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

understanding the

***Complexity** to*
***Simplicity** to*
Complexity

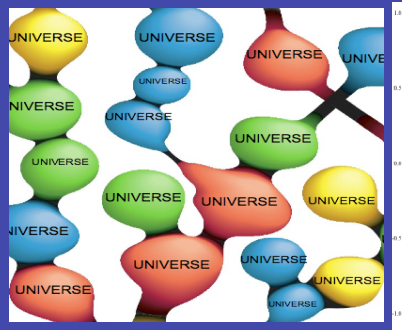
of the Universe = IT

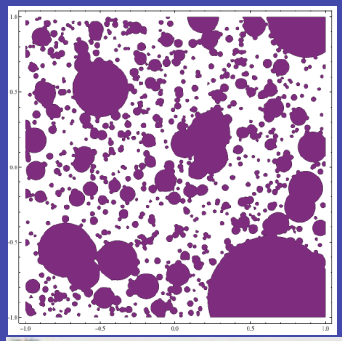
given that we are constrained to see only a BIT of IT

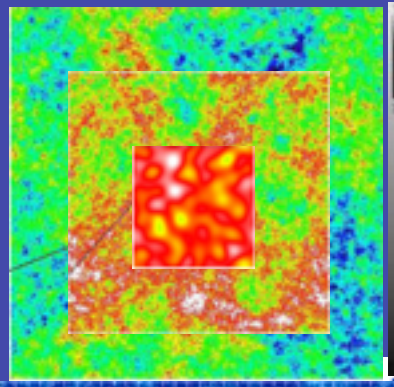
with rather few BITS from/in IT

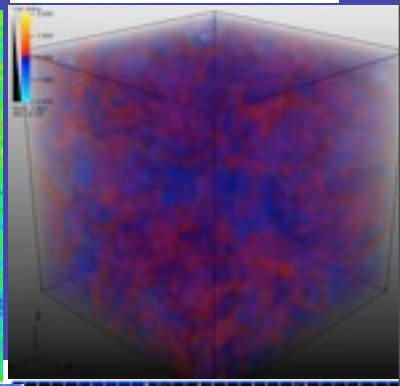
information quantity = entropy *Shannon 1948*

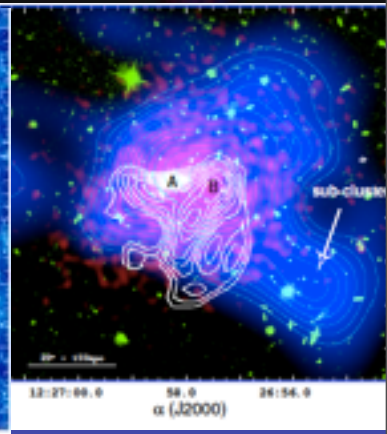
information quality = IQ *essence*











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

Bond@IAP 12.09.28

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

=Bond@IAP 12.09.28

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

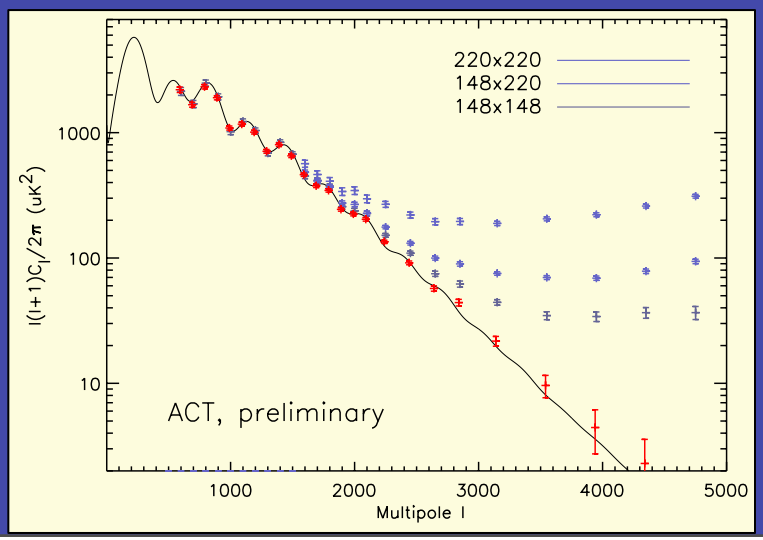
=Bond@IAS 12.10.04

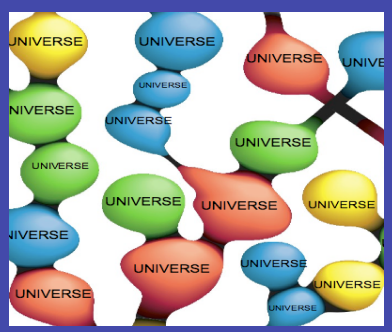
info& *primarily-****primaryCMB***

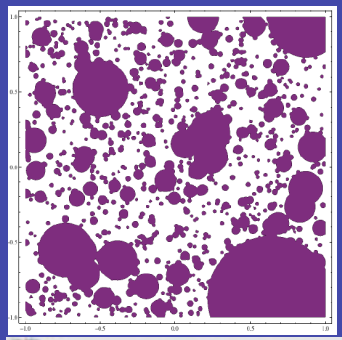
=Bond@APC 12.10.30

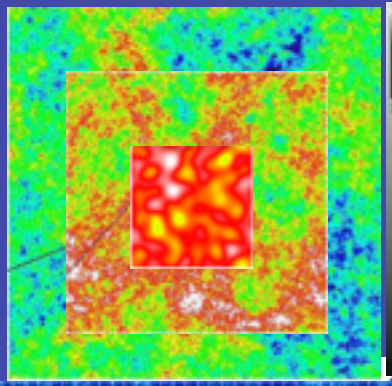
Damping Tail & Recombination History

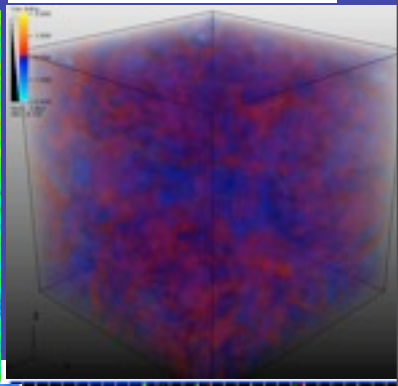
new ACT12+SPT12 *+ Planck13 to come*

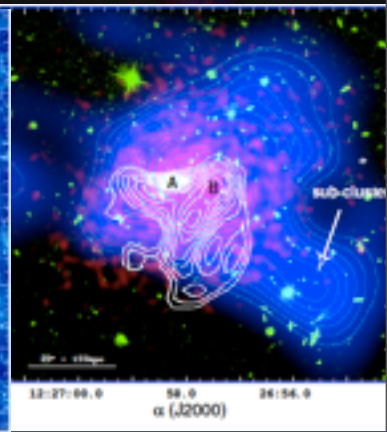












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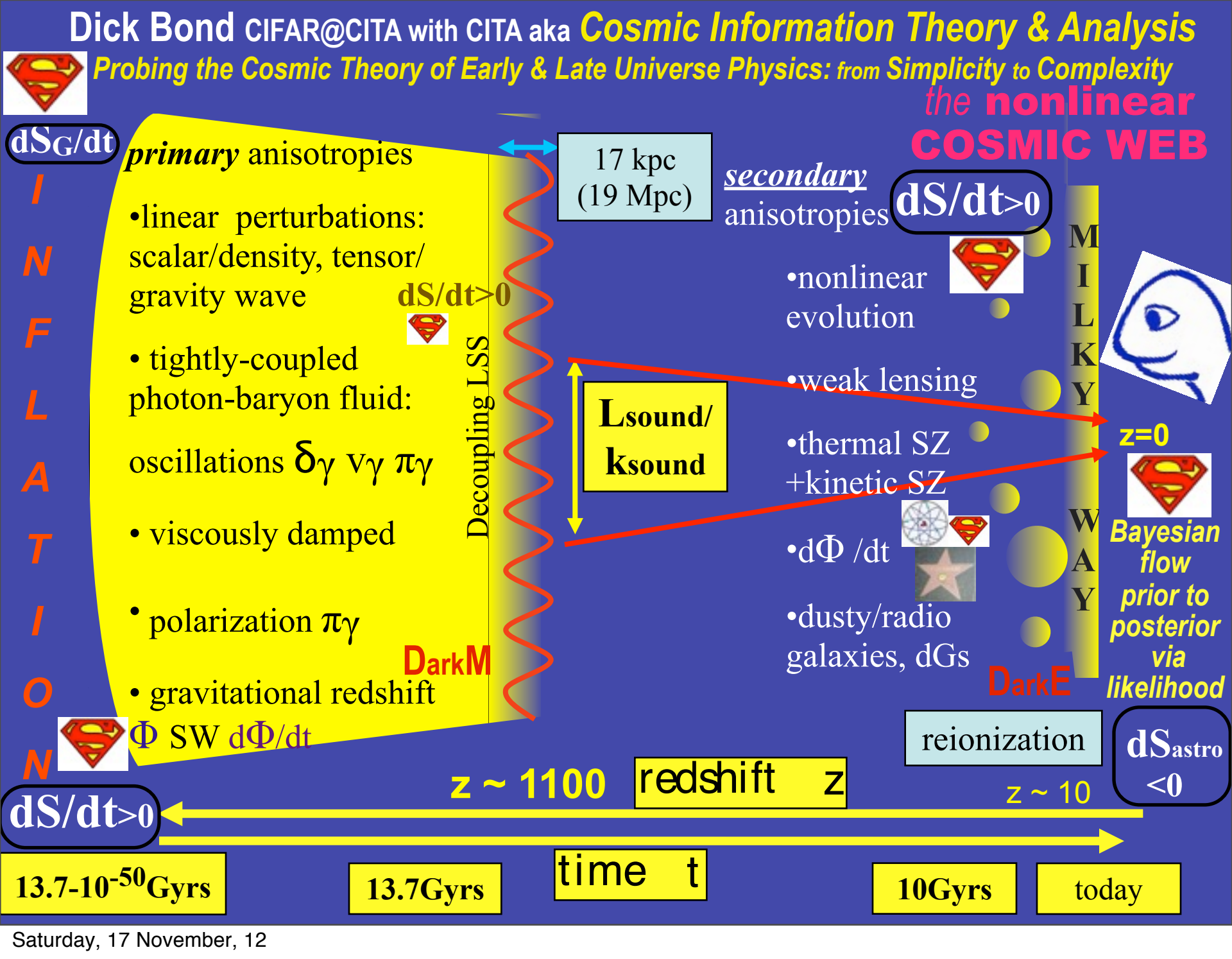
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IT from BIT *from BITs in IT*

"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*

$S_{th,cl} \sim 10^{76}$

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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en-TANGO-ment the dance of $U = R \cup S$

our **Cosmoticians' Agenda:** *Statistical Paths in Cosmic Theory & Data via the Bayesian chain drawing what we know of It from Its Bits*

$P(q|D,T) = P(D|q,T)P(q|T)P(T)/P(D|T)$ *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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$$S_{fi}(D,T) = \int dq\, P_f \ln[P_f^{-1} P_i]$$

cf. $S_f - S_i$

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 Shannon entropy = - *Kullback Leibler divergence*

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

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 eqⁿs*

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. $S_G \sim 10^{121.9}$

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Studying the Cosmic Tango

☆ ***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
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early & late inflation as low energy flows/trajectories on a (string) landscape

some non-early U applications of "CITA" to cosmic-complexity

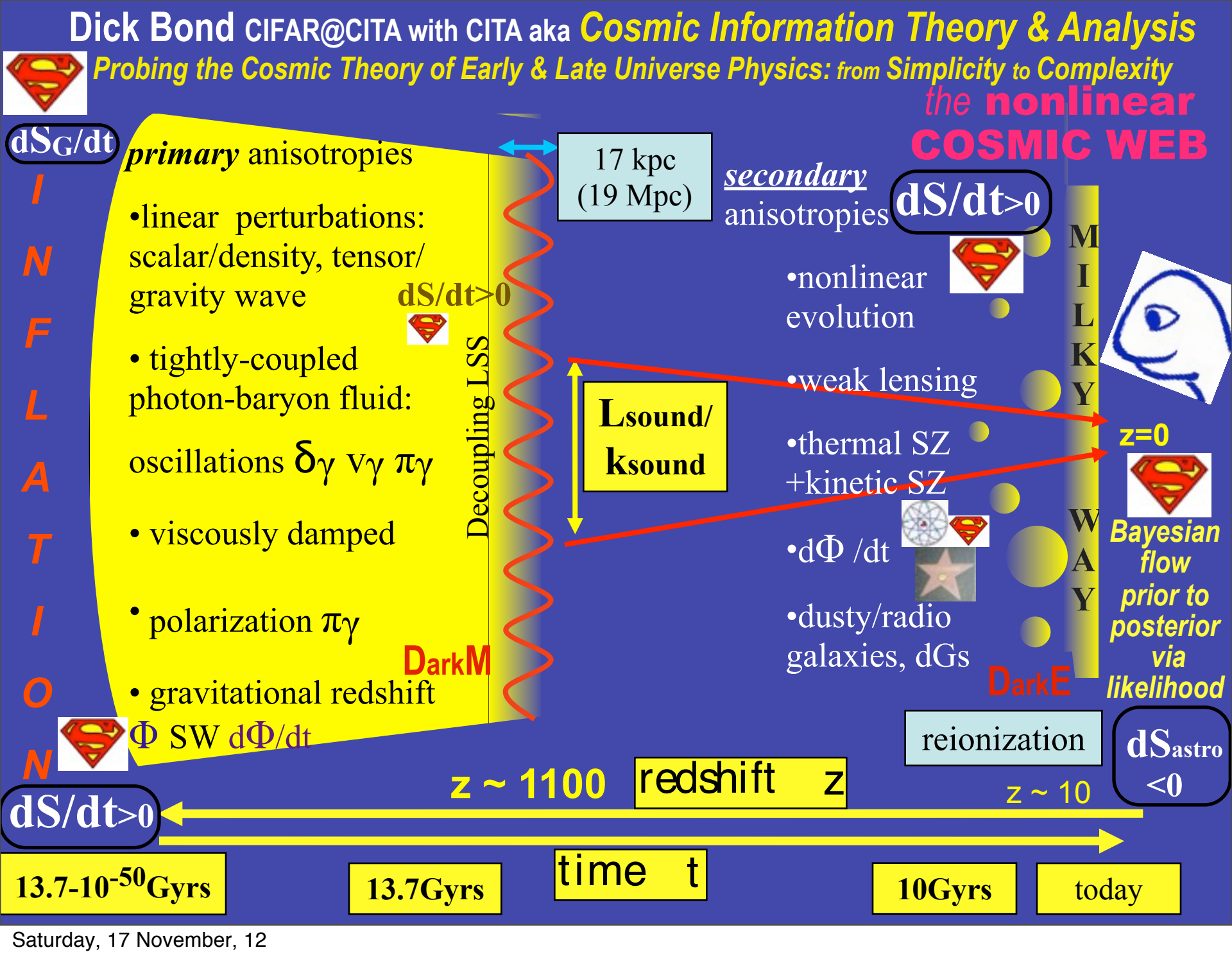
☛ information in **nearly-Gaussian** density/potential random **fields** of U, & in weakly and strongly non-linear fields. *ergodic theorem & constrained fields*

☛ 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 & ... ΔS(q,DT)*** *(cf. ACT10),* ***q=r, w, n_s, ...***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MHD turbulence entropy with cooling & grain polarized emission - CMB fgnd

- **nr Sackur-Tetrode: $\Delta s = 1/2 \mathrm{Tr}\, ln \langle \Delta \mathrm{Pressure}_{ij} / \rho \rangle + ln\, \rho^{-1}$**

(+clumping+anisotropy..)

dS/dt 2

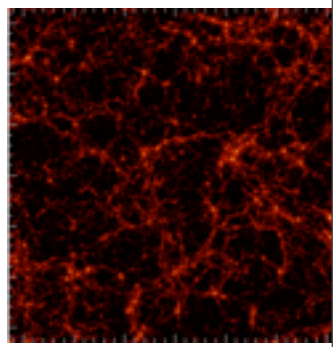
Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)

how most of the entropy in baryons & dark matter was generated

$S_{th,cl} \sim 10^{76}$

strain waves break => clusters/groups (galaxies/dwarfs) in the cosmic web collapse => shocked gas & extreme nonlinear phase space entanglement of dark matter / stars

then the baryons feed back entropy: exploding stars, accreting black holes, dusty CIB radiation



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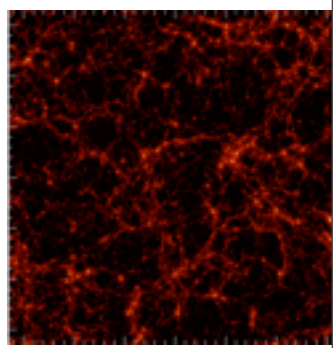


Learning the Cluster Tango

$S_{th,cl} \sim 10^{76}$

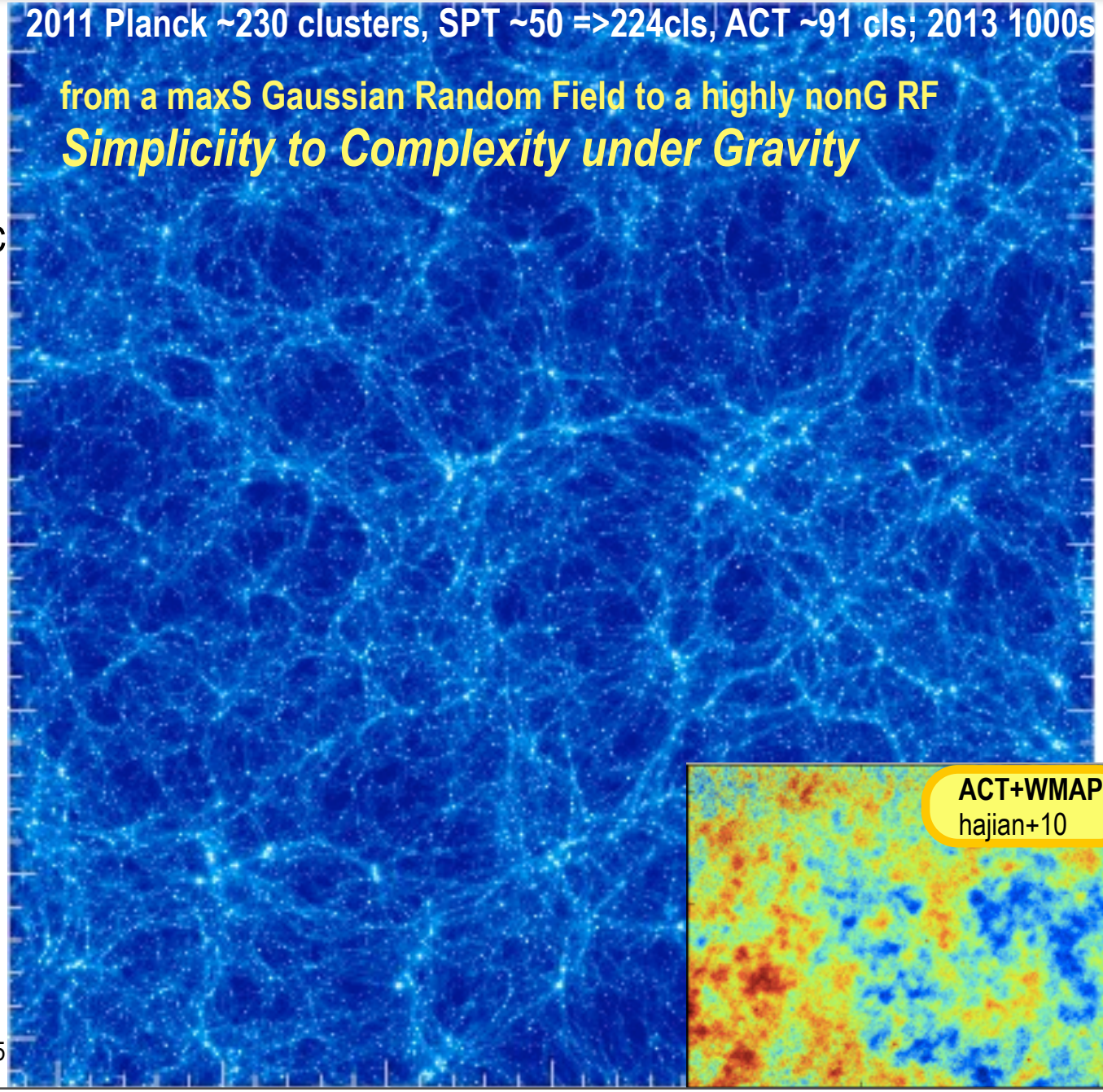
cf. $S_{U,m+r} \sim 10^{88.6}$

***Cosmic Hydro Sims** include all effects -*
except of course those not included Thou Shalt Mock
(10+10+20 256^3 SPH gas+DM)
(1+1+1 512^3 gas+DM) *ΛCDM* + ...

nr Sackur-Tetrode: $\Delta s = 1/2 \mathrm{Tr}\, ln \langle \Delta P_{ij} / \rho \rangle + ln\, \rho^{-1}$ *(+clumping+anisotropy..)*

fine-*macro-small***-grain 10^6 baryons in cubic metres** cf. **sph--***macro-large***- grain 10^{65} baryons. ~26 dims per sph-grain, huge dimensional reduction, scaled-radial-***resolution***-grain further dim reduction. entanglement of fine & coarse & EFT. feedback.**

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

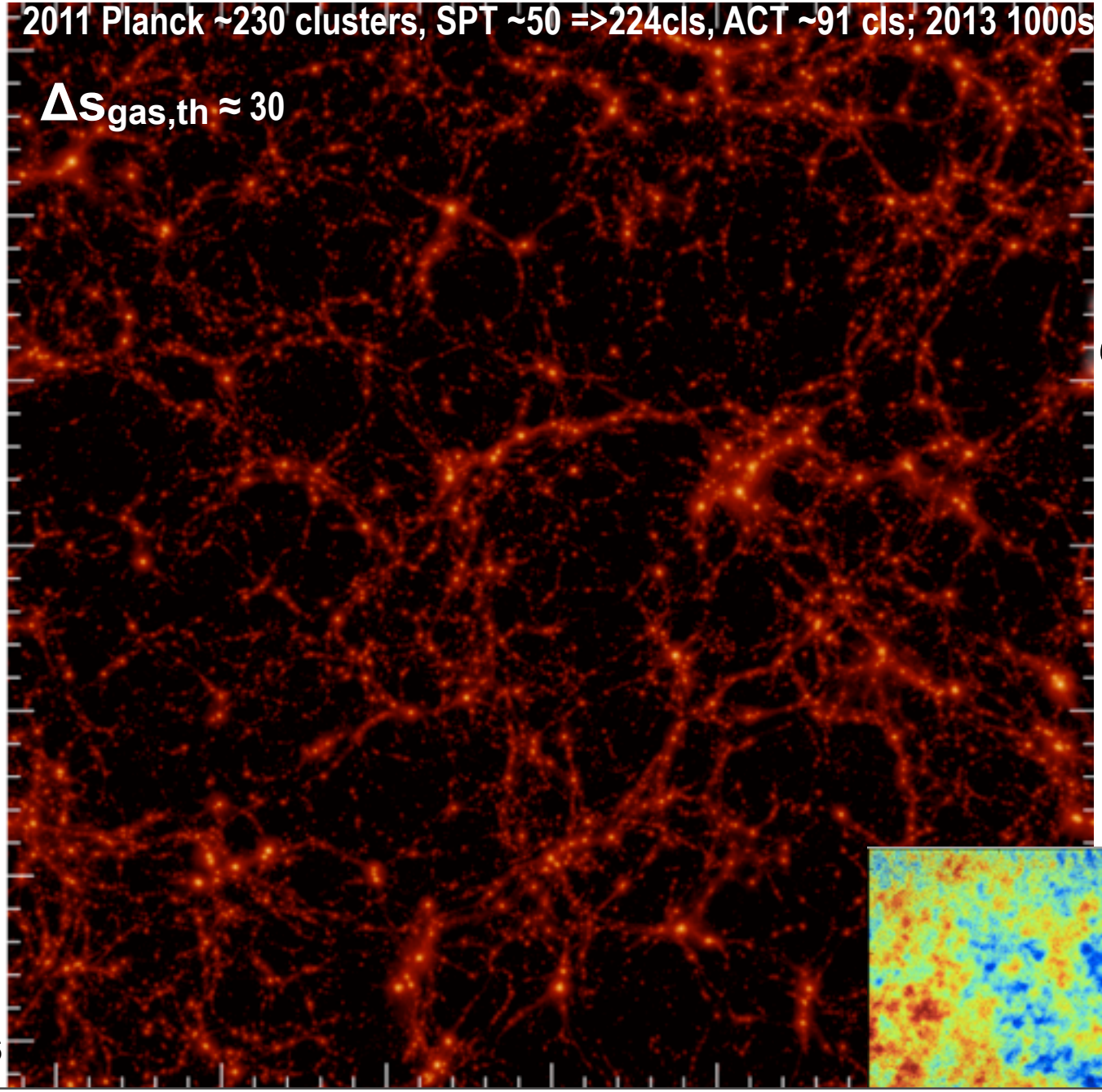
512^3

BBPSS10

BBPS1,2,3,4,5

a~e^{-7}~1/1100

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



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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

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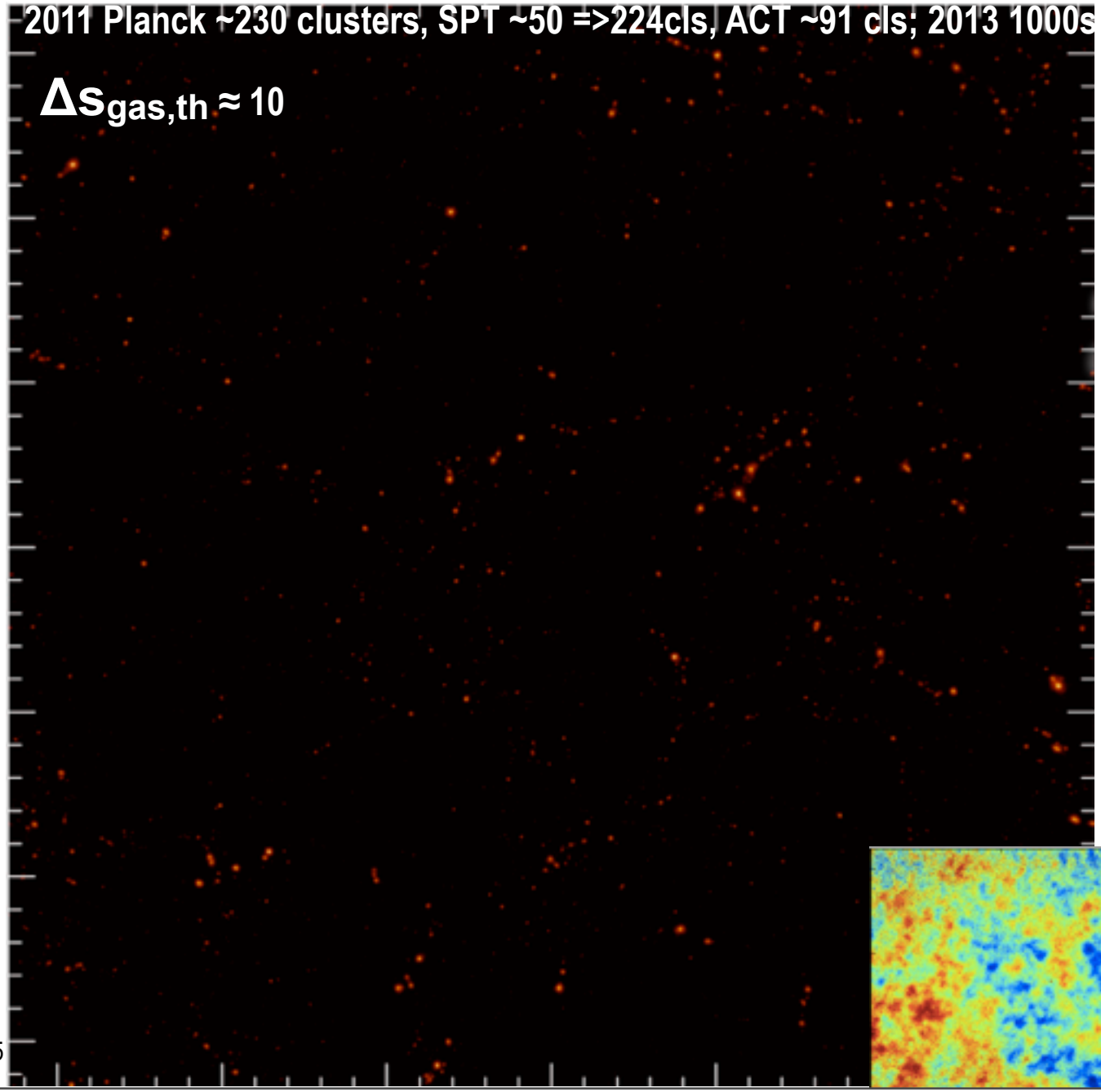

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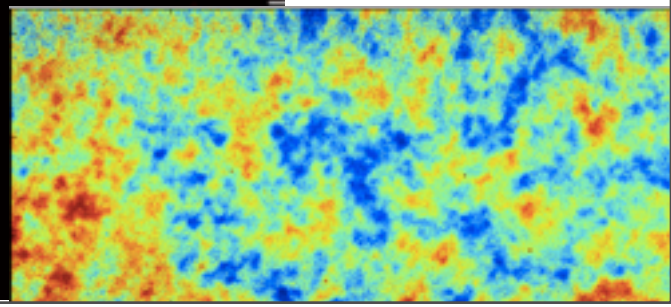

pressure intermittency *in the cosmic web, in cluster-group concentrations probed by* **tSZ**

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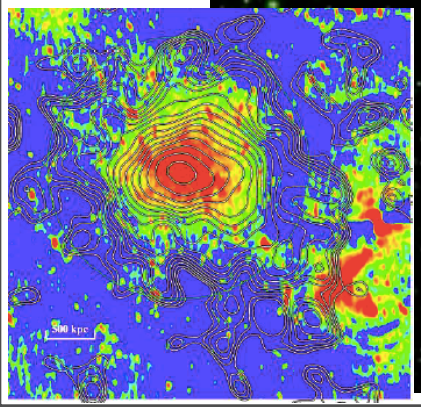
(tSZ, kSZ, WL, reion, CIB; hydro)

$p_e(x,t)$

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

Planck's
Coma
2012.08
pip10



the ***thermal Sunyaev Zeldovich Probe***

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

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

$y = \sigma_T \int p_e \, d\text{line-of-sight}$

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

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

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

Optical Dark Matter X-ray Gas

Bullet Cluster merger @ z=0.3, 1.1Gpc

DM evidence Clowe+06 17.4 ± 2.5 kev

GBT's Mustang HiRes-SZ

A

B

sub-cluster

A2319

CL1226 z=0.89

SZ cf. X-ray

combined interferometry allison+12

CBI+CBI2+SZA+BIMA+OVRO

A1689 z=0.18,

$M=1.4\times10^{15}M_{sun}$

RIGHT ASCENSION (J2000)

bullet-like merger - even more spectacular

ACT's el Gordo z=0.87

$2\times10^{15}M_{sun}$, T_X=14.5kev

Menanteau+12

IRAC 3.6μm and 4.5μm

Gas Peak

SPT's Phoenix z=0.60

$2.5\times10^{15}M_{sun}$

massive starburst +AGN

=>FEEDBACK

20"

133 kpc

Clusters are Complex Systems!

Information Quantity (Shannon Entropy) & IQuality

input cluster: M_{500}=5.4e14, z=0.7

GBT-beam 0.15'

Mustang2 on GBT sim

SPT-beam 1'

SZA@30 GHz beam

A520 z=0.21

Train Wreck

44GHz

Planck+11

FLUX

100 Frequency (GHz)

Planck followup to 35σ in 1 hr @10"

<= Planck beam at 150 GHZ =>

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New: *Menanteau+12, Hasselfield+12*
ACT Celestial Equator cls, 68 (49+19 in SDSS, half z>.5, 1 z~1.1 $10^{15}M_{sun}$ 502 sq deg =>*91 in* 952 deg^2, 0.1<z<1.3

100% purity for S/N>5. 60% > 4.5
No significant evidence of SZ/BCG offset
M_{SZ}-N_{200} weak correlation, large scatter

to get **cosmological parameters** from
$n_{cl}(Y(M),z)$ &
$C_L^{tSZ,kSZ}$
cluster complexity => requires full "mocking" simulations

the thermal Sunyaev Zeldovich Probe

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

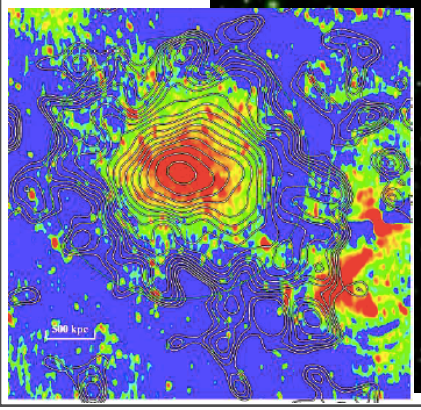
$\langle \Delta E_\gamma/E_\gamma \rangle = 4T_e/m_ec^2$

$y = \sigma_T \int p_e$ d*line-of-sight*

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

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

Planck's
Coma
2012.08
pip10



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*

Shannon entropy $S_f(D,T) = -\int dq\, P_f \ln P_f$ **=information with no Quality measure on the bits IQ**

~ von-Neumann entropy= Trace $\varrho \ln \varrho^{-1}$, $\varrho(U) = \varrho(S,R) = \varrho(R|S)\,\varrho(S)$ entanglement of phase & probability

Gaussian random field *with correlation function* C *weight matrix* C^{-1}

$S = (\text{Trace } \ln C + N_{dof} \ln 2\pi + N_{dof})/2 = \langle \ln V_{phase\text{-}space} \rangle + N_{dof}/2$

=Shannon entropy subject to the constraint $\int dq\, P_f\, \delta q^i \delta q^j = C^{ij}$

relative Shannon entropy $S_{fi} = \text{Tr}\{\ln C_f\, C_i^{-1} + 1 - C_f\, C_i^{-1}\}/2$

cf. ***grand canonical ensemble: constrained*** E_{tot} & N_A & V

Lagrange multipliers (conjugate variables) $\beta = 1/T$ & $-\beta\mu_A$ & β*p*ressure; *in LTE, functions of (x)*

non-eq thermodynamics*: flux* $J_{heat}^{\ i}(x)$ $J_n^{Ai}(x)$ *conjugate thermodynamical forces* B_i $(\sim \partial_i \beta)$

more constraints (e.g., higher point correlations & more complexity) reduce entropy by limiting the freedom of the degrees of freedom q: ***non-Gaussian distributions have lower S***

Lagrange multipliers: out-of-equilibrium drivers κ_i *for* $\langle \delta q^i \rangle$ *and* K_{ij} *for* $C^{ij} \langle \delta q^i \delta q^j \rangle$

problem: ***Dimensional Reduction*** *when eigenvalues of C ~ 0, S ~* $-\infty$ *: but cold degrees of freedom should have S=0 (3rd). Bose-Einstein & Fermi-Dirac statistics - indistinguishable cf. distinguishable. Condensates form when too much N for E.*

nr Sackur-Tetrode: $\Delta s = \frac{1}{2}\text{Tr } \ln \langle \Delta P_{ij}/\rho \rangle + \ln \rho^{-1}$ *(+clumping+anisotropy..)*

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

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

$\Delta s_{gas,th} \approx 30$

$S_{th,cl} \sim 10^{76}$

Entropy-per-gas-baryon

$\Delta s_{gas,cluster} \approx$
3 *ln* X ~12bits/b +
1 bit/b non-thermal

$P_{kin}/P_{th} \sim 0.1\text{-}0.6!$

zero point $S_{th,0}$ ~ 130 nats
~ 190 bits/baryon

400 Mpc

ΛCDM

WMAP5

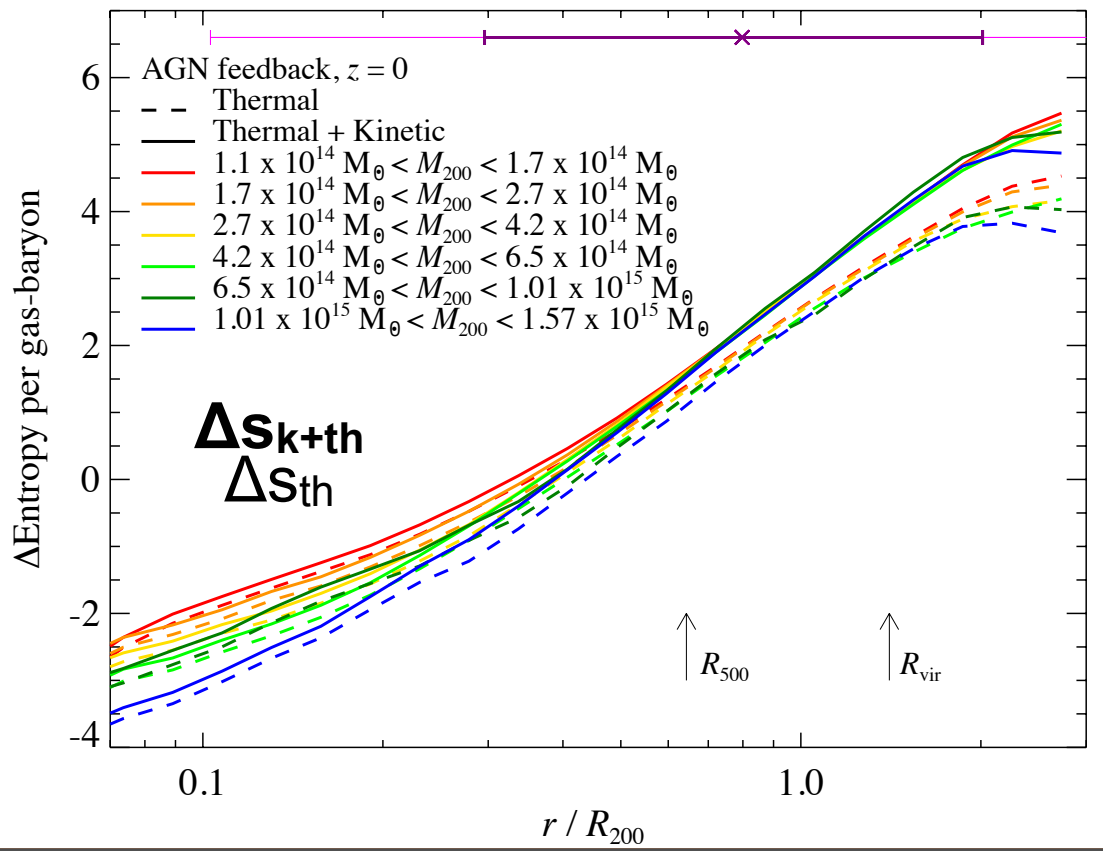
gas pressure

Gadget-3 SF+ SN E+ winds +CRs

512^3

BBPSS10

BBPS1,2,3,4,5



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$S_{th,cl} \sim 10^{76}$

$S_{U,m+r} \sim 10^{88.6}$ ***5.2 bits/Υ***

cf. S_m~1.4 bits/baryon atmosphere

after CMB+CvB, most $S_{U,m+r}$ is CIB = the waste heat from dust re-emission of starlight

400 Mpc

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WMAP5

gas pressure

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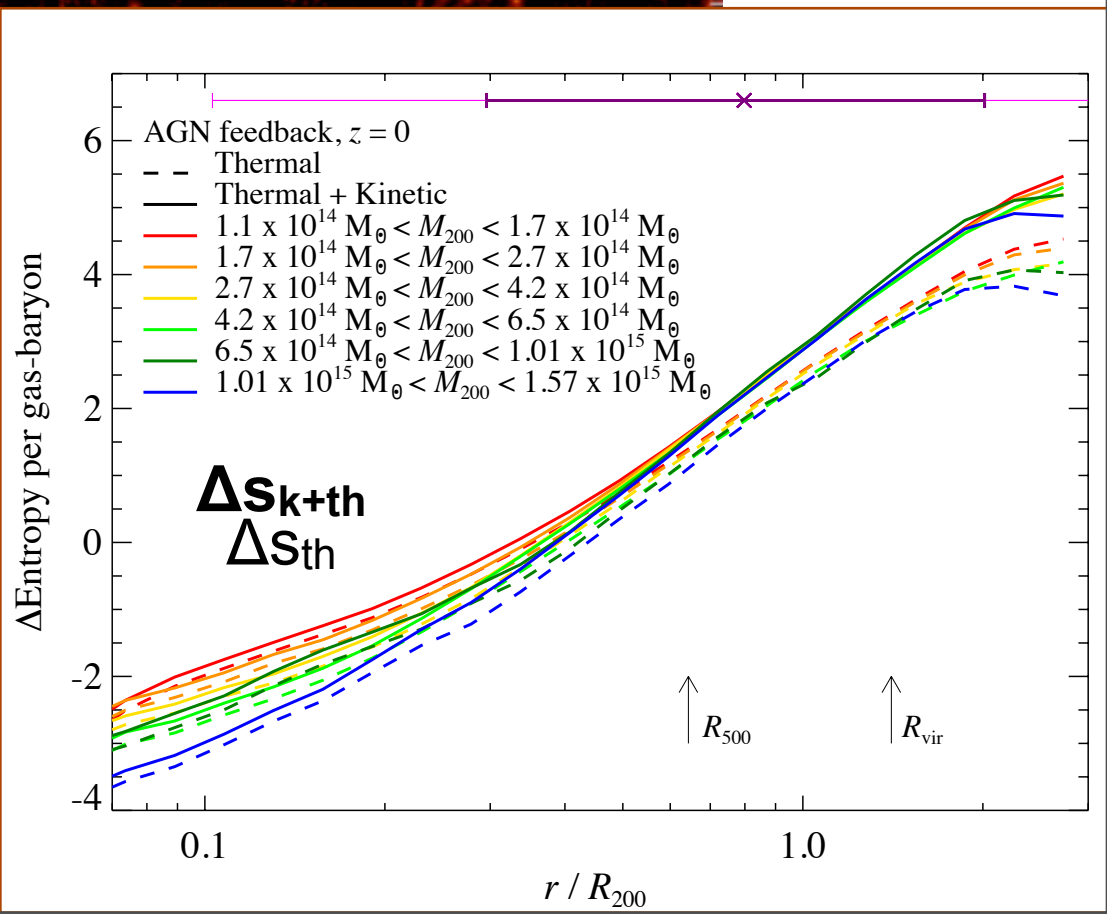
512^3

BBPSS10

BBPS1,2,3,4,5



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1 bit/b non-thermal

$P_{kin}/P_{th} \sim 0.1\text{-}0.6$!

Entropy-per-dark-matter

$\Delta s_{dm,halo}$
= 15/8 *ln* X
~7 *bits/DM*

beyond NFW

400 Mpc

ΛCDM

WMAP5

gas pressure

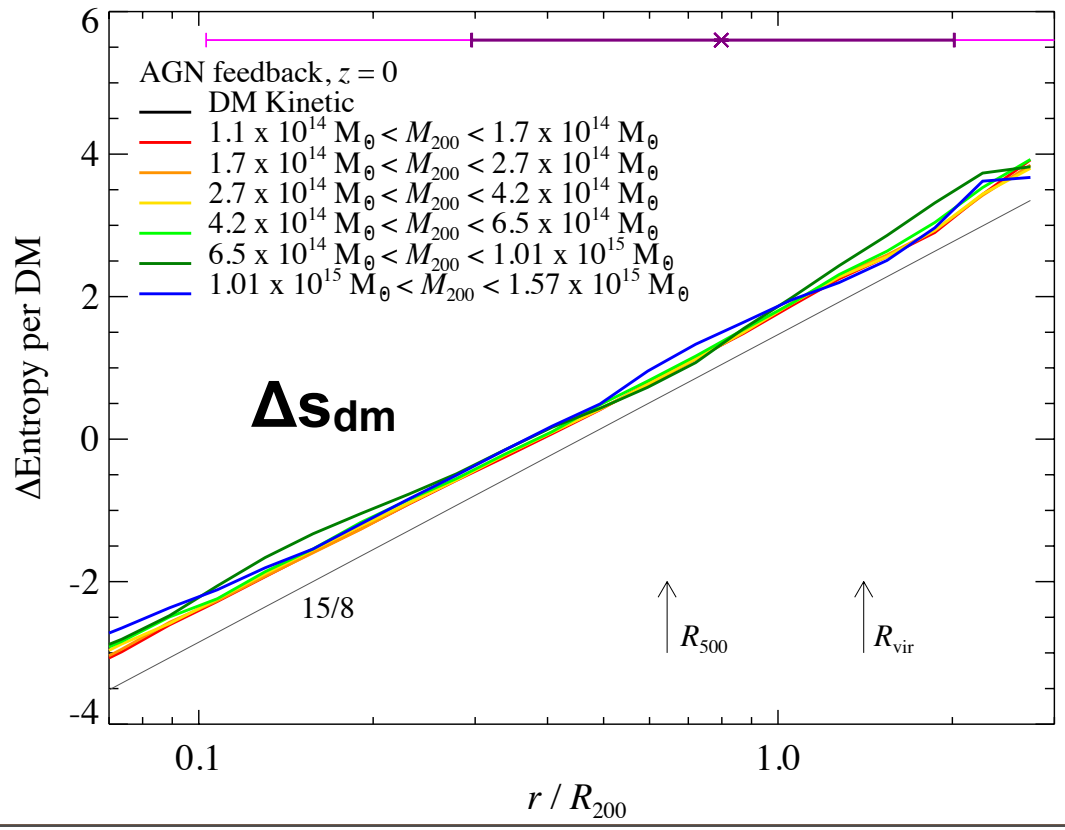
Gadget-3 SF+ SN E+ winds +CRs

512^3

BBPSS10

BBPS1,2,3,4,5

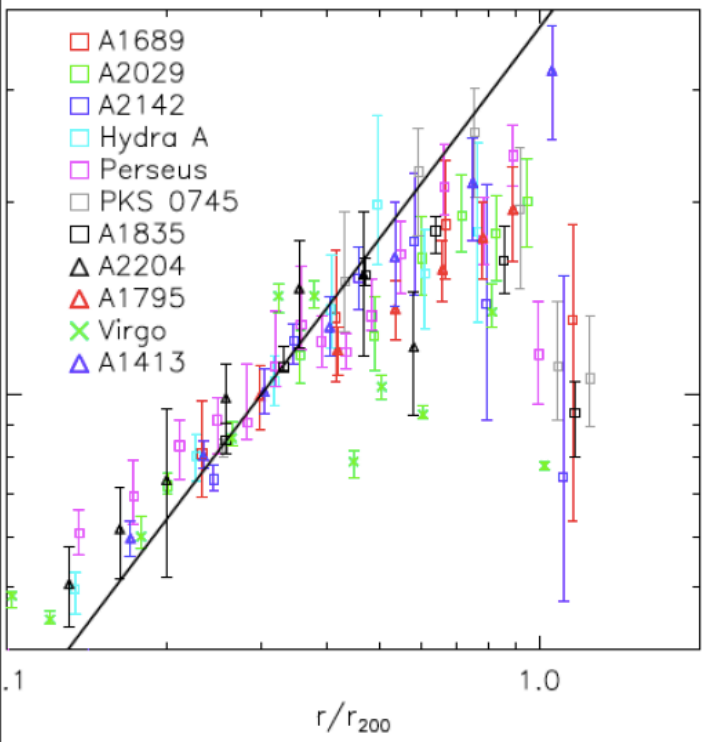
slope~self-similar radial infall Navarro
ongoing mystery - why halos have this entropy growth law

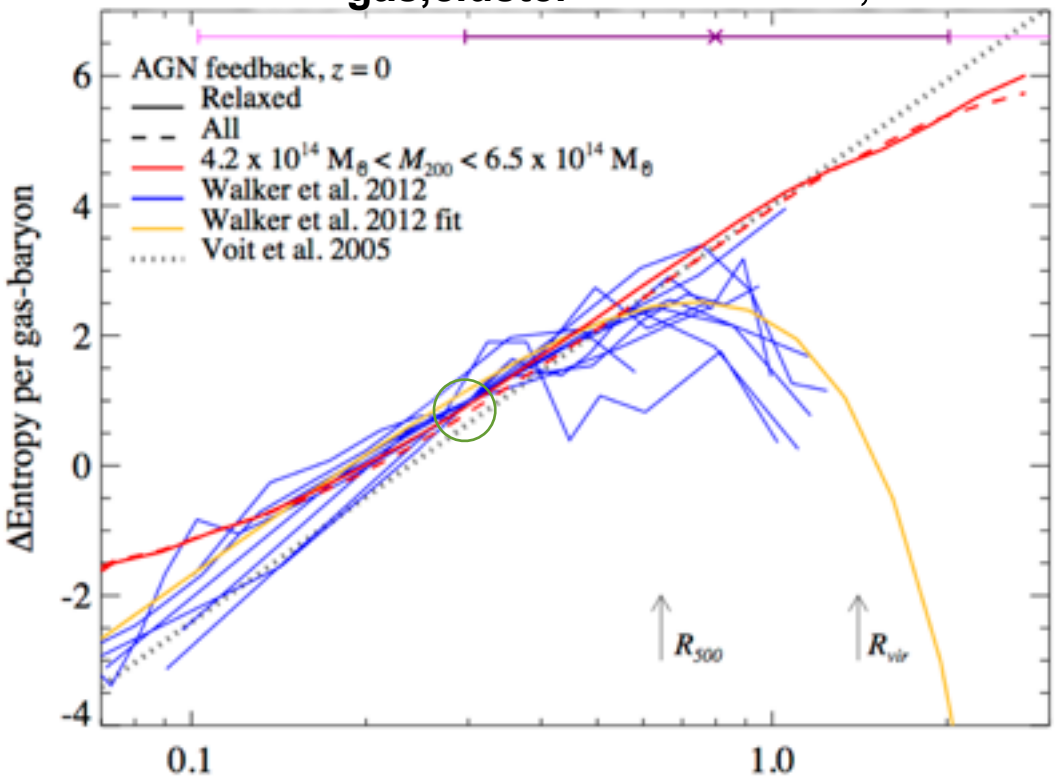


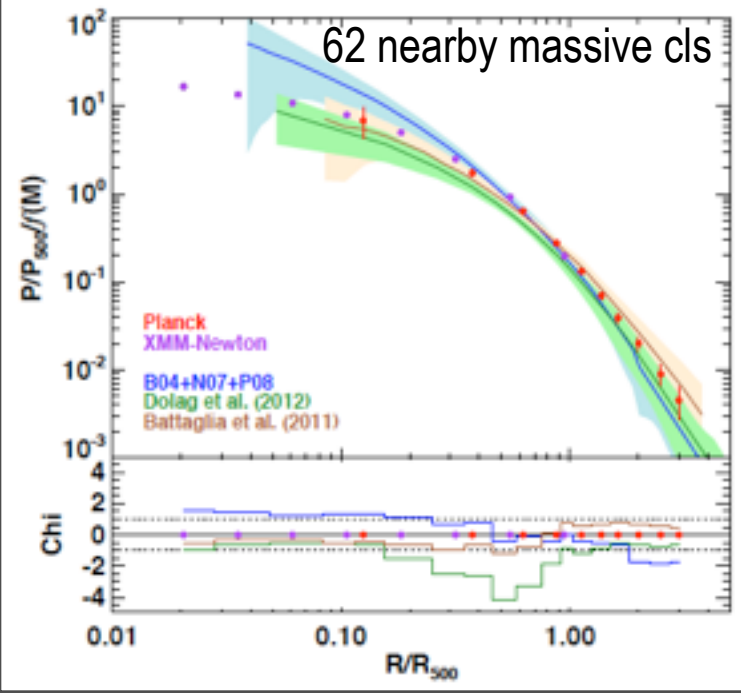
Universal Entropy Profile?

evidence for relaxed cool core clusters Walker, Fabian, Sanders, George12

Walker+ form $\Delta s_{gas,cluster} \approx 3 ln X - X^2 / B$, *B a fit*







Universal Pressure Profile?

X-ray version" (Arnaud+10) fails >R_{500}

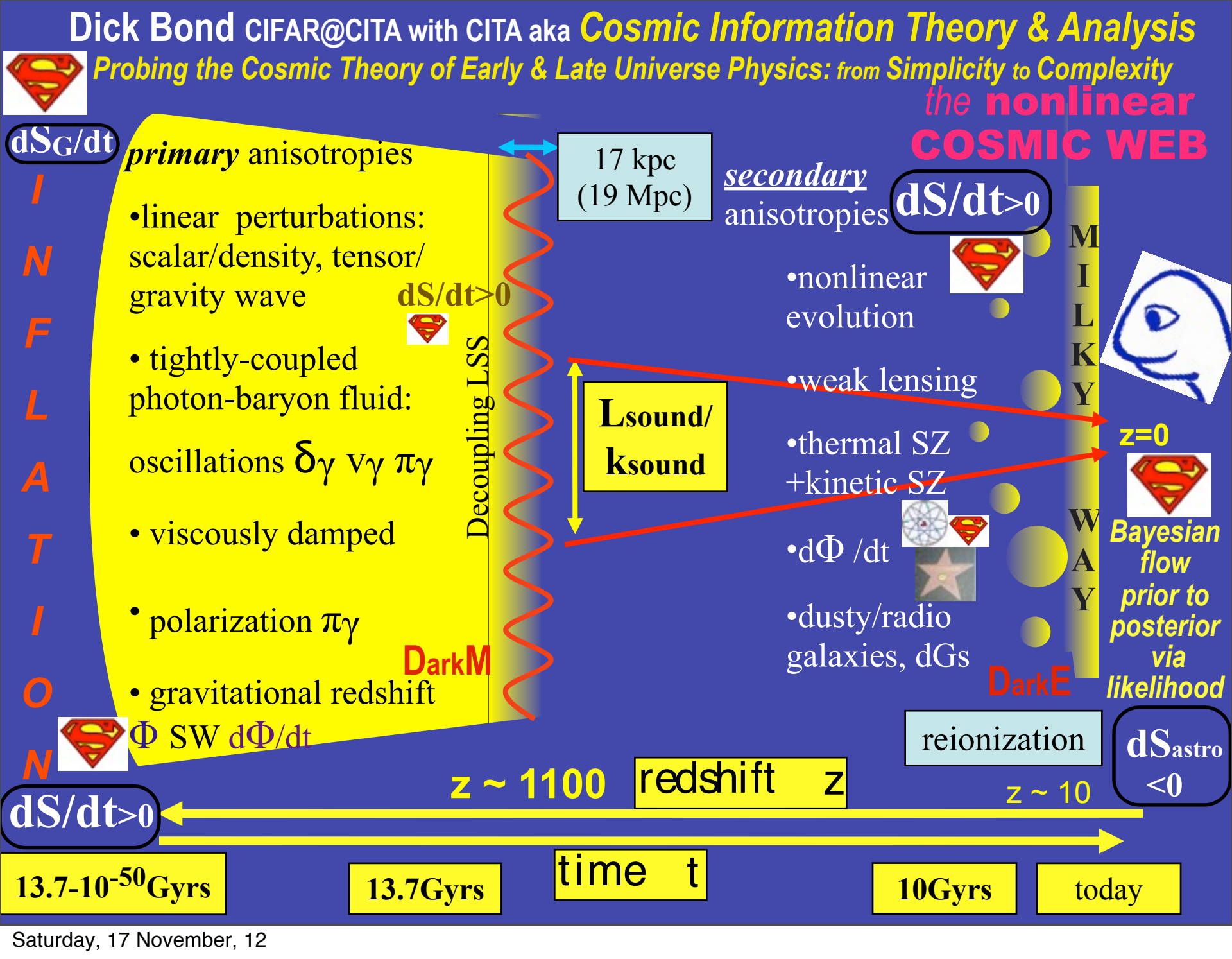
=> PUPPY: Planck12 universal pressure profile

BBPSS11, BBPS12 **AGN feedback pressure profiles fit > R_{500} SZ data better than other hydro sims. nearly "universal"(M,z)**

fits Planck12-COMA as well

pressure clumping R_{500} ↑ 3 R_{500} => δp/p ~0.2 ↑ ~1

& density clumping, kinetic turbulent pressure. complexity


Dick Bond CIFAR@CITA with CITA aka Cosmic Information Theory & Analysis
Probing the Cosmic Theory of Early & Late Universe Physics: from Simplicity to Complexity
the nonlinear COSMIC WEB
dSG/dt
INFLATION
primary anisotropies
•linear perturbations: scalar/density, tensor/ gravity wave
dS/dt>0
• tightly-coupled photon-baryon fluid:
oscillations δγ vγ πγ
• viscously damped
• polarization πγ
DarkM
• gravitational redshift
Φ SW dΦ/dt
17 kpc (19 Mpc)
Decoupling LSS
Lsound/ ksound
secondary anisotropies
dS/dt>0
•nonlinear evolution
•weak lensing
•thermal SZ +kinetic SZ
•dΦ /dt
•dusty/radio galaxies, dGs
DarkE
MILKY WAY
z=0
Bayesian flow prior to posterior via likelihood
reionization
dSastro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
time t
13.7-10-50Gyrs
13.7Gyrs
10Gyrs
today

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

how (most of) the entropy in matter

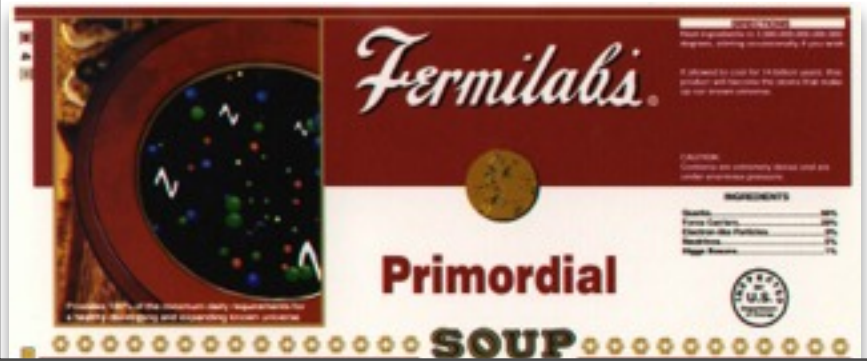
=> *GUT plasma/quark soup* => $S(\gamma,\nu)$ was generated *(through a shock-in-time)*

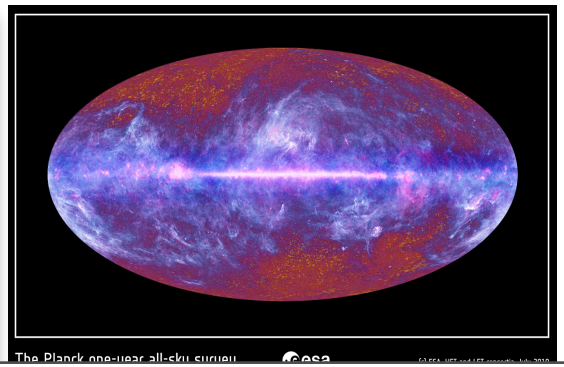
via nonlinear coupling of the inflaton to new interaction channels g,χ_a *ultimately to standard model degrees of freedom*

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

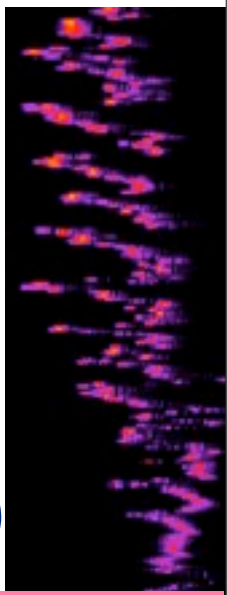
exactly who, what, where, when, why?

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

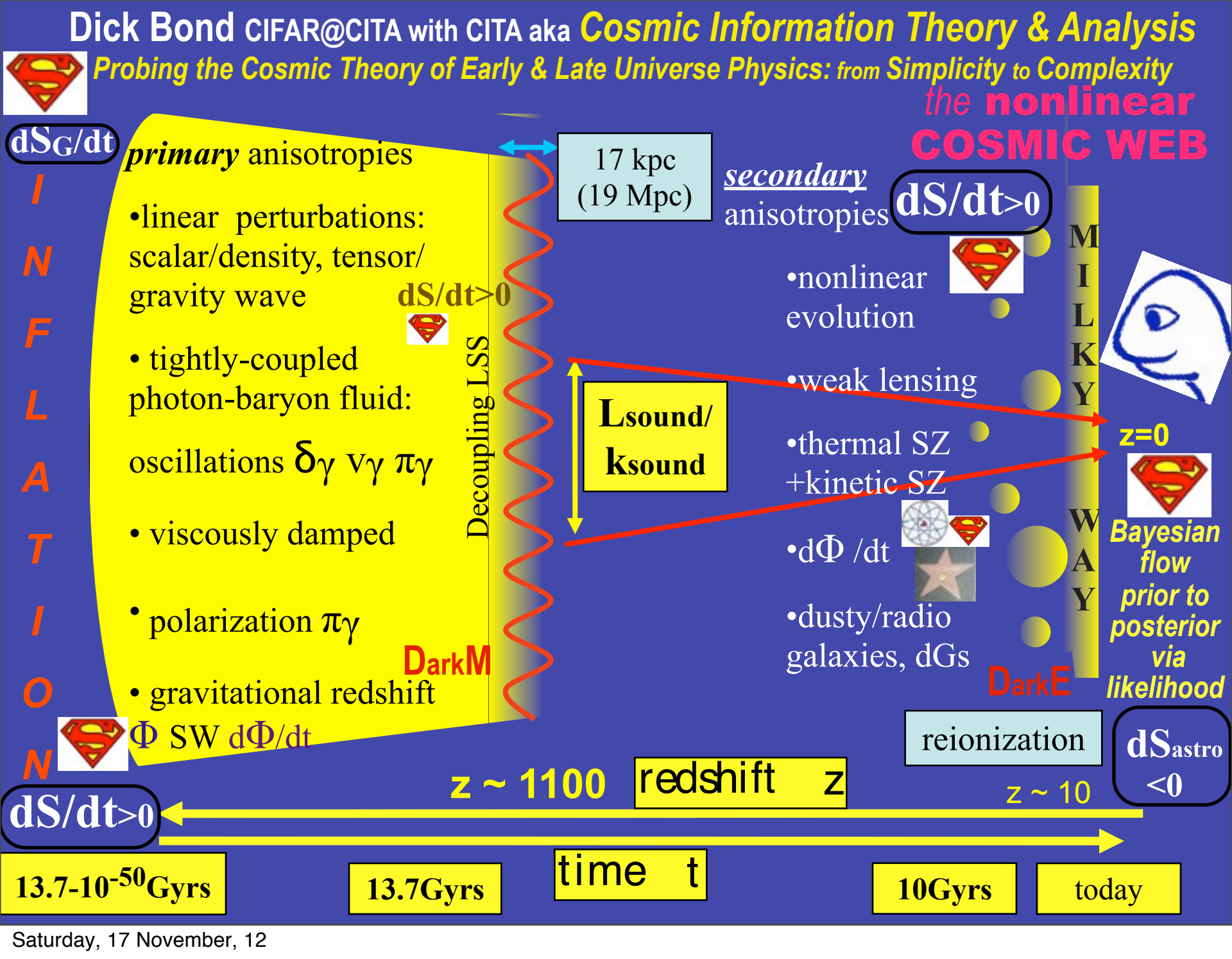




$a_{Shock}(g)$



non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating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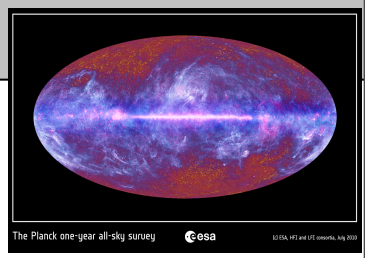
time t
13.7-10-50Gyrs
13.7Gyrs
10Gyrs
today

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

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

$\Omega_{er} h^2$ $\Omega_{m\nu} h^2$ X_{He}

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

1+w0, wa

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

ne(a)

$\sim \ln \sigma_8^2$

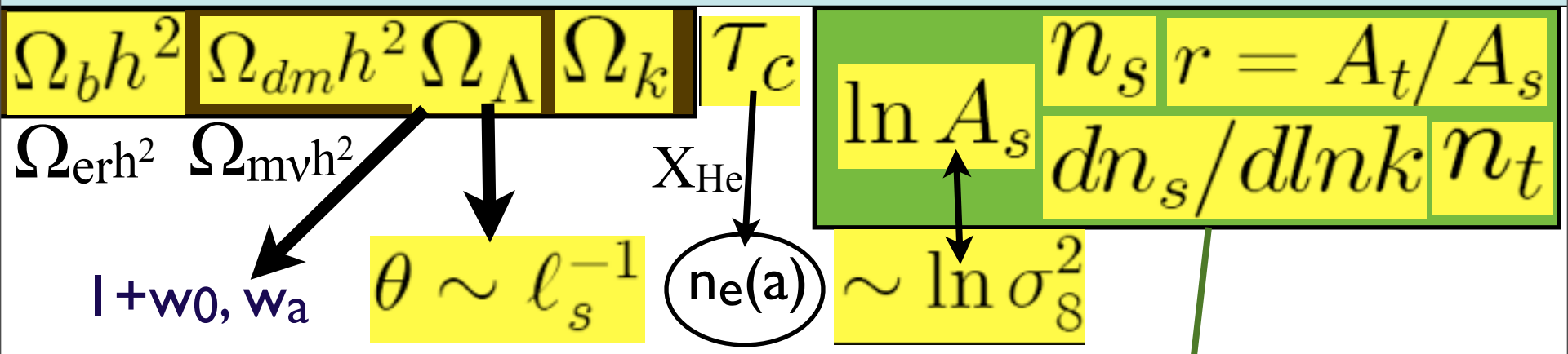
new parameters: **trajectory probabilities for early-inflatons & late-inflatons**

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

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

Inflation Histories
(CMBall+LSS+SN+WL)

Standard Parameters of Cosmic Structure Formation



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

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(CMBall+LSS+SN+WL)

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Dark Energy Histories
(SN+WL+BAO+CMB+cls)

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Inflation Histories
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Reionization Histories
(Planck+21-cm)

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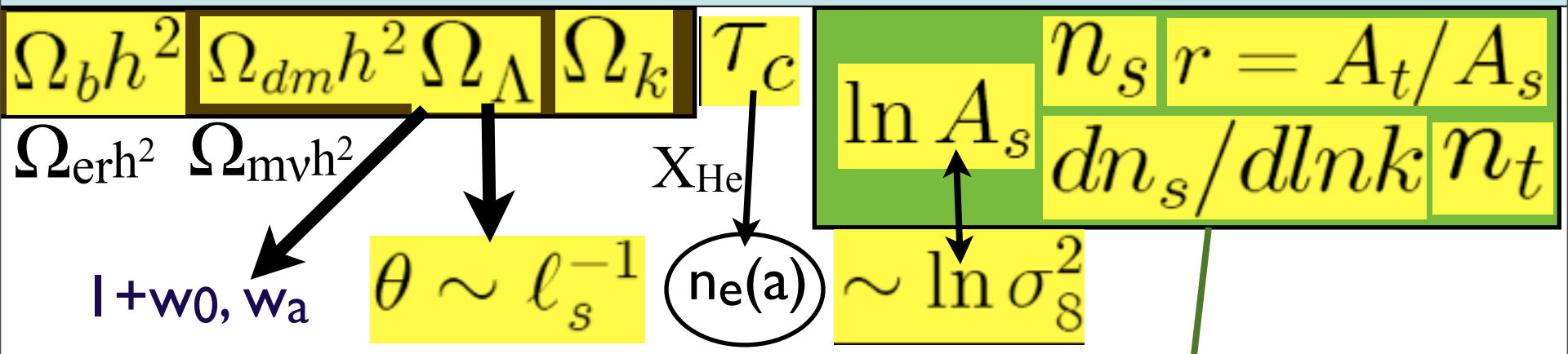

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Recombination Histories
(RecFast => CosmoRec, HyRec (Planck +ACTpol+SPTpol)

Reionization Histories
(Planck+21-cm)

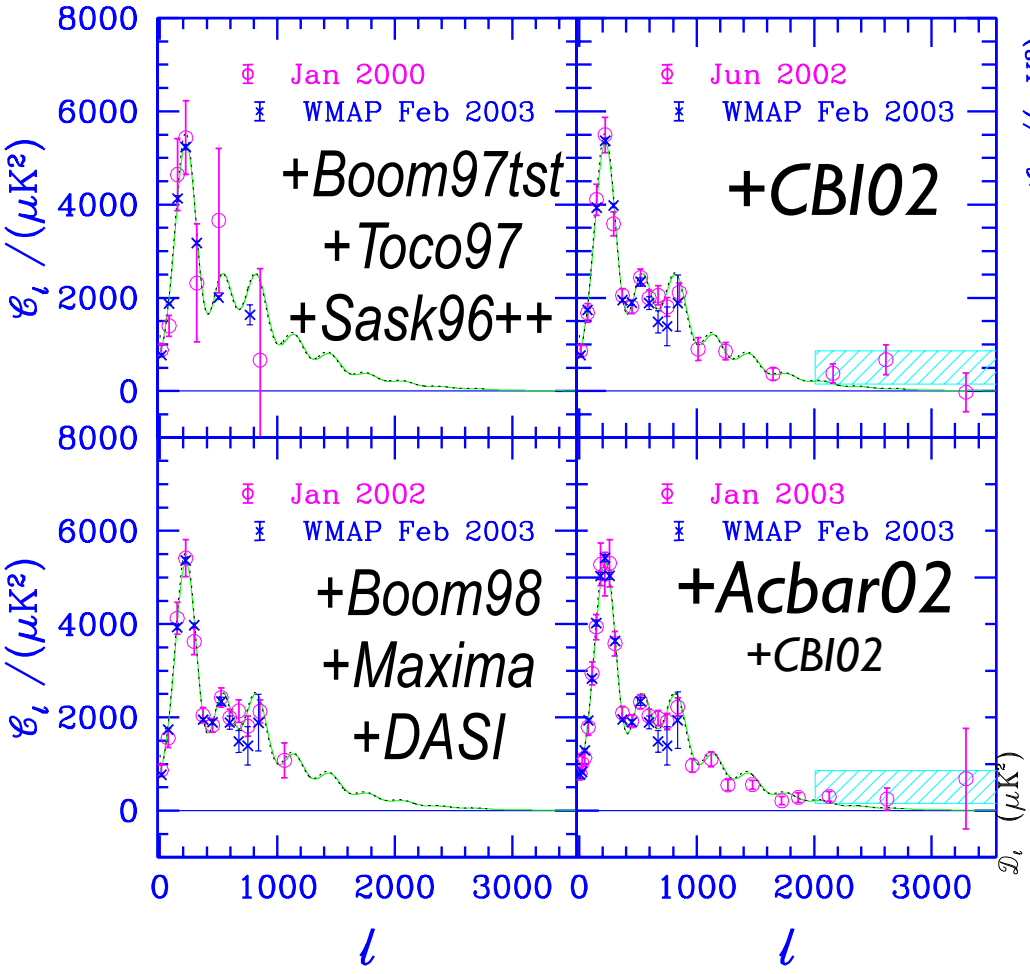
Inflation Histories
(CMBall+LSS+SN+WL)

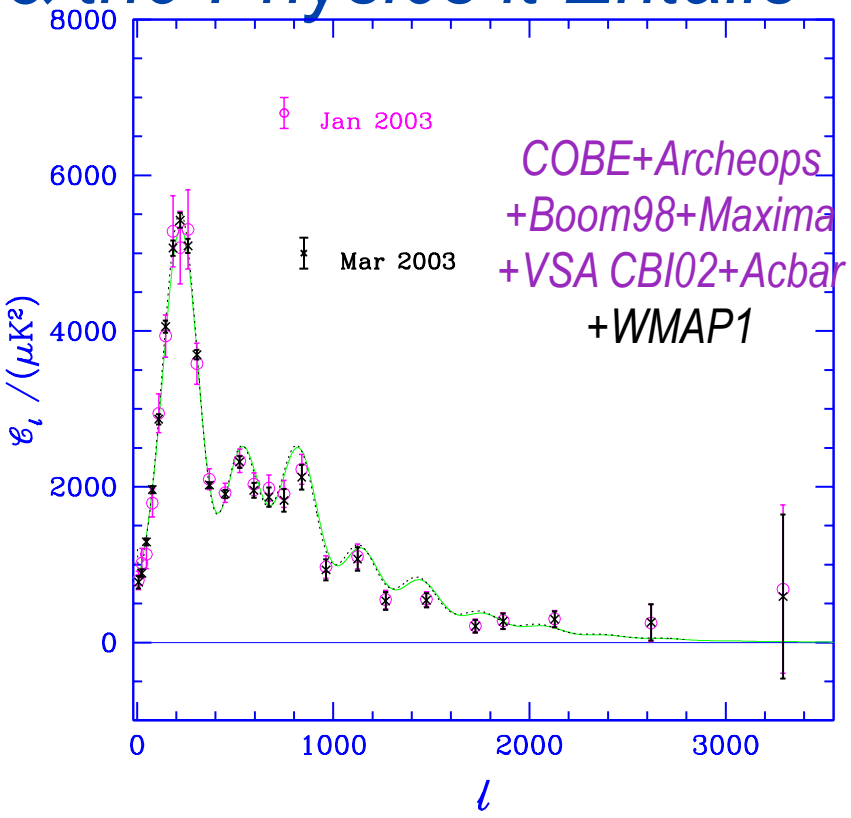
CMB Polarization, Gravity Waves
(Planck, ACTpol, ABS, Spider, Quiet2)
r=T/S, **acceleration trajectories**

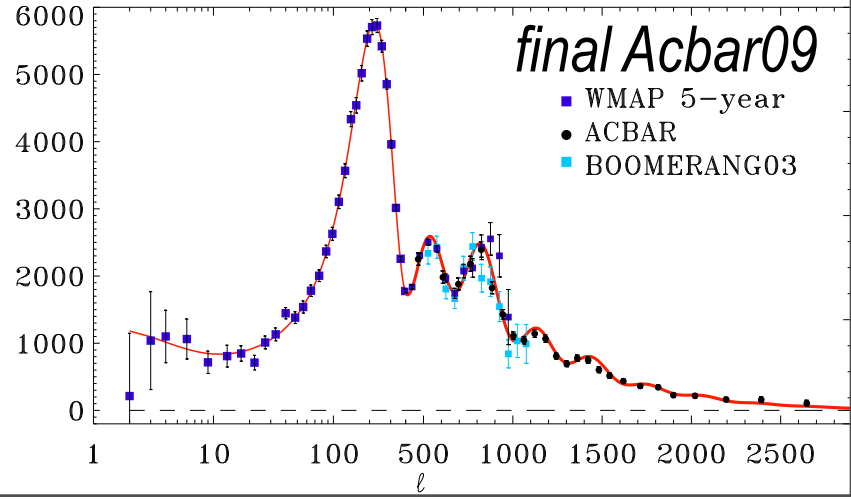
in Quest of the Damping Tail & the Physics it Entails

Grand Unified Spectra *aka* **GUS**

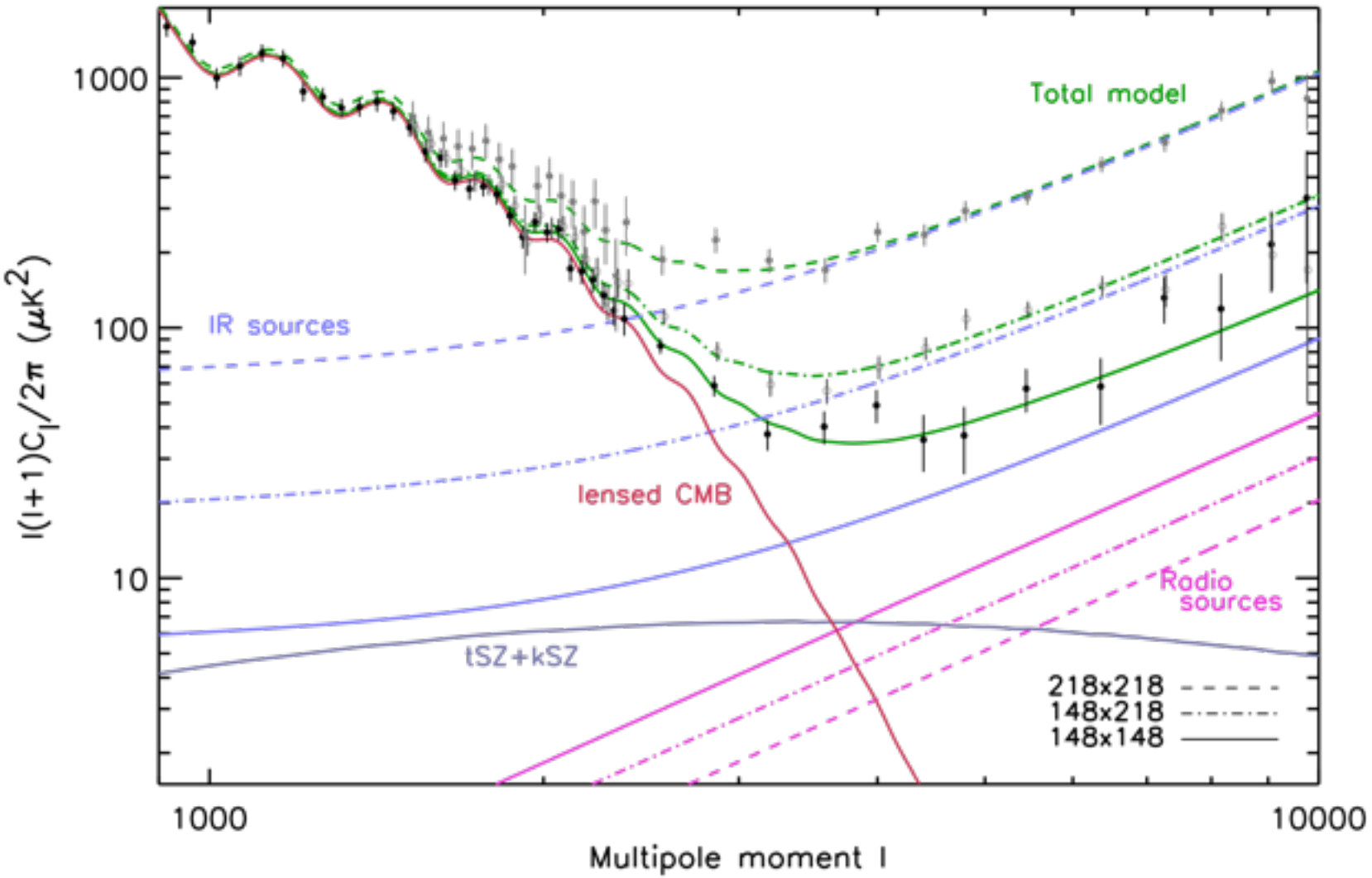
*COBE***EXT**





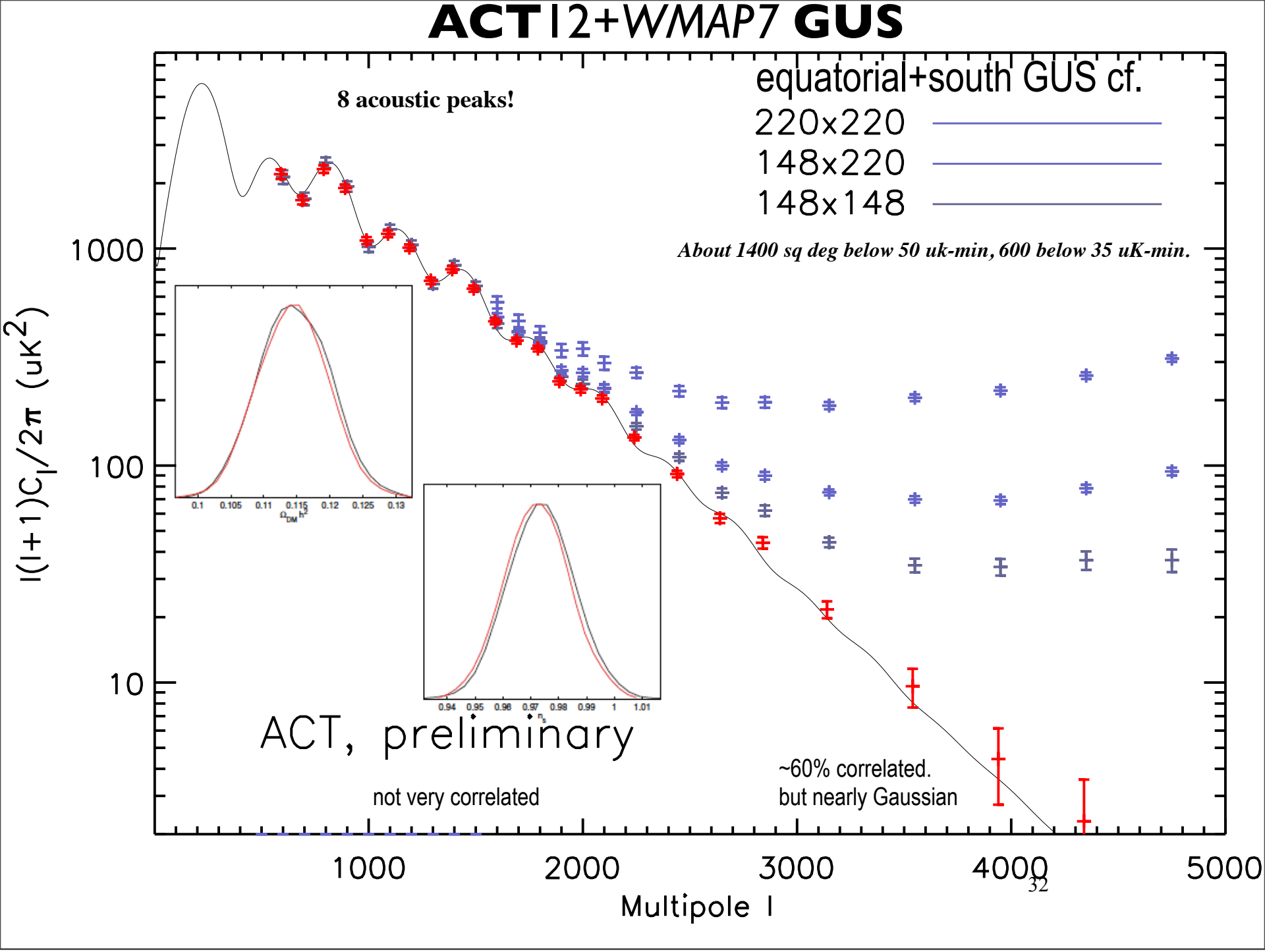


primordial (lensed) CMB + veils, *the veils = radio sources, the CIB, tSZ and kSZ (& Milky Way dust and synchrotron at lower multipoles)*



Dunkley+. 2010

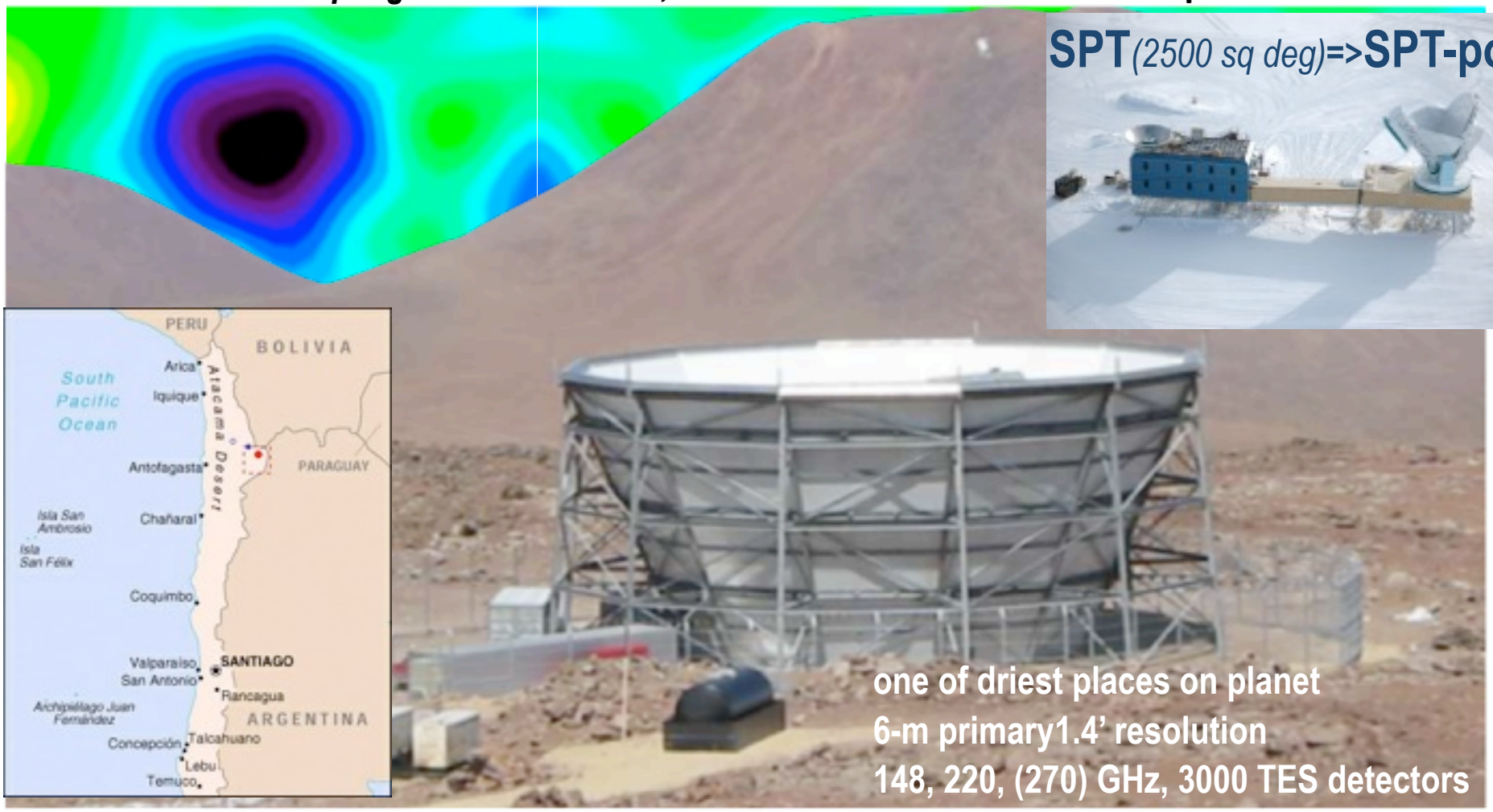
ACT12+*WMAP7* GUS



Atacama Cosmology Telescope @ 5200m

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

***About 1400 sq deg below 50 uk-min, 600 below 35 uK-min.* next is ACTpol**



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]
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M.D. Niemack [11,6]
* M.R. Nolta [8]
L.A. Page (PI) [6]
L. Parker [6]
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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)
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[6] Princeton University Physics (USA)
[7] University of Rome "La Sapienza" (Italy)
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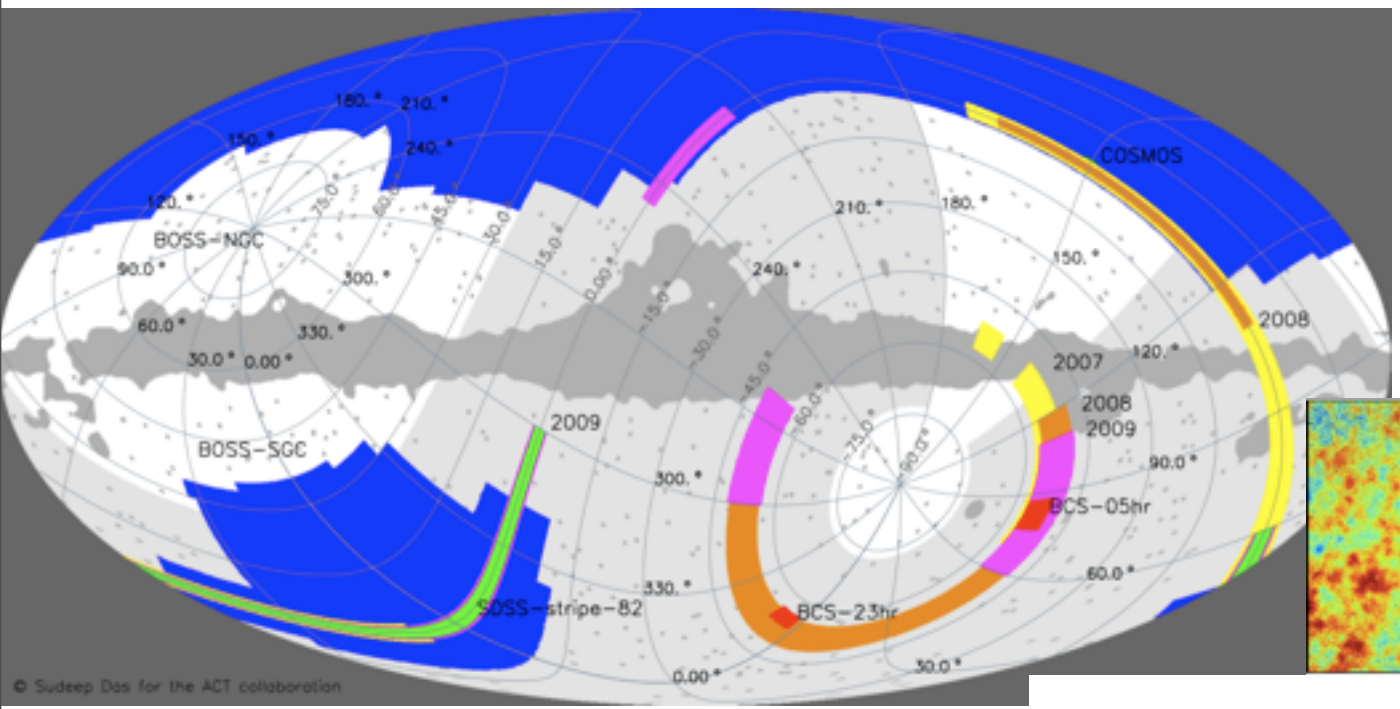
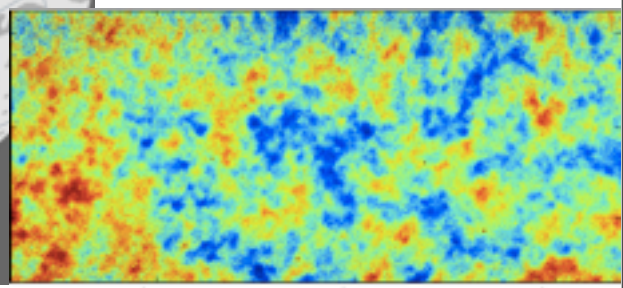
[13] Max Planck Institut fur Astrophysik (Germany)
[14] University of KwaZulu-Natal (South Africa)
[15] South African Astronomical Observatory
[16] University of Miami (USA)
[17] INAOE (Mexico)
[18] Rutgers (USA)
[19] Institute de Ciencies de L'Espai (Spain)
[20] KIPAC, Stanford (USA)
[21] Columbia University (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.

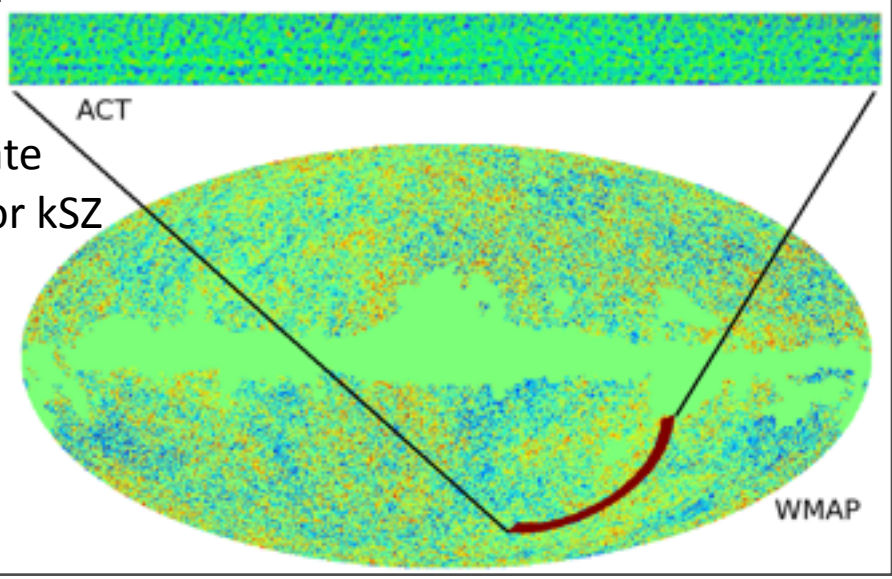
next step is ACTpol

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





Hajian et al (2010)

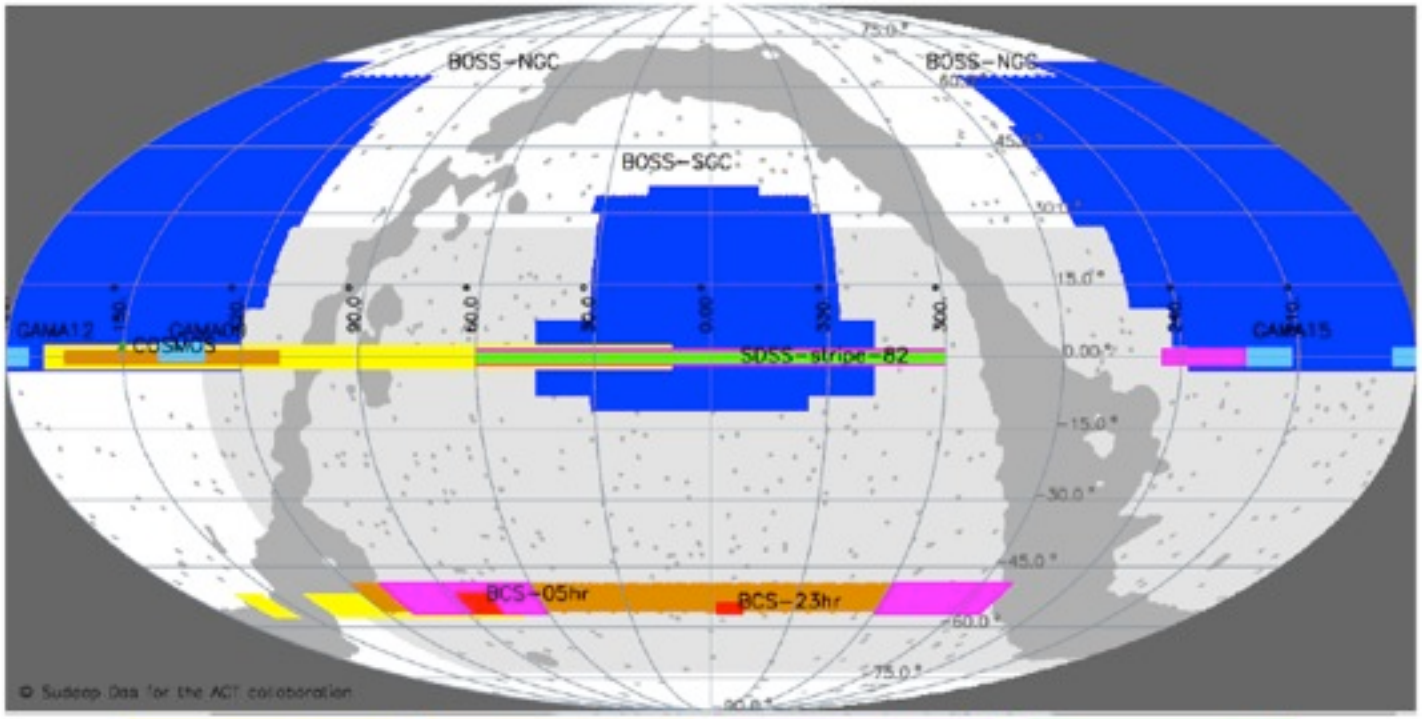


<ACT SZ x other data (opt, X, submm)>, ... X correlate overlaps SDSS III BOSS in the ACT equatorial strip, for kSZ

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.

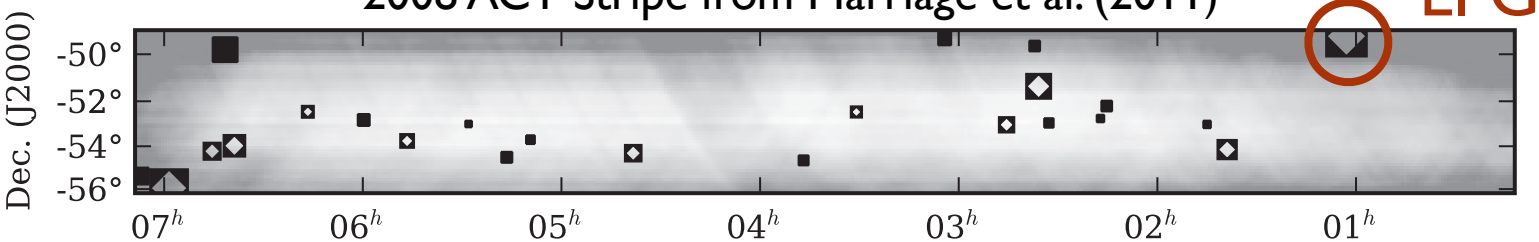


2007 | 2008 | 2009+2010 | Stripe 82

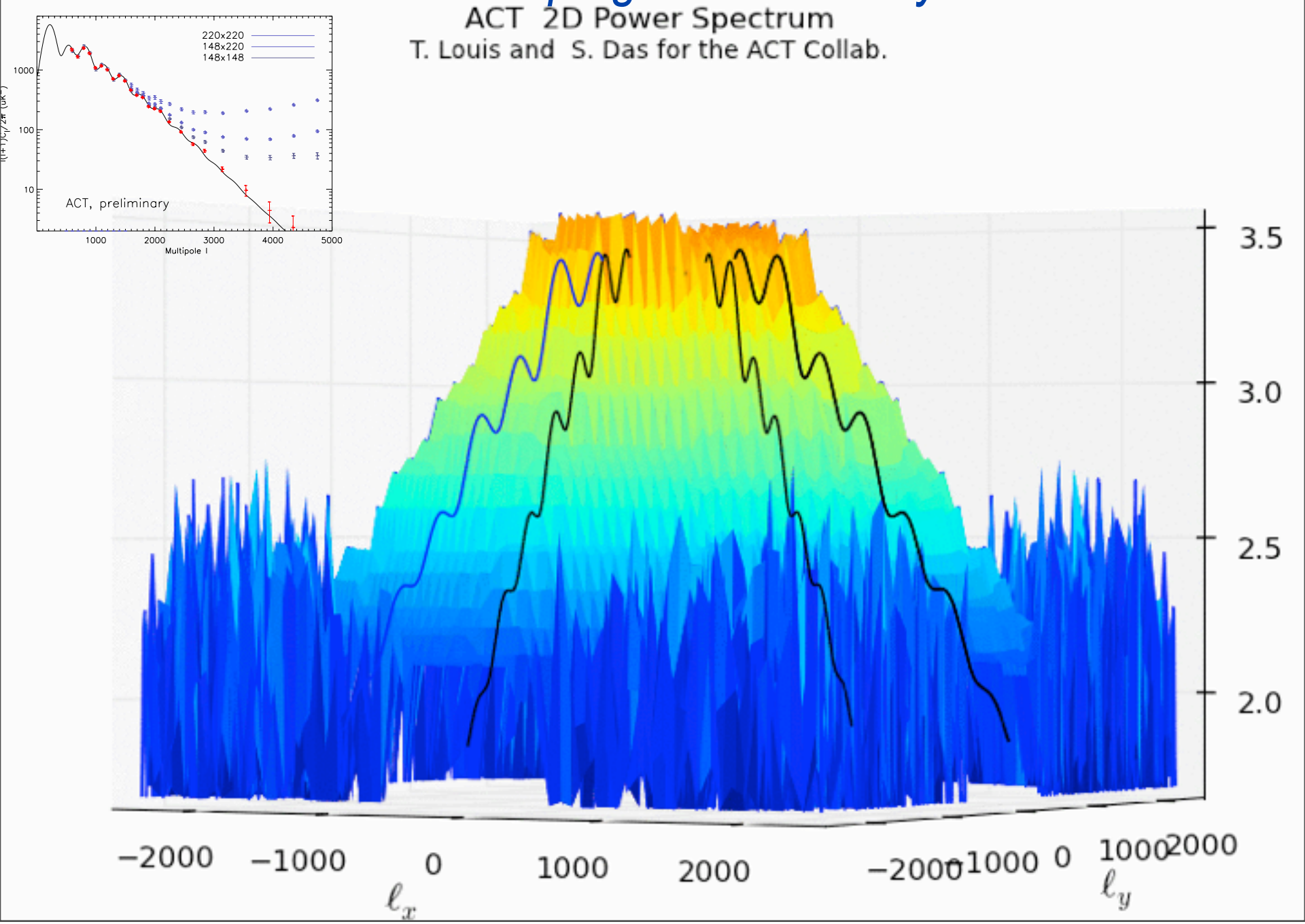
BCS | BOSS | GAMA | ACT Range | Mask

2008 ACT Stripe from Marriage et al. (2011)

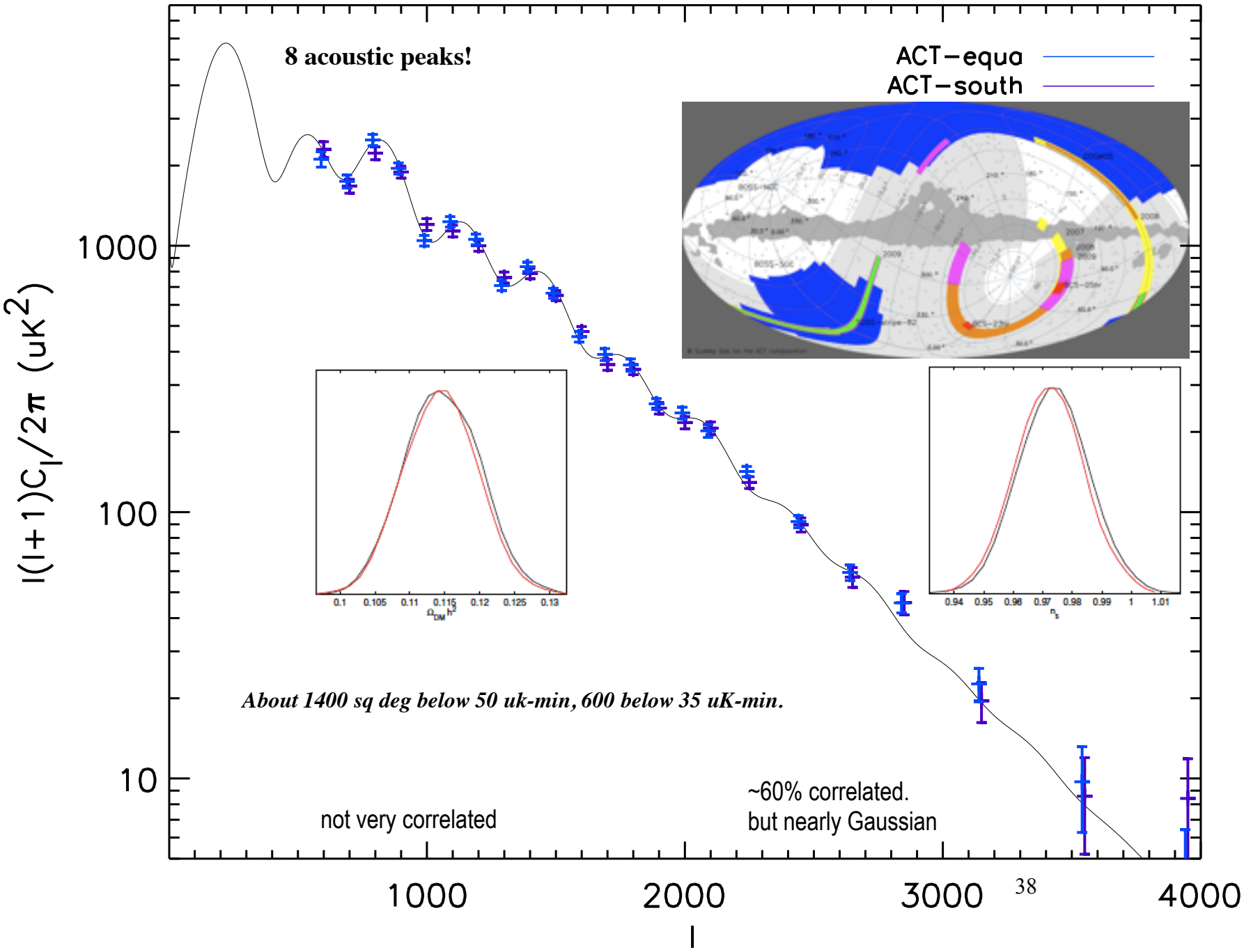
El Gordo



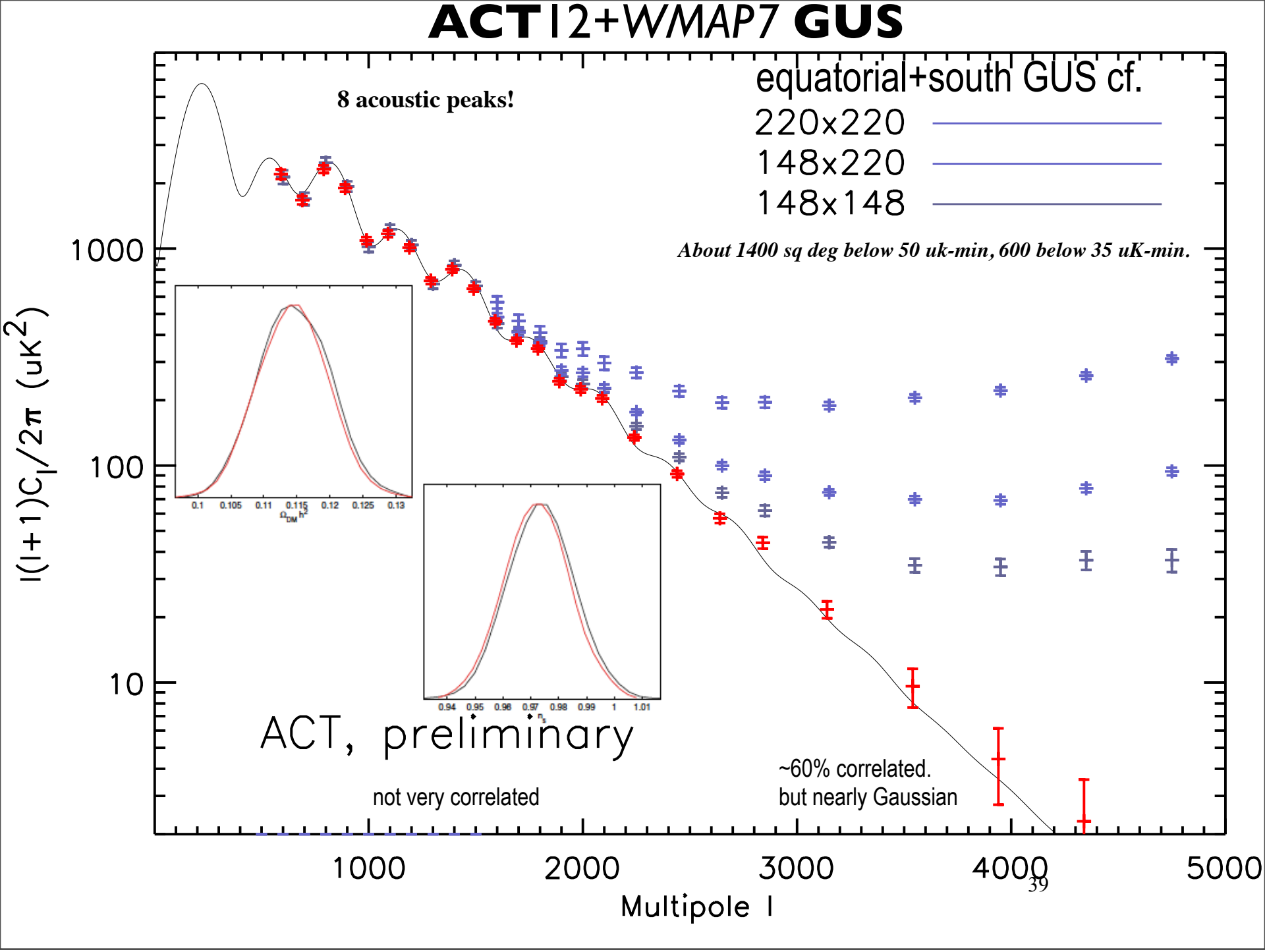
in Quest of the Damping Tail & the Physics it Entails



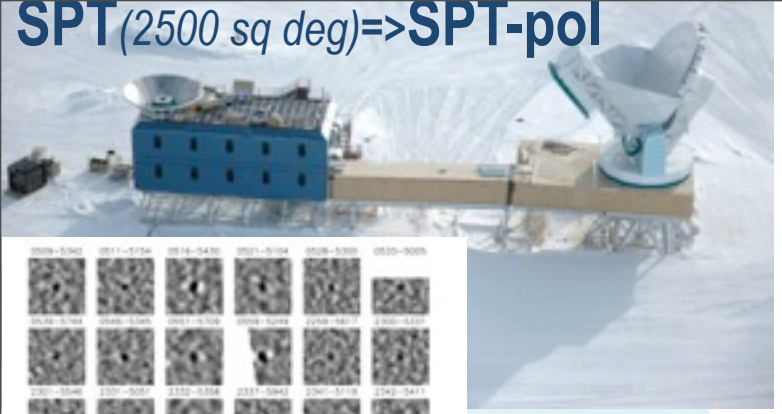
ACT+*WMAP7* GUS

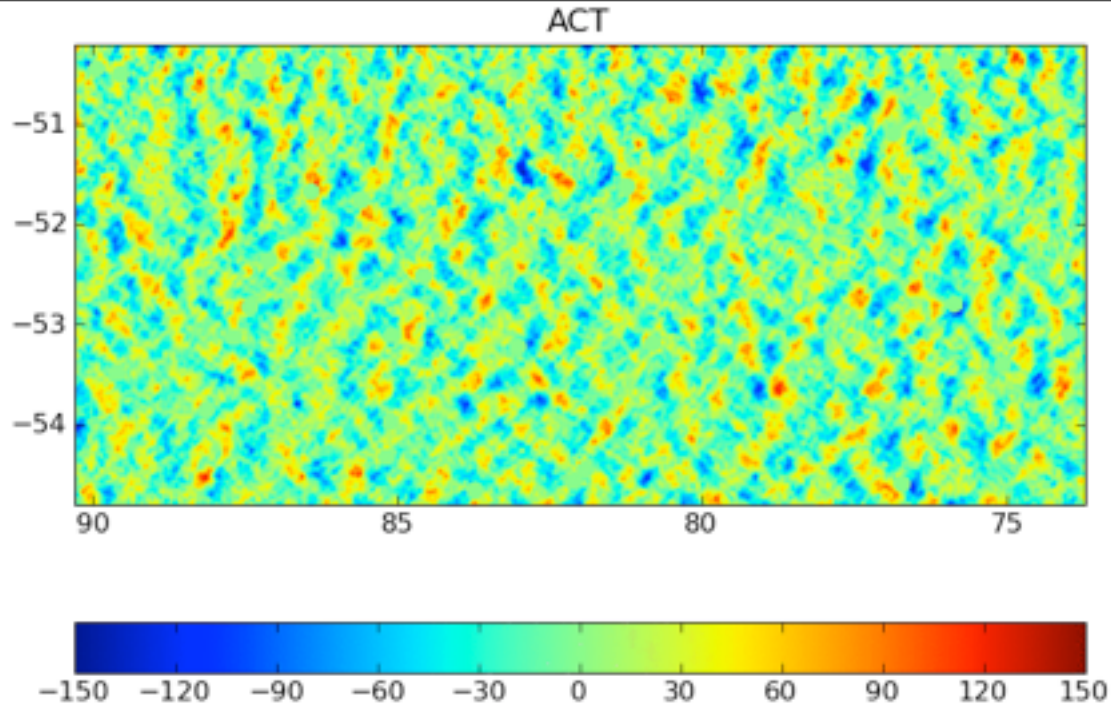


ACT12+*WMAP7* GUS



SPT*(2500 sq deg)*=>SPT-pol





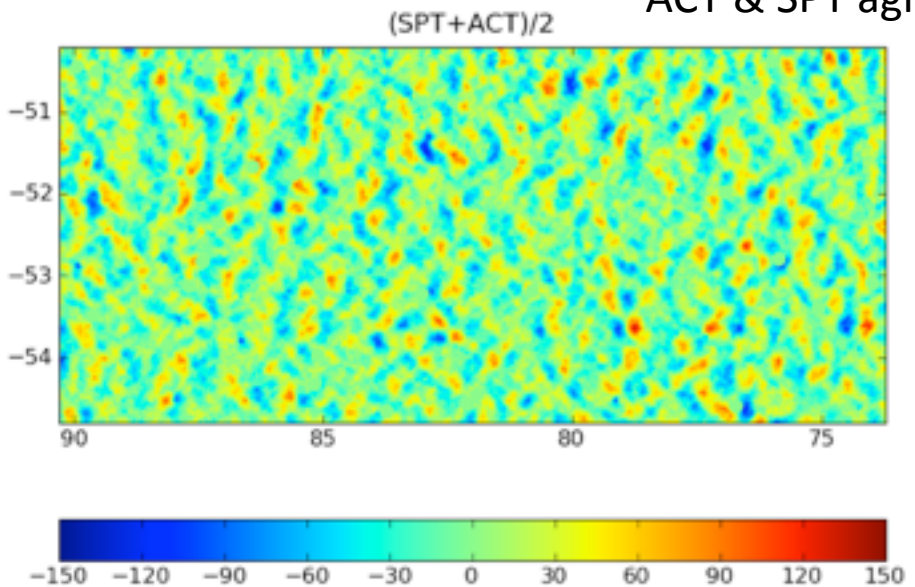
SPT clusters ~50, ~500 detected

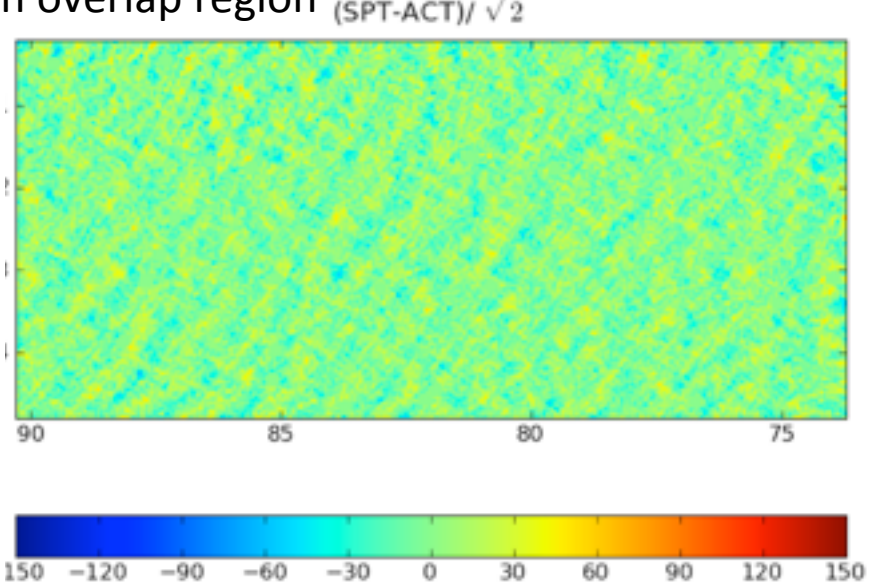
andersson+11 (15), vanderlinde+11 (21), foley+11 (z=1.14), benson+12

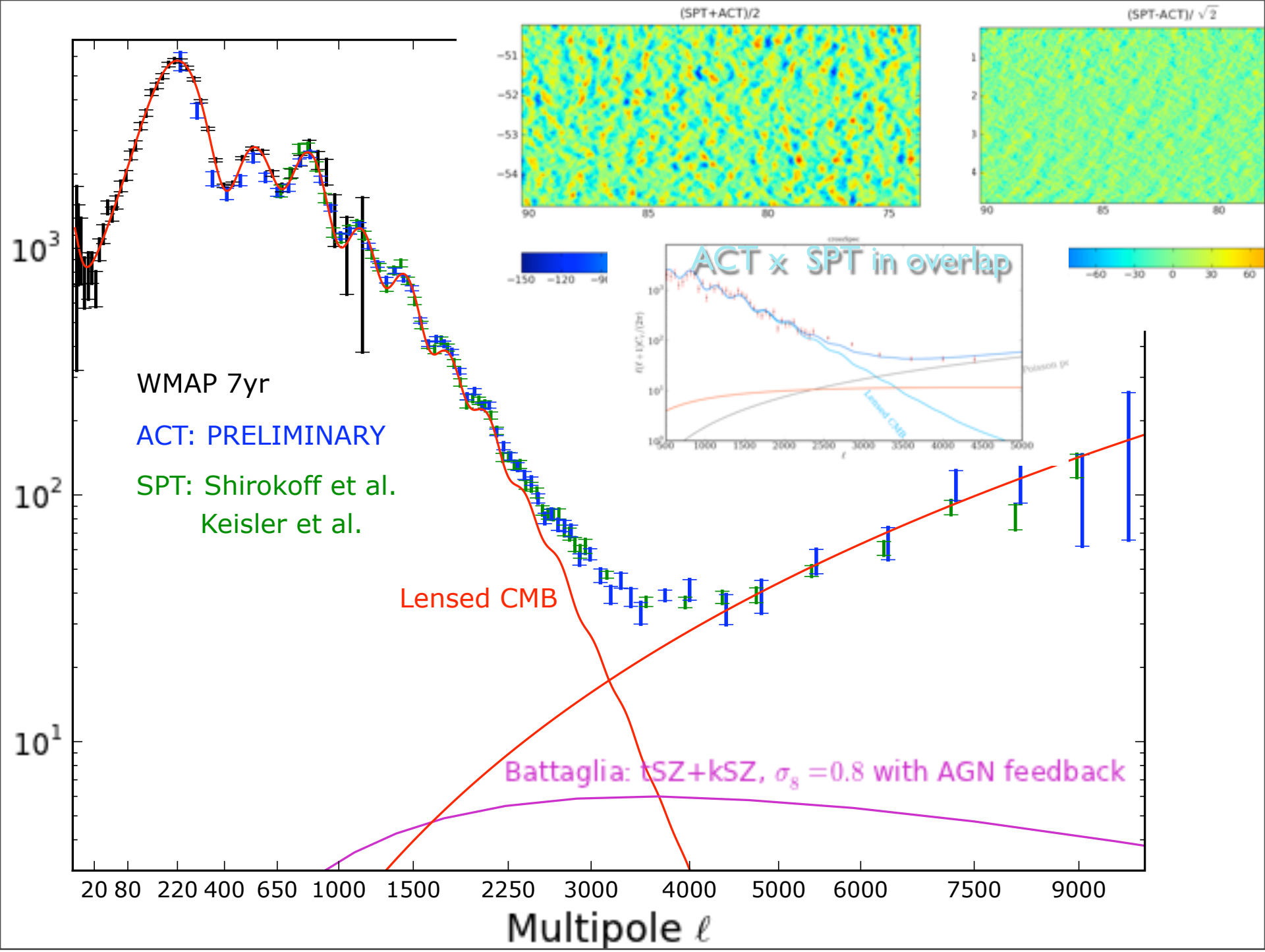
rare event: SPT-CL J2106-5844 (z=1.14)

$M_{200} = (1.27 \pm 0.21) \times 10^{15}\, h_{70}^{-1}\, M_{\odot}$

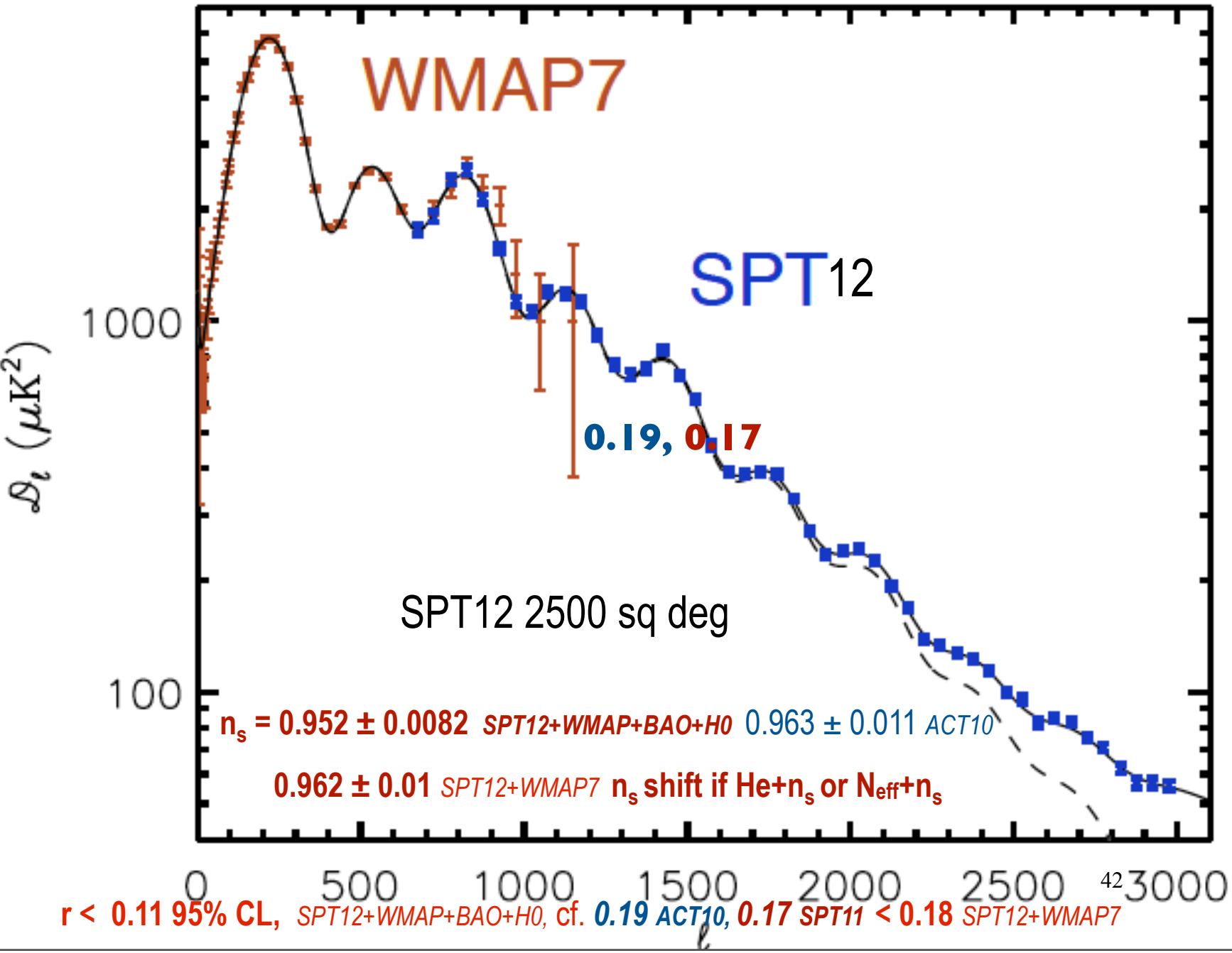
ACT & SPT agree in overlap region






(SPT+ACT)/2
(SPT-ACT)/ √2
ACT x SPT in overlap
WMAP 7yr
ACT: PRELIMINARY
SPT: Shirokoff et al.
Keisler et al.
Lensed CMB
Battaglia: tSZ+kSZ, σ8 =0.8 with AGN feedback
10^3
10^2
10^1
20 80 220 400 650 1000 1500 2250 3000 4000 5000 6000 7500 9000
Multipole ℓ

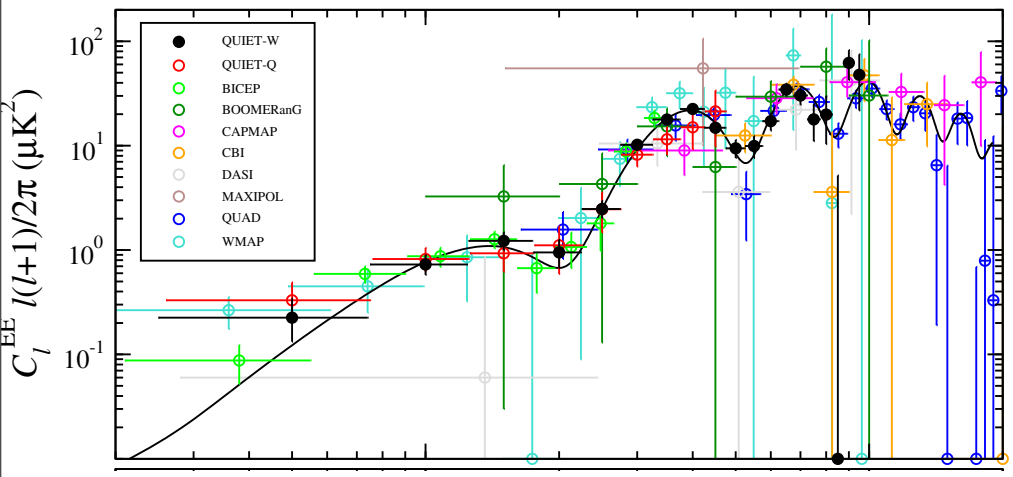
SPT12 1210.7231 Story+12 out Monday **Oct 29!**



$n_s = 0.952 \pm 0.0082$ *SPT12+WMAP+BAO+H0* 0.963 ± 0.011 *ACT10*

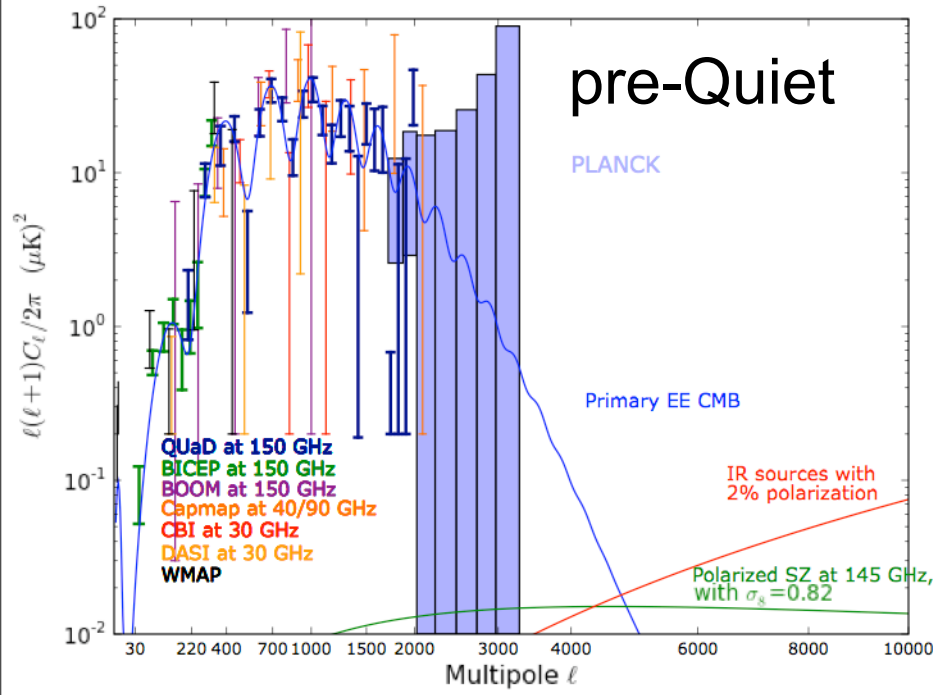
0.962 ± 0.01 *SPT12+WMAP7* **n_s shift if He+n_s or N_{eff}+n_s**

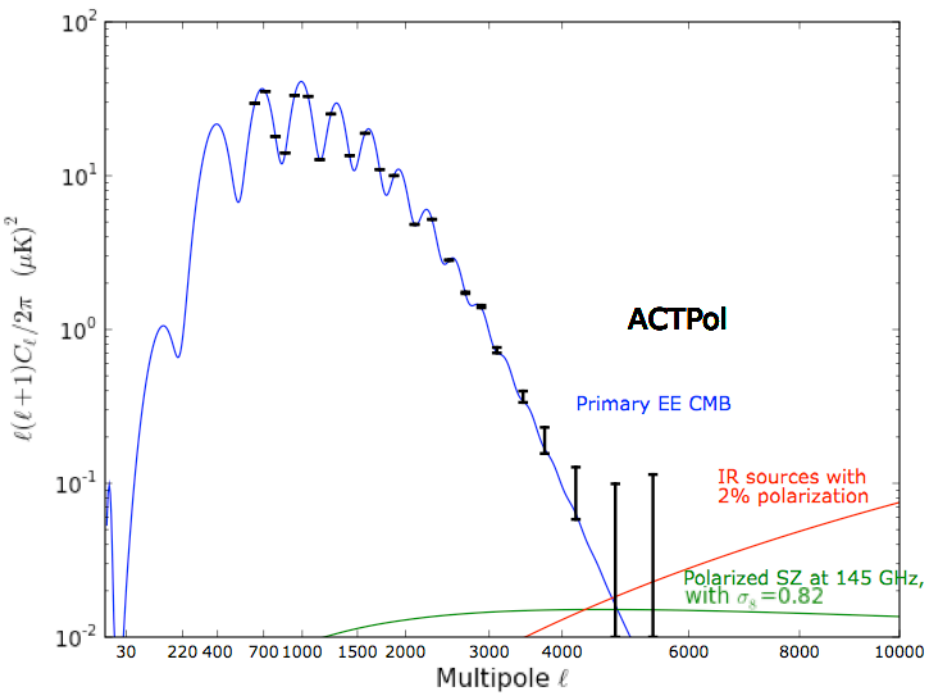
r < 0.11 95% CL, *SPT12+WMAP+BAO+H0,* cf. ***0.19 ACT10, 0.17 SPT11*** **< 0.18** *SPT12+WMAP7*



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

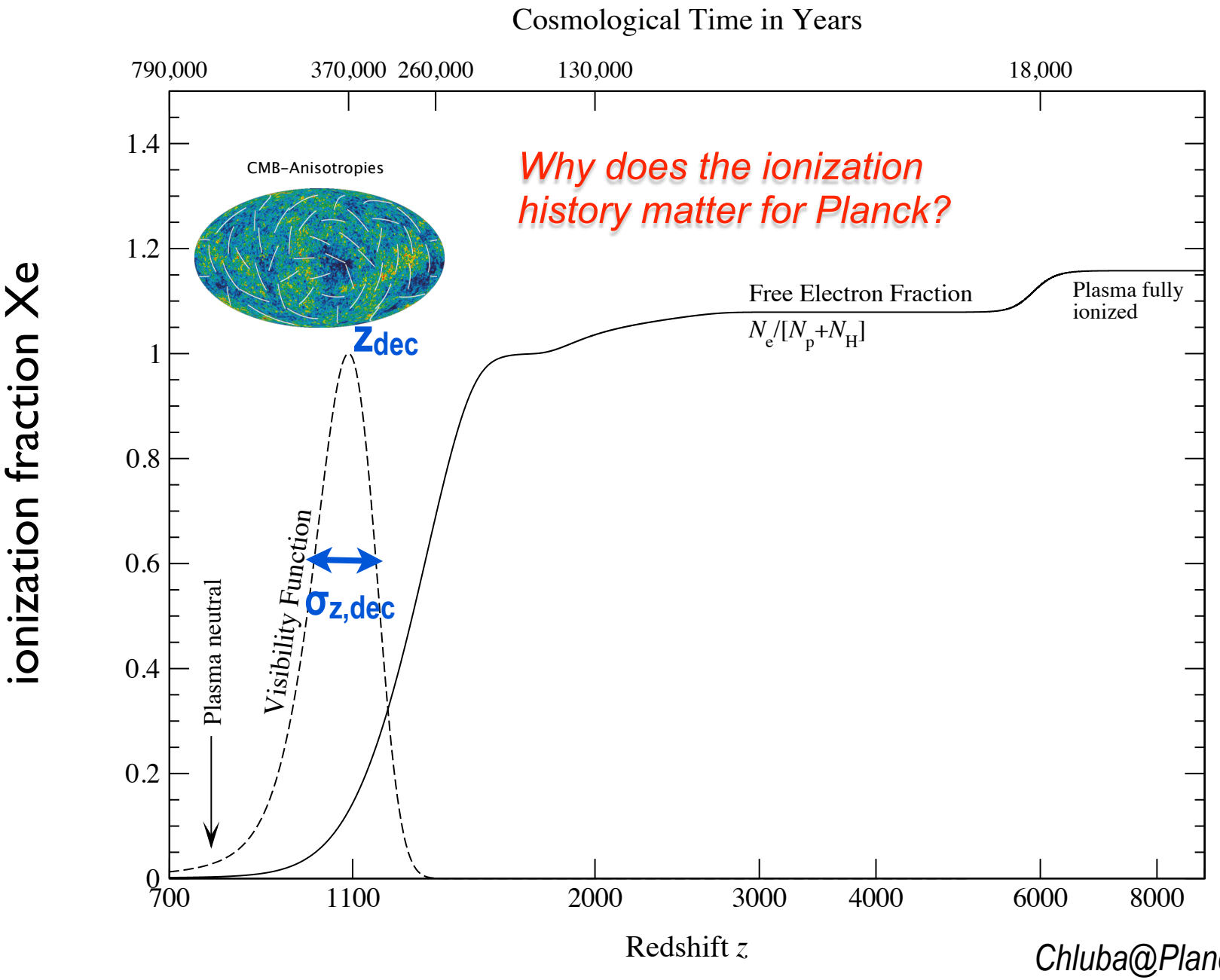
ACTpol forecast. SPTpol similar





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

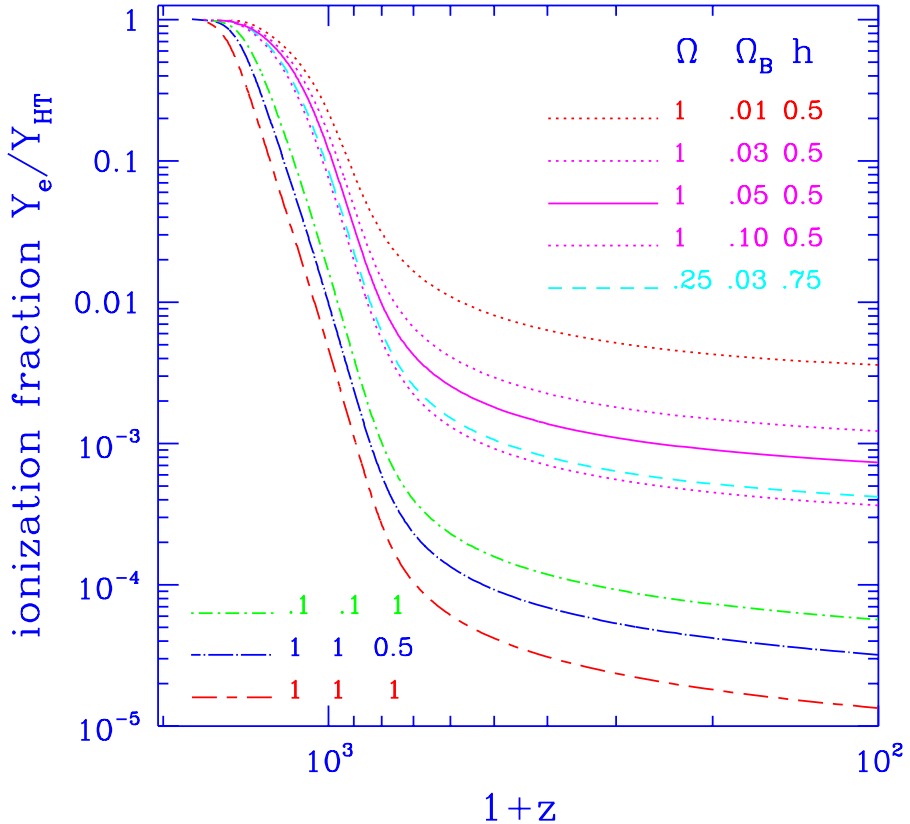
Standard Recombination History

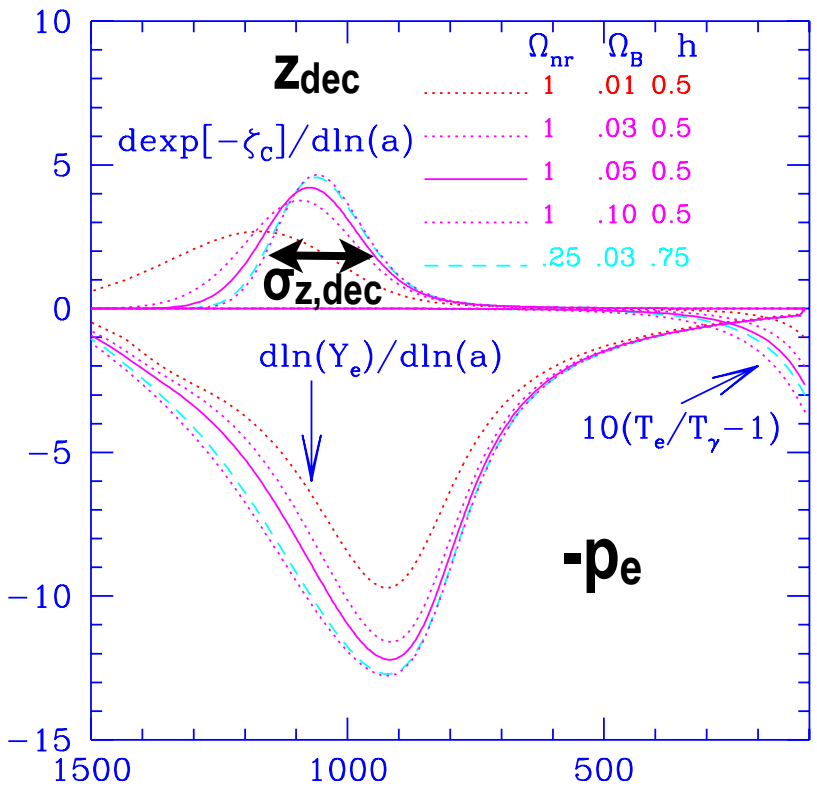


Chluba@Planck2011

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*

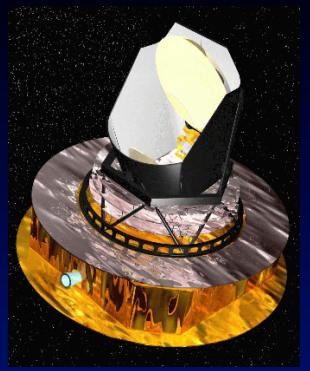
differential visibility = running of the visibility $n_e\sigma_T/H\ exp[-\int n_e\sigma_T/H\ d\ln a]$

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)*

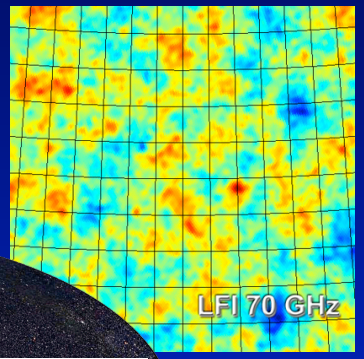
WKB baryon-photon tight coupling $L_D \sim (p_e + 2)(1+z_{dec})^{1/2} \sim (1+z_{dec})^{1/2}/\sigma_{z,dec}$

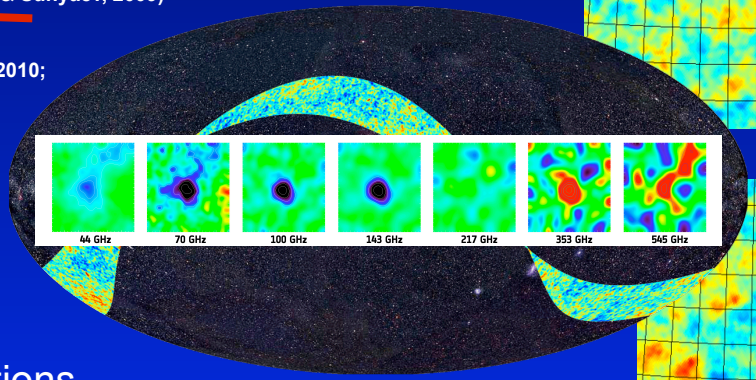
Getting Ready for Planck

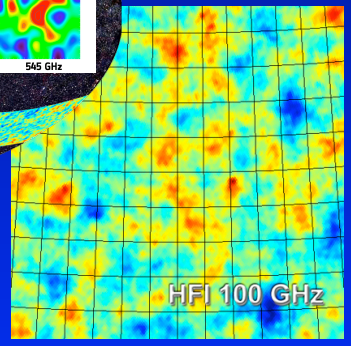


Hydrogen recombination

- 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)







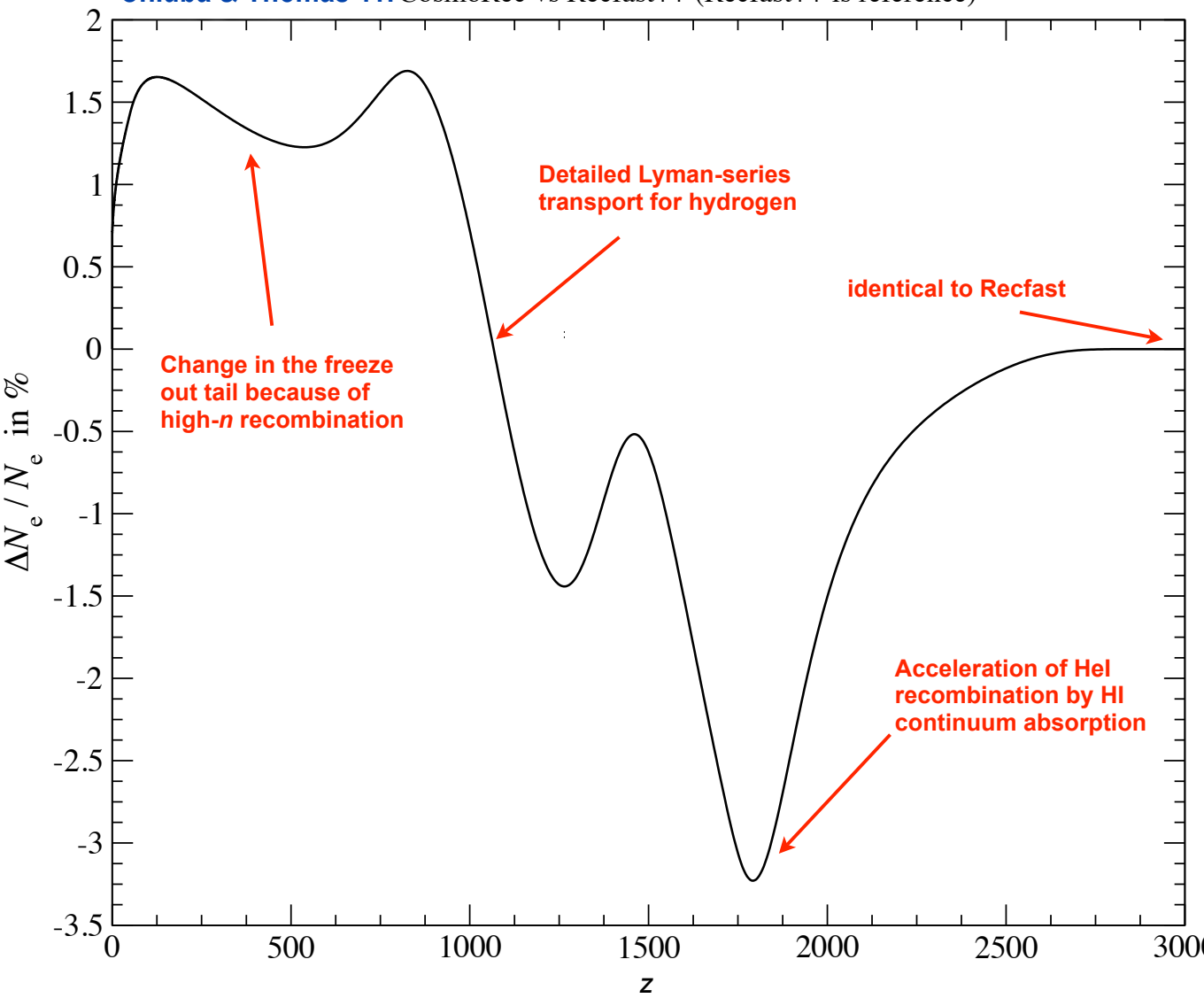
Helium recombination

- 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.*

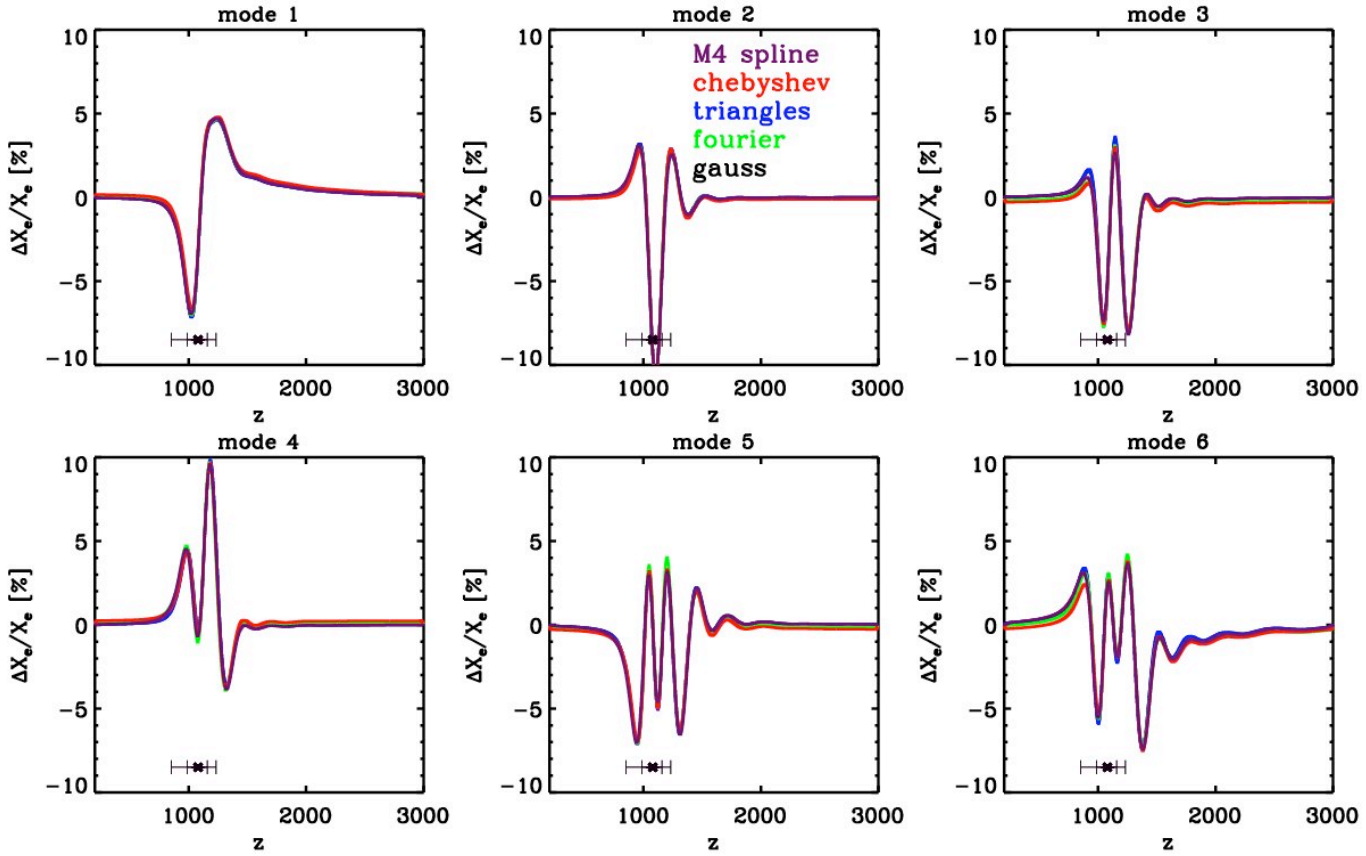
eXeM x_e-perturbations marginalized over other cosmological parameters

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

e.g., ln (x_e + σ_e) fahrang+bond+chluba11,f+b+switzer+c12

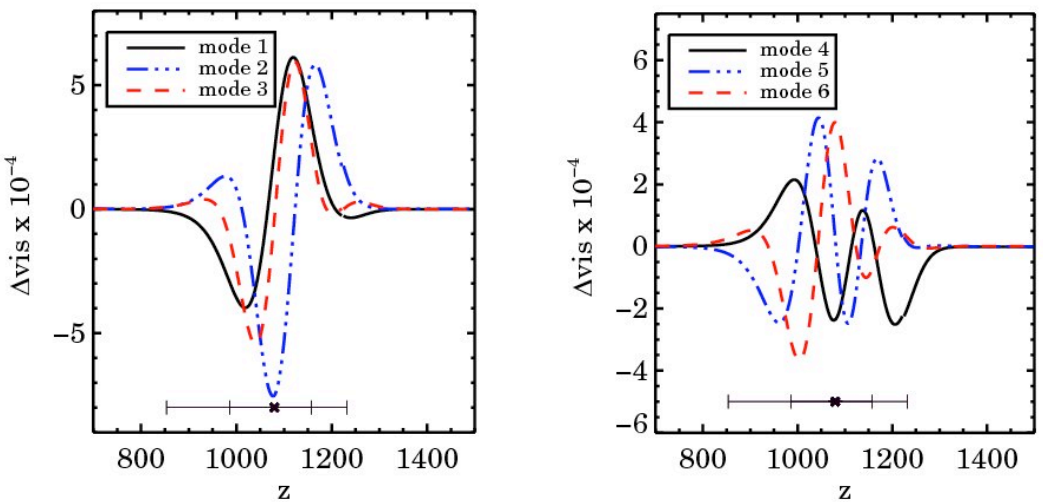
XeMs

$\Delta x_e/x_e$



XeMs in visibility

Δvisibility

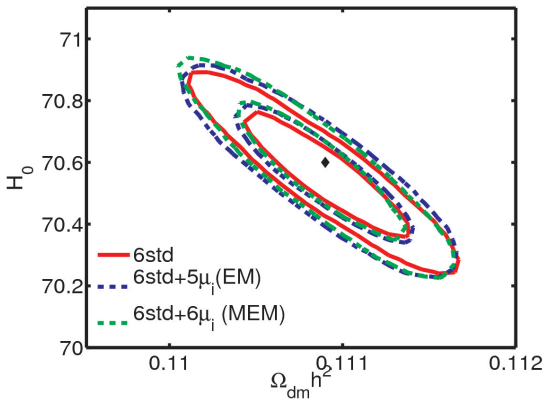


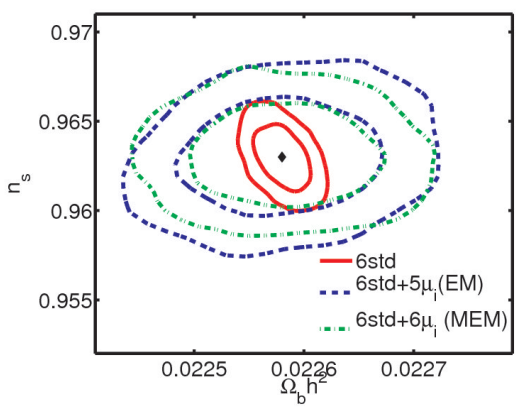
fahrang,bond,chluba*11*

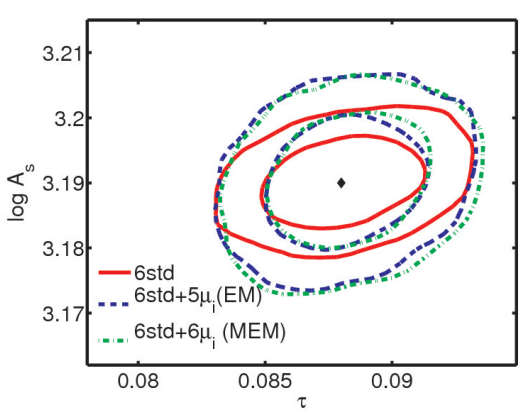
XeM's confirm a correct recombination model

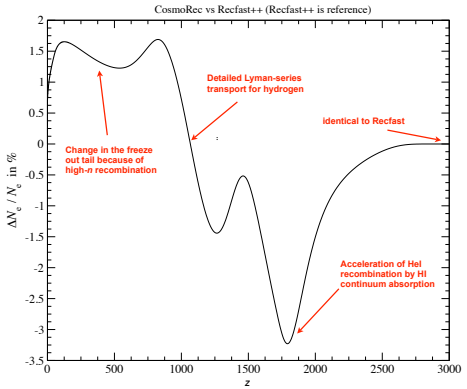
XeM's detect recfast is wrong => cosmorec change

ideal CVL expt.





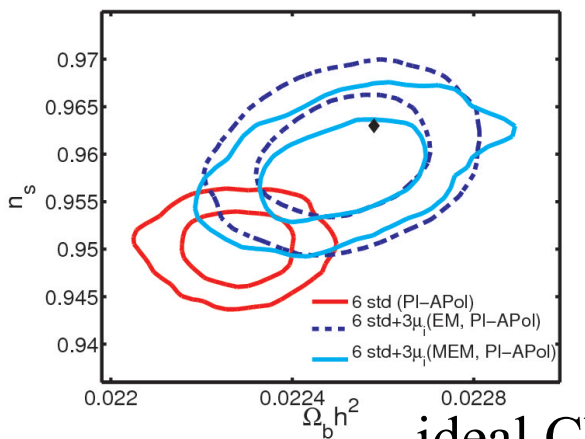


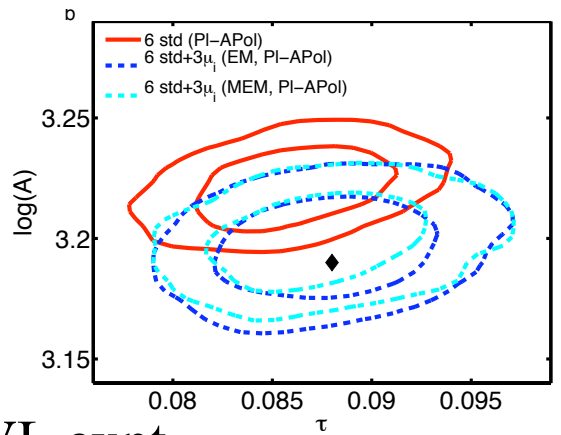


Chluba & Thomas, 2011

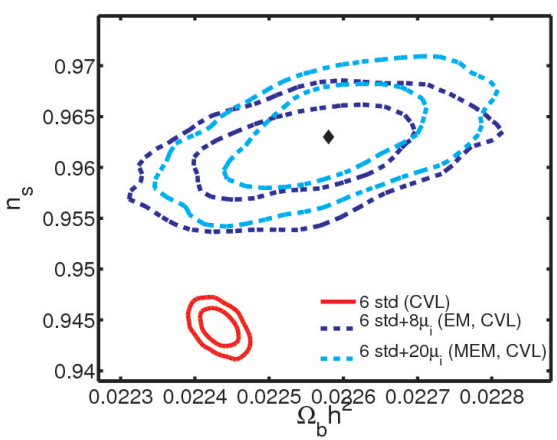
Planck+ACTPol-like

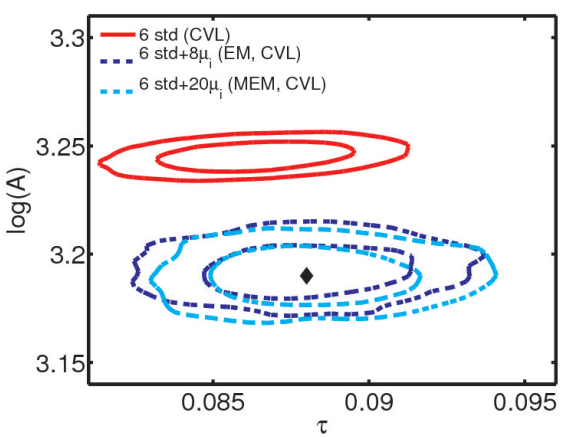
fahrang**,bond,chluba**11





ideal CVL expt.



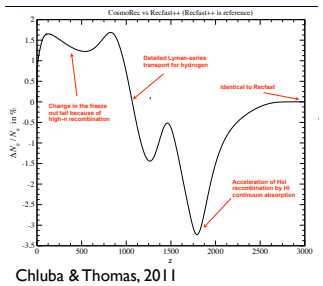


Reconstructed x_e-perturbations

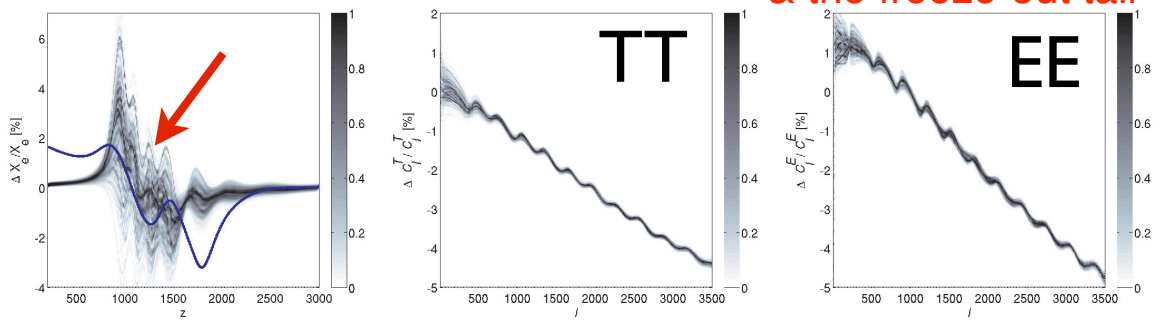
input:
CosmoRec-Recfast

Recovery in high sensitivity region. insensitive to He recomb & the freeze-out tail

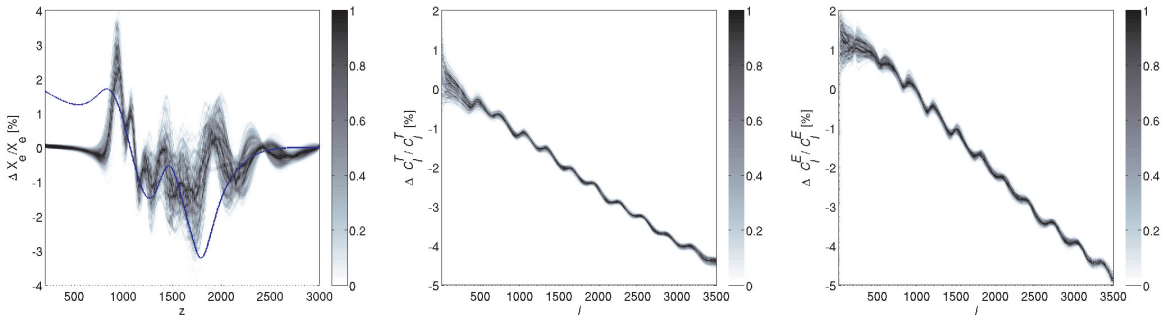
ideal expt
6 XeMs



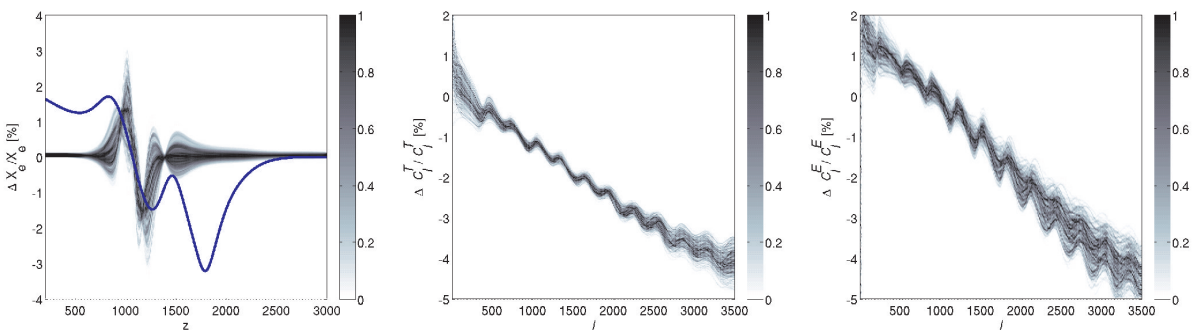
Chluba & Thomas, 2011



ideal expt
10 eXeMs



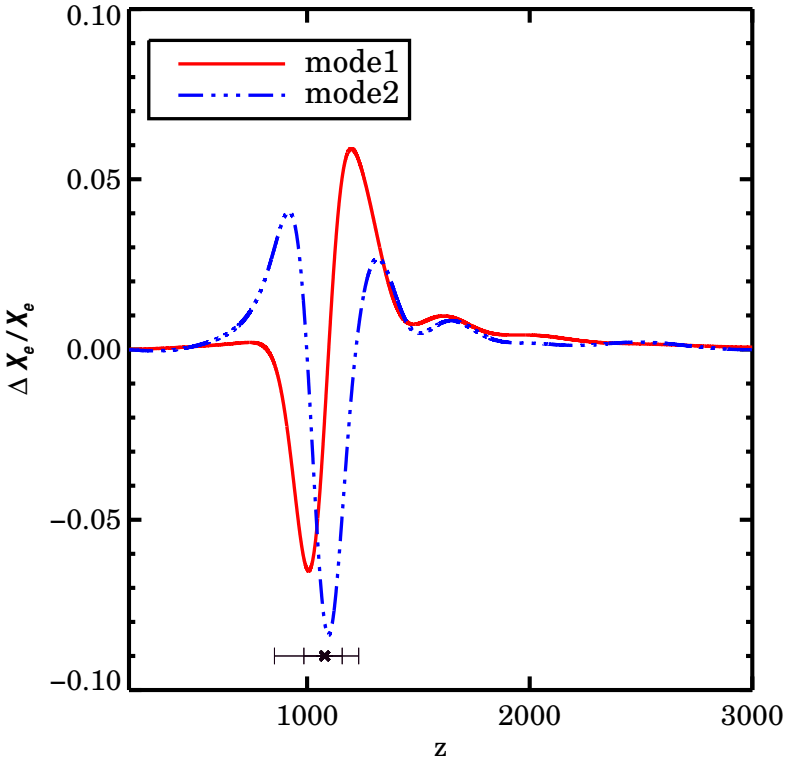
Planck+ACT/SPTPol-like
3 eXeMs

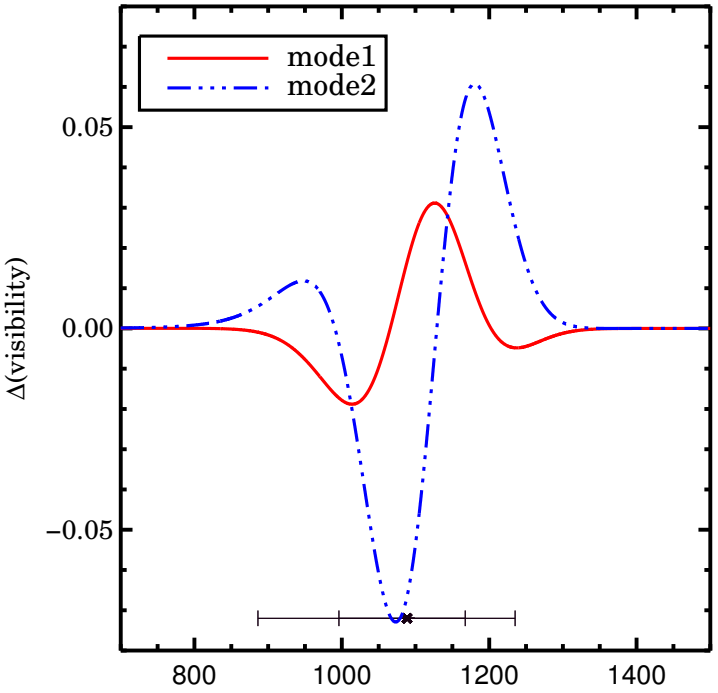


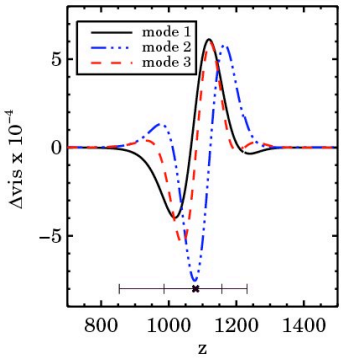
characteristic $\Delta C_L/C_L$ shape = perturbed damping tail

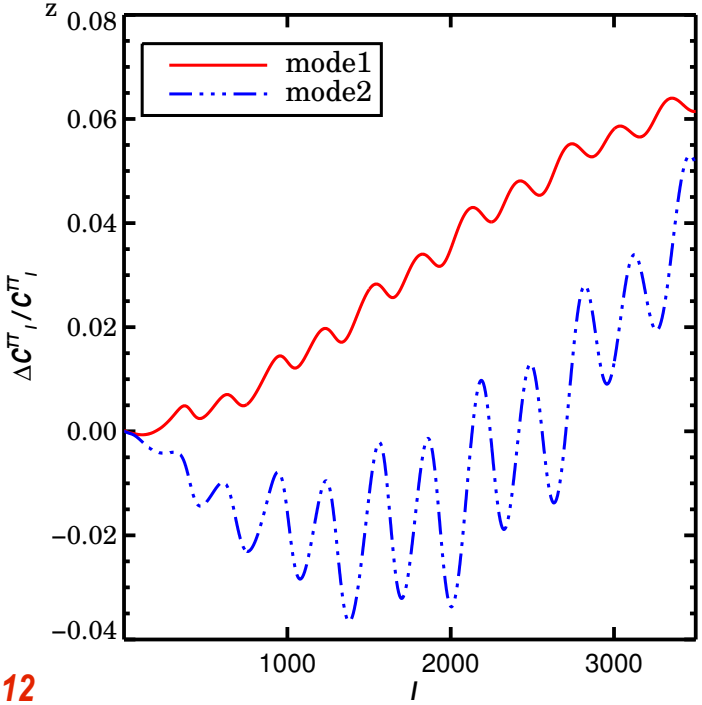
fahrang,*bond,chluba**11***

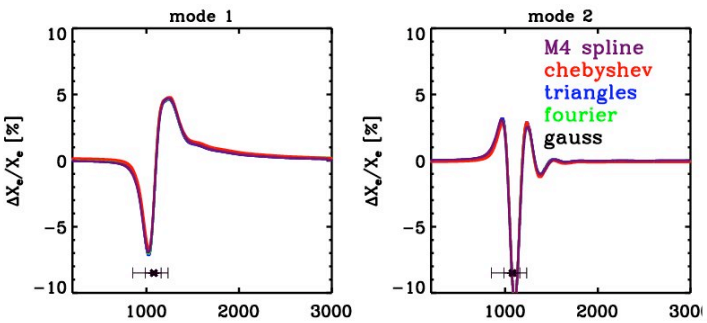
WMAP7+SPT11 2 XeMs



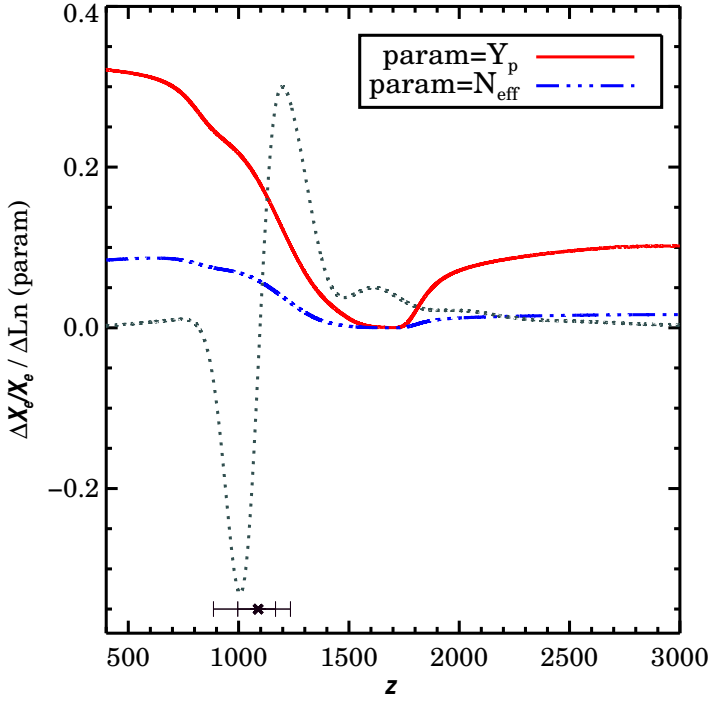


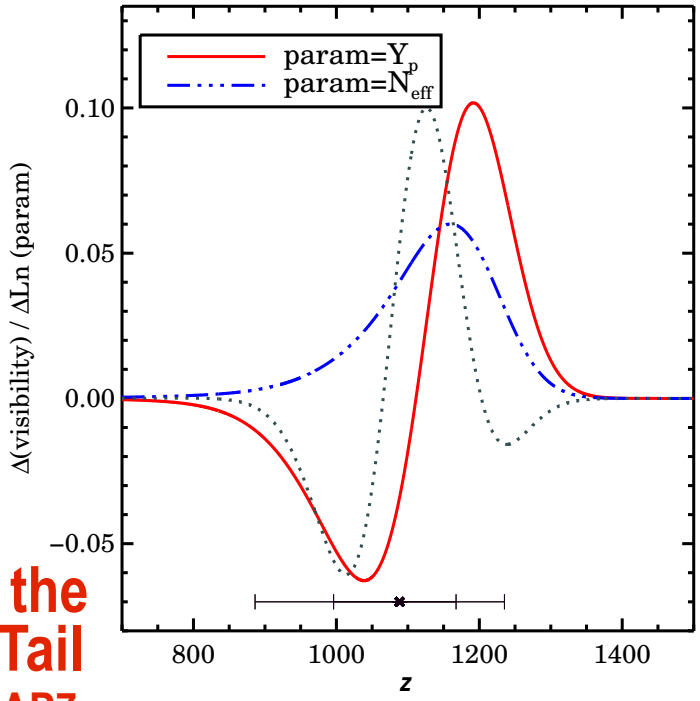






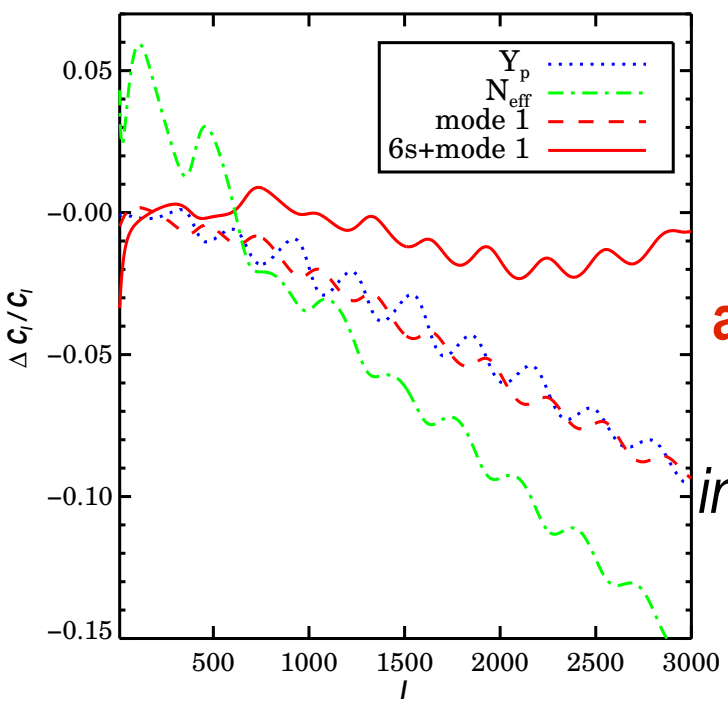
fahrang, *bond,* ***switzer,*** *chluba* ***12***

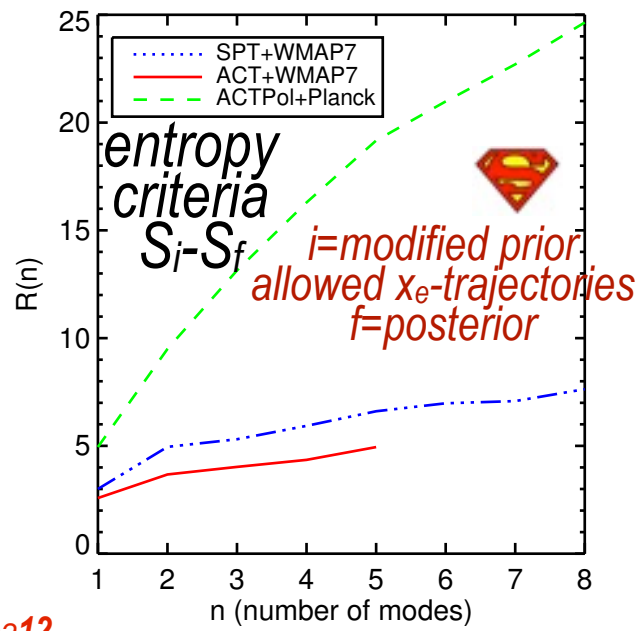




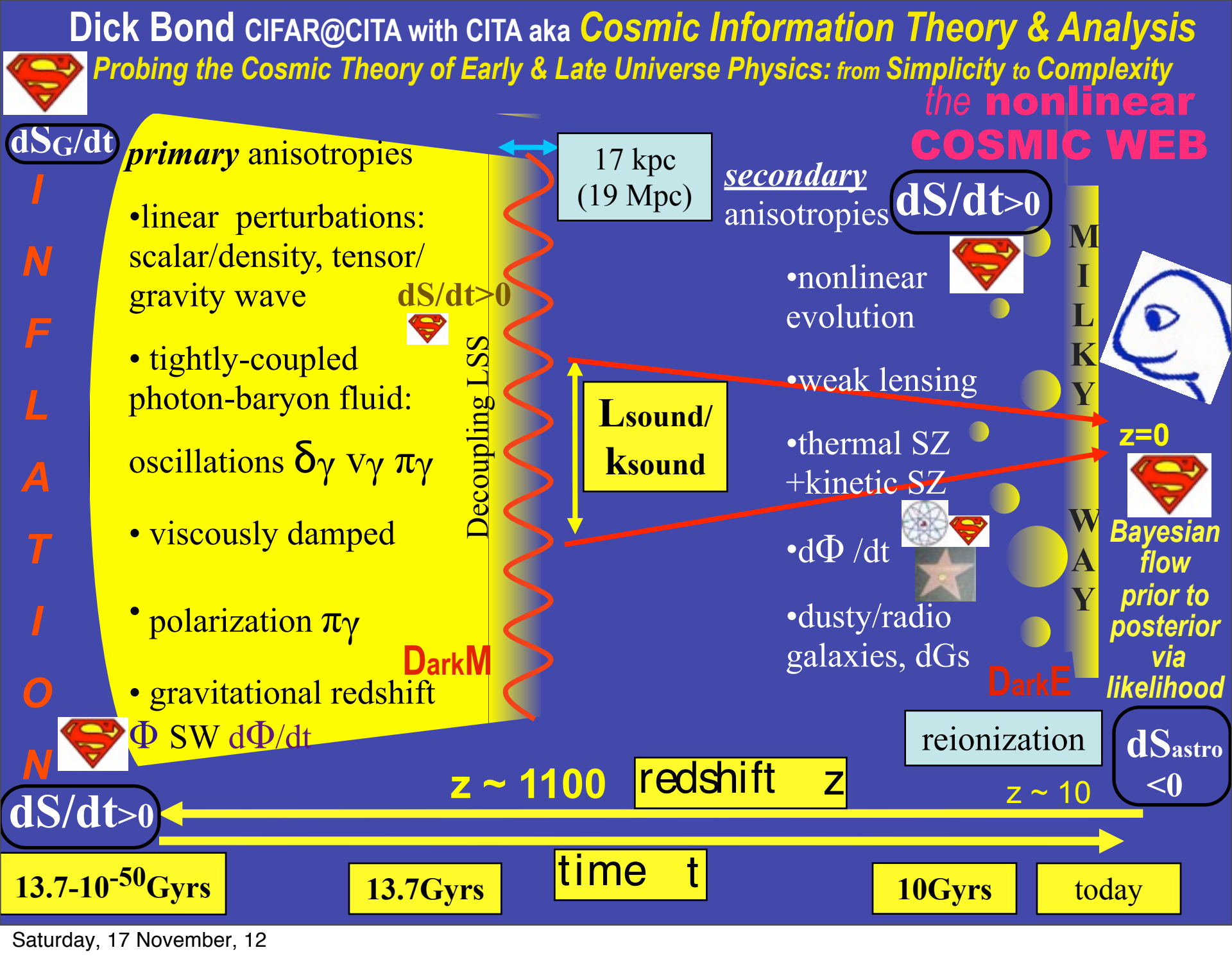
Probes of the Damping Tail
SPT11+WMAP7:
Y_P=.30 *cf.* .25
N_{eff}=4 *cf.* 3.06

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





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


Dick Bond CIFAR@CITA with CITA aka Cosmic Information Theory & Analysis
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dSastro <0
z ~ 1100
redshift z
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time t
13.7-10-50Gyrs
13.7Gyrs
10Gyrs
today

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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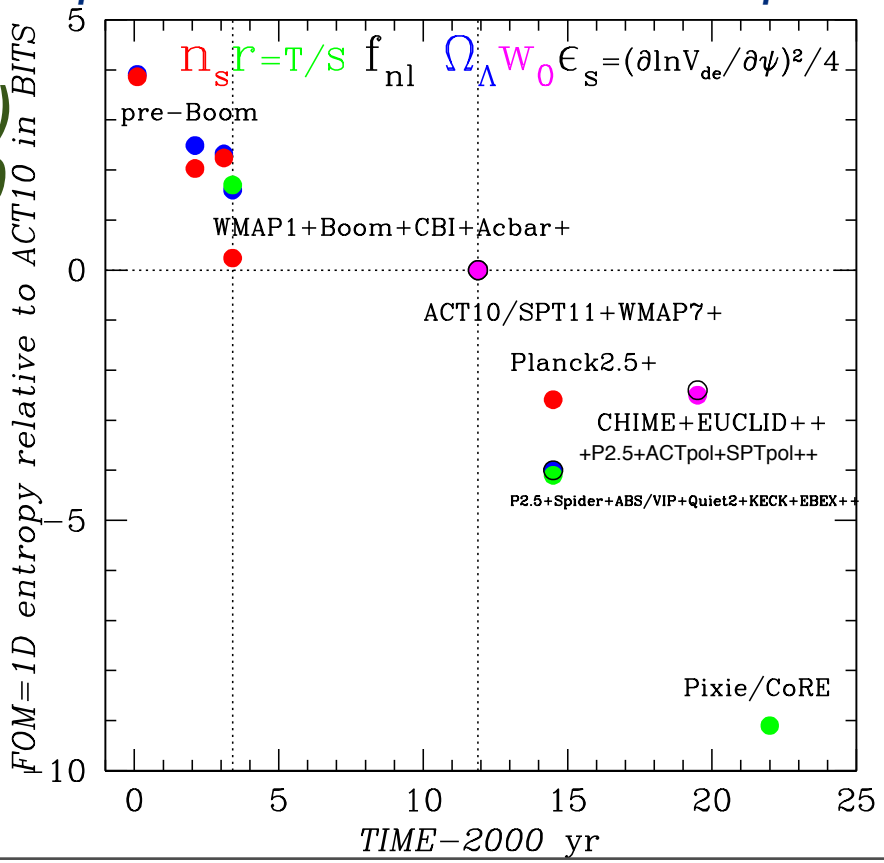
ΔS(q,DT)
i=ACT10



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

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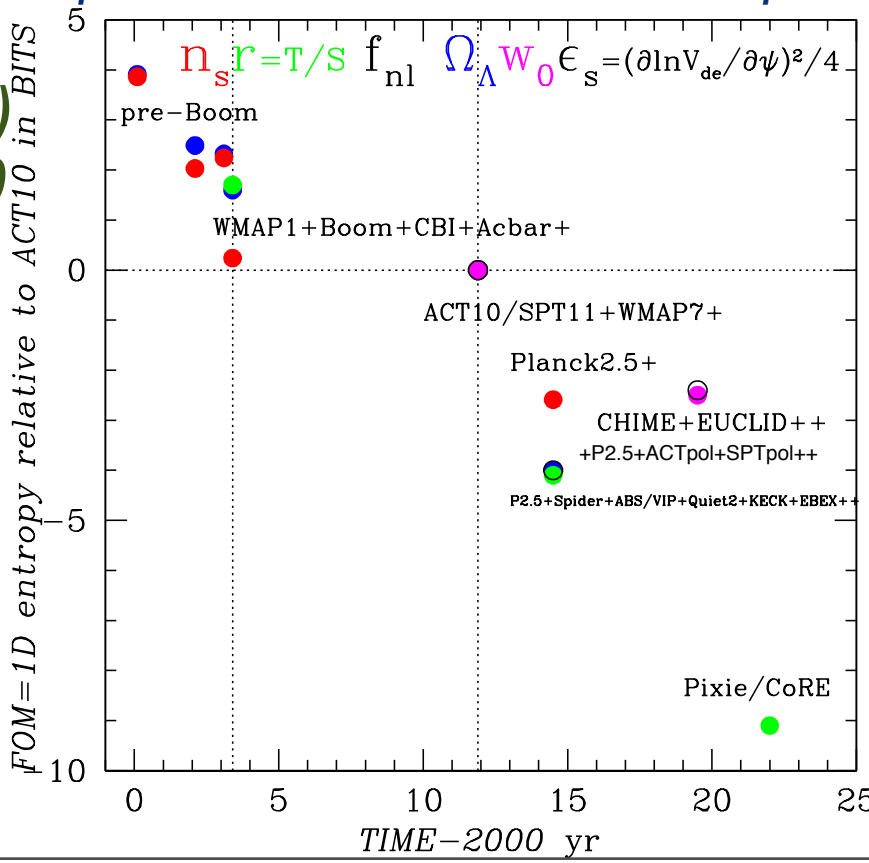
$\Delta S(q,DT)$ *i=ACT10*



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

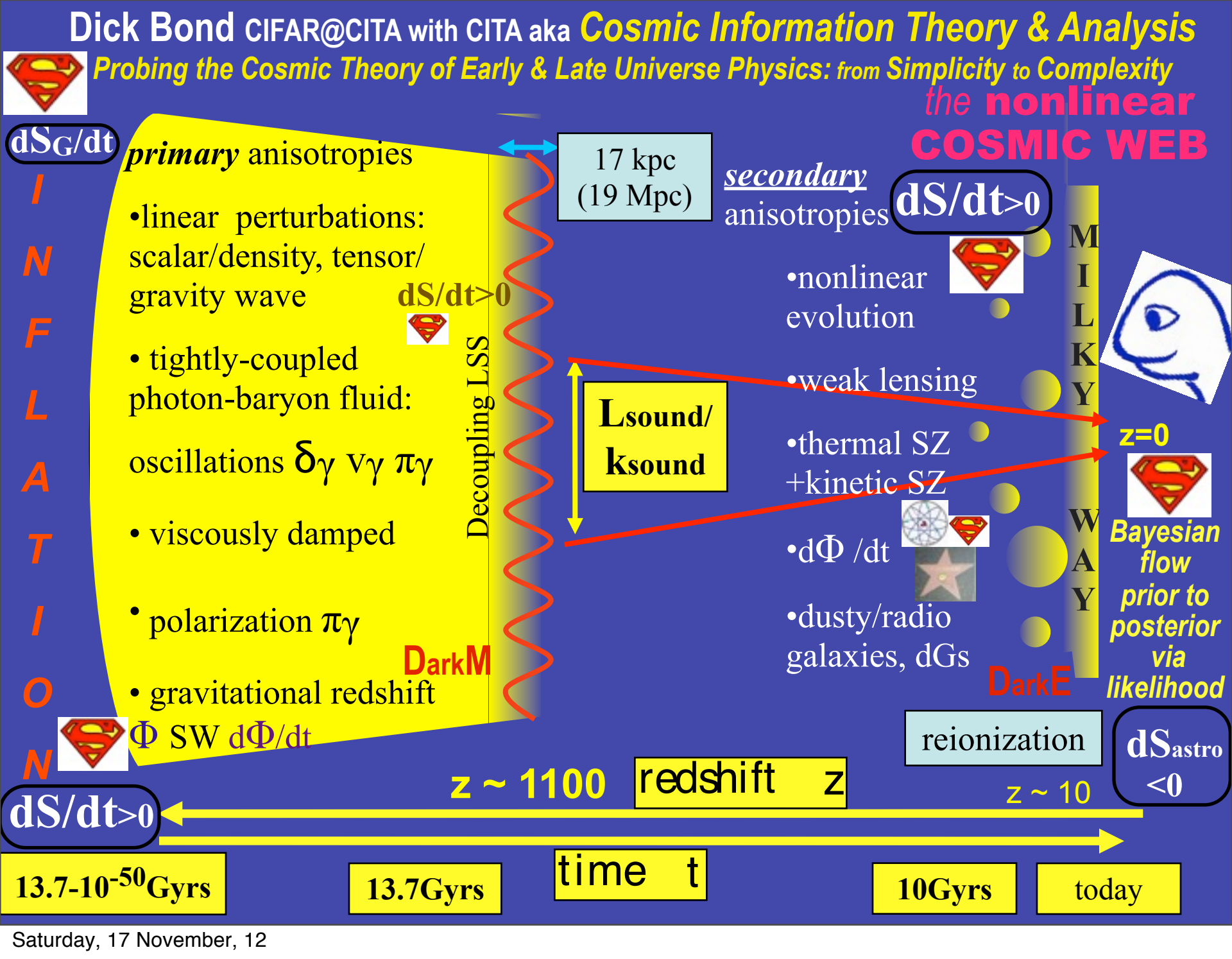
Ω_Λ: ± 0.012 =>± 0.001 (Pext)

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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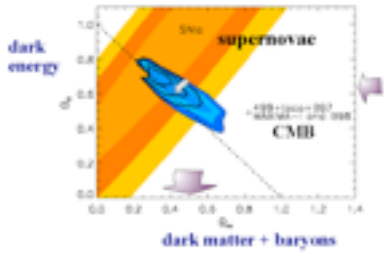


future fate of

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

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

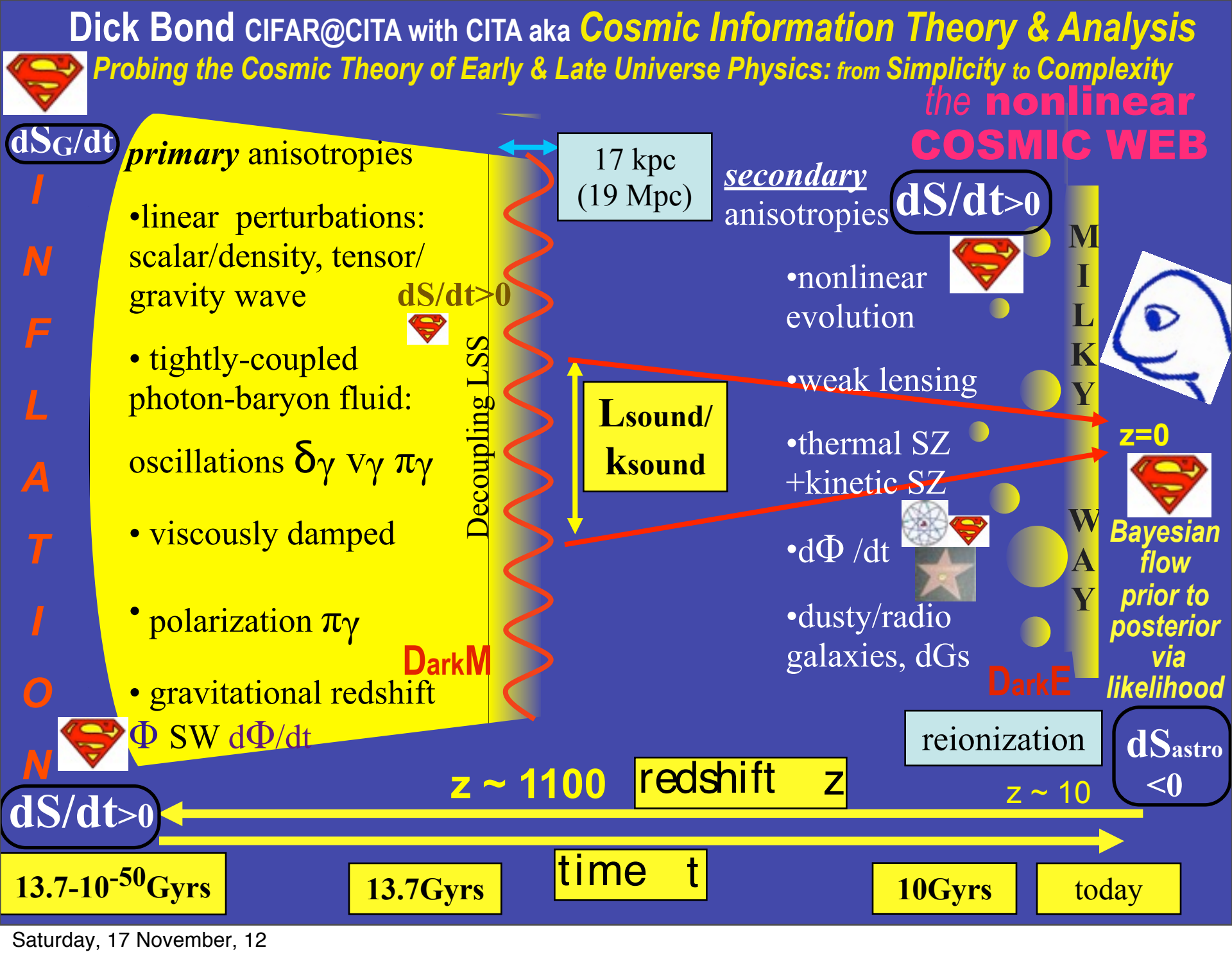
beats incoherence (Υ,ν,h_{+x},..p,n,e)

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)

ENDshorter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today

early U applications of "CITA" to cosmic-complexity

☆ ***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")

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

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

$S_{th,cl} \sim 10^{76}$

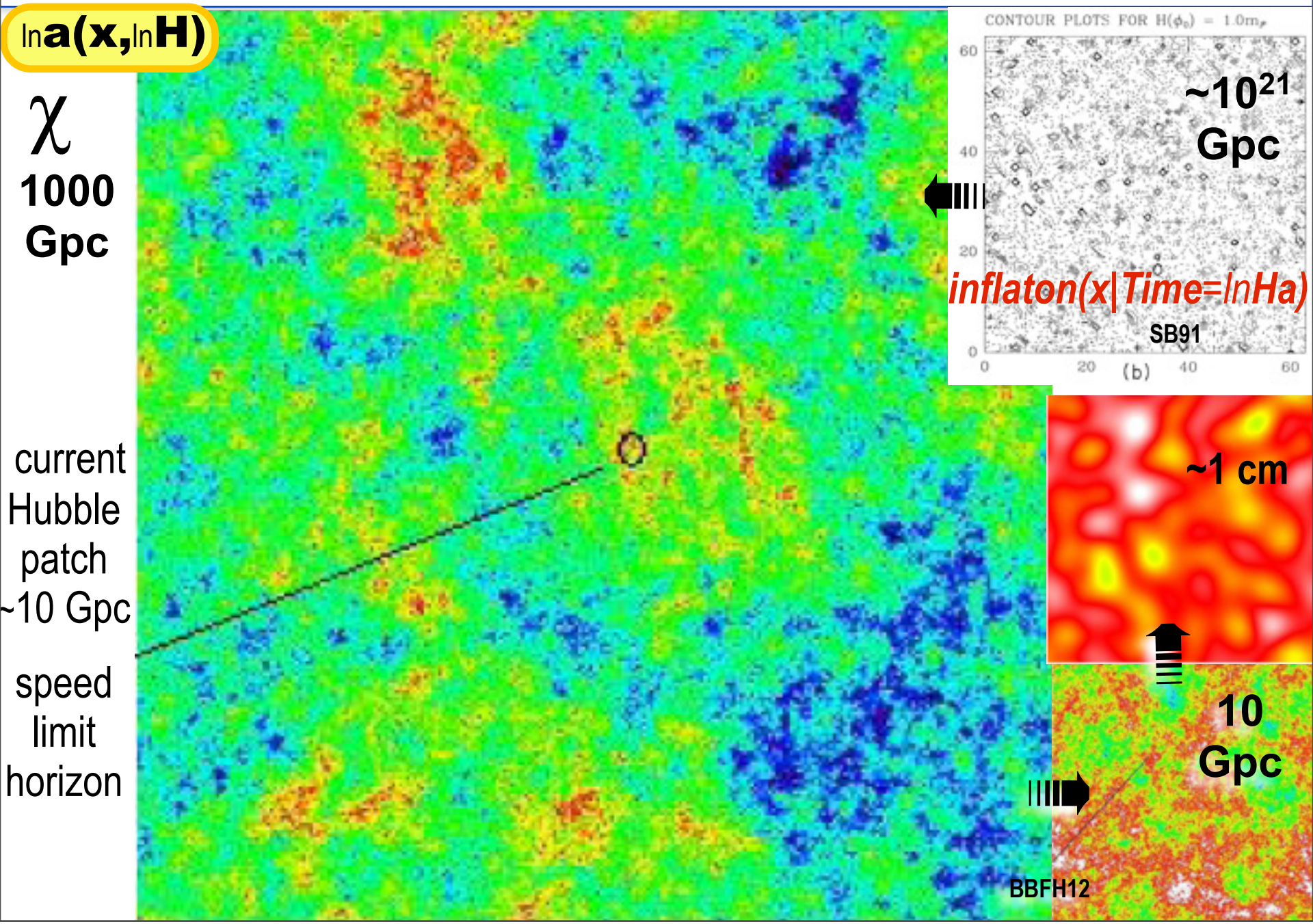
Studying the Cosmic Tango

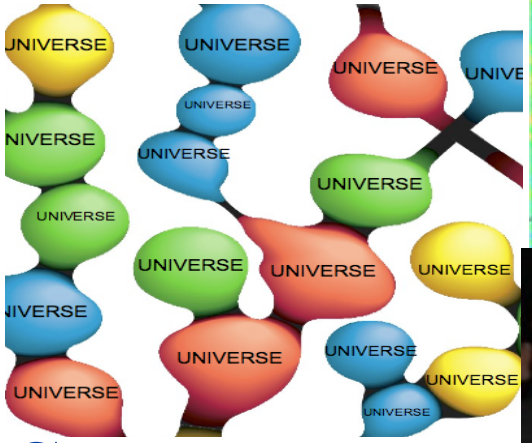
P(q|D,T) =P(D|q,T)P(q|T)P(T)/P(D|T) ***D=CMB,LSS,SN,..,complexity, life***
T=baryon, dark matter, vacuum mass-energy densities,...,
early & late inflation as low energy flows/trajectories on a (string) landscape

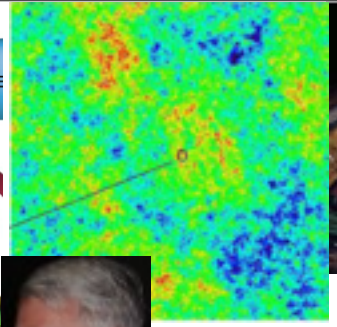
Old: Theory prior = delta function of THE correct one&only

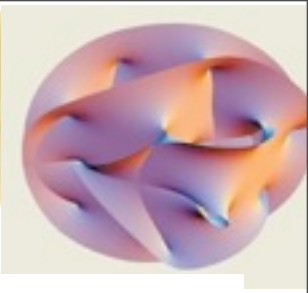
New: Theory prior = probability distribution of **late-*ish*-flows** on a **LANDSCAPE**

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









$S_{U,UUUULSS} = \langle \ln P[U|Time]^{-1} \rangle$

measure problem

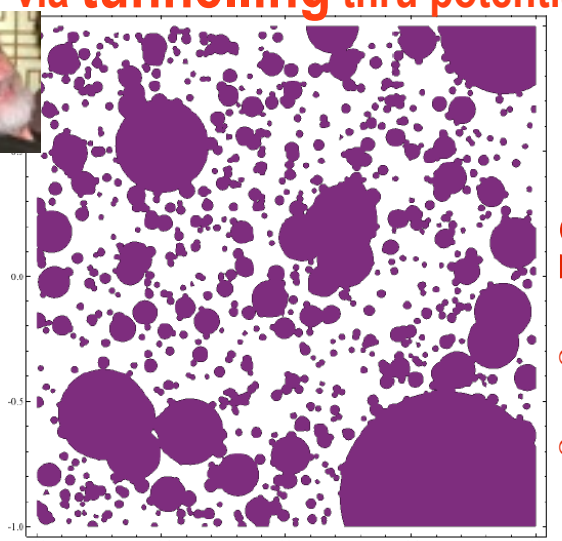
when quantum kicks

beat **classical drifts**

we are in the

semi-ETERNAL INFLATION regime

or via tunnelling thru potential wells



=> the

hubble

bubble U

$S_{G,GH}$

$\propto m_P^2/H_V^2$

$\propto m_P^4/\rho_V$

statistical mini-landscapes e.g.,

Roulette Inflation in a holey U *cf.* braney Us

Preheating After

Roulette Inflation

$\langle \tau \rangle =$

quantum diffusion

spatial jitter

drift

$\ln a(x, \ln H)$

semi ETERNAL INFLATION

let there be

heat

$= \langle \ln P[U|Time]^{-1} \rangle$

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

isocon

$\chi(\mathbf{x})$

or

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

or..

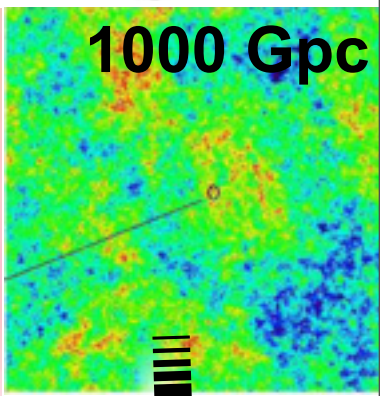
ϕ

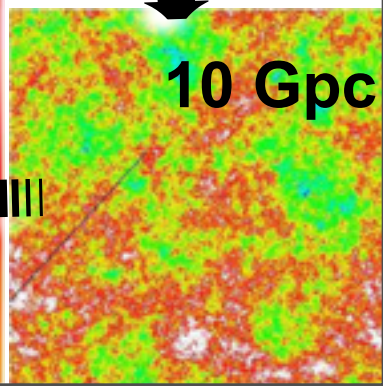
inflaton

pre-heating patch (~1cm)

Parametric Resonance

$g^2/\lambda \sim 1$





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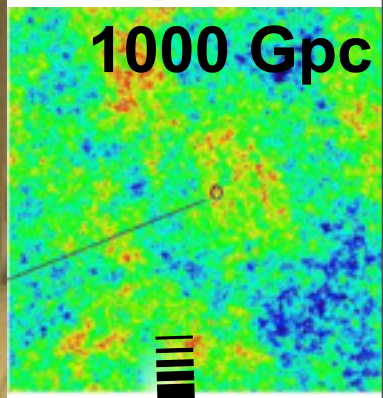
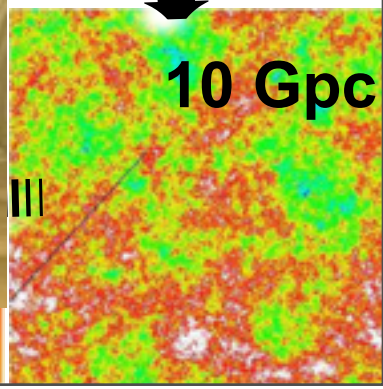
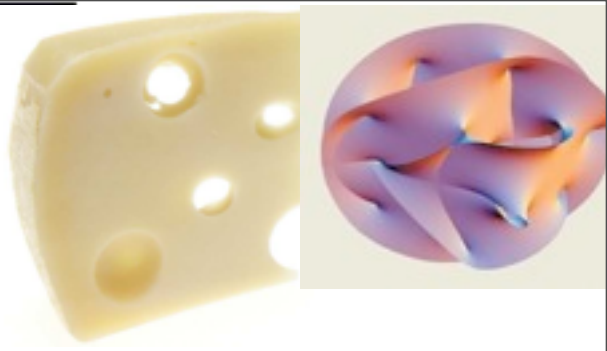




B^2FH12 @ifaUH aka Waikiki Feb12

entropy generation in preheating** from the **coherent inflaton (origin of all matter)



pre-heating patch (**<1cm**-now, **<10^{-30} cm**-then)

Barnaby,Bond,Huang,Kofman09

semi ETERNAL INFLATION

quantum diffusion

spatial jitter

drift

let there be

heat

www.youtube.com/watch?v=FW__su-W-ck&NR=1

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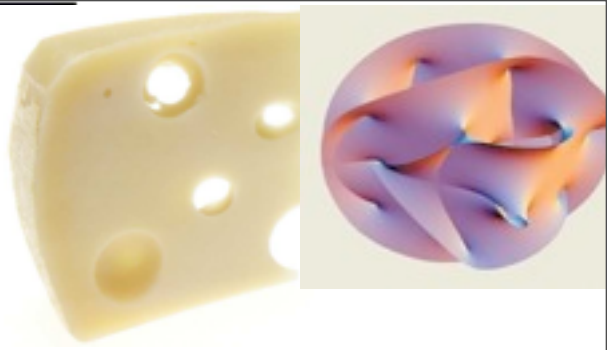


pre-heating patch (**<1cm**-now, **<10^{-30} cm**-then)

$a =$ 1

A visualized 2D slice

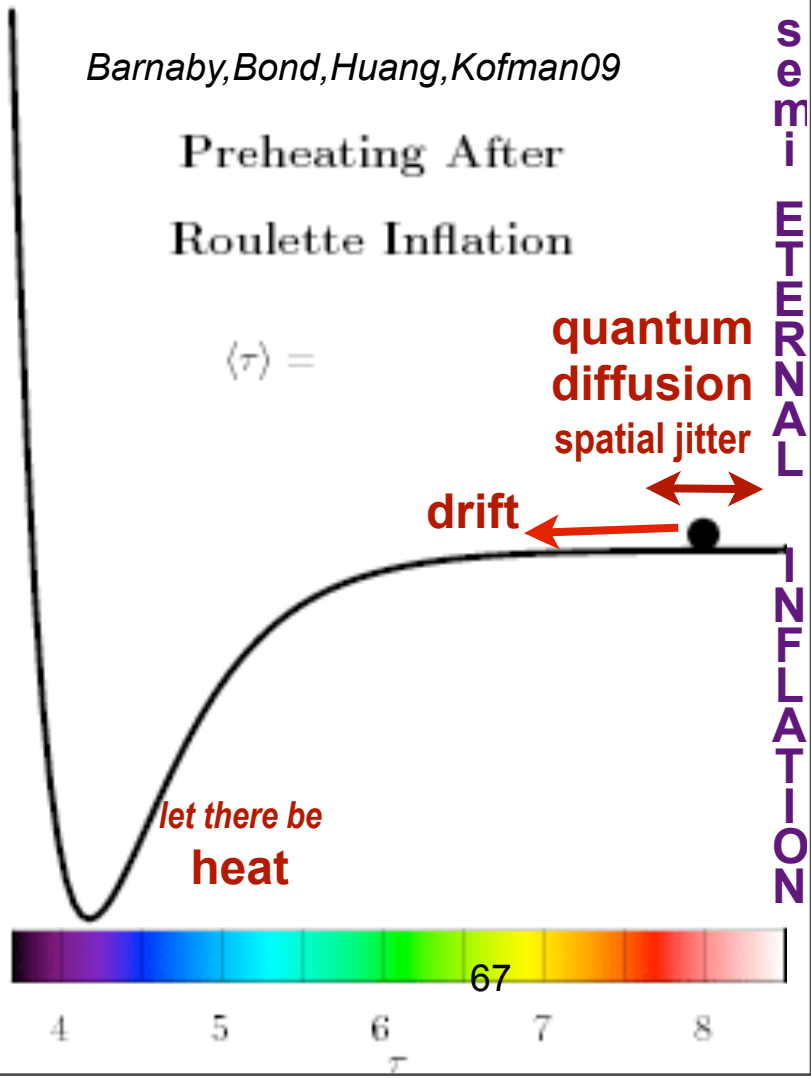
in lattice simulation

Barnaby,Bond,Huang,Kofman09

Preheating After

Roulette Inflation

$\langle \tau \rangle =$



semi ETERNAL INFLATION

67

www.youtube.com/watch?v=FW__su-W-ck&NR=1

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

how (most of) the entropy in matter

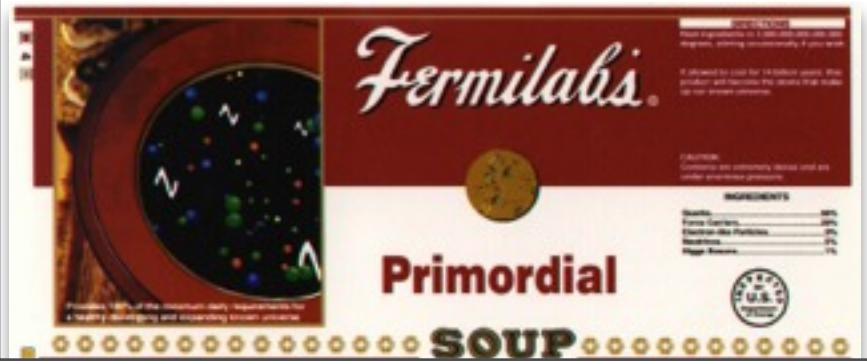
=> *GUT plasma/quark soup* => $S(\gamma,\nu)$ was generated *(through a shock-in-time)*

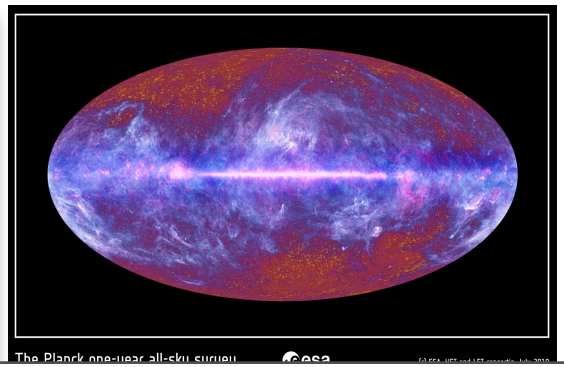
via nonlinear coupling of the inflaton to new interaction channels g,χ_a *ultimately to standard model degrees of freedom*

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

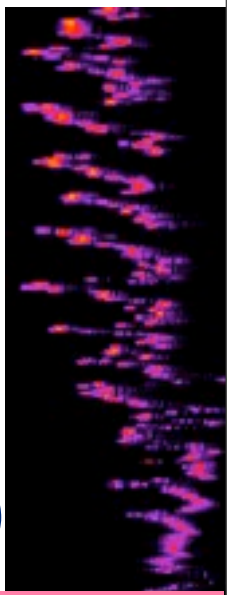
exactly who, what, where, when, why?

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

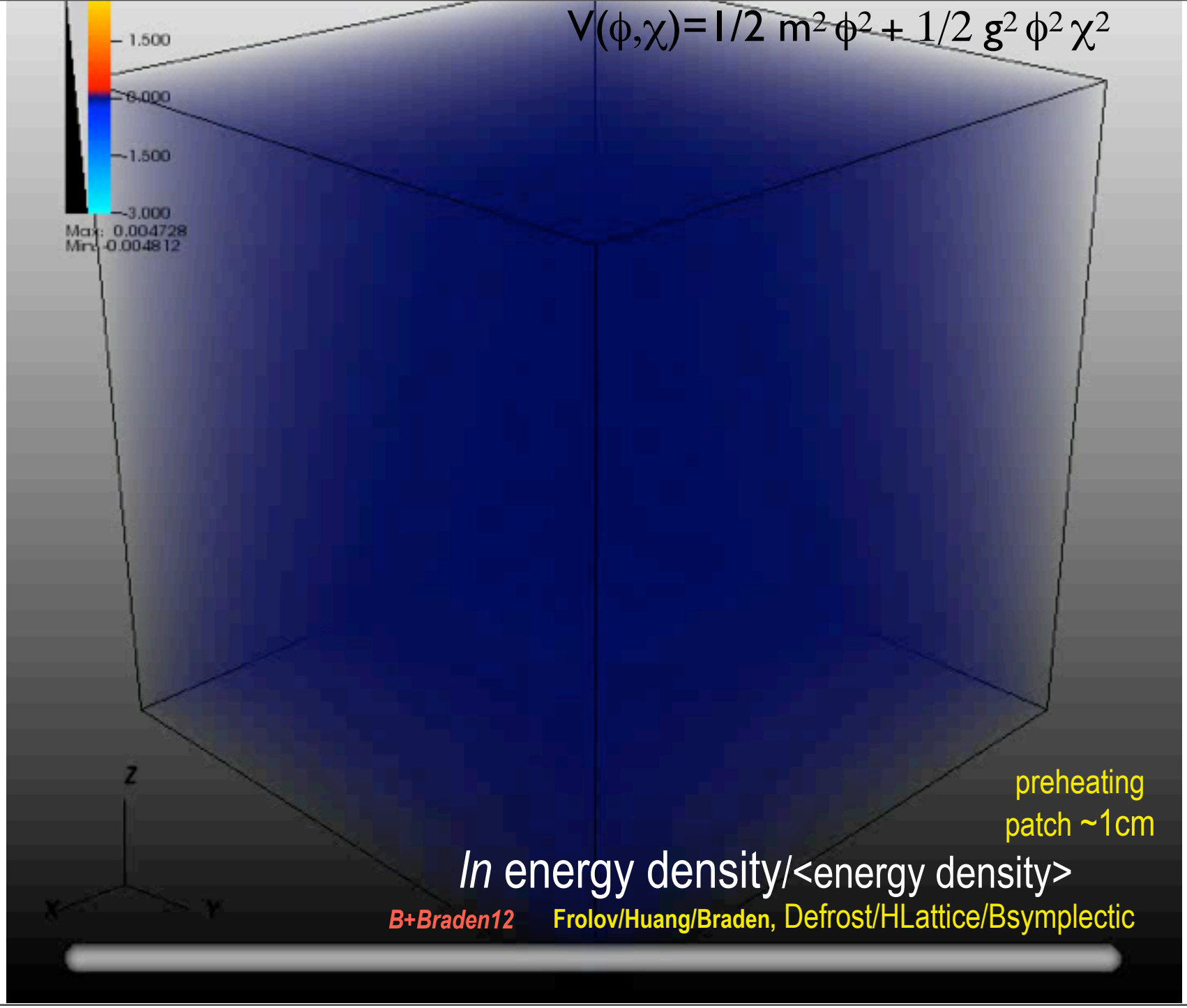




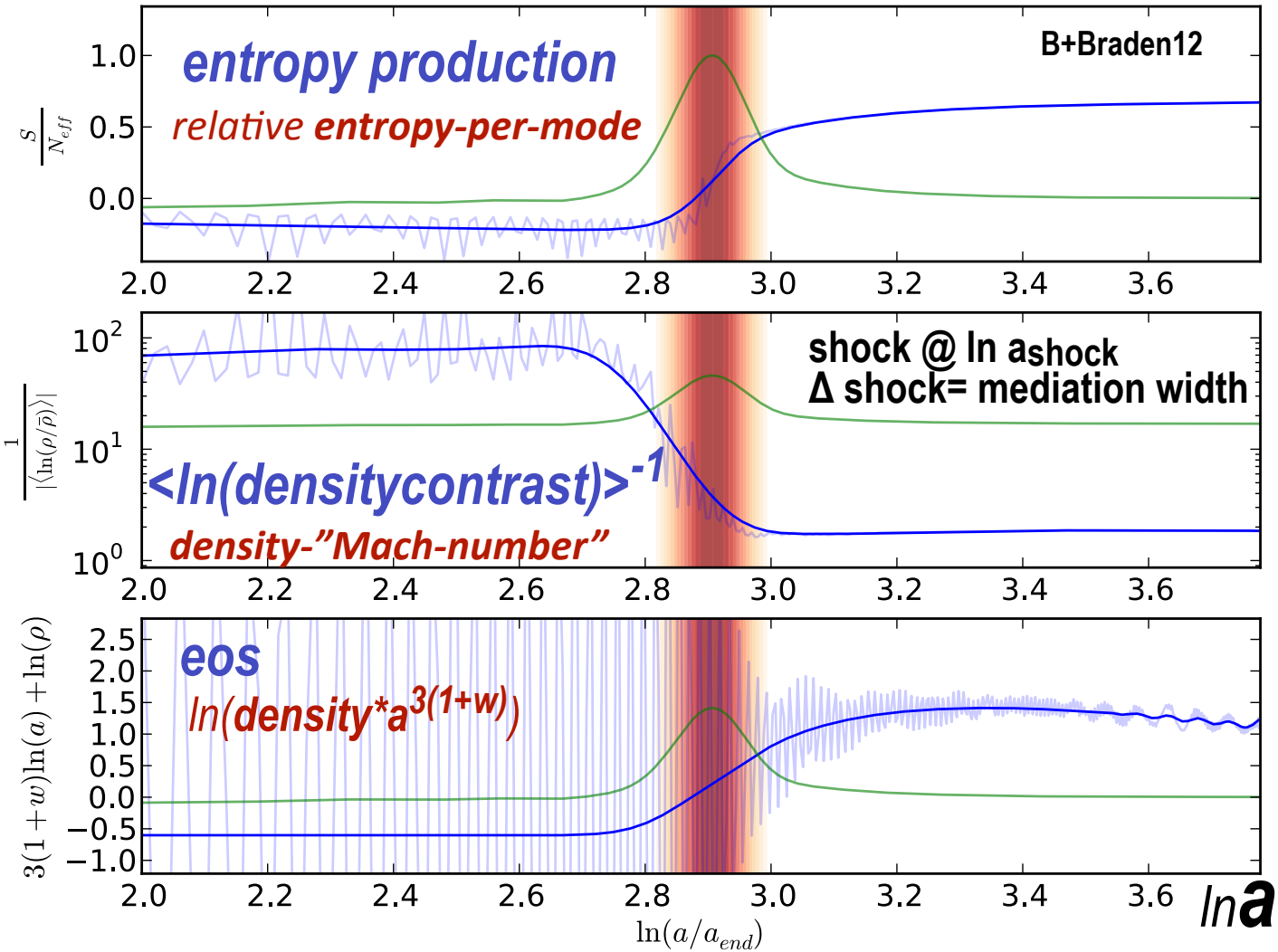
$a_{Shock}(g)$



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

eU S: Δs =Δ 1/2Tr C*ln*ρ*ln*ρ info-content in phonons σ = - *ln* [ρ V/E]



true thermal equilibrium far off

➤

& on to coupling to standard model degrees of freedom

the **Shock-in-time:** constrained coarse-grained ***Shannon-entropy(ln a)*** minus the initial Gaussian random field entropy (from band-limited quantum fluctuations)

there is indeed a spike of entropy production at the shock front.

$V(\phi,\chi)=1/2\ m^2\ \phi^2+1/2\ g^2\ \phi^2\ \chi^2$

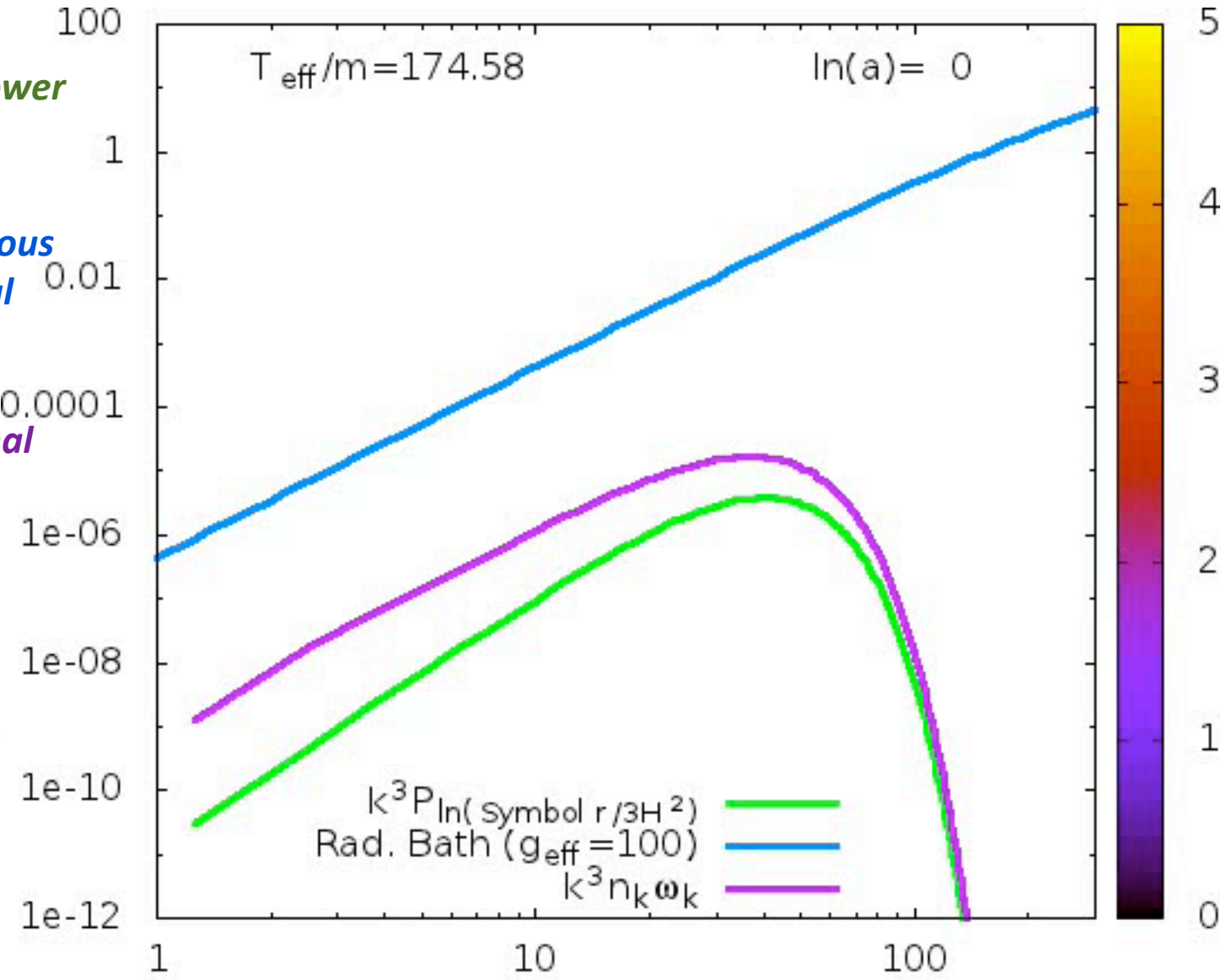
post-shock ⇒ Hydrodynamics phonon description

nearly Gaussian in ln ρ/<ρ>(x) ln ρ/<ρ>(k)& v

coherent inflaton => incoherent mode cascade of fields thru a shock-in-time to thermal equilibrium

$s_{Ui\sim 0}$; $s_{Utot,m+r}/n_b \sim 1.66\times10^{10}$ bits/b; $s_\gamma / n_\gamma = 5.2$ bits/Υ = 2130/411; $s_v = 21/22\ s_\gamma$

ln ρ/<ρ> power spectrum cf. instantaneous full thermal spectrum cf. conventional energy spectrum using a pseudo particle occupation number



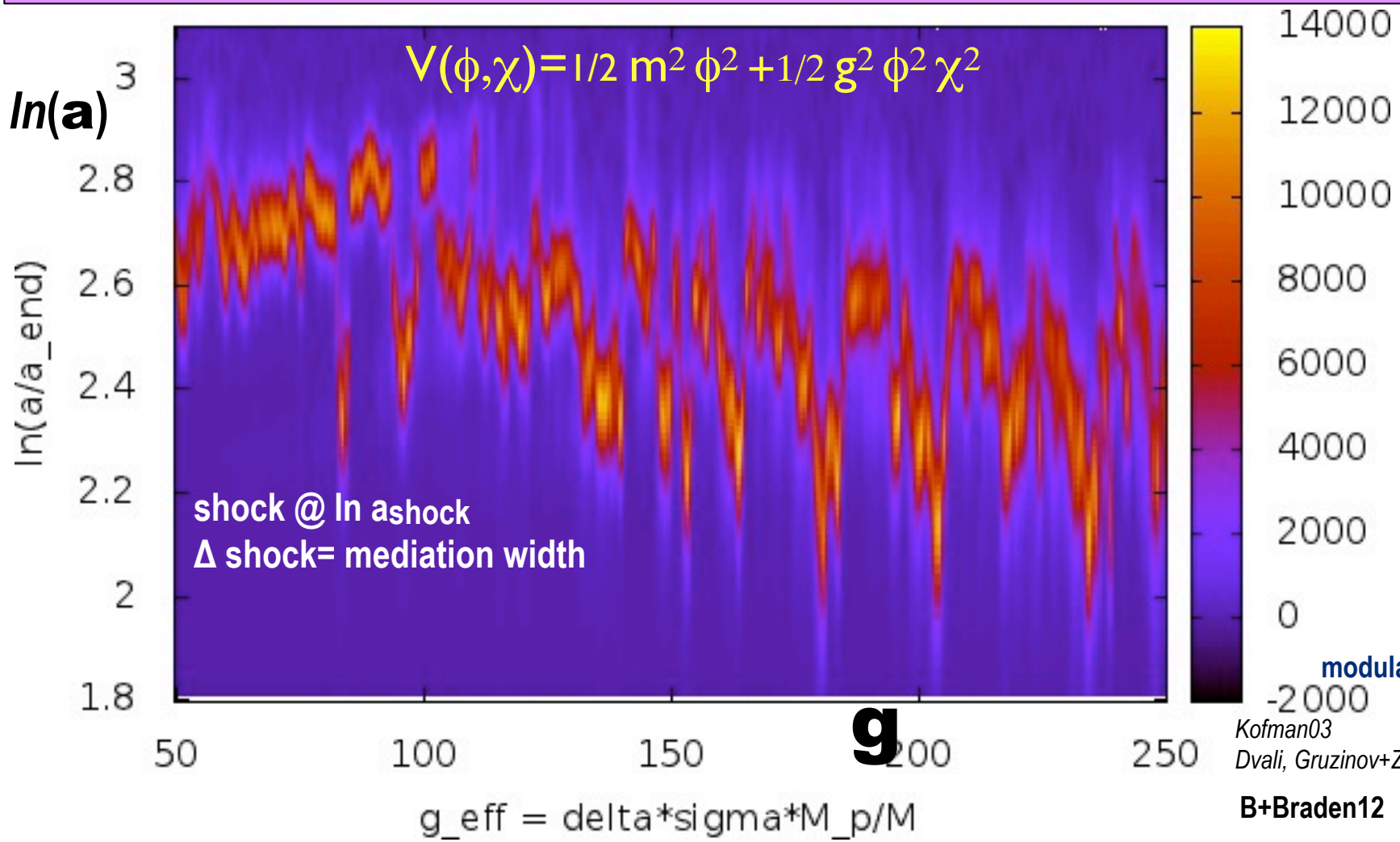
$V(\phi,\chi)=1/2\ m^2\phi^2+1/2\ g^2\phi^2\chi^2$

B+Braden12

dS/dt(t,g) => *the Shock-in-time: entropy production rate*

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

$\delta ln a_{shock}$ (**g**(σ(**x**)) => modulated non-Gaussianity from preheating!



Kofman03
Dvali, Gruzinov+Zaldarriaga03

B+Braden12

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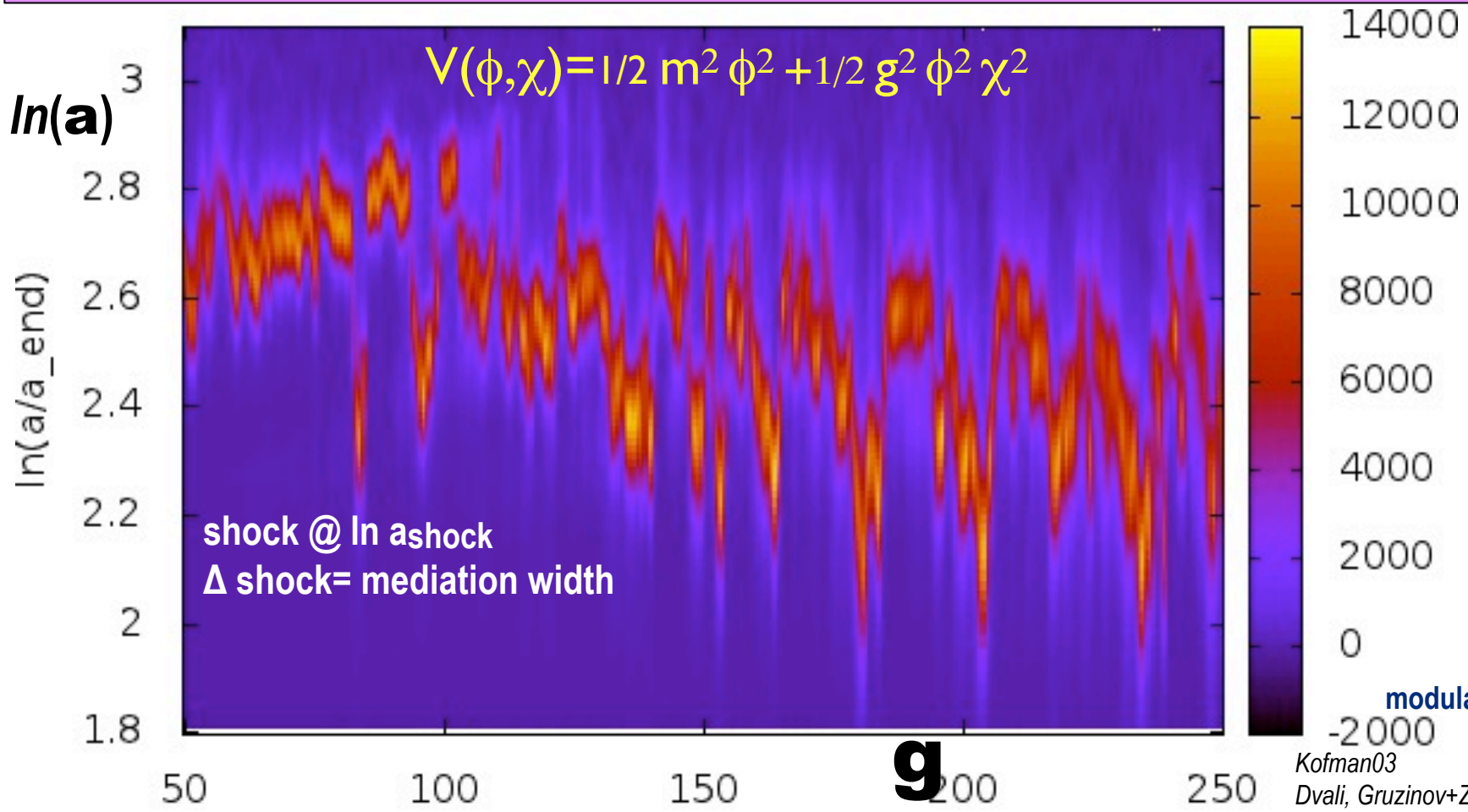


Kofman03
Dvali, Gruzinov+Zaldarriaga03

B+Braden12

Chaotic Billiards NonG $V(\phi,\chi)=1/4\ \lambda\phi^4 +1/2\ g^2\phi^2\chi^2$ *B+Frolov, Huang, Kofman 09*
B+Braden, Frolov, Huang 12

$\delta ln a_{shock}(\chi i(x)\ |g^2/\lambda))$ => *NonG of cold spots ++*

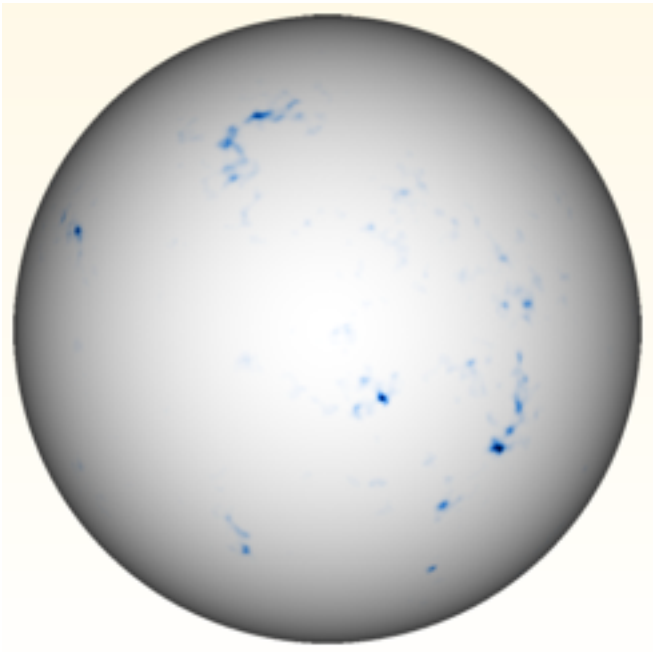
B+Braden+Mersini 2012

BBM12: 3D Oscillons & Colliding Bubbles?

dS/dt(t,g) => *the Shock-in-time: entropy production rate*

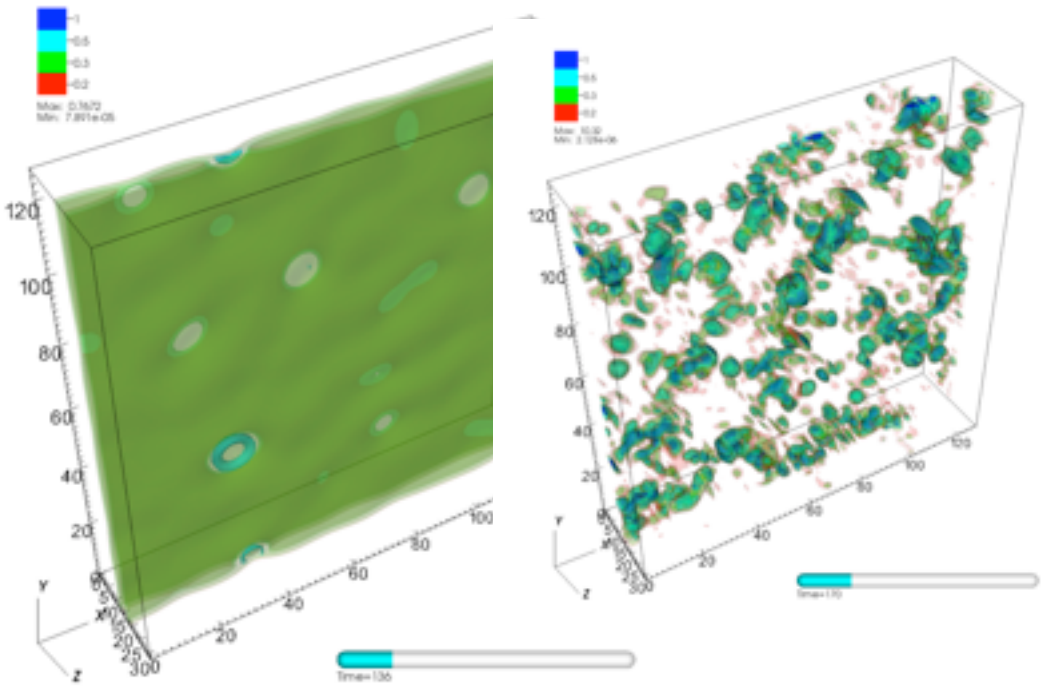
non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating

$\delta ln a_{shock}$ (**g**(σ(**x**)) => modulated non-Gaussianity from preheating!



& f_{NL}^{equiv}

modulated nonG



when "vacuum" bubbles collide in full 3D lattice sims
with tiny zero point & wall fluctuations
=> burst of scalar radiation at c + long-lived oscillons, ~m-1

Chaotic Billiards NonG $V(\phi,\chi)=1/4\ \lambda\phi^4 + 1/2\ g^2\phi^2\chi^2$ *B+Frolov, Huang, Kofman 09*
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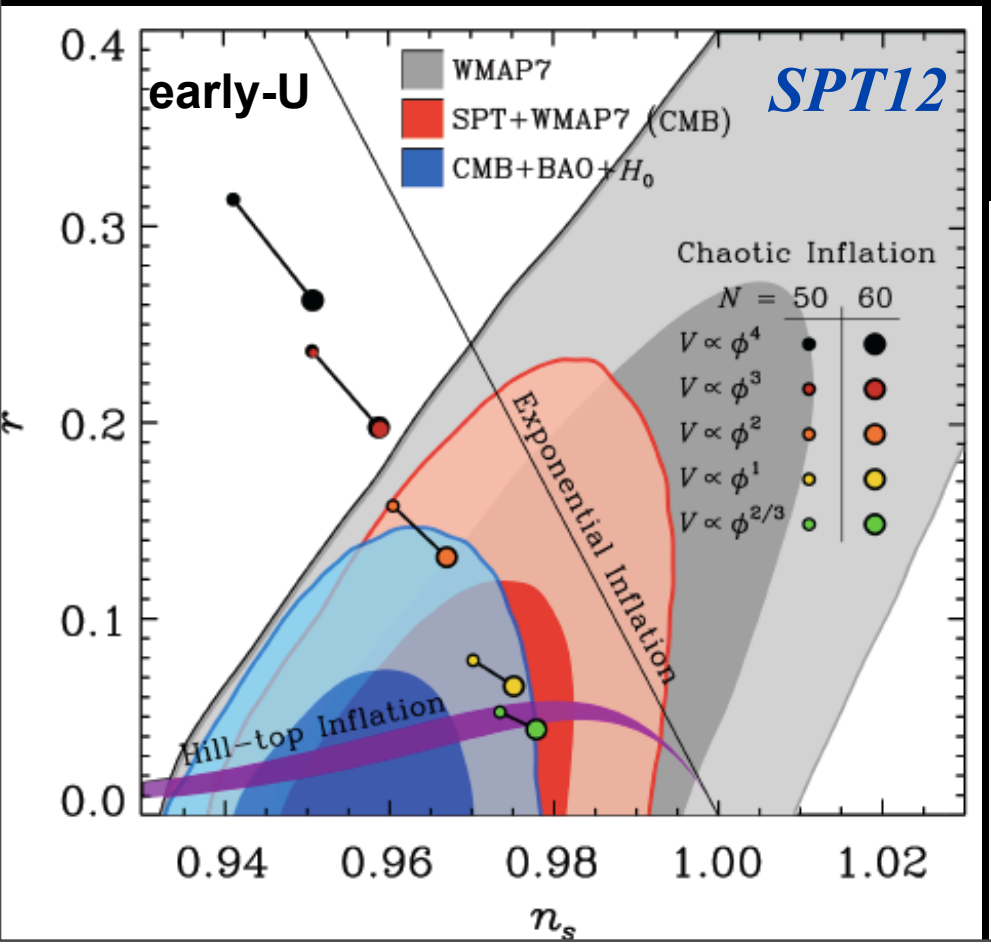
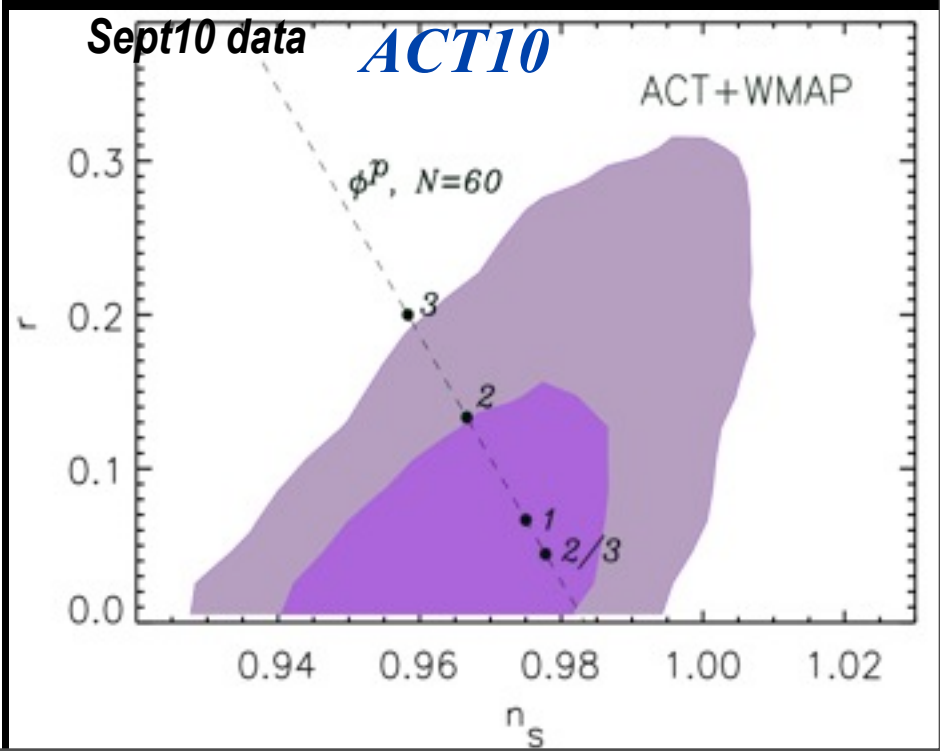
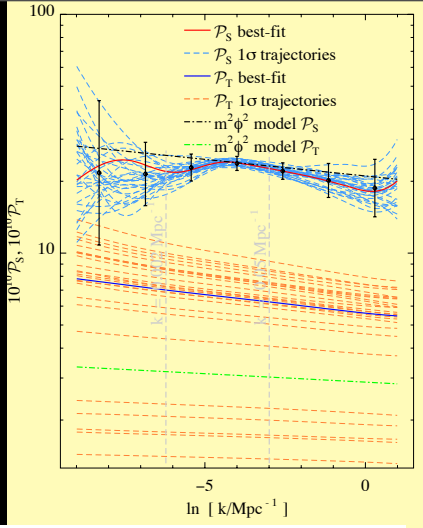
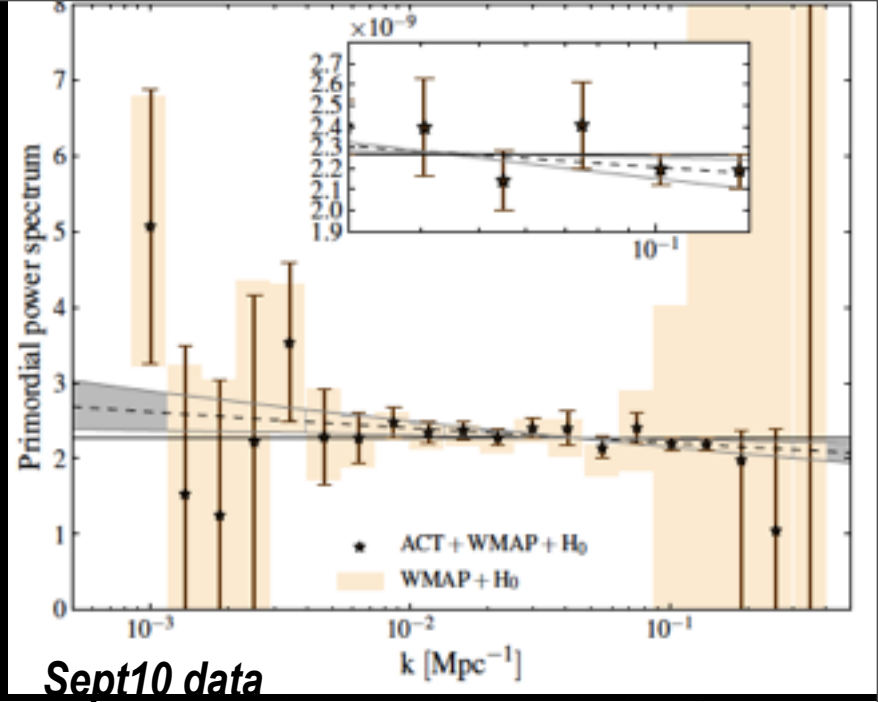
B+Braden+Mersini 2012

BBM12: 3D Oscillons & Colliding Bubbles?

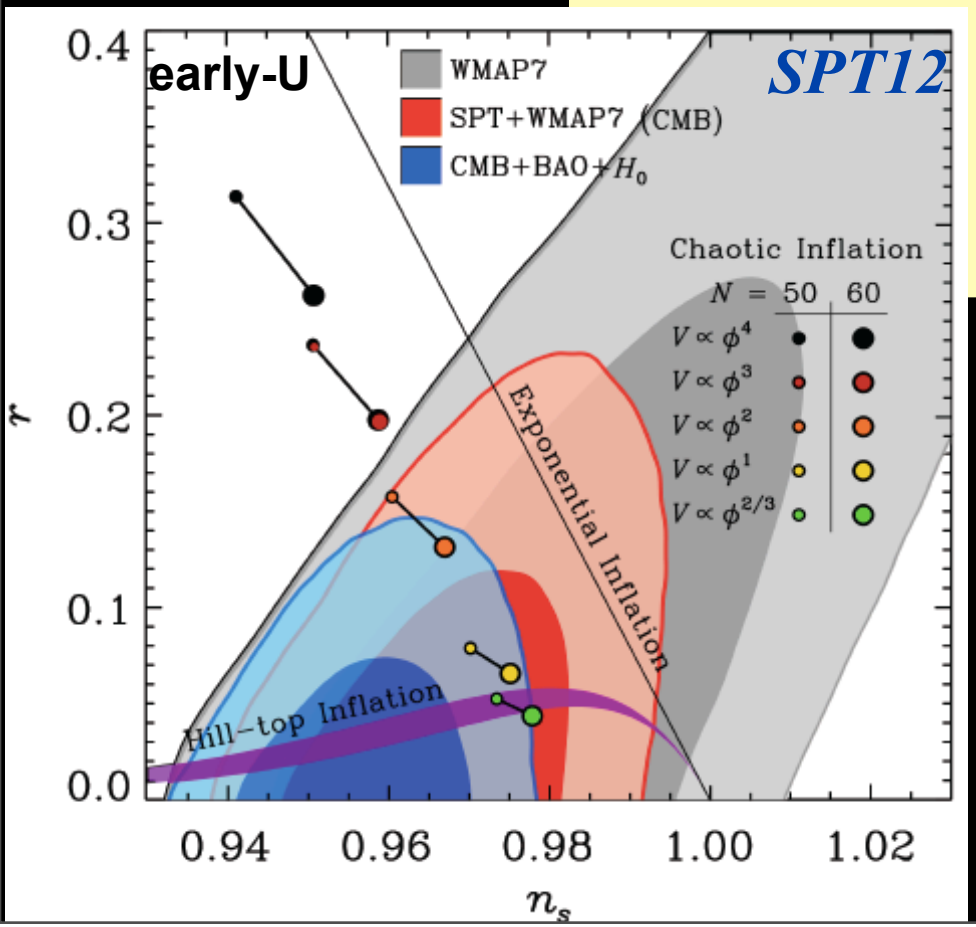

early-U
SPT12
WMAP7
SPT+WMAP7 (CMB)
CMB+BAO+H_0
Chaotic Inflation
N = 50 60
$V \propto \phi^4$
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^1$
$V \propto \phi^{2/3}$
Exponential Inflation
Hill-top Inflation
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
n_s


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


$\mathcal{P}_S$ best-fit
$\mathcal{P}_S$ 1σ trajectories
$\mathcal{P}_T$ best-fit
$\mathcal{P}_T$ 1σ trajectories
$m^2\phi^2$ model $\mathcal{P}_S$
$m^2\phi^2$ model $\mathcal{P}_T$
$10^{10}\mathcal{P}_S, 10^{10}\mathcal{P}_T$
ln [k/Mpc^{-1}]


Primordial power spectrum
k [Mpc^{-1}]
ACT + WMAP + H_0
WMAP + H_0

Sept10 data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Exponential Inflation
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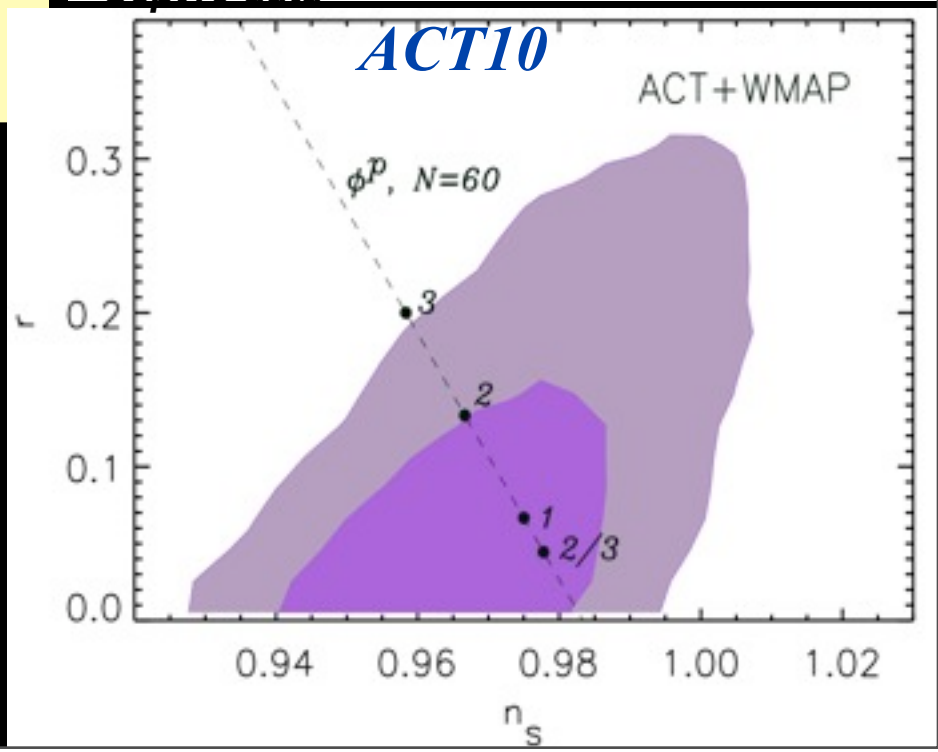
r
n_s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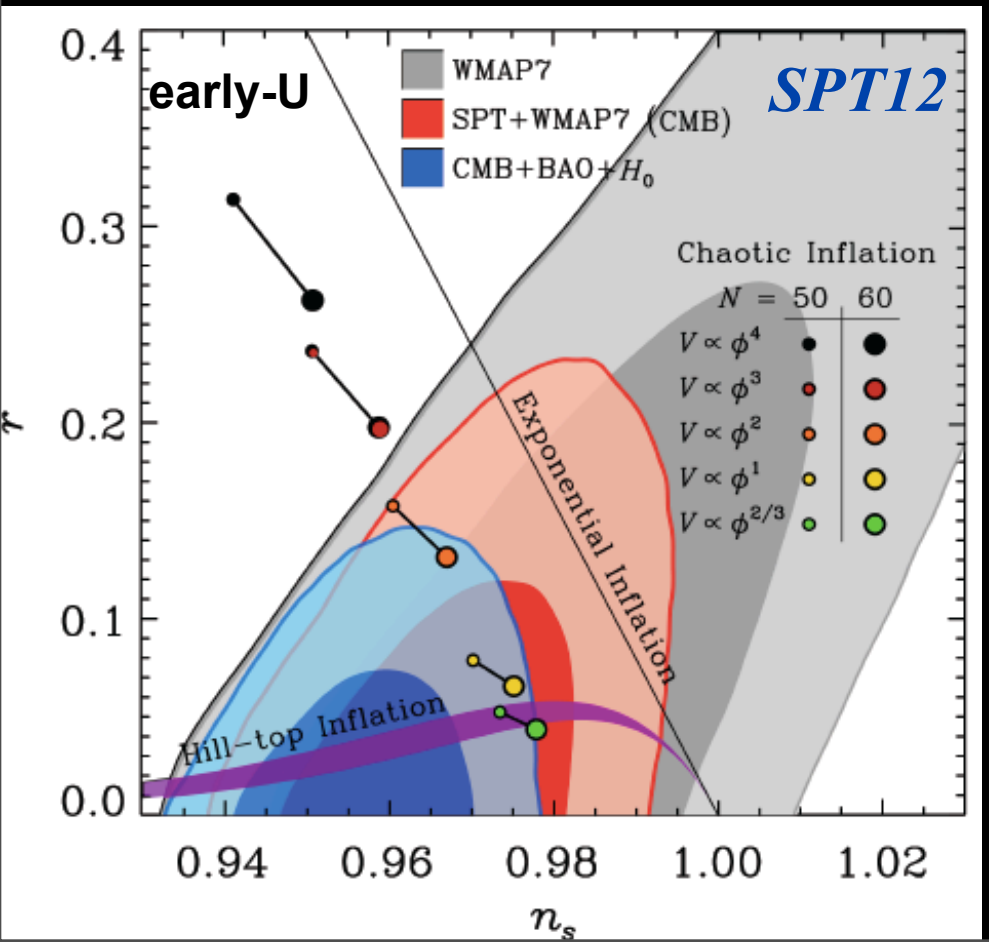
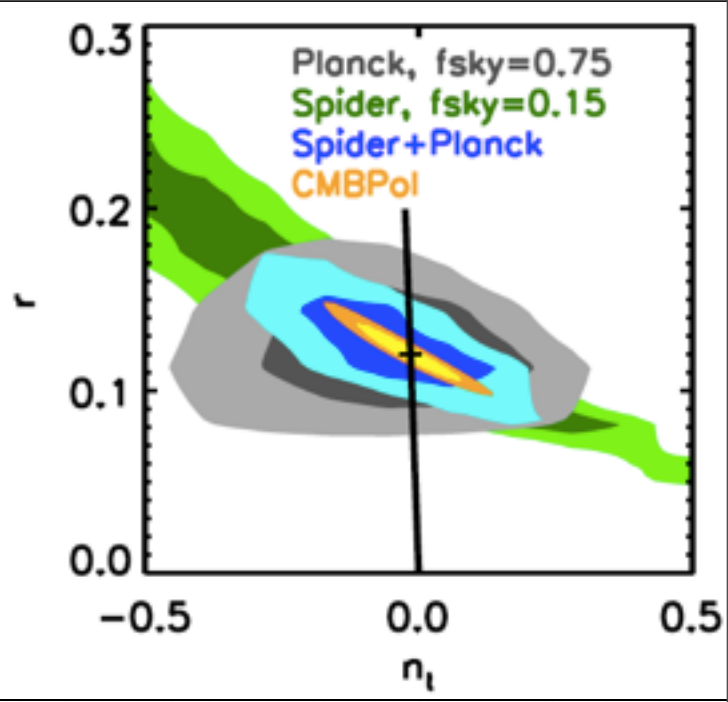
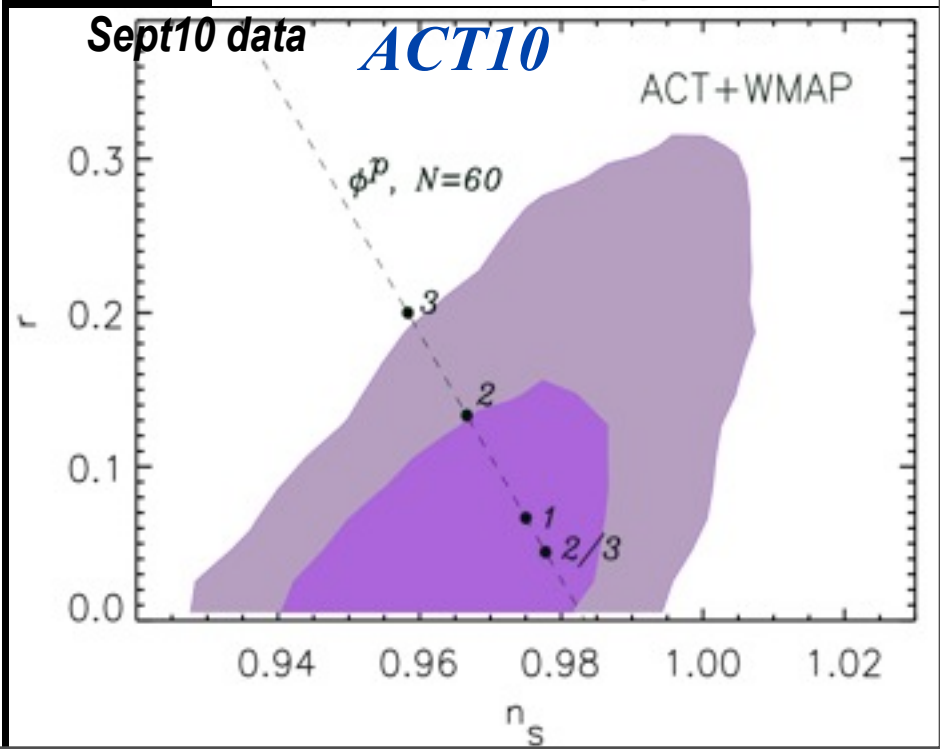
Farhang, Bond, Dore, Netterfield 11/12





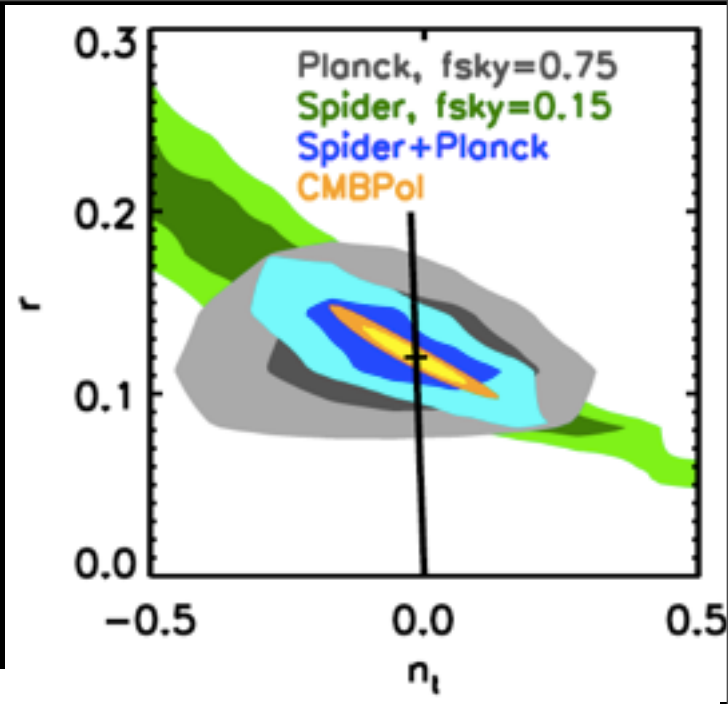


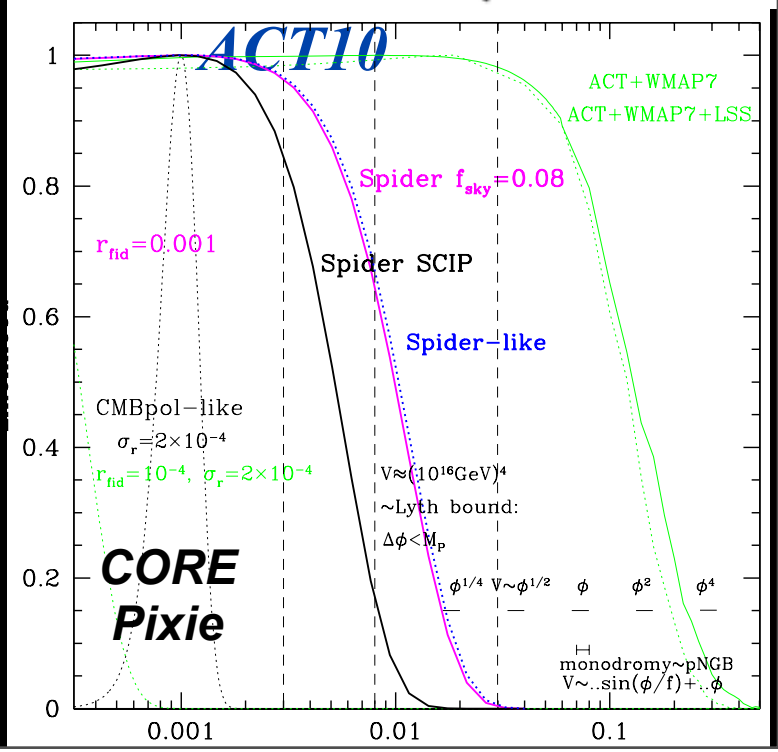
Farhang, Bond, Dore, Netterfield 11/12

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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Farhang, Bond, Dore, Netterfield 11/12

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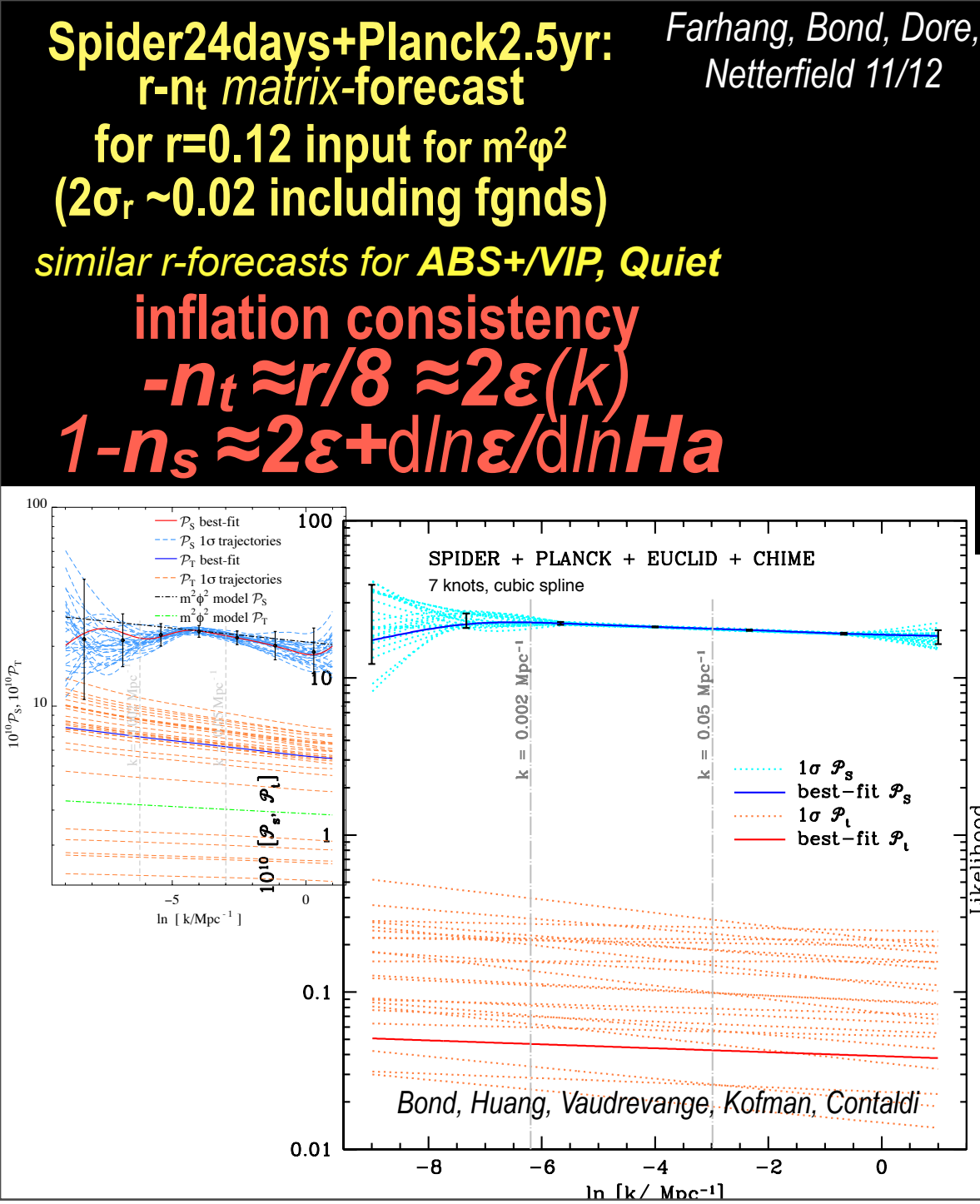
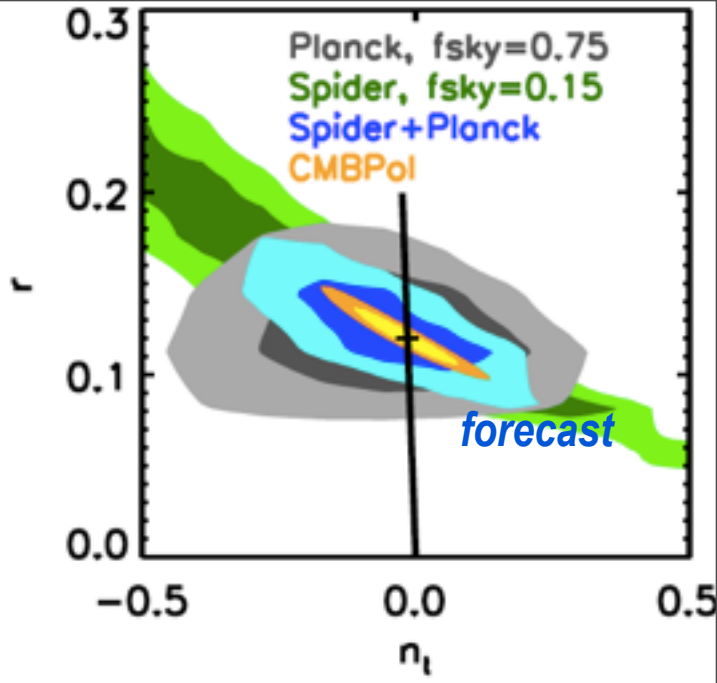
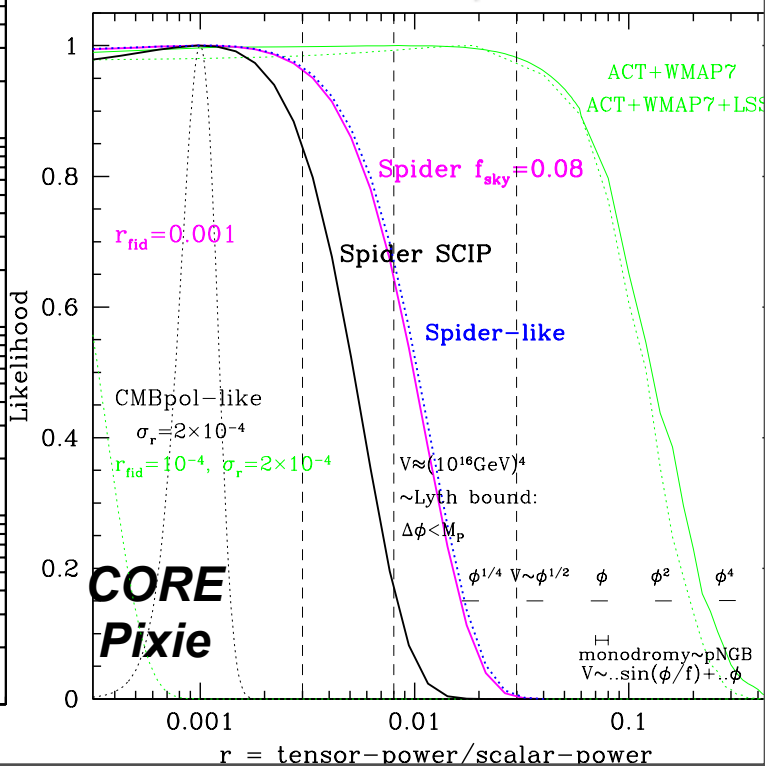
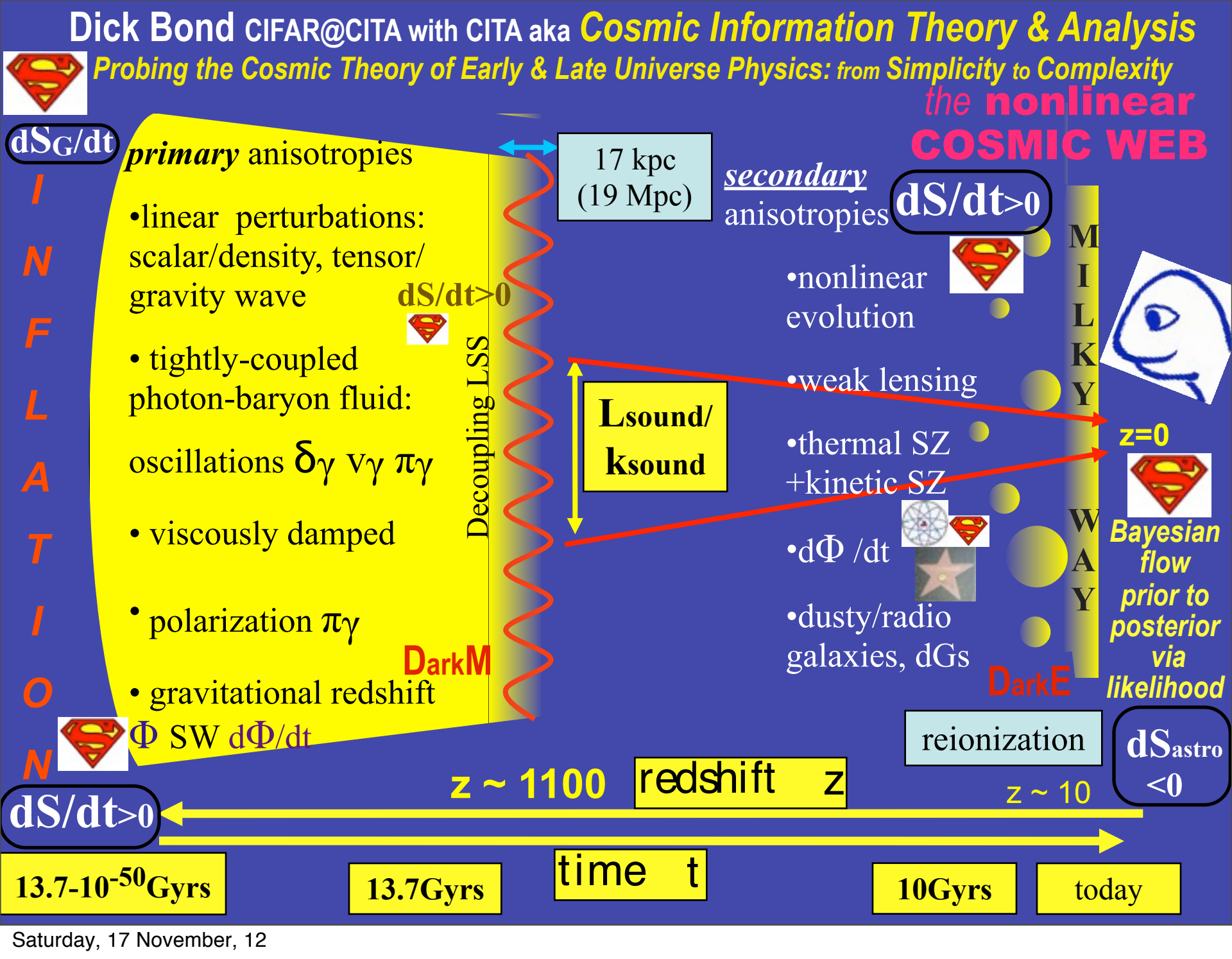
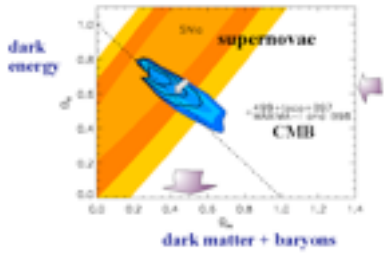







Dick Bond CIFAR@CITA with CITA aka Cosmic Information Theory & Analysis
Probing the Cosmic Theory of Early & Late Universe Physics: from Simplicity to Complexity
the nonlinear COSMIC WEB
dSG/dt
INFLATION
primary anisotropies
•linear perturbations: scalar/density, tensor/ gravity wave
dS/dt>0
• tightly-coupled photon-baryon fluid:
oscillations δγ vγ πγ
• viscously damped
• polarization πγ
DarkM
• gravitational redshift
Φ SW dΦ/dt
17 kpc (19 Mpc)
Decoupling LSS
Lsound/ ksound
secondary anisotropies
dS/dt>0
•nonlinear evolution
•weak lensing
•thermal SZ +kinetic SZ
•dΦ /dt
•dusty/radio galaxies, dGs
DarkE
MILKY WAY
z=0
Bayesian flow prior to posterior via likelihood
reionization
dSastro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
time t
13.7-10-50Gyrs
13.7Gyrs
10Gyrs
today



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)

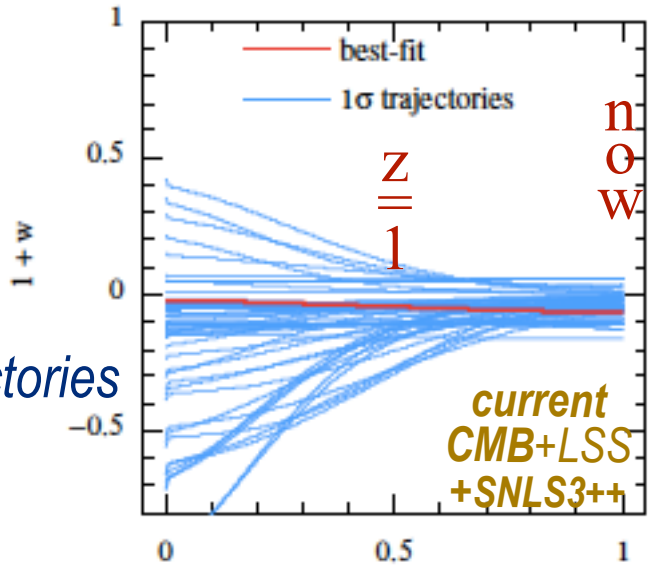
w_0: ± 0.06 =>± 0.01 (Pext) (± 0.14 =>± 0.03 if w_a)

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

+2 other w-trajectory parameters BHK11,BH12

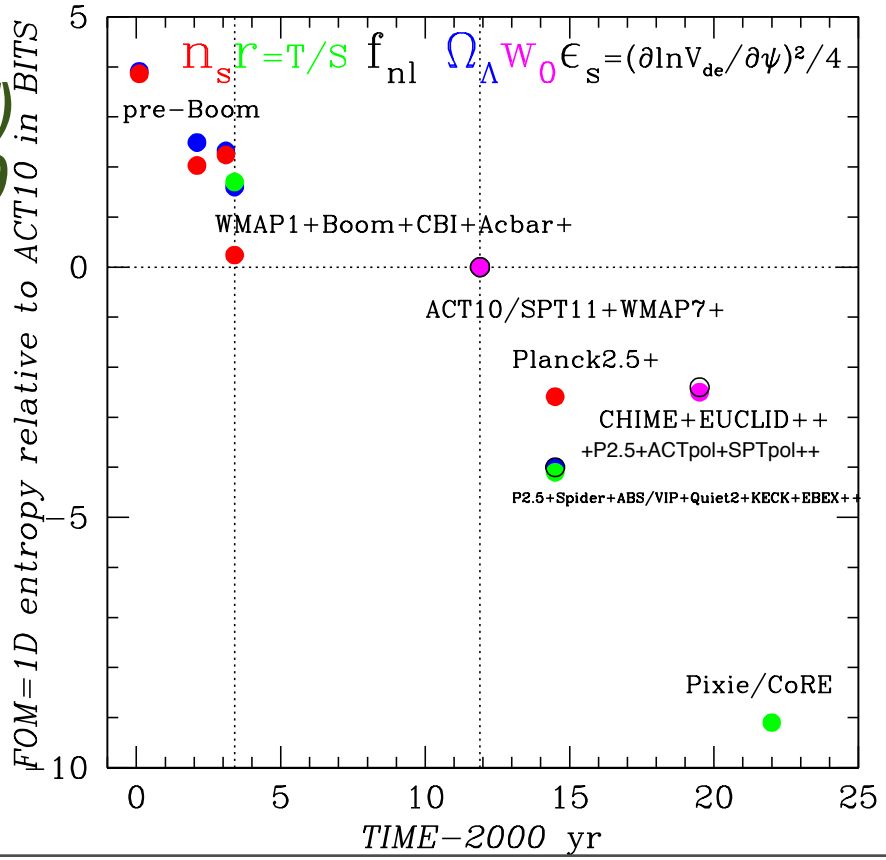
2D ΔS_{2f} for DarkE ($\varepsilon_s \varepsilon_{de\infty}$ or w_0 w_a) improves by ~5 bits

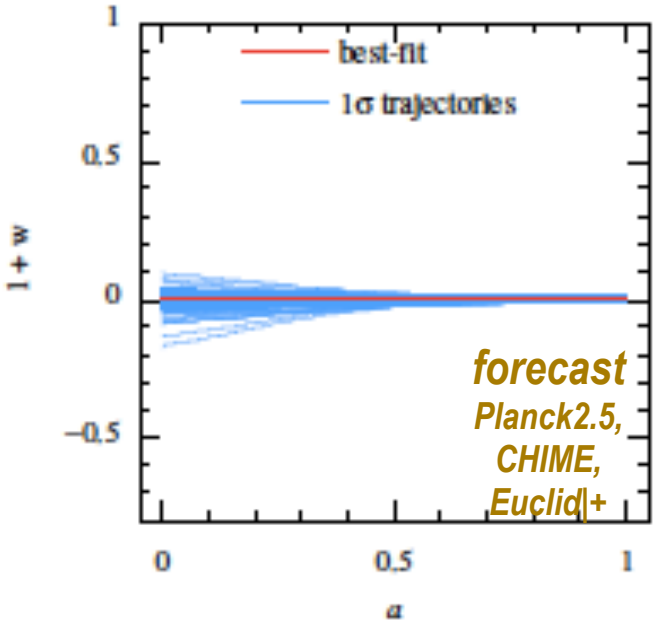
informed $\mathbf{w(a|\varepsilon_s \varepsilon_{de\infty} \varsigma_s)}$ *fits even wild late-inflaton trajectories*



Bond, Huang 2012

ΔS(q,DT)
i=ACT10





informed=

3-parameter

w_ϕ

$W_{de}(a|V(\psi),IC)$

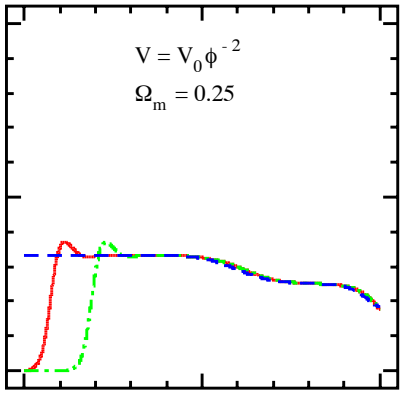
$= w(a|\varepsilon_s \varepsilon_{de\infty} \varsigma_s)$

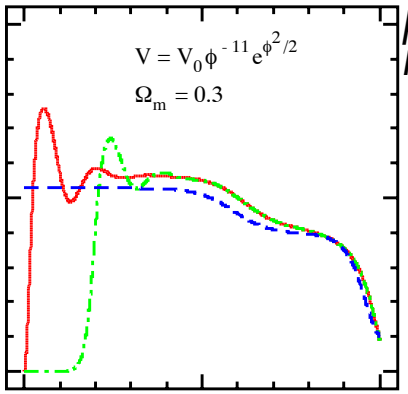
paves even wild late-inflaton trajectories

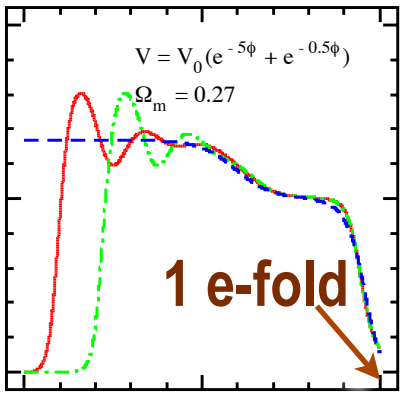
cf. w_ϕ

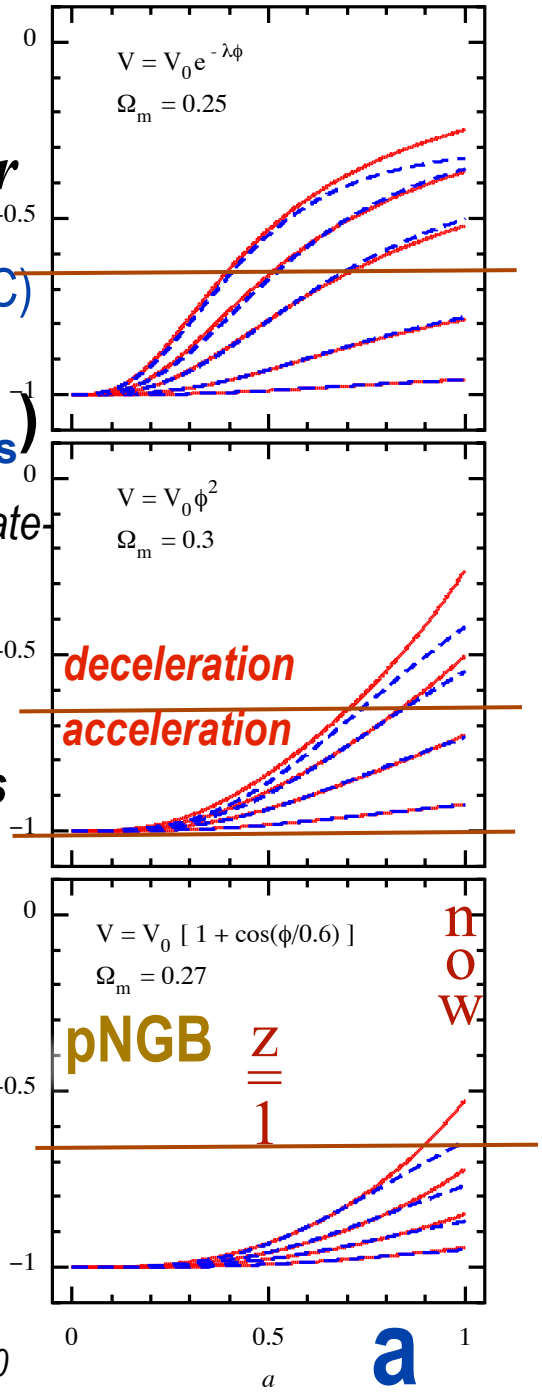
semi-blind eigen-analysis

W_{de} w_ϕ



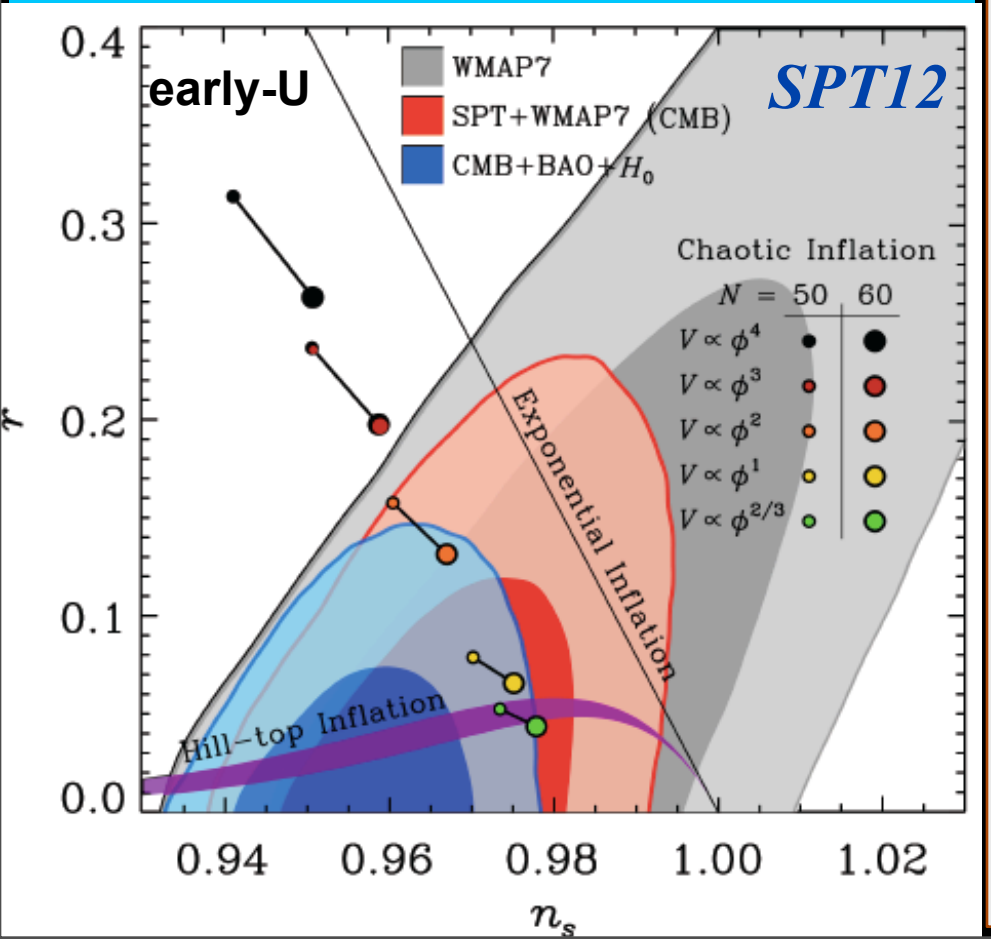


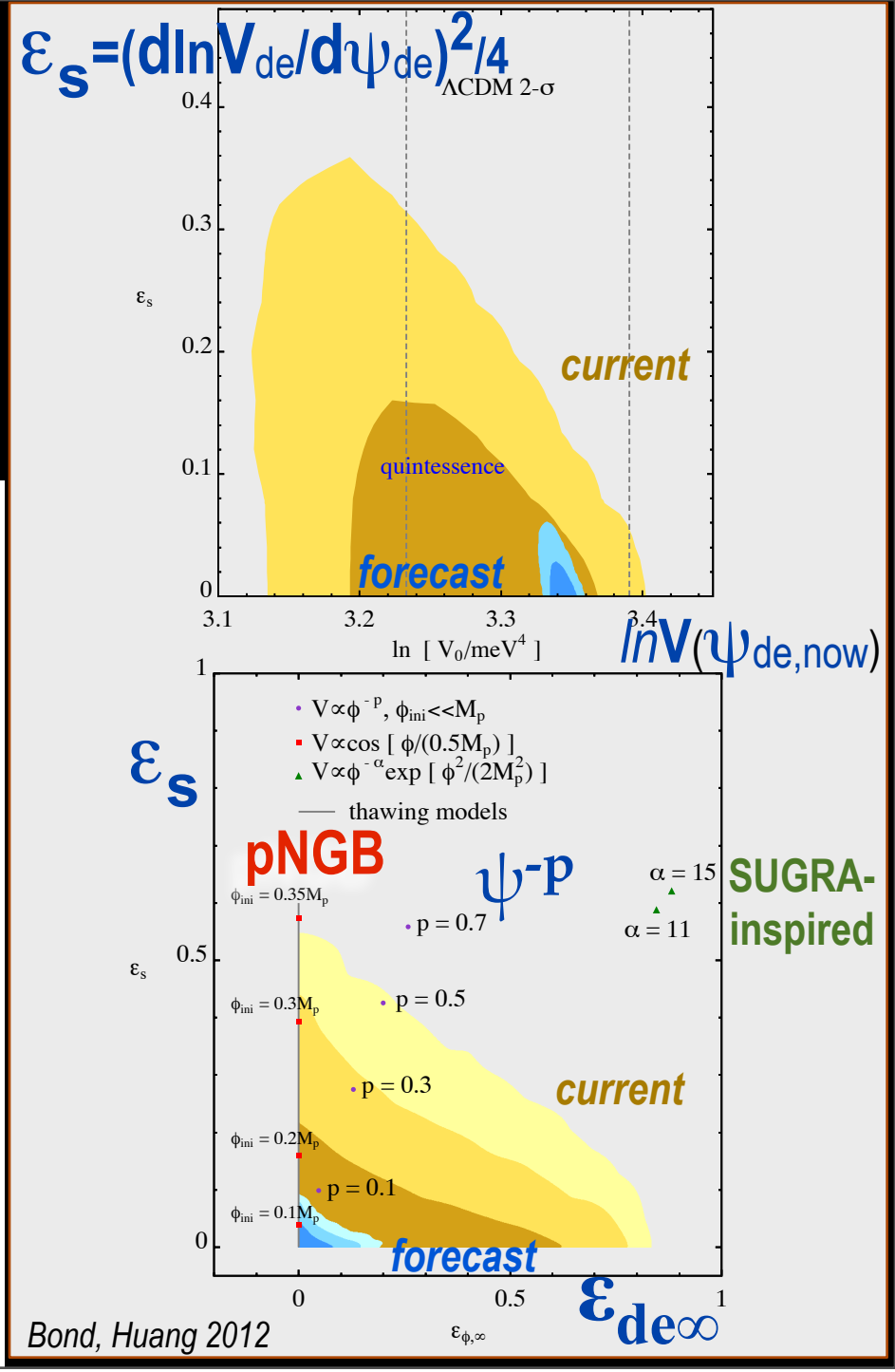




Bond, Kofman, Huang 2010

introduce a late-U DE plot littered with theory models similar to the early-U r-n_s plot. with HBK10/BH11 parameterization of the DE trajectories this can be done.





Bond, Huang 2012

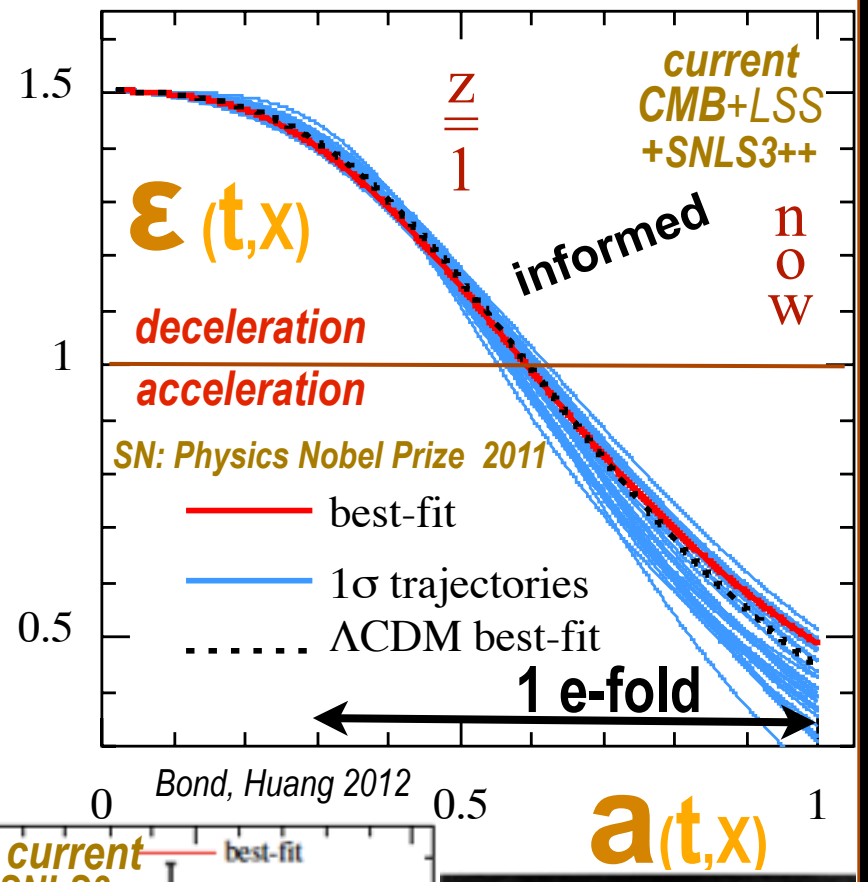
to DE (t,x) or not to DE (t,x) that is the question

modify Einstein equations?! nein

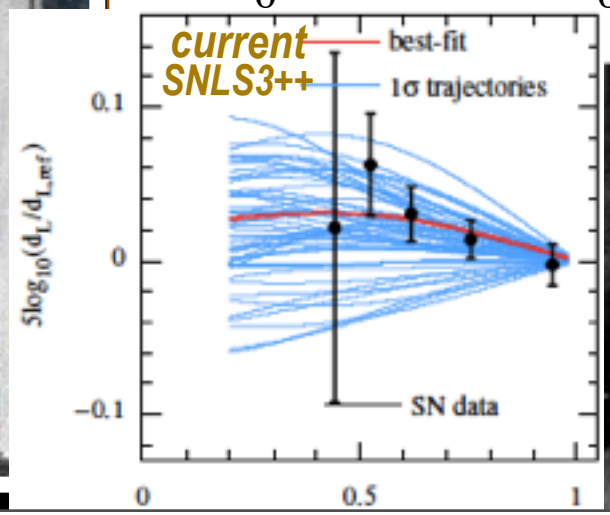
CITA ICAT

SN: Physics Nobel Prize 2011

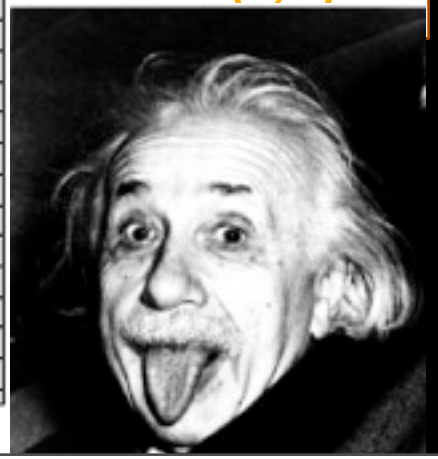
$1+W_t=-d\ln\rho_t / d\ln a^3=2/3\,\varepsilon(t)$

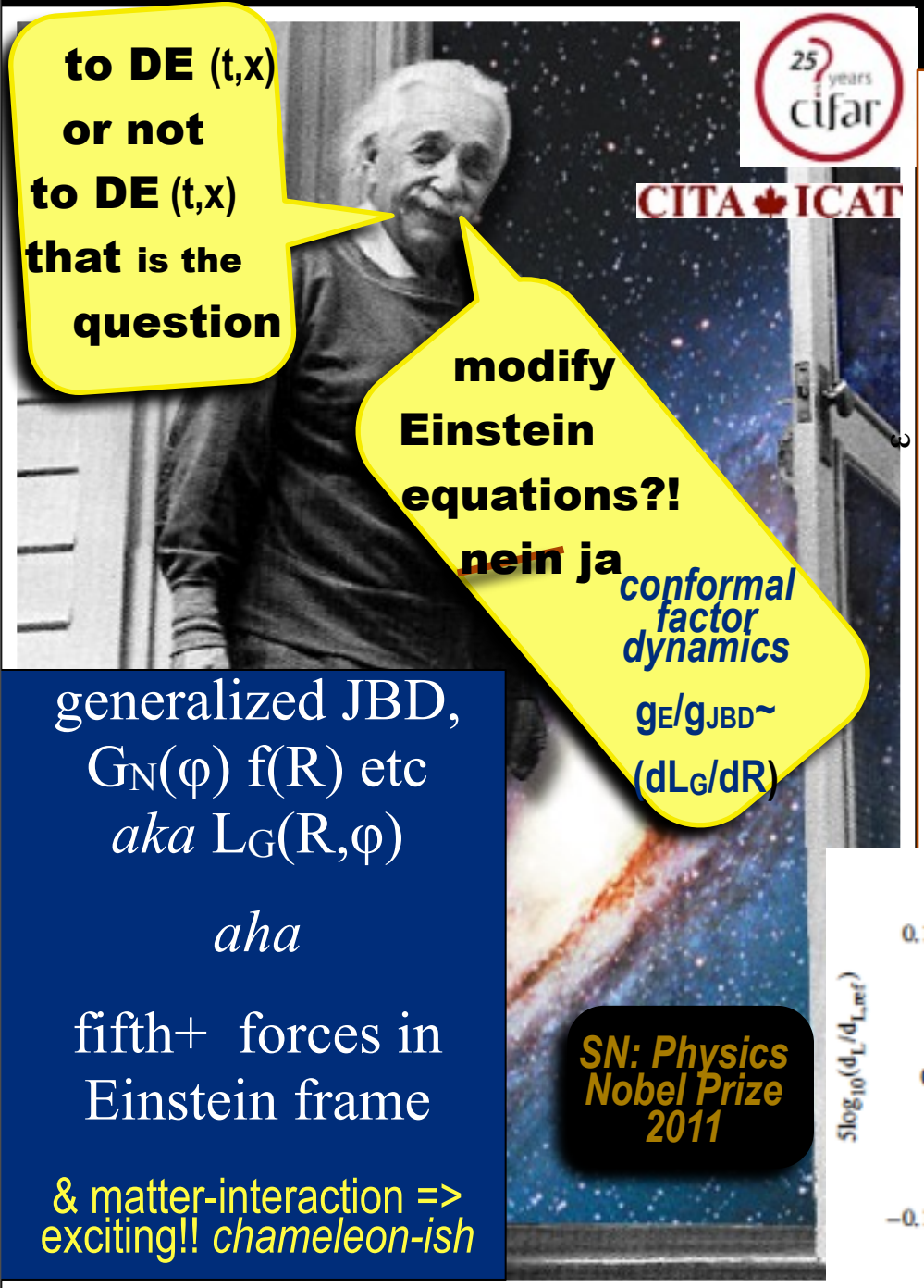


Bond, Huang 2012



a(t,x)





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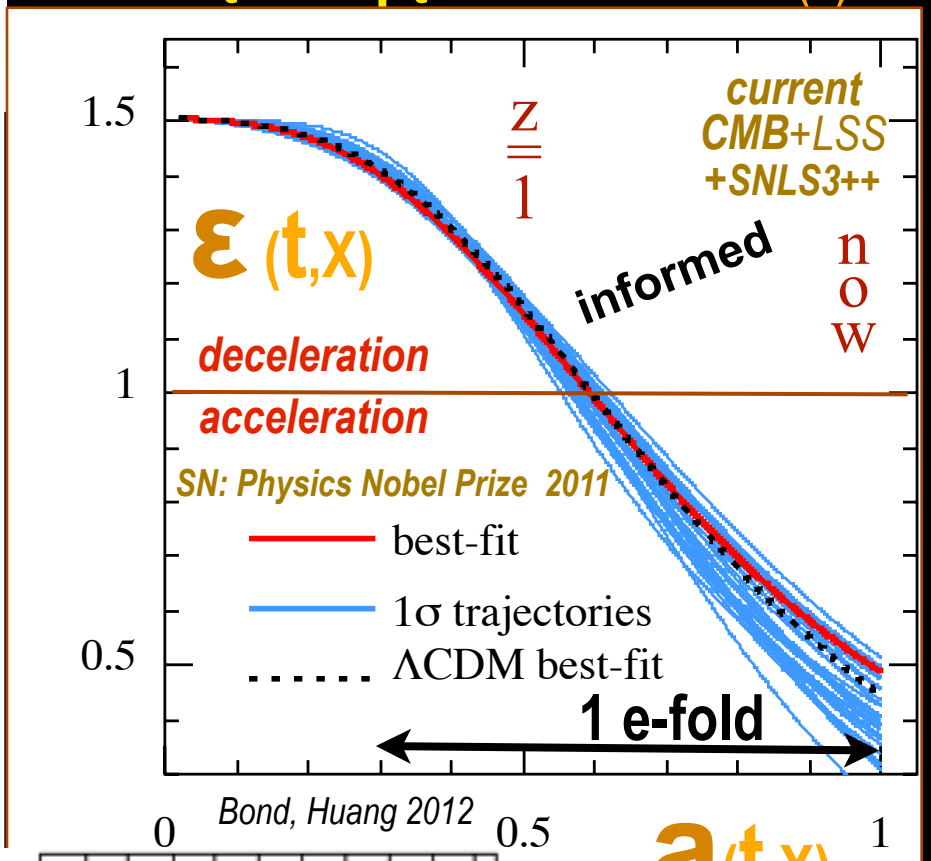


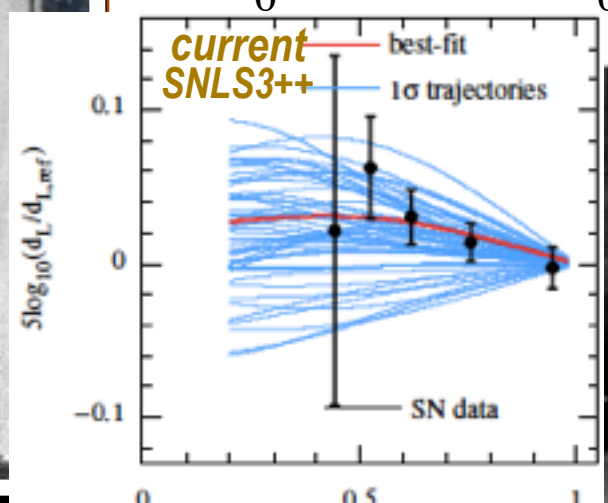
Bond, Huang 2012

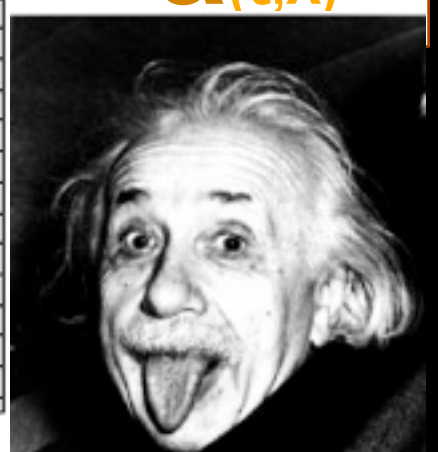
generalized JBD,
$G_N(\varphi)$ f(R) etc
aka $L_G(R,\varphi)$

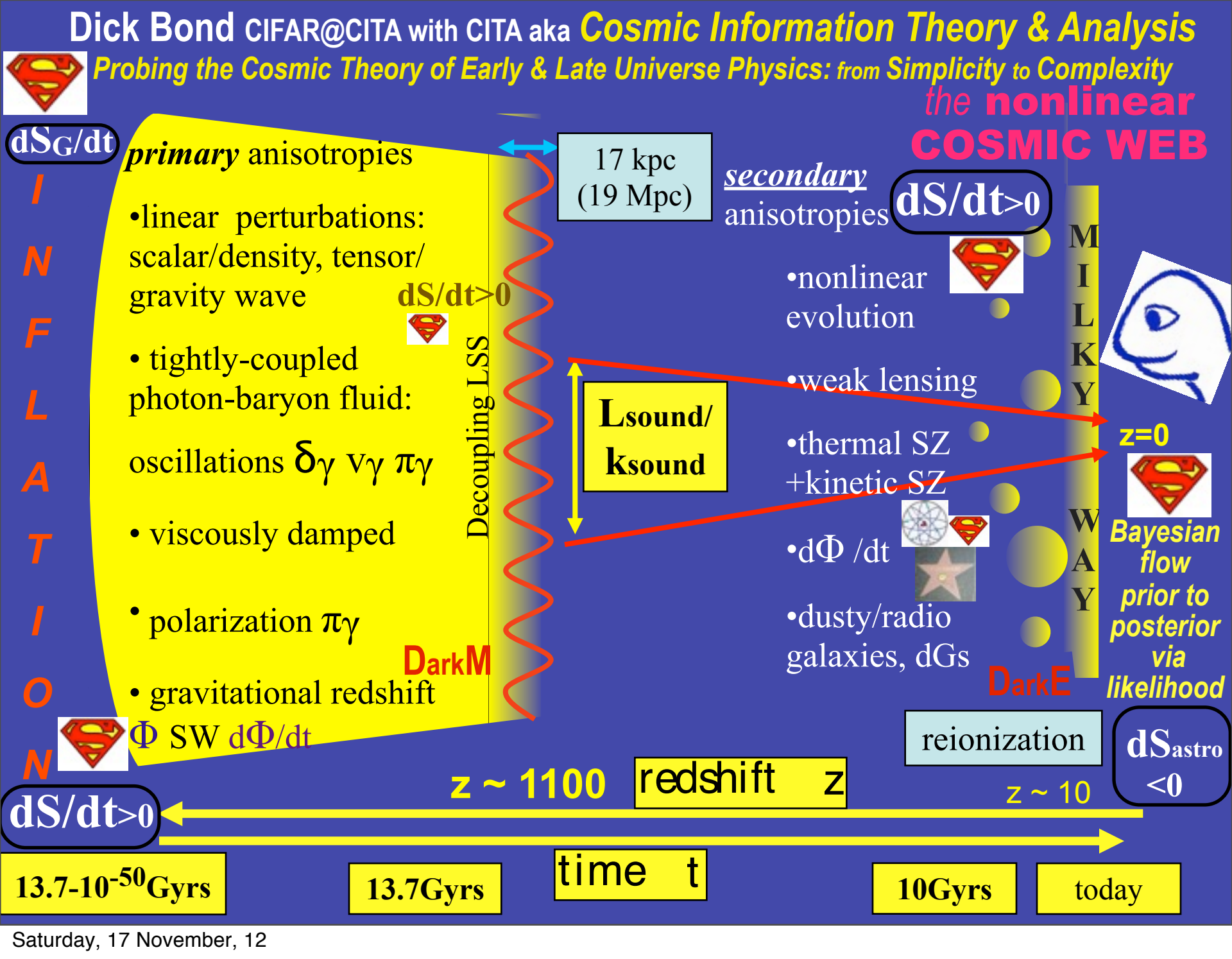
aha

fifth+ forces in
Einstein frame

& matter-interaction =>
exciting!! *chameleon-ish*



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DarkE
MILKY WAY
z=0
Bayesian flow prior to posterior via likelihood
reionization
dSastro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
time t
13.7-10-50Gyrs
13.7Gyrs
10Gyrs
today

ENDlong