B^2FH12 @ifaUH aka Waikiki Feb12

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

how (most of) the entropy in matter

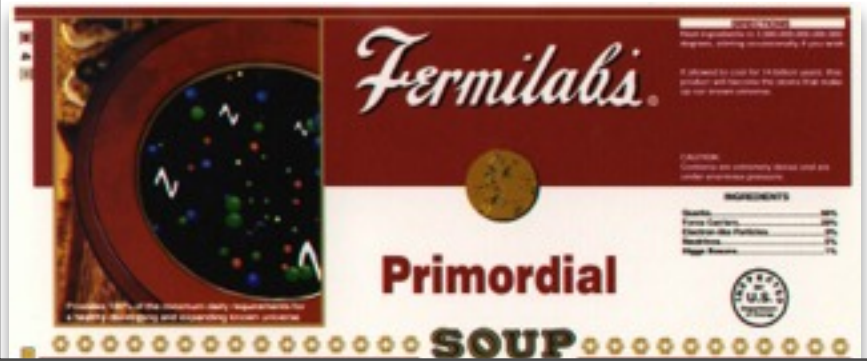
=> *GUT plasma/quark soup* => $S(\gamma,\nu)$ was generated *(through a shock-in-time)*

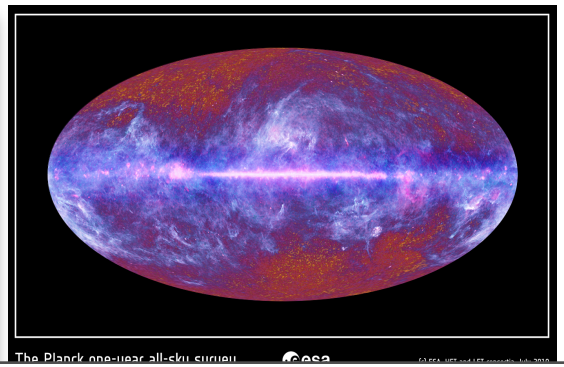
via nonlinear coupling of the inflaton to new interaction channels g,χ_a *ultimately to standard model degrees of freedom*

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

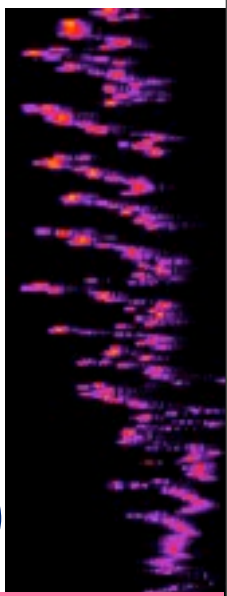
exactly who, what, where, when, why?

we search for fossil "non-Gaussian" structures from this period with Planck +WMAP9

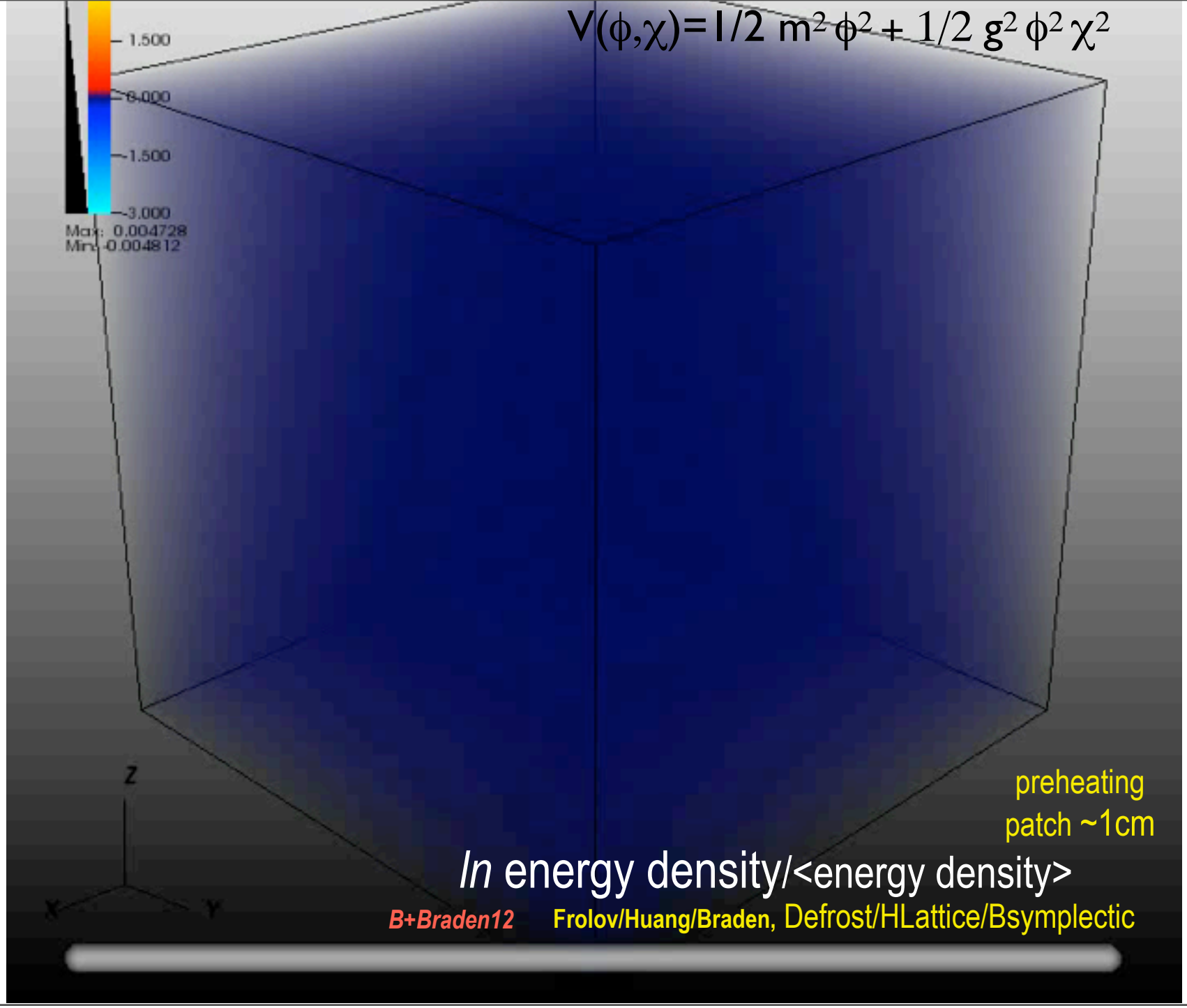




$a_{Shock}(g)$



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


$V(\phi,\chi)=1/2\ m^2\phi^2+1/2\ g^2\phi^2\chi^2$
1.500
0.000
-1.500
-3.000
Max: 0.004728
Min: -0.004812
Z
X
Y
preheating
patch ~1cm
ln energy density/<energy density>
B+Braden12
Frolov/Huang/Braden, Defrost/HLattice/Bsymplectic

Dick Bond CIFAR@CITA with CITA aka *Cosmic Information Theory & Analysis*

Cosmic Information from the Microwave Background Radiation

the **nonlinear COSMIC WEB**

dS$_G$/dt

INFLATION

primary anisotropies

- linear perturbations: scalar/density, tensor/ gravity wave **dS/dt>0**
- tightly-coupled photon-baryon fluid:

oscillations $\delta\gamma$ $v\gamma$ $\pi\gamma$

- viscously damped
- polarization $\pi\gamma$
- gravitational redshift

Φ SW $d\Phi/dt$

DarkM

Decoupling LSS

17 kpc (19 Mpc)

secondary anisotropies **dS/dt>0**

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

DarkE

Lsound/ ksound

MILKY WAY

z=0

Bayesian flow prior to posterior via likelihood

reionization

dS$_{astro}$ <0

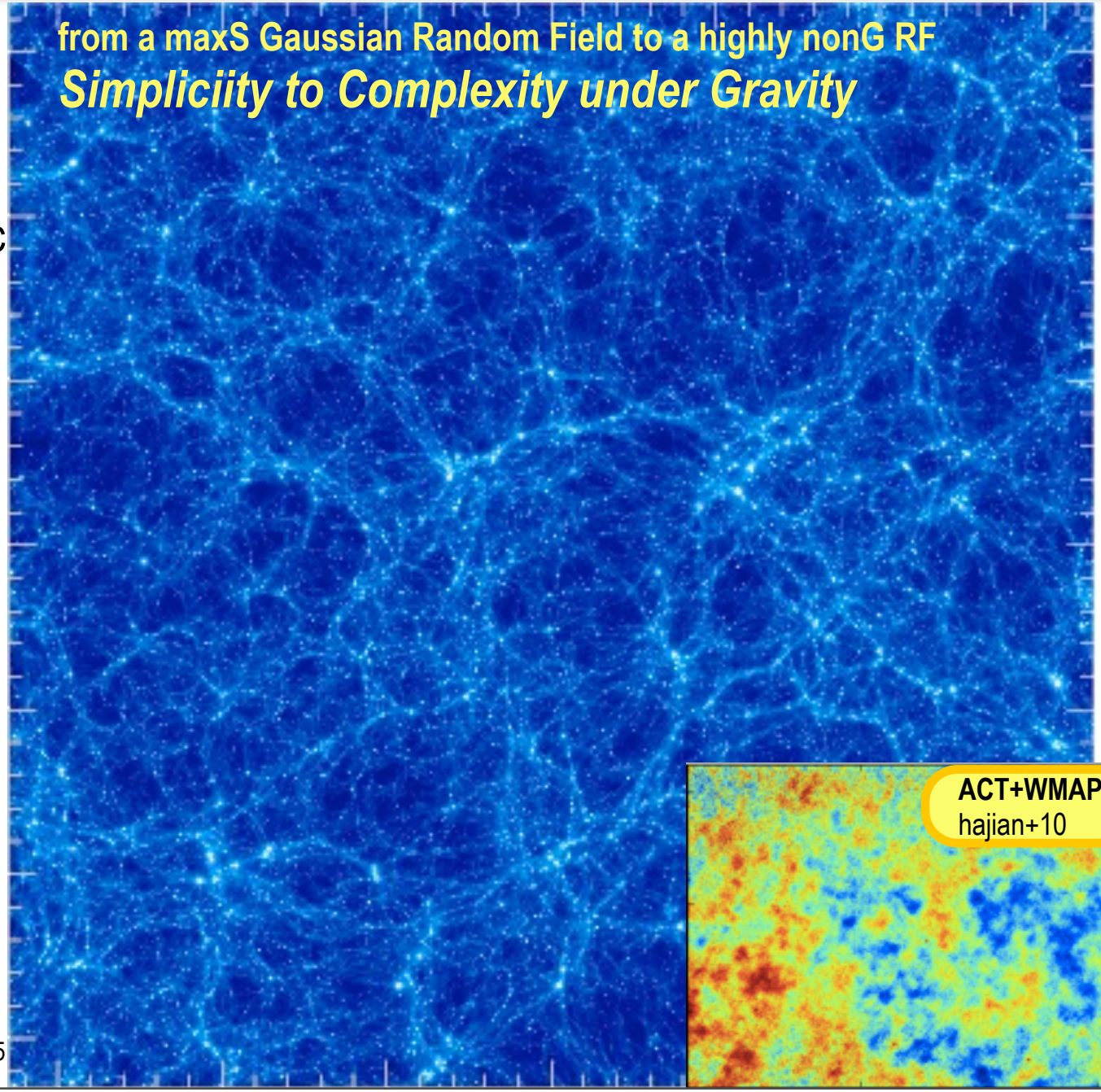
dS/dt>0

z ~ 1100 redshift z z ~ 10

time t

13.7-10^{-50}Gyrs **13.7Gyrs** **10Gyrs** today

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



$\rho_g(x,t)$

a~1 now

400 Mpc

ΛCDM

WMAP5

gas density

Gadget-3

SF+ SN E+ winds +CRs

512^3

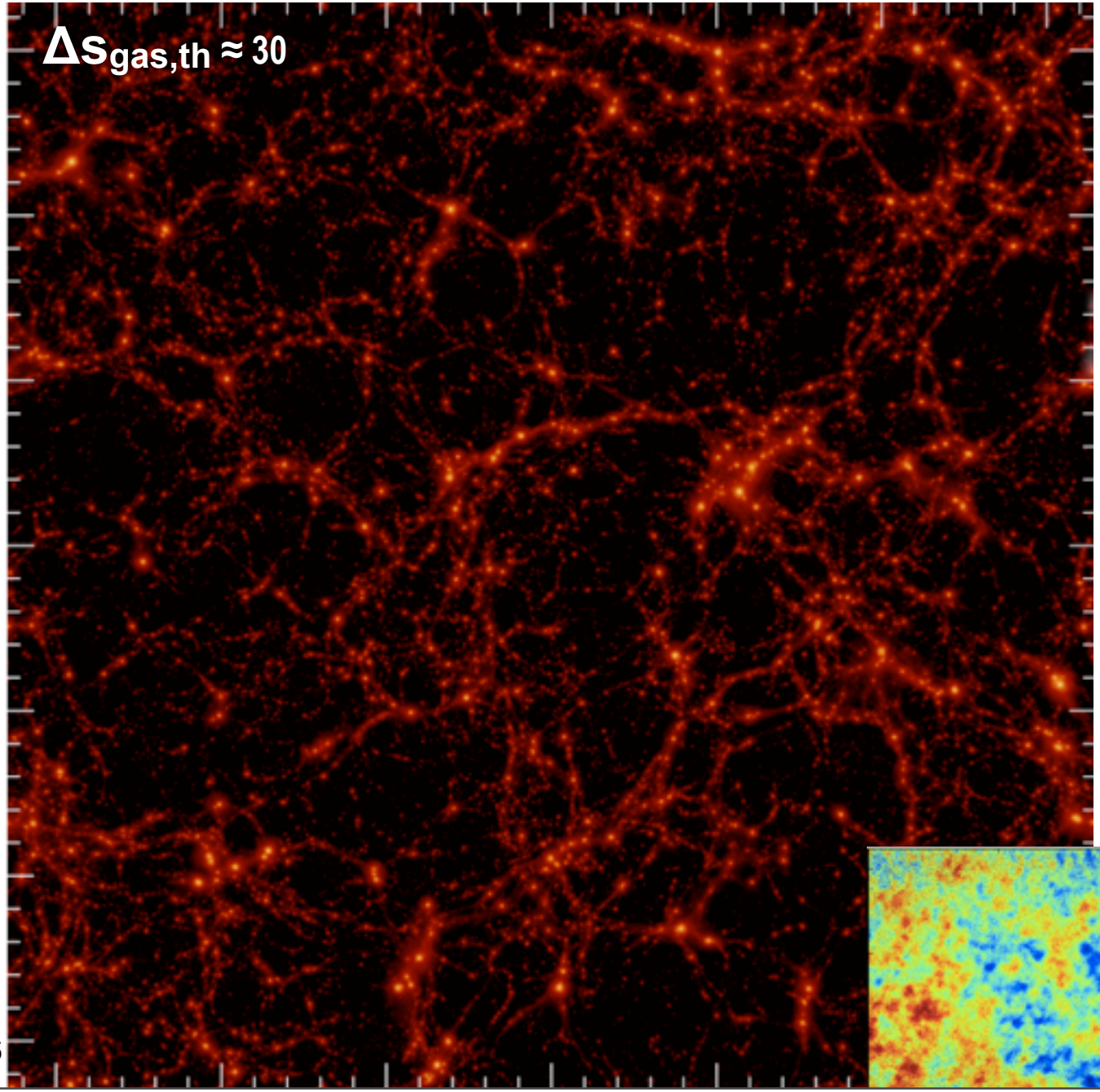
BBPSS10

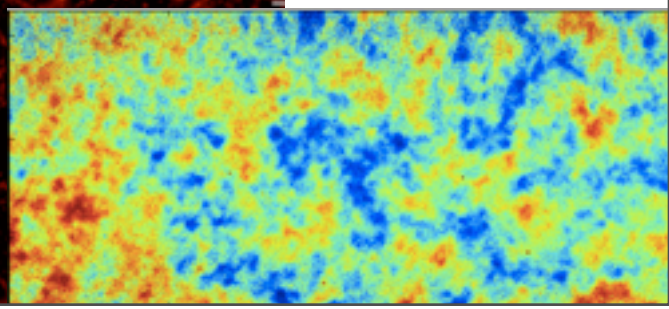
BBPS1,2,3,4,5

$a \sim e^{-7} \sim 1/1100$

entropy intermittency *in the cosmic web, via gravitation-induced shocks (then E/S-feedback)*

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





$s_{b,th}(x,t)$

CMB gets entangled in the cosmic web

descending into the real gastrophysics of cosmic weather

the energetic, turbulent, dissipative, compressive

life of the IGM/ICM/ISM

400 Mpc

ΛCDM

WMAP5

gas pressure

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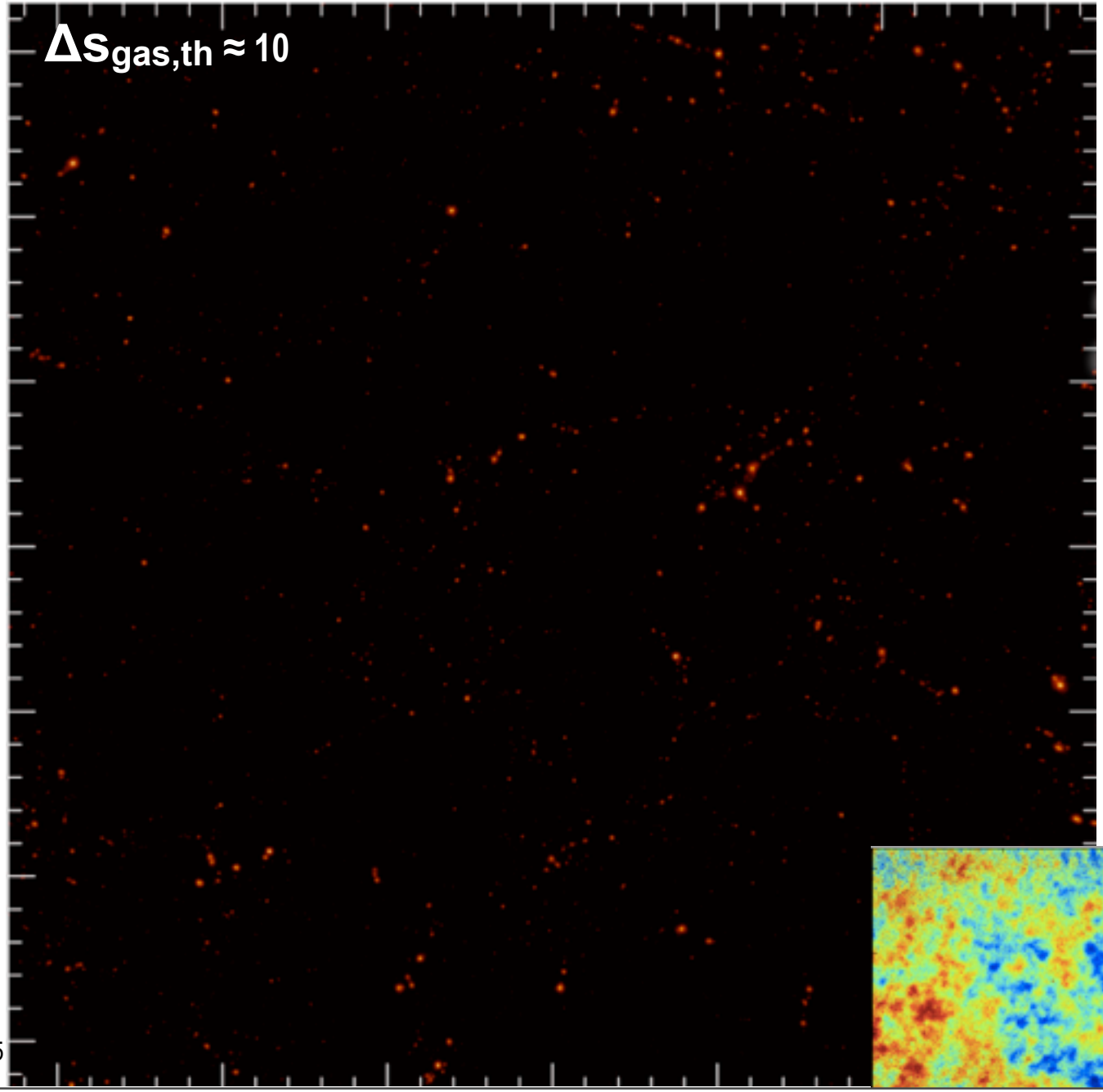

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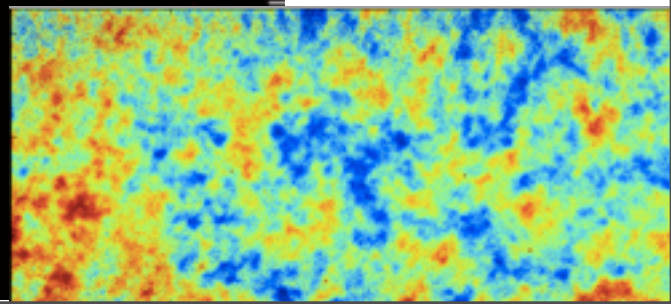


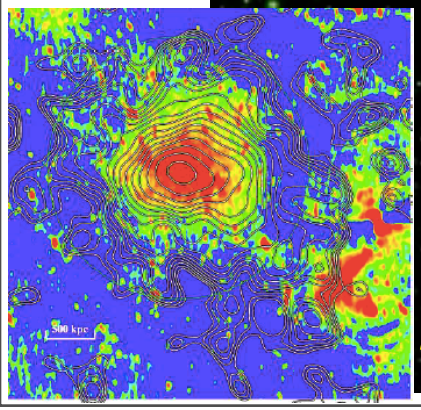
pressure intermittency *in the cosmic web, in cluster-group concentrations probed by* **tSZ**

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

$p_e(x,t)$

2011 Planck ~230 clusters, SPT ~50 =>224cls, ACT ~91 cls; 2013 1000s

Planck's
Coma
2012.08
pip10



info&earlyU=Bond@IAP 12.09.28
info&clusters/SZ=Bond@IAS 12.10.04
info&CMB now&then=Bond@APC 12.10.30

the thermal Sunyaev Zeldovich Probe

$\gamma+e \rightarrow \gamma+e$
Compton cooling of hot cosmic web gas

$\langle \Delta E_\gamma / E_\gamma \rangle = 4T_e/m_ec^2$

$y = \sigma_T \int p_e$ *dline-of-sight*

$\Delta T/T = y * (x(e^x+1)/(e^x-1)-4)$,
$x = h\nu/T_\gamma$

$Y_\Delta \sim E_{th}/D_A^2$

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