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

CIAR 25 years cifar

Early & Late Universe Inflation

Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

CMB*ology* & *x*CDM, *x*=Λ+*tilt*: the cosmic standard model n_s $r=T/S$ ρ_{de}

Cosmic history: what is U made of? $\Rightarrow \rho_{dm}/\rho_b = 5.1 \Rightarrow \rho_m/\rho_{de} = .38$

and Ω_m=0.268 ±.012, Ω_Λ=0.736 ±.012 $\Rightarrow$(**0.276 ±.016, 0.724 ±.016**)

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 the U: dark energy properties driving late inflation

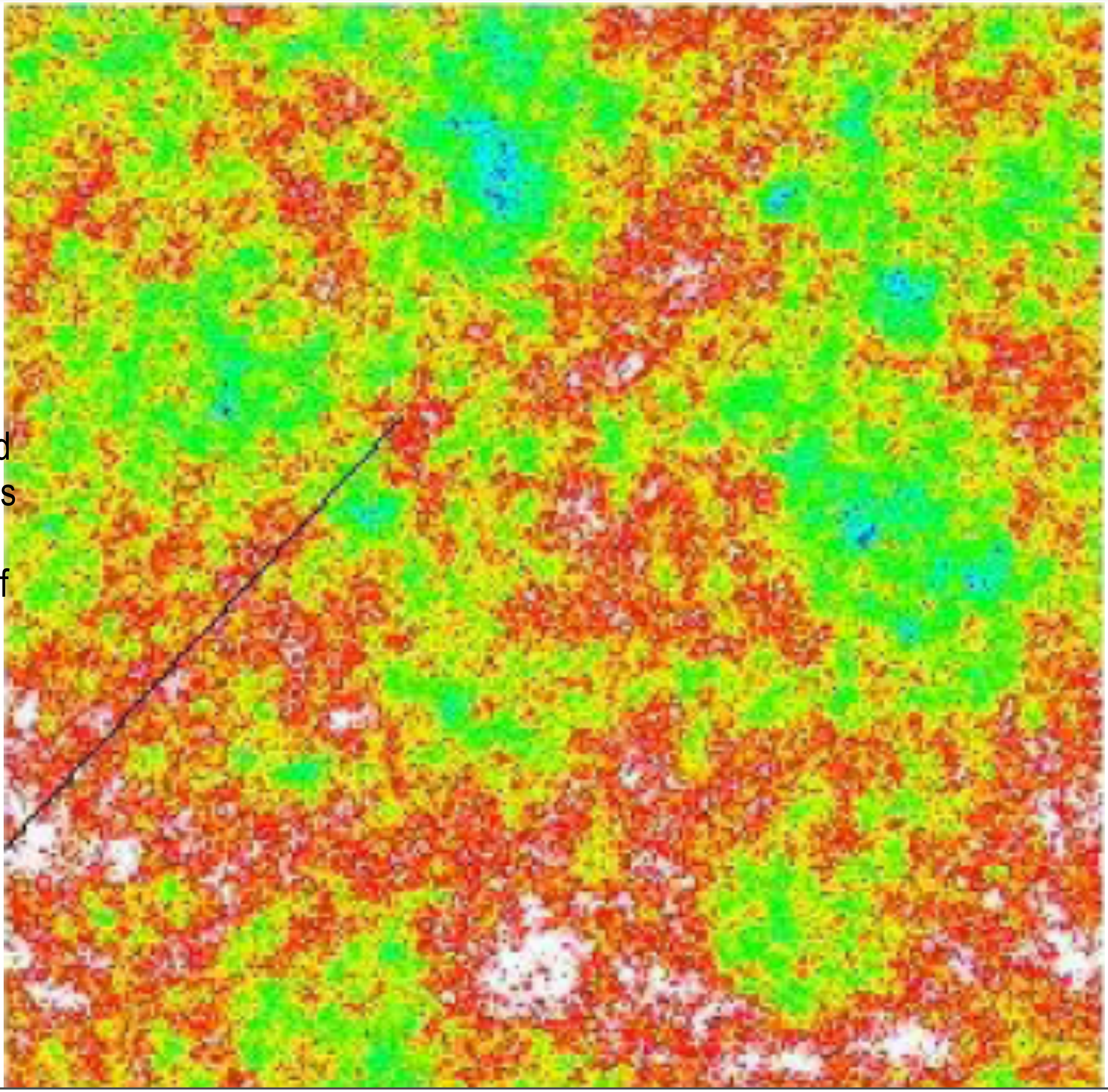
Cosmotician ***statistics of theory as well as data is now fundamental physics.***

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

observables & constraints: acceleration paths for B-modes & dark energy; the amplitude & structure of primordial non-Gaussianity

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

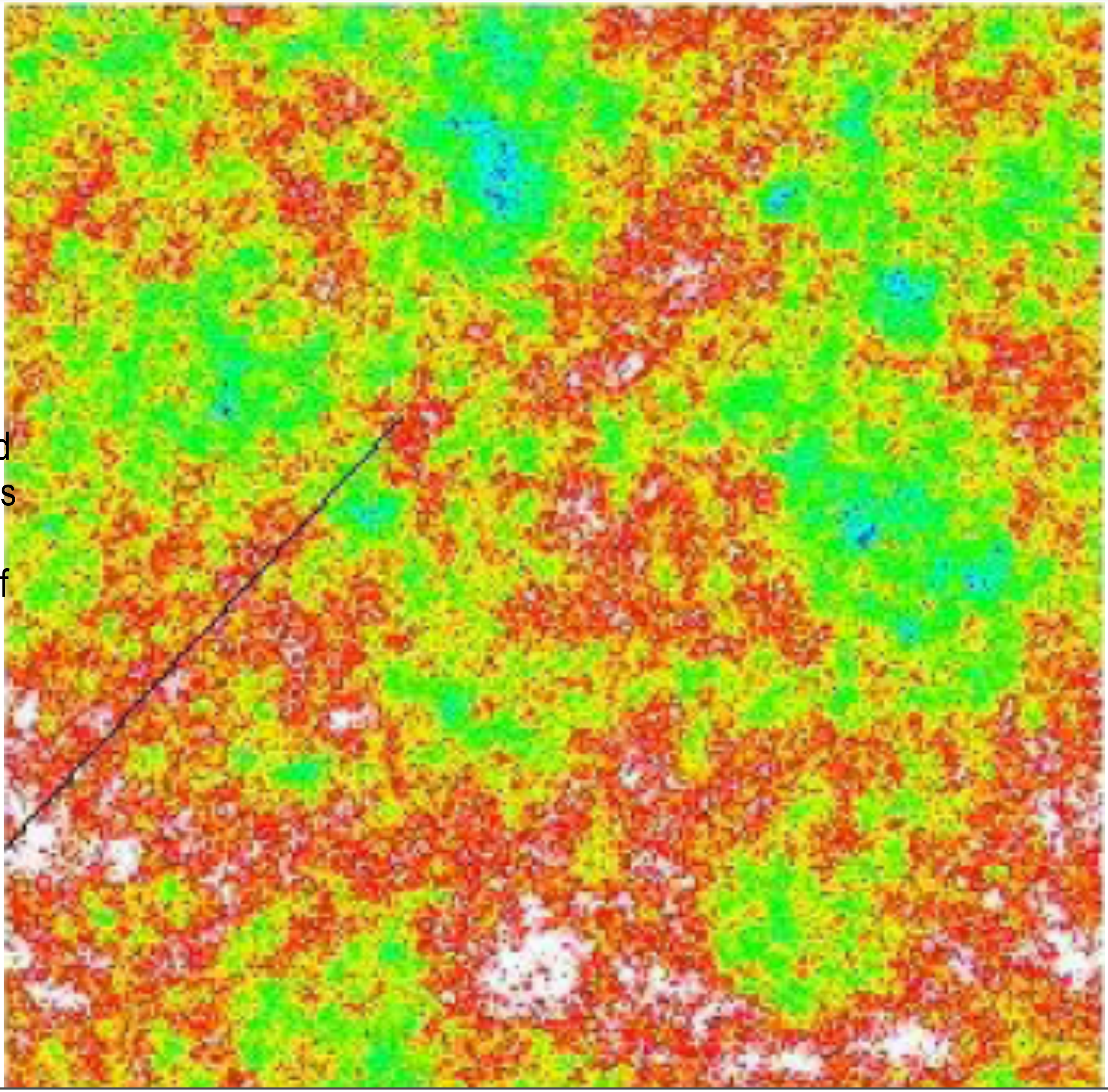
fluctuations in the **early universe "vacuum" grow** to *all* **structure**



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

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

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



evolve from early U vacuum potential and vacuum noise

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

400 Mpc

ΛCDM

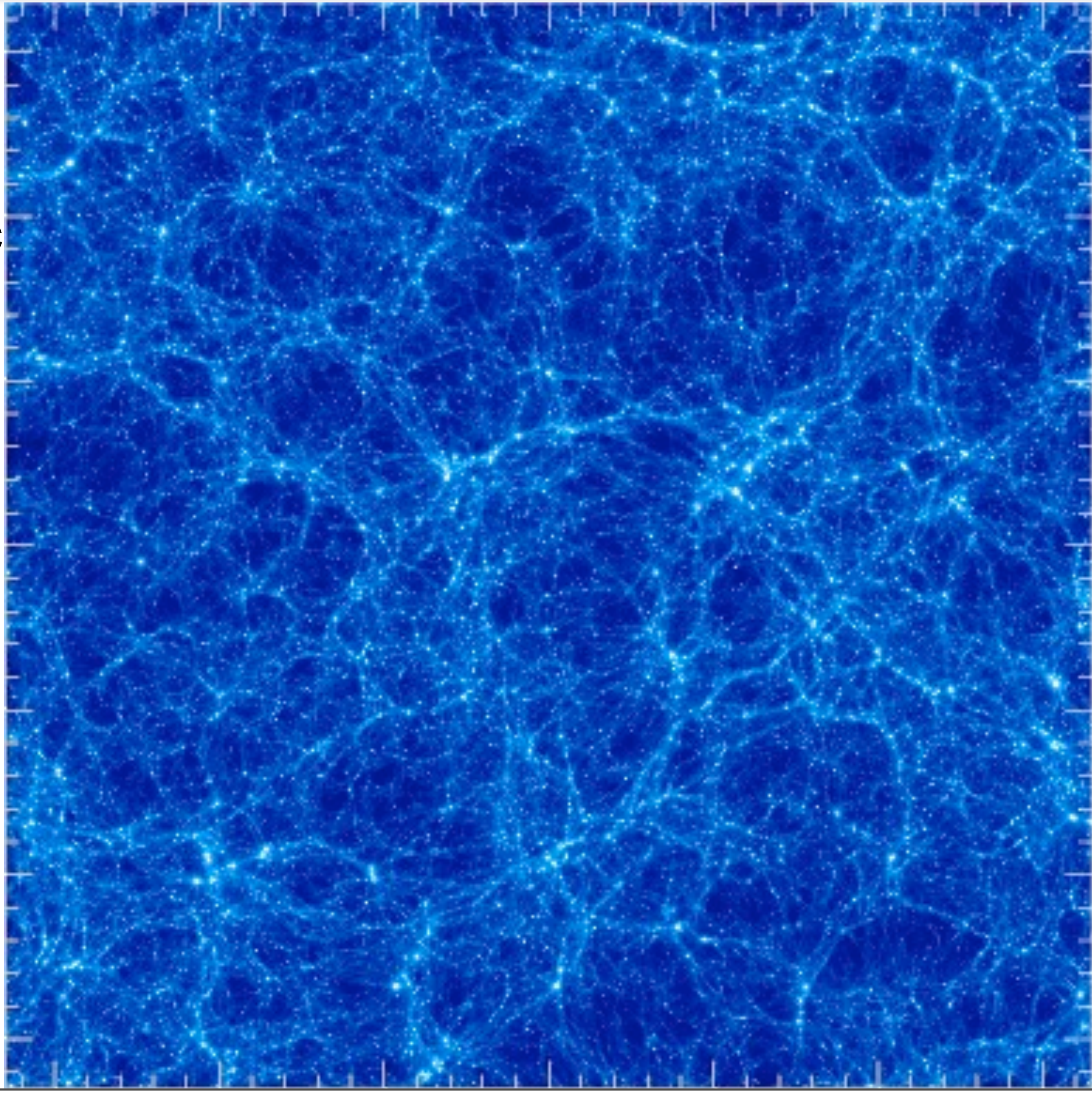
WMAP5

gas density

Gadget-3

SF+ SN E+ winds +CRs

512^3



all this can

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**

400 Mpc

ΛCDM

WMAP5

gas pressure

Gadget-3

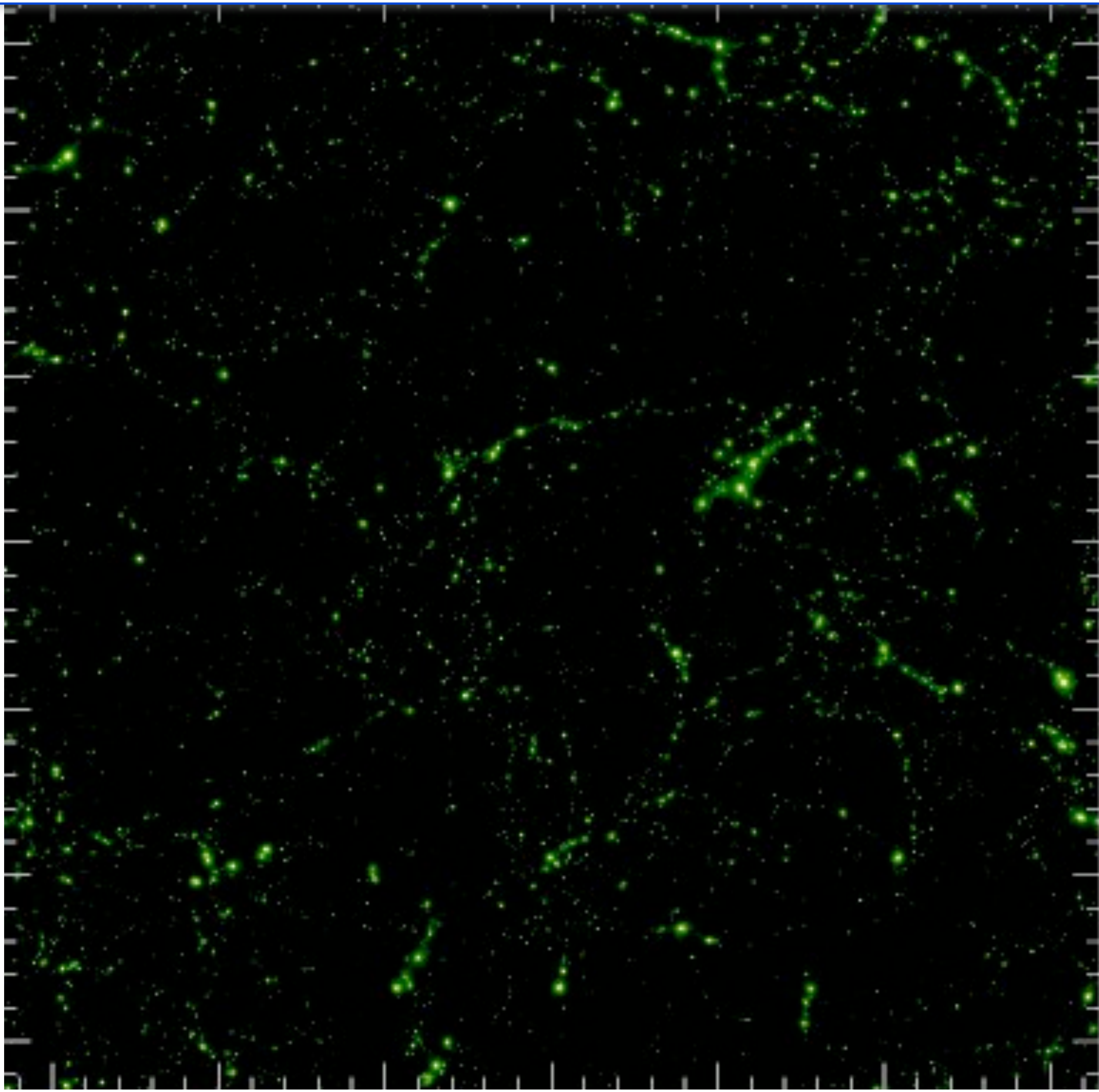
SF+

SN E+

winds

+CRs

512^3



entangled in the cosmic web

descending into the real astronomy

of

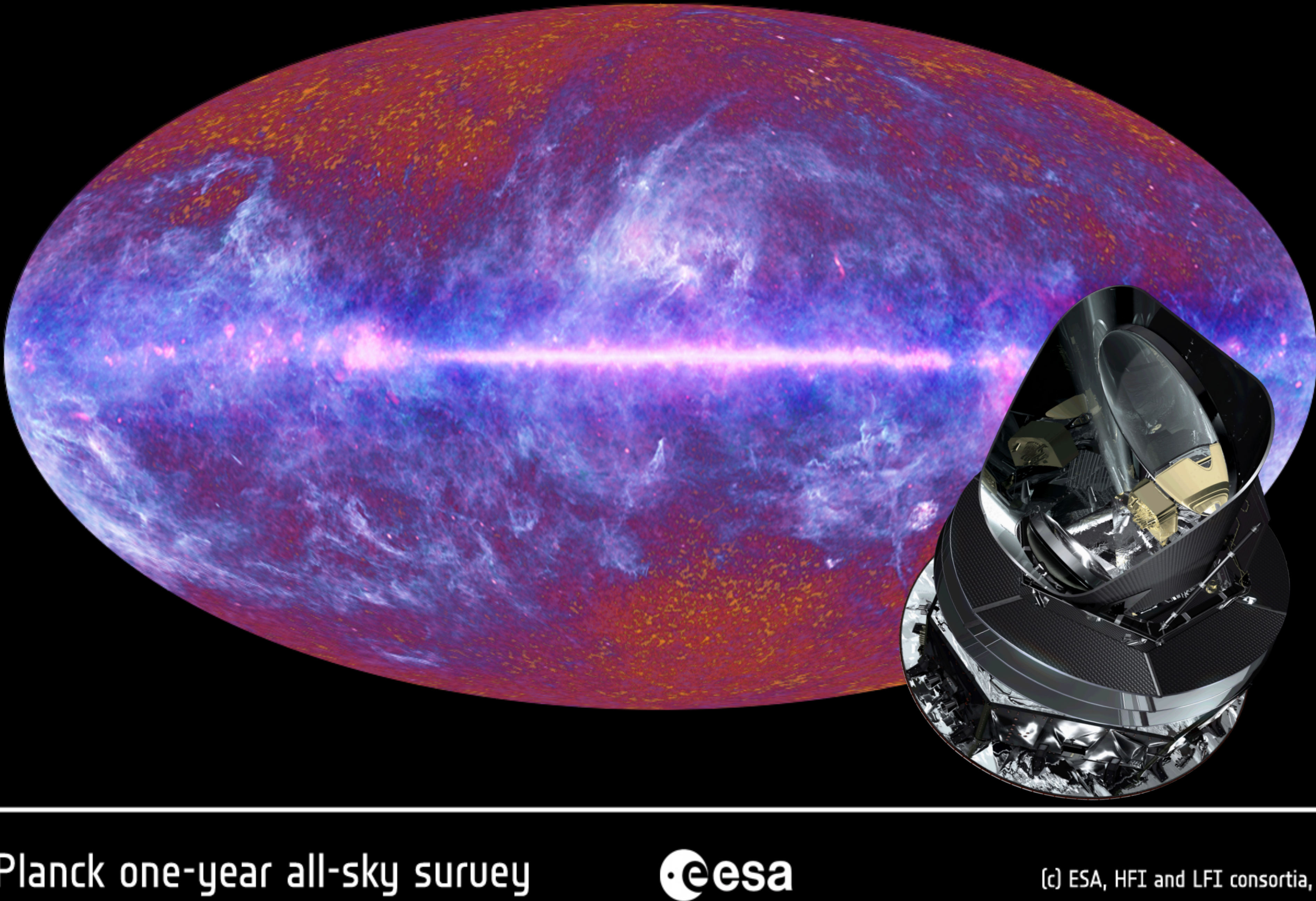
IGM/ISM/ICM

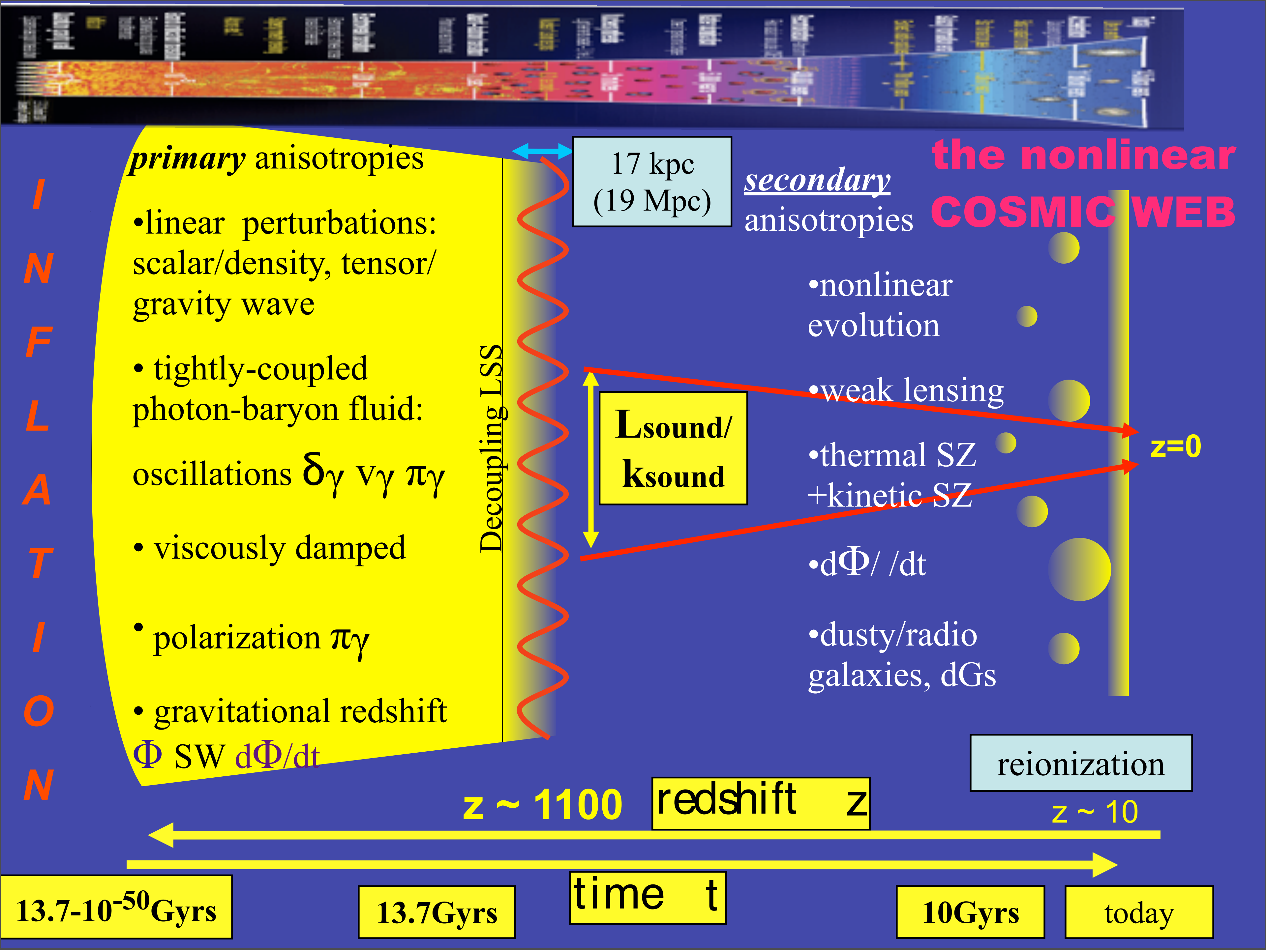
weather, dust storms

&

turbulent times

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




INFLATION
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
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^-50Gyrs
13.7Gyrs
10Gyrs
today

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?

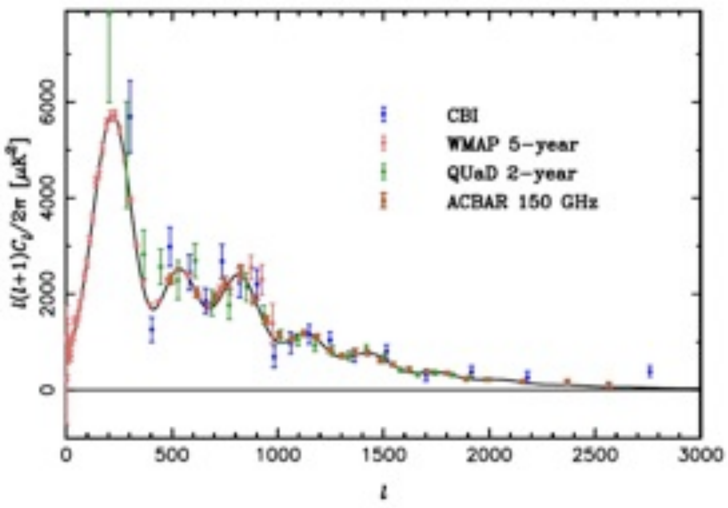
very early U early to middle to now U **very late U**

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} $\rho_{de} \sim H^2 M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$

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+w0, wa

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

ne(a)

$\sim \ln \sigma_8^2$

+ subdominant

isocurvature, cosmic string,

& fgnds, tSZ,kSZ, ...

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

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

$\varepsilon_\phi \times 2/3 = 1+w_{de}(a)$

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

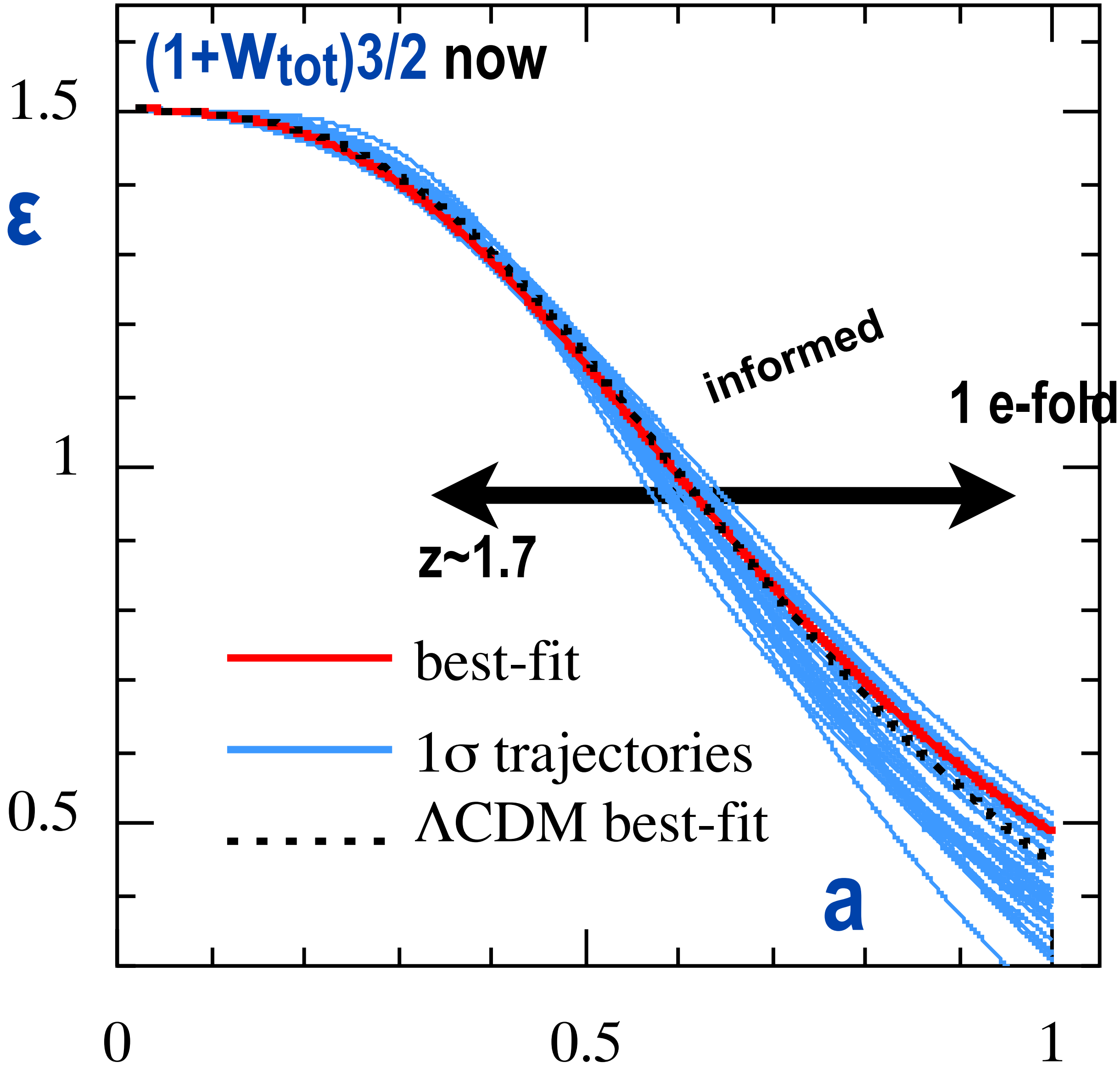
+ subdominant

isocurvature, cosmic string,

& fgnds, tSZ,kSZ, ...

current acceleration trajectories NOW

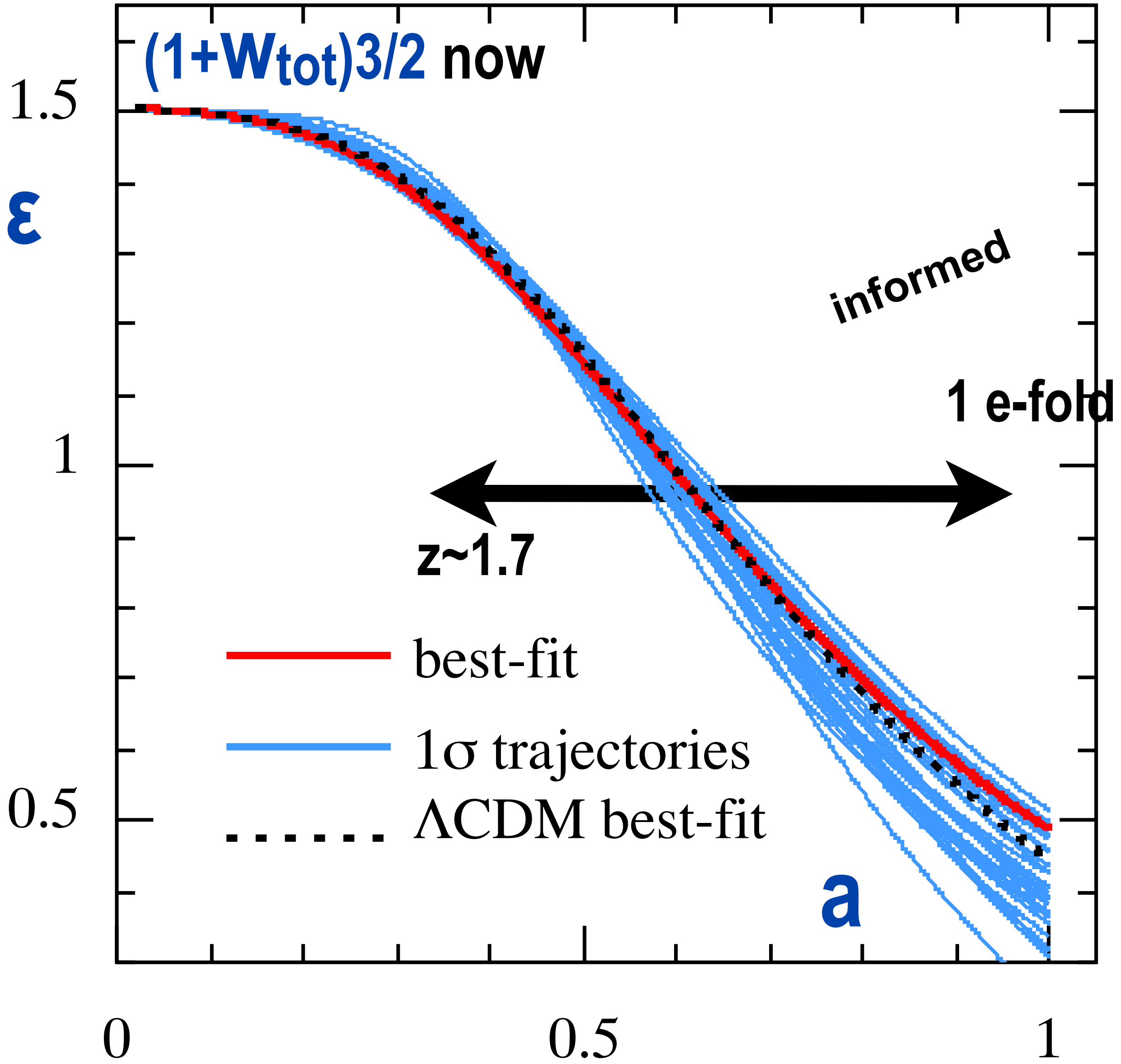
$(1+w_{tot}) = -\, d\ln\rho_{tot} / d\ln a^3 = 2/3\ \epsilon = -\, 2/3\ d\ln H / d\ln a$

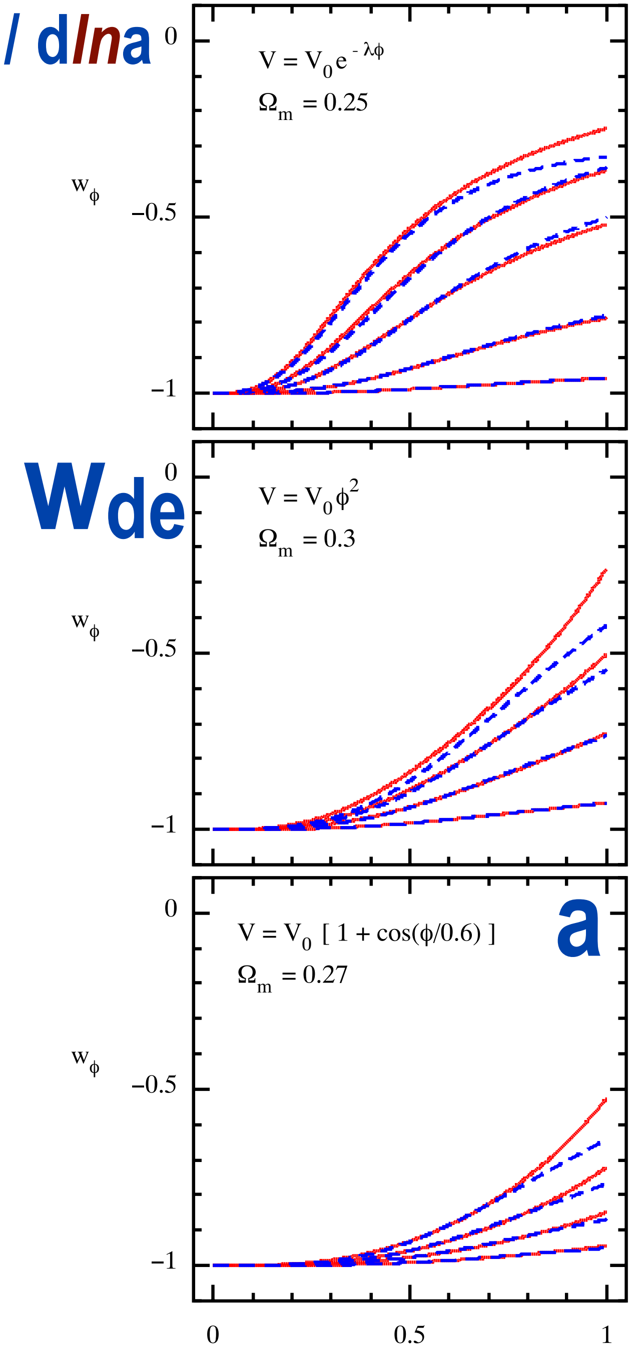


informed = 3-parameter w_{de} (z|V(ψ),IC)

current acceleration trajectories NOW

$(1+W_{tot}) = - d\,ln\rho_{tot} / d\,ln a^3 = 2/3\ \varepsilon = - 2/3\ d\,ln H / d\,ln a$

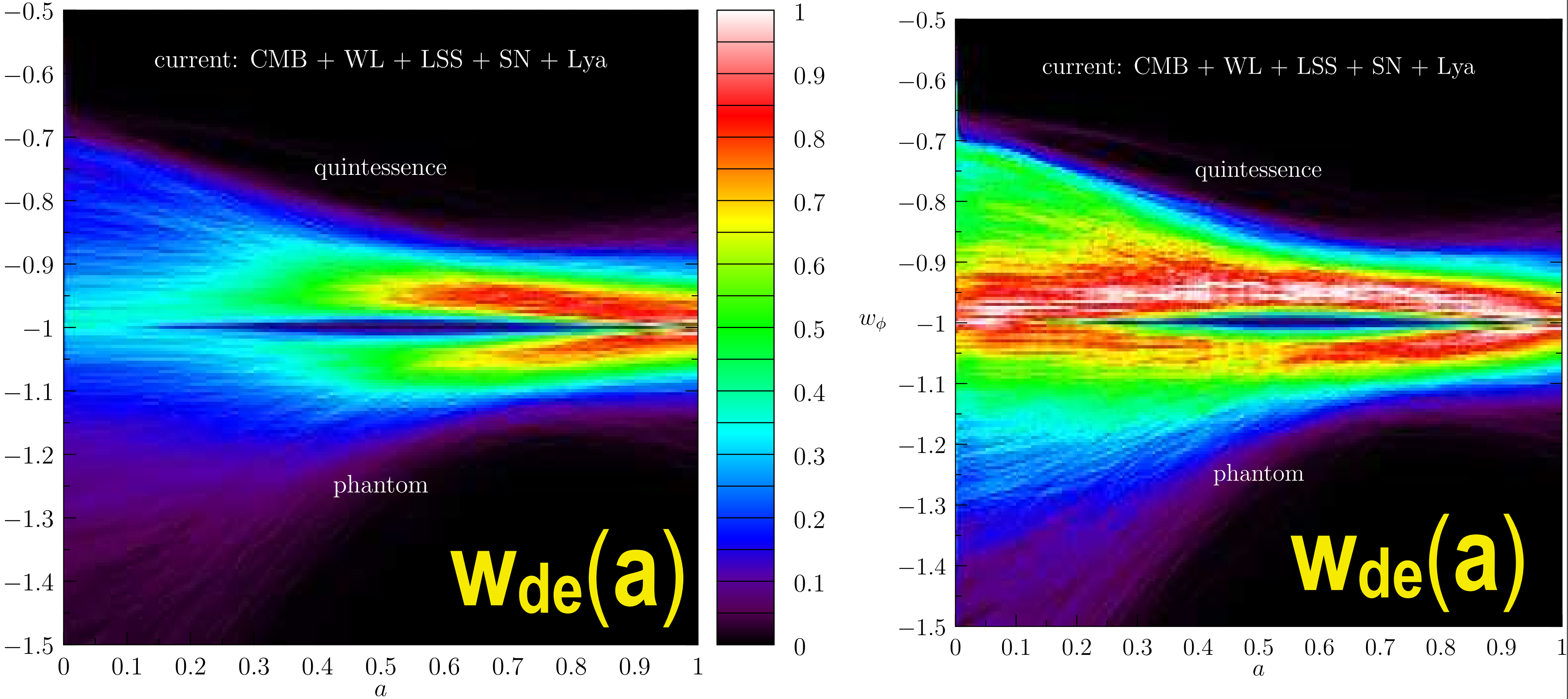




informed = 3-parameter w_{de} $(z|V(\psi),IC)$

current DE equation of state trajectories NOW

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

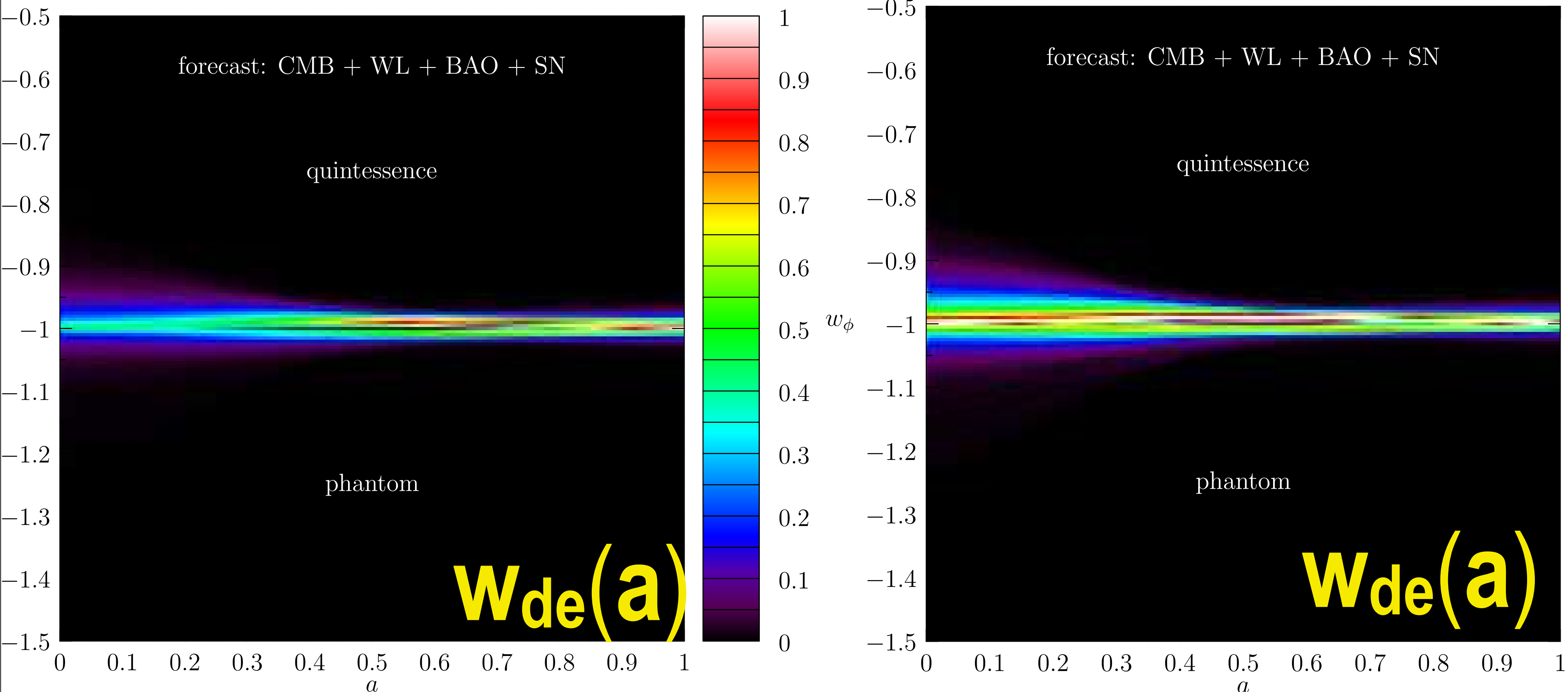


3-parameter w_{de} (z|V(ψ),IC) paves even wild late-inflaton trajectories

semi-blind w_{de} (z) in many z-bands determines only ~2 eigenvalues

future DE equation of state trajectories NOW

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



future = Planck2.5+CHIME-BOSS-BAO+"JDEM-SN+Euclid-WL"

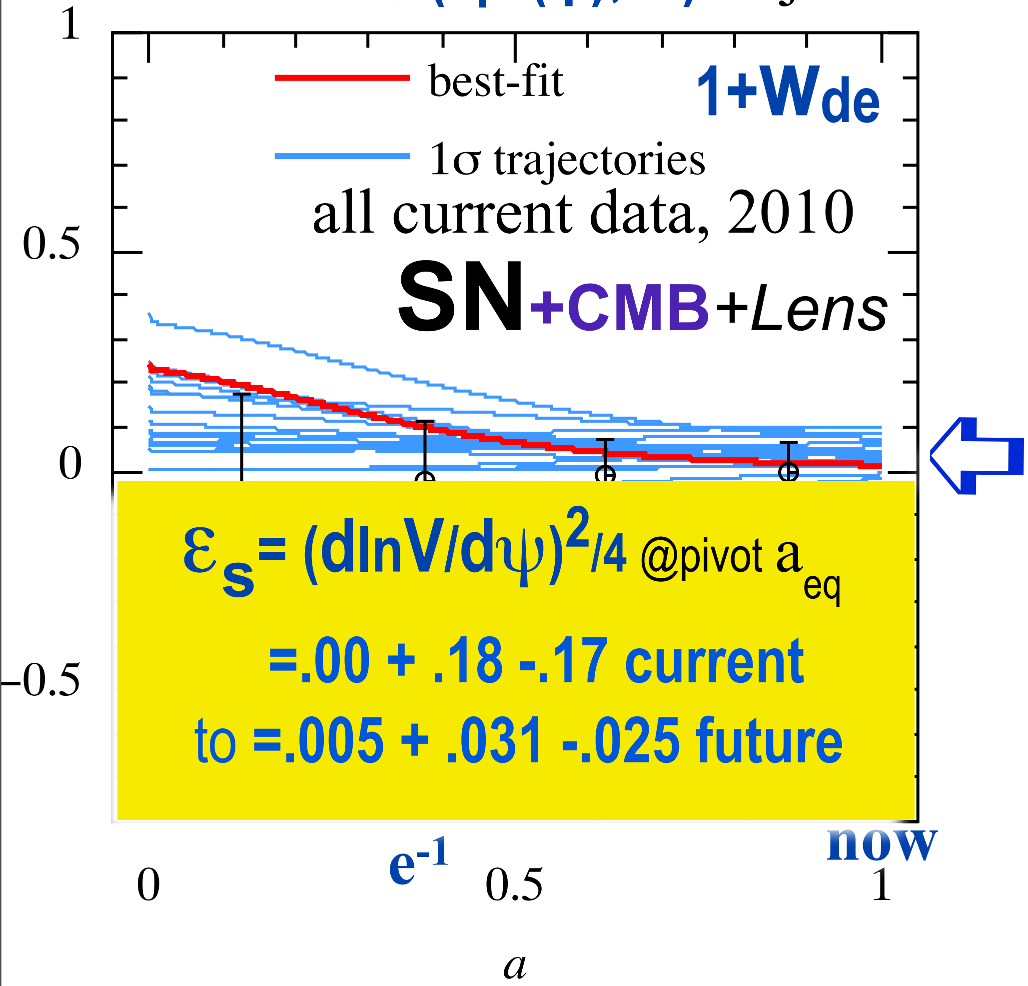
3-parameter w_{de} $(z|V(\psi),IC)$ paves even wild late-inflaton trajectories

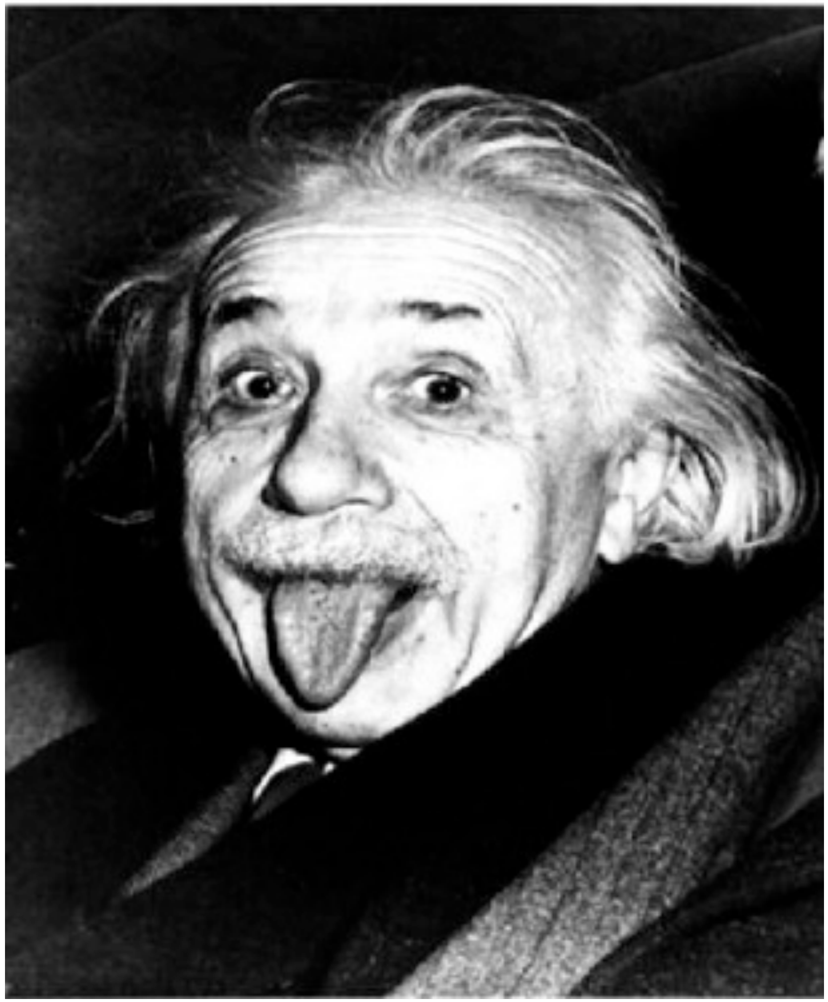
semi-blind w_{de} (z) in many z-bands determines only ~2 eigenvalues

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

3-parameter paves even wild late-inflaton w_{de} $(z|V(\psi),IC)$ trajectories

cf. semi-blind mode expansion





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

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

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

primordial non-Gaussianity

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

local smooth

+ 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

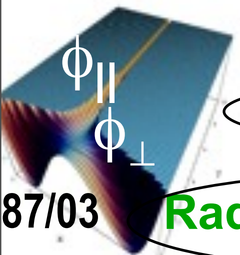
6/7 tiny extra dimensions

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

fibre inflation

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

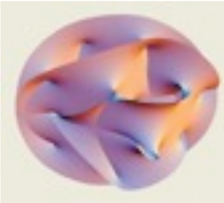
WHAT IS PREDICTED?

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

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 ⇒ r<.007)

Bond, Kofman, Prokushkin,Vaudrevange 07, **Roulette Inflation with Kahler Moduli and their Axions**

Barnaby, Bond, Zhiqi Huang, Kofman 09, **Preheating after Modular Inflation**

monodromy (V=cosine+linear) & fibre inflation give larger r~.03

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

r < 0.16 (no running, all data sets)

r < 0.32 (no running, CMB-only data sets)

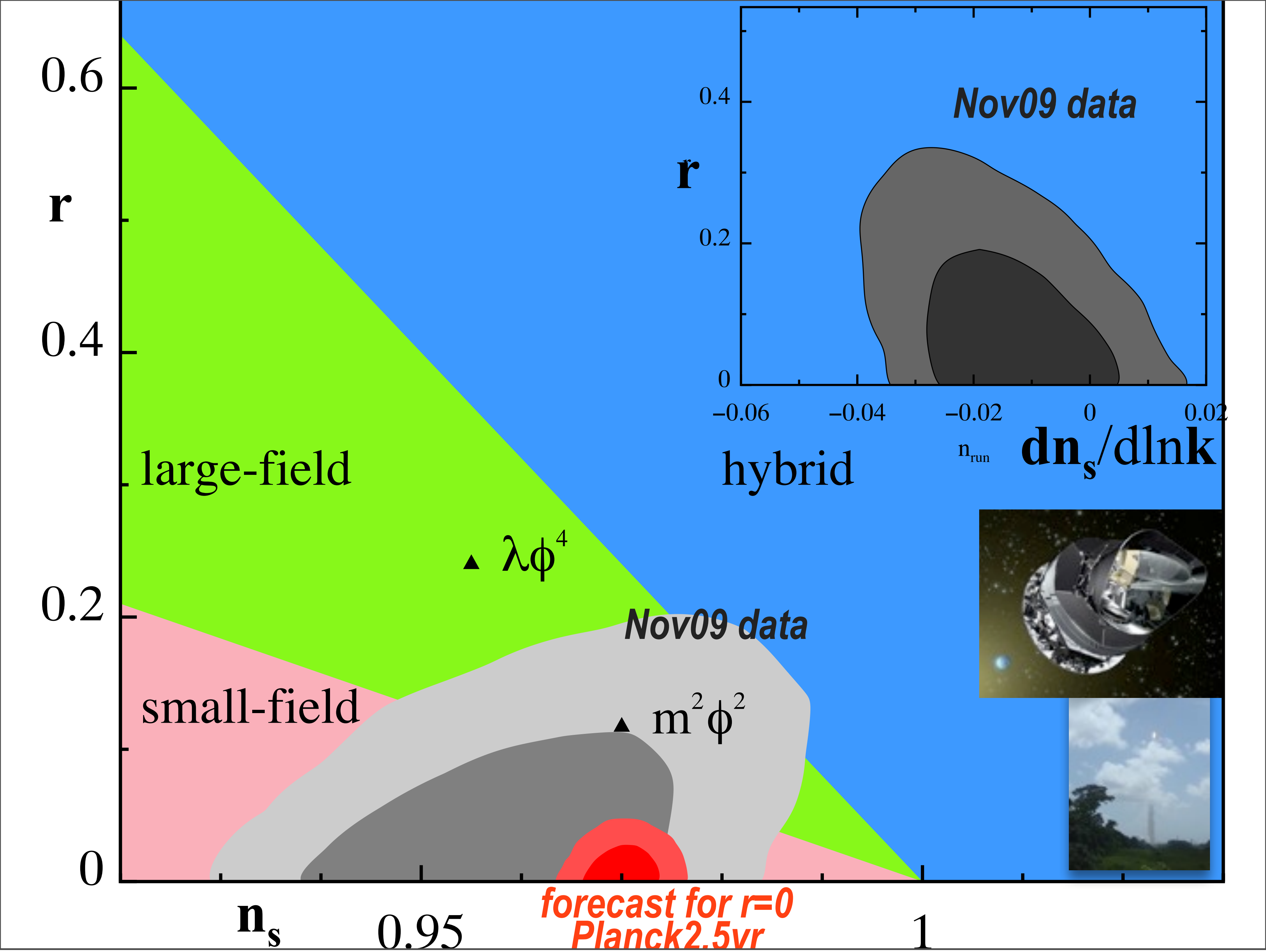
r < 0.27 (with running, all data sets)

& $f_{NL}<1$ typical cf. $-4< f_{NL} <80$ (+- 5 Planck)

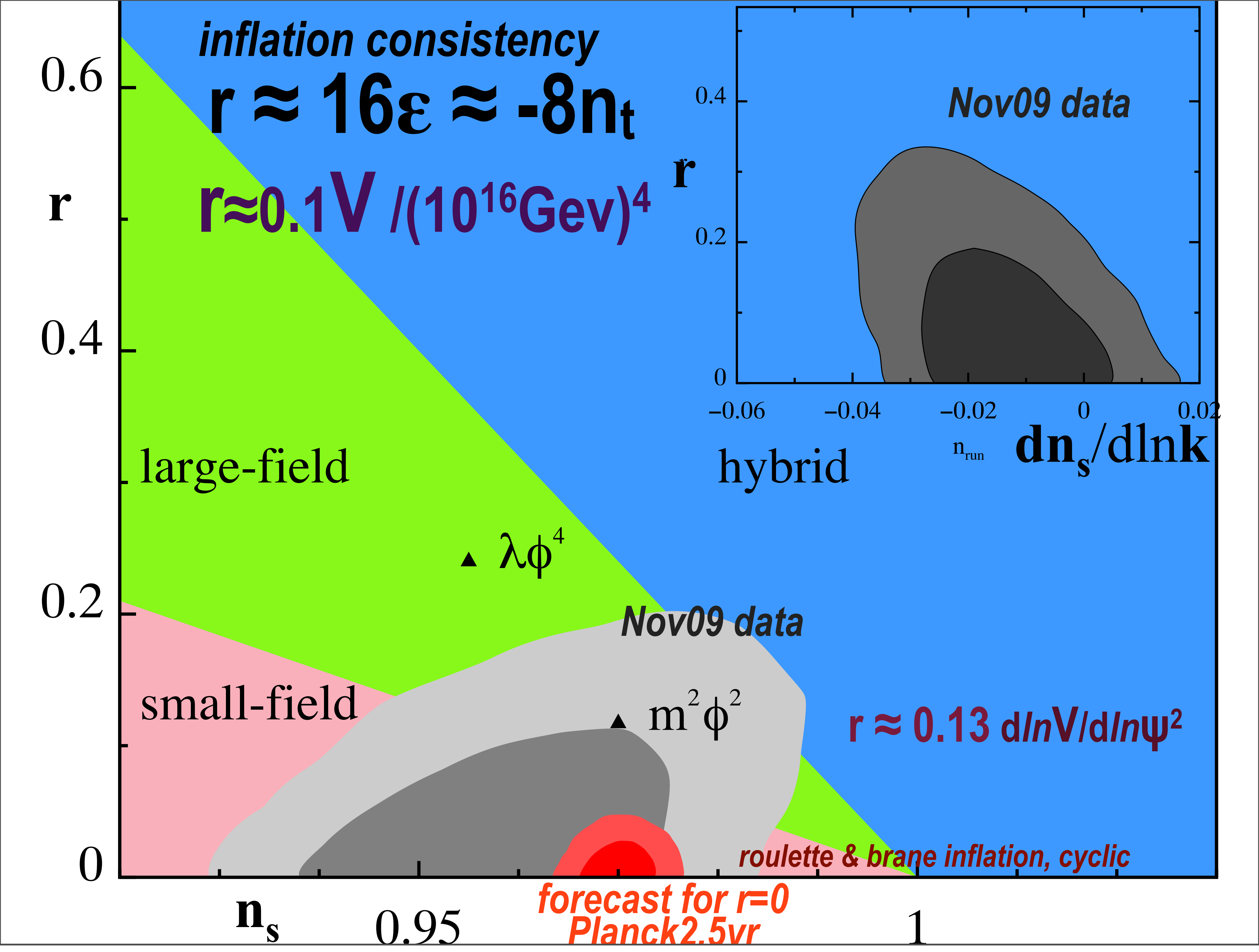
inflation consistency

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

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



0.6
r
0.4
0.2
0
large-field
small-field
λφ⁴
m²φ²
hybrid
Nov09 data
n_s
0.95
1
forecast for r=0
Planck2.5yr
r
0.4
0.2
0
−0.06
−0.04
−0.02
0
0.02
n_run
dn_s/dlnk



inflation consistency
r ≈ 16ε ≈ -8n_t
r≈0.1V /(10^16Gev)^4
r ≈ 0.13 dlnV/dlnψ^2
large-field
hybrid
small-field
λφ^4
m^2φ^2
Nov09 data
roulette & brane inflation, cyclic
forecast for r=0
Planck2.5yr
r
0.6
0.4
0.2
0
n_s
0.95
1
Nov09 data
r
0.4
0.2
0
−0.06
−0.04
−0.02
0
0.02
n_run
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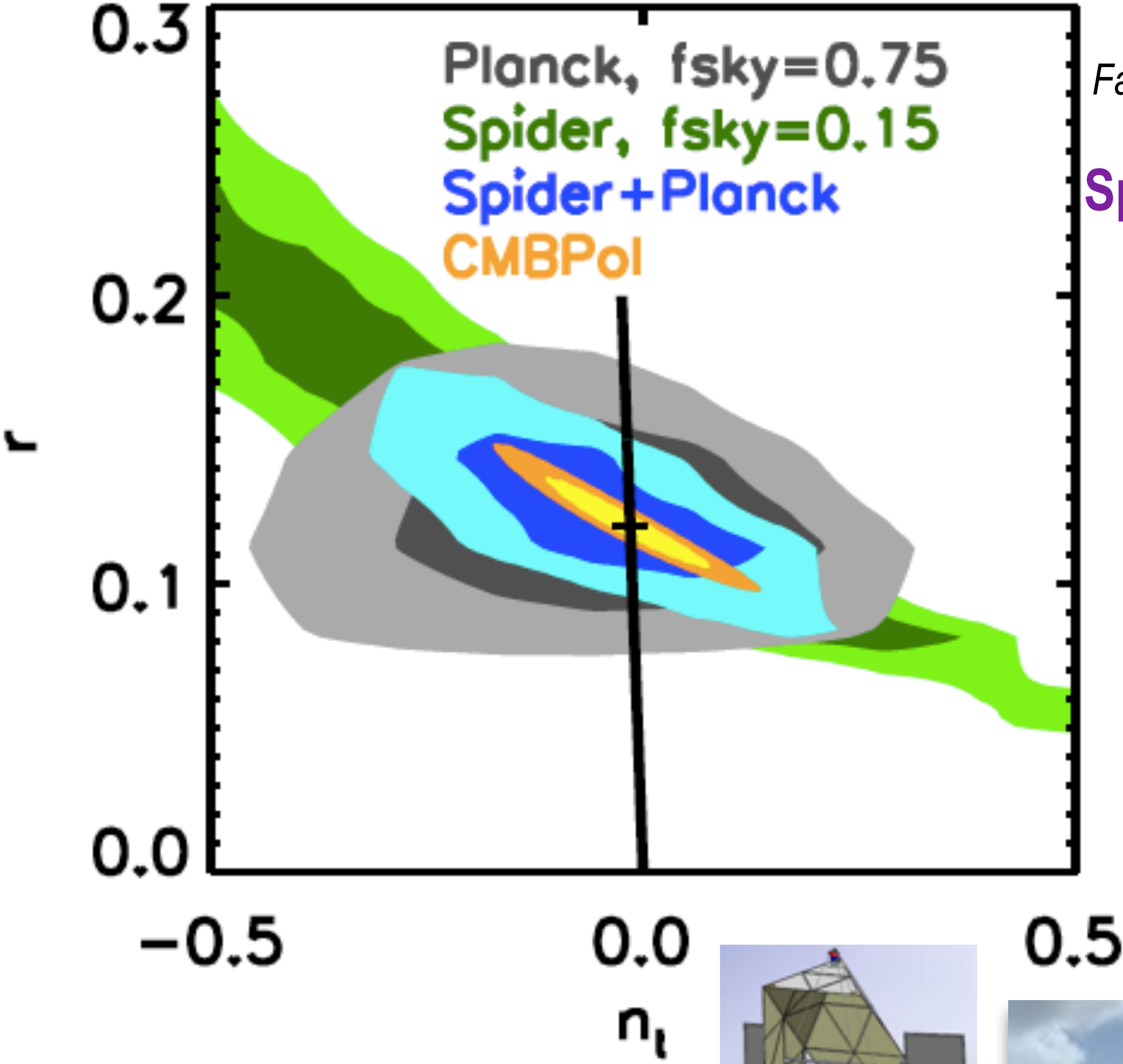
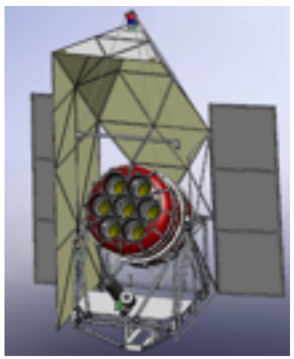
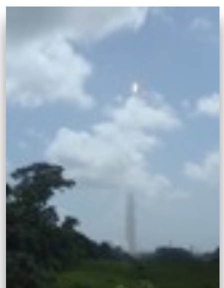


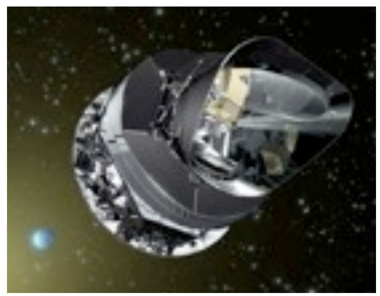
Farhang, Bond, Dore, Netterfield 2011

Spider-24days+Planck-2.5yr
r-n_t forecast
for r=0.12 input for $m^2\varphi^2$
(including fgnds)

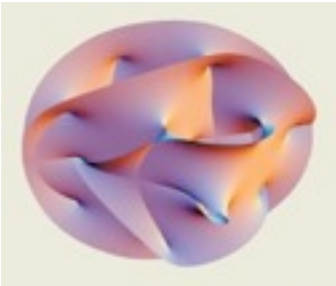
r to ± 0.02







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



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

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

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

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

(partially) blind cf. informed "theory" priors

$lnP_s(lnk)$ & $r(k_p)$ & $lnP_t(lnk)$

$\varepsilon_\phi x2/3 = 1+w_{de}(a)$

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

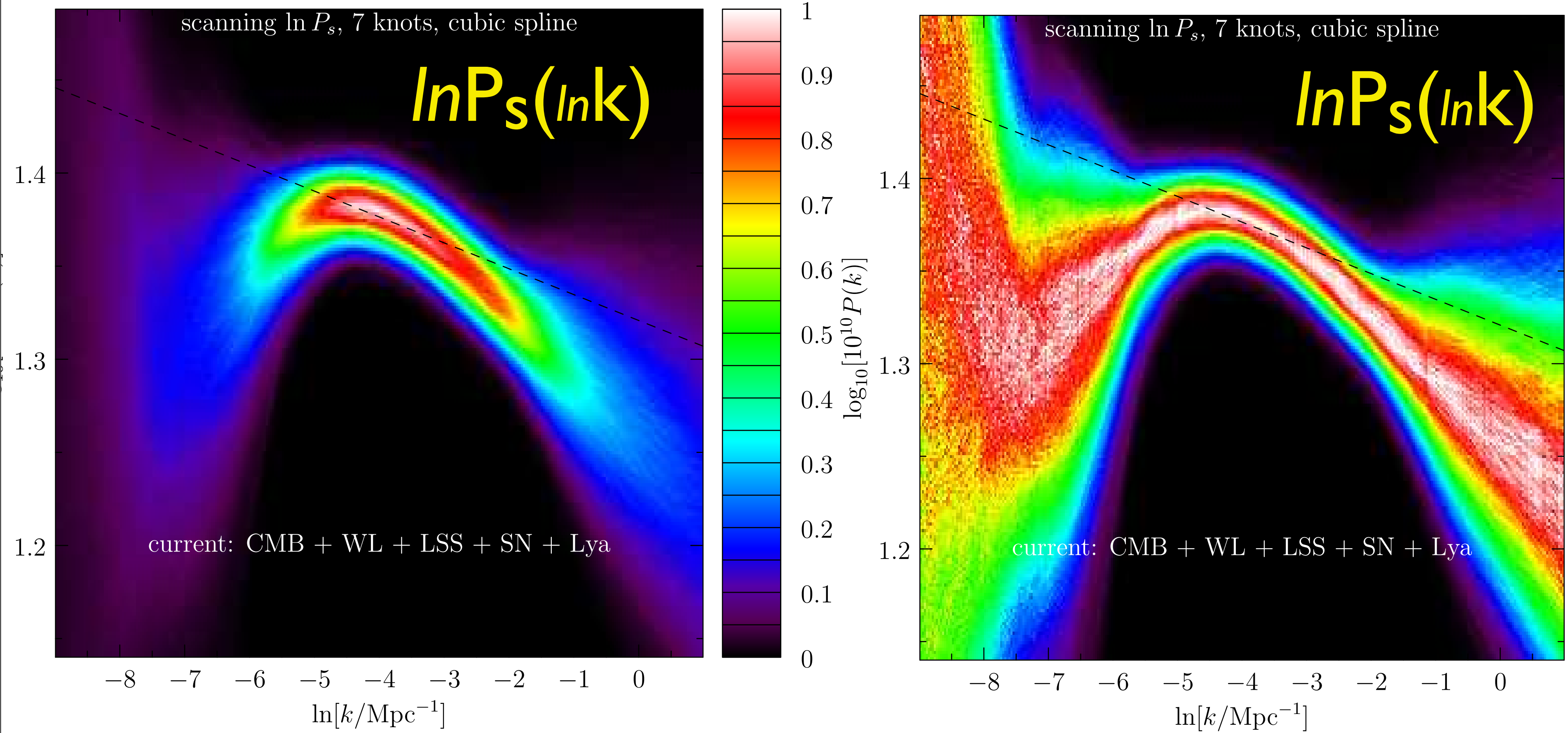
+ subdominant

isocurvature, cosmic string,

& fgnds, tSZ,kSZ, ...

current scalar power spectrum trajectories

scan $\ln \mathbf{P_s}(\ln k)$, $\mathbf{A_t} = P_t(k_{pivot,t})$, $\mathbf{n_t}\ (k_{pivot,t})$ $(r = A_t/A_s)$

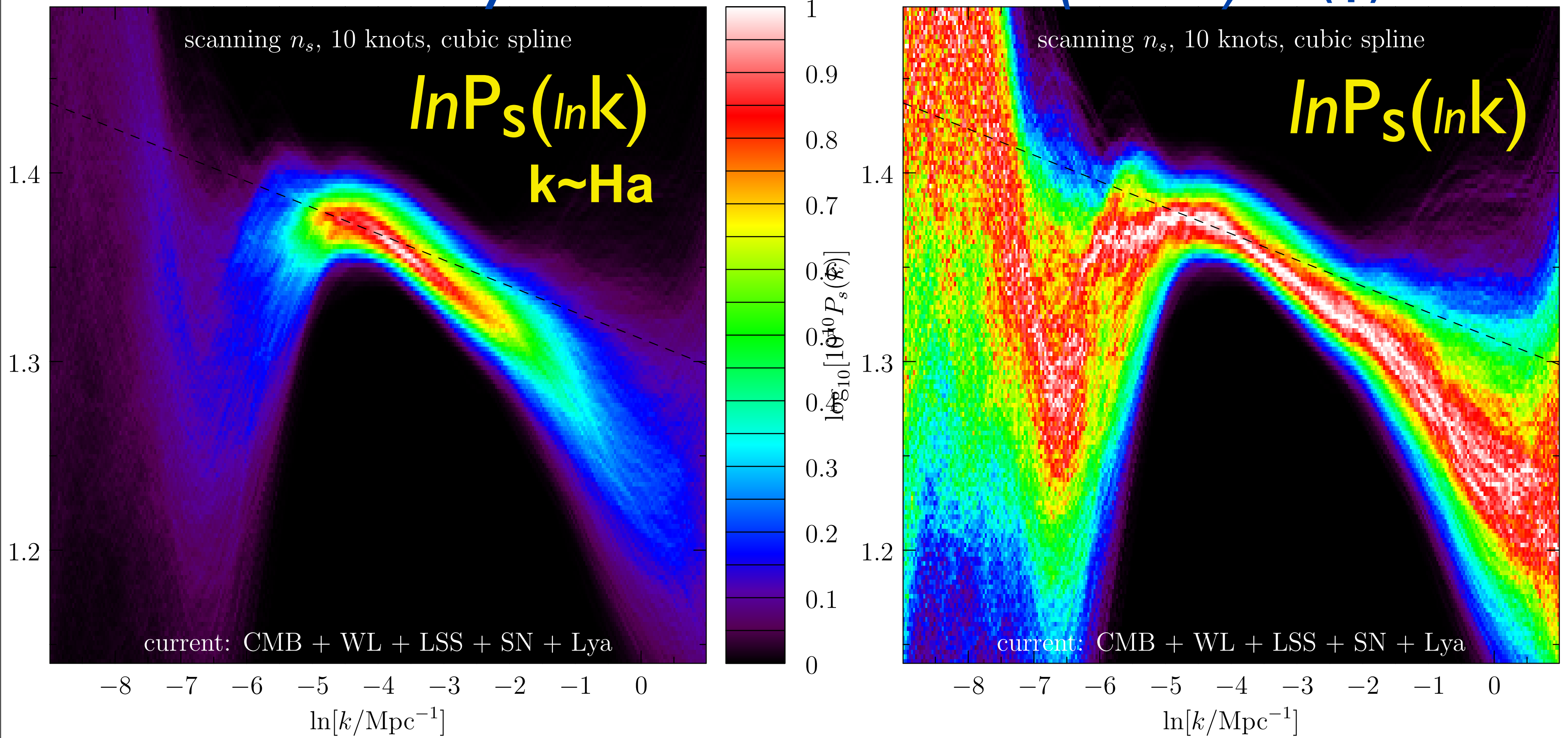


Bond, Contaldi, Huang, Kofman, Vaudrevange 2011

current scalar power spectrum trajectories

scan $\mathbf{n_s}(\ln k)$, $\ln \mathbf{A_s} = \ln P_s(k_{pivot,s})$, $\mathbf{r}(k_{pivot,t})$;

consistency => reconstruct $\varepsilon(\ln Ha)$, $V(\psi)$



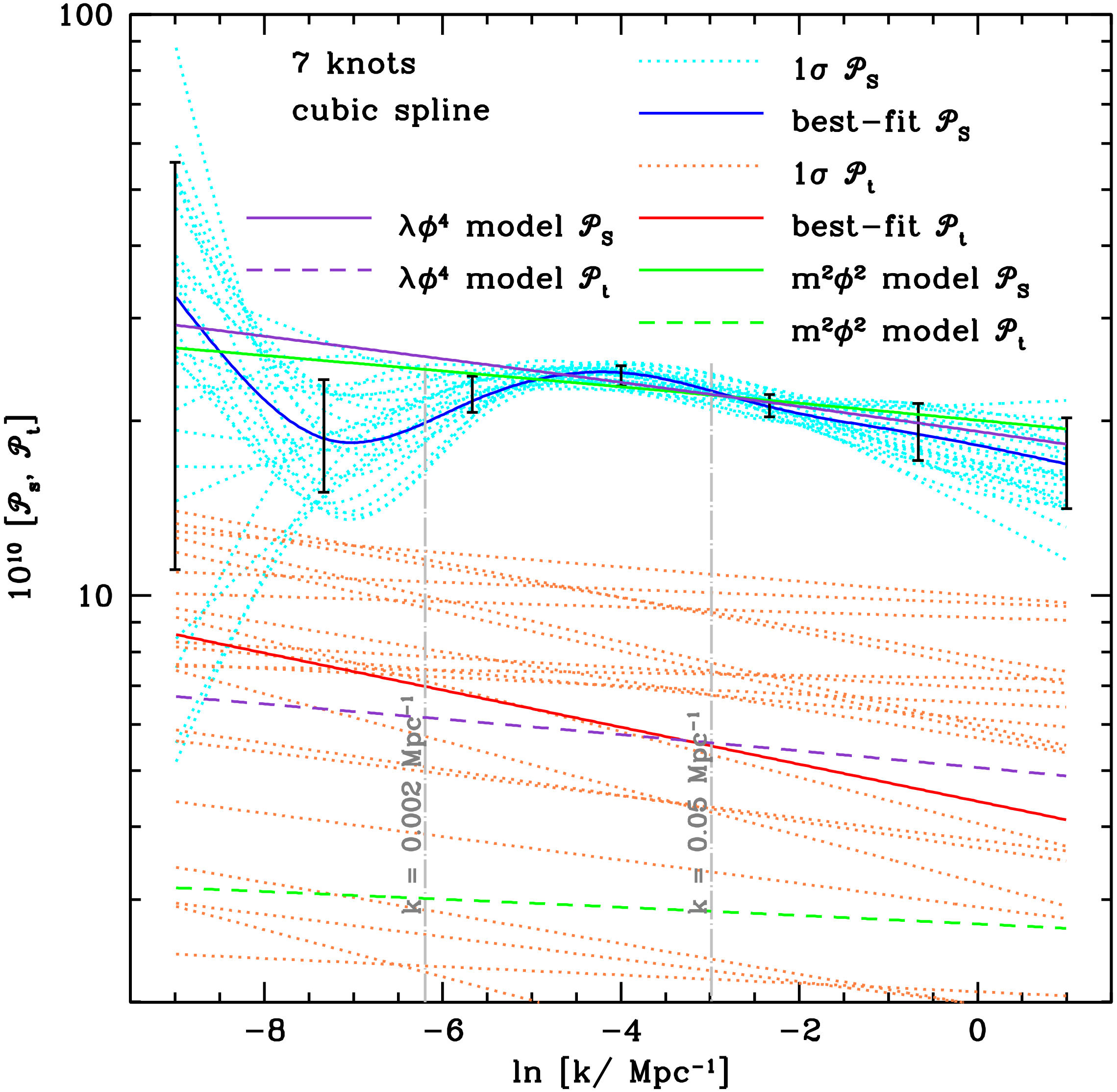
$\varepsilon_\psi \approx \varepsilon = -\, d\ln H / d\ln a$; $V(\psi) \approx 3M_P^2H^2(1-\varepsilon/3)$; $d\psi/ d\ln a = \pm\sqrt{\varepsilon}$

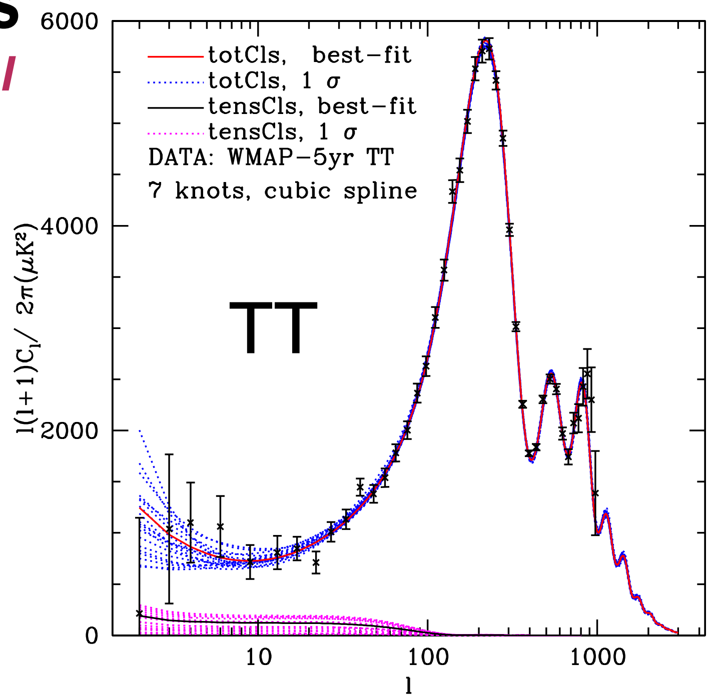
GW/S≡ $r \approx 16\varepsilon$

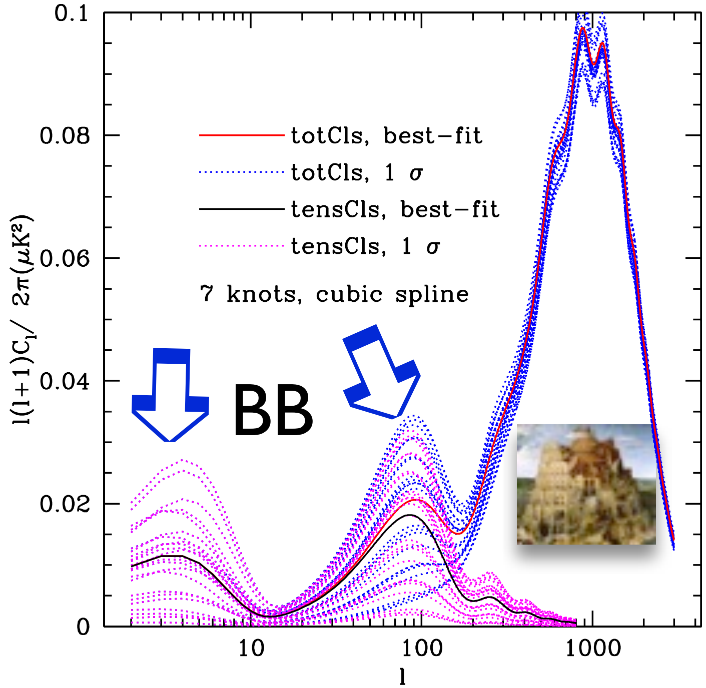
$r \approx 0.1 V / (10^{16} \text{Gev})^4$

compress data onto non-top-hat k-modes

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



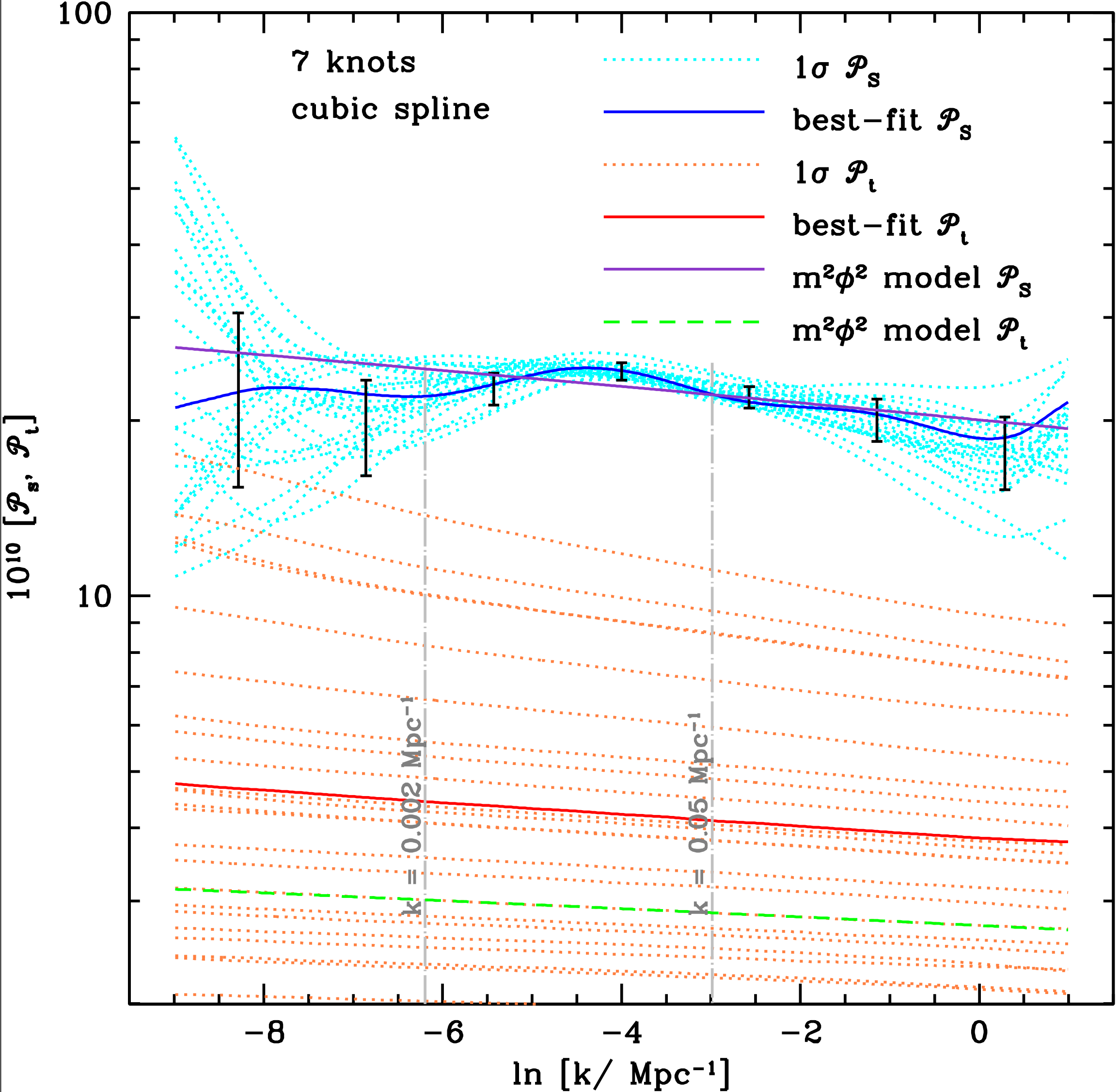


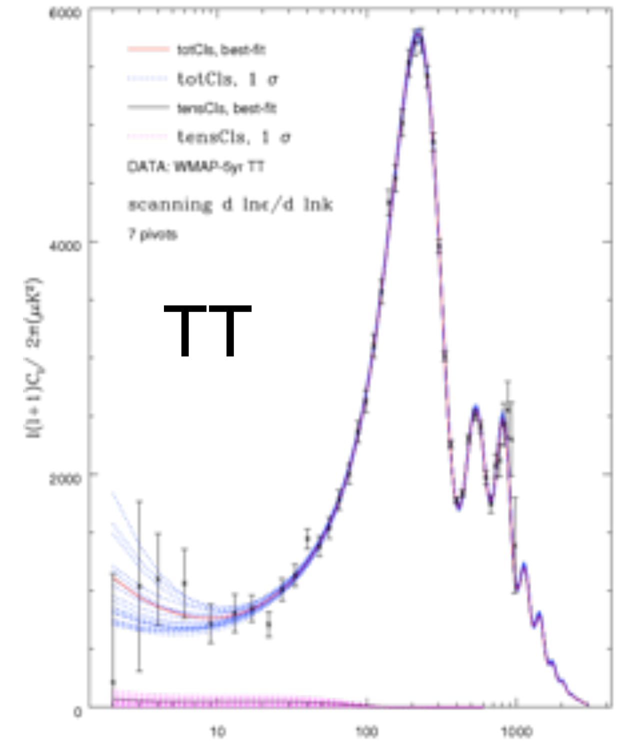


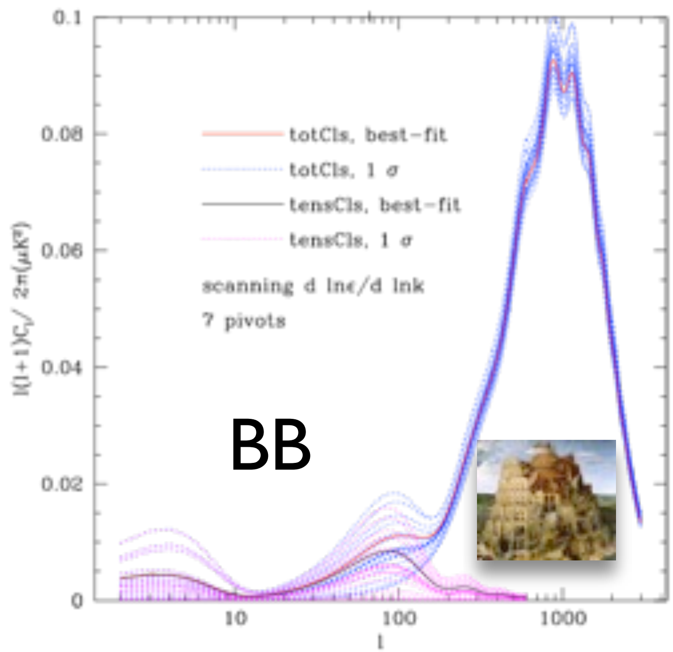
Bond, Contaldi, Huang, Kofman, Vaudrevange 2011

compress data onto non-top-hat k-modes

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



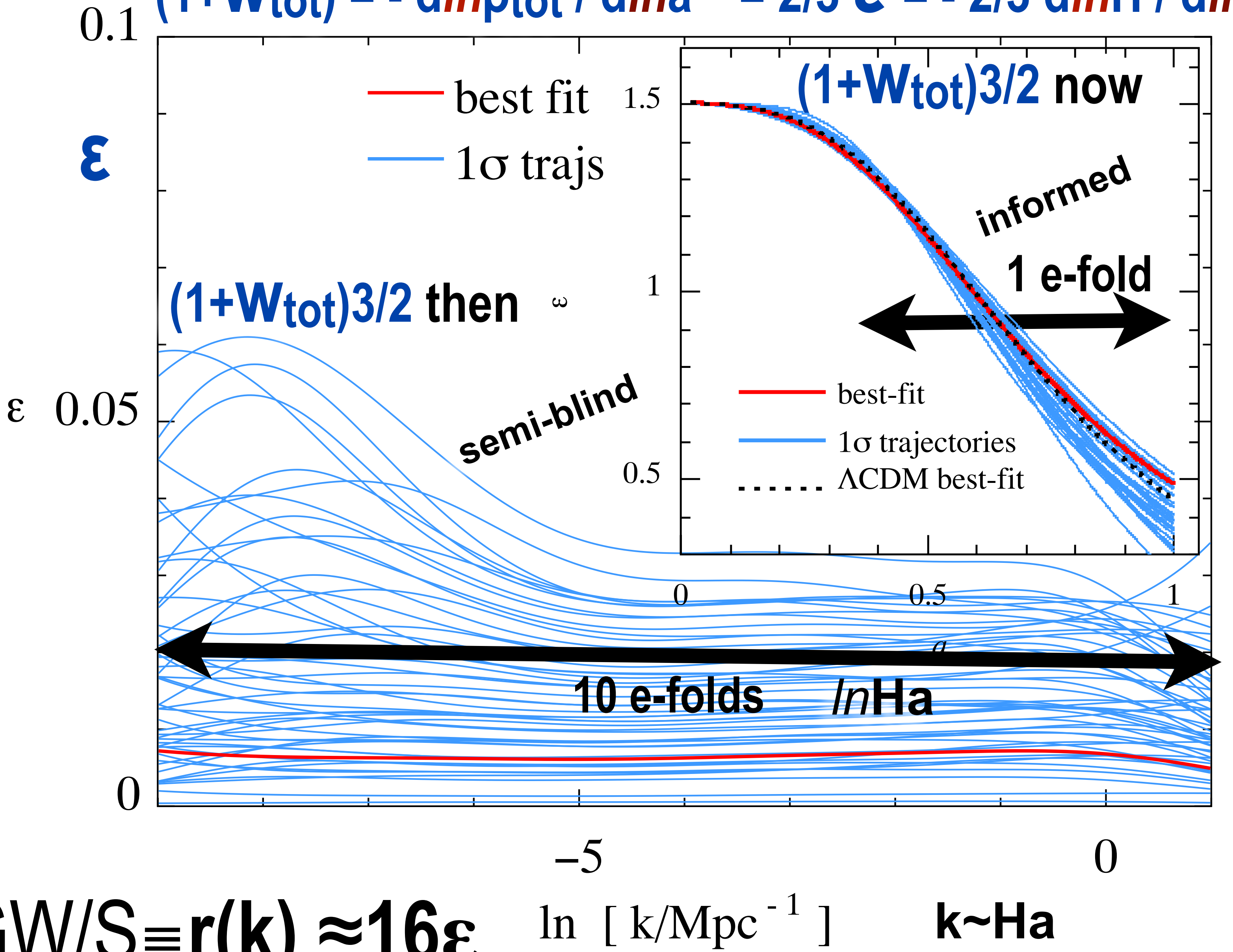




Bond, Contaldi, Huang, Kofman, Vaudrevange 2011

acceleration trajectories: current data

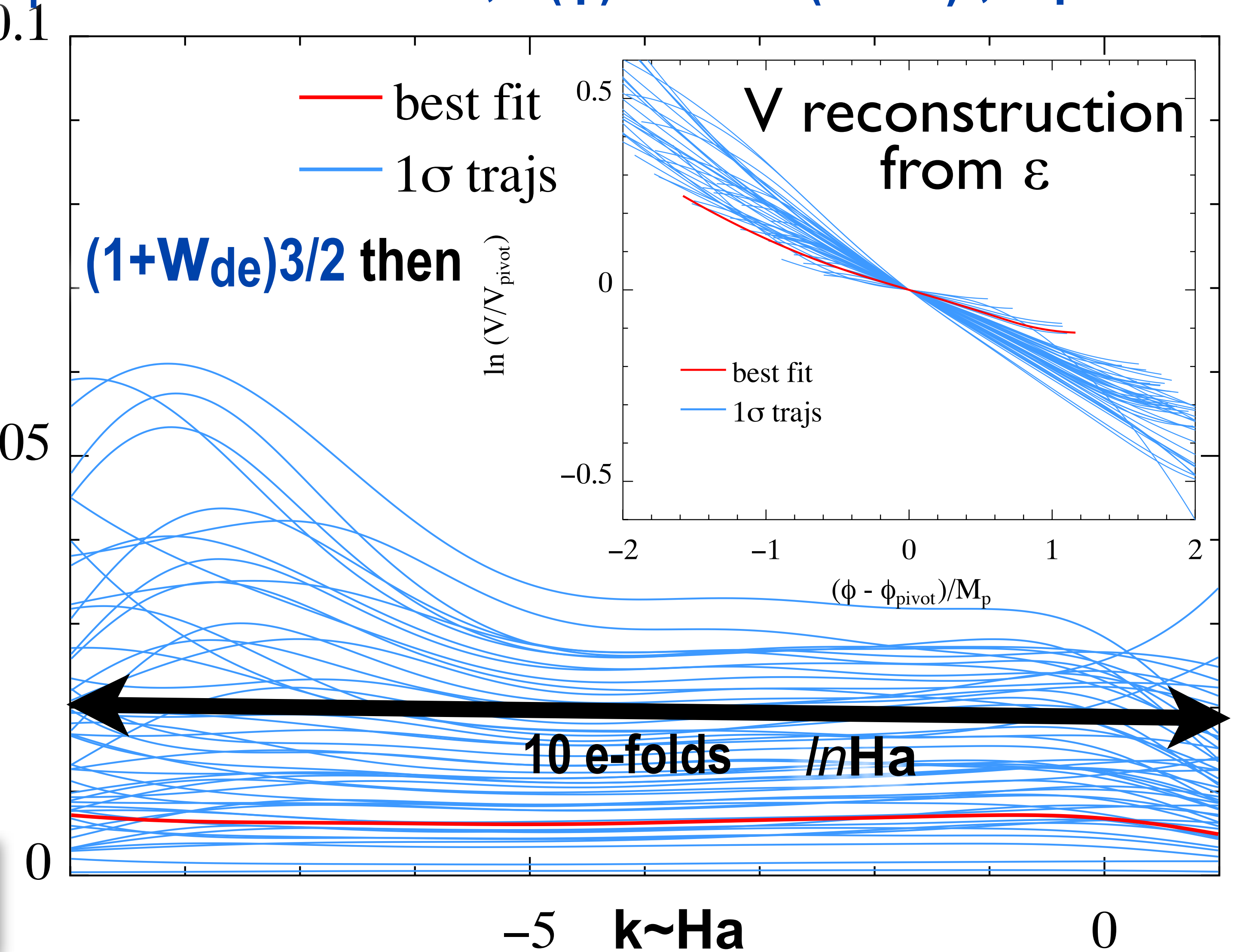
$(1+W_{tot}) = -\, d\,ln\rho_{tot} / d\,ln a^3 = 2/3\ \varepsilon = -\, 2/3\ d\,ln H / d\,ln a$

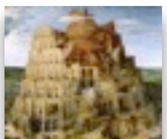


GW/S≡r(k) ≈16ε

acceleration & potential trajectories then

$\varepsilon_\psi \approx \varepsilon = -\, d\ln H / d\ln a$; $V(\psi) \approx 3M_P^2 H^2 (1-\varepsilon/3)$; $d\psi / d\ln a = \pm\sqrt{\varepsilon}$



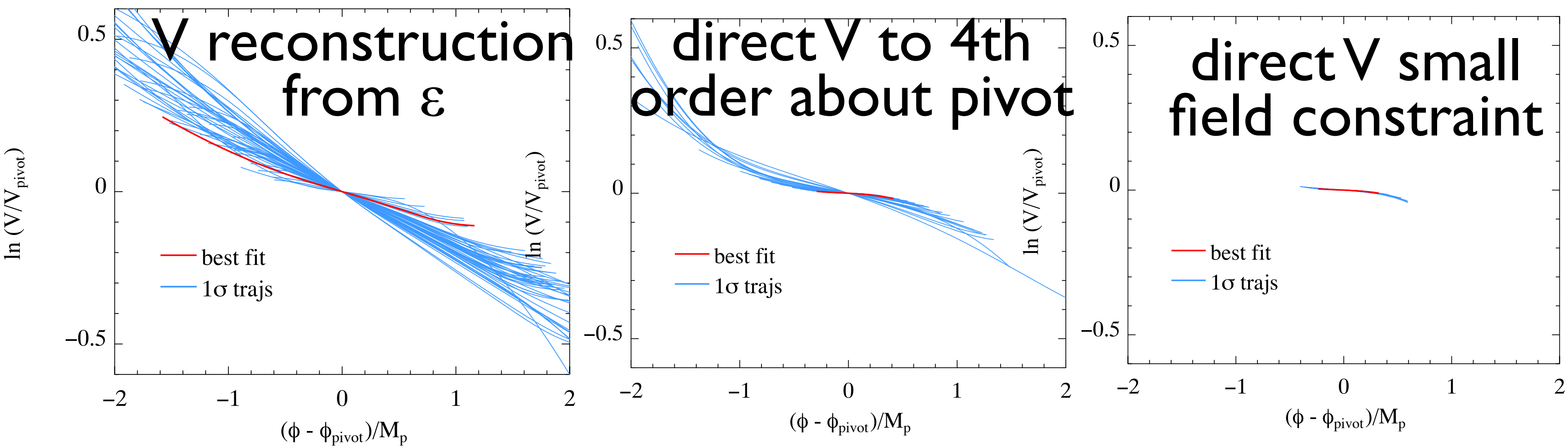


GW/S≡r ≈16ε

$r \approx 0.1\, V / (10^{16}\mathrm{Gev})^4$

other approaches to **potential reconstruction**

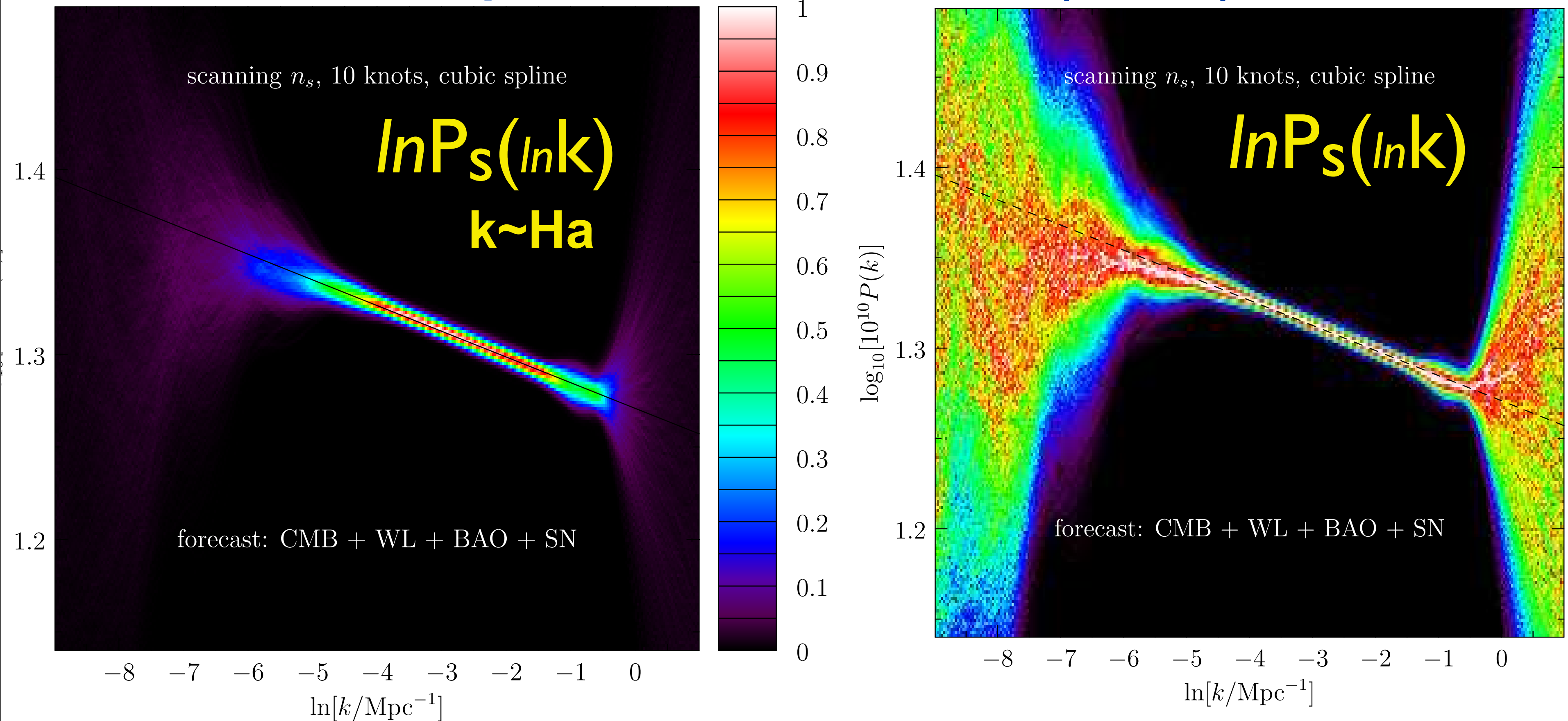
running around pivots



future scalar power spectrum trajectories

scan $\mathbf{n_s}(\ln k)$, $\ln\mathbf{A_s} = \ln P_s(k_{pivot,s})$, $\mathbf{r}(k_{pivot,t})$;

consistency => reconstruct $\varepsilon(\ln Ha)$, $V(\psi)$



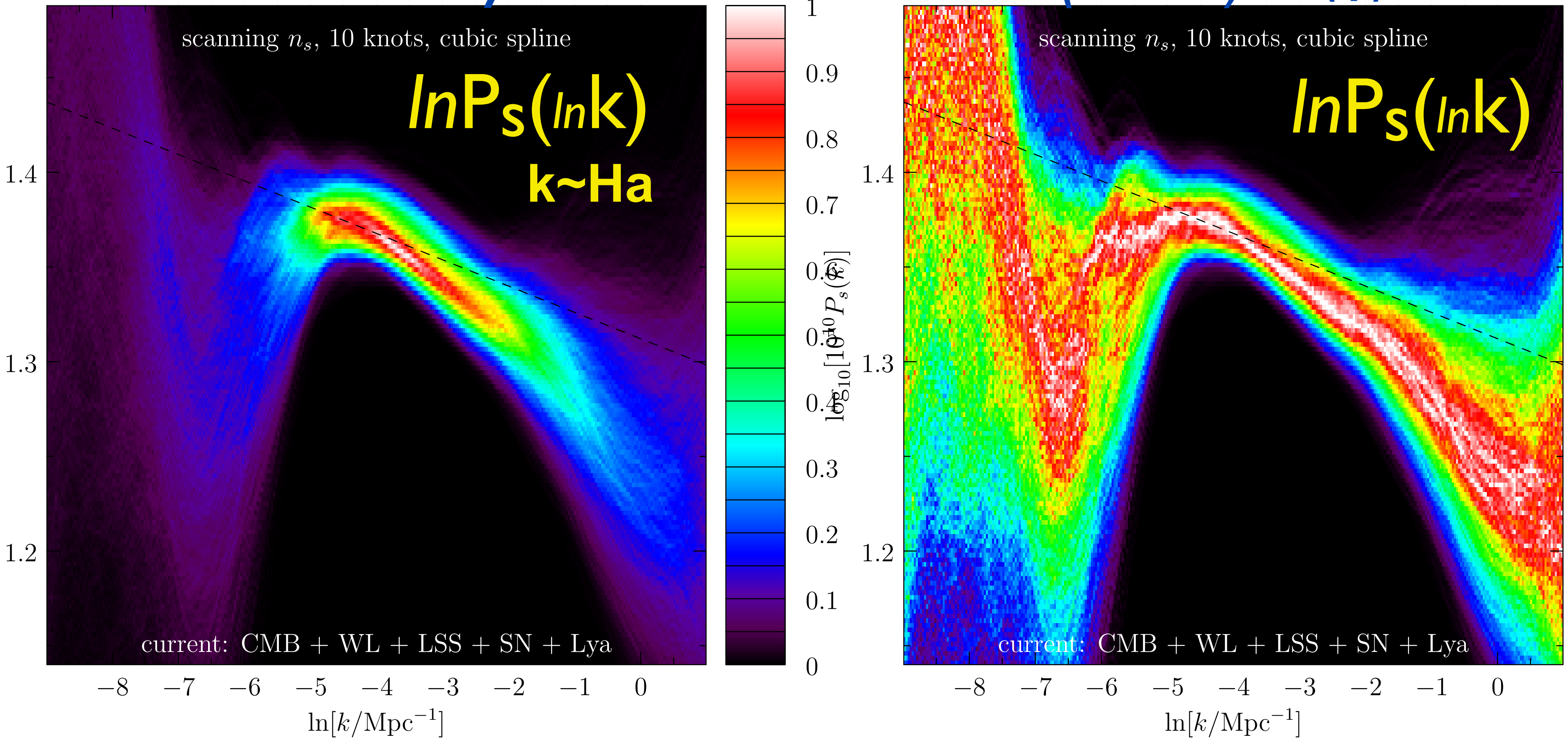
$\varepsilon_\psi \approx \varepsilon = -\, d\ln H / d\ln a$; $V(\psi) \approx 3M_P^2H^2(1-\varepsilon/3)$; $d\psi / d\ln a = \pm\sqrt{\varepsilon}$

$GW/S \equiv r \approx 16\varepsilon$ $\quad$ $r \approx 0.1\, V / (10^{16}\,\text{Gev})^4$

current scalar power spectrum trajectories

scan $\mathbf{n_s}$(*ln*k), *ln*$\mathbf{A_s}$=*ln*$P_s(k_{pivot,s})$, $\mathbf{r}(k_{pivot,t})$;

consistency => reconstruct ε(*ln*Ha), V(ψ)



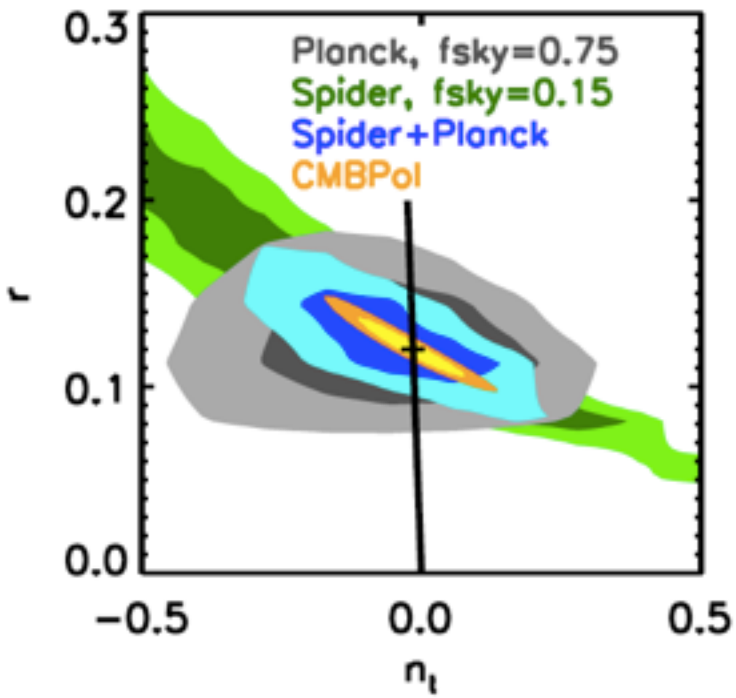
$\varepsilon_\psi \approx \varepsilon = -\, d\,lnH / d\,lna$; $V(\psi) \approx 3M_P^2 H^2 (1-\varepsilon/3)$; $d\psi / d\,lna = \pm\sqrt{\varepsilon}$

GW/S≡r ≈16ε

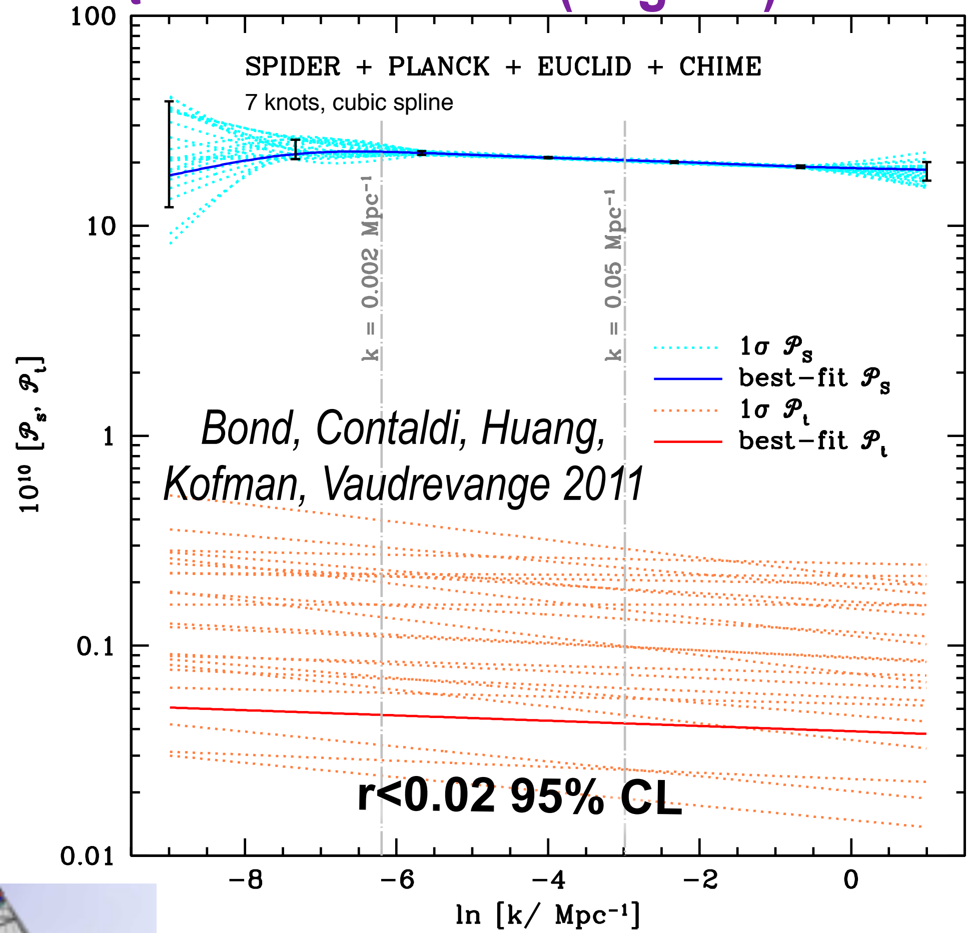
$r \approx 0.1\, V / (10^{16}\text{Gev})^4$

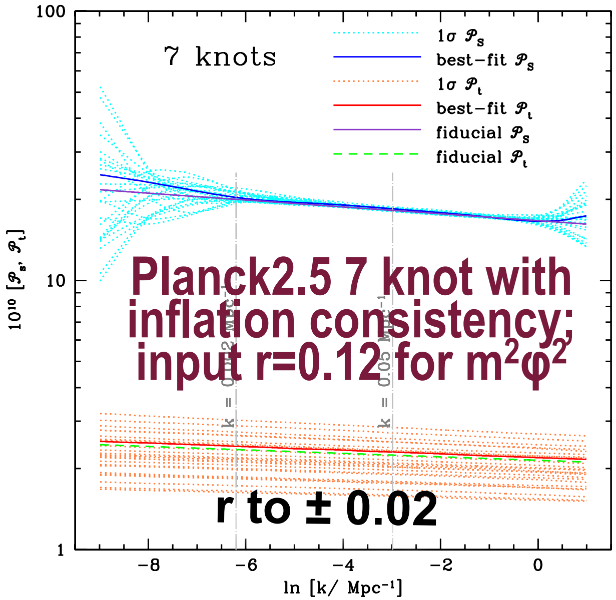
compress data onto non-top-hat k-modes

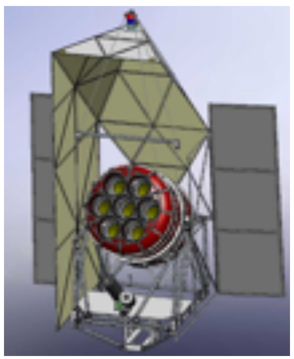
Farhang, Bond, Dore, Netterfield 2011

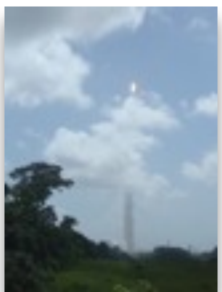


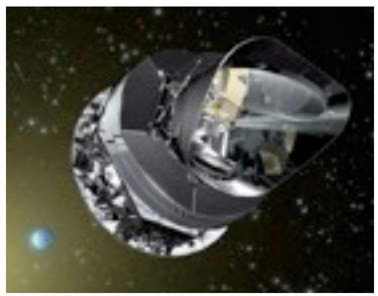
Spider-24days + Planck-2.5yr + ... 7 knot $\ln P_s$ +r-n_t forecast for r=0 (+ fgnds)





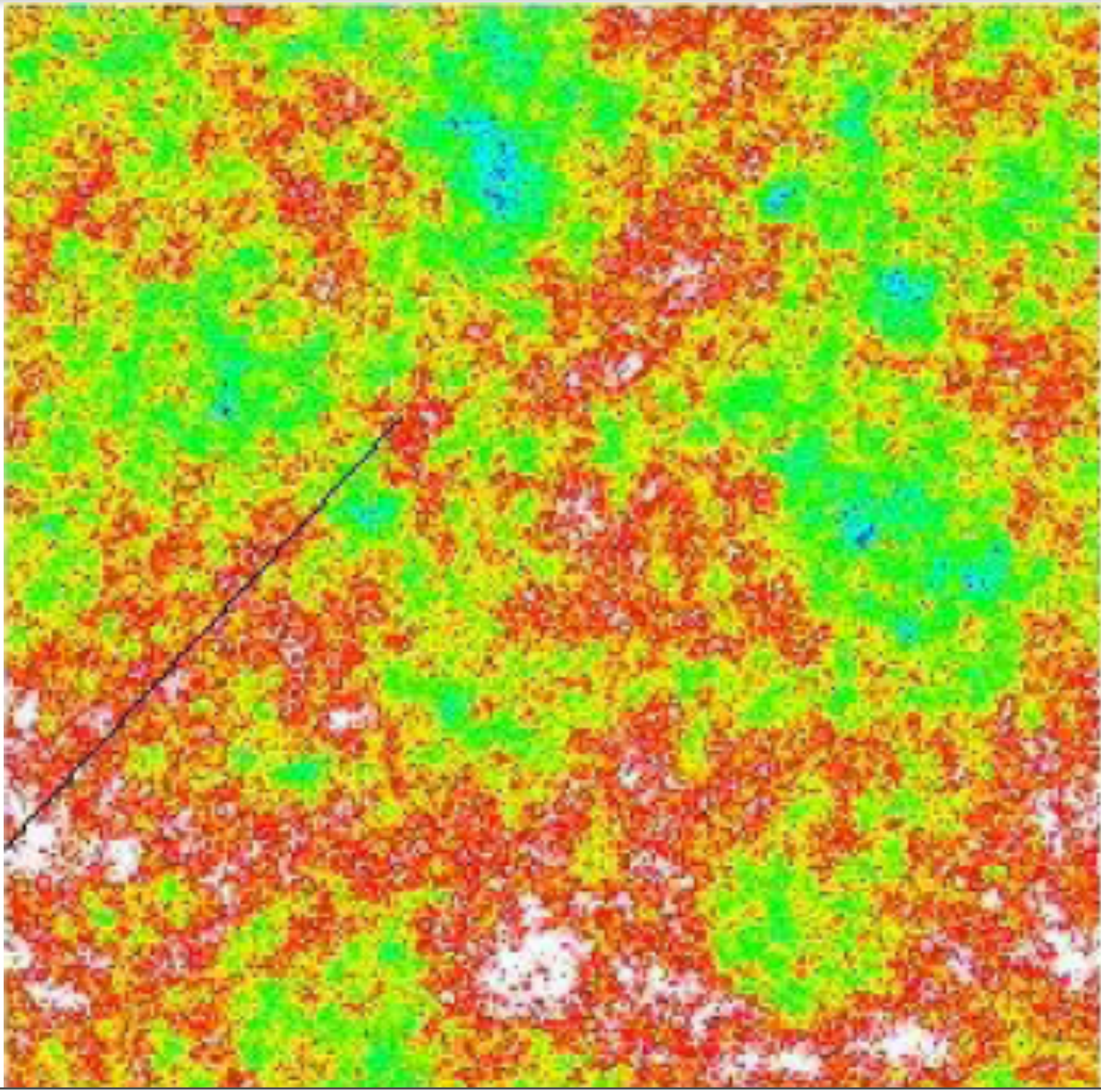






fluctuations in the **early universe "vacuum" grow** to ***all*** **structure**

χ



patterns in the quantum jitter evolve under gravity

(& gas dynamics)

pre-heating patch (~1cm)

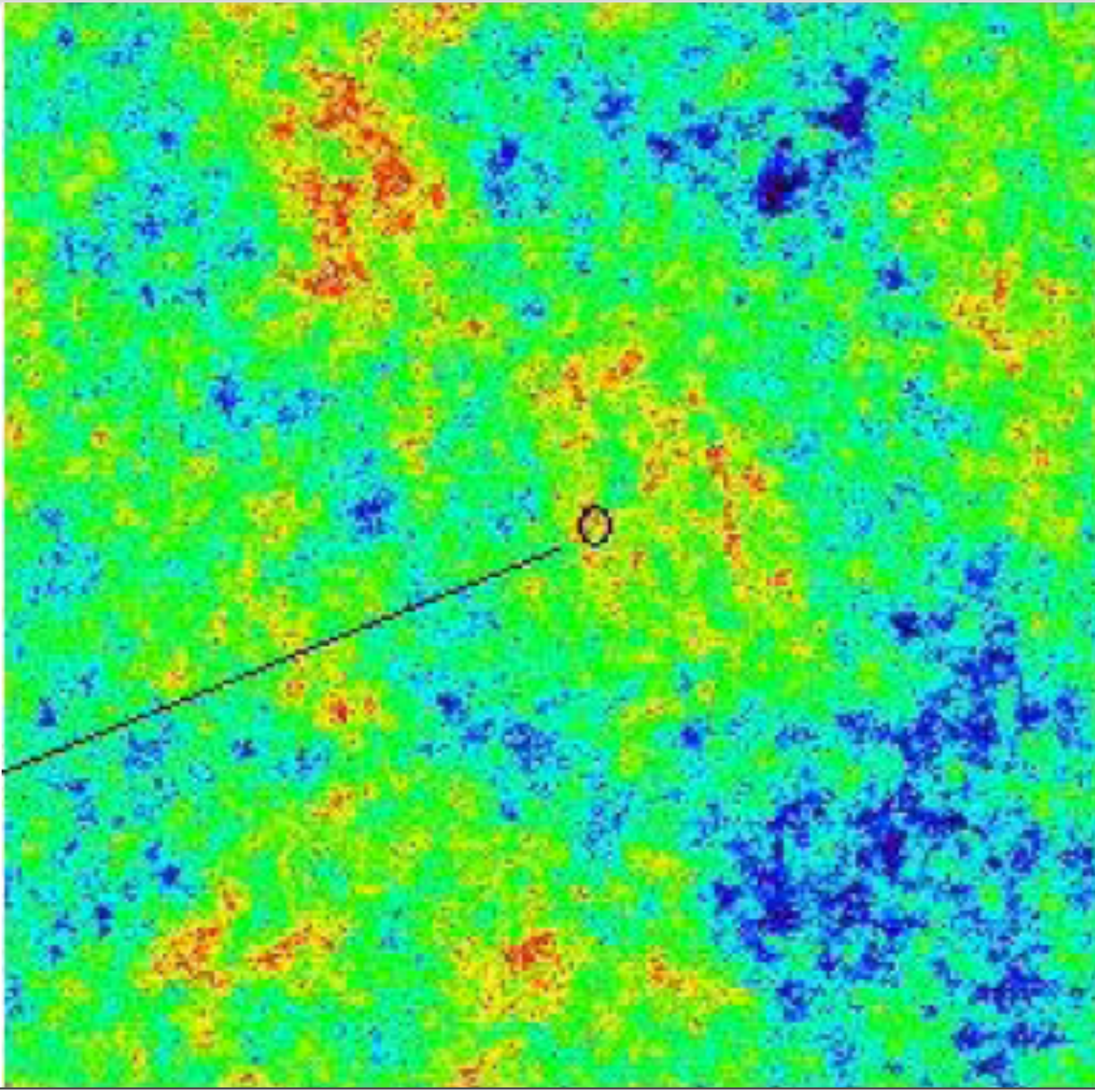
10 Gpc

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

χ

current Hubble patch ~10 Gpc

speed limit horizon

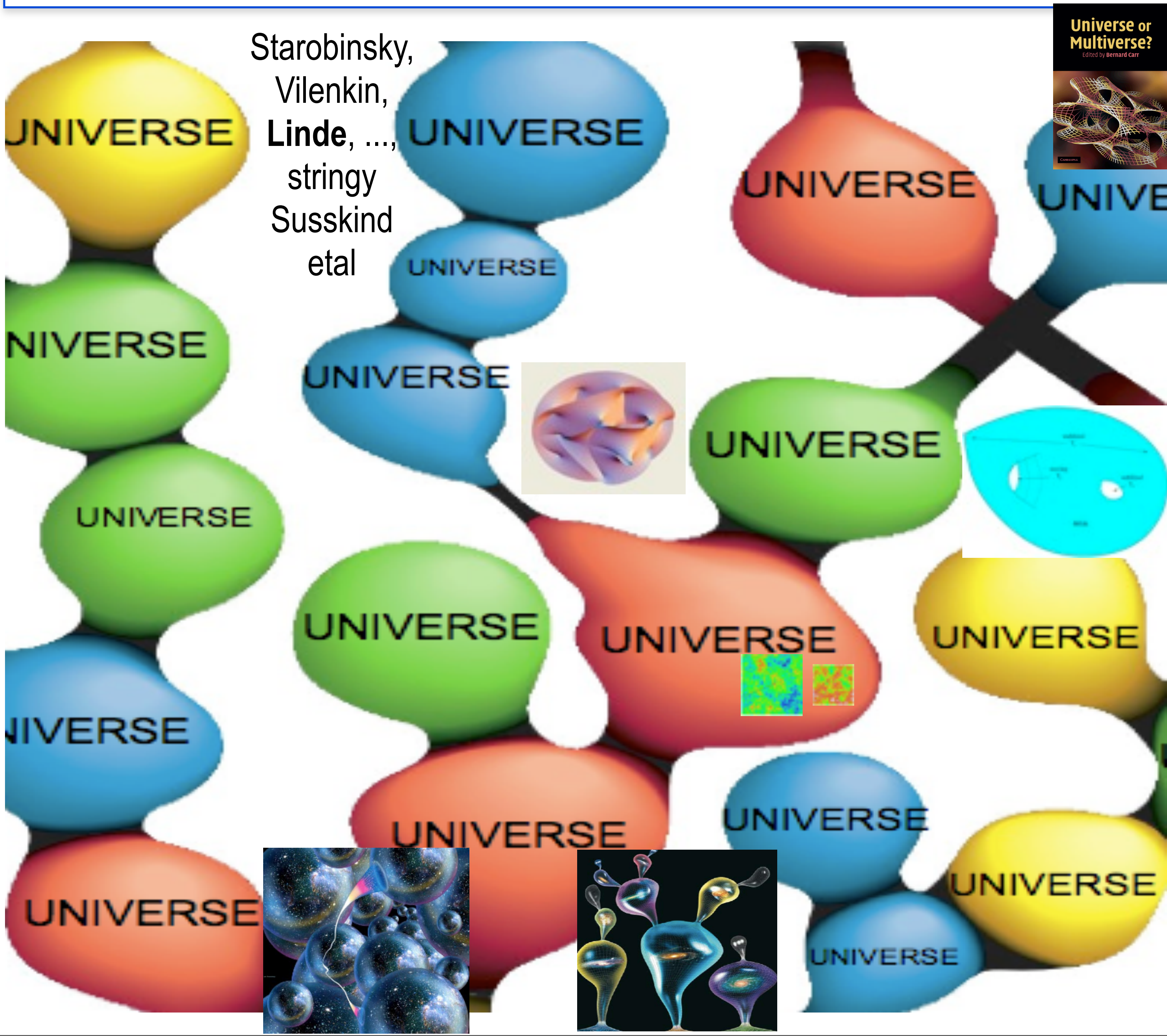


patterns in the quantum jitter evolve under gravity

(& gas dynamics)

1000 Gpc

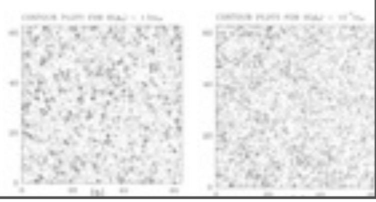
the **quantum stochastic non-G landscape** cf. the **stringy landscape**



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 $H_i \sim 10^{-5} m_p$**

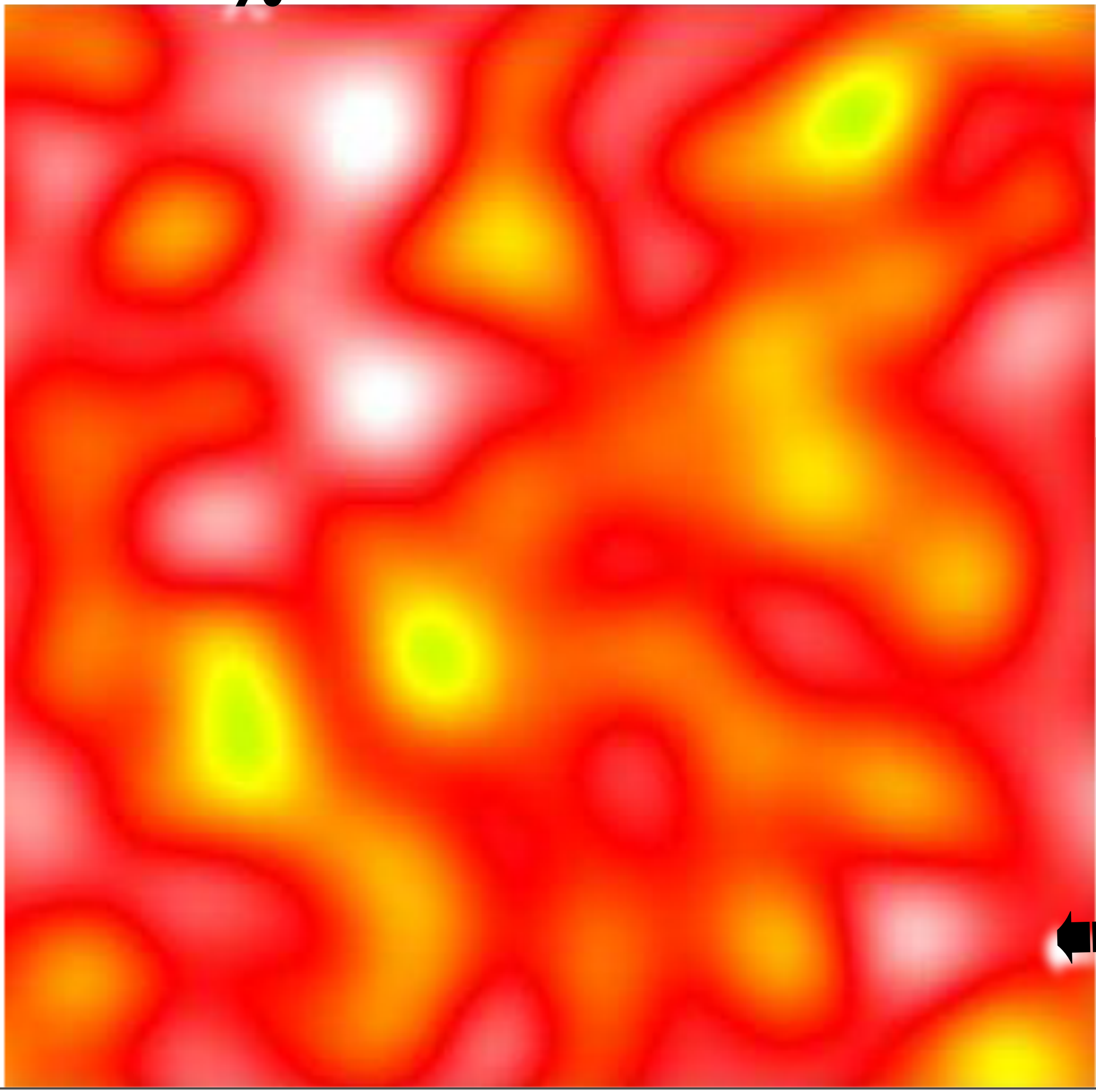
asymptotic flat eternal inflation V has similar behaviour

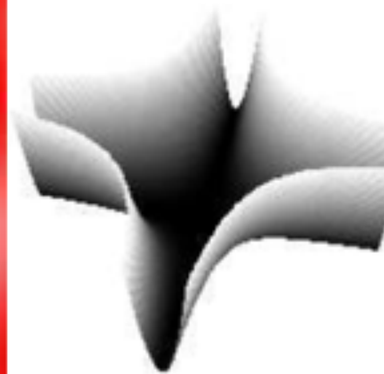


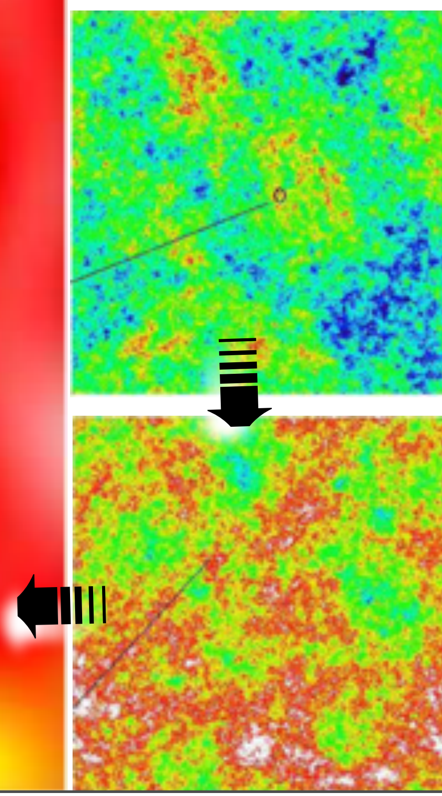
ϕ inflaton χ isocon $V(\phi,\chi) = 1/4\ \lambda\ \phi^4 + 1/2\ g^2\ \phi^2\ \chi^2$

Parametric Resonance

$g^2/\lambda \sim 1$







pre-heating patch (~1cm)

end of inflation @$\varepsilon=1$
through **preheating**

(linear resonance, nonlinear backreaction $\delta\psi,\delta\chi$)

to thermal equilibrium

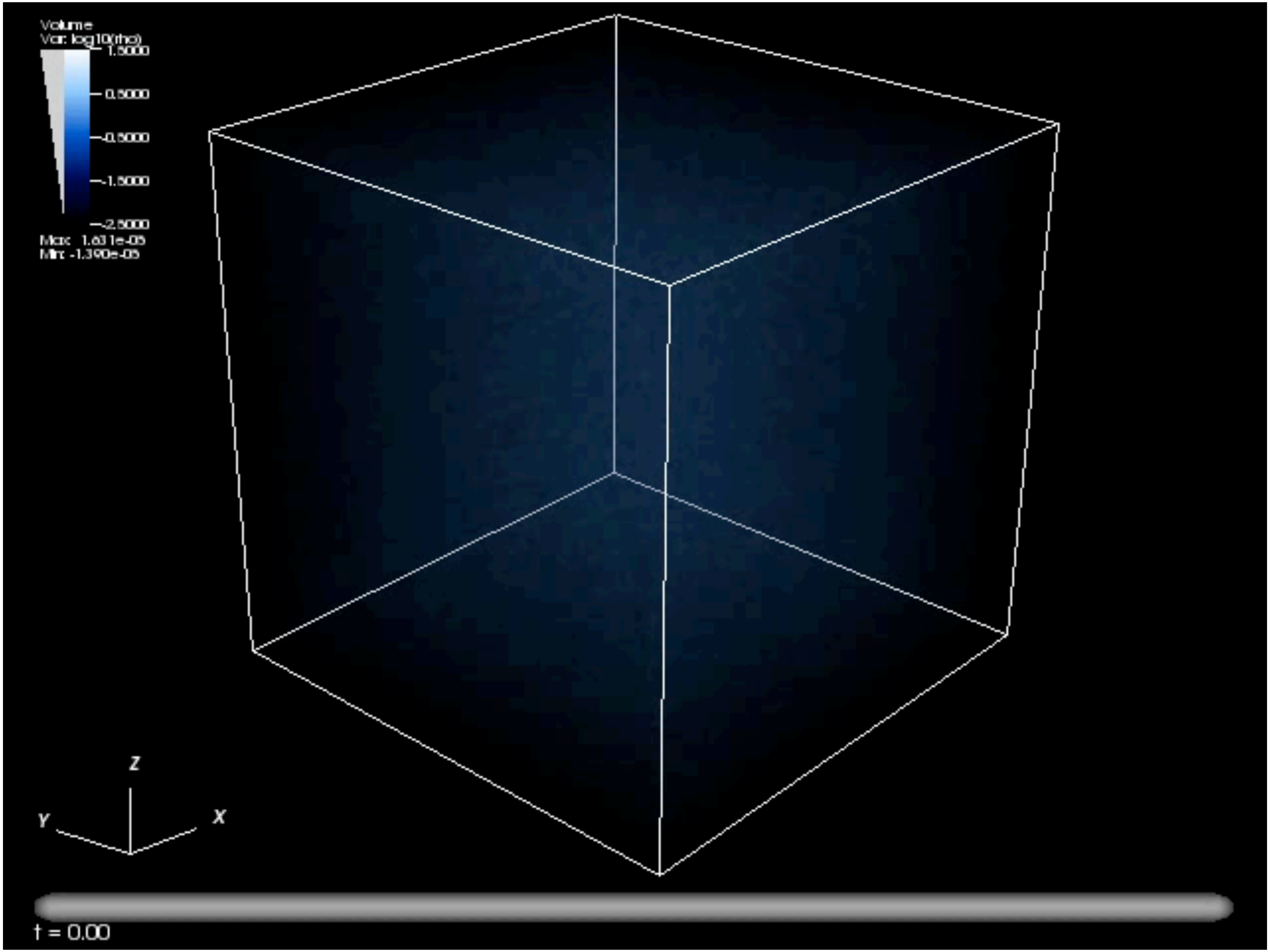
$$ln(n_k^{-1}+1) \Rightarrow k/T, \ \rho_k \sim E_k(n_k+1/2)$$

from coherent "background" field with nearly-Gaussian linear fluctuations to incoherent heat bath through a turbulence-like cascade: development of complexity: information (multi-scale entropy) *bond,* ***braden*** *& frolov 2011*

@ $k>H_{end}^{-1}$

=> no effect on k-observed? BUT relics (e.g., strings, isocons), HF gravity waves (kHz-GHz cf. 10^{-19}Hz), isocon modulation & non-Gaussianity

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

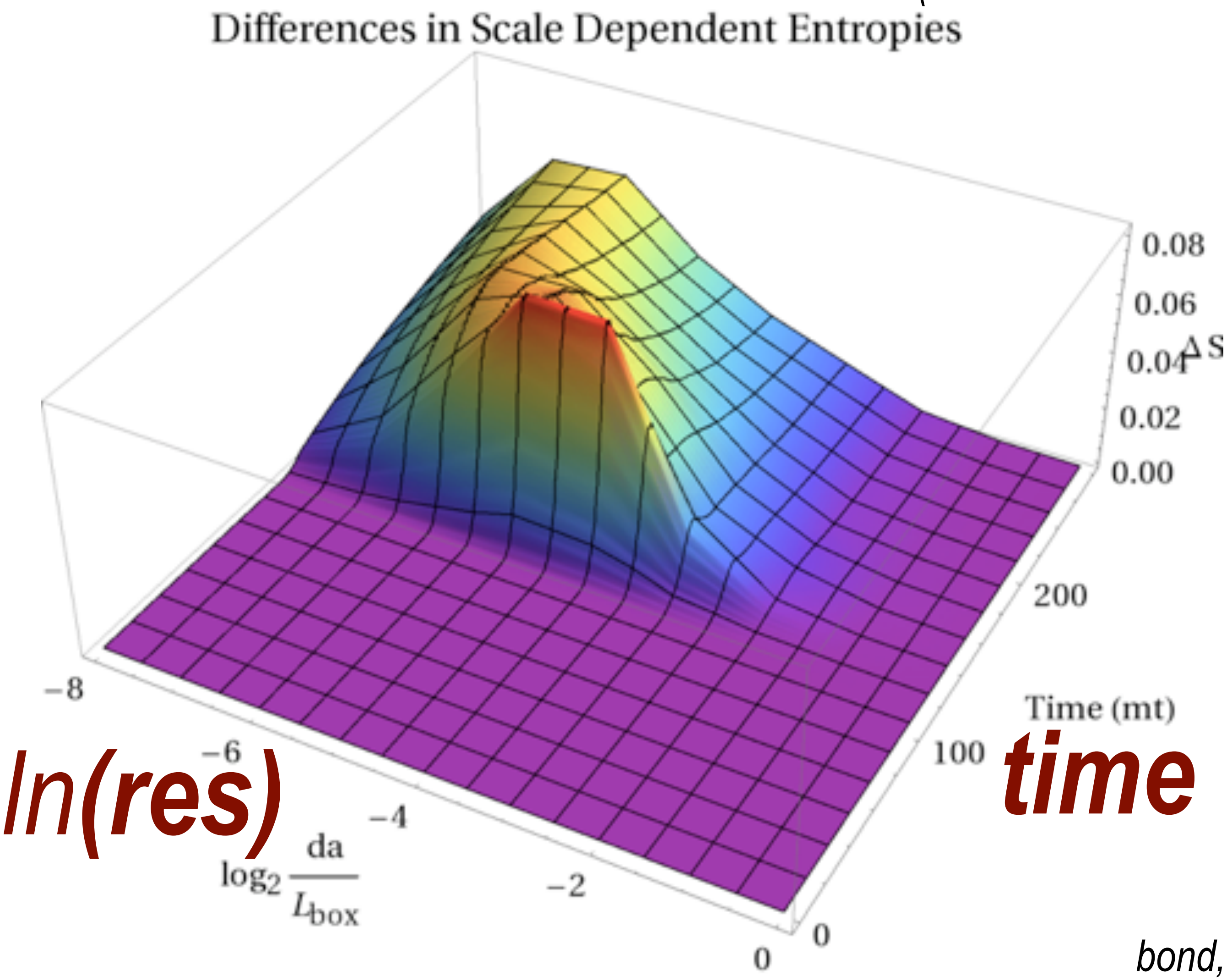


information content as a function of **scale** in the lattice ***=multi-scale entropy***

$$S(\text{res-scale}) = -\int dv\, \rho_s/E\, [\ln(\rho_s/E) - C], \text{ with } \int dv\, \rho_s/E = 1$$

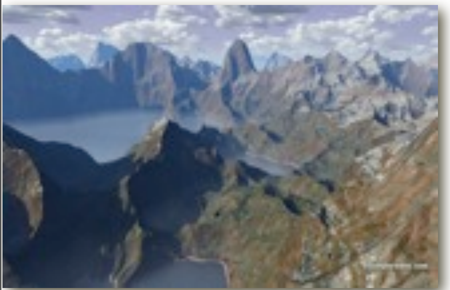
ρ_s ***energy density smoothed on a hierarchy of resolutions***

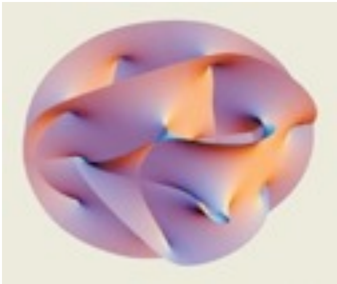
("Wilsonian renormalization group" block-smoothing)



bond, jonathan ***braden*** *& frolov 2011*

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

Balasubramanian, Berlund, Conlon, Quevedo, · · ·

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

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

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

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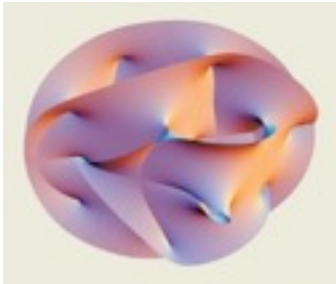

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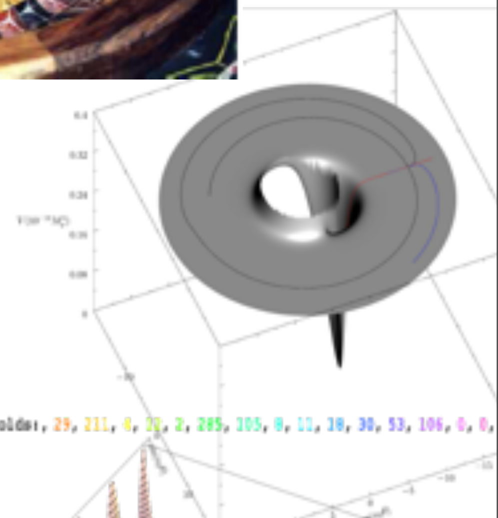

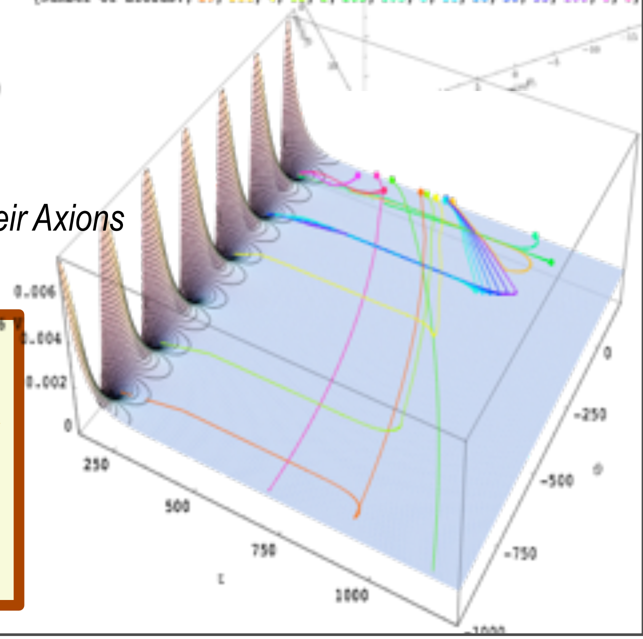

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theory prior ~ probability of trajectories given potential parameters of the collective coordinates X probability of the potential parameters X probability of initial conditions

Barnaby, Bond, Huang, Kofman 2009

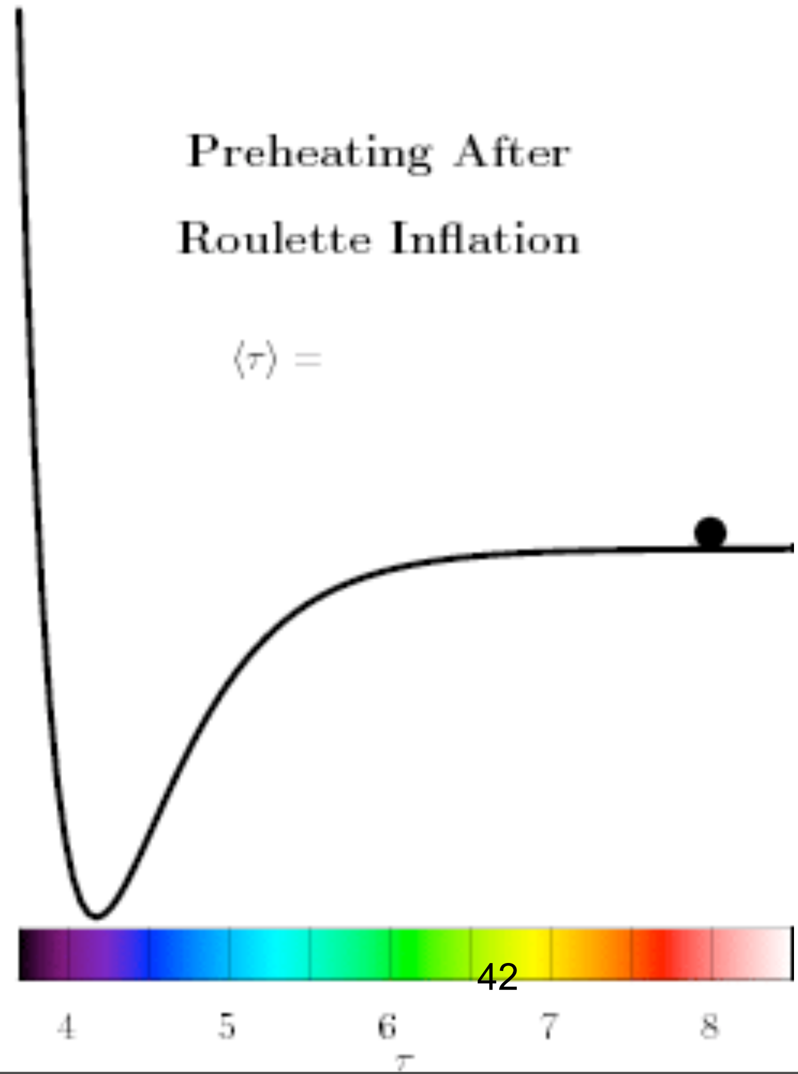
Preheating After Roulette Inflation

pre-heating patch (<1cm)

HLattice code: arbitrary number of fields, hybrid symplectic, to ~ trillionth accuracy!
Huang 2011 added full metric back action

$a = \quad 1$

A visualized 2D slice
in lattice simulation



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

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

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

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

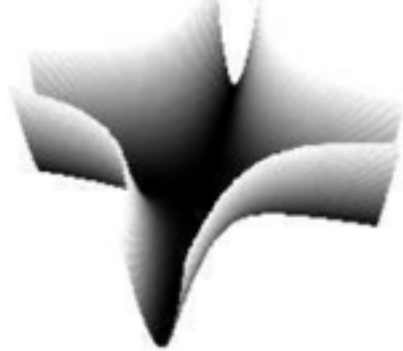
$\Phi(x) = \Phi_G(x) + F_{NL}(\chi_b) - \langle F_{NL} \rangle$

resonant preheating

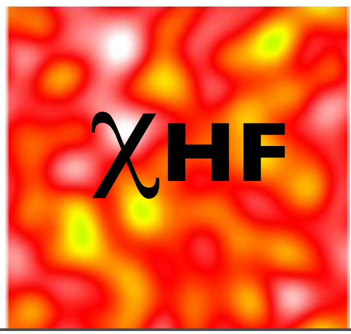
+ subdominant

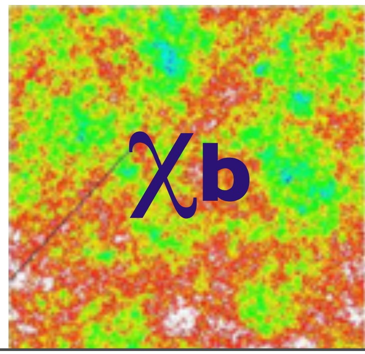
isocurvature, cosmic string,

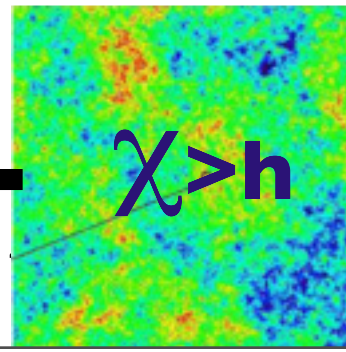
& fgnds, tSZ,kSZ, ...



$$\chi(x,t) = \chi_{HF} + \chi_{b} + \chi_{>h}$$



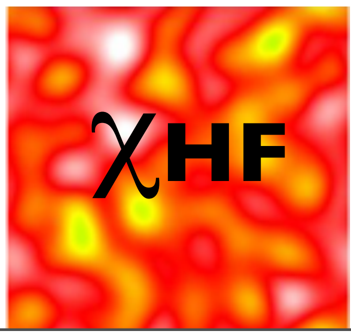




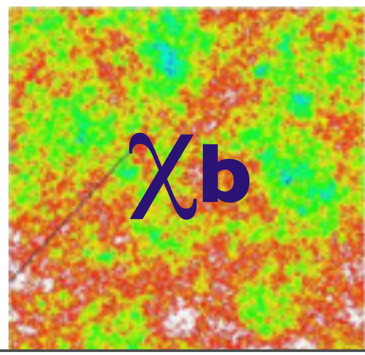
curvature $F_{NL}(\chi(x,t)) = \delta \ln a|_H (\chi_i)$

highly nonlinear function of a Gaussian random 'isocon' field

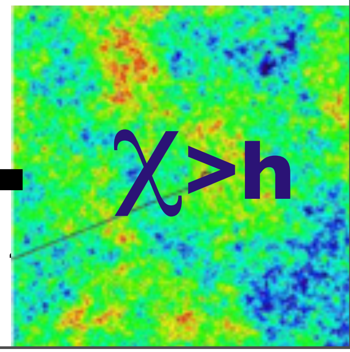
$\chi(x,t) =$



+

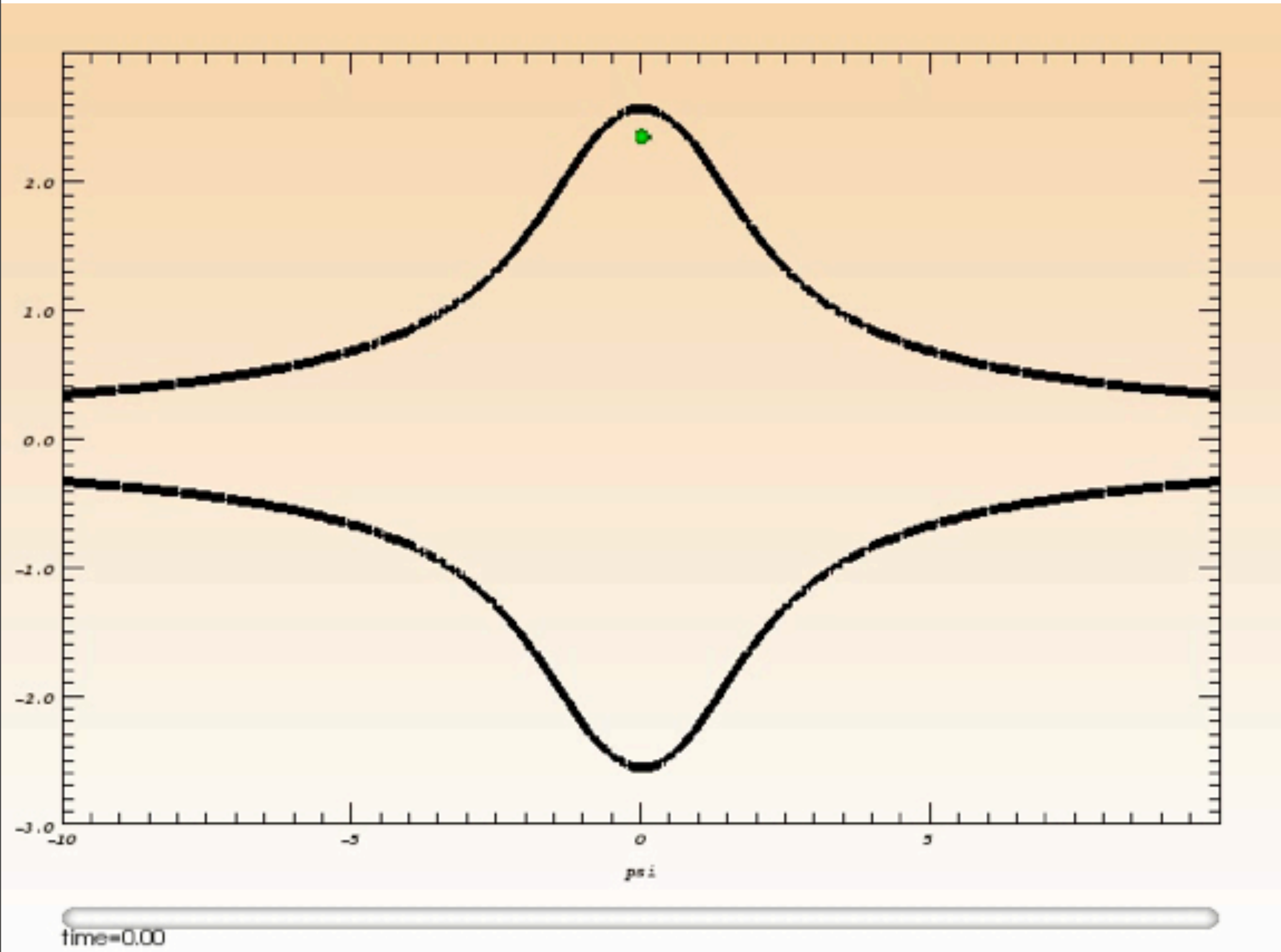


+



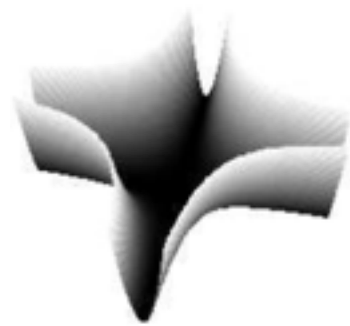
calculate $\delta \ln a [\chi_i(x,t)]$ *from* $\varepsilon=1$ *(end of inflation)* ***through preheat***
(copious mode-mode-coupling aka particle creation) ***to thermal equilibrium***

Bond, Andrei Frolov, Zhiqi Huang, Kofman 09



linear regime of zero-modes:
$\phi_0(t+T) = \phi_0(t)$
$\chi_0(t+T) = \chi_0(t) \exp[\mu_0 T]$
$\Rightarrow$ ***spikes are***

log χ_i ***spaced***

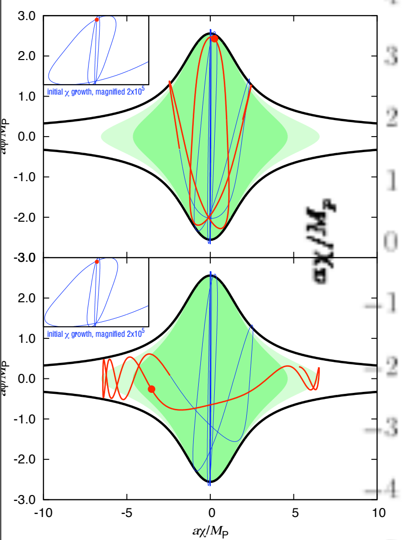


Wednesday, February 9, 2011

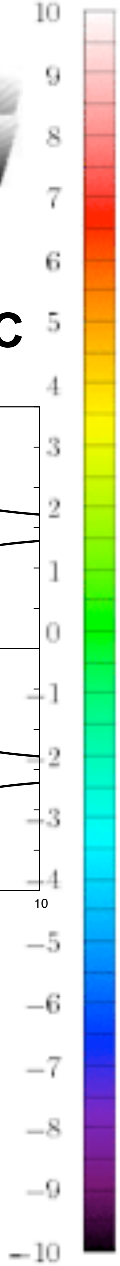
Cosmic Chaotic Billiards: NonGaussianity from Parametric Resonance in Preheating

Bond, Andrei Frolov, Zhiqi Huang, Kofman 09

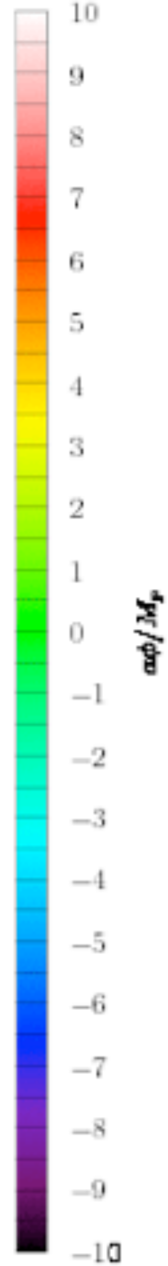
non-spike IC



spike IC



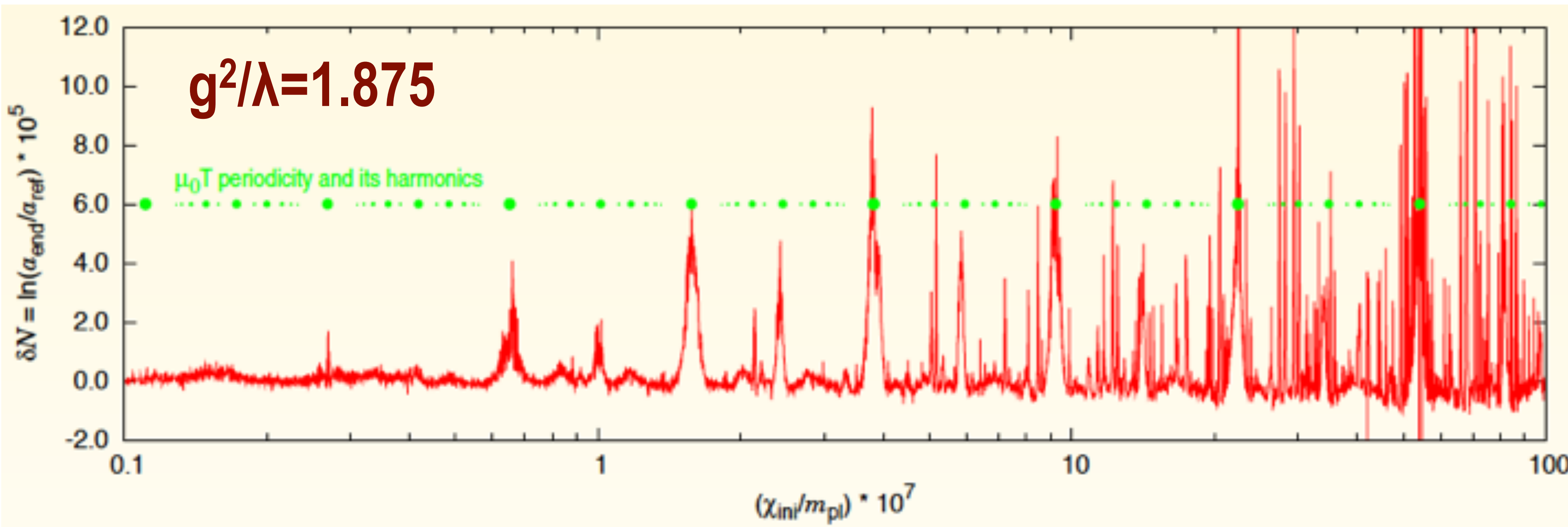
Preheating in model $V = \lambda\phi^4 + 1/2 g^2\phi^2\chi^2$



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

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

highly nonlinear function of a Gaussian random 'isocon' field



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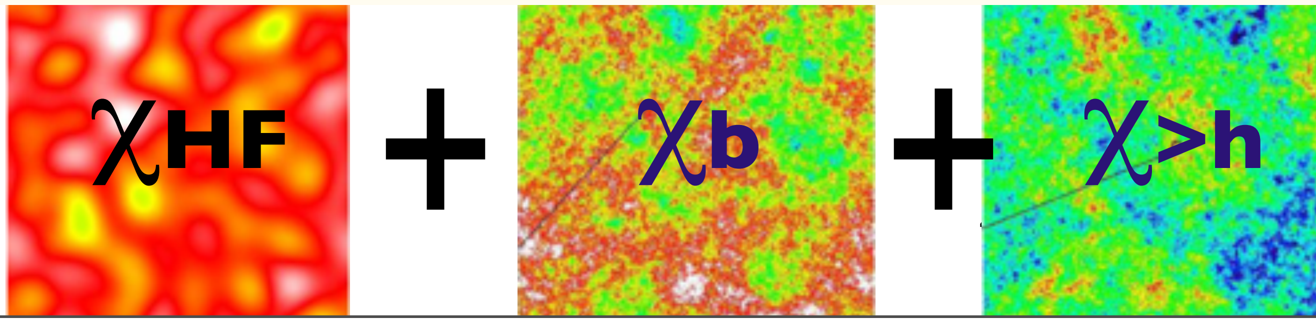
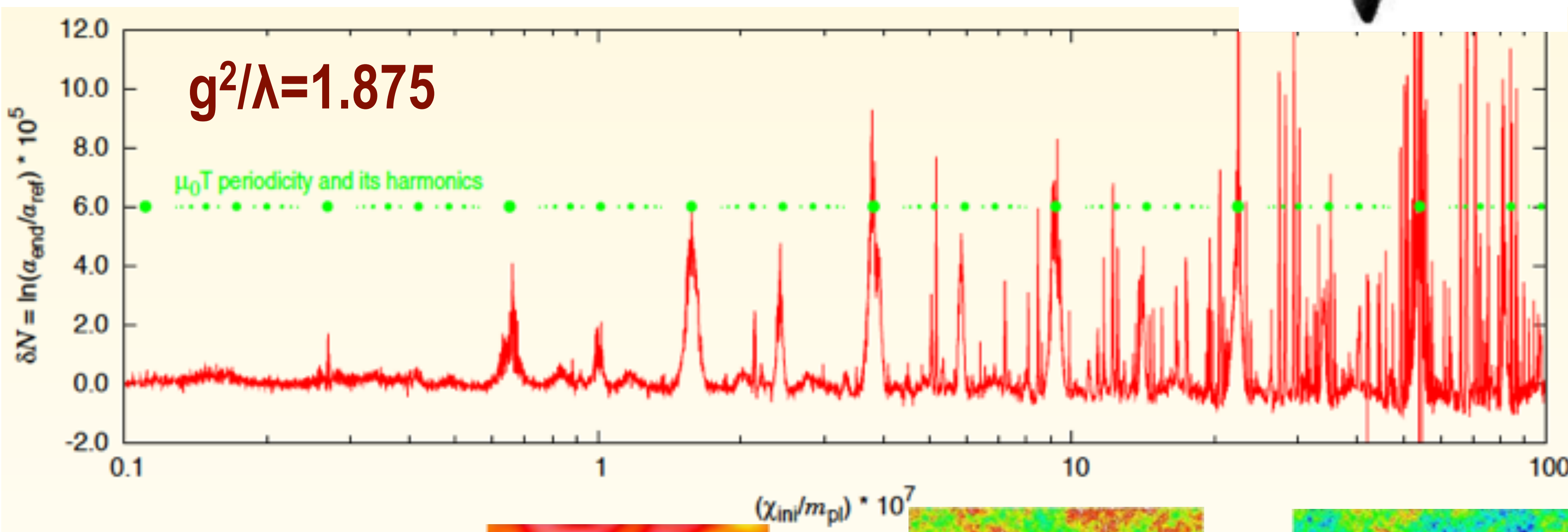


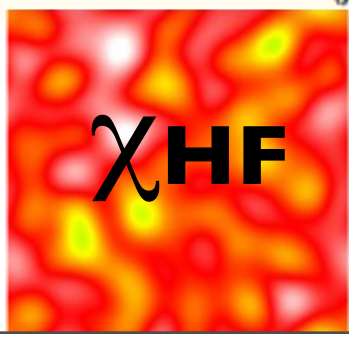
to develop the $ln\,a(\chi_i)$ response curve, we perform > 10^4 lattice simulations for each g^2/λ

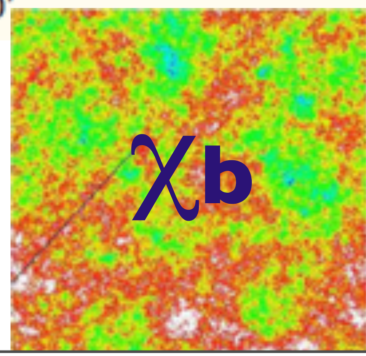
curvature $F_{NL}(\chi(x,t)) = \delta \ln a|_H(\chi_i)$

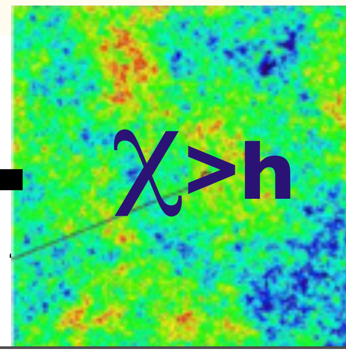
highly nonlinear function of a Gaussian random 'isocon' field



$\chi(x,t) = \chi_{HF} + \chi_b + \chi_{>h}$







Wednesday, February 9, 2011

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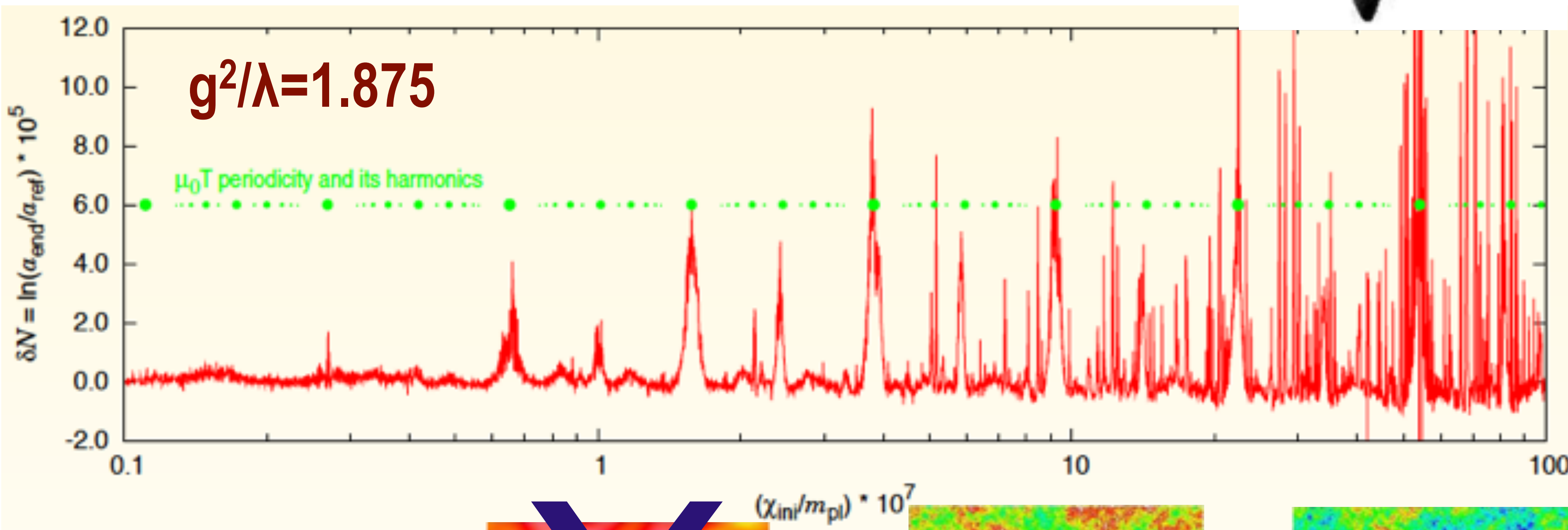
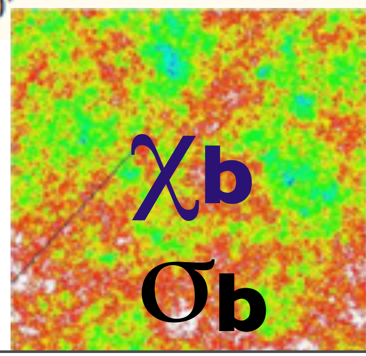


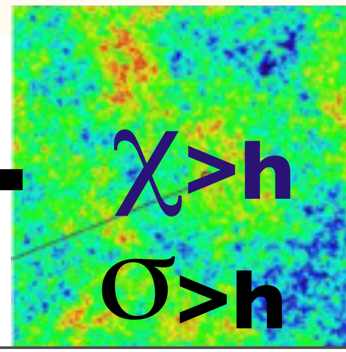
effective field theory

$\chi_{eff}(x,t) =$

+



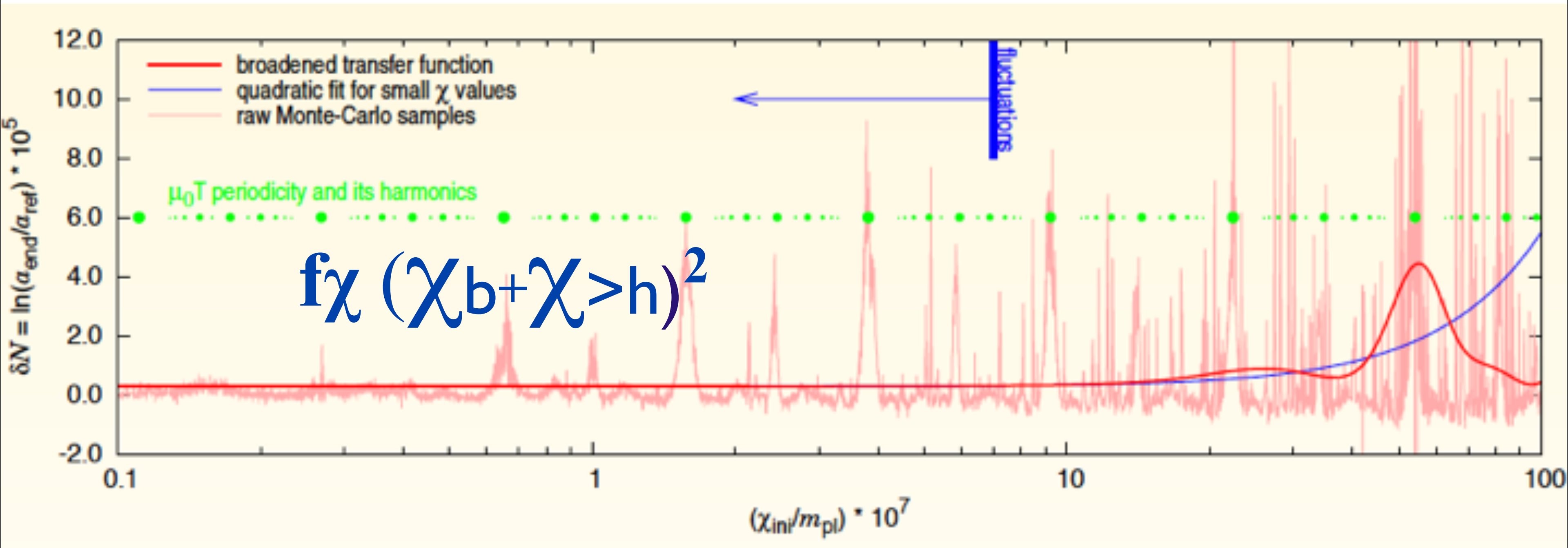
+



field smoothing over χ_{HF}

field smoothing over χ_{HF} over ~50 e-folds of HF structure

$$< F_{NL} | \chi_b + \chi_{>h} >$$

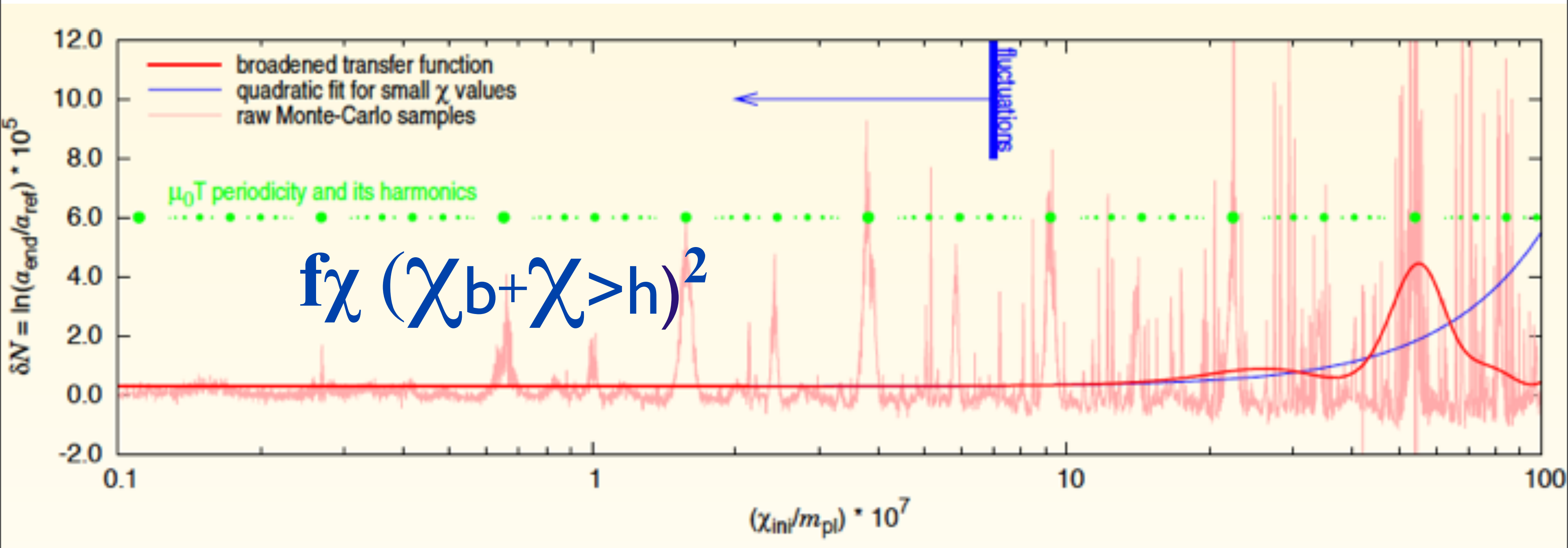


$$f_\chi \, (\chi_b + \chi_{>h})^2$$

field smoothing over χ_{HF} over ~50 e-folds of HF structure

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

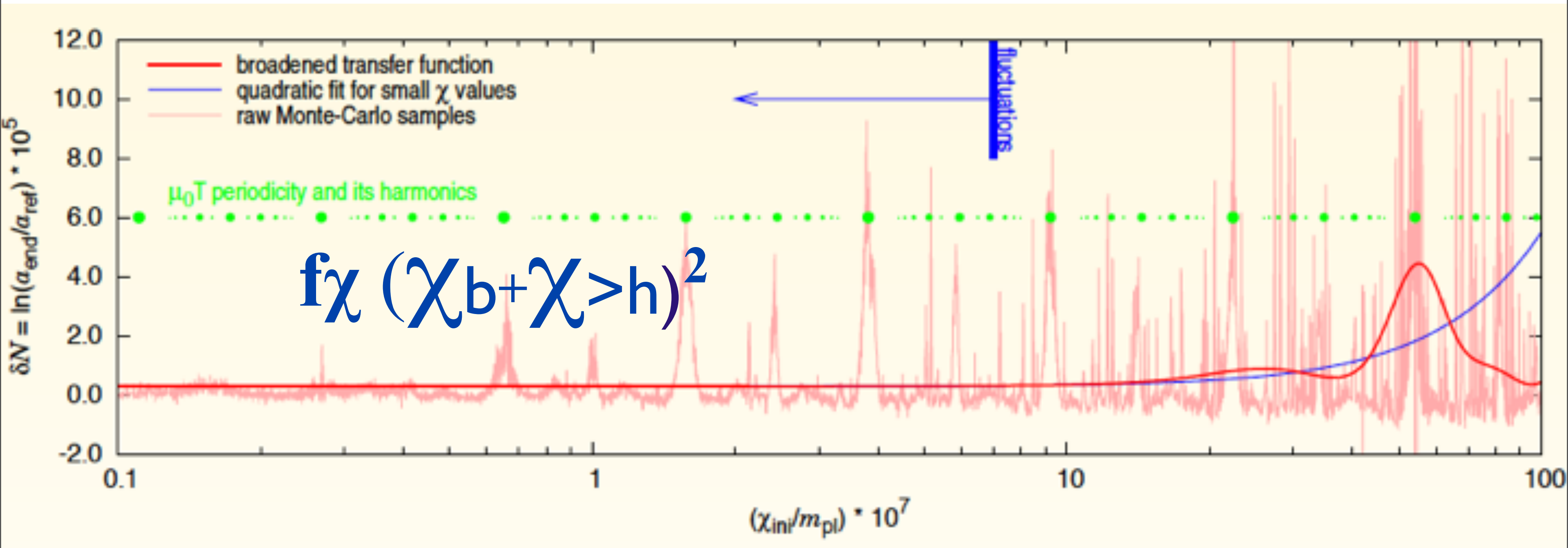
cf. $\Phi(x) = \Phi_G(x) + f_{NL}\,\Phi_G^2(x)$



field smoothing over χ_{HF} over ~50 e-folds of HF structure

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

cf. $\Phi(x) = \Phi_G(x) + f_{NL}\,\Phi_G^2(x)$



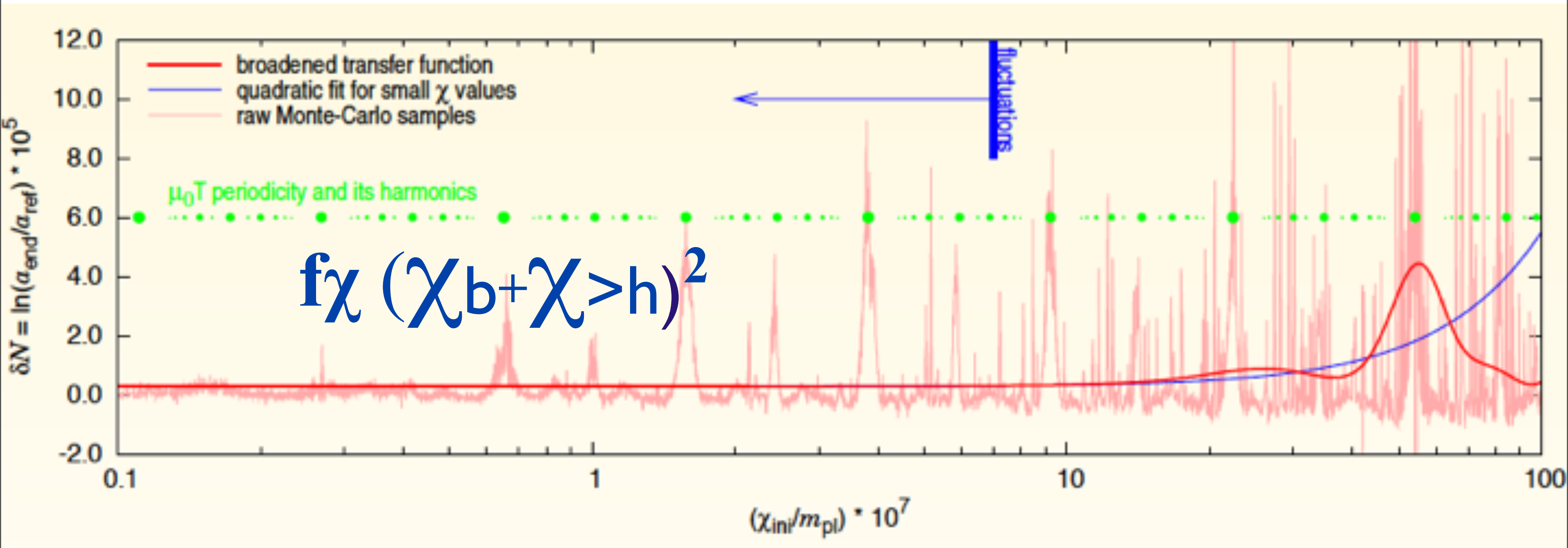
$$f_{NL}^{equiv} = \beta^2 f_\chi\,[P_\chi/P_\phi]^2(k_{pivot})$$

=> constrain $f_\chi^3\,\chi_{>h}^2$ ($P_\chi/P_\phi \sim 2\varepsilon$ => *relaxed limit)*

field smoothing over χ_{HF} over ~50 e-folds of HF structure

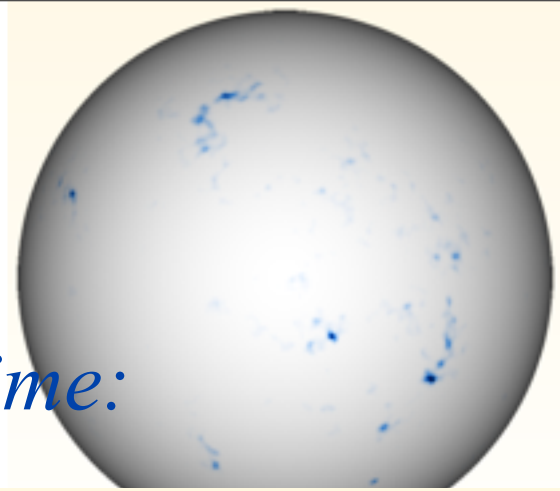
$$< F_{NL} | \chi_b + \chi_{>h} > \sim \beta(\chi_{>h})\, \chi_b + f(\chi_{>h})\, \chi_b^2 + \ldots$$

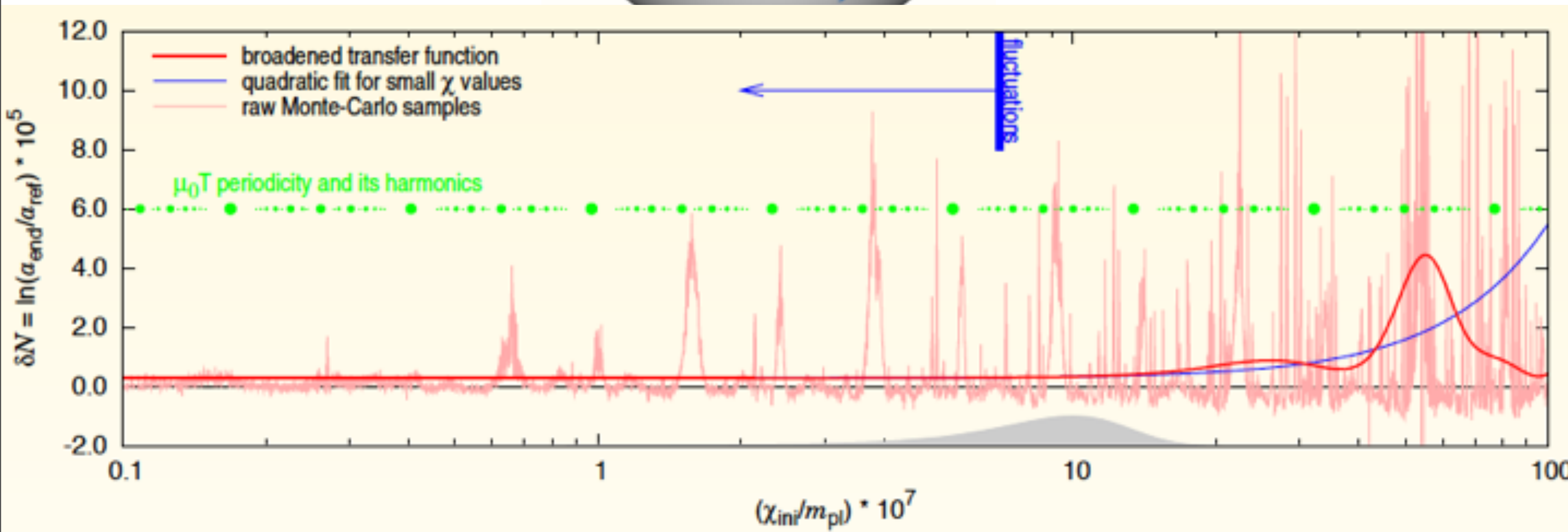
cf. $\Phi(x) = \Phi_G(x) + f_{NL}\, \Phi_G^2(x)$



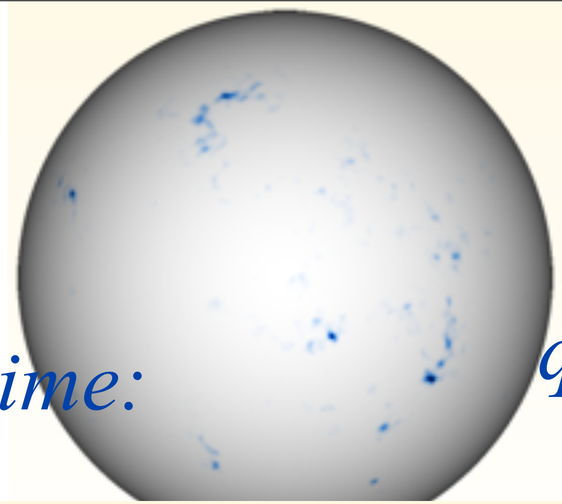
$f_{NL}^{equiv} = \beta^2 f_\chi\, [P_\chi / P_\phi]^2 (k_{pivot})$ **-4< f_{NL}<80 WMAP5 (± 5 Planck)**

=> constrain $f_\chi^3\, \chi_{>h}^2$ ($P_\chi/P_\phi \sim 2\varepsilon$ => *relaxed limit*) *medium χ>h regime:*



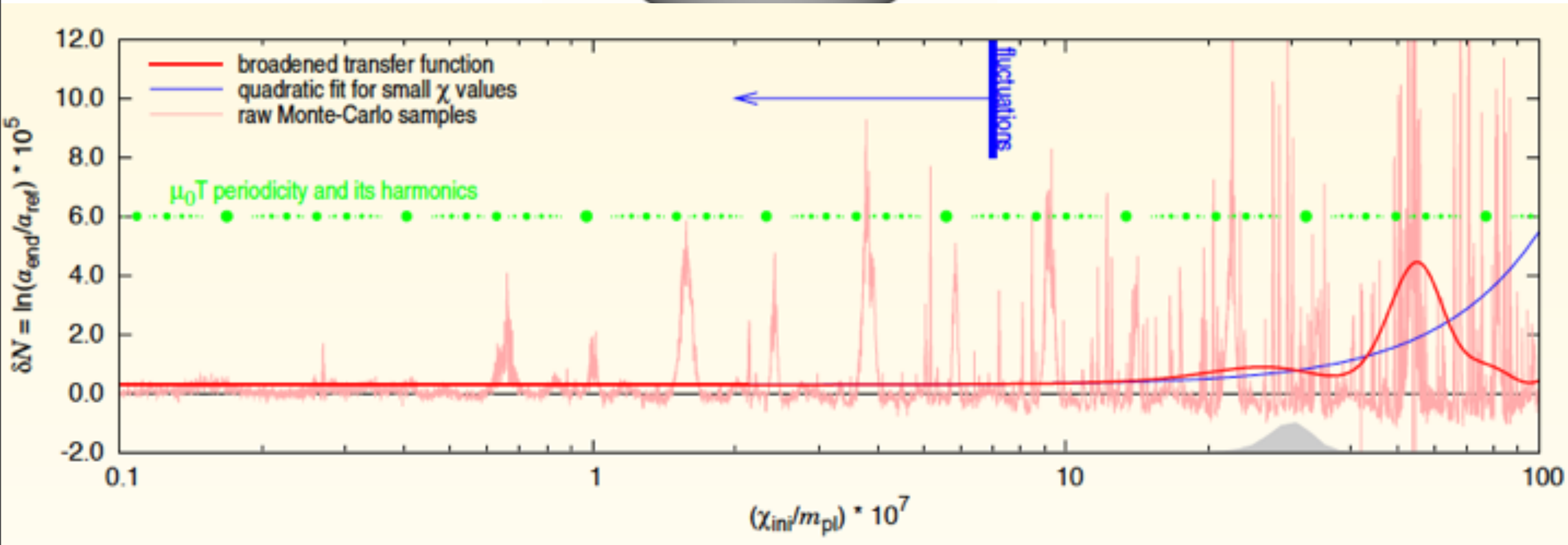


large-ish χ>h *regime:*

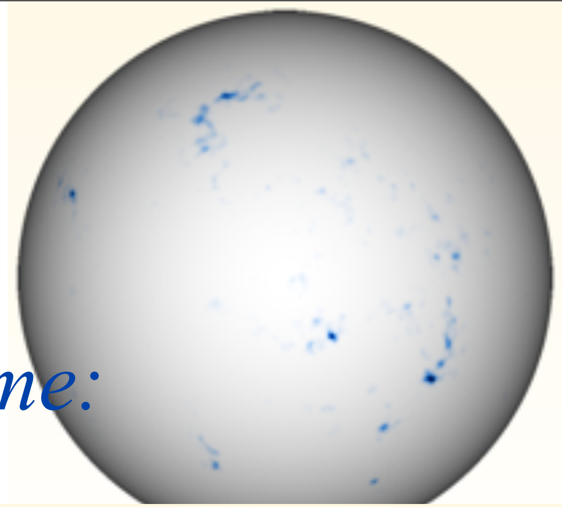


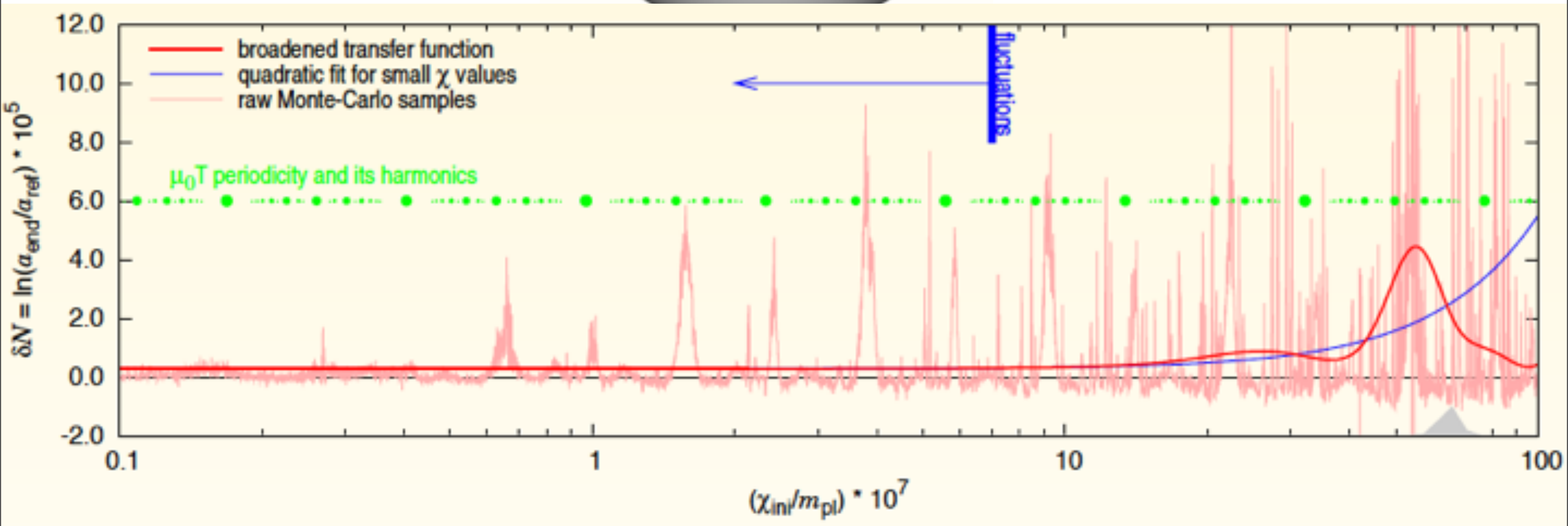
*quadratic+***cold spot**

"rare events"

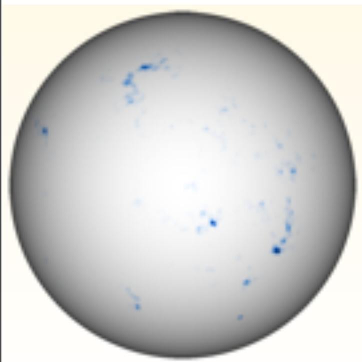


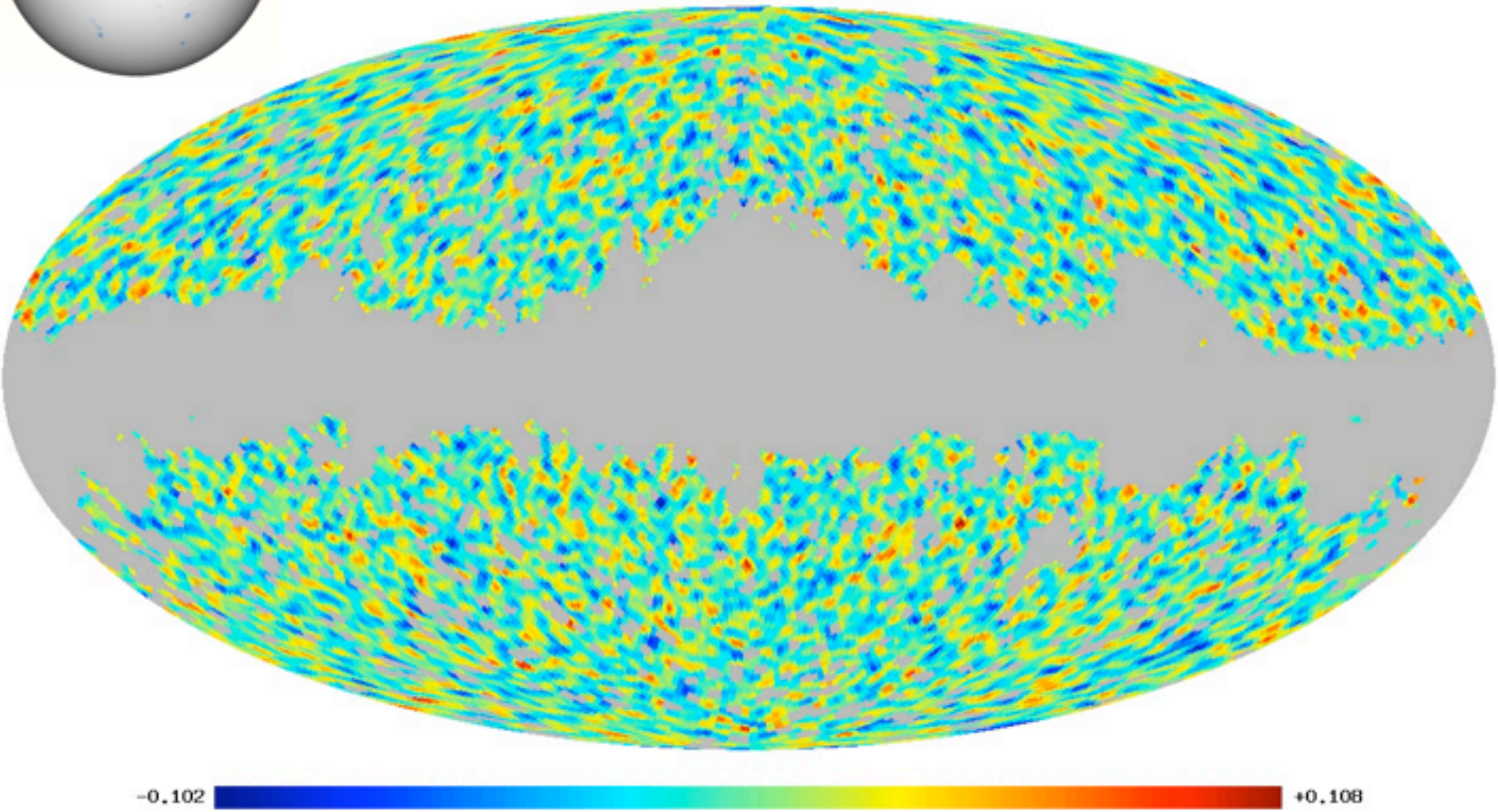
large χ>h *regime:*





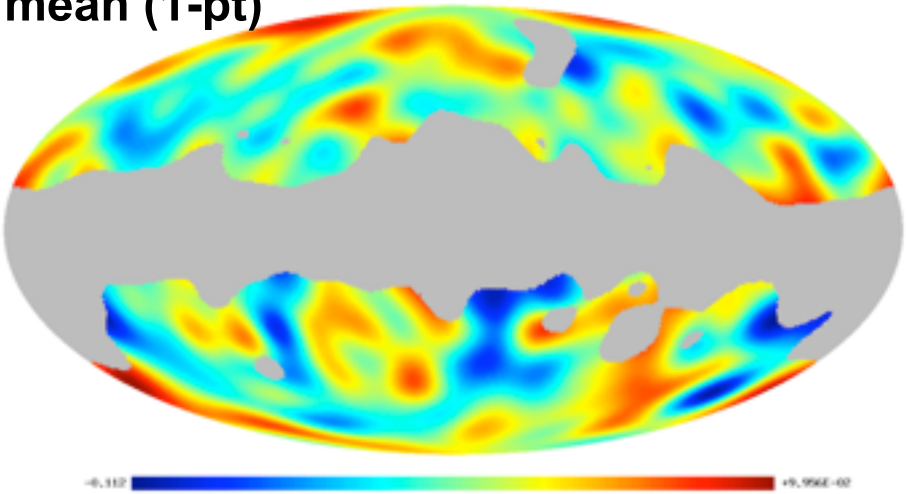
CMB peaks (hot&cold) => the WMAP Cold Spot



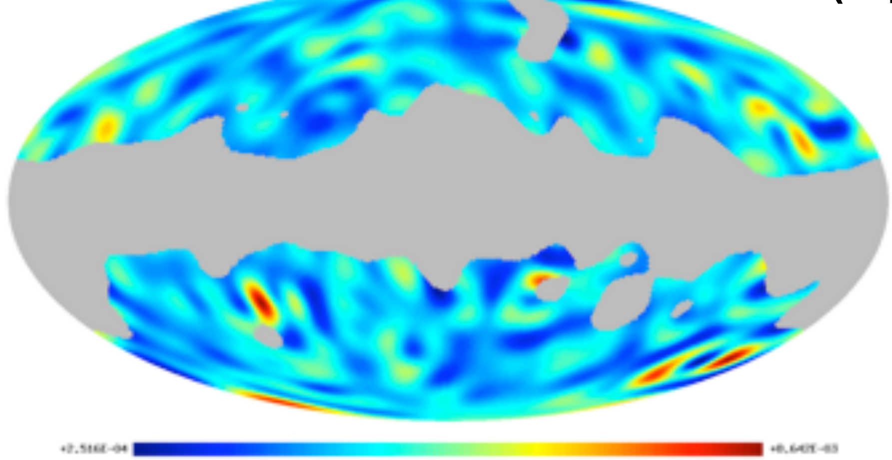


variable scale (SSG42) filtering sweep after pre-whitening the CMB signal (optimally weighting the signal is similar)

mean (1-pt)

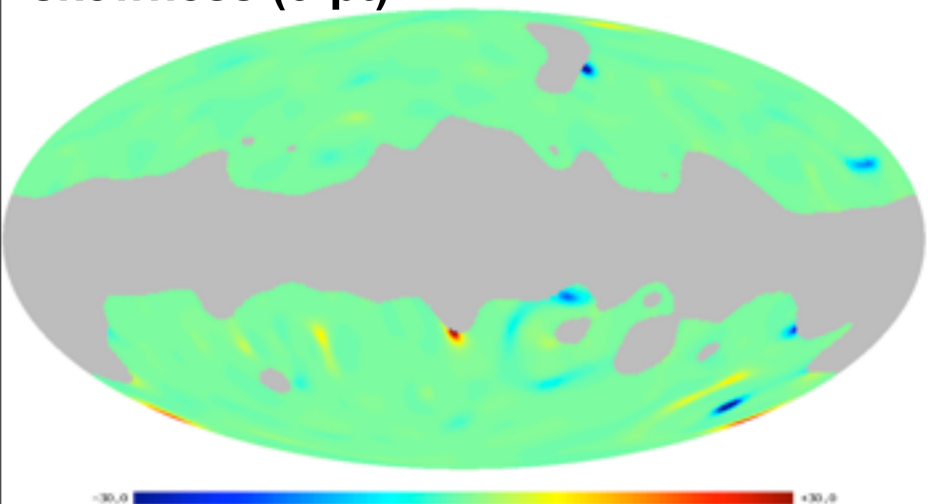


variance (2-pt)

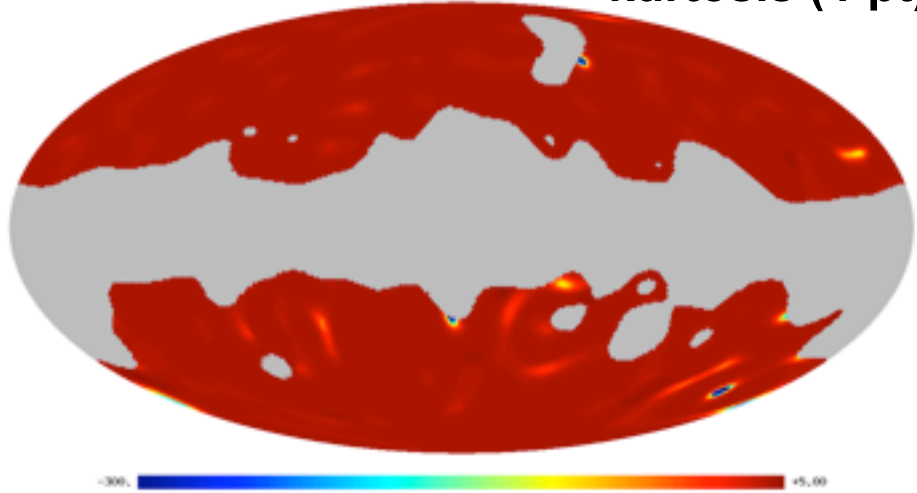


the WMAP Cold Spot dominates skewness (3-point) & kurtosis (4-point) maps

skewness (3-pt)



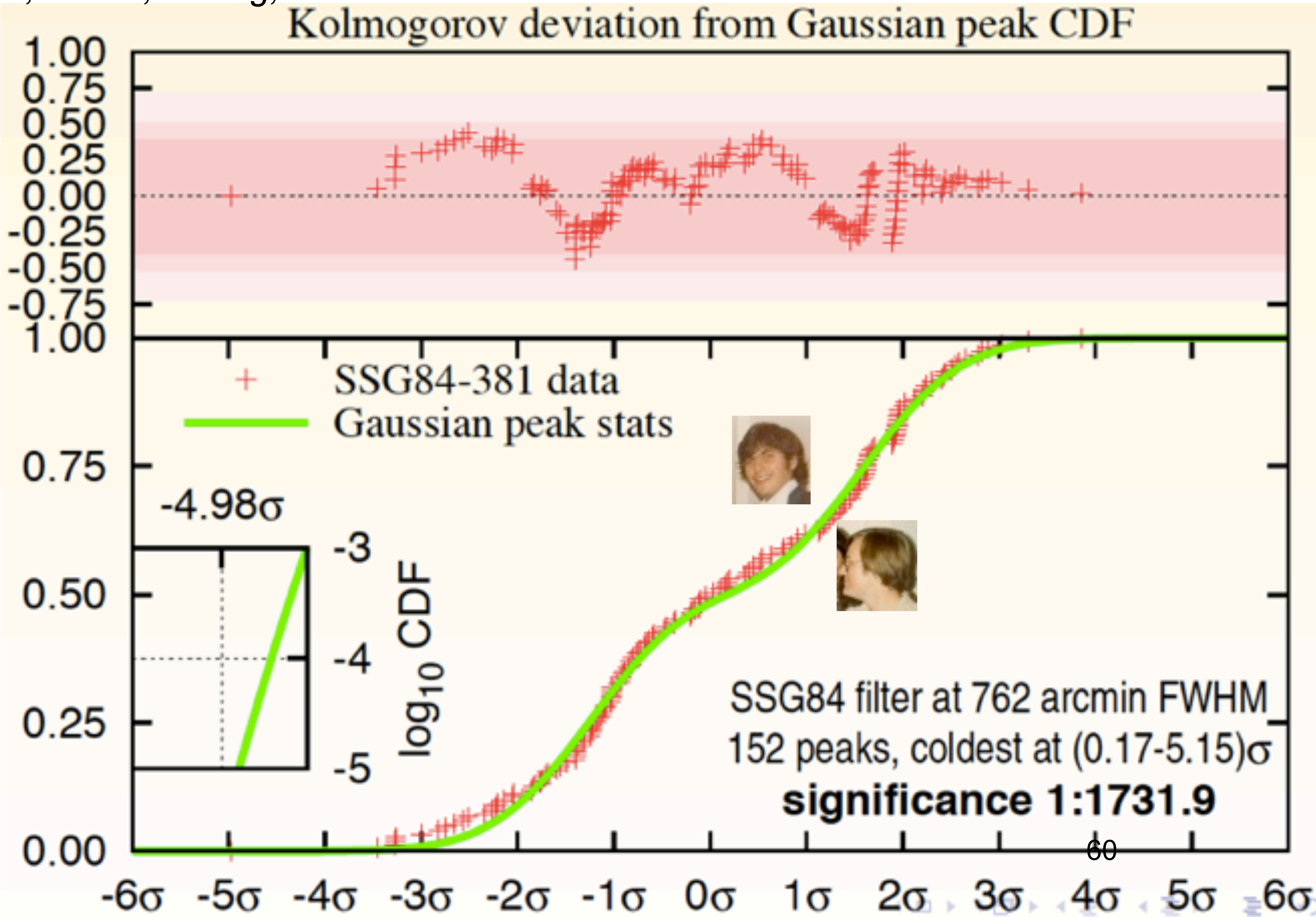
kurtosis (4-pt)



SSG84 381 arcmin HWHM filter-band maps, on scales where the cold spot is a maximum. the skewness & kurtosis are band-averages of the bispectrum & trispectrum. implications of intermittency for fNL determinations TBD?

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, Nolta 11



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%

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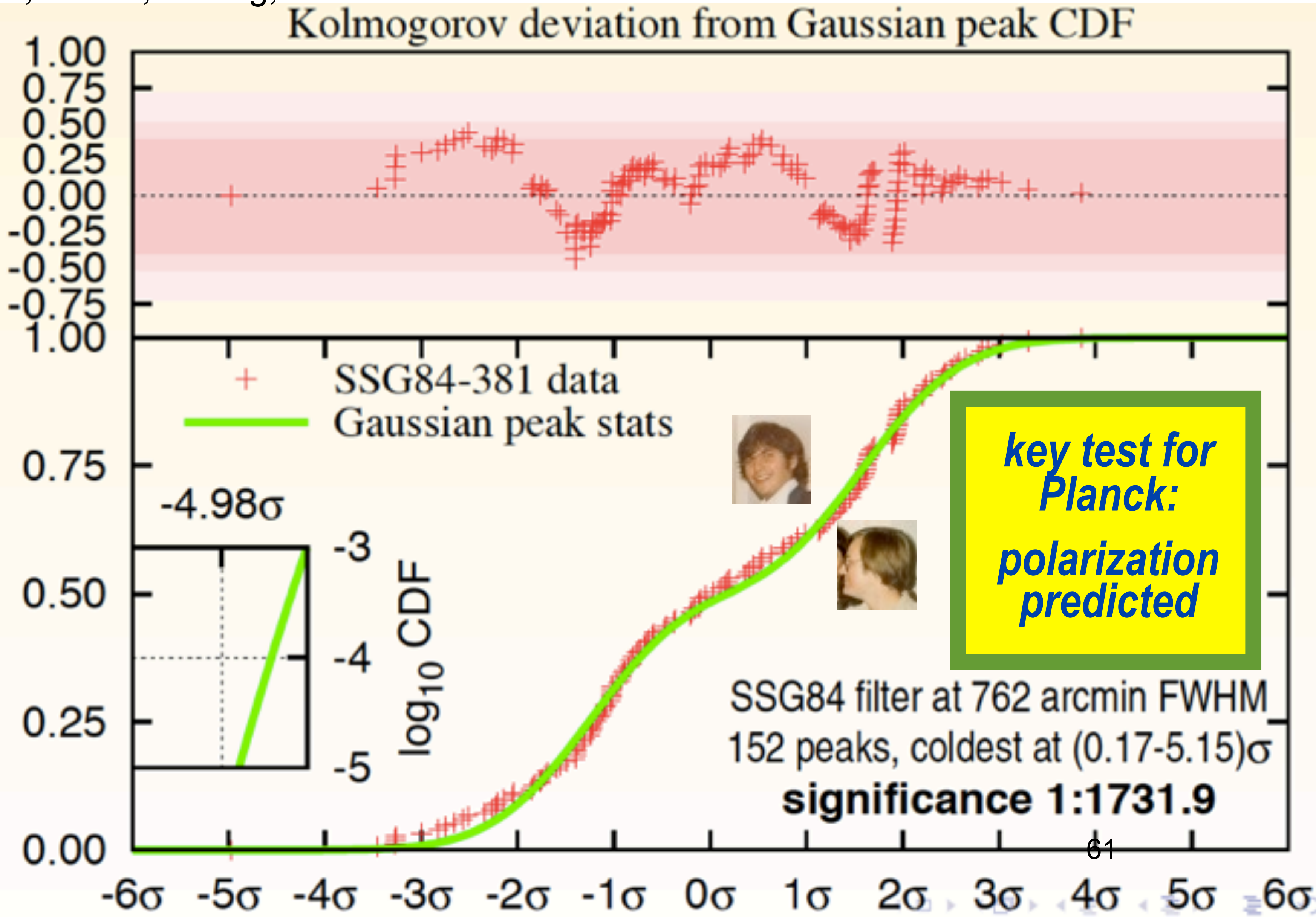


Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ 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

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

& $\ln P_t(\ln k)$

$\varepsilon_\phi \times 2/3 = 1 + w_{de}(a)$

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

+ subdominant isocurvature, cosmic string,

& fgnds, tSZ,kSZ, ...

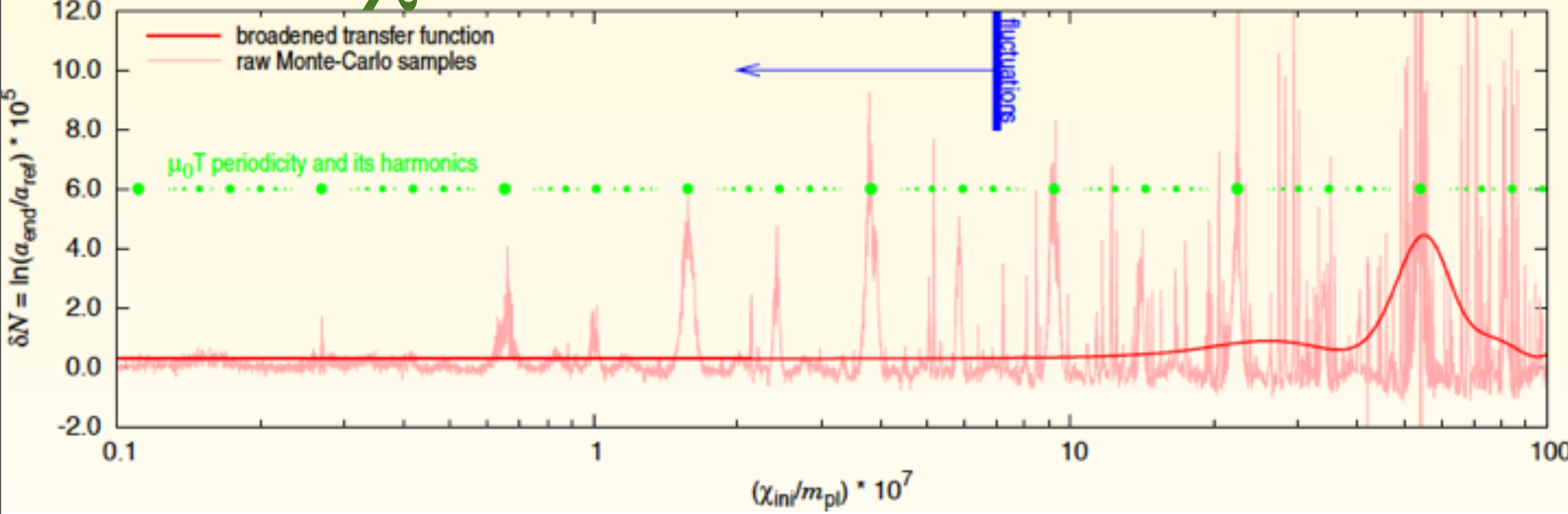
end

field smoothing over χ_{HF} σ_{HF} ~7x10^{-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: σ_b ~5x10^{-7} ~10 e-folds

LSS χ_b: σ_b ~3x10^{-7} ~10 e-folds



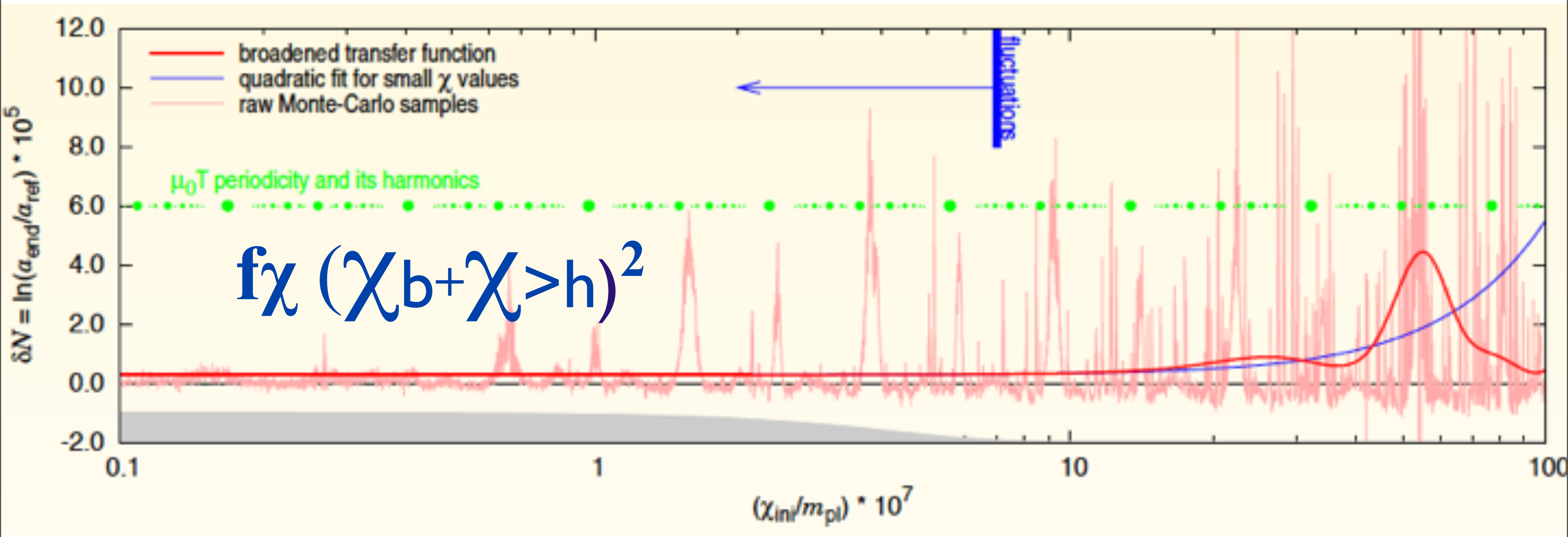
super-horizon $\chi_{>h}$: $\sigma_{>h}$ ~$N_{>h}^{1/2}$x10^{-7} $N_{>h}$~10^2-10^{4++}

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

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

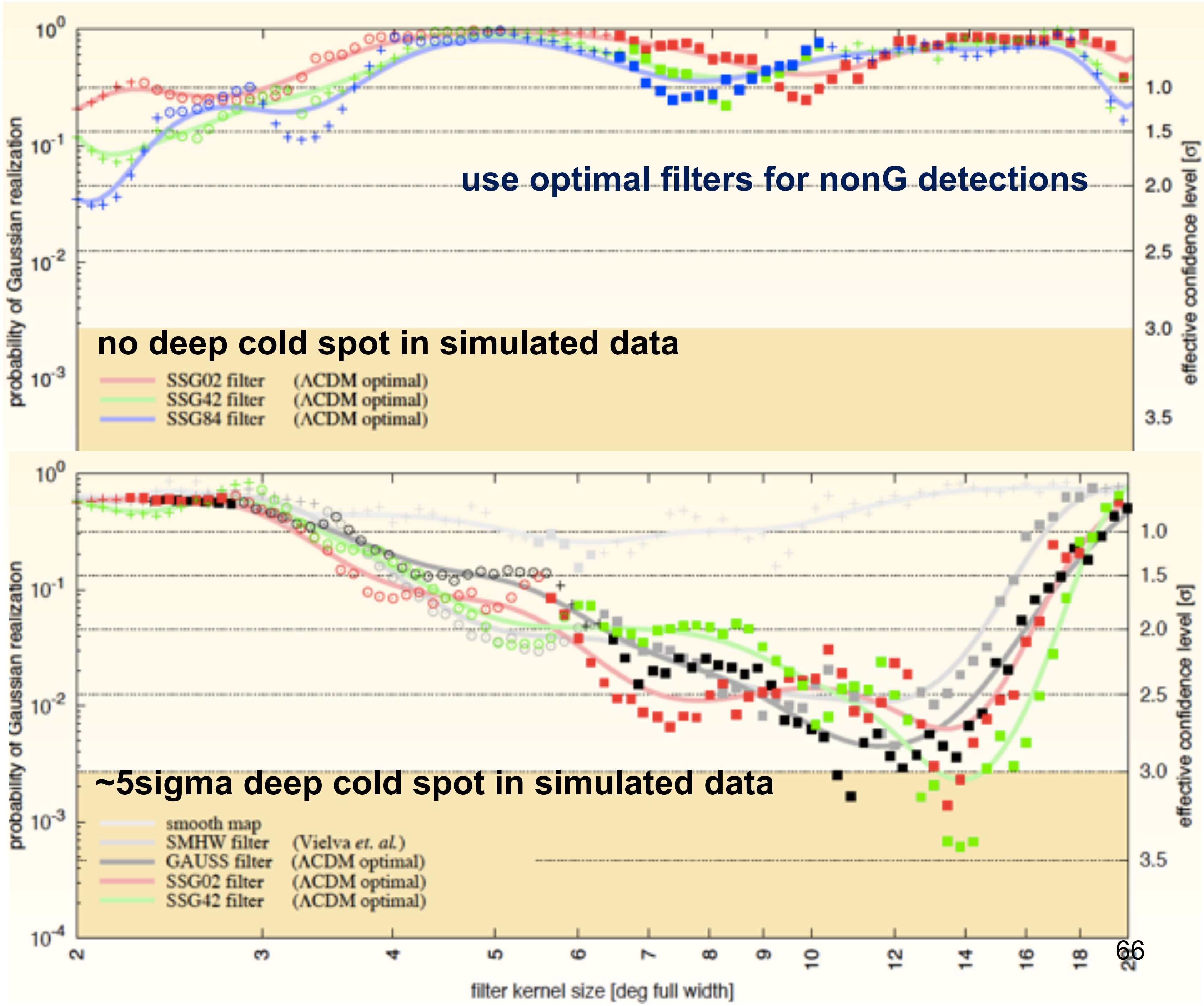
maps into (considerably relaxed) $< F_{NL} | \chi_b + \chi_{>h} >$ constraint

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



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

$\Rightarrow$ constrain $f_\chi^3 \chi_{>h}^2$ *(*$P\chi/P\phi \sim 2\varepsilon$ $\Rightarrow$*relaxed limit)*


use optimal filters for nonG detections
no deep cold spot in simulated data
SSG02 filter (ΛCDM optimal)
SSG42 filter (ΛCDM optimal)
SSG84 filter (ΛCDM optimal)
~5sigma deep cold spot in simulated data
smooth map
SMHW filter (Vielva et. al.)
GAUSS filter (ΛCDM optimal)
SSG02 filter (ΛCDM optimal)
SSG42 filter (ΛCDM optimal)
probability of Gaussian realization
effective confidence level [σ]
filter kernel size [deg full width]