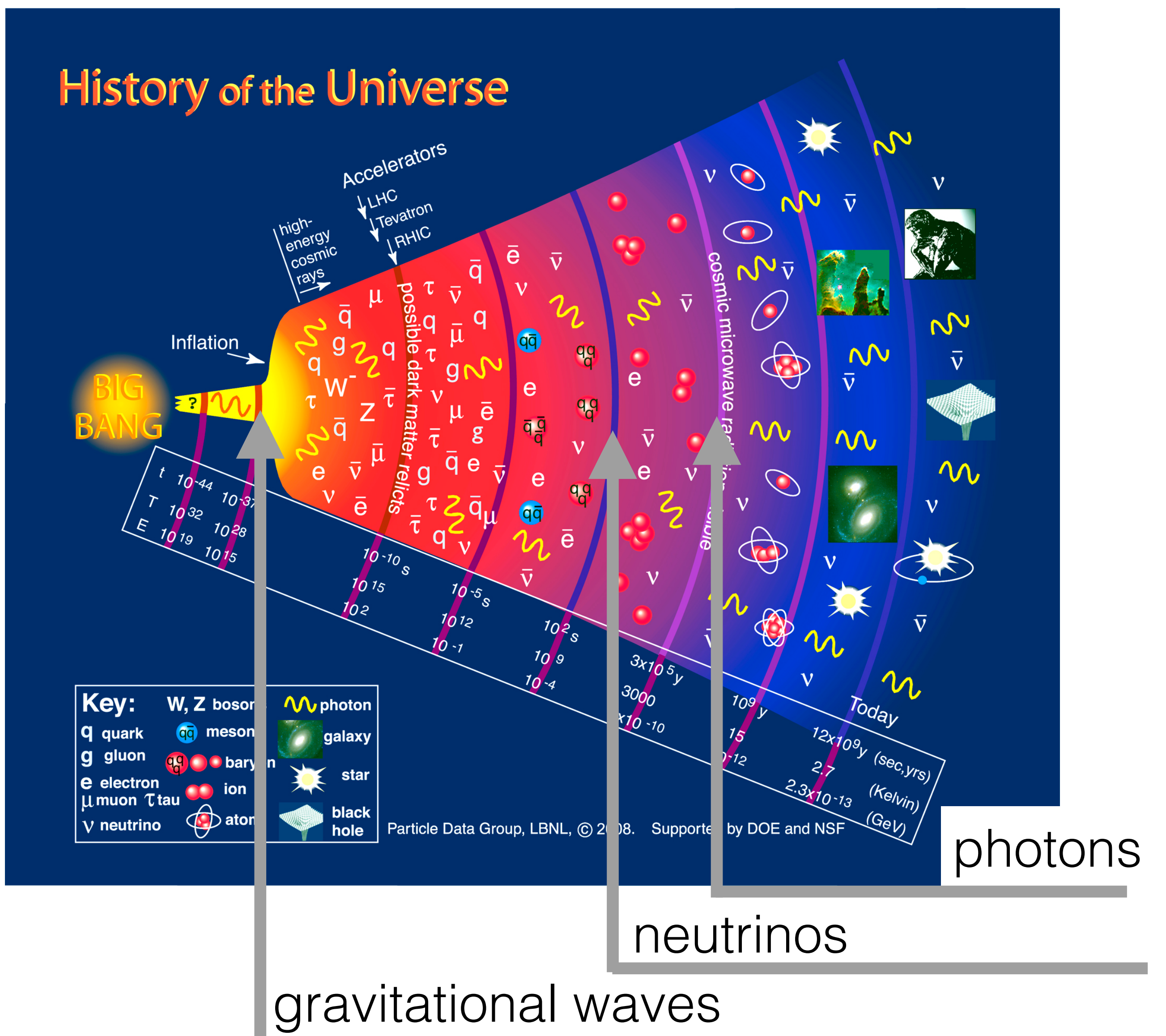
Cosmological sources of GWs

Probing the early universe with GWs



Valerie Domcke
APC, Paris

IPA, 5. - 9.9.2016
LAL, Orsay

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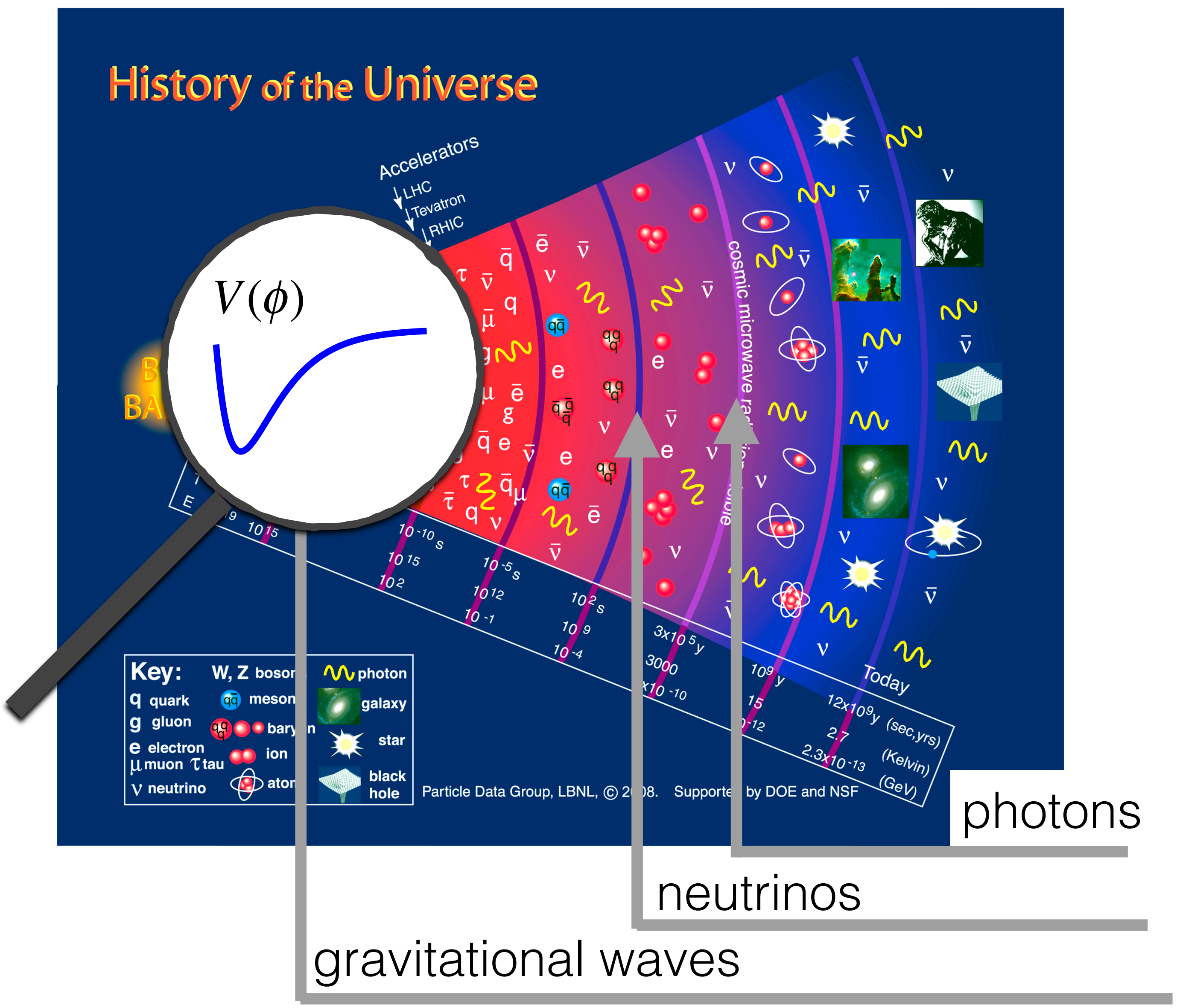

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Outline

stochastic
GW backgrounds

- Primordial GW background

……..GWs from cosmic inflation

……..how to read to cosmic GW history book

……..searching for GWs: CMB versus direct detection

……..enhanced primordial GW background ?

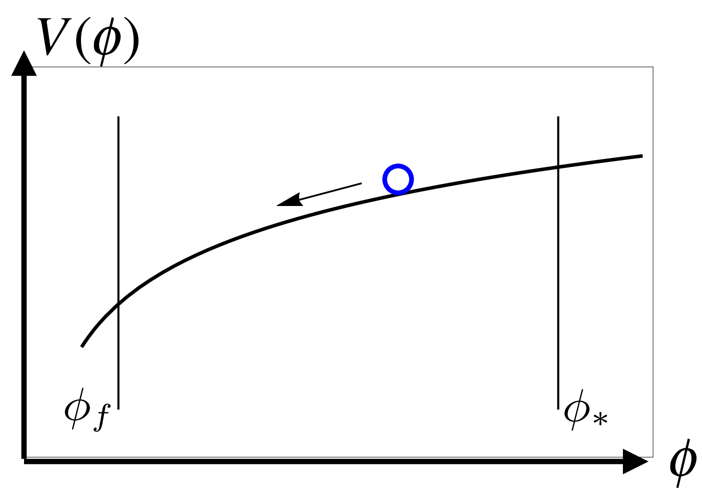
- Further GW sources in the early Universe

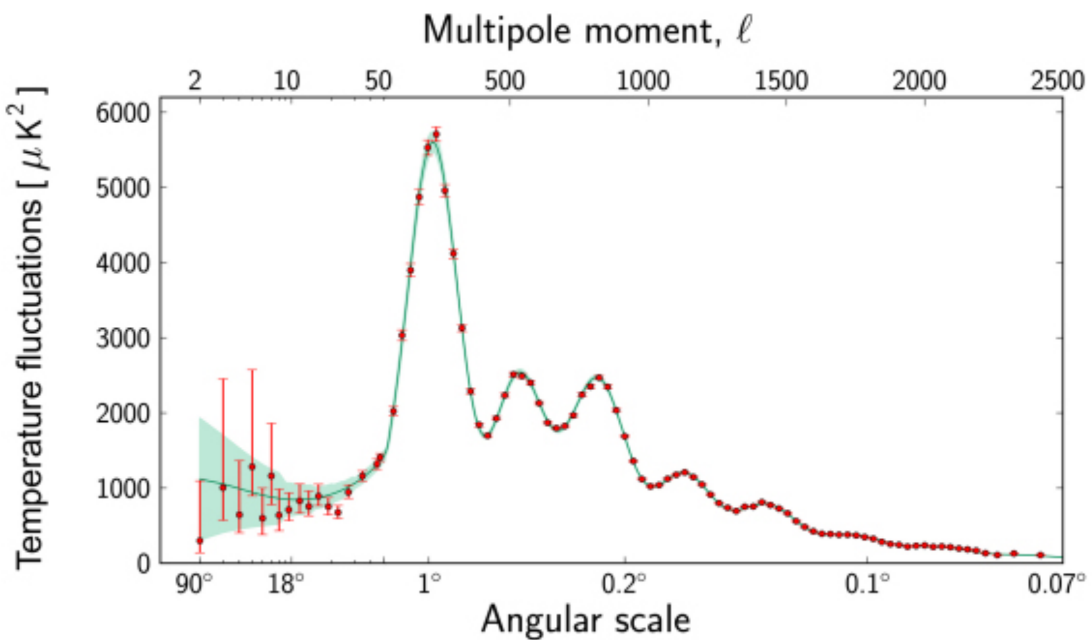
……..cosmic strings

……..first-order phase transitions

……..primordial black holes

The paradigm of slow-roll inflation





Planck collaboration

large vacuum energy → exponential expansion → homogeneity of CMB

quantum fluctuations → become classical → tiny anisotropies in the CMB

The big question: $V(\phi) = ??$ → $\Delta_s^2 = \frac{V(\phi)}{24\pi^2\epsilon(\phi)}, \quad \Delta_t^2 = \frac{2V(\phi)}{3\pi^2}; \quad \epsilon = \frac{\dot{\phi}^2}{2H^2} \simeq \frac{1}{2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2$

scalar spectrum, tensor spectrum

very successful paradigm, but very many possible realizations

Scales and horizons

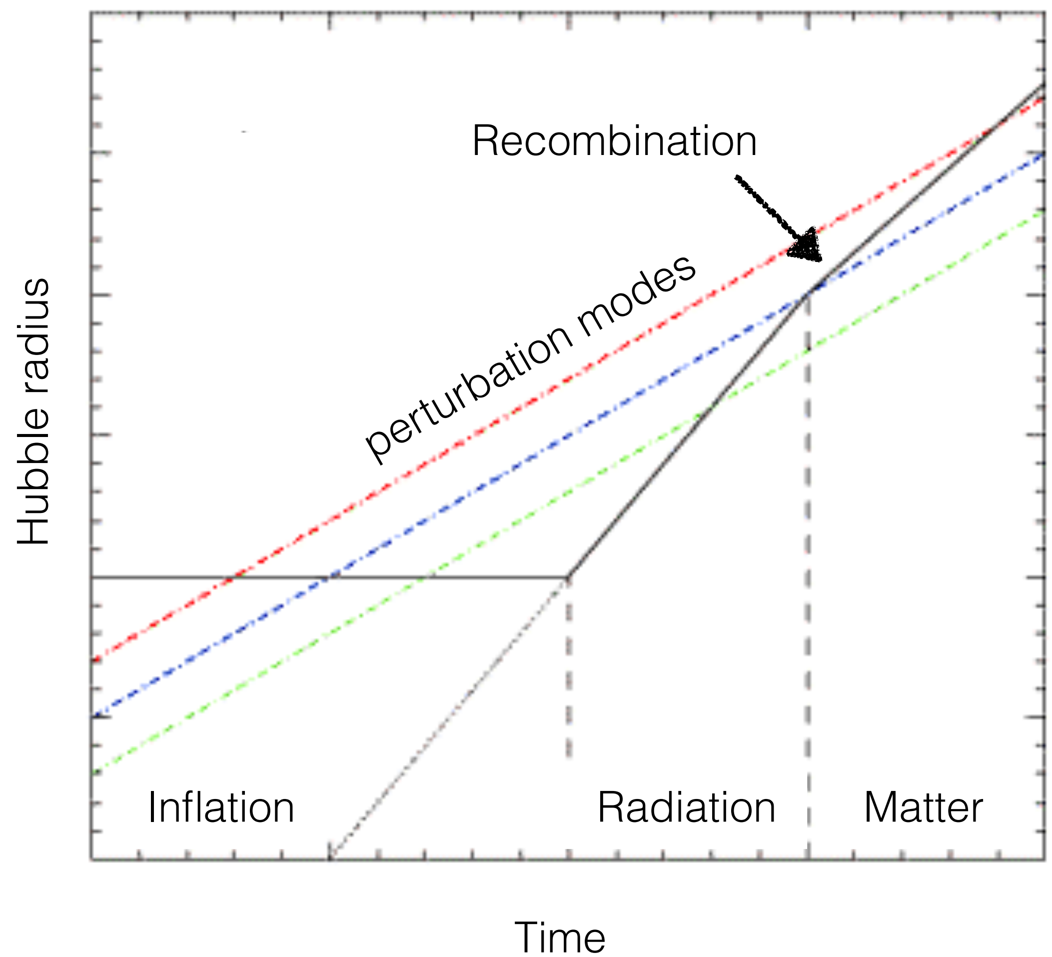
co-moving perturbation modes
leave Hubble horizon during inflation,
re-enter after inflation

↓

perturbation with given frequency today
corresponds to fixed time during inflation
and re-entry

↓

1:1 relation: $f \rightarrow k \rightarrow N_k \rightarrow V(\phi_k)$



$$N = N_{\rm CMB} + \ln \frac{k_{\rm CMB}}{0.002\ {\rm Mpc}^{-1}} - 44.9 - \ln \frac{f}{10^2\ {\rm Hz}}, \qquad N = \int H\ dt$$

spectrum sensitive to primordial spectrum (scalar potential) and post-inflationary expansion

Some useful properties of GWs

perturbations of the background metric: $ds^2 = a^2(\tau)(\eta_{\mu\nu} + h_{\mu\nu}(\mathbf{x},\tau))dx^\mu dx^\nu$

governed by linearized Einstein equation $(\tilde{h}_{ij} = a h_{ij},\ \mathrm{TT\ \text{-}\ gauge})$

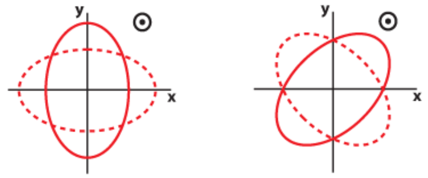
$$\tilde{h}''_{ij}(\boldsymbol{k},\tau) + \underbrace{\left(k^2 - \frac{a''}{a}\right)}_{\sim a^2 H^2} \tilde{h}_{ij}(\boldsymbol{k},\tau) = \underbrace{16\pi\, G\, a\, \Pi_{ij}(\boldsymbol{k},\tau)}_{\text{source term from } \delta T_{\mu\nu}}$$

source: anisotropic (not spherical symmetric) stress-energy tensor

$$k \gg aH:\ h_{ij} \sim \cos(\omega\tau)/a\,, \quad k \ll aH:\ h_{ij} \sim \text{const.}$$

a useful plane wave expansion: $$h_{ij}(\boldsymbol{x},\tau) = \sum_{P=+,\times} \int_{-\infty}^{+\infty} \frac{dk}{2\pi} \int d^2\hat{\boldsymbol{k}}\ h_P(\boldsymbol{k})\ \underbrace{T_k(\tau)}_{\sim a(\tau_i)/a(\tau)}\ e^{P}_{ij}(\hat{k})\, e^{-ik(\tau - \hat{\boldsymbol{k}}\boldsymbol{x})}$$

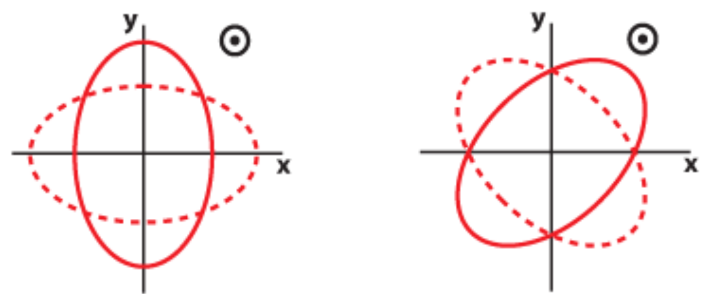
transfer function , expansion coefficients , polarization tensor $P = +, \times$



observational quantity in direct detection

$$\Omega_{GW} = \frac{1}{\rho_c} \frac{\partial \rho_{GW}(k,\tau)}{\partial \ln k}, \quad \rho_{GW}(\tau) = \frac{1}{32\pi G} \left\langle \dot{h}_{ij}(\boldsymbol{x},\tau)\, \dot{h}^{ij}(\boldsymbol{x},\tau) \right\rangle$$

Hunting for primordial GWs



CMB

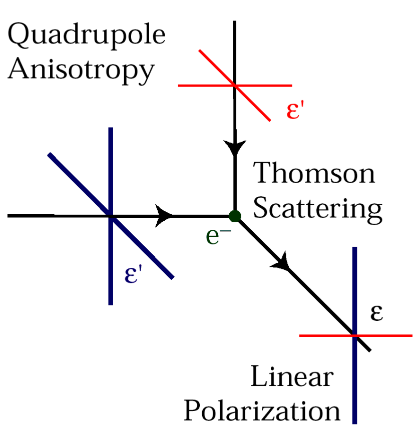
direct

tensor anisotropies
on last scattering surface

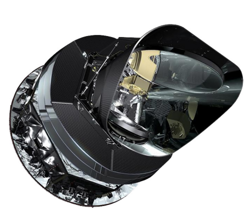
GW travels freely until today

polarization of CMB photons
through Thomson scattering

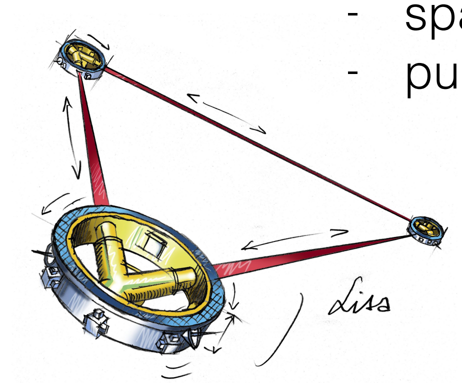
distortion of space as GW
passes detector



- Lensing: T -> E
- dust contaminates primordial signal
- B - modes most sensitive



- ground-based interferometers
- space-based interferometers
- pulsar timing arrays

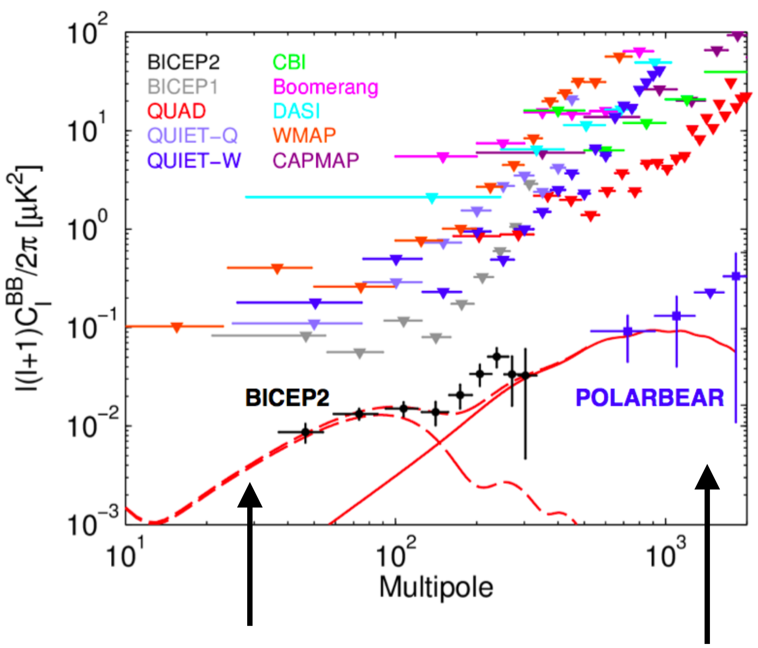


Hunting for primordial GWs

CMB

$$r = \Delta t^2 / \Delta s^2$$

BICEP2 '14



hypothetical primordial contribution with r ~ 0.17

Lensing

sensitive to CMB scales

Hunting for primordial GWs

CMB

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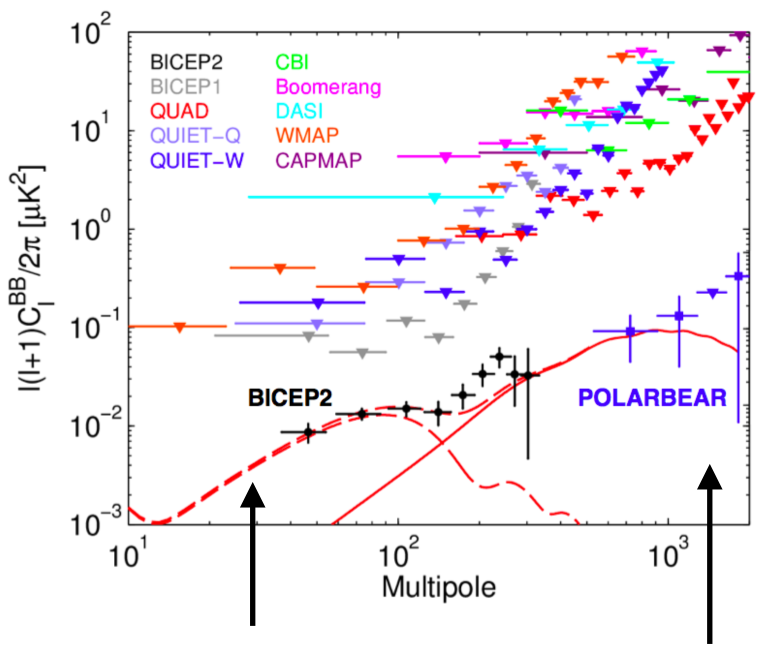


hypothetical primordial contribution with r ~ 0.17

Lensing

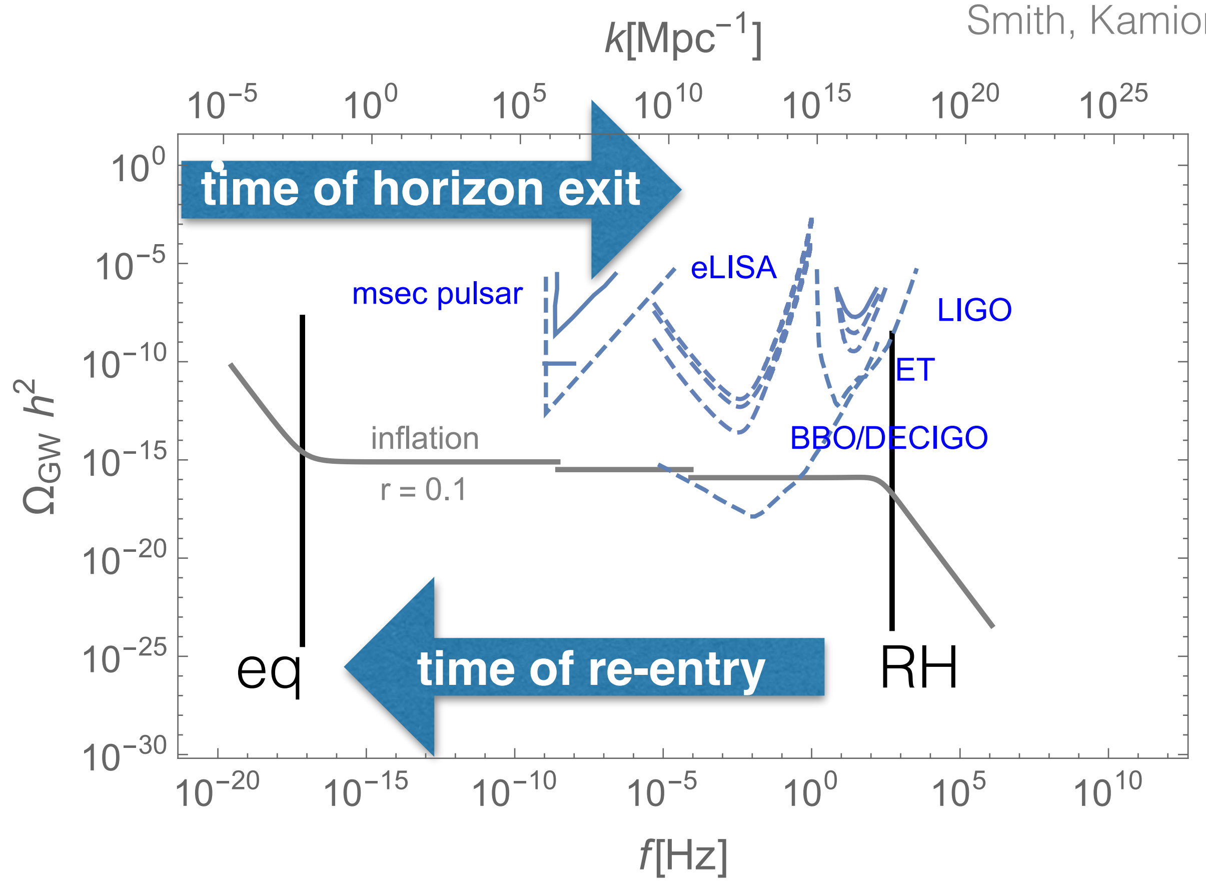
sensitive to CMB scales

direct

$$\Omega_{\rm GW}(k) = \frac{\Delta_t^2}{12} \frac{k^2}{a_0^2 H_0^2} T_k^2 \simeq \frac{\Delta_t^2}{12} \Omega_r$$

for $k_{\rm eq} \ll k \ll k_{\rm RH}$

Rubakov '82
Turner, White, Lidsey '93
Seto, Yokoyama '03
Smith, Kamionkowski '05



with suitable detectors, probe 30 orders of magnitude

But this is not the end of the story…

Non-standard sources during inflation

Cook, Sorbo 2012
Biagetti, Fasiello, Riotto 2014

- scalars: spectator fields (enhanced by $c_s < 1$)

Anber, Sorbo '06./'10/'12,
Barnaby, Namba, Peloso '11,
Barnaby, Pajer, Peloso '12 , …

- gauge fields: pseudoscalar inflation
- phase transition(s) during inflation

Freese, Spolyar 2004

see also Hebecker, Jaeckel, Rompineve, Witkowski '16
for PT just after inflation

Non-standard evolution after inflation

Spookily '93; Joyce '96;
Giovannini '99; Sa, Henriques '10

- stiff equation of state during reheating

Second order gravitational waves

Assadulahi, Wands '09

- sourced by large scalar perturbations

Bouncing cosmologies, broken spacial diffeomorphism, ………… + your favorite model I forgot to mention

See also: eLISA inflation working group report, to appear soon;
Guzzetti, Bartolo, Liguori, Matarrese '16

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pseudoscalar inflation

a generic coupling for a pseudoscalar inflaton:

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi) - \frac{\alpha}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} .$$

Turner, Widrow '88,
Garretson, Field, Caroll '92,
Anber, Sorbo '06./'10/'12,
Barnaby, Namba, Peloso '11,
Barnaby, Pajer, Peloso '12 ,
.....

resulting background equations of motion:

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = \frac{\alpha}{\Lambda}\langle \vec{E}\vec{B}\rangle .$$

$$\frac{d^2 A^a_\pm(\tau,k)}{d\tau^2} + \left[k^2 \pm 2\,k\,\frac{\xi}{\tau}\right] A^a_\pm(\tau,k) = 0\,, \qquad \xi = \frac{\alpha\dot{\phi}}{2\Lambda H}$$

- → tachyonic instability for the gauge field, controlled by $\xi \propto \sqrt{\epsilon} = \dot{\phi}/(\sqrt{2}H)$
- → exponential growth of gauge field modes towards end of inflation
- → backreaction on inflaton eom, new friction term: $\langle \vec{E}\vec{B}\rangle \simeq \mathcal{N} \cdot 2.4 \cdot 10^{-4}\frac{H^4}{\xi^4}e^{2\pi\xi}$

+ additional source for scalar and tensor fluctuations

power spectrum of scalar and tensor perturbations affected

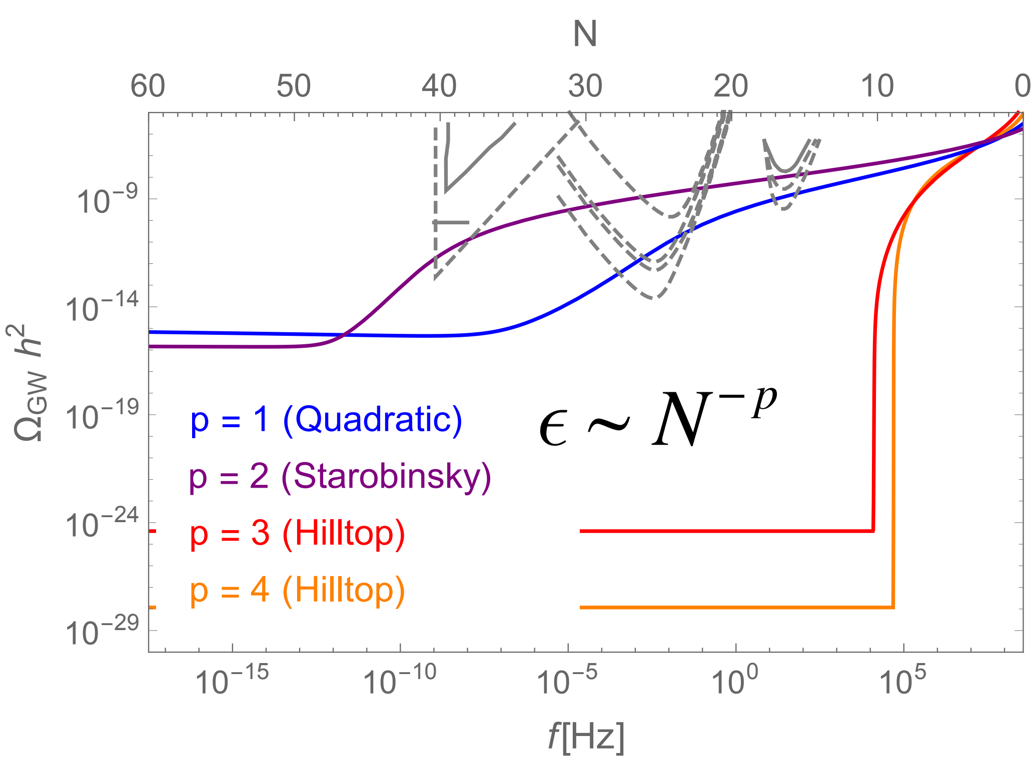
GW spectrum of pseudoscalar inflation

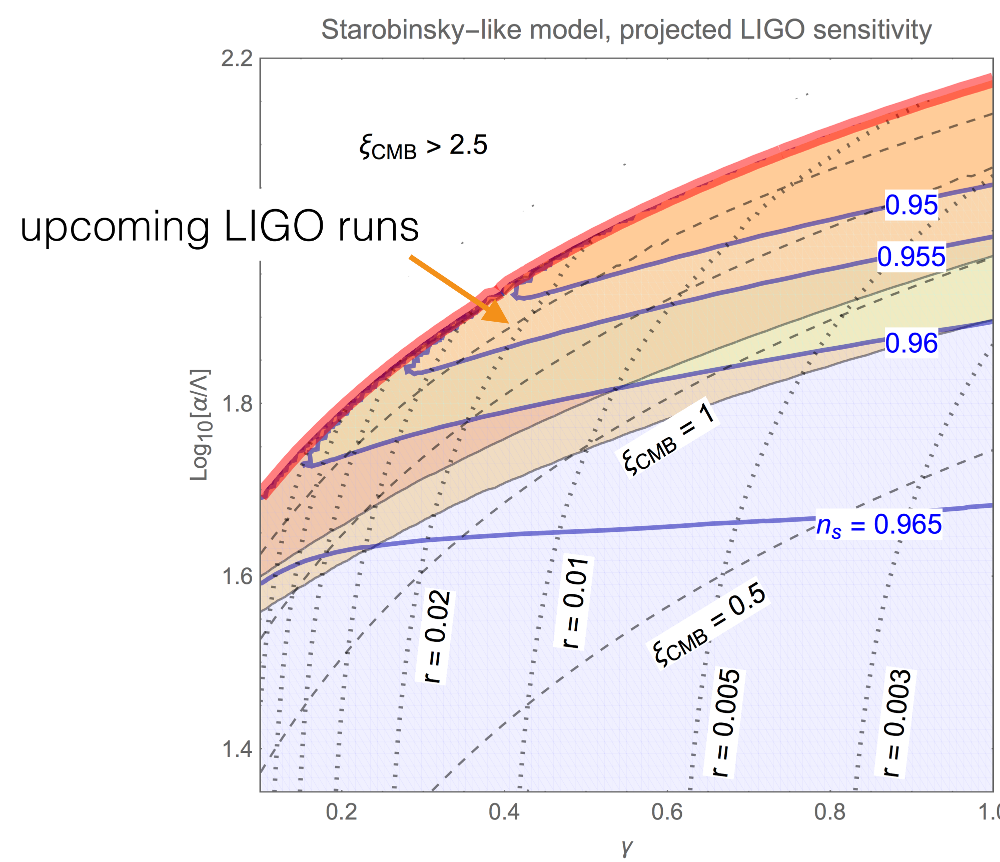
VD, Pieroni, Binetruy 2016

$$\Omega_{\rm GW} = \frac{1}{12}\left(\frac{H}{\pi M_P}\right)^2 \left(1 + 4.3\times10^{(-7)} \frac{H^2}{M_P^2 \xi^6} e^{4\pi\xi}\right)$$

Starobinsky-type model

$$V(\phi) = V_0\left(1 - e^{-\gamma\phi}\right)^2$$



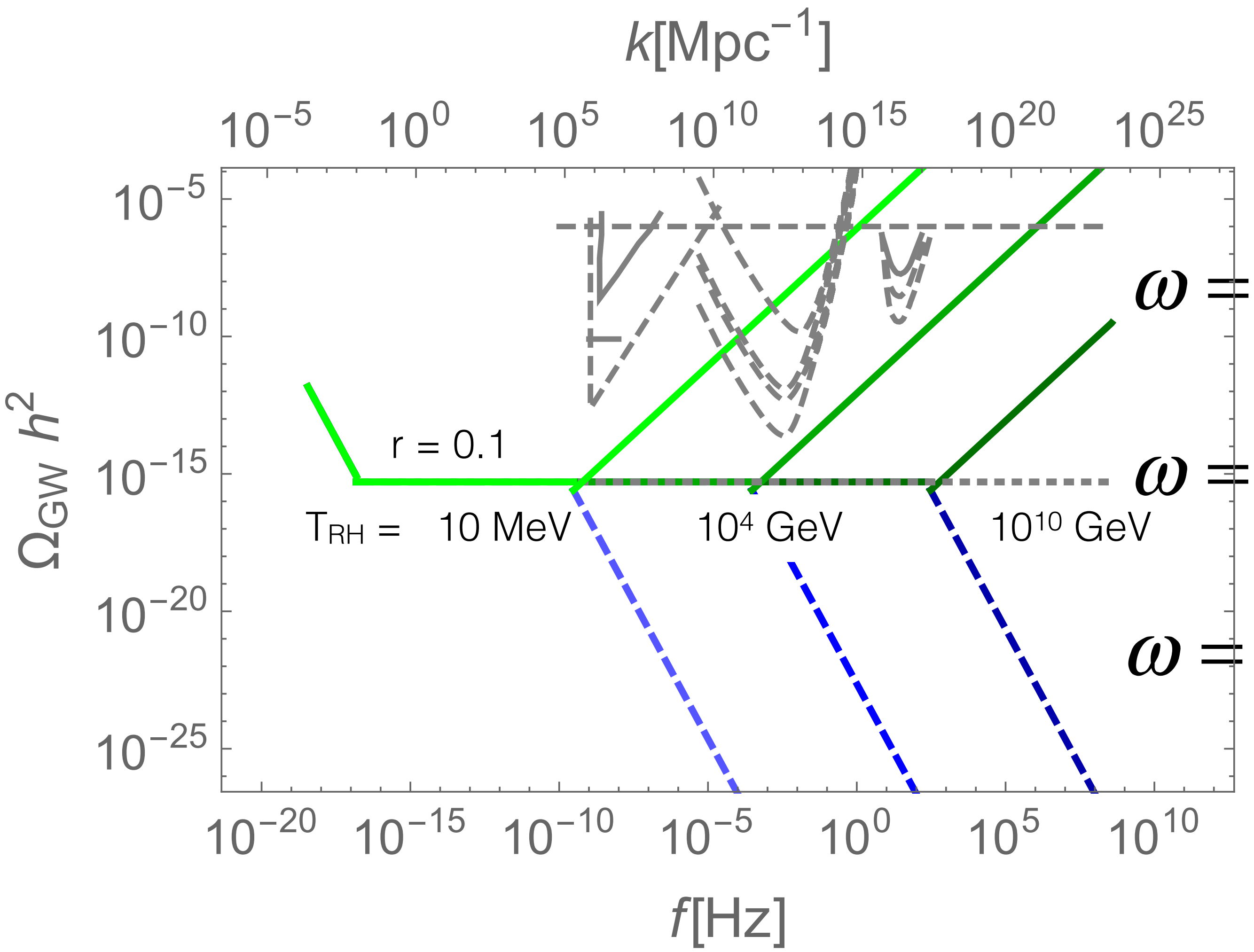


- generically very blue spectrum
- low scale models feature stronger increase

observable signal for direct detection, sensitive to underlying inflation model

non-standard equation of state after inflation

$$\Omega_{GW}(k) = \frac{\Delta_t^2}{12}\frac{k^2}{a_0^2 H_0^2}T_k^2\,, \quad T_k(t) = \frac{a(t_i)}{a(t)} = \left(\frac{t_i}{t}\right)^{\frac{2}{3(1+\omega)}} \quad \rightarrow \quad \Omega(f) = \Omega(f_0)\left(\frac{f}{f_0}\right)^{\frac{2(3\omega-1)}{1+3\omega}}$$



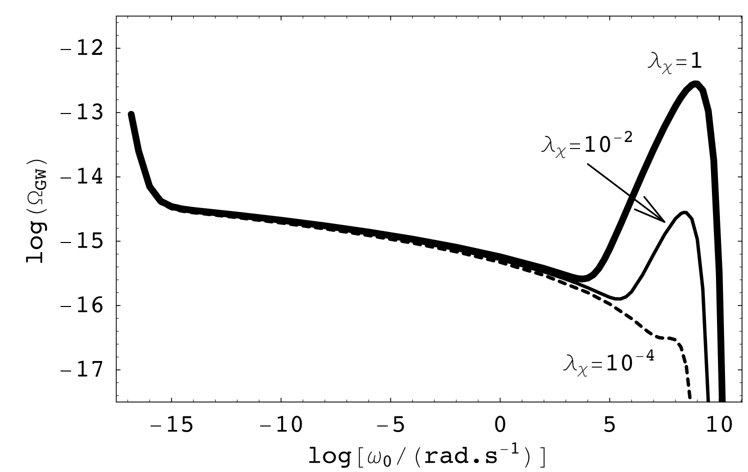
$\omega = 1$ kinetic energy

$\omega = 1/3$ radiation

$\omega = 0$ matter

kination phase after inflation:
Spookily '93; Joyce '96

GW production in
(hybrid) quintessential models:
Giovannini '99; Sa, Henriques '10



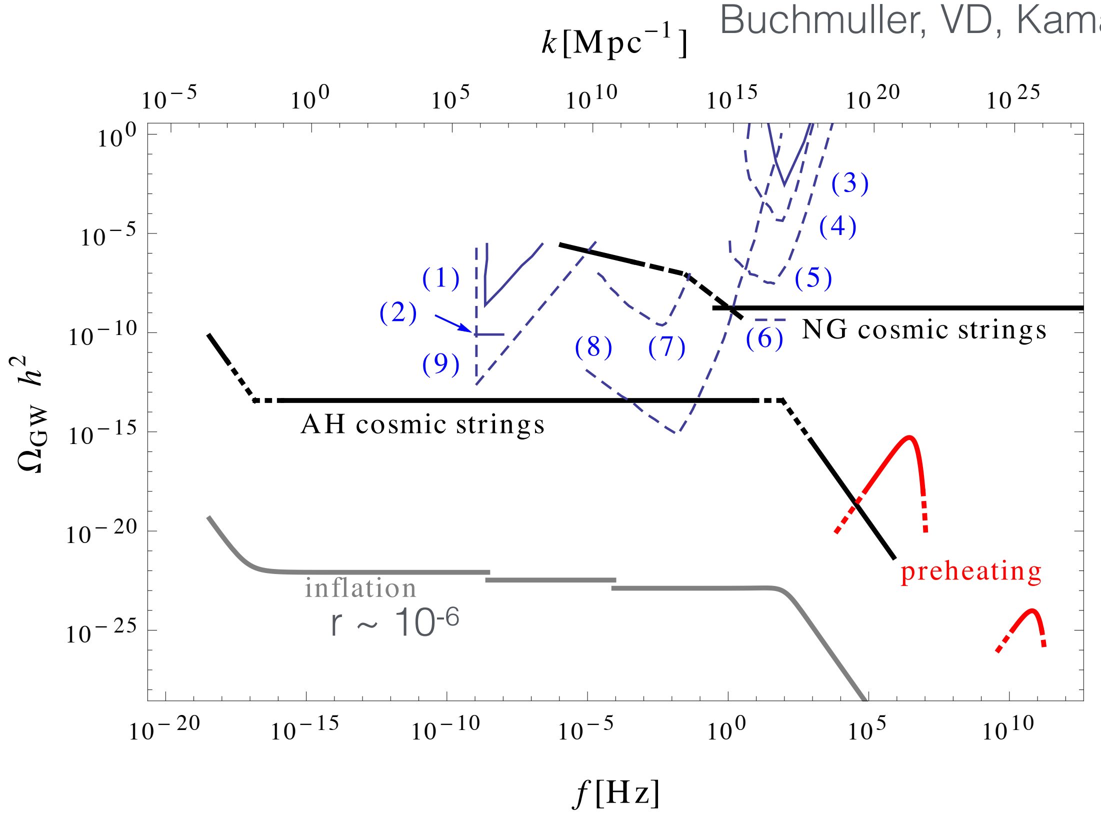
stiff equation of state during reheating can enhance primordial GW signal

Other (stochastic) backgrounds

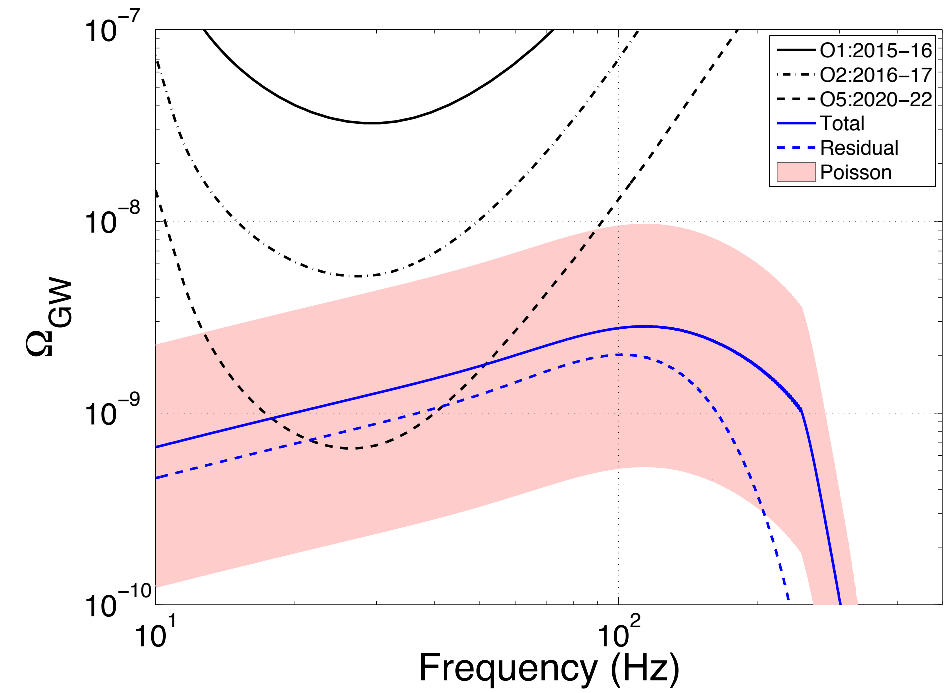
(incomplete list)

Cosmic strings from GUT-scale phase transition

Buchmuller, VD, Kamada, Schmitz '12



LIGO/VIRGO collaboration '16,

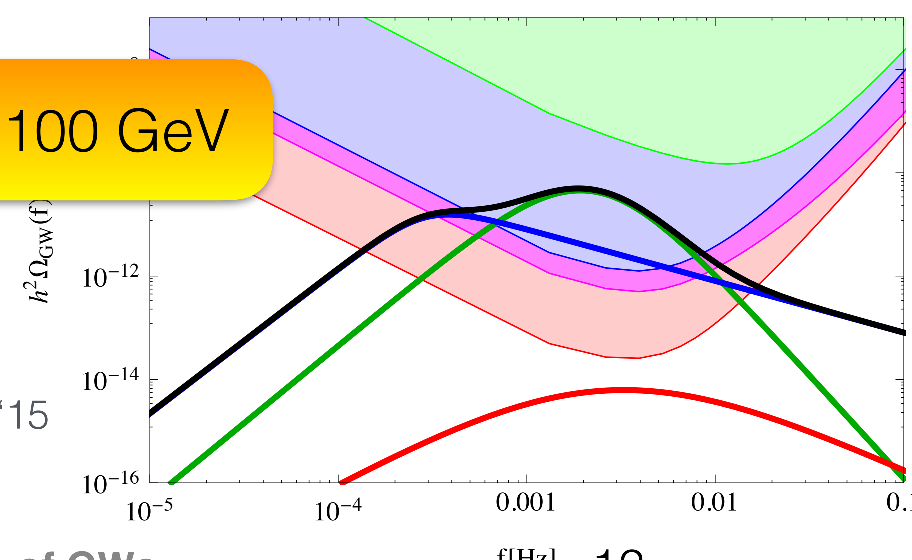


unresolved BH mergers

…. primordial black holes?

phase transition at 100 GeV

Caprini et al '15



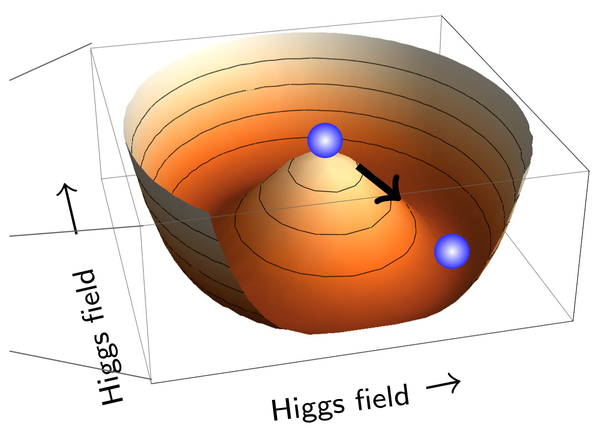
scalar field

sound waves

turbulence

Cosmic strings

U(1) phase transition in the early universe (after inflation) -> cosmic strings



Cosmic string network, topologically stable but looses energy into GWs (and particles)

Evolution of cosmic string network can be studied numerically in the "Abelian Higgs" or "Nambu Goto" model

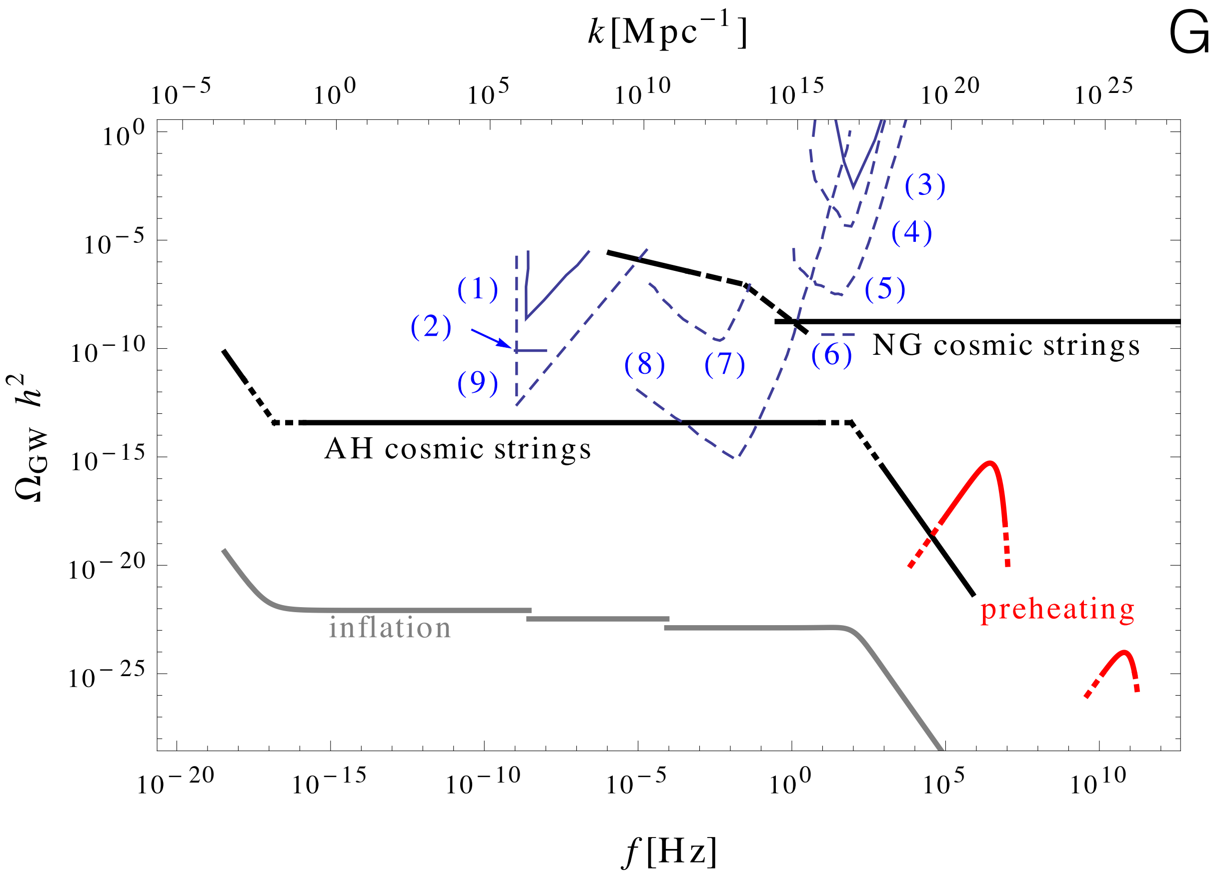
- Abelian Higgs model: Main source for GWs are horizon sized cosmic strings

- Nambu Goto model: Main source for GWs are small cosmic string loops

Vilenkin '81, Hindmarsh '12

Cosmic strings

direct detection

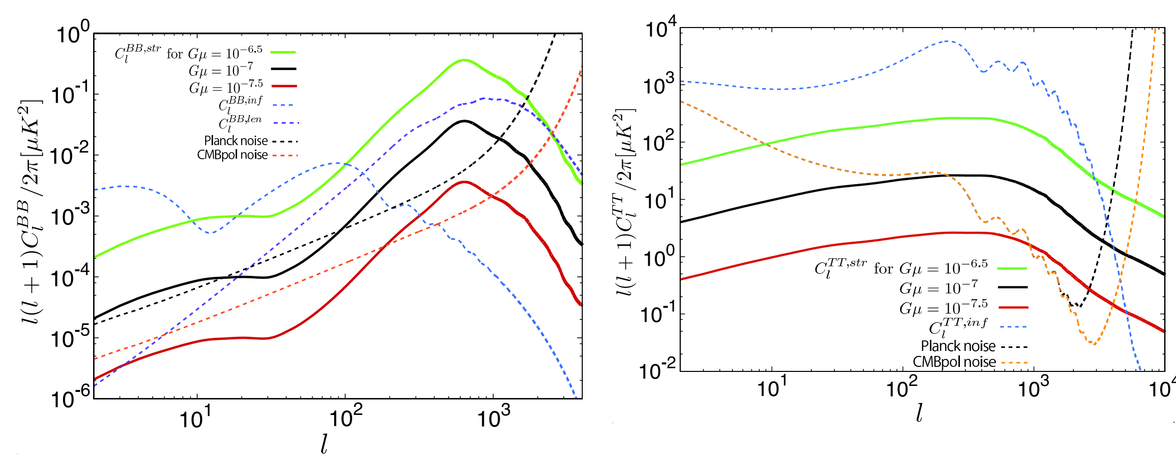


GUT-scale phase transition after hybrid inflation,

Buchmueller, VD, Kamada, Schmitz '12

- similar to inflation signal but amplitude determined by scale of phase transition: can be strongly enhanced!
- large theoretical uncertainty
- as for inflation, sensitive to cosmological history

CMB: direkt search for cosmic strings:



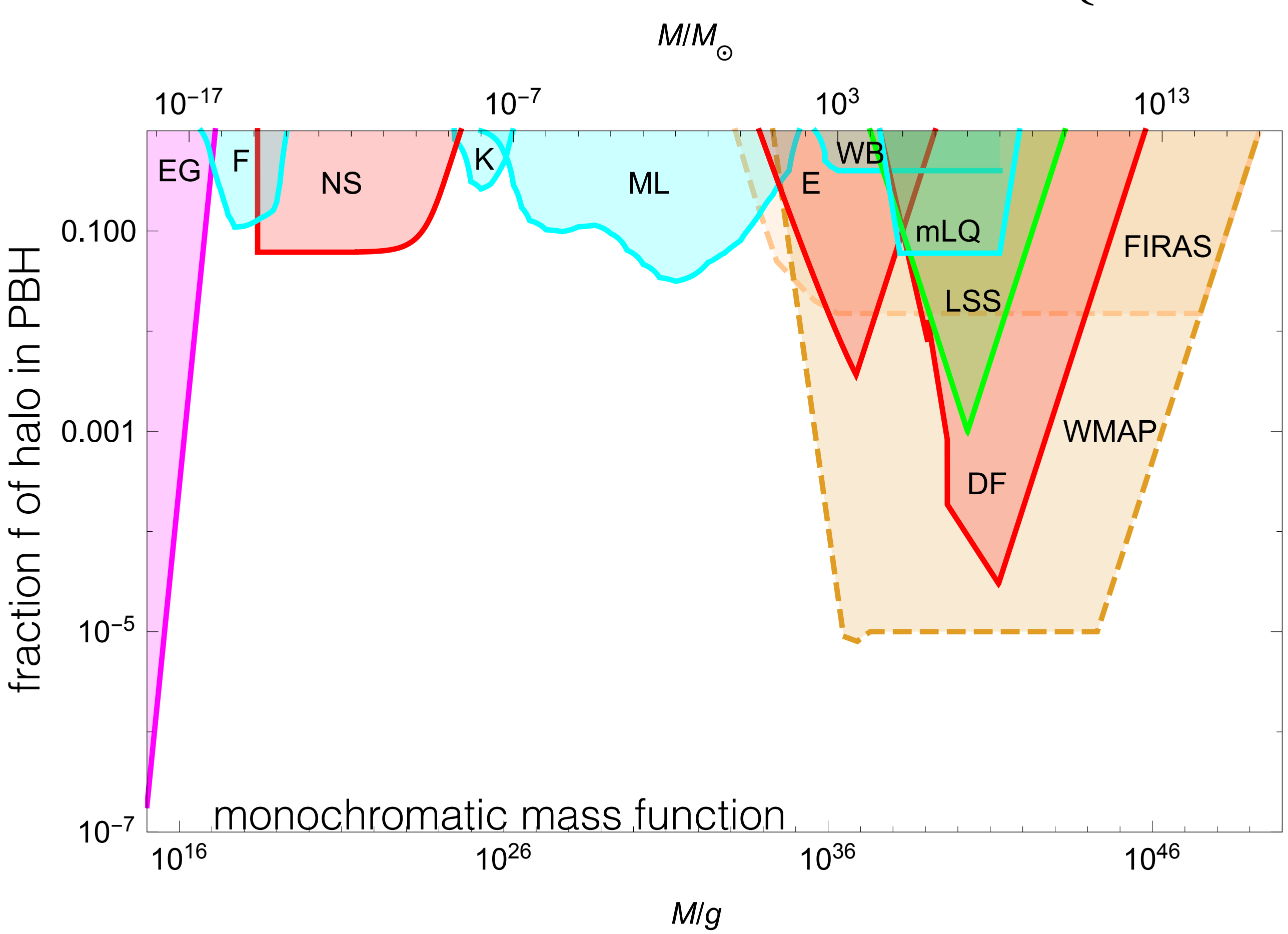
Silk et al '13

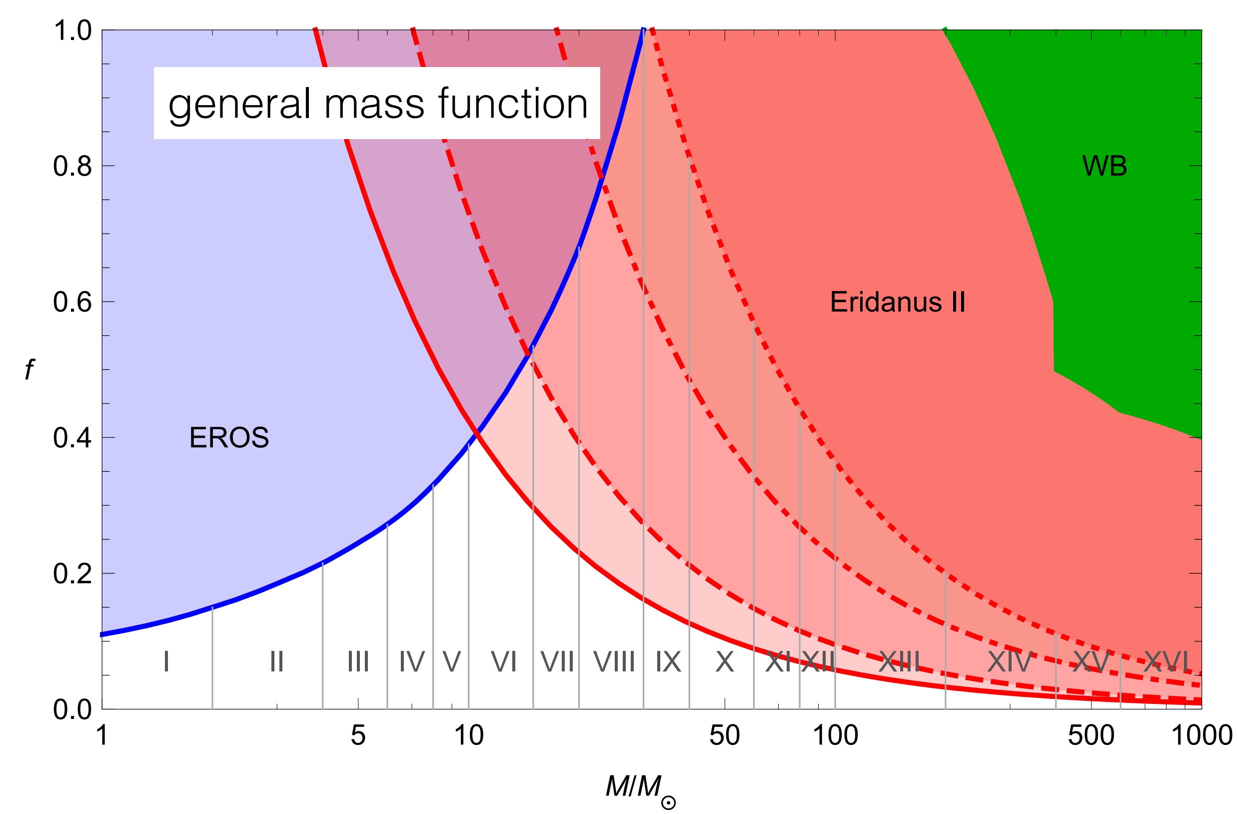
primordial black holes

- scalar fluctuations larger than a critical value collapse into PBHs after horizon re-entry
- very large range of mass scales possible - very different to stellar BHs:

$$M \sim \frac{c^3 t}{G} \sim 10^{15}\, g \left(\frac{t}{10^{-23}\, s} \right) \sim \begin{cases} 10^{-5}\, g & \text{for} \quad t = 10^{-43}\, s \\ 10^{5}\, M_\odot & \text{for} \quad t = 1\, s \end{cases}$$

Carr, Kohri, Sendouda, Yokohama 2010,
Carr, Kuhnel, Sandstad 2016





could still form 100% of DM for suitable broad mass function

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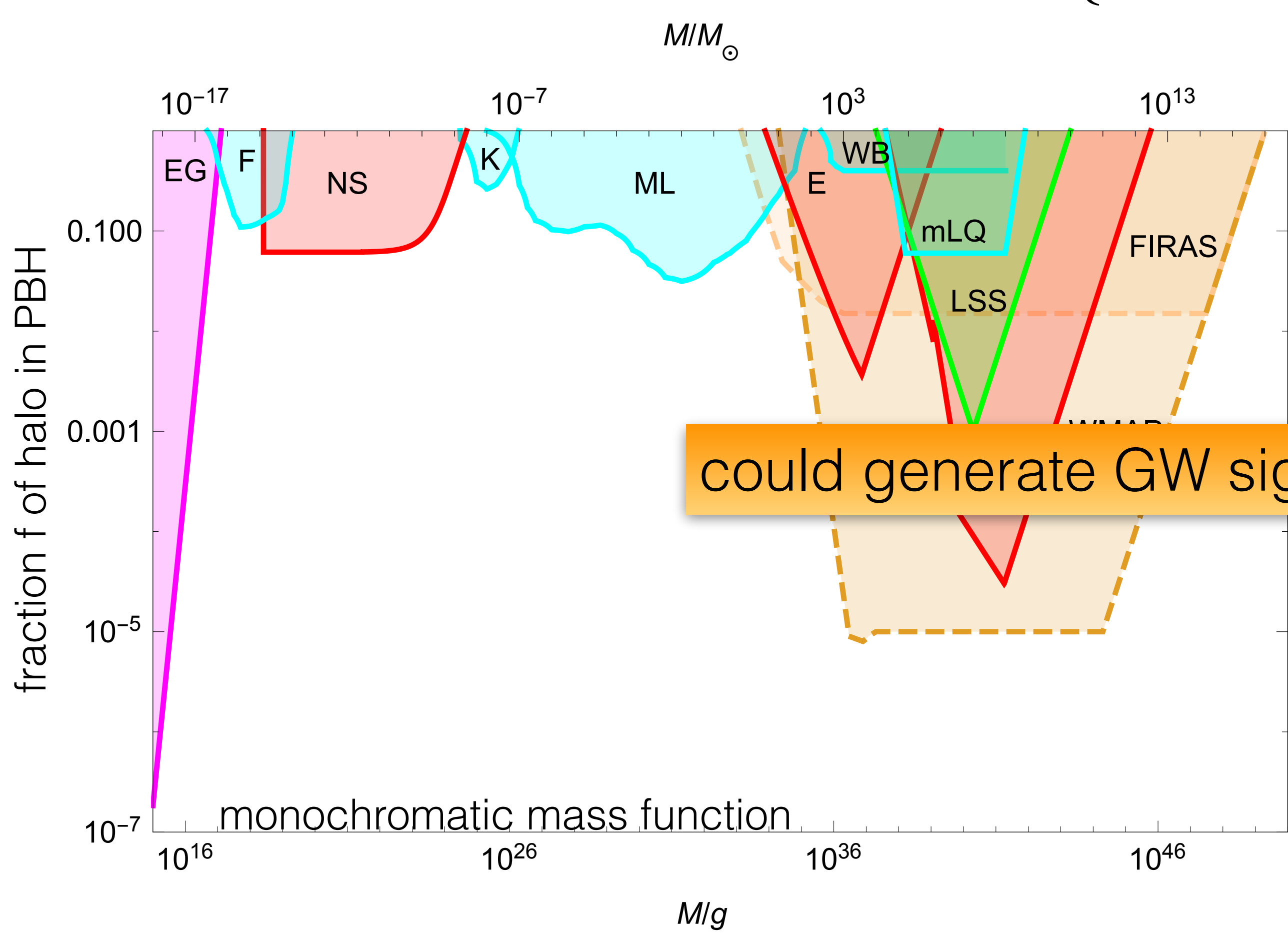

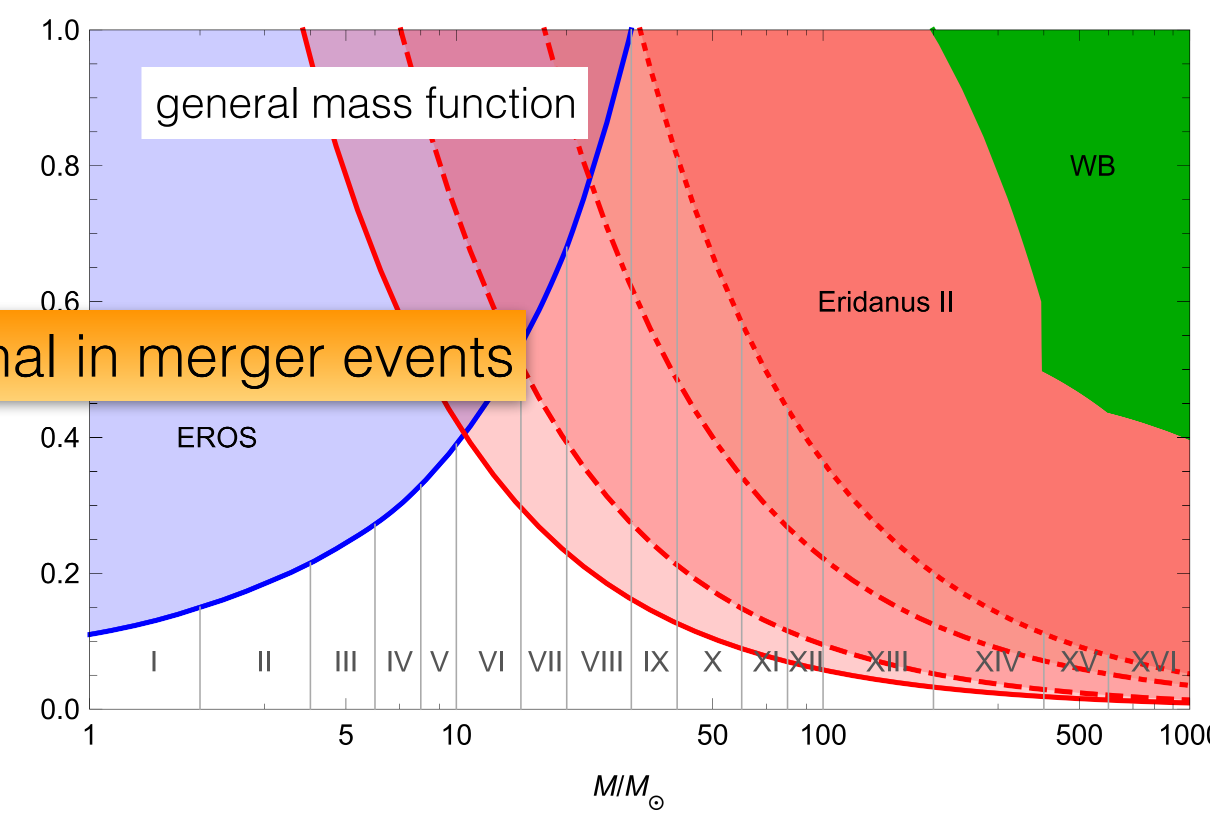

could generate GW signal in merger events

could still form 100% of DM for suitable broad mass function

Conclusion and Outlook

- There is no guaranteed early Universe GW signal for upcoming detectors - but many interesting models will be probed
- The stochastic background of cosmic inflation is an extremely powerful tool: It would shed light on the microphysics of inflation, as well as the entire subsequent cosmological history
- The complementarity of CMB and direct GW measurements provides a powerful probe of the physics of cosmic inflation.
- For the simplest models of inflation, the primordial GW signal is unobservable by upcoming GW interferometers. But possible game changers are:
    - non-standard sources during inflation
    - stiff equation of state during reheating
    - second order tensor perturbations
- Other potential GW sources linked to the early universe are preheating, cosmic strings, merger of primordial black holes, phase transitions…

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Thank you!

backup slides

second order GW production

Tomita '67, ……

Assadulahi, Wands '09

Large scalar perturbations re-entering the horizon after inflation

↓

grow in a matter-dominated reheating phase

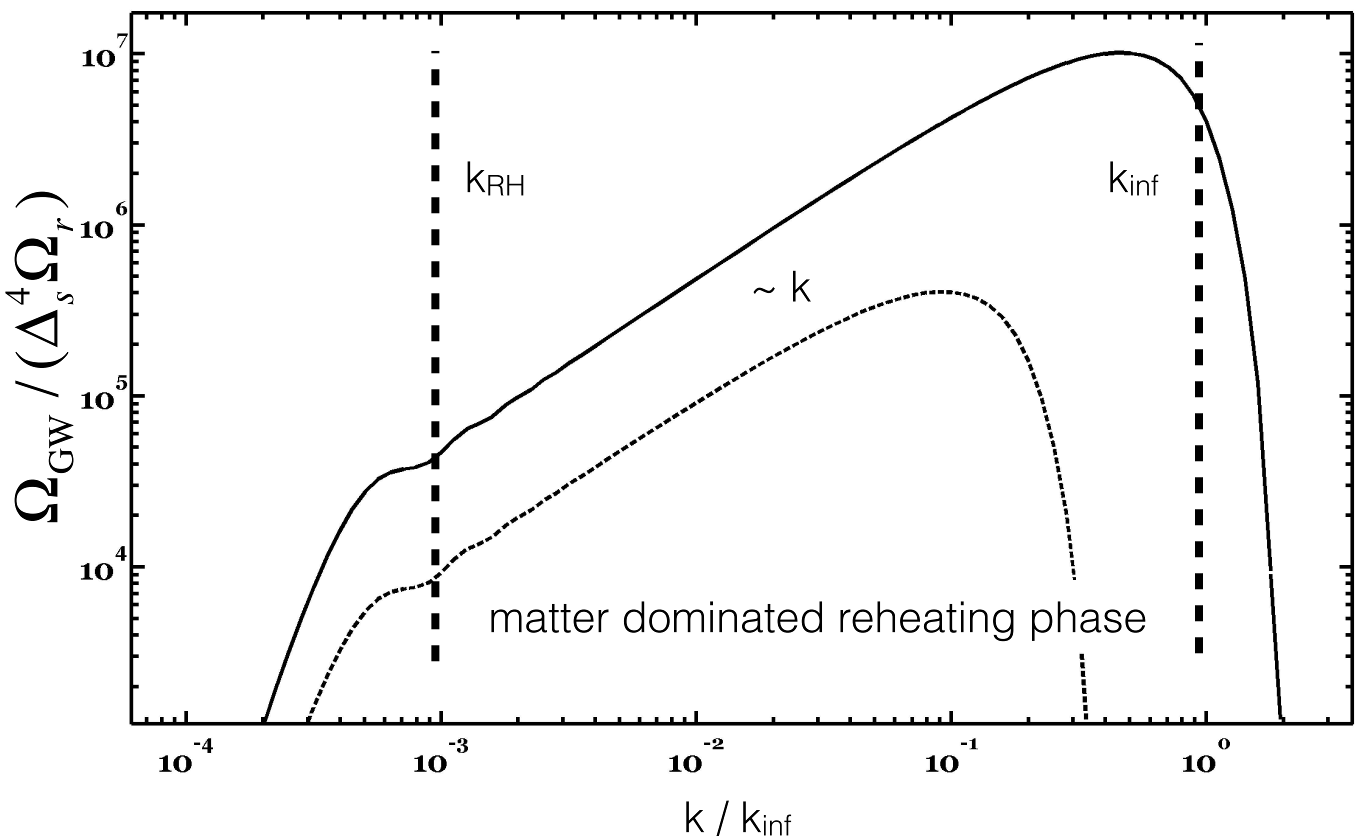
↓

source second order tensor perturbations

max. amplitude: $\Omega_{\rm GW}^{\rm max} \approx \Delta_s^4 \Omega_r \left(\frac{k_{\rm inf}}{k_{\rm RH}} \right)^2$

detectable signal for eLISA/LIGO/VIRGO for relatively small reheating temperatures and

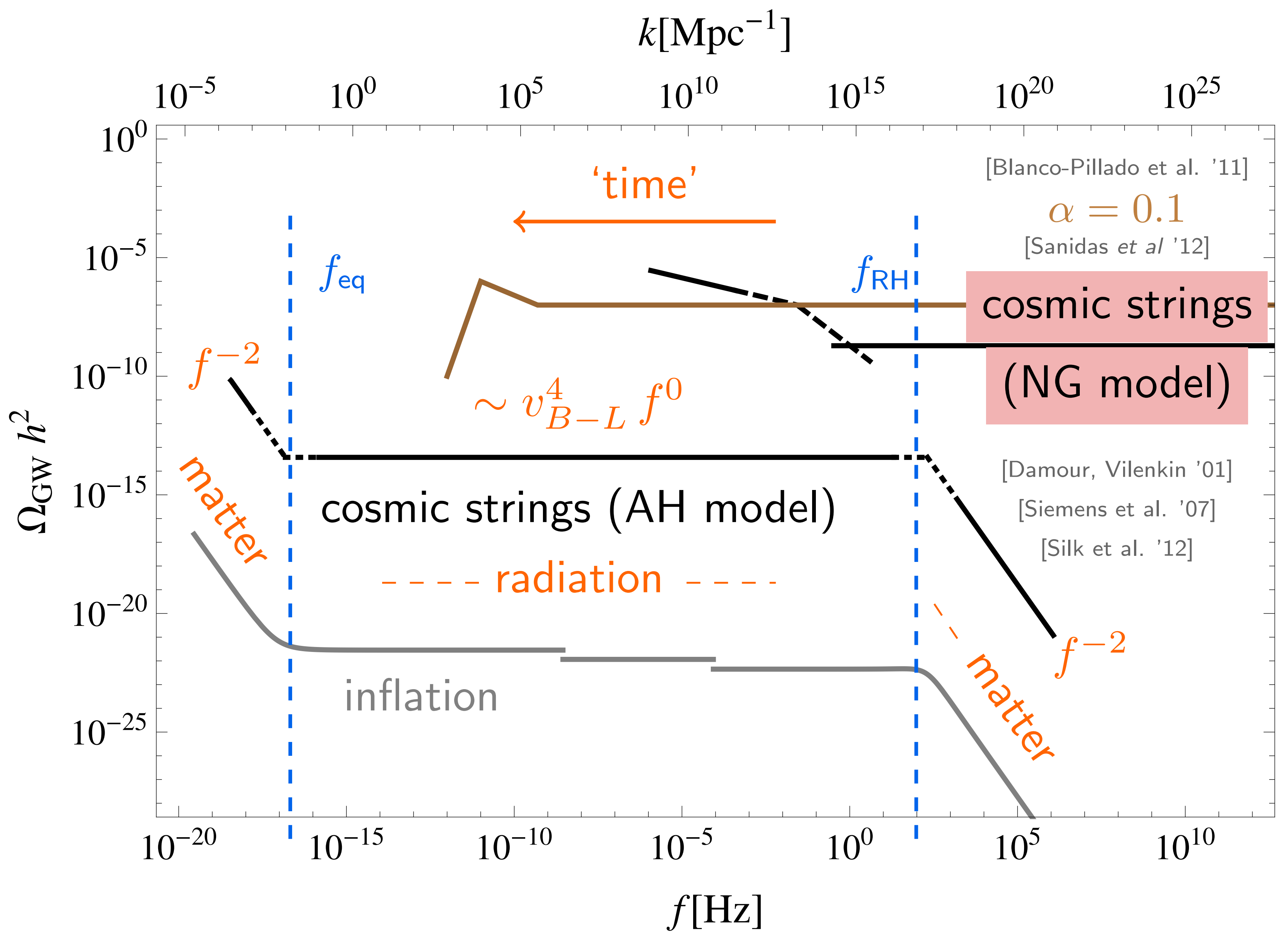
$$(\Delta_s^2)_{\text{small scales}} \gg (\Delta_s^2)_{\rm CMB}$$



note: very large Δ_s^2 on small scales leads to the formation of primordial black holes, which in turn can produce GWs in merger processes.

primordial scalar fluctuations can source gravitational waves after inflation

Cosmic strings (Nambu-Goto)



effect of loop-size α in NG model. $\alpha = 1$ preferred by most recent simulations.

pseudoscalar inflation observational signatures

A brief overview:

- CMB: scalar and tensor fluctuations, in particular non-gaussianities, but also spectral index and μ-distortions. — Barnaby, Namba, Peloso '11, Barnaby, Peloso '11, Barnaby, Pajer, Peloso '12, Meerburg, Pajer '12
- blue GW signal (enhanced on small scales), maximally chiral. suppressed at CMB scales but interesting for LISA, LIGO/VIRGO,… — Anber, Sorbo '12
- PBH formation due to enhanced scalar power on small scales — Linde, Mooij, Pajer '12
- indirekt bound on tensor spectrum from $N_{\rm eff}$ in BBN and CMB — Allen '96, Pagano, Salvati, Melchiorre '15

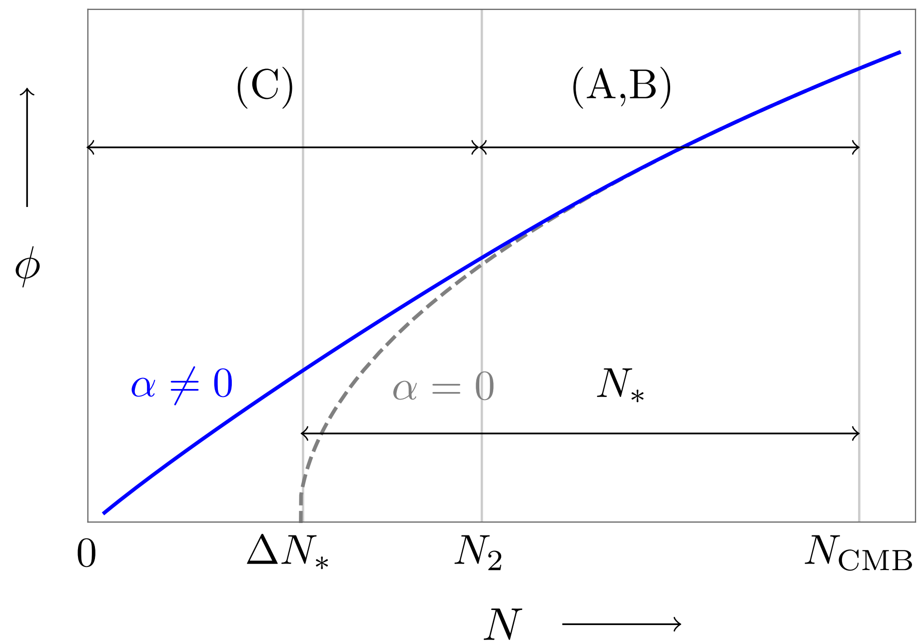
→ very interesting setup for multi-messenger analysis

main focus here on CMB and direct GW observations,
can the inflaton gauge field coupling enable us to probe the microphysics of inflation?

pseudoscalar inflation background dynamics

a useful classification of inflation models: $\epsilon_V = \frac{\beta}{N^p} + O(1/N^{p+1})$ Mukhanov '13 → **3 parameters: α, β, p**

evolution of the inflation field

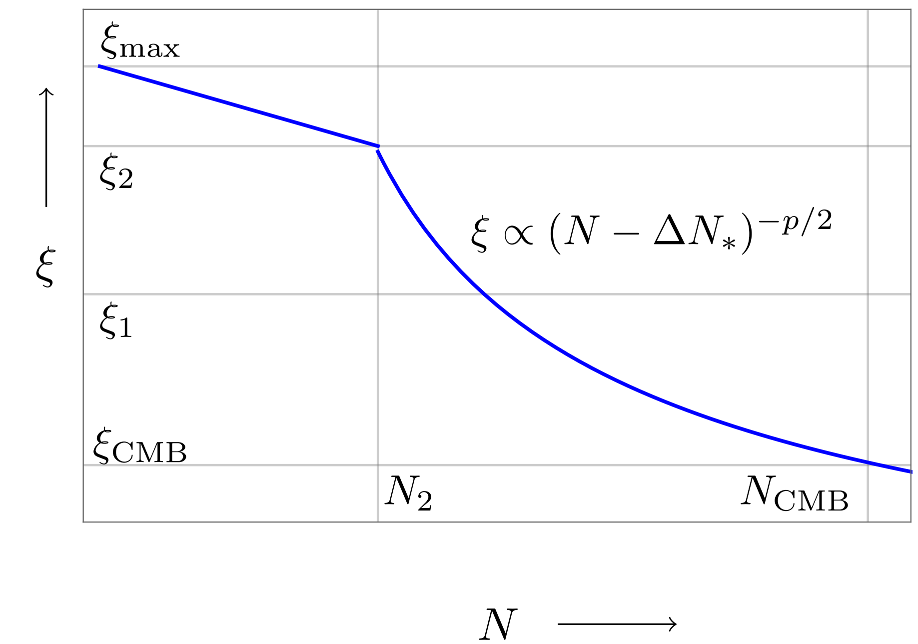


- additional friction, CMB observables evaluated at 'later' point on $V(\phi)$

$$n_s \simeq 1 - \frac{\mathcal{O}(1)}{N_*}, \quad r = \frac{16\,\beta}{N_*}, \qquad N_* < N_{\rm CMB} \simeq 60$$

n_s reduced, r increased

evolution of $\xi \propto \sqrt{\epsilon} = \dot{\phi}/(\sqrt{2}H)$



- rapid increase of ξ for large values of p, enters eom exponentially

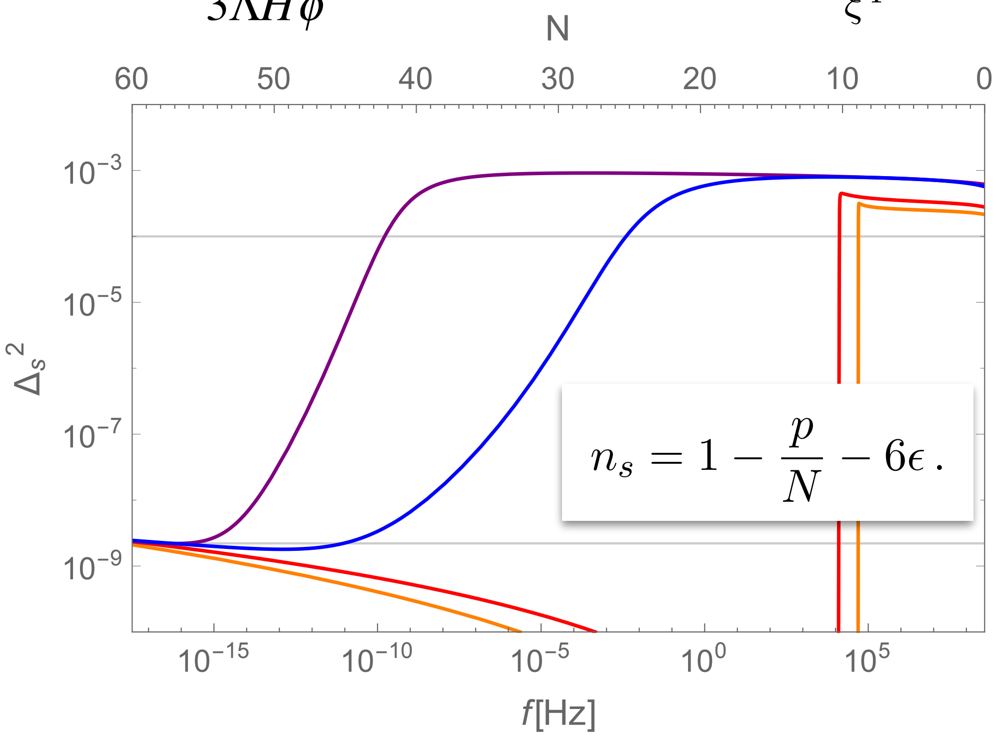
large gauge field effects at the end of inflation, in particular for large p (small r!)

pseudoscalar inflation perturbation power spectra

$$\Delta_s^2(k) = \Delta_s^2(k)_{\rm vac} + \Delta_s^2(k)_{\rm gauge} = \left(\frac{H^2}{2\pi|\dot\phi|}\right)^2 + \left(\frac{\alpha\langle\vec E\vec B\rangle}{3bH\dot\phi}\right)^2$$

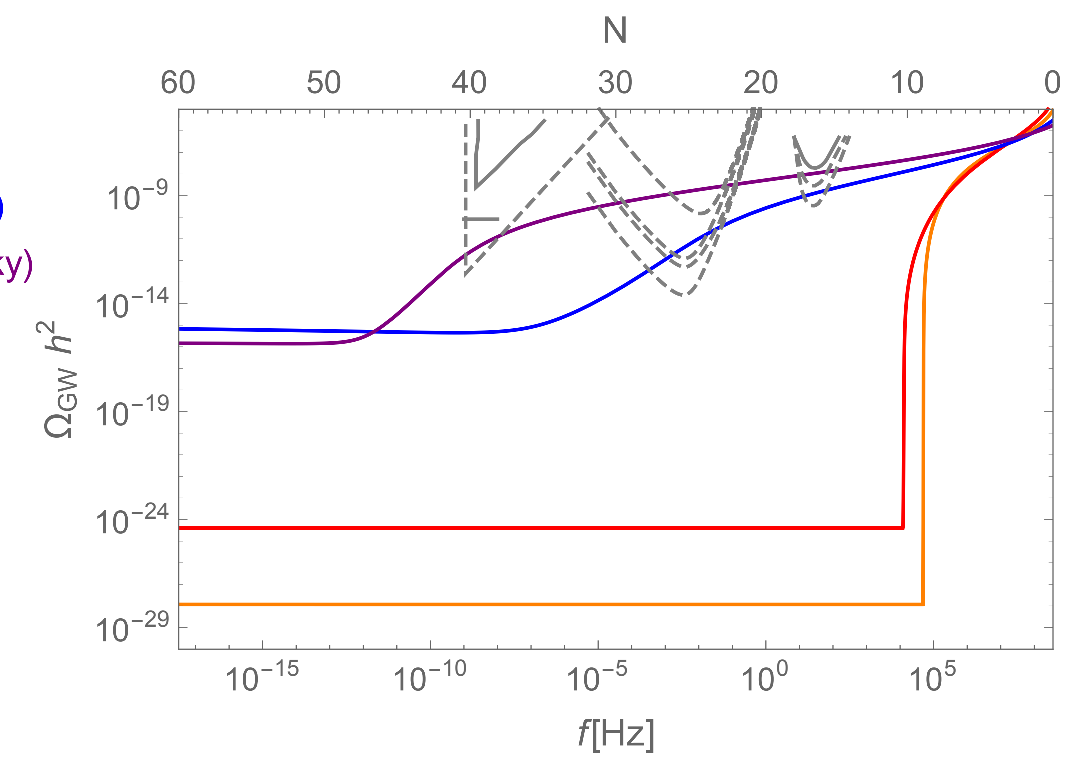
$$b = 1 - 2\pi\xi\frac{\alpha\langle\vec E\vec B\rangle}{3\Lambda H\dot\phi}, \qquad \langle\vec E\vec B\rangle \simeq \mathcal{N}\cdot 2.4\cdot 10^{-4}\frac{H^4}{\xi^4}e^{2\pi\xi}$$

$$\Omega_{\rm GW} = \frac{1}{12}\left(\frac{H}{\pi M_P}\right)^2\left(1 + 4.3\times 10^{(-7)}\frac{H^2}{M_P^2\xi^6}e^{4\pi\xi}\right)$$



p = 1 (Quadratic)
p = 2 (Starobinsky)
p = 3 (Hilltop)
p = 4 (Hilltop)

$$\epsilon_V \simeq \frac{\beta}{N^p}$$



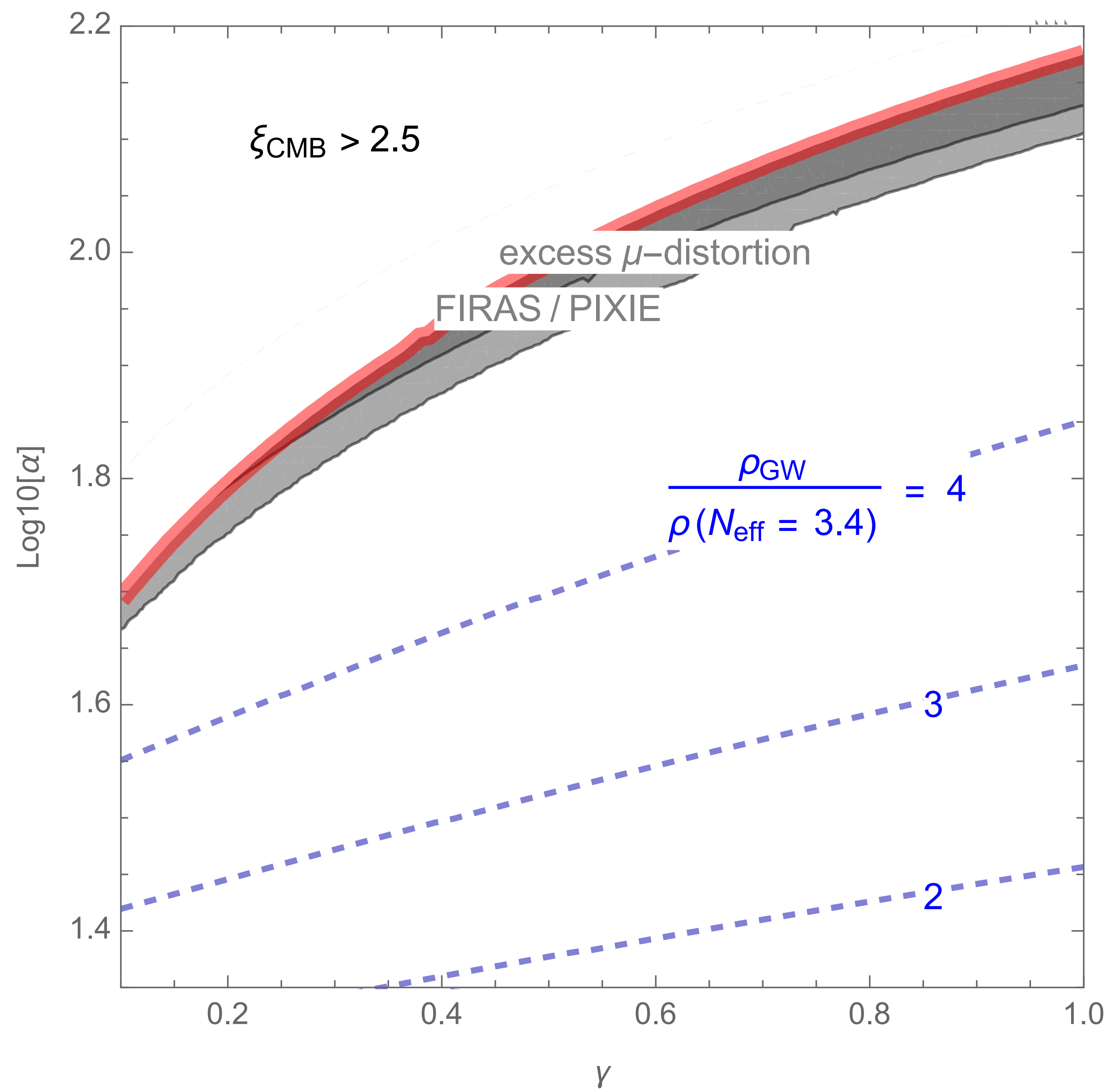
- amplitude @ N_{CMB} fixes one parameter
- large power on small scales -> PBHs
- nearly universal amplitude on small scales

- increase at small scales to universal value
- low scale models feature stronger increase
- Onset of increase depends on coupling α

uncertainties in strong back reaction regime, Sloth '15, Peloso '16

we find both universal and inflation model specific features

pseudoscalar inflation
mu - distortion and N_eff



pseudoscalar inflation
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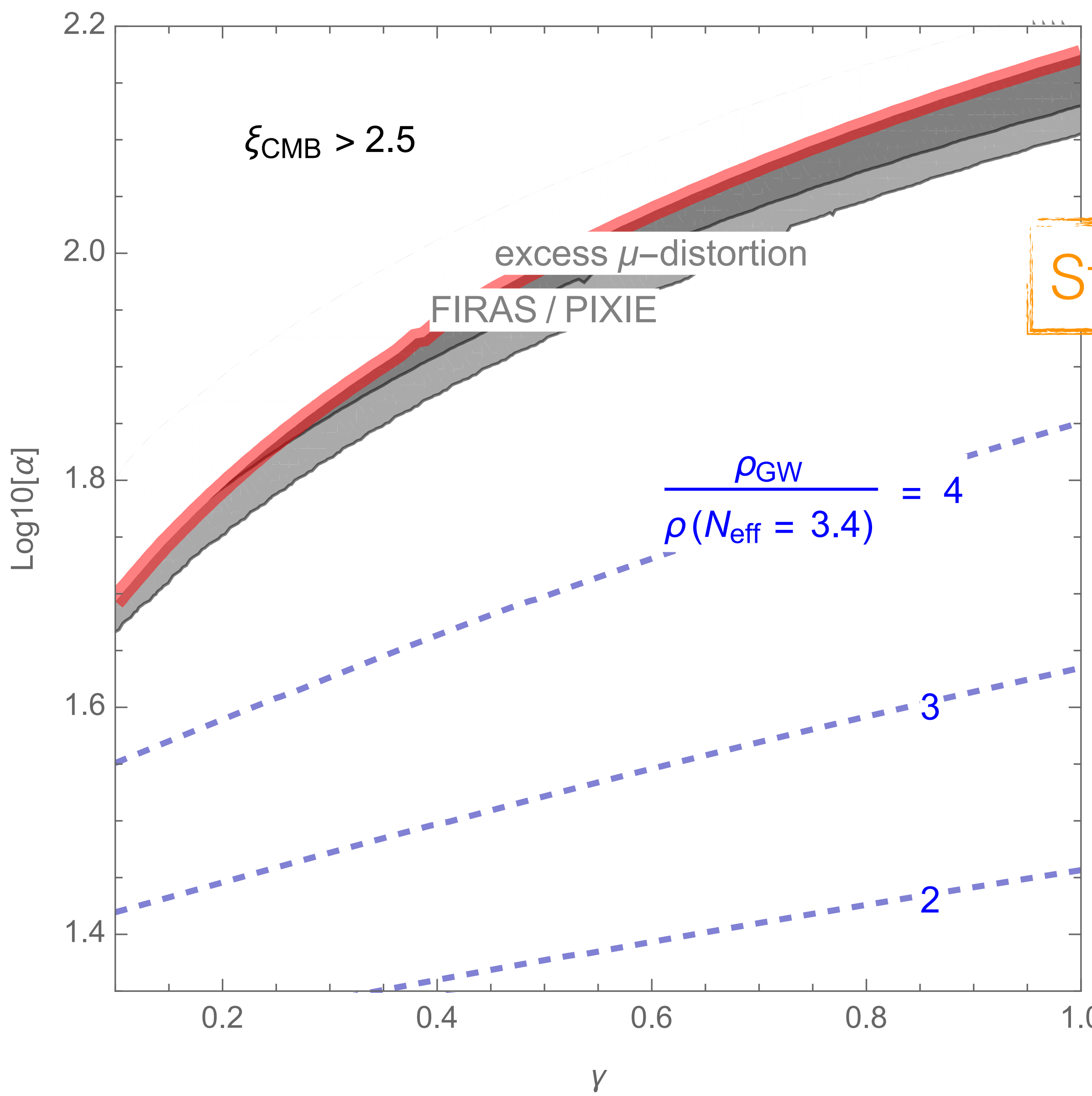

Starobinsky-like model