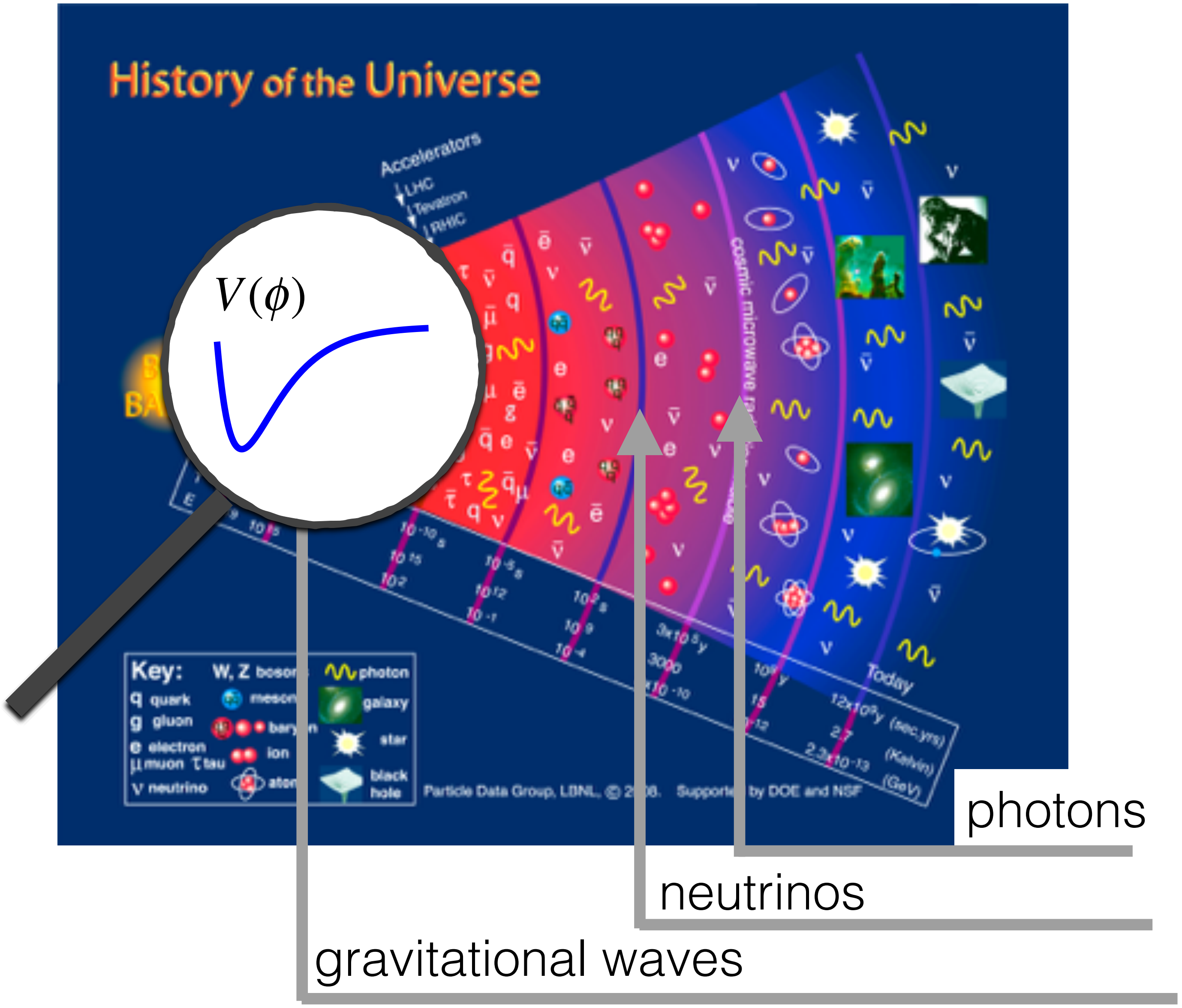
Probing the early universe with GWs



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GRAMPA, 29.8. - 2.9.2016
IAP, Paris

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

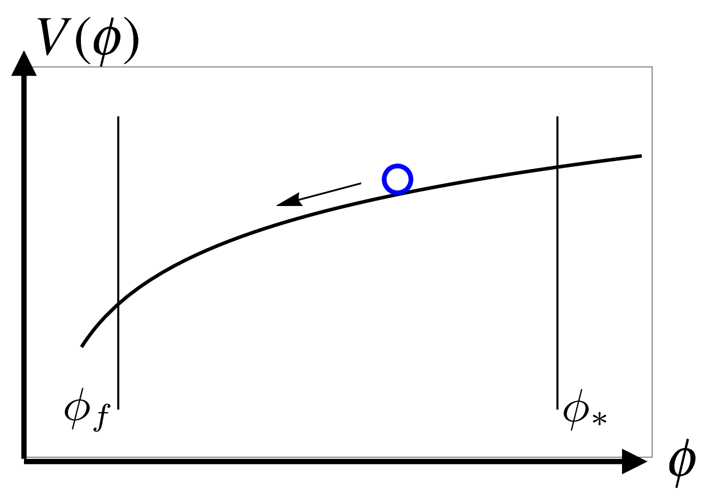
……..non-standard sources during inflation

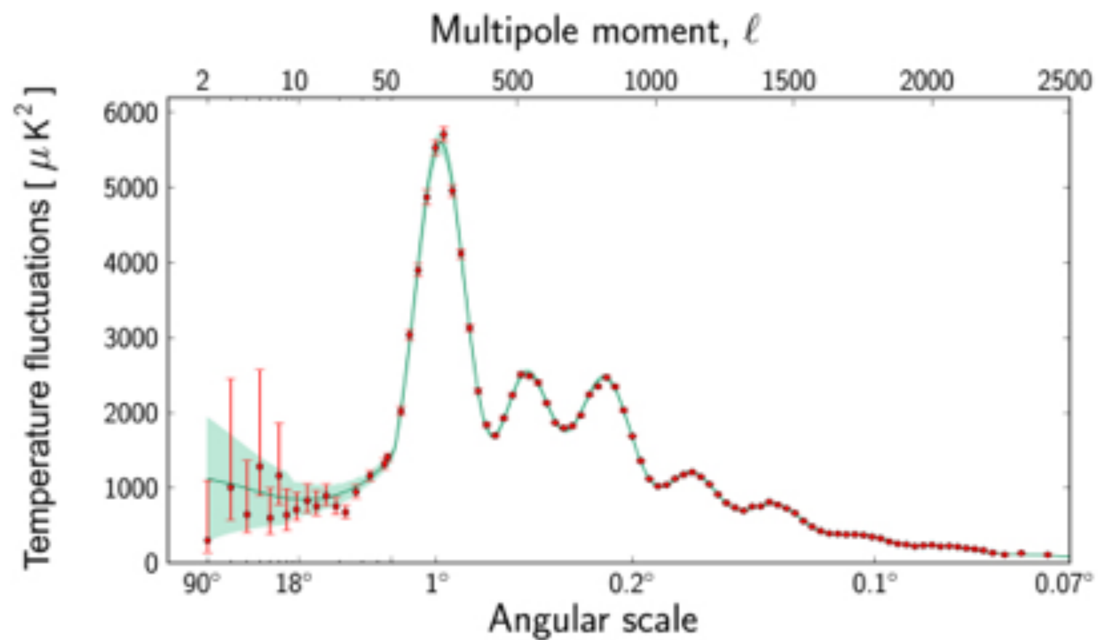
……..non-standard evolution after inflation

……..second order GW production

- Further GW sources in the early Universe

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

scalar spectrum, tensor spectrum

very successful paradigm, but very many possible realizations

Scales and horizons

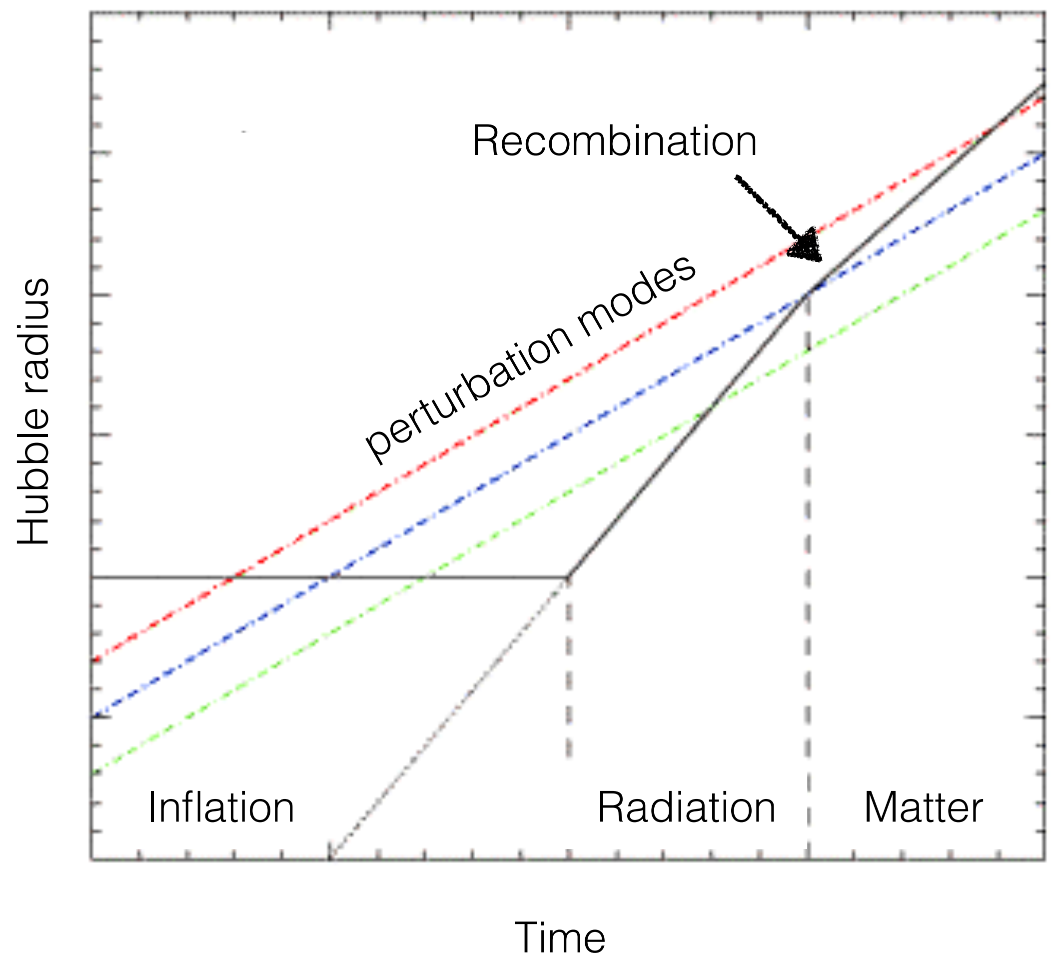
co-moving perturbation modes
leave Hubble horizon during inflation,
re-enter after inflation

↓

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

↓

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



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

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 $(\tilde{h}_{ij} = a h_{ij}, \text{ TT - gauge})$

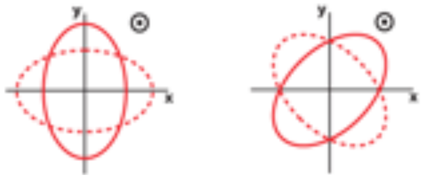
$$\tilde{h}_{ij}''(\boldsymbol{k},\tau) + \underbrace{\left(k^2 - \frac{a''}{a}\right)}_{\sim a^2 H^2} \tilde{h}_{ij}(\boldsymbol{k},\tau) = \underbrace{16\pi\, G\, a\, \Pi_{ij}(\boldsymbol{k},\tau)}_{\text{source term from } \delta T_{\mu\nu}}$$

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

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

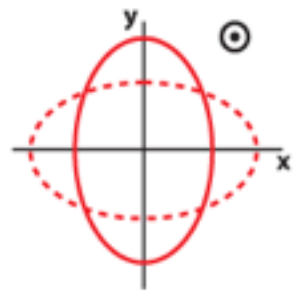


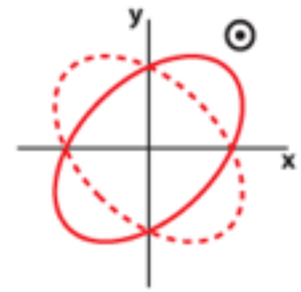
observational quantity in direct detection

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

Hunting for primordial GWs

CMB

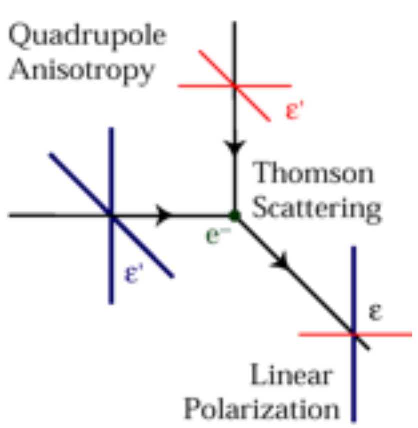




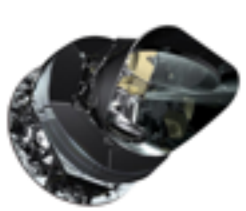
direct

tensor anisotropies
on last scattering surface

polarization of CMB photons
through Thomson scattering

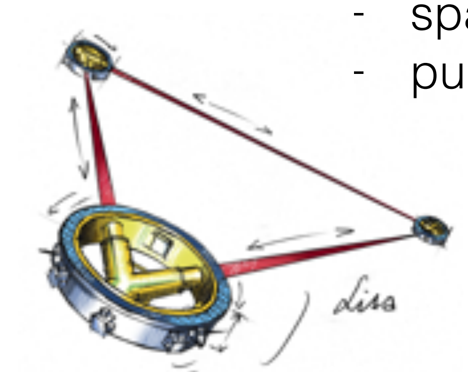


- Lensing: T -> E
- dust contaminates primordial signal
- B - modes most sensitive



GW travels freely until today

distortion of space as GW
passes detector



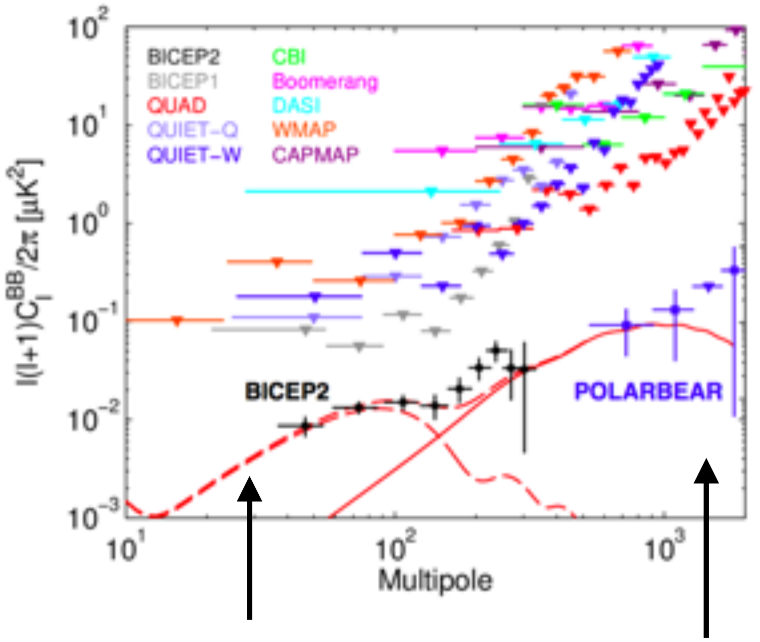
- ground-based interferometers
- space-based interferometers
- pulsar timing arrays

Hunting for primordial GWs

CMB

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

BICEP2 '14



hypothetical primordial contribution with r ~ 0.17

Lensing

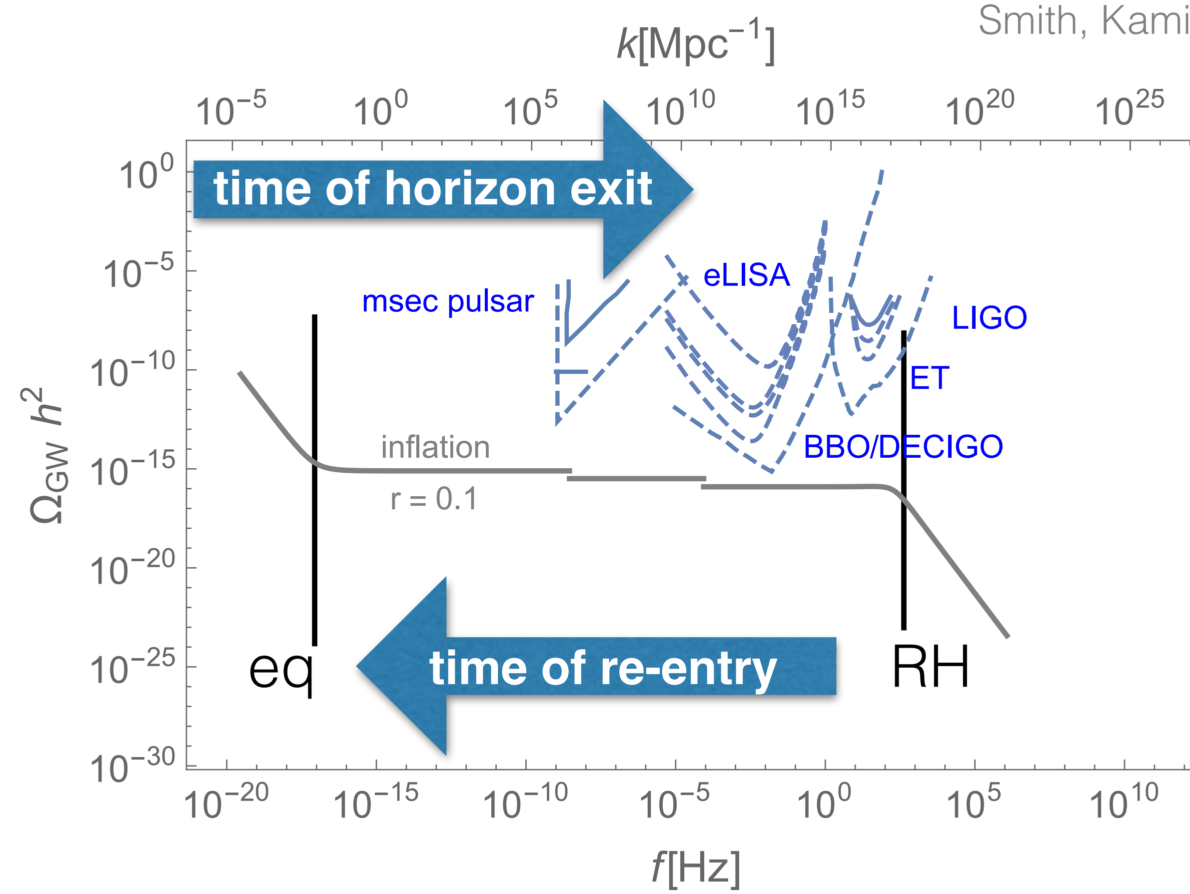
sensitive to CMB scales

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 $c_s < 1$)

gauge fields: pseudoscalar inflation → see next talk by Mauro Pieroni

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

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

stiff equation of state during reheating

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

Second order gravitational waves

sourced by large scalar perturbations

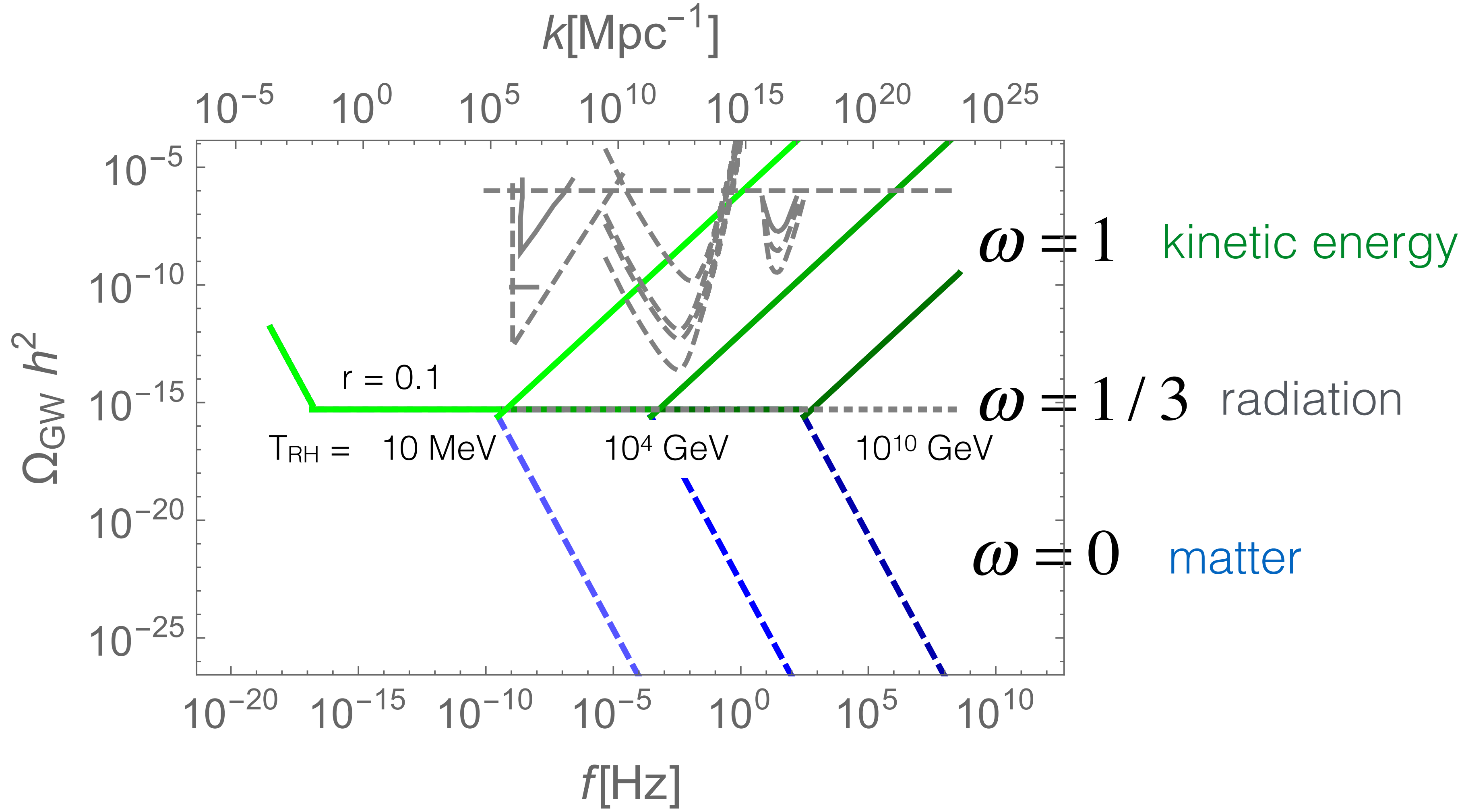
Assadulahi, Wands '09

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

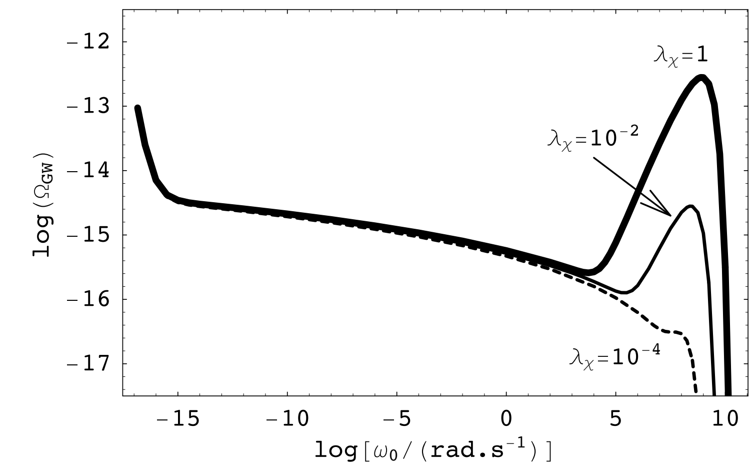
non-standard equation of state after inflation

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



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

second order GW production

Large scalar perturbations re-entering the horizon after inflation

Tomita '67, ……

Assadulahi, Wands '09

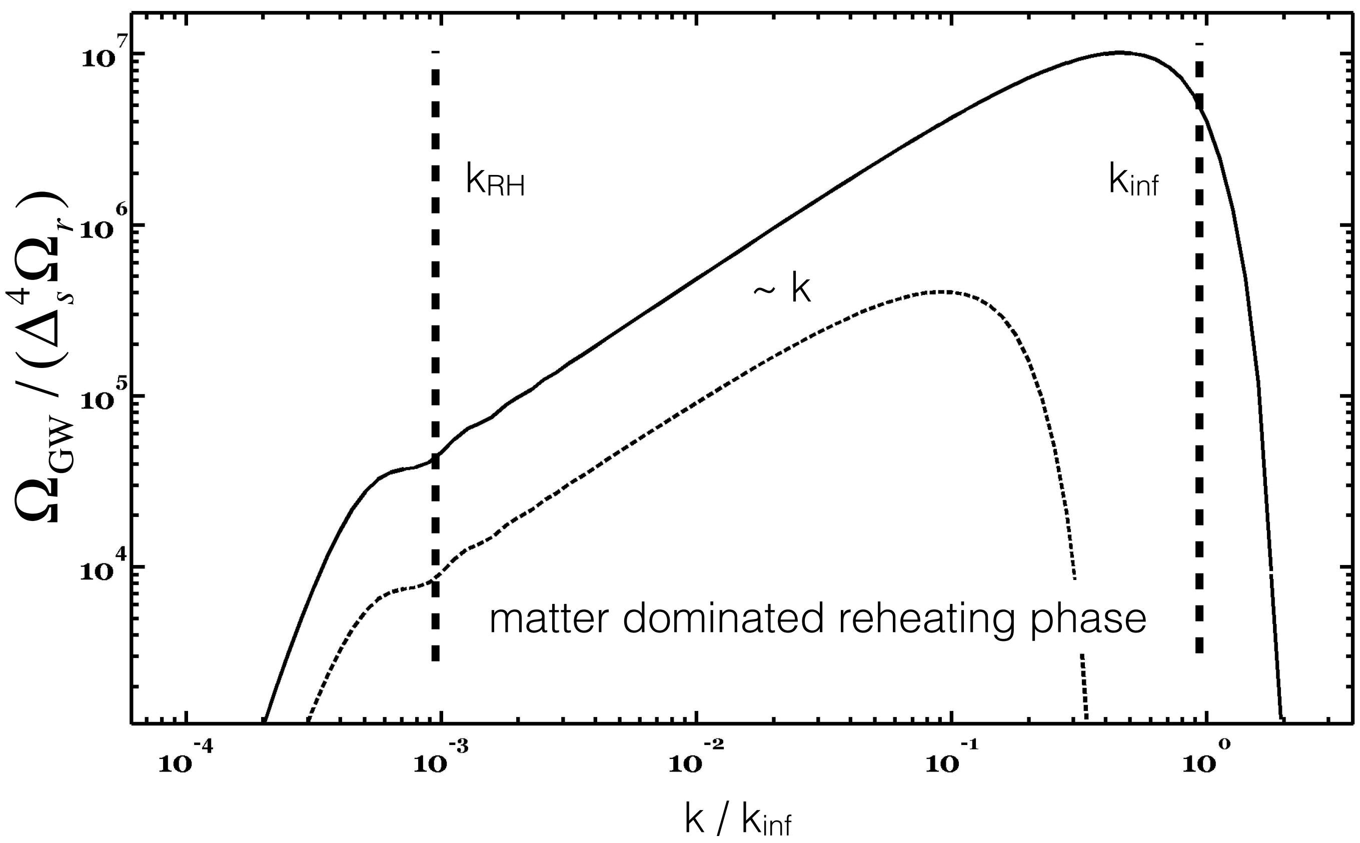
↓

grow in a matter-dominated reheating phase

↓

source second order tensor perturbations

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



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

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

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

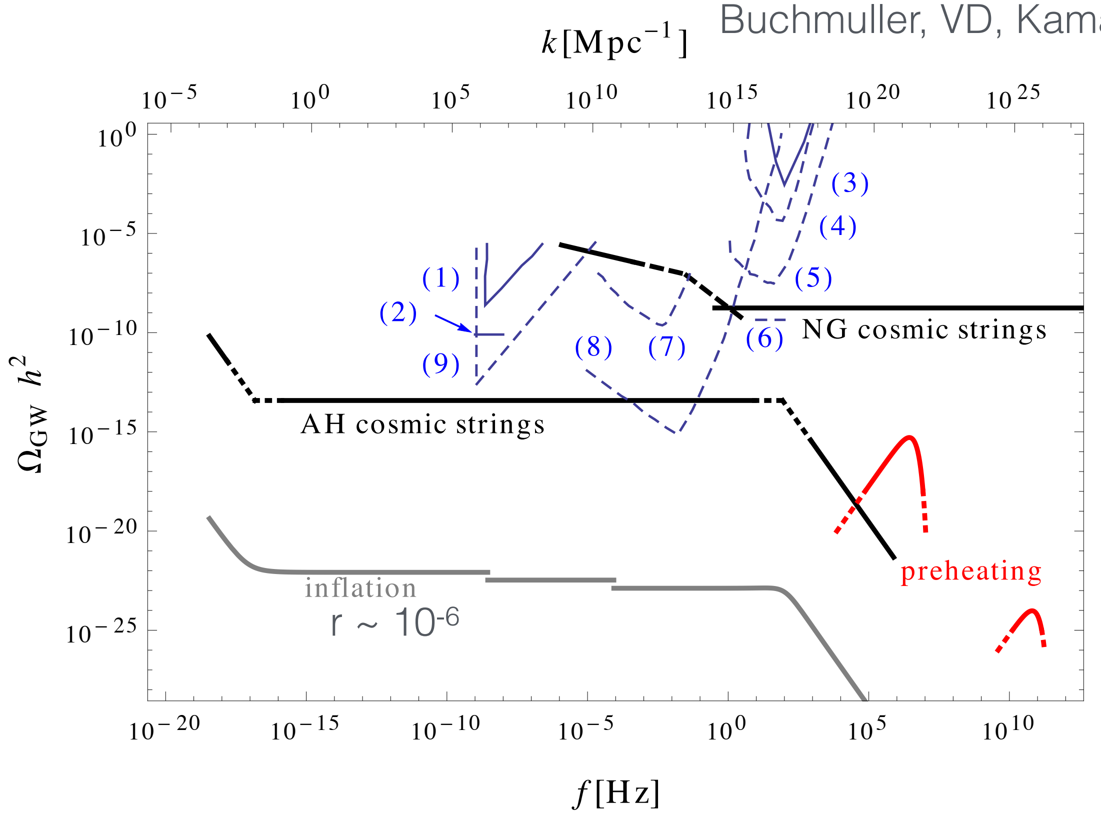
Other stochastic backgrounds

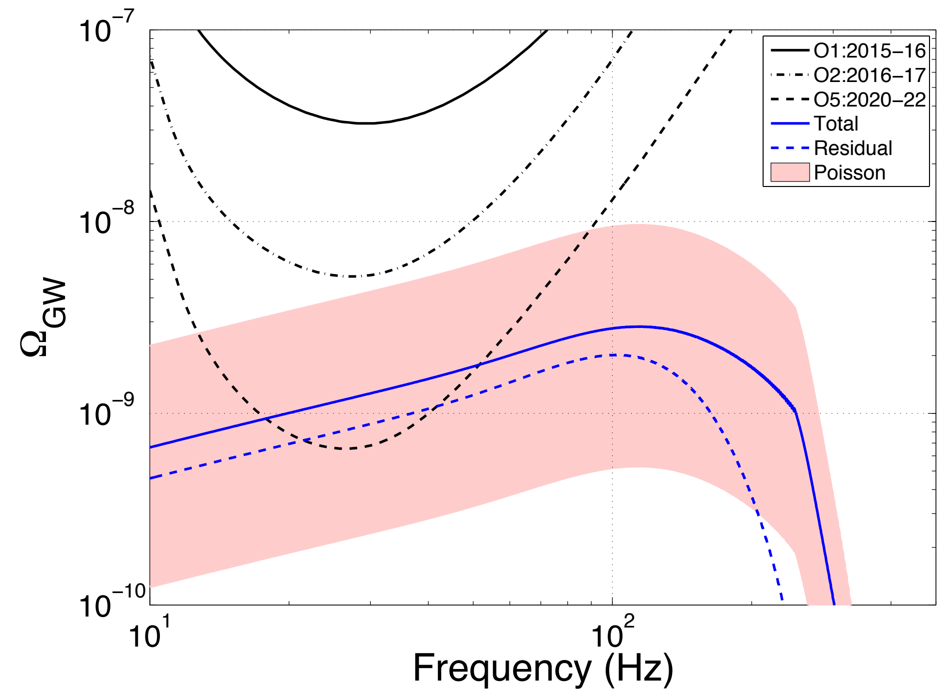
(incomplete list)

LIGO/VIRGO collaboration '16,

GUT-scale phase transition after hybrid inflation

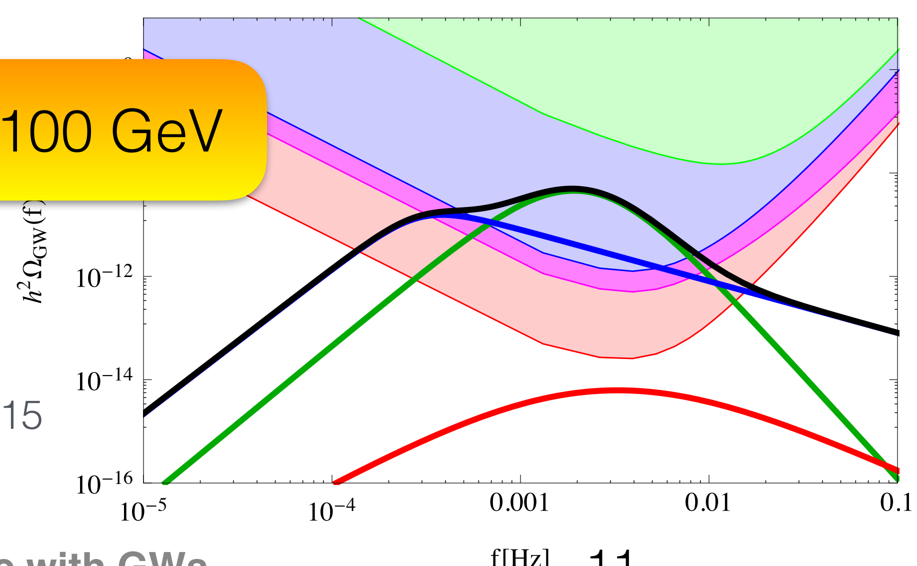
Buchmuller, VD, Kamada, Schmitz '12





unresolved BH mergers

phase transition at 100 GeV

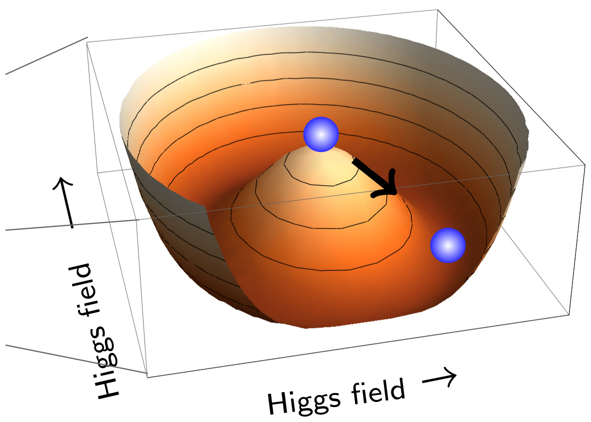


Caprini et al '15

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

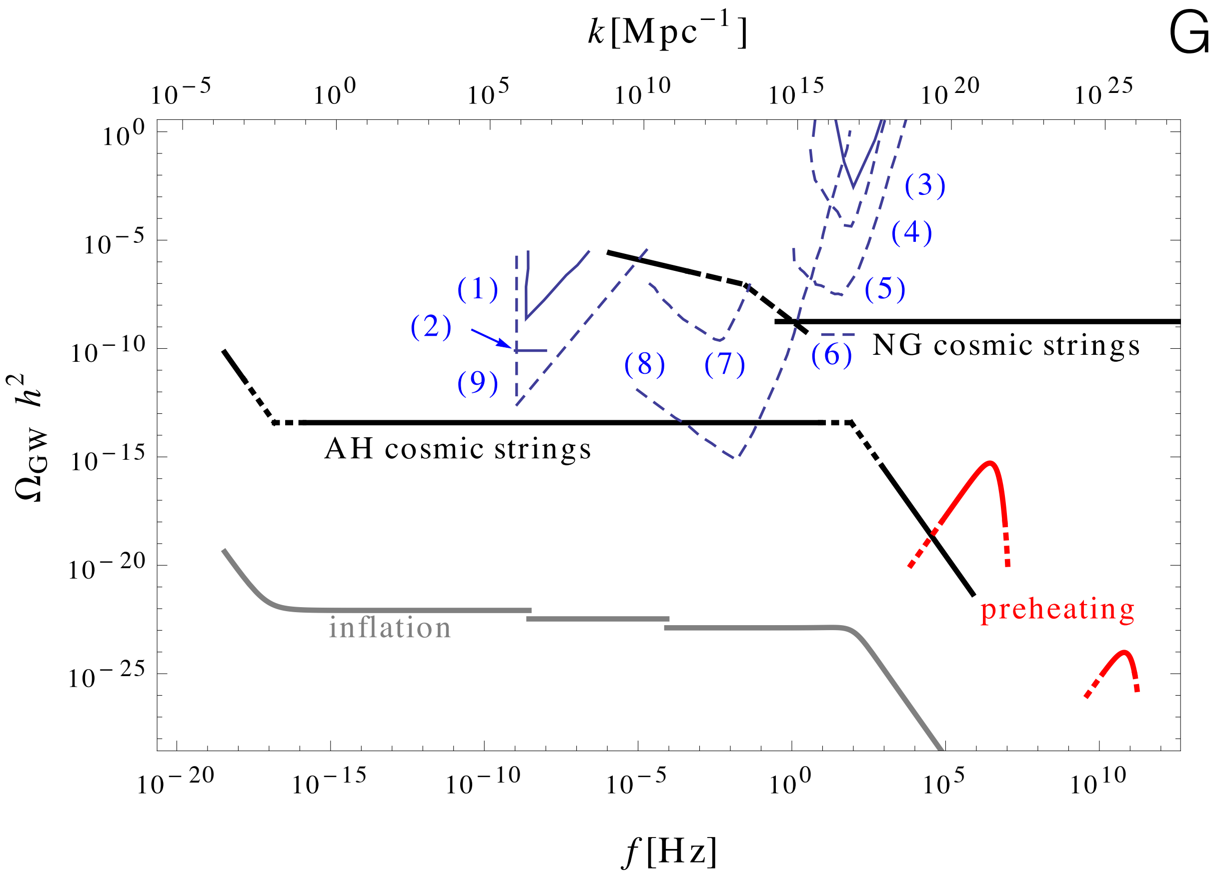
- Abelian Higgs model: Main source for GWs are horizon sized cosmic strings

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

Vilenkin '81, Hindmarsh '12

Cosmic strings

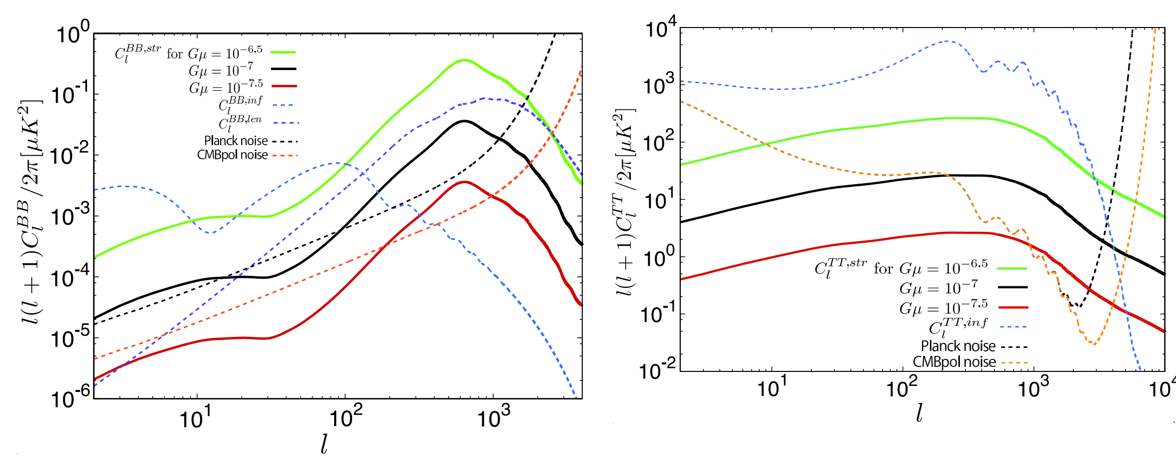
direct detection



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

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…

Thank you!