Axions in the Early Universe: an Overview

Lorenzo Sorbo

Axions in Stockholm 2025

July 3, 2025

UMass Amherst

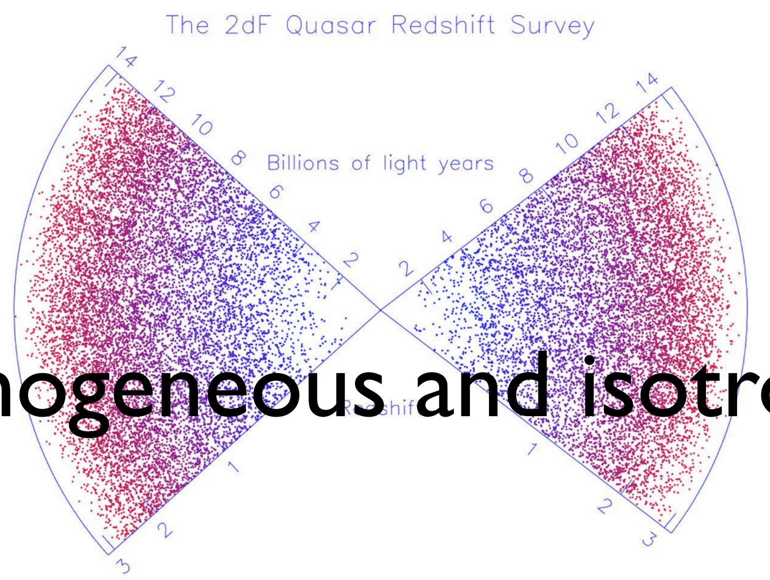
Plan

- Why you should like axions as inflatons
- Not only cosines
- Axion inflaton coupled to $U(1)$ gauge fields: phenomenology
- Axion inflaton coupled to $U(1)$ gauge fields: strong backreaction
- (Some) other situations

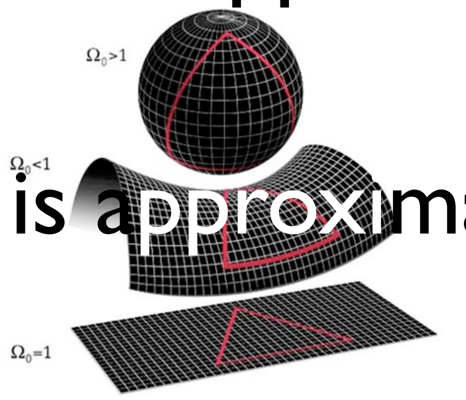
Inflation and radiative stability

5 BIG FACTS ABOUT THE UNIVERSE

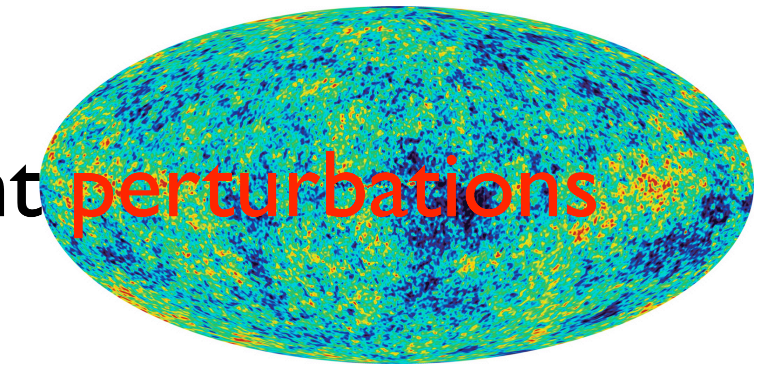
- it is old and very large



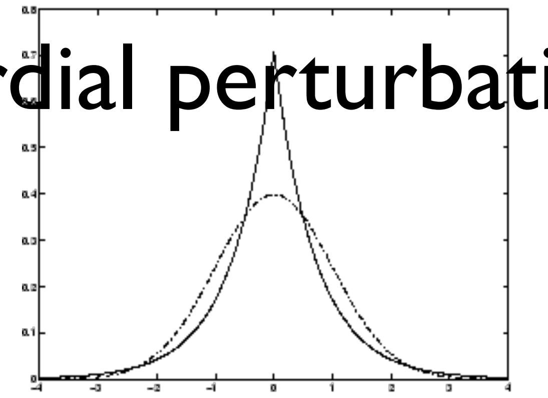
- in first approximation it is homogeneous and isotropic



- it is approximately flat



- structure grew out of small, scale invariant perturbations



- spectrum of primordial perturbations was gaussian

...can all be explained by primordial inflation!

Inflation and radiative stability

A classical inflationary potential will receive
radiative corrections

How to make sure that radiative effects are under control?

The situation is actually not so horrible...

Smolin 80, Linde 88

<u>If</u> we have a 4d theory where ϕ interacts only with gravity

<u>then</u> ***perturbative*** quantum gravity corrections are not a problem!

Indeed: for potential $V(\phi)$, quantum gravity effects are

$\mathcal{O}(1)\ V(\varphi)^2/M_P^4$ and $\mathcal{O}(1)\ V''(\varphi)\ V(\varphi)/M_P^2$

negligible during inflation

Softly broken shift symmetry!

However, in general there will be couplings to other fields

reheating

moduli in string th

How to guarantee radiative stability?

Impose the shift symmetry!

(Naturally realized if the inflaton is a pseudo-Nambu—Goldstone boson)

pNGb$\equiv$ALP$\equiv$axion

(more general than QCD axion)

Incidentally…

For the same reason why axions
are good inflaton candidates,
they are excellent quintessence candidates

(bonus: they do not mediate fifth forces!)

Carroll 98

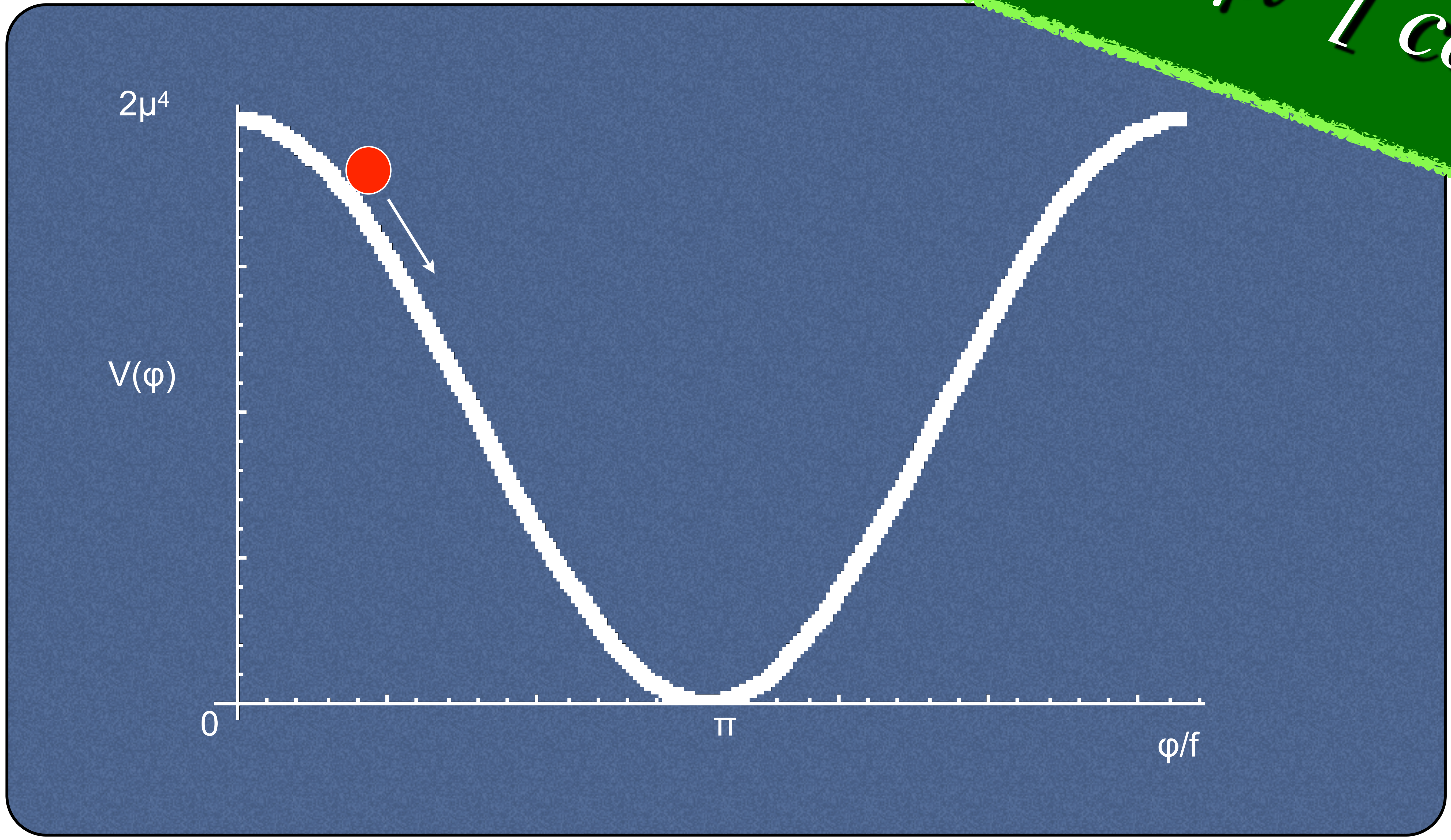
Back to inflation…

Inflation and radiative stability

Natural inflation

Freese et al 1990

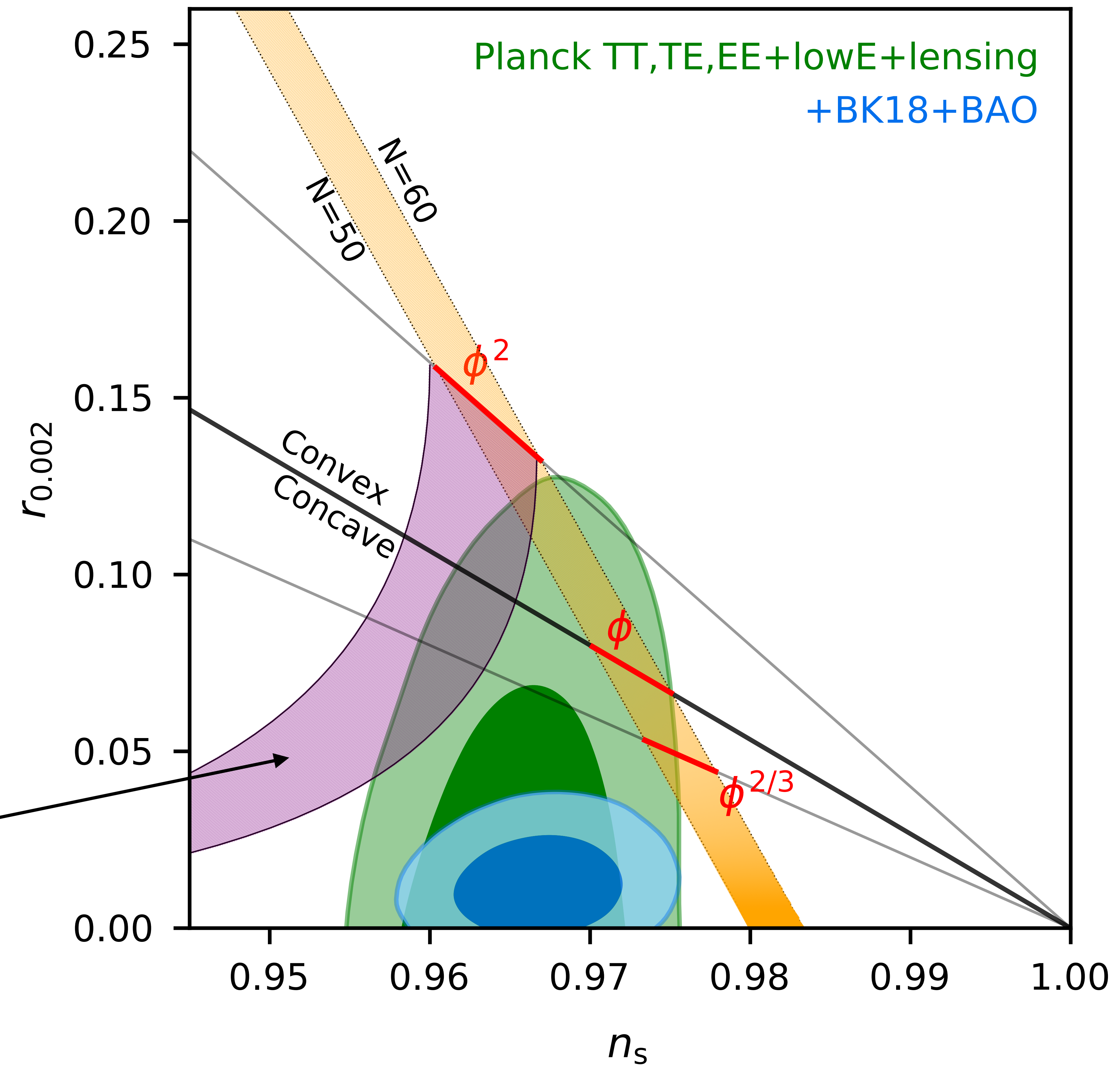
$$V(\phi)=\mu^4\,[\,\cos(\phi/f)+1\,]$$



Inflation and radiative stability

But data…

BICEP/Keck 2021



Natural inflation

…but let's keep pressing! 💪

Inflation and radiative stability

Stringy models of natural inflation?

YES!

(*in principle*)

(string theory contains a plethora of axions)

Liam's talk

However

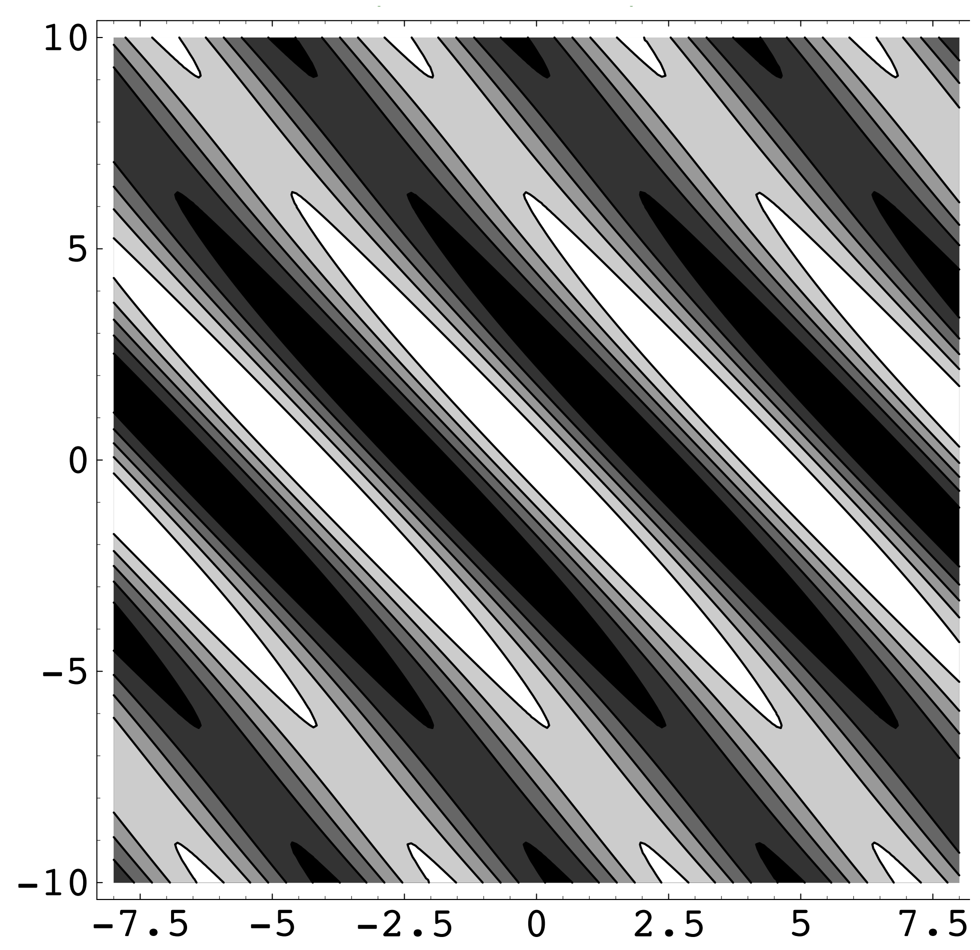
Banks, Dine, Fox and Gorbatov 03
Arkani-Hamed, Motl, Nicolis, Vafa 06

String Theory appears to require $f<M_P$

(not only disfavored by data, if $f<M_P$ the cosine potential cannot sustain inflation at all!)

Inflation and radiative stability

Ways out?

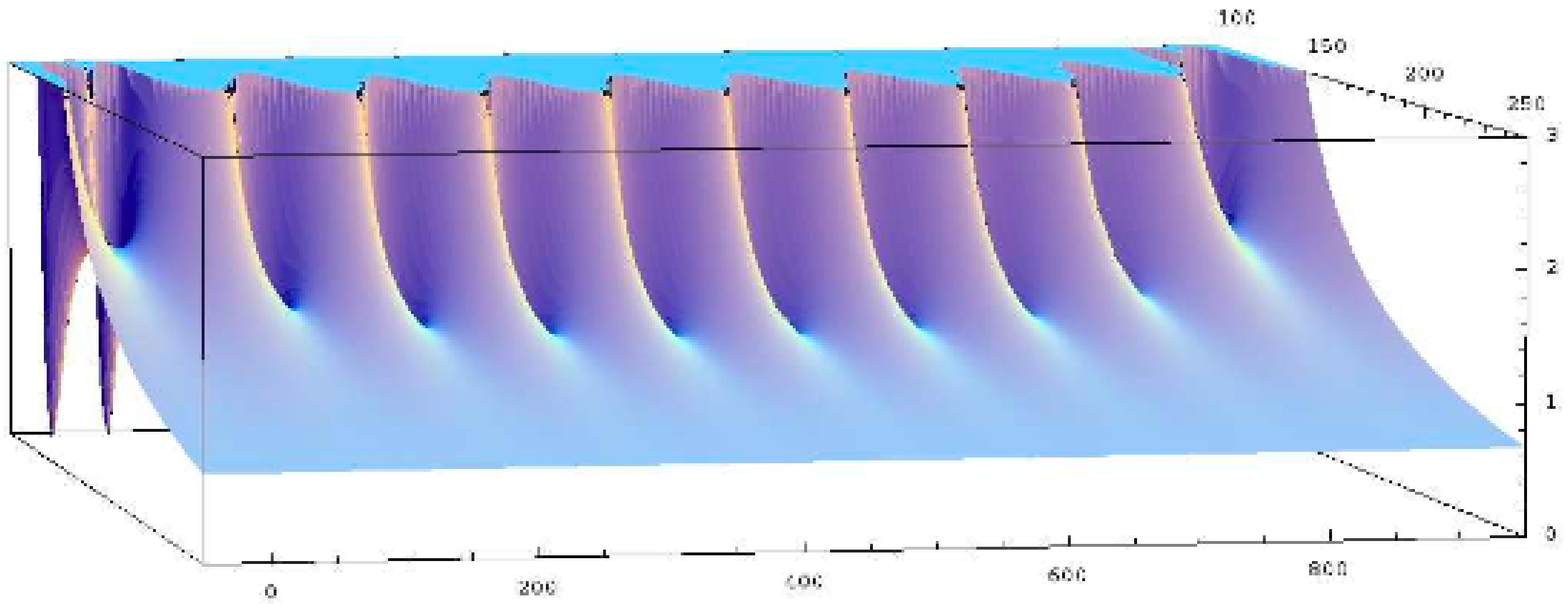


- Use *two* axions

Kim, Nilles and Peloso 2004

- Use axions and moduli

Blanco-Pillado et al 2004



$$\mathcal{L} = -\sqrt{-g}\sum_{i=1}^{N}\left\{\frac{1}{2}\left(\partial\phi_i\right)^2 + \Lambda_i^4\left[1+\cos(\phi_i/f_i)\right]\right\}$$

- Use *many* axions

Dimopoulos et al 2005

- ...

...all based on multi field dynamics

(nota bene: “string inspired”≠ “string theoretical”)

Inflation and radiative stability

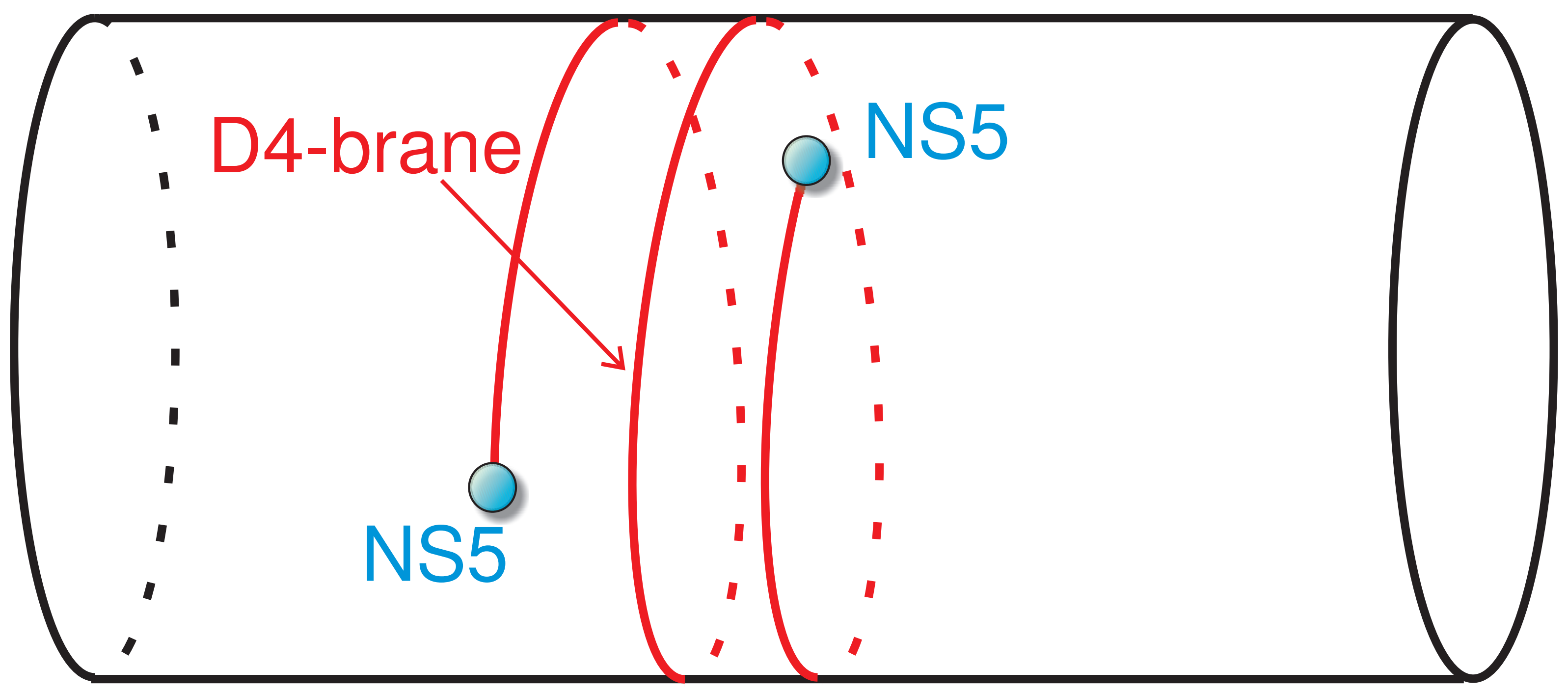
Or, just forget about periodic potentials!

McAllister, Silverstein, Westphal 08

Monodromy:

energy depends on number
of times brane looped around a cycle

$$V(b) = \frac{\epsilon}{g_s(2\pi)^5\alpha'^2}\sqrt{\ell^4 + b^2}$$



Inflation and radiative stability

A four-dimensional incarnation

Kaloper, LS 08

$$\mathcal{S}_{bulk} = \int d^4x \sqrt{g}\Big(\frac{M_{Pl}^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - \frac{1}{48}F_{\mu\nu\lambda\sigma}^2 + \frac{\mu\phi}{24}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}F_{\mu\nu\lambda\sigma} + \dots\Big)$$

Di Vecchia and Veneziano 1980
Quevedo and Trugenberger 1996
Dvali and Vilenkin 2001
Beasley and Witten 2002
Dvali 2005

$$\boxed{F_{\mu\nu\varrho\lambda} = \partial_{[\mu} A_{\nu\varrho\lambda]}}$$

Action invariant under shift symmetry:

under $\phi \to \phi + c$, $L \to L + c\,\mu\,\varepsilon^{\mu\nu\varrho\lambda} F_{\mu\nu\varrho\lambda}/24$

total derivative!

(ϕ is an axion!)

A four-dimensional incarnation

Kaloper, LS 08

$$\mathcal{S}_{bulk} = \int d^4x \sqrt{g}\Big(\frac{M_{Pl}^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - \frac{1}{48}F^2_{\mu\nu\lambda\sigma} + \frac{\mu\phi}{24}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}F_{\mu\nu\lambda\sigma} + \dots\Big)$$

Variation of the action

$$\begin{cases} \nabla^\mu(F_{\mu\nu\varrho\lambda} - \mu\, \varepsilon_{\mu\nu\varrho\lambda}\, \phi) = 0 \\ \nabla^2\phi + \mu\, \varepsilon^{\mu\nu\varrho\lambda} F_{\mu\nu\varrho\lambda}/24 = 0 \end{cases}$$

After simple manipulations

$$\begin{cases} F_{\mu\nu\varrho\lambda} = \varepsilon_{\mu\nu\varrho\lambda}\,(q + \mu\,\phi) \\ \nabla^2\phi - \mu^2\,(\phi + q/\mu) = 0 \end{cases}$$

Shift symmetric action describes massive field!

q = integration constant

Inflation and radiative stability

A four-dimensional incarnation

$$\mathcal{S}_{bulk} = \int d^4x \sqrt{g}\Big(\frac{M_{Pl}^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - \frac{1}{48}F^2_{\mu\nu\lambda\sigma} + \frac{\mu\phi}{24}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}F_{\mu\nu\lambda\sigma} + \ldots\Big)$$

Shift symmetric action describes massive field!

But isn't $m^2\phi^2$ inflation ruled out?

Yes, but corrections can flatten out potential at large ϕ

D'Amico, Kaloper, Lawrence 17

Moving to phenomenology…

Axion inflation

Pseudoscalar, quasi-shift symmetric inflaton, radiatively stable

theoretically very attractive

Coupling to *U(1)* gauge fields:

$$\mathcal{L}(\varphi,\, A^\mu) = \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{\alpha}{4f}\varphi F^{\mu\nu}\tilde{F}^{\mu\nu}$$

EOM for helicity-λ modes of photon

$$A''_\lambda + \left(\mathbf{k}^2 + \lambda\frac{\alpha\,\phi'}{f}|\mathbf{k}|\right) A_\lambda = 0$$

Phenomenology

$$A_\lambda'' + \left(\mathbf{k}^2 + \lambda \frac{\alpha\,\phi'}{f}|\mathbf{k}|\right) A_\lambda = 0$$

for λ=-, the “mass term” is negative
and large for ~*1* Hubble time:

Exponential amplification of **left-handed modes only**
(parity violation)

$$A_- \propto \exp\left\{\frac{\pi}{2}\,\frac{\alpha\,\dot{\phi}}{f\,H}\right\}$$

Phenomenology

A (large) population of chiral vector fields
during inflation

potential for a very rich phenomenology!

Cosmological magnetic fields

(Observed up to $\sim Mpc$ scales, $\sim 10^{-17}G$, uncertain origin)

Carroll, Field, Garretson 93
Anber, LS 06
Durrer et al 10
Sharma et al 24
...

Blue spectrum, $B(k) \propto k^2$
too weak at large scales

…but *inverse cascade*
(MHD effect for chiral gauge fields,
amplifying large scale spectrum)

Phenomenology

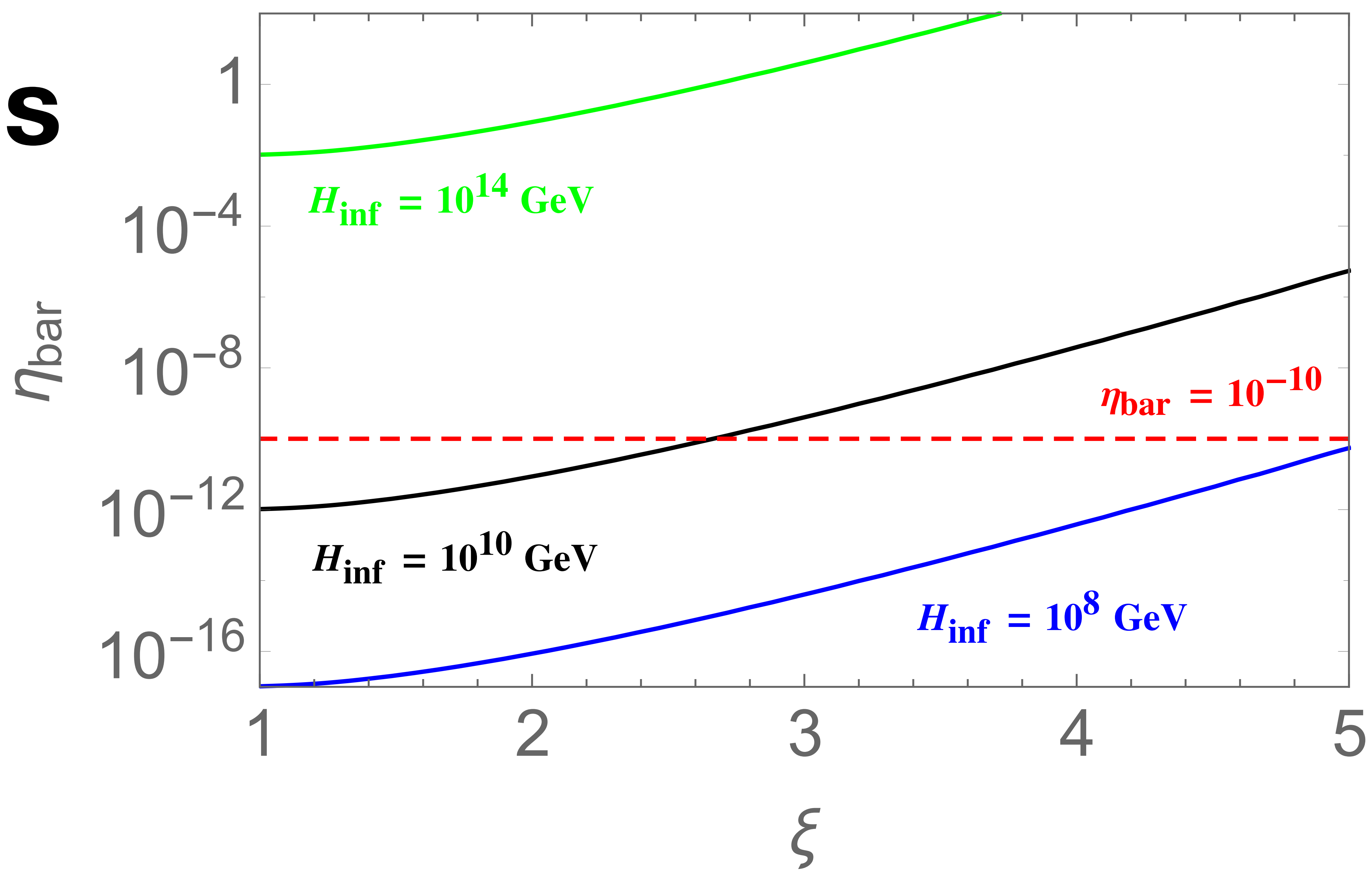
Nonvanishing net helicity

+

chiral anomaly

Baryogenesis

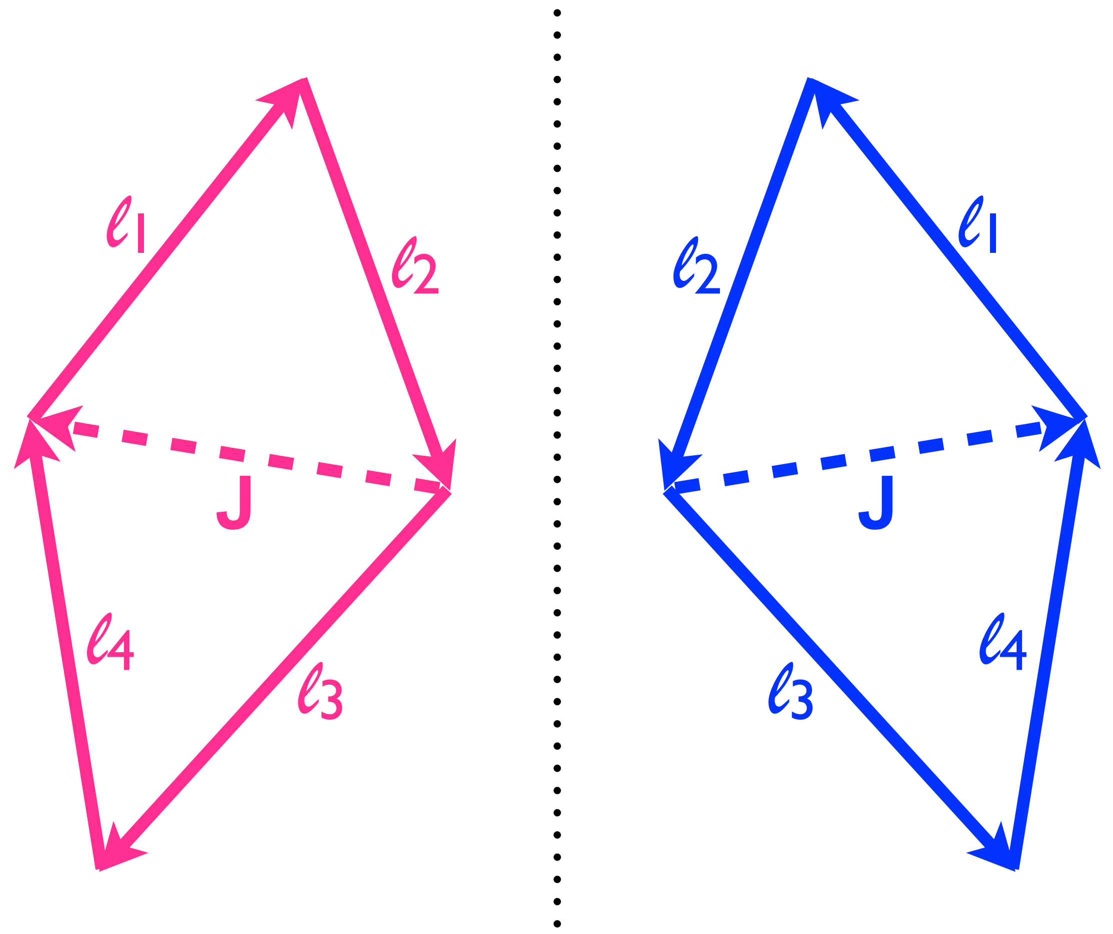
Anber Sabancilar 16
Domcke von Harling Morgante Mukaida 19



Parity violation in the scalar sector

Shiraishi 16

Possible to see at the trispectrum level (see Sha's talk on Monday)

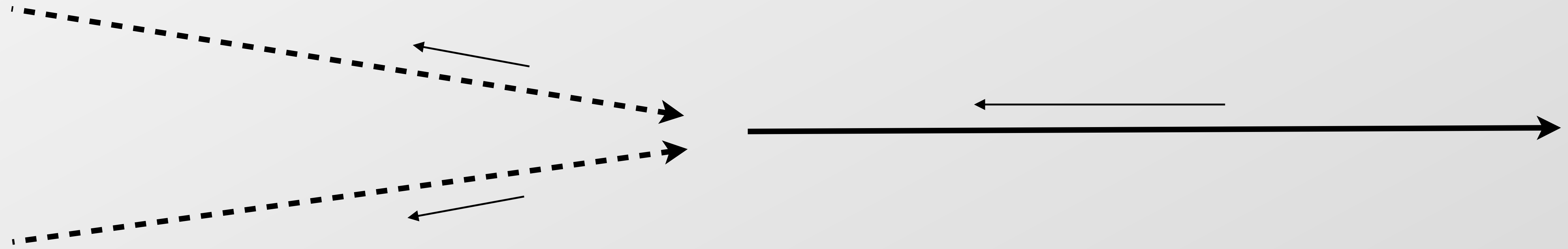


(Chiral) gravitational waves

LS 11

$$A_\mu + A_\nu \rightarrow \delta g_{\mu\nu}$$

in the limit of small transverse momentum two LH photons cannot create a RH graviton



Phenomenology

(Chiral) gravitational waves

$$A_\mu + A_\nu \to \delta g_{\mu\nu}$$

$$\mathcal{P}_{L}(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 9 \times 10^{-7}\,\frac{H^2}{M_P^2}\,\frac{e^{4\pi\xi}}{\xi^6}\right)$$

$$\mathcal{P}_{R}(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 2 \times 10^{-9}\,\frac{H^2}{M_P^2}\,\frac{e^{4\pi\xi}}{\xi^6}\right)$$

"standard"
parity-invariant part

parity-violation

$$\xi \equiv \frac{\alpha \dot{\phi}}{2\,f\,H} \gtrsim 1$$

Parity violation in CMB, $<EB>\neq 0$?

Phenomenology

...but also, very large f_{NL}

Barnaby Peloso 10

$$A_\mu + A_\nu \to \delta\varphi$$

When effect of photons is large enough, f_{NL}~10^4

LARGE AXION INDUCED TENSORS AT CMB SCALES **RULED OUT**

(at least in simple models)

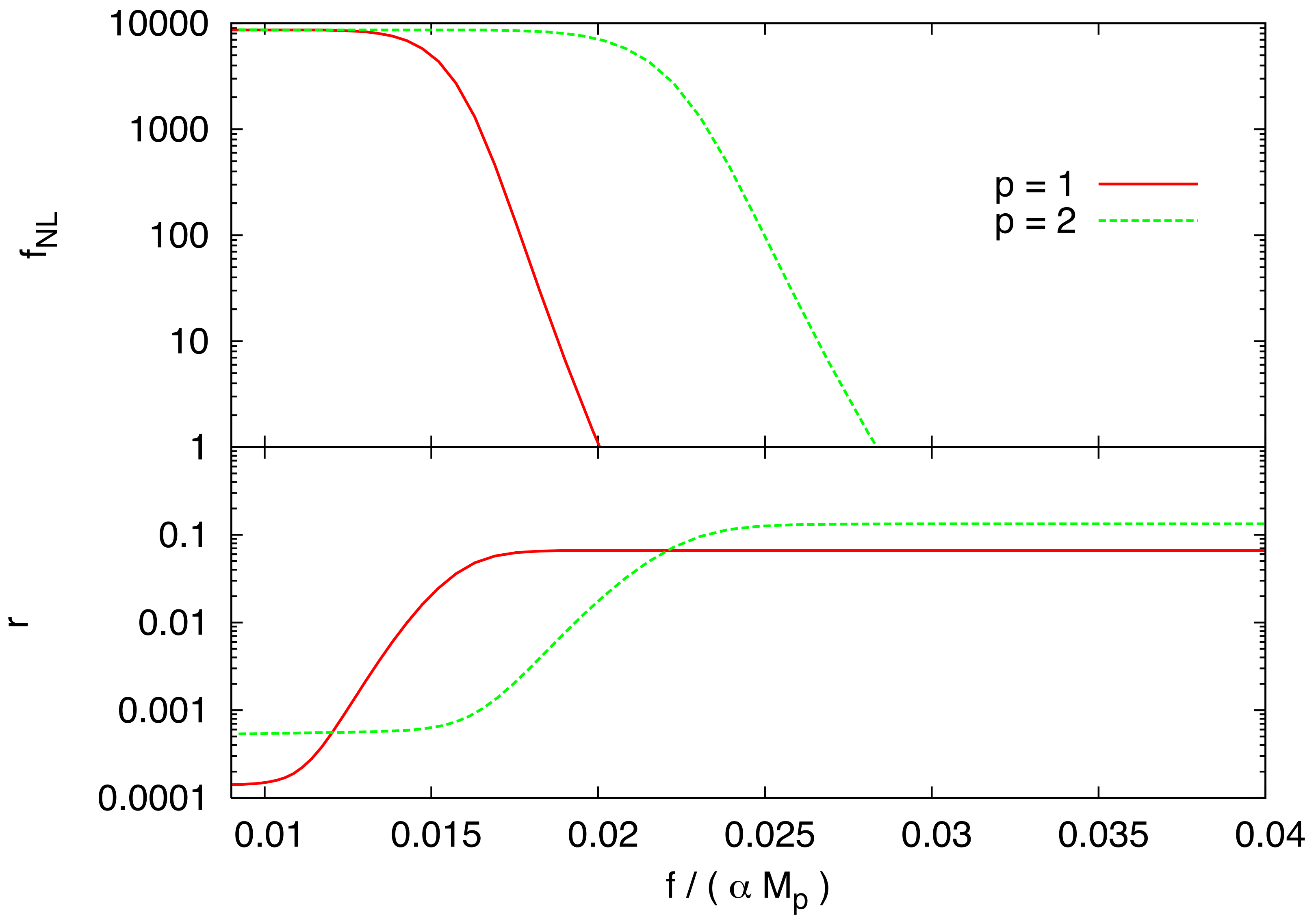


FIG. 2: Observational predictions for the large-field power-law inflation model (11) with $p = 1, 2$ and assuming $N_e \cong 60$. The spectral index is $n_s = 0.975, 0.967$ for $p = 1, 2$. At small f/α the coupling of ϕ to $F\tilde{F}$ is stronger and nongaussianity is large. The tensor-to-scalar ratio decreases at strong coupling; however, the decrease is important only at values of f/α which are ruled out by the current bound on $f_{NL}^{\rm equil}$.

Phenomenology

How about an axion in a transient roll?

Namba, Peloso, Shiraishi, LS, Unal 15
(see Caravano, Peloso 24 for a recent analysis)

Field σ $(\neq\varphi)$ coupled to gauge fields rolls only for a finite number of efoldings

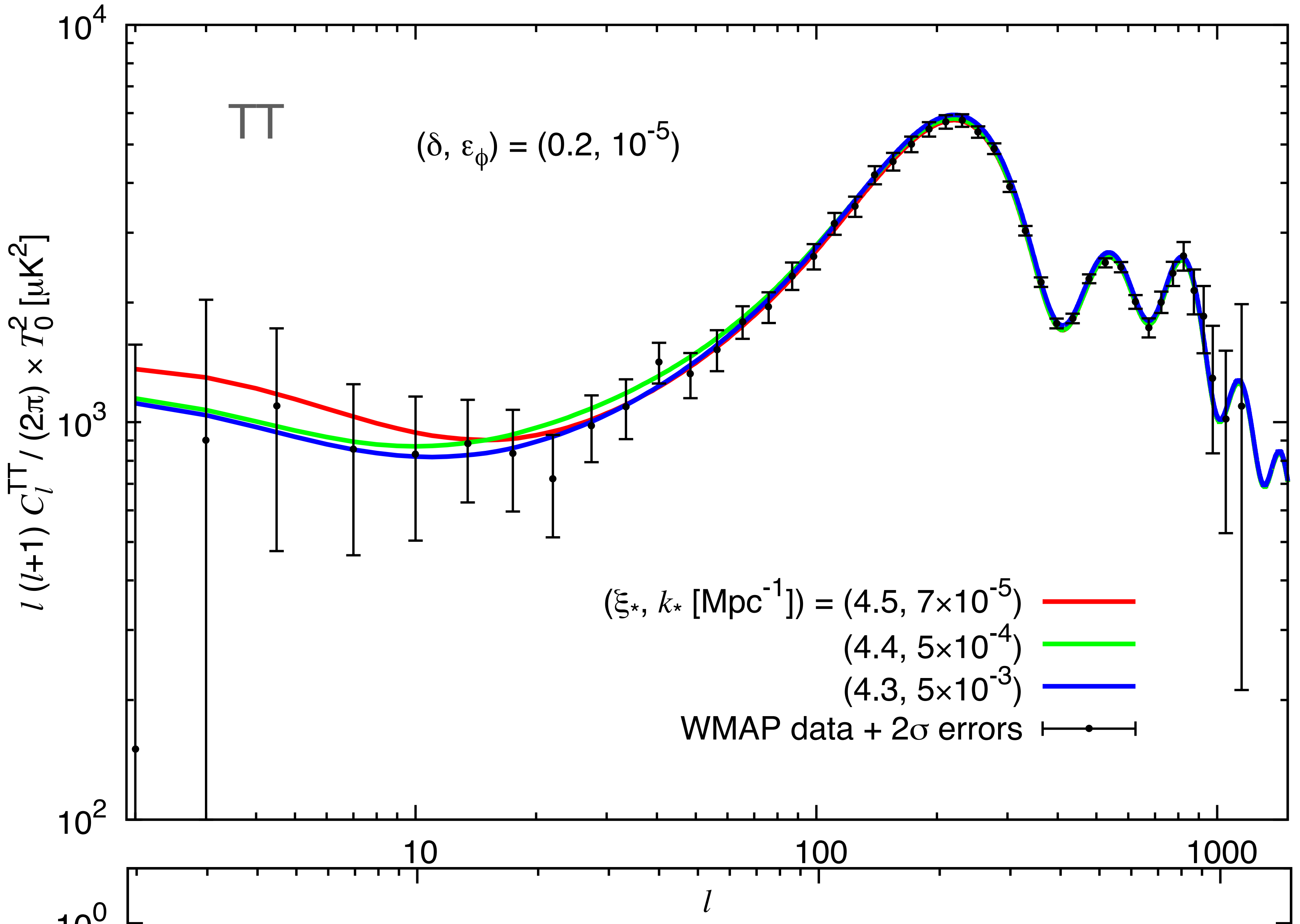
$$V_\sigma\left(\sigma\right)=\frac{\Lambda^4}{2}\left[\cos\left(\frac{\sigma}{f}\right)+1\right]$$

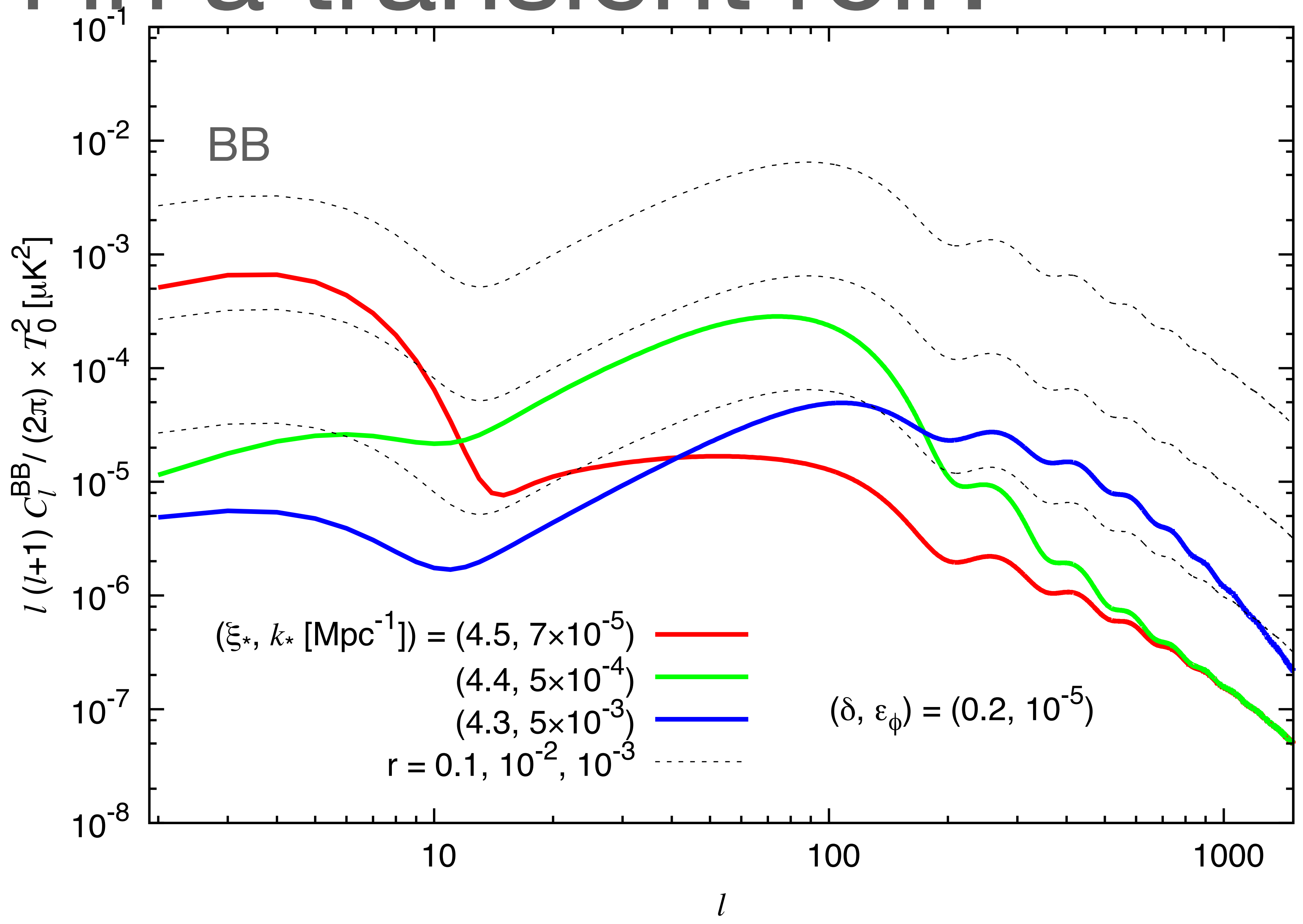
its effects will be visible only on a finite range of multipoles

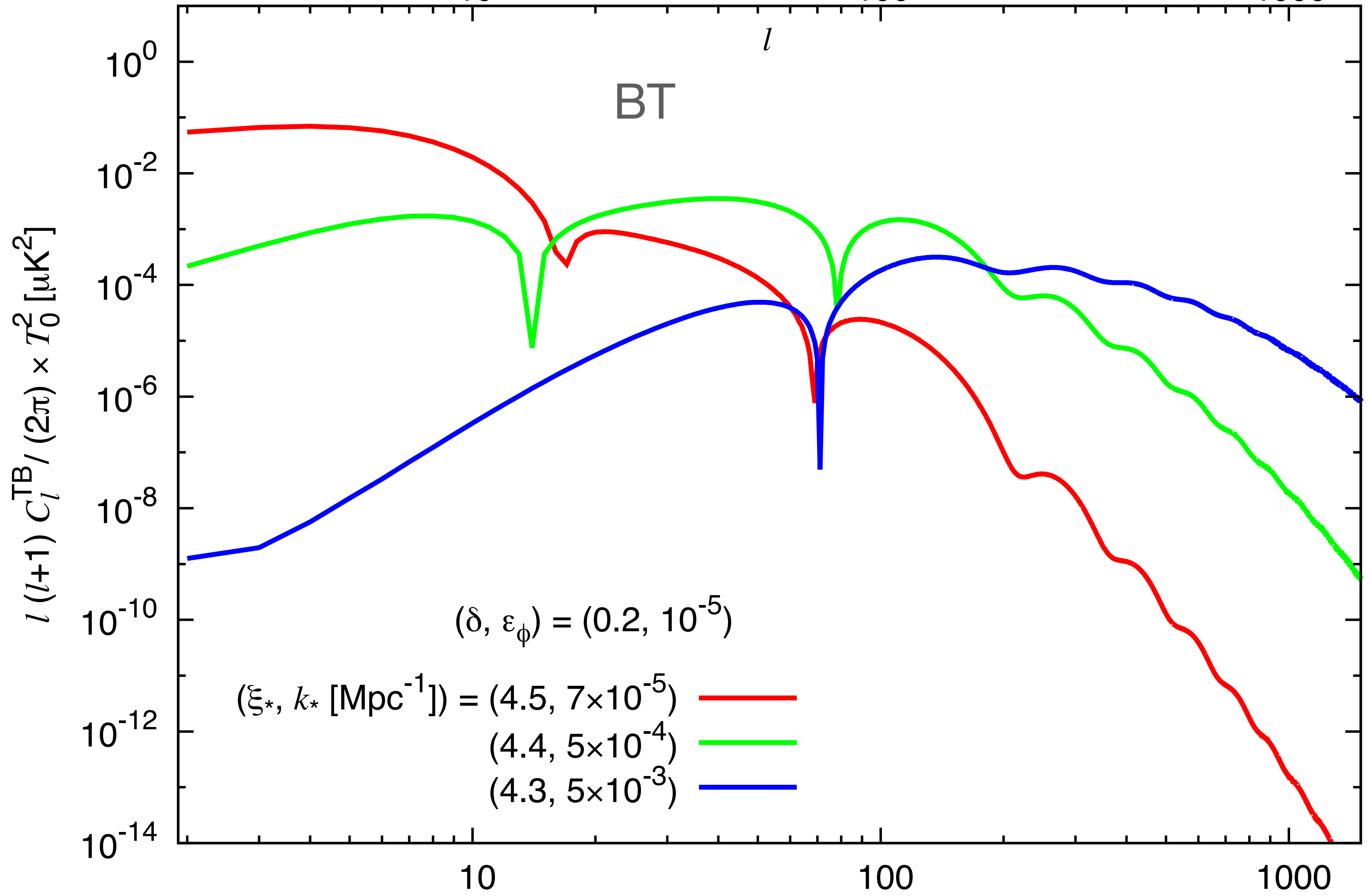
Nongaussianities in the T fluctuations are weakly constrained because of cosmic variance

Phenomenology

How about an axion in a transient roll?







Should vanish in parity-even Universe

Phenomenology

Important! Constraints on f_{NL} on CMB scales only!

$$\mathcal{P}_L(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 9\times 10^{-7}\,\frac{H^2}{M_P^2}\,\frac{e^{4\pi\xi}}{\xi^6}\right)$$
$$\mathcal{P}_R(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 2\times 10^{-9}\,\frac{H^2}{M_P^2}\,\frac{e^{4\pi\xi}}{\xi^6}\right)$$

Cook LS 11

$$\xi \equiv \frac{\alpha\,\dot{\phi}}{2\,f\,H} \gtrsim 1$$

ξ typically *increases* during inflation

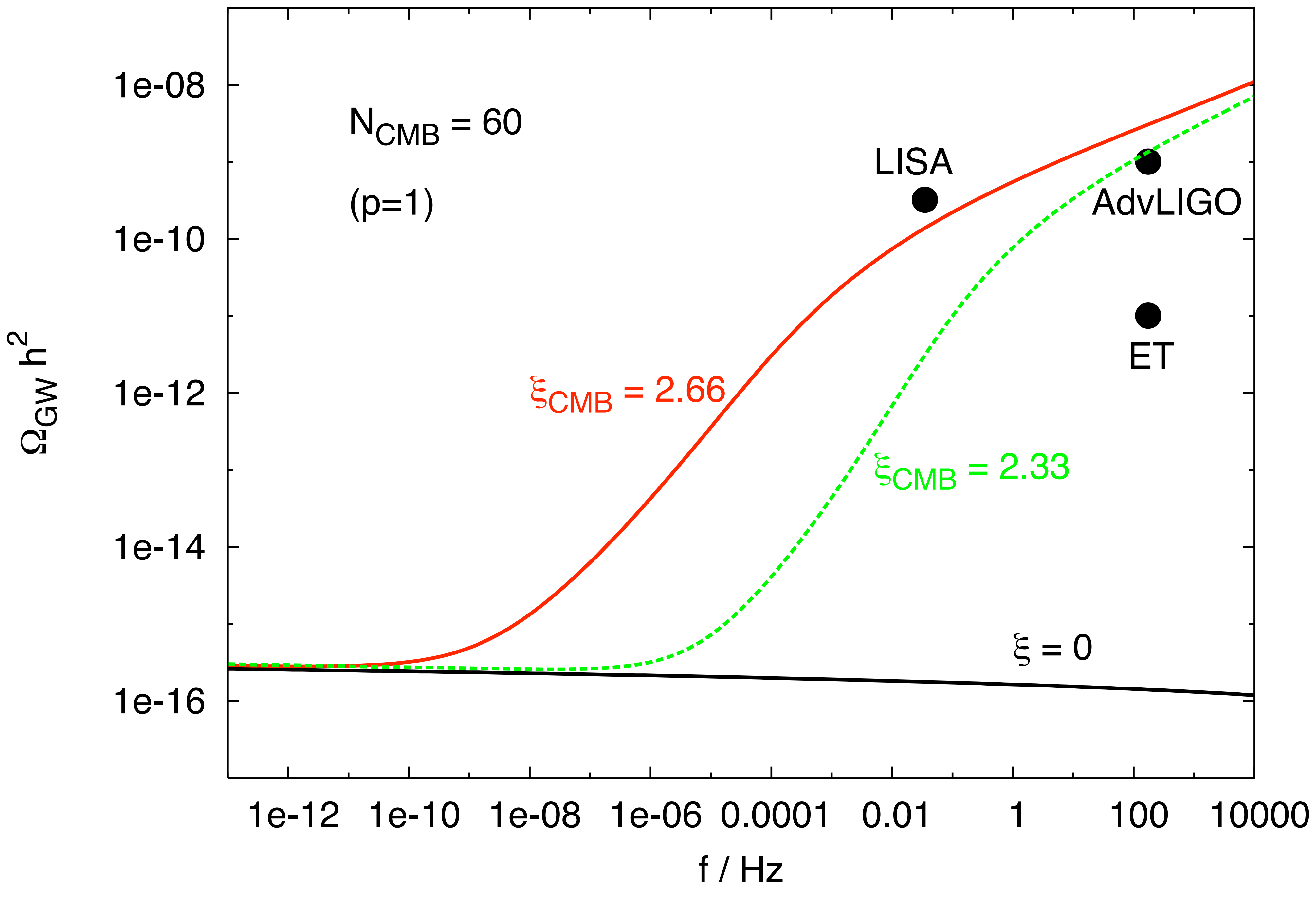
GWs produced towards the end of inflation (i.e., at smaller scales) have larger amplitude

might be detected by GW interferometers!

GWs at smaller scales

Important! Constraints on f_{NL} on CMB scales only!

Inflationary gravitational waves for LIGO (LISA…)?



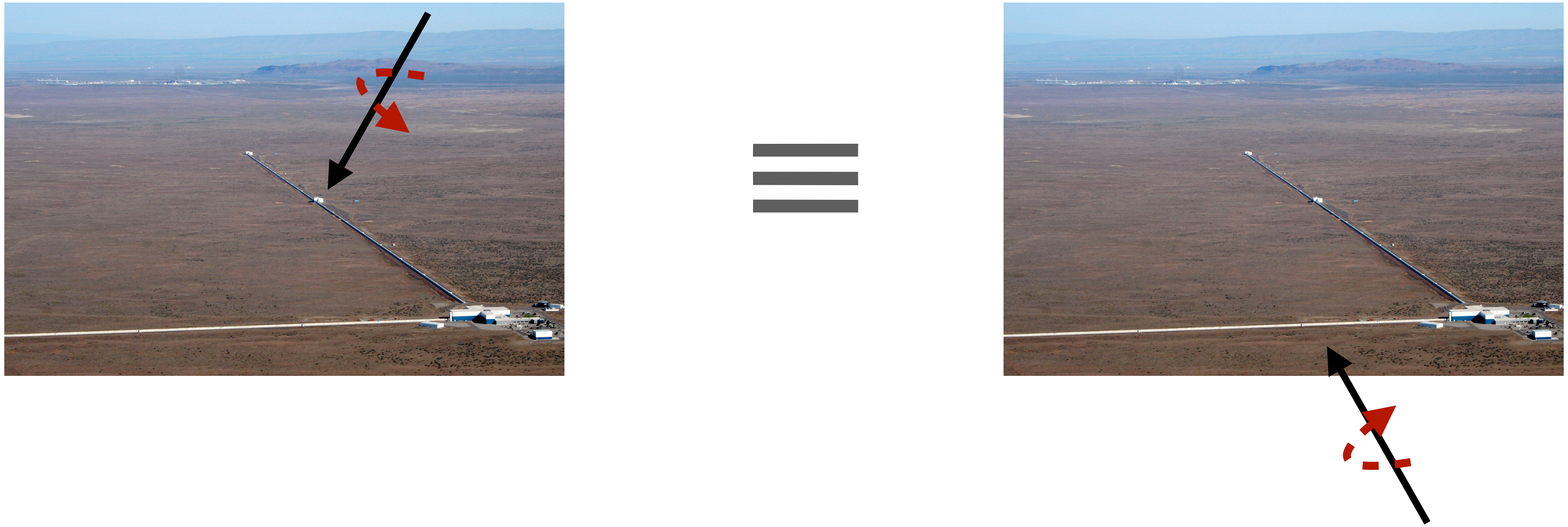
Barnaby Pajer Peloso 11

Phenomenology

Is parity violation in stochastic GWs detectable by interferometers?

Seto Taruya 07

Not as long as system is Z_2-symmetric!



Phenomenology

Is parity violation in stochastic GWs detectable by interferometers?

Seto 06, Domcke et al 19

The presence of cosmic GW background dipole breaks the symmetry

for LISA

$$\mathrm{SNR} \simeq \left(\frac{v}{10^{-3}}\right) \left|\frac{\sum_\lambda \lambda\, \Omega_{GW}^\lambda h^2}{1.4 \cdot 10^{-11}}\right| \sqrt{\frac{T}{3\,\mathrm{years}}}\,.$$

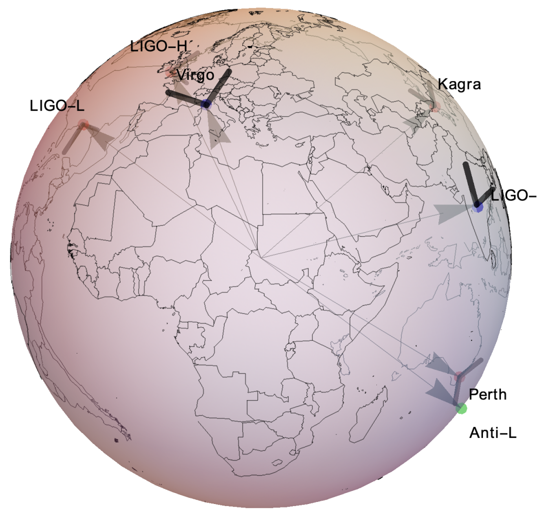
Additional detectors break the Z_2 symmetry

Crowder et al 12

for maximal chirality need $\Omega_{GW}\sim 10^{-8}$ for LIGO/Virgo/Kagra (already ruled out)

Domcke et al 19

an extra interferometer to maximize sensitivity?



Phenomenology

Other features?

Corba' LS 24

GW interferometers have poor but nonzero angular sensitivity

Bartolo et al 22

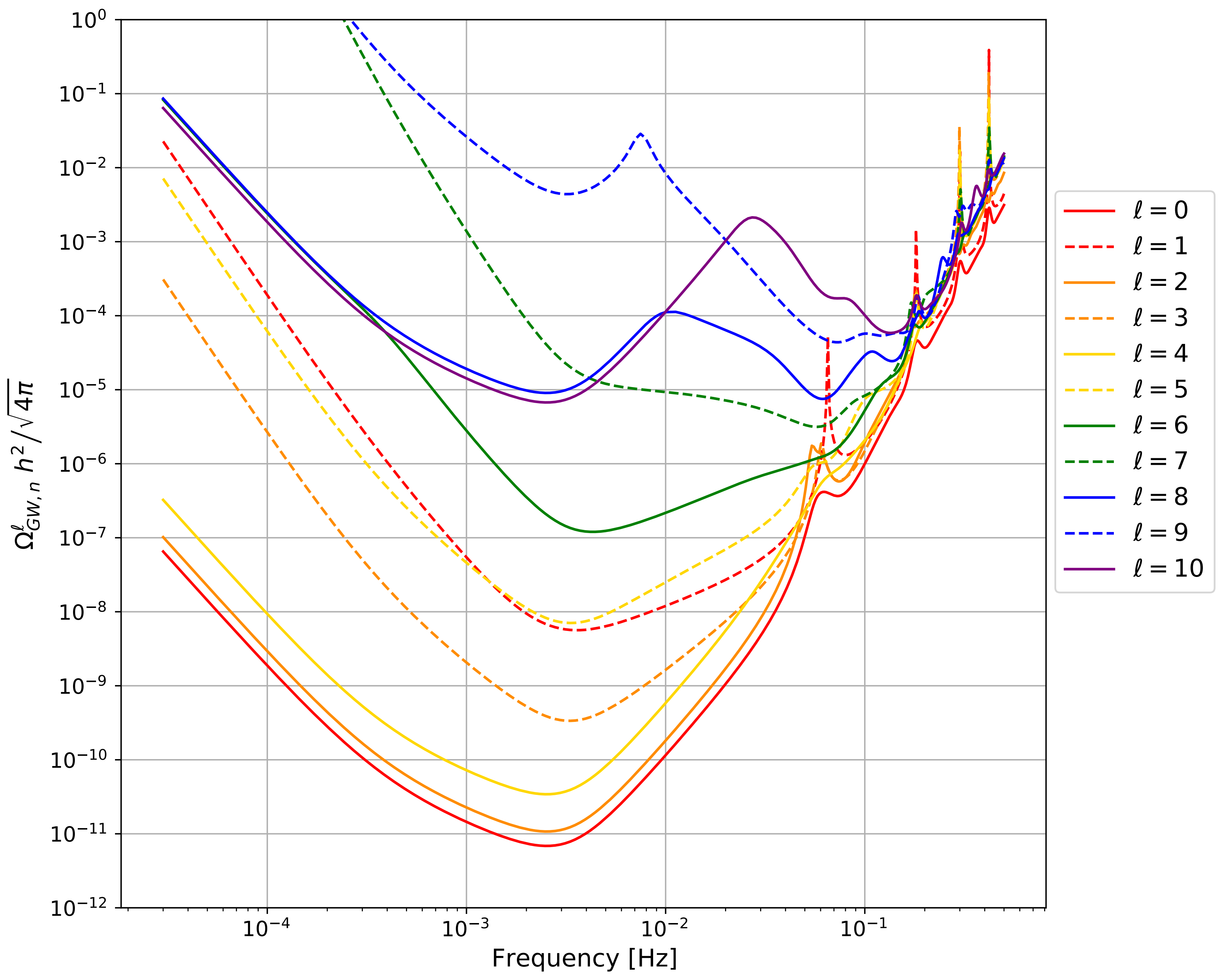


Figure 9: *Estimated LISA sensitivity to a given multipole ℓ of the SGWB, for multipoles up to $\ell = 10$. Even (odd) multipoles are shown with solid (dashed) lines. The sensitivity is obtained by optimally summing over the LISA channels, see Eqs. (4.42) and (4.43).*

Angular correlations of energy in GWs with scalar CMB perturbations?

Other features?

Corba' LS 24

Two sources of correlation

$$\Phi \longrightarrow A_\mu \begin{array}{l} \nearrow h_{\mu\nu} \\ \searrow \delta\Phi \end{array}$$

$$\boxed{\Phi+\delta\Phi \longrightarrow A_\mu+\delta A_\mu \longrightarrow h_{\mu\nu}+\delta h_{\mu\nu}}$$

Dominant

Bartolo et al 19

Angular correlations of energy in GWs with scalar CMB perturbations?

$$\frac{1}{\Omega_{GW}^{\rm INT}\sqrt{\mathcal{P}_\zeta^{\rm CMB}}}\frac{k^3}{2\pi^2}\langle\Omega_{GW}(\mathbf{k},\,t_0)\,\zeta(-\mathbf{k},\,t_0)\rangle' \simeq -4\pi\,\xi\,\Delta\mathcal{N}_*\,(2\epsilon-\eta)\,\sqrt{\mathcal{P}_\zeta} \simeq \boxed{10^{-4}\div 10^{-2}}$$

Other features?

Corba' 25

Two sources of correlation

$$\Phi \longrightarrow A_\mu \begin{cases} \nearrow h_{\mu\nu} \\ \searrow \delta\Phi \end{cases}$$

$$\boxed{\Phi+\delta\Phi \longrightarrow A_\mu+\delta A_\mu \longrightarrow h_{\mu\nu}+\delta h_{\mu\nu}}$$

Dominant

Angular anisotropies in Ω_{GW}

$$\frac{1}{\Omega_{GW}^2}\frac{k^3}{2\pi^2}\langle\Omega_{GW}(\mathbf{k},\,t_0)\,\Omega_{GW}(-\mathbf{k},\,t_0)\rangle' \simeq \frac{9.8\times10^{-5}}{\delta^2}\left(2\pi\frac{d\xi}{d\phi_0}\frac{\dot\phi_0}{H}\right)^2 \simeq \boxed{10^{-5}\div10^{-1}}$$

$$\delta \approx .05 \div .2$$

Phenomenology

Linde, Mooij, Pajer 12
Garcia-Bellido, Peloso, Unal 16

Many vectors at small scales $\Longrightarrow$
very large scalar perturbations

Primordial black holes

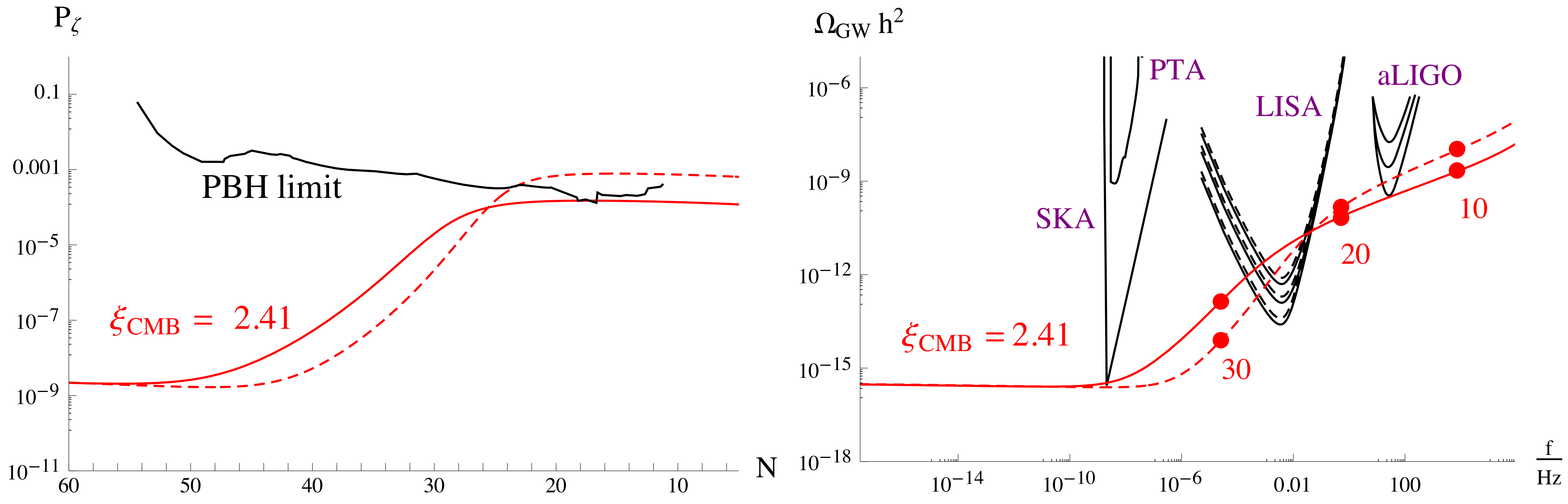


Figure 5. Scalar and tensor signals for a linear inflation potential. The solid lines show the signal if $\mathcal{N} = 6$ gauge fields are amplified. For comparison, the dashed lines show the signal when 1 gauge field is amplified.

Strong backreaction

Anber LS 09

Exponentially large occupation numbers for vectors

$\Downarrow$

backreaction becomes quickly important:

$$\ddot{\phi} + 3\,H\,\dot{\phi} + V'(\phi) = -\frac{\alpha}{f}\langle\vec{E}\cdot\vec{B}\rangle \qquad \langle\mathbf{E}\cdot\mathbf{B}\rangle \propto e^{\pi\frac{\alpha\,|\dot{\phi}|}{f\;H}}$$

Strong backreaction regime:

$$\boxed{V'(\phi) = -\frac{\alpha}{f}\langle\vec{E}\cdot\vec{B}\rangle} \;\Rightarrow\; \boxed{\dot{\phi} \simeq \frac{f\,H}{\alpha\pi}\log\left(\ldots\right)}$$

Strong backreaction

NOTE: strong backreaction happens quite generally towards the end of inflation in phenomenologically interesting models

IMPORTANT

that we understand it well!

Strong backreaction

Looking more carefully into the backreacted equations…

$$\ddot{\phi} + 3\,H\,\dot{\phi} + V'(\phi) = -\frac{\alpha}{f}\langle \mathbf{E}\cdot\mathbf{B}\rangle$$

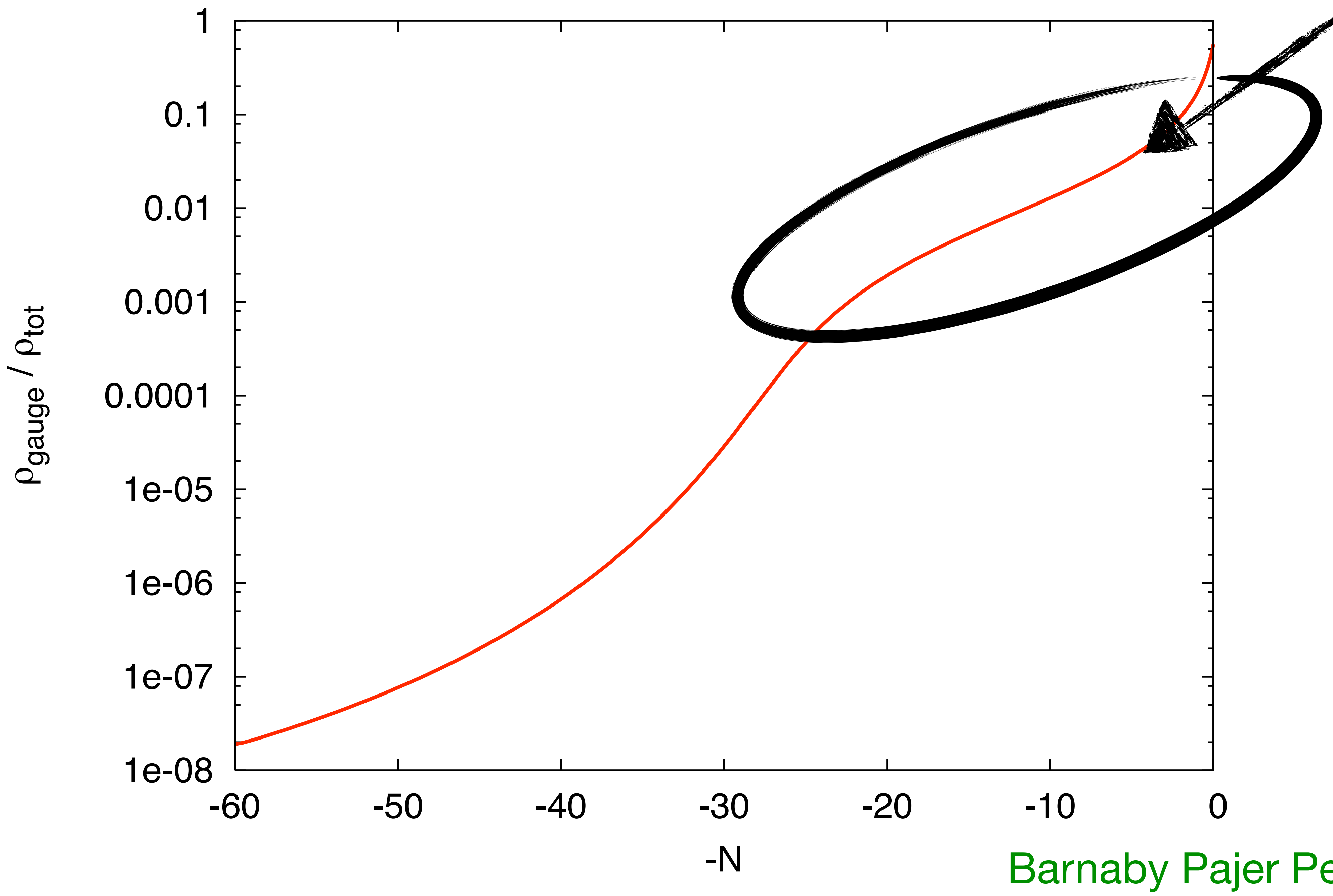
Backreaction

with $\langle \mathbf{E}\cdot\mathbf{B}\rangle \propto e^{\pi\,\frac{\alpha}{f}\frac{|\dot{\phi}|}{H}}$

Increases during inflation

…an equation for ϕ only?

Backreaction in action



Barnaby Pajer Peloso 11

Strong backreaction

But remember $\langle \mathbf{E}\cdot\mathbf{B}\rangle = \int \mathbf{E}(\mathbf{k})\cdot\mathbf{B}(\mathbf{k})\, d^3\mathbf{k}$

where $\mathbf{E}(\mathbf{k}, \mathrm{t})$ and $\mathbf{B}(\mathbf{k}, \mathrm{t})$ depend on $\mathbf{E}(\mathbf{k}, \mathrm{t'}<\mathrm{t})$, $\mathbf{B}(\mathbf{k}, \mathrm{t'}<\mathrm{t})$

Cannot use single equation local in time, **need numerics!**

$$\Phi'' + 2aH\Phi' + a^2 V' = -\frac{\alpha^2}{4\pi^2 a^3 f}\int dk\, k^2 \frac{\partial}{\partial\tau}\left|A_+\right|^2$$

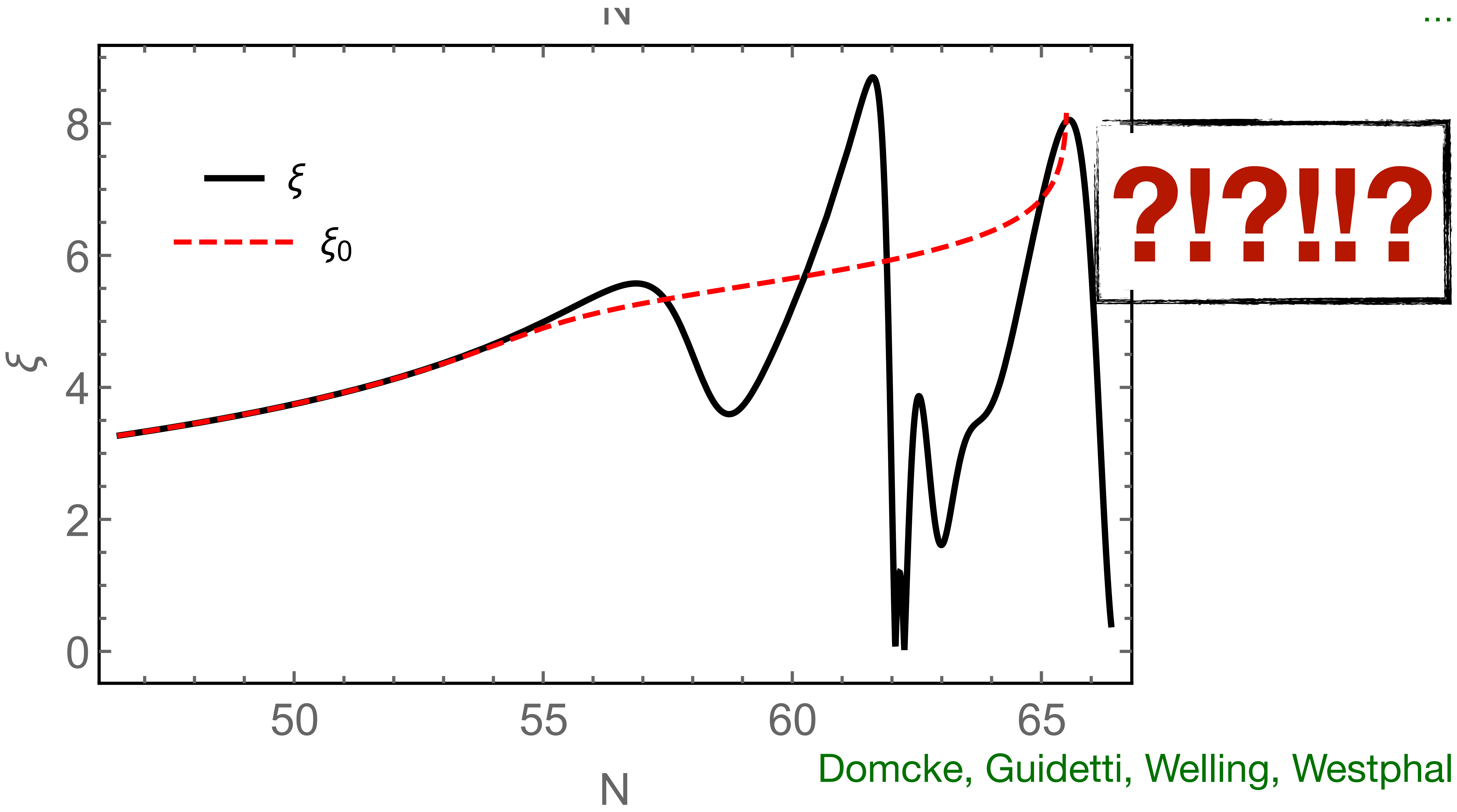
$$A_+'' + k^2 A_+ - \frac{\alpha\,\Phi'}{f} A_+ = 0$$

(neglecting inflation gradients and non-amplified helicity of gauge field)

Strong backreaction

Numerical result with uniform inflaton and one helicity of photon only

Cheng, Lee, Ng, 15
Notari, Tywoniuk 16
Dall'Agata, Gonzalez-Martin, Papageorgiou, Peloso 19
Domcke, Guidetti, Welling, Westphal 20
Gorbar, Schmitz, Sobol, Vilchinwskii 21
...



Domcke, Guidetti, Welling, Westphal 20

Strong backreaction

Where is this coming from?

Notari, Tywoniuk 16
Domcke, Guidetti, Welling, Westphal 20

$\langle \mathbf{E} \cdot \mathbf{B} \rangle$ does not react instantly to change in ξ

$$\cancel{\ddot{\phi}(t) + 3\,H\,\dot{\phi}(t) + V'(\phi(t)) = -\frac{\alpha}{f}\langle \mathbf{E} \cdot \mathbf{B} \rangle(t)}$$

$$\ddot{\phi}(t) + 3\,H\,\dot{\phi}(t) + V'(\phi(t)) = -\frac{\alpha}{f}\int^{t} K(t,\,t')\langle \mathbf{E} \cdot \mathbf{B} \rangle(t')\,dt' \simeq -\frac{\alpha}{f}\langle \mathbf{E} \cdot \mathbf{B} \rangle(t-\Delta t)$$

Strong backreaction

So…. why oscillations?

Baby example: try to solve $f'(t) = f(t+q)$, with q real

solution $f(t)=e^{a\,t}$, where a must satisfy $a=e^{a\,q}$

Equation has two real roots a_1, a_2 for $q<e^{-1}$

but most importantly:

Looking for complex $a=a_R+i\,a_I$…

Infinite solutions!

(with $q\,a_I \simeq \pi/2+n\,\pi$ at large n)

Of course,
NOT a Cauchy problem!

Strong backreaction

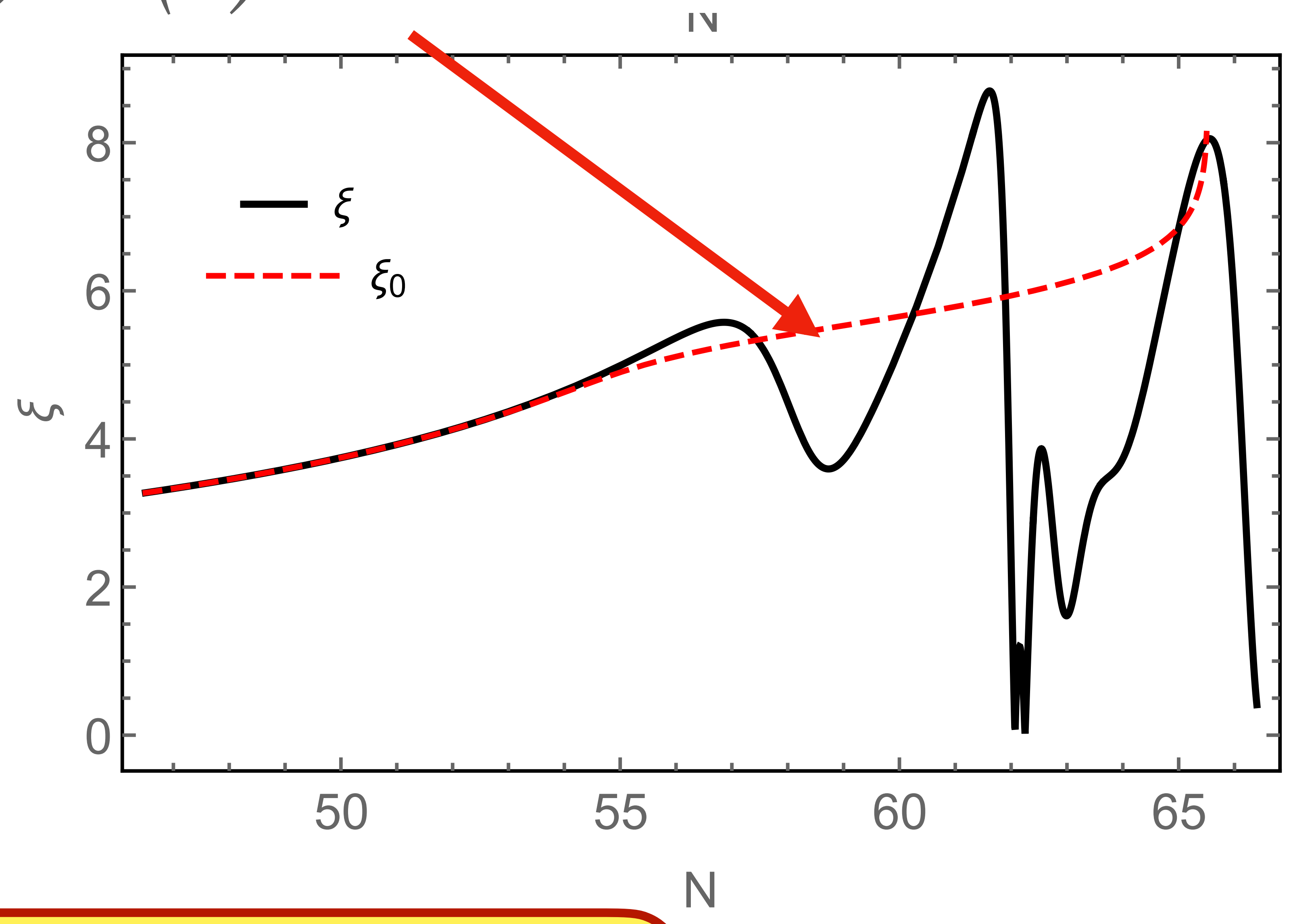
Analytical study for small perturbations around $\phi(t)=\bar{\Phi}(t)$…

Peloso, LS 22

where… $$\ddot{\bar{\Phi}} + 3\,H\,\dot{\bar{\Phi}} + V'(\bar{\Phi}) = -\frac{\alpha}{f}\langle \mathbf{E}\cdot\mathbf{B}\rangle(H,\,\dot{\bar{\Phi}})$$

with the RHS computed assuming $H,\ \dot{\bar{\Phi}}(t)=const.$

writing $$\Phi = \bar{\Phi} + \delta\Phi \quad , \quad A = \bar{A} + \delta A$$



look for solution $$\delta\Phi \propto (-\tau)^{\alpha}$$

Always at least one root with α complex and $Re[\alpha]<-0$!

Strong backreaction

Inflationary gravitational waves for LIGO (LISA…)?

$$\mathcal{P}_L(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 9\times 10^{-7}\,\frac{H^2}{M_P^2}\,\frac{e^{4\pi\xi}}{\xi^6}\right)$$

$$\mathcal{P}_R(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 2\times 10^{-9}\,\frac{H^2}{M_P^2}\,\frac{e^{4\pi\xi}}{\xi^6}\right)$$

ξ increases during inflation

large amplitude at short (interferometer) scales

How does this change with more realistic $\xi(t)$?

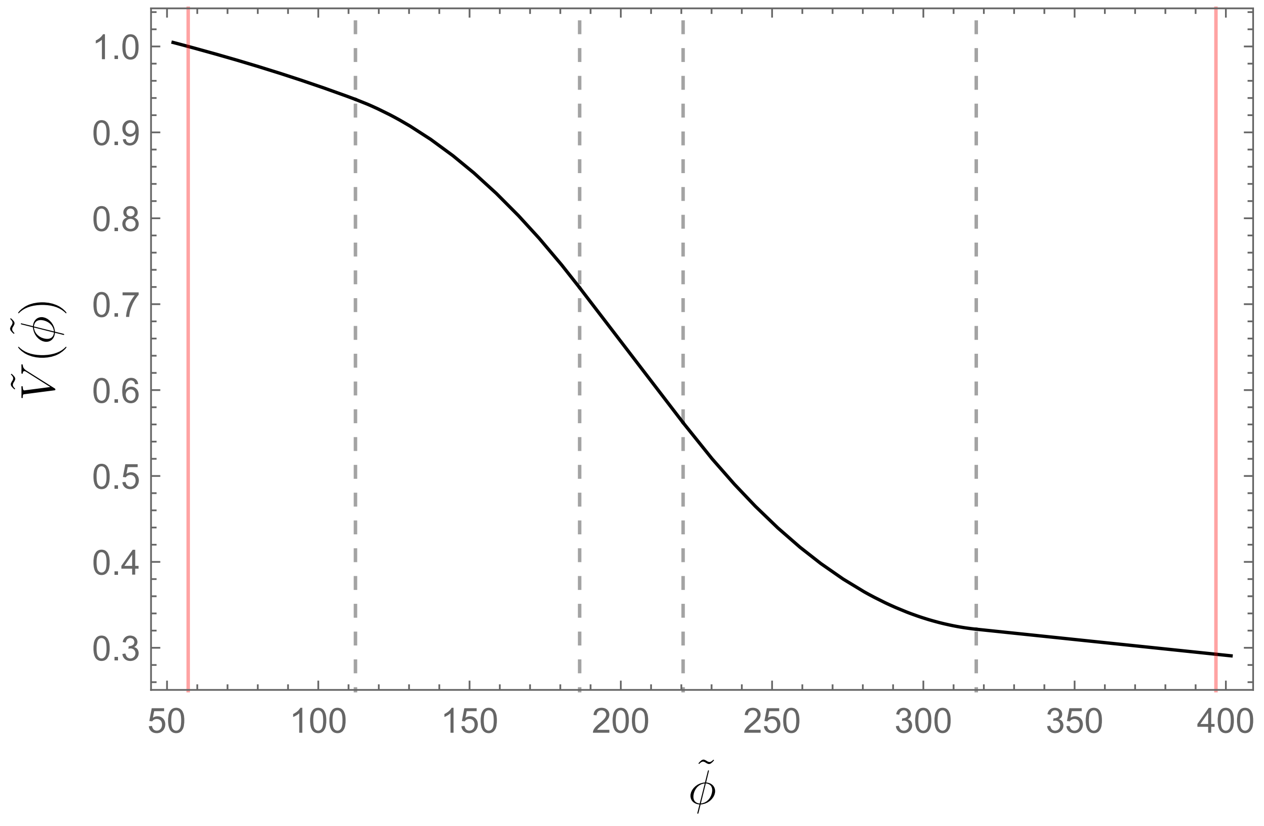
Strong backreaction

Need numerical solution of background

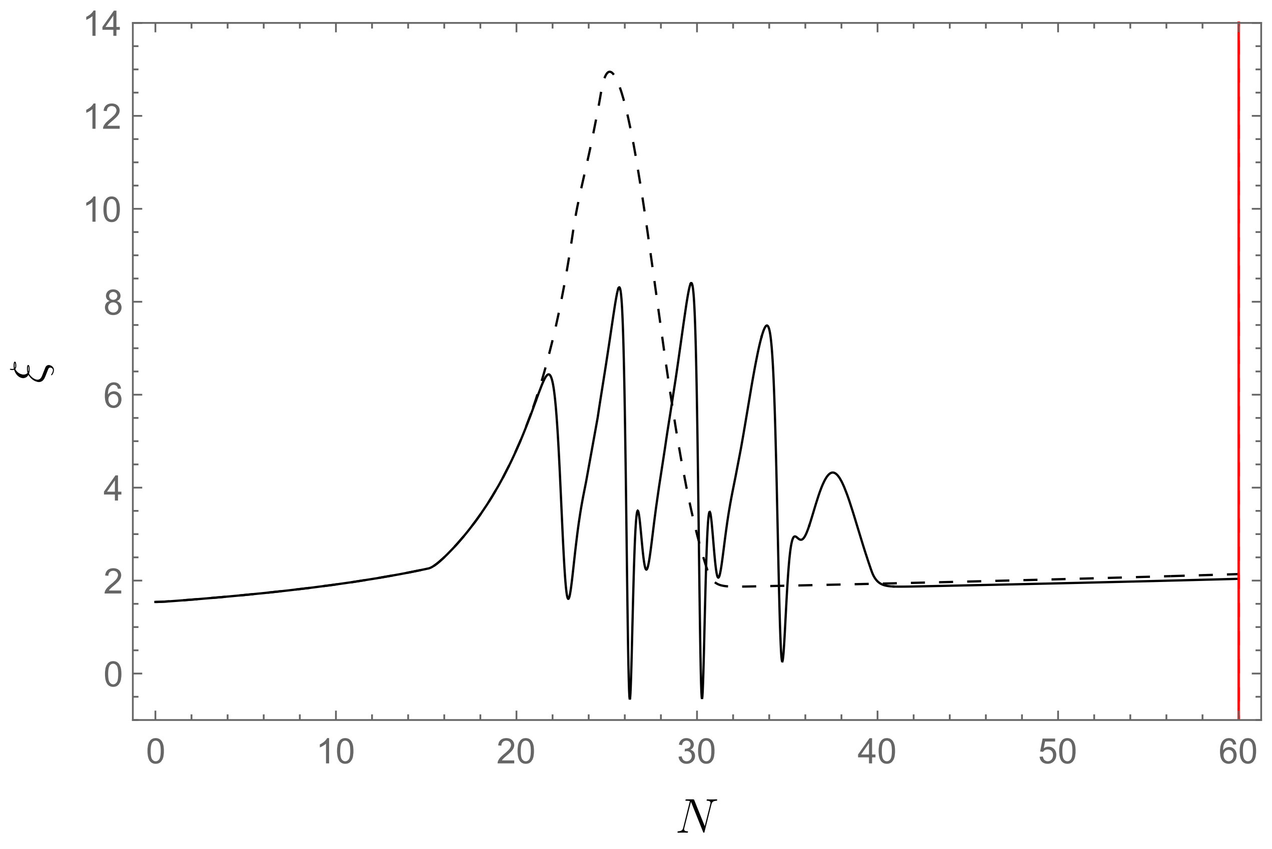
Garcia-Bellido, Papageorgiou, Peloso, LS 23

Example for steep-ish potential @ intermediate times

$V(\phi)$



$\xi(N)$



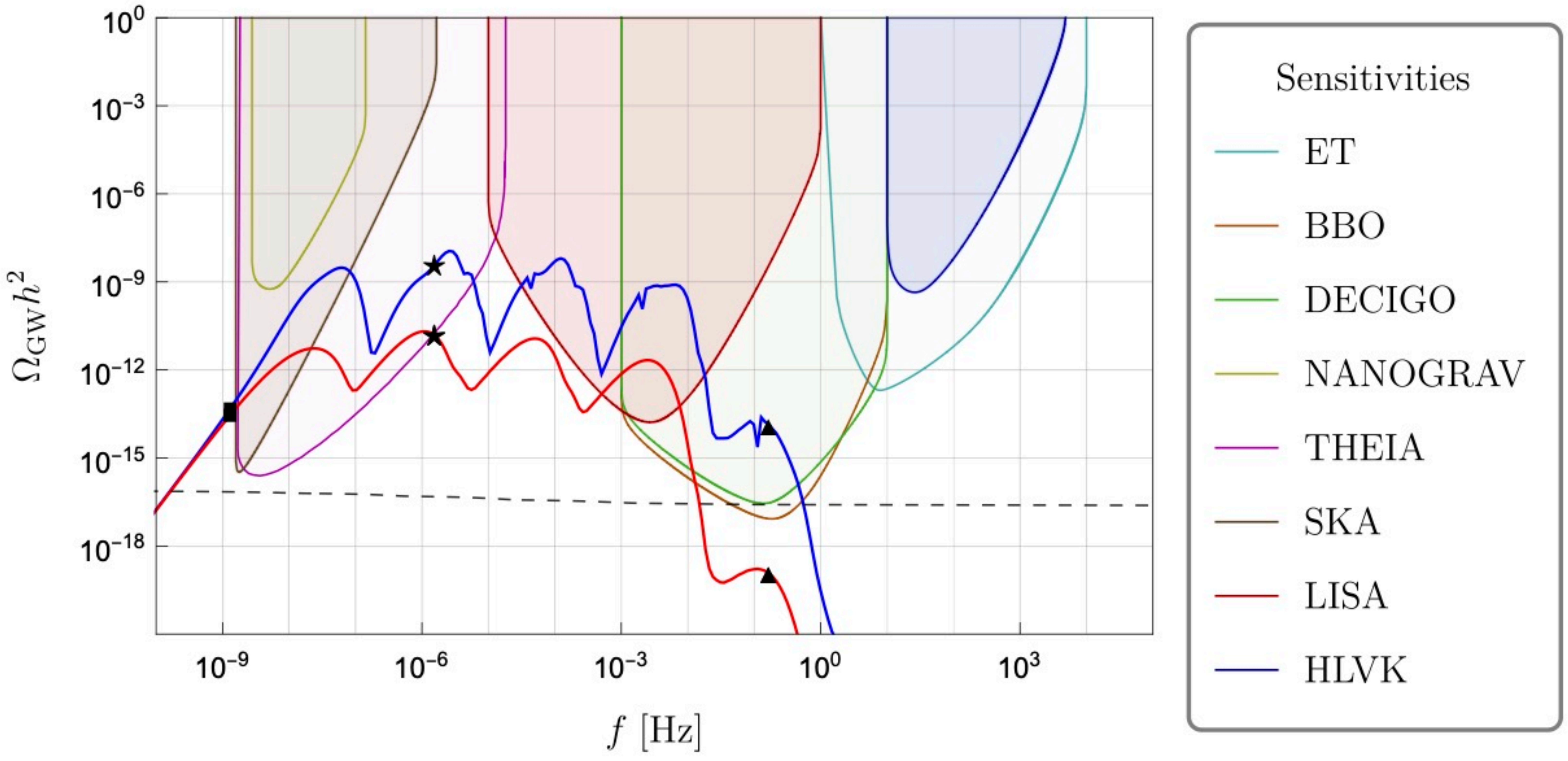
Strong backreaction

Flashes of gravitational waves from axion inflation

Garcia-Bellido, Papageorgiou, Peloso, LS 23

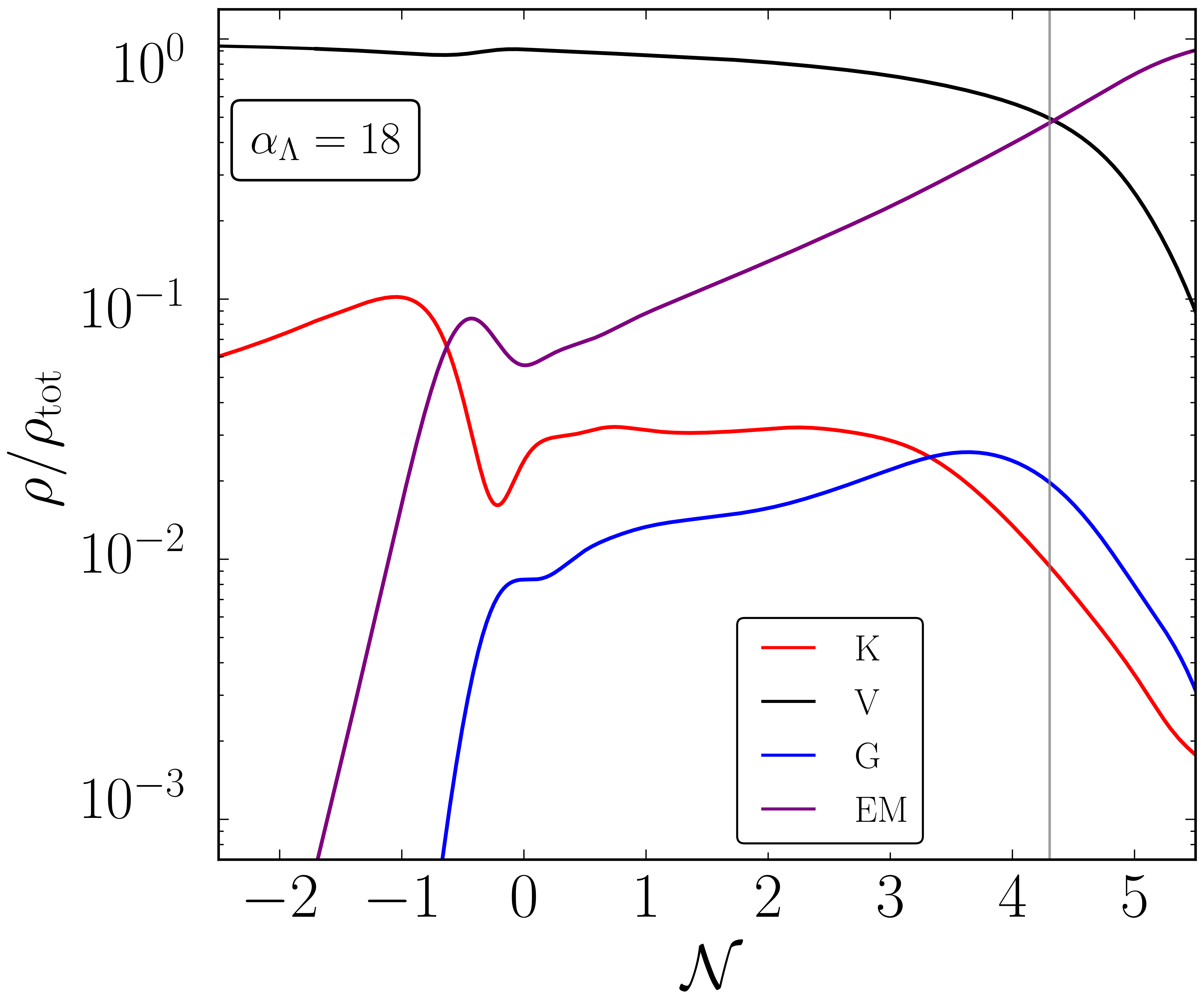
Example for steep-ish potential @ intermediate times

- *Peaks!*
- *Parity violation!*
- *PTAs!*
- *LISA!*



Strong backreaction

But, lattice studies show that oscillations do not last



Caravano, Komatsu, Lozanov, Weller 22
Figueroa et al 23, 24
Sharma Brandenburg Subramanian Vikman 25
(see also Caravano Peloso 24)

Inflaton gradients appear to be large and to affect the dynamics ***a lot***! Only one oscillation or so in ξ

Strong backreaction

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Example for steep-ish potential @ intermediate times

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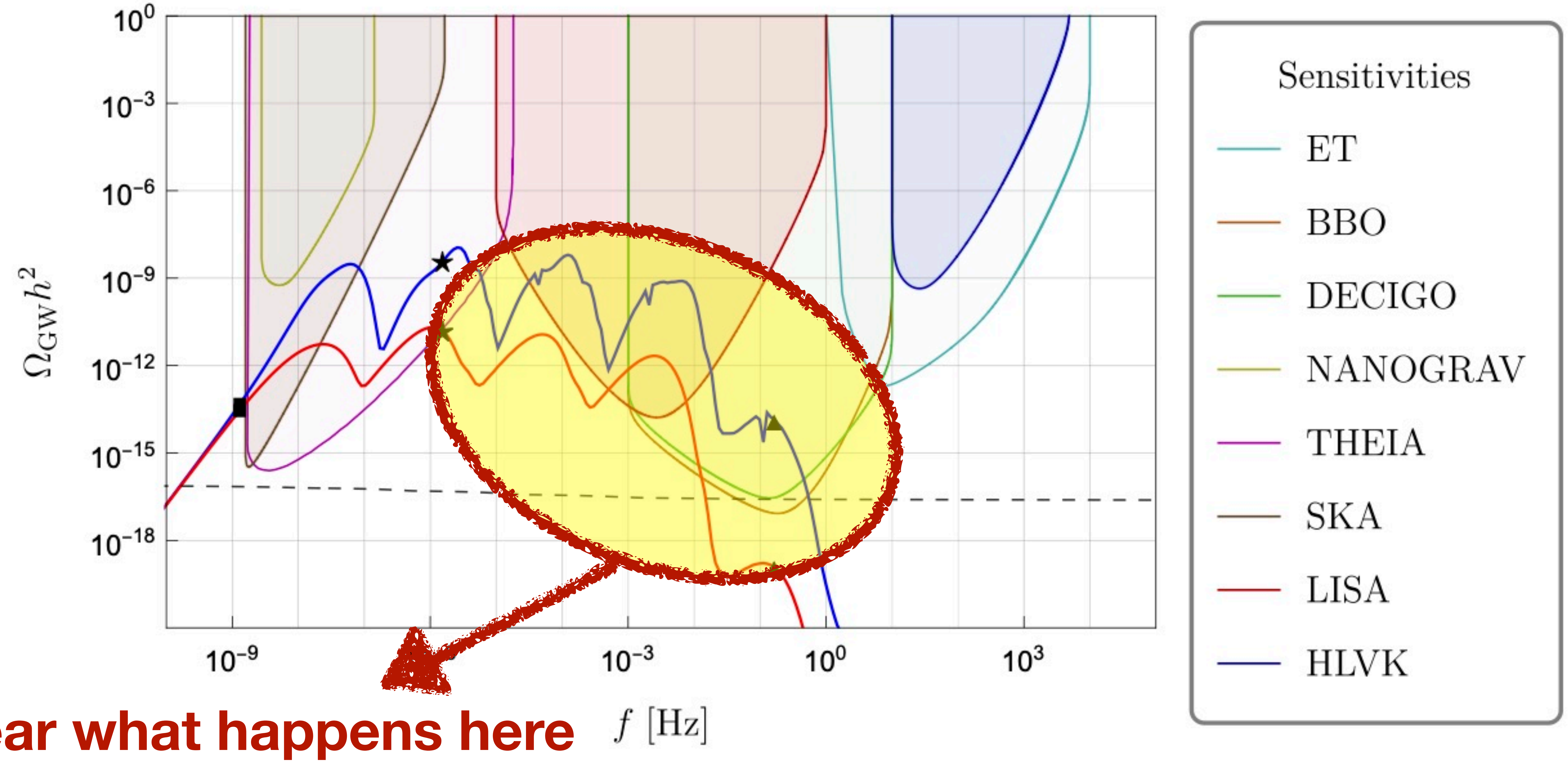


Not clear what happens here

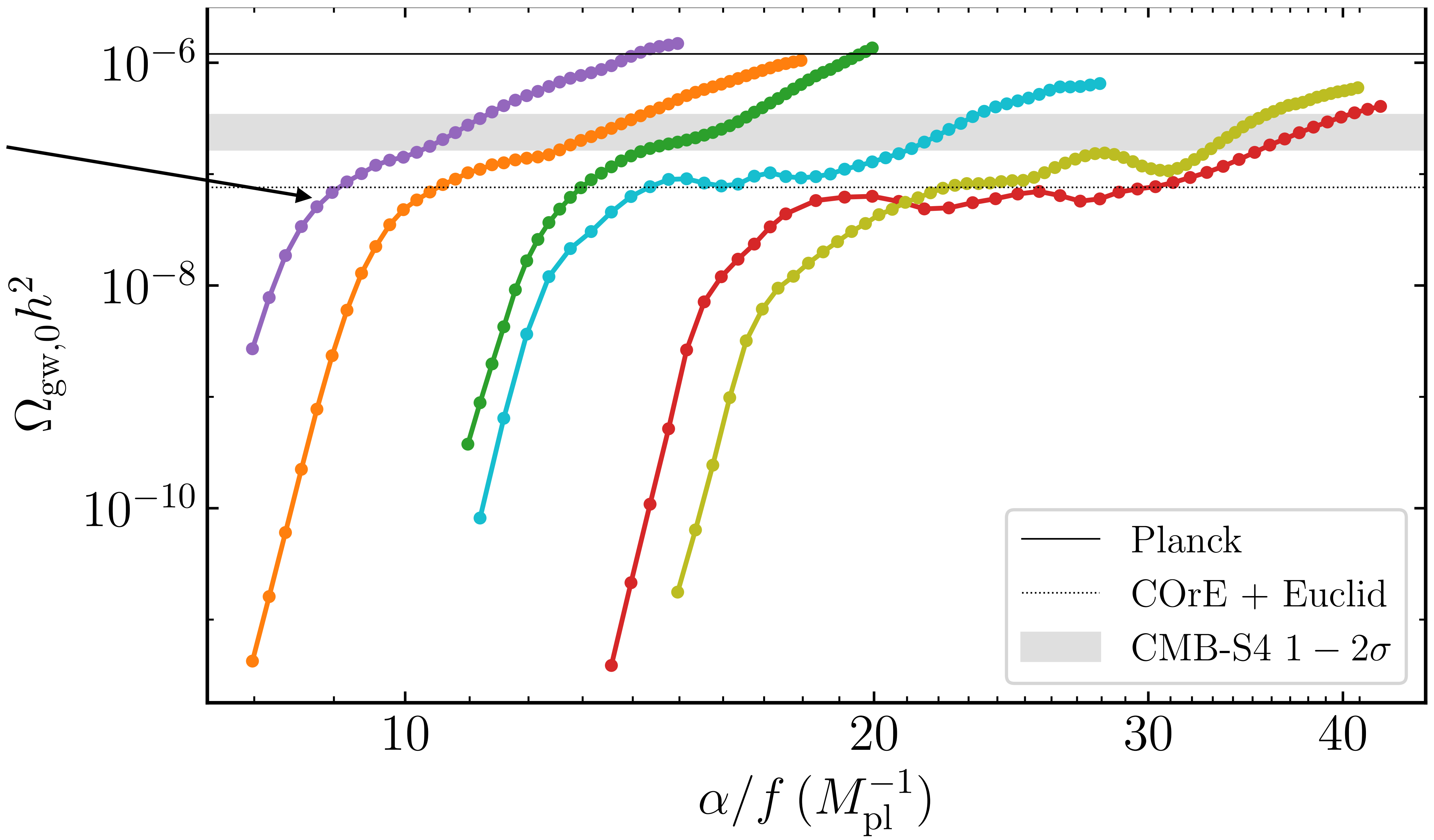
Strong backreaction

Too many gravitational waves from the end of inflation?

Adshead, Giblin, Pieroni, Wiener 19

If axion inflation ends in a very strong backreaction regime, then GW can be overproduced at the end of inflation, violating constraints from N_{Eff}

chaotic inflation



(but, model dependence during reheating!)

Kyohei talk yesterday

Strong backreaction

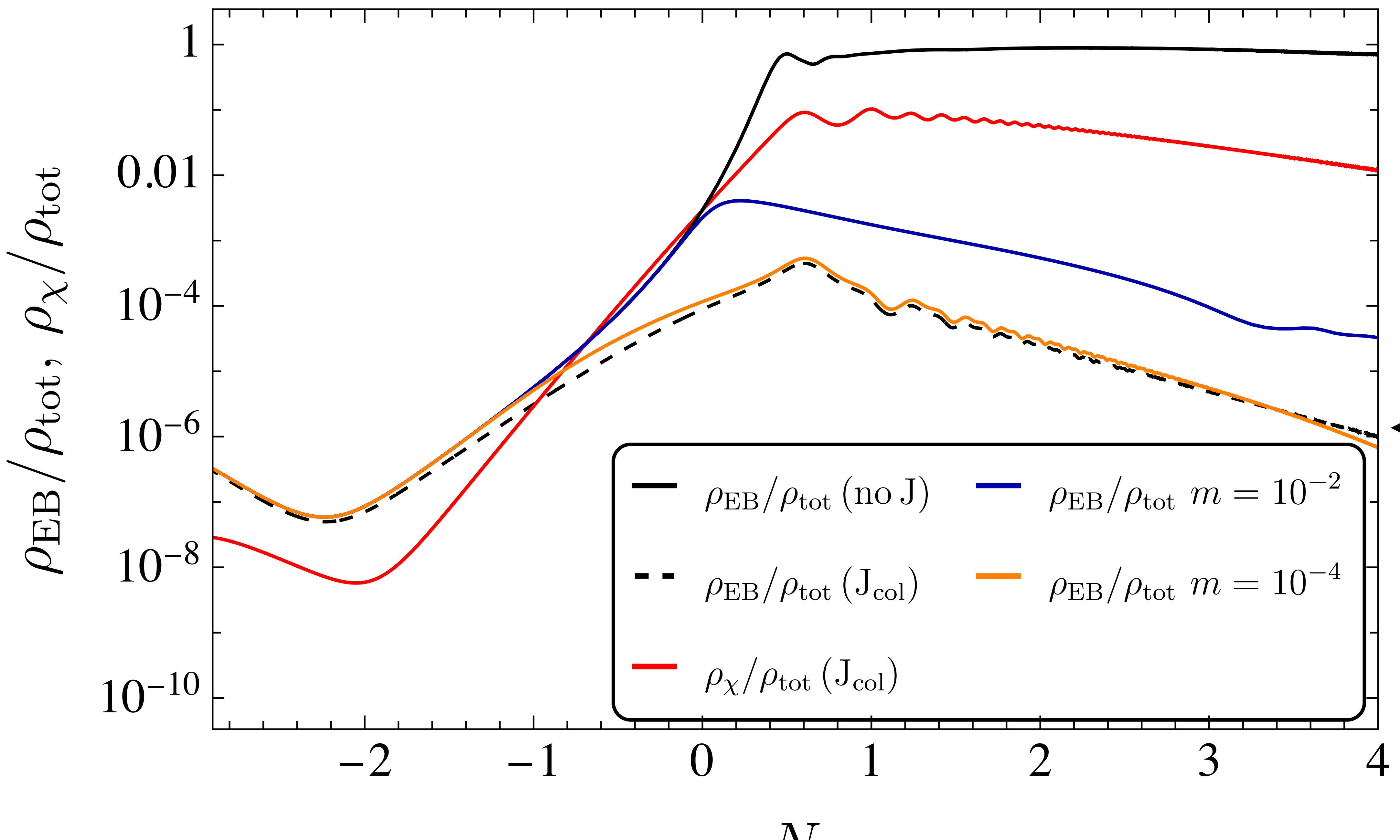
…but, are there other ingredients in the model?

If the gauge field is the SM photon in interaction with SM matter, then thermalization!

Ferreira, Notari 17

Schwinger pair production!

Domcke, Ema, Mukaida, Sato 19
Iarygina, Sfakianakis, Brandenburg 25



No Schwinger effect

Schwinger effect, massless fermions

Other settings!

Chromonatural inflation

Adshead, Wyman 12

Coupling to *SU(2)* gauge fields:

$$\mathcal{L}(\varphi,\, A^\mu) = \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F_a^{\mu\nu}F_{\mu\nu}^a - \frac{\alpha}{4f}\varphi F_a^{\mu\nu}\tilde{F}_a^{\mu\nu}$$

Can find a configuration with *background* gauge field which respects *SO(3)*:

$SU(2) \approx SO(3)$

$$A_0^a = 0 \quad , \quad A_i^a = \delta_i^a a(t)Q(t) \, ,$$

Chromonatural inflation

Equations of motion…

$$\ddot{\phi} + 3\,H\,\dot{\phi} - V'(\phi) = -3\,g\,\frac{\lambda}{f}\,Q^2\,\left(\dot{Q} + H\,Q\right)$$

$$\ddot{Q} + 3\,H\,\dot{Q} + (\dot{H} + 2\,H^2)\,Q + g\,Q^2\left(2\,g\,Q - \frac{\lambda}{f}\,\dot{\phi}\right) = 0$$

…complicated, but one can show slow roll!

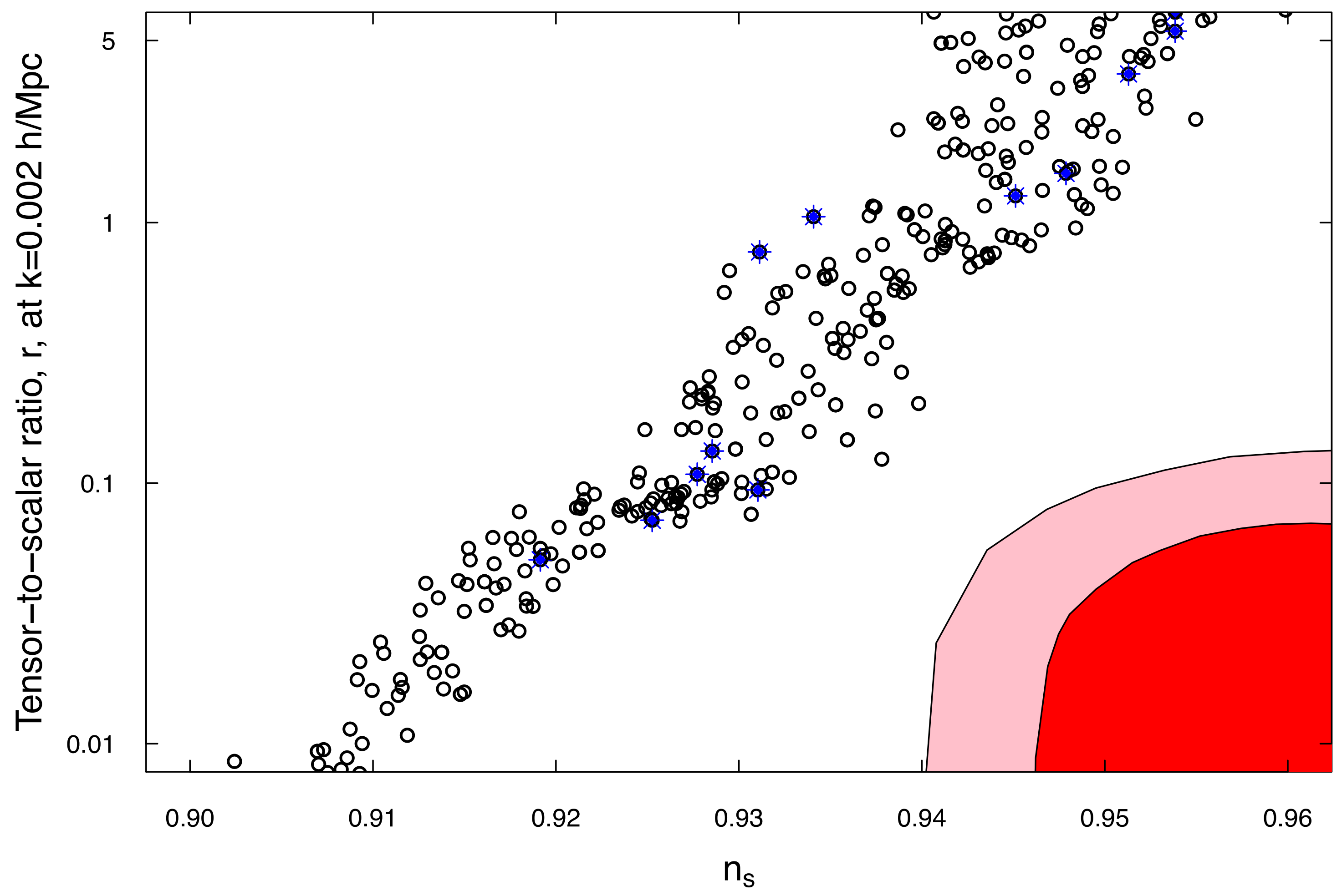
Chromonatural inflation

Perturbations: 2 tensors, 1 vector and 3 scalars…

Dimastrogiovanni, Peloso 13
Adshead, Martinec, Wyman 13

Either scalar spectrum is too red,
or too many tensors

Ruled out ☹️



…but can be revived if the rolling axion is not the inflaton!

Dimastrogiovanni, Fasiello, Fujita 16

(and large chiral gravitational waves!)

To sum up…

Inflationary axion dynamics is well motivated and very rich

Motivates search in data!