Lev Kofman June 17, 1957 - November 12, 2009

Ph.D 1984, Inst Ap & Atmos Phys, Tartu, Estonian Acad Sci & Landau Institute, Moscow. Advisor: Alexei Starobinsky

1987-90 Senior Fellow, 83-87 Fellow, Estonian Acad Sci, Tartu

1987 Medal, Soviet Acad Sci in Phys (<35)

2008-09 CITA Acting Director
2006-08 CITA Associate Director
1998-2009 CITA & UofT Professor
CIFAR Fellow
1993-98 Inst for Astronomy, U of Hawaii, Associate Professor, CIFAR Associate
1992-93 CITA Sr RA, CIFAR Scholar
1992 Princeton U, Ap Sci, Lecturer
1991 CITA Postdoctoral Fellow

2007 Fellow American Physical Society
2006 Humboldt Award, Germany
2006 FInstPhys
1999 Ont Premier Research Excellence Award
1998 Fellow CIFAR
1993-98 Associate CIFAR
1992 Scholar CIFAR

Memorial for Lev Kofman

Wednesday December 9, 2009
Koffler House, University of Toronto
569 Spadina Avenue
5:30 p.m.

Prof. Norman Murray, Director
Canadian Institute for Theoretical Astrophysics

Prof. Richard Bond
Canadian Institute for Theoretical Astrophysics &
Canadian Institute for Advanced Research

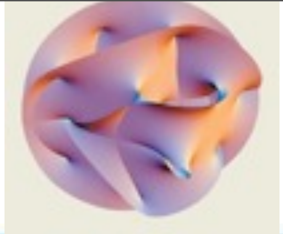
Prof. Peter Martin
Canadian Institute for Theoretical Astrophysics

Dr. Melvin Silverman, Vice-President Research
Canadian Institute for Advanced Research

Prof. Sergei Shandarin
University of Kansas

Ms. Anna Chandarina

Reception to follow on 2nd floor



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Zhiqi Huang, Pascal Vaudrevange





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

CIAR 25 years cifar

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

Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

Cosmotician *P(cosmic parameters|D,T), P(D|T) D=CMB,LSS,SN,..,complexity, life T=baryon, dark matter, vacuum mass-energy densities,...,early and late inflation,structure of manfolds (extra compactifying 7 + 3+1), holes, branes, fibres, strings,vacuua landscape, physical coupling 'constants'* **Anthrostatician**

Cosmic history: what is U made of? $\Rightarrow \rho_{dm}/\rho_b = 5.1 \Rightarrow \rho_m/\rho_{de} = .30$ **and** Ω_m=0.268 ±.012, Ω_Λ=0.736 ±.012 $\Rightarrow$ (0.294 ±.011, 0.706 ±.011)

How Structure in the Universe Arose?: ***from nearly Gaussian early Inflation vacuum fluctuations in curvature, isocurvature & Gravity Wave fields morphs into the nonlinear Cosmic Web: clusters, filaments, voids; galaxies***

What is the fate of U: dark energy properties driving late inflation

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CMB*ology* & *x*CDM, *x*=Λ+*tilt*: the cosmic standard model, status@Nov09:

Boomerang, CBI, Acbar, WMAP, DASI, QuAD, .. P(D|T) paths for early & late inflation

is there a y to x? @2011-12 from new expts: *ACT, Planck,* Spider, Keck, ACTpol
SPT, EBEX, Bicep, Quiet, SPTpol,.. acceleration paths for B-modes, dark energy probes

What is the Universe made of?

*NOW: **baryons + (cold-ish) dark matter + dark energy/inflaton + tiny curvature energy** (+light neutrinos+photons). ??a bit of strings/textures/PBHs??* ***web of galaxies/clusters***

THEN: coherent inflaton /**"vacuum" energy** plus **zero-point fluctuations** in all fields (≈*Gaussian RF*) & then preheat via mode coupling to incoherent cascade to thermal equilibrium aka **quark-gluon plasma**

& how was it, is it & will it be distributed?

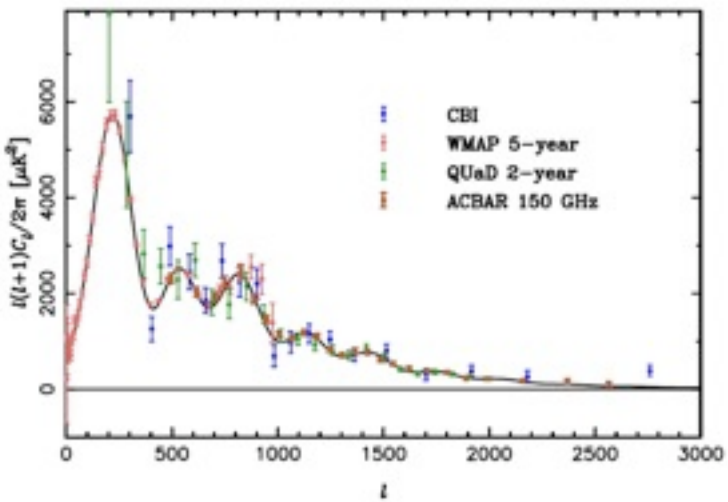
very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

inflation cyclic baryogenesis dark matter BBN νdec **dark energy**

$V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$?



$V_{eff}(\psi_{inf})$?

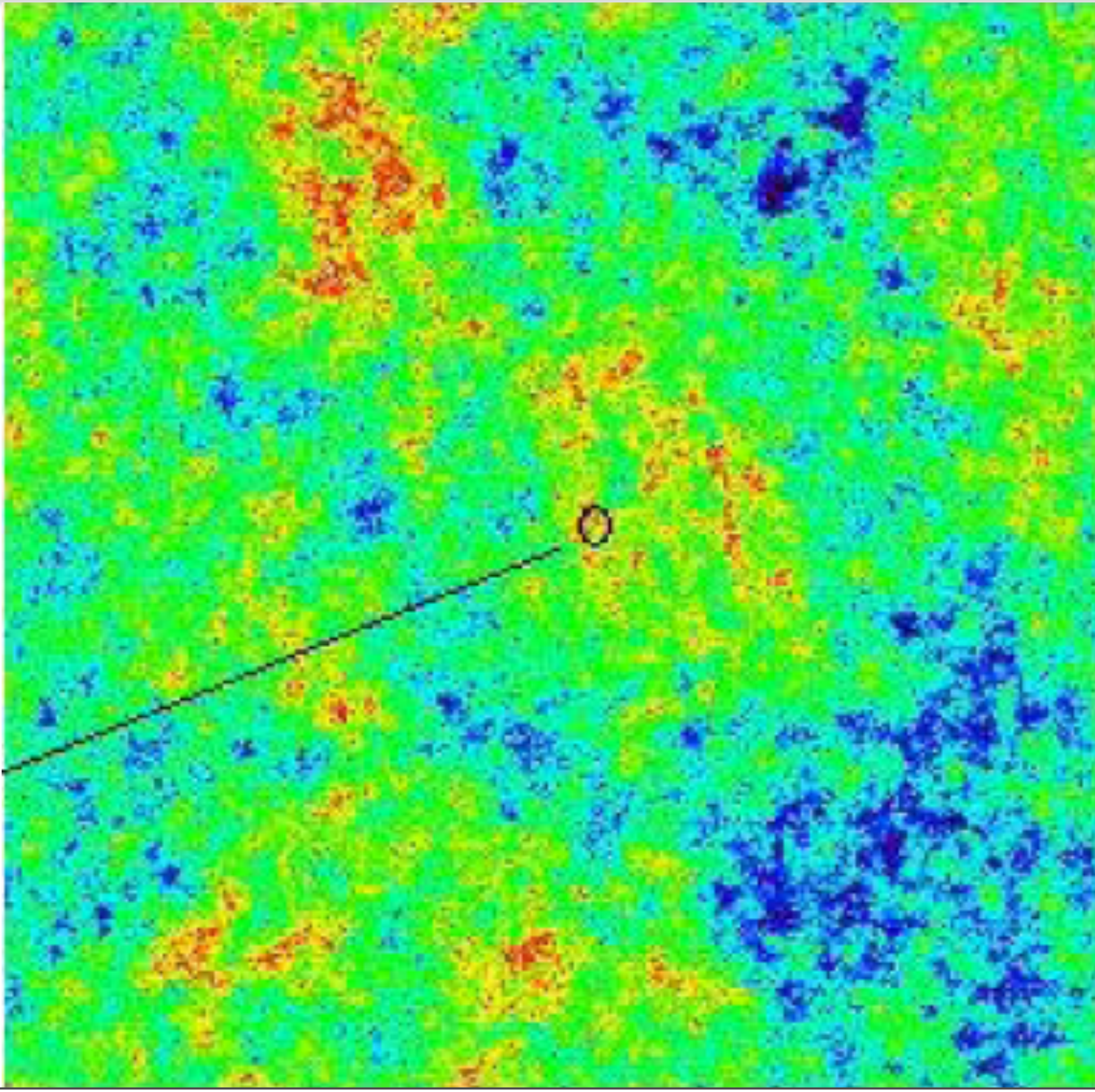
$K_{eff}(\psi_{inf})$?

cosmic mysteries

n_b/n_γ ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de} \sim H^2 M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$

fluctuations in the **early universe “vacuum” grow** to *all* **structure**

χ



current Hubble patch ~10 Gpc

speed limit horizon

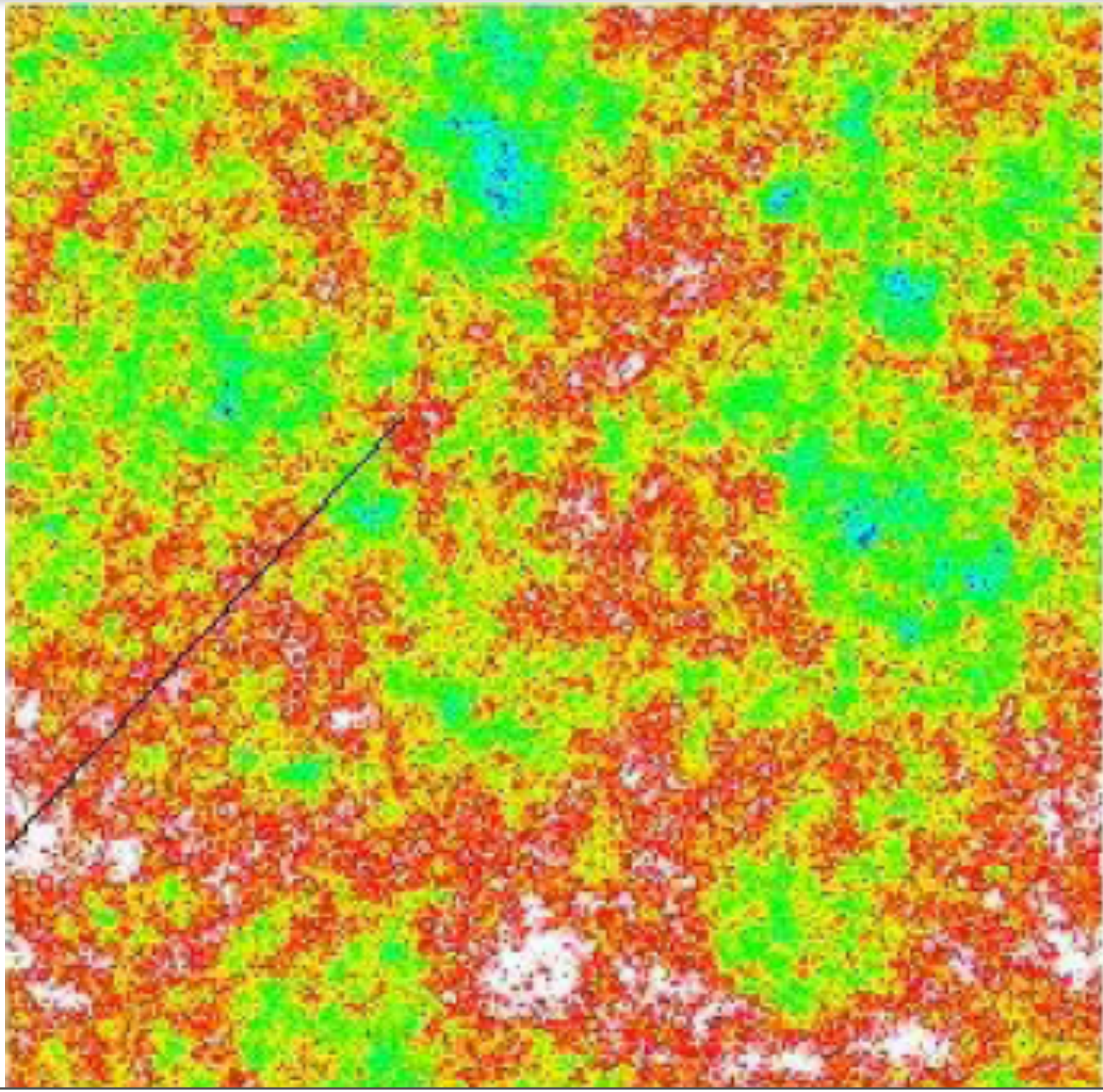
patterns in the quantum jitter evolve under gravity

(& gas dynamics)

1000 Gpc

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

χ



pre-heating patch (~1cm)

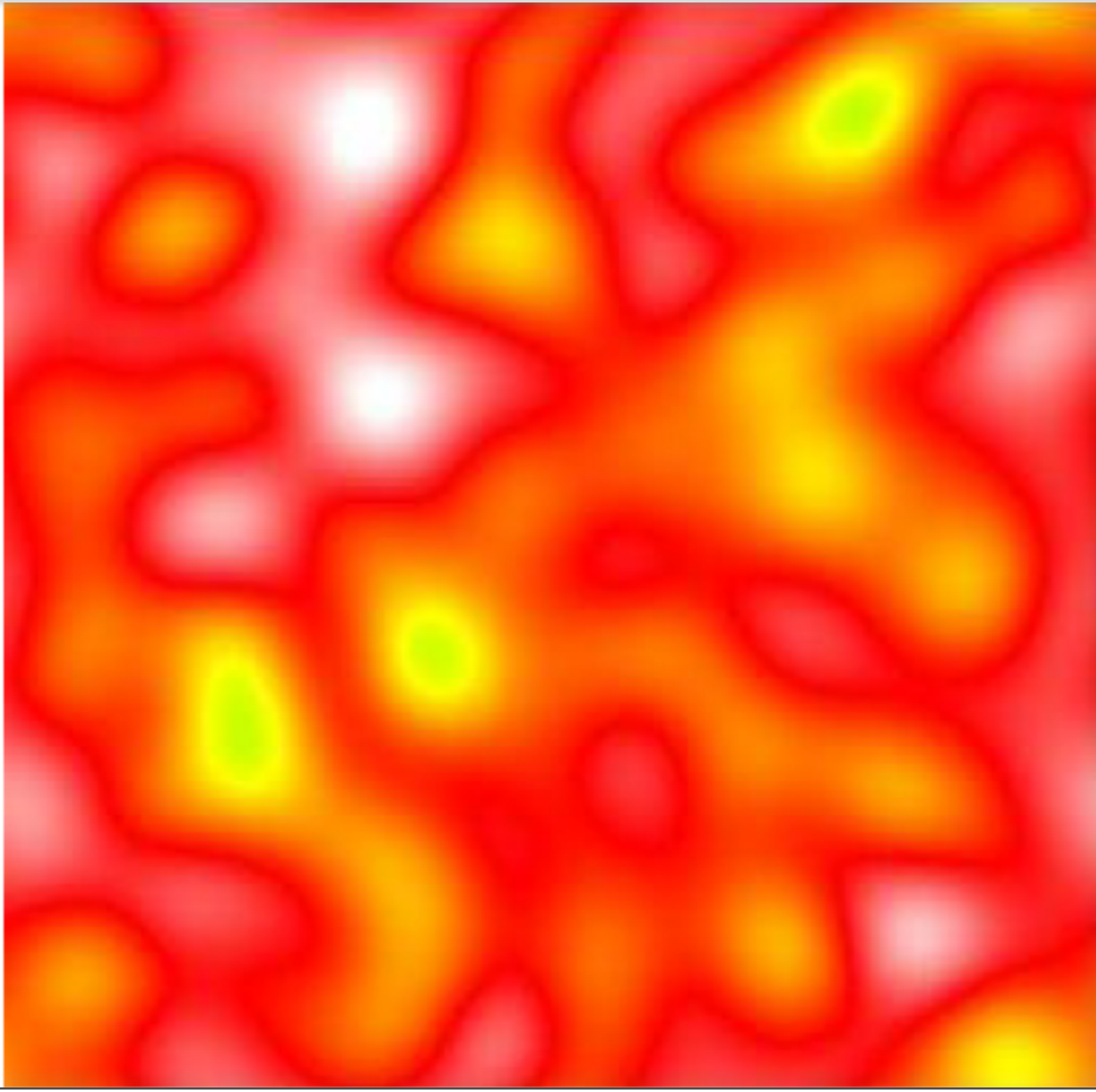
patterns in the quantum jitter evolve under gravity

(& gas dynamics)

10 Gpc

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

χ



patterns in the quantum jitter evolve under gravity

(& gas dynamics)

pre-heating patch (~1cm)

~1 cm

Old view: **Theory prior = delta function of THE correct one and only theory**

New: Theory prior = probability distribution of late-flows on an energy LANDSCAPE

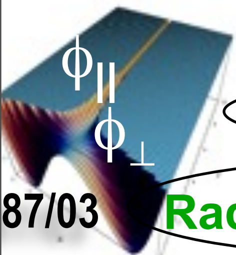
6/7 tiny extra dimensions

1980

R^2 -inflation

Old Inflation

Chaotic inflation



New Inflation

Double Inflation

Power-law inflation

SUGRA inflation

87/03 **Radical BSI inflation**

running (nee variable M_P) inflation

Extended inflation

1990

Natural pNGB inflation

Hybrid inflation

KLS94 preheating

SUSY F-term inflation

SUSY D-term inflation

Assisted inflation

Brane inflation

2000

SUSY P-term inflation

Super-natural Inflation

K-flation

2003 KKLT

N-flation

ekpyrotic/ cyclic

D3,D7 brane inflation

DBI inflation

moving brane separations

Racetrack inflation

Tachyon inflation

Warped Brane inflation

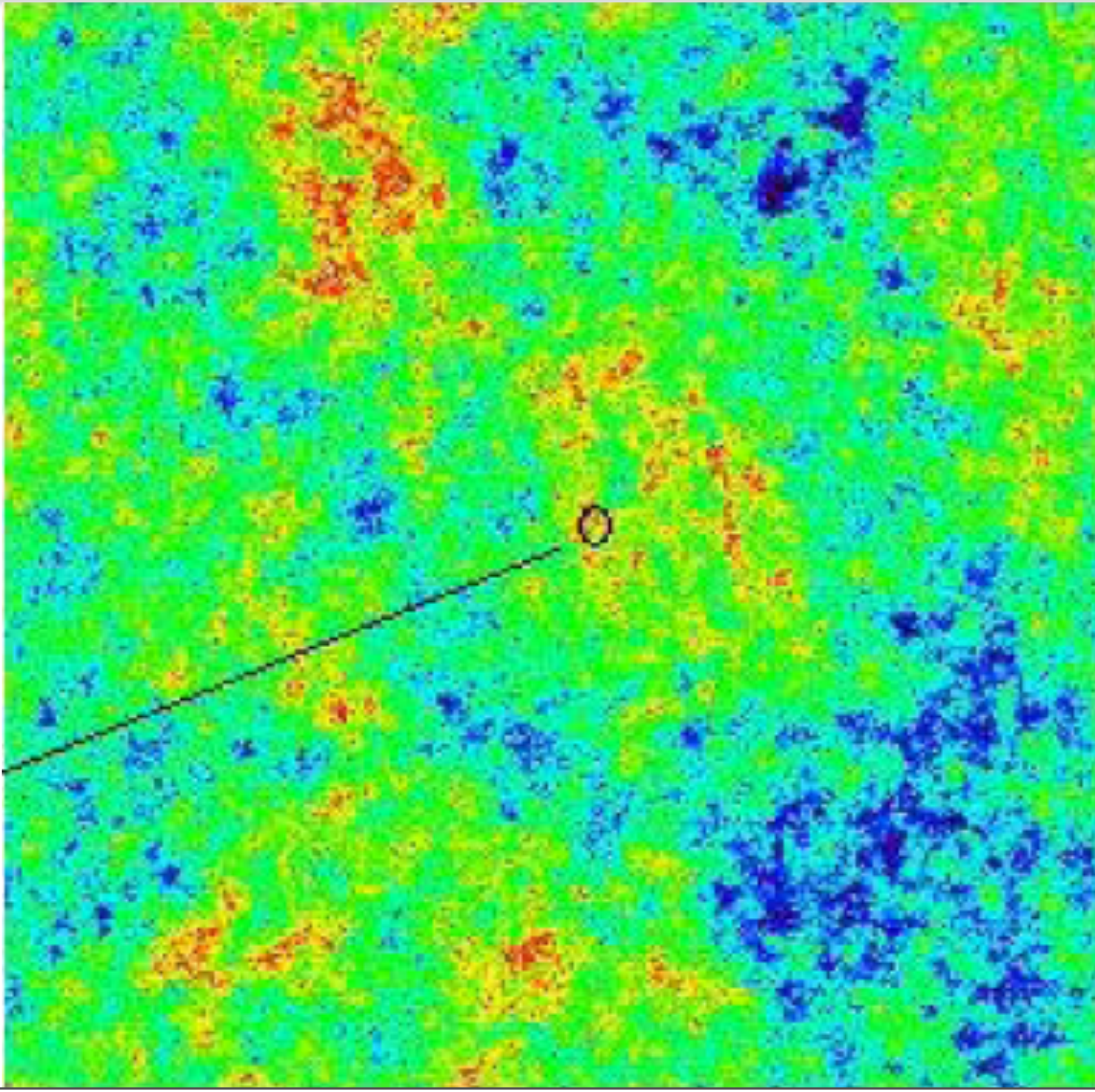
moduli fields

monodromy

Roulette inflation **Kahler moduli/axion**

fiber inflation

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



χ

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speed limit horizon

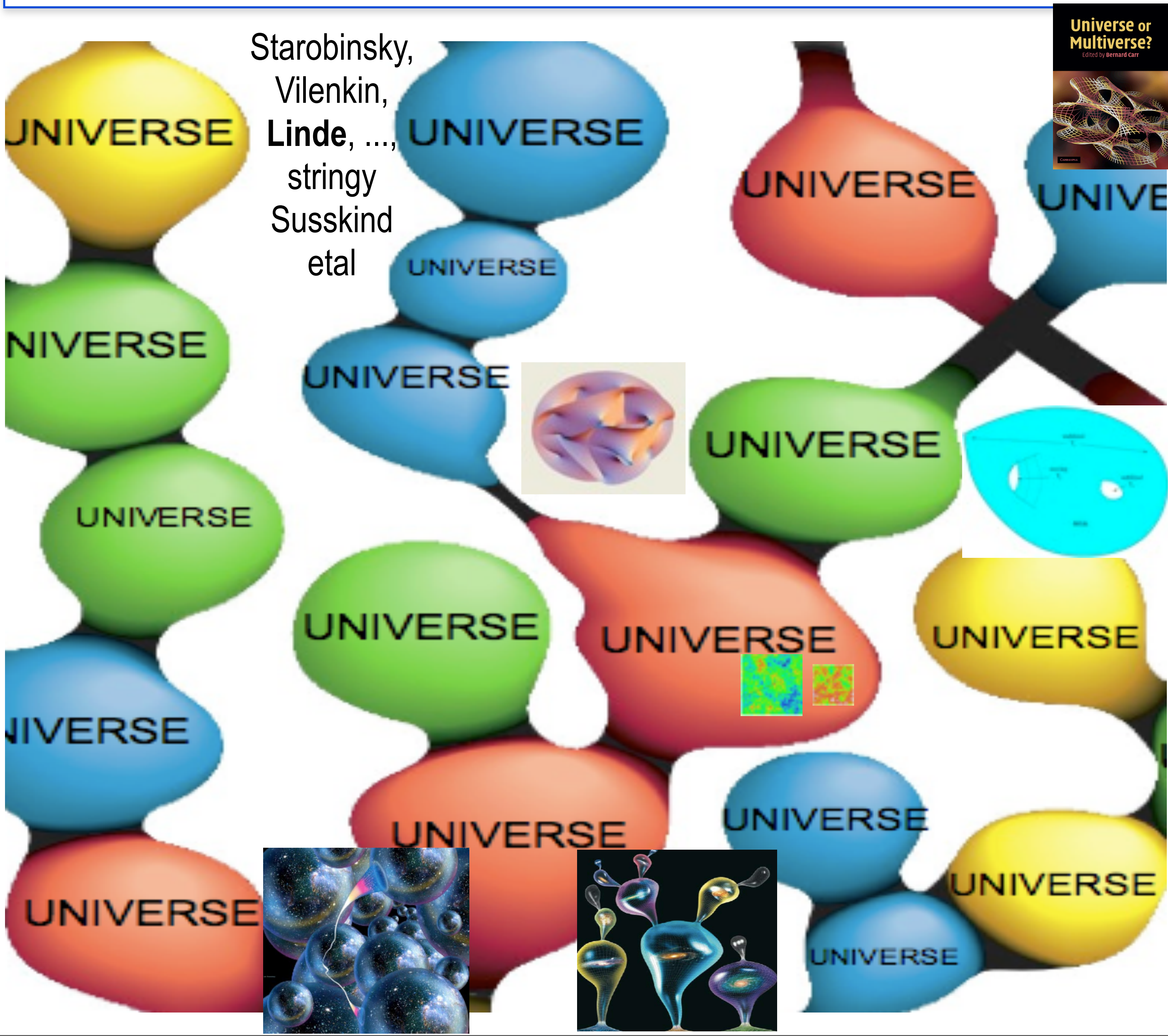
patterns in the quantum jitter evolve under gravity

(& gas dynamics)

1000 Gpc

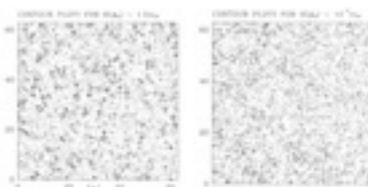
the **quantum stochastic non-G landscape** cf. the **stringy landscape**

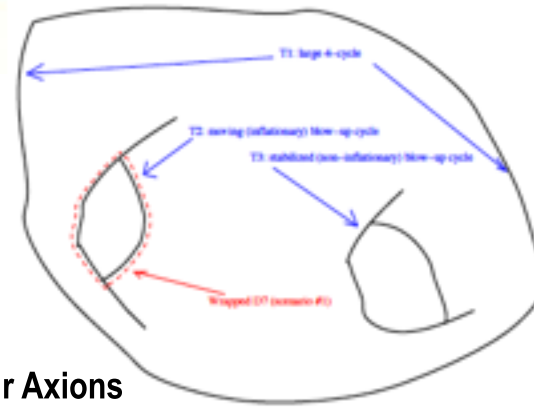
Starobinsky, Vilenkin, **Linde**, ..., stringy Susskind etal



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



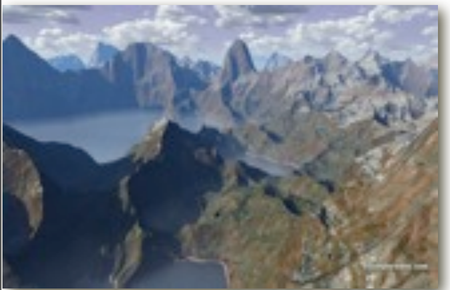


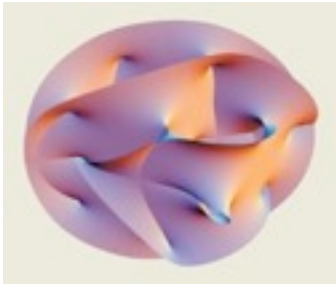
Balasubramanian, Berlund, Conlon, Quevedo, · · ·

Bond, Kofman, Prokushkin,Vaudrevange 2007, Roulette Inflation with Kahler Moduli and their Axions

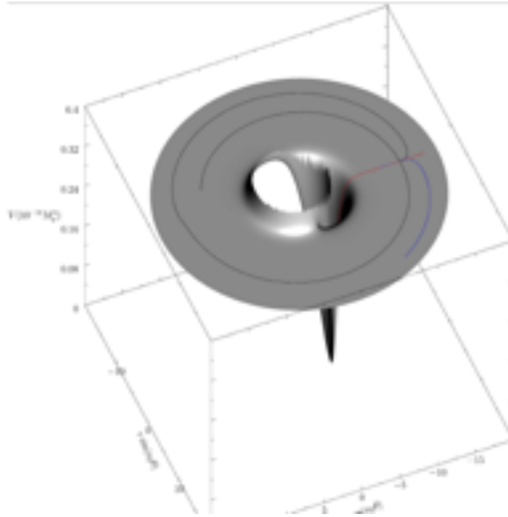
Neil Barnaby, Bond, Zhiqi Huang, Kofman, hep-th/0909.0503, Preheating after Modular Inflation

Old view: Theory prior = delta function of THE correct one and only theory





The 'house' plays roulette as well as dice with the world.

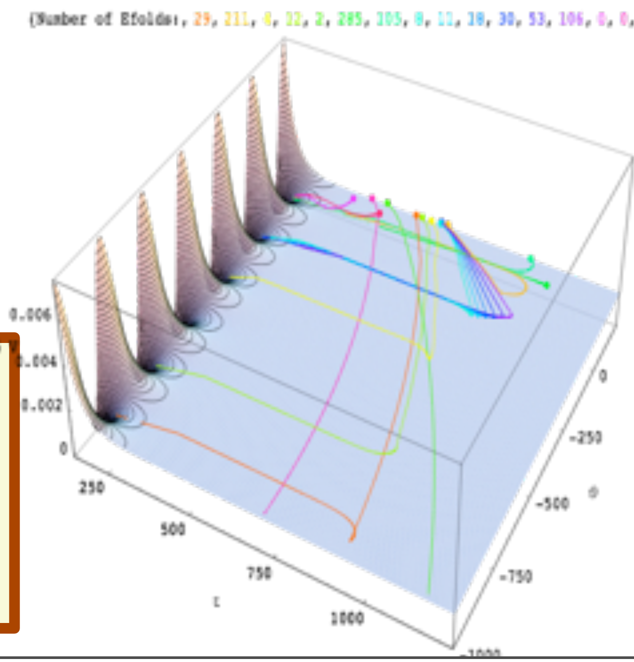


New view: Theory prior = probability distribution on an energy landscape whose features are at best only glimpsed,

huge number of potential minima, inflation the late stage flow in the low energy structure toward these minima. Critical role of collective coordinates in the low energy landscape:

moving brane/antibrane separations (D3,D7)
moduli fields, sizes and shapes of geometrical structures such as holes in a dynamical extra-dimensional (6D) manifold approaching stabilization

Roulette inflation
Kahler moduli/axion



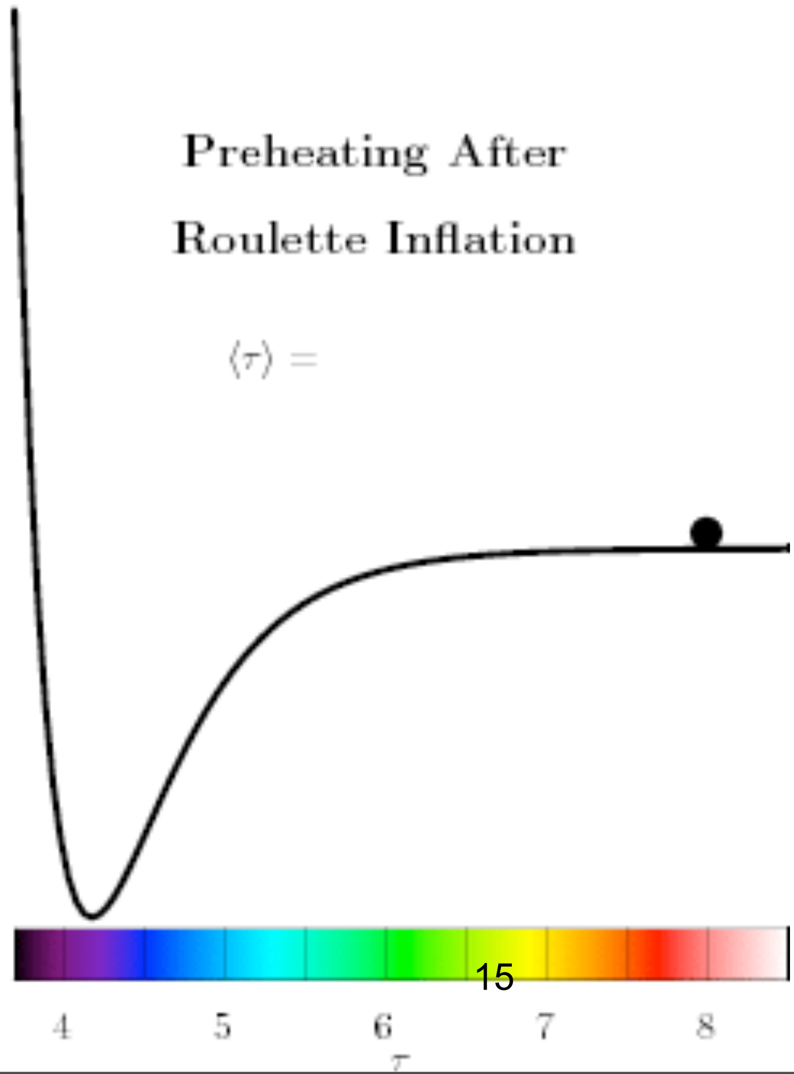
theory prior ~ probability of trajectories given potential parameters of the collective coordinates X probability of the potential parameters X probability of initial conditions

Preheating After Roulette Inflation

Barnaby, Bond, Huang, Kofman 2009
HLattice code: arbitary number of fields,
hybrid symplectic, to ~ trillionth accuracy!

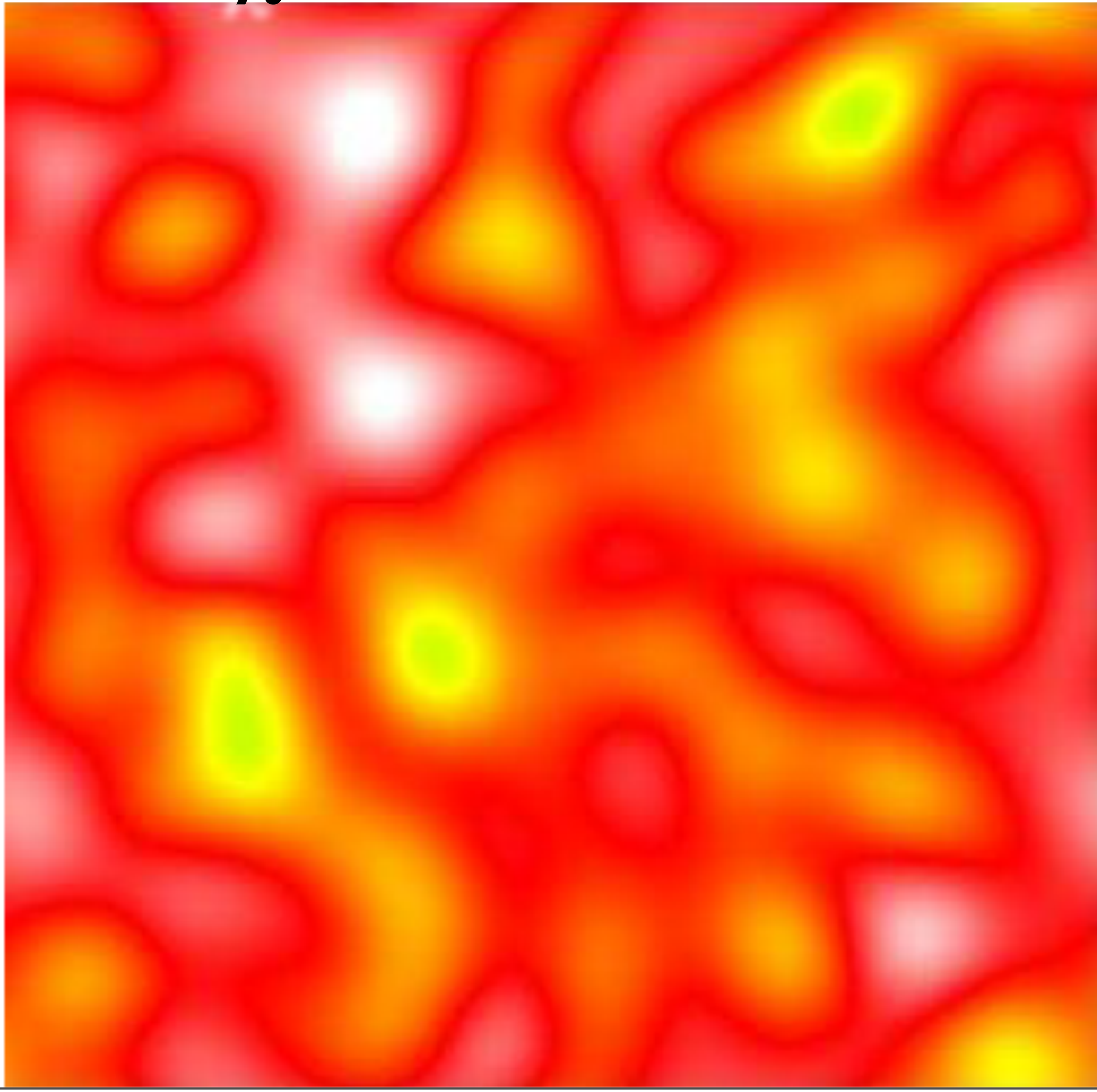
$a = \quad 1$

A visualized 2D slice
in lattice simulation



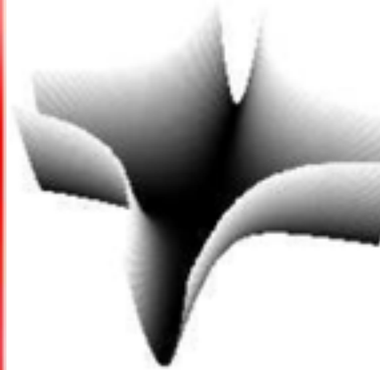
www.youtube.com/watch?v=FW__su-W-ck&NR=1

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



Parametric Resonance

$g^2/\lambda \sim 1$



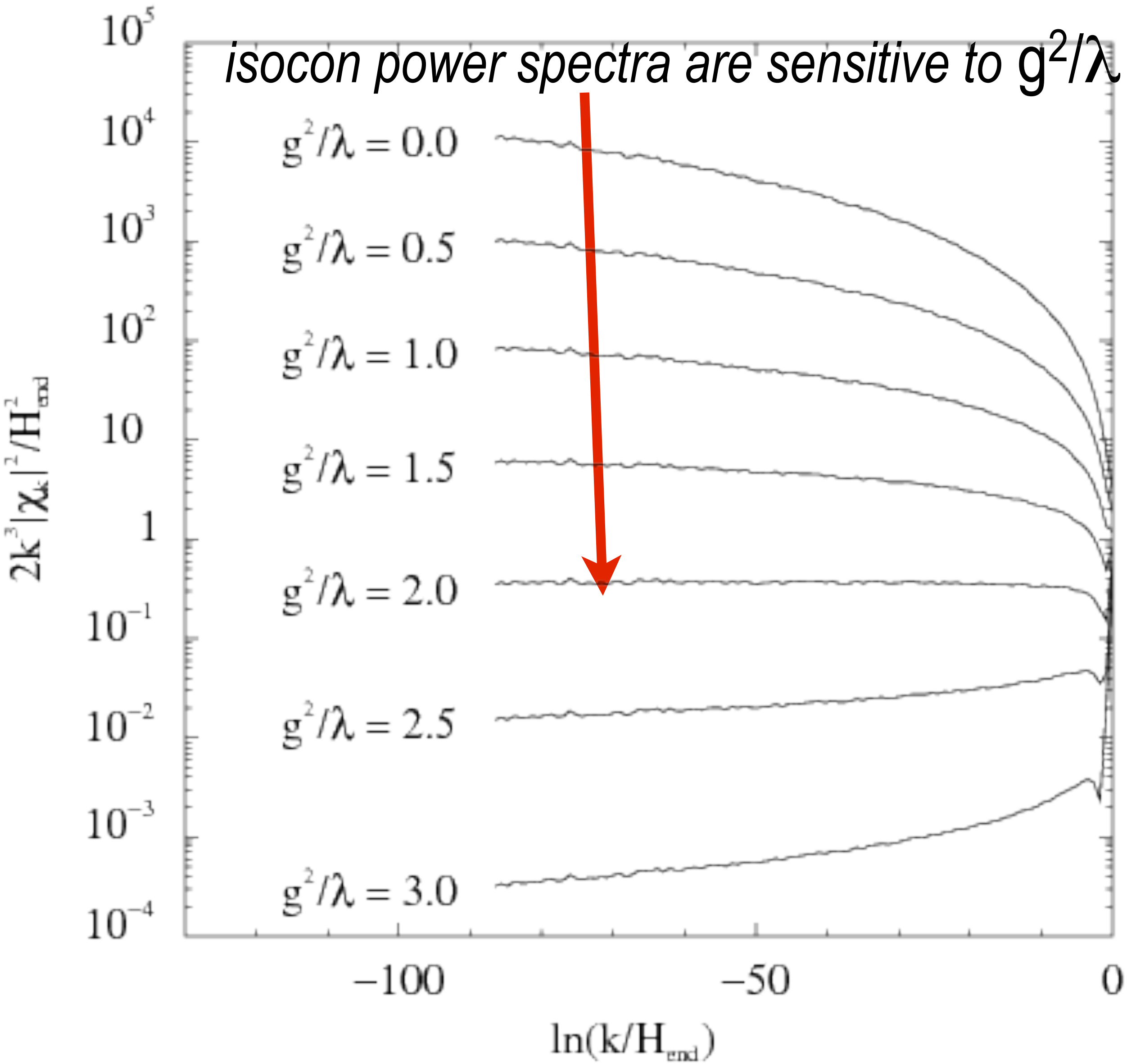
pre-heating patch (~1cm)

~1 cm

80s-90s arena for BSI & non-Gaussianity near EOI, isocon fields couple in

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

$\chi_i(x,t)$ power



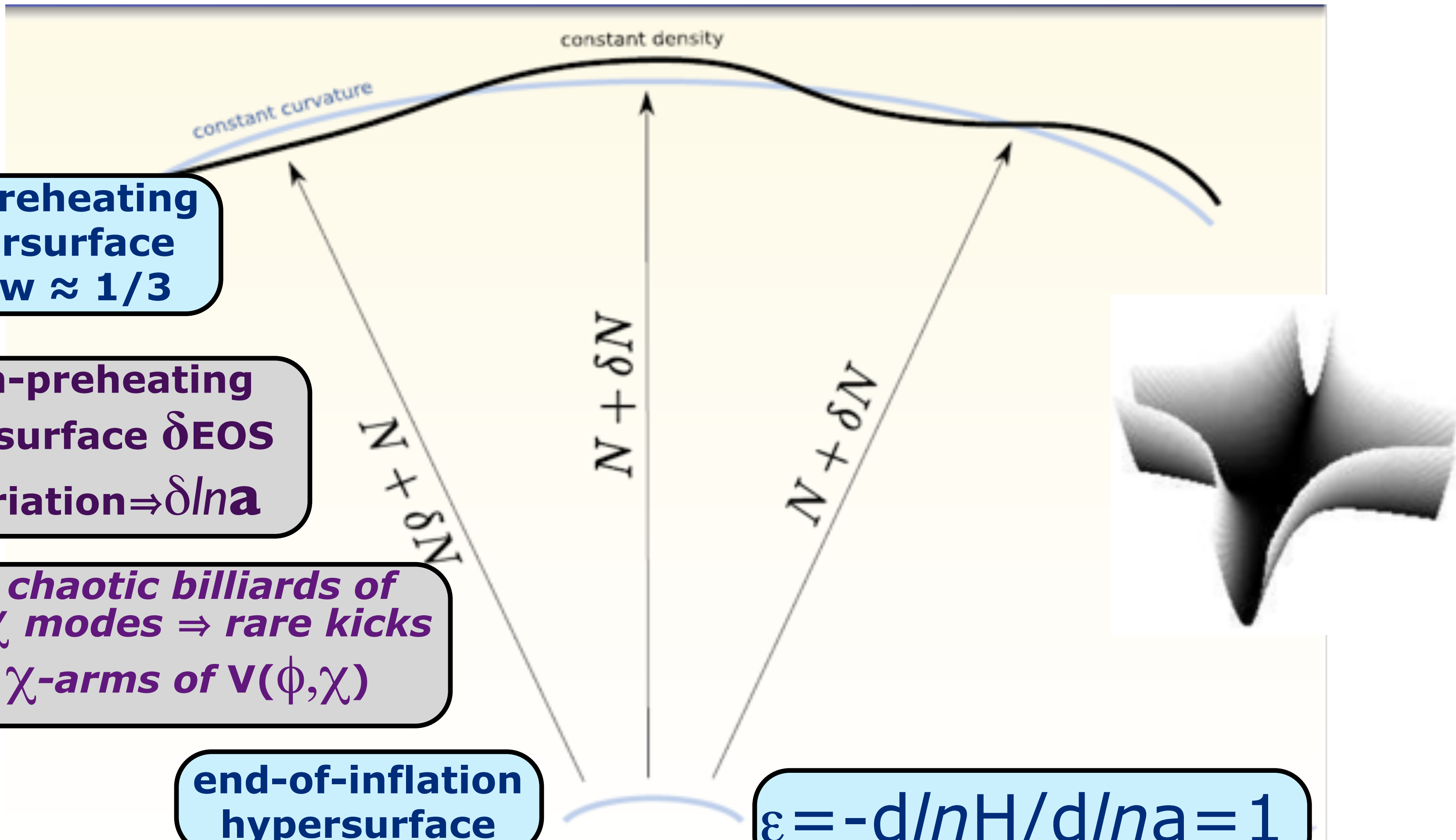
expected k~Ha rule would apply. pre-heating surprise!

$\ln a[\chi_i(x,t)]$ from "subgrid" $\propto H_e^{-1}$ lattice simulations of ϕ_{UHF} χ_{UHF}

Bond, Andrei Frolov, Zhiqi Huang, Kofman 09:

calculate how the expansion factor from the end of accelerated expansion (end of inflation) through preheating (copious mode-mode-coupling aka particle creation) to the onset of thermal equilibrium depends on $\chi_i(x,t)$

$$\delta N = \delta \ln a|_H = \text{curvature fluctuation}$$



end-preheating hypersurface EOS w ≈ 1/3

begin-preheating hypersurface δEOS w-variation⇒δlna

linear chaotic billiards of k≈0 ϕ,χ modes ⇒ rare kicks into χ-arms of V(ϕ,χ)

end-of-inflation hypersurface

$\varepsilon = -d\ln H/d\ln a = 1$

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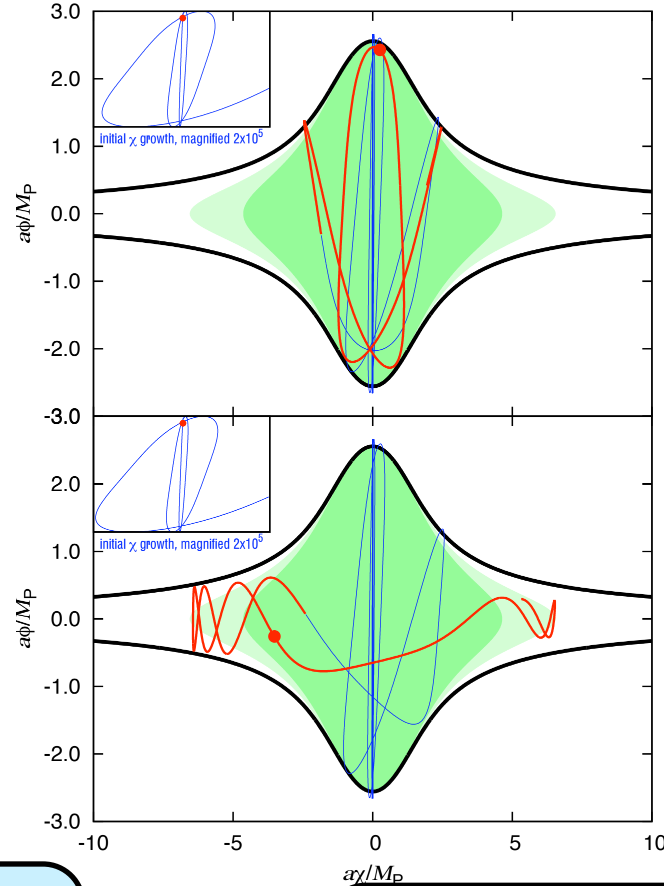
end-of-inflation hypersurface



linear regime of zero-modes:

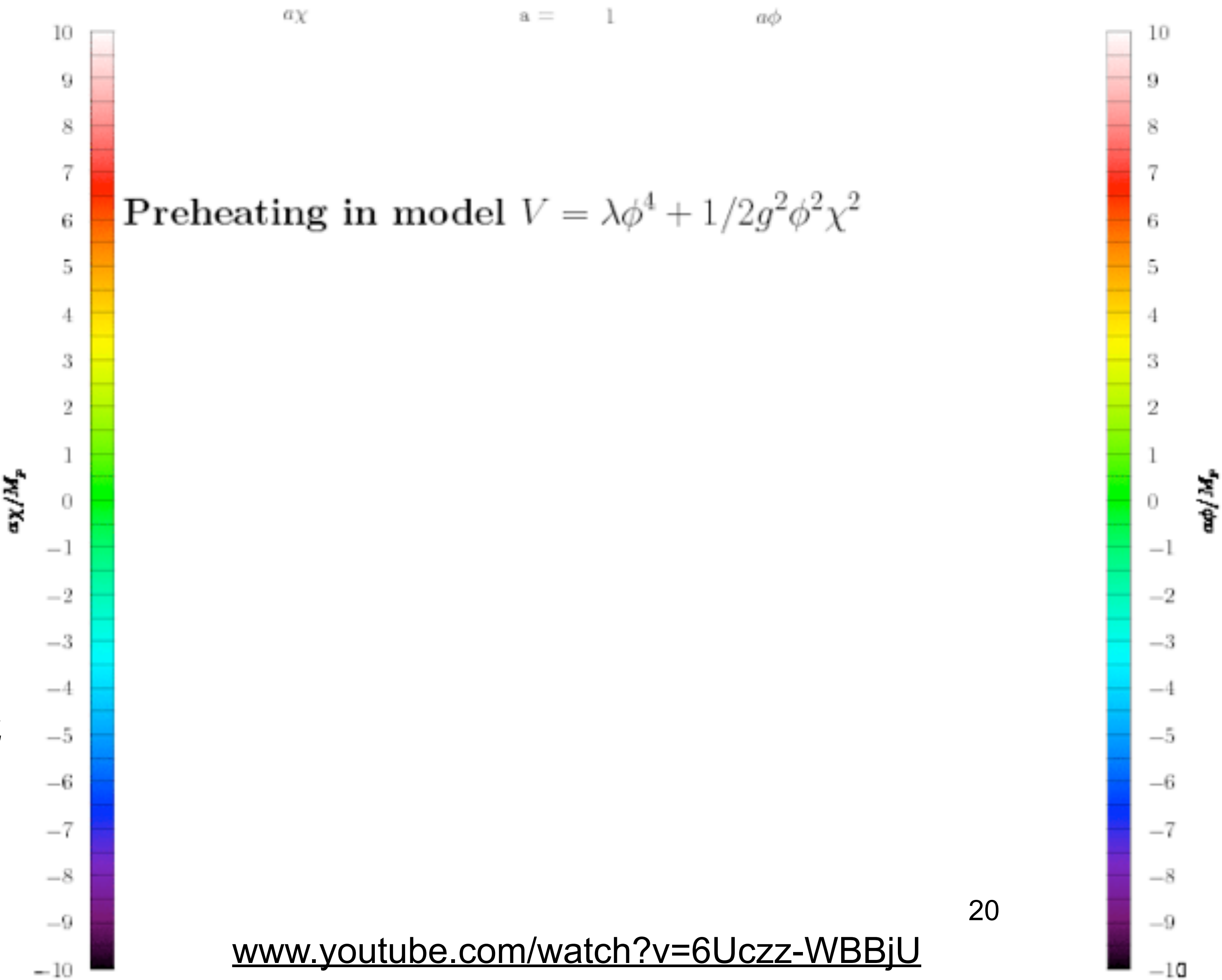
$\phi_0(t+T) = \phi_0(t)$

$\chi_0(t+T) = \chi_0(t) \exp[\mu_0 T]$

⇒ ***spikes are log χ_i spaced***

$\varepsilon = -d\ln H/d\ln a = 1$

Cosmic Chaotic Billiards: Nongaussianity from Parametric Resonance in Preheating

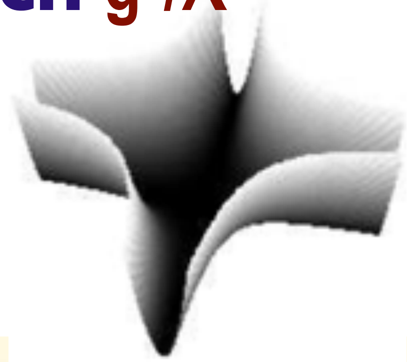


***preheating ideas**: 90s Kofman, Linde, Starobinsky, .., Greene, Felder, Frolov, ...*

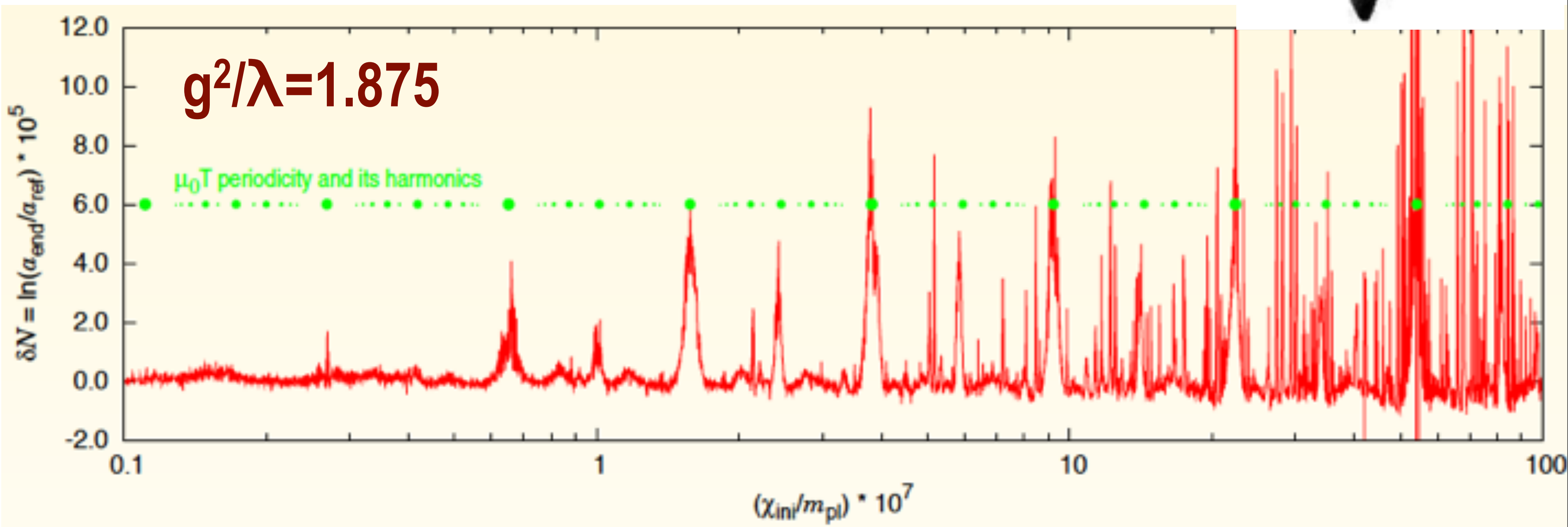
***nonG ideas** Bond, Frolov, Huang,Kofman 2009*

www.youtube.com/watch?v=6Uczz-WBBjU

to develop the $\ln a(\chi_i)$ response curve, we perform > 10^4 lattice simulations for each g^2/λ



$$F_{NL}(\chi) = \delta \ln a|_H (\chi_i)$$



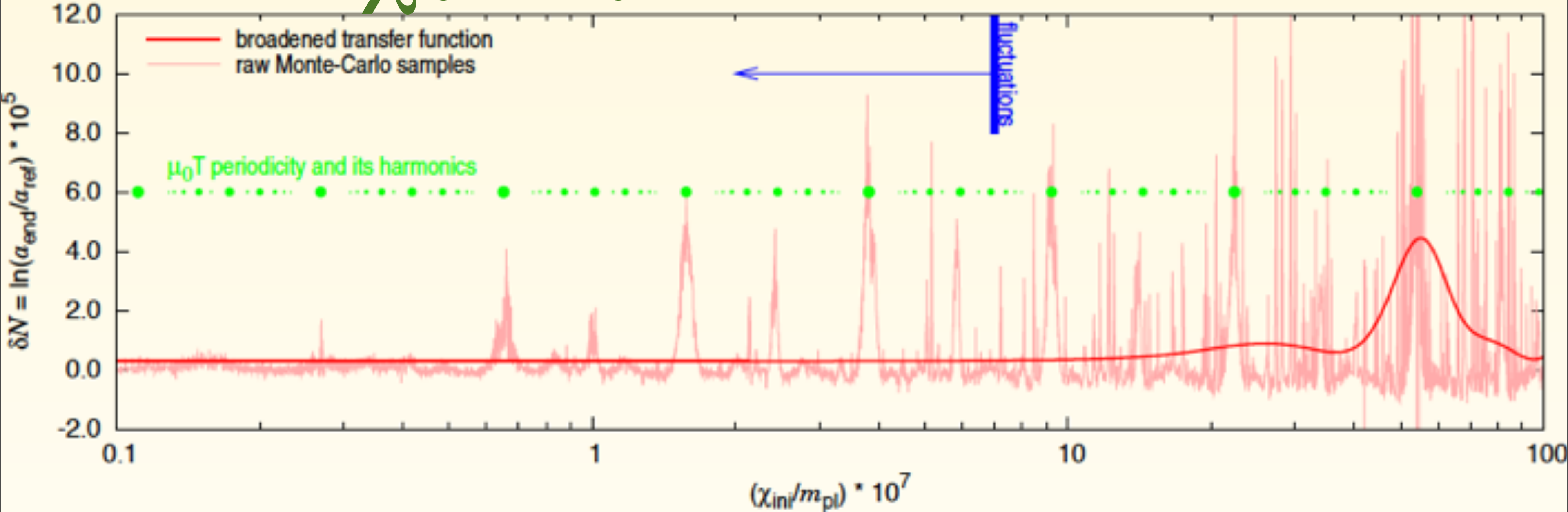
21

field smoothing over χ_{HF} $\sigma_{HF} \sim 7 \times 10^{-7}$ ~50 e-folds

$P(\chi|\chi_{LF}) \sim \exp[-(\chi-\chi_{LF})^2 / 2\sigma_{HF}^2]$ $\Rightarrow < F_{NL}|\chi_b + \chi_{>h} >$

SSS χ_b: $\sigma_b \sim 5 \times 10^{-7}$ ~10 e-folds

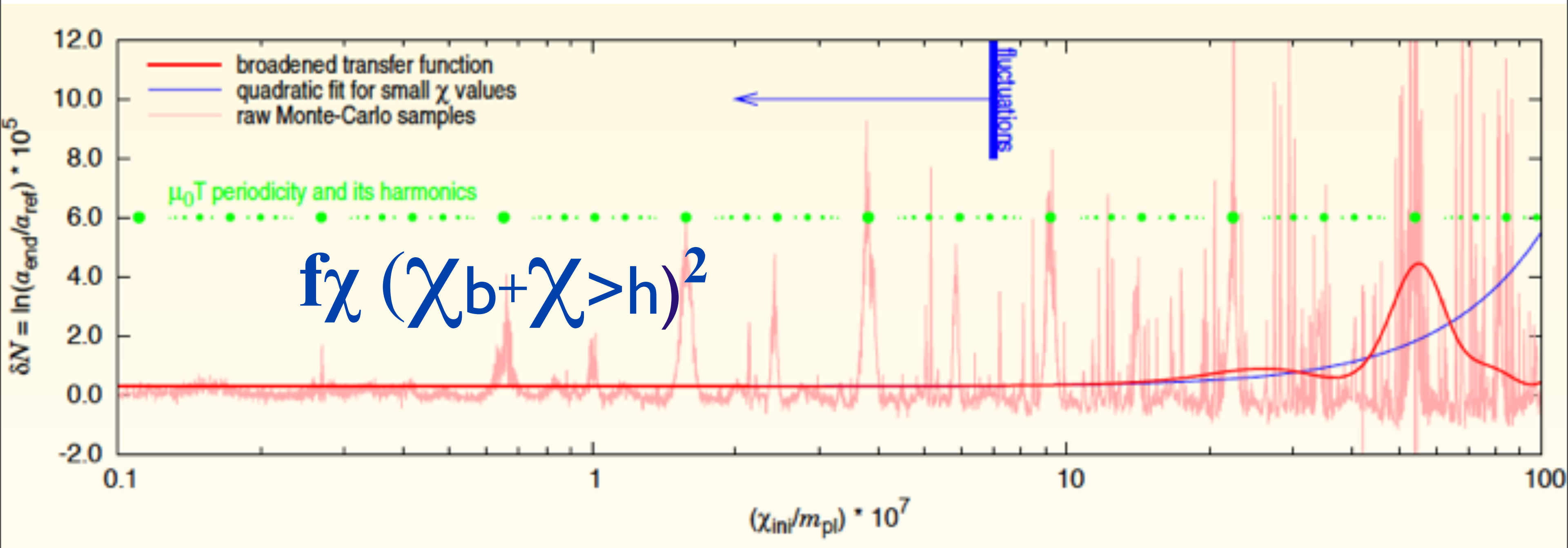
LSS χ_b: $\sigma_b \sim 3 \times 10^{-7}$ ~10 e-folds



super-horizon $\chi_{>h}$: $\sigma_{>h} \sim N_{>h}^{1/2} \times 10^{-7}$ $N_{>h} \sim 10^2 - 10^{4++}$

"observed" $\chi_{>h}$ is a random throw of the dice $P(\chi_{>h}) \sim \exp[-\chi_{>h}^2 / 2\sigma_{>h}^2]$

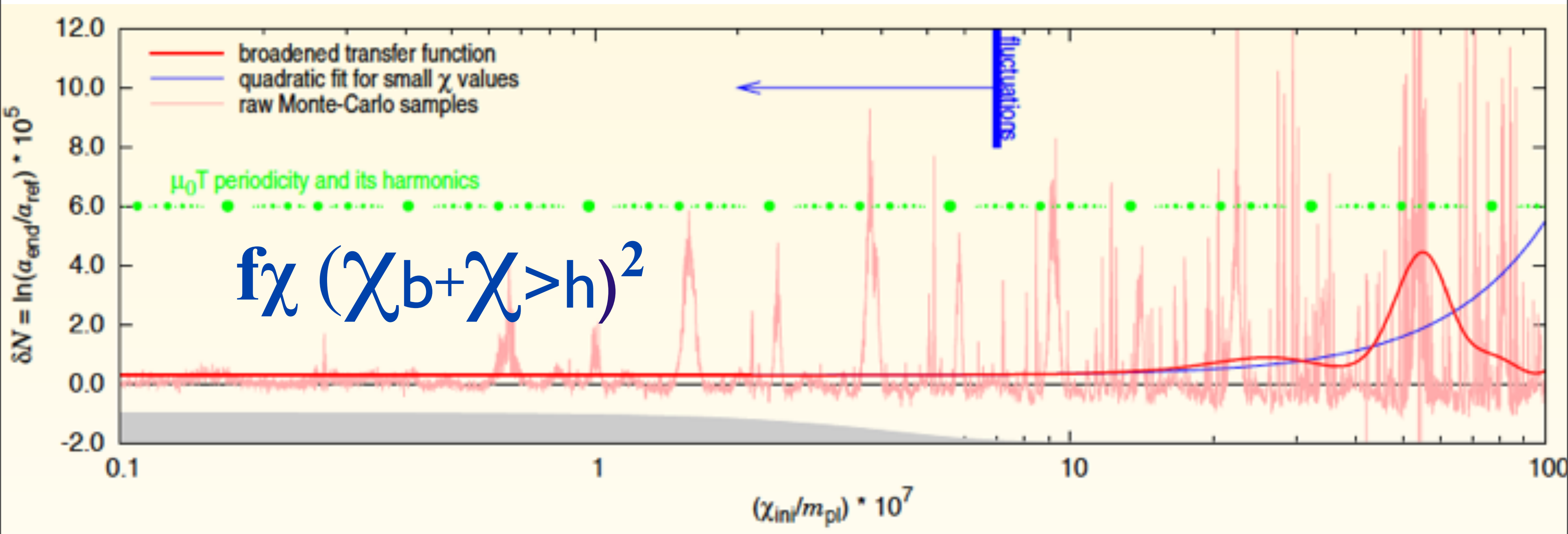
$$< F_{NL}|\chi_b+\chi_{>h}> \quad \sim \beta(\chi_{>h})\,\chi_b + f(\chi_{>h})\,\chi_b^2 + \ldots$$



local quadratic non-G constraint: $-9 < f_{NL} < 111 \Rightarrow -4 < f_{NL} < 80$ WMAP5 (± 5-10 Planck1yr)

maps into (considerably relaxed) $< F_{NL} | \chi_b + \chi_{>h} >$ constraint

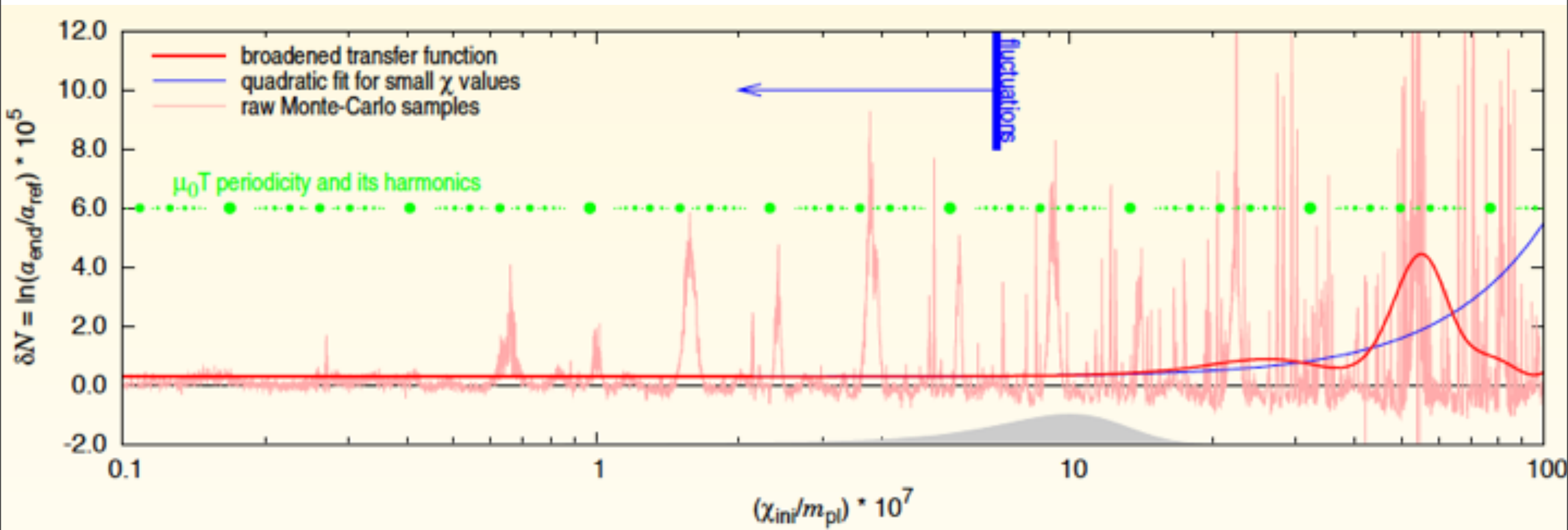
small $\chi_{>h}$ *regime:* $\beta = 2\, f_\chi\, \chi_{>h}$ $\quad f = f_\chi$



$f_{NL}^{equiv} = \beta^2 f_\chi\, [P\chi/P\phi]^2 (k_{pivot})$

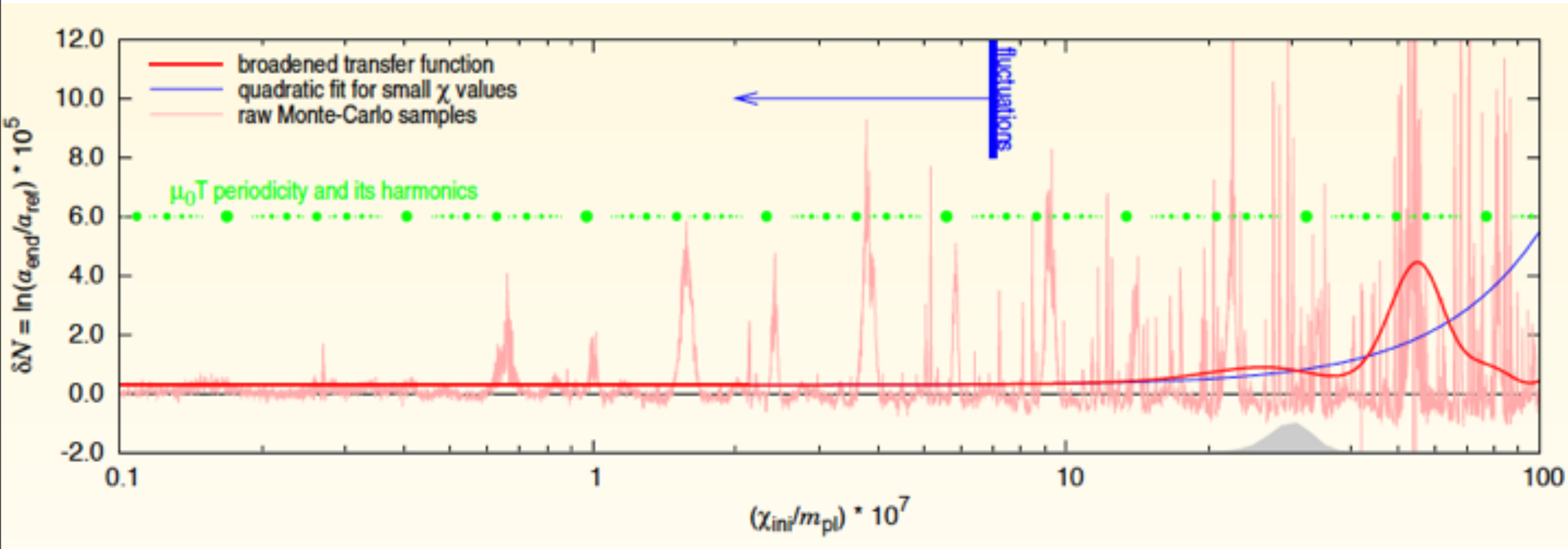
naive $P\chi/P\phi = 2\varepsilon$

medium χ>h *regime:*

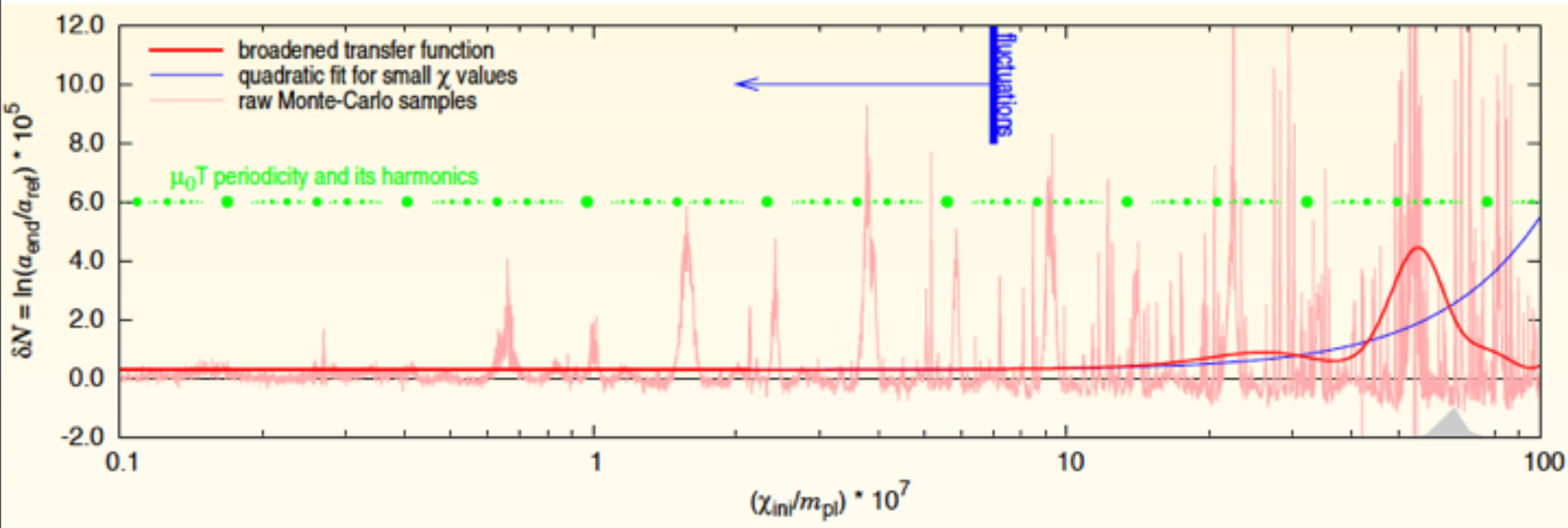


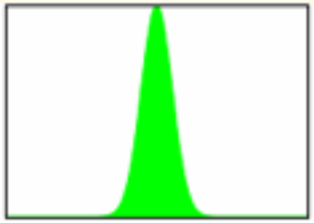
large-ish χ>h *regime:*

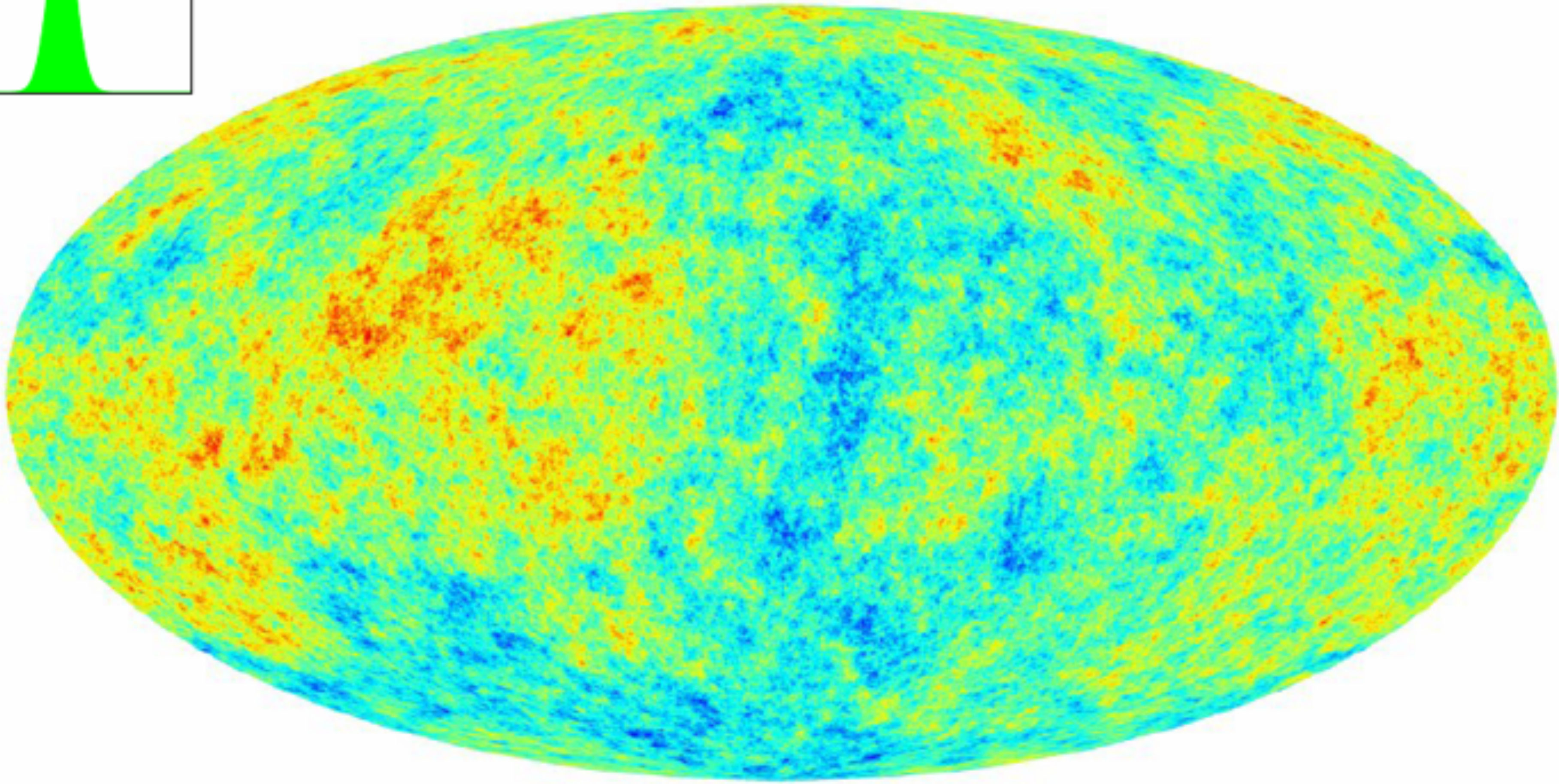
quadratic + cold spot
"rare events"

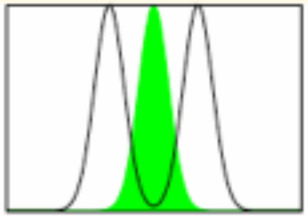


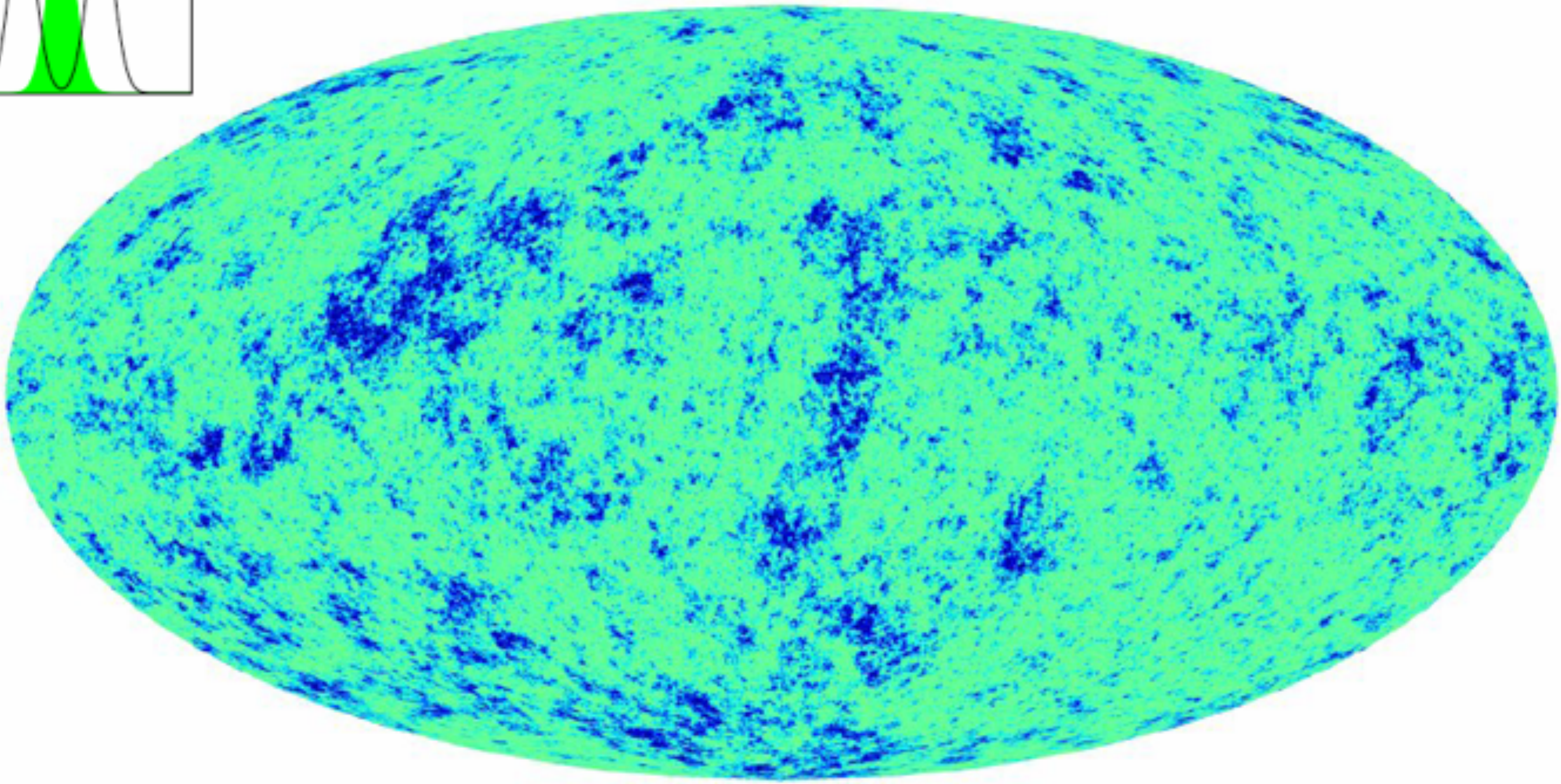
large χ>h *regime:*

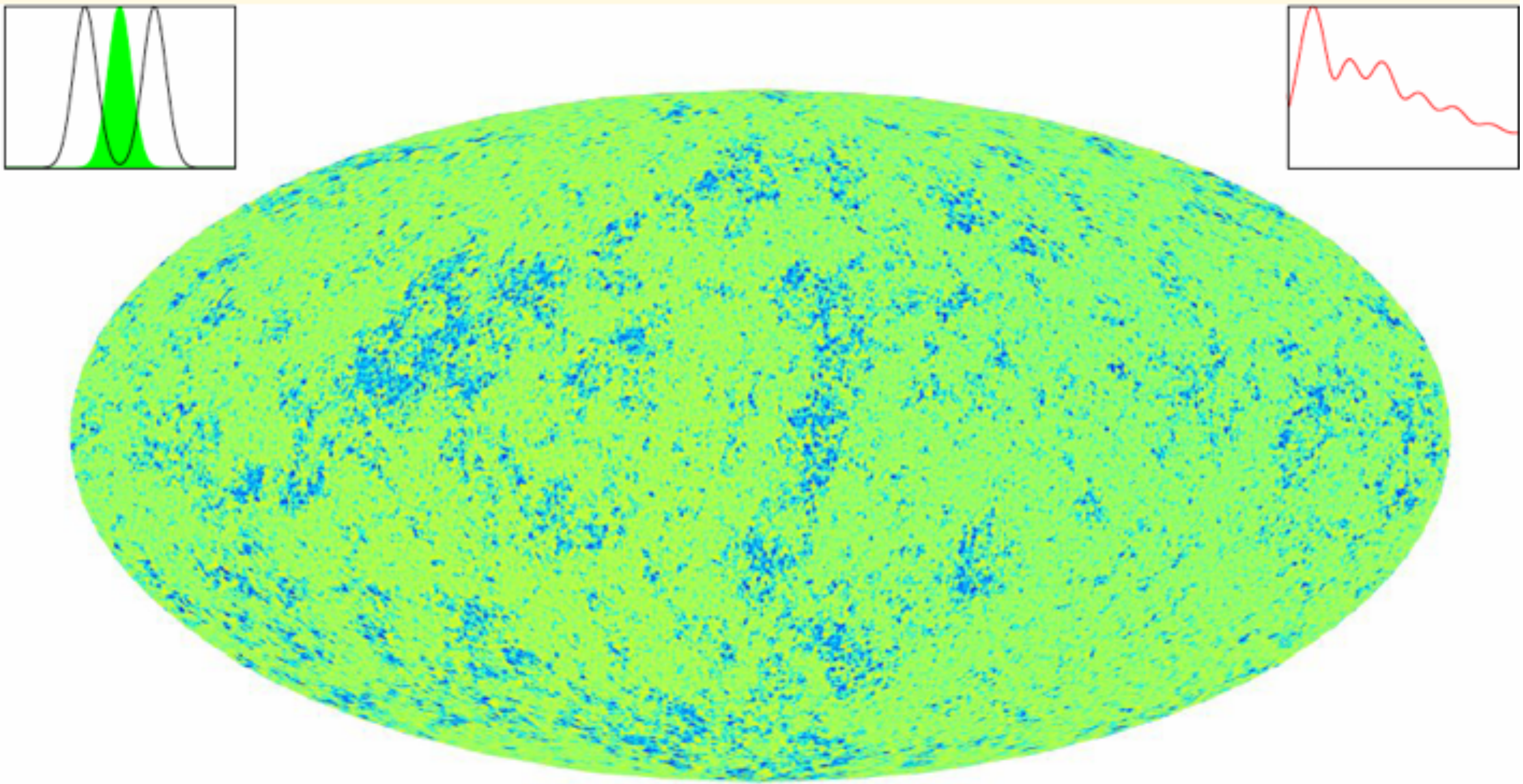


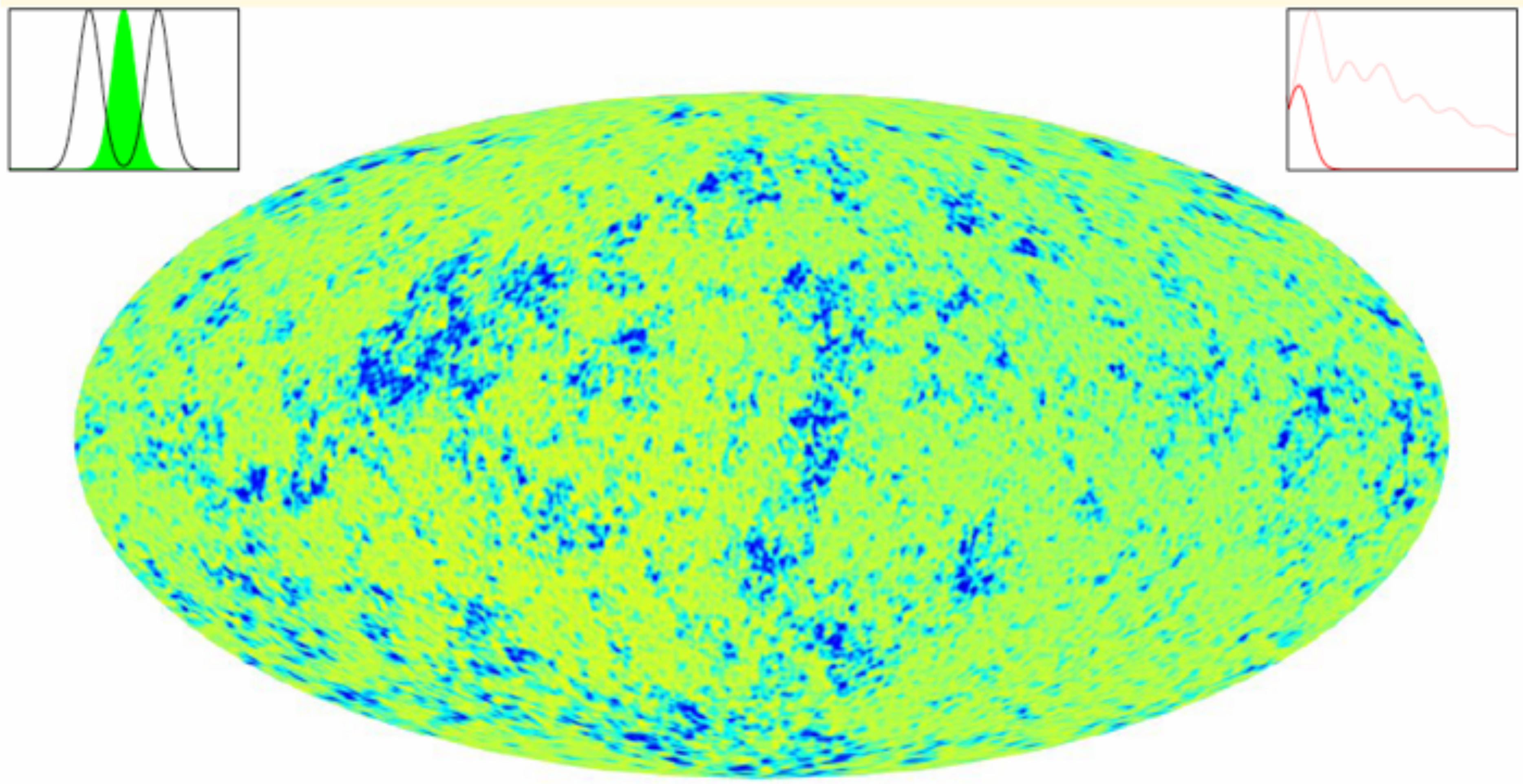


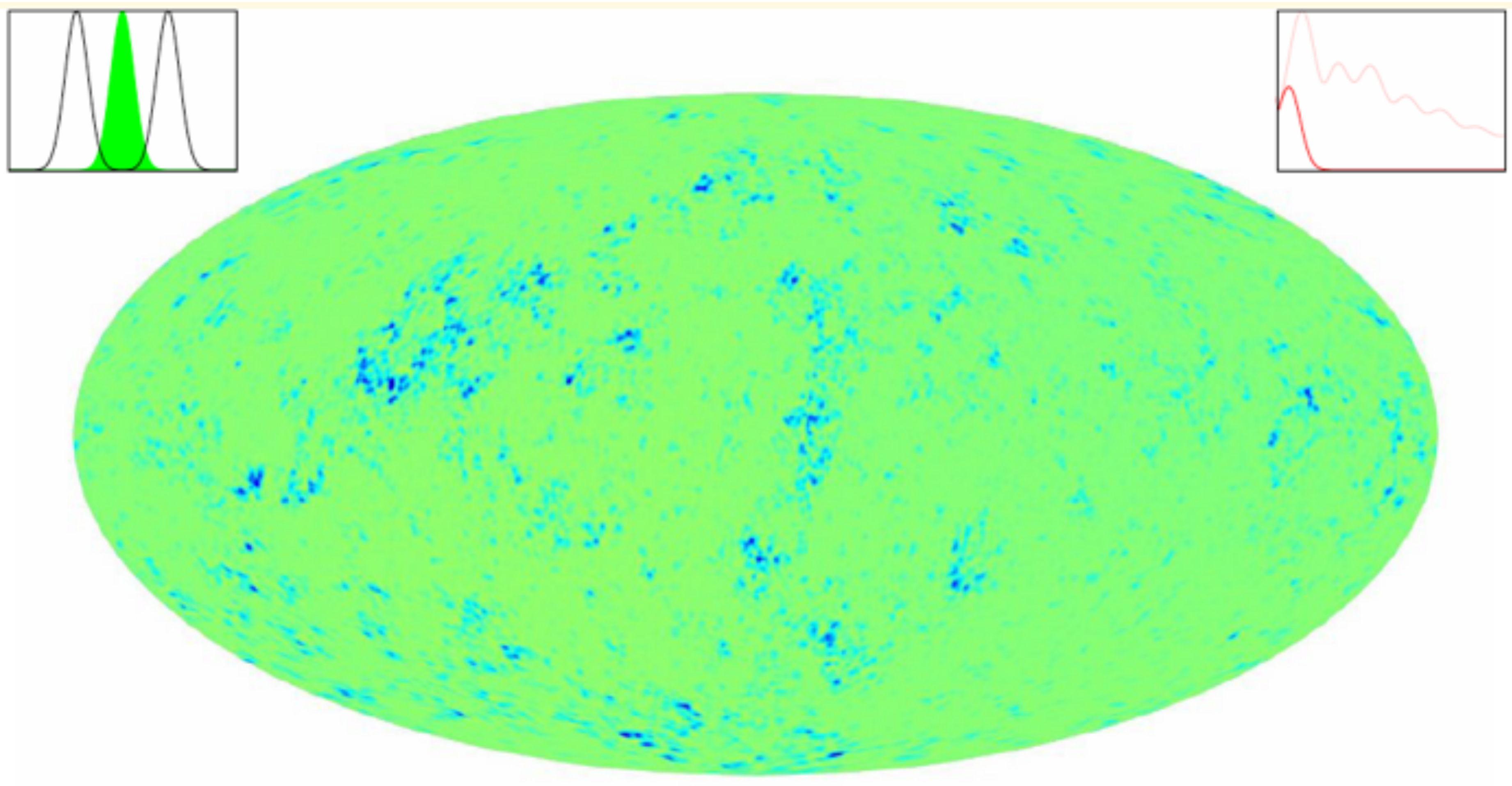




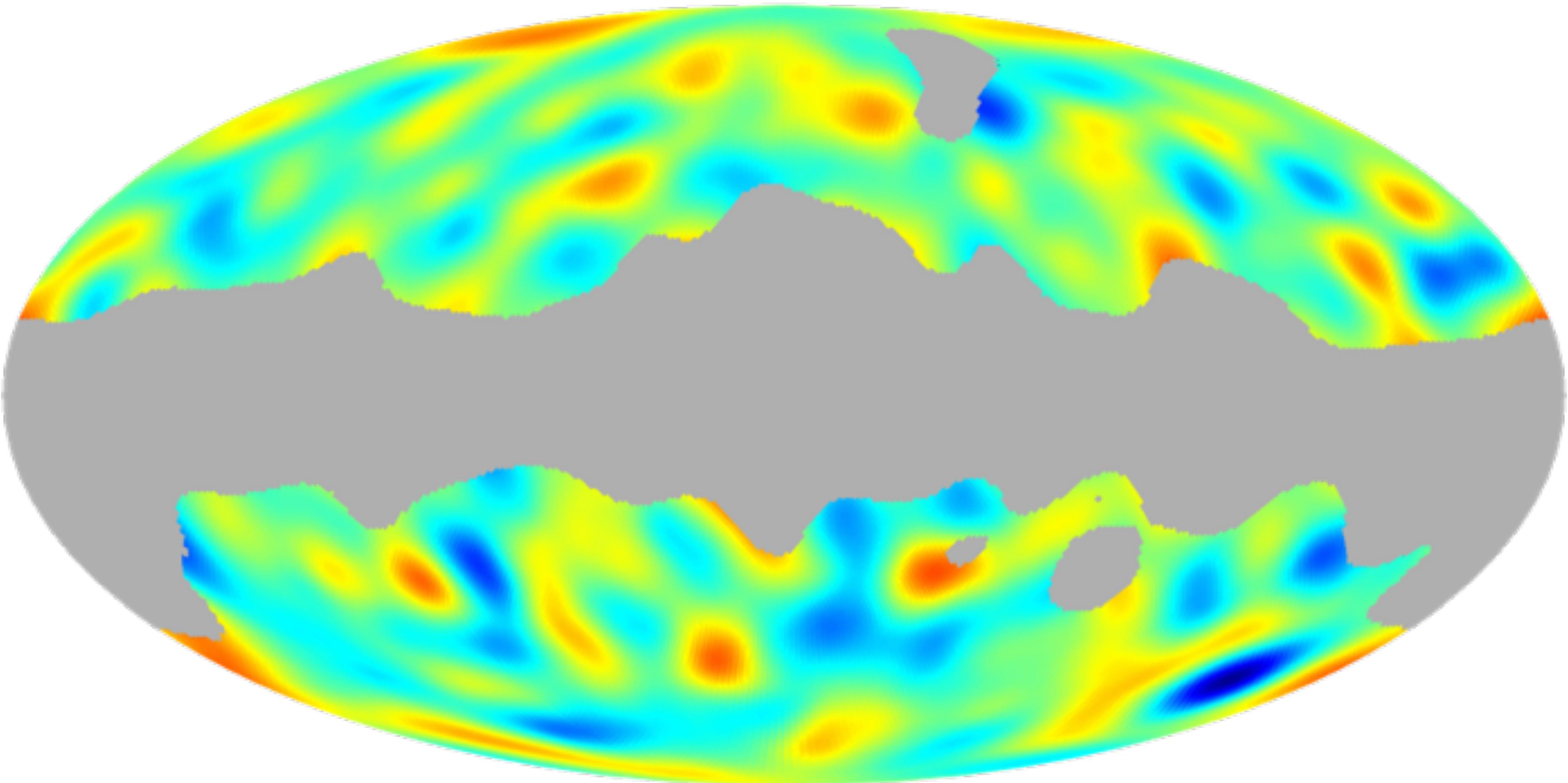








the WMAP Cold Spot: Vielva, Martinez-Gonzalez, Barr, Sanz, Cayon 2004 wavelets in WMAP1, ... Cruz etal 07 in WMAP3, & in WMAP5: needlets, steerable wavelets: ~4.5σ, others ~3σ; Zhang & Huterer 09, not as significant with other filters 20%



Bond, Frolov, Huang, Kofman, Nolta: Cold Spot testing: spherical SavitzkyGolay filters (compact polynomials) on pre-whitened WMAP5 data: -5.02σ, at 831 arcmin fwhm, 149 peaks, 1/1099 significance

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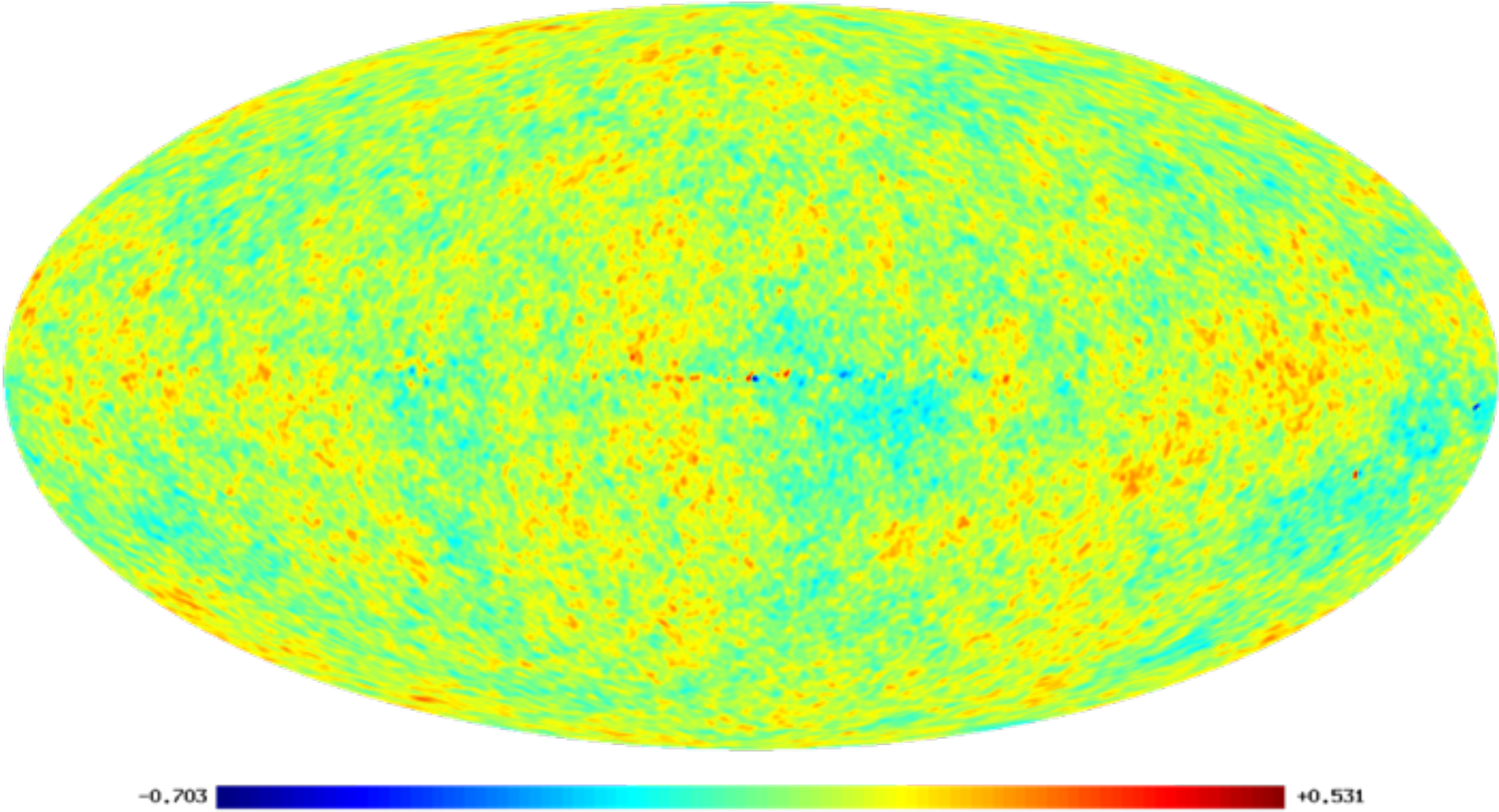

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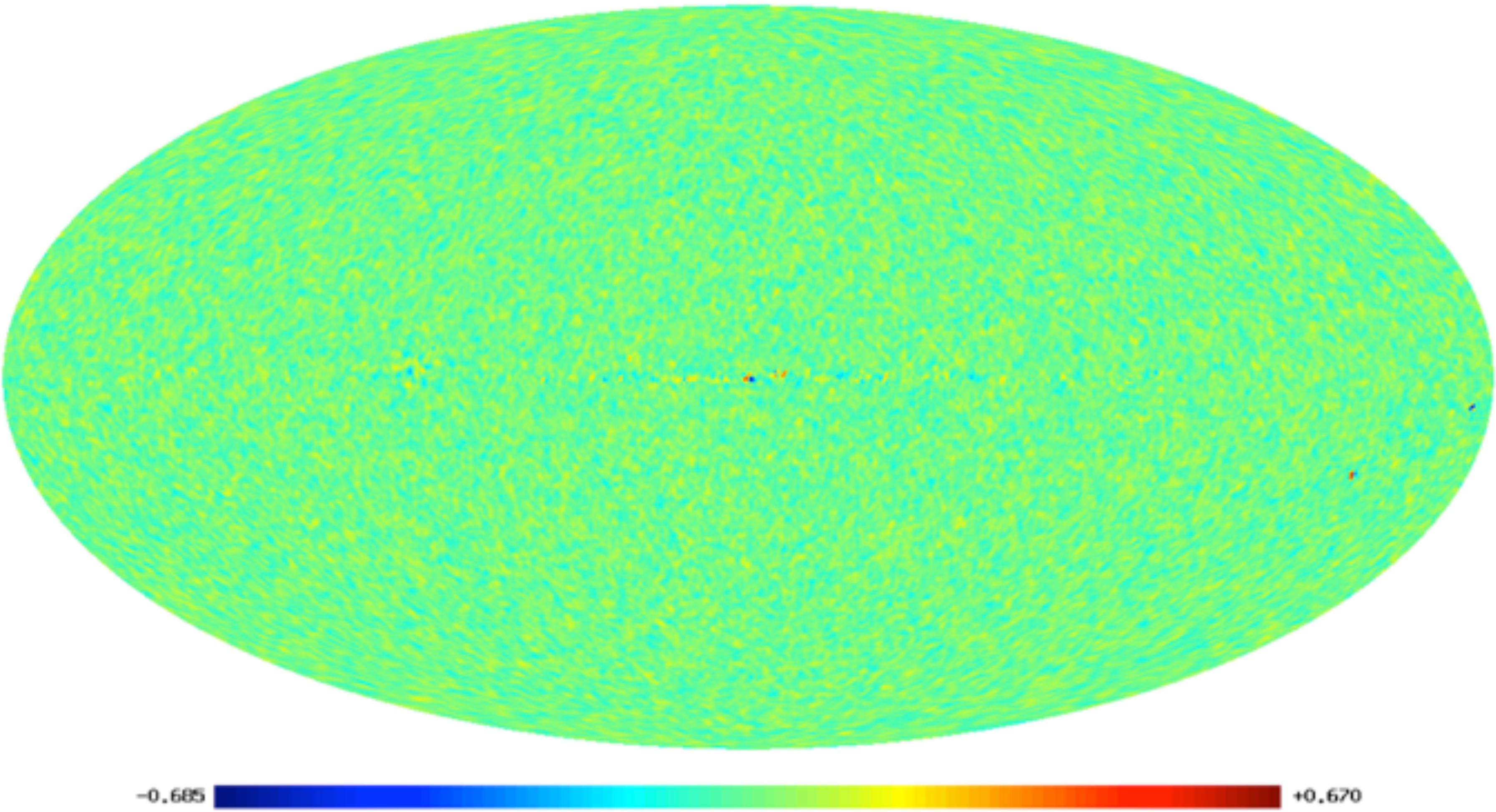

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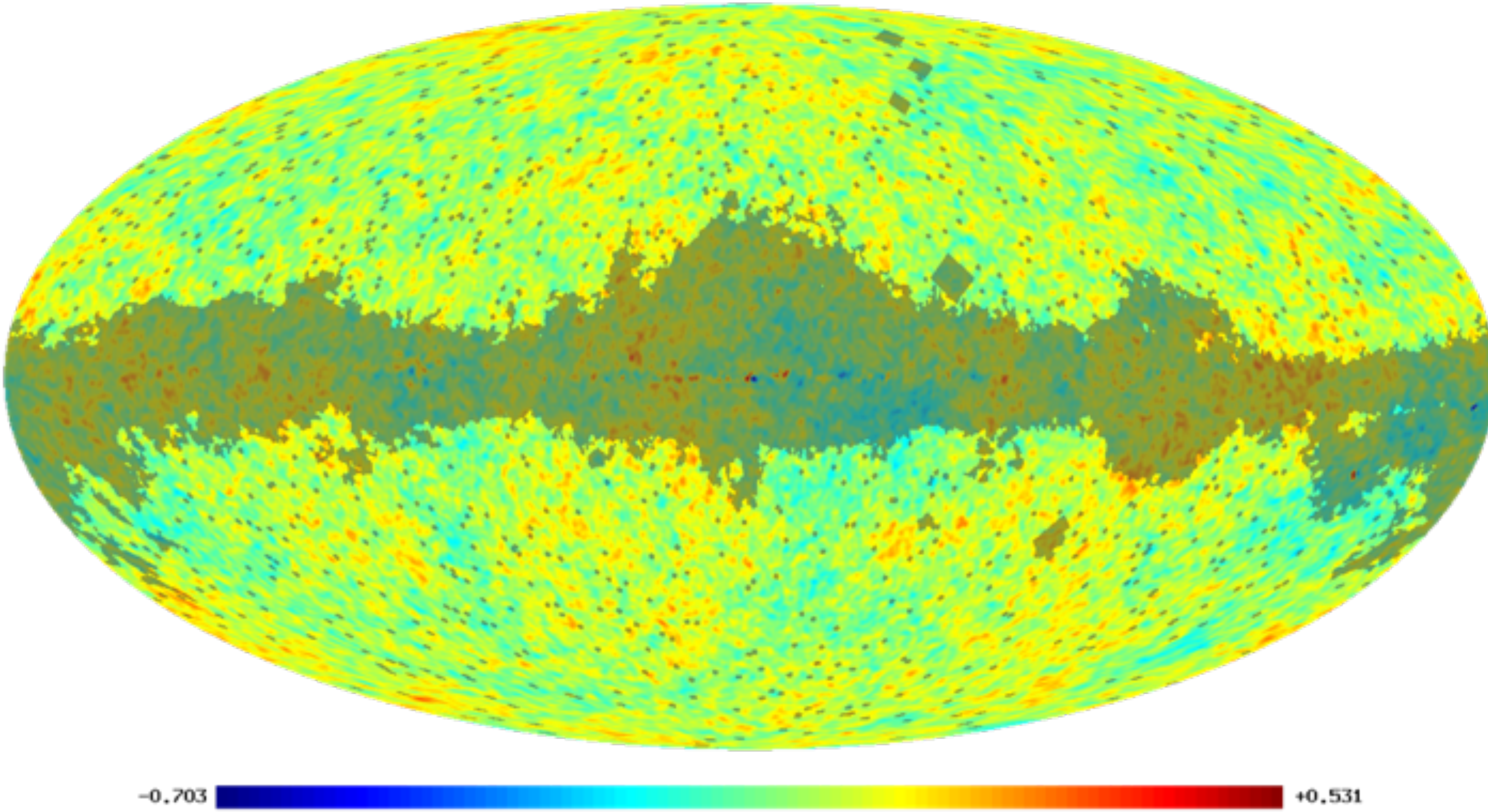
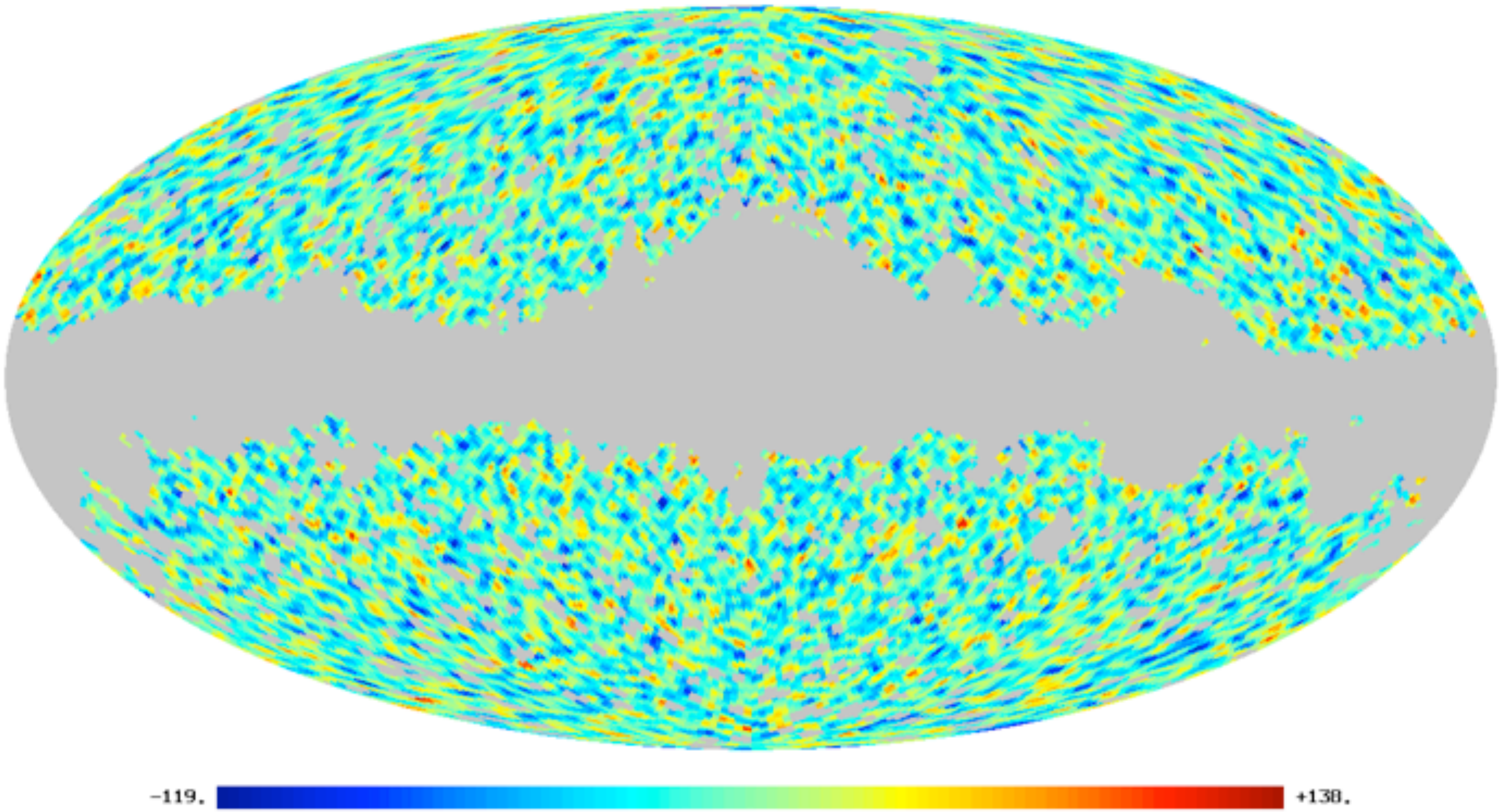
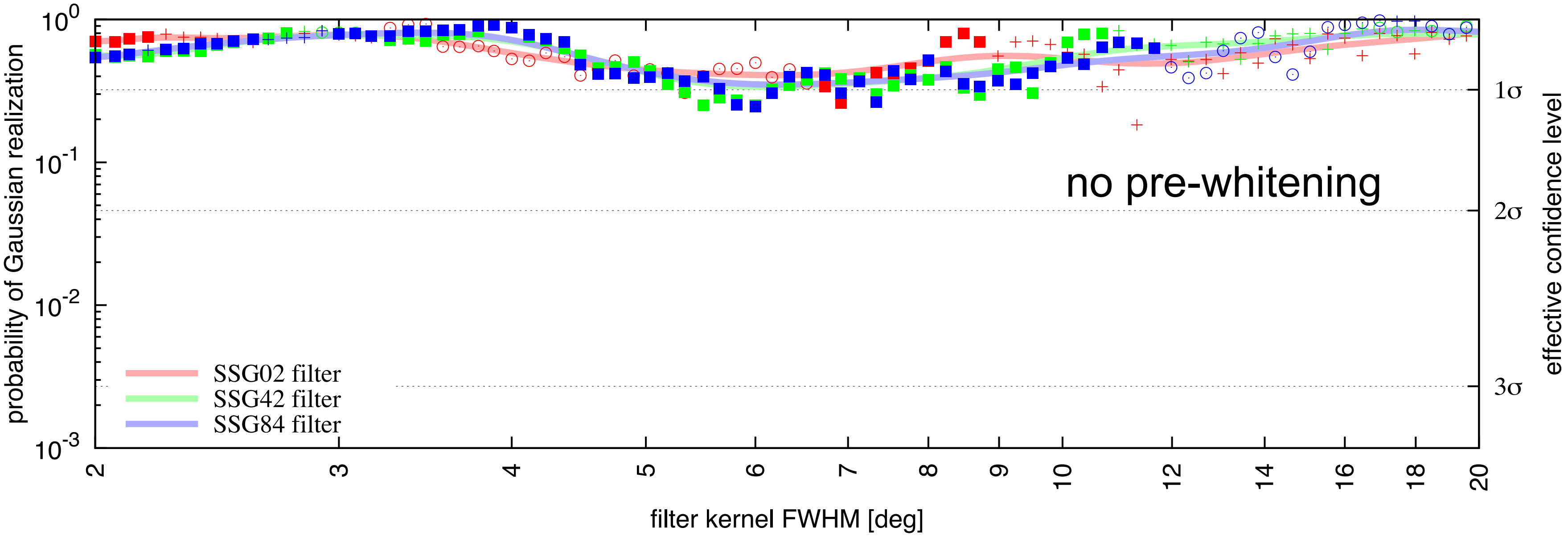
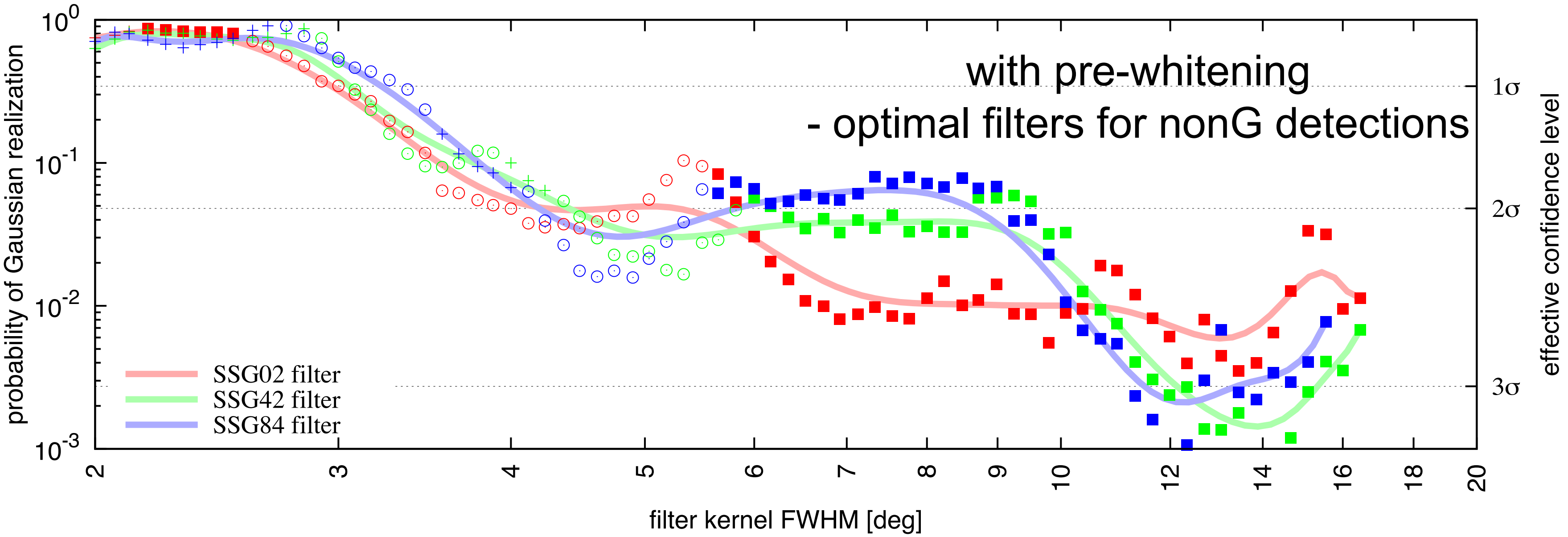


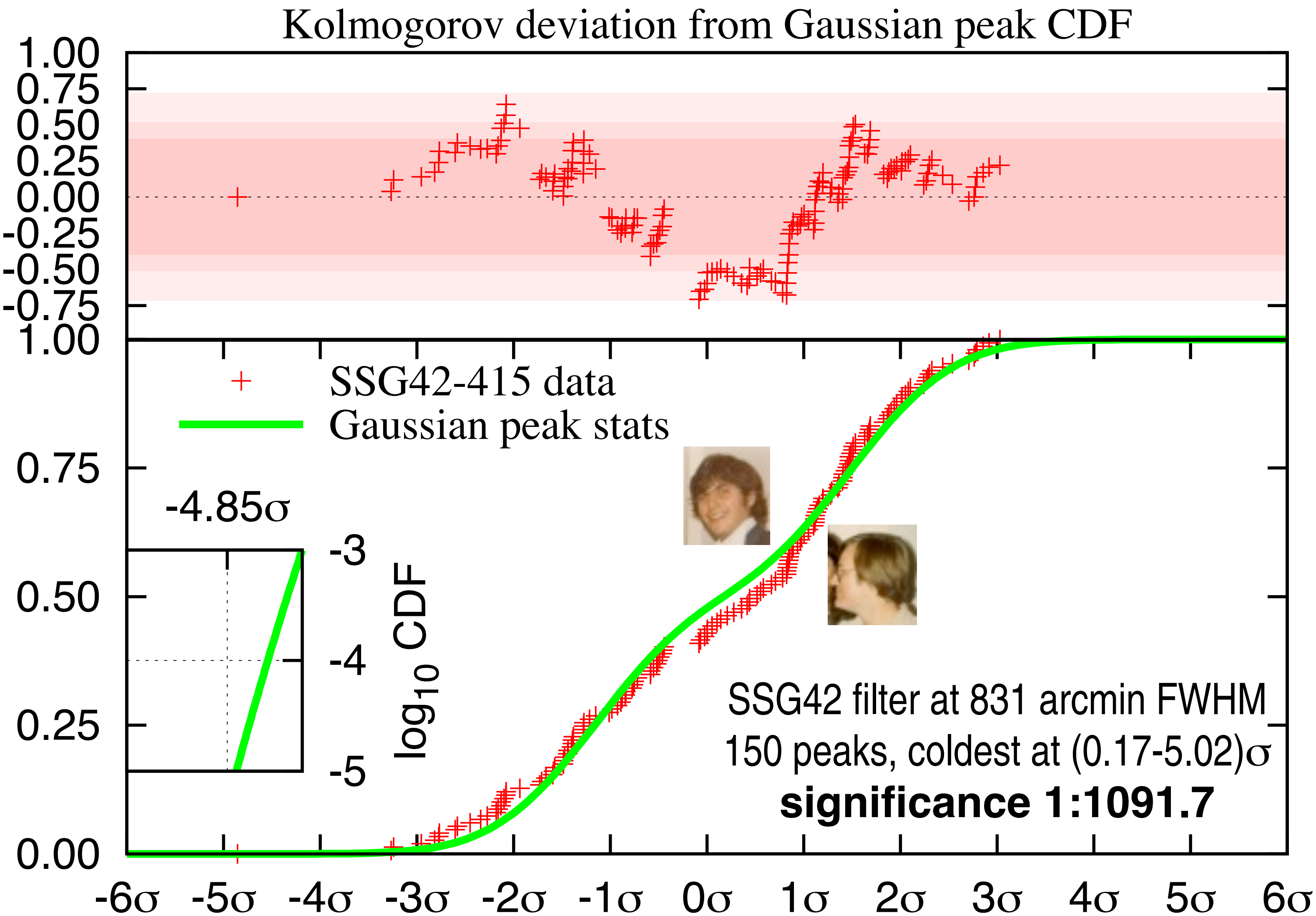
Bond, Frolov, Huang, Kofman, Nolta: Cold Spot testing: spherical SavitzkyGolay filters (compact polynomials) on **pre-whitened** **WMAP5 data: -5.02σ, at 831 arcmin fwhm, 149 peaks, 1/1099 significance**


-119.
+138.

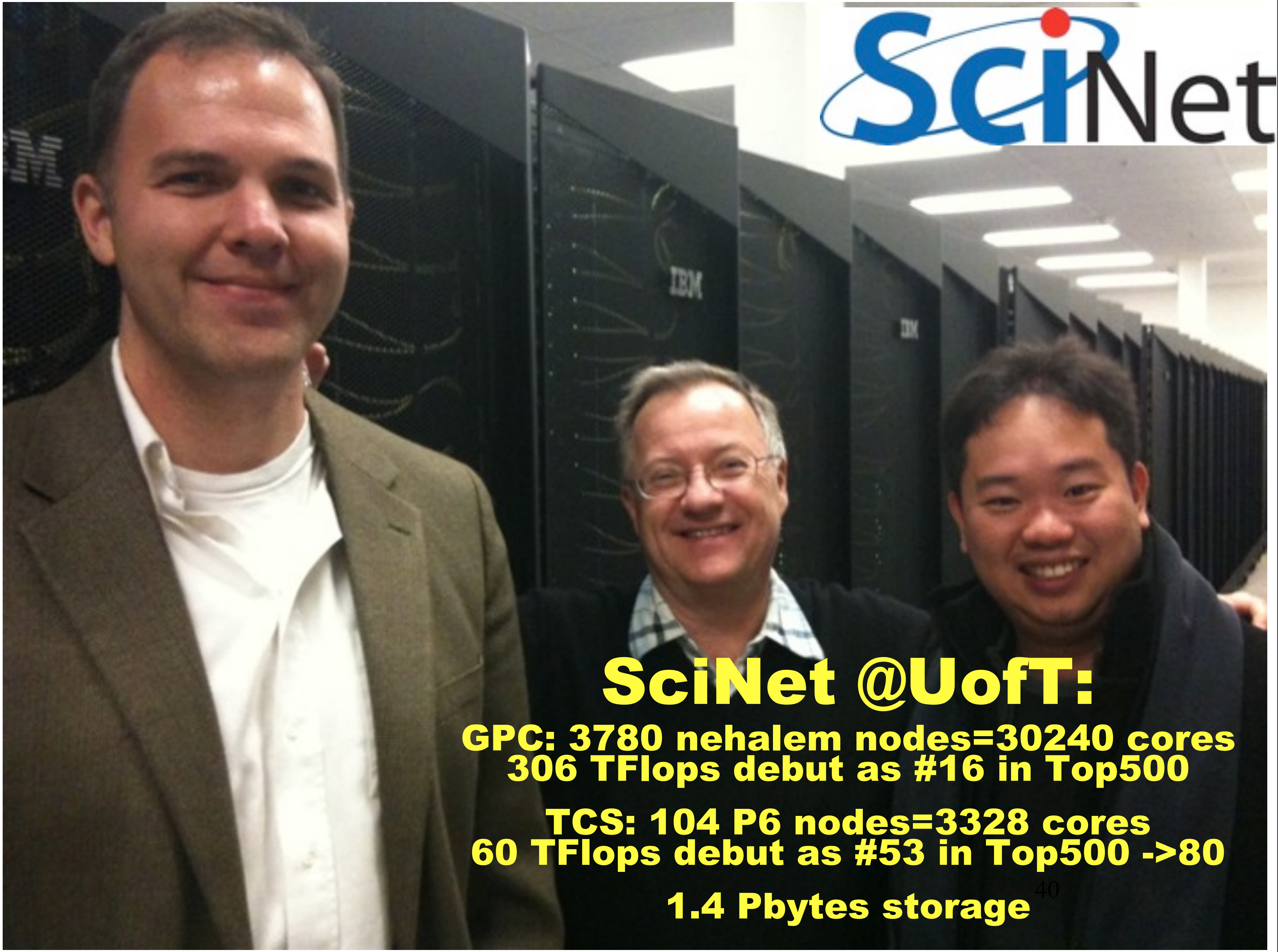

no pre-whitening
probability of Gaussian realization
effective confidence level
filter kernel FWHM [deg]
SSG02 filter
SSG42 filter
SSG84 filter
1σ
2σ
3σ


with pre-whitening
- optimal filters for nonG detections
probability of Gaussian realization
effective confidence level
filter kernel FWHM [deg]
SSG02 filter
SSG42 filter
SSG84 filter
1σ
2σ
3σ

the WMAP Cold Spot: Vielva, Martinez-Gonzalez, Barr, Sanz, Cayon 2004 wavelets in WMAP1, ... Cruz etal 07 in WMAP3, & in WMAP5: needlets, steerable wavelets: ~4.5σ, others ~3σ; Zhang & Huterer 09, not as significant with other filters 20%



Bond, Frolov, Huang, Kofman, Nolta 09


SciNet
SciNet @UofT:
GPC: 3780 nehalem nodes=30240 cores
306 TFlops debut as #16 in Top500
TCS: 104 P6 nodes=3328 cores
60 TFlops debut as #53 in Top500 ->80
1.4 Pbytes storage
40

CBI pol to Apr'05 @Chile **CBI2**

QUaD @SP

Quiet1 @Chile

Quiet2 1000 HEMTs

Boom03@LDB

Bicep @SP

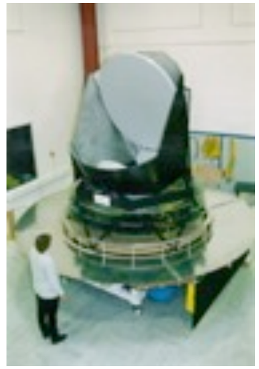
Bicep2

Keck/Spud@SP

WMAP @L2 to 2010

Planck09.4

52 bolometers
+ HEMTs @L2
9 frequencies



EBEX @LDB

Spider
2312 bolos
@LDB

DASI @SP

CAPMAP

Herschel

BLAST

CHIP

2004 2006 2008 LHC 2011 **Bpol** @L2

2005 2007 2009

Acbar to Jan'06, 08f @SP

SPT
1000 bolos
@SPole

BLASTpol

Clover @Chile

SZA
@Cal

ACT
3000 bolos
3 freqs @Chile

Polarbear
300 bolos
@Cal/Chile

SPTpol

ACTpol

AMI

APEX
~400 bolos
@Chile

SCUBA2

12000 bolos
JCMT @Hawaii

ALMA
@Chile

GBT

LMT@Mexico

V. Acquaviva [1,2]
P. Ade [3]
P. Aguirre [4]
M. Amiri [5]
J. Appel [6]
E. Battistelli [7,5]
J. R. Bond [8]
B. Brown [9]
B. Burger [5]
J. Chervenak [10]
S. Das [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]
M. Halpern [5]
M. Hasselfield [5]
C. Hernandez-Monteagudo [13,2]
G. Hilton [11]
M. Hilton [14,15]
A. D. Hincks [6]
R. Hlozek [12]
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.H. Lupton [1]
T.A. Marriage [1,6]
D. Marsden [2]
K. Martocci [23,6]
P. Mauskopf [3]
F. Menanteau [18]
K. Moodley [14]
H. Moseley [10]
B. Netterfield [24]
M.D. Niemack [11,6]
M.R. Nolta [8]
L.A. Page (PI) [6]
L. Parker [6]
B. Partridge [25]
H. Quintana [4]
B. Reid [19,1]
N. Sehgal [20,18]
J. Sievers [8]
D. Spergel [1]
S.T. Staggs [6]
O. Stryzak [6]
D. Swetz [2]
E. Switzer [23,6]
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]

the **ACTers**

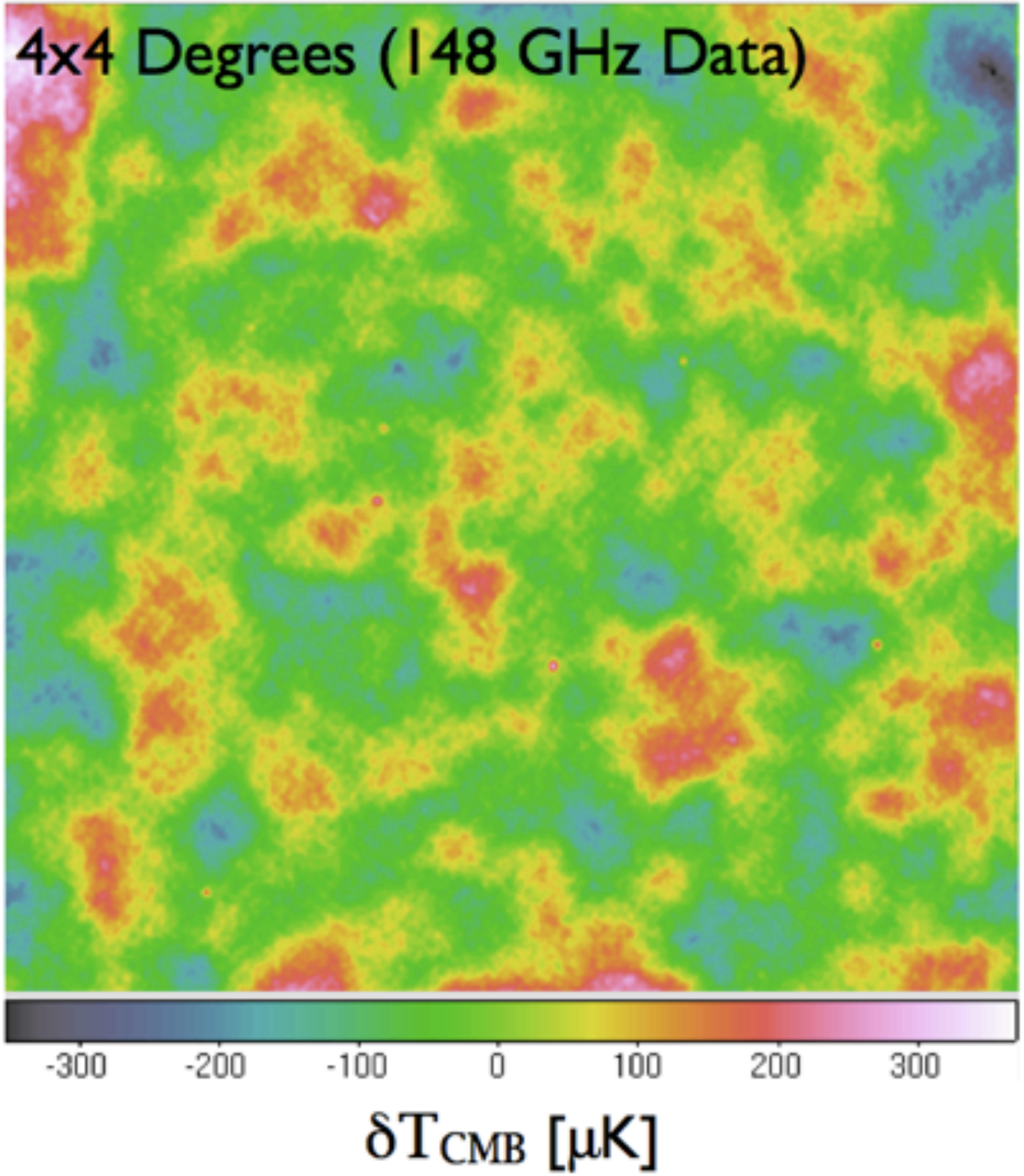
[1] Princeton University Astrophysics (USA)
[2] University of Pennsylvania (USA)
[3] Cardiff University (UK)
[4] Pontifica Universidad Catolica de Chile (Chile)
[5] University of British Columbia (Canada)
[6] Princeton University Physics (USA)
[7] University of Rome "La Sapienza" (Italy)
[8] CITA, University of Toronto (Canada)
[9] University of Pittsburgh (USA)
[10] NASA Goddard Space Flight Center (USA)
[11] NIST Boulder (USA)
[12] Oxford University (UK)
[13] Max Planck Institut fur Astrophysik (Germany)
[14] University of KwaZulu-Natal (South Africa)
[15] South African Astronomical Observatory
[16] University of Miami (USA)
[17] INAOE (Mexico)
[18] Rutgers (USA)
[19] ICCUB (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)

Mapping

Jon Sievers etal ACTers

- Input data: 5 TB
- ML map solved iteratively
- ~1000 iterations
- 4000 CPU Cores for 1.5 days
- ~20 CPU years for one map
- Unbiased estimate of all modes from *ell* ~ 100 - 10000

ACT Maps are made at U. Toronto's Scinet cluster, ranked in top 20 fastest.



Mapping

Jon Sievers etal ACTers

Unbiased estimate of all modes

from *ell* ~ 100 - 10000

Atmosphere: 2 deg

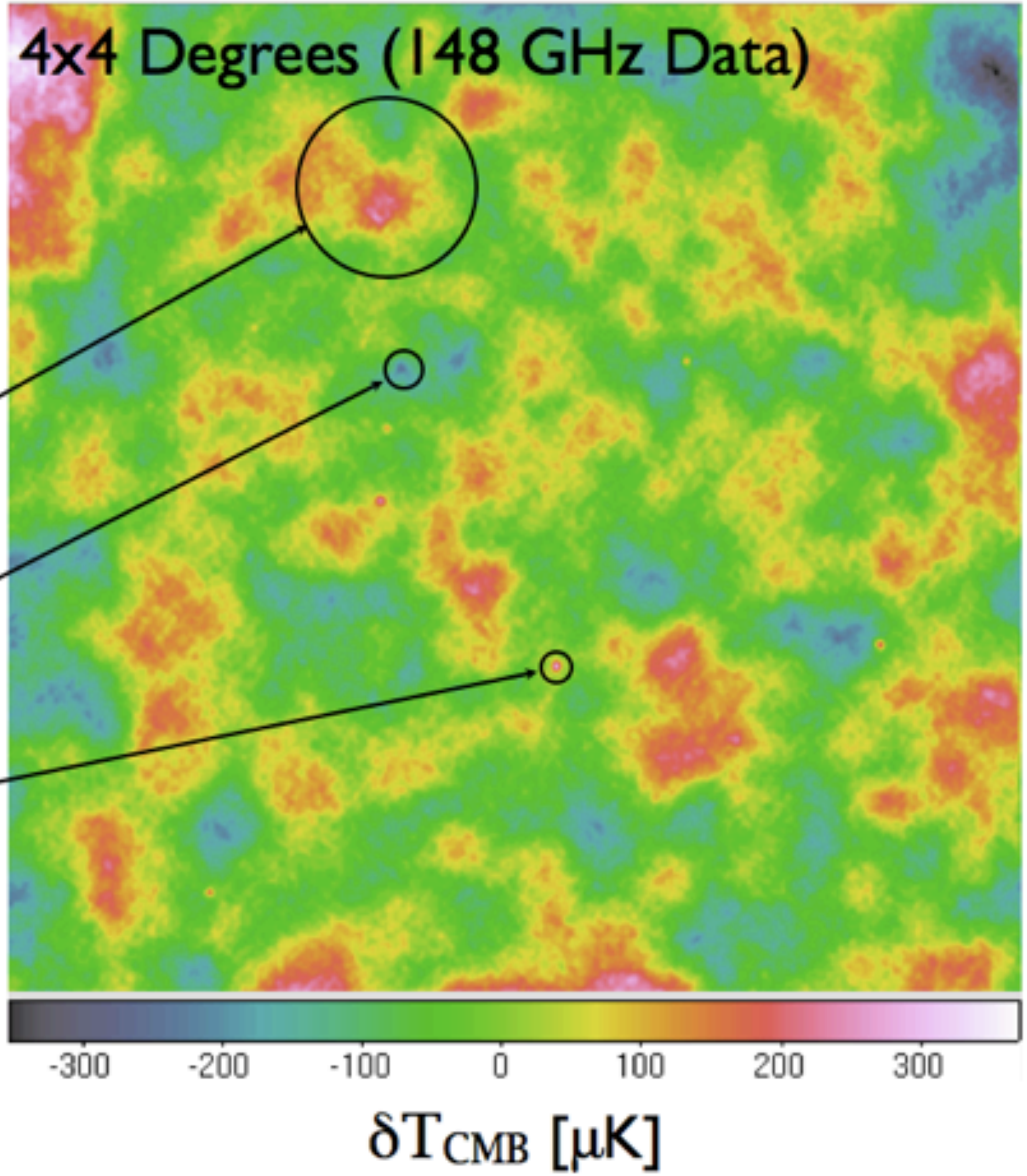
(Filtered Here)

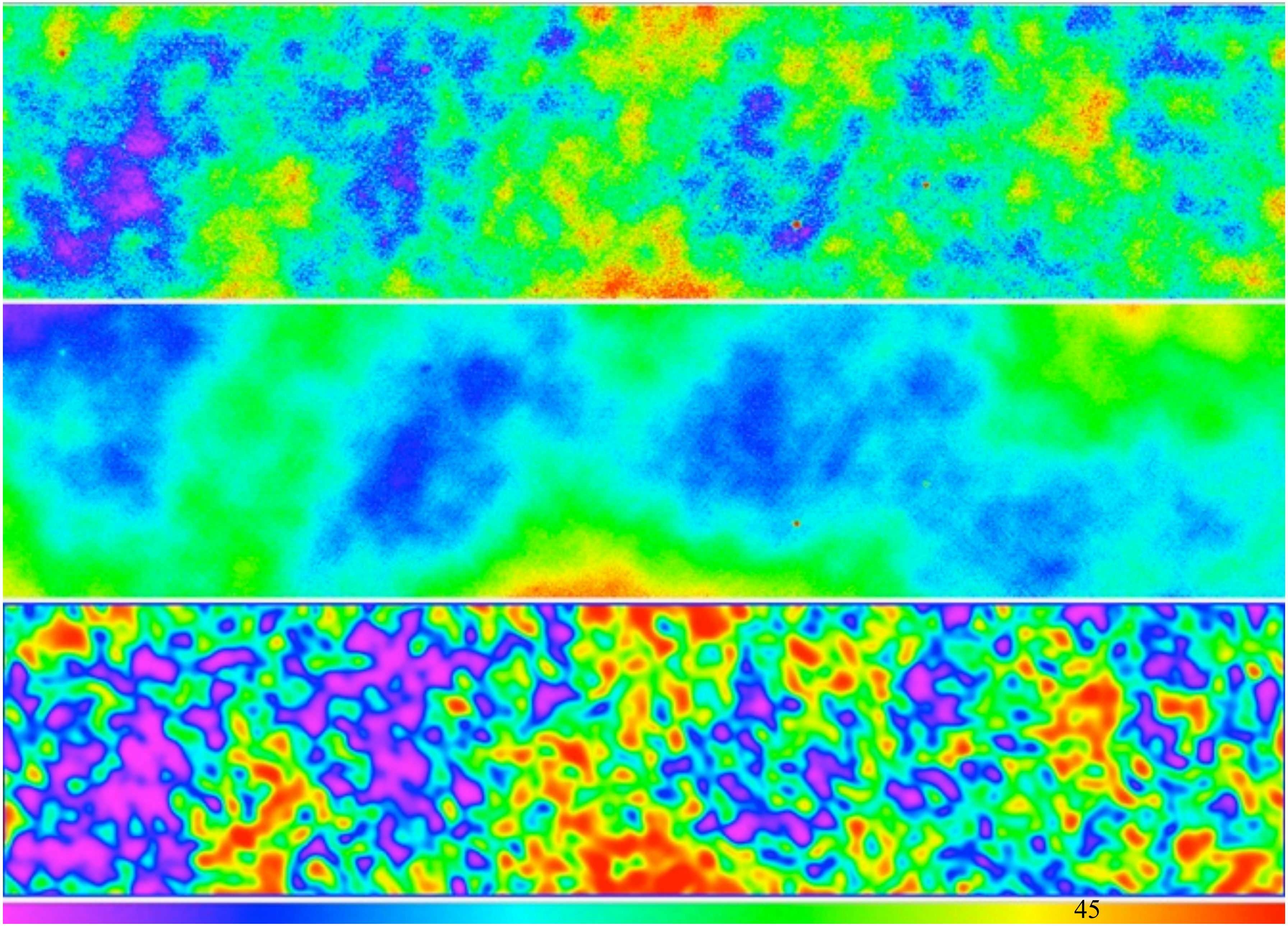
CMB: 1 deg

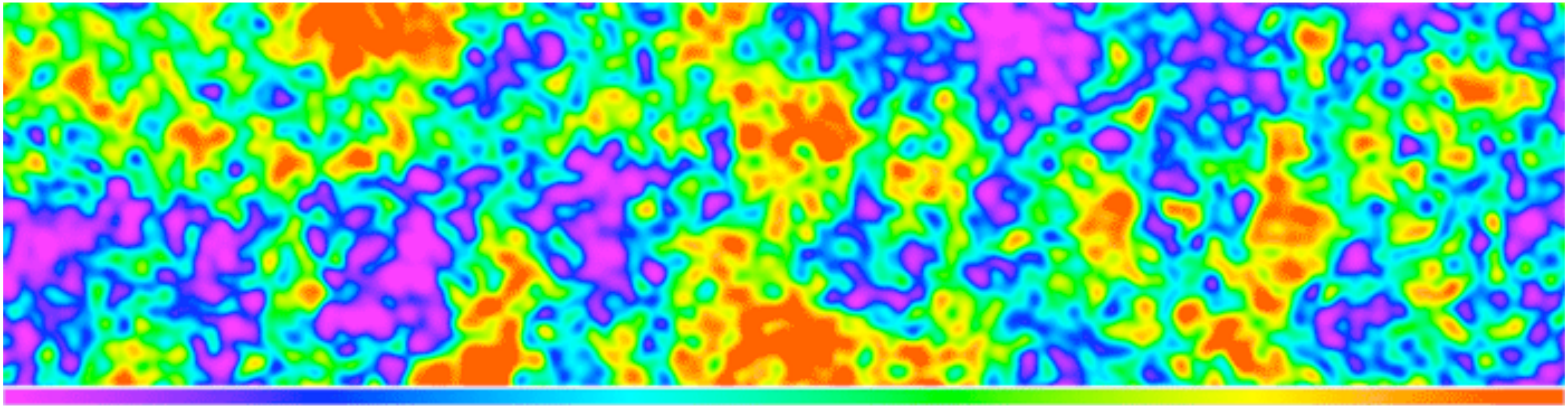
Clusters*: (>1.4')-4'

Sources*: 1.4'

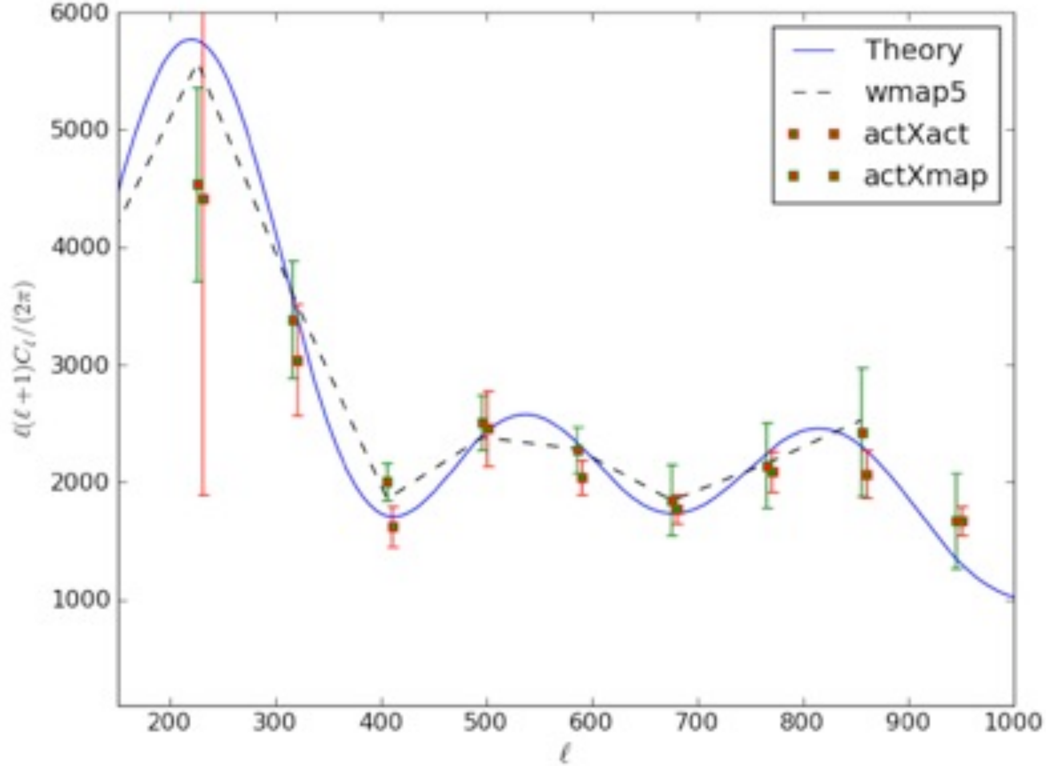
* Minimum size set by beam

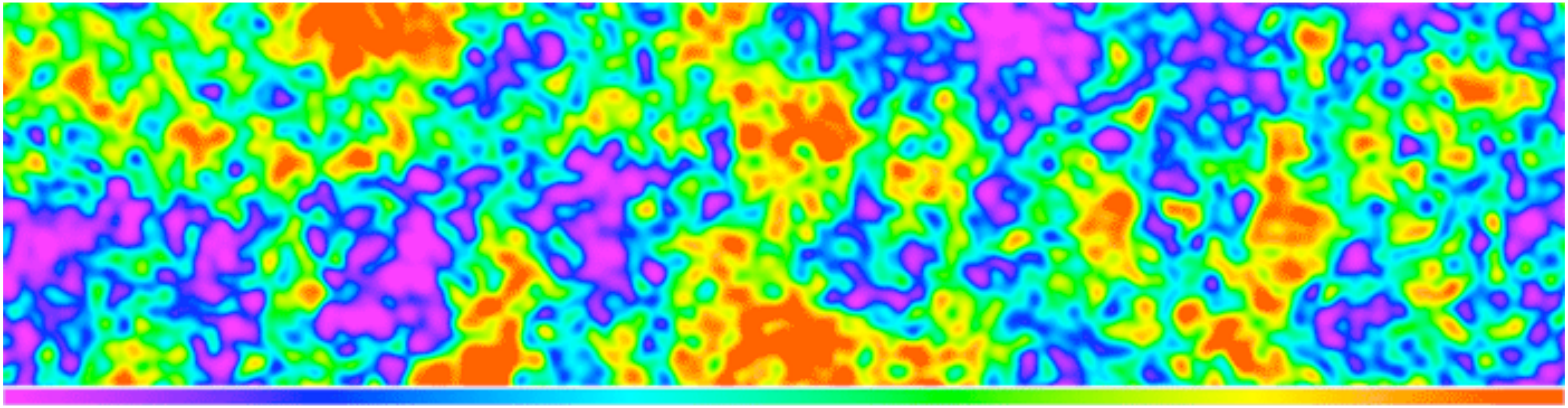




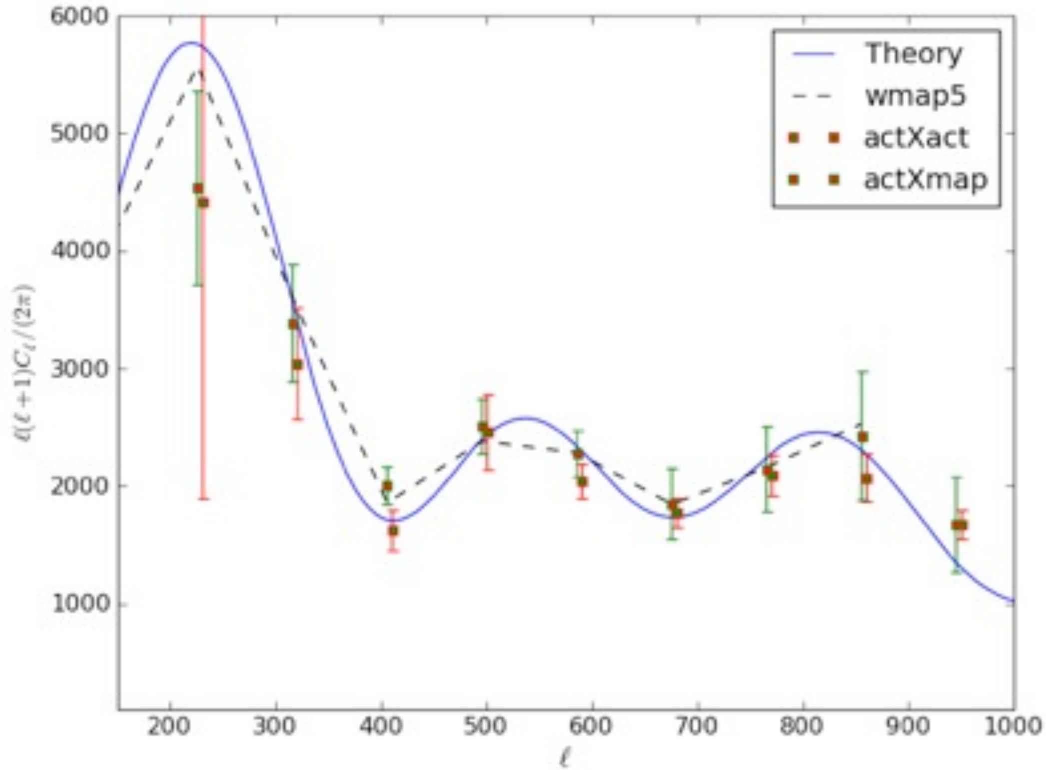


Amir Hajian etal ACTers

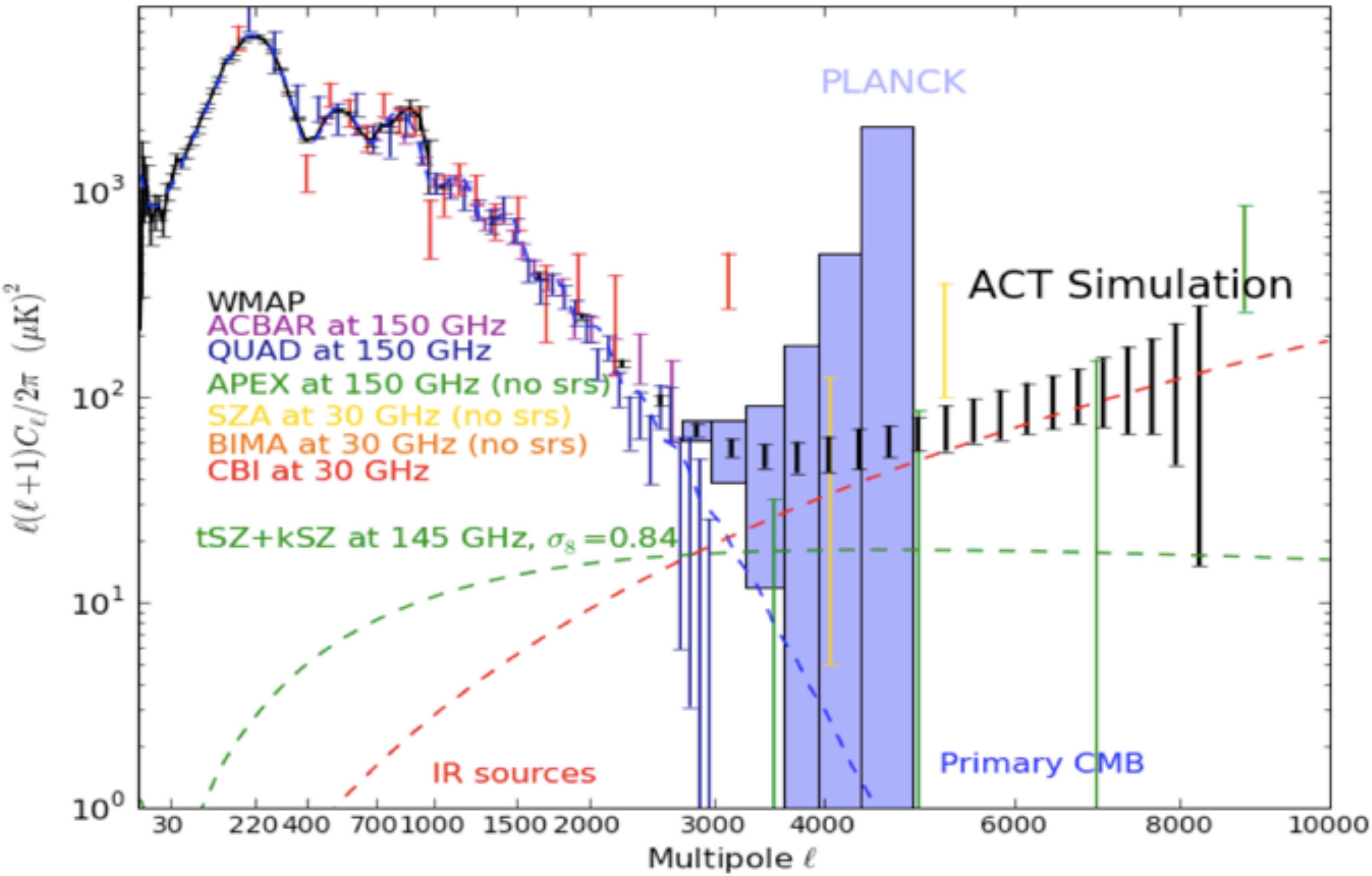




Amir Hajian etal ACTers



Power Spectrum



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

400
Mpc

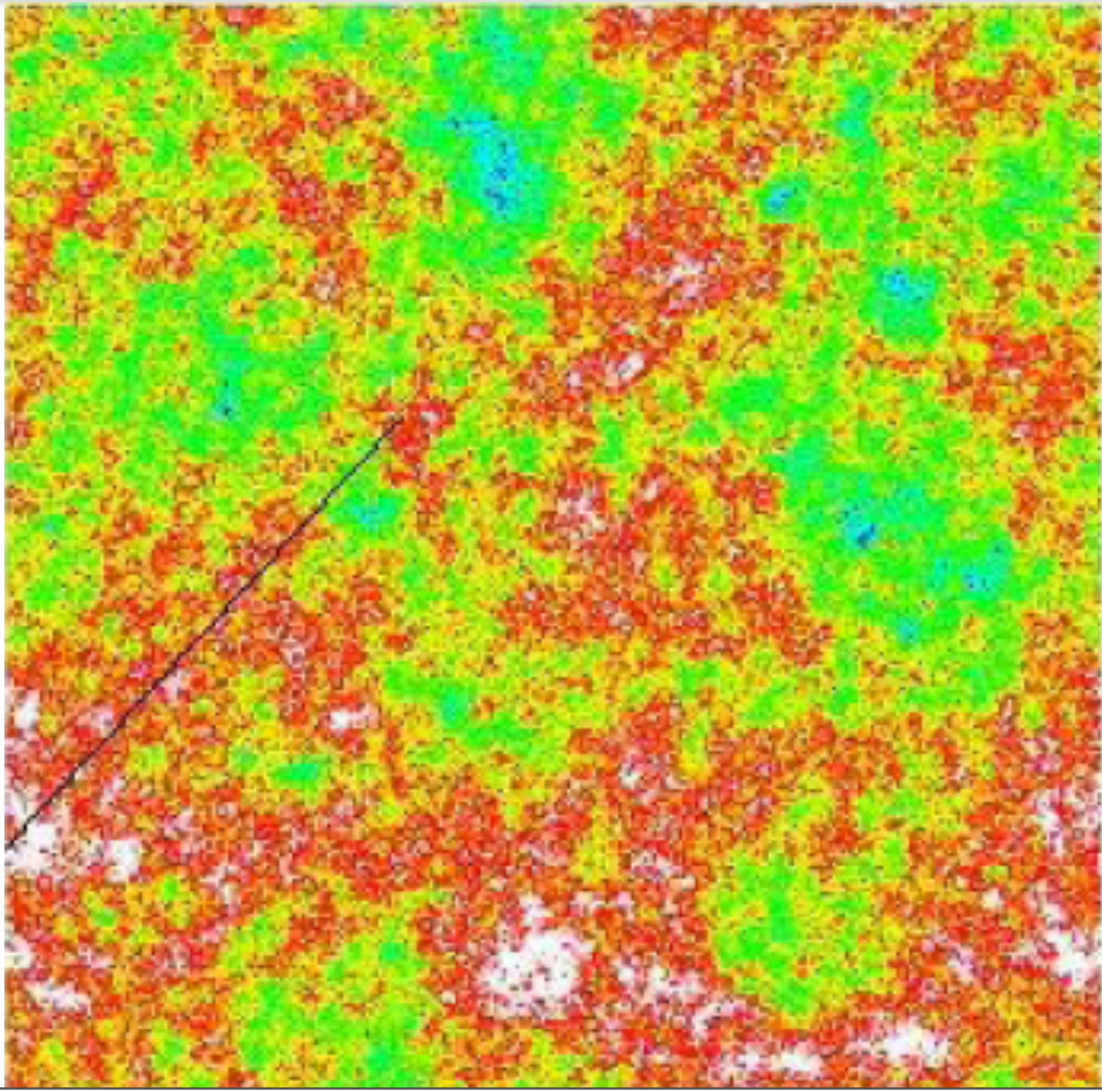
ΛCDM

WMAP5

gas
density

Gadget-3
SF+
SN E+
winds
+CRs

512^3



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

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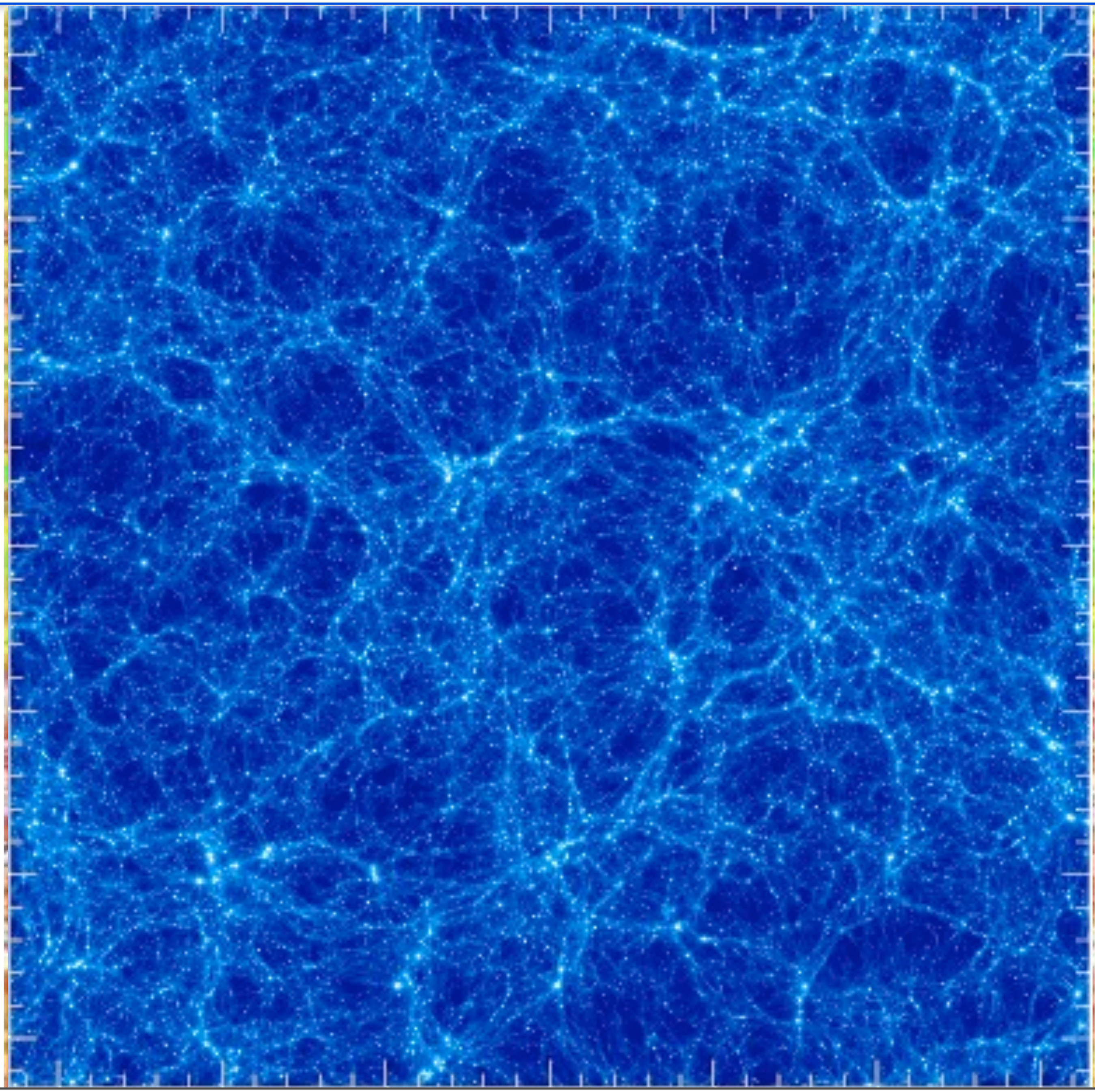

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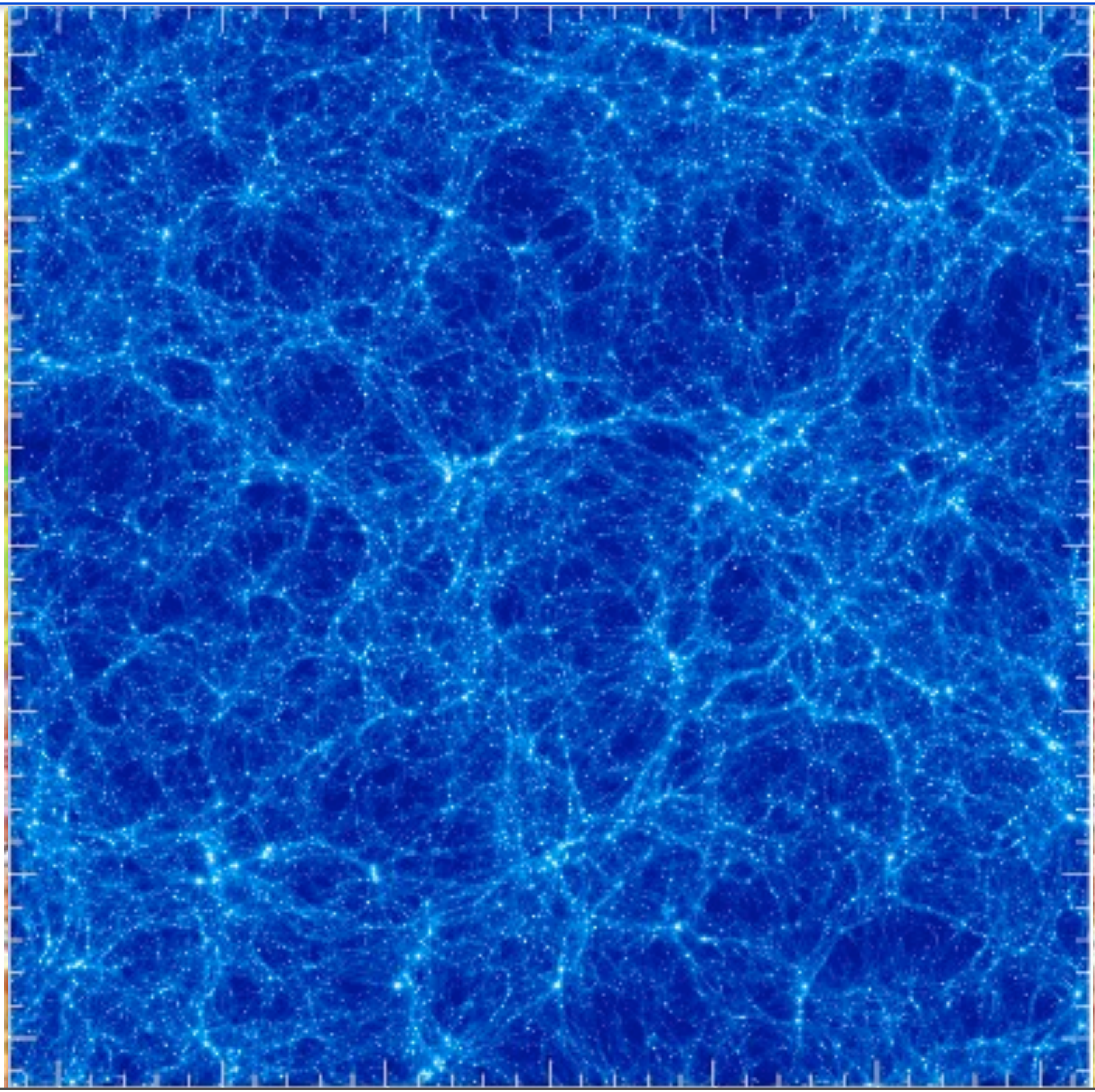


all this can

evolve from early U vacuum potential and vacuum noise

in the presence of late U vacuum potential

aetherial!

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

400
Mpc

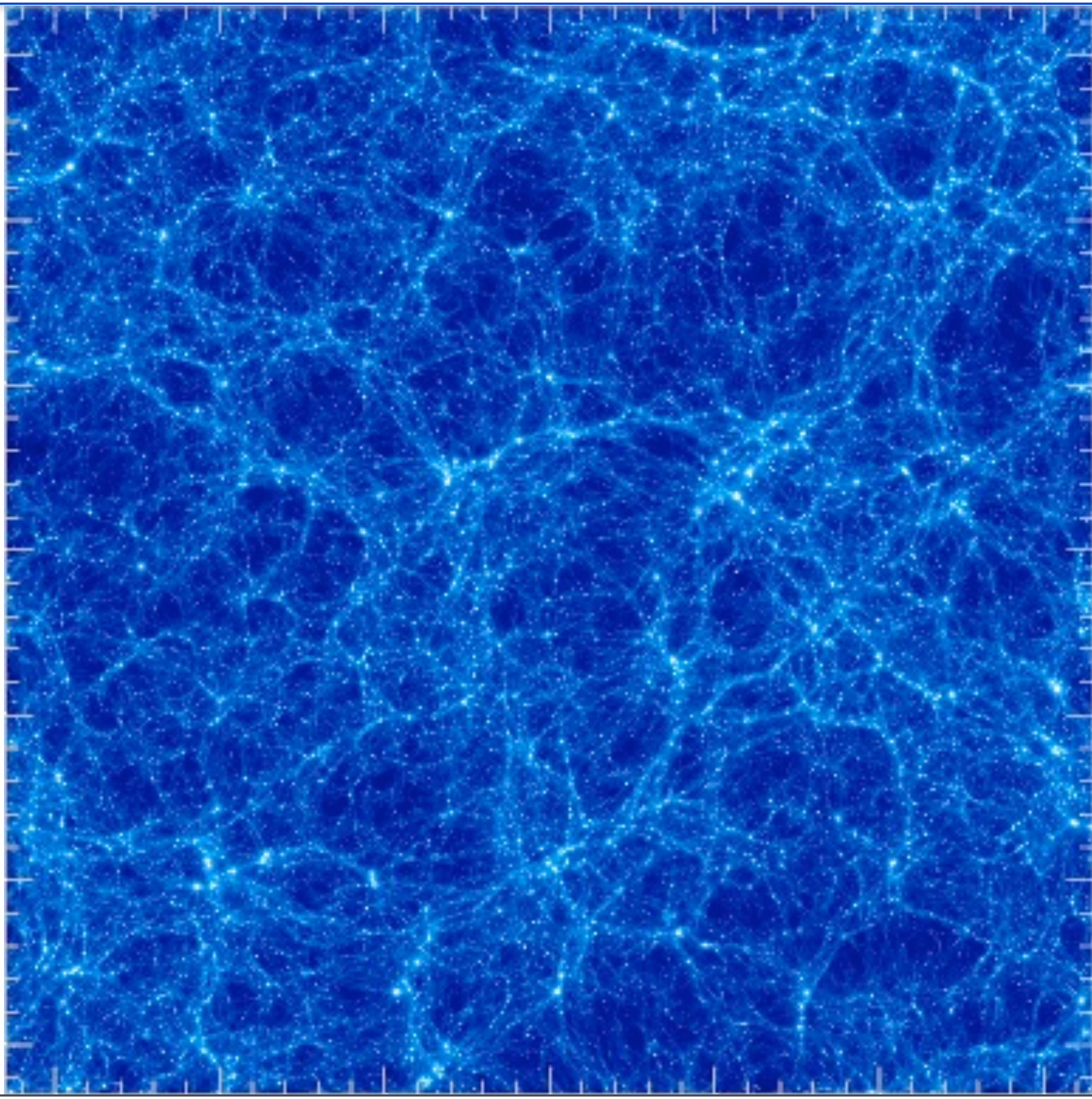
ΛCDM

WMAP5

gas
pressure

Gadget-3
SF+
SN E+
winds
+CRs

512^3



*all this
can*

*evolve
from
early U
vacuum
potential
and
vacuum
noise*

*in the
presence
of late U
vacuum
potential*

aetherial!

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

400
Mpc

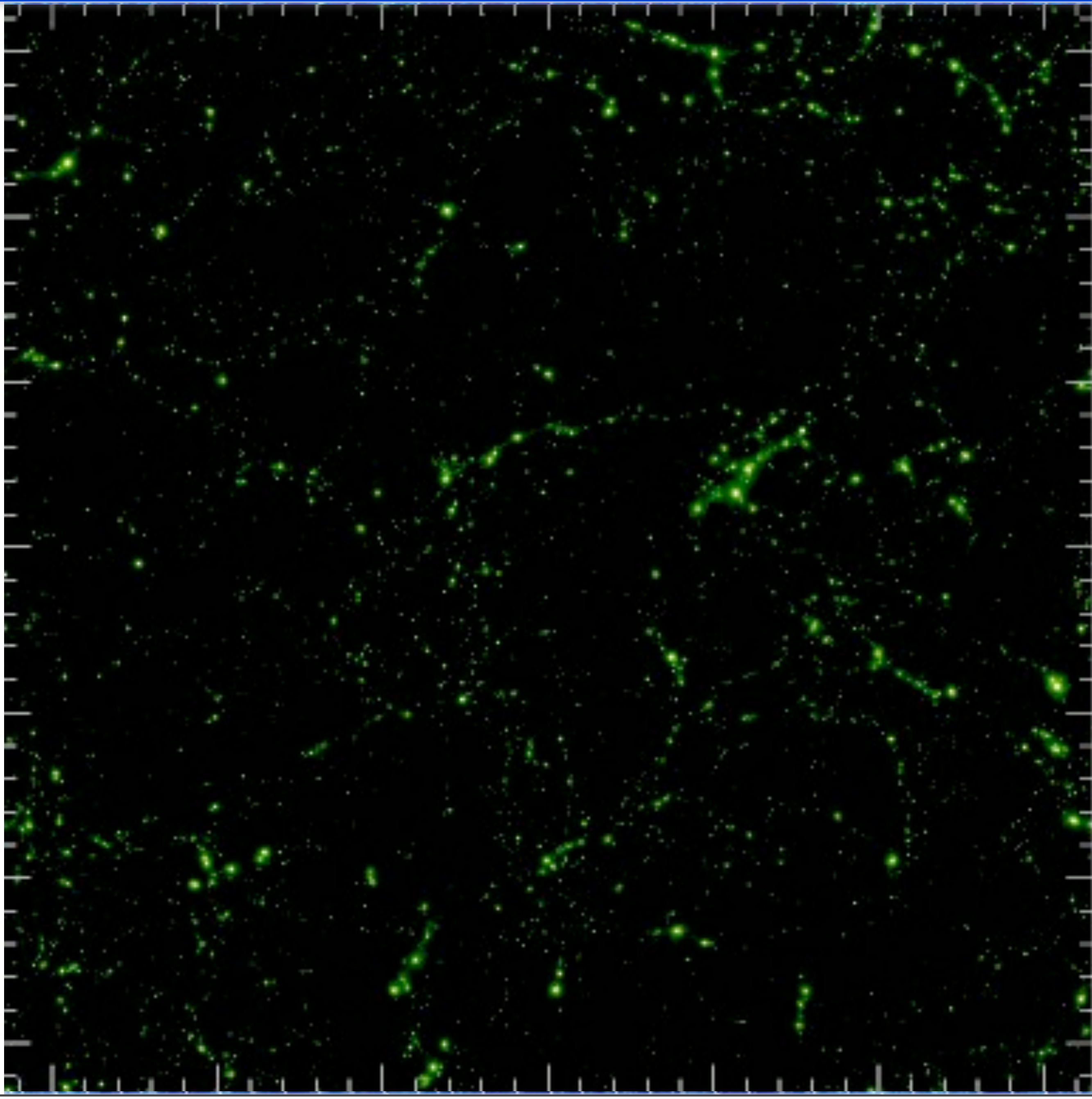
ΛCDM

WMAP5

gas
pressure

Gadget-3
SF+
SN E+
winds
+CRs

512^3



all this can

evolve from early U vacuum potential and vacuum noise

in the presence of late U vacuum potential

aetherial!

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

400 Mpc

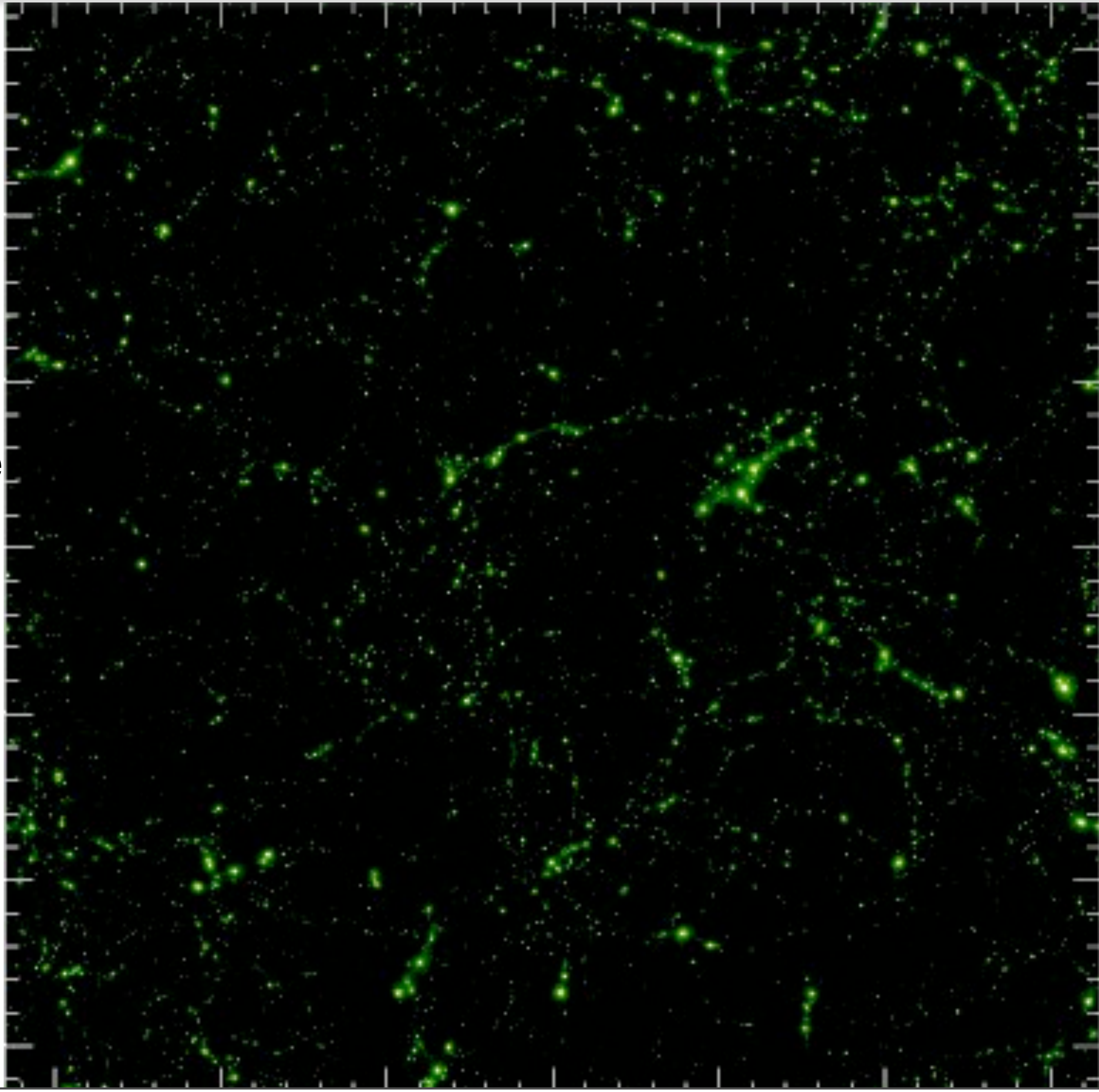
ΛCDM

WMAP5

gas pressure

Gadget-3 formation shocks only aka adiabatic

512^3



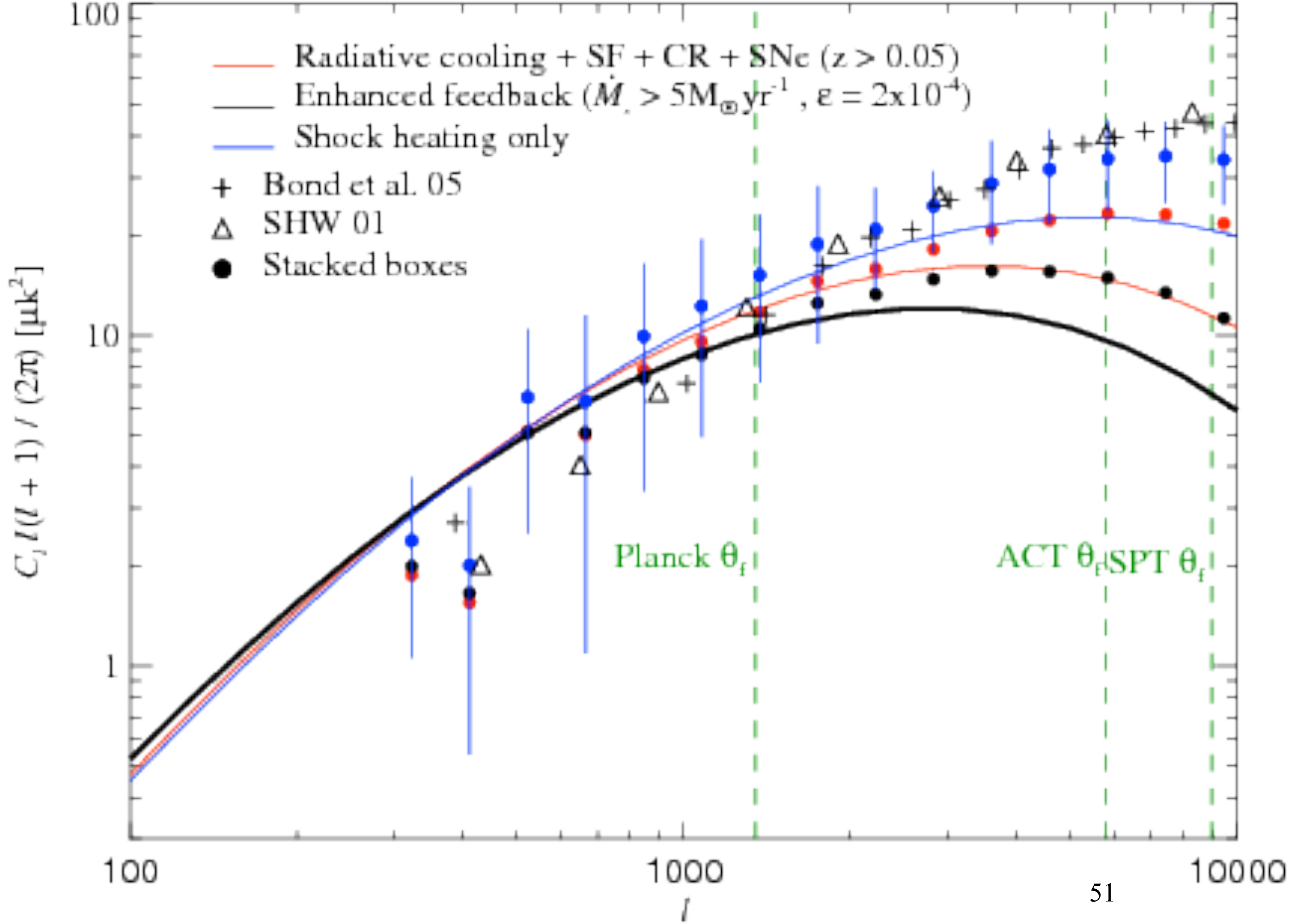
all this can

evolve from early U vacuum potential and vacuum noise

in the presence of late U vacuum potential

aetherial!

C_L^{SZ} systematic uncertainties, via large computer simulations



Battaglia, Bond, Pfrommer,Sievers, Sijacki 09

November 2009 data

Cosmic Microwave Background (CMB): WMAP5yr (09), Acbar (09), QUAD (09), BICEP (09), CBI (08), Boomerang (06), DASI (05), VSA (04), MAXIMA (00)

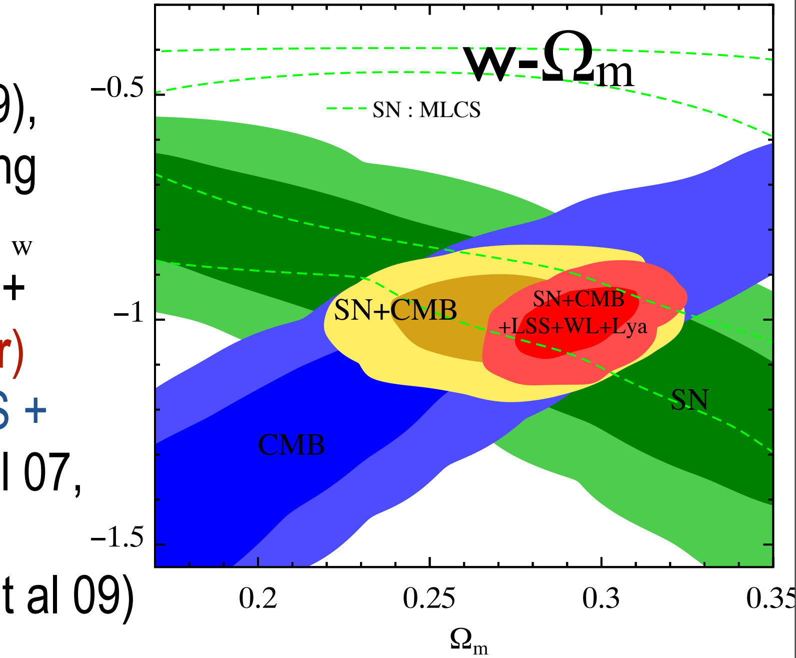
Type Ia Supernova (SN): LOWZ + SDSS + ESSENCE + SNLS1yr + HST (Kessler et al 09) **(soon will + SNLS3yr)**

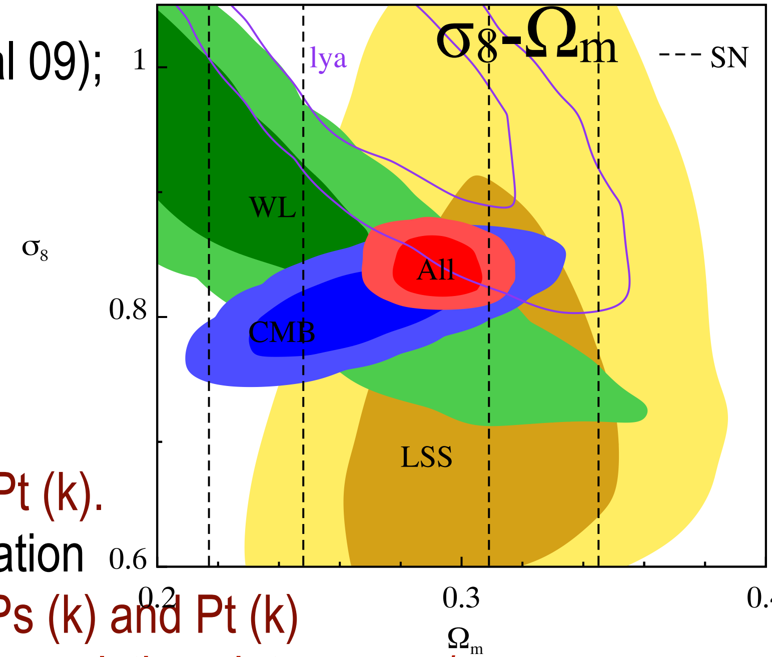
Weak Lensing (WL): COSMOS + CFHTLS-wide + RCS + VIRMOS + GaBoDS (Massey et al 07, Lesgourgues et al 07, Benjamin et al 07)

Large Scale Structure (LSS): SDSS-DR7 LRG (Reid et al 09)

Lya Forest (Lya): SDSS Lya(McDonald et al 05, 06)

Others: HST constraint on Hubble parameter (Riess et al 09); Cluster x-ray gas mass fraction (Allen et al 08)





COSMOMC plug-ins (Zhiqi Huang)

Decaying dark matter

CMB, WL, SN, BAO mock data simulator

arbitrary Primordial Power spectra functions Ps (k) and Pt (k).

full Ps (k) & Pt (k) integrator for arbitrary single-field inflation

automatic adjust L, k interpolations for more oscillatory Ps (k) and Pt (k)

Dark energy equation of state: arbitrary w(z), with built-in analytic quintessence/ phantom parametrization.

Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c $\ln A_s$ n_s $r = A_t/A_s$ $dn_s/d\ln k$ n_t

$1+w_0, w_a$ $\theta \sim \ell_s^{-1}$ $n_e(a)$ $\sim \ln \sigma_8^2$

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

(partially) blind cf. informed "theory" priors

primordial non-Gaussianity

$\Phi(x) = \Phi_G(x) + f_{NL} (\Phi_G^2(x) - \langle\Phi_G^2\rangle)$

local smooth

DBI inflation: non-quadratic kinetic energy

cosmic/fundamental strings/defects

from end-of-inflation & preheating

$\Phi(x) = \Phi_G(x) + F_{NL}(\chi_b) - \langle F_{NL}\rangle$

resonant preheating

$\ln P_s(\ln k)$ & $r(k_p)$

& $\ln P_t(\ln k)$

$\varepsilon_\phi \times 2/3 = 1 + w(a)$

$= - d\ln\rho_\phi / d\ln \mathbf{a}^3$

+ subdominant

isocurvature, cosmic string,

& fgnds, tSZ, kSZ, ...

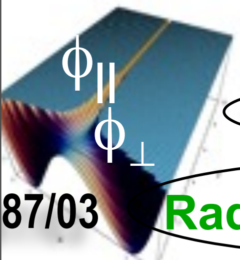
Old view: **Theory prior = delta function of THE correct one and only theory**

New: Theory prior = probability distribution of **late-flows** on an **energy LANDSCAPE**

6/7 tiny extra dimensions

1980 R^2-inflation | Old Inflation | **Chaotic inflation**

New Inflation



Double Inflation | Power-law inflation | SUGRA inflation

87/03 **Radical BSI inflation** | running (nee variable M_P) inflation | Extended inflation

1990 **Natural pNGB inflation** | Hybrid inflation

KLS94 **preheating**

SUSY F-term inflation | SUSY D-term inflation | Assisted inflation | Brane inflation

2000 SUSY P-term inflation | Super-natural Inflation | K-flation

2003 KKLT → N-flation | *ekpyrotic/cyclic*

D3,D7 brane inflation | DBI inflation

moving brane separations Racetrack inflation | Tachyon inflation | Warped Brane inflation

moduli fields monodromy

Roulette inflation Kahler moduli/axion | fiber inflation

Saturday, December 12, 2009

INFLATION THEN

"standard inflation space": $\mathbf{n_s}$ $\mathbf{dn_s/dlnk}$ $\mathbf{r}$ **@k-pivots**

WHAT IS PREDICTED?

Smoothly broken scale invariance by nearly uniform braking (standard of 80s/90s/00s) r~0.03-0.5

large field inflation (field moves > Planck mass)

or highly variable braking r tiny

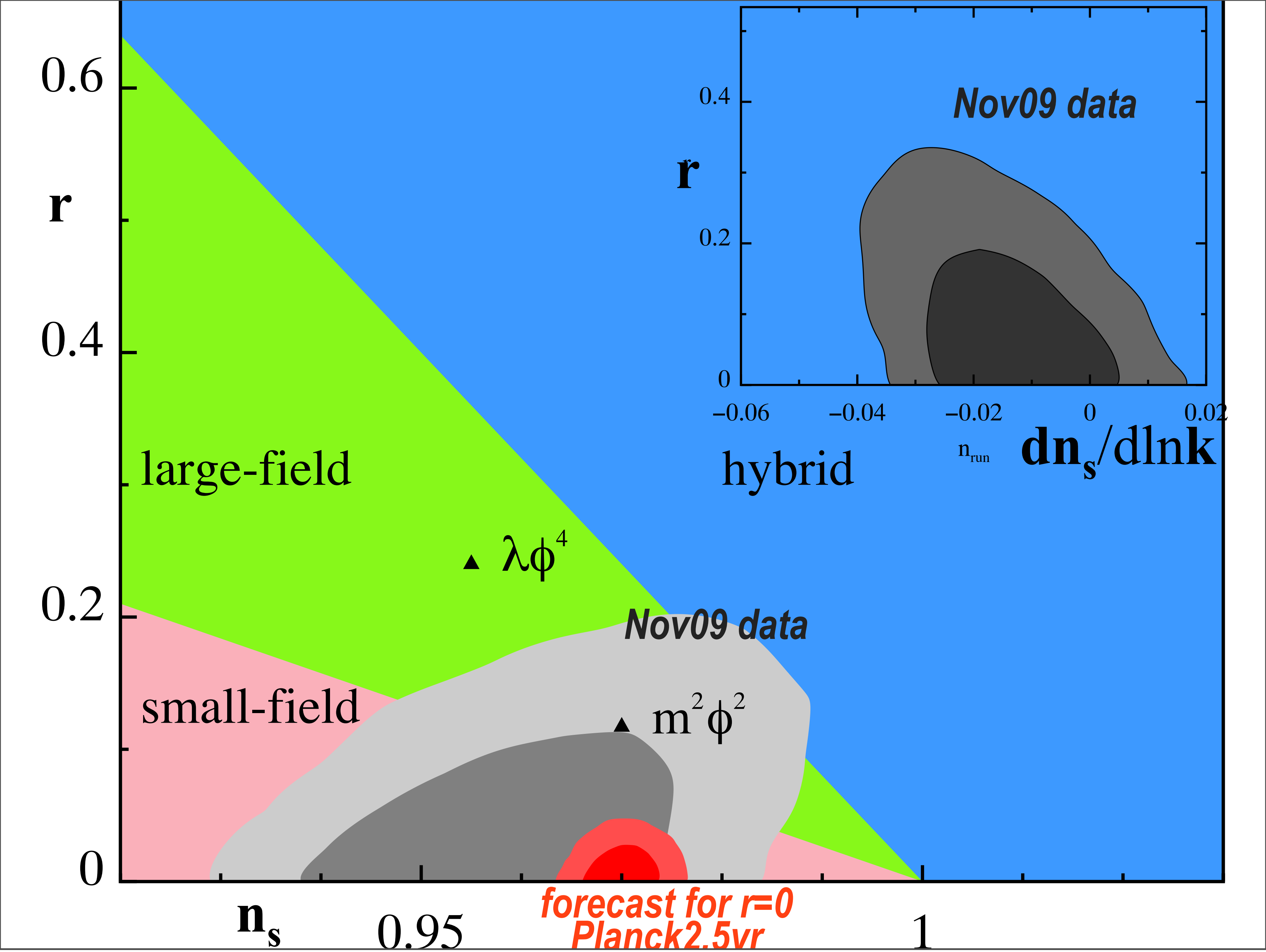
(stringy cosmology) $r<10^{-10}$

small field inflation (field moves < Planck mass)

monodromy & fiber inflation give larger r

current constraints on r (95%CL) - prior sensitive

r < 0.16 (no running, all data sets)
r < 0.32 (no running, CMB-only data sets)
r < 0.27 (with running, all data sets)



0.6
r
0.4
0.2
0
large-field
small-field
hybrid
λφ^4
m^2φ^2
Nov09 data
forecast for r=0
Planck2.5yr
n_s
0.95
1
Nov09 data
r
0.4
0.2
0
−0.06
−0.04
−0.02
0
0.02
n_run
dn_s/dlnk

very early U | early to middle to now U | **very late U**

inflation *string theory/landscape/higher dimensions* **dark energy**

$V_{eff}(\psi_{inf})$? partial shape reconstruction | reconstruct gradient $V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$? | $1+\mathbf{w_0}$ = -0.0 ± 0.06 | $K_{eff}(\psi_{inf})$?

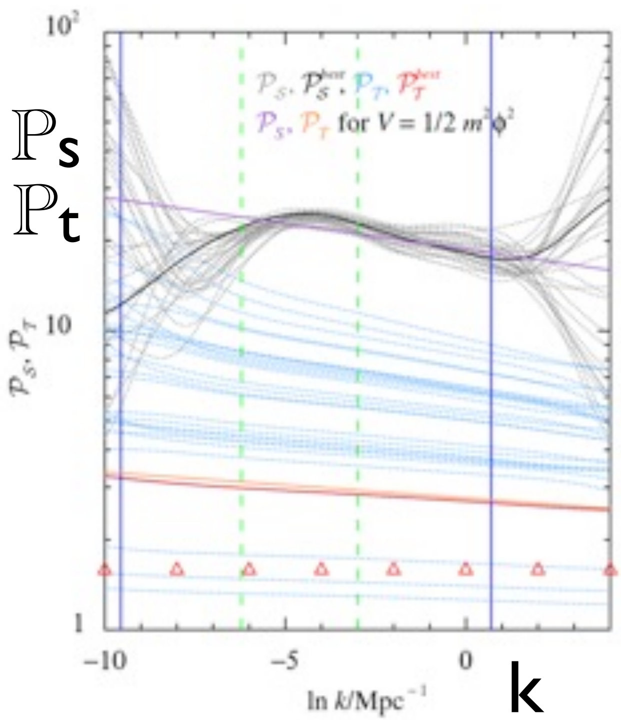
trajectory probability

$-d\ln\rho_{tot}/d\ln a\ /2$

$=\varepsilon(k)=1+q$, $k\sim Ha$

$\Rightarrow \mathbb{P}_s, \mathbb{P}_t$

$\mathbb{V}_{eff}(k)$, $\psi_{inf}(k)$



trajectory probability

$-d\ln\rho_\psi/d\ln a\ /2$

$=\varepsilon_\psi(a)=(1+w)2/3$

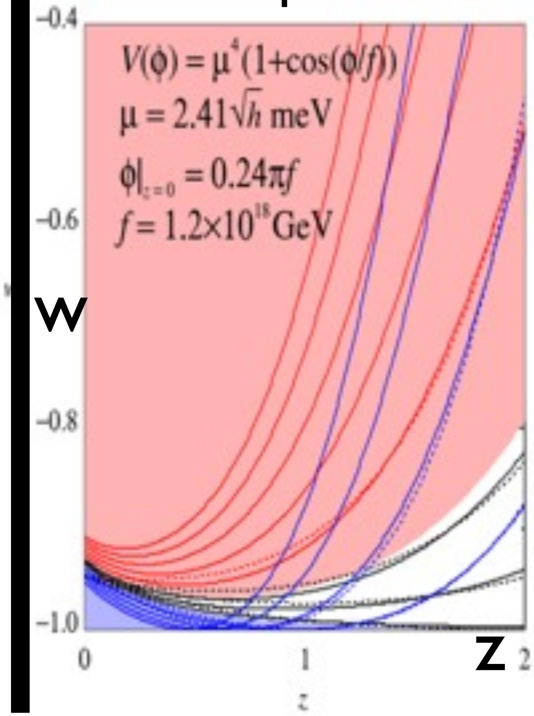
$\Rightarrow$

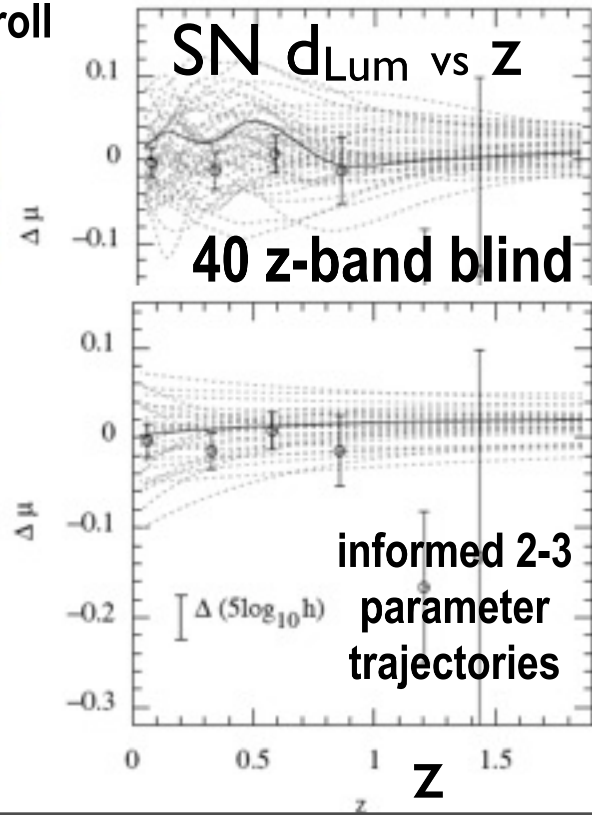
$\varepsilon_V=(d\ln V/d\psi)^2/4$

@pivot a_{eq} ε_s **yes**

$d^2\ln V/d\psi^2/4$ **no**

slow-to-moderate roll quintessence





Bond, Contaldi, Huang, Kofman, Vaudrevange 2005-2010

Semi-blind phenomenology: mode function expansions of $ln P_s$ ($ln k$) & P_t ($ln k$): generalized running via Chebyshev; nodal-point Cheb, splines, physical shapes @ knots

Inflation functional **Consistency** built in: solve P_s ($ln k$) & P_t ($ln k$)

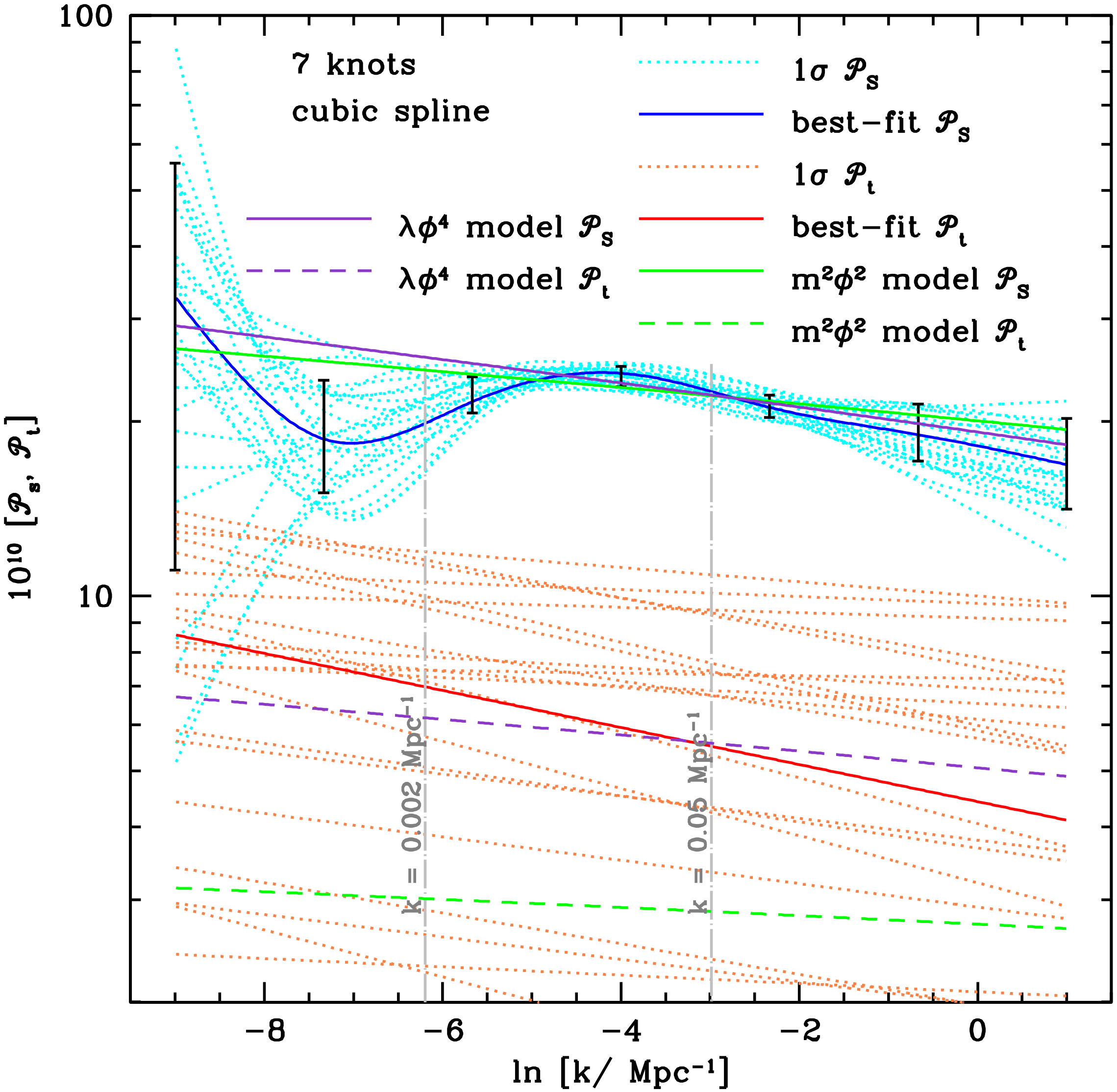
exactly for mode function expansions of possible acceleration histories ε($ln Ha$)

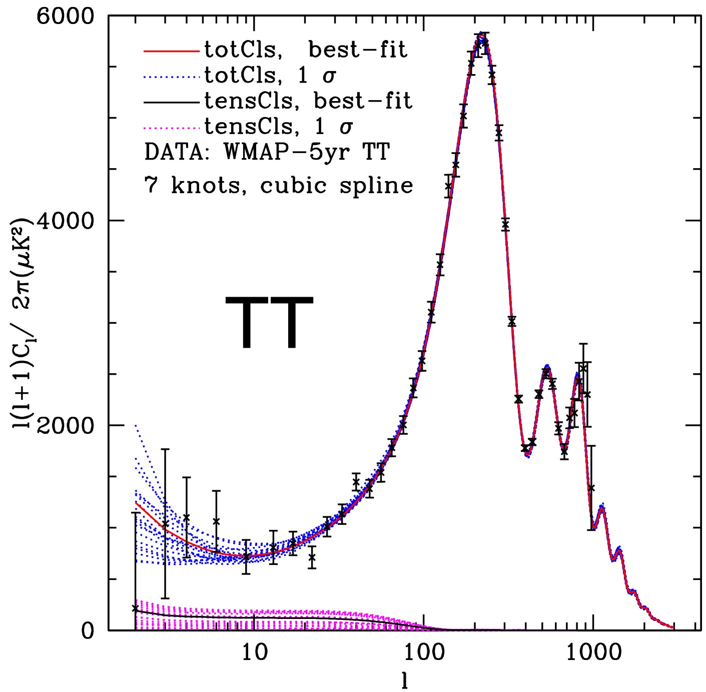
results depend on prior measure for expansion coefficients for current data, less so with CMB experiments targeting the B-mode of polarization

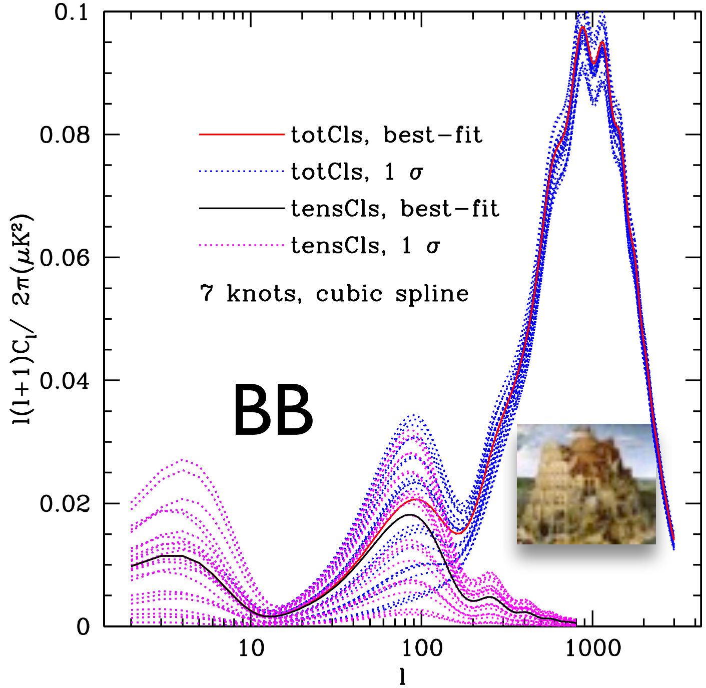
Reconstruction has been much explored over the years, since the 90s. recent examples:

Simple binning techniques: Bridle etal 03; Hannestad 04; Bridges etal 06, 07; Spergel etal 07;
Direct inversion: Shafieloo etal 04,08; Kogo etal 04; Tocchini-Valentini etal 05 06; Nagata etal 08; Nicholson etal 09a,09b;
Basis function expansion: Mukherjee 05; Leach 06;
Cubic spline interpolation: Sealfon et al 05; Peiris et al 08 09;
Slow-roll reconstruction (flow equations): Peiris etal 03,06a,06b; Easther 06; Adshead etal 09;

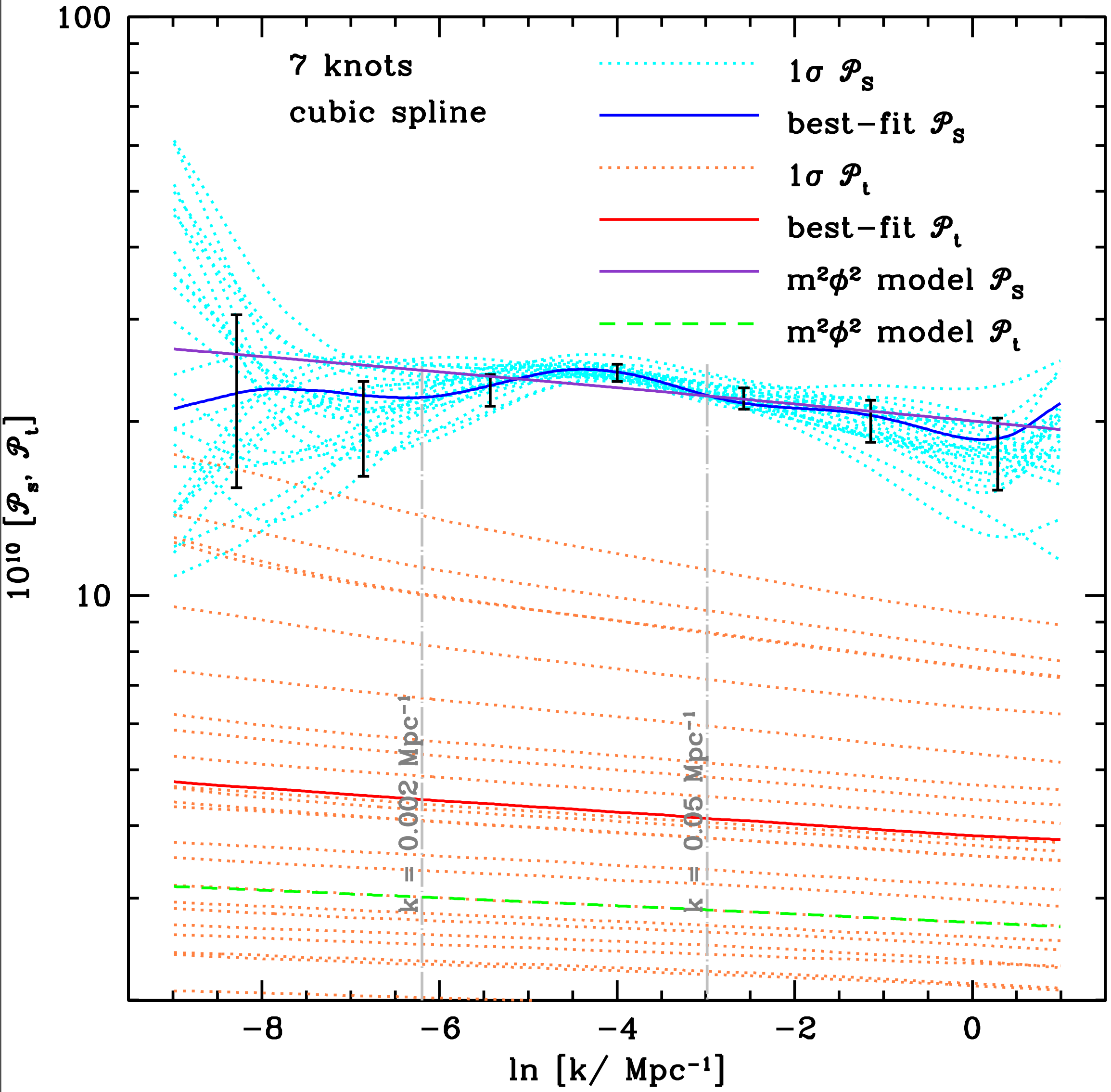
partially-blind scalar power trajecteries & usual r-n_t tensor - no consistency relation. Nov09 data

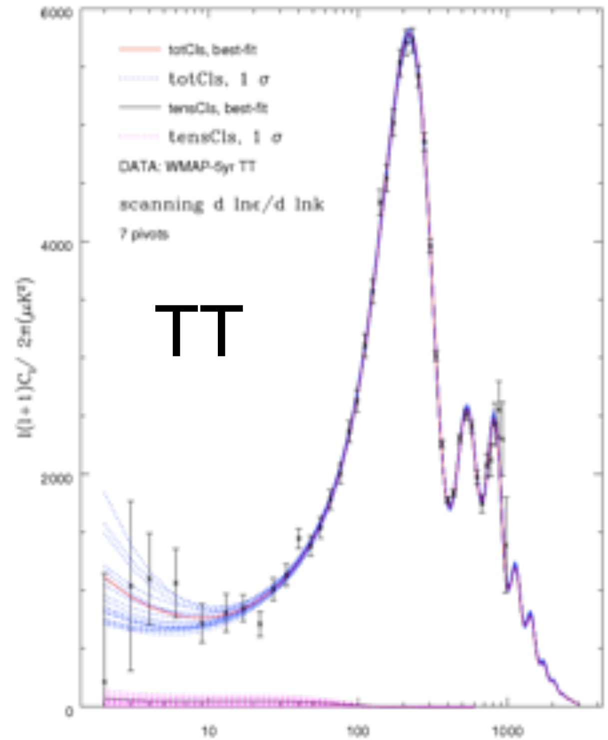


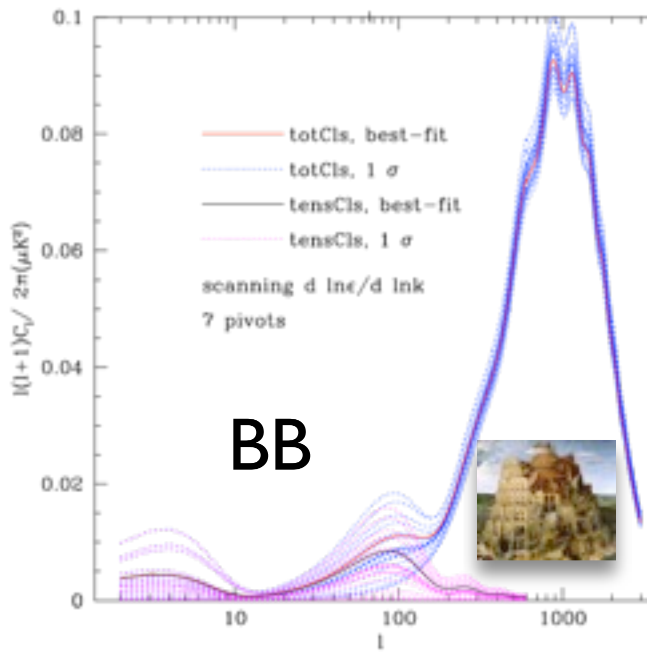


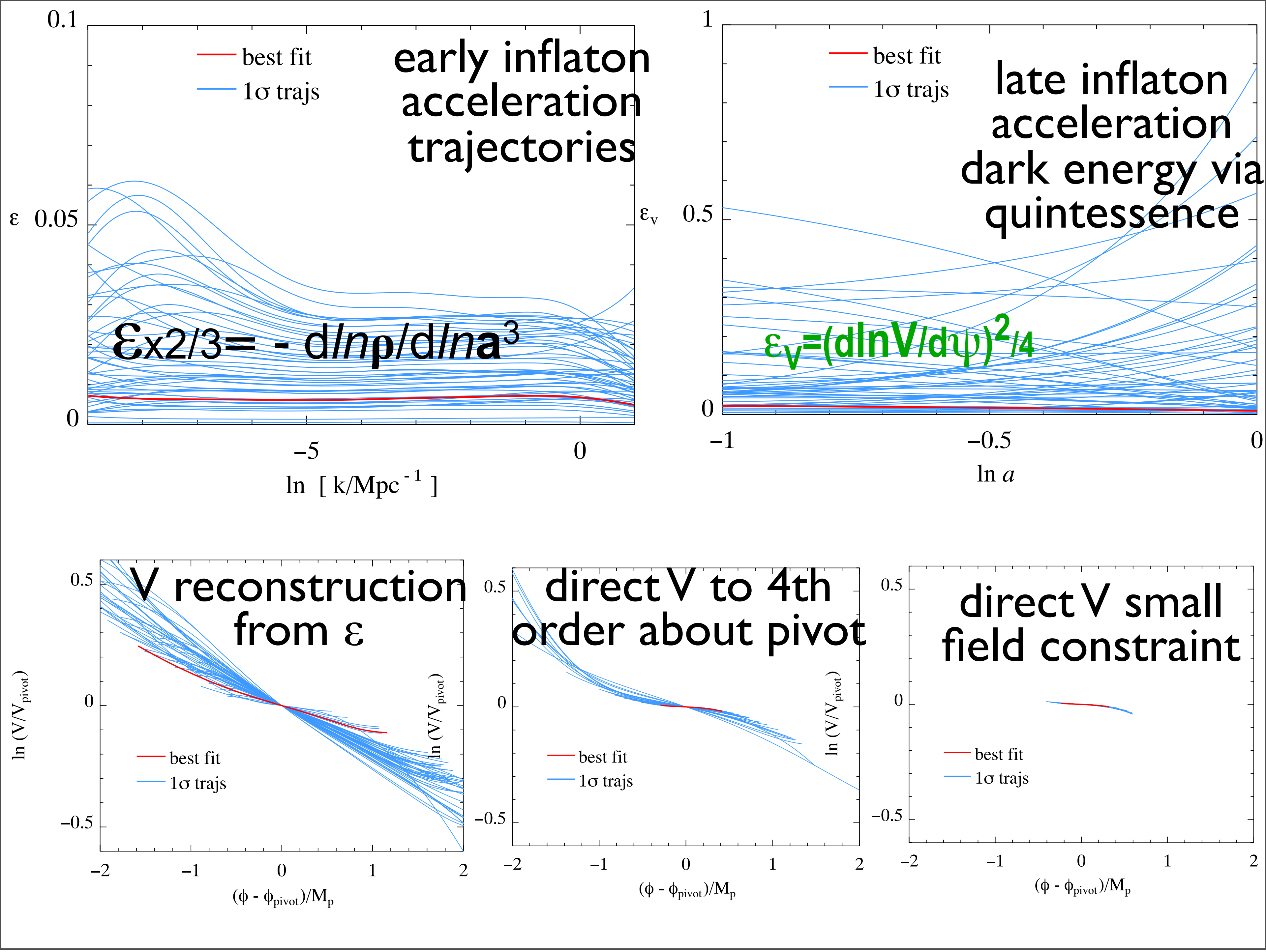


partially-blind acceleration trajecteries obeying tensor/scalar consistency relation. Nov09 data



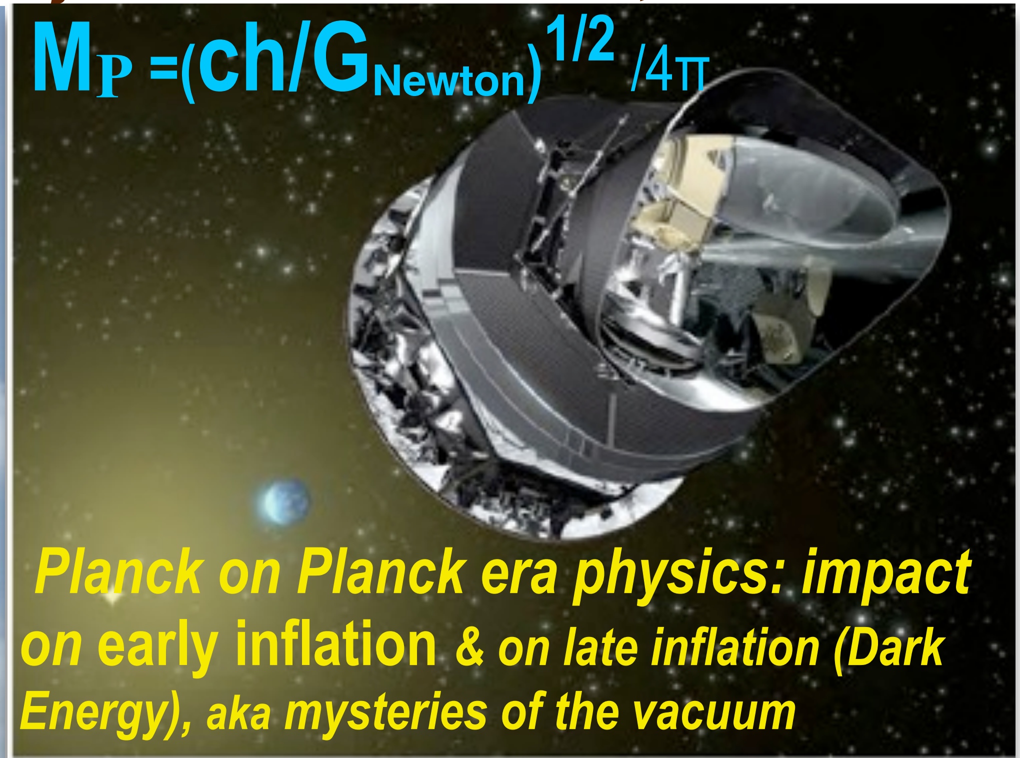





early inflaton acceleration trajectories
best fit
1σ trajs
εx2/3= - dlnρ/dlna3
ε
0.1
0.05
0
−5
0
ln [k/Mpc-1]
late inflaton acceleration dark energy via quintessence
best fit
1σ trajs
εV=(dlnV/dψ)2/4
εV
1
0.5
0
−1
−0.5
0
ln a
V reconstruction from ε
direct V to 4th order about pivot
direct V small field constraint
ln (V/Vpivot)
(φ - φpivot)/Mp
0.5
0
−0.5
−2
−1
0
1
2
best fit
1σ trajs

Entering the Planck Era > May 14, 2009

status A-OK, first all sky survey finishes Feb 2010; 5 in all

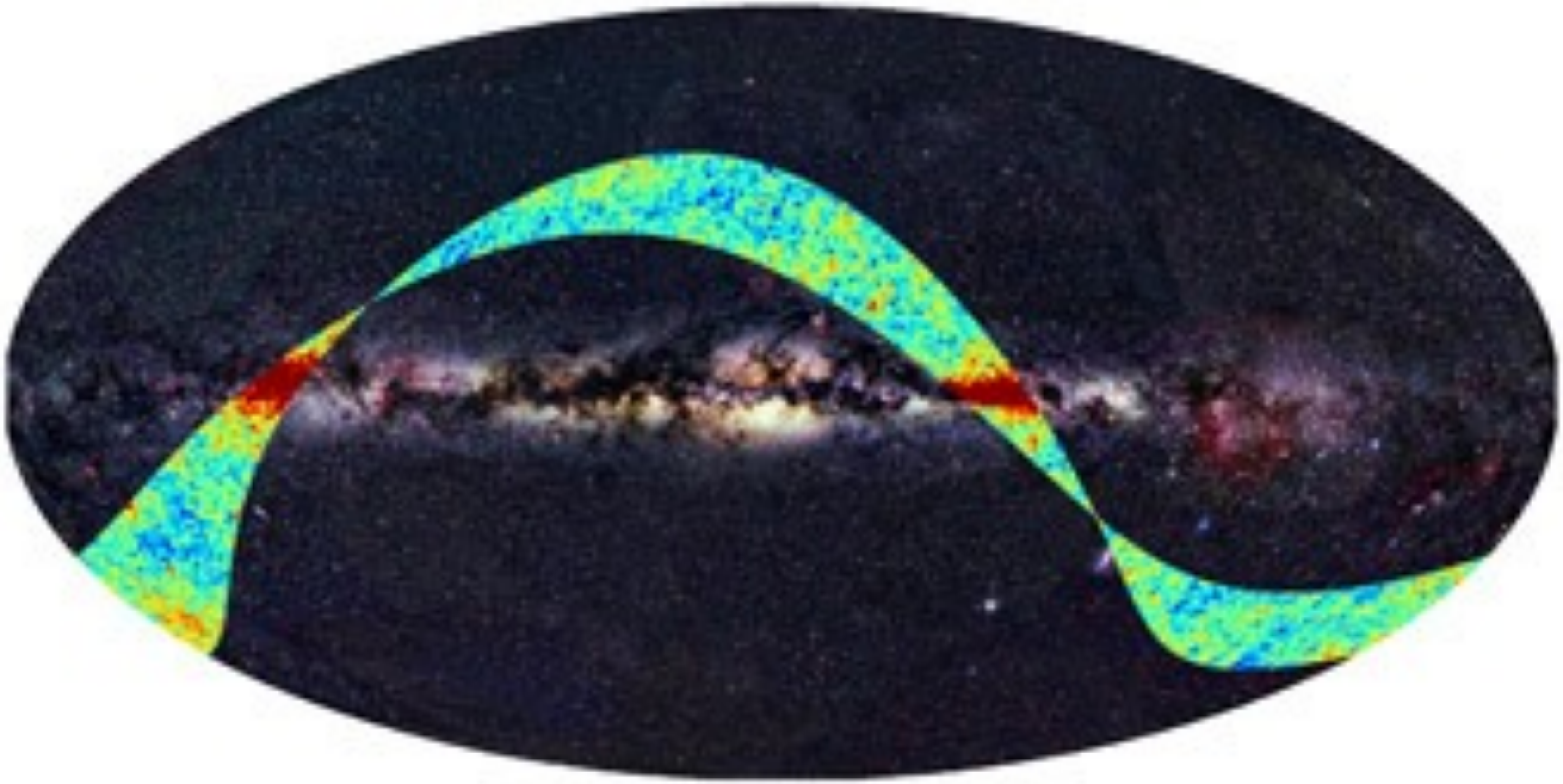


n_s(k), GW: Tensor(k)

subdominant isocurvature, cosmic strings, textures,

nonGaussian **F_{NL} (x)**

ESA /NASA /CSA Toronto HFI QLA/KST, TA, ... *Barth & Dick, Marc-Antoine Miville-Deschenes, Carrie MacTavish, Brendan Crill, Olivier Dore, Carlo Contaldi, Mike Nolta, Peter Martin, Francine Marleau,* UBC LFI



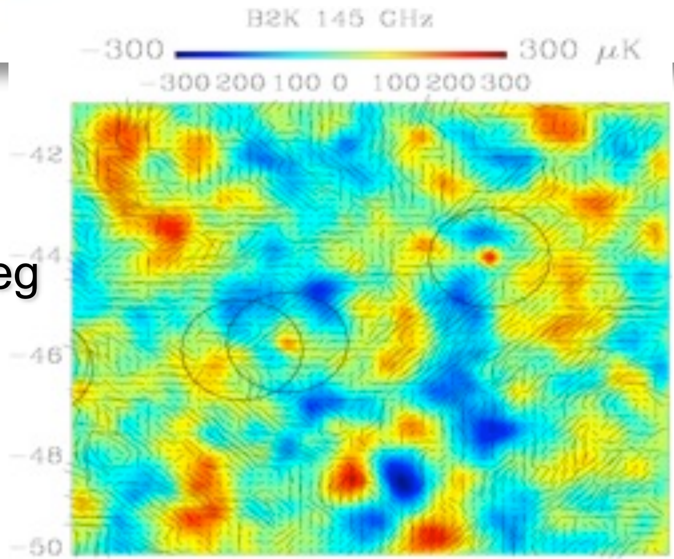
Planck “First Light” Survey Aug 2009

BoomPol deep

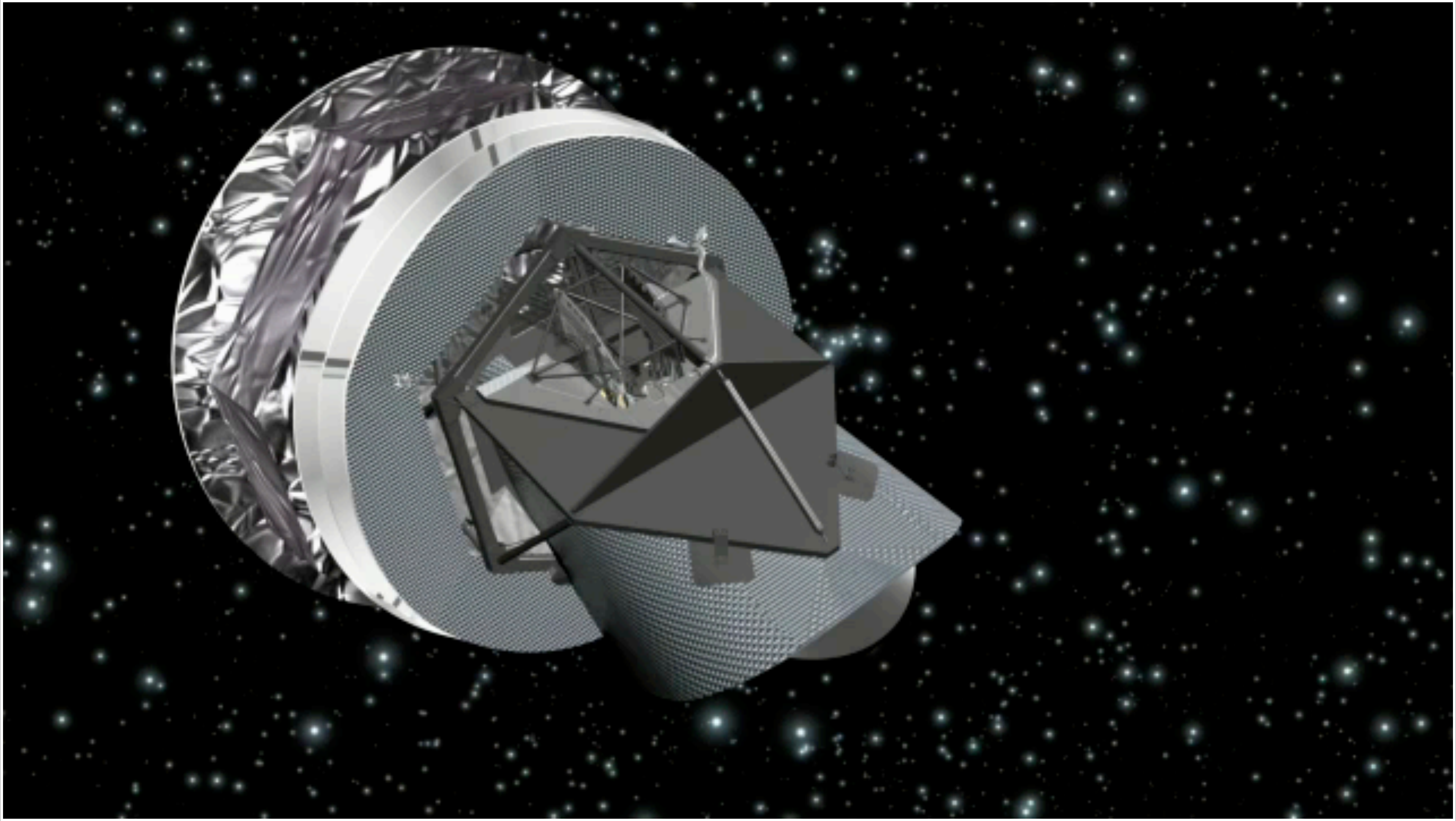
2003.1, Jul05, Dec09

125 hours, $\mathbf{f_{sky}=0.28\%}$ 115sq deg

Planck is ~ as deep, but all sky, with similar bolometers (but more) and better resolution



Planck 1st of 5 all Sky Surveys 09.7-10.1



Future Forecasts

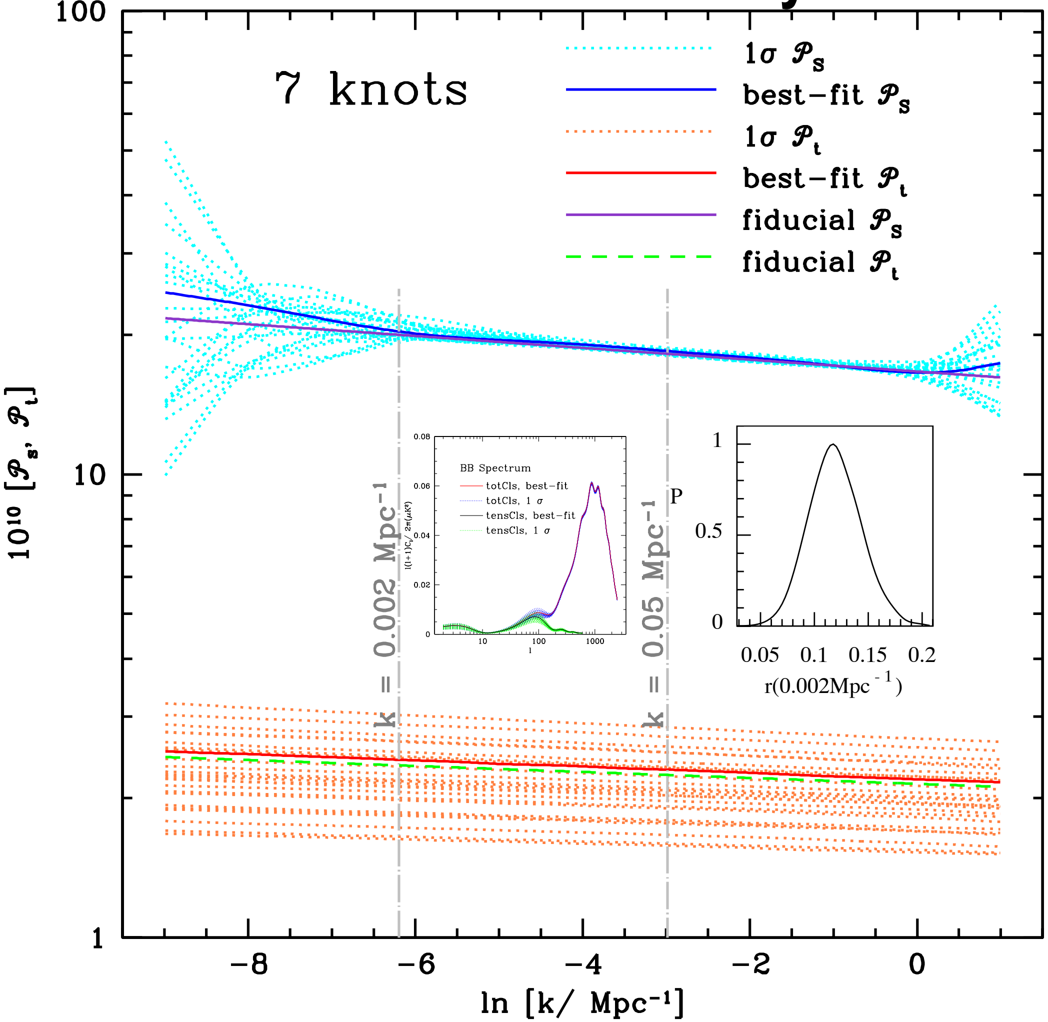
CMB: Planck2.5yr, using 3 channels (70GHz, 100GHz, 143GHz), *assuming 5% foreground residual (synchrotron + dust)*, fsky = .75, Lmax = 2500.
other future polarization experiments: SPIDER, EBEX, QUIET, KECK, ... CMBPol

WL: DUNE-like weak lensing tomography, 20000 sq deg,
depth z~1, 35 galaxies/arcmin^2, two redshift bins, Lmax = 1500. → Euclid
other proposed deep and wide WL surveys: JDEM, PanStarrs, LSST, ...

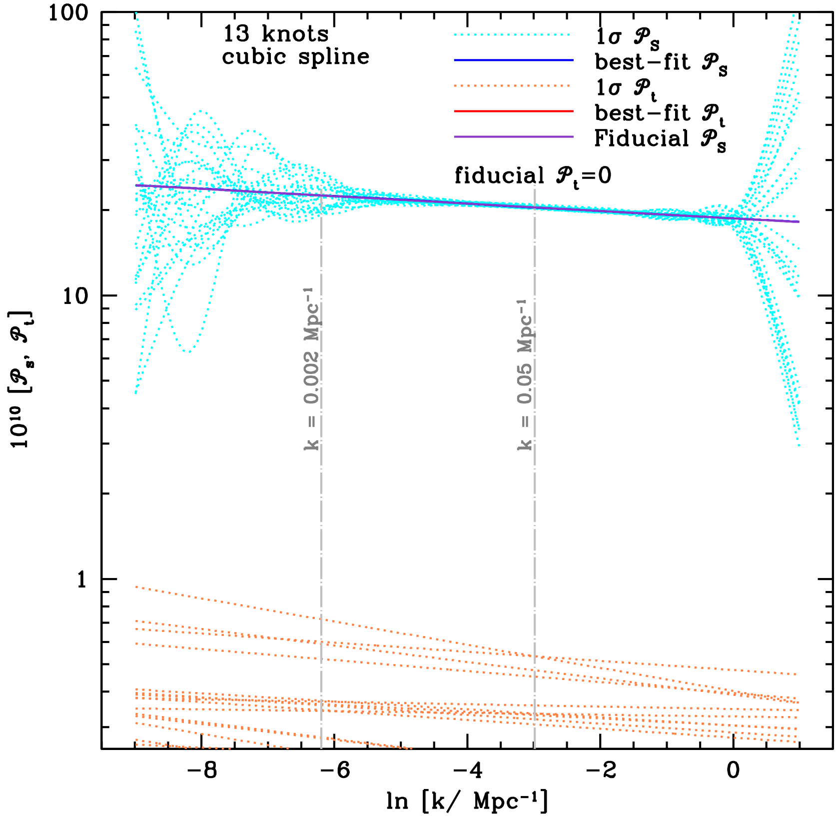
SN: JDEM-like, 500 LOWZ (z < 0:03) + 2500 HIGHZ (0:03 < z < 1:7)
other ongoing/future SN surveys: SNLS, SDSS, LSST ...

BAO: JDEM, 10000 degree2, 0:5 < z < 2, 10 redshift bins
other ongoing/future BAO surveys: WIGGLEZ, CHIME, BOSS, LSST, ...

Planck2.5 forecast with inflation consistency



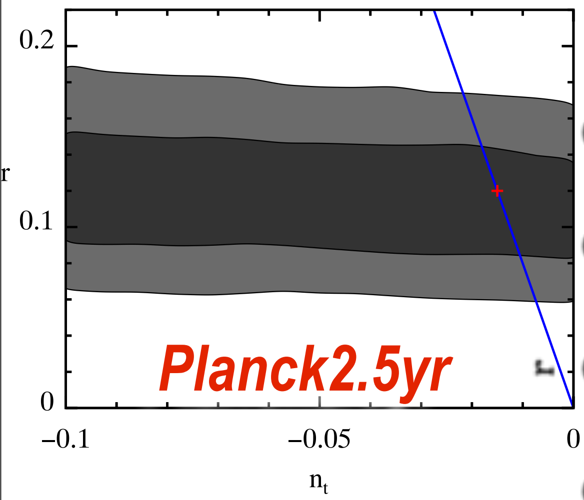
Planck2.5 r=0 forecast for 13 knot semi-blind P_s +r-n_t

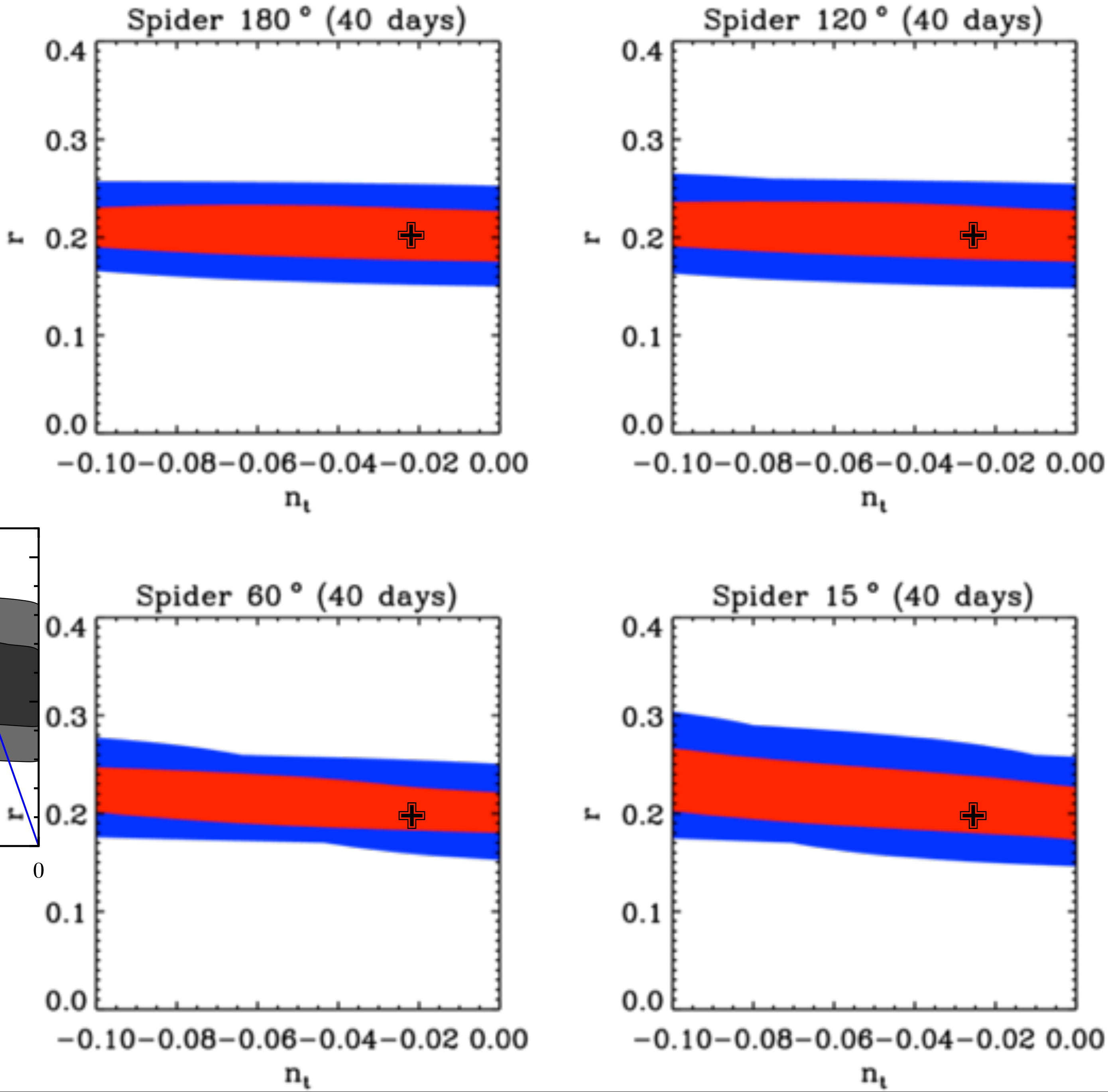


$r \approx -8n_t$

poor $n_t \Rightarrow$

inflation consistency *cannot be checked with Spider or Planck2.5yr*

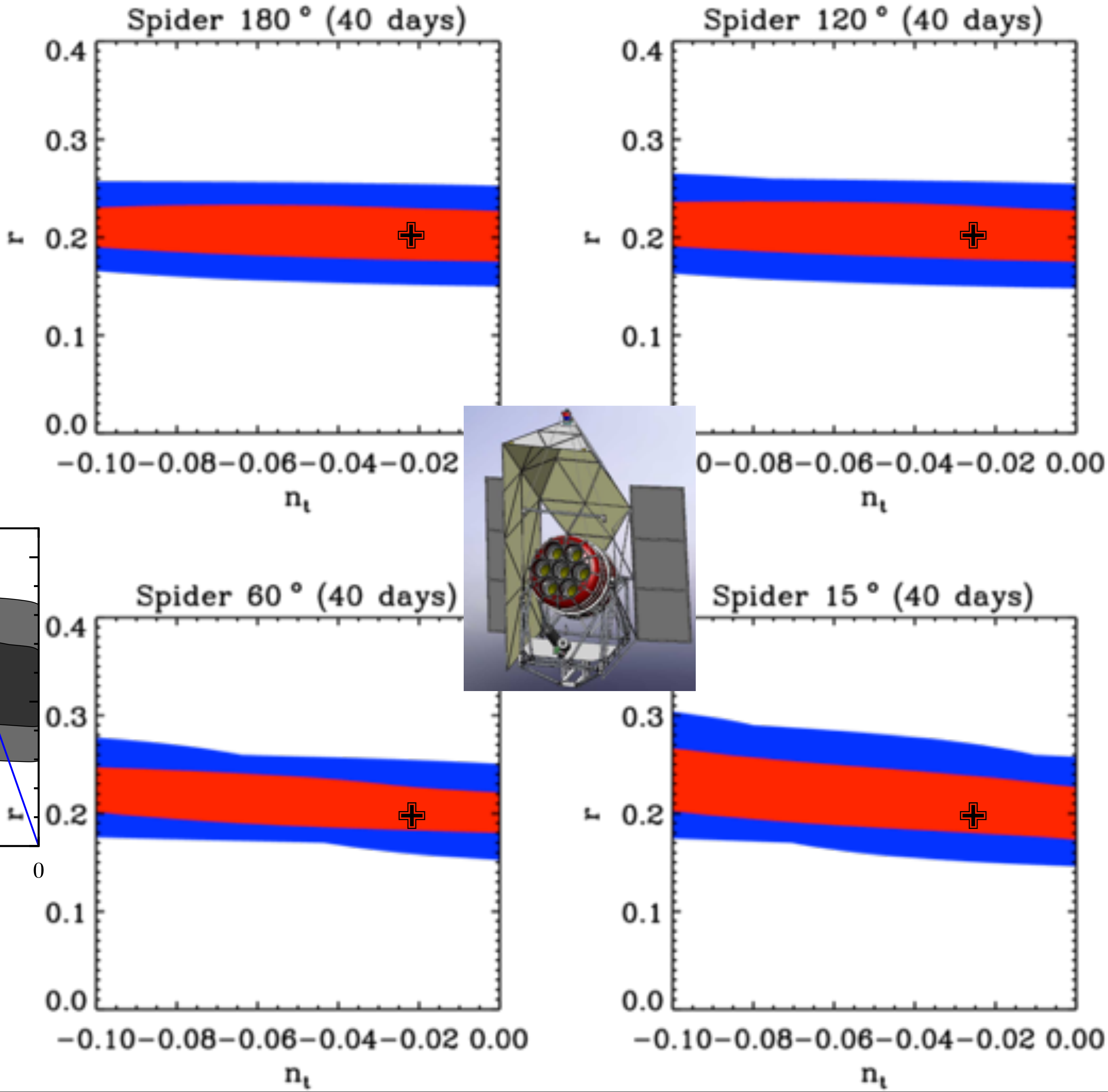


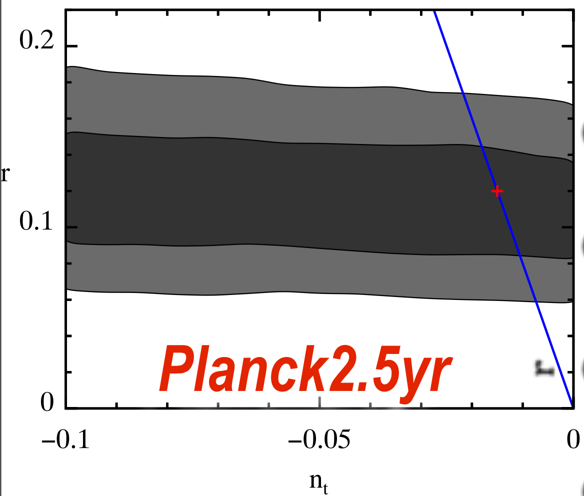


$r \approx -8n_t$

poor $n_t \Rightarrow$

inflation* *consistency
cannot be checked with Spider or Planck2.5yr





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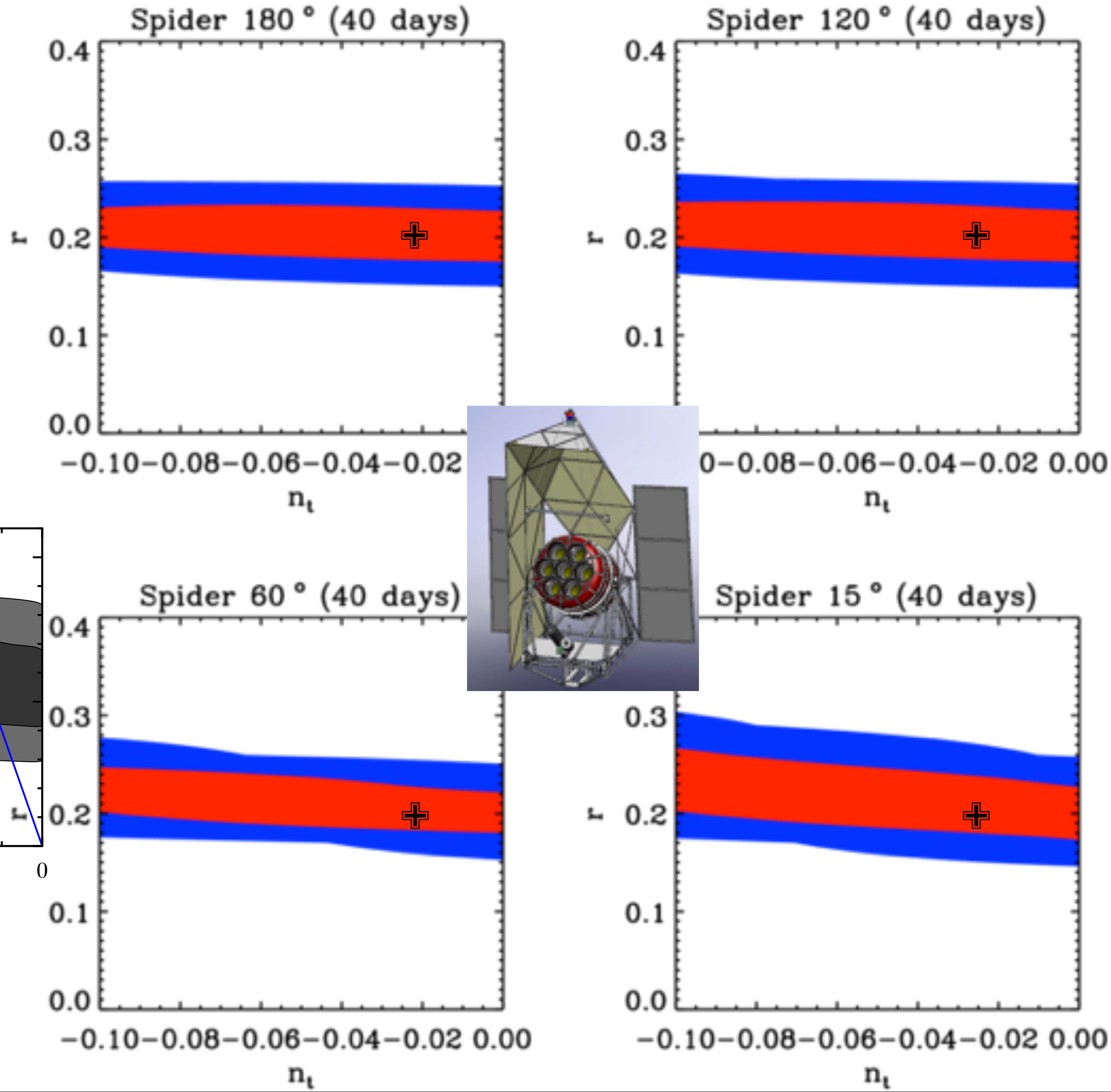
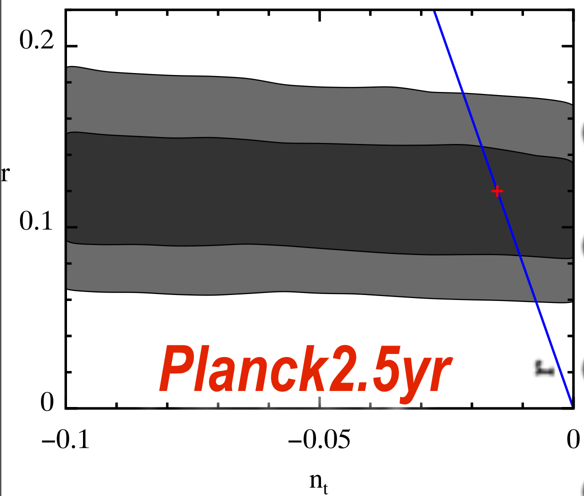
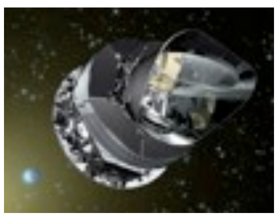
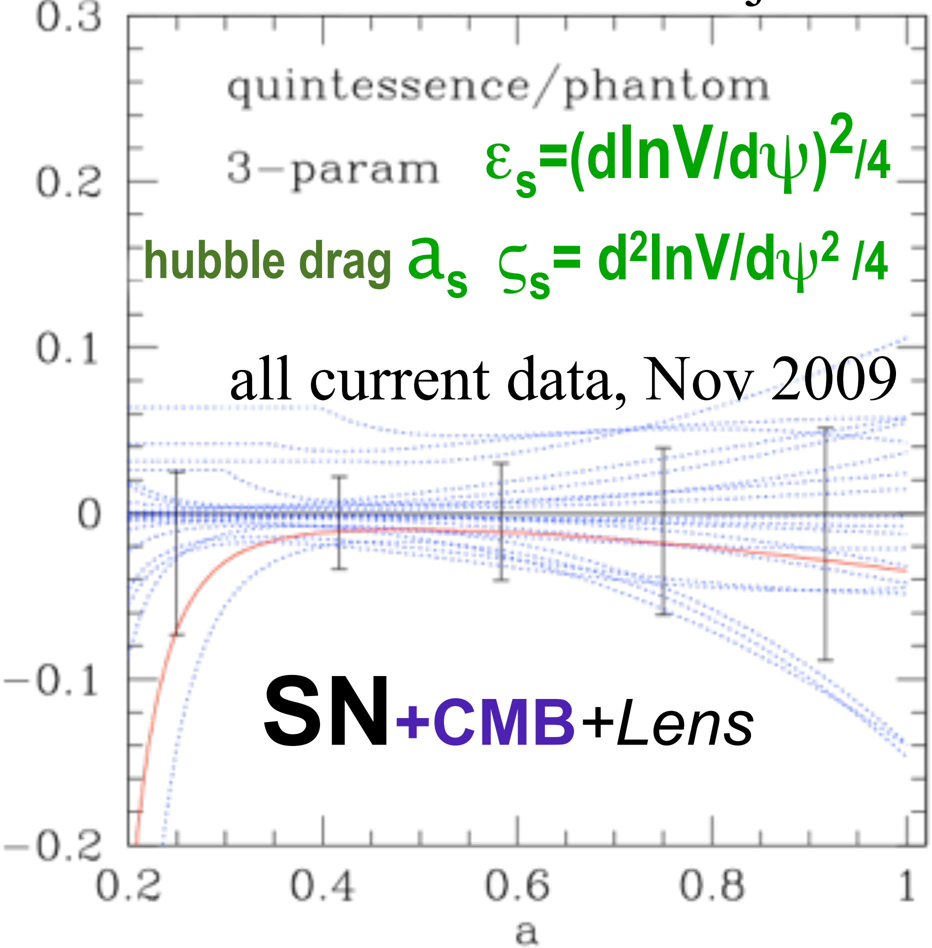




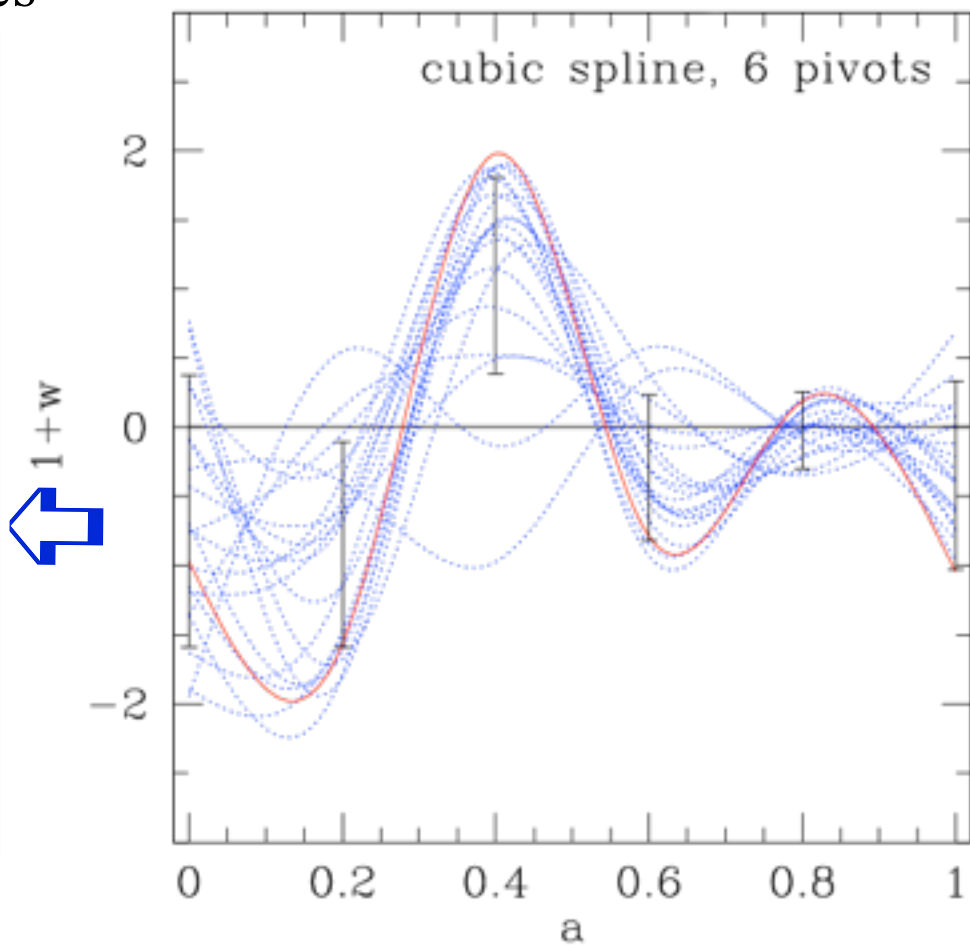


is the **dark energy** "vacuum potential energy" ?

a 3-parameter expansion paves even wild late-inflaton trajectories



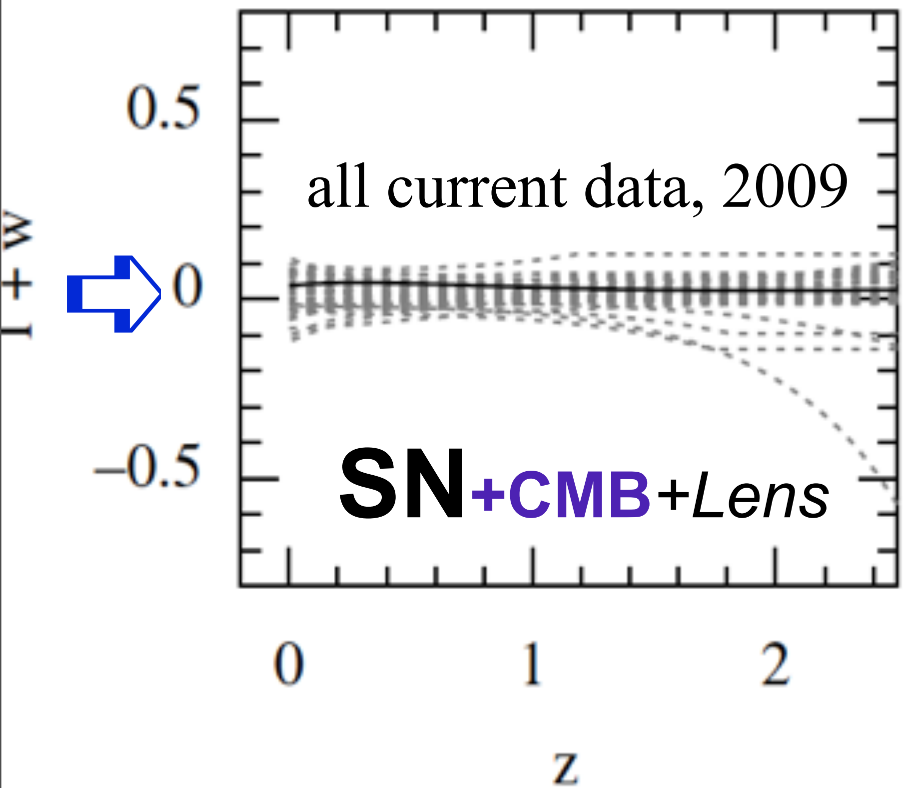
semi-blind mode expansion

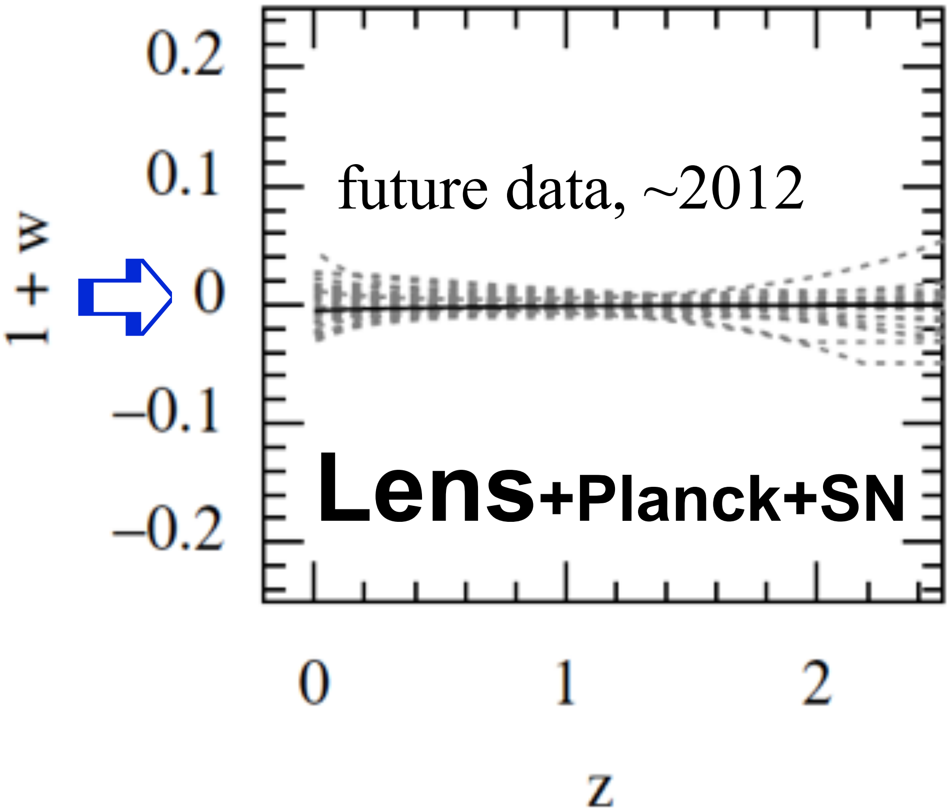


TEST: within errors, energy-density does not change with expansion ⇨Einstein's cosmological constant is best fit so far

cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag

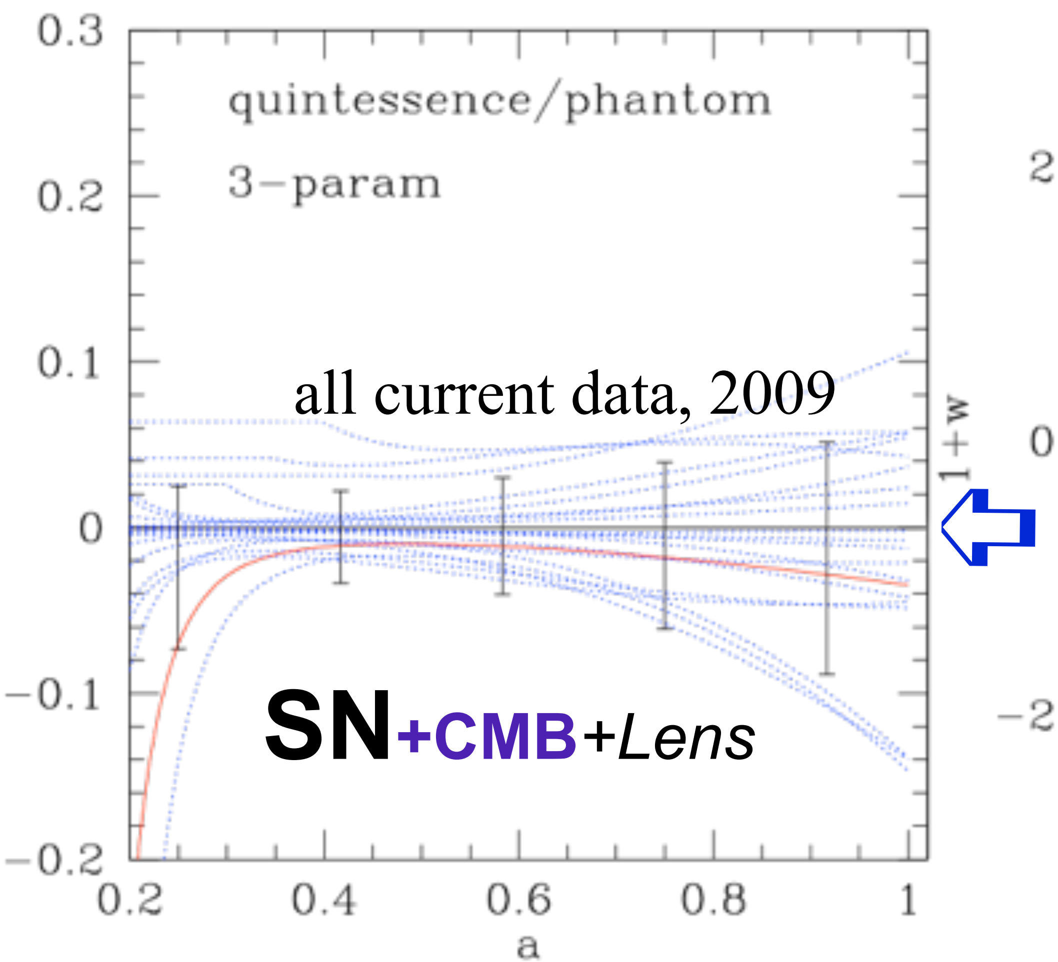
is the **dark energy** "vacuum potential energy" ?

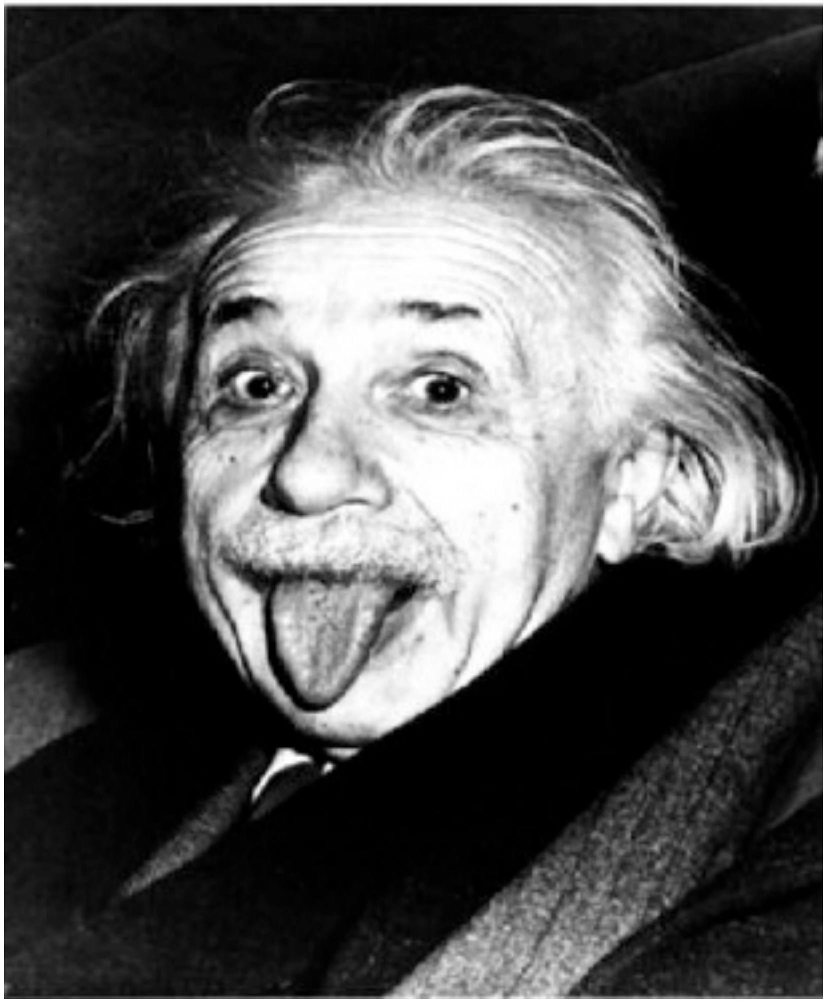




TEST: within errors, energy-density does not change with expansion ➪Einstein's cosmological constant is best fit so far

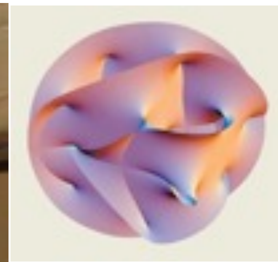
is the **dark energy** "vacuum potential energy" ?





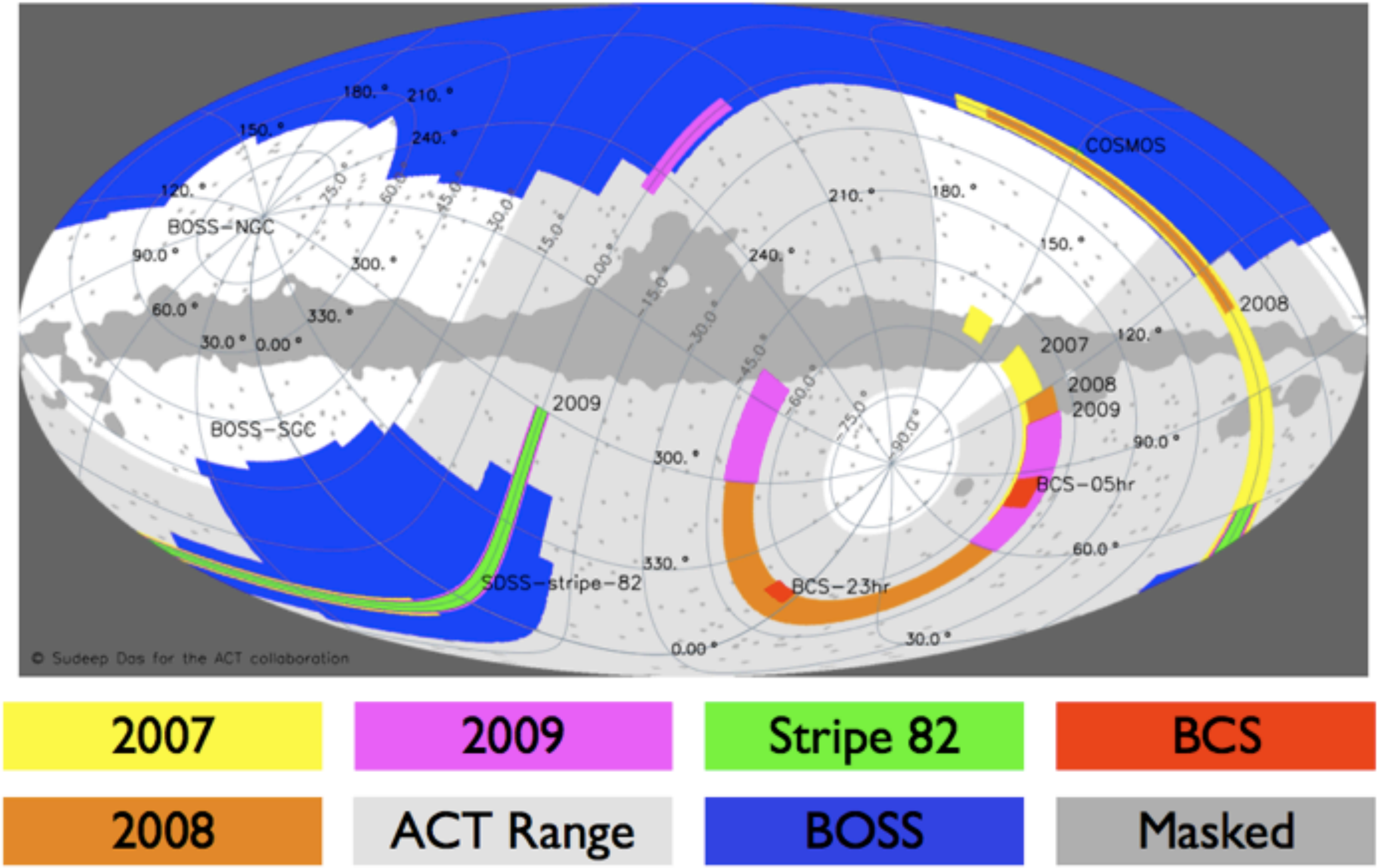
TEST: within errors, energy-density does not change with expansion ⇨Einstein's cosmological constant is best fit so far

Lev Kofman June 17, 1957 - November 12, 2009



end

ACT Survey Coverage

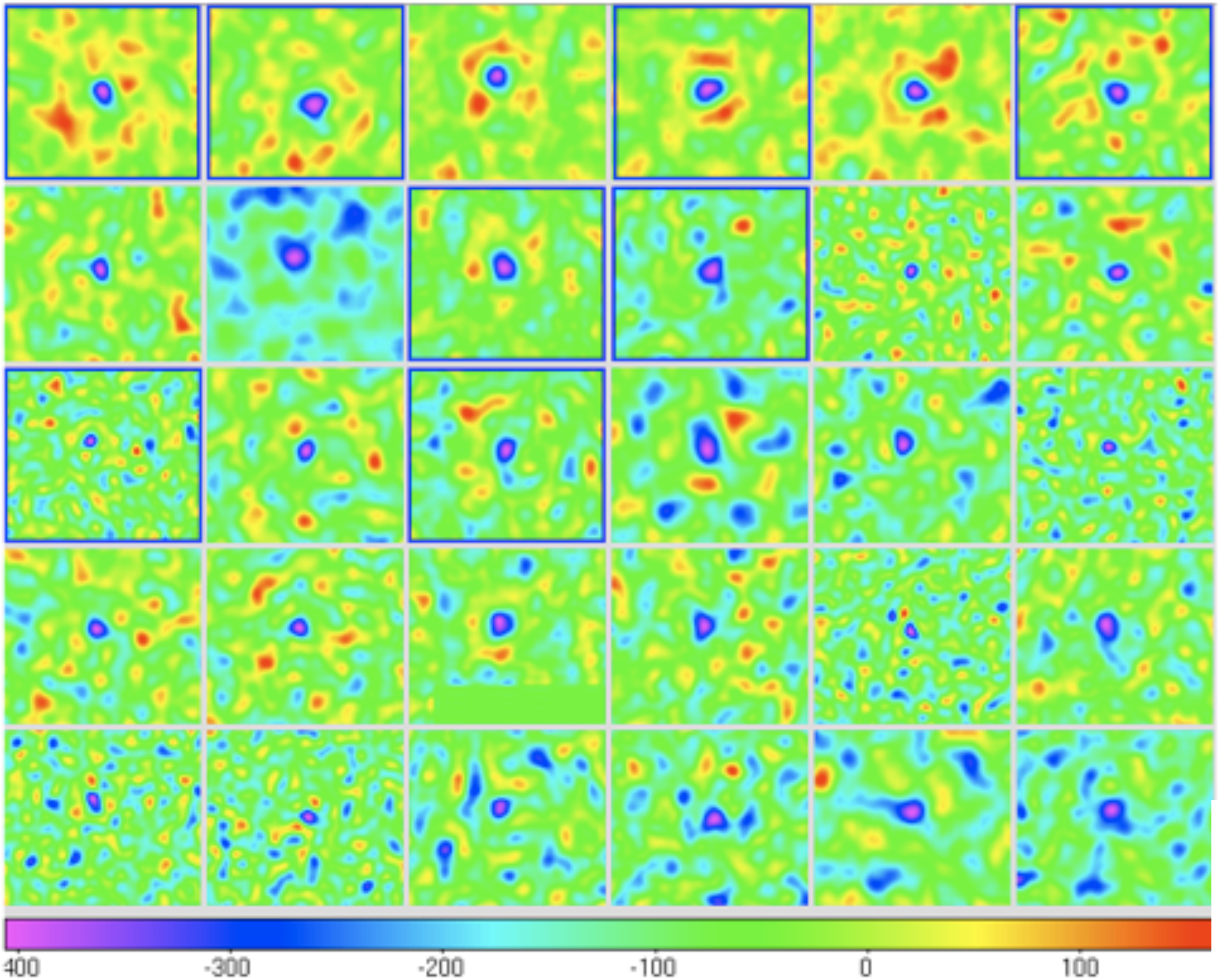


Tobias A. Marriage etal ACTers

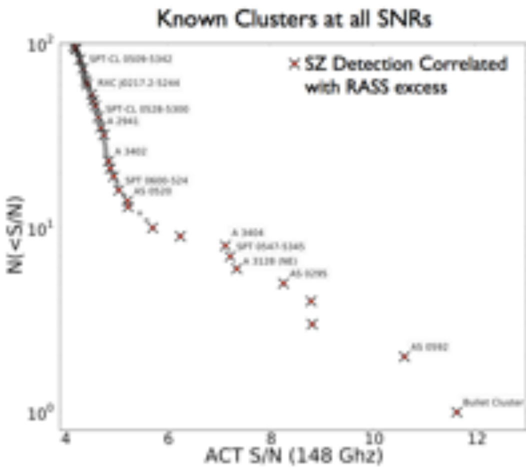
Fall 2009

148 GHz SZ Decrements

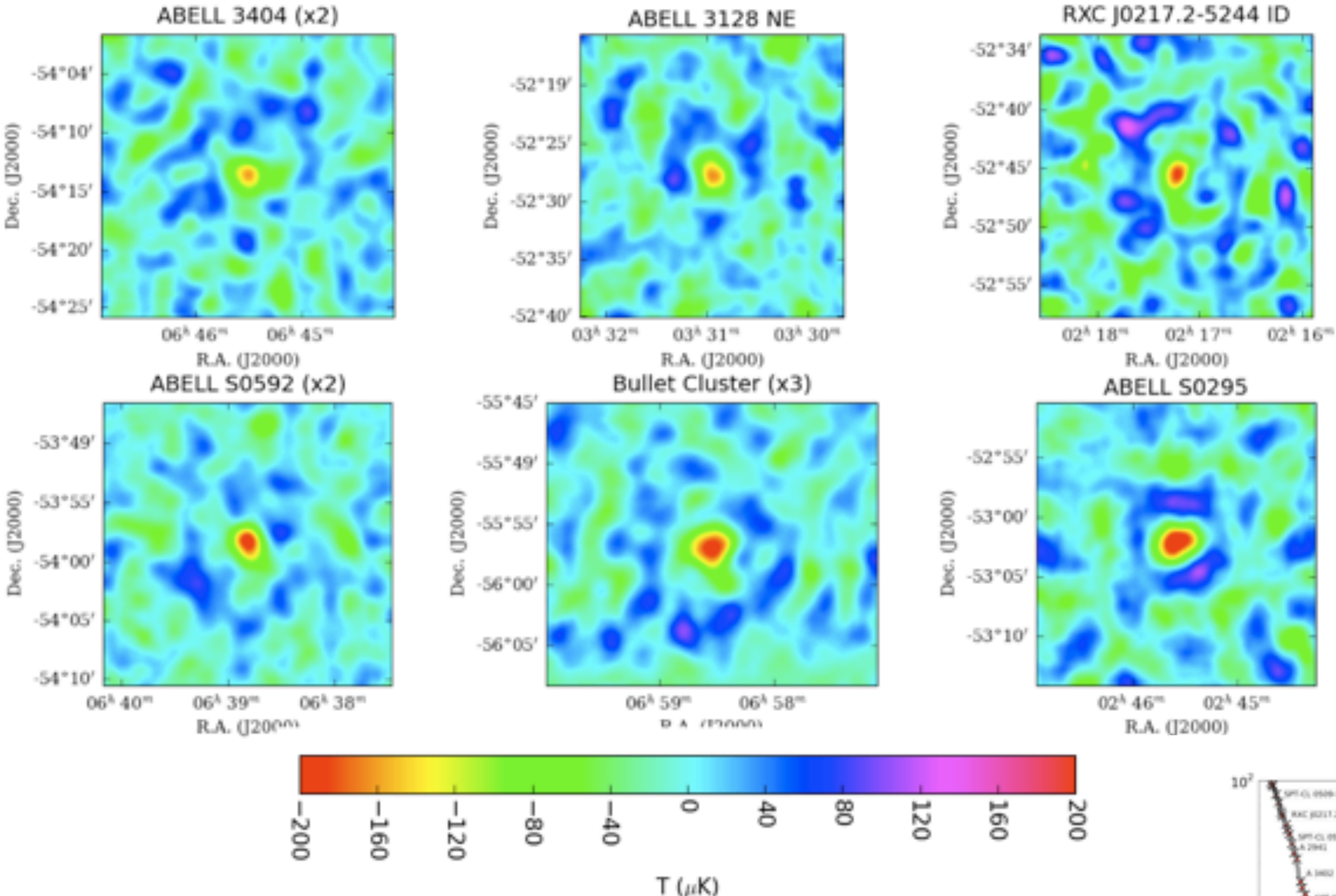
: Previously Known

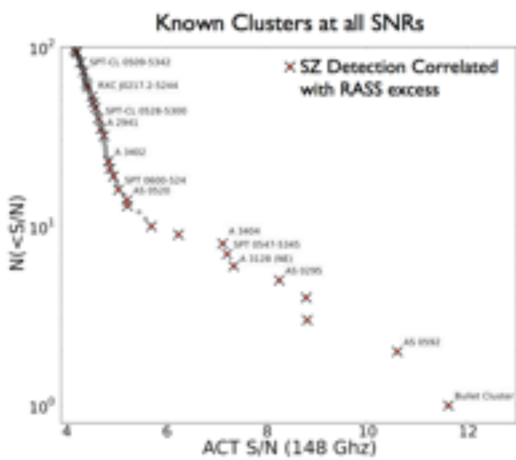


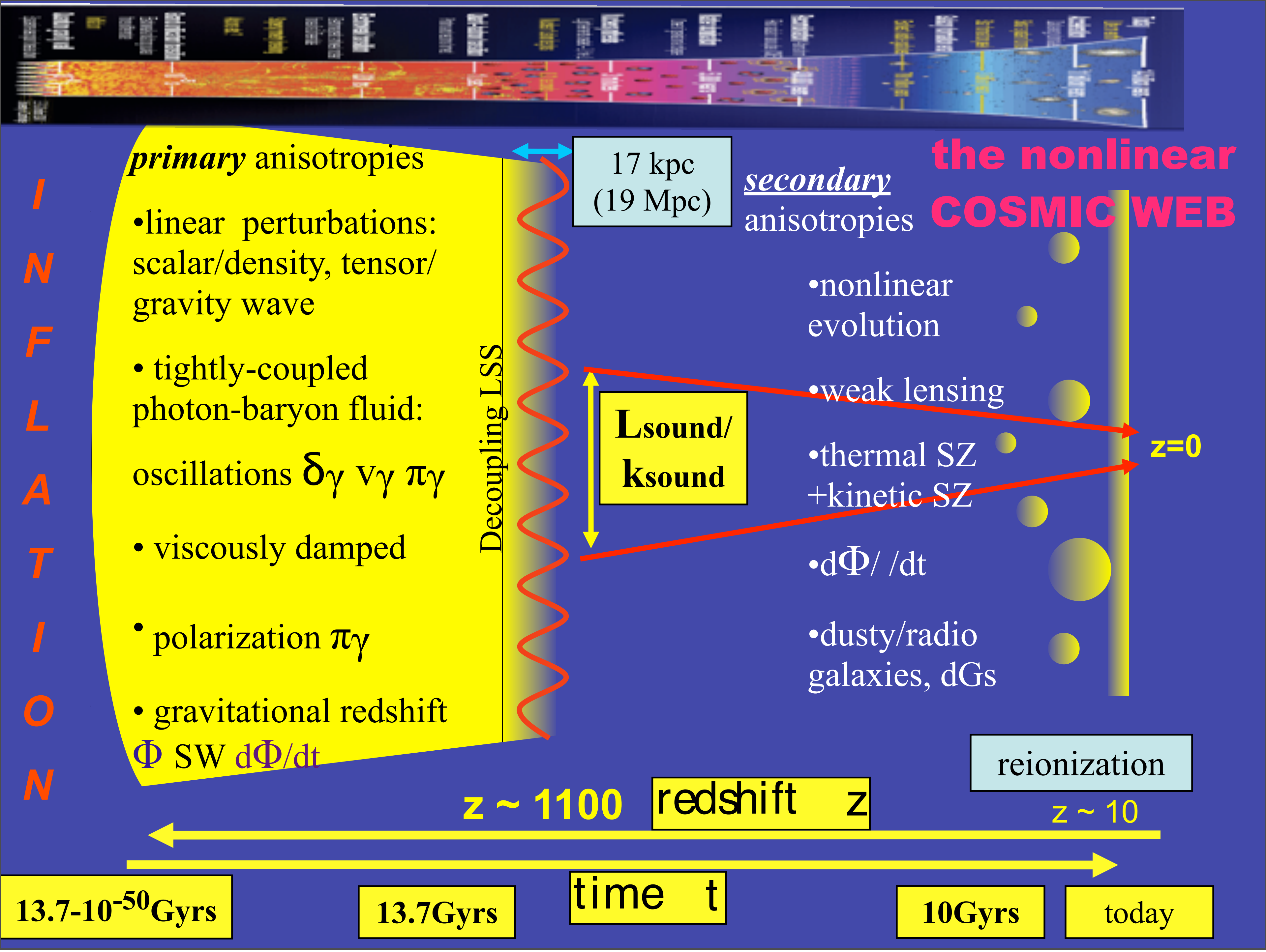
δT_{CMB} [μK] (Only for top left candidate)



Some Known Clusters






primary anisotropies
•linear perturbations: scalar/density, tensor/ gravity wave
• tightly-coupled photon-baryon fluid:
oscillations δγ vγ πγ
• viscously damped
• polarization πγ
• gravitational redshift
Φ SW dΦ/dt
INFLATION
Decoupling LSS
17 kpc
(19 Mpc)
Lsound/
ksound
secondary anisotropies
the nonlinear
COSMIC WEB
•nonlinear evolution
•weak lensing
•thermal SZ
+kinetic SZ
•dΦ/ /dt
•dusty/radio galaxies, dGs
z=0
reionization
z ~ 1100
redshift z
z ~ 10
time t
13.7-10^-50 Gyrs
13.7Gyrs
10Gyrs
today