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

"black hole" ="gravitationally completely collapsed object"
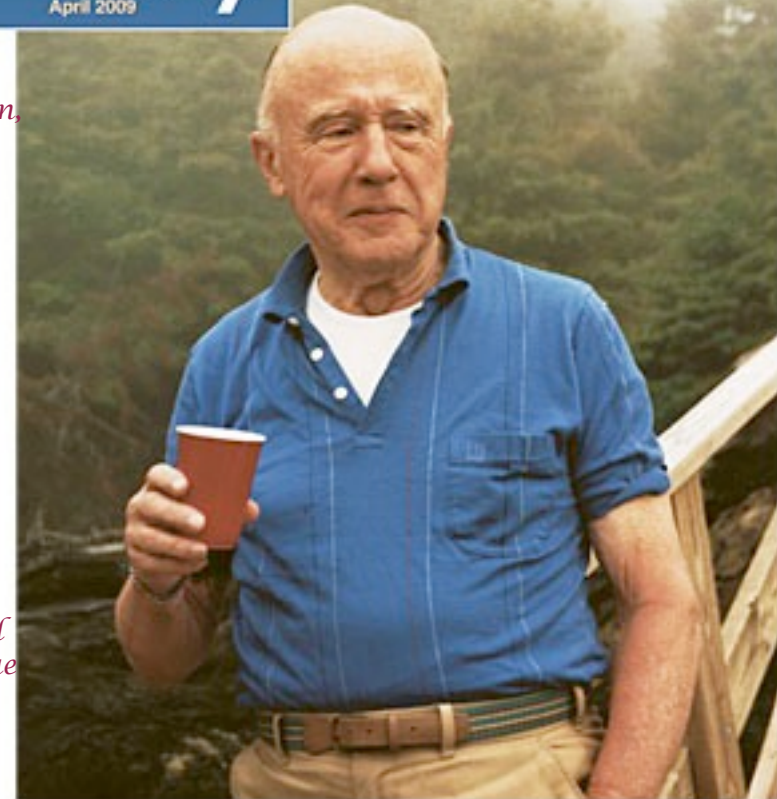*measurement problem—the role of the observer in defining what "is."*
"What do we mean by 'reality' except the results of observations?"
the observer confers "reåality" on the past by observing it, and offered the Big Bang as an example

physics today
www.physicstoday.org
April 2009
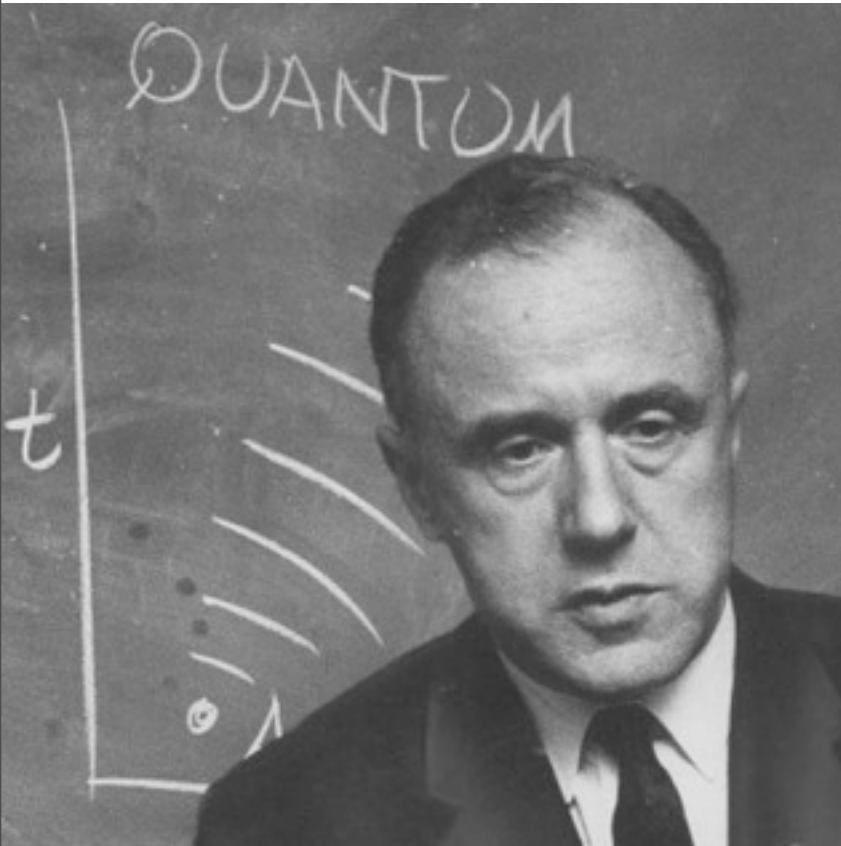
"Now I am in the grip of a new vision, that Everything Is Information. The more I have pondered the mystery of the quantum and our strange ability to comprehend this world in which we live, the more I see possible fundamental roles for logic and information as the bedrock of physical theory. ... I continue to search."

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

Special issue:
John Archibald Wheeler

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

Dick Bond

25 years cifar

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

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**

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

$s_m / n_b \sim 1$ 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 $\Delta s_{dm} \sim 7$ *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 $\Rightarrow$ 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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*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($g_{\mu v},\phi,\chi_i,\psi,A_\mu,\rho_m,p_m$),
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*
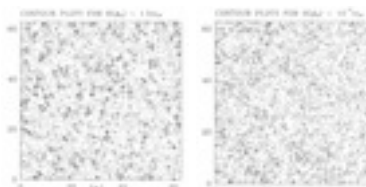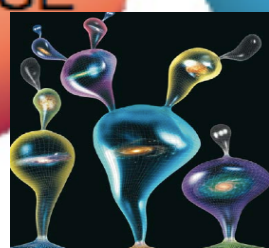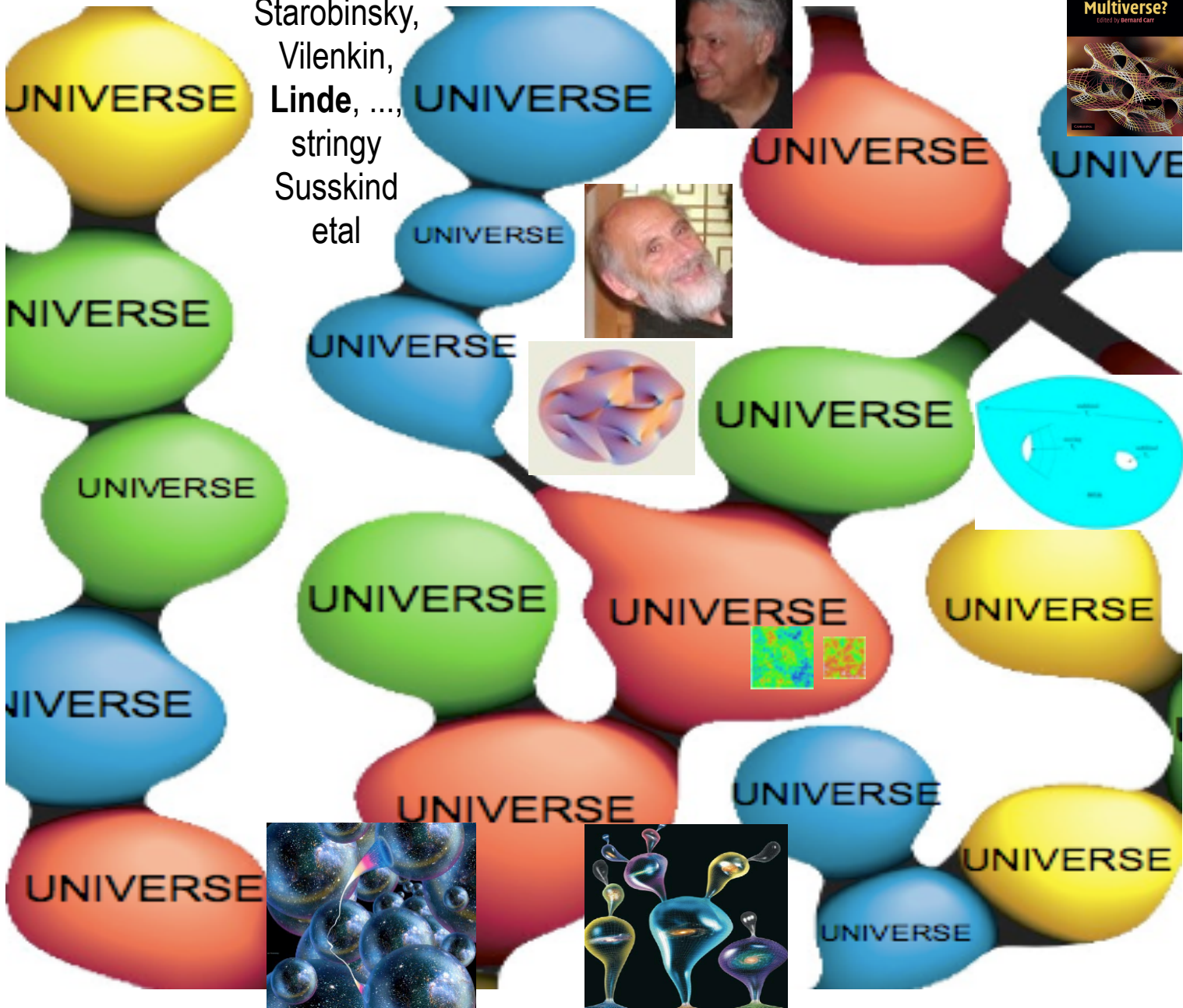
the **quantum stochastic non-G landscape** cf. the **stringy landscape**

Starobinsky, Vilenkin, **Linde**, ..., stringy Susskind etal
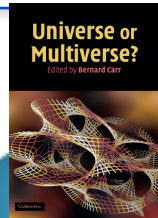
$\ln \mathbf{a(x,} \ln \mathbf{H)}$

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**

UNIVERSE

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inflation now: DarkEnergy(t,*x*), amplitude V_0 **& slope** d*ln*V/d*Inflaton* **of an effective potential**

inflation then: amplitude/slope **of scalar-curvature & tensor-curvature (GW) fluctuations,** n_s r

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

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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)

$\rho_{dm}/\rho_b = 5.1$ $\rho_m/\rho_{de} = .30$ $\Omega_m = 0.268 \pm .012$ $\Omega_\Lambda = 0.736 \pm .012$

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

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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,..

the gatherers of cosmic information

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

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

then & now & then

The Planck one-year all-sky survey — eesa — (c) ESA, HFI and LFI consortia, July 2010

Planck+Herschel Launch May14 09 Fr. Guiana
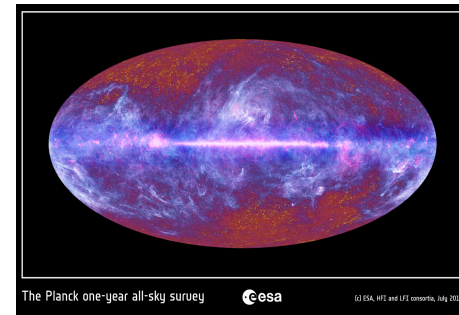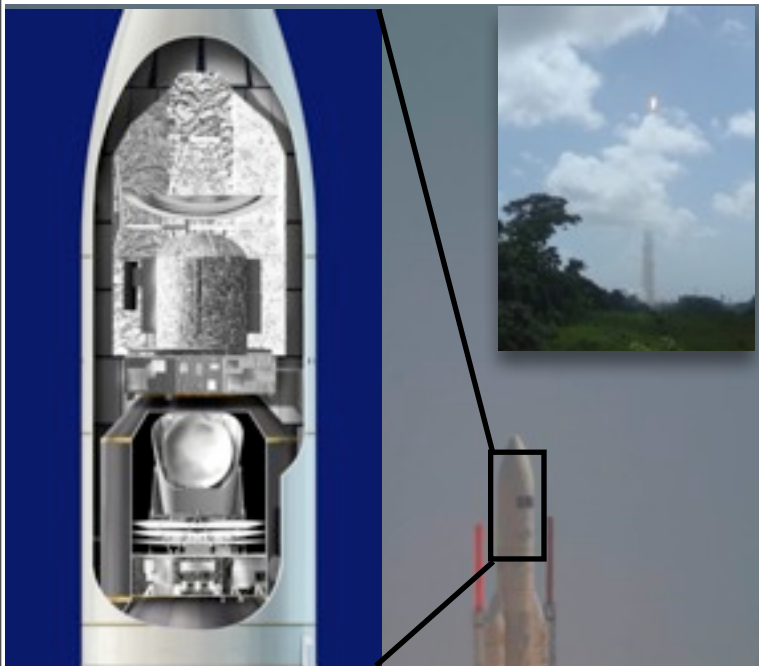
1.5m telescope, HFI bolometers @6freq <100mK, LFI HEMTs@3freq, some bolometers & all HEMTS are polarization sensitive

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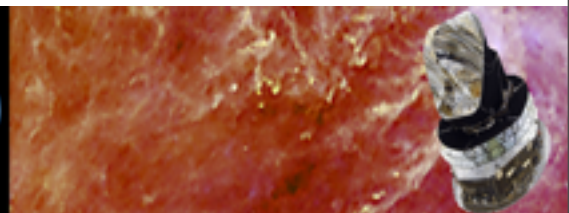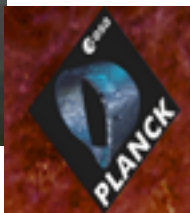
Left earth at ~10 km/s, 1.5 million km in 45 days, cooling on the way (20K, 4K, 1.6K, 0.1K 4 stage). @L2 on July 2 09 -almost no trajectory correction @operational temp; Survey started on Aug 13 09 spin@1 rpm, 40-50 minutes on the same circle, covers all-sky in ~6 month, ~4 surveys Aug11, ~5 total

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
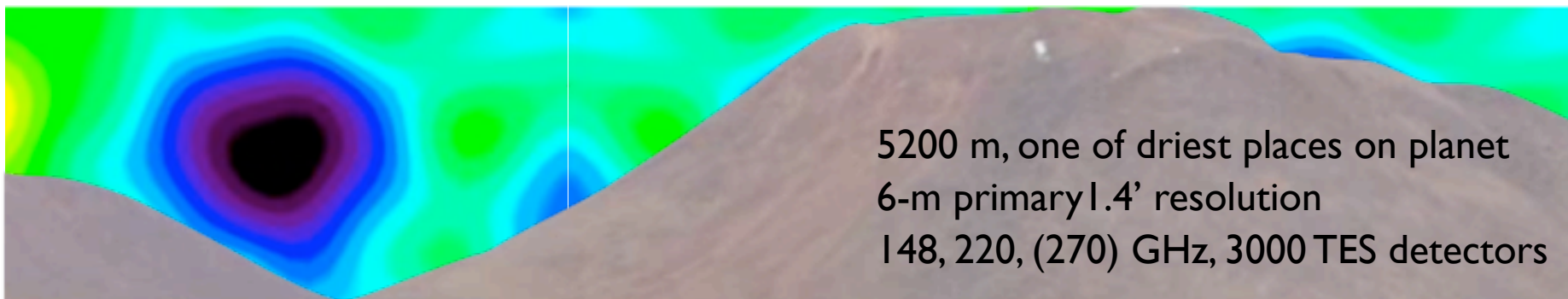
5200 m, one of driest places on planet
6-m primary 1.4' resolution
148, 220, (270) GHz, 3000 TES detectors

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

Planck & ACT

7 veils(ν)+CMB

Dick Bond

9 ν, pol,
HFI-bolos
+LFI-hemts
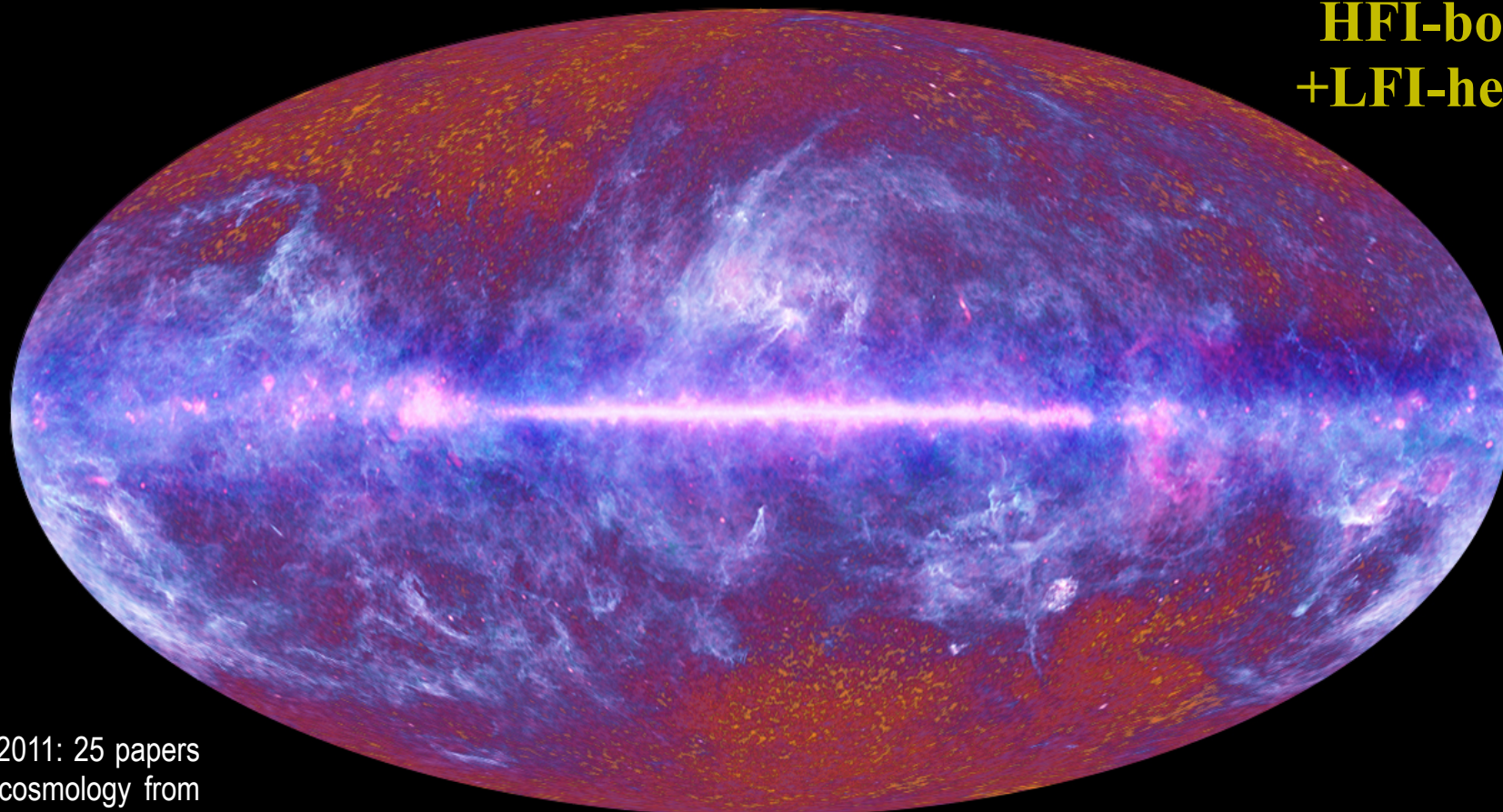
Jan 2011: 25 papers
first cosmology from
Planck early 2013,
major pol early 2014

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
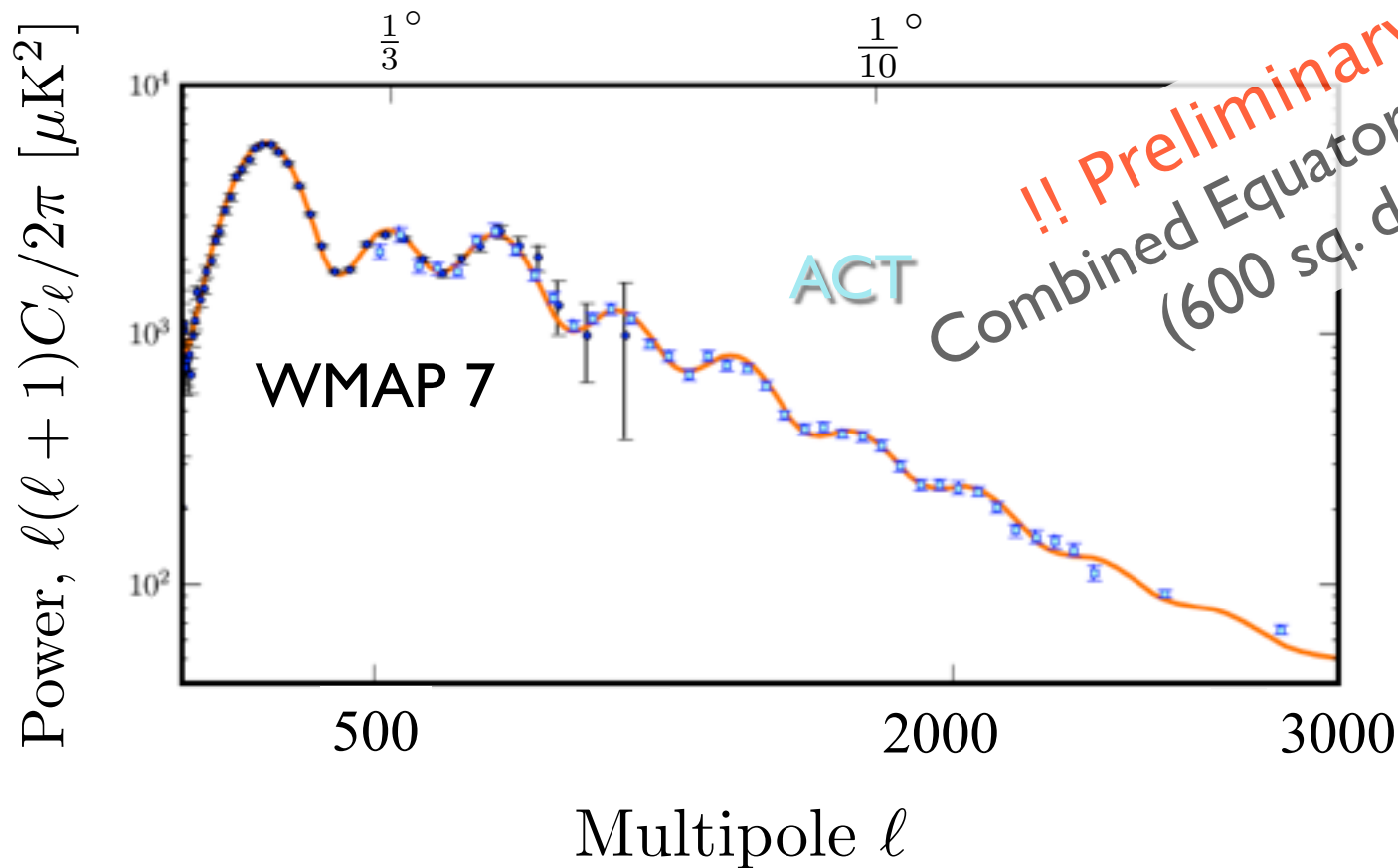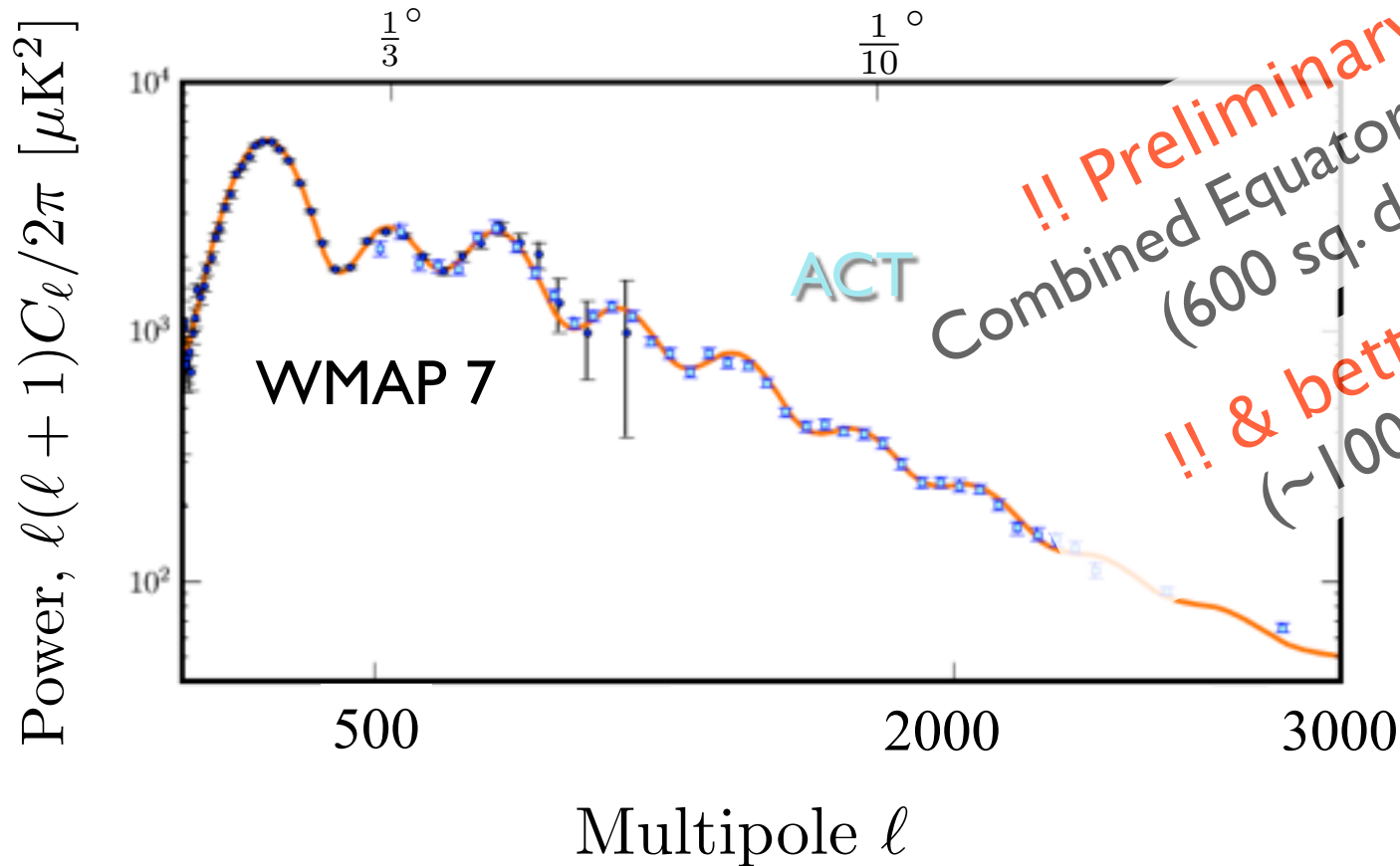
HIGH RESOLUTION POWER SPECTRUM from ACT: OLD

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_v, X_{He}, r, $dn_s/dlnk$, $n_s(k)$ in bands, CMB lensing, .. & we have (strings, isocurvature,..)

HIGH RESOLUTION POWER SPECTRUM from ACT: NEW

Angular Scale

!! Preliminary !!
Combined Equatorial+South
(600 sq. deg.)

ACT

WMAP 7

Power, $\ell(\ell+1)C_\ell/2\pi$ $[\mu K^2]$

Multipole ℓ

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!! & better now !!
(~1000 sq. deg.)

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CBI pol to Apr'05 @Chile   CBI2

Quiet1 @Chile

Quiet2 1000 HEMTs

QUaD @SP

Bicep2

Keck@SP

Boom03@LDB

Bicep @SP

ABS@ Chile

EBEX @LDB

WMAP @L2 to 2010

Planck09.4

Spider

52 bolometers + HEMTs @L2

2312 bolos @LDB

DASI @SP

9 frequencies

CAPMAP

Herschel

2013

BLAST

Pixie/ COrE/ LiteBird @space

2004   2006   2008   LHC 2011

2005   2007   2009

Piper

Acbar to Jan'06, 08f @SP

SPT 1000 bolos @SPole

BLASTpol

Polarbear @Chile

SZA @Cal

ACT 3000 bolos 3 freqs @Chile

SPTpol

APEX ~400 bolos @Chile

ACTpol

AMI

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)*

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

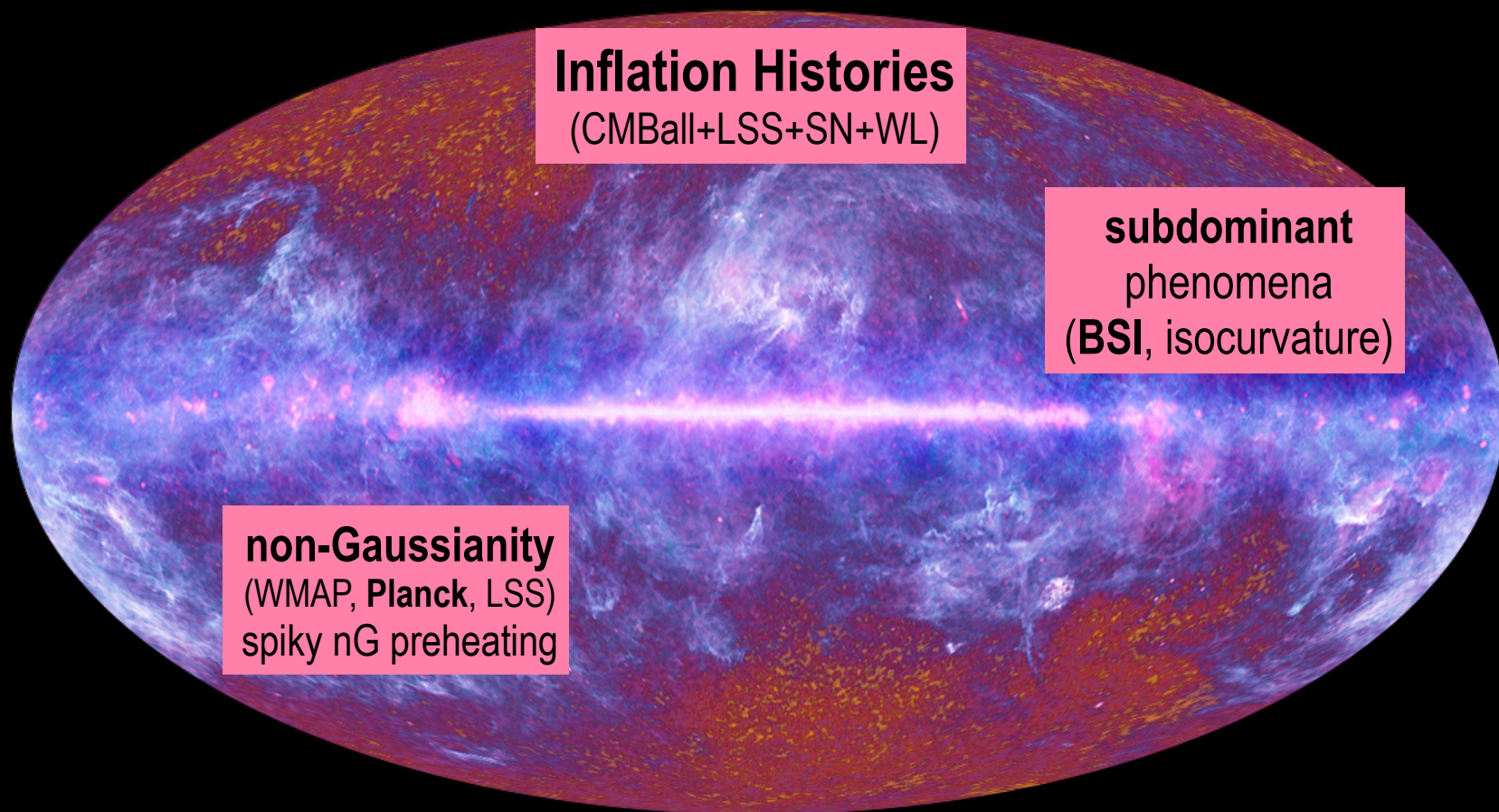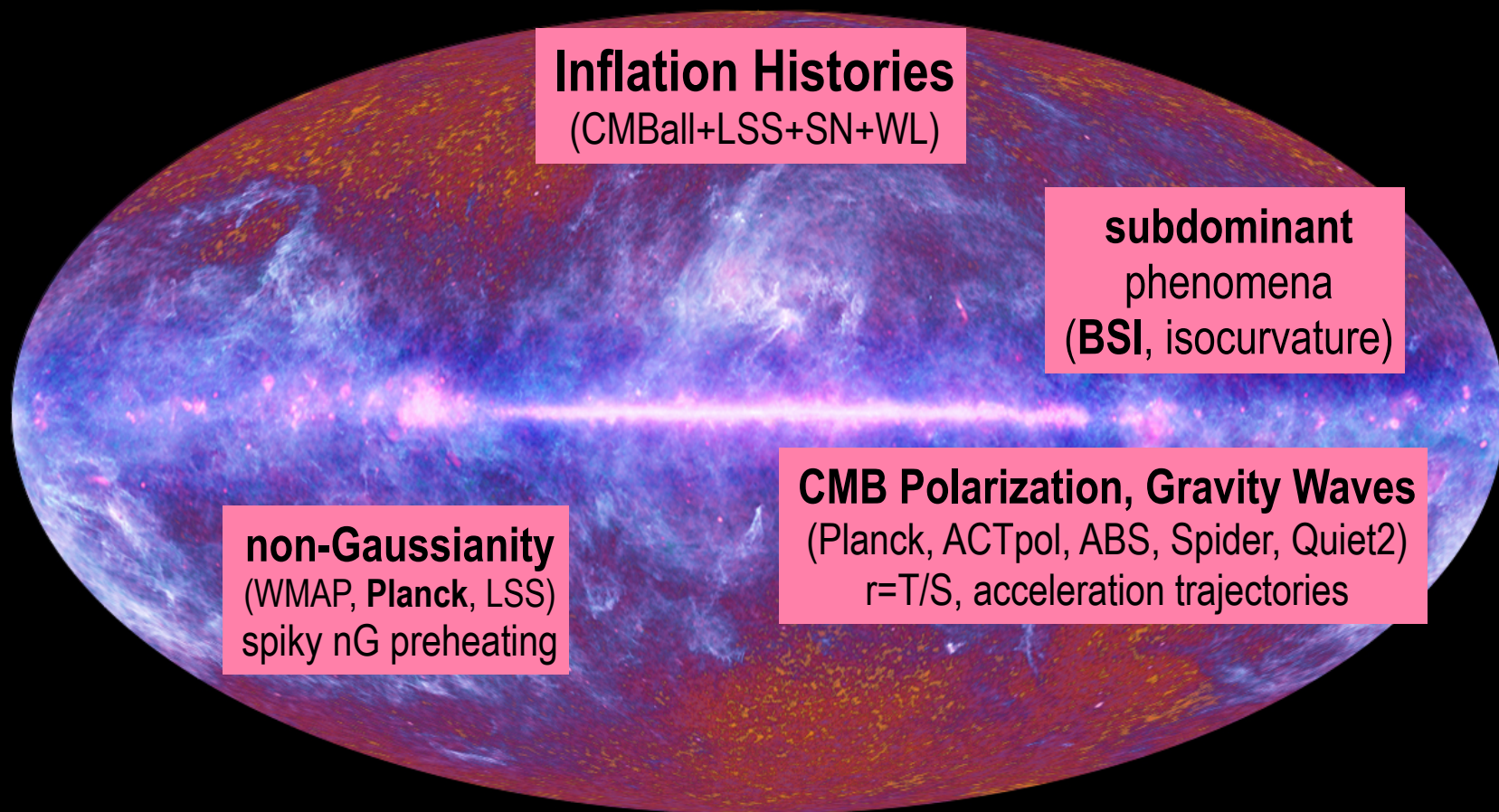***gastrophysical simulations with feedback from AGN / starbursts / SN .. confront CMB+LSS data***

The Planck one-year all-sky survey   ·eesa   (c) ESA, HFI and LFI consortia, July 2010

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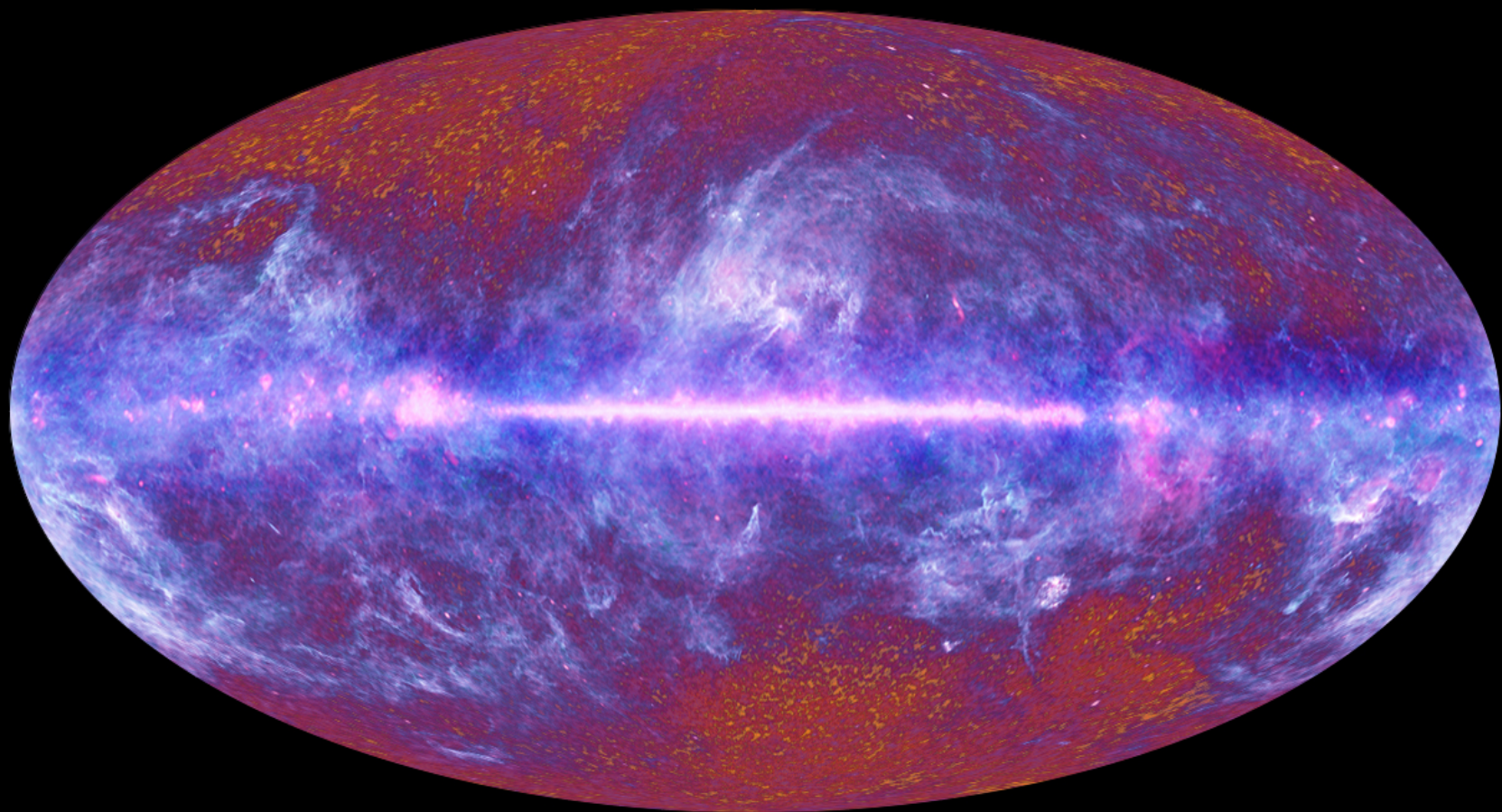
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(CMBall+LSS+SN+WL)

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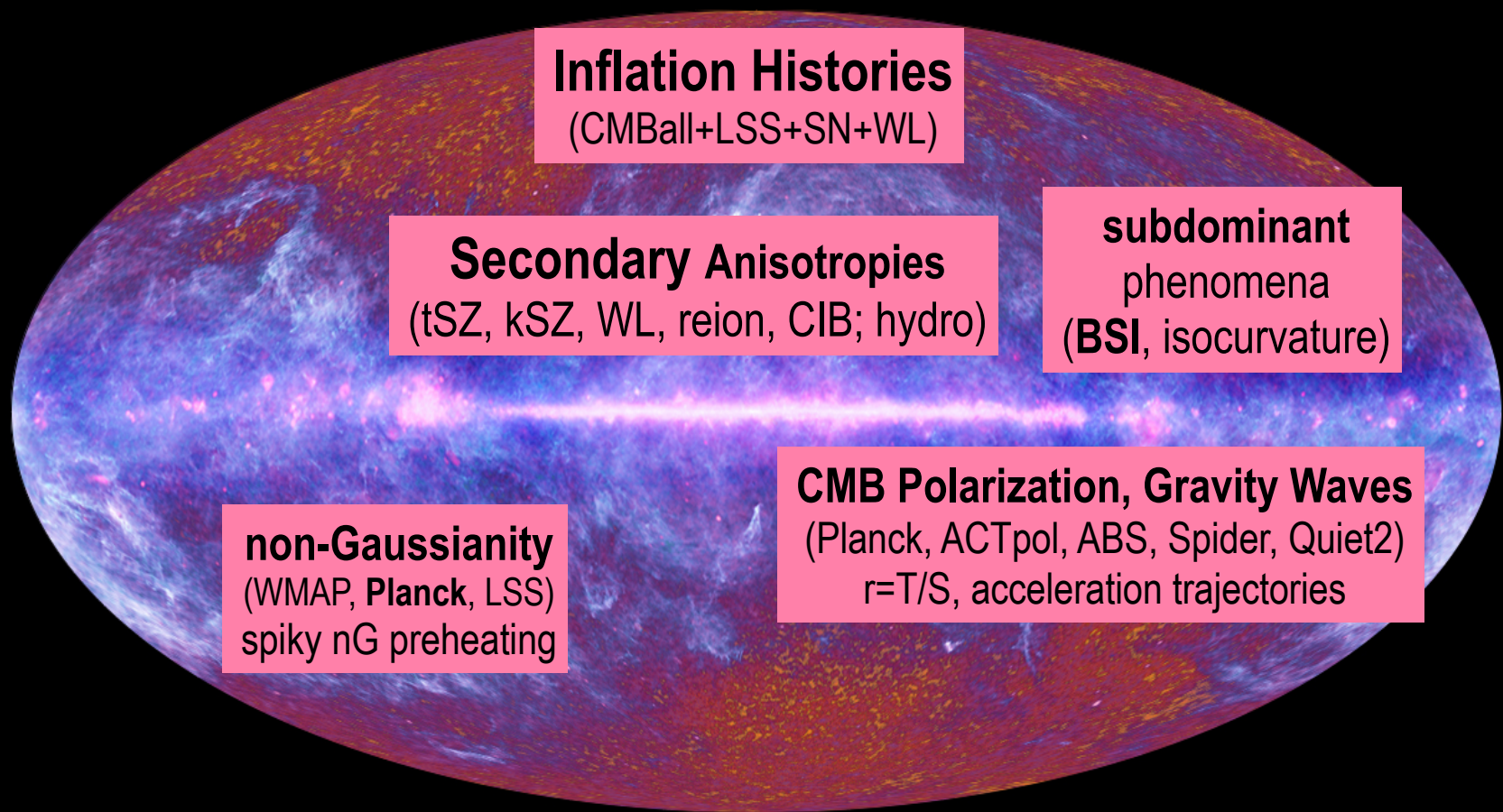
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·eesa

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subdominant
phenomena
(**BSI**, isocurvature)

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

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

Inflation Histories
(CMBall+LSS+SN+WL)

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

subdominant
phenomena
(**BSI**, isocurvature)

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

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

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

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

The Planck one-year all-sky survey

·eesa

(c) ESA, HFI and LFI consortia, July 2010

Beyond the standard model: tilted ΛCDM + x

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

Inflation Histories
(CMBall+LSS+SN+WL)

subdominant
phenomena
(**BSI**, isocurvature)

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

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⚬esa

Wednesday, 30 November, 11

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

CMB Polarization, Gravity Waves
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•eesa

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future fate?
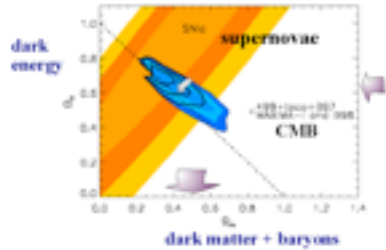
the cold-death of the

Universe (cf. 1800s heat-death)

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

beats incoherence ($\Upsilon, \nu, h_{+x,..}p,n,e$)

but entropy/particle

remains (for those particles that survive)

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

THE ACCELERATING UNIVERSE
Breakthrough of the Year

current Type Ia Supernova data Apr 2011

472: 123 low-z+ 242 **SNLS**3yr +93 SDSS1yr + 14 HST

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

current SNLS3++

best-fit
1σ trajectories

SN data
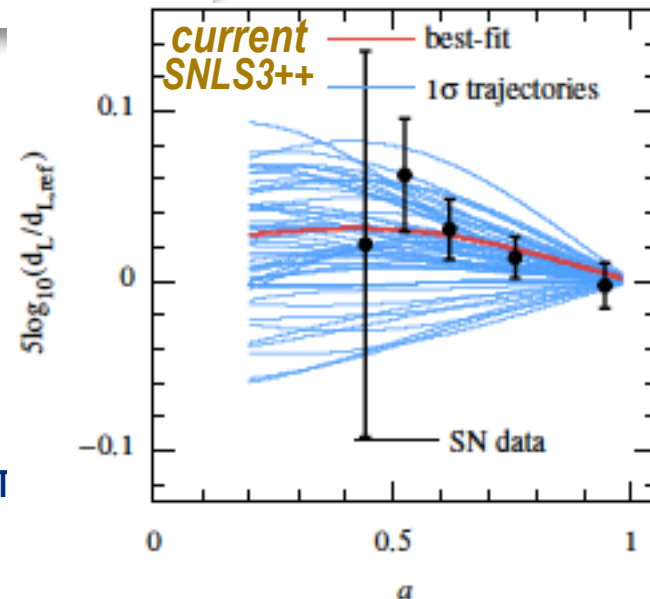
vintage 1998 conclusions
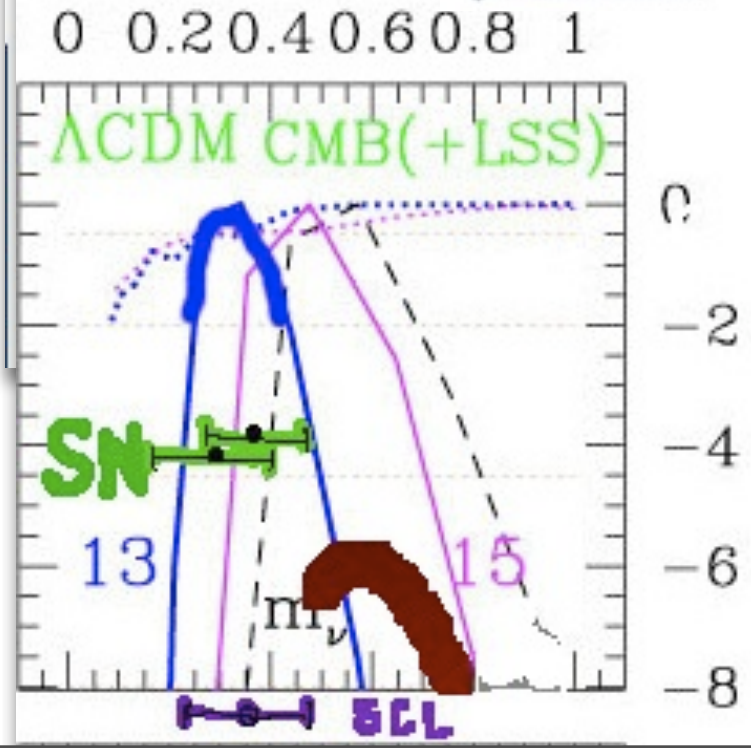
⇒ evidence for "dark energy" aka the cosmological constant

BOOM 2000

dark energy

SNIa

supernovae

Lange et 2001, Jaffe et 2001

499+toco+B97
+ MAXIMA-I and B98

CMB

Ω_Λ

Ω_m
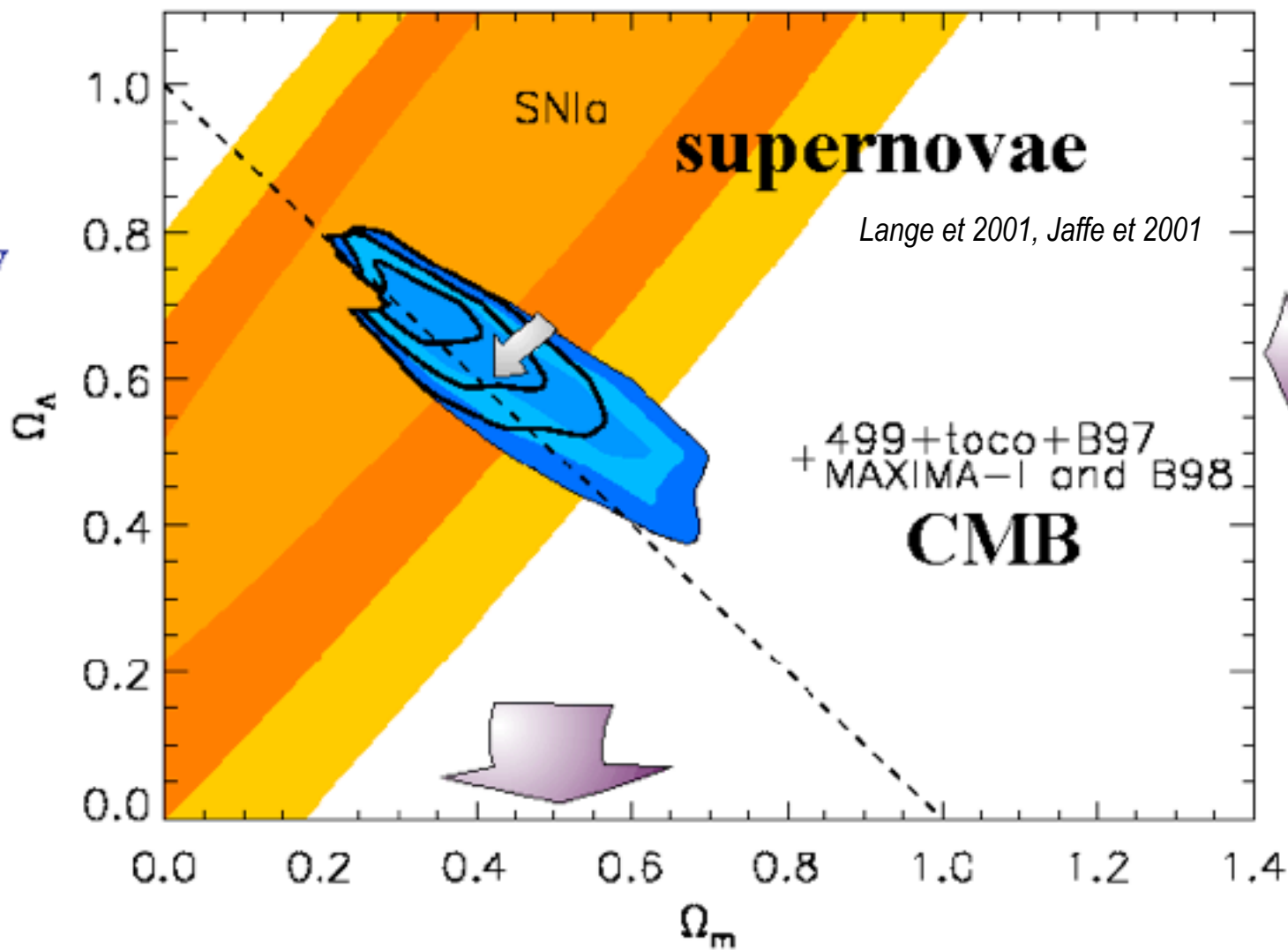
dark matter + baryons

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

Wednesday, 30 November, 11

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

ACT 2011

Sherwin et 2011: Λ from CMB alone

dark energy
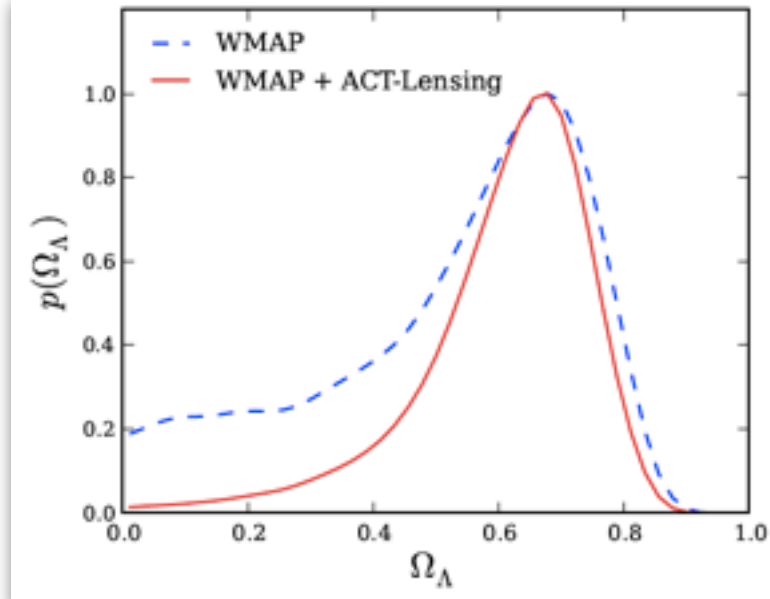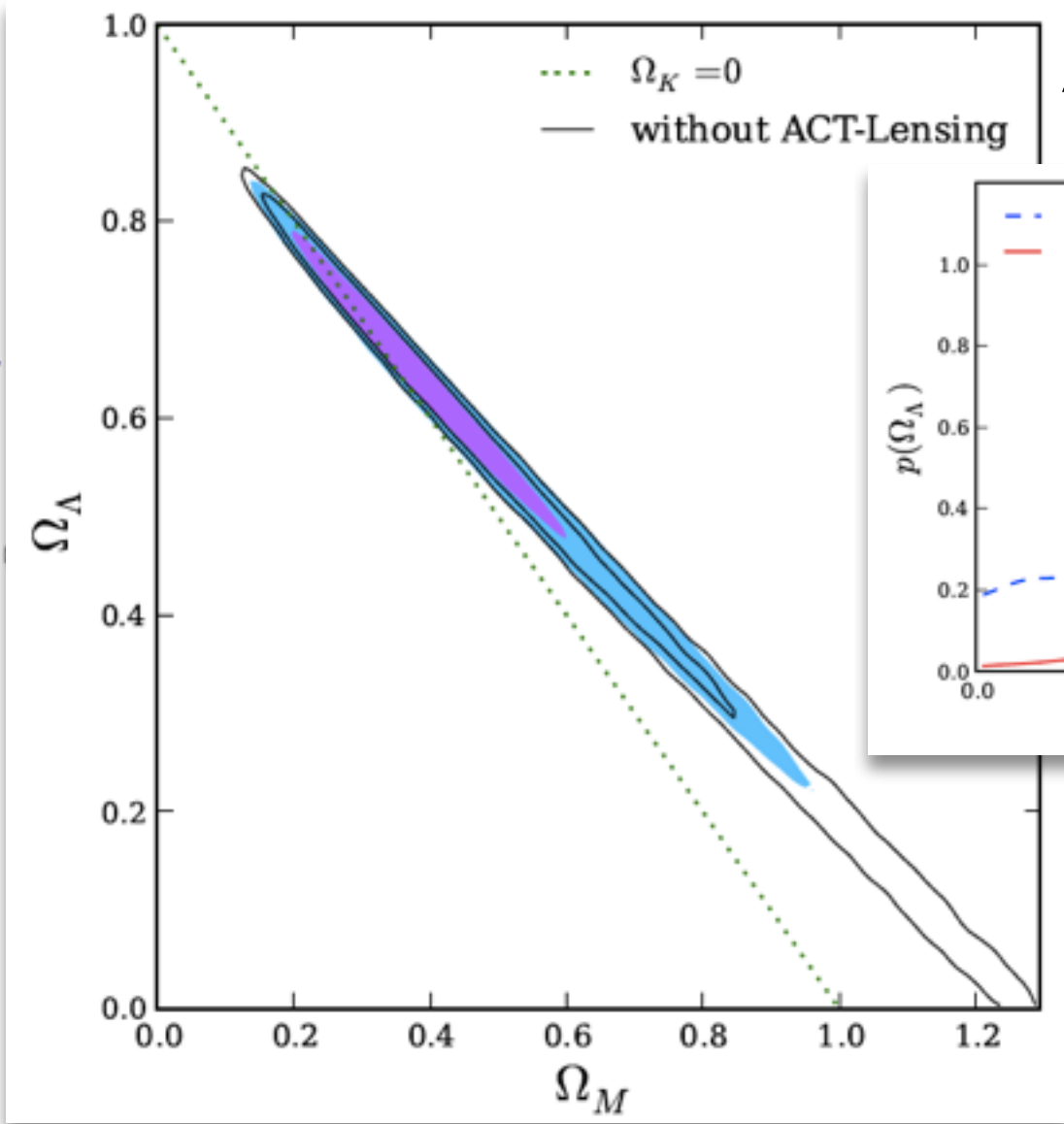
Dunkley et 2011 cosmic parameters

$\Omega_\Lambda = 0.736 \pm .012$

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

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

$1+W_{de}(a)$

current CMB+LSS +SNLS3++

best-fit

1σ trajectories

Huang, Bond, Kofman 2010; Bond, Huang 2011

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

3parameter form paves even wild late-inflaton trajectories

NOW & future DE equation of state trajectories
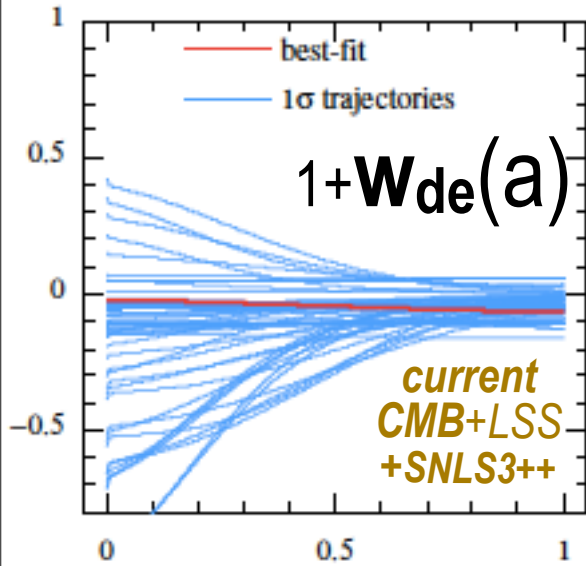
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$1+\mathbf{w_{de}}(a)$

current CMB+LSS +SNLS3++

Current Data
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$1+\mathbf{w_{de}}(a)$
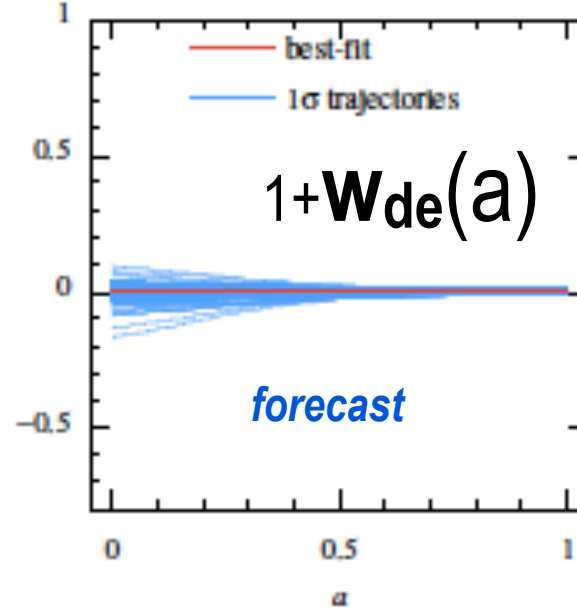
forecast

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

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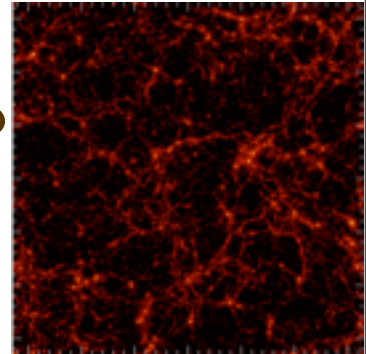
Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)

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

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

pre-
heating
patch
(~1cm)

$\chi(\mathbf{x}, \ln \mathbf{a})$

$\ln \mathbf{a}(\mathbf{x}, \ln \mathbf{H})$
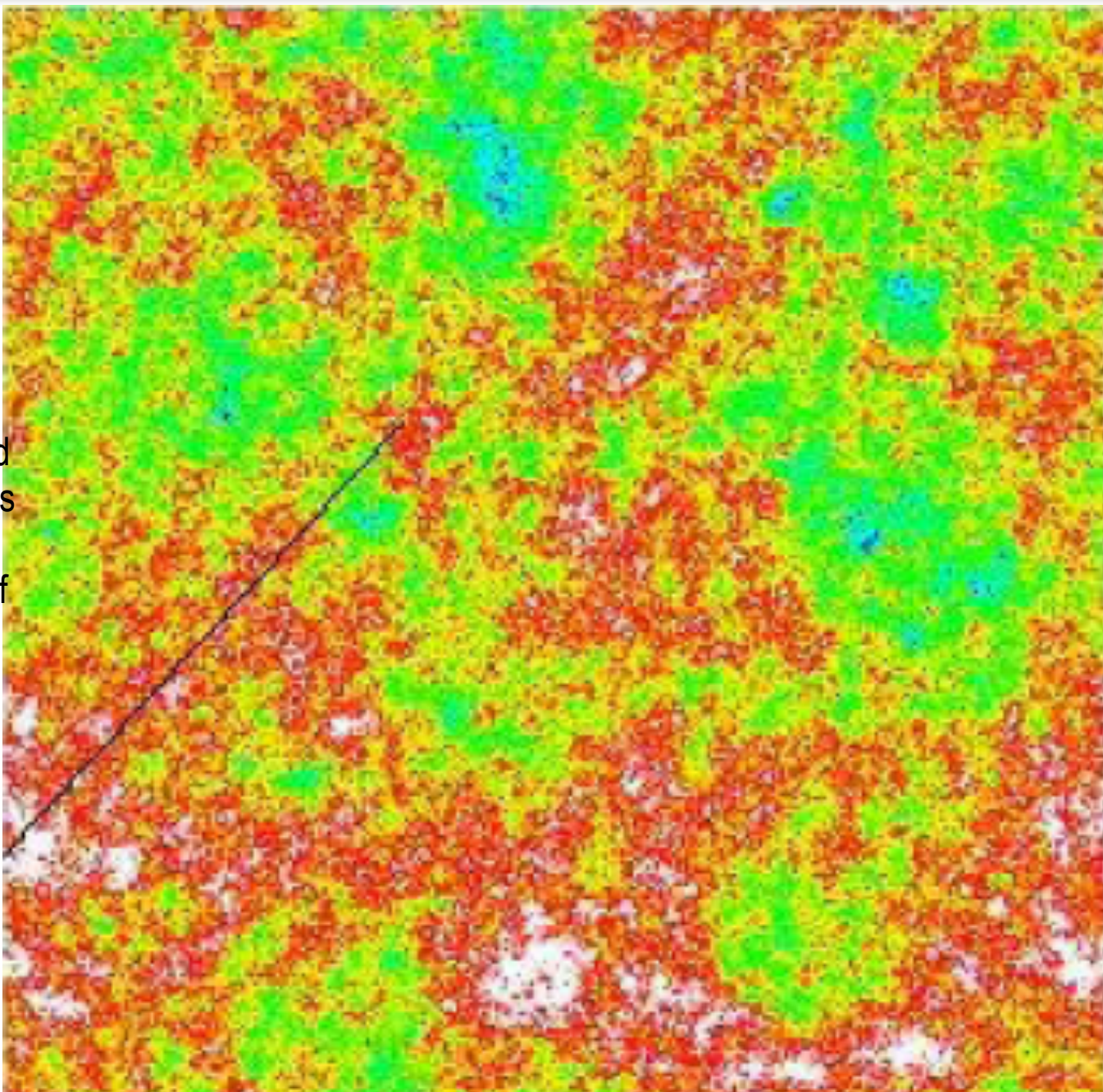
*evolve
from early
U vacuum
potential
and
vacuum
noise*

10 Gpc

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

χ

$_{\ln}\mathbf{a(x,}_{\ln}\mathbf{H)}$

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

pre- heating patch (~1cm)

evolve from early U vacuum potential and vacuum noise
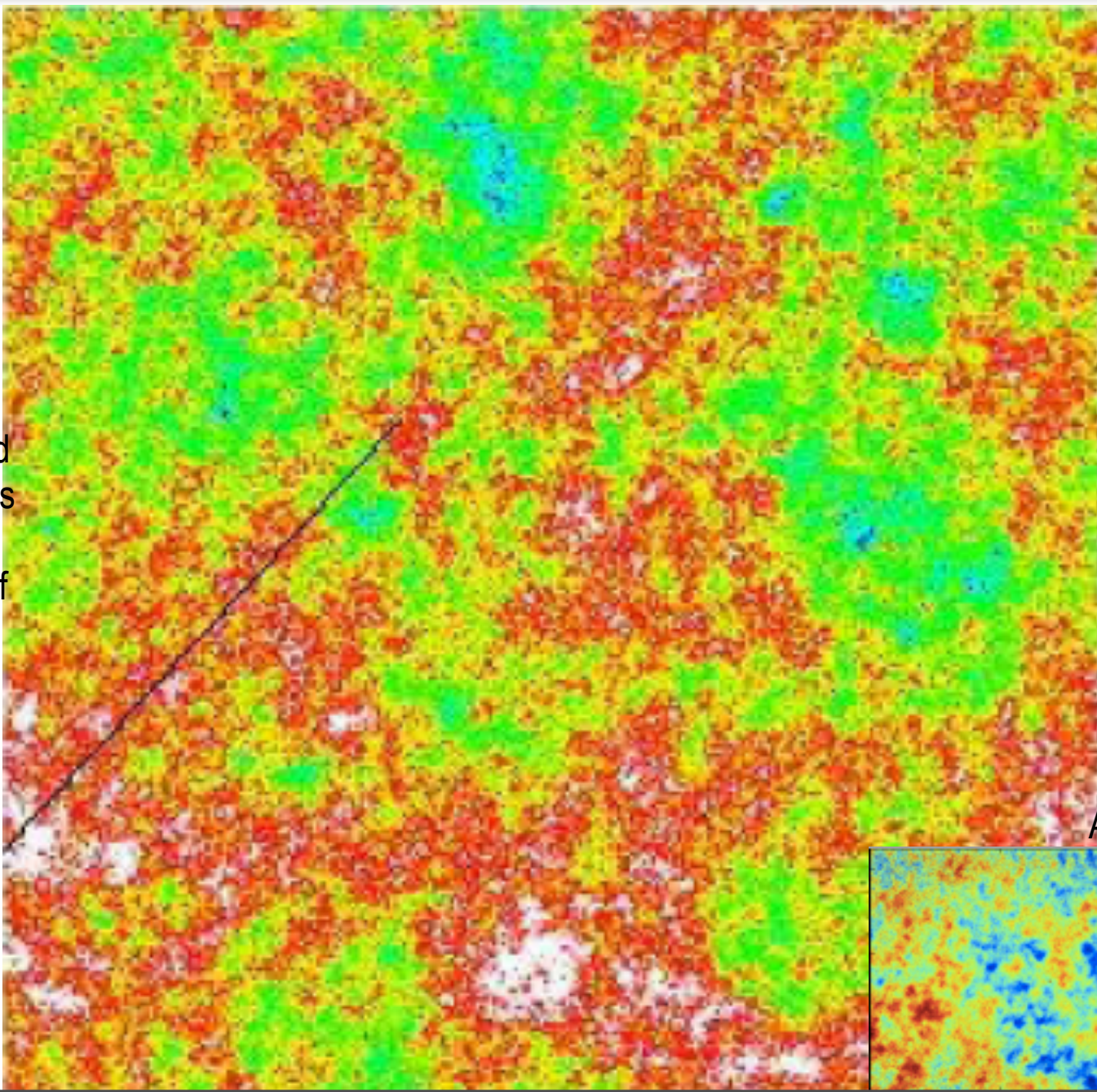
ACT+WMAP7 hajian+10

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

$\rho_g(x,t)$

400 Mpc

ΛCDM

WMAP5

gas
density

Gadget-3
SF+ SN
E+
winds
+CRs

512^3

BBPSS10

BBPS1,2,3,4

evolve from early U vacuum potential and vacuum noise

in the presence of late U vacuum potential aka dark energy
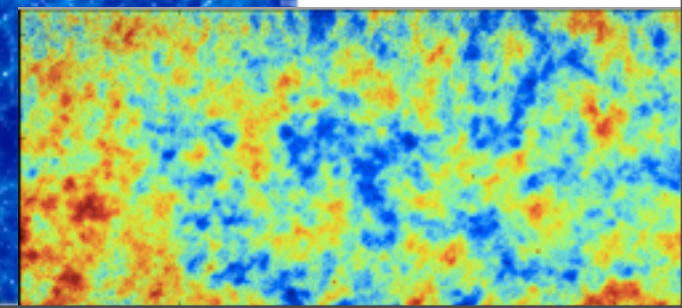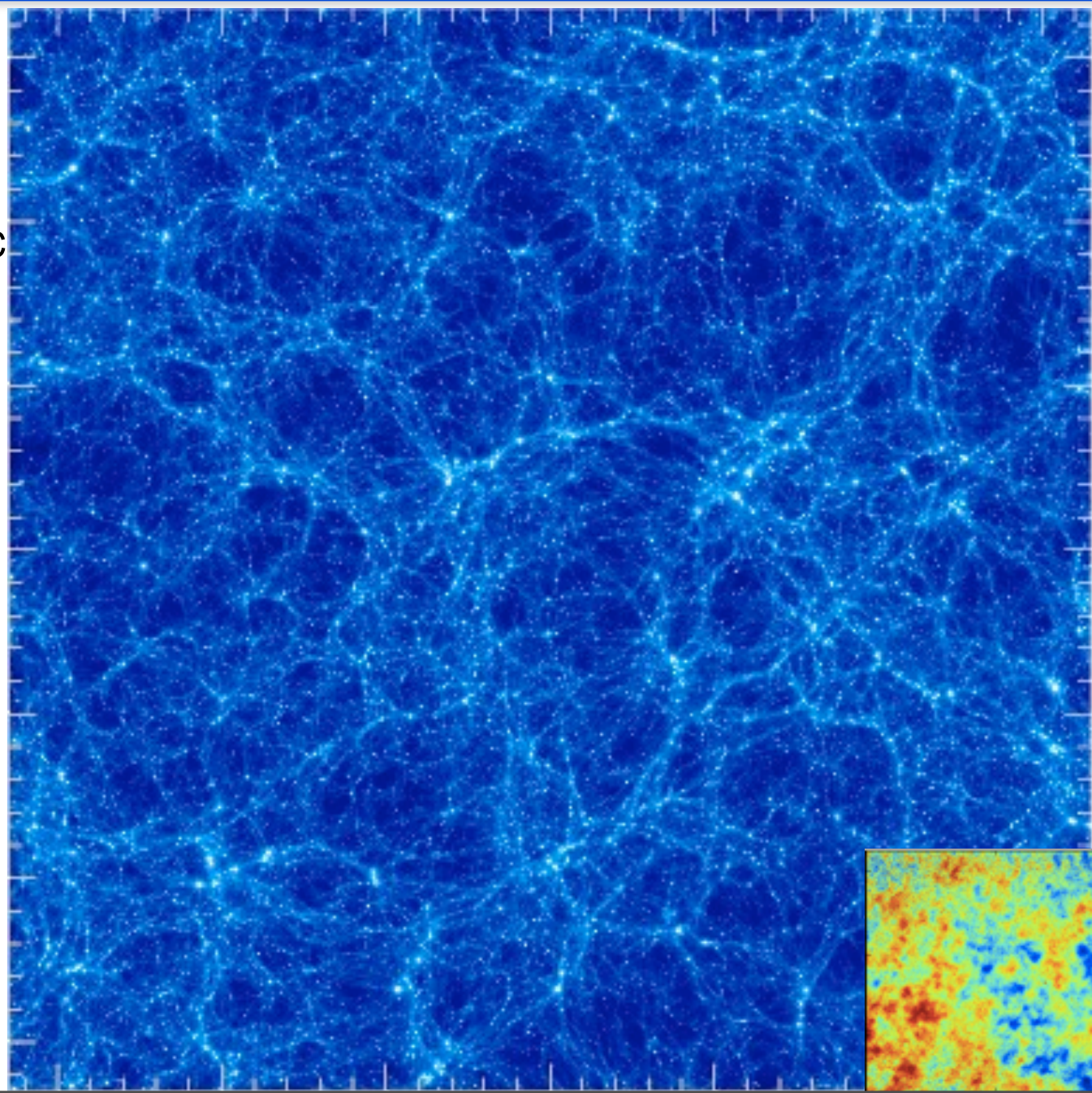
pressure intermittency *in the cosmic web, in cluster-group concentrations probed by* **tSZ**
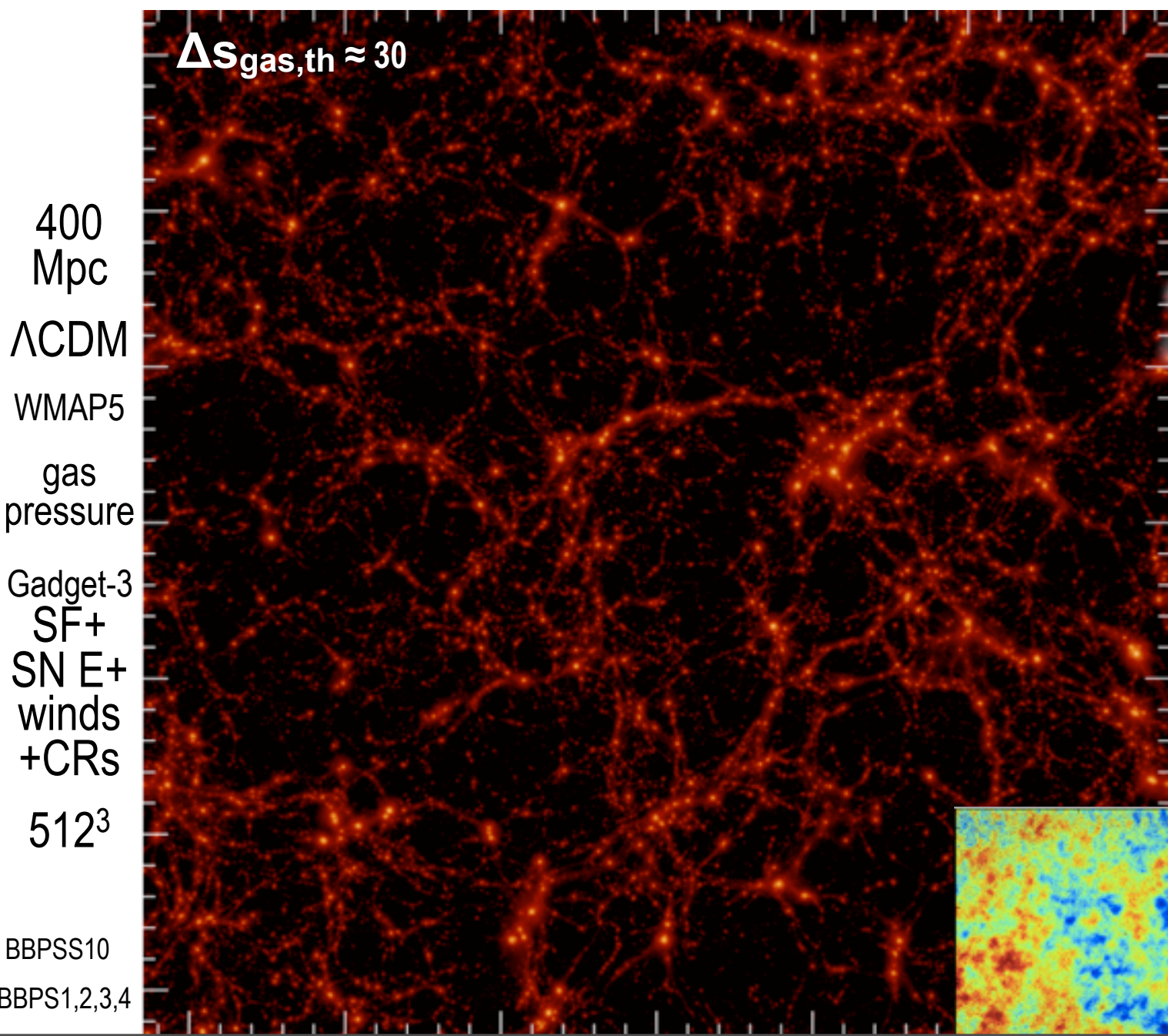
$p_e(x,t)$

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

400 Mpc

ΛCDM

WMAP5

gas pressure

Gadget-3
SF+
SN E+
winds
+CRs

512^3
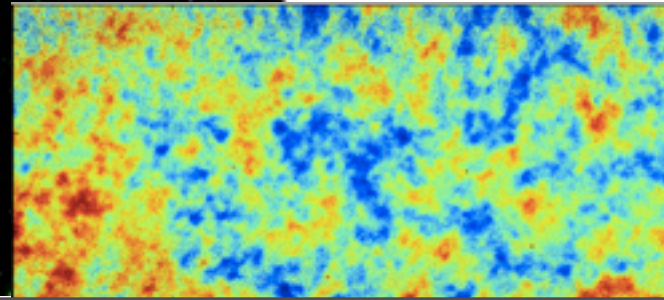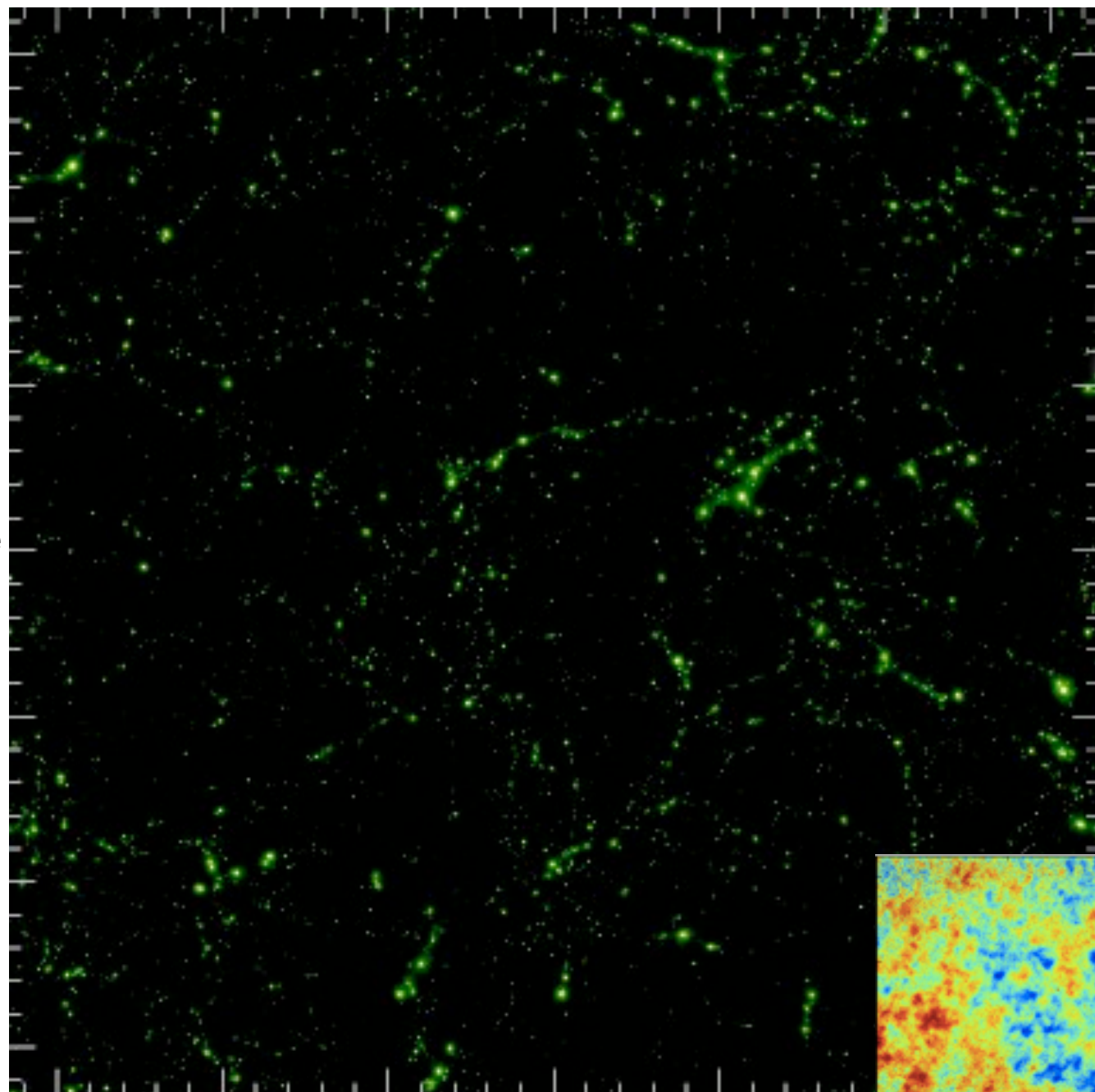
BBPSS10

BBPS1,2,3,4

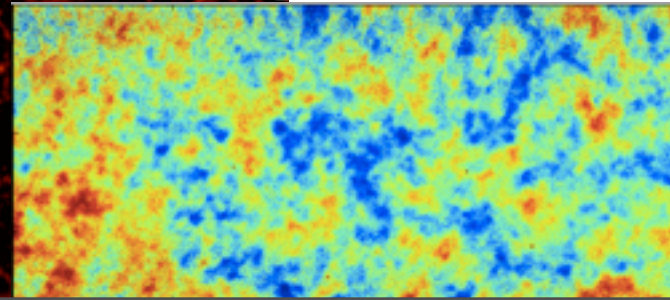# entropy intermittency *in the cosmic web,* *via* *gravitation-induced shocks (then E/S-feedback)*
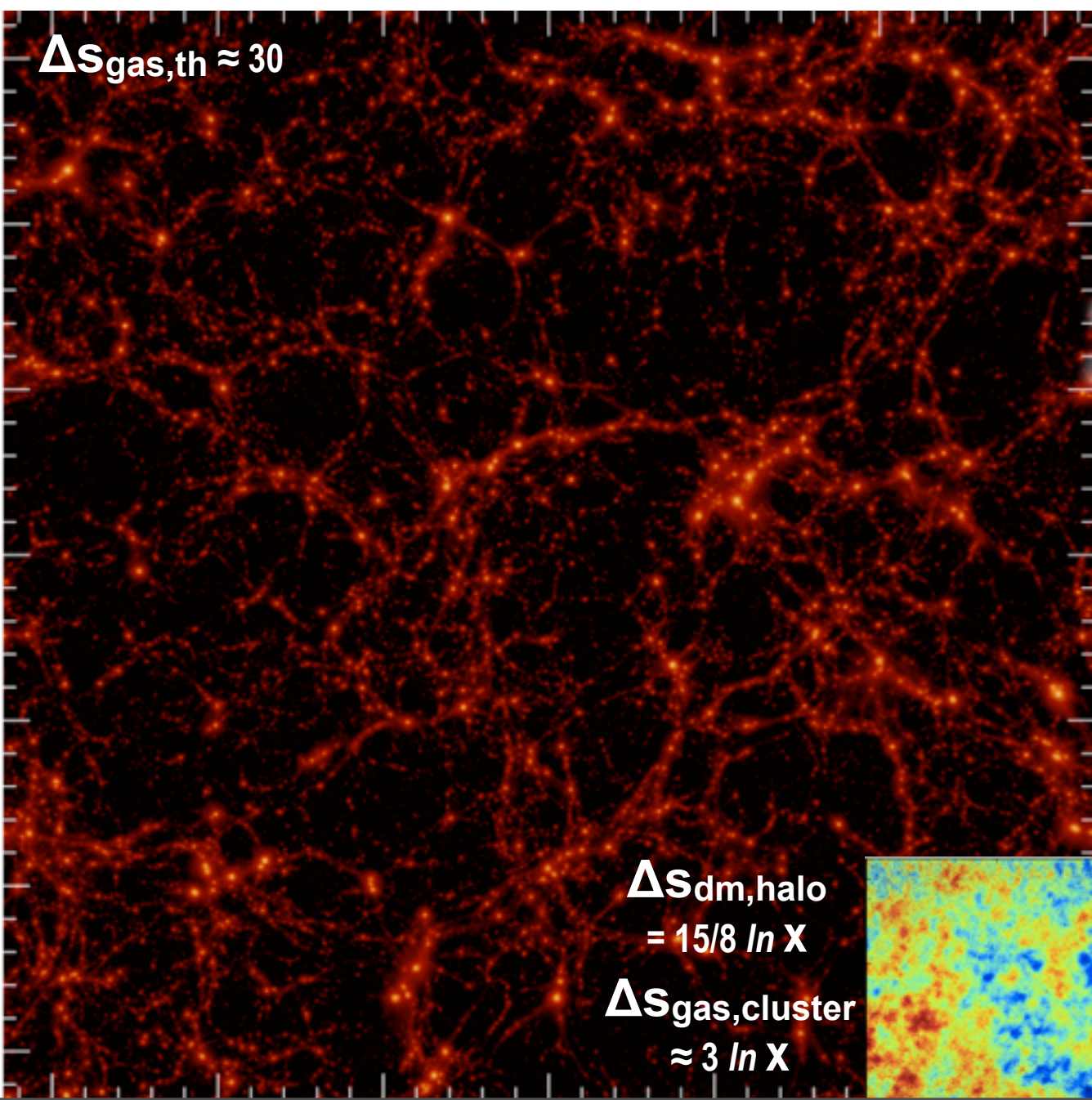
$s_{b,th}(x,t)$

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

$\Delta s_{gas,th} \approx 10$

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

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the energetic, turbulent, dissipative, compressive

life of the IGM/ICM/ISM

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

400 Mpc

ΛCDM

WMAP5

gas pressure

Gadget-3
SF+
SN E+
winds
+CRs

512^3

BBPSS10

BBPS1,2,3,4

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

400 Mpc

ΛCDM

WMAP5

gas pressure

Gadget-3
SF+
SN E+
winds
+CRs

512^3

BBPSS10

BBPS1,2,3,4

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

$\Delta s_{gas,cluster}$
≈ 3 *ln* X

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

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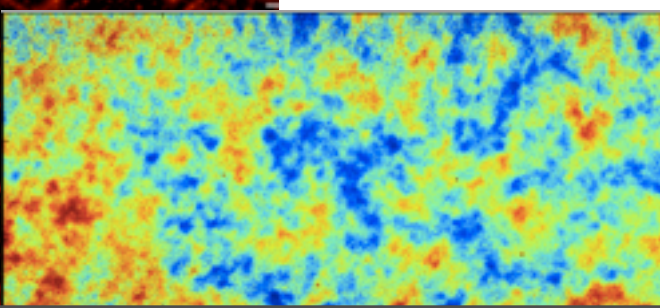
h_{+x} gravitons generated as zero point fluctuations during early universe inflation induce CMB (B + E) polarization

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

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

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

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

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?
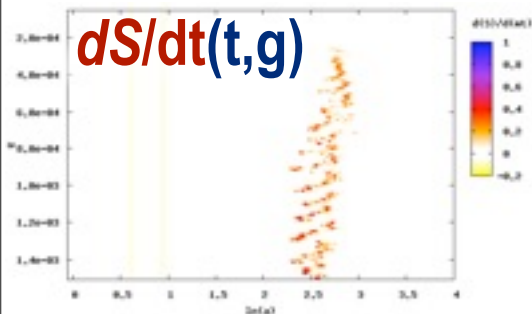
dS/dt(t,g)

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

χ

ₗₙ**a(x,**ₗₙ**H)**

current
Hubble
patch
~10 Gpc

speed
limit
horizon

patterns
in the
quantum
jitter
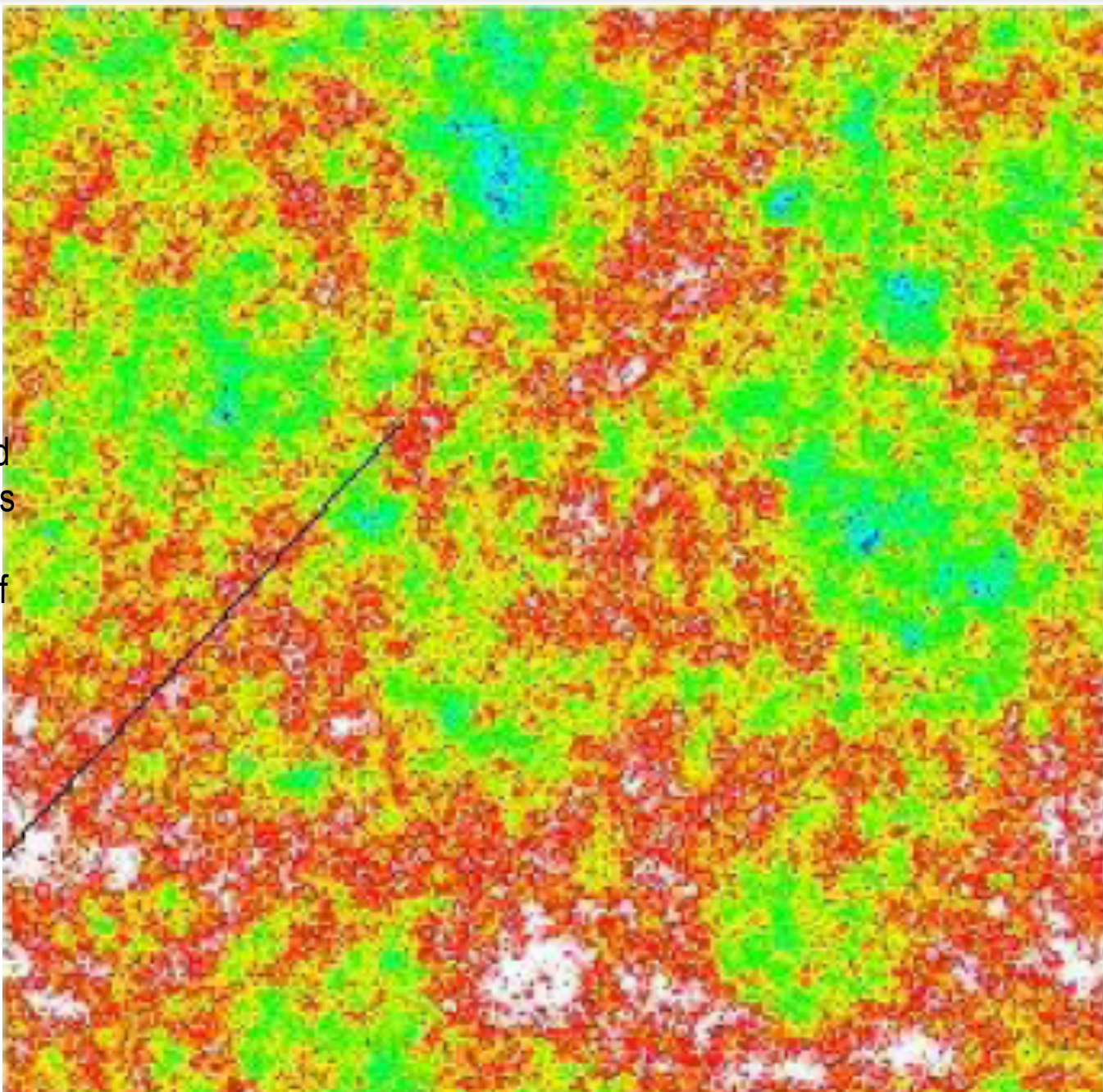evolve
under
gravity

(& gas
dynamics)
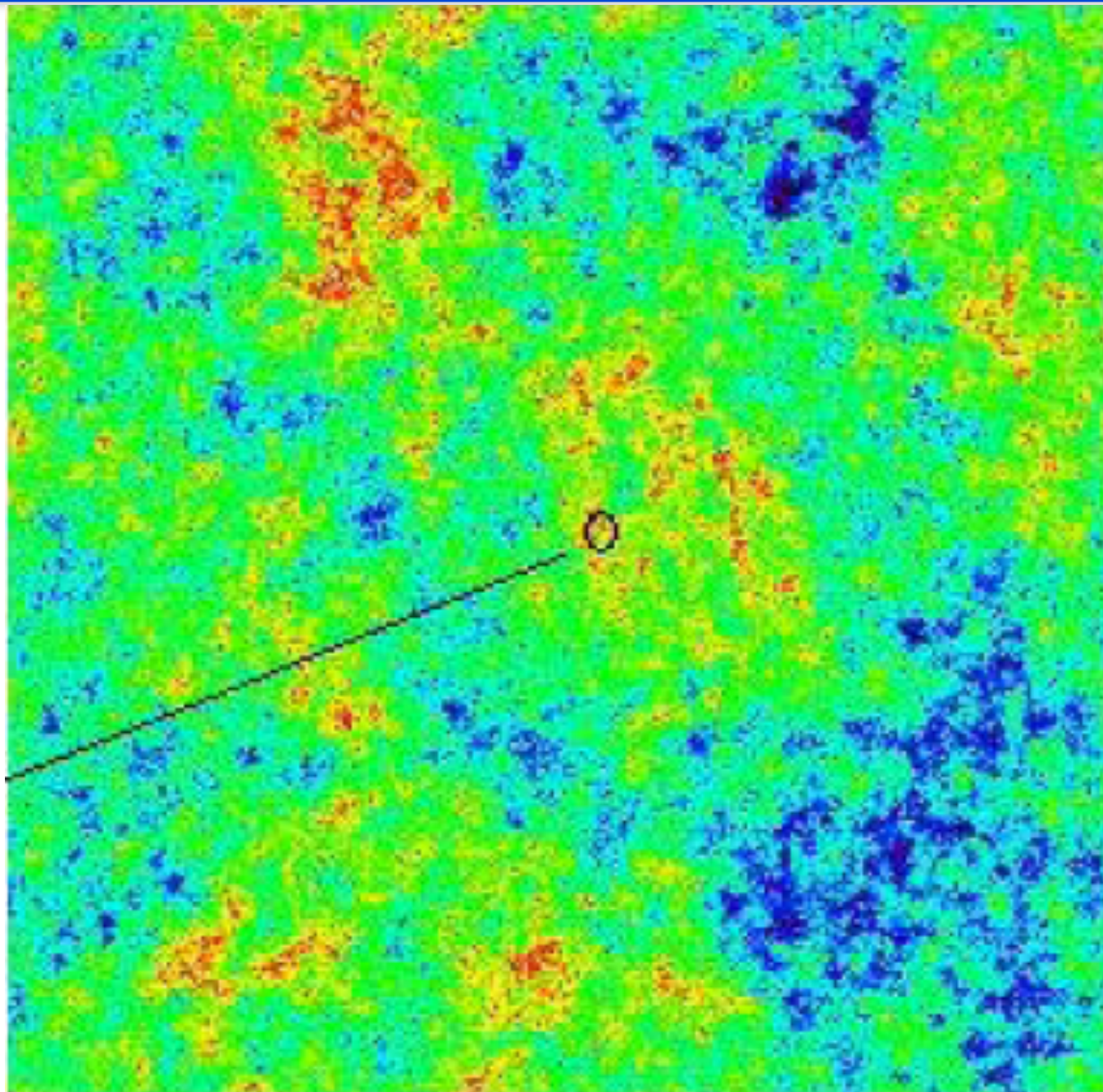
1000 Gpc

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

χ

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

pre-heating patch (~1cm)

$\chi(\mathbf{x},_{\ln}\mathbf{a})$

$_{\ln}\mathbf{a}(\mathbf{x},_{\ln}\mathbf{H})$

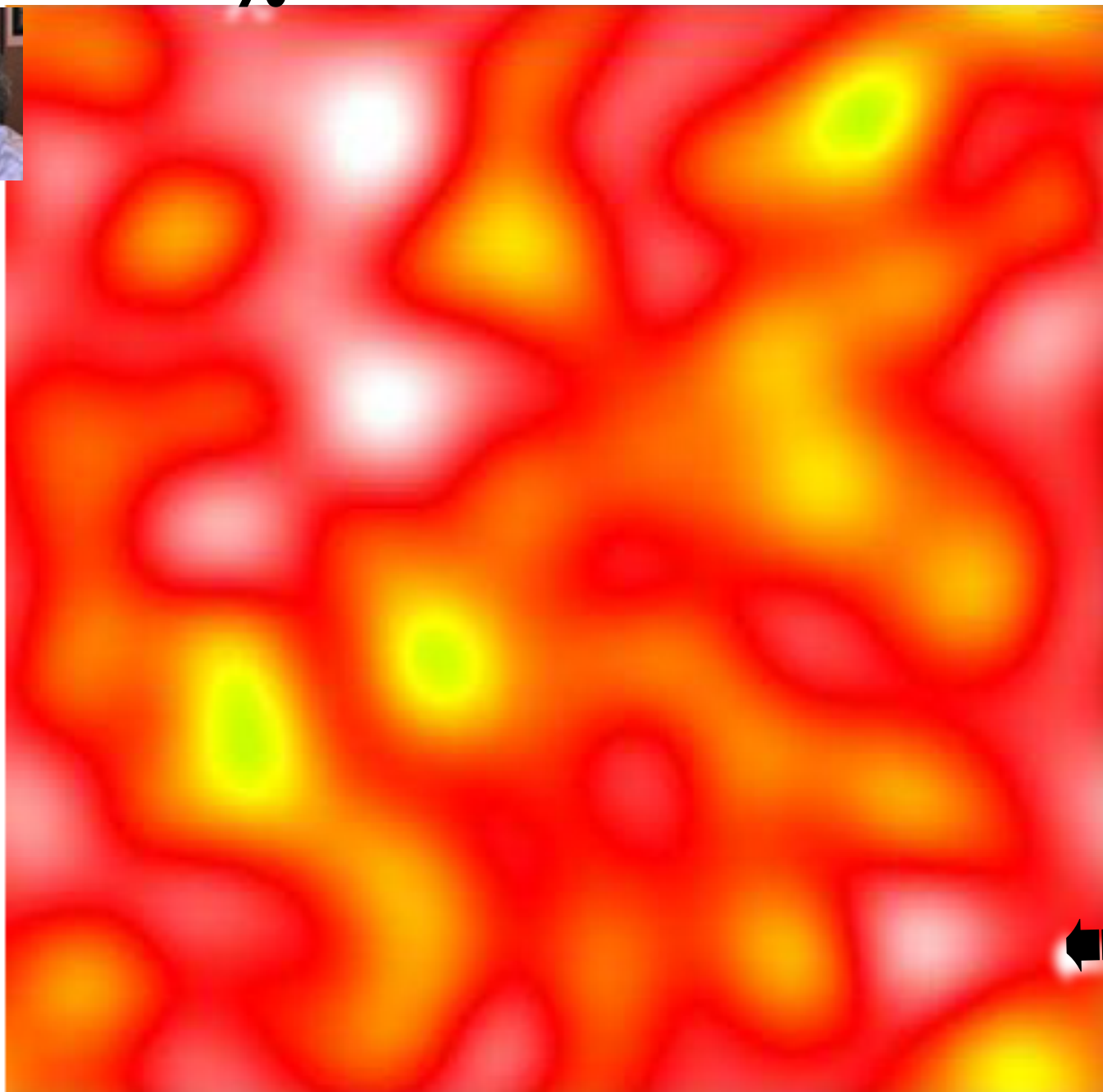*evolve from early U vacuum potential and vacuum noise*
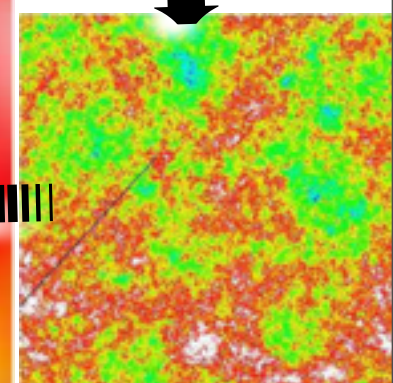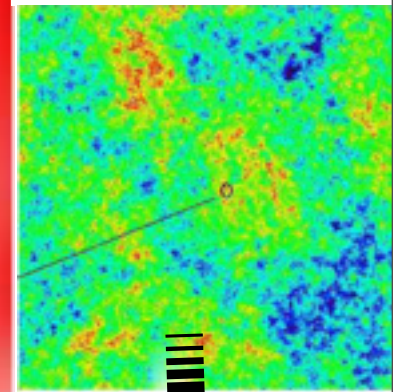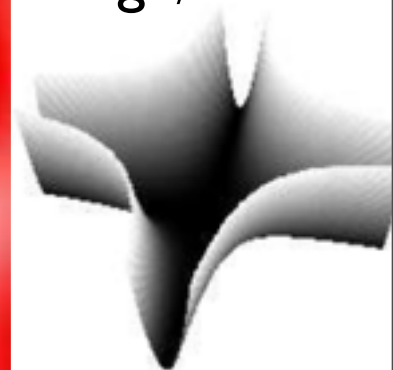
10 Gpc

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

Parametric Resonance

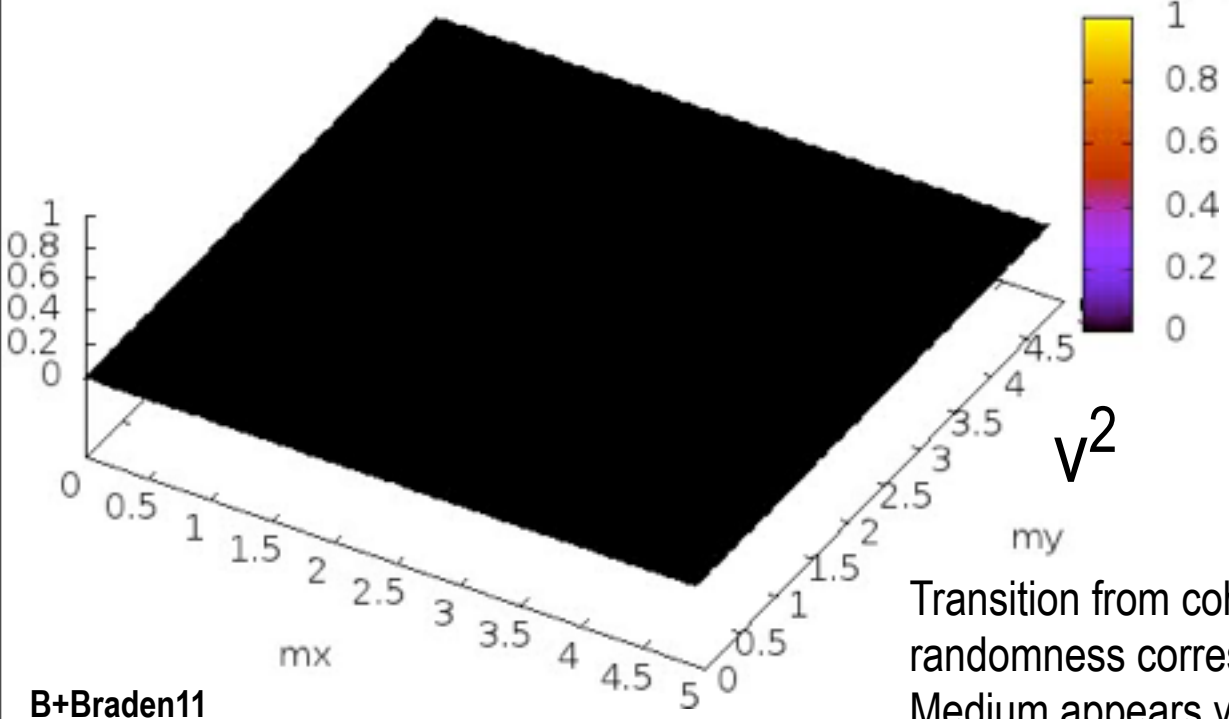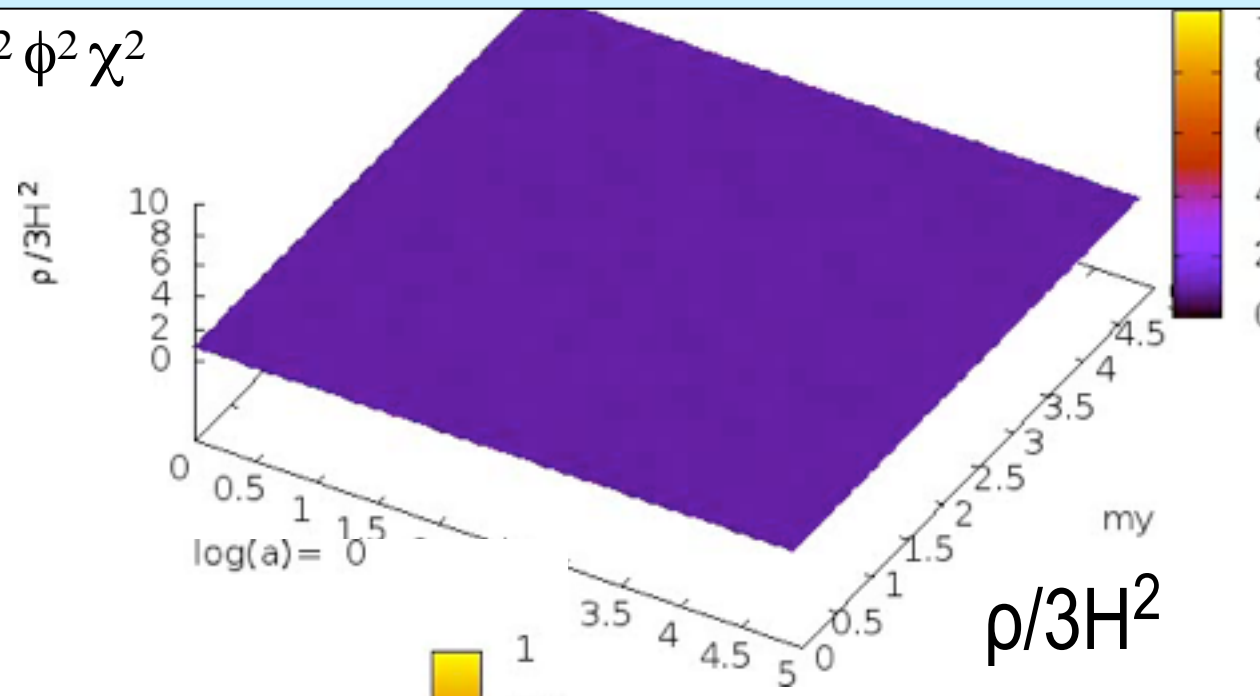$g^2/\lambda \sim 1$

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 $\Rightarrow$
Hydrodynamic Description

$$\rho = -T^0_0 \qquad P = -T^i_i$$

$$v^i = aT^i_0 / (\rho + P)$$

$\rho/3H^2$
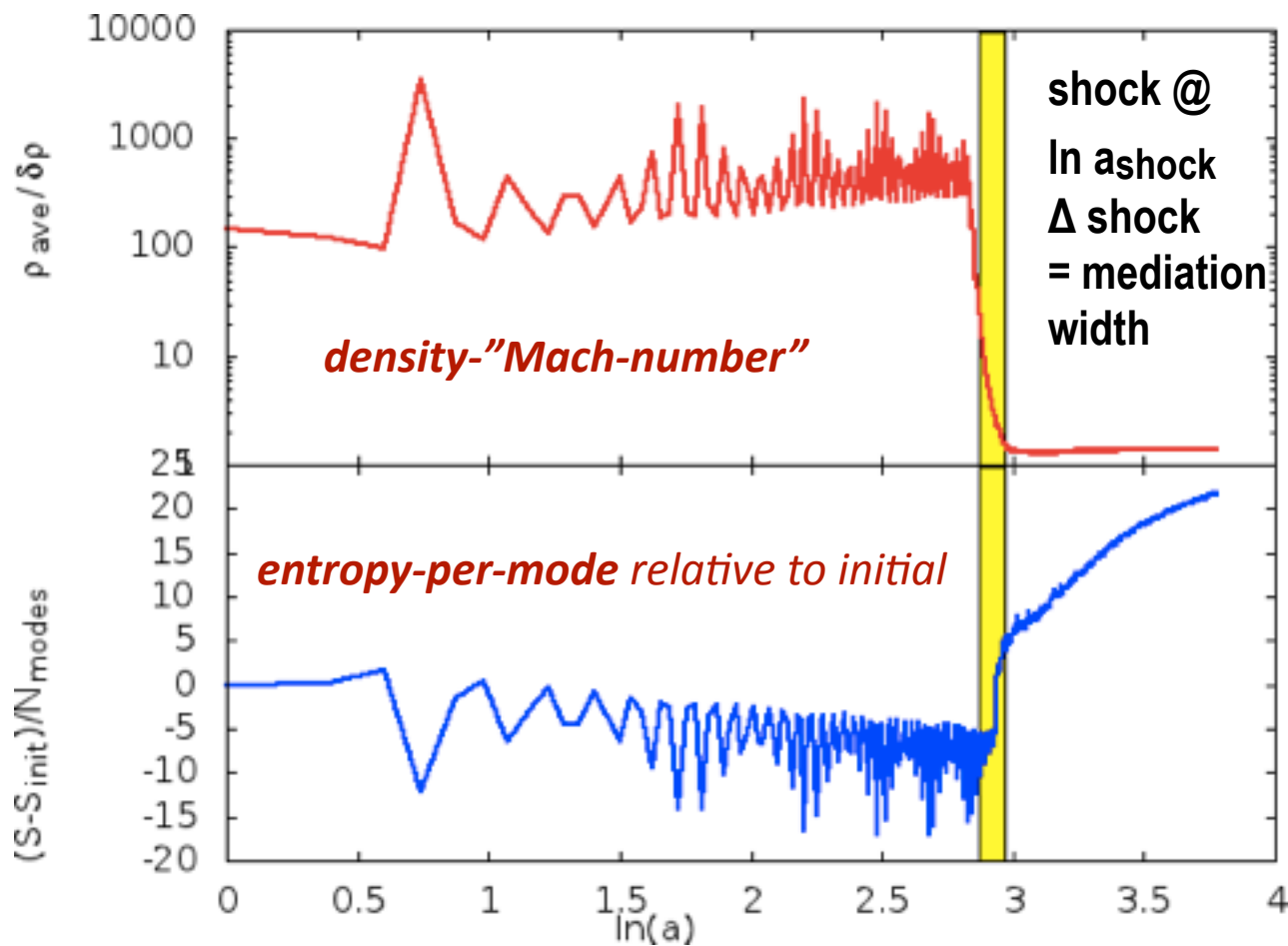
v^2

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

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

shock @
ln a$_{shock}$
Δ shock
= mediation
width

density-"Mach-number"

entropy-per-mode *relative to initial*

true
thermal
equilibrium
far off

➤

& on to
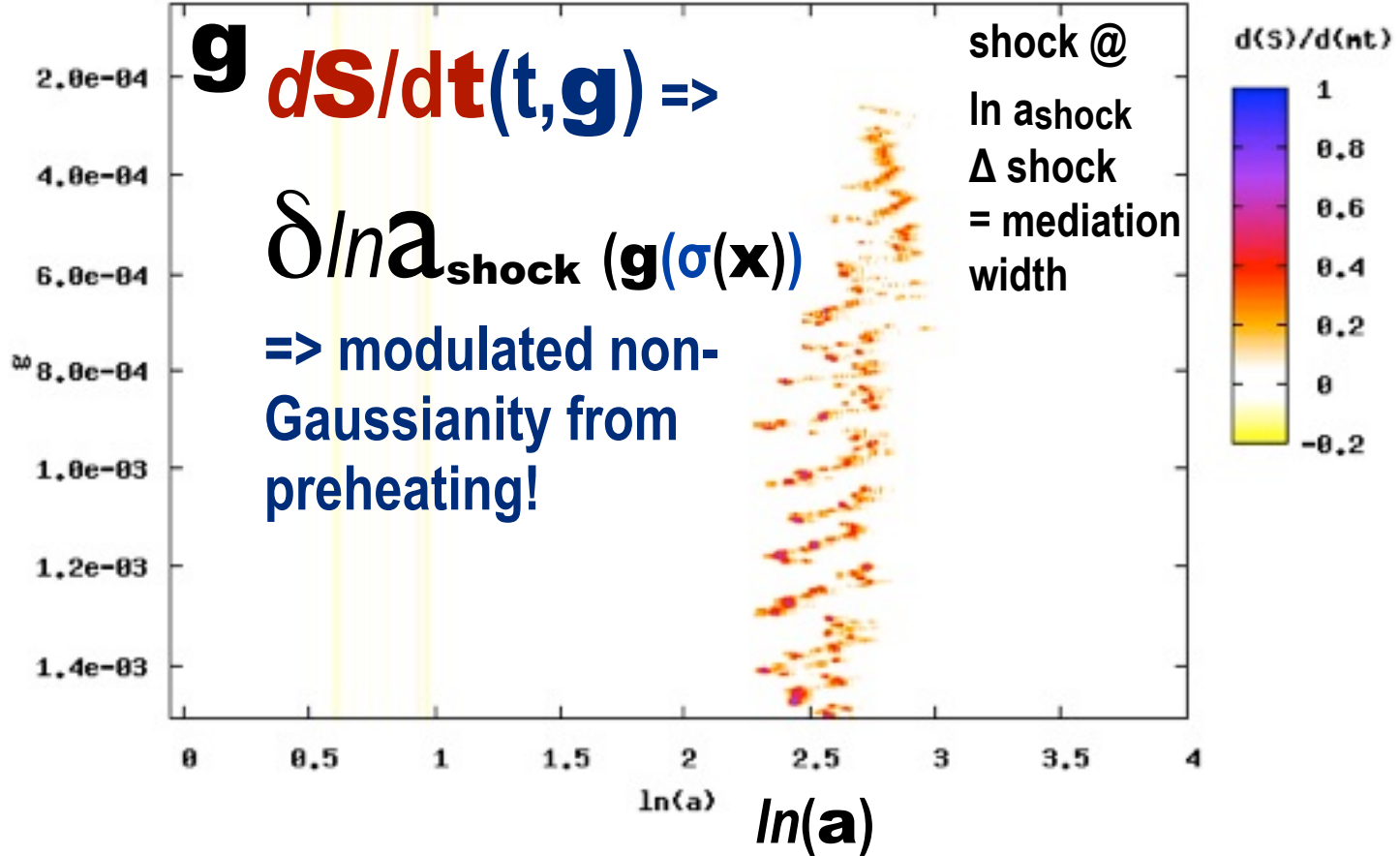coupling to
standard
model
degrees of
freedom

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

g $d\mathbf{S}/d\mathbf{t}(\mathbf{t},\mathbf{g}) =>$

$\delta ln\mathbf{a}_{\text{shock}}\ (\mathbf{g}(\sigma(\mathbf{x})))$

=> modulated non-Gaussianity from preheating!

shock @

ln a_shock
Δ shock
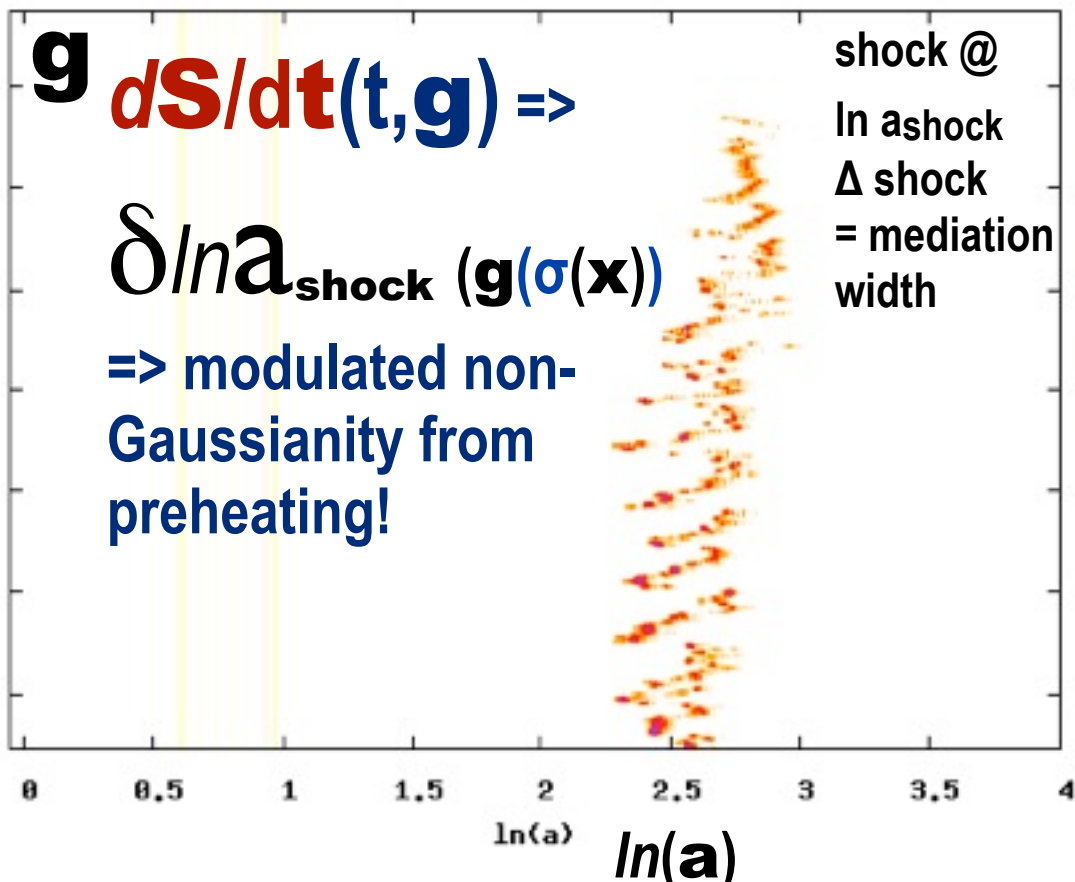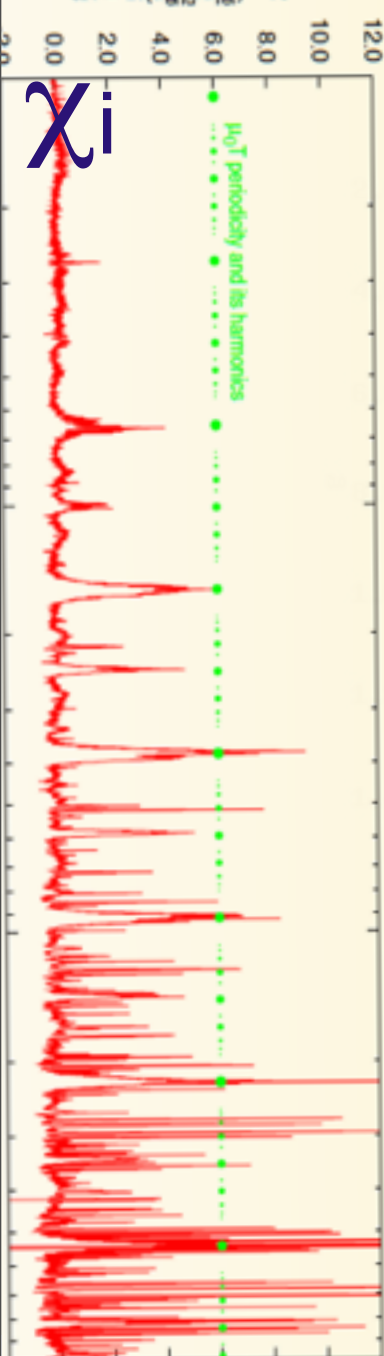**= mediation**
width

$ln(\mathbf{a})$

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

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

modulated non-G Kofman03
B+Braden11

the Shock-in-time: entropy production rate

$g^2/\lambda = 1.875$

χ_i

$\mu_0 T$ periodicity and its harmonics

$\delta N = ln(a_{end}/a_{infl})$

g $d\mathbf{S}/d\mathbf{t}(t, \mathbf{g}) \Rightarrow$

$\delta ln\mathbf{a}_{shock}\,(\mathbf{g}(\sigma(\mathbf{x})))$

=> modulated non-Gaussianity from preheating!

shock @

ln a shock
Δ shock
= mediation
width

$d(S)/d(nt)$

$ln(\mathbf{a})$

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

Chaotic Billiards: NonGaussianity from Parametric Resonance in Preheating

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

$\delta ln\mathbf{a}\ (\chi_i(x,t))$

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

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

B+Braden11

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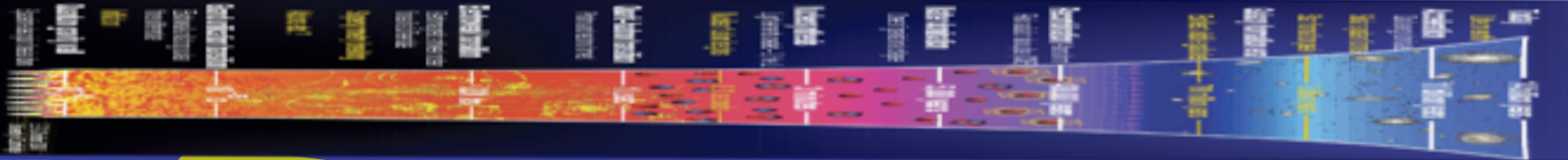
primary anisotropies

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

- tightly-coupled photon-baryon fluid:

oscillations δ_γ v_γ π_γ

- viscously damped

- polarization π_γ

- gravitational redshift Φ SW dΦ/dt

I N F L A T I O N

Decoupling LSS

17 kpc (19 Mpc)

Lsound/ ksound

secondary anisotropies

- nonlinear evolution

- weak lensing

- thermal SZ +kinetic SZ

- dΦ /dt

- dusty/radio galaxies, dGs

the nonlinear **COSMIC WEB**

dS/dt

M I L K Y

W A Y

z=0

reionization

z ~ 10

dS/dt

z ~ 1100   redshift   z

time   t

$13.7\text{-}10^{-50}$Gyrs   13.7Gyrs   10Gyrs   today

Wednesday, 30 November, 11

end