
Origin of the observed entropy in the Universe and SMpp/BSMpp particles
- coarse-grained coherent condensate breaks up into fine-grained fluctuations
- particle creation = instability => stretch and break via mode-mode coupling
Dick Bond?
Lev Kofman
Misao Sasaki
Bond+Braden+Frolov+Huang+Morrison
담배
세탁
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조기매운탕
동태매운탕
Chilsung Cider
Coca-Cola

The Kinematics of Inflation, Preheating and Heating: a Playground for Kolmogorov-Sinai and Shannon Entropies

Dick Bond @ ipmu18 11 29

*what are the **degrees of freedom / parameters** of the **ultra early Universe**? TBD*

begin-inflate => inflate => end-inflate => preheat => non-equilibrium heat+entropy
=> *Standard Model particle physics* QG plasma radiation dominated
=> dark matter dominated *structure via gravitational instability* => dark energy now

$$d\zeta(x,t) = (dE + p dV)/3(E + pV) = d\, \ln \rho_c / 3(1+w) + \mathrm{Trace}\, d\alpha^i{}_j$$

***fit into** a UV-complete theory (ultra-high energy to the Planck scale) strings, landscape, ..*
& IR-complete theory (post-inflation heating -> quark/gluon plasma)??? TBD

role of (1) ***instabilities after inflation***
entropy generation via the breakup of the coherent low-k inflaton condensate into incoherent high-k fluctuations at a "shock-in-time" => **nonGaussianity**

role of (2) ***instabilities during inflation***
phenomenology of in-states propagating through localized unstable potential structures to out-states, like scattering theory => **nonGaussianity**

(3) ***|cg <=> fg> condensate/fluctuation framework****, for both using coherent states classical-like approach with* ***hbar****. includes* ***Bogoliubov*** *transformations for fluctuations as condensate evolves*
=> ***particle creation*** *interpretation in both heating and inflating regimes.*

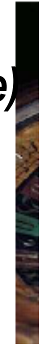
single field V heating slow, oscillating

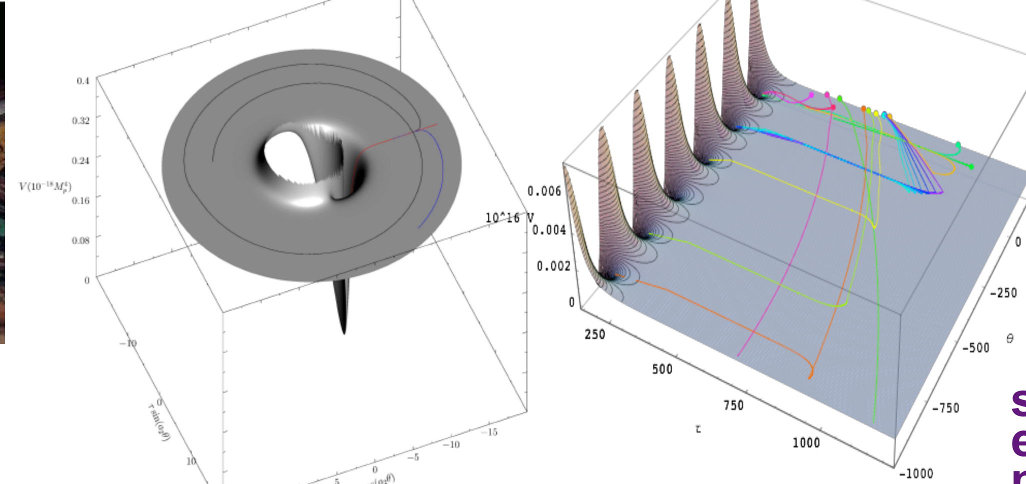
but shaped V can give rapid heating (roulette)

coarse-grain cm-horizon =>
fine-grain fluctuations = S generation

longitudinal instability
KS yes but no LSS modulation

$a =\quad 1$





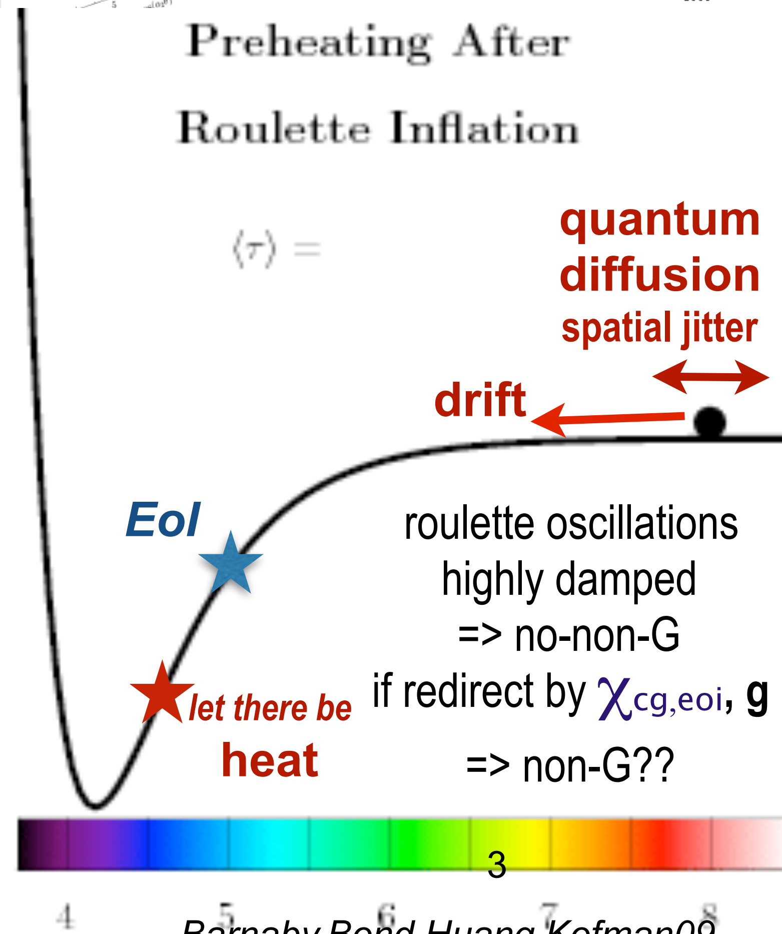
Preheating After

Roulette Inflation

$\langle\tau\rangle =$

A visualized 2D slice

in lattice simulation



semi ETERNAL INFLATION

EoI horizon ~ 1cm comoving

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

Barnaby,Bond,Huang,Kofman09

the true quadratic ζ-Websky of the ζ-scape

Planck 2018 X inflation: TTTEEE lowL Epol + CMBlens + BK15 BB + *BAO*

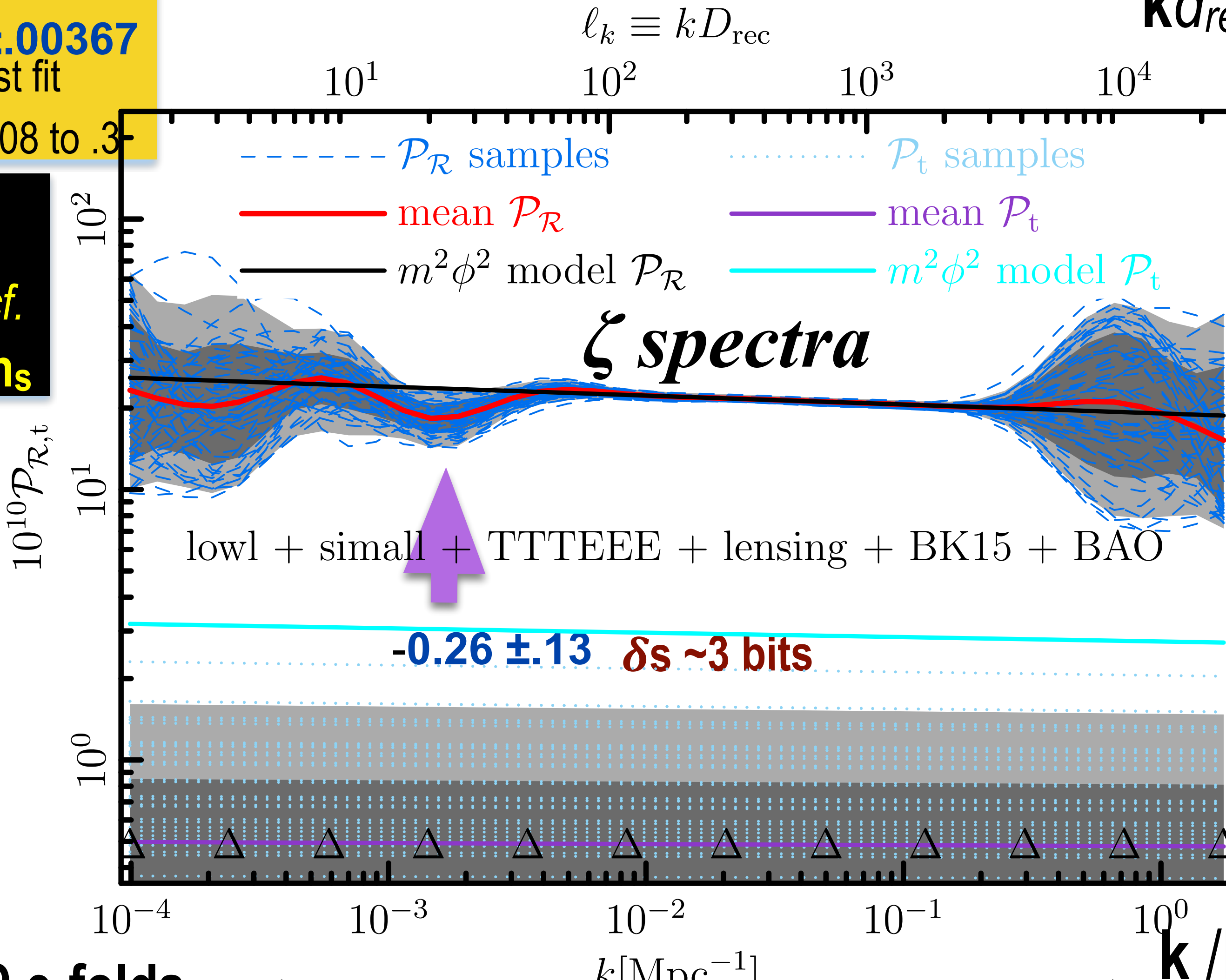
CMB TT power L~ 20-30 dip => ζ-Spectrum k-dip; *includes CMB lensing, parameter marginalization*

uniform **n_s=0.9669±.00367**
P18+BK15 LSS best fit
superb 12-knot fit k~ .008 to .3

P18+BK15
r<.069 95%CL *cf.*
r<0.061 uniform n_s

stochastic inflation
$|\phi_{cg}\,;\,\phi_{fg}\rangle$
coherent state picture
of coarse-grain
condensate
+ fine-grain
bugoliubov fluctuations
QM-correct

$kd_{rec} \gtrsim L$



=> lots of room for large ζ =>

=> V(ϕ)

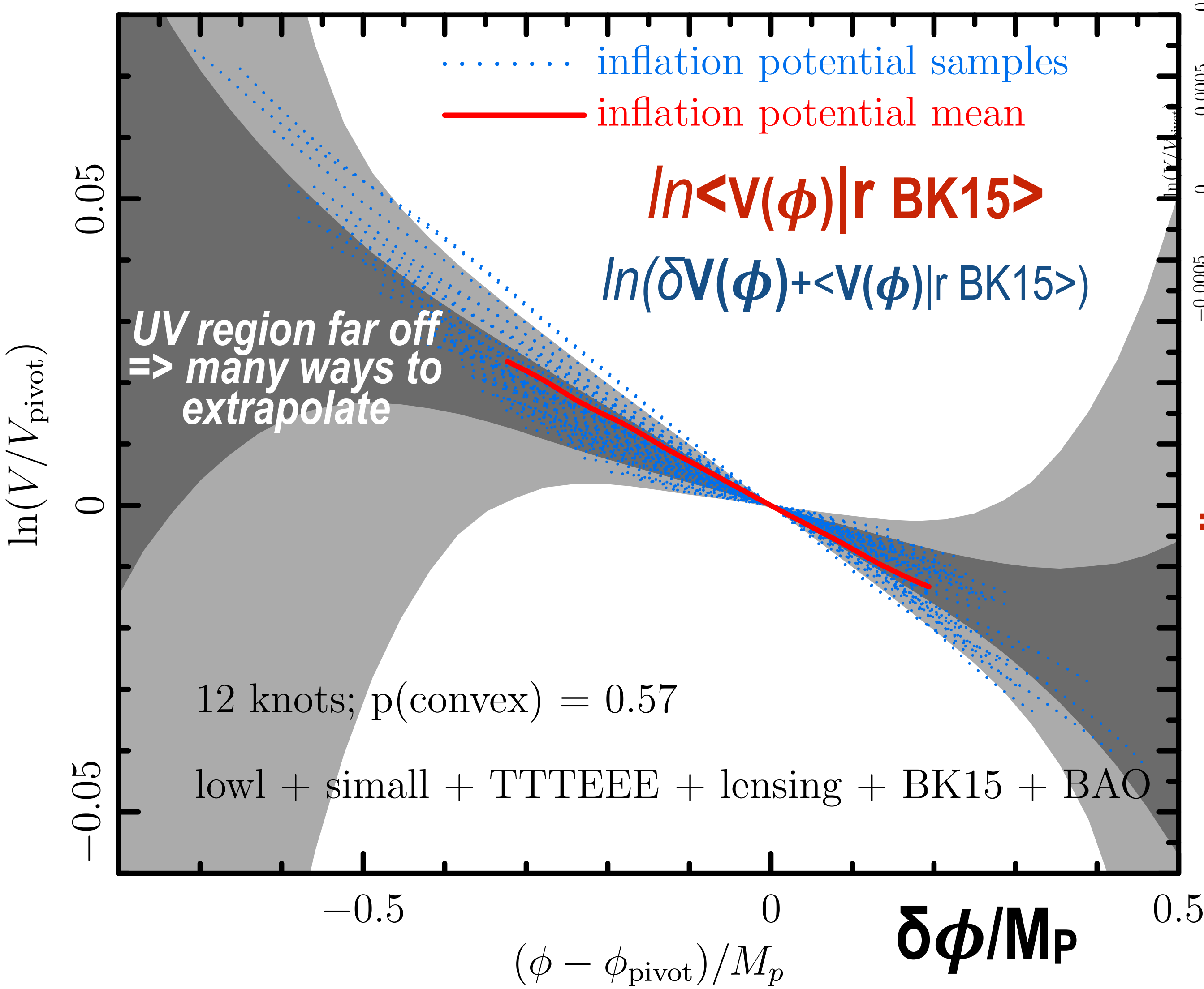
k /Mpc

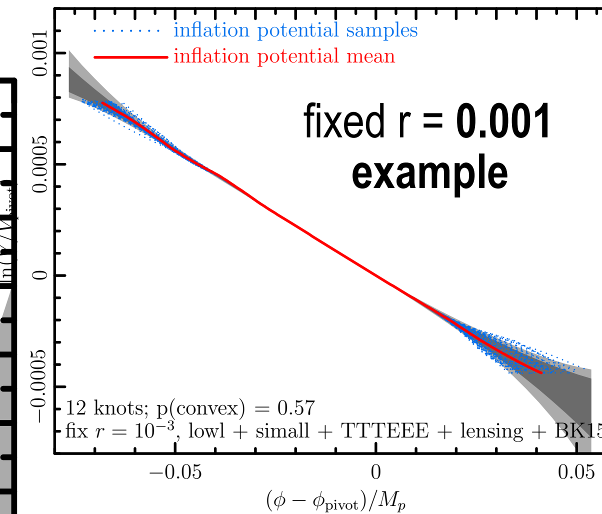
9 e-folds

inflaton $V(\phi)$-maps $=3M_P^2 H^2 (1-\varepsilon/3)$ *HJ eqn,* $d\phi/M_P / d\ln a = \pm\mathrm{sqrt}(2\varepsilon)$

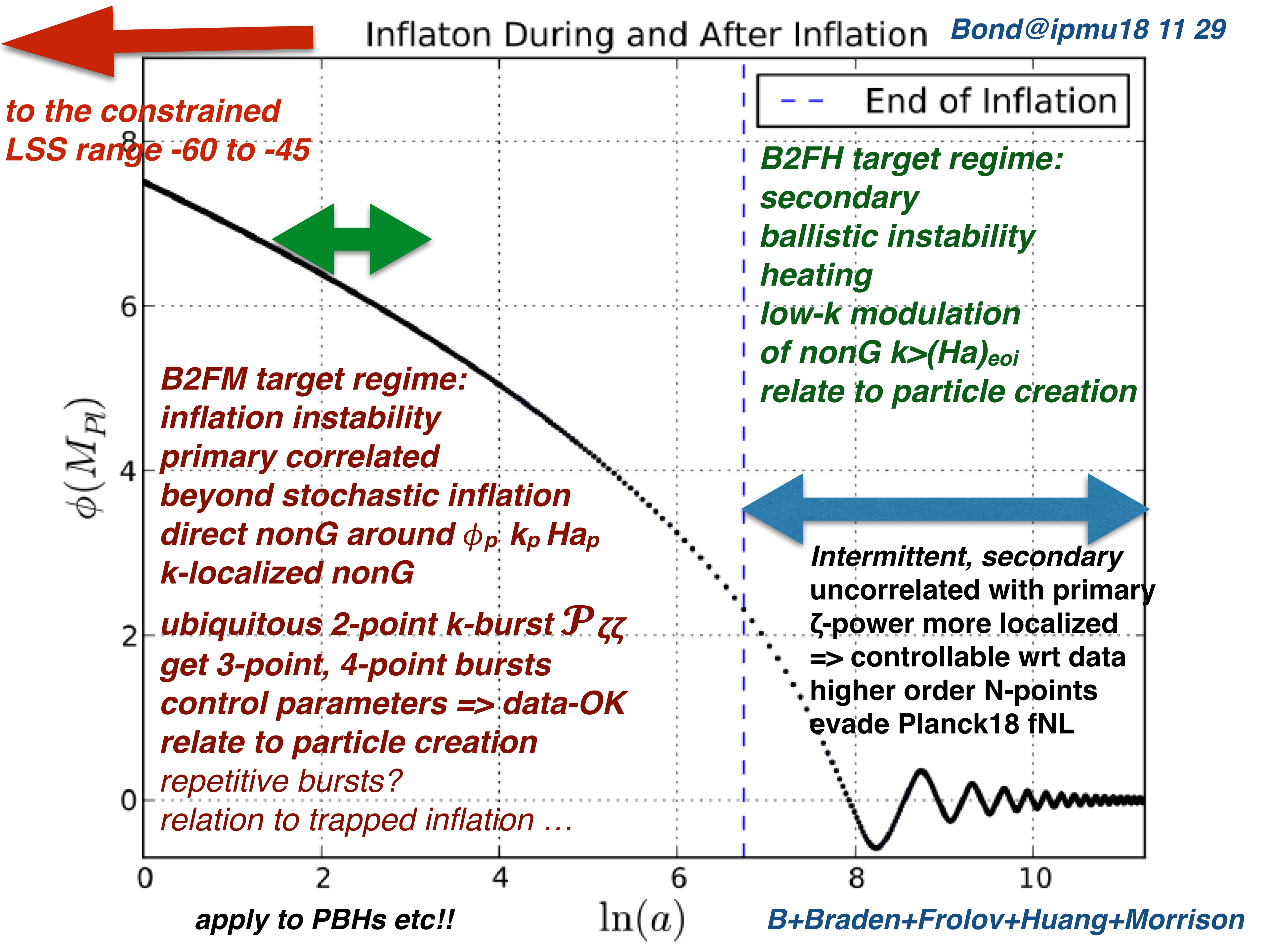
along the gradient / Morse flow

Planck 2018 X





IR heating region is far off => many ways to extrapolate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Inflaton During and After Inflation
End of Inflation
to the constrained
LSS range -60 to -45
B2FH target regime:
secondary
ballistic instability
heating
low-k modulation
of nonG k>(Ha)eoi
relate to particle creation
B2FM target regime:
inflation instability
primary correlated
beyond stochastic inflation
direct nonG around ϕ_p k_p Ha_p
k-localized nonG
ubiquitous 2-point k-burst $\mathcal{P}_{\zeta\zeta}$
get 3-point, 4-point bursts
control parameters => data-OK
relate to particle creation
repetitive bursts?
relation to trapped inflation …
Intermittent, secondary
uncorrelated with primary
ζ-power more localized
=> controllable wrt data
higher order N-points
evade Planck18 fNL
$\phi(M_{Pl})$
$\ln(a)$
0
2
4
6
8
10
apply to PBHs etc!!
B+Braden+Frolov+Huang+Morrison

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what are the degrees of freedom / parameters of the ultra early Universe? TBD

Quantum Inflation - if quantum energy then quantum gravity (entangled) then gravitons

Phonons *density fluctuations = Trace strain = spatial 3-volume fluctuations*

=> *combined* **entropy-like measure** ζ =inflaton

Gravitons *tensor perturbations transverse traceless strain $P_{GW} = r\, P_\zeta$ grail $r < .06$ now, to $< .001$*

Isocons *when multiple particle-species - orthogonal scalar degrees of freedom to inflaton/phonon*

Dilatons *4-volume fluctuations - Higgs inflation $L_G(R)$ gravity - conformally-flatten potentials*

moduli, axions *connection to particle physics models "fundamental scalars" .. string theory*

fermions, vector gauge fields, Higgs *Standard model of particle physics* **. vector perturbations**

$$\frac{\mathrm{d}\zeta}{\mathrm{d}t} = \sum_i \frac{\nabla\dot{\phi}_i \cdot \nabla\phi_i + \dot{\phi}_i \nabla^2 \phi_i}{3a^2(\rho + P)}$$

nonlinear multi-field classical coupled system. evolve using lattice simulations. via ***symplectic defrost++ code + spectral code*** *=> high accuracy to unveil small effects after and during inflation*

CMB/LSS observations give access to limited partial operator-paths in field-space aka **kinematics** => *limited glimpse of a* ***UV/IR complete theory*** *aka* ***dynamics***. so far just through the **ζ-fluctuation spectrum** encoding the quantum diffusion of (**longitudinal/inflaton**) paths.

Transverse *field-motion aka* ***isocons*** *may influence* $\mathcal{P}_{\zeta\zeta}(k)$ *and* ***ζ-nonG***

stochastic dynamical systems theory for kinematics of cg variables

coarse-grained *stochastic inflation k~Ha resolution/dynamics relation*

$d\zeta(x,Ha) = [\mathcal{P}_{\zeta\zeta}(k)]^{1/2} \, [d\,ln\,Ha]^{1/2} \eta_{GRD}(x,Ha)$ ***quantum fluctuations & no drift***

order parameters from the ultra early U? so far *ζ ≈GRF,* $\mathcal{P}_{\zeta\zeta}(k)$ *2 ζ-params*

ζ = **an adiabatic invariant**, conserved even with large field-strains
to get nonG need to break adiabaticity => nonlinear fluctuations

role of (1) ***instabilities after inflation***
entropy generation via the breakup of the coherent low-k inflaton condensate into incoherent high-k fluctuations at a "shock-in-time" => **nonGaussianity**

stochastic dynamical systems theory for kinematics of cg variables

ζ **= an adiabatic invariant**, conserved even with large field-strains
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Kinematics of Preheating:
BBFH are developing a **trajectory bundle evolution framework** for nonG in **post-inflation preheating -> heating**. field-space path deviations aka strains and their shear can characterize smoothed-bundle "ballistic" chaotic evolutions. arrested by nonlinear fluctuation-mode generation. **metric entropy (KS) in the ballistic phase -> Shannon entropy in the fluctuation-mode phase**.

condensate evolves chaotically? => phase-transition-like melting into phonon+ modes, fast scramble of fundamental fields, evolution of statistically-simple energy-density phonons can one use coherent states to address this quantum mechanically? TBD

$$d\zeta_{fi}(x,t) = d\ln \rho_c / 3(1+w) + \mathrm{Trace}\,(d\alpha)$$

cf. $ds_{fi} = ds_{KSfi} - d\mathrm{Tr}\varepsilon_{fi} = \delta s_{fi}$ *(fg-> cg)* *FokkerPlanck eqn for Prob(δs_{fi}| control)*

$\zeta_{NL}(x)$ from *"isocon" degrees of freedom cf.* $\zeta_{NL}(x)$ from ***inflaton***

modulated heating, ***ballistic chaos, caustics, shock-in-time,***

modulators isocon $\chi(x)$, ***axionic-isocon***(x) ***couplings*** $g(x)$ super-horizon accessible

complex field configs *Oscillons, Stringy configurations, curvatons, .. Bubble Collisions*

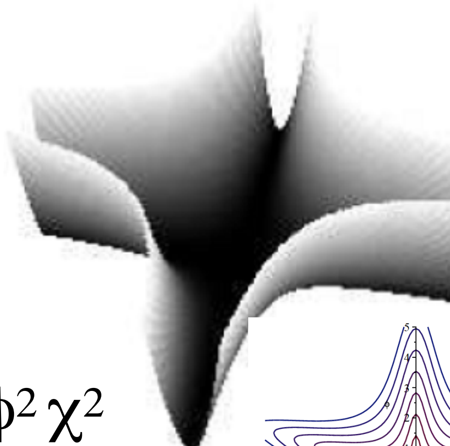
what is the inflaton+isocons potential?

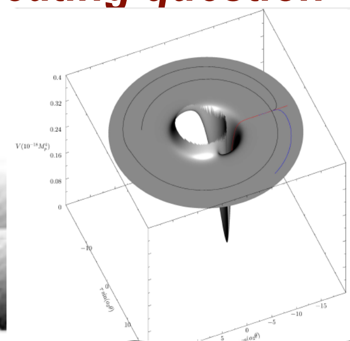
around a minimum is the *HOT /heating question*

how was *matter & entropy* generated at the end of *acceleration = inflation*?

Relate to Higgs & standard model?

2 filament?

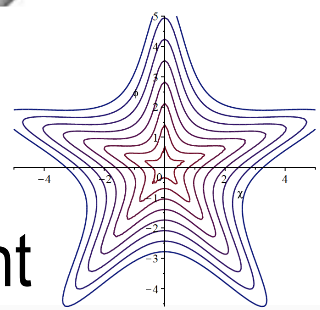




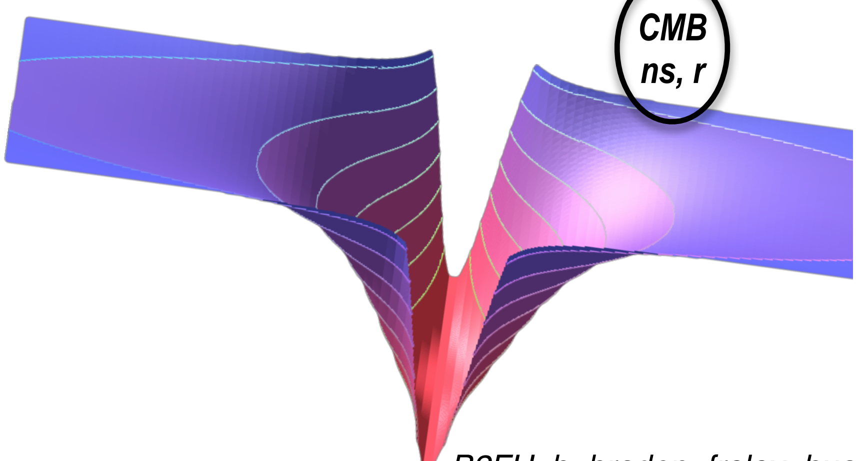
4 filament

$1/4\lambda\phi^4 + 1/2 g^2 \phi^2 \chi^2$

3-filament   5-filament

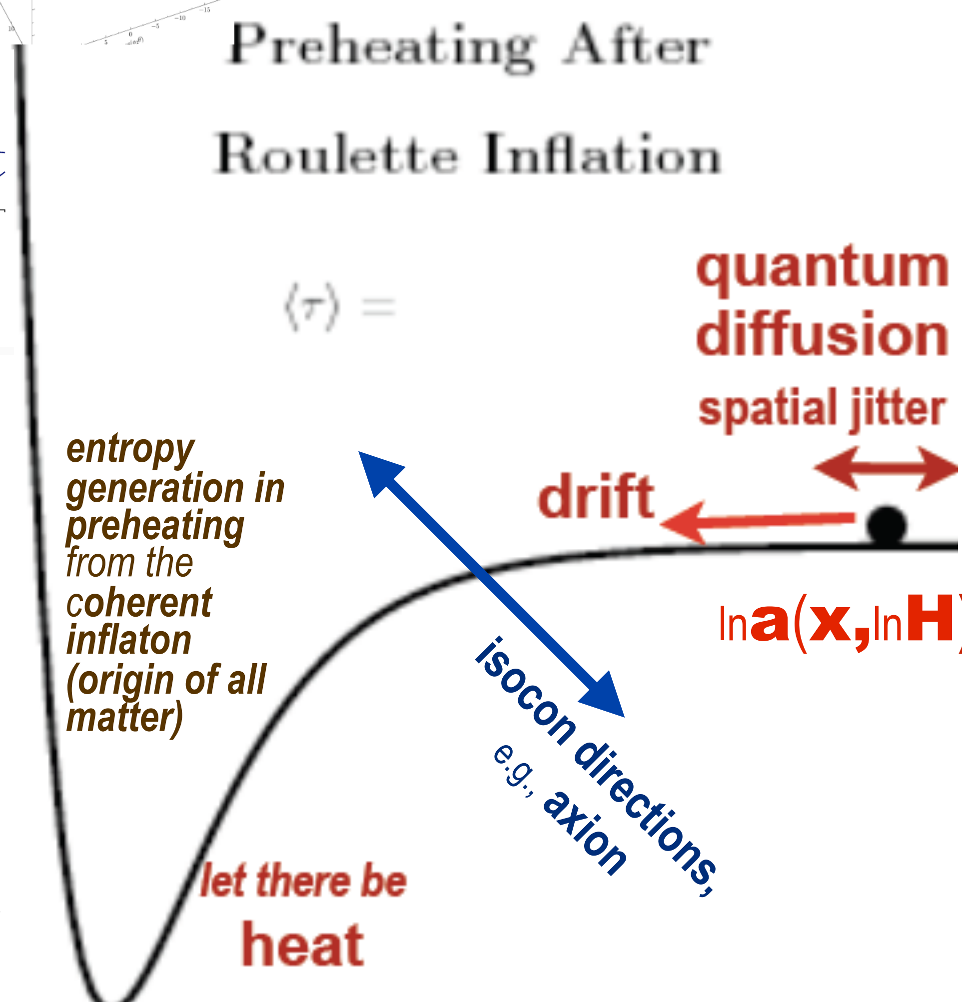


angles pNGB natural inflation, monodromy, ..



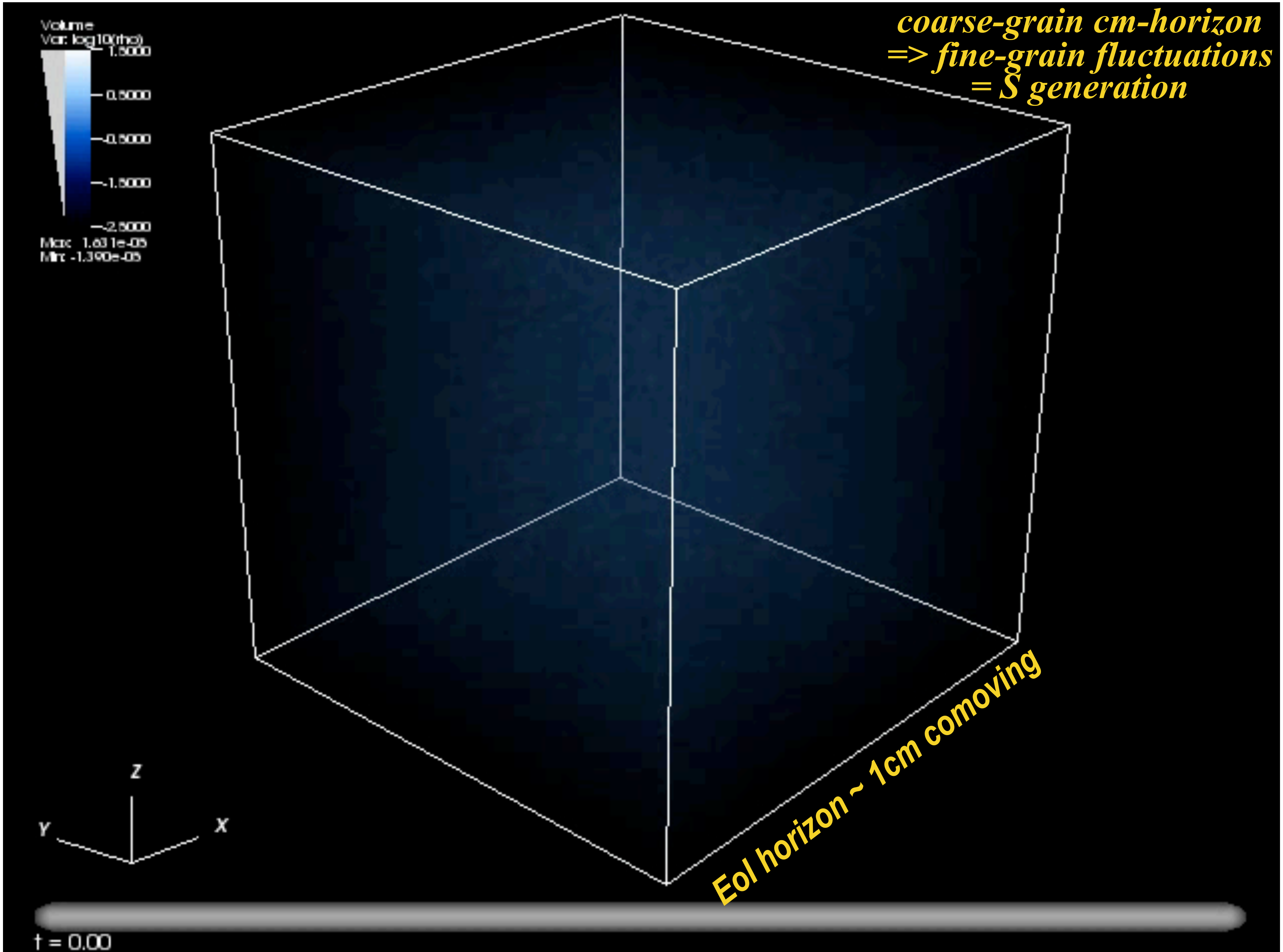
B2FH, b+braden+frolov+huang

conformal potential-flattening eg Higgs inflation *SBB89 etc*



semi ETERNAL INFLATION

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

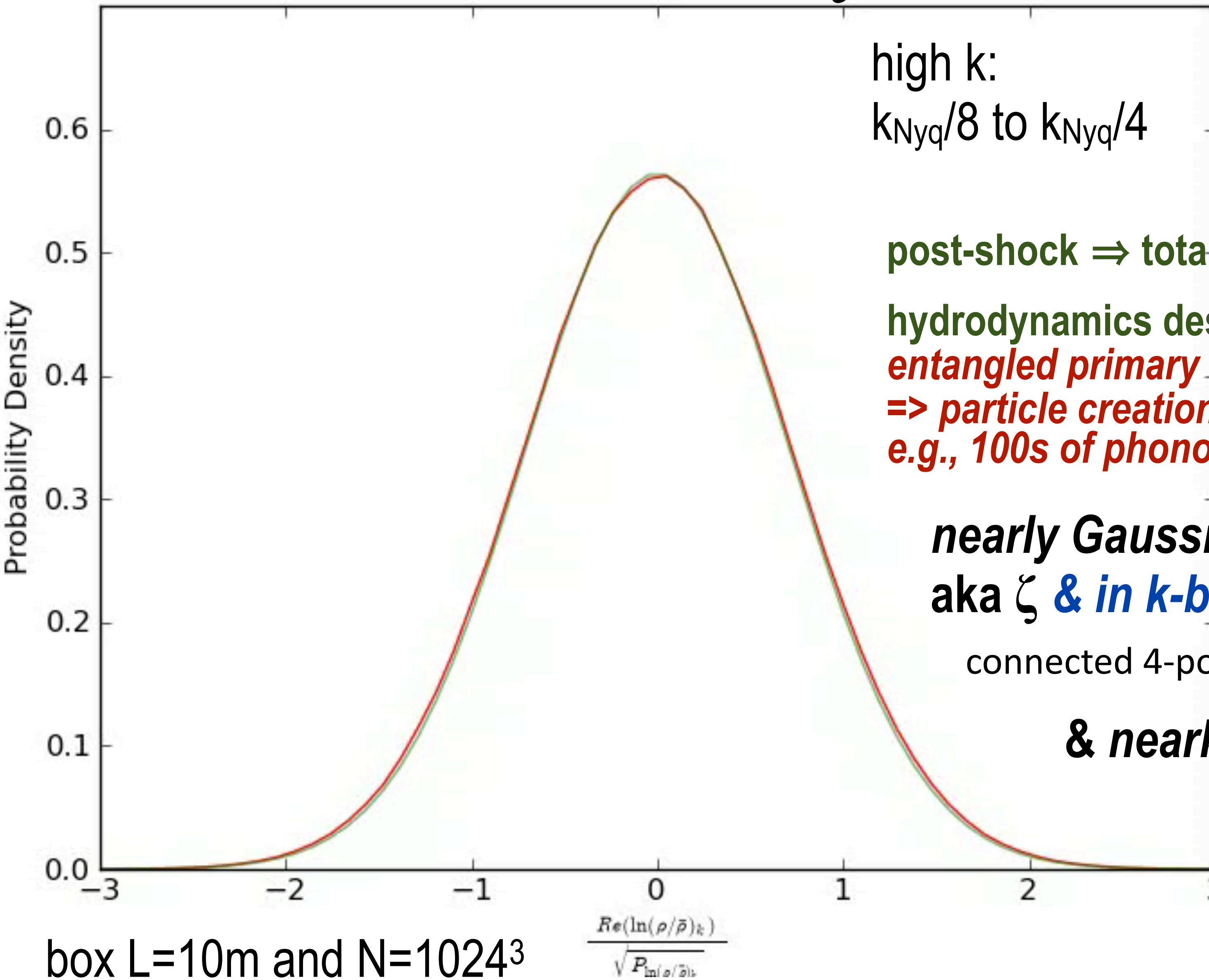


log-normal pdf (density *aka* ζ***)****, in k-bands too; normal pdf (velocity)*

but Statistical Simplicity

Prob(ζ): FourierTransform(ln density) PDF
~ log-normal after initial transient

coarse-grain <ζ> <=> fine-grain $\delta\zeta_k$ gradients, δV



high k:
$k_{Nyq}/8$ to $k_{Nyq}/4$

Prob(ζ)

post-shock ⇒ total stress-energy $T^a{}_b$

hydrodynamics description **phonons**

entangled primary fields $(\varphi, \Pi_\varphi, \chi, \Pi_\chi)$
=> particle creation description
e.g., 100s of phonons at a time

nearly Gaussian in ln ρ/<ρ>
aka ζ *& in k-bands!*

connected 4-point power is small

& nearly Gaussian in v

box L=10m and N=1024^3

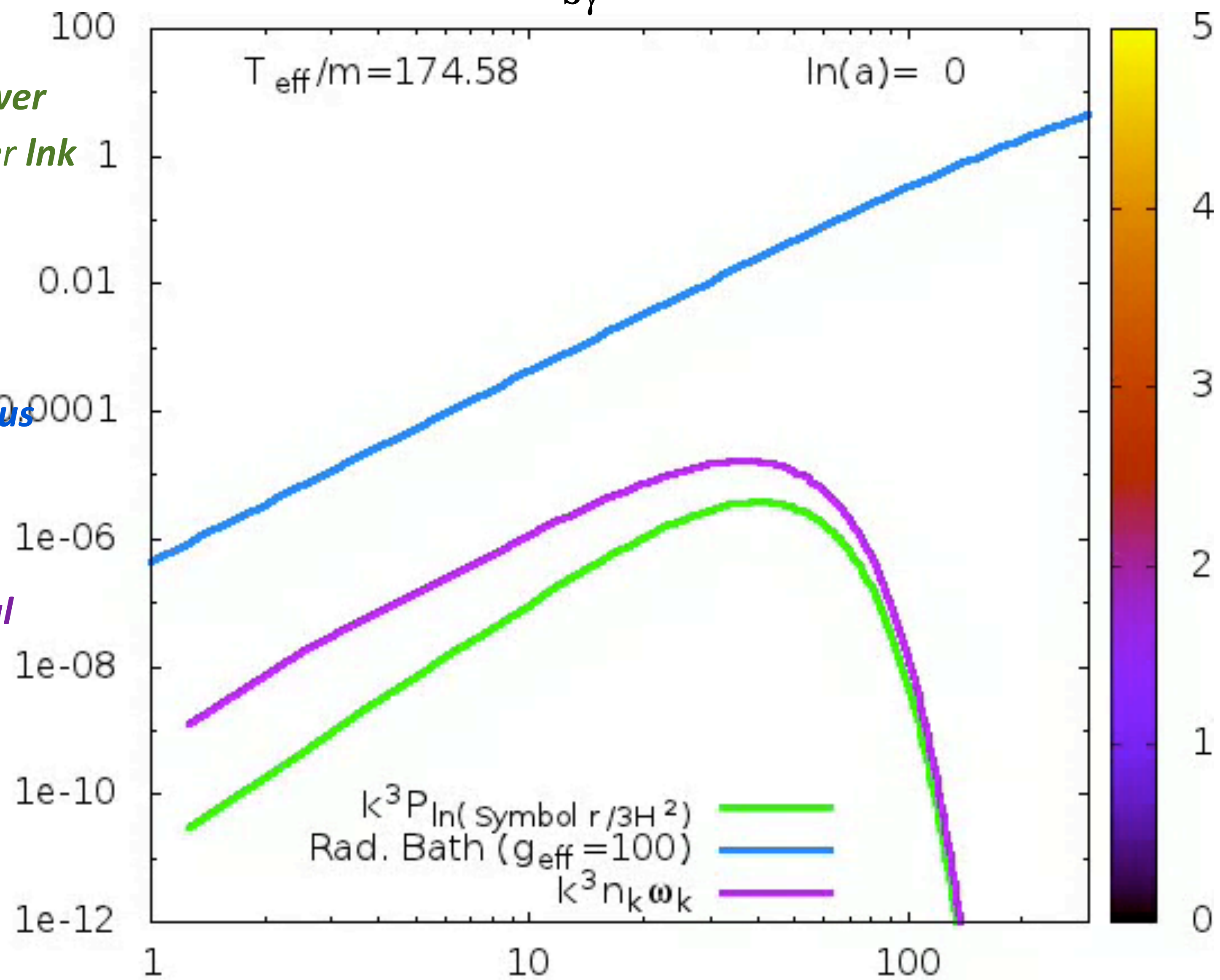
B+Braden+Frolov

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

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

s_γ

ln ρ/<ρ> power spectrum per lnk
aka entropy
aka phonon
aka ζ
cf. instantaneous full thermal spectrum
cf. conventional energy spectrum using a pseudo particle occupation number

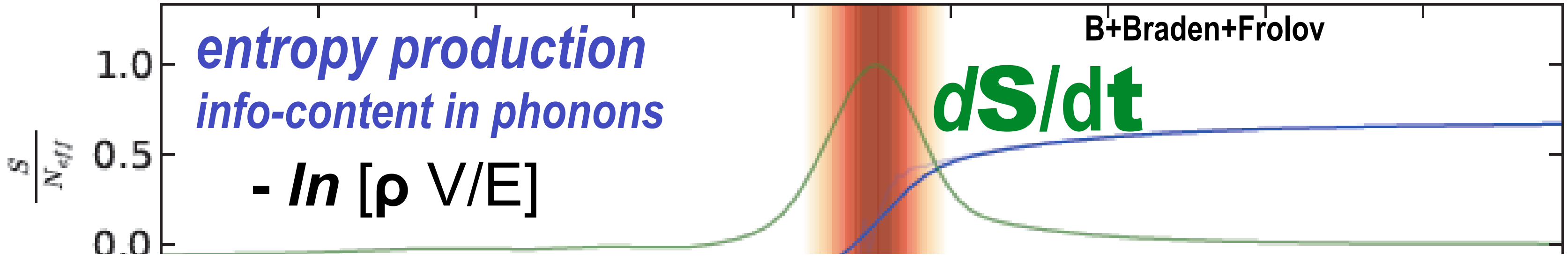


$V(\phi,\chi) = 1/2\, m^2 \phi^2 + 1/2\, g^2 \phi^2$

momentum

B+Braden+Frolov

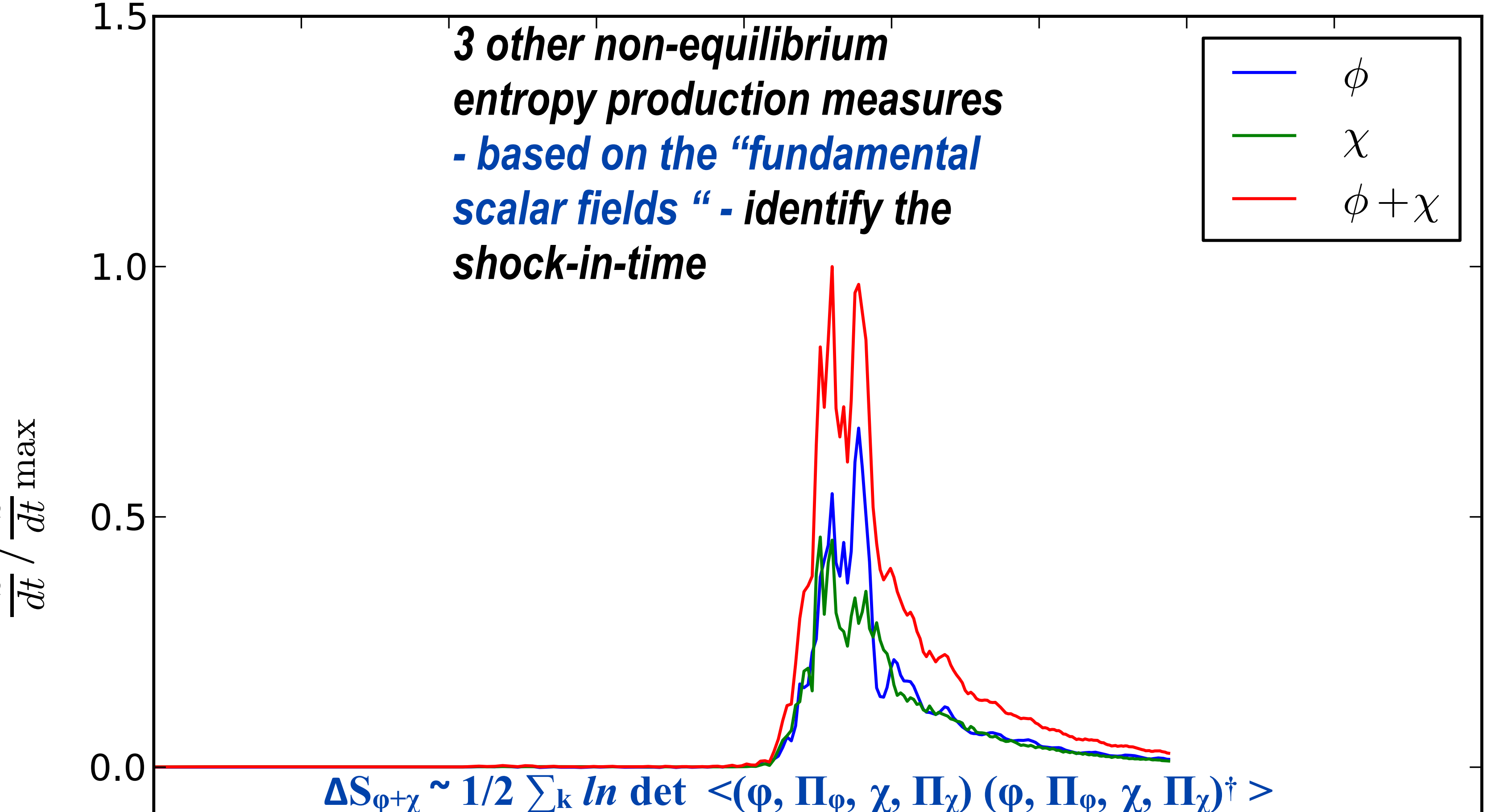
nonG from large-scale modulations of the shock-in-times of preheating



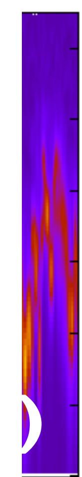
true thermal equilibrium far off ➤

entangled primary fields $(\varphi, \Pi_\varphi, \chi, \Pi_\chi)$

decay rates (Feynman diagrams) and transport theory difficult to make accurate through preheating



3 other non-equilibrium entropy production measures - based on the "fundamental scalar fields " - identify the shock-in-time



$\Delta S_{\varphi+\chi} \sim 1/2 \sum_k \ln \det \langle(\varphi, \Pi_\varphi, \chi, \Pi_\chi) (\varphi, \Pi_\varphi, \chi, \Pi_\chi)^\dagger \rangle$

A Shocking End to Post Inflation Mean Field Dynamics

Shock-in-space t = const

$v_{bulk}^2 > c_s^2 \Rightarrow v_{bulk}^2 < c_s^2$

supersonic ⇒ subsonic

Characteristic spatial scale

Jump Conditions: $\Delta T^{\mu\nu}$

Randomizing Shock Front: ΔS

Mediation: width via viscosity or collisionless dynamics

post-shock evolution, slow, of temperature, etc.

coherent condensate breakup?

Shock-in-time x = const (deviations for nonG)

$\langle\rho\rangle \gg \delta\rho \Rightarrow \langle\rho\rangle \ll \delta\rho$

Homogeneous ⇒ Fluctuations

Characteristic temporal scale

Jump Conditions: $\Delta T^{\mu 0}$

Randomizing mode cascade & Particle Production: ΔS

Mediation: width via gradients and nonlinearities

post-shock evolution, slow, of fluctuations

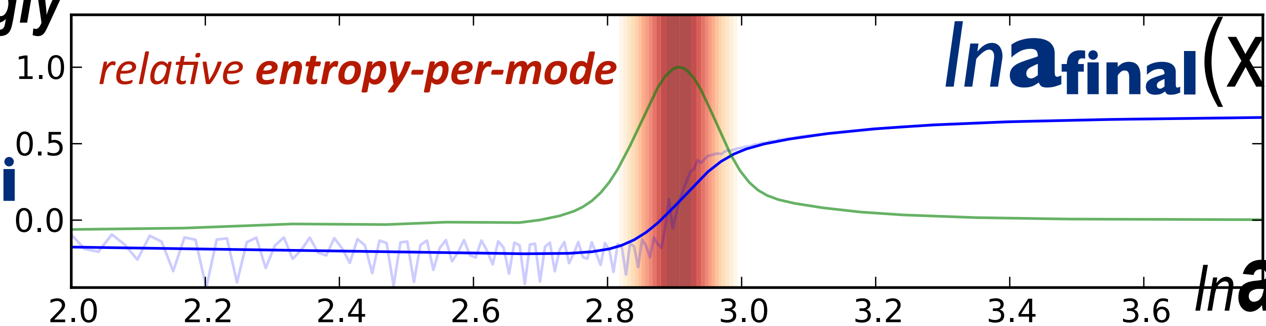
coherent condensate breakup E-phonon soup

- a difference: chaotic lead in to shock

Preheating is a shockingly efficient entropy source

$ln\ \mathbf{a_{shock}}(x)/\mathbf{a_{eoi}}$

& the mediation width

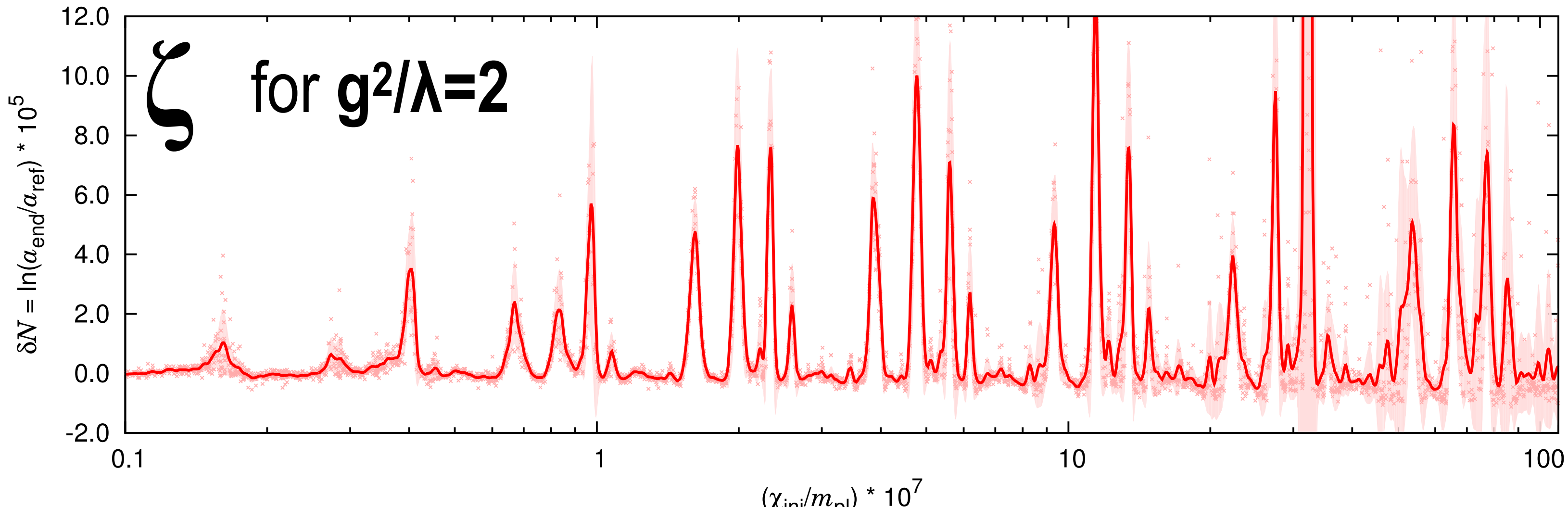


dS/dt(t,g) => *the Shock-in-time: entropy production rate*

$\zeta_{shock}(\chi_{cg,eoi}(x) \mid g^2/\lambda)$ => ***Chaotic Billiards: NonG** from **Parametric Resonance** in **Preheating***

B+Frolov, Huang, Kofman 09
B+Braden, Frolov, Huang 19

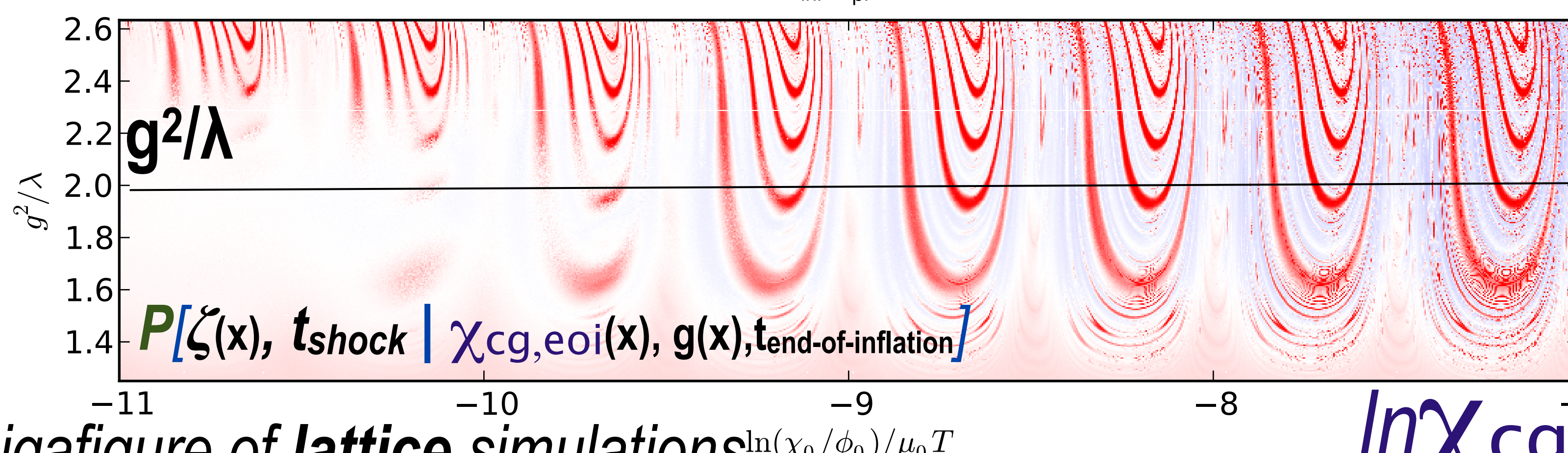
$$V(\phi,\chi) = 1/4\ \lambda\phi^4 + 1/2\ g^2\phi^2\chi^2$$



computational tour de force

huge number of 64^3 sims to show the wondrous complexity of

$\zeta(\chi_i, g^2/\lambda)$



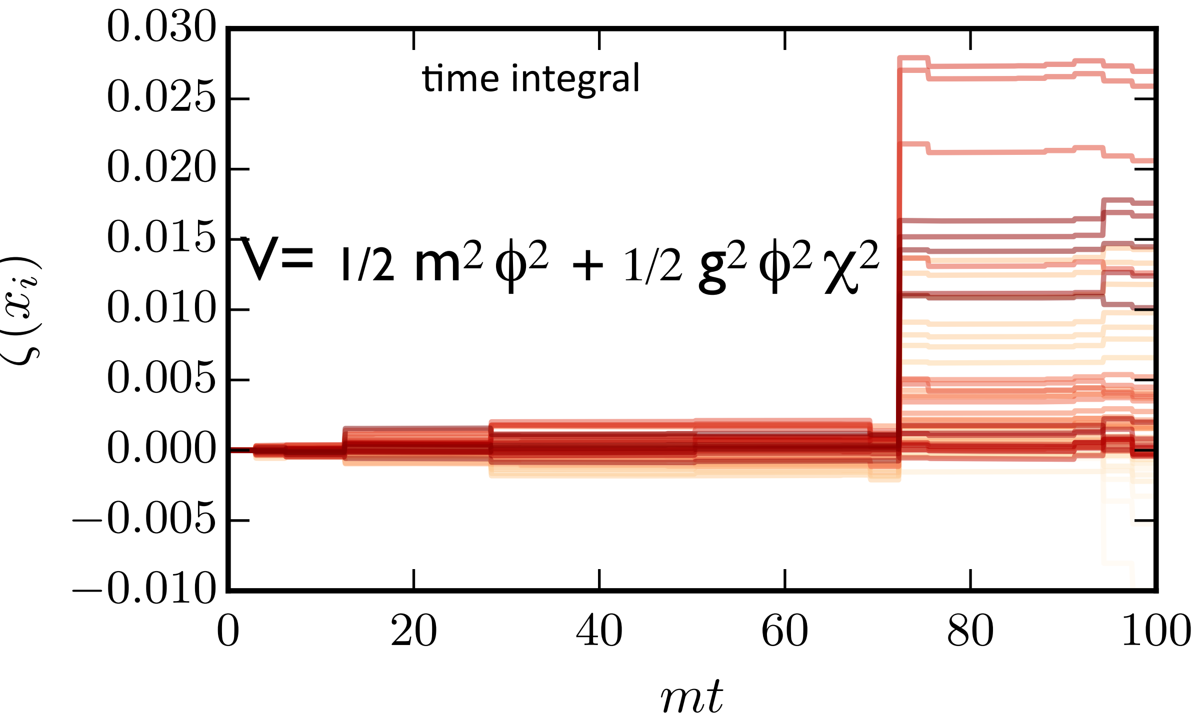
*gigafigure of **lattice** simulations*

$\ln\chi_{cg,eoi}$

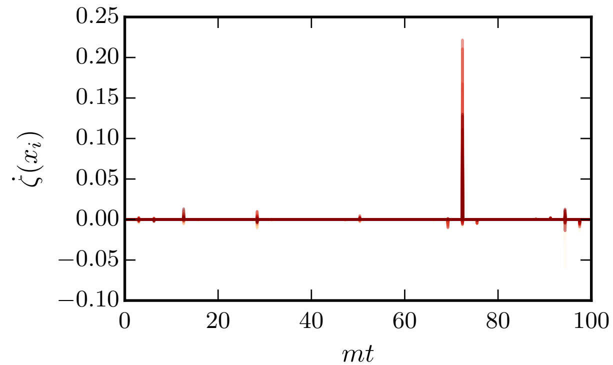
ζ conserved along trajectories until the "shock-in-time" when high **k** fluctuations (fine-grain) develop from coarse-grain, measure is $s_{Shannon} = - \ln \mathcal{P}\sqrt{g}$

but $-D\ln \mathcal{P}/dt$ = Trace $d\mathcal{E}/dt$ does change ~ KS entropy (rate)

stretching of phase strings. begin with anisotropic Gaussian at EoI and watch it stretch, $\mathcal{E}$ grows, rotates, locally OK as distorted ellipsoid, but strain depends upon the central value => phase tubes



evolution of the ζ source term



$$\zeta_{final}(x, t_f \,|\, \chi_{cg,eoi}(x), g^2/\lambda) \sim \zeta_{shock}$$

caustics in <q^A> *ballistic* orbits

$<\delta q^A\, Xt2 \;|\; \delta q^B\, Xti> \sim \exp(\mathcal{E}(Xt2\,|\,Xt1))^A{}_C <\delta q^C\, Xt1 \;|\; \delta q^B\, Xti>$

early U parameters: **final φ, Π_φ, χ, Π_χ, *ln* a, ln ρ, initial $\chi_{cg,eoi}$, *couplings* g, λ, ..**

parameter strain tensor in field space $\mathcal{E}^A{}_C(Xt2\,|Xt1)$ deformation $e^{\mathcal{E}}$

$d\mathcal{E}^A{}_C/dt$ strain rate ~local Lyapunov coefficients *Floquet instability charts*

instability to have nearby parameters diverge => chaotic billiards

Kolmogorov-Sinai entropy: ~ Sum of positive evalues of $d\mathcal{E}/dt$

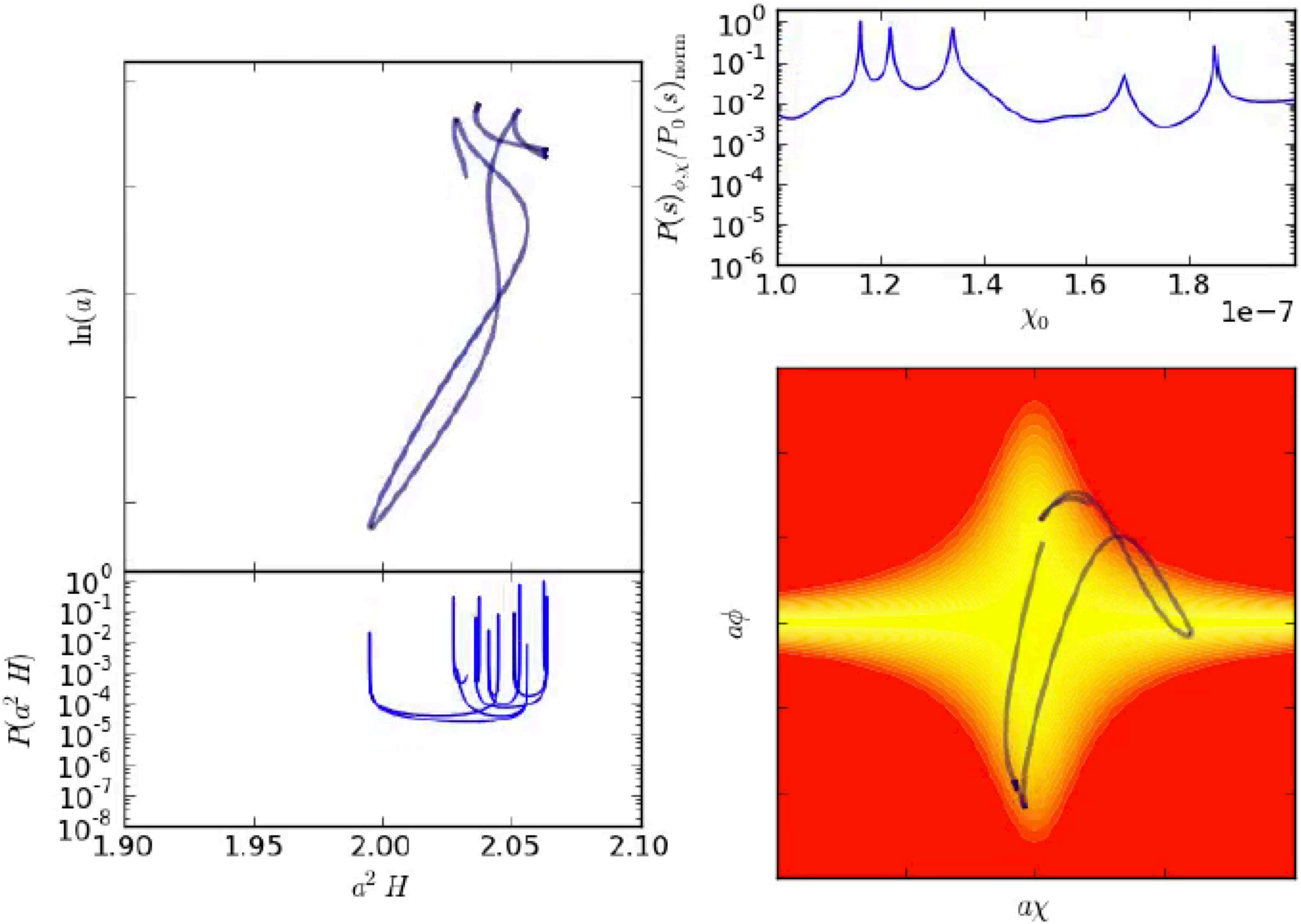
small $\mathcal{E}^A{}_A$ eigenvalues=> coherent trajectory bundles (for a time)

= caustics (inverse -> ∞) **1/ [$\partial\, \alpha\, /\, \partial\, \chi_{cg,eoi}$];** => peaks in $\zeta\, (\chi_{cg,eoi})$

stopping time **tstop ($\chi_{cg,eoi}$)** when $\mathcal{E}^A{}_A$ evalues get large <=> local gradients $\Uparrow$

cf. LargeScaleStructure: final Eulerian position <= initial Lagrangian position

1LPT aka Zeldovich: $\partial x/\partial r = \exp(\mathcal{E}) \to 0$ density $\rho \sim \exp(-\mathrm{Tr}(\mathcal{E})) \to \infty$

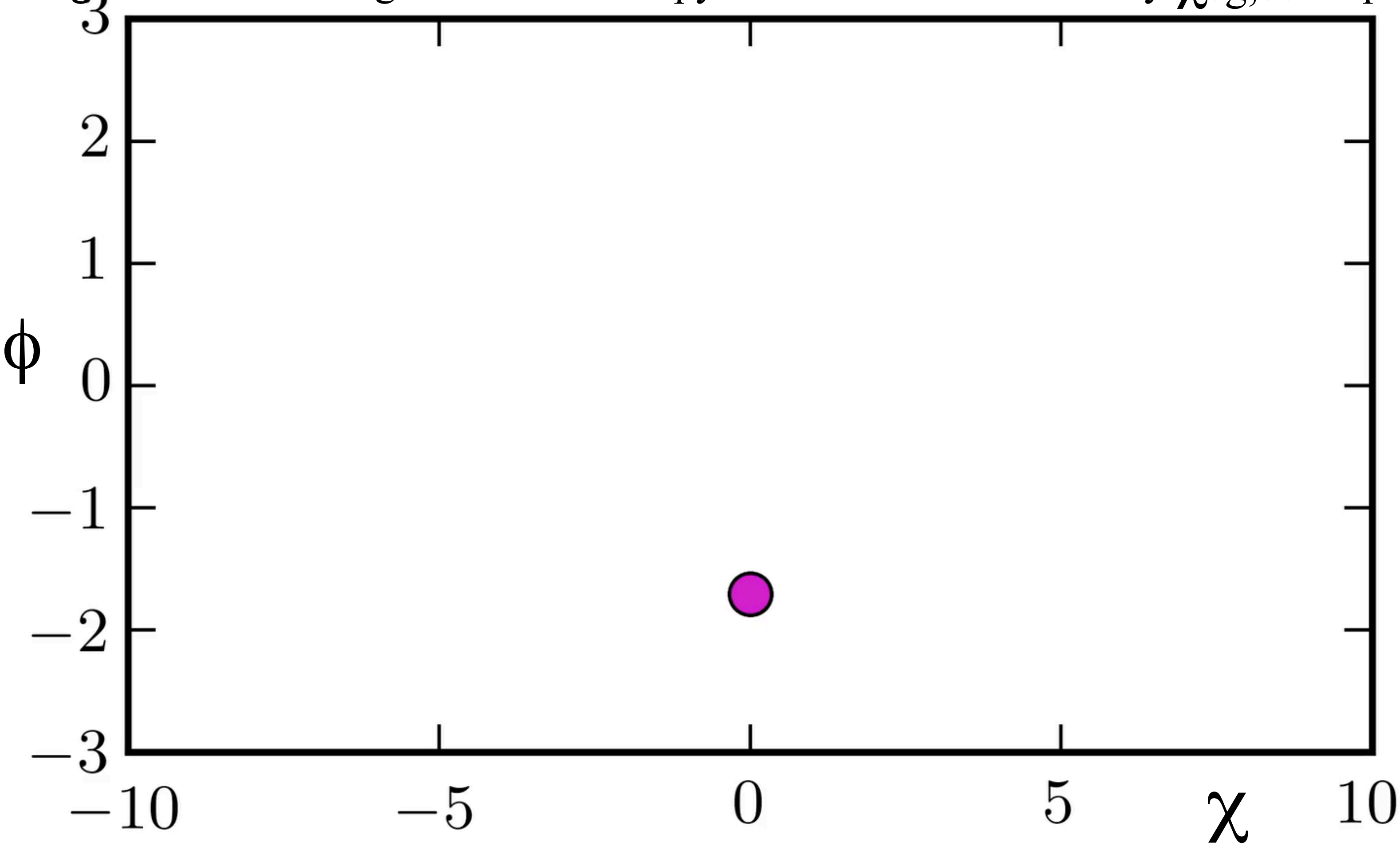


ln(a)
$P(a^2\ H)$
$a^2\ H$
1.90
1.95
2.00
2.05
2.10
$P(s)_{\phi,\chi}/P_0(s)_{\rm norm}$
χ_0
1e−7
1.0
1.2
1.4
1.6
1.8
$a\phi$
$a\chi$

ballistic billiards k=0 mode phase space string evolution

2D constrained distribution functions

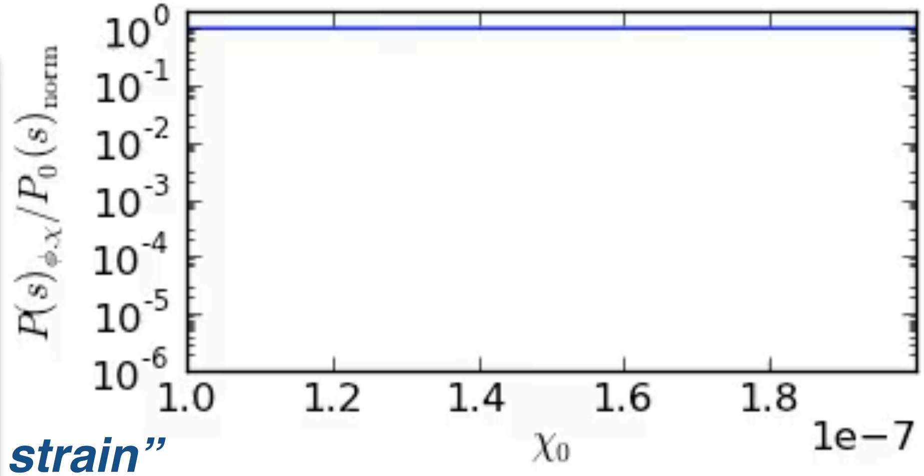
stopping criterion when coarse-grained entropy of field variables rises <=> strain ε high,
ie when integral of the Kolomgorov-Sinai entropy reaches a threshold - very $\chi_{cg,eoi}$ dependent



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

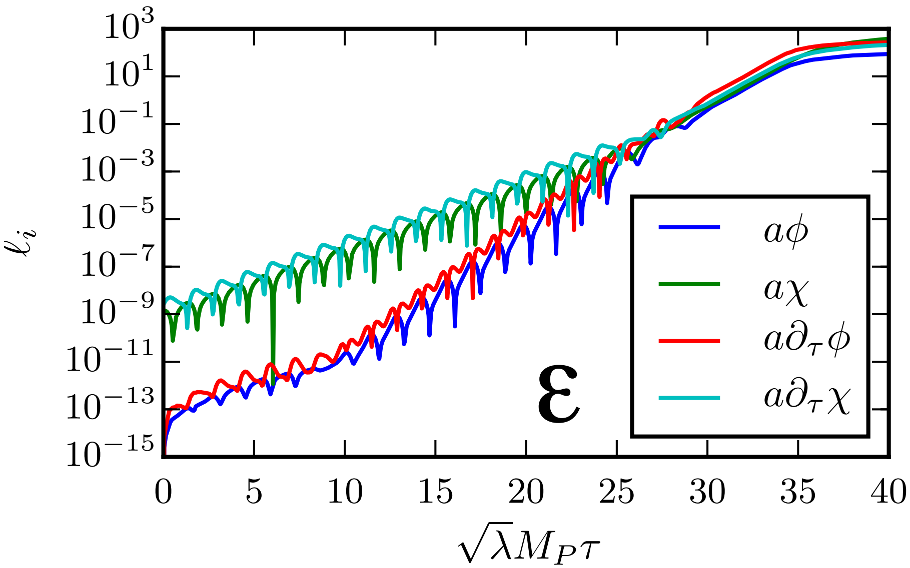
phase space strings

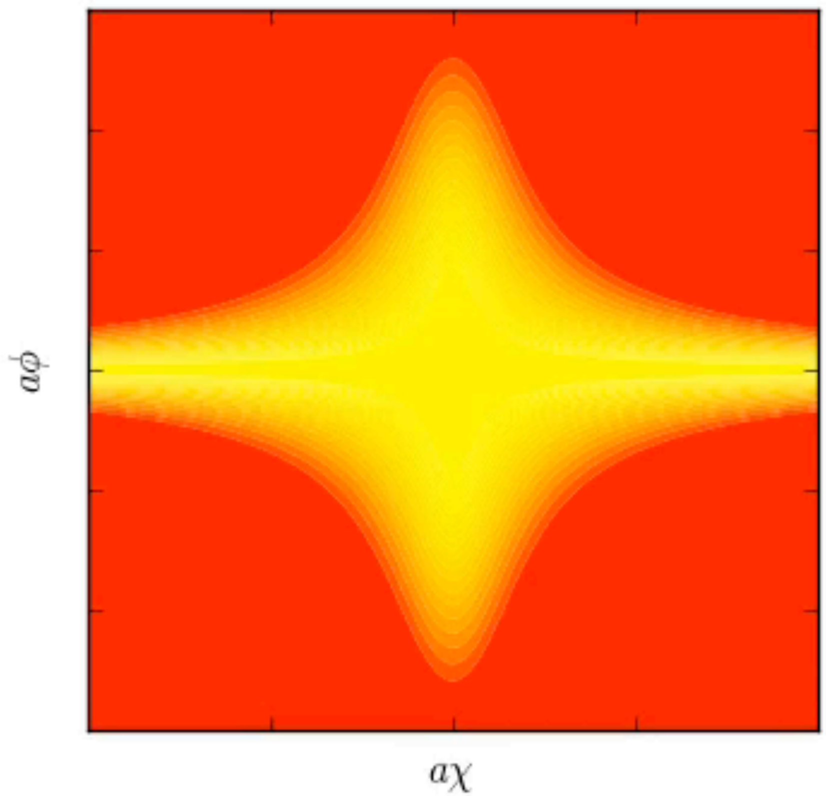
caustics are ubiquitous



2D constrained distribution functions

phase string growth in time "parameter strain"
***integral of Kolmogorov-Sinai entropy** rate*





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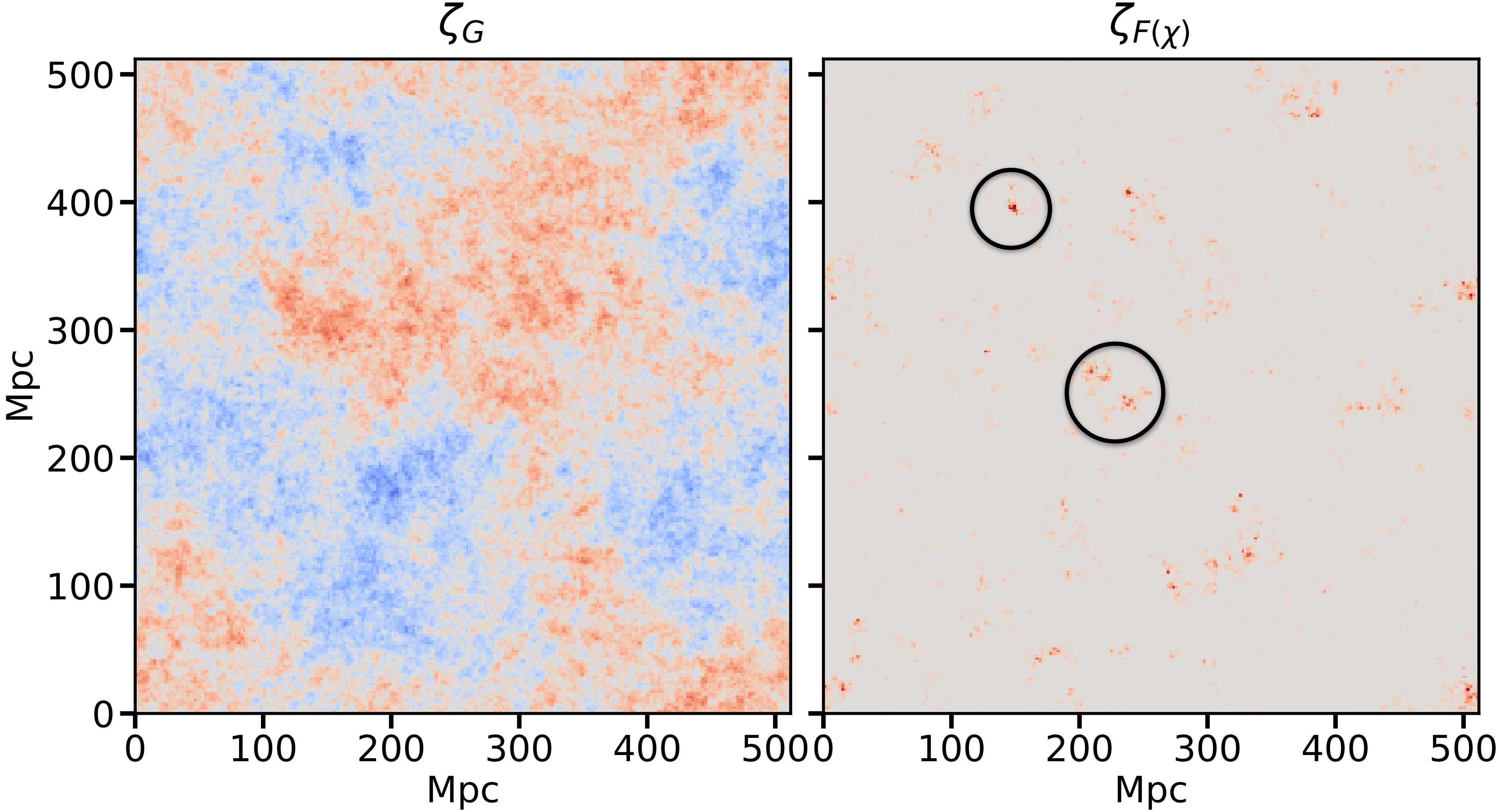
=> 3D constrained distribution functions

B2FH, b+braden+frolov+huang

Primordial Non-Gaussianity in observable Webskys constructed with the mass-Peak Patch method
+ gas-halo response functions/susceptibilities

Intermittent Non-Gaussian case

uncorrelated **ζ[GRF]**

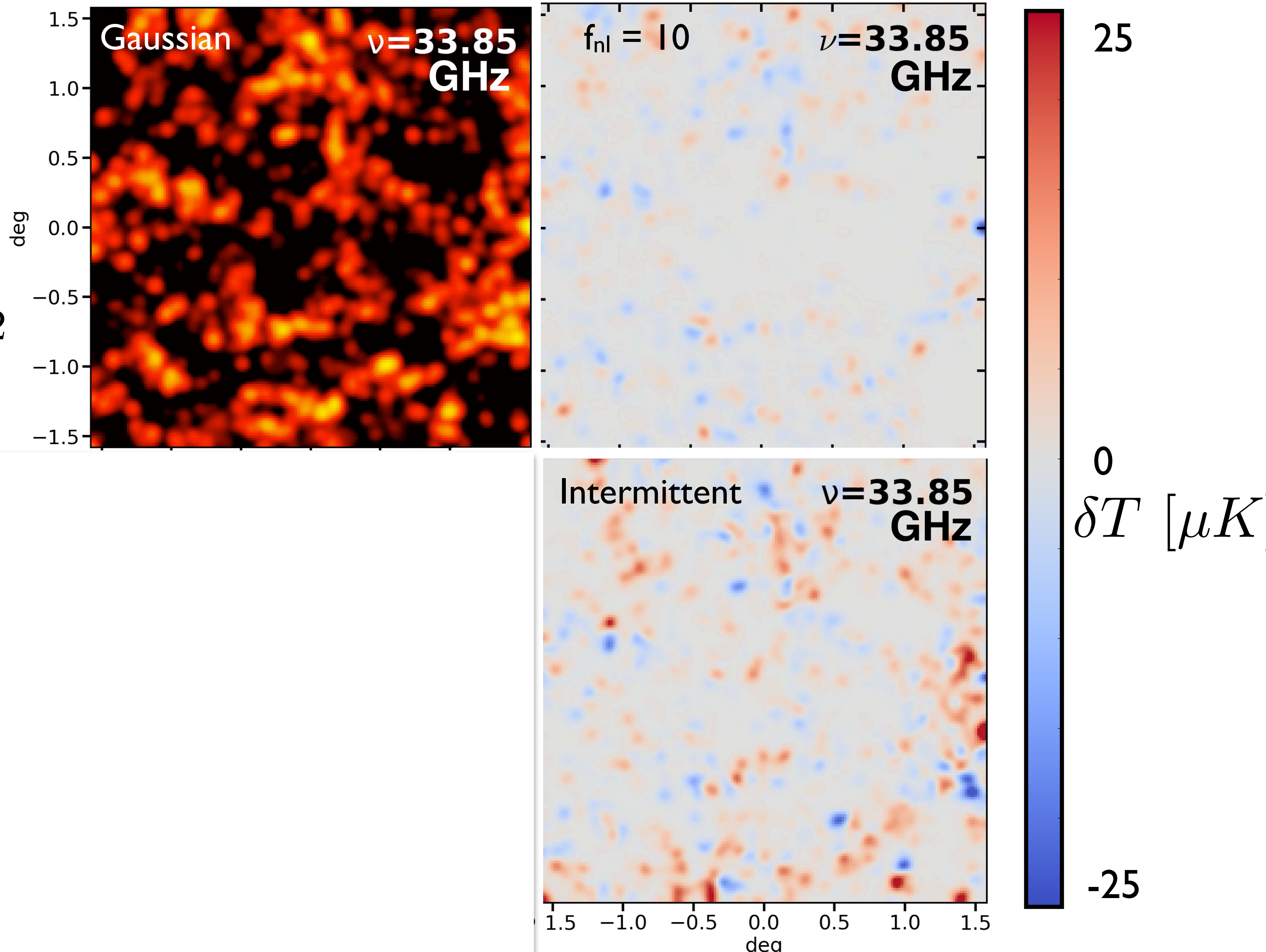


Bond , Huang, Stein; Braden, Morrison, …

Primordial Non-Gaussianity in CO; large scale => CHIME much larger volume is better

$\sigma_8 = 0.82$

In all cases



role of (2) ***instabilities during inflation***
phenomenology of in-states propagating through localized unstable potential structures to out-states, like scattering theory => **nonGaussianity**

role of "classical evolution/instabilities" in "particle creation" *(1) in heating* ✔ ***(2) during inflation***

*Bond+Braden+Frolov+****Morrison - work very much in experimental/exploratory phase***

map ballistic extreme-parameter-strain view of (pre-) heating into inflating regime i.e., role of classical instabilities during inflation, need to start with quantum fluctuations but then classical "particle creation"

what about particles? tie to entropy old & new way: $n_{Ak} \sim \rho_{Ak}/\hbar\omega_{Ak}(t) \sim \exp(\Delta s_{Ak})$

quantum fluctuations are there, but ***only as seeds for instabilities*** in which trajectories diverge: *little probability Gaussian blobs stretch into highly deformed elongated surfaces. "phase strings" in 2D, 3D*

history (for me). sbb87-89 $\langle \delta\mathscr{P}_{\phi^A\phi^A}(k) \,|\, \delta V, \delta m^2_{eff} \rangle, \;\; \langle \delta\mathscr{P}_{\zeta\zeta}(k) \,|\, \delta V(\phi,\chi) \text{ controls} \rangle$

multifield hybrid, mountains/valleys of extra power. role in non-Gaussianity. role of Higgs etal.

tool: full linearized k evolution, from inside to outside

build on vilenkin/starobinsky stochastic inflation: sb90, 91

used the attractor, aka reduced Hamilton principal function, $\mathbf{S_{reduced} \sim -2M_P^2 H}$ gives $\boldsymbol{\pi}_A$

B91 more general Langevin network leads to $P(\phi A, \boldsymbol{\pi}_A, H|\alpha)$ or better $P(\phi A, \boldsymbol{\pi}_A, H|Ha)$

=> nice expression in terms of quantum diffusion velocity/current

today:

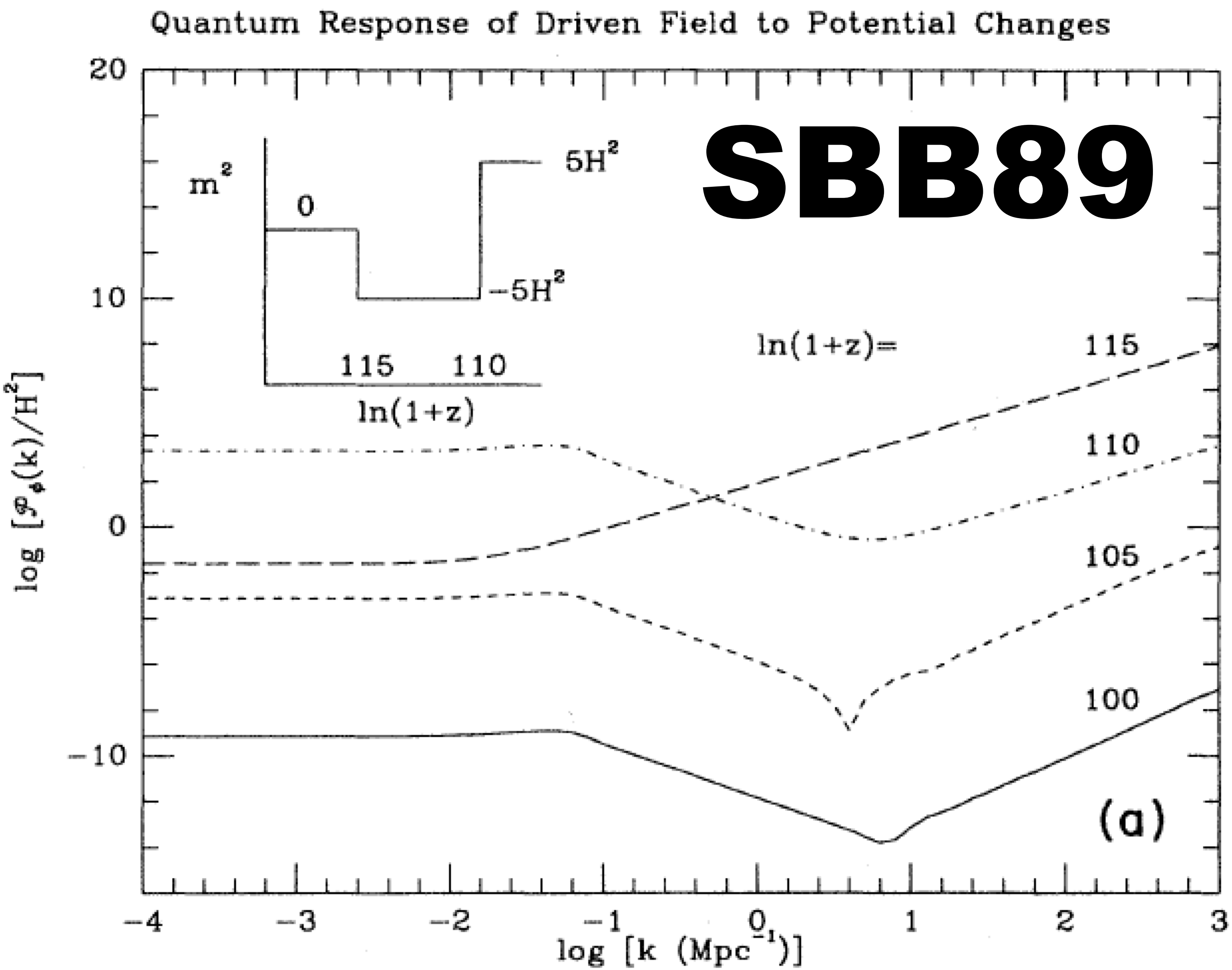
dilemma 1: missing terms in crossing horizon (coarse grain / fine grain flow)

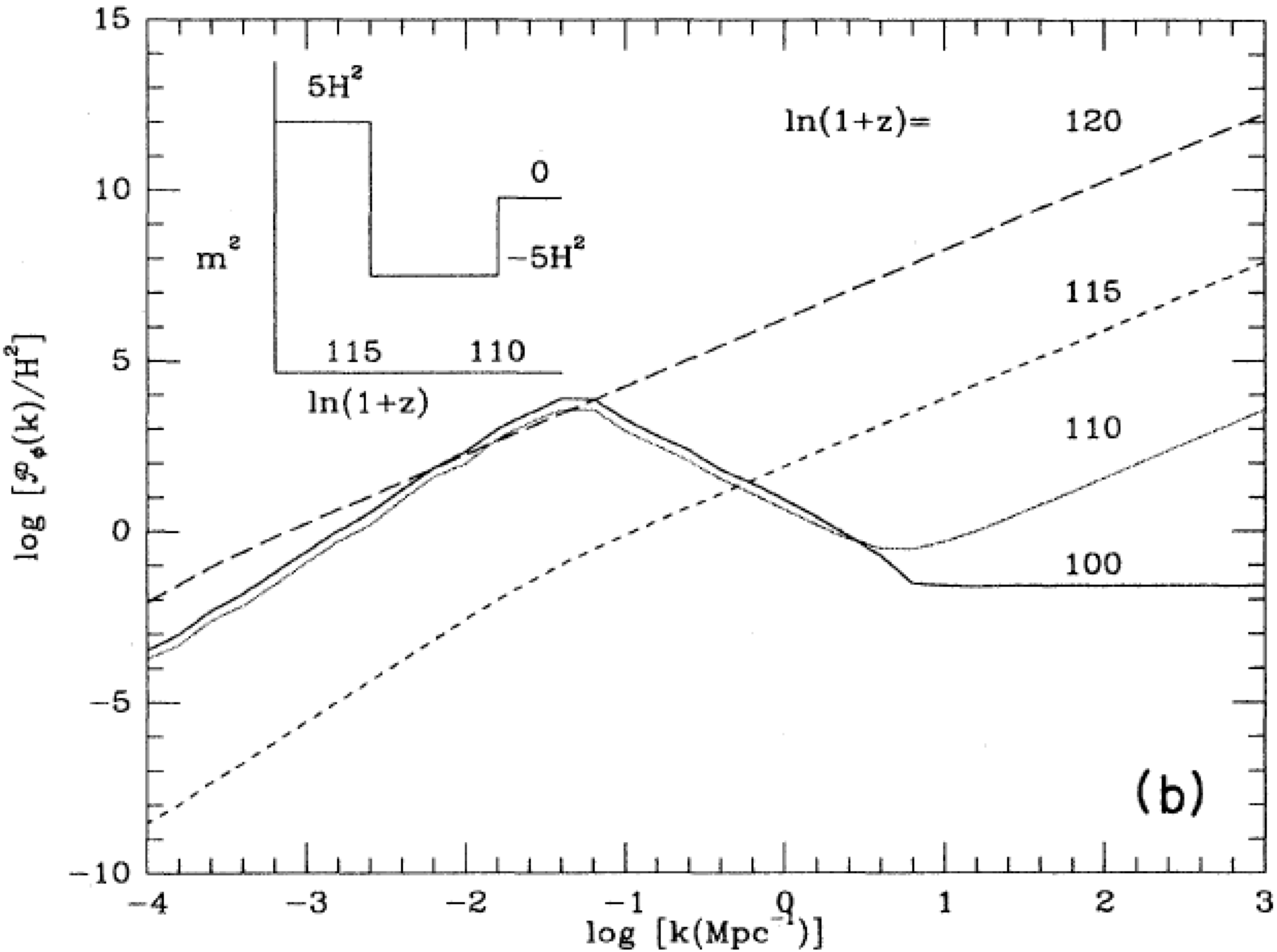
dilemma 2: outside horizon is a condensate. how to express this

dilemma 3: phase coherence as in classical realizations are useful

- incorporate via coherent state condensates and fluctuations upon them??

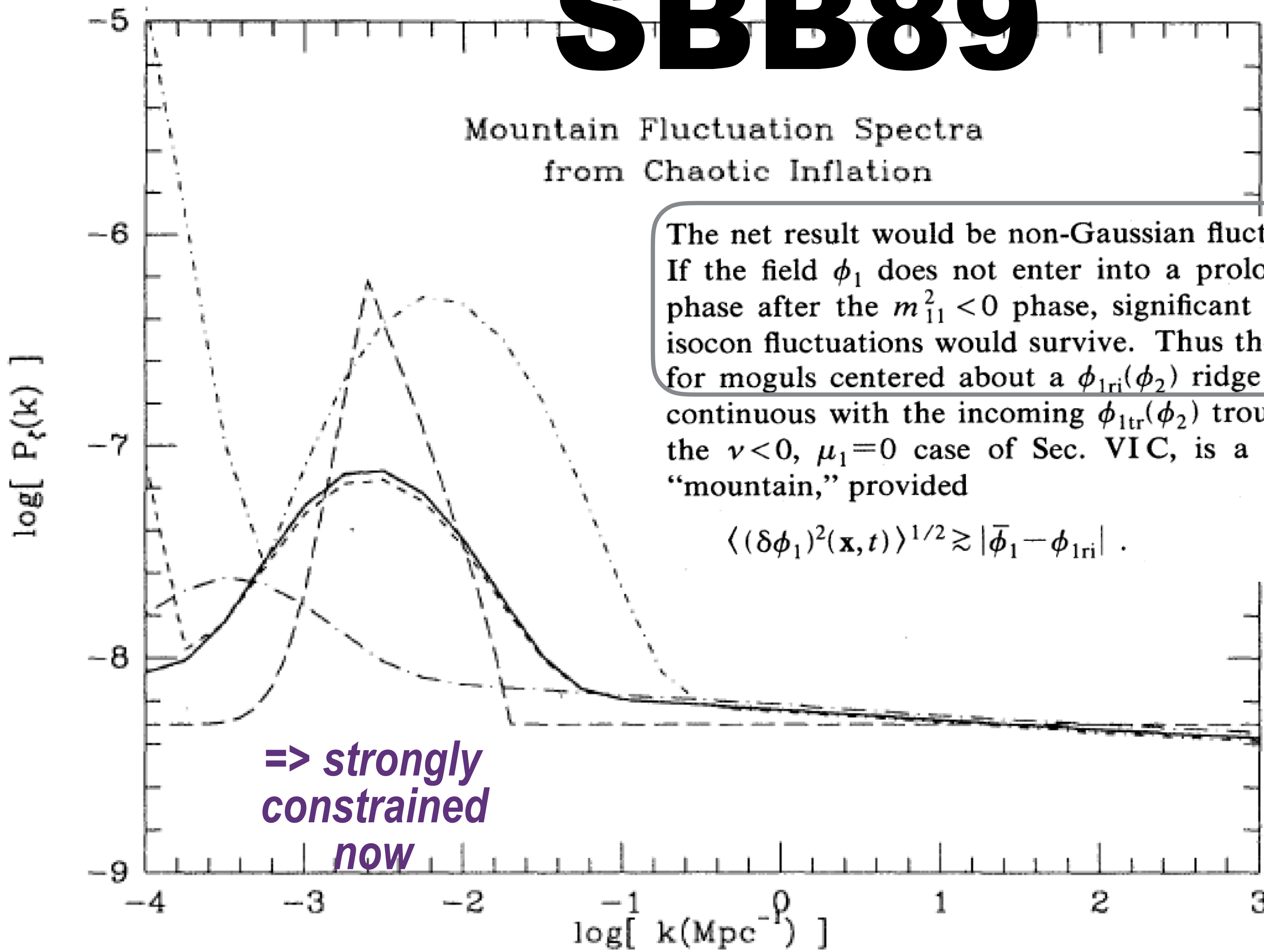
instabilities with quantum fluctuations the tiny seeds


Quantum Response of Driven Field to Potential Changes
SBB89
m²
0
5H²
−5H²
115
110
ln(1+z)
ln(1+z)=
115
110
105
100
(a)
log [𝒫φ(k)/H²]
log [k (Mpc⁻¹)]
20
10
0
−10
−4
−3
−2
−1
0
1
2
3



15
10
5
0
−5
−10
−4
−3
−2
−1
0
1
2
3
log [$\mathcal{P}_\phi(k)/H^2$]
log [k(Mpc^{-1})]
ln(1+z)=
120
115
110
100
m^2
$5H^2$
0
$-5H^2$
115
110
ln(1+z)
(b)

SBB89

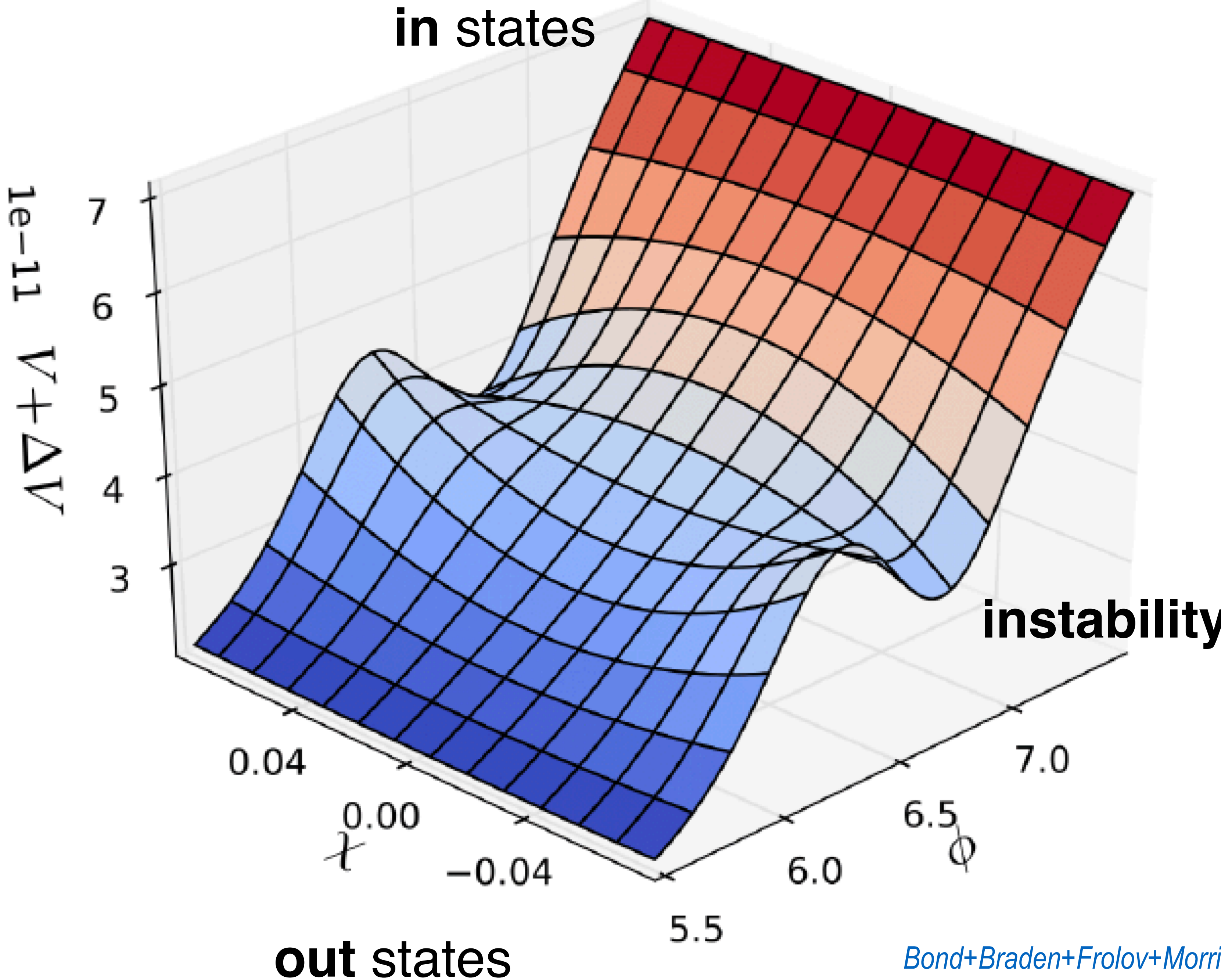


The net result would be non-Gaussian fluctuations in ϕ_2. If the field ϕ_1 does not enter into a prolonged $m_{11}^2>0$ phase after the $m_{11}^2<0$ phase, significant non-Gaussian isocon fluctuations would survive. Thus the generic case for moguls centered about a $\phi_{1ri}(\phi_2)$ ridge line which is continuous with the incoming $\phi_{1tr}(\phi_2)$ trough line, as in the $\nu<0$, $\mu_1=0$ case of Sec. VI C, is a non-Gaussian "mountain," provided

$$\langle(\delta\phi_1)^2(\mathbf{x},t)\rangle^{1/2} \gtrsim |\bar{\phi}_1-\phi_{1ri}| \ . \qquad (6.13)$$

=> lots of room for large ζ =>

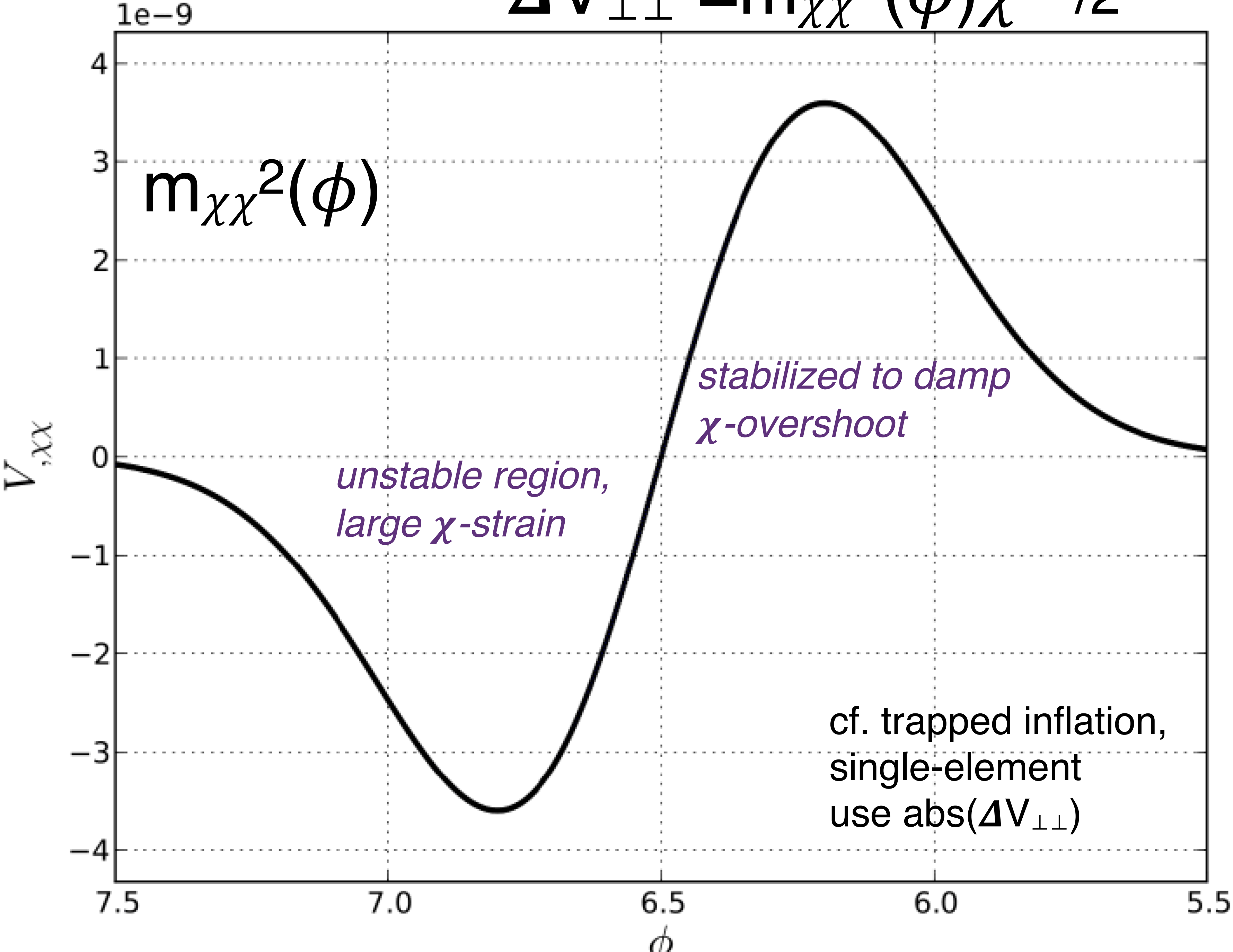
experiment χ-light



Bond+Braden+Frolov+Morrison

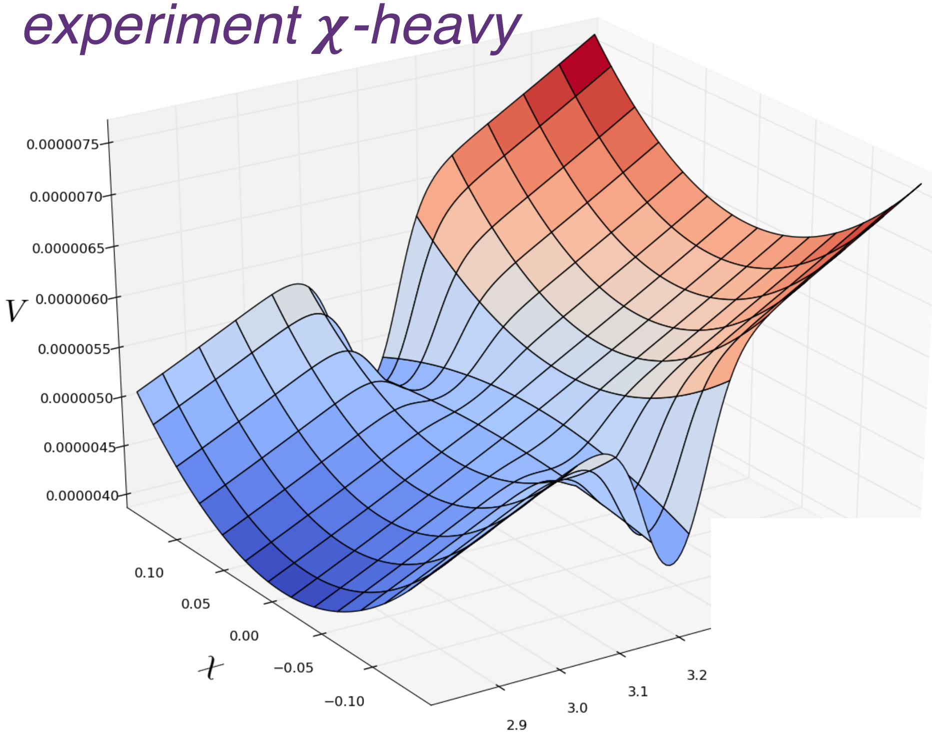
experiment χ-light

$$\Delta V_{\perp\perp} = m_{\chi\chi}^2(\phi)\chi^2 \; /2$$



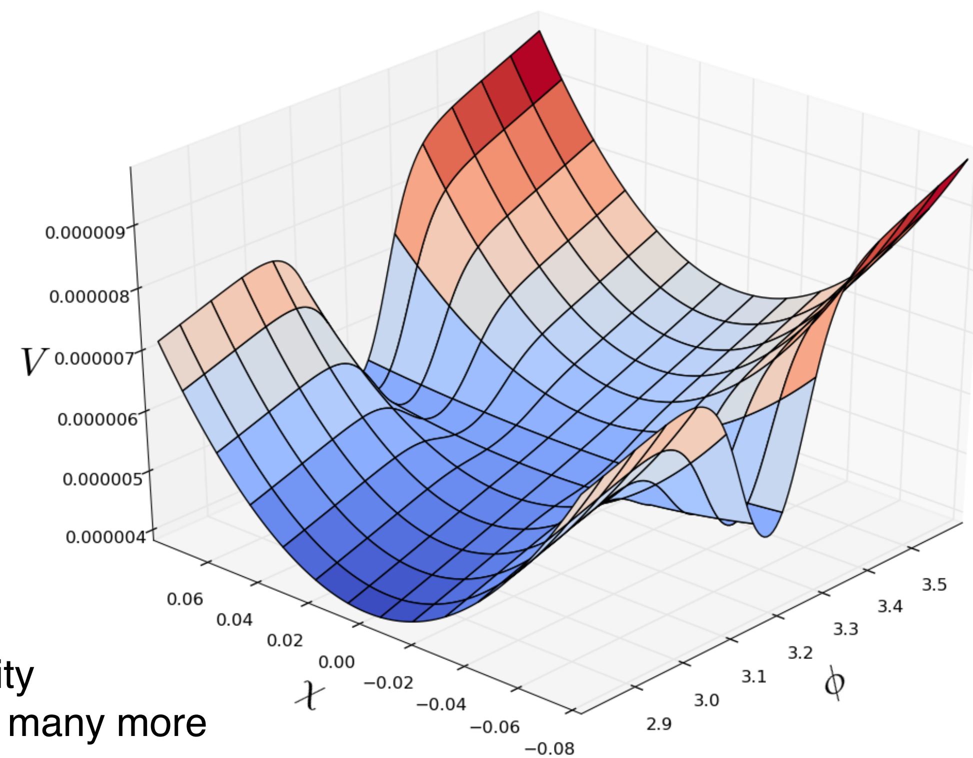
experiment χ-heavy

Bond+Braden+Frolov+Morrison



potential surface instability

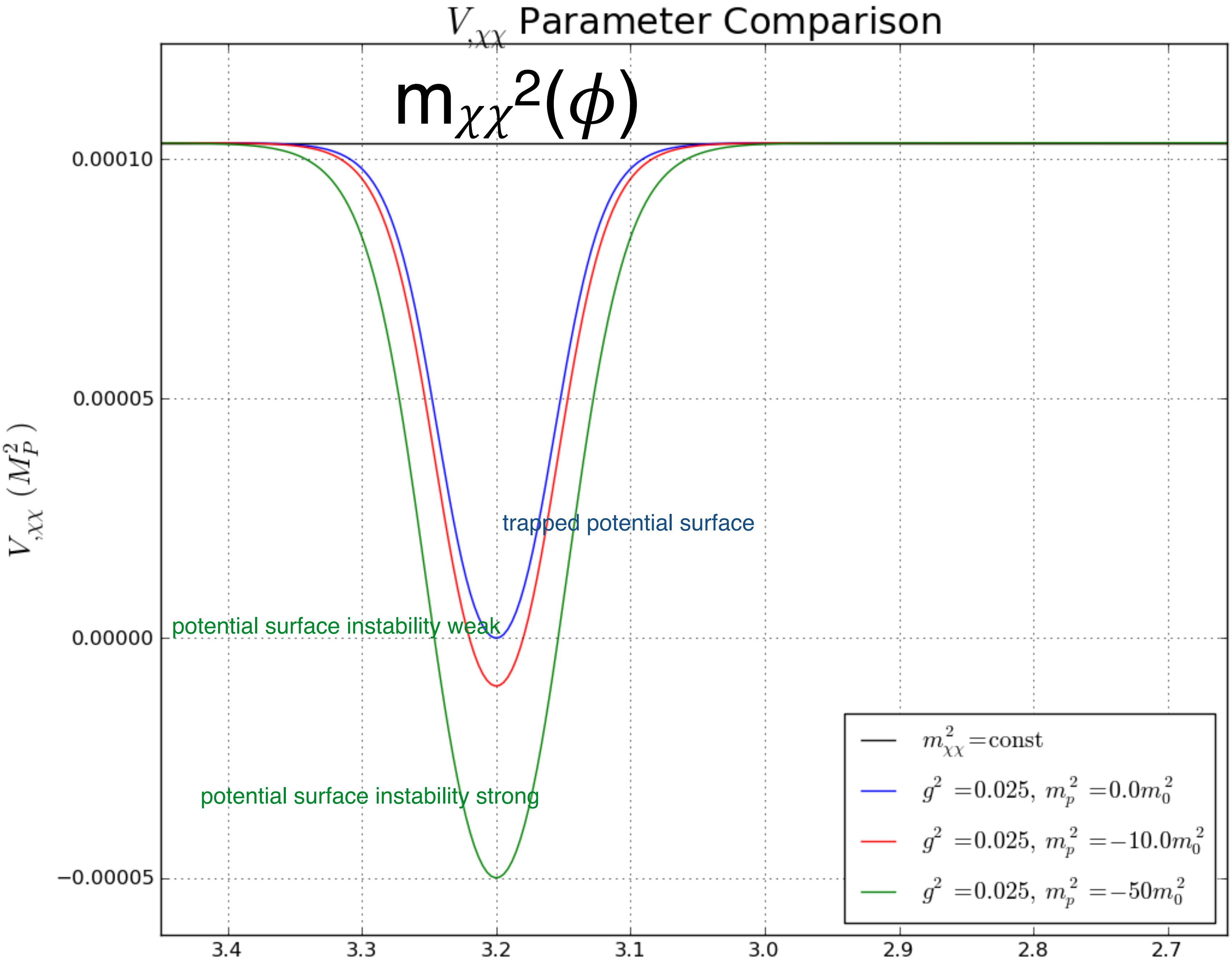
trapped potential surface

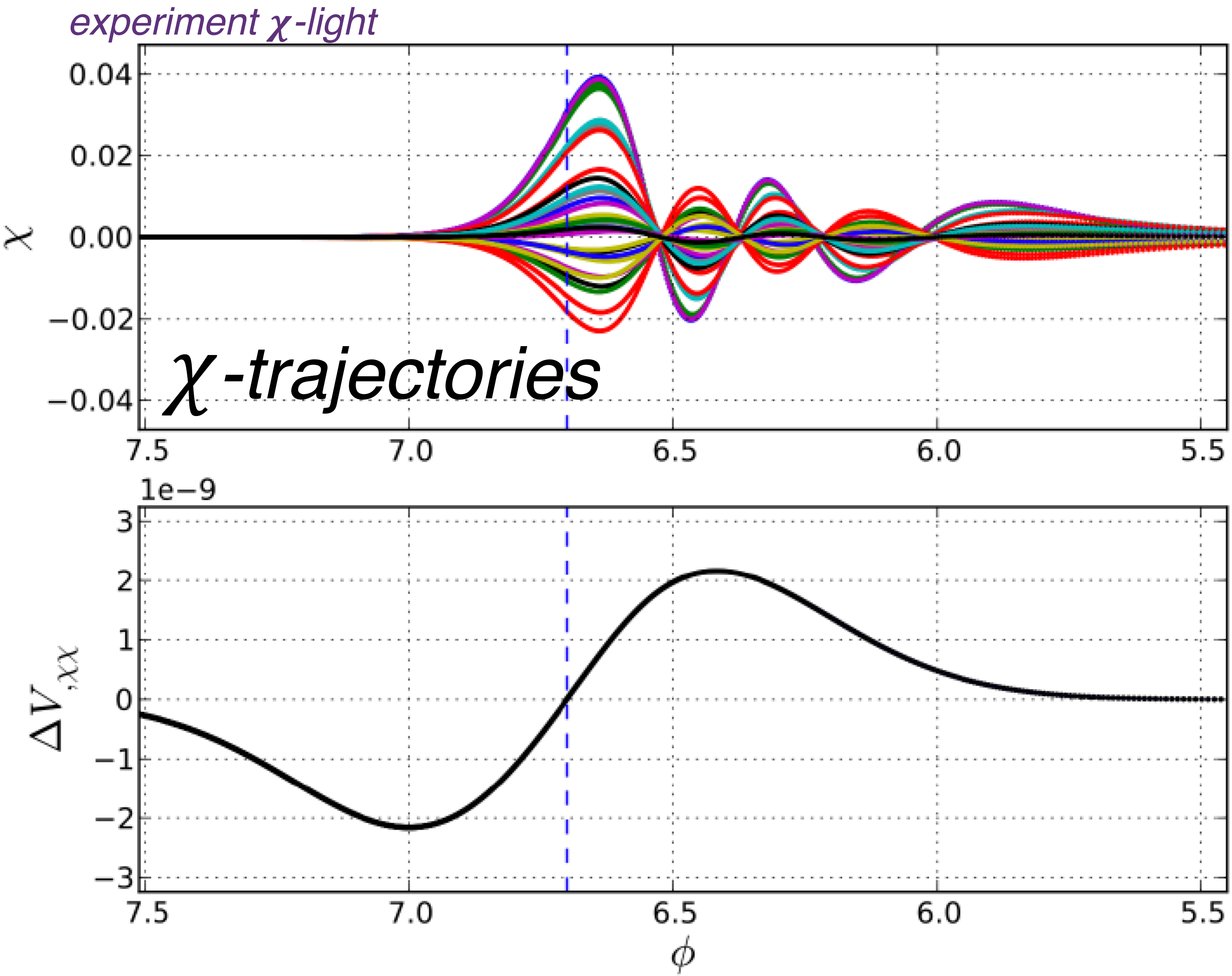


trapped inflation: *same parameters,* no instability

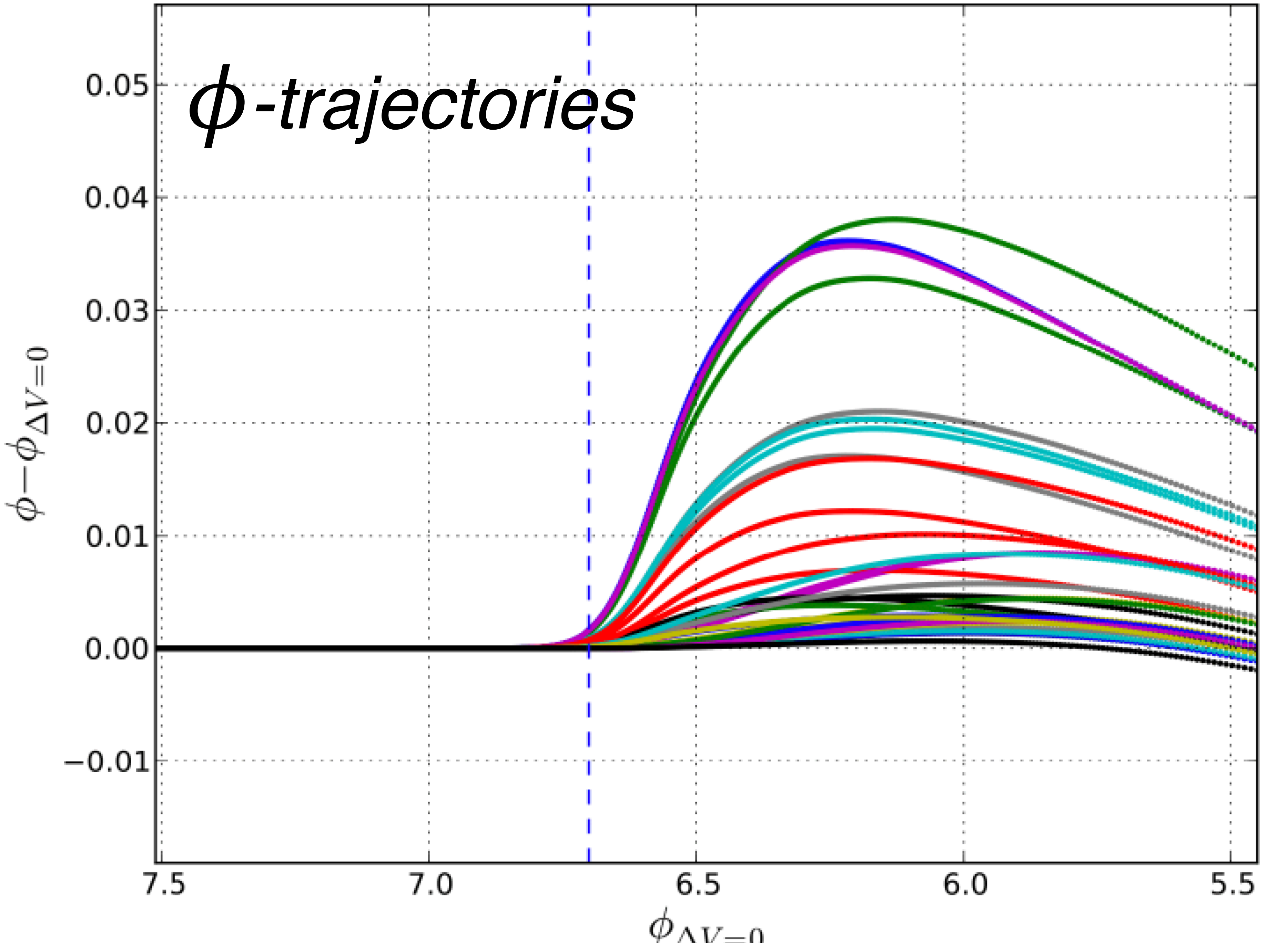
.. Kofman, Silverstein, Green, Barnaby, Huang, many more

experiment χ-heavy

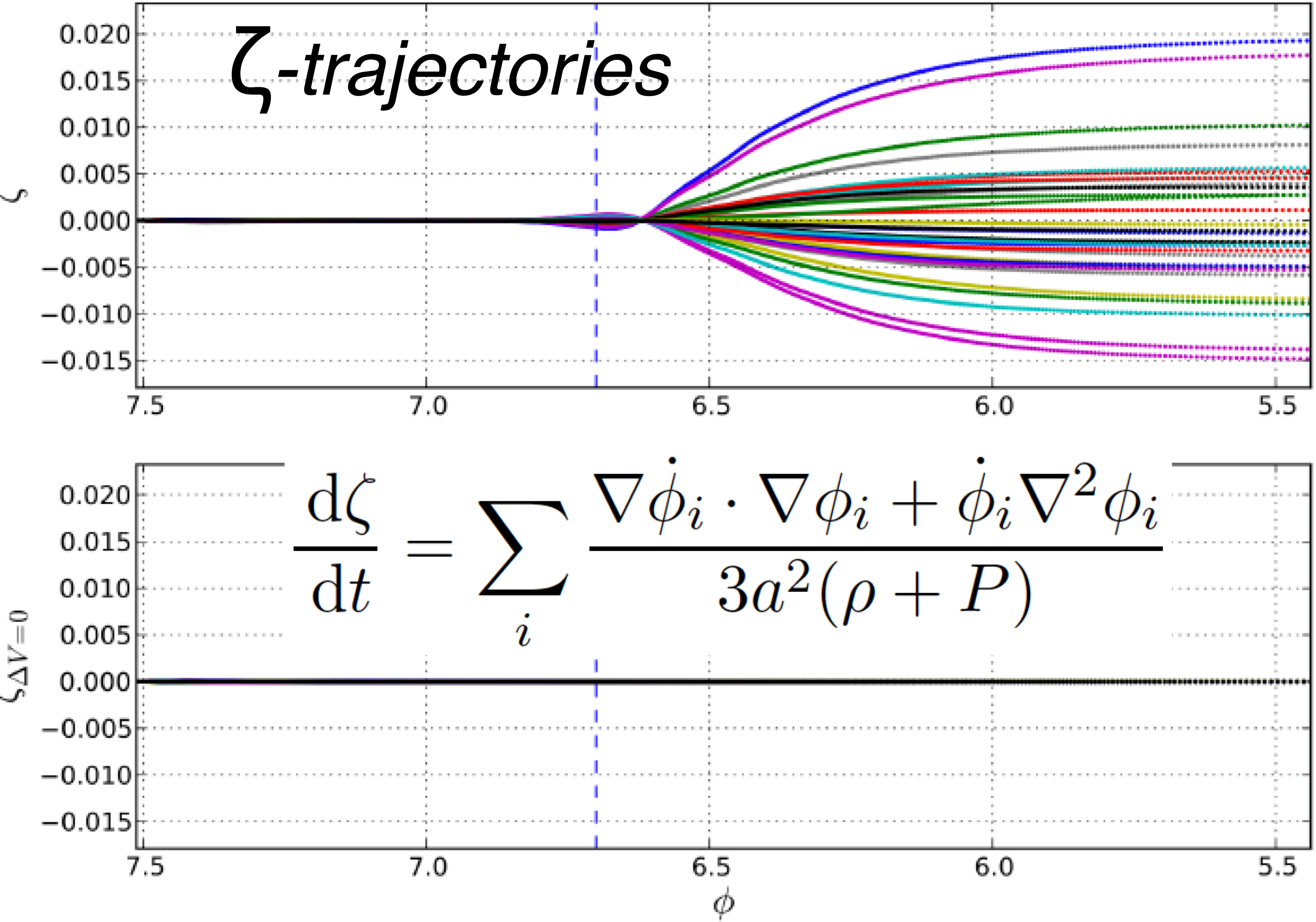



experiment χ-light
χ-trajectories
χ
0.04
0.02
0.00
−0.02
−0.04
7.5
7.0
6.5
6.0
5.5
1e−9
ΔV,χχ
3
2
1
0
−1
−2
−3
ϕ

experiment χ-light

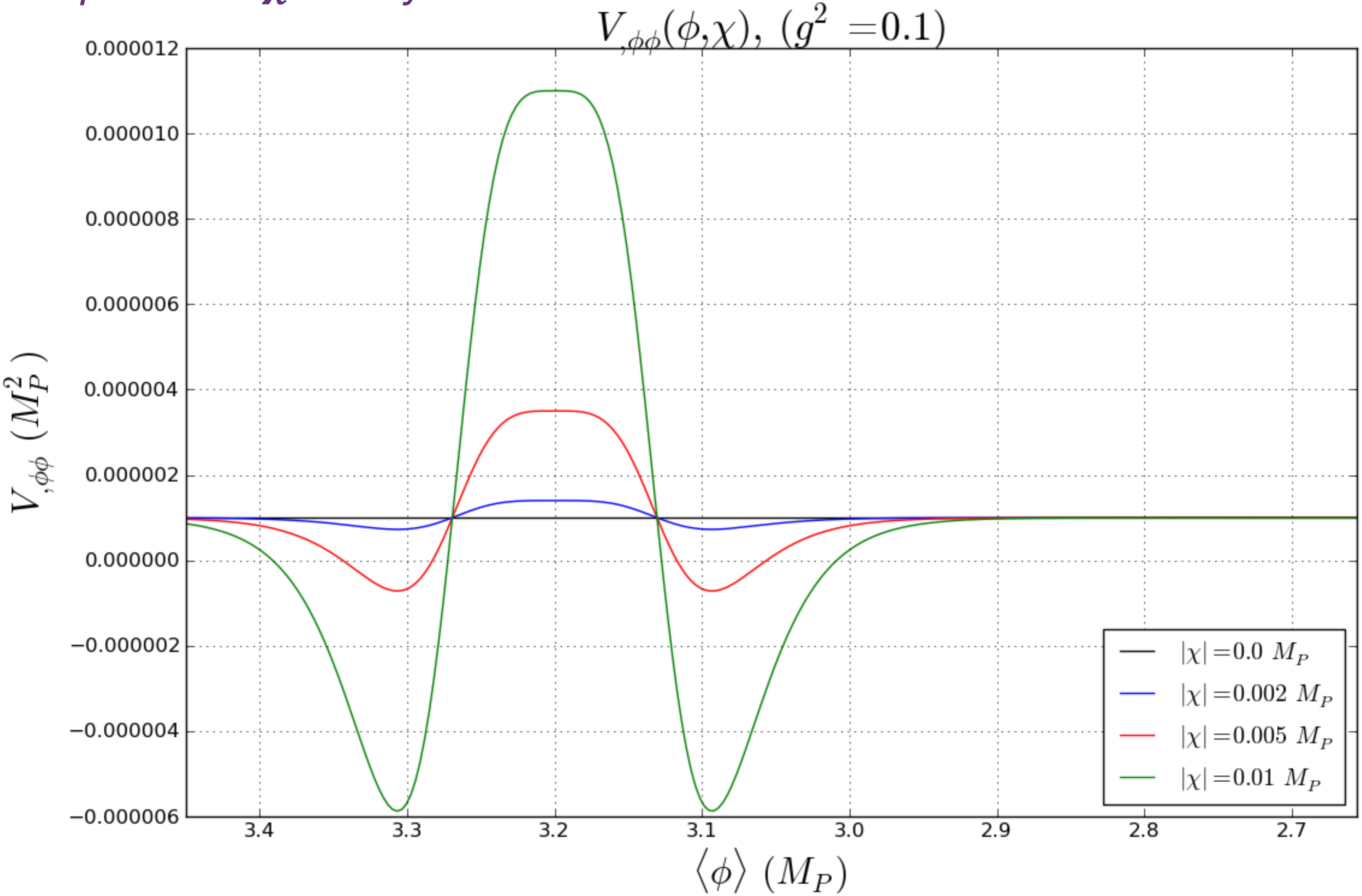


experiment χ-light

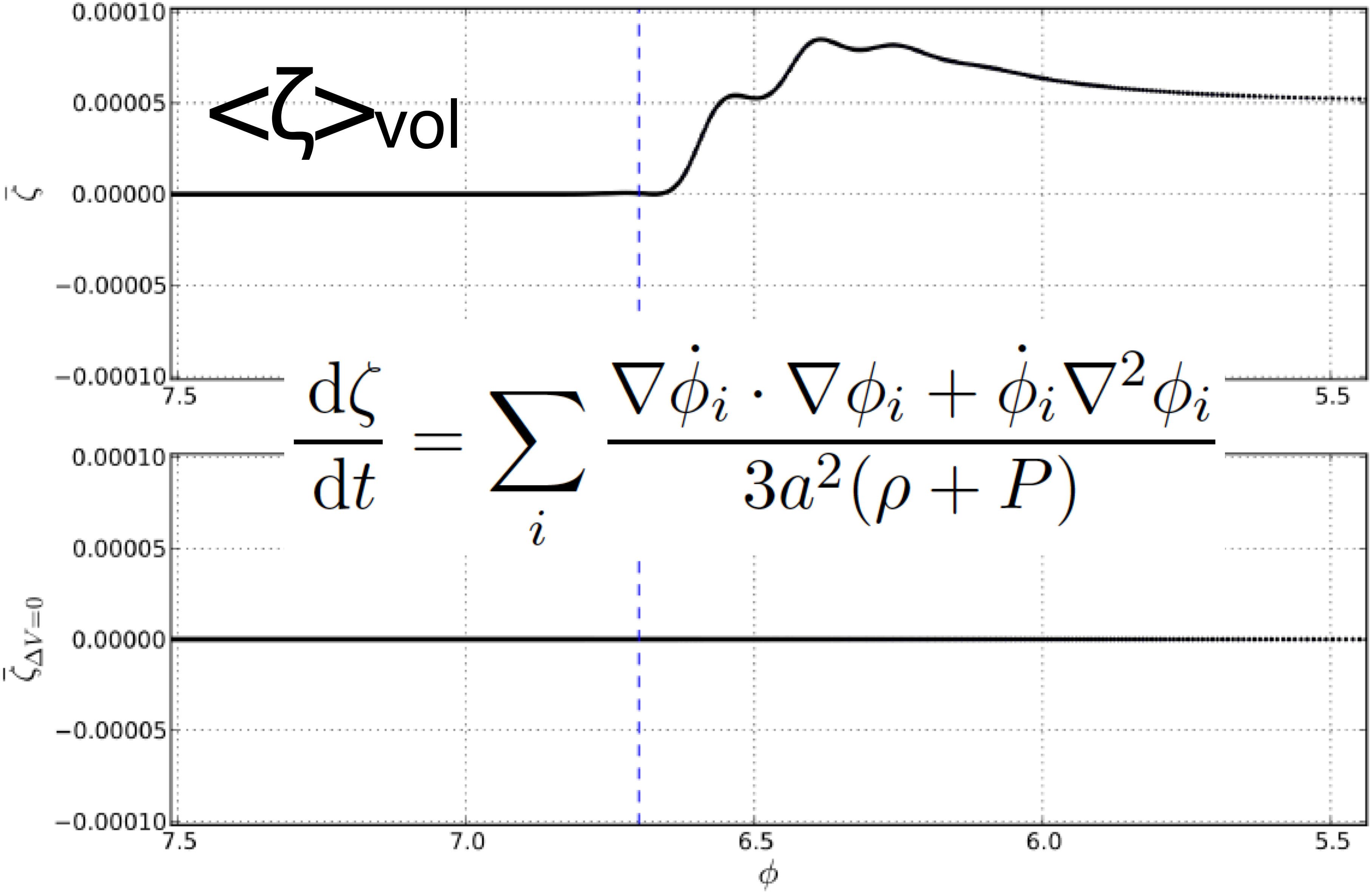


$$\frac{\mathrm{d}\zeta}{\mathrm{d}t} = \sum_i \frac{\nabla\dot{\phi}_i \cdot \nabla\phi_i + \dot{\phi}_i \nabla^2 \phi_i}{3a^2(\rho + P)}$$

experiment χ-heavy

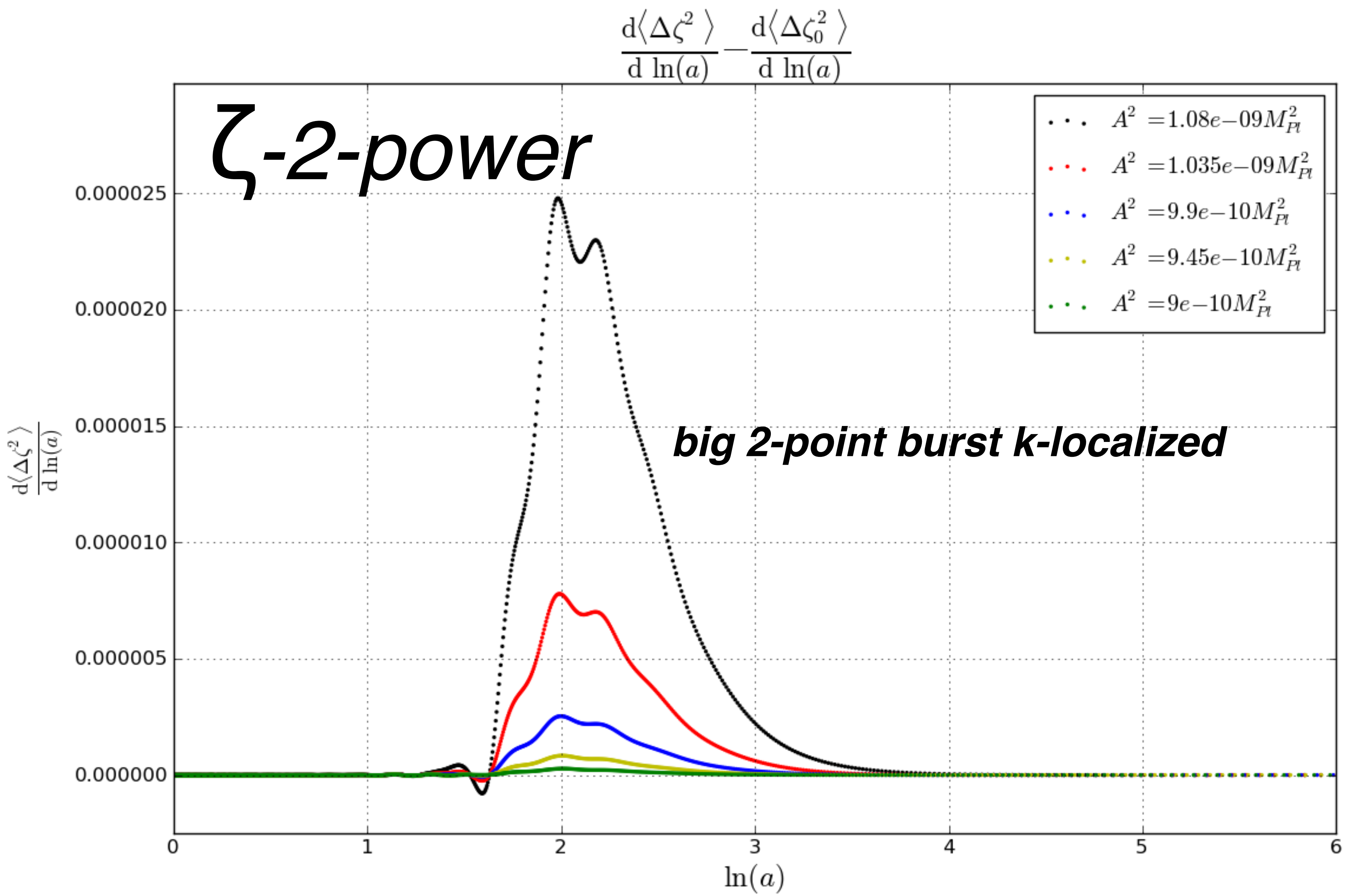


experiment χ-light

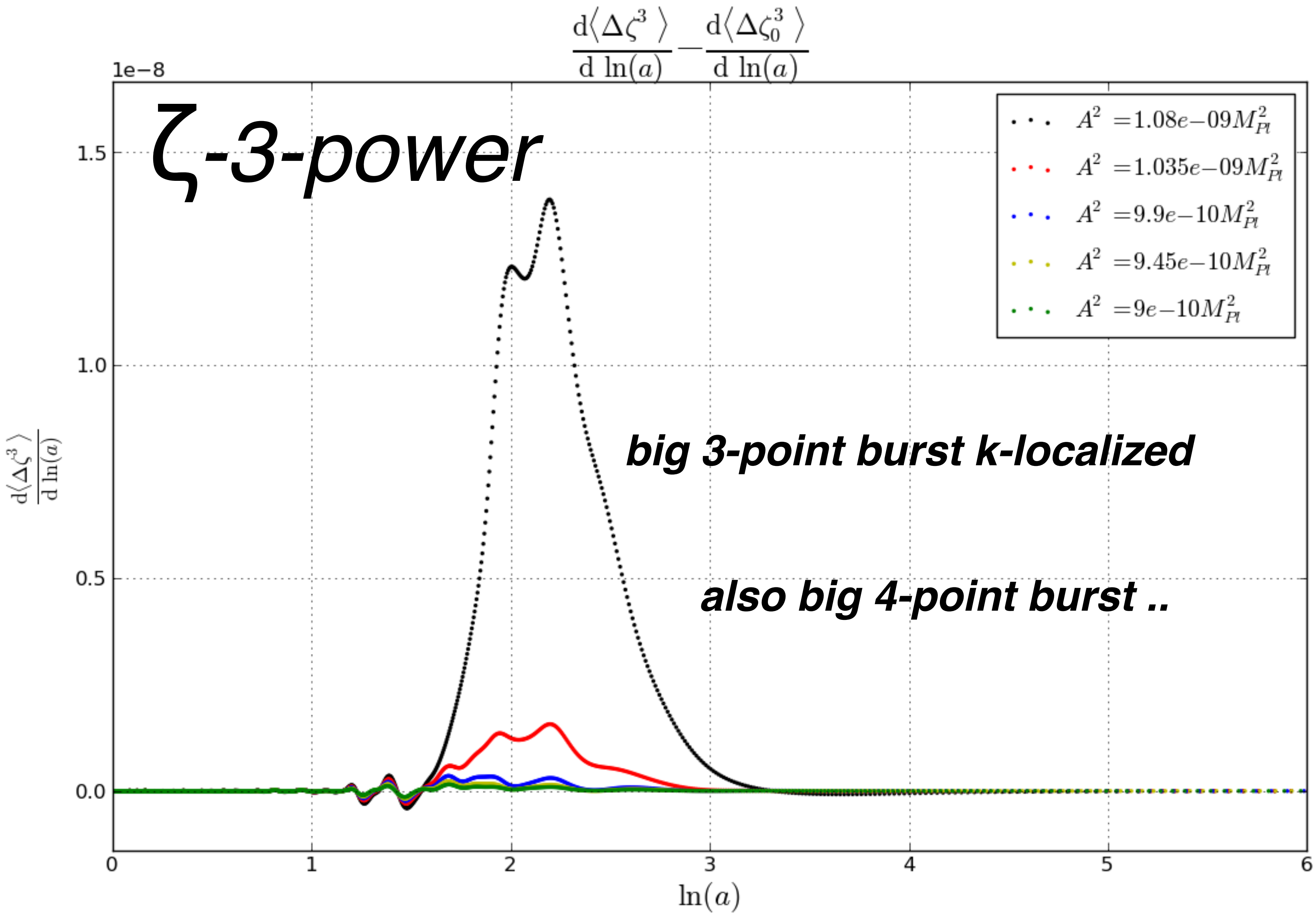


$$\frac{\mathrm{d}\zeta}{\mathrm{d}t} = \sum_i \frac{\nabla\dot{\phi}_i \cdot \nabla\phi_i + \dot{\phi}_i \nabla^2\phi_i}{3a^2(\rho + P)}$$

experiment χ-light



experiment χ-light



occupation numbers & particle creation ~ “Gaussian entropy” in the single A-field

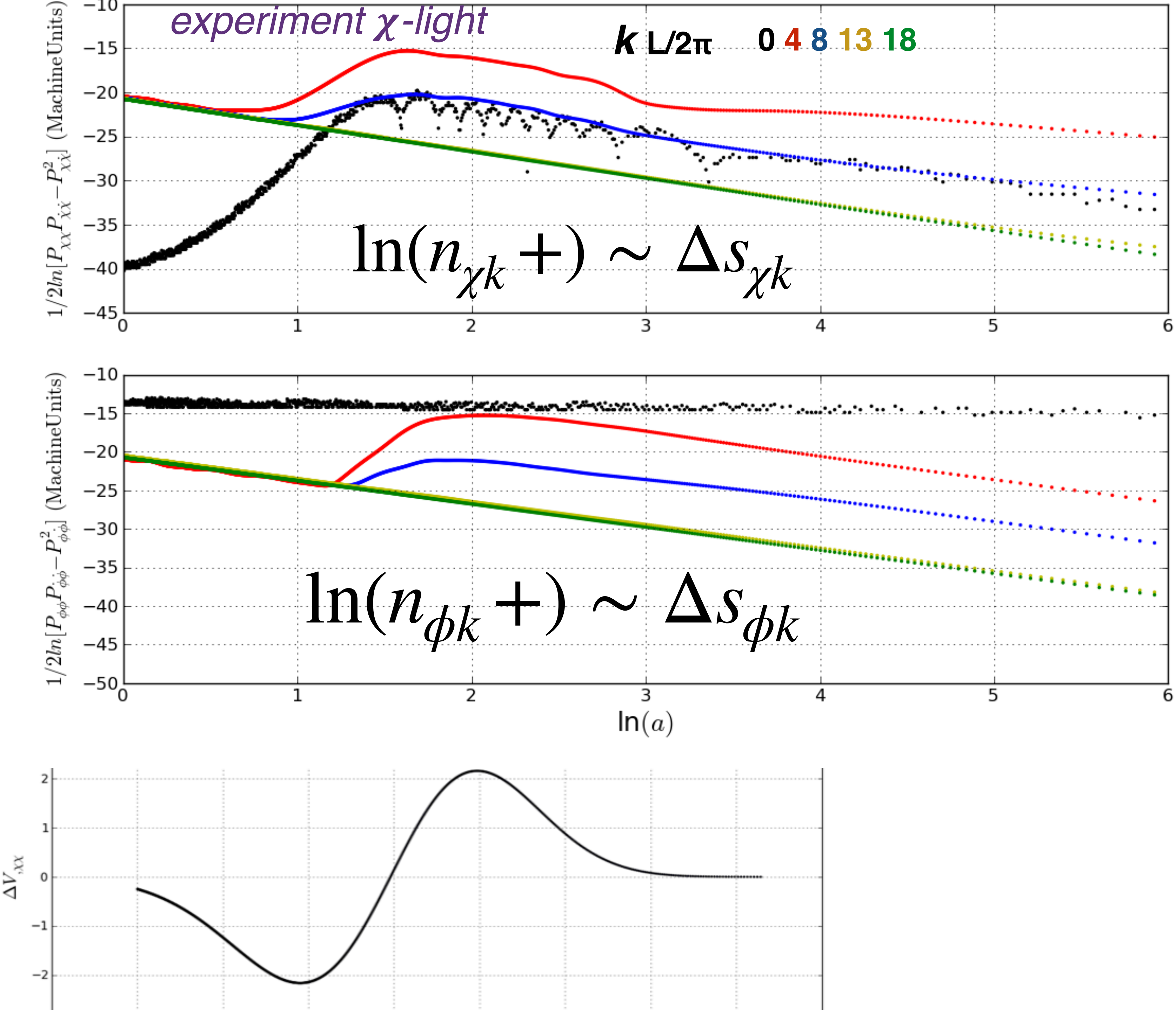
$$\ln(n_{\phi^A k} +) \sim \Delta s_{\phi^A k} \sim \qquad \frac{1}{2}\mathrm{Trace}\,\ln[C_{\phi^A\phi^A}C_{\Pi_A\Pi_A} - C^2_{\phi^A\Pi_A}]$$

occupation ~ $n_{Ak} \sim e^{\Delta s_{Ak}}$

old way if well defined mode energies $\omega_{Ak}(t) \qquad \ln(n_{Ak} + 1/2) \sim \ln[\rho_A/\hbar\omega_{Ak}]$

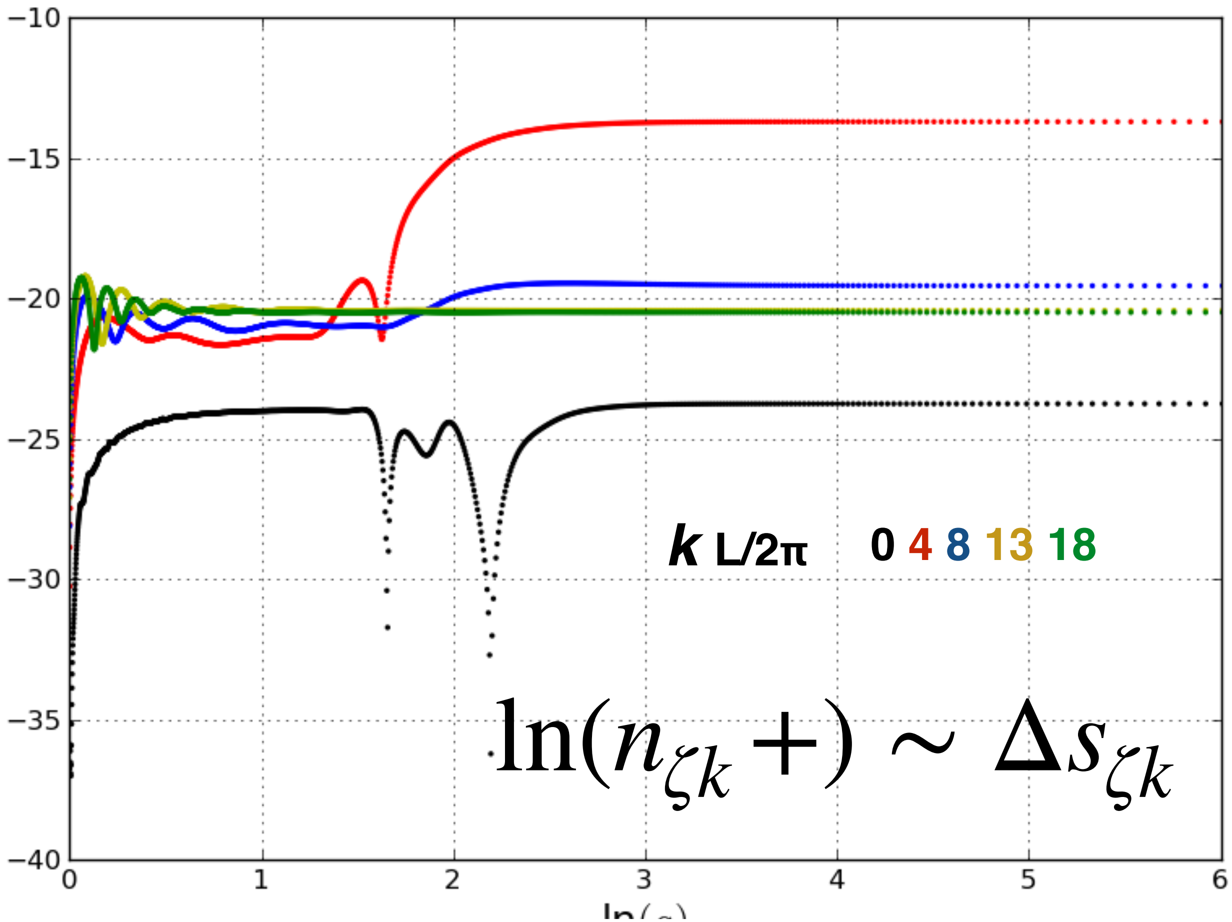
full “Gaussian entropy” in the 2 fields, C are k-mode correlations = power spectra - generalized Sackur-Tetrode

$$\Delta s_{A+B,k} = \frac{1}{2}\mathrm{Trace}\,\ln[C_{\phi^A\phi^B}C_{\Pi^A\Pi^B} - C_{\phi^A\Pi^B}C_{\Pi^A\phi^B}]$$

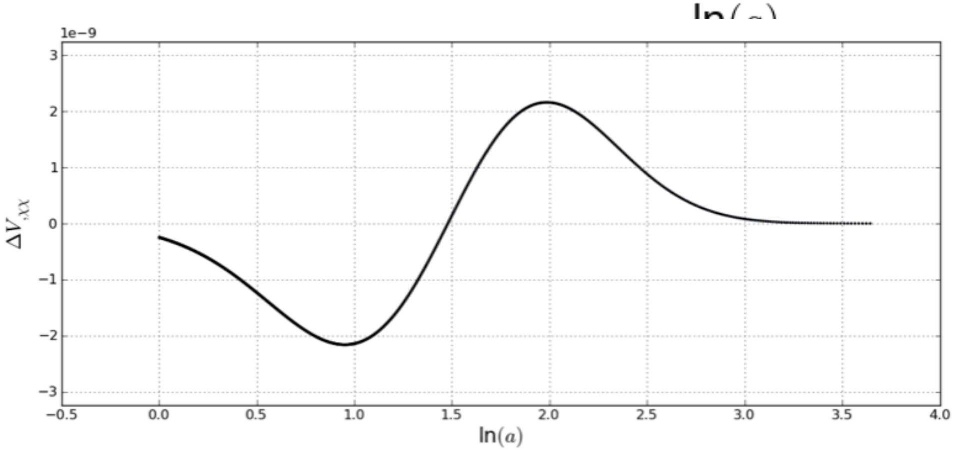

experiment χ-light
k L/2π 0 4 8 13 18
ln(n_χk +) ~ Δs_χk
1/2ln[P_χχ P_χ̇χ̇ − P²_χχ̇] (MachineUnits)
ln(n_φk +) ~ Δs_φk
1/2ln[P_φφ P_φ̇φ̇ − P²_φφ̇] (MachineUnits)
ln(a)
ΔV,χχ

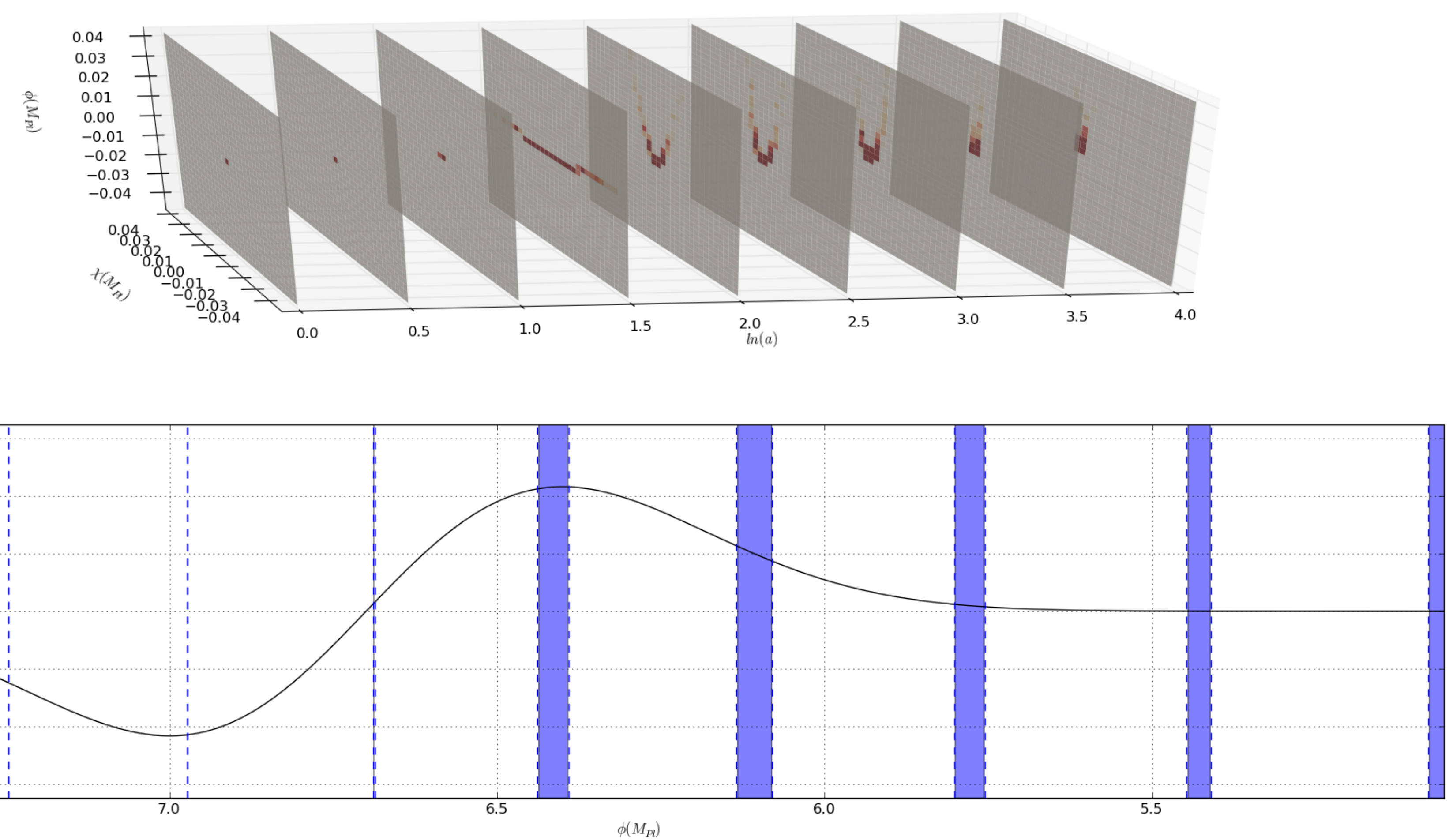
experiment χ-light

$\ln(P_{\zeta\zeta})$

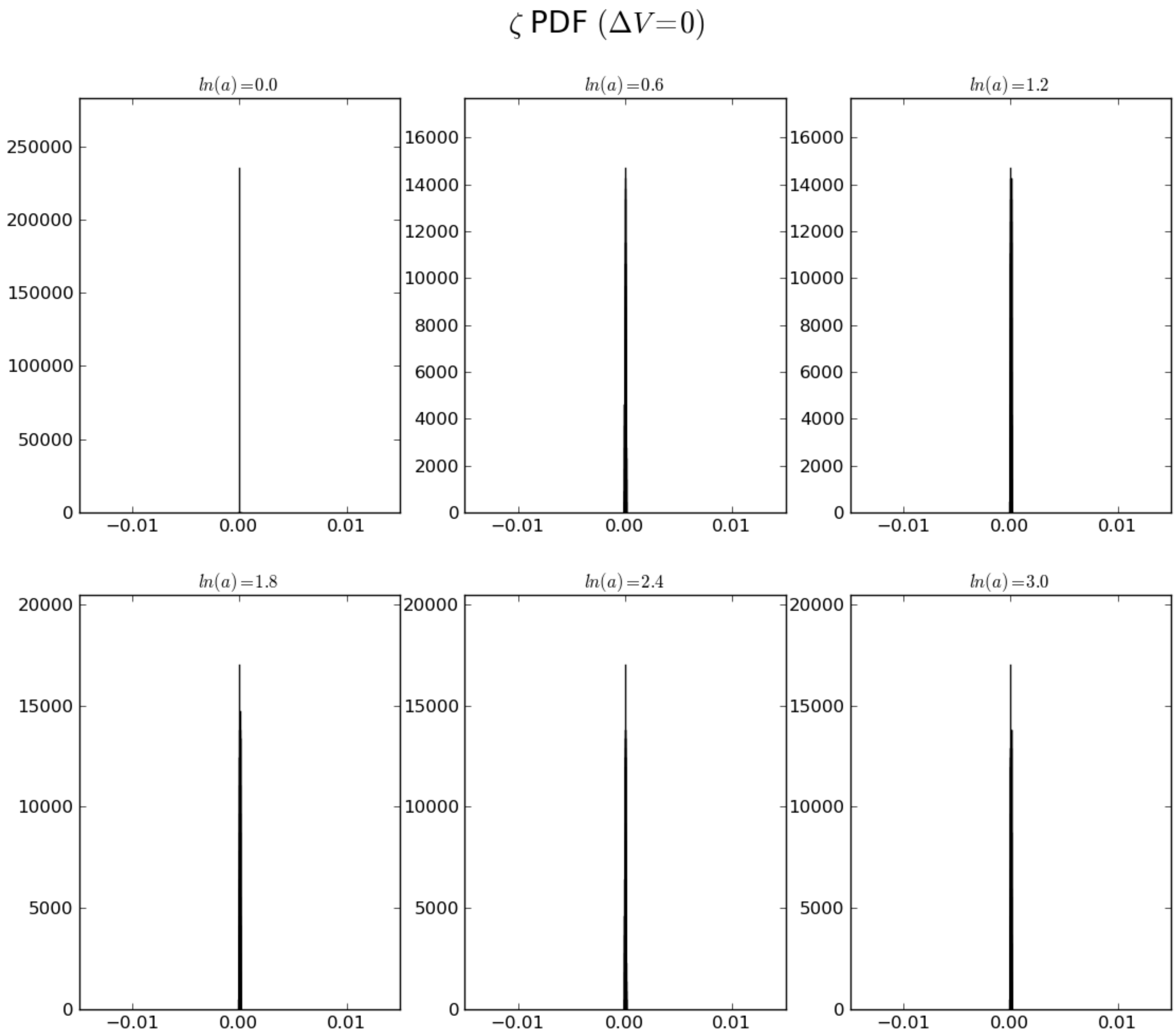


phonon occupation

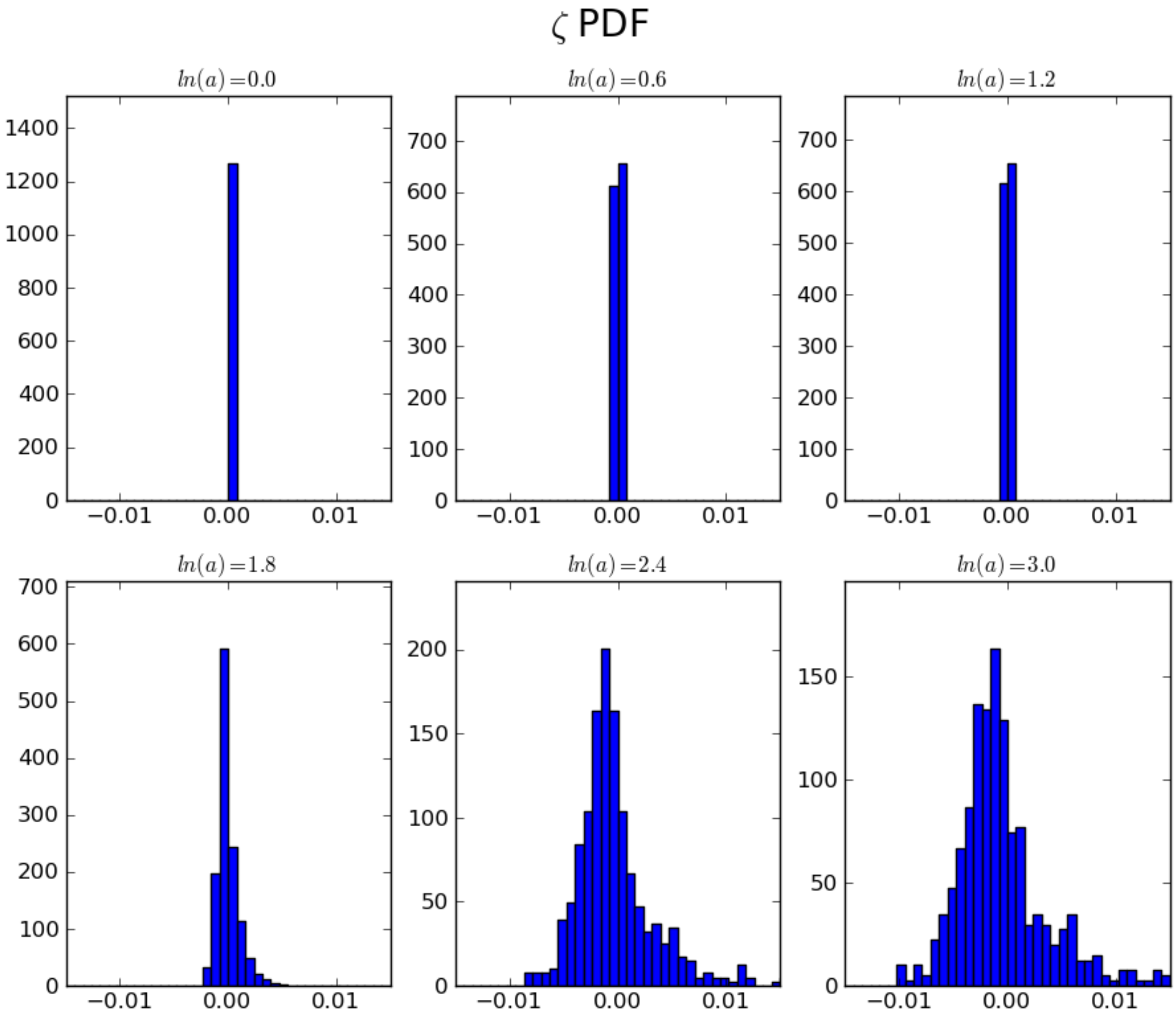




0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
$\phi(M_{Pl})$
$\chi(M_{Pl})$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
$ln(a)$
1e−9
3
2
1
0
−1
−2
−3
$\Delta V_{,\chi\chi}$
7.5
7.0
6.5
6.0
5.5
$\phi(M_{Pl})$

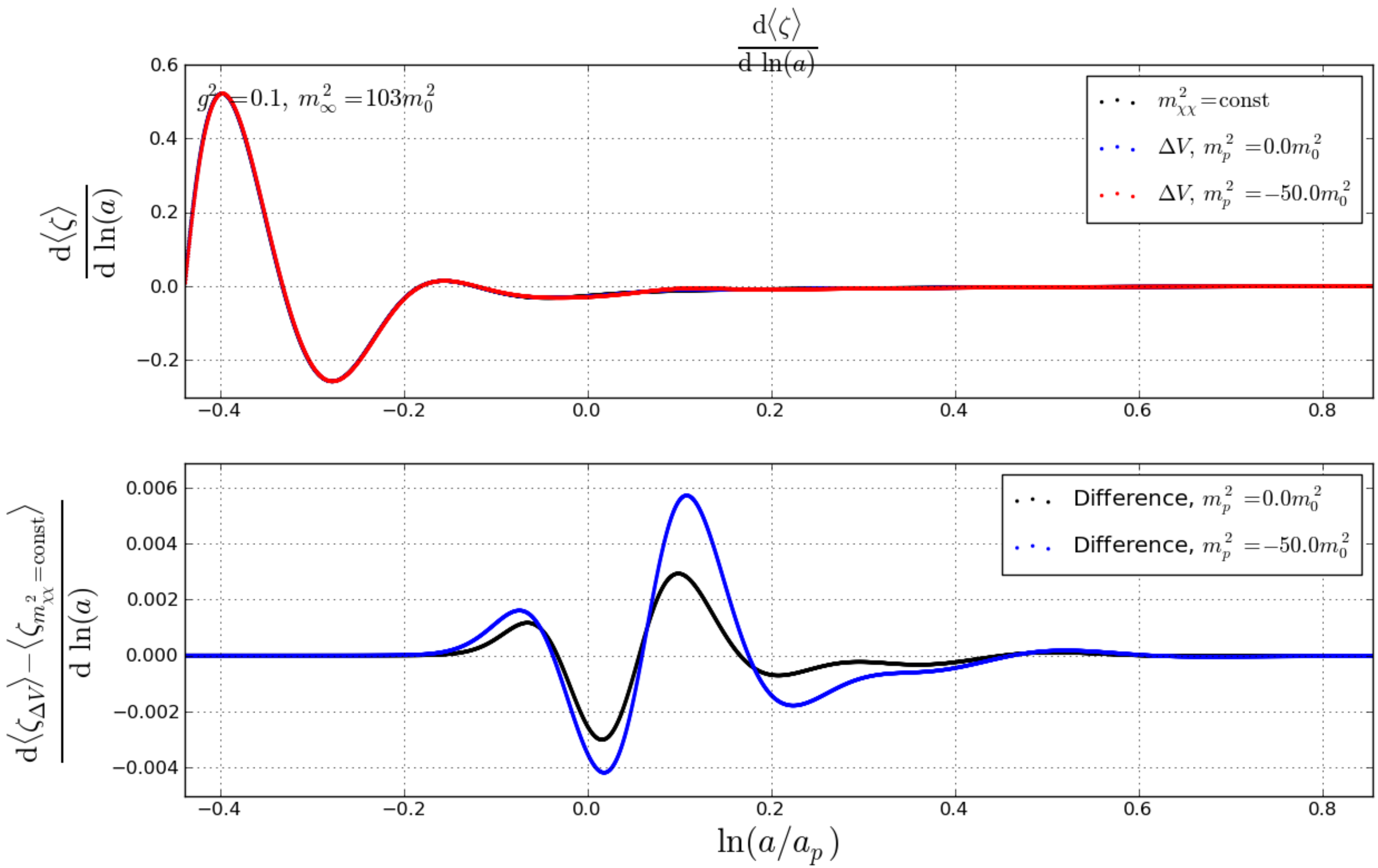


ζ PDF (ΔV=0)
ln(a)=0.0
ln(a)=0.6
ln(a)=1.2
ln(a)=1.8
ln(a)=2.4
ln(a)=3.0
250000
200000
150000
100000
50000
0
16000
14000
12000
10000
8000
6000
4000
2000
20000
15000
10000
5000
−0.01
0.00
0.01

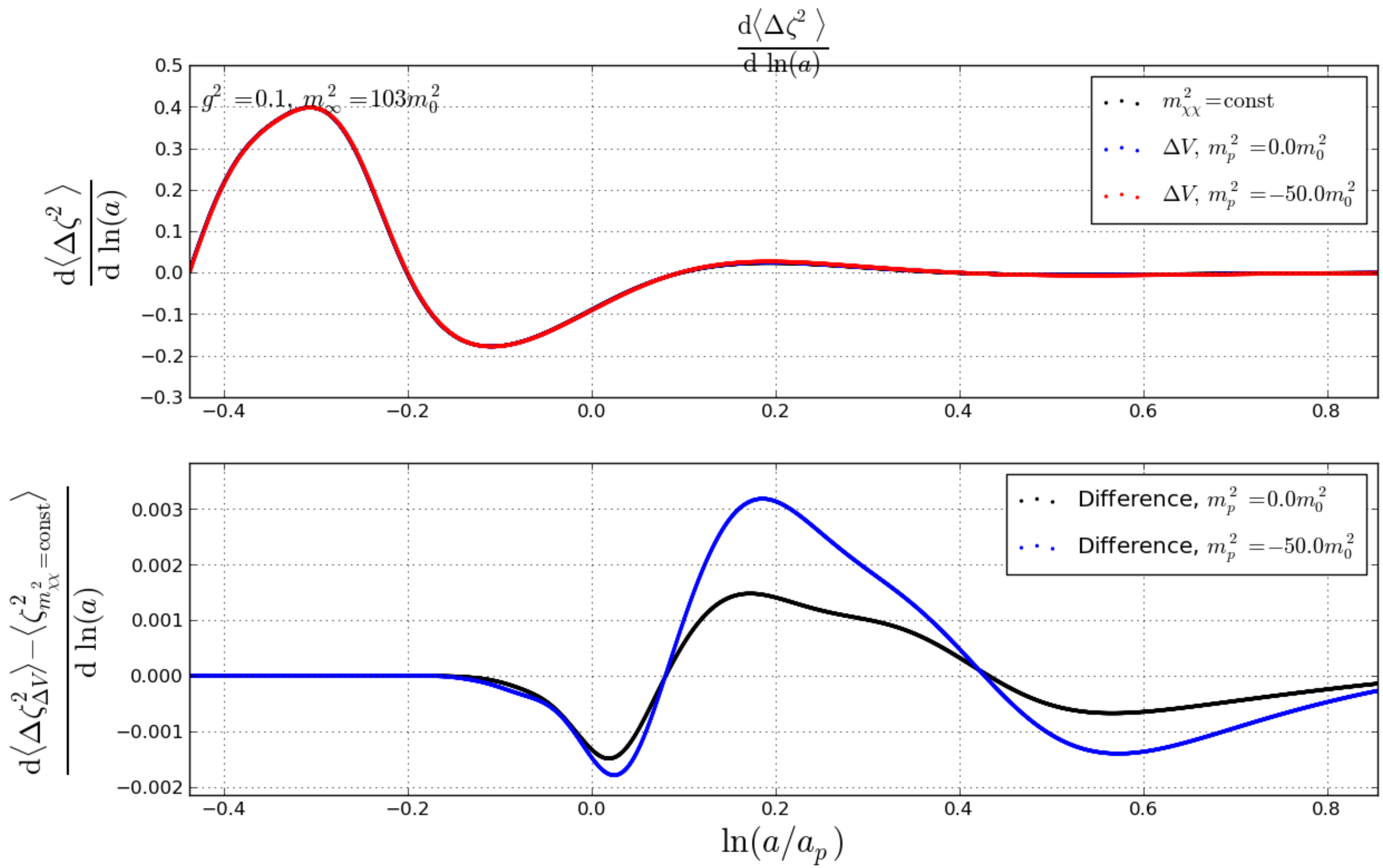


ζ PDF
ln(a)=0.0
ln(a)=0.6
ln(a)=1.2
ln(a)=1.8
ln(a)=2.4
ln(a)=3.0
1400
1200
1000
800
600
400
200
0
700
500
300
100
150
50
−0.01
0.00
0.01

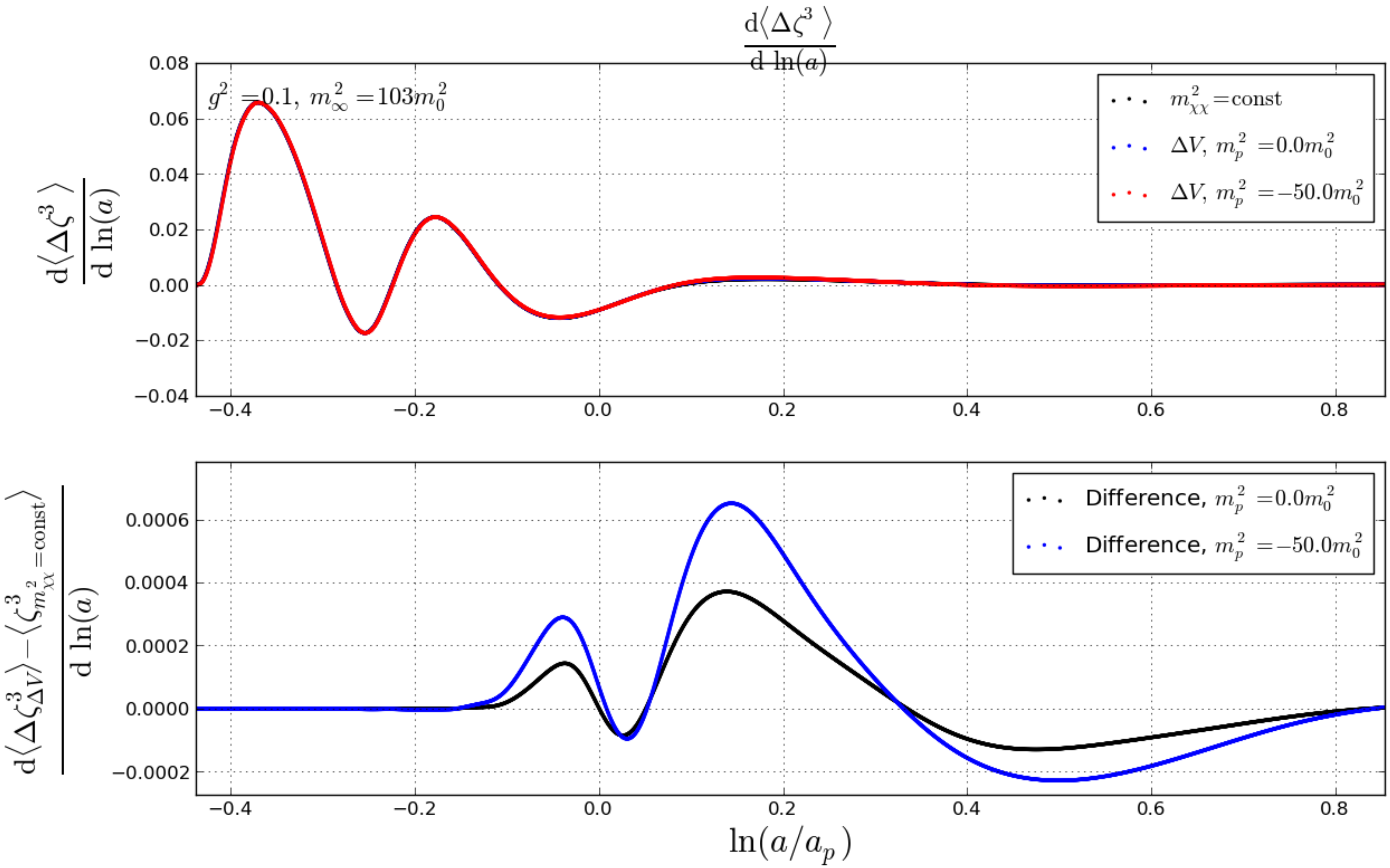
experiment χ-heavy *unstable χ cf. trapped*



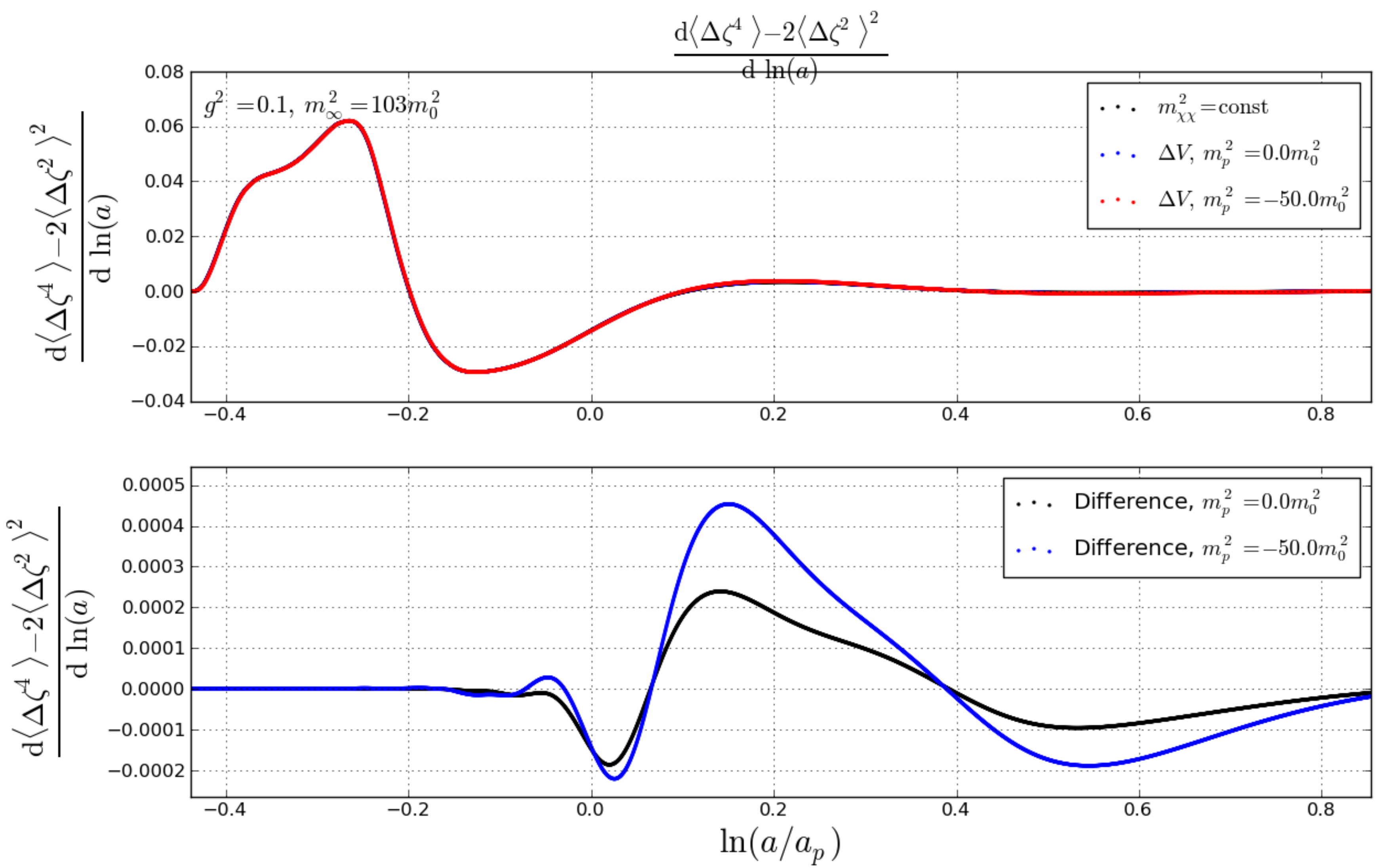
experiment χ-heavy *unstable χ cf. trapped*



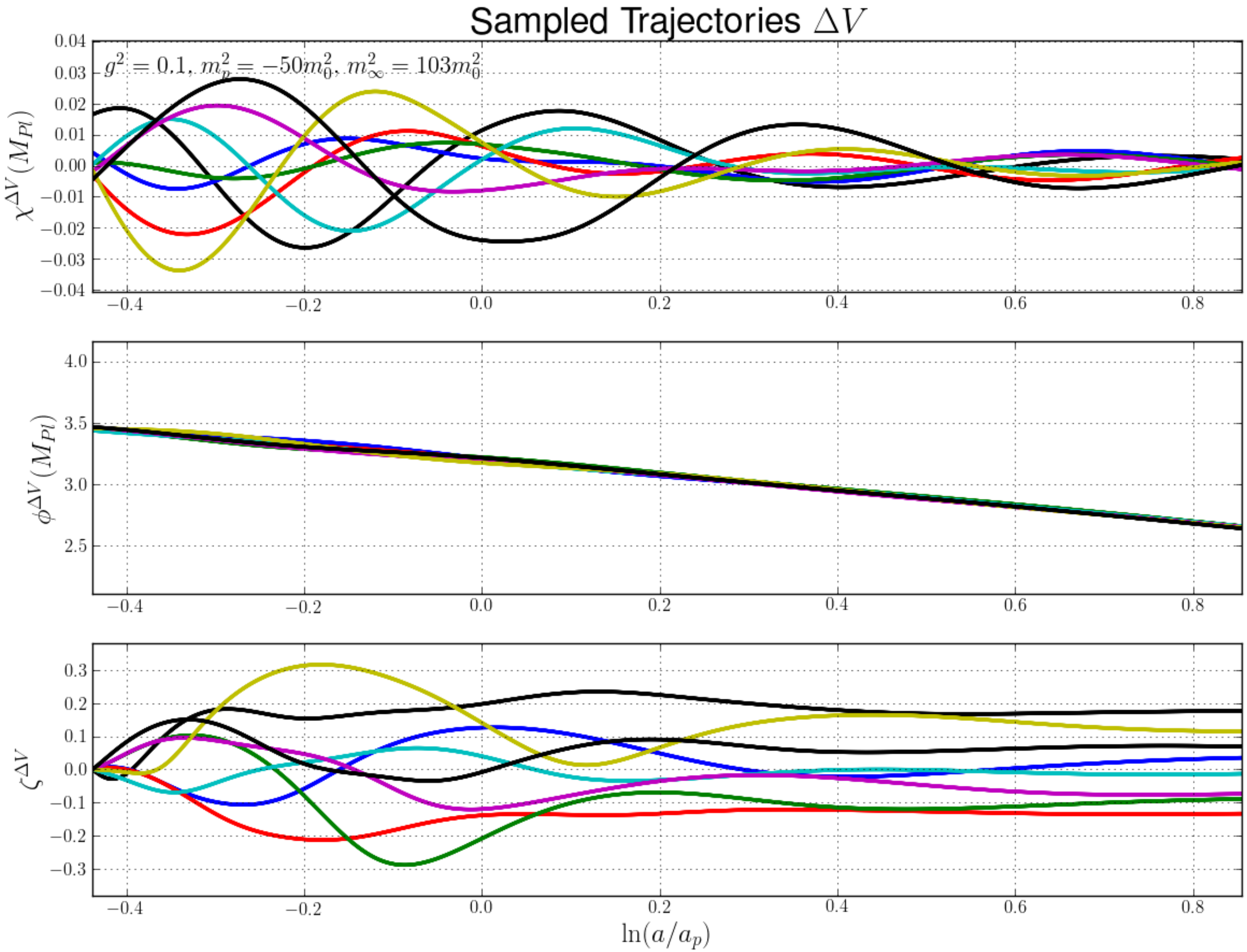
experiment χ-heavy *unstable χ cf. trapped*



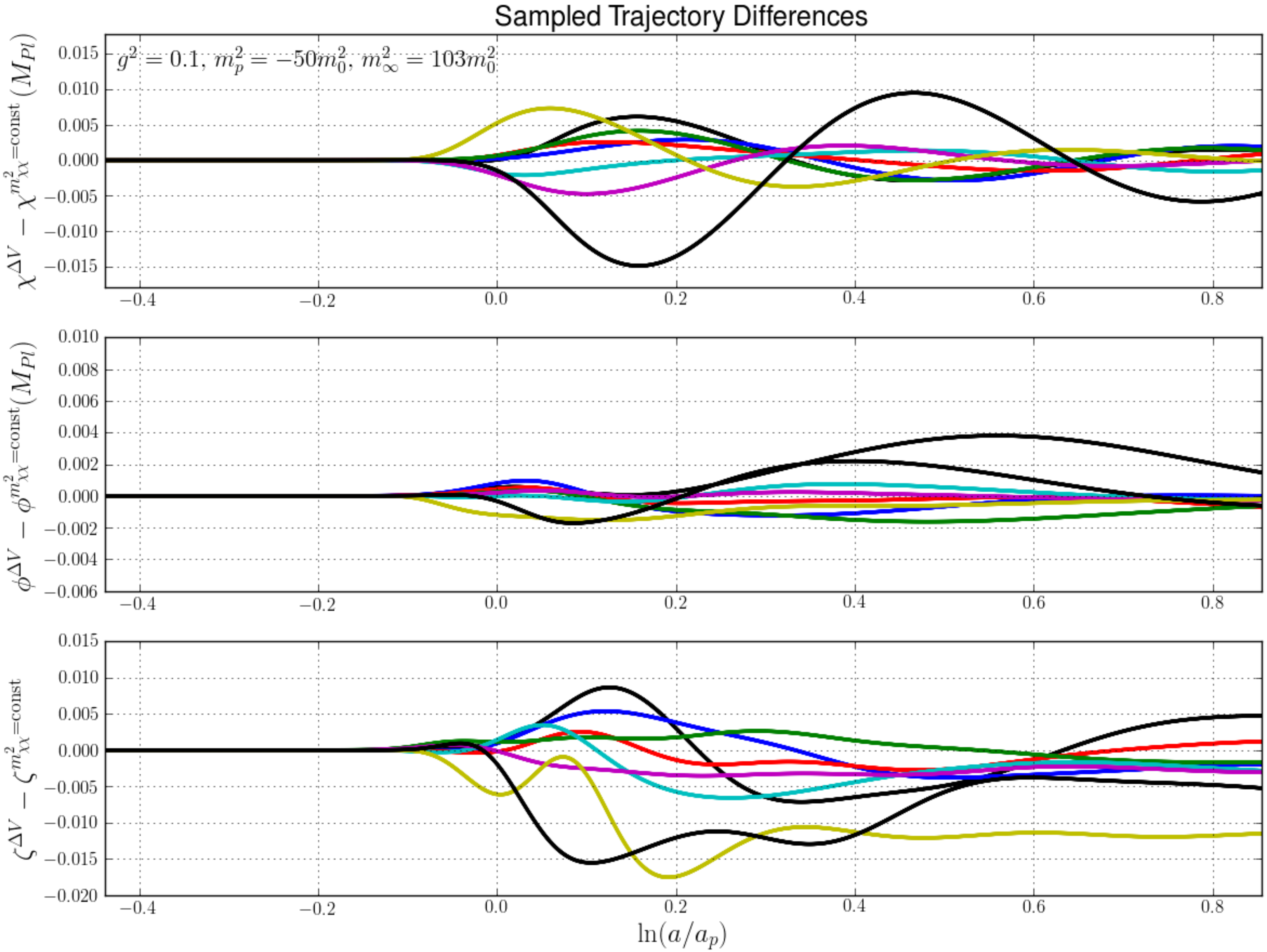
experiment χ-heavy *unstable χ cf. trapped*



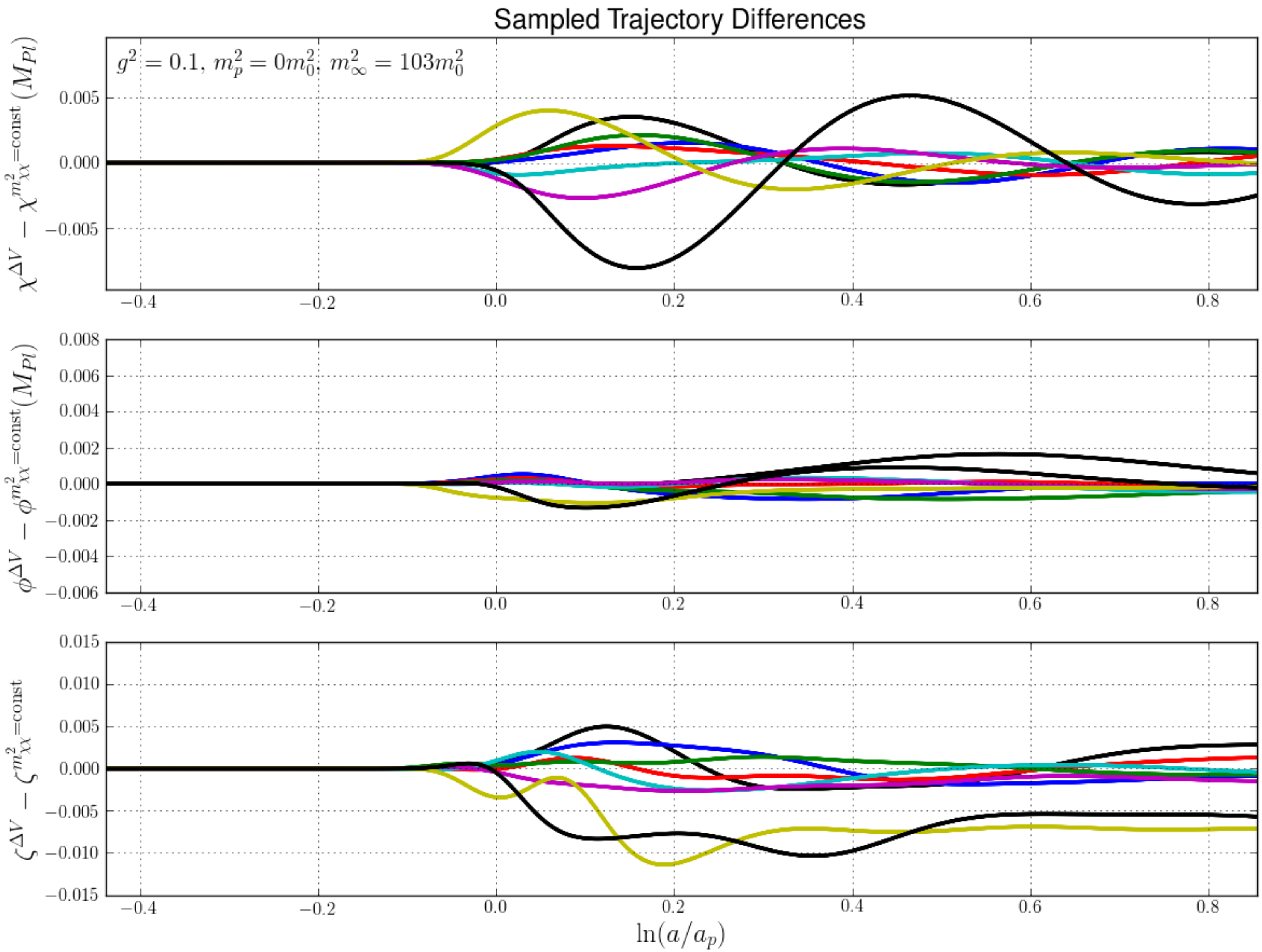
experiment χ-heavy *unstable χ*



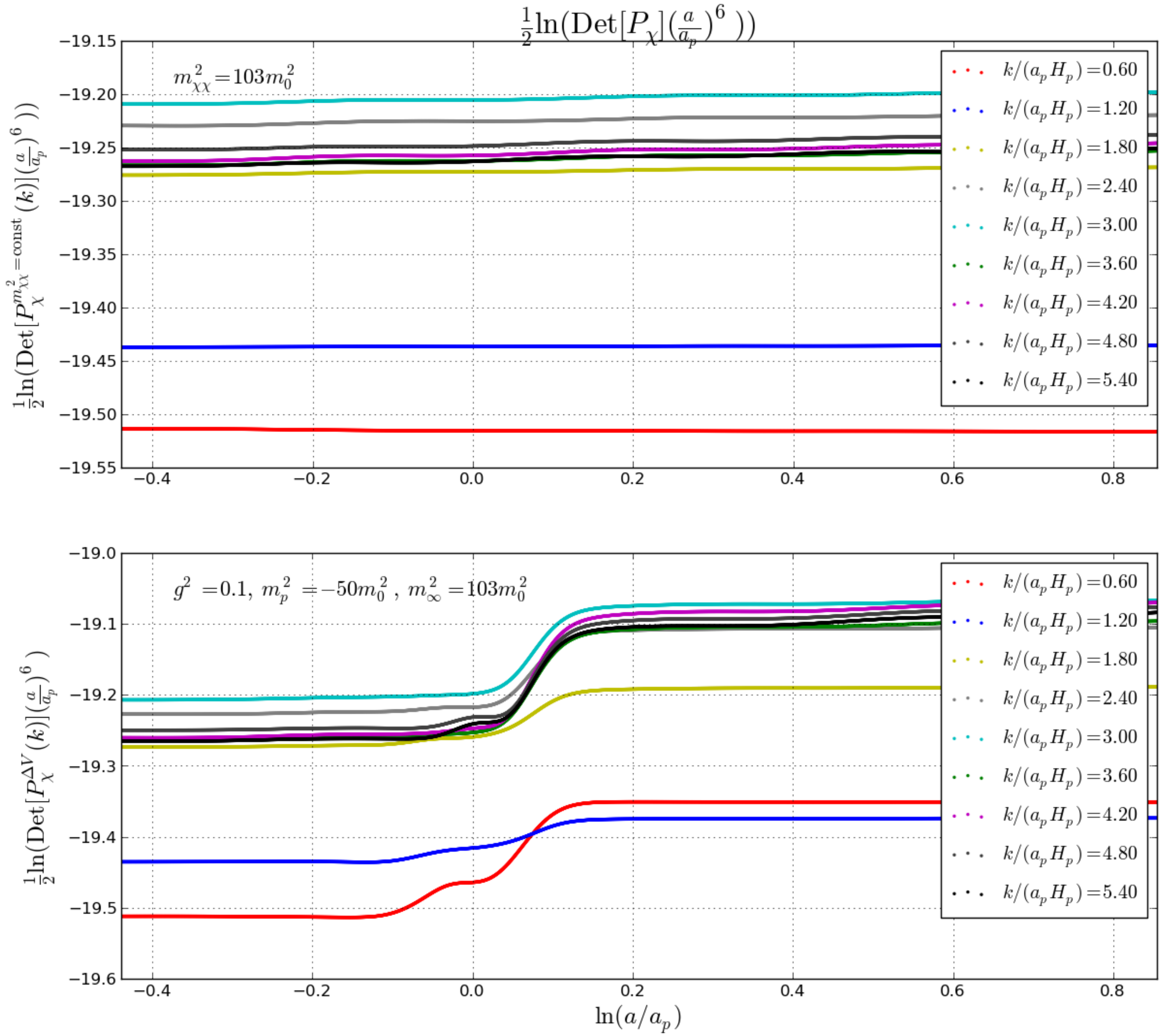
experiment χ-heavy *unstable χ*



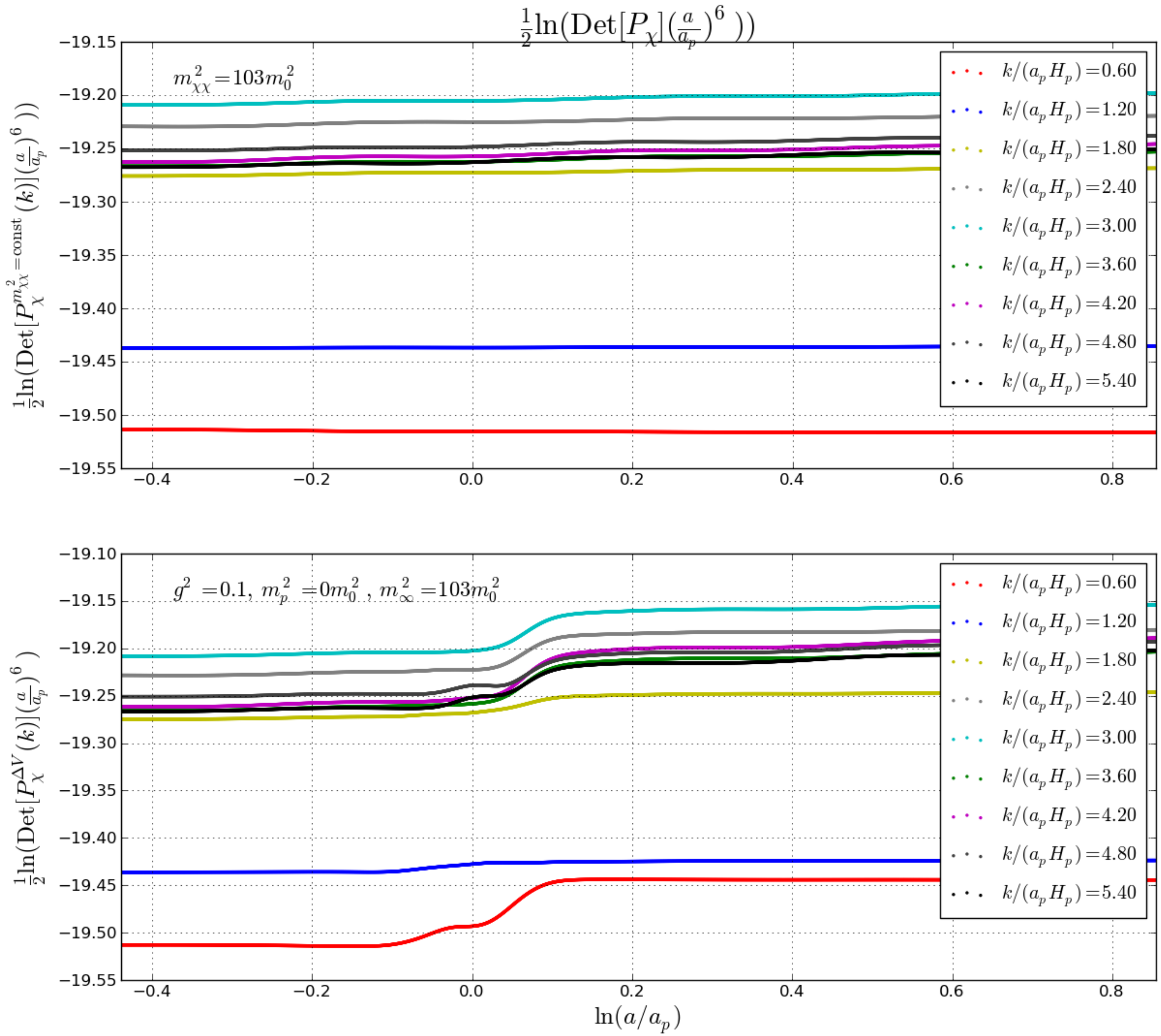
experiment χ-heavy *trapped χ*



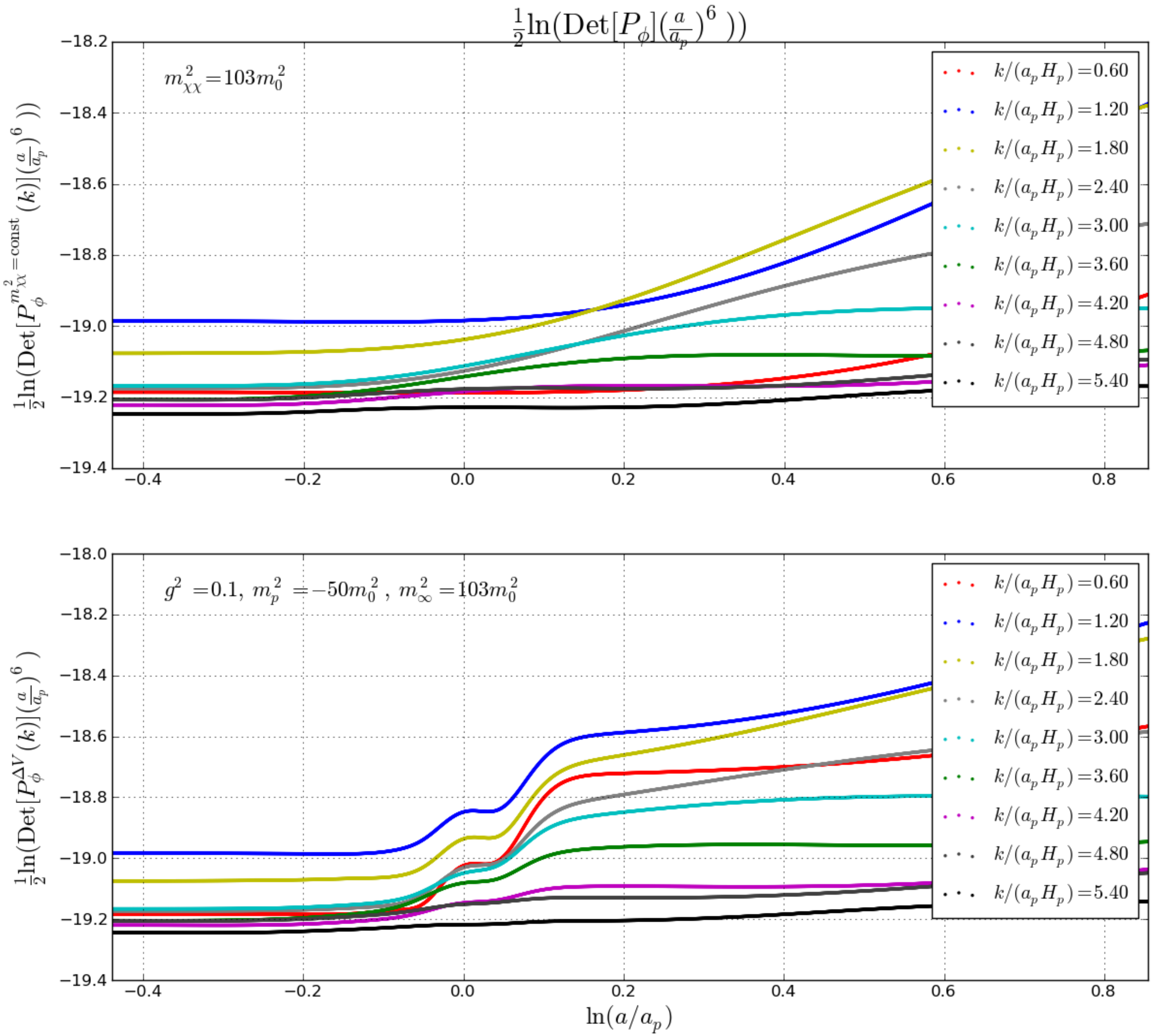
experiment χ-heavy *unstable χ*



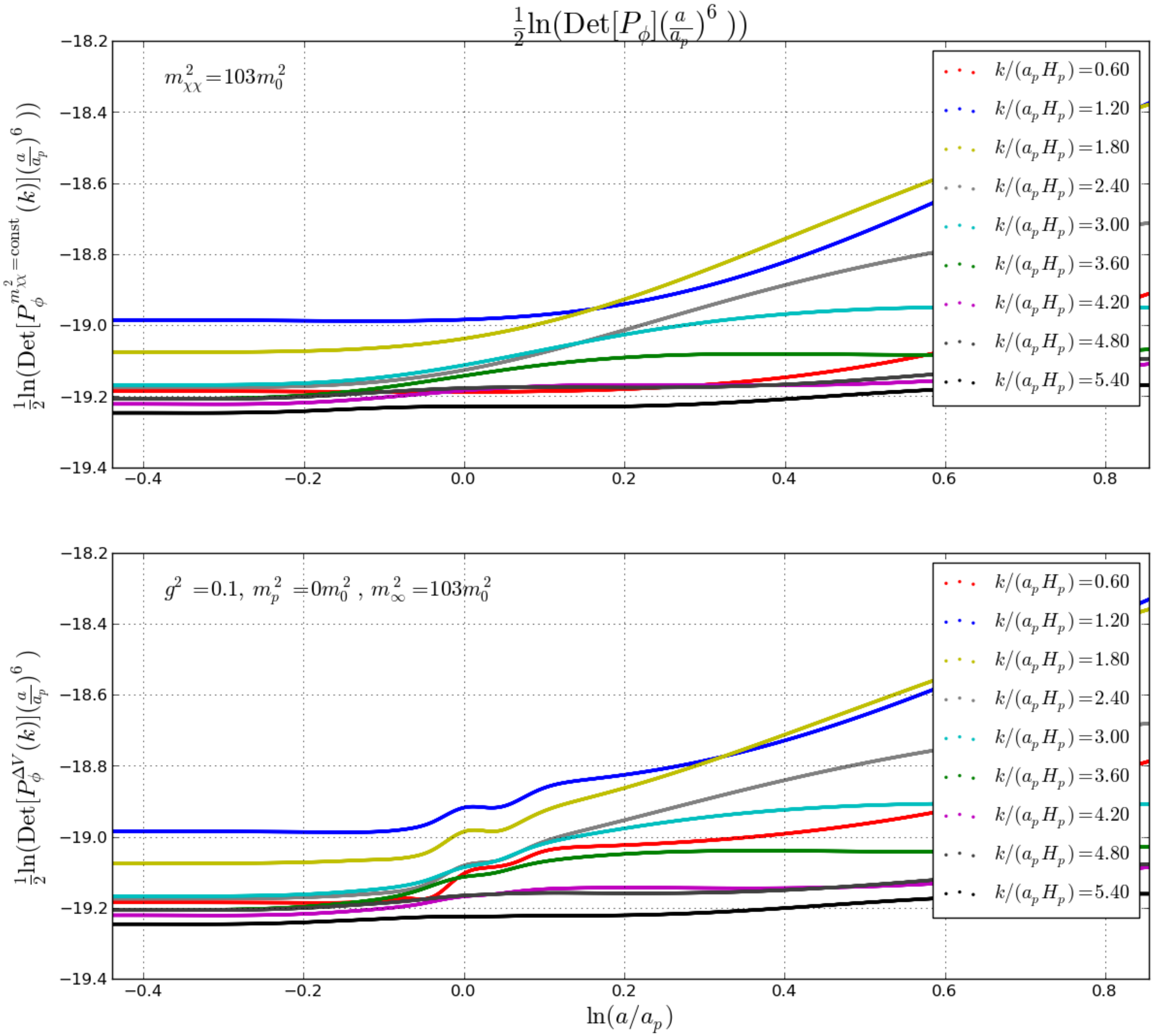
experiment χ-heavy *trapped χ*



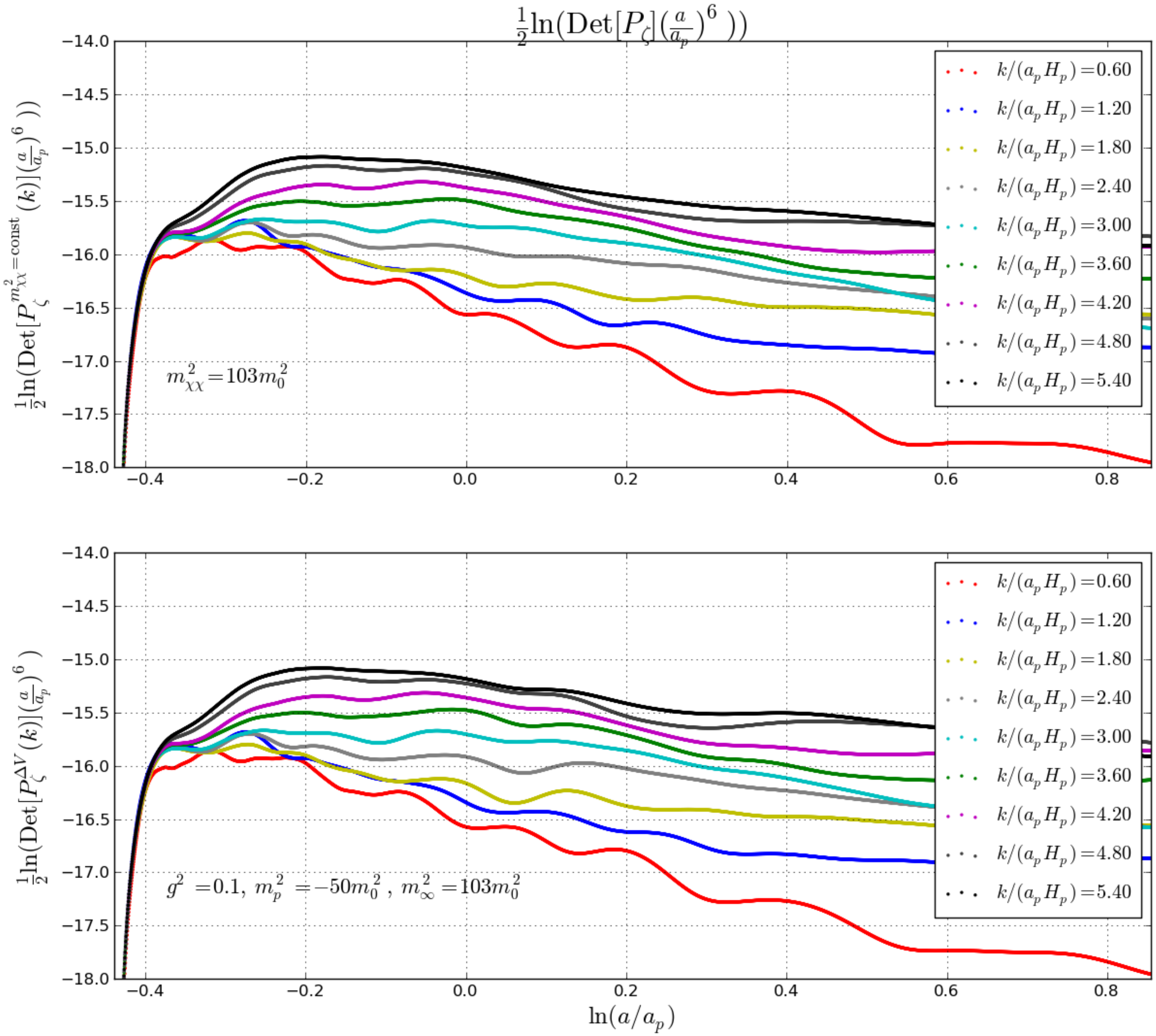
experiment χ-heavy *unstable χ*



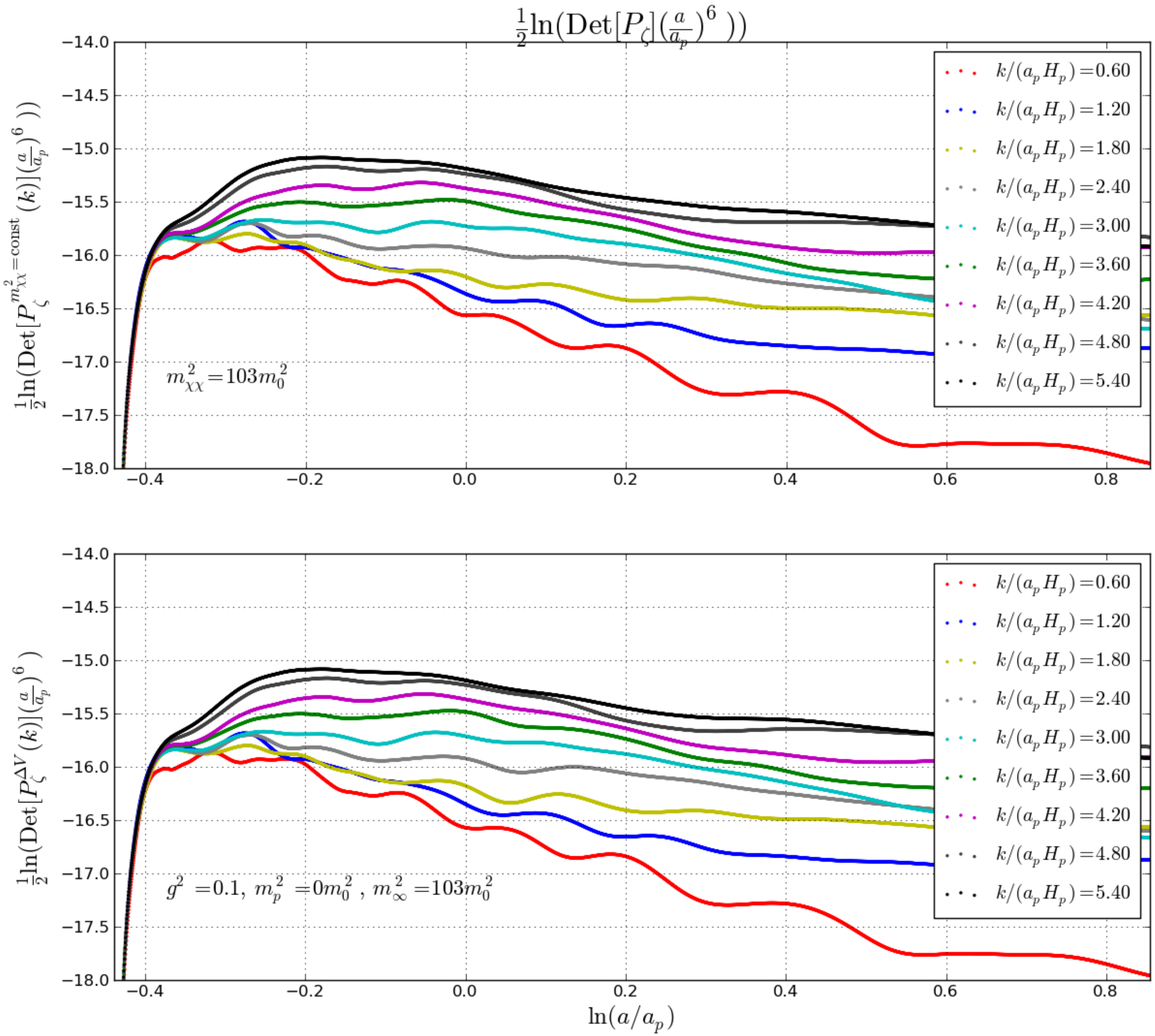
experiment χ-heavy *trapped χ*



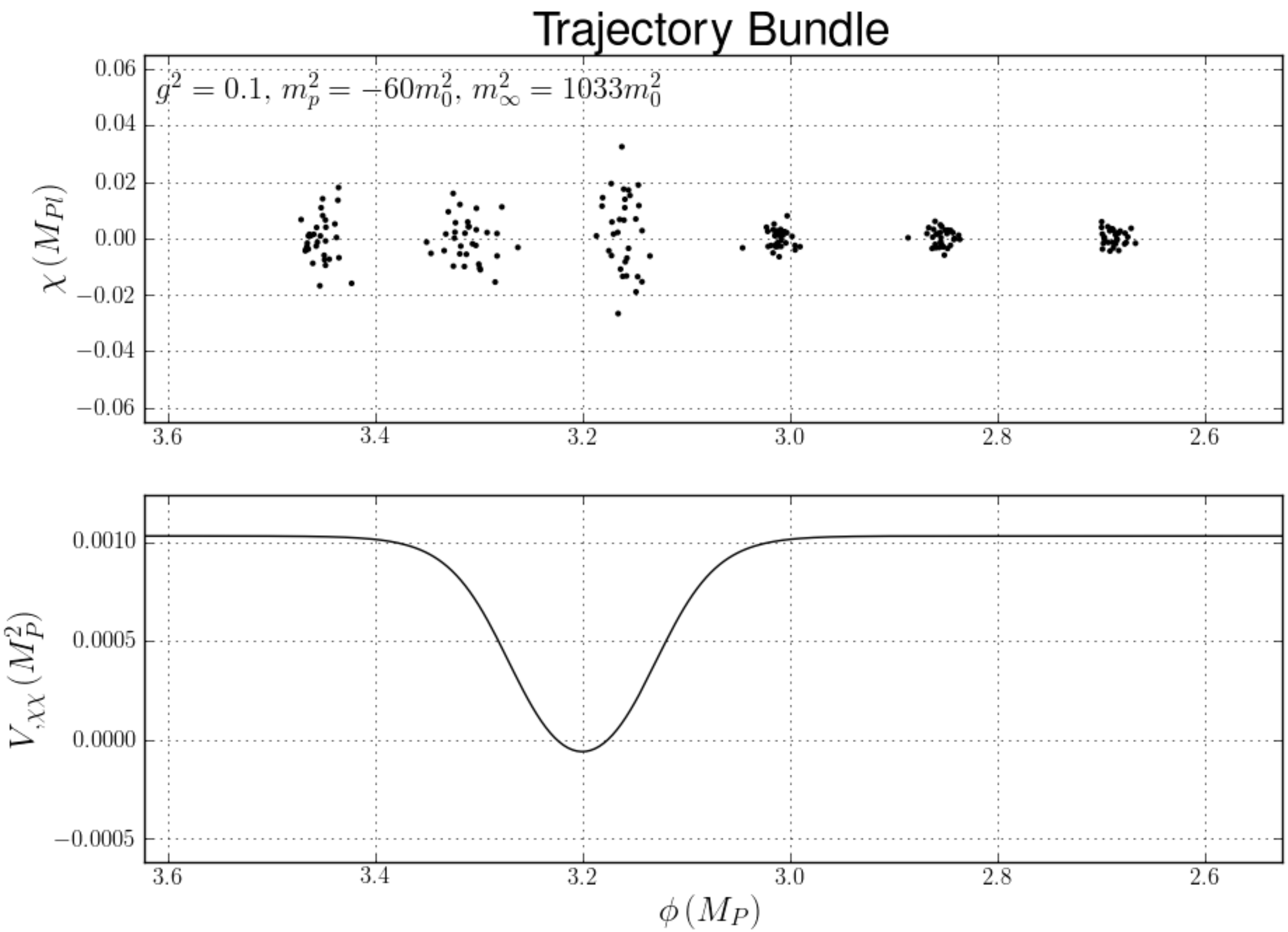
experiment χ-heavy *unstable χ*



experiment χ-heavy *trapped χ*



experiment χ-heavy *unstable χ*



(3) ***|cg <=> fg> condensate/fluctuation framework****, for both using coherent states classical-like approach with* ***hbar****. includes* ***Bogoliubov*** *transformations for fluctuations as condensate evolves*
=> ***particle creation*** *interpretation in both heating and inflating regimes.*

condensate/fluctuation framework, classical-like approach with hbar + Bogoliubov transformations for fluctuations as condensate evolves => particle creation & fluctuation freeze-out into new condensate

stochastic inflation **| q_c ; q_f>** instead of **$dq_c^A = V_c^A dT + K^A_\nu \sqrt{dT}\, \eta^\nu$**(GRD)

Langevin network evolution step: **$q_c(X,T+dT) = q_c(X,T) + V_c dT + \delta q_f$**

cf. **condensate evolution** step **$|q_c(T+dT)\rangle = \exp(V_c dT) \exp(\delta q_f) |q_c(T)\rangle$**

schematic $\delta q_f(x,T) = \sum_{k\text{-band}} (Q_k^*(x,T) a_k^T - Q_k(x,T) a_k)$

$V_c dT = V_c(x,T) dT (a_x^T - a_x)$

annihilation/creation operators in position and momentum a_x, a_x^T a_k, a_k^T

fluctuating part $|q_f\rangle \sim \exp(\sum \delta q_f) | 0\rangle$ *a coherent state description?*

what is the relation to the usual $q_{f,op} = \sum_k (Q_k^*(x,T) a_k^T + Q_k(x,T) a_k)$ operator linear in Bunch Davies vacuum operators a_k, a_k^T (sign difference)

it is an **overcomplete basis representation**, **but it conforms to a classical lattice simulation of inflation (no bipartite split).**

still use the gradient expansion for **$|q_c(T)\rangle$**

& mixed operators $V_c dT$ and $\delta q_f(x,T)$ - promising approach?

The Kinematics of Inflation, Preheating and Heating: a Playground for Kolmogorov-Sinai and Shannon Entropies

Dick Bond @ ipmu18 11 29

what are the degrees of freedom / parameters of the ultra early Universe? TBD

begin-inflate => inflate => end-inflate => preheat => non-equilibrium heat+entropy
=> *Standard Model particle physics* QG plasma radiation dominated
=> dark matter dominated *structure via gravitational instability* => dark energy now

$$d\zeta(x,t) = (dE+pdV)/3(E+pV) = d\, ln\rho_c / 3(1+w) + \mathrm{Trace}\, d\alpha^i_j$$

***fit into** a UV-complete theory (ultra-high energy to the Planck scale) strings, landscape, ..*
& IR-complete theory (post-inflation heating -> quark/gluon plasma)??? TBD

role of (1) ***instabilities after inflation***
entropy generation via the breakup of the coherent low-k inflaton condensate into incoherent high-k fluctuations at a "shock-in-time" => **nonGaussianity**

role of (2) ***instabilities during inflation***
phenomenology of in-states propagating through localized unstable potential structures to out-states, like scattering theory => **nonGaussianity**

(3) ***|cg <=> fg> condensate/fluctuation framework**, for both using coherent states classical-like approach with **hbar**. includes **Bogoliubov** transformations for fluctuations as condensate evolves*
*=> **particle creation** interpretation in both heating and inflating regimes.*