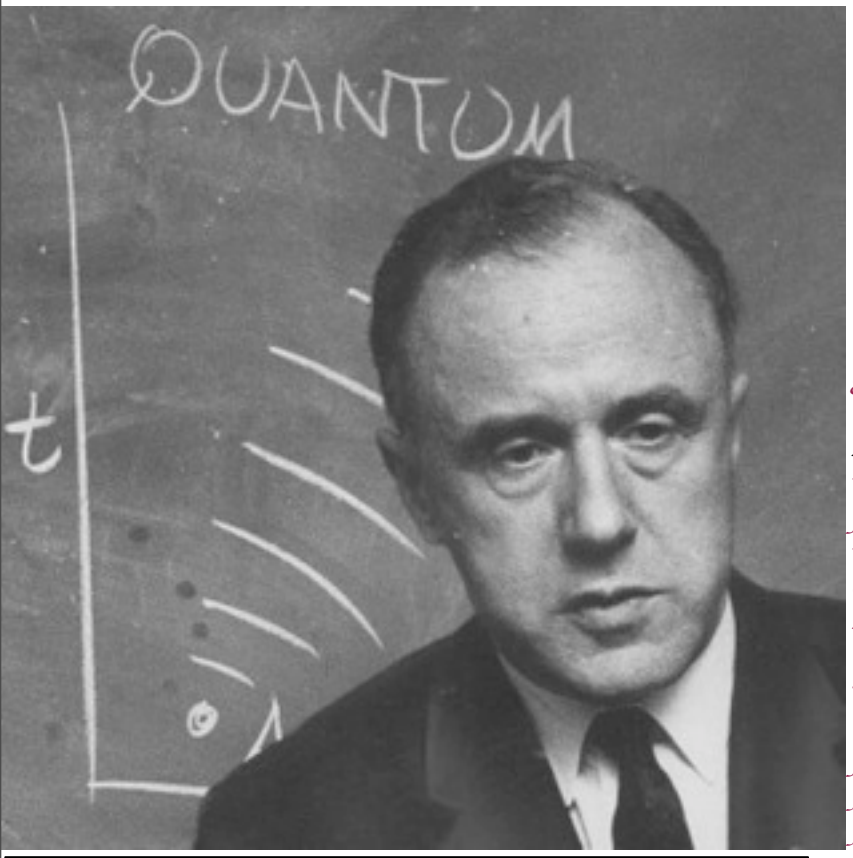
CITA = Cosmic Information Theory & Analysis: *IT from BIT, from BITs in IT*

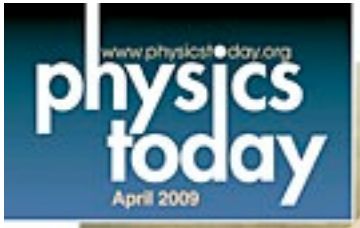
"black hole" =”gravitationally completely collapsed object"

measurement problem—the role of the observer in defining what "is."

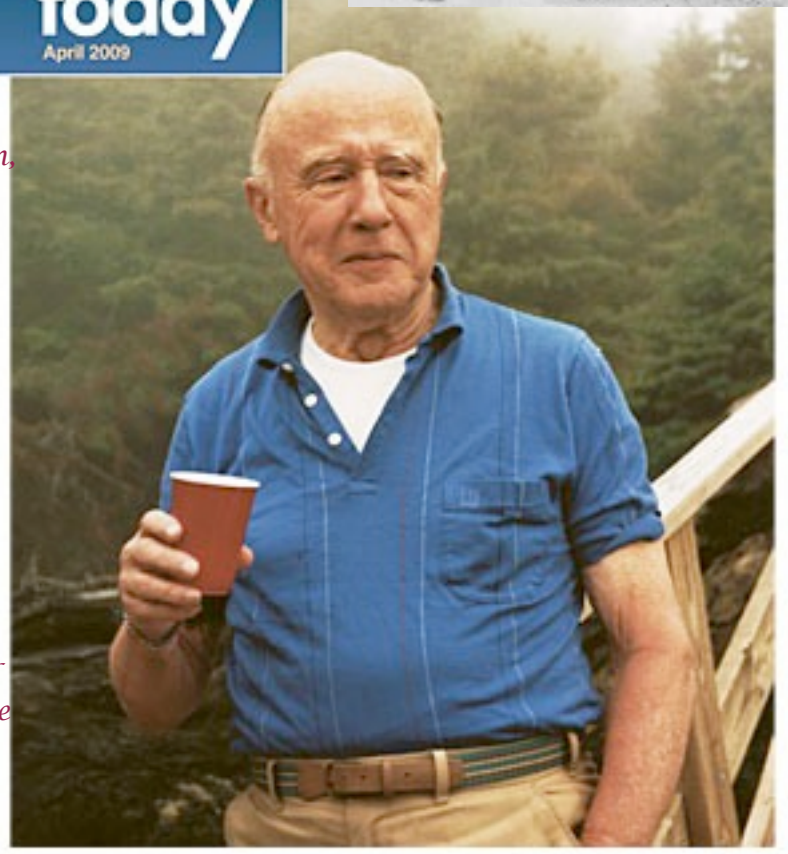
"What do we mean by 'reality' except the results of observations?"

the observer confers "reality" on the past by observing it, and offered the Big Bang as an example





"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."



Special issue:
John Archibald Wheeler

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

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

CITA ICAT Canadian Institute for Theoretical Astrophysics / L'institut canadien d'astrophysique theorique

Dick Bond

25 years cifar

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

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

s_{Ui}~*0;* $s_{Utot,m+r}/n_b$ ~*1.66x10*^{10} bits/b; s_γ / n_γ = ***5.2 bits/Y*** = *2130/411*; s_ν =*21/22* s_γ

s_m/n_b ~1 bits/b atmosphere ~1 preSN collapse, ~27 centre of sun, ~190 in clusters, s_{kin+th}-s_{th} non-equilibrium entropy of density fluctuations & of cosmic structures Δs_{dm} ~*7 bits/DM-particle*

Studying the Cosmic Tango

en-Tango-ment, the dance of S+R=U
Universe=System(s)+Reservoir,
=Signal(s)+Residual *noise*,
=Effective Theory+*Hidden variables*,
observer(s)+observed,
ruled by (information) entropy, entangled. ***the fine grains in the coarse grains***

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

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)**

$dS/dt>0$

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S_G (HubbleΛVolume)~$10^{121.9}$;$S_{Utot,m+r}$ (HubbleVolume)~$10^{88.6}$ compressed onto T_γ ≈2.725K & H0≈70km/s/Mpc

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

filter, compress, reduce, marginalize

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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***

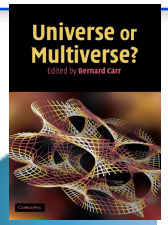
T=baryon, dark matter, vacuum mass-energy densities,...,

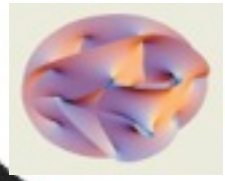
early & late inflation as low energy flows on a (string) landscape (point process of vacuua, river-flow trajectories), $L(g_{\mu\nu},\phi,\chi_i,\psi,A_\mu,\rho_m,p_m)$***, structure of manifolds (compactifying extra dims 7+3+1, moduli ~ "collective coordinates" of holes, branes, fibres, coupling 'constants')***

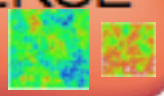
Anthrostatician=superHorizon measurer, ***of the information beyond UUUULSS***

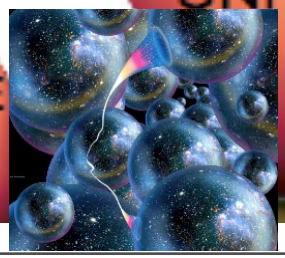
the **quantum stochastic non-G landscape** cf. the **stringy landscape**

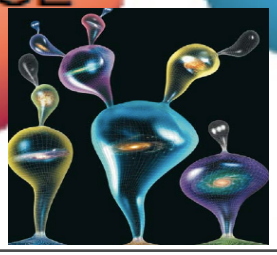
Starobinsky, Vilenkin, **Linde**, ..., stringy Susskind etal







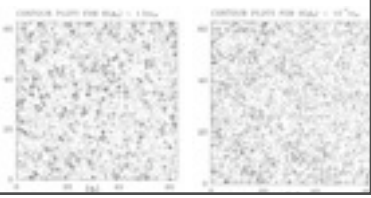




ln$a(x,\ln H)$

SB91: non-G on uniform Ha-hypersurfaces from a simple exponential potential via quantum kicks > drift at high $H_i \sim m_p$ uuUULSS cf. observable nearly-Gaussian at low $H_i \sim 10^{-5} m_p$

asymptotic flat eternal inflation V has similar behaviour



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entropy production: ***Post-inflation shock-heat*** & weak nonGaussianity F_{NL}

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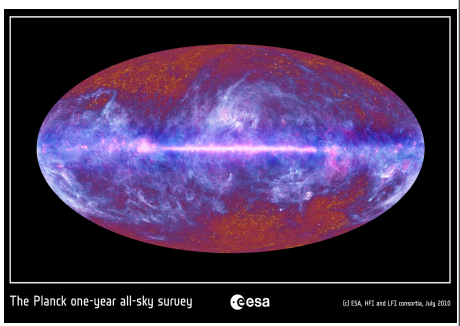
the gatherers of cosmic information

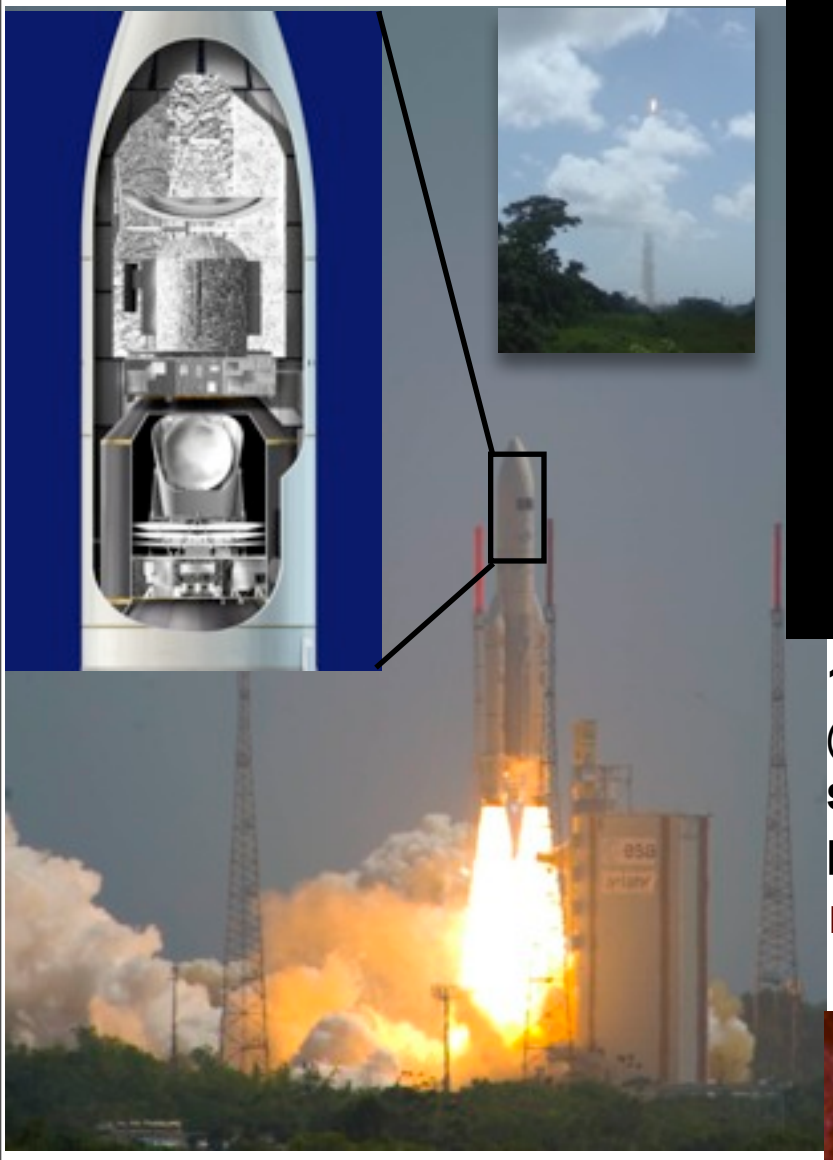
Cosmic **M**icrowave **B**ackground +

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

then & now & then



Planck+Herschel Launch May14 09 Fr. Guiana



1.5m telescope, HFI bolometers @6freq <100mK, LFI HEMTs@3freq, some bolometers & all HEMTS are polarization sensitive

HFI+LFI **performance** to **spec** or better

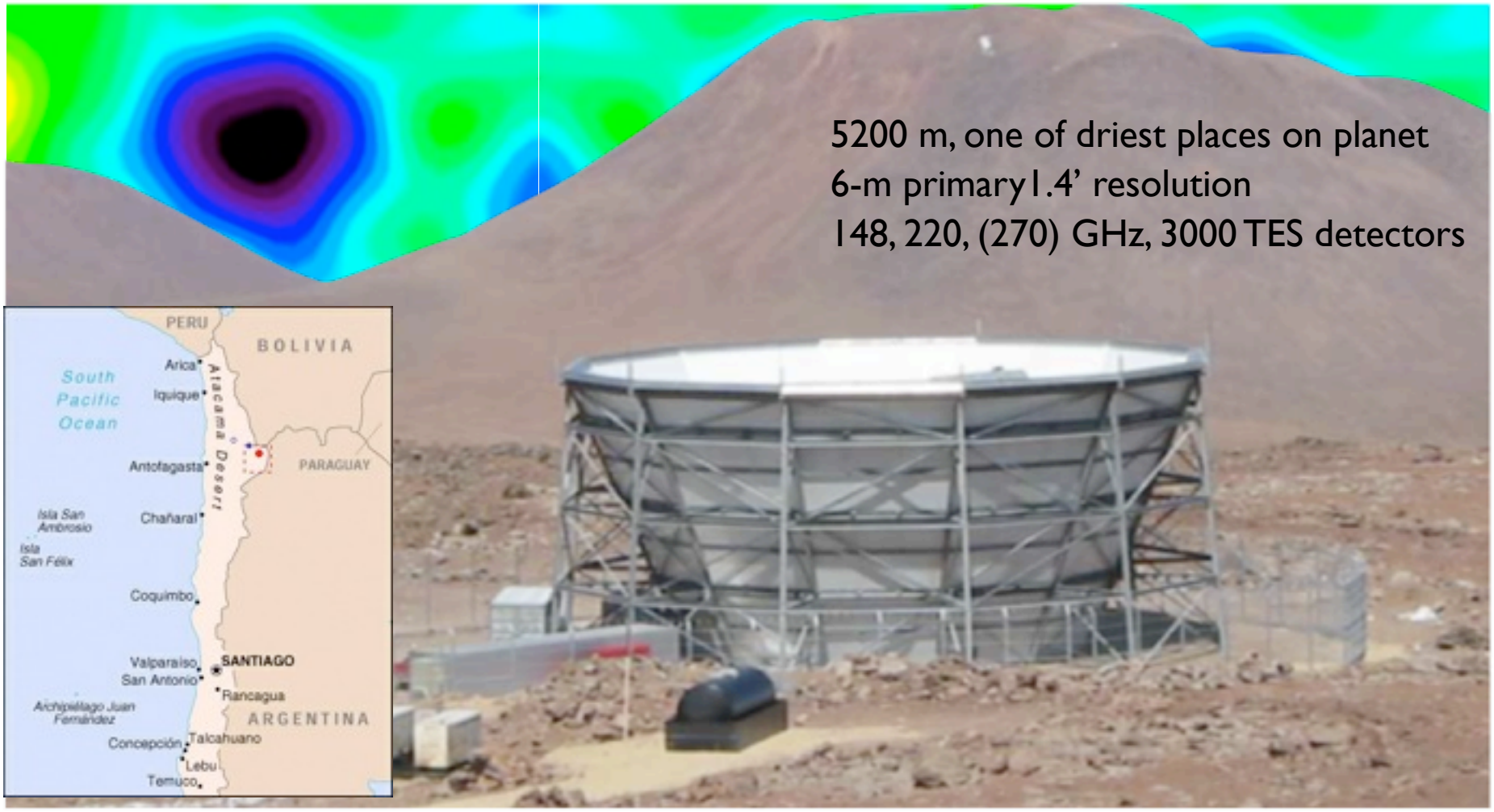
Left earth at ~10 km/s, 1.5 million km in 45 days, cooling on the way (20K, 4K, 1.6K, 0.1K 4 stage). @L2 on July 2 09 -almost no trajectory correction @operational temp; Survey started on Aug 13 09 spin@1 rpm, 40-50 minutes on the same circle, covers all-sky in ~6 month, ~4 surveys Aug11, ~5 total

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency -- ESA -- with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Bond since 1993, Canada since 2001, 1st CSA pre-launch contract 2002-09, post-launch 2010-11, 2011-13

Cosmology From 5200 metres:
the Atacama Cosmology Telescope



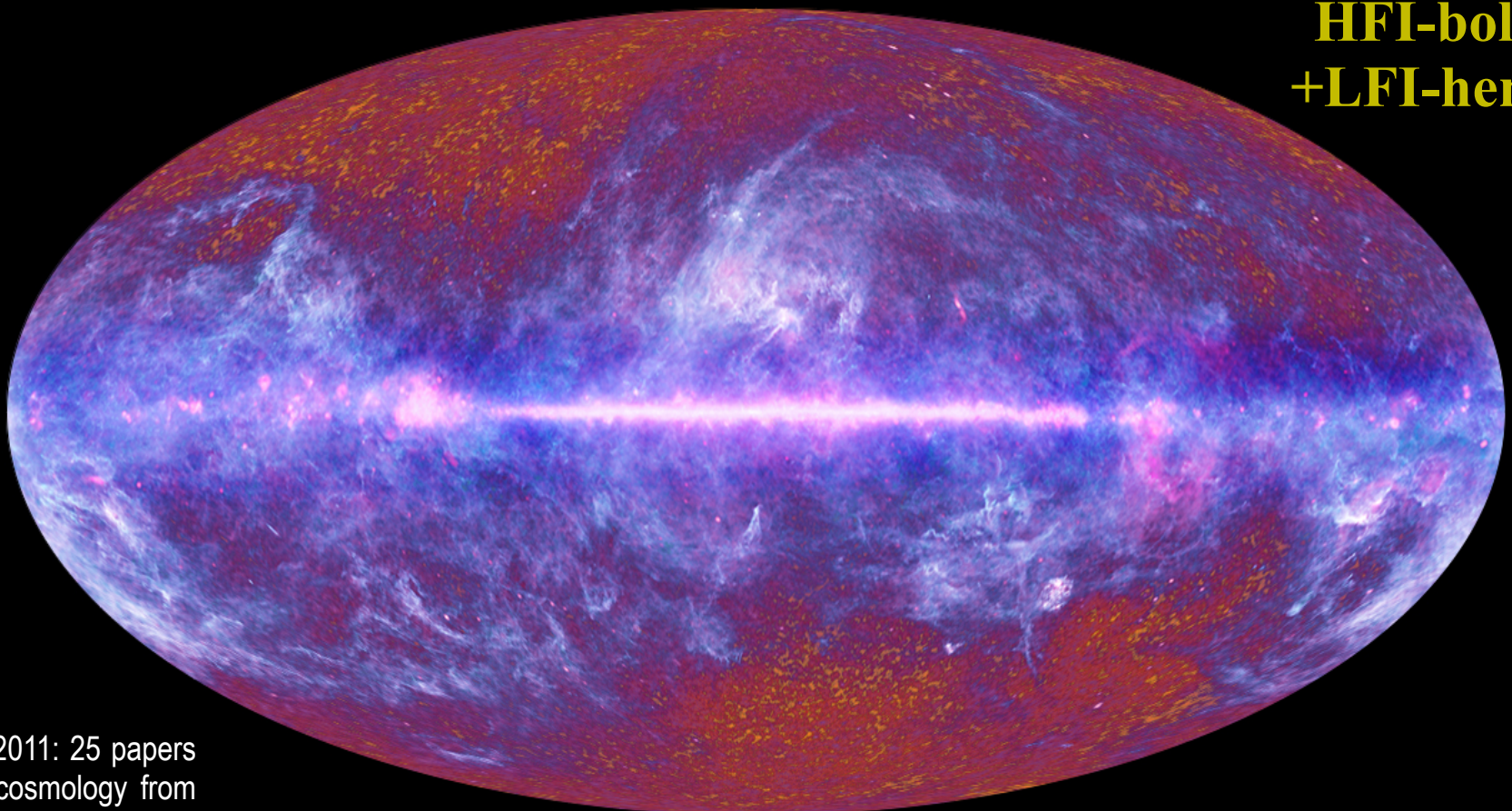
CMB@CITA: Boomerang, Acbar, CBI1,2, Planck, ACT, Spider, Blast, & ACTpol, ABS, QUIET90-2;
GBT-Mustang2, CARMA/SZA, SCUBA2, ALMA

Planck & ACT

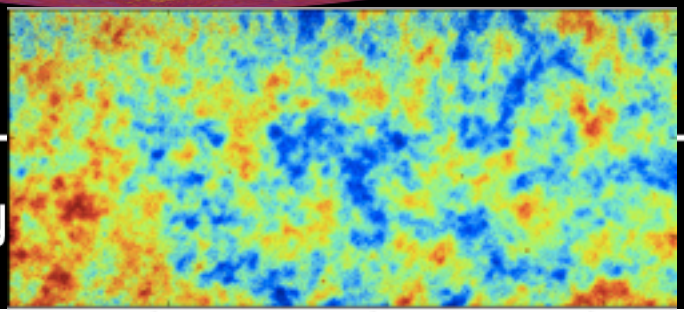
Dick Bond

7 veils(v)+CMB

9 v, pol, HFI-bolos +LFI-hemts



Jan 2011: 25 papers first cosmology from Planck early 2013, major pol early 2014



ACT+WMAP7 hajian+10

The Planck one-year all-sky survey

ESA, HFI and LFI consortia, July 2010

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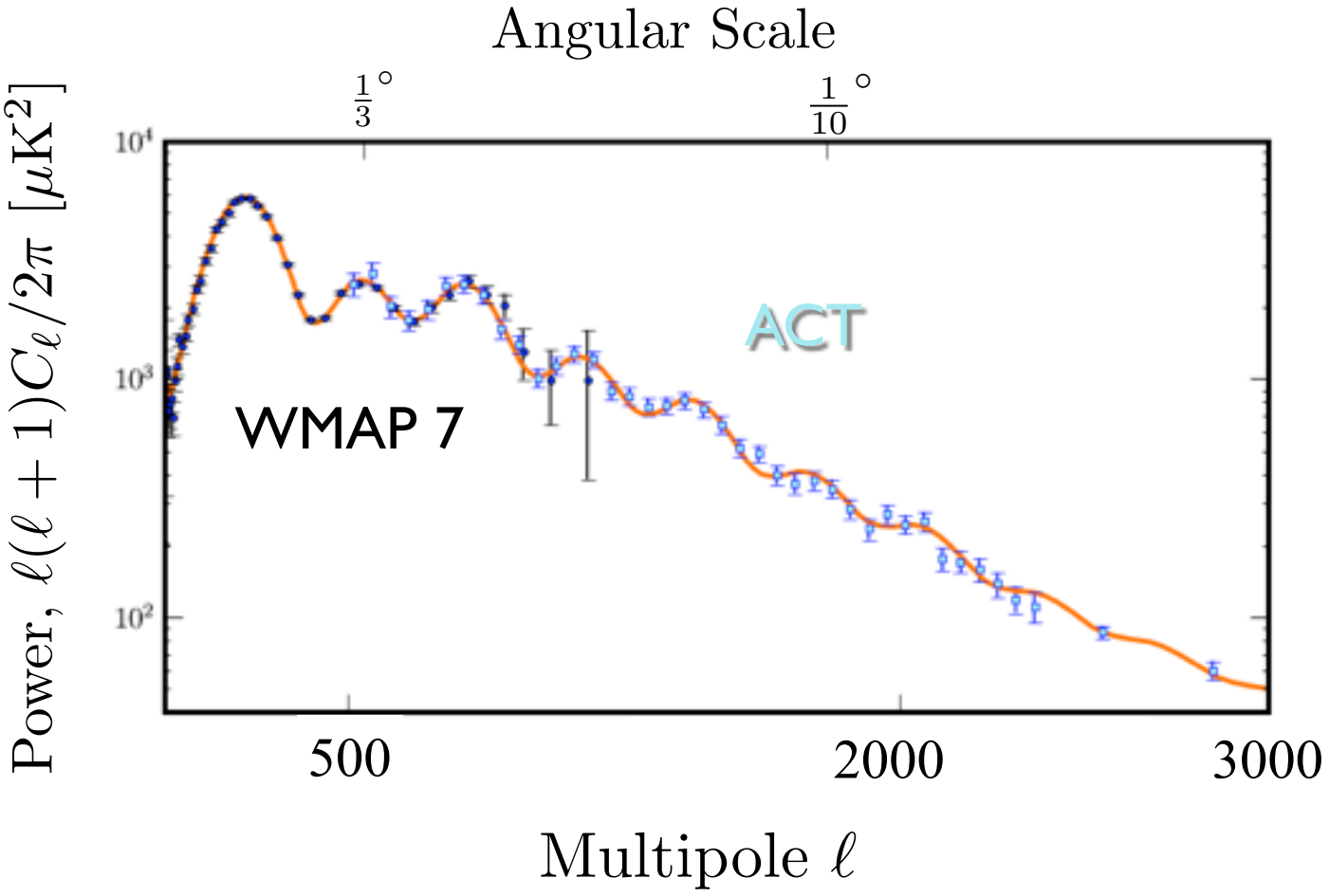
WMAP: 1.15 Tbits in 9yrs, cf. MyLifeBits, Gordon Bell, 1.28 Tbits in 9yrs, Planck 36 Tbits, ACT 304 Tbits. Radically Compress to high quality Bits. Terabit=10^{12}bits=125 GigaBytes.

(radically) compress: ~0.3 PetaBits of the ~3000 detector timestreams from 3 years => 3 frequency maps, with noise variance, => isotropic Fourier/Y_{LM} -transformed temperature power spectra, ~8000 numbers + variances, => further bandpower compressed at high L

HIGH RESOLUTION POWER SPECTRUM from ACT: OLD



Das+ 2011, ApJ, 729:62, Hajian_2011, **Dunkley+.2011**, Hlozek+ 2011, Das+2011, Sherwin+2011, ..., **Sievers+2012**

tilted ΛCDM a very good fit (n_s constant); data are good enough to search for subdominant cosmic parameters N_ν, X_{He}, r, $dn_s/d\ln k$, $n_s(k)$ in bands, CMB lensing, .. & we have (strings, isocurvature,..)

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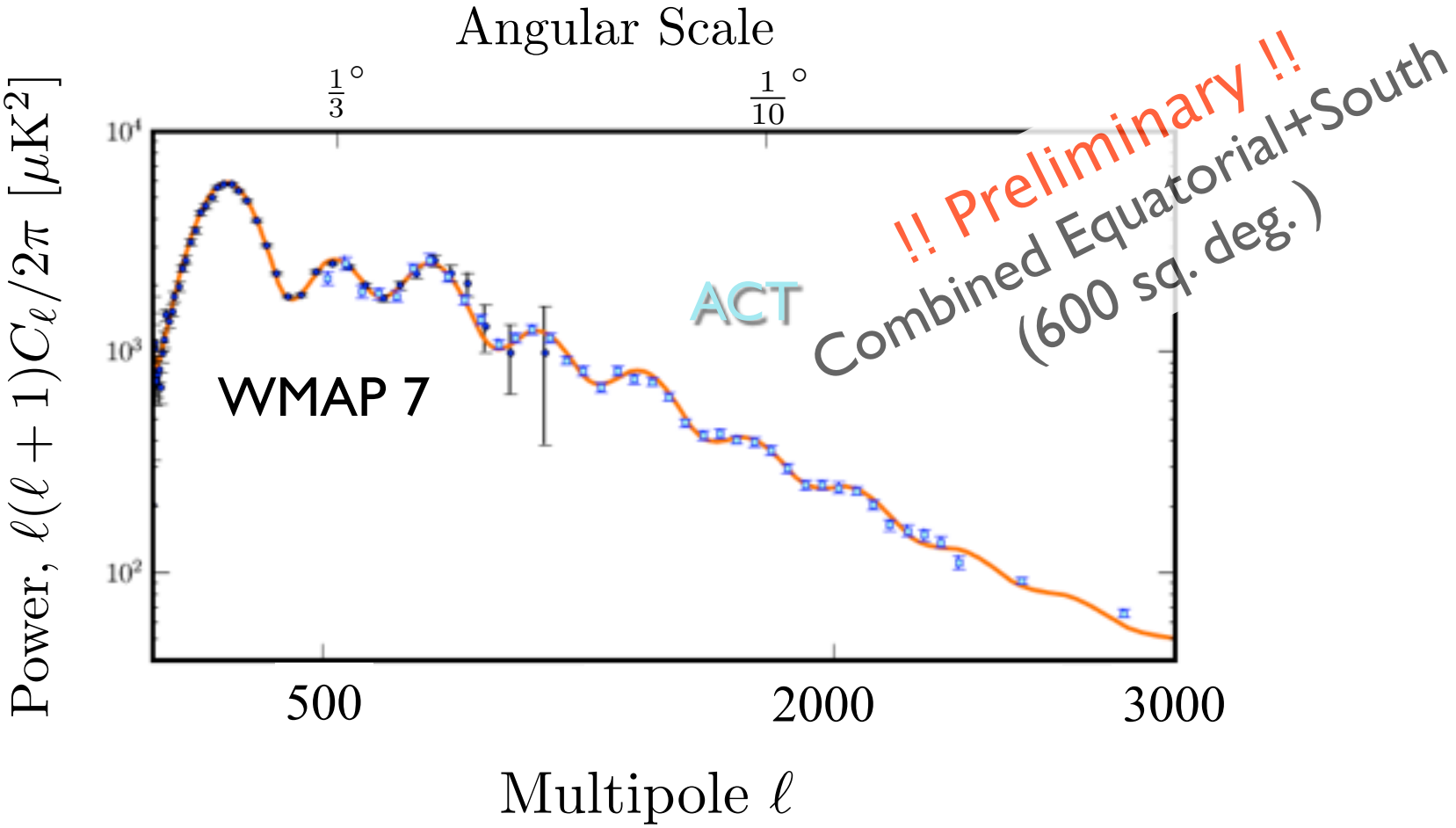
HIGH RESOLUTION POWER SPECTRUM from ACT: NEW



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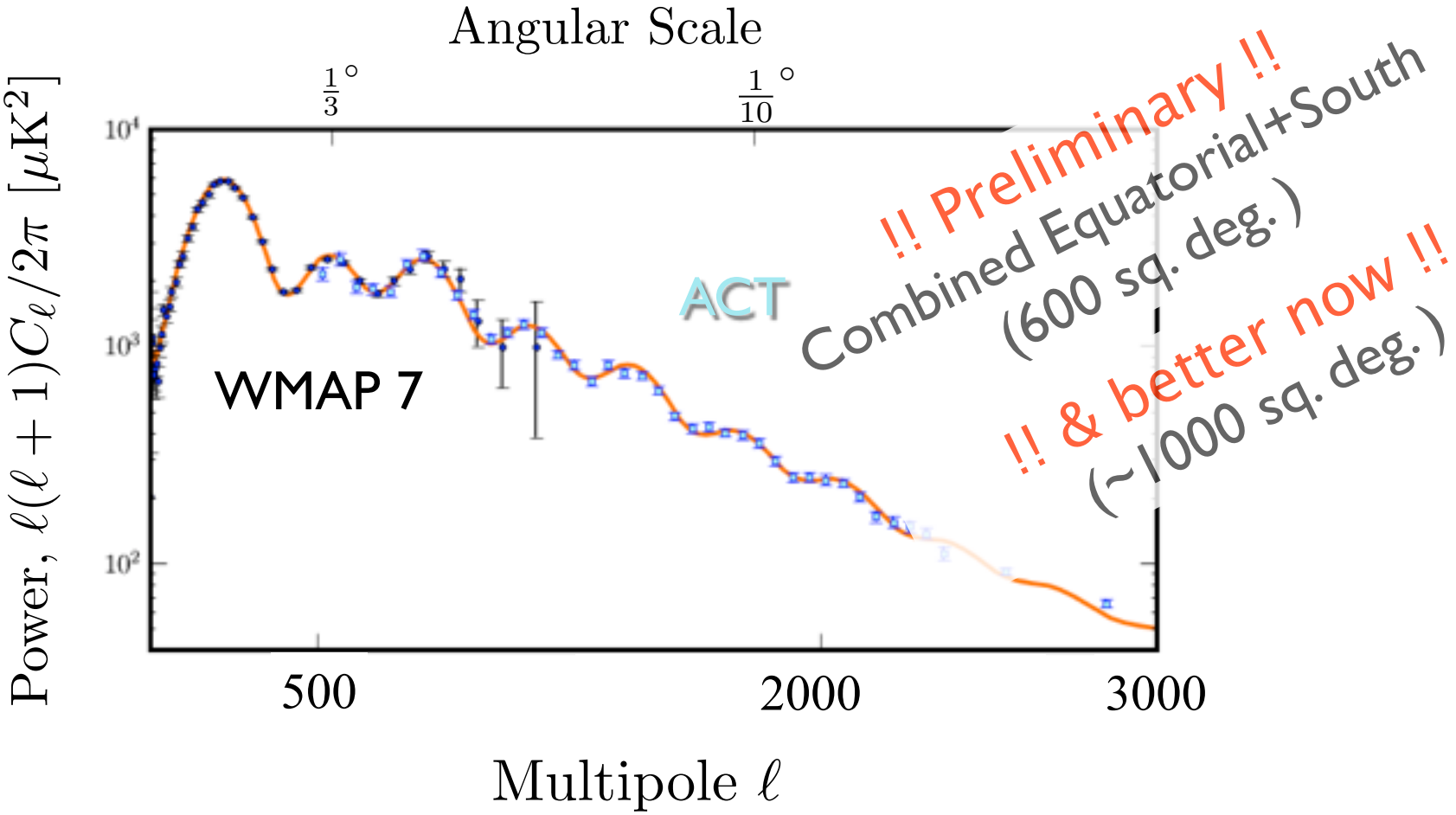

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CBI pol to Apr'05 @Chile

CBI2

Quiet1 @Chile

Quiet2 1000 HEMTs

QUaD @SP

Keck@SP

Boom03@LDB

Bicep @SP

Bicep2

ABS@ Chile

EBEX @LDB

WMAP @L2 to 2010

Planck09.4

52 bolometers + HEMTs @L2

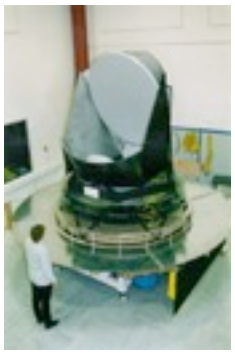
9 frequencies

Herschel

Spider 2312 bolos @LDB

DASI @SP

CAPMAP



2013

BLAST

Pixie/ COrE/ LiteBird @space

2004 2006 2008 LHC 2011

2005 2007 2009

SPT 1000 bolos @SPole

BLASTpol

Piper

Acbar to Jan'06, 08f @SP

SZA @Cal

Polarbear @Chile

ACT 3000 bolos 3 freqs @Chile

SPTpol

ACTpol

AMI

APEX ~400 bolos @Chile

SCUBA2 12000 bolos JCMT @Hawaii

ALMA

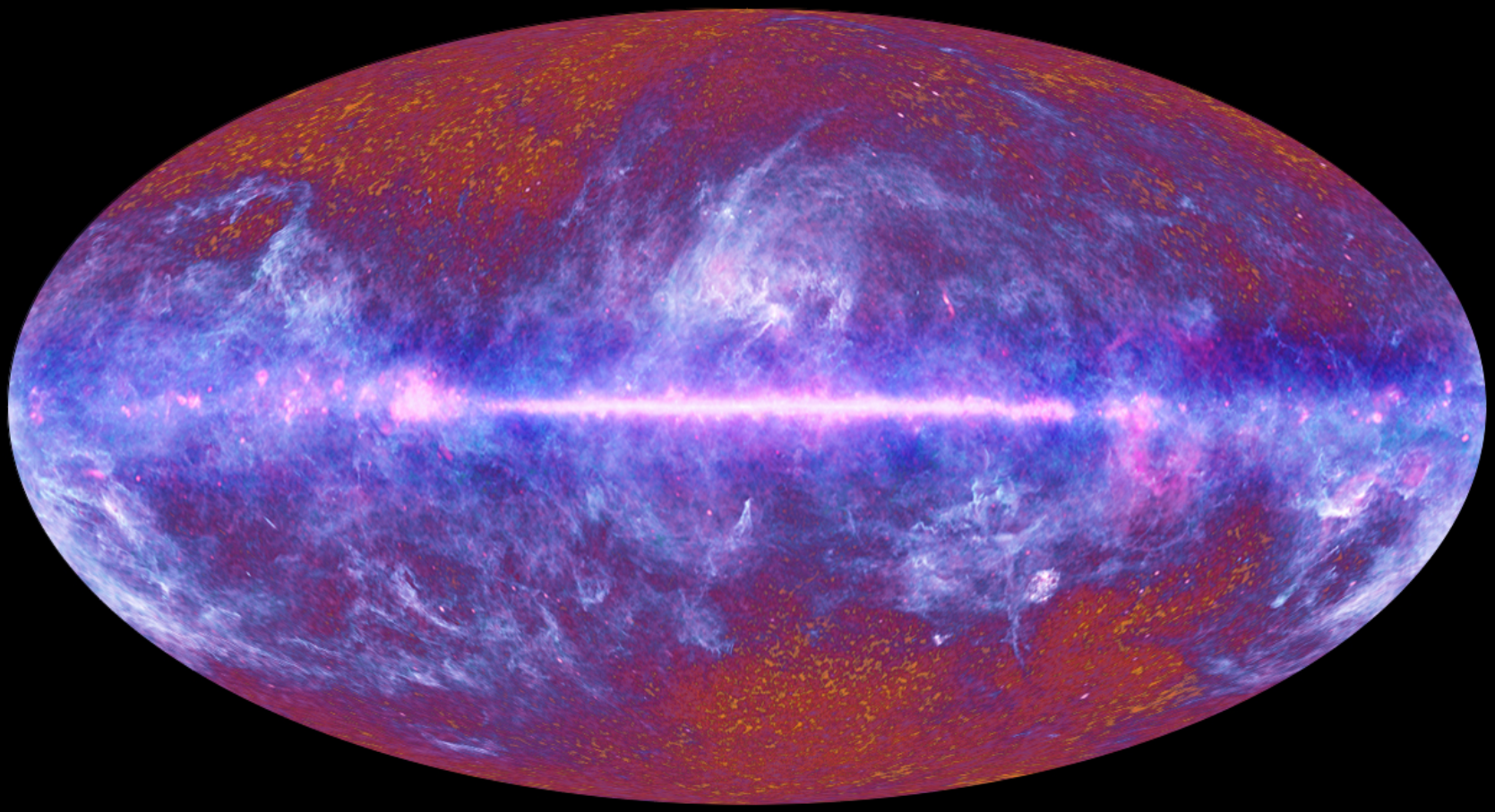
CCAT@Chile

GBT

LMT@Mexico

Beyond the standard model: tilted ΛCDM + x

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



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The Planck one-year all-sky survey

esa

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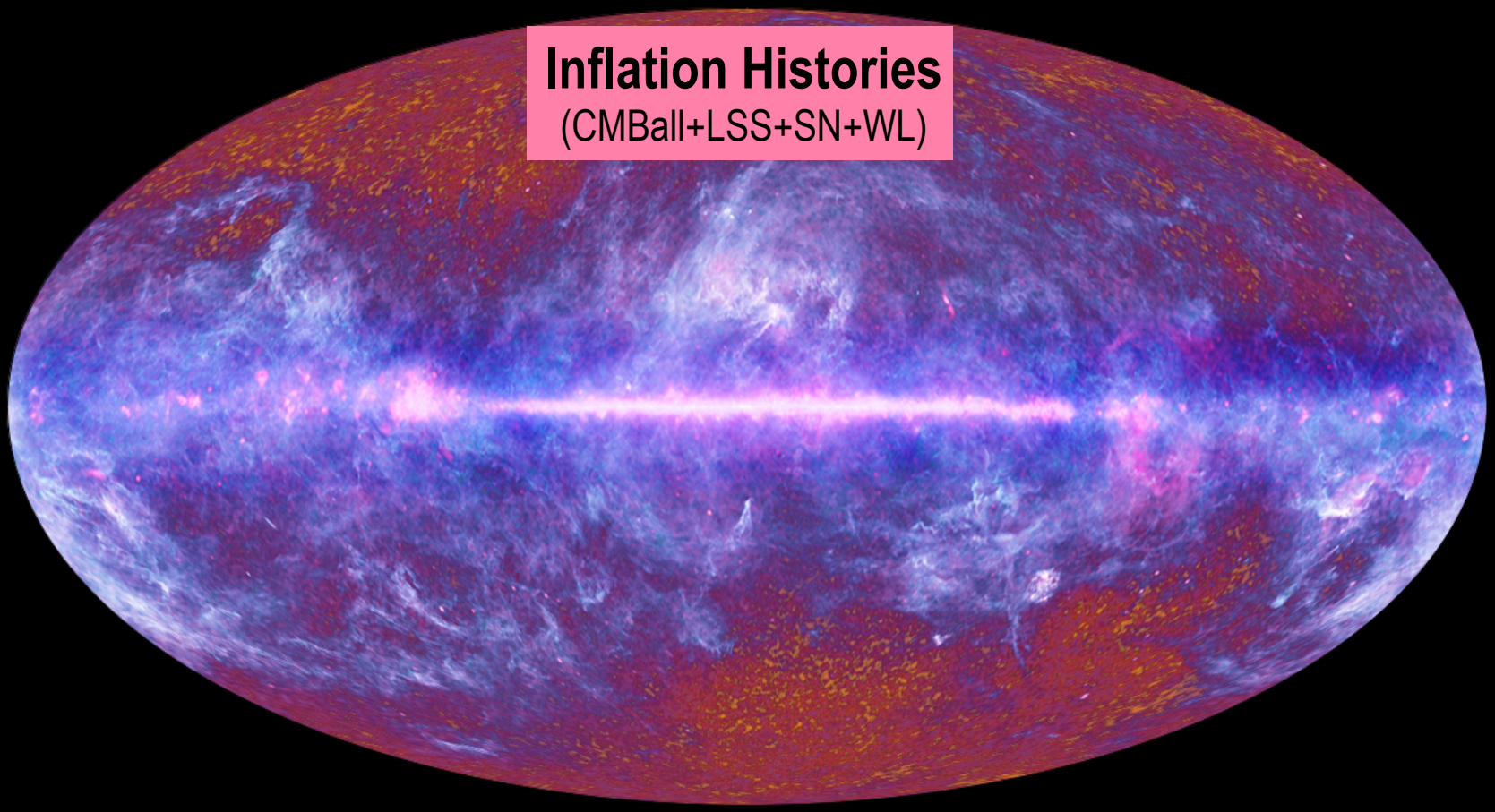

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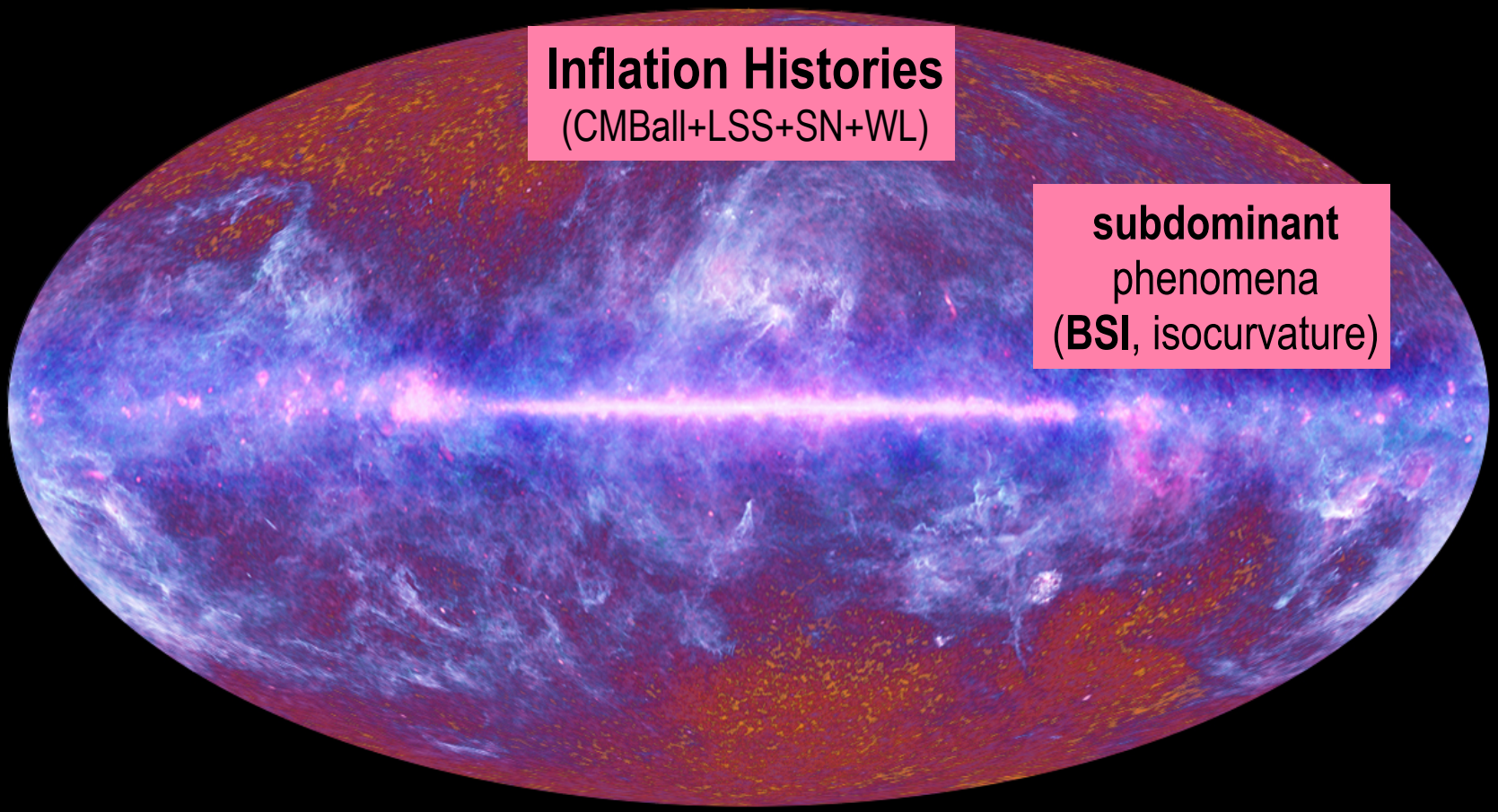

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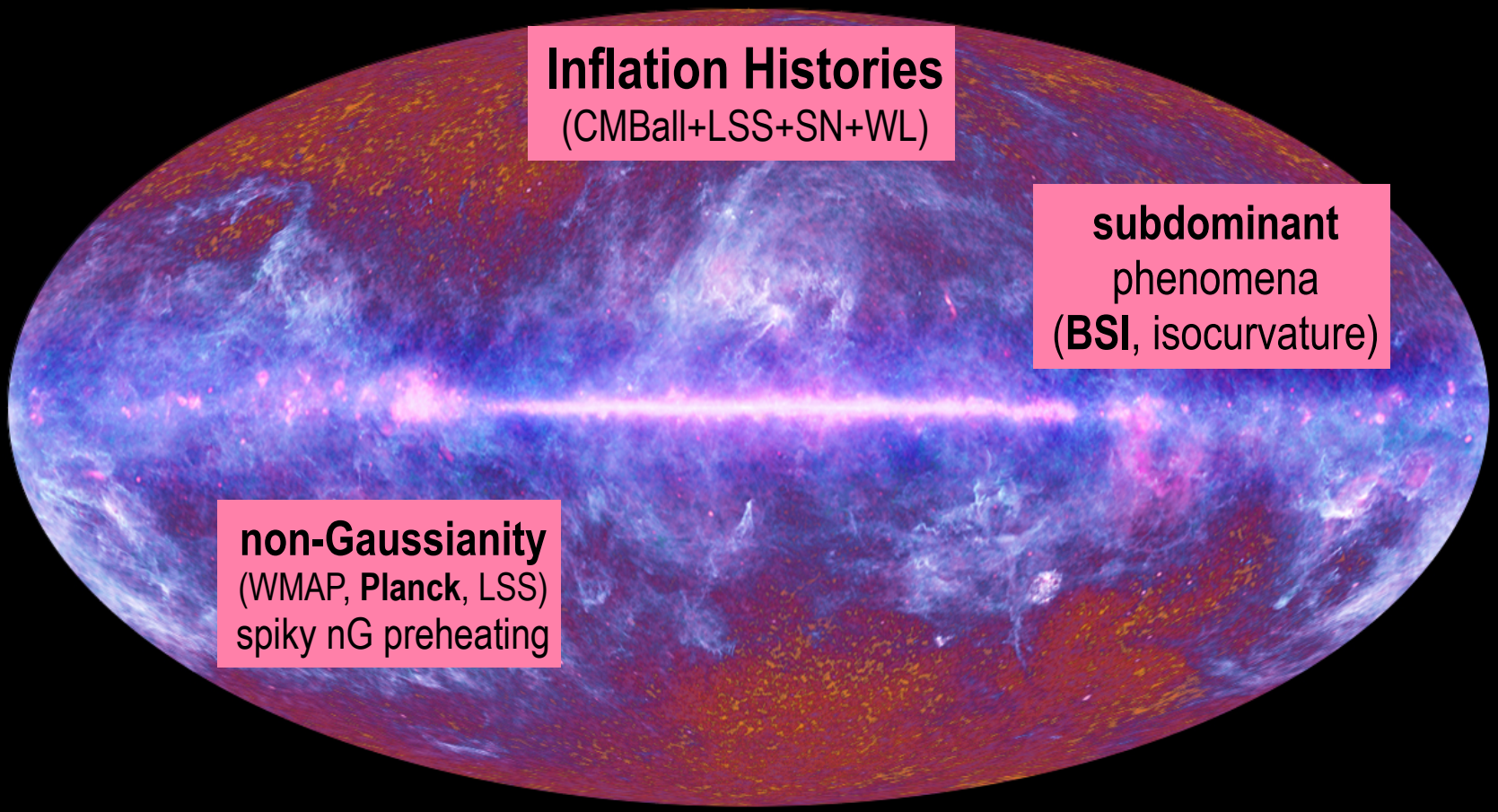

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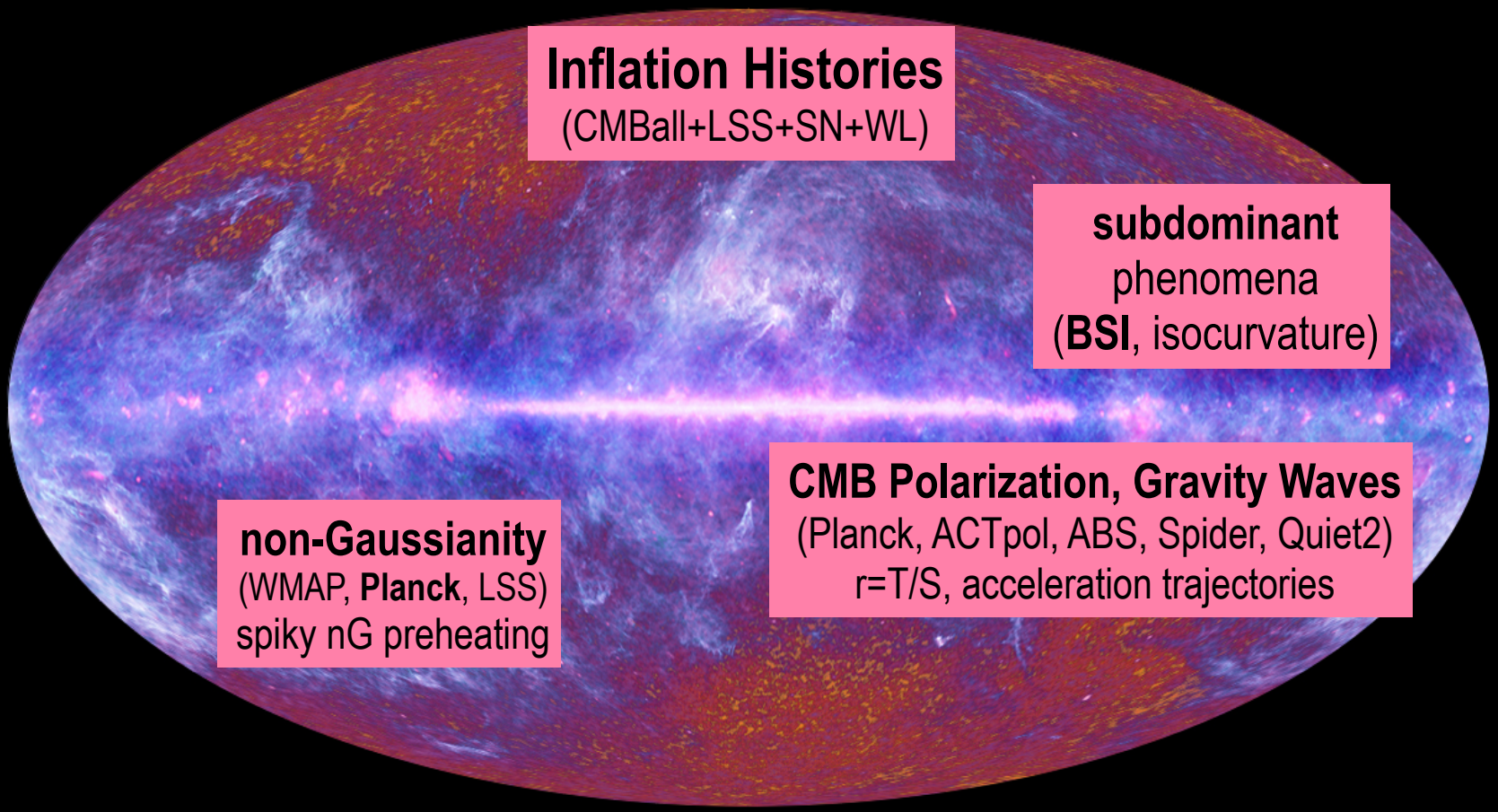

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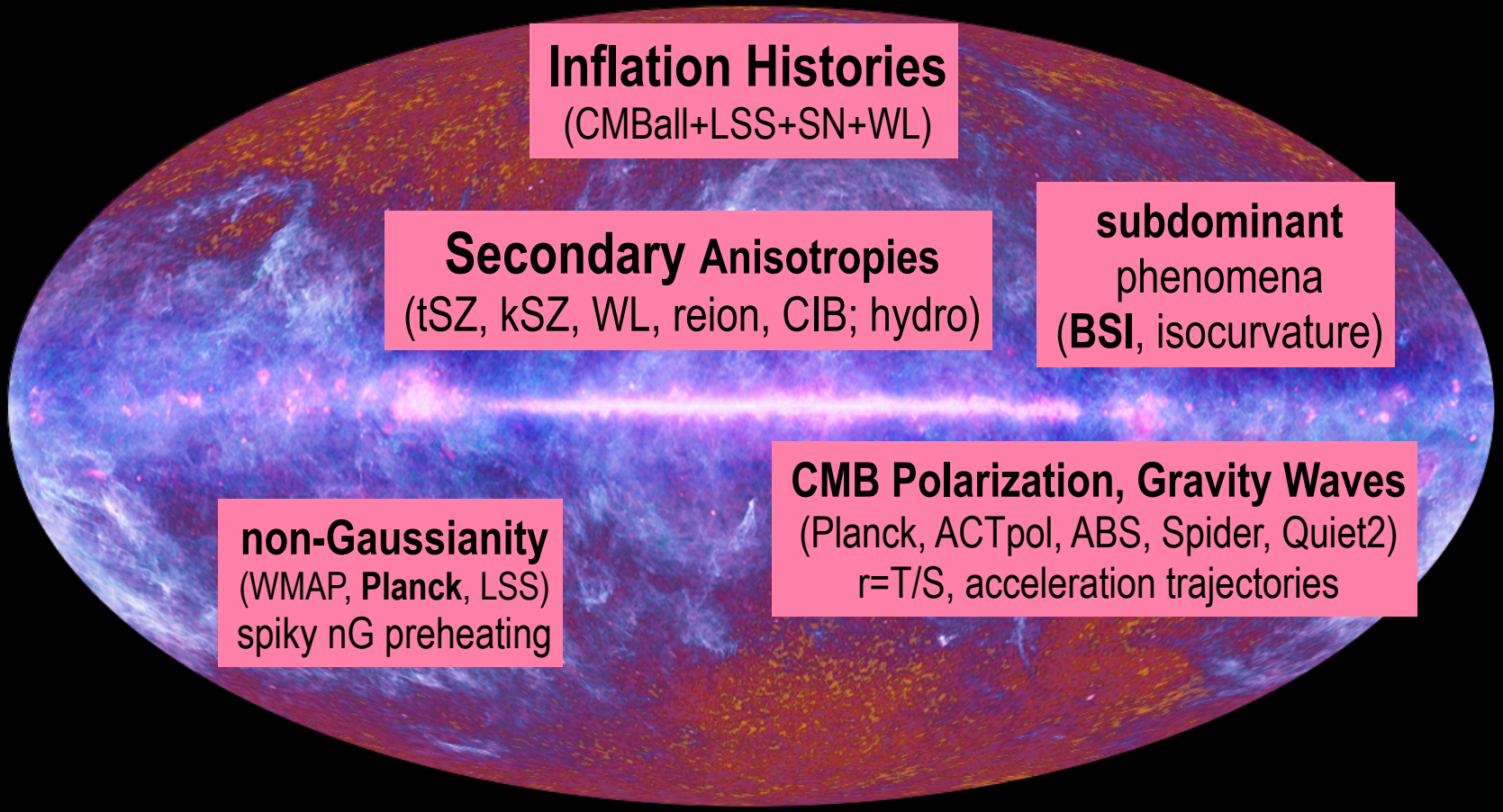

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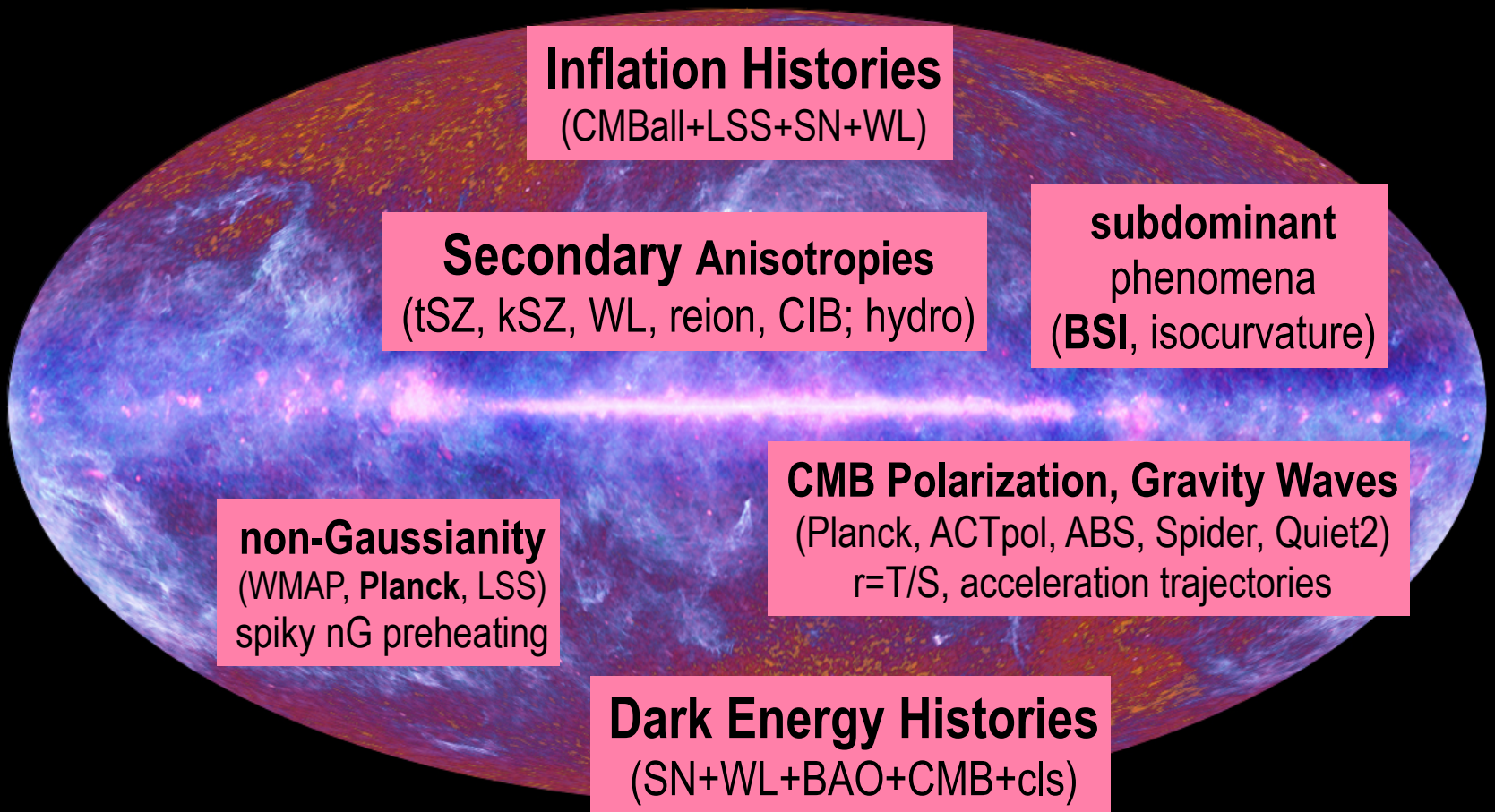

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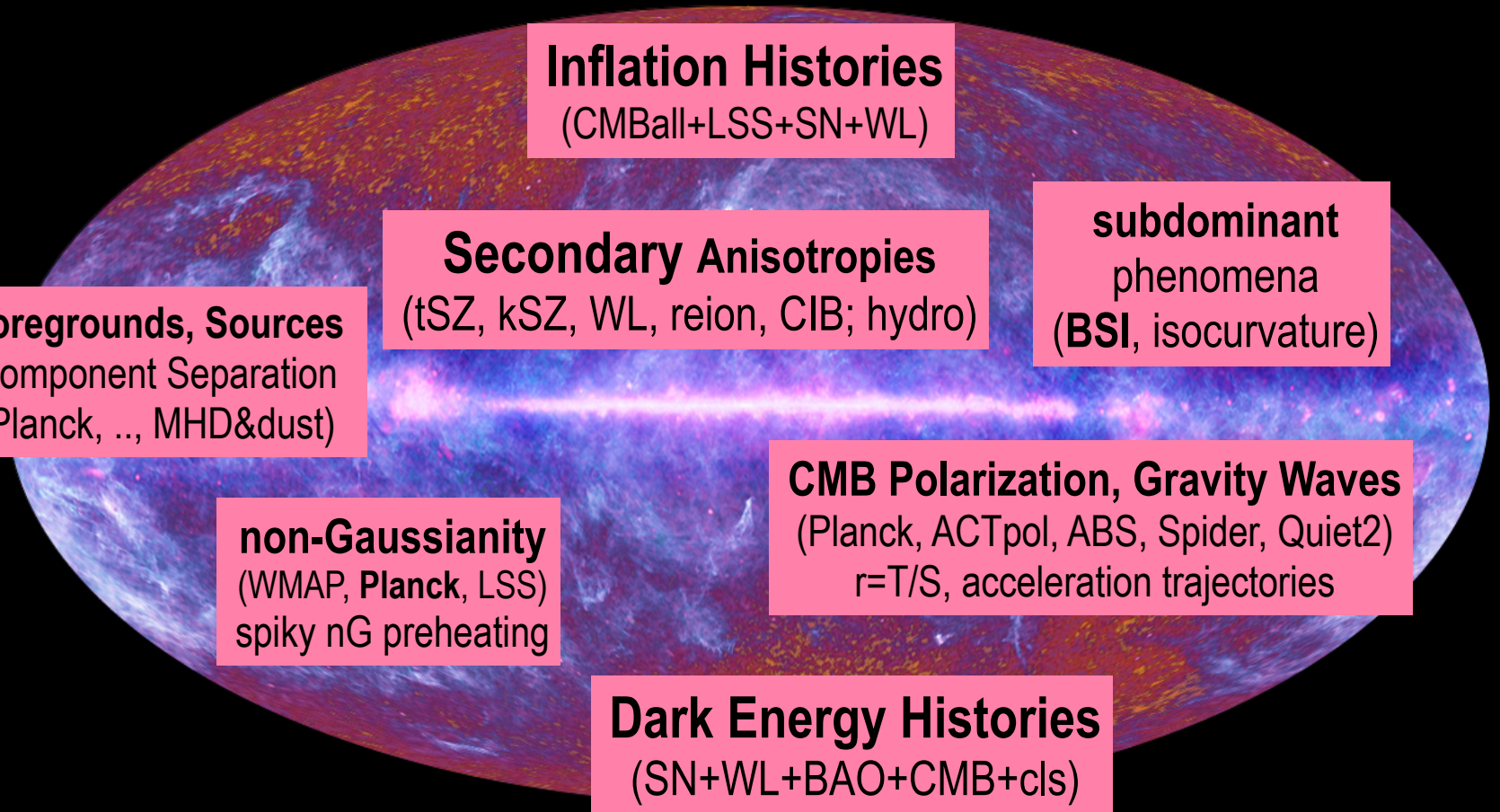

Inflation Histories
(CMBall+LSS+SN+WL)

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

subdominant
phenomena
(**BSI**, isocurvature)

Foregrounds, Sources
Component Separation
(Planck, .., MHD&dust)

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

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

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

morphs** into the nonlinear **Cosmic Web: clusters, filaments, voids; galaxies (SZ)

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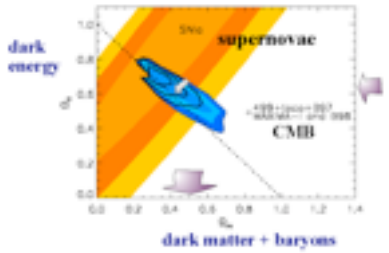


Dark Energy Histories
(SN+WL+BAO+CMB+cls)

future fate?

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 those particles that survive)*

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

Photo: Ariel Zambelich, Copyright © Nobel Media AB

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

ΛCDM was the standard "concordance" model since ~1995;

much invoked since

Peebles 1985

a neo-Lemaitrian

WYSIWYG

BBE87, PR88, Weinberg87, ...

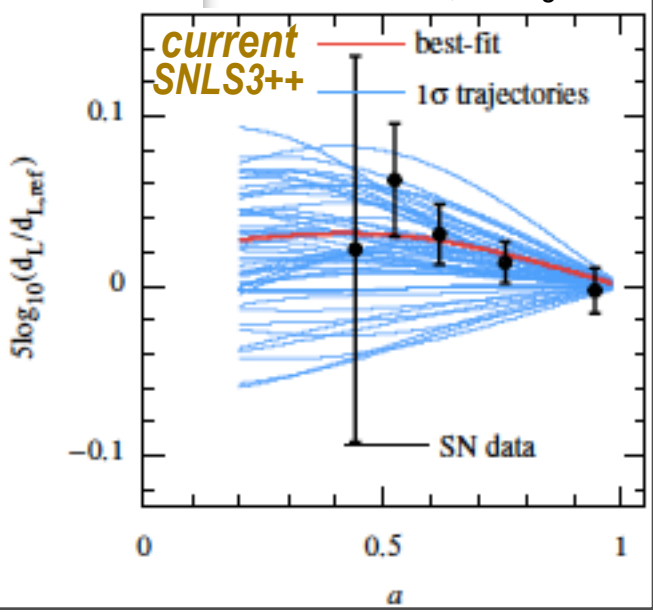
Bond, Huang 2011

Physics Nobel Prize 2011

current Type Ia Supernova data Apr 2011

472: 123 low-z+ 242 SNLS3yr +93 SDSS1yr + 14 HST

HubbleST constraint H0 = 73.8 +-2.4 km/s/Mpc



CMB ⇓ CMB⊕LSS ⇓

$n_s \simeq 1 \pm .05$

nearly SCALE INVARIANT FLUCTUAT^{N}S

vintage 1998 conclusions

CMB⊕LSS ⇓ oCDM << ΛCDM

SNIa ⇓

high z CLUSTERS ⇓

$\Omega_{cdm} \sim .3$

$\Omega_B \sim .04$

$H_0 \sim 65\text{-}70$

$t_0 \simeq 12\text{-}14\,Gyr$

$\Omega_\nu \sim .0014 \left(\frac{m_\nu}{.07\,eV}\right)\frac{2\nu}{2}$

$(\ddot{x}, t) \approx \frac{2}{3}$

Λ vac φ LATE TIME

INFLATION is NOW

$\rho_\Lambda^{1/4} \sim$ milli eV

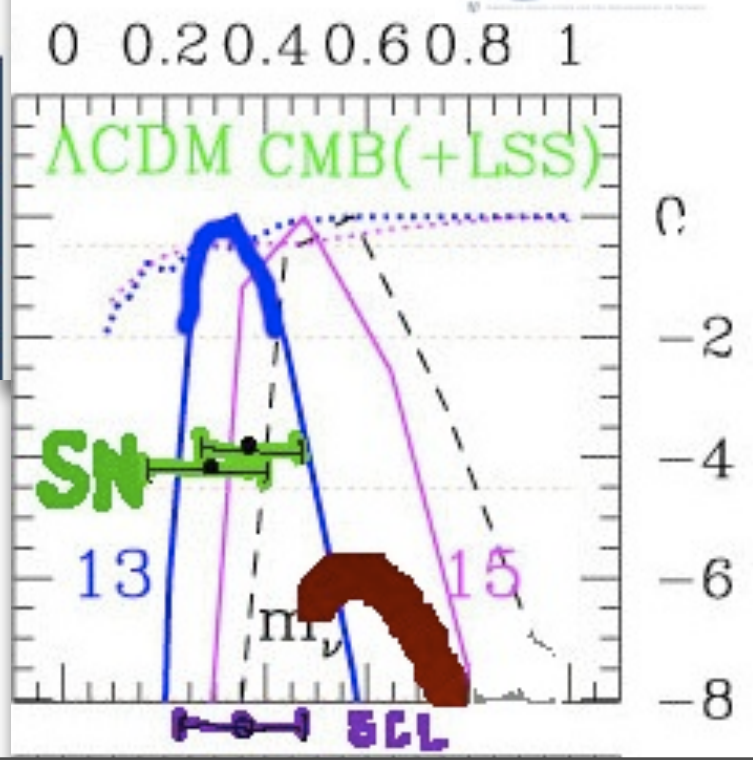
B+Jaffe'96,'98 $(13\,Gyr/t_0)$

$\Omega_\Lambda \approx 2/3 \pm .07$ +LSS

$n_s =$

$.98 \pm .07$

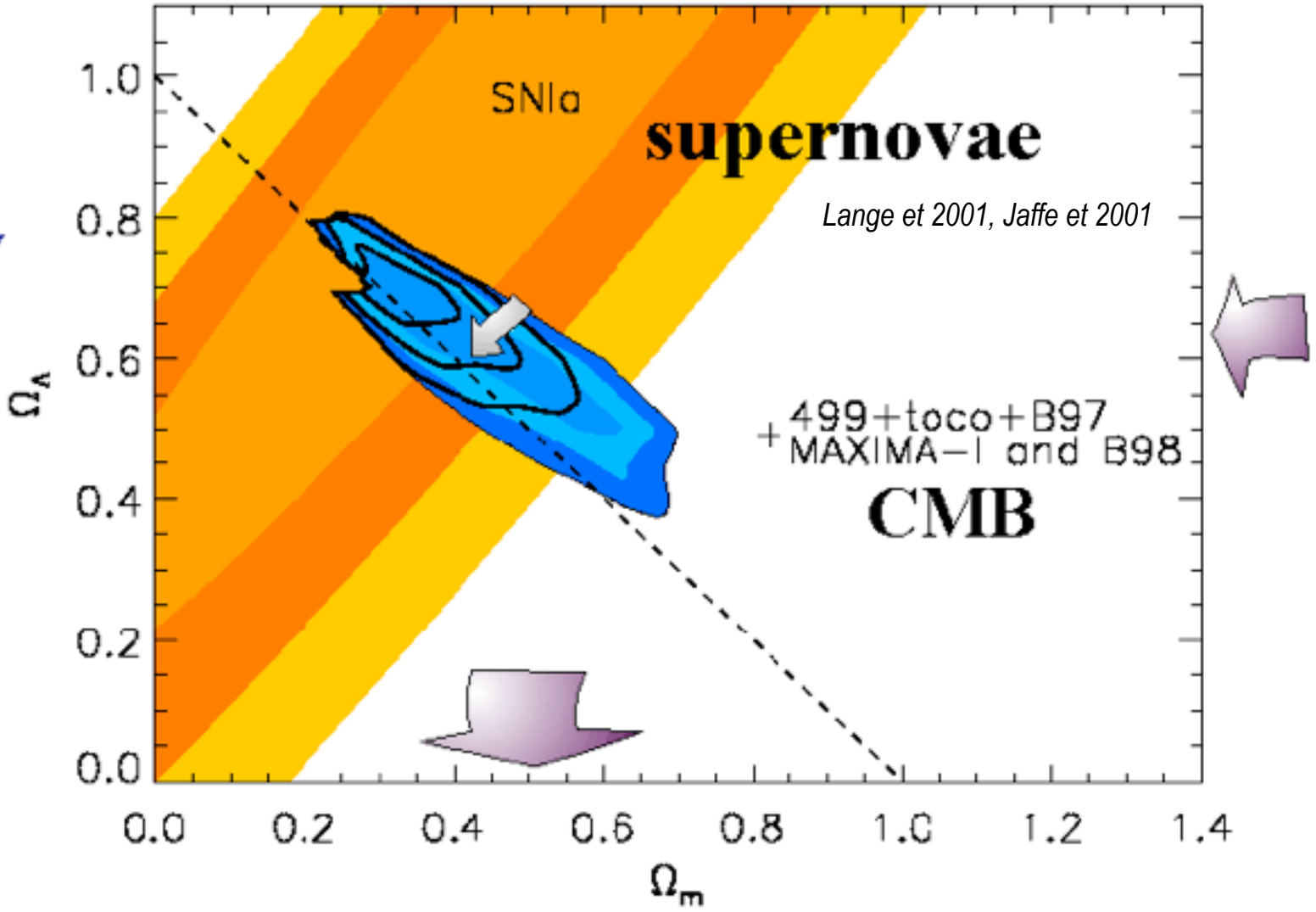
$.96 \pm .06$



⇒evidence for **"dark energy"** aka **the cosmological constant**

BOOM 2000

dark energy



dark matter + baryons

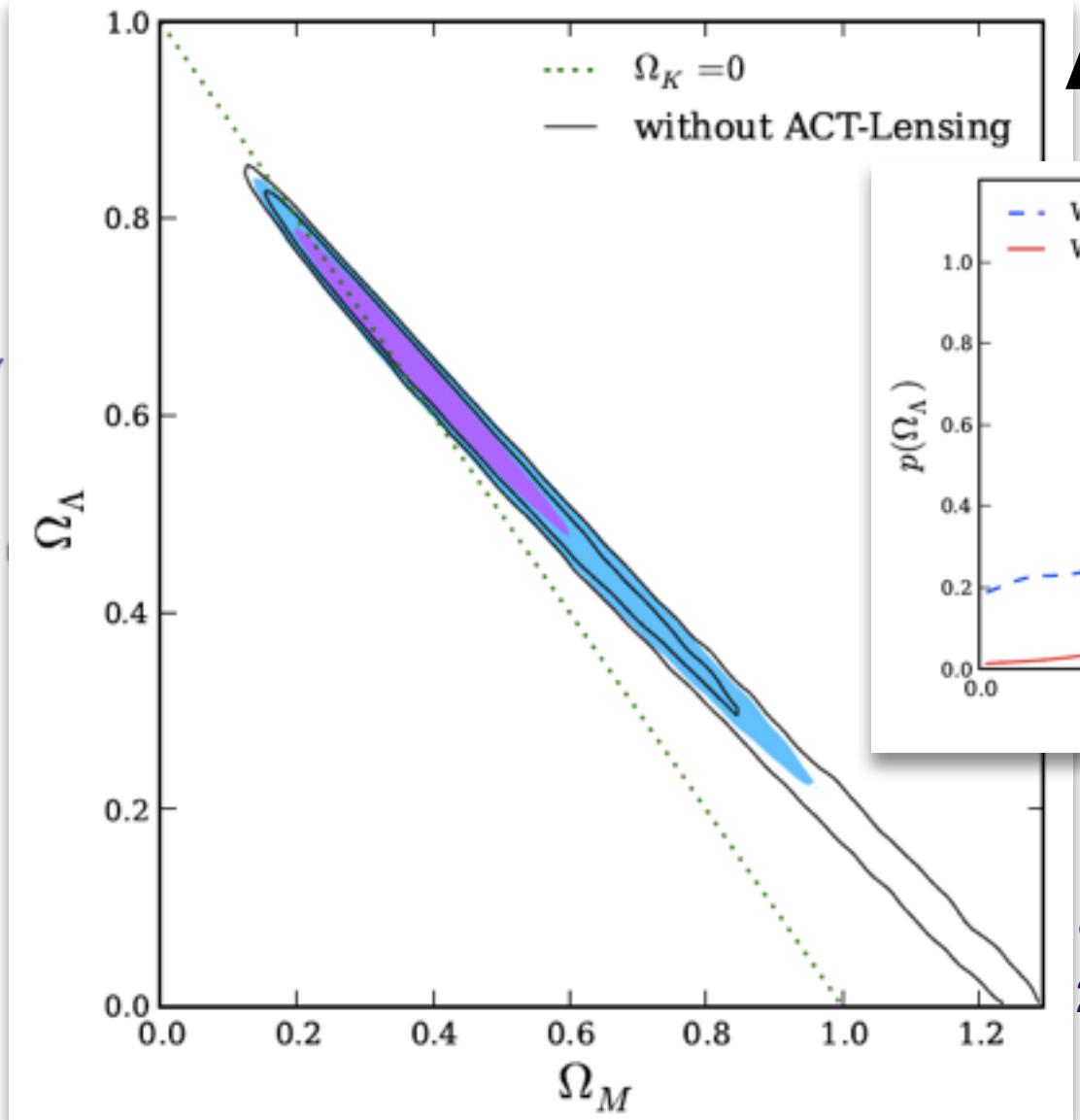
Dark Energy Histories
(SN+WL+BAO+CMB+cls)

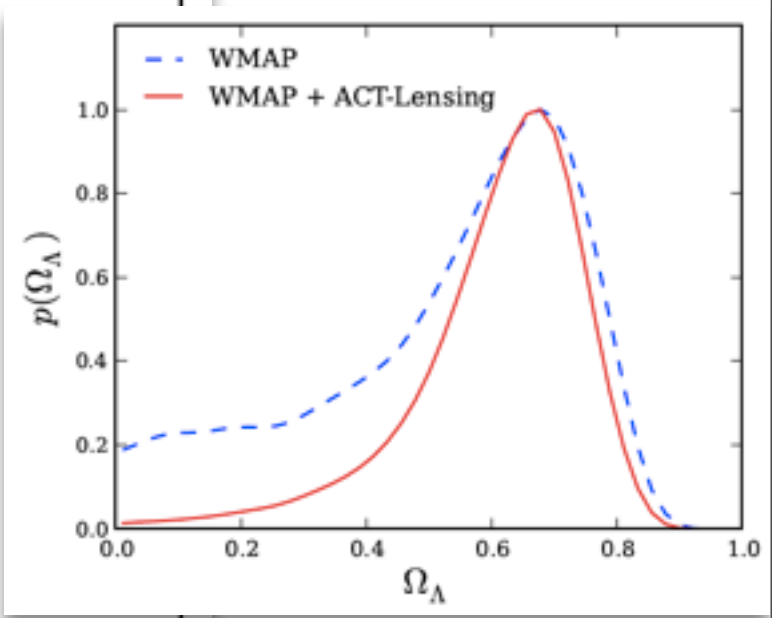
⇒evidence for "dark energy" aka the cosmological constant

ACT 2011

Sherwin et 2011: Λ from CMB alone

dark energy





Dunkley et 2011 cosmic parameters

Ω_Λ=0.736 ±.012

2011: WMAP7+ACT+BAO+H0

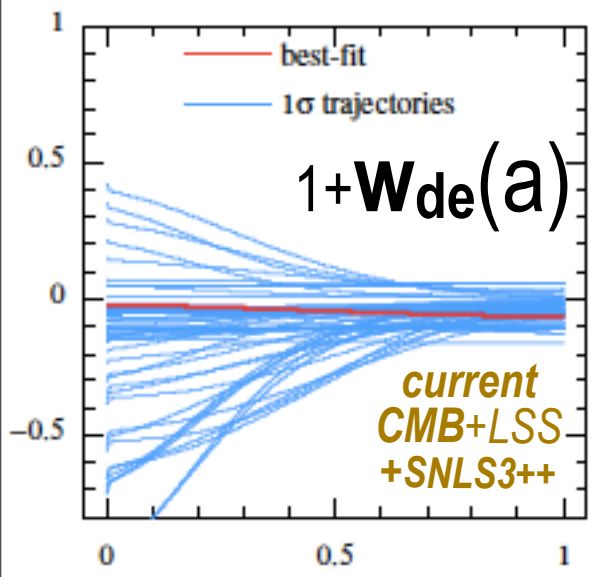
=>± 0.001 (Pext) B+Huang 2011

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

dark matter + baryons

NOW & future DE equation of state trajectories

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



Current Data

CMB: **ACT+WMAP7**, **Acbar** (2009), QUAD (2009), BICEP (2009), **CBI** (2008), **Boomerang**-pol, VSA, MAXIMA

Type Ia Supernova 472: 123 low-z+ 242 SNLS3yr +93 SDSS1yr + 14 HST

HST constraint H0 = 73.8 +-2.4 km/s/Mpc

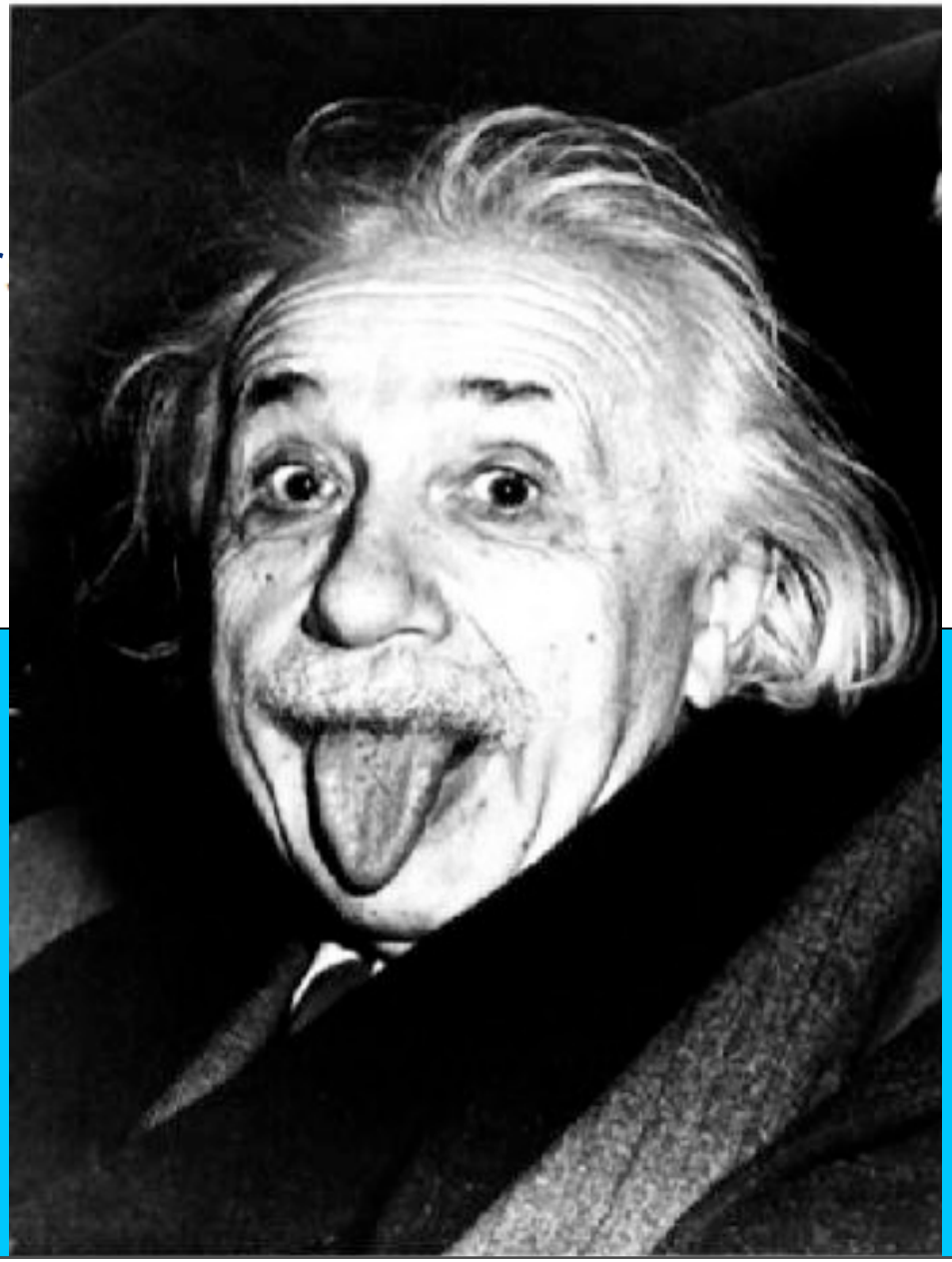
Weak Lensing: COSMOS + CFHTLS-wide + RCS +VIRMOS +GaBoDS

LSS: SDSS-DR7 LRG (2009)

Lya Forest: SDSS

Huang, Bond, Kofman 2010; Bond, Huang 2011

3parameter form paves even wild late-inflaton trajectories



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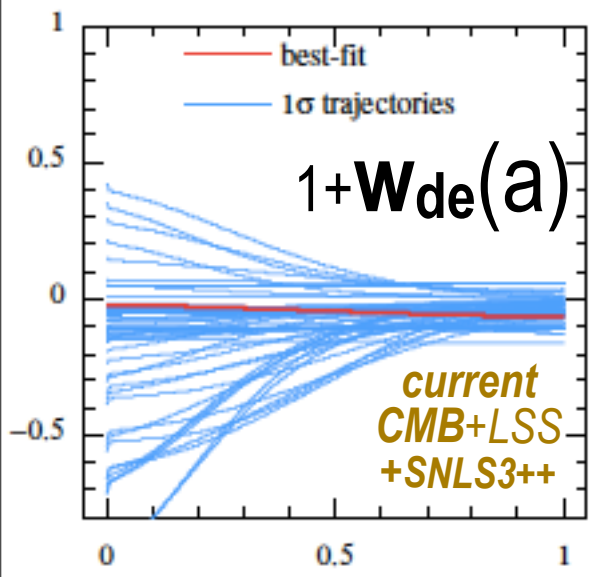

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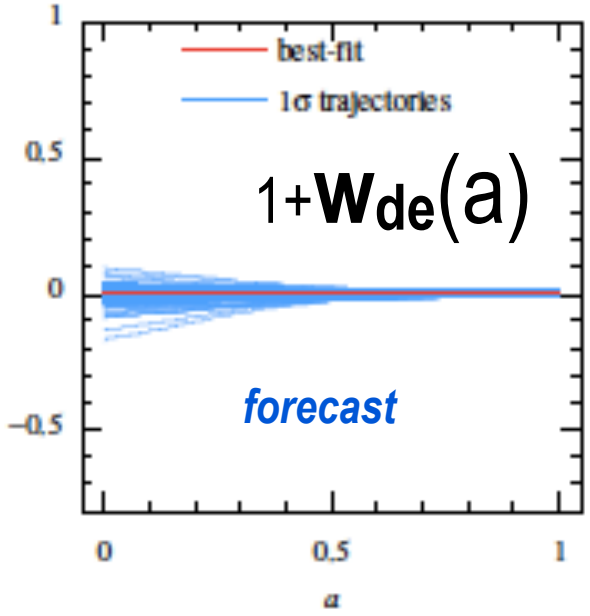


Forecast Data

CMB: Planck2.5yr, LSS: EUCLID spectroscopic redshift survey; 21-cm CHIME BAO survey: EUCLID weak lensing survey

Huang, Bond, Kofman 2010; Bond, Huang 2011

3parameter form paves even wild late-inflaton trajectories

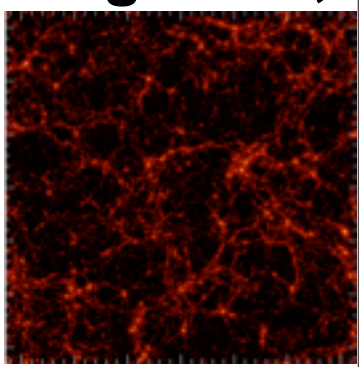
dS/dt 2

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

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 radiation,

... who, what, where,when, why?



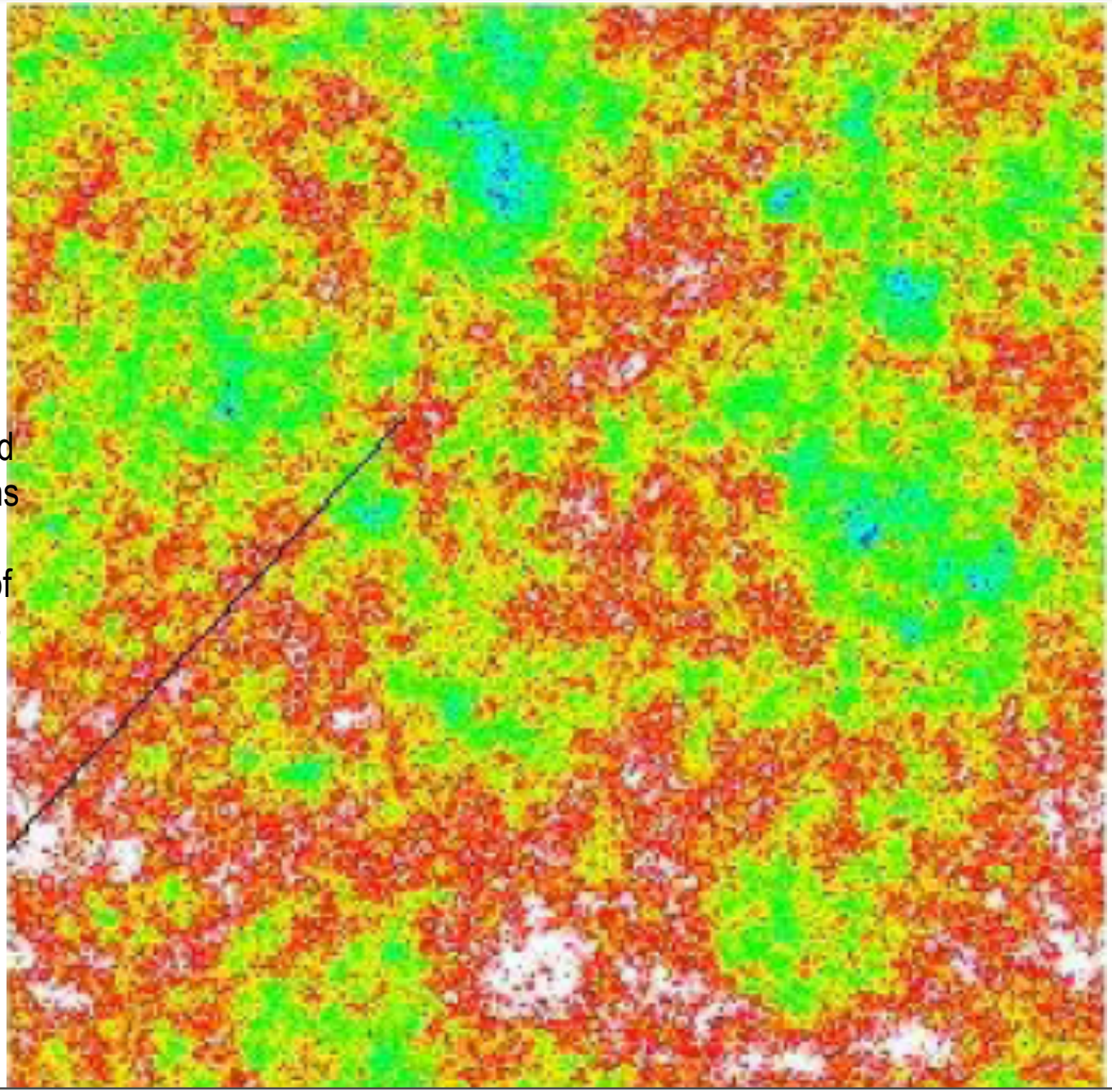
Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)

morphs *into the nonlinear* ***Cosmic Web: clusters, filaments, voids; galaxies*** **(SZ)**

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

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

χ



$\chi(x, \ln a)$

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

evolve from early U vacuum potential and vacuum noise

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

pre-heating patch (~1cm)

10 Gpc

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

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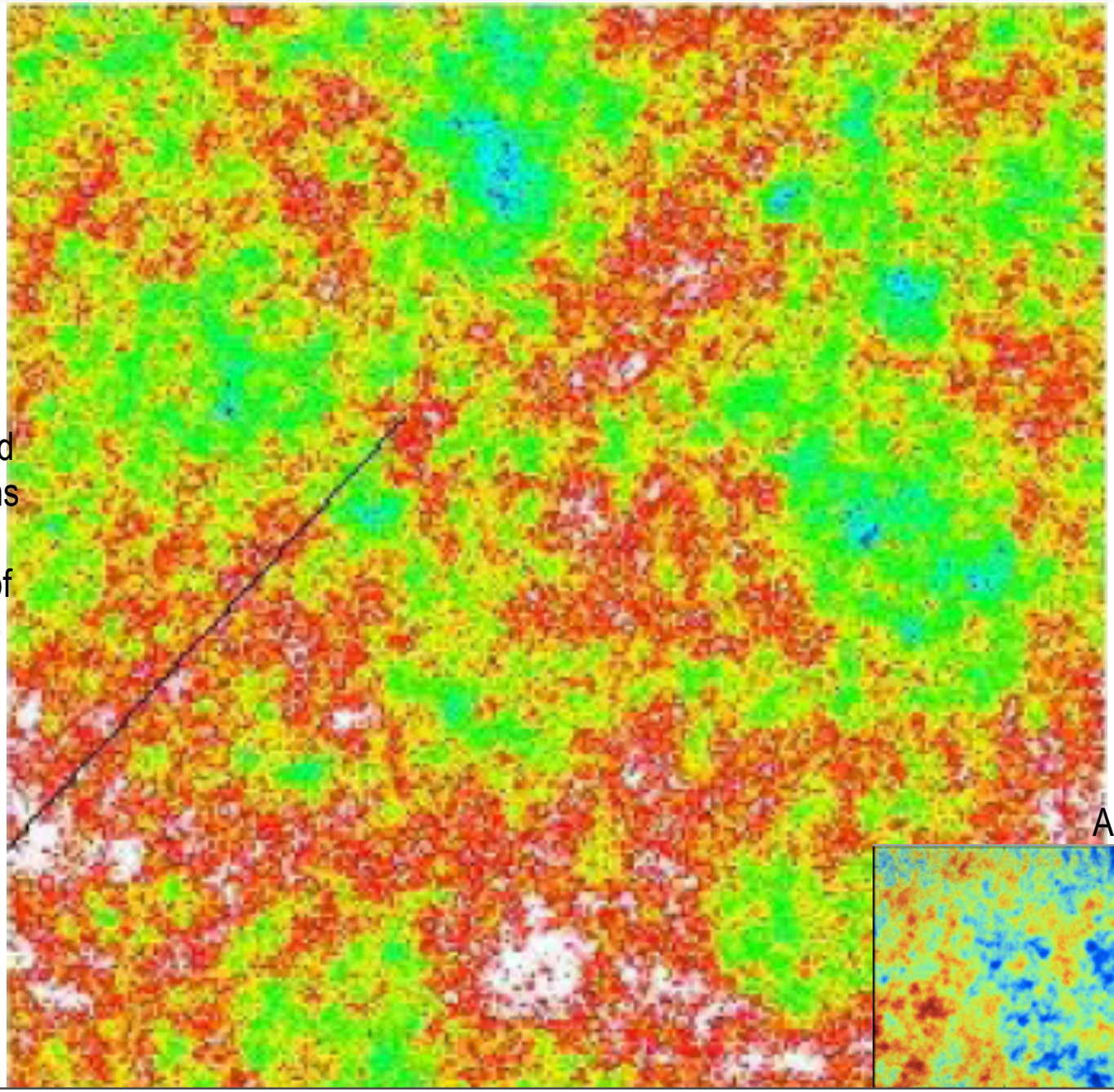

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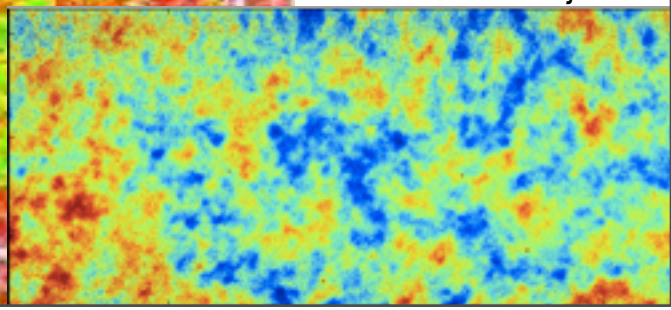
ACT+WMAP7 hajian+10



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

400 Mpc

ΛCDM

WMAP5

gas density

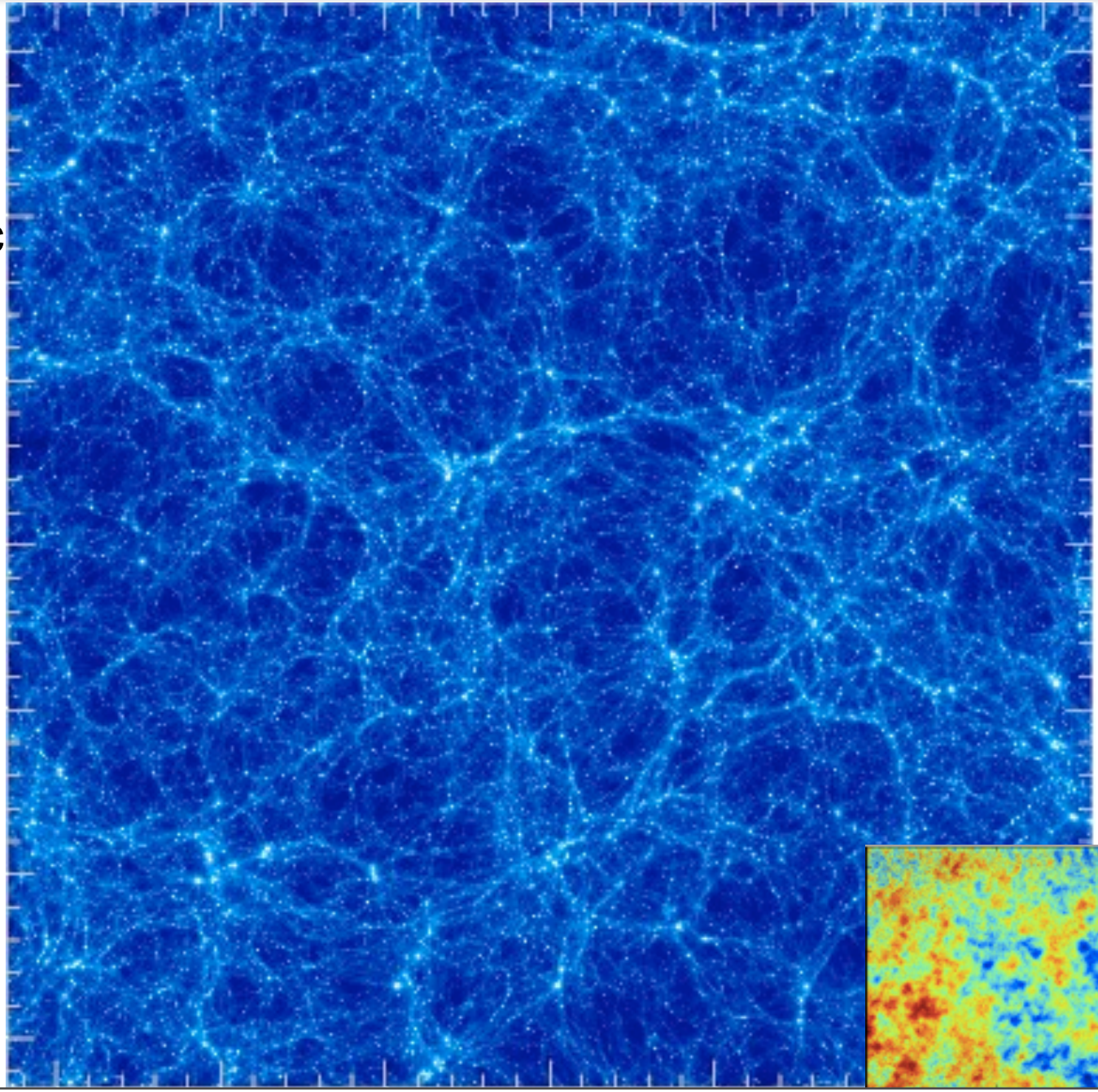
Gadget-3

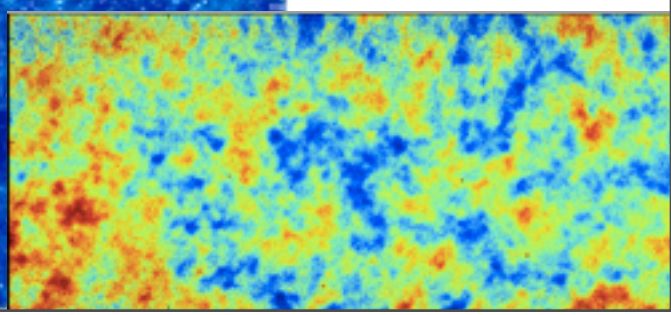
SF+ SN E+ winds +CRs

512^3

BBPSS10

BBPS1,2,3,4





$\rho_g(x,t)$

evolve from early U vacuum potential and vacuum noise

in the presence of late U vacuum potential aka dark energy

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

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

$p_e(x,t)$

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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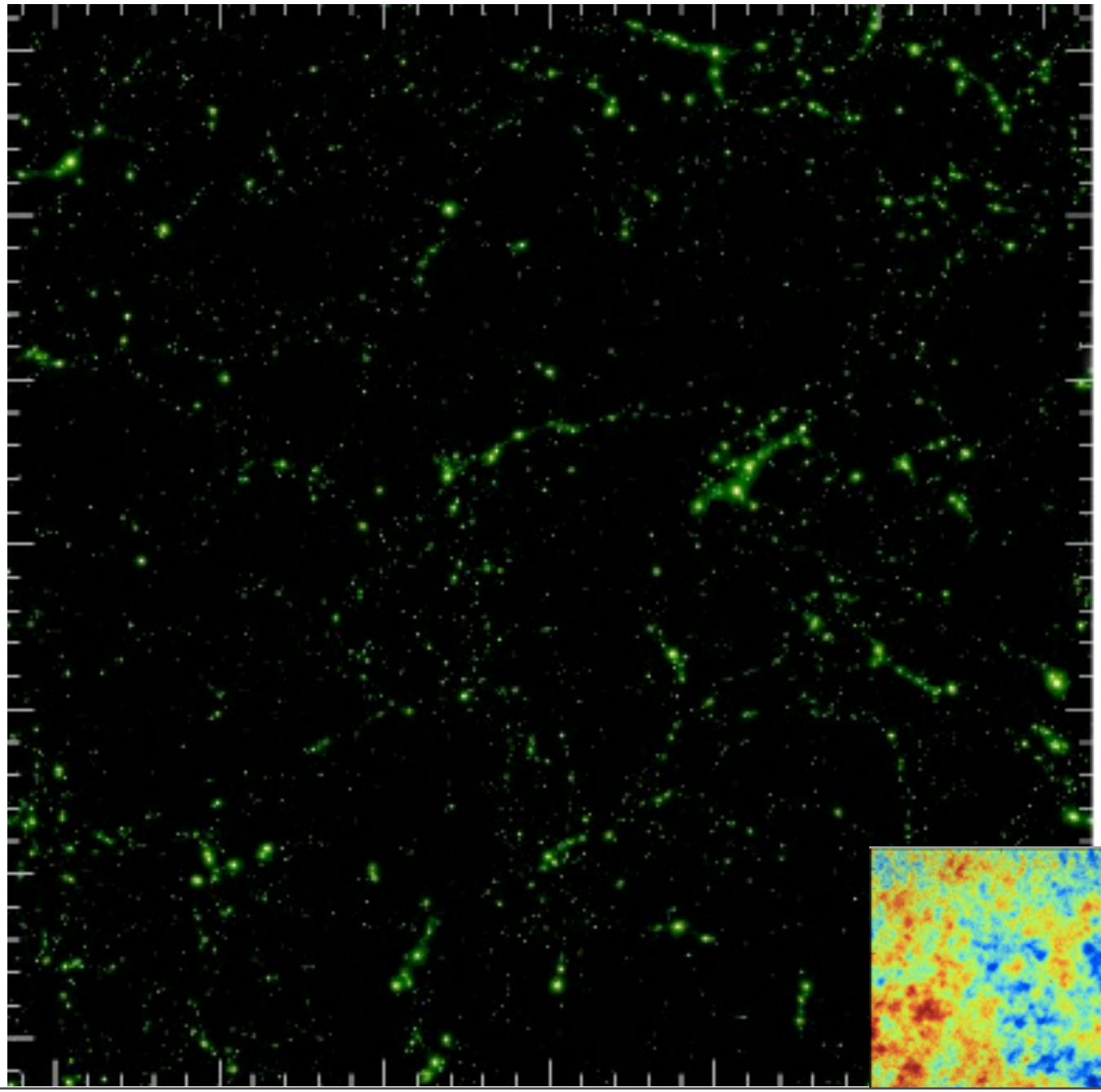
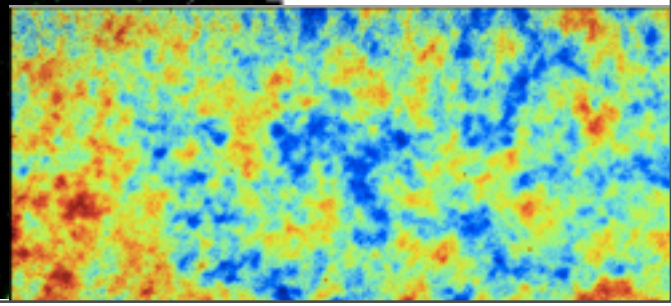
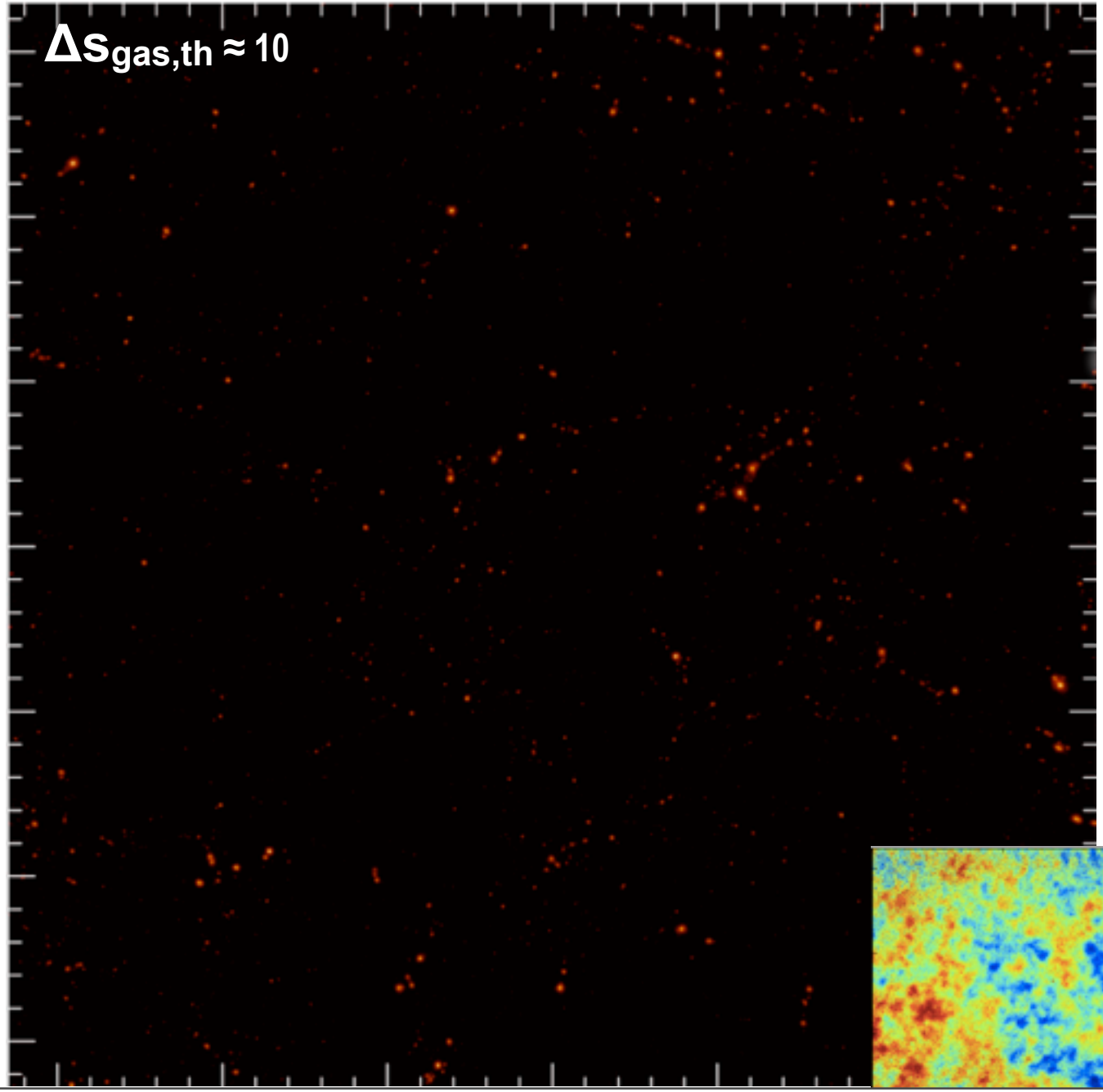




entropy intermittency *in the cosmic web, via gravitation-induced shocks (then E/S-feedback)*

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



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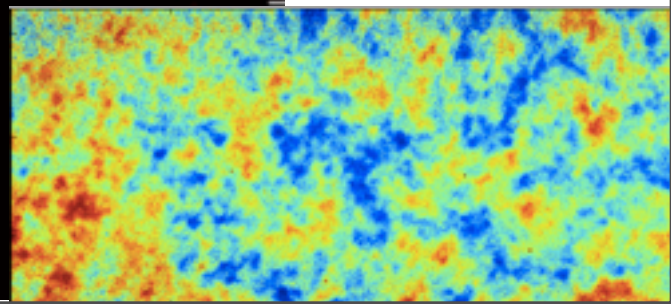

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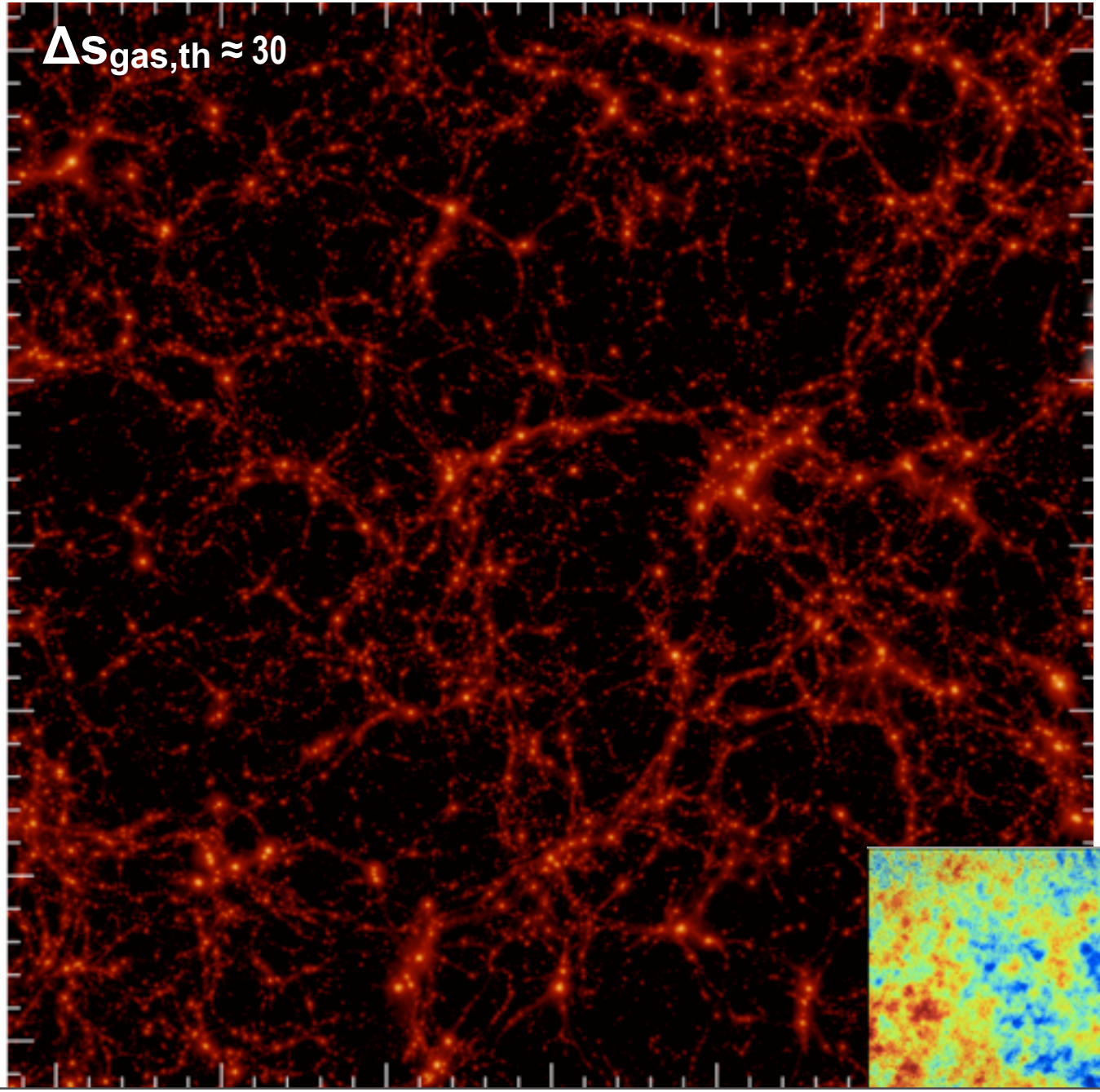

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WMAP5

gas pressure

Gadget-3 SF+ SN E+ winds +CRs

512^3

BBPSS10

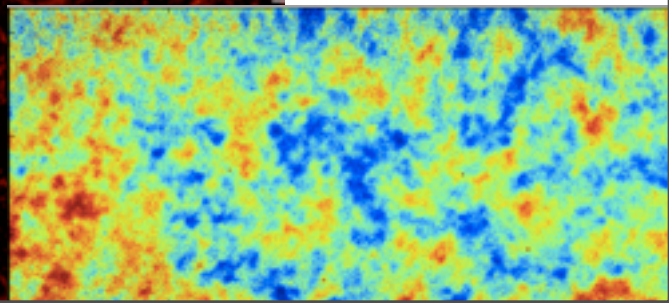
BBPS1,2,3,4

CMB gets entangled in the cosmic web

descending into the real gastrophysics of cosmic weather

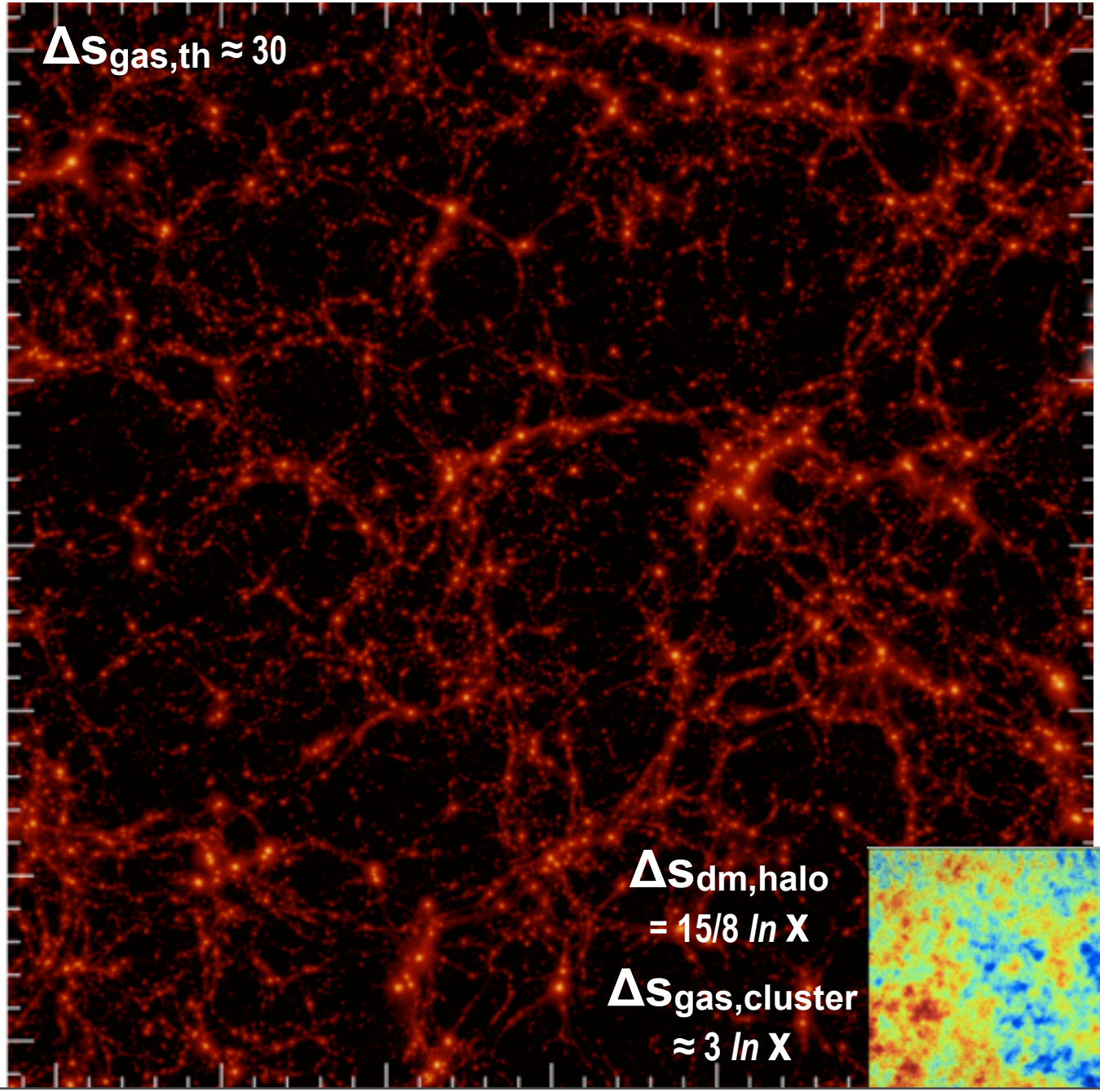
the energetic, turbulent, dissipative, compressive

life of the IGM/ICM/ISM



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

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



400 Mpc

ΛCDM

WMAP5

gas pressure

Gadget-3 SF+ SN E+ winds +CRs

512^3

BBPSS10

BBPS1,2,3,4

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

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

CBI pol to Apr'05 @Chile

53+35 cls (>=40)

CBI2

QUaD @SP

189 +10 cls (>=1000)

Planck09.4

52+ bolometers
+ HEMTs @L2

9 frequencies

WMAP @L2 to 2010

2004 2006 2008 LHC 2011

Bpol @L2

2005 2007 2009

21+26~50 (>=750)

Acbar@SP

~1 blind

AMIBA

6 cls

SPT

1000 bolos

@SPole

>96

OVRO /BIMA

array

38 cls

SZA@Cal

3 cls (z>1), x?

ACT

23+27~50 cls

3000 bolos

3 freqs @Chile

AMI

7+1 cls >=50+25

APEX

~400 bolos@Chile

~25 cls

SCUBA2

12000 bolos

JCMT @Hawaii

SPTpol

ACTpol

ALMA

CCAT@Chile

LMT@Mexico

80s-90s

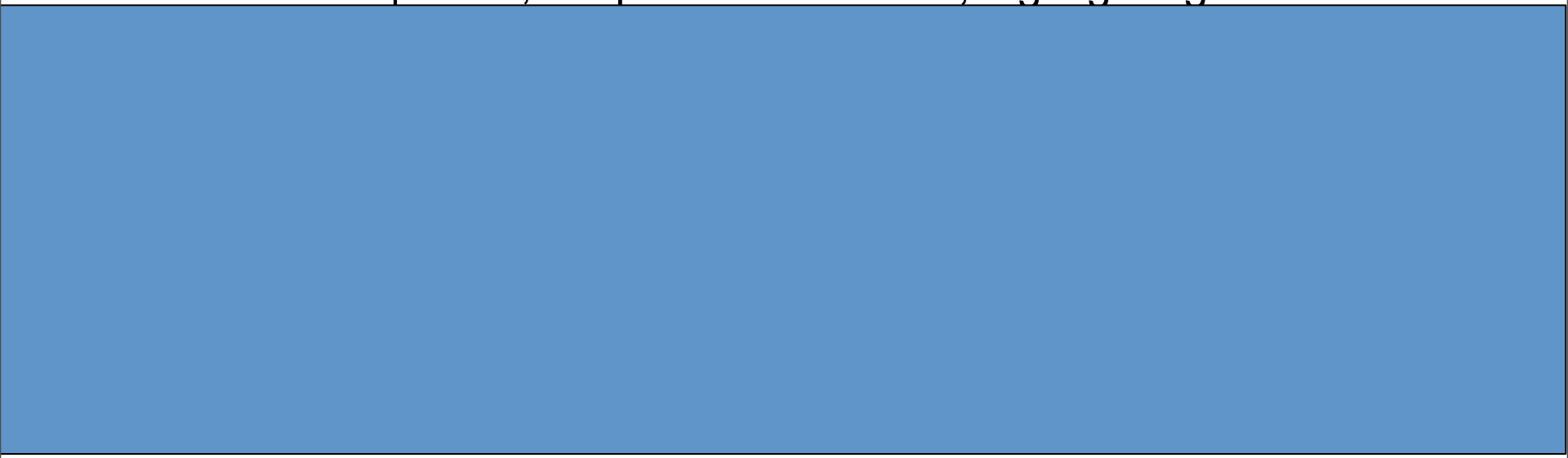
Ryle

OVRO

GBT

4 cls (~25 CLASH)

25 papers & a large fraction of the papers at Planck2011 were unveiled for 10 months & 9-freq T data, + a press conference, highlighting: **HFI & LFI work**



near-future cosmology => PlanckEXT

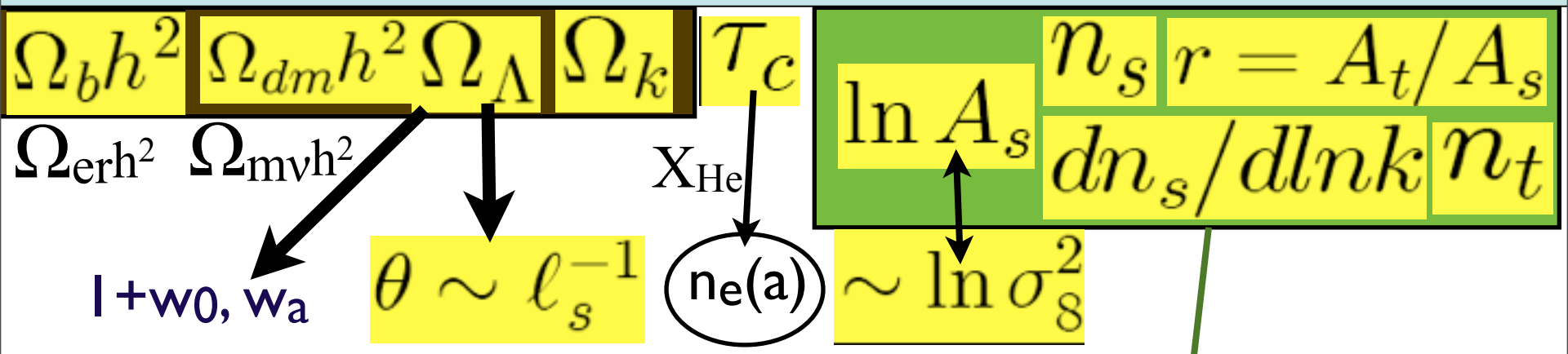
EXT=many observatories & expts enabling the cosmology/astro

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

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**, **CCAT**, eRosita, PanStarrs, DES, HSC, LSST, ***CHIME***, *EUCLID, ...* $\subset$ **EXT**

Standard Parameters of Cosmic Structure Formation



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

(partially) blind cf. informed "theory" priors

*ln***Power$_s$**~*ln***25x10^{-10} ± 0.03** Dunkley+ 2010 ACT+WMAP7

n_s = 0.963 ± 0.011 (ACT+WMAP+BAO+H0)

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

r < 0.19 (95% CL, ACT+WMAP+BAO+H0)

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

Inflation Histories
(CMBall+LSS+SN+WL)

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

h_{+x} gravitons generated as zero point fluctuations during early universe inflation induce CMB (B + E) polarization

how much is model-dependent & tied to the energy scale V of inflation

r=GW power/scalar-curvature power $\approx 0.008 V/(10^{16}\text{Gev})^4$

inflation consistency

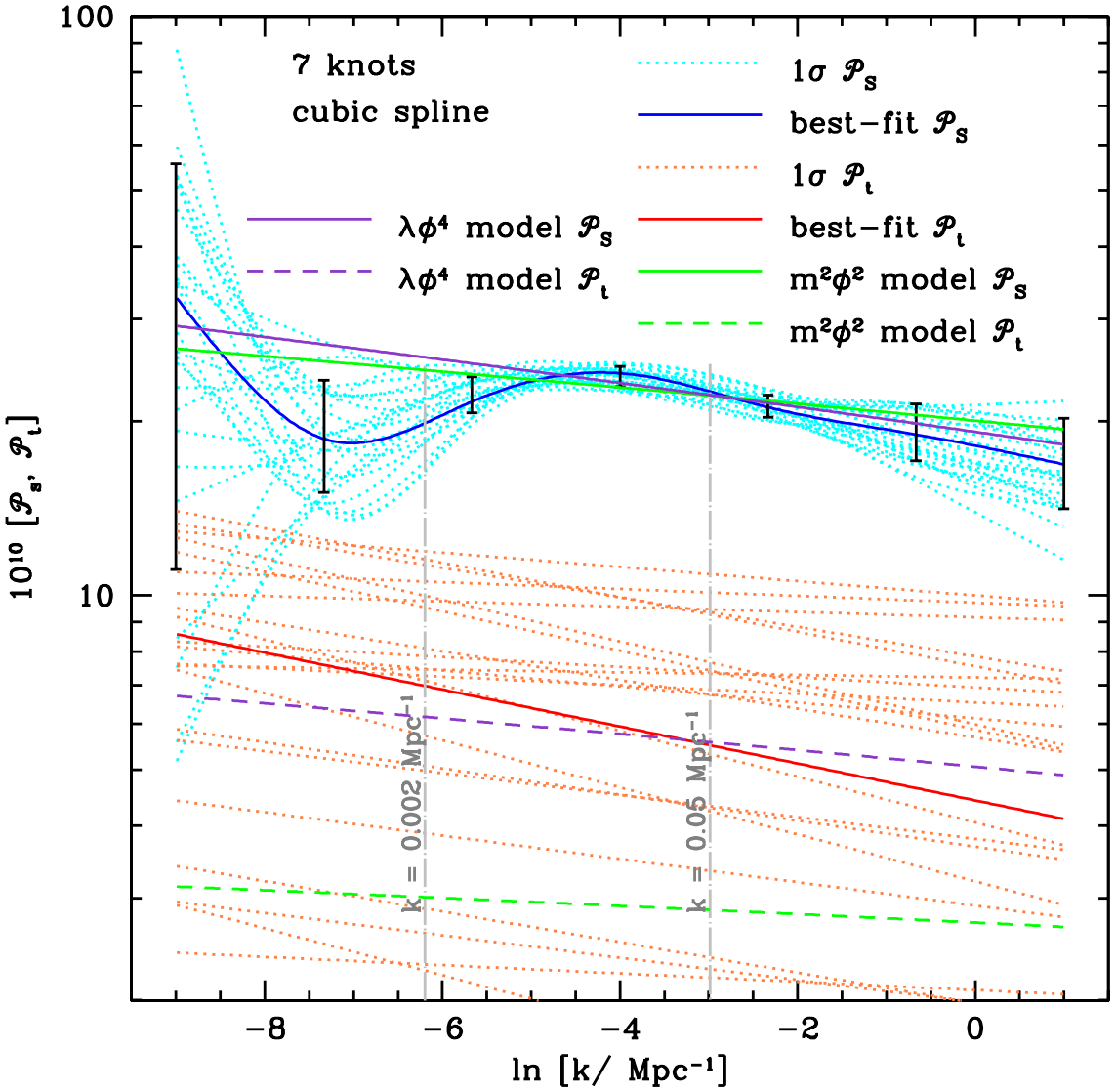
$-n_t \approx r/8 \approx 2\varepsilon(k)$

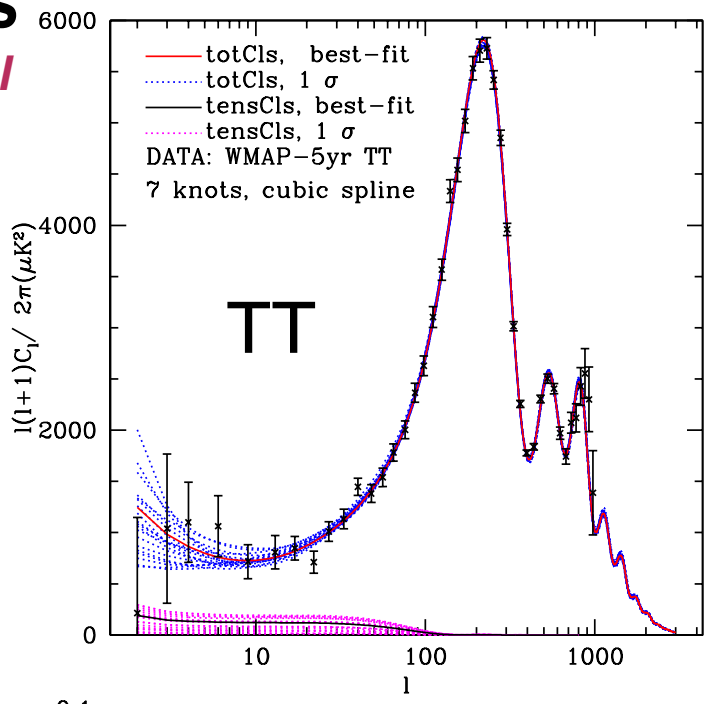
$1-n_s \approx 2\varepsilon + d\ln\varepsilon/d\ln Ha$

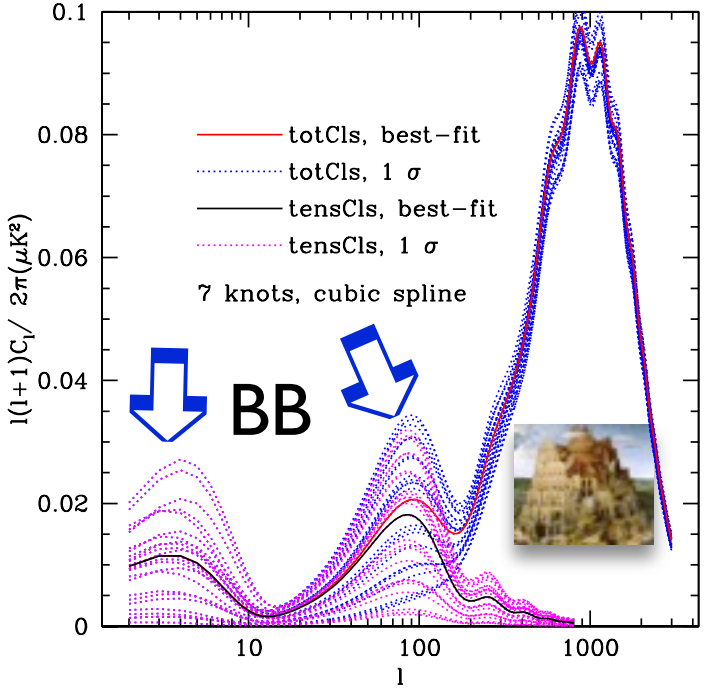
$(1+W_t) = -\, d\ln\rho_t / d\ln a^3 = 2/3\, \varepsilon$

compress data onto non-top-hat k-modes

partially-blind scalar ln-power trajecteries & usual r-n_t tensor - no consistency relation. Nov09 data







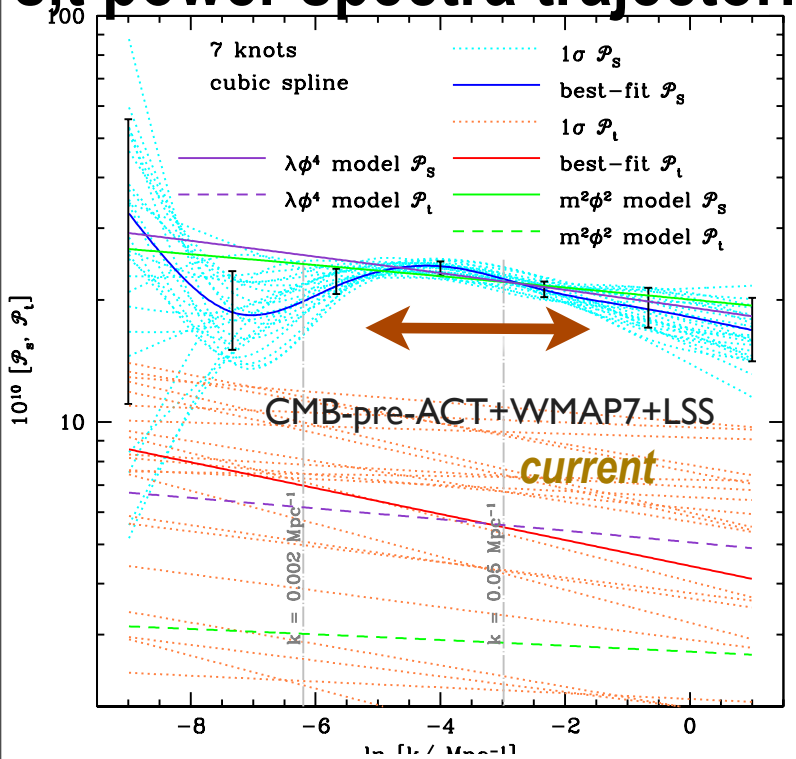
Inflation Histories
(CMBall+LSS+SN+WL)

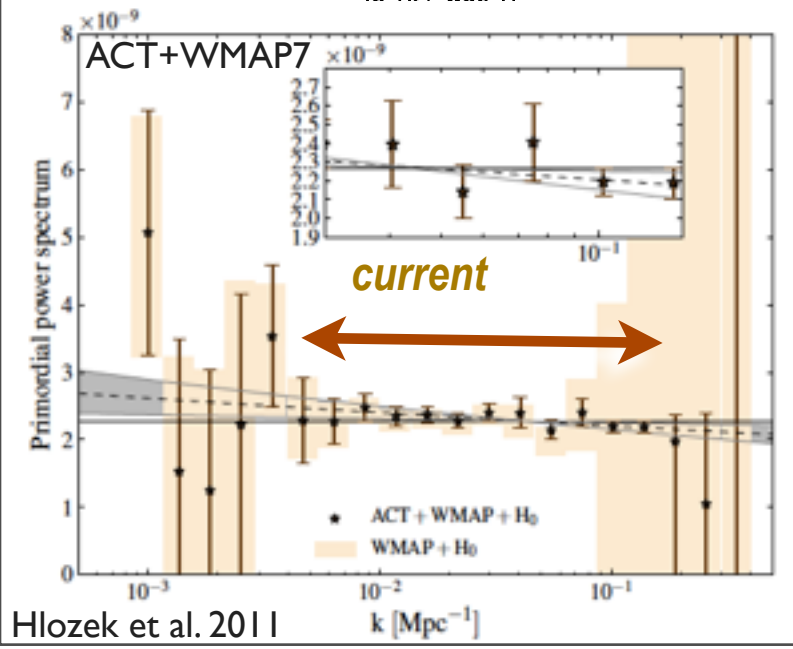
Bond, Contaldi, Huang, Kofman, Vaudrevange 2011

s,t power spectra trajectories: compress data onto non-top-hat k-modes

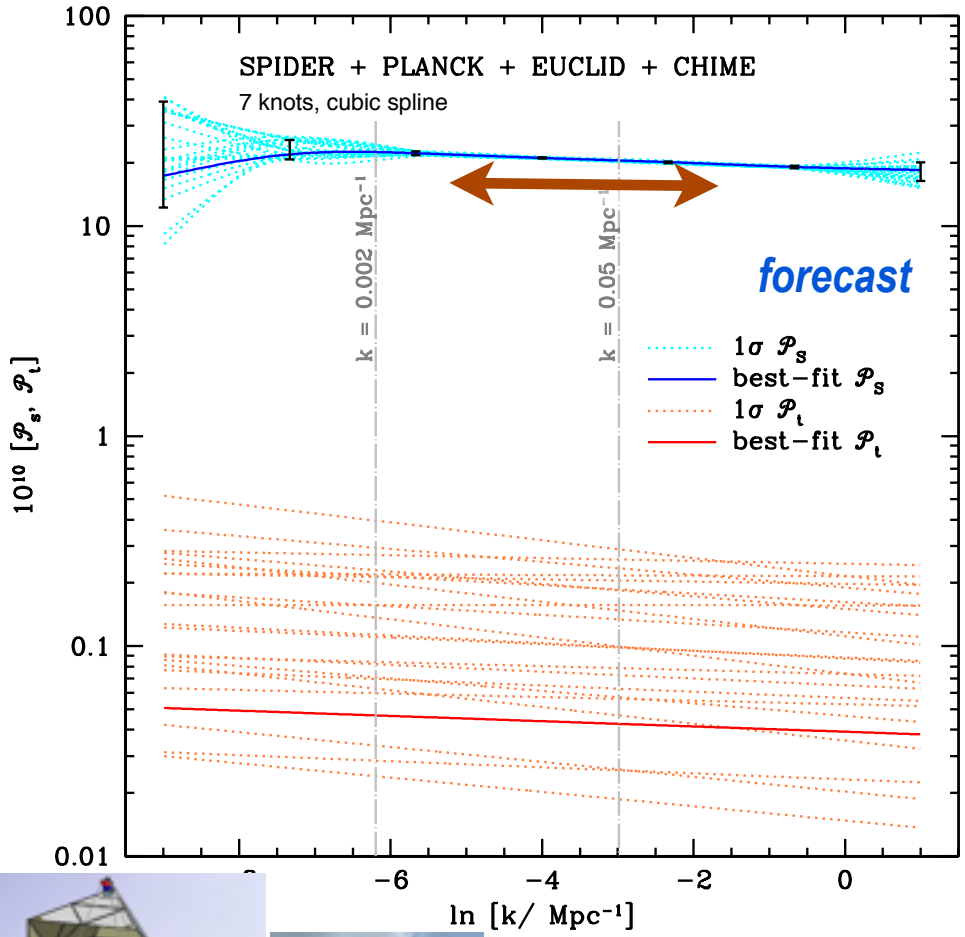
Bond, Contaldi, Huang, Kofman, Vaudrevange 2011

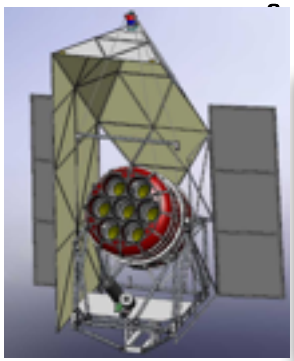
Spider-24days + Planck-2.5yr + ... 7 knot $\ln P_S$ +r-n_t forecast for r=0 (+ fgnds)

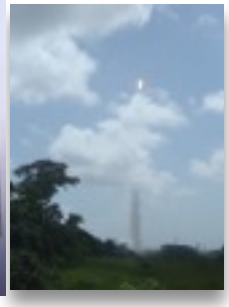


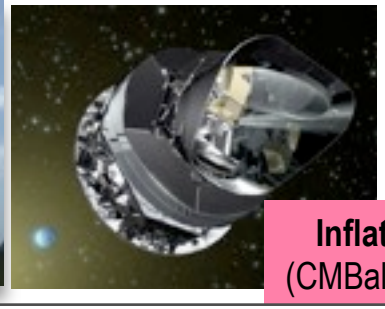


Hlozek et al. 2011

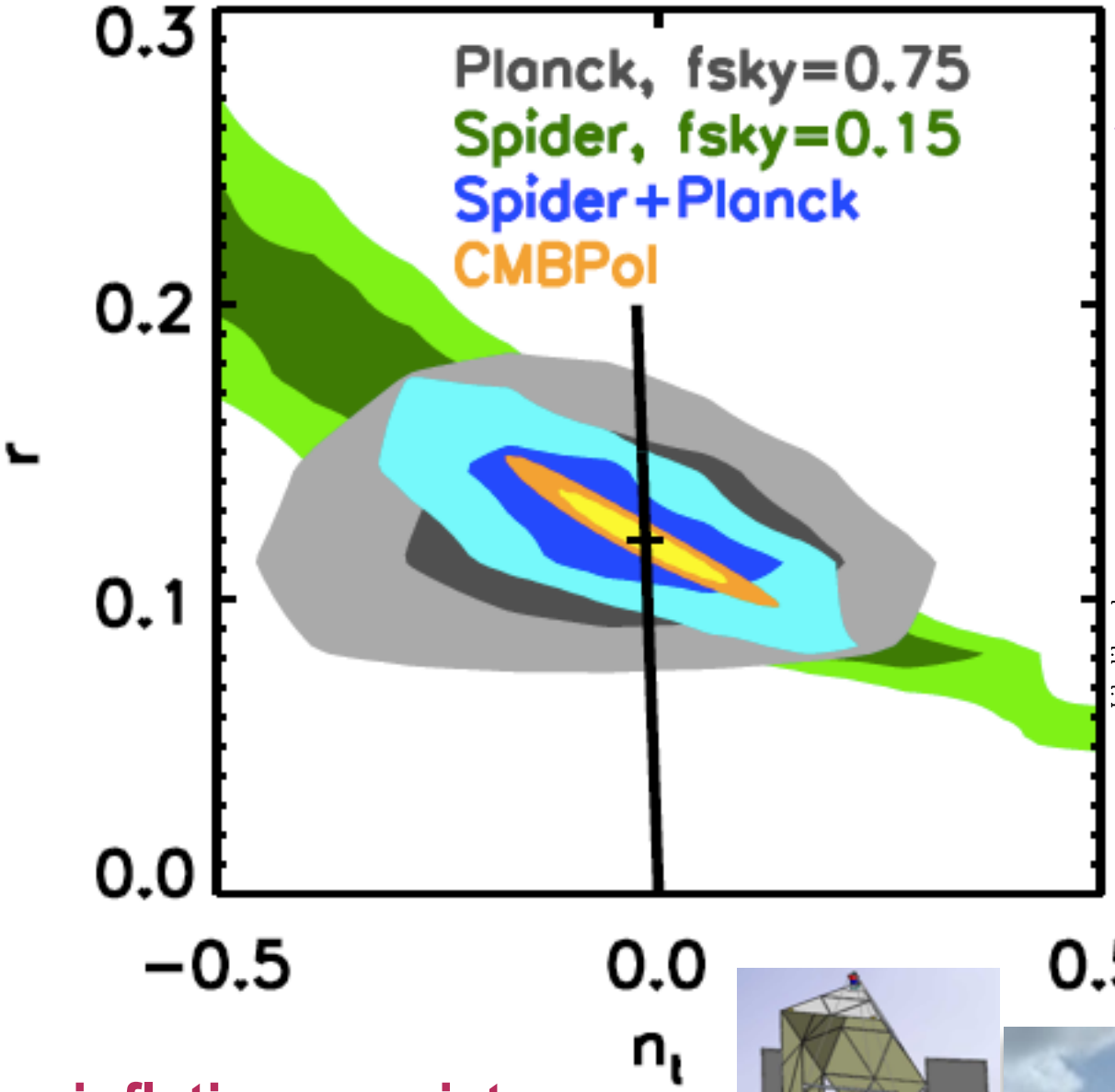








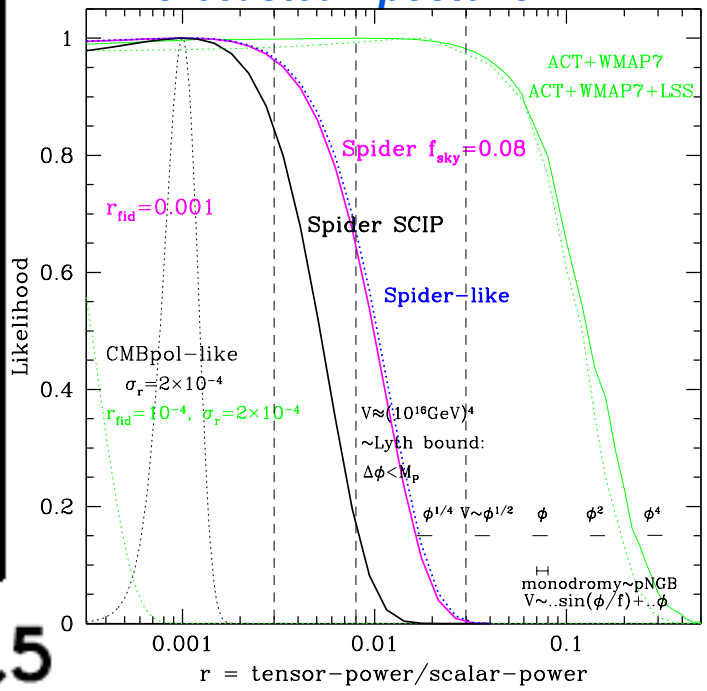
Inflation Histories
(CMBall+LSS+SN+WL)



Farhang, Bond, Dore, Netterfield 2011

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

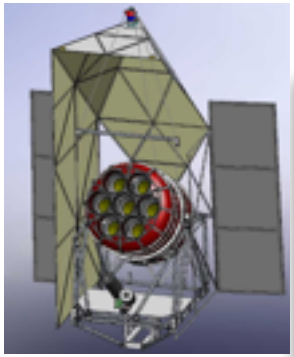
forecasted r-posterior

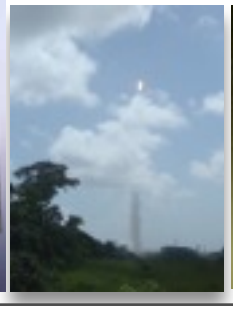


inflation consistency

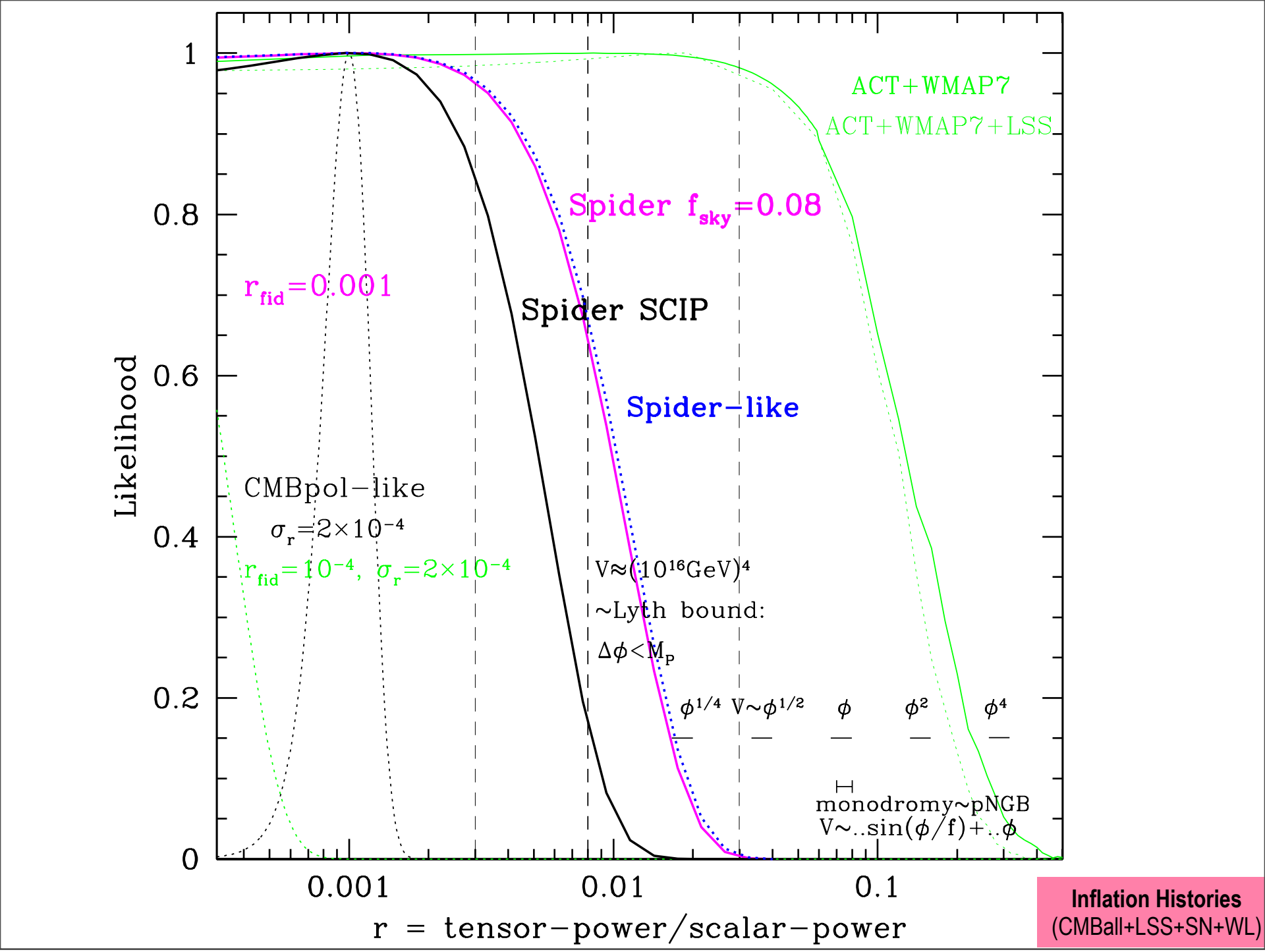
$-n_t \approx r/8 \approx 2\varepsilon(k)$

$1-n_s \approx 2\varepsilon + d\ln\varepsilon/d\ln Ha$

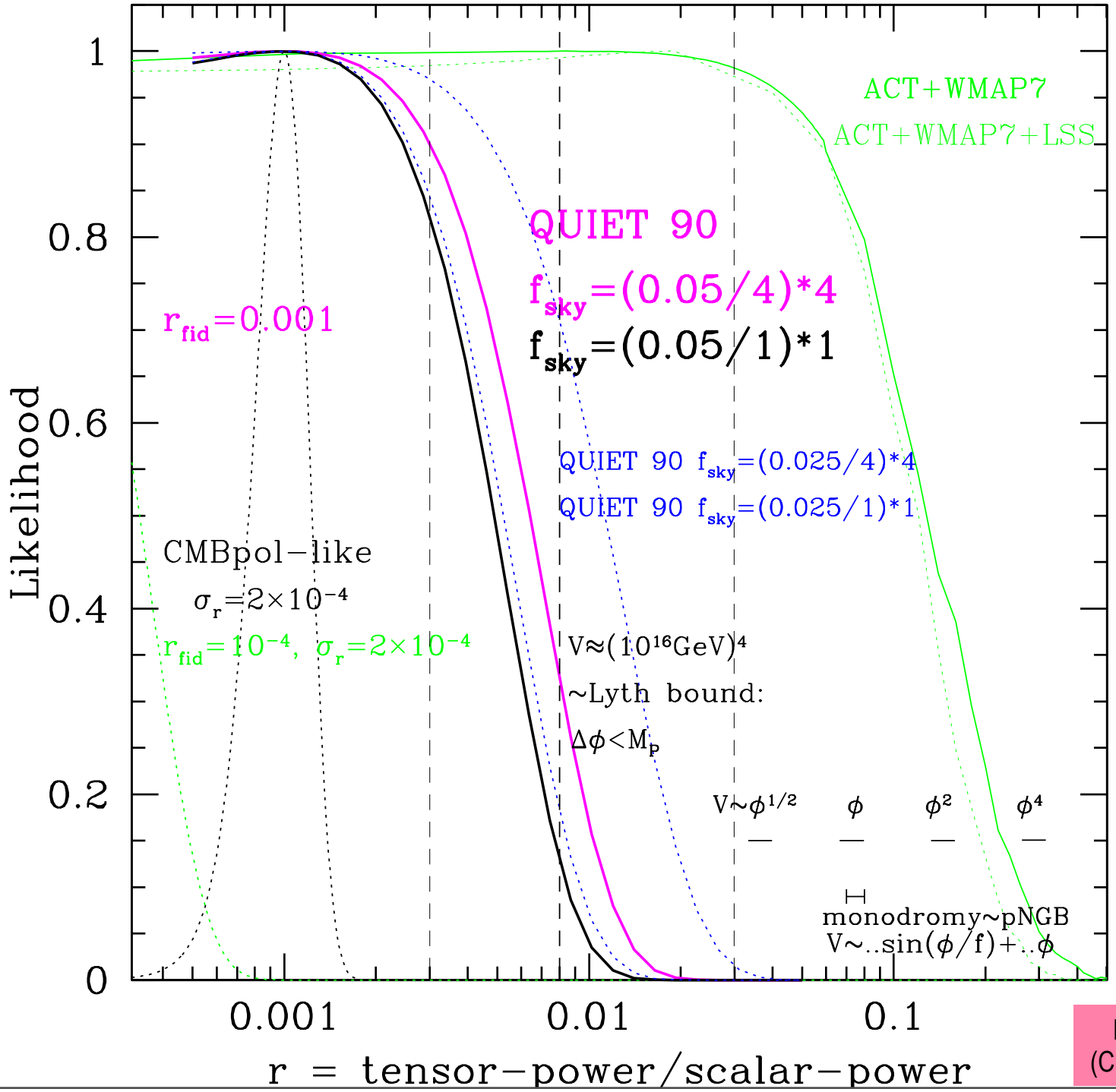




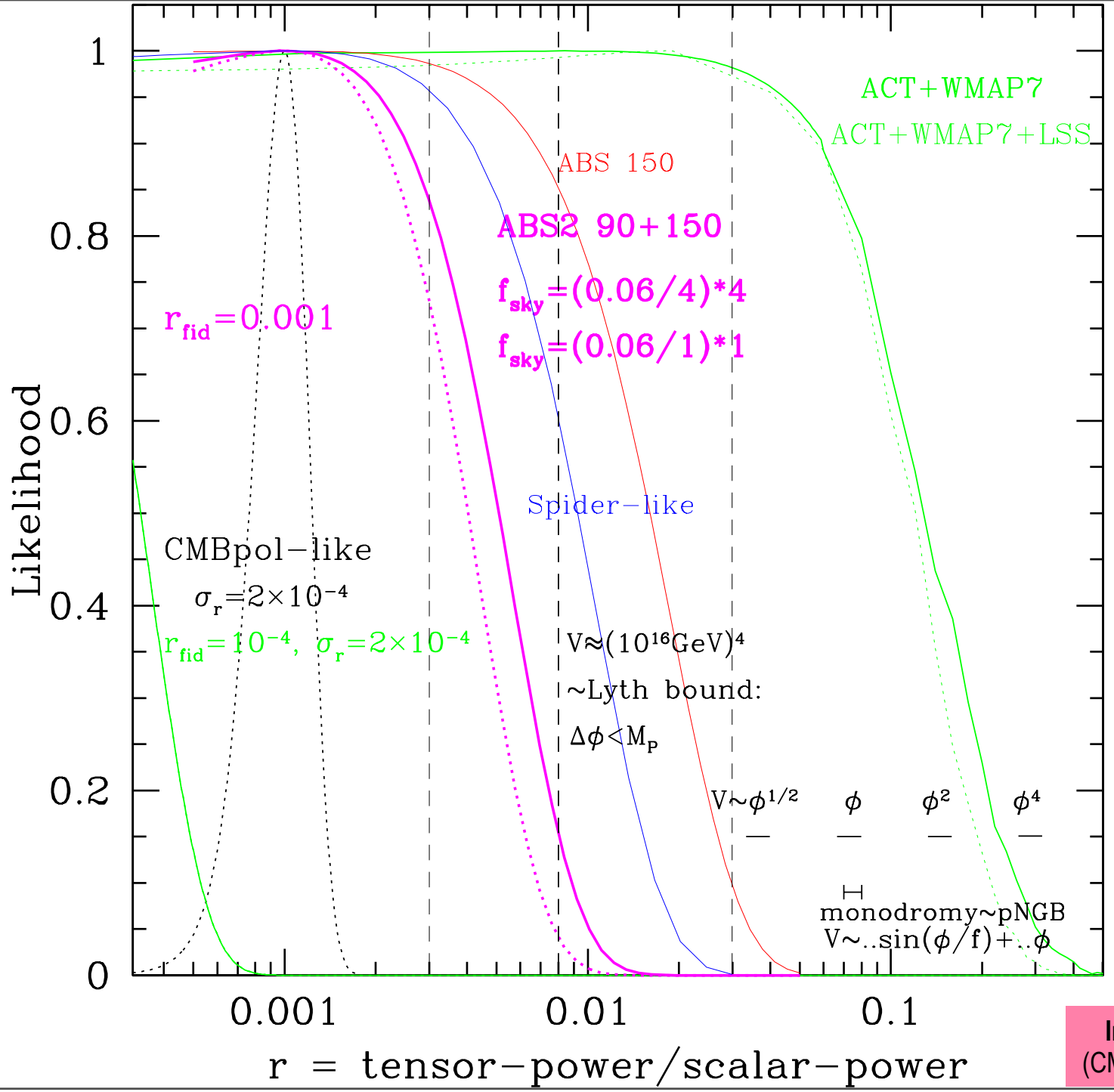
Inflation Histories
(CMBall+LSS+SN+WL)



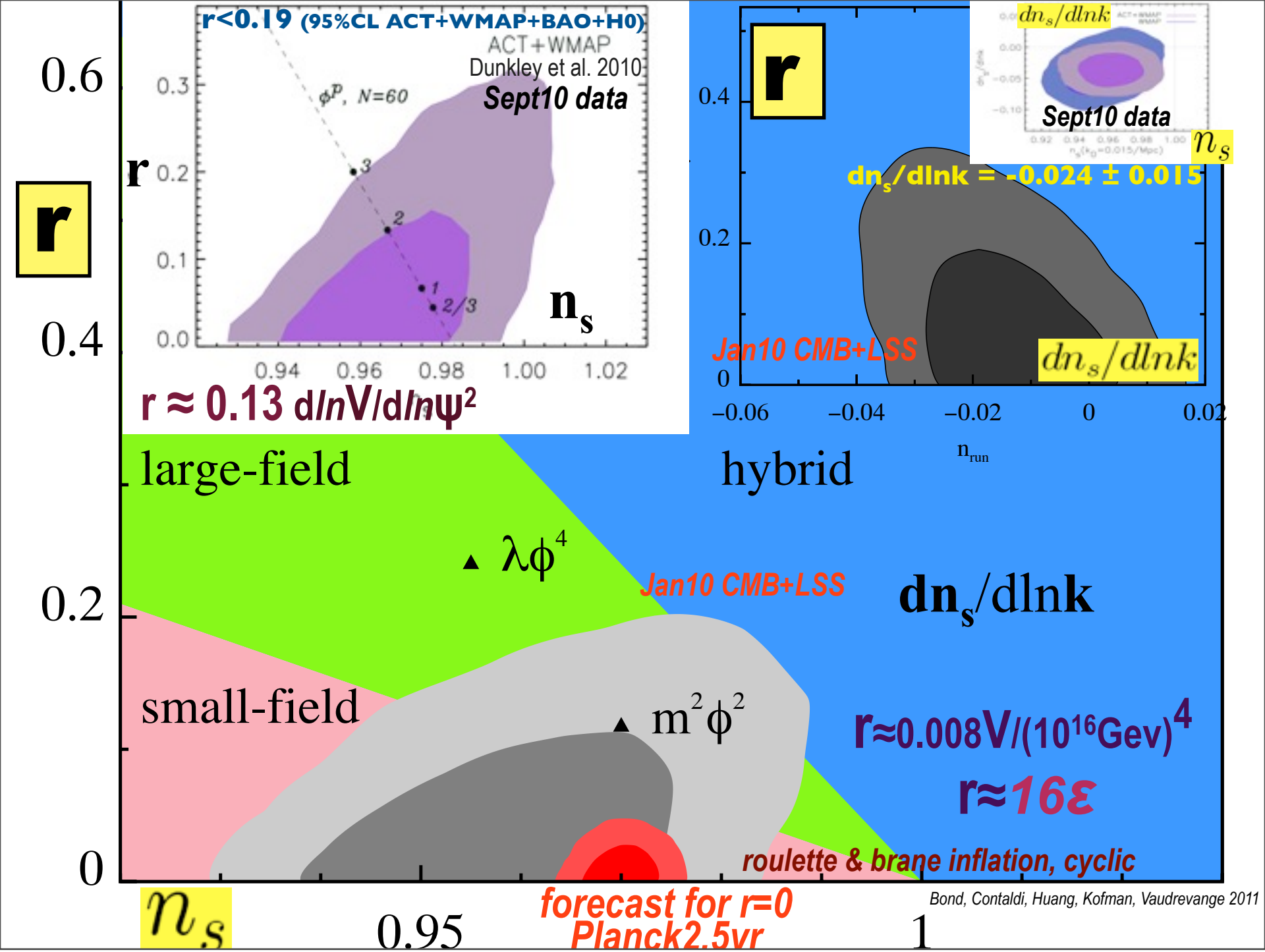
Inflation Histories
(CMBall+LSS+SN+WL)



Inflation Histories
(CMBall+LSS+SN+WL)



Inflation Histories
(CMBall+LSS+SN+WL)


r<0.19 (95%CL ACT+WMAP+BAO+H0)
ACT+WMAP
Dunkley et al. 2010
Sept10 data
ϕ^p, N=60
r
n_s
r ≈ 0.13 d*ln*V/d*ln*ψ²
r
Sept10 data
$dn_s/dlnk$
n_s
$dn_s/dlnk$ = -0.024 ± 0.015
Jan10 CMB+LSS
$dn_s/dlnk$
n_{run}
hybrid
large-field
$\lambda\phi^4$
Jan10 CMB+LSS
$dn_s/dlnk$
small-field
$m^2\phi^2$
r≈0.008V/(10¹⁶Gev)⁴
r≈16ε
roulette & brane inflation, cyclic
forecast for r=0
Planck2.5yr
Bond, Contaldi, Huang, Kofman, Vaudrevange 2011
0.6
0.4
0.2
0
0.95
1

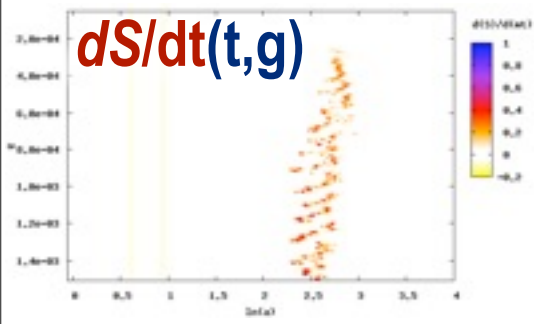
dS/dt 1

how (most of) the entropy in matter *(GUT plasma/quark soup)* was generated *(a shock-in-time)*

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

.. role of *decaying particles, 1st order phase transitions?*

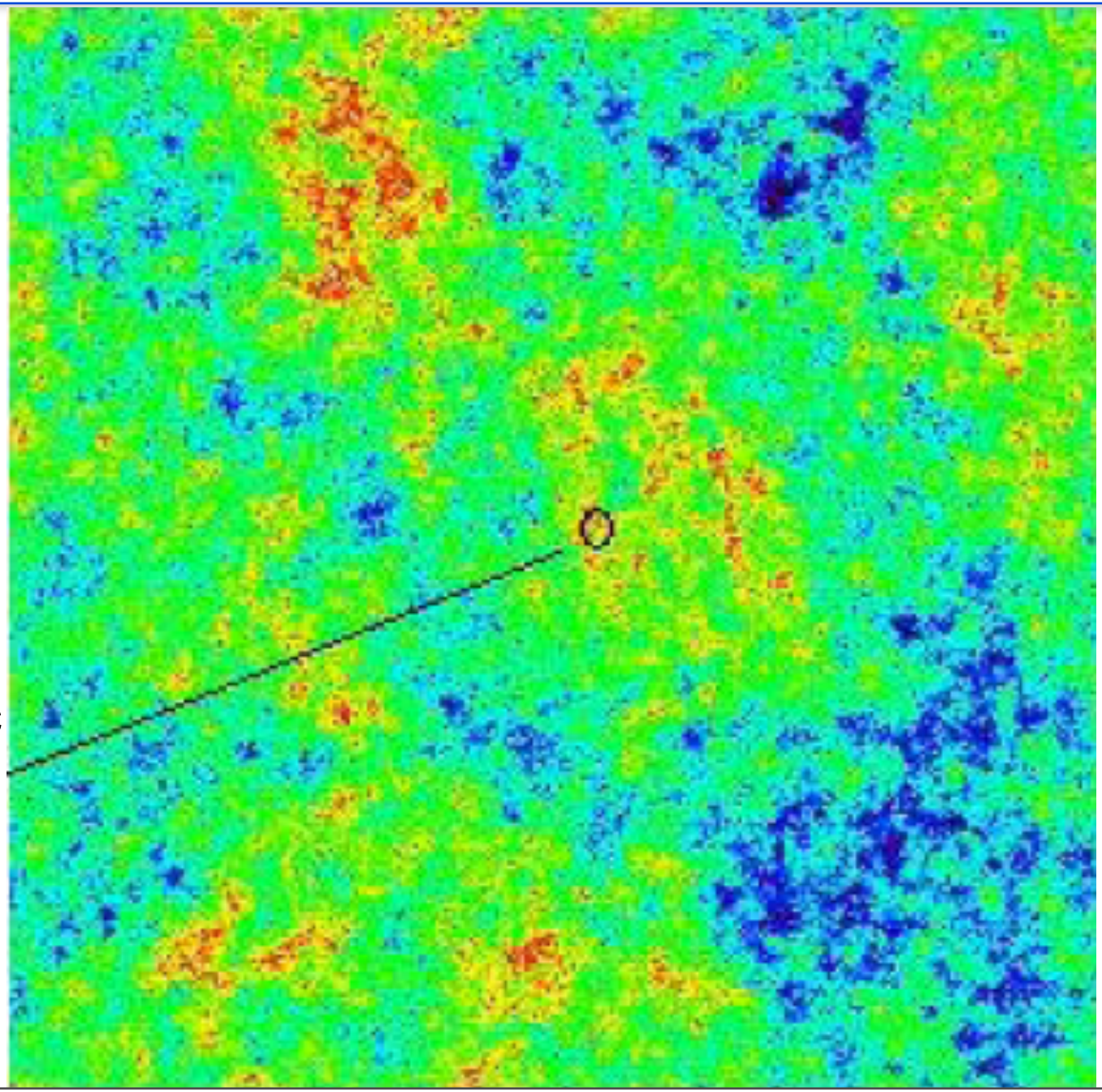
exactly who, what, where, when, why?



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

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

χ



ln**a(x,**ln**H)**

patterns in the quantum jitter evolve under gravity

(& gas dynamics)

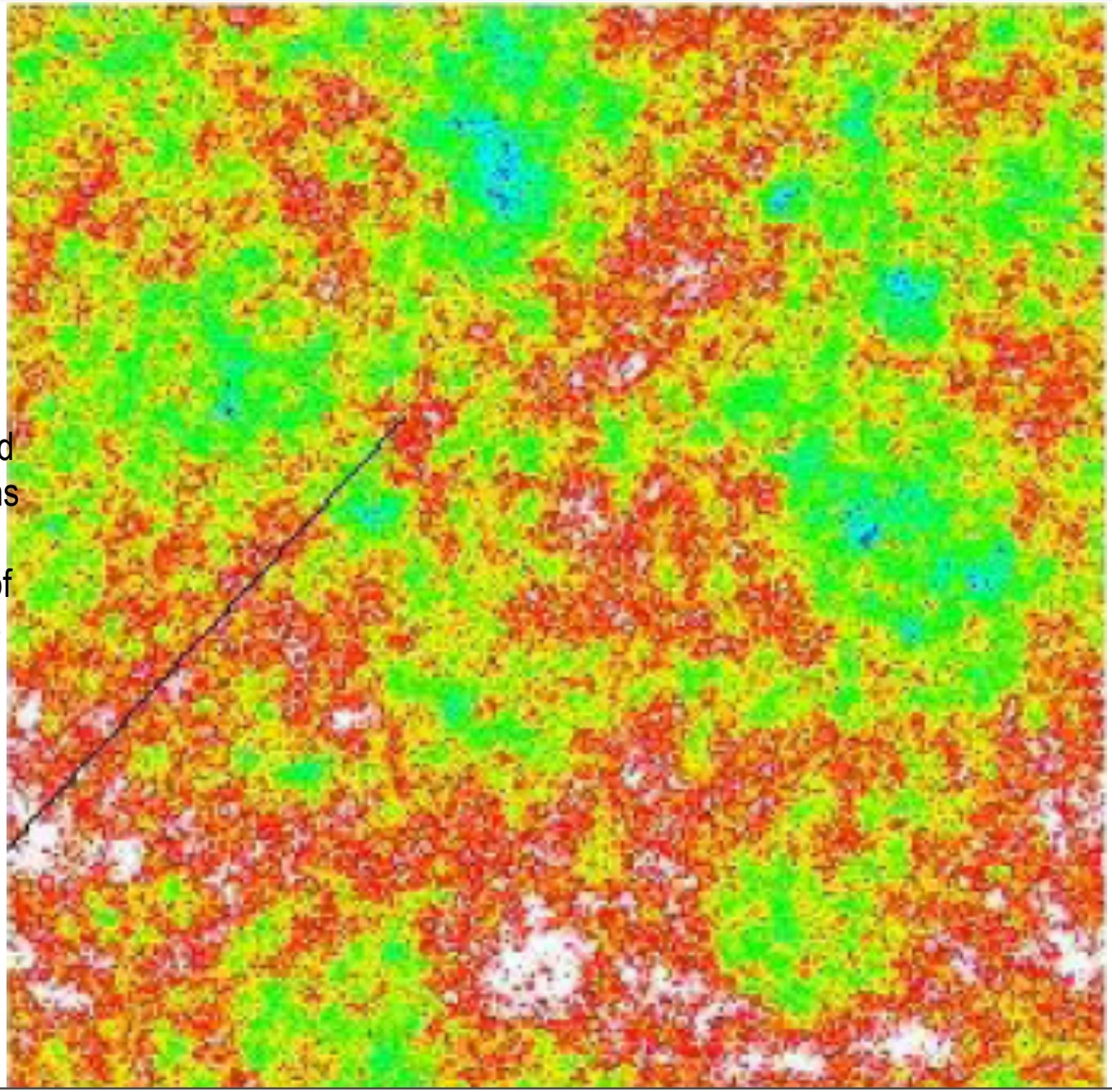
current Hubble patch ~10 Gpc

speed limit horizon

1000 Gpc

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

χ



$\chi(x, \ln a)$

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

evolve from early U vacuum potential and vacuum noise

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

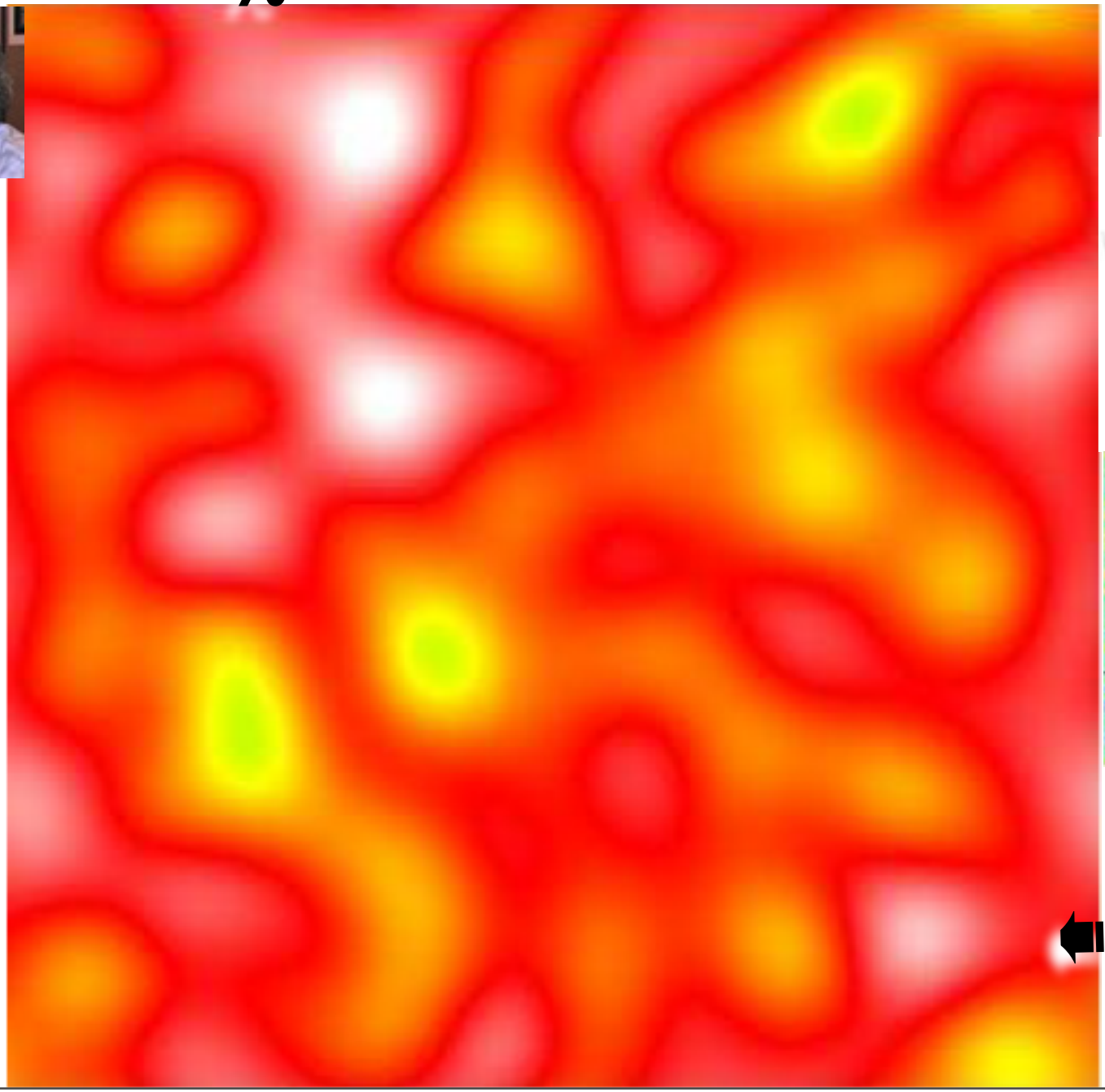
pre-heating patch (~1cm)

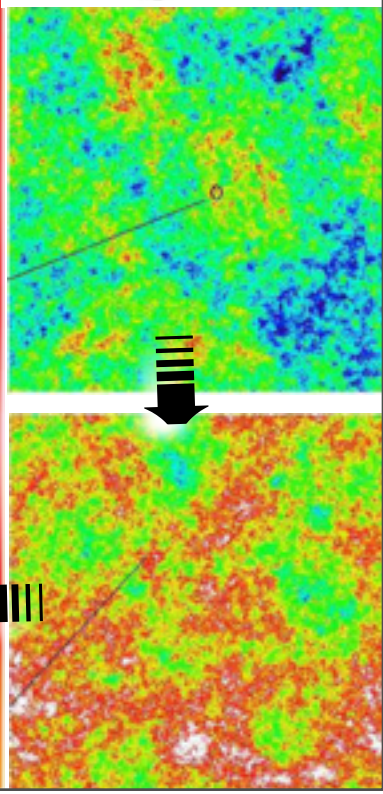
10 Gpc

ϕ inflaton χ isocon $V(\phi,\chi)=1/4\,\lambda\,\phi^4+1/2\,g^2\,\phi^2\,\chi^2$

Parametric Resonance

$g^2/\lambda \sim 1$





pre-heating patch (~1cm)

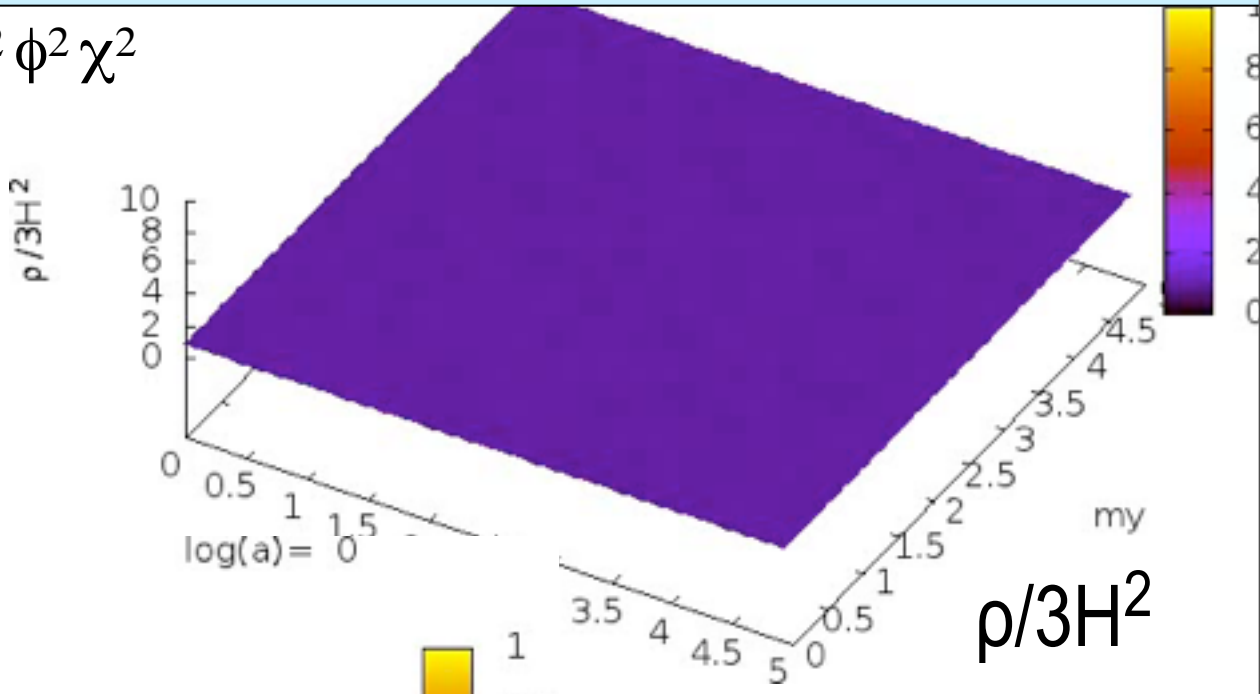
coherent inflaton => incoherent mode cascade of fields thru a shock-in-time to thermal equilibrium

$V(\phi,\chi)=1/4\ \lambda\ \phi^4 + 1/2\ g^2\ \phi^2\ \chi^2$

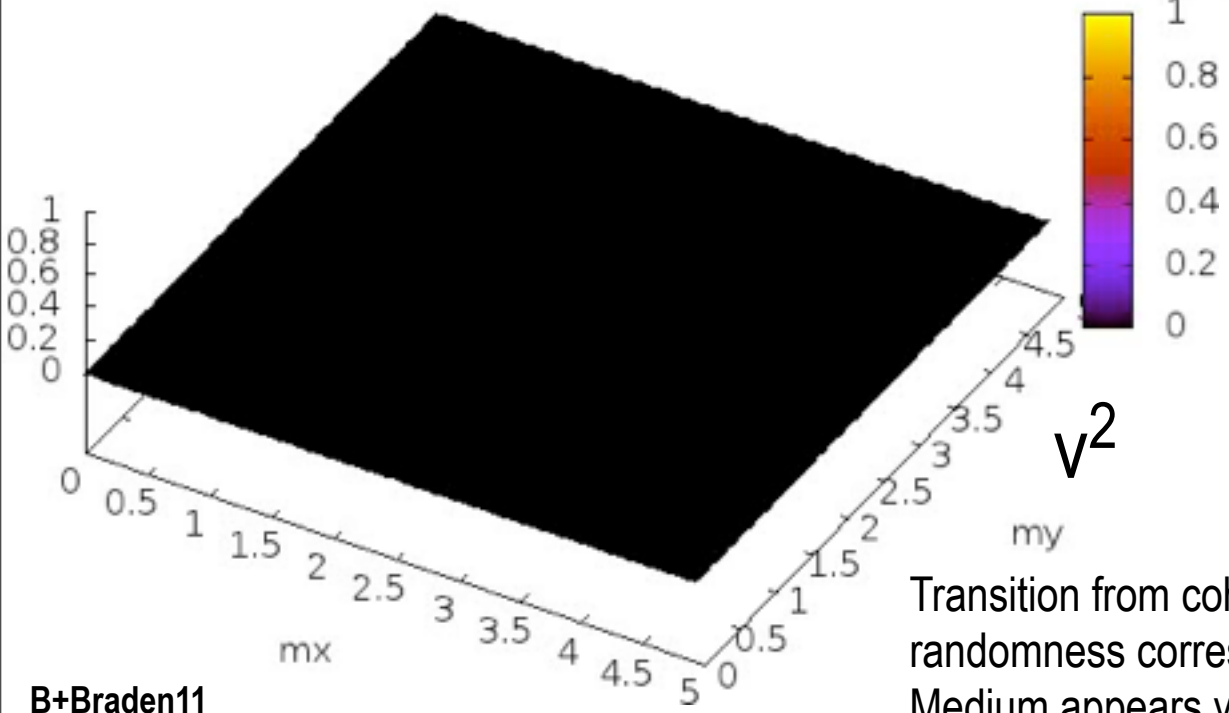
Slow Dynamics of IR Modes ⇒
Hydrodynamic Description

$\rho=-T^0{}_0 \quad P=-T^i{}_i$

$v^i=aT^i{}_0/(\rho+P)$



$\rho/3H^2$



v^2

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

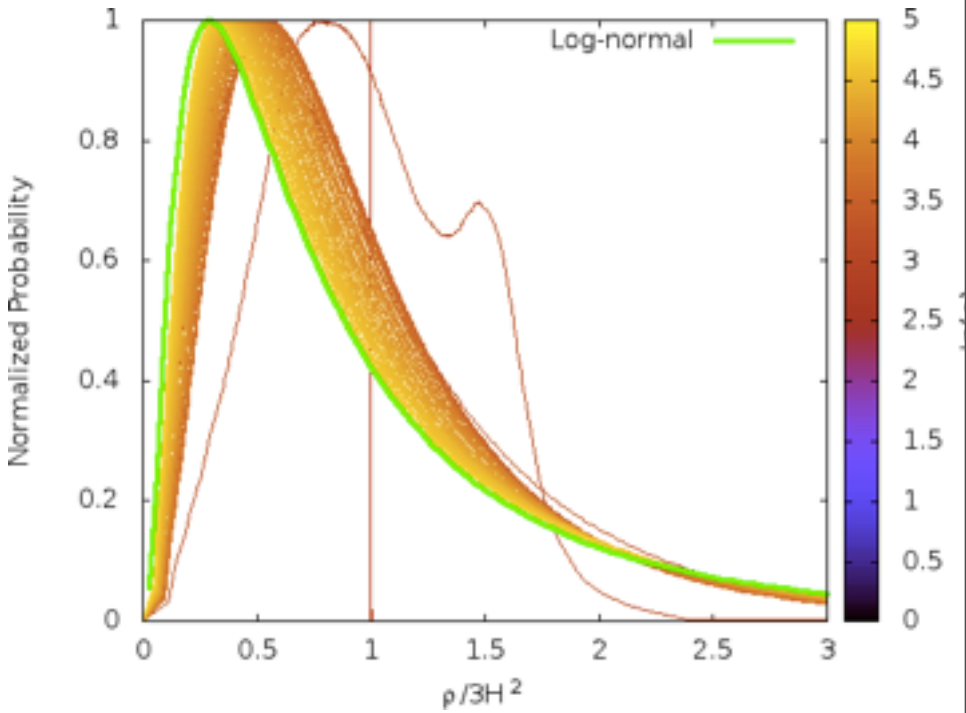
Transition from coherent wall-like structures to randomness corresponds to the shock-in-time.
Medium appears very complex in space and time, but ...

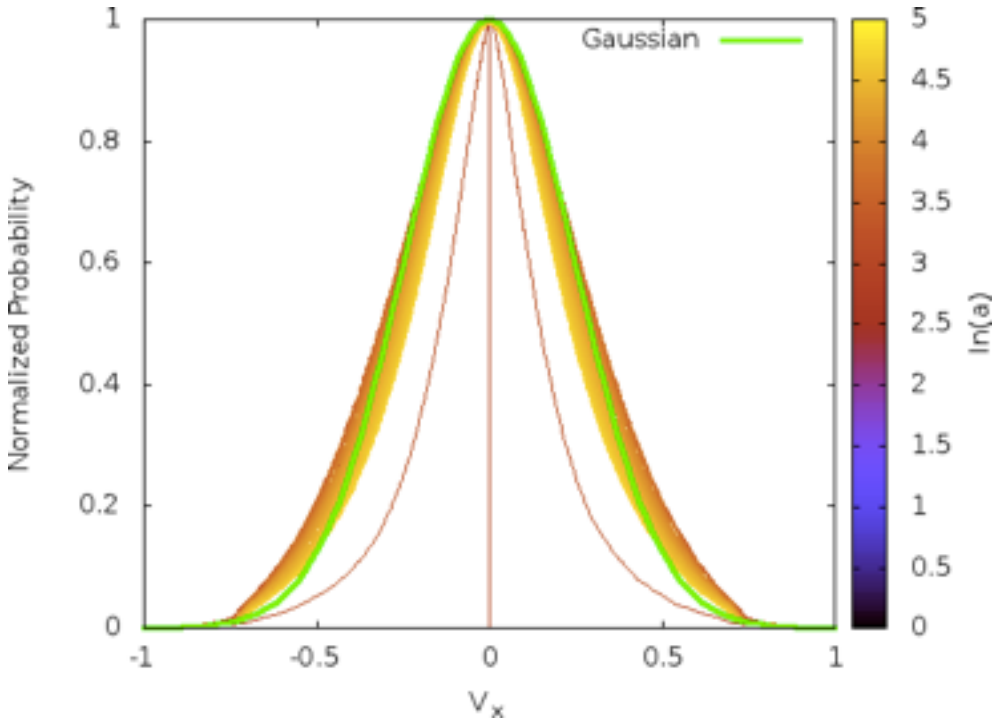
B+Braden11

but Statistical Simplicity

Density PDF~ log-normal after initial transient Frolov

Velocity components ~ Gaussian PDF

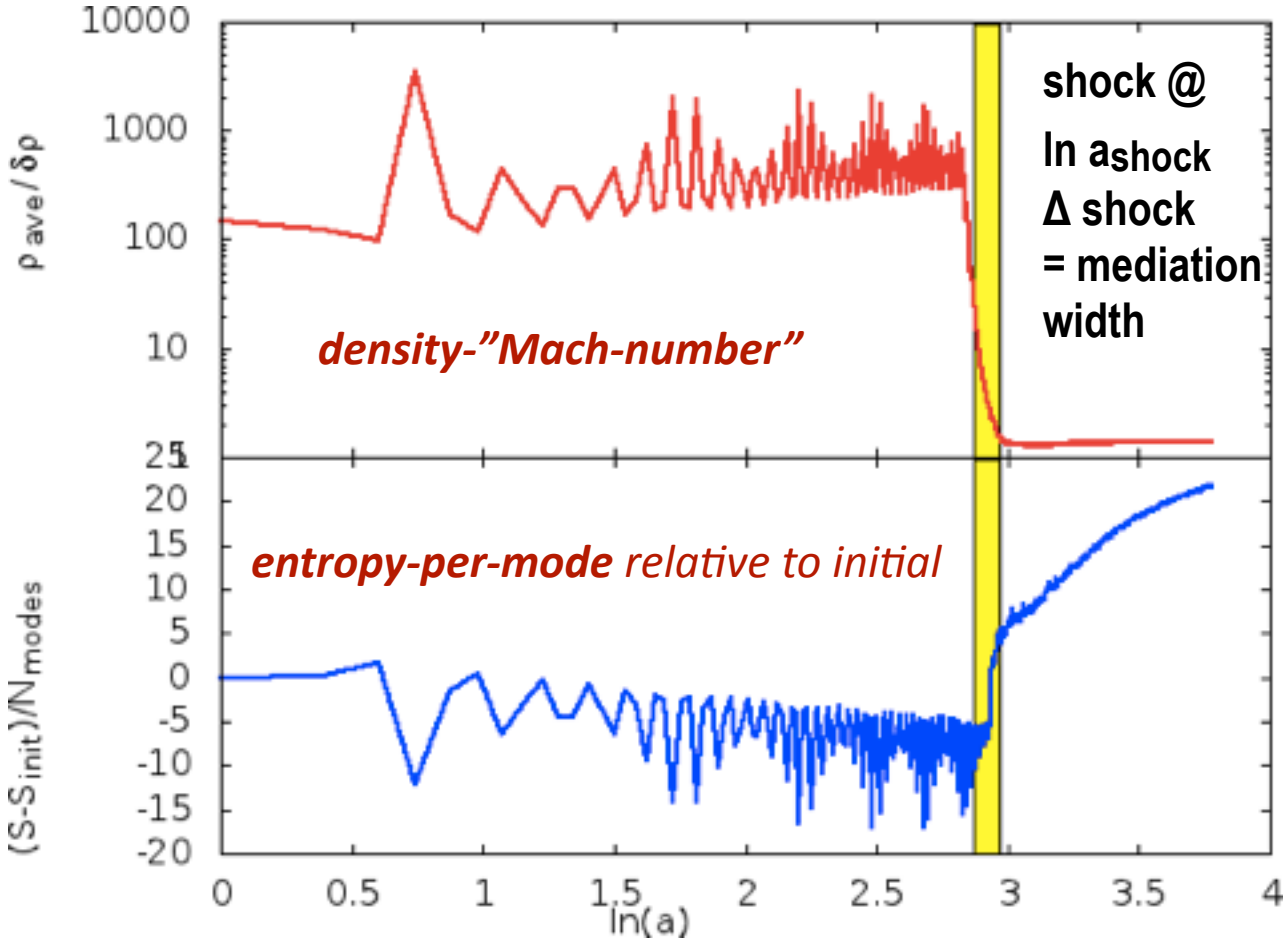




non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating

B+Braden11

the Shock-in-time: entropy production & (density-contrast)$^{-1}$



true thermal equilibrium far off

➤

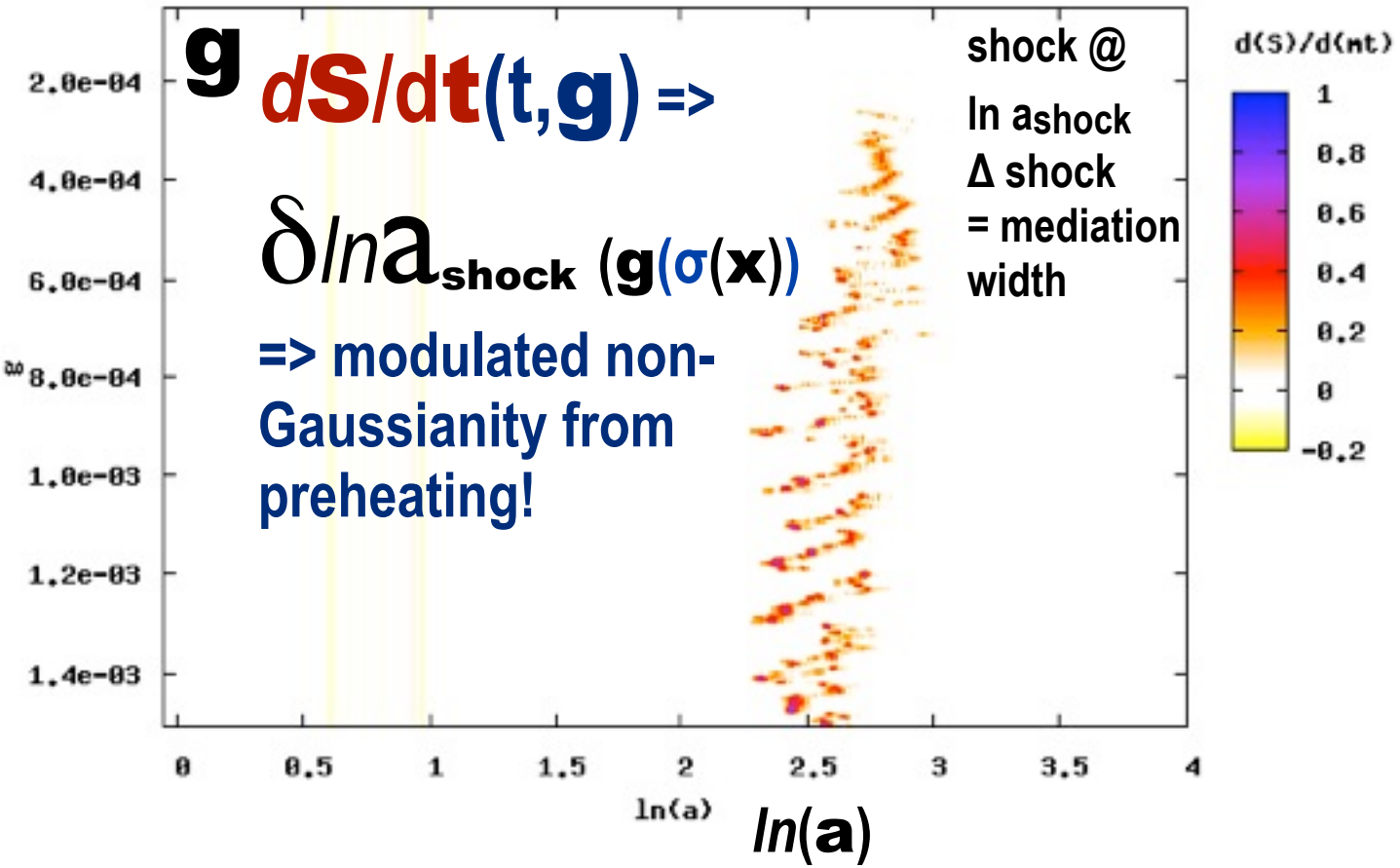
& on to coupling to standard model degrees of freedom

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.

non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating
B+Braden11

the Shock-in-time: entropy production rate



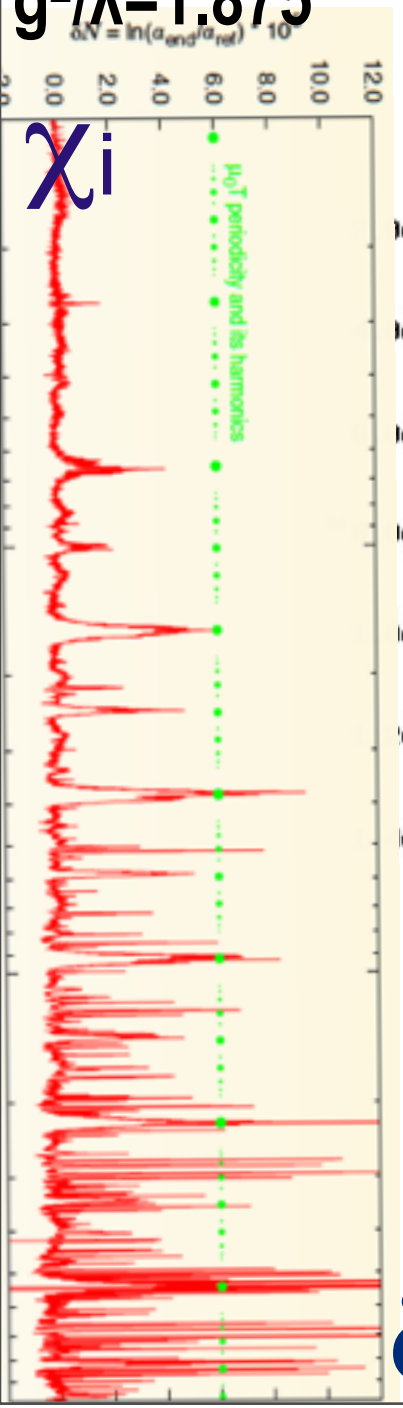
$$V(\phi,\chi)=1/2\, m^2 \phi^2 + 1/2\, g^2 \phi^2 \chi^2$$

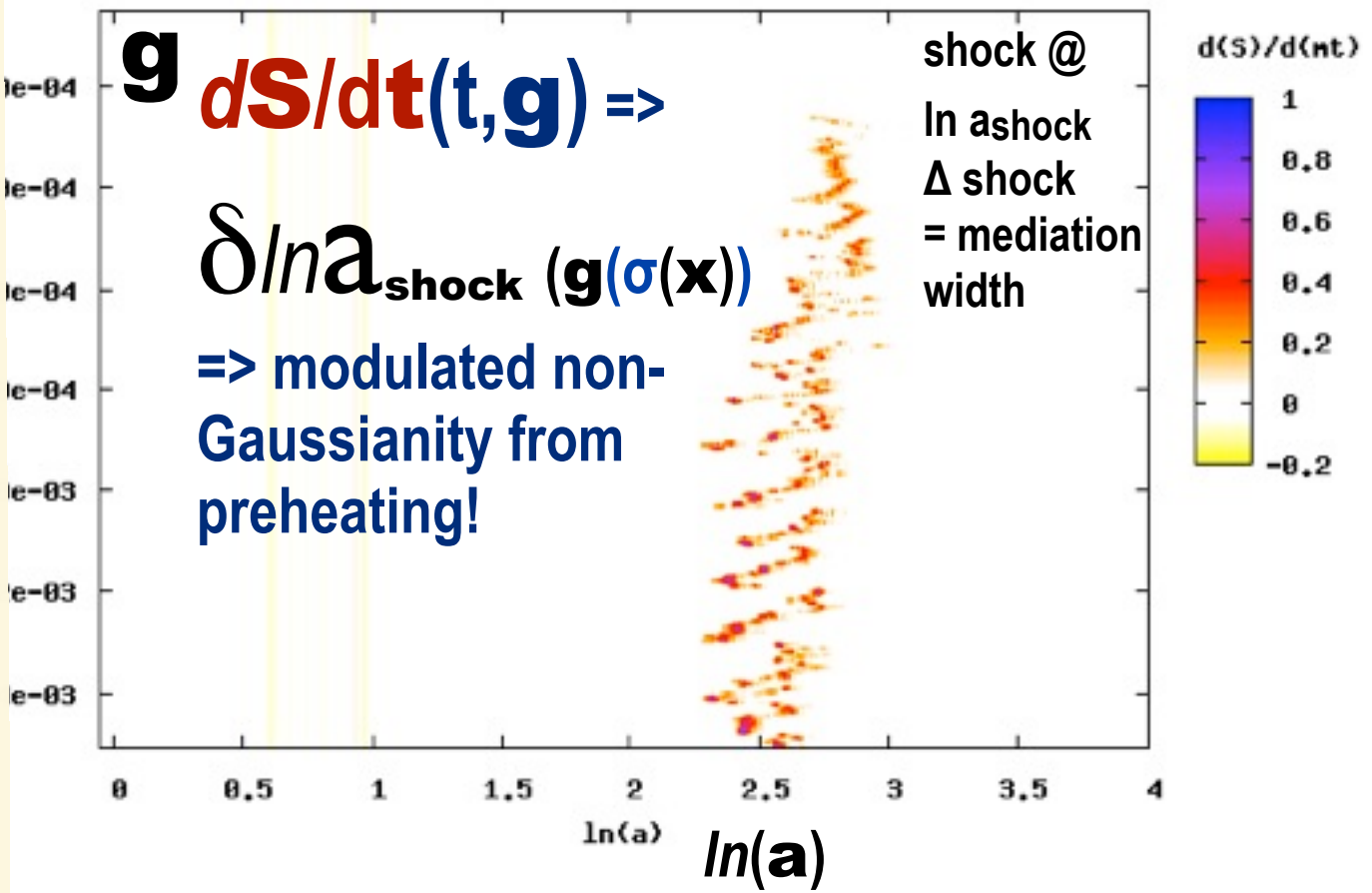
non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating

modulated non-G **Kofman03**
B+Braden11

$g^2/\lambda=1.875$

the Shock-in-time: entropy production rate





Chaotic Billiards: NonGaussianity from Parametric Resonance in Preheating

$V(\phi,\chi)=1/4\ \lambda\phi^4+1/2\ g^2\phi^2\chi^2$

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

$\delta ln a\ (\chi_i(x,t))$

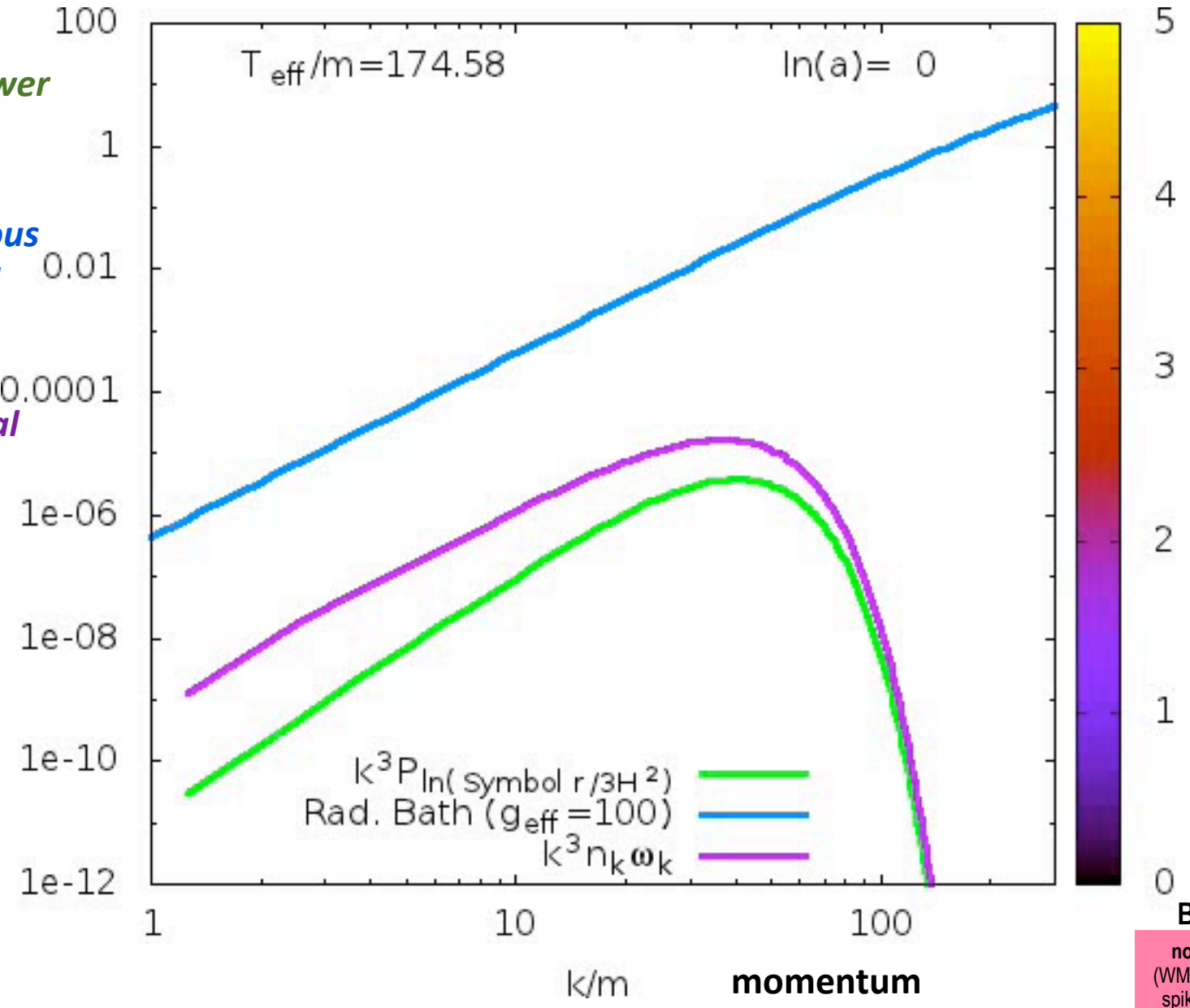
B+Frolov, Huang, Kofman 09
B+Braden, Frolov, Huang 12

non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating
B+Braden11

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_γ

In $\rho/3H^2$ power spectrum cf. instantaneous full thermal spectrum cf. conventional energy spectrum using a pseudo particle occupation number



B+Braden11

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

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*

CITA ICAT Canadian Institute for Theoretical Astrophysics / L'institut canadien d'astrophysique theorique

Dick Bond

25 years cifar

the Cosmotician's *Agenda: Statistical Paths in Cosmic Theory & Data via the Bayesian chain*

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.

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, changed as the experiments became more & more precise:

	now ACT1	Mar03	Jan03	Jan02	Jan00	Jan13-15	then	$\sum m_\nu \lesssim 0.06$ eV (Pext-ACTpol)
$\Delta S_{1f}(\Omega_\Lambda)$	0	1.60	2.32	2.49	3.91	-4.00		± 0.012 =>± 0.001 (Pext)
$\Delta S_{1f}(w_0)$	0	-	-	-	-	-2.5 (-2.2)		± 0.06 =>± 0.01 (Pext) (± 0.14 =>± 0.03)
ΔS_{1f} (V-slope^2)	0	-	-	-	-	-2.4		0.0± 0.18 =>± 0.03 (Pext)
$\Delta S_{1f}(n_s)$	0	0.24	2.24	2.03	3.86	-2.59		0.963± 0.011 =>± 0.002 (Pext)
$\Delta S_{1f}(r)$	0	0.92	-	-	-	-3.70		< 0.17 => < 0.007-0.013 (Pext)
$\Delta S_{1f}(f_{nl})$	0	-	-	-	-	-4.00		-10< f_{NL} <74 => ± 5 (Pext)

INFLATION

primary anisotropies

•linear perturbations: scalar/density, tensor/ gravity wave

• tightly-coupled photon-baryon fluid:

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

• viscously damped

• polarization $\pi\gamma$

• gravitational redshift Φ SW $d\Phi/dt$

Decoupling LSS

17 kpc (19 Mpc)

Lsound/ ksound

secondary anisotropies

the nonlinear COSMIC WEB

dS/dt

•nonlinear evolution

•weak lensing

•thermal SZ +kinetic SZ

•$d\Phi$ /dt

•dusty/radio galaxies, dGs

MILKY WAY

z=0

reionization

z ~ 10

z ~ 1100

redshift z

dS/dt

time t

13.7-10^{-50}Gyrs

13.7Gyrs

10Gyrs

today

end

Studying the Cosmic Tango

en-Tango-ment, the dance of S+R=U
Universe=System(s)+Reservoir,
=Signal(s)+Residual *noise*,
=Effective Theory+*Hidden variables*,
observer(s)+observed,
ruled by (information) entropy, entangled. ***the fine grains in the coarse grains***

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

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

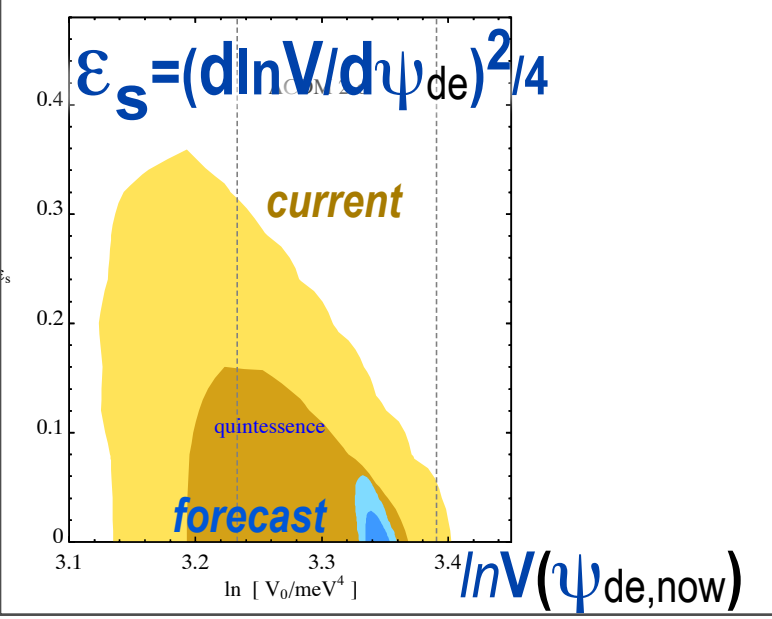
let there be heat: entropy generation in **preheating** from the coherent inflaton **(origin of all matter)**

S of Gaussian fields
spatial **CMB entropy**
& how we capture it.
dark matter entropy,
cluster/protocluster / cosmic web entropy.
info-entropy flow from CMB time-streams to marginalized cosmic parameters via Bayesian chains
MHD turbulence S

NOW & future DE equation of state trajectories

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

Huang, Bond, Kofman 2010; Bond, Huang 2011

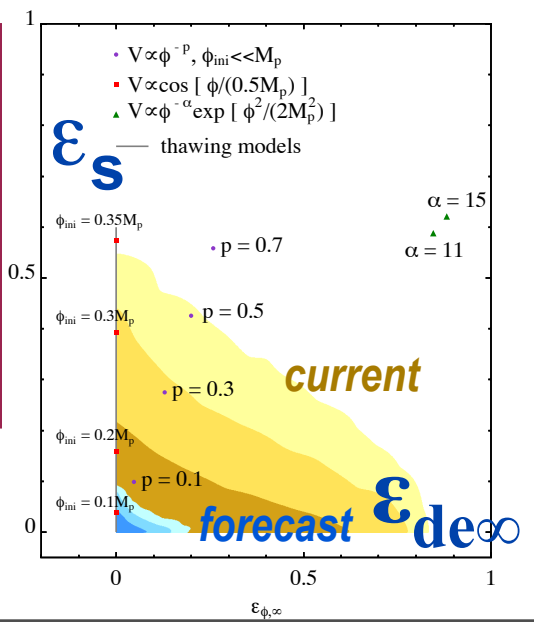


Quintessence $w_{de}(a|V(\psi),IC)$

$\Rightarrow w(a|\varepsilon_s\, \varepsilon_{de\infty}\, \zeta_s)$

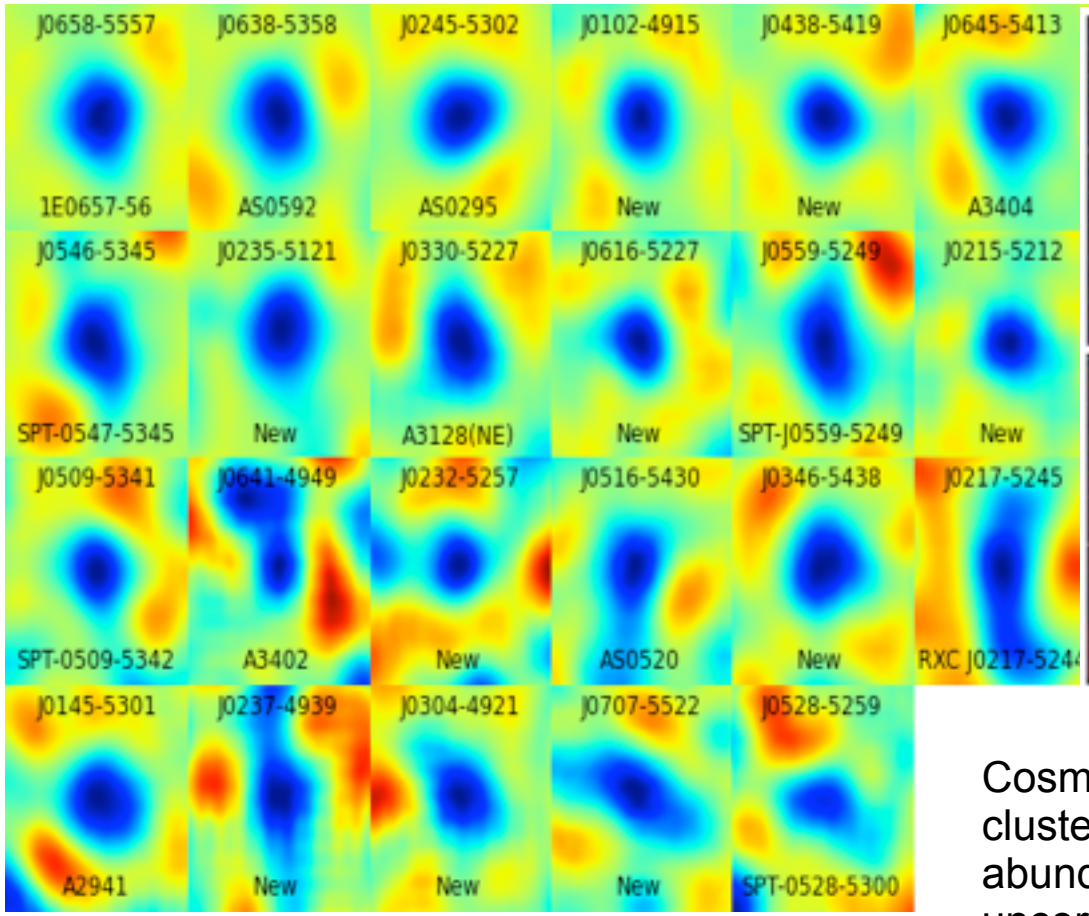
3parameter form paves even wild late-inflaton trajectories

$\psi_{de}=\phi/\sqrt{2}M_P$ = late-inflaton in Planck mass units

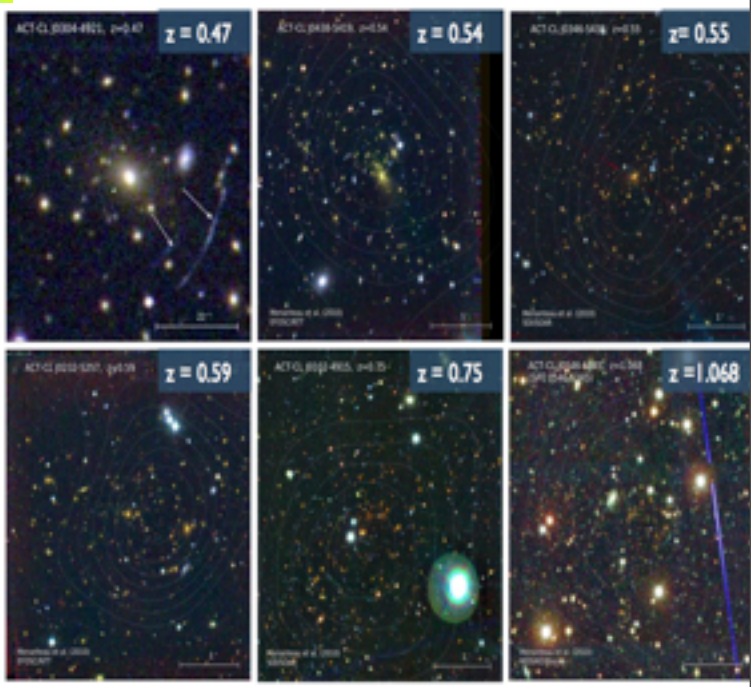


23 Galaxy Clusters Found by ACT via SZ Signal

Marriage et al 2010 (1010.1065)



Optical Observations Menanteau et al 2010 (1006.5126)



Cosmic Parameters from 9 confirmed clusters (Sehgal et al.2010) using cluster abundances => mass calibration still too uncertain (e.g. σ_8=0.82±0.05 to 0.85±0.12). attempt at Dark Energy equation of state, little leverage

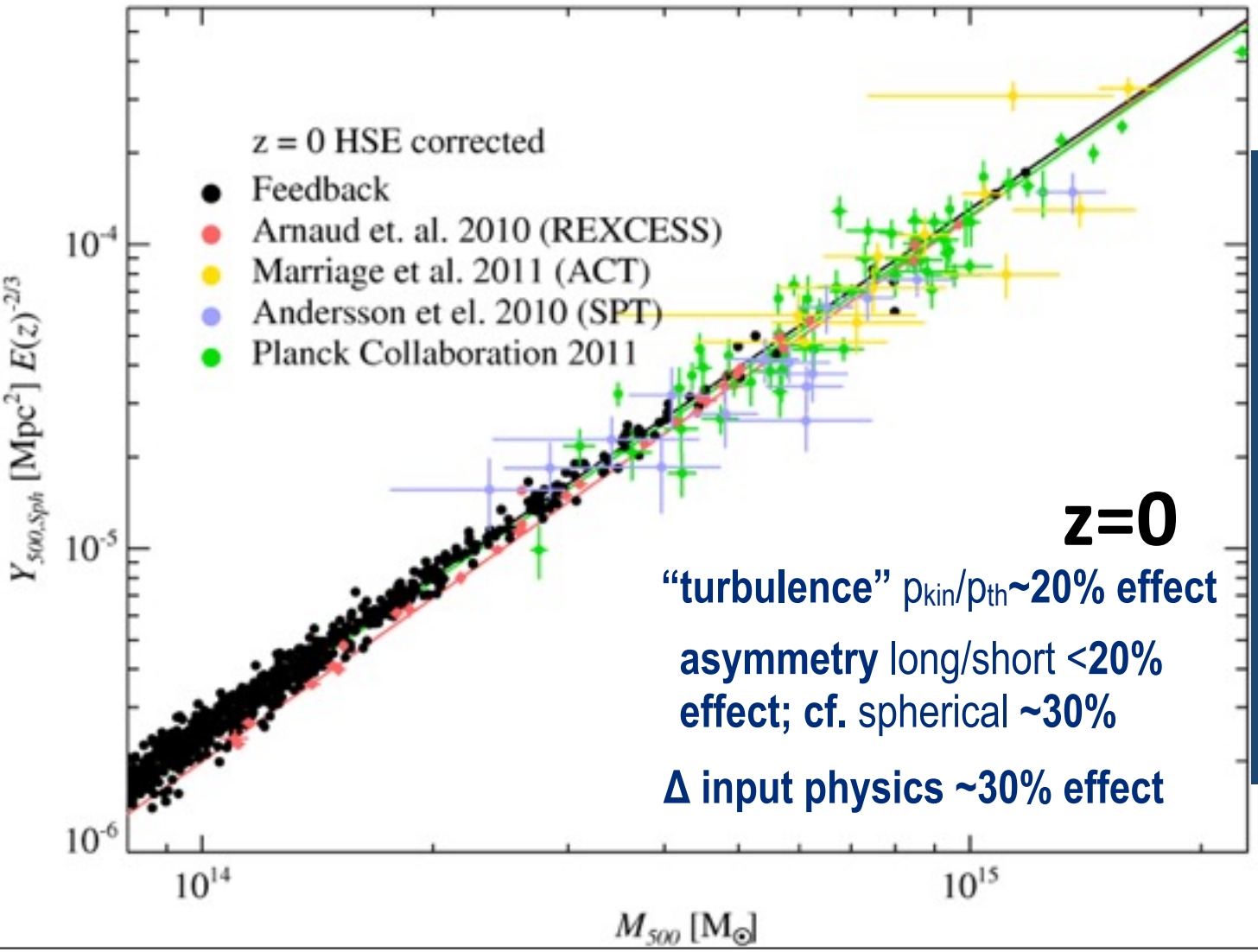
With the ACT equatorial strip, >50 clusters.

Menanteau+11, el Gordo, a “bullet”-like Cluster at z~0.87, discovered in 2009 data by Manenteau+10, highest SZ flux in 755 sq deg Marriage+2011, much follow-up

$E_{e,th}(<r_\Delta)$-$M(<r_\Delta)$ relation, *where*

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

Battaglia, Bond, Pfrommer, Sievers 1,2, (3,4) 2011: non-eq processes, p-profiles, YM, C_L^{SZ}

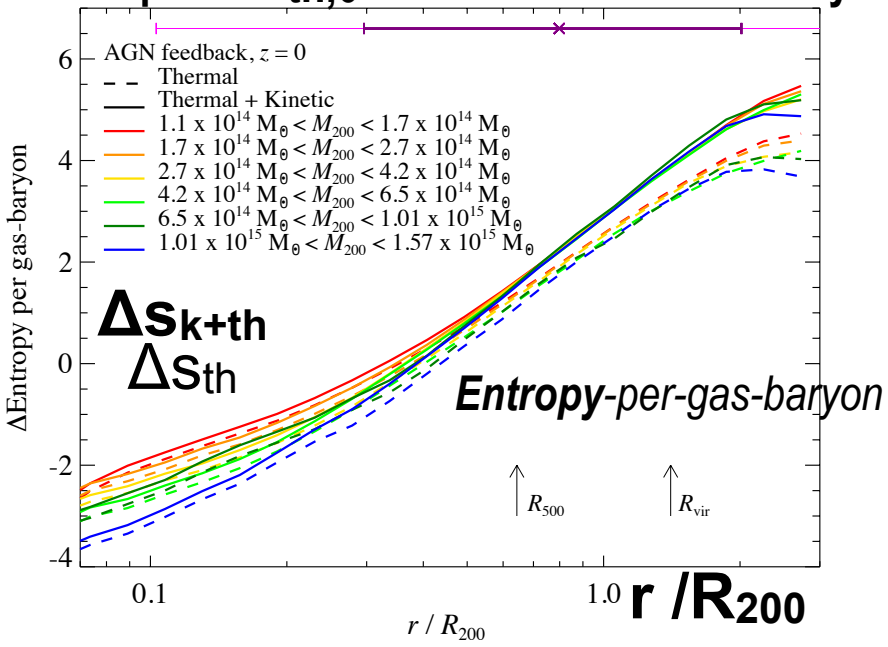


Planck-ESZ gives Y_{5R500}

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

non-equilibrium and non-thermal ***Entropy Profiles (M | z=0) for Mass-binned Scaled Stacked Clusters***

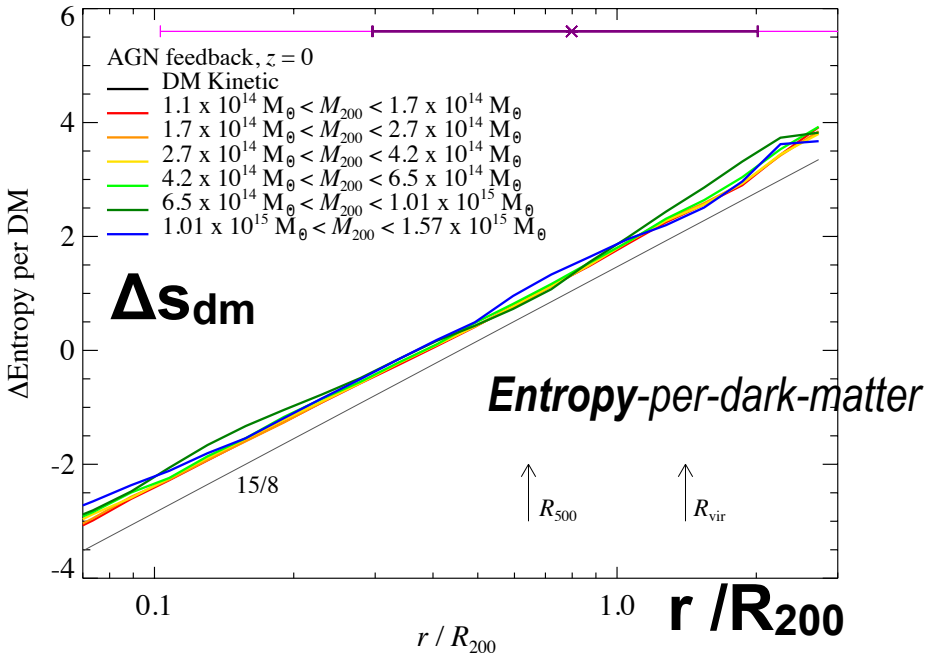
zero point $S_{th,0}$ ~ 130 nats ~ 190 bits/baryon



slope~3.04 =X-ray Voit

P_{kin}/P_{th}~0.1-0.6!

$\langle(\Delta v)^2\rangle/c_s^2$ affects hydrostatic equilibrium



slope~15/8 =self-similar radial infall Navarro

better-than-NFW fit to DM-only simulation density profiles.

gas/star effect affect NFW-ism.

ongoing mystery - why halos have this entropy growth law

gps-cls ~150-190 bits/baryon, Δs_{th}***~12 bits/b ;*** s_{kin+th}**-**s_{th}***~1bit/b***

$$\Delta s_{dm} = 1/2\ \mathrm{Tr}\ ln\langle(p_{kin}\, I + \Pi_{kin})/\rho_{dm}\rangle - ln\ \rho_{dm} \quad \sim 7\ bits/DM$$

zero point depends on type of DM, WIMP or axion or ...

cf. $s_{\gamma+\nu}/n_b \sim 1.66 \times 10^{10}/(1+\delta_b)$ **bits/b**

cf. **AGN's black hole entropy** $S_{bh} = M_{bh}^2/2M_P^2 \sim 10^{22}\, S_b$; but $\tau_{bh} \sim 10^{120}$ yrs

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*

CITA ICAT Canadian Institute for Theoretical Astrophysics / L'institut canadien d'astrophysique theorique

Dick Bond 25 years cifar

the Cosmotician's *Agenda: Statistical Paths in Cosmic Theory & Data via the Bayesian chain*

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

ρ_{dm}/ρ_b=5.1 ρ_m/ρ_{de} =.30 Ω_m=0.268 ±.012 Ω_Λ=0.736 ±.012

$Power_s$=25x10^{-10} $Tilt_s$ =0.963±0.013 running=-0.024 ± 0.015 r=T/S<0.19 T_{cmb} =2.725

CMB*ology* **uses WMAP7+ACT** (SPT), **past: Boom, CBI, Acbar,..** (QuAD, ...). **LSS*ology*** **BAO H0** ***SN lens, clusters***. coming: ***Planck*** **cosmology** Jan2013,14 **cosmic parameters** Jan11(25p), Feb12
SZ,CIB,ISM ***ACTpol, ABS, Spider, Quiet-2,..*** *CARMA, Mustang2 on GBT, CCAT, ALMA,..*CHIME, EUCLID,..

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.

	now ACT1 Mar03 Jan03 Jan02 Jan00 Jan13-15 then	$\sum m_\nu \lesssim 0.06$ ev
$\Delta S_{1f}(\Omega_\Lambda)$	0 1.60 2.32 2.49 3.91 -4.00	± 0.012 =>± 0.001 (Pext)
$\Delta S_{1f}(w_0)$	0 - - - - -2.5 (-2.2)	± 0.06 =>± 0.01 (Pext) (± 0.14 =>± 0.03)
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$\Delta S_{1f}(n_s)$	0 0.24 2.24 2.03 3.86 -2.59	0.963± 0.011 =>± 0.002 (Pext)
$\Delta S_{1f}(r)$	0 0.92 - - - -3.70	< 0.17 => < 0.007-0.013 (Pext)
$\Delta S_{1f}(f_{nl})$	0 - - - - -4.00	-10< f_{NL} <74 => ± 5 (Pext)

cosmology forecasts for PlanckEXT

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

current CMB+LSS+WL+SN1a+Lyα **PEXT**=Planck2.5yr + low-z-BOSS + CHIME + Euclid-WL + JDEM-SN

Huang, Bond, Kofman 2010, Bond, Huang 2011

$n_s = 0.963 \pm 0.011 \Rightarrow \pm 0.002$ (Pext)

$Power_s \sim 25\times10^{-10}$ $\ln A_s = \pm 0.03 \Rightarrow \pm 0.008$ (Pext)

Farhang, Bond, Dore, Netterfield 2011 ***forecasting QU not EB***

Spider $2\sigma_r \sim 0.013$ => ~ 0.02 for $0.02 < f_{sky} < 0.15$

Planck2.5yr $2\sigma_r \sim 0.02$ => ~ 0.05 (foregrounds)

quadratic local nonG $-10 < f_{NL} < 74$ (+- 5 Planck)

$\Omega_m = \pm 0.012 \Rightarrow \pm 0.001$ (Pext) $1-\Omega_{\Lambda de}$ ie, V_{de}

$w_0 = \pm 0.06 \Rightarrow \pm 0.01$ (Pext) if $w_a=0$ $\pm 0.14 \Rightarrow \pm 0.03$ $w_a \neq 0$

DEslope $(d\ln V/d\psi)^2/4$ @pivot a_{eq} $= 0.0 \pm 0.18 \Rightarrow \pm 0.03$ (Pext)

$z_{re} = \pm 1.2 \Rightarrow \pm 0.3$ (Pext)

$\sigma_8 = \pm 0.016 \Rightarrow \pm 0.002$ (Pext)

$\Delta \sum m_\nu \sim 0.06$ eV

Planck + ACTPol

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique

25 years cifar

CITA = Cosmic Information Theory & Analysis:
IT from BIT, from BITs in IT, Studying the Cosmic Tango

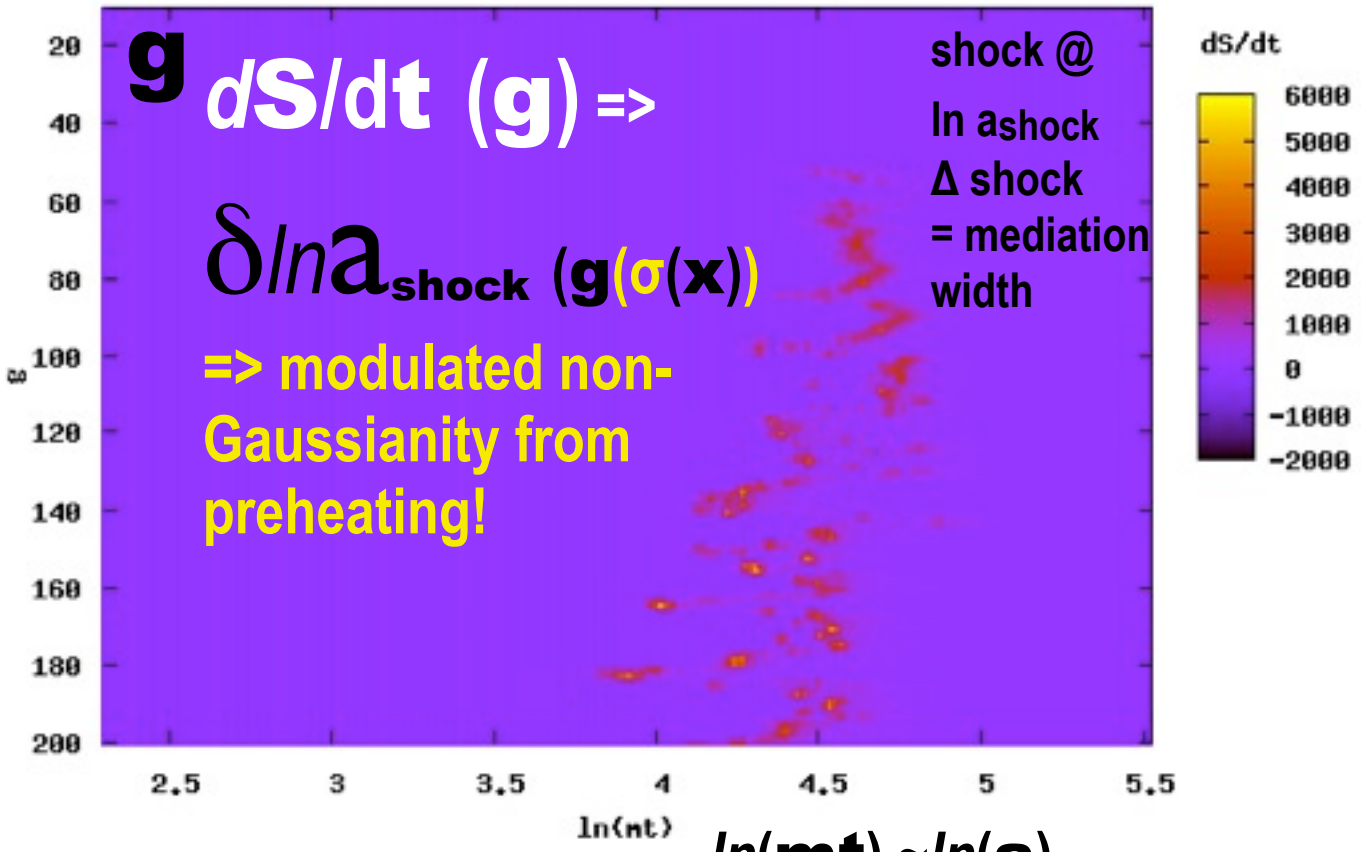
Dick Bond CIAR

Universe=System+Res =Data+Theory en-TANGO-ment

the Cosmotician's Agenda: Statistical Paths in Cosmic Theory & Data

We consider the Universe to be fundamentally quantum and statistical, the many-paths/many-worlds story. This lecture uses Cosmic Information Theory and Analysis, CITA, as a unifying theme to explore the vast sweep of our current ideas of the Universe and the experiments we use to probe them, ranging from the ultra-early beginnings to our far-future fate. I describe the intimate entanglement of theory with precision "first-light" and other cosmic data, in particular from the satellite Planck and the Andes-based ACT. Such data are the BITs in IT informing us of the physics that defines the BIT of the Universe accessible to us from which we hope to learn of that vast IT which encodes all Cosmic Information. The mysterious dark energy that drives the cosmic acceleration we observe happening now and its early universe counterpart, inflation, will be a focus.

the Shock-in-time: entropy production rate



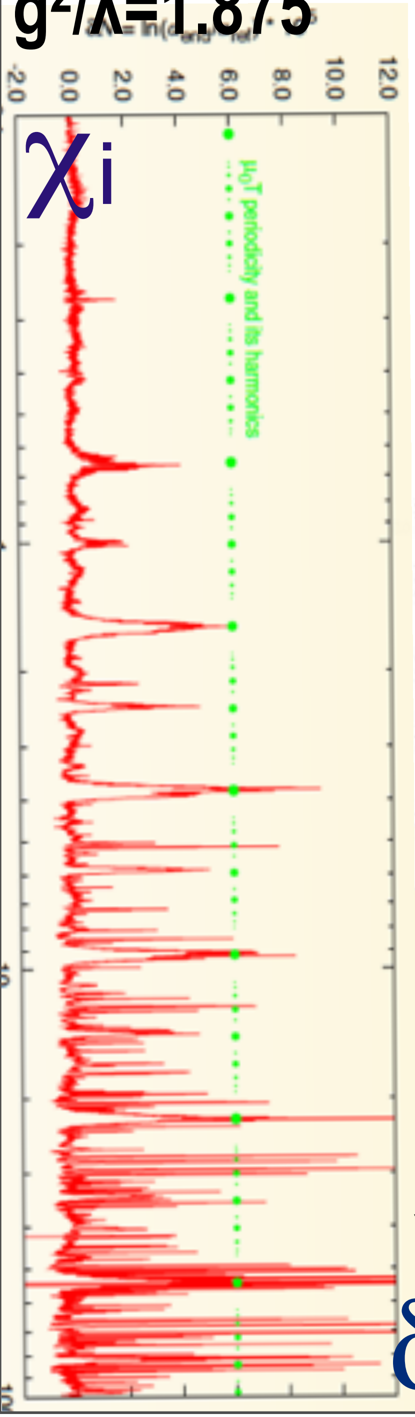
***ln*(mt) ~*ln*(a)**

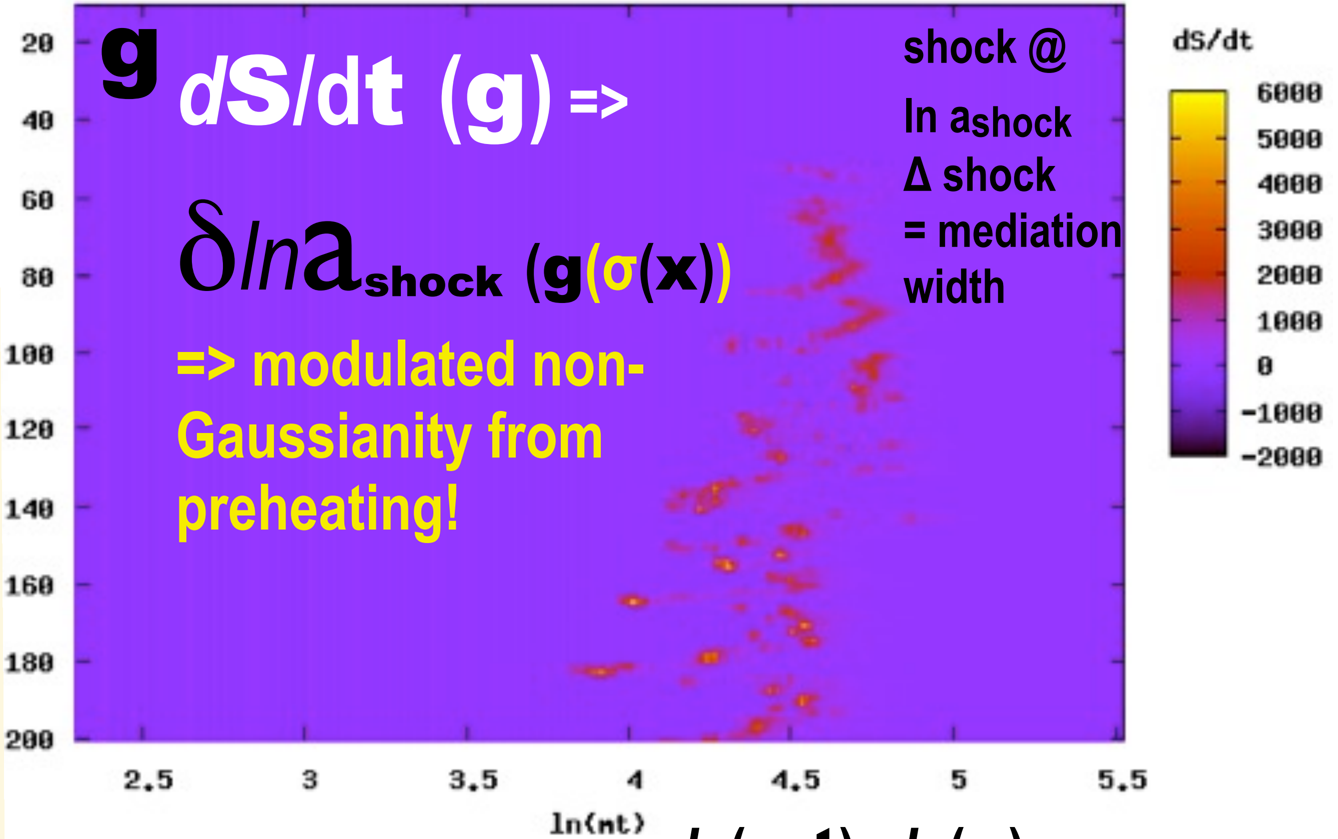
$$V(\phi,\chi)=1/2\, m^2 \phi^2 + 1/2\, g^2 \phi^2 \chi^2$$

non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating
B+Braden11

$g^2/\lambda = 1.875$

the Shock-in-time: entropy production rate





g ***d*S/dt (g) =>**

$\delta \ln a_{\mathbf{shock}}$ **(g(σ(x))**

=> modulated non-Gaussianity from preheating!

shock @
ln a_{shock}
Δ shock
= mediation width

$\ln(\mathbf{mt}) \sim \ln(\mathbf{a})$

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

Chaotic Billiards: NonGaussianity from Parametric Resonance in Preheating

$V(\phi,\chi) = 1/4\, \lambda\phi^4 + 1/2\, g^2 \phi^2 \chi^2$

$\delta \ln a\ (\chi_i(x,t))$

B+Frolov, Huang, Kofman 09
B+Braden, Frolov, Huang 12

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

B+Braden11