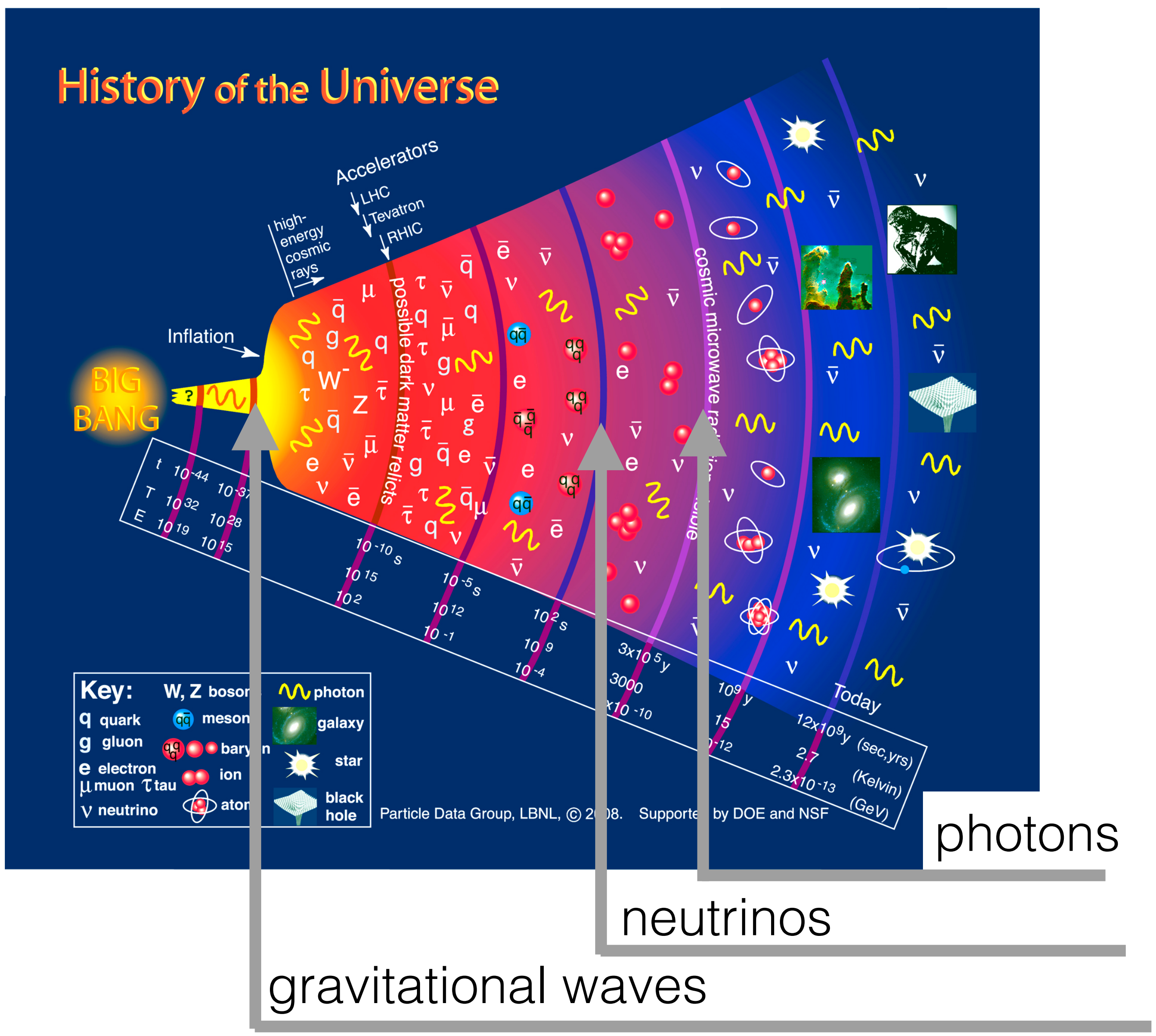
Inflation and Gravitational Waves

Probing the early Universe with gravitational waves



Valerie Domcke
APC, Paris

Saha Theory Workshop
Kolkata
16. - 20.1.2017

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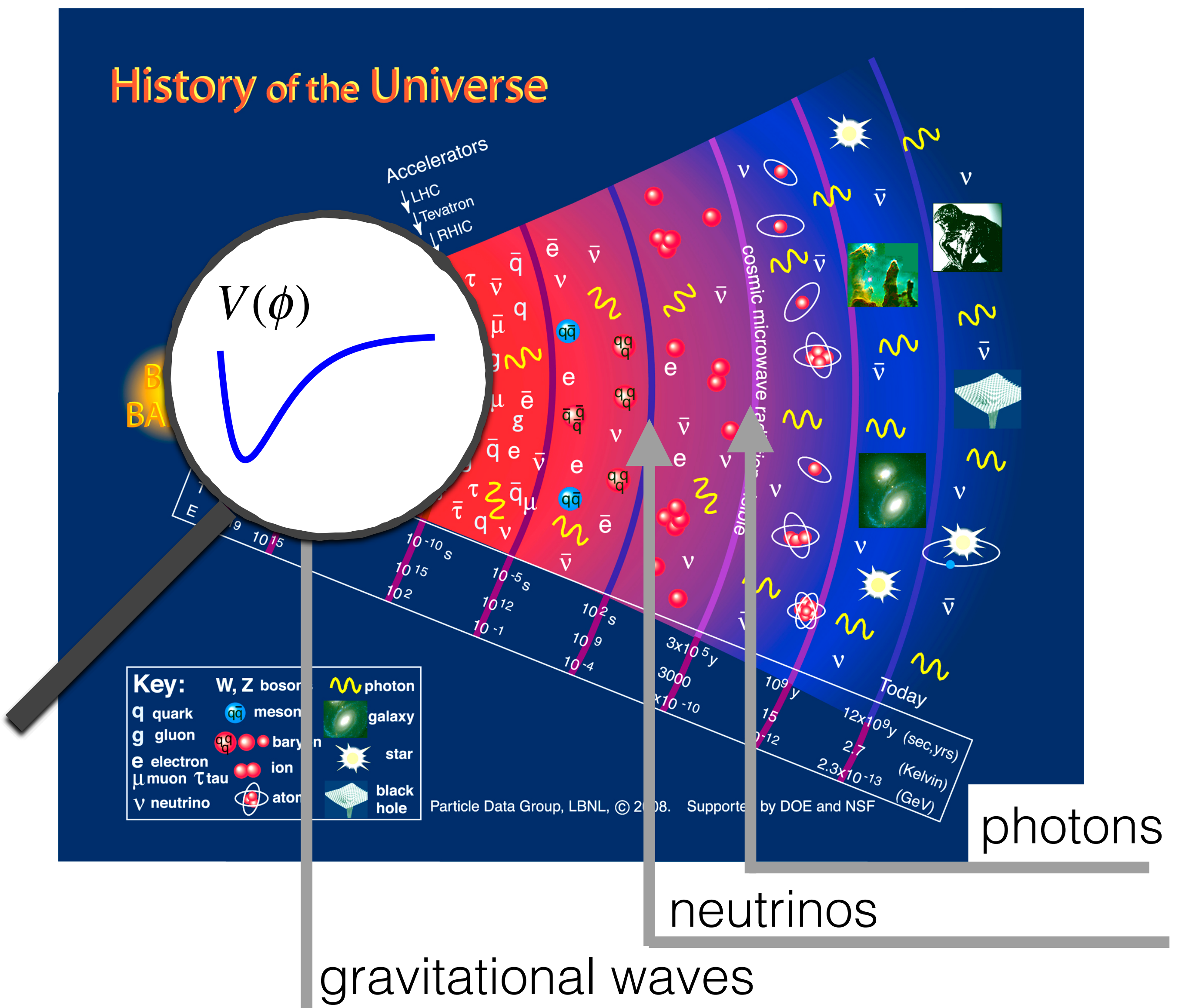

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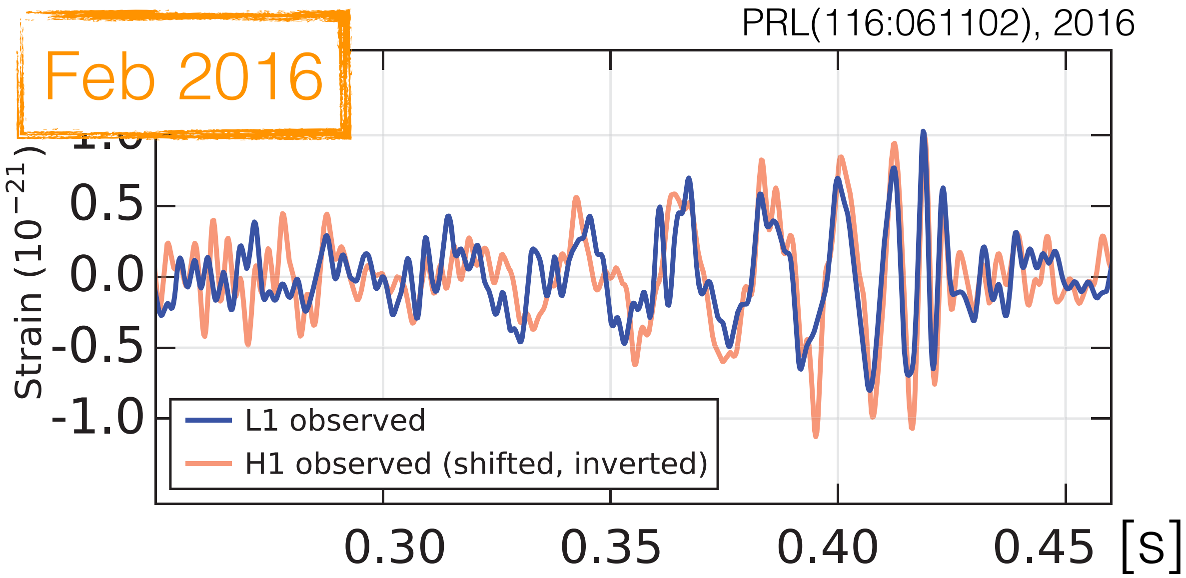
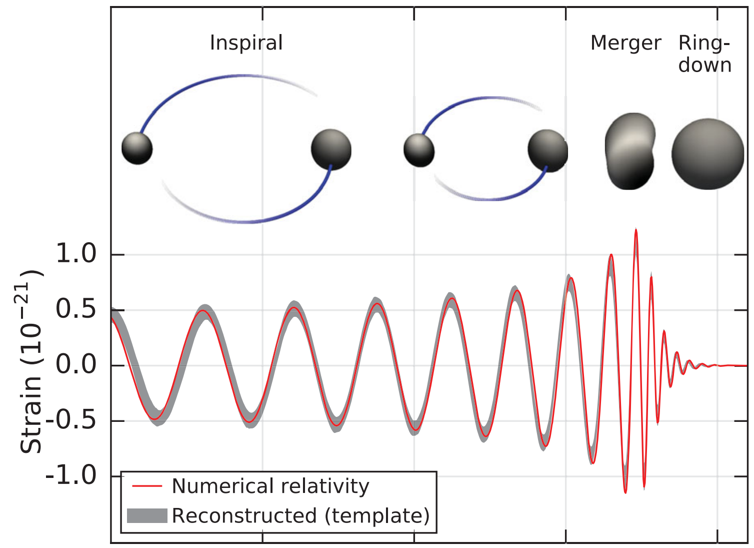
GWs in 2016

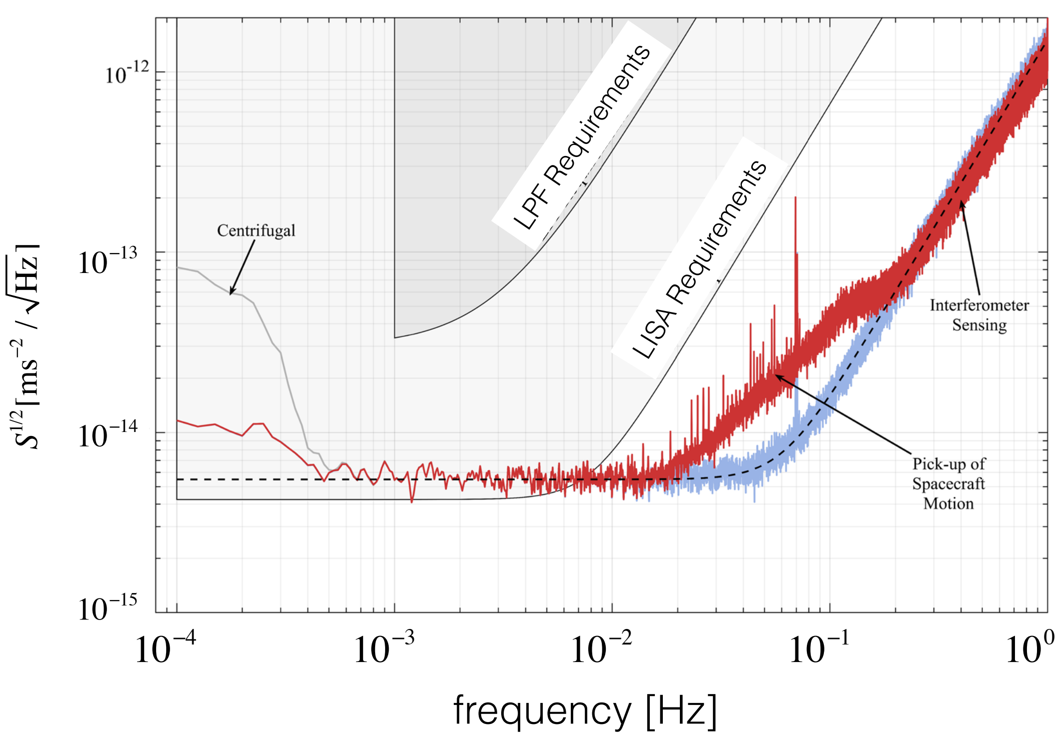
PRL(116:061102), 2016





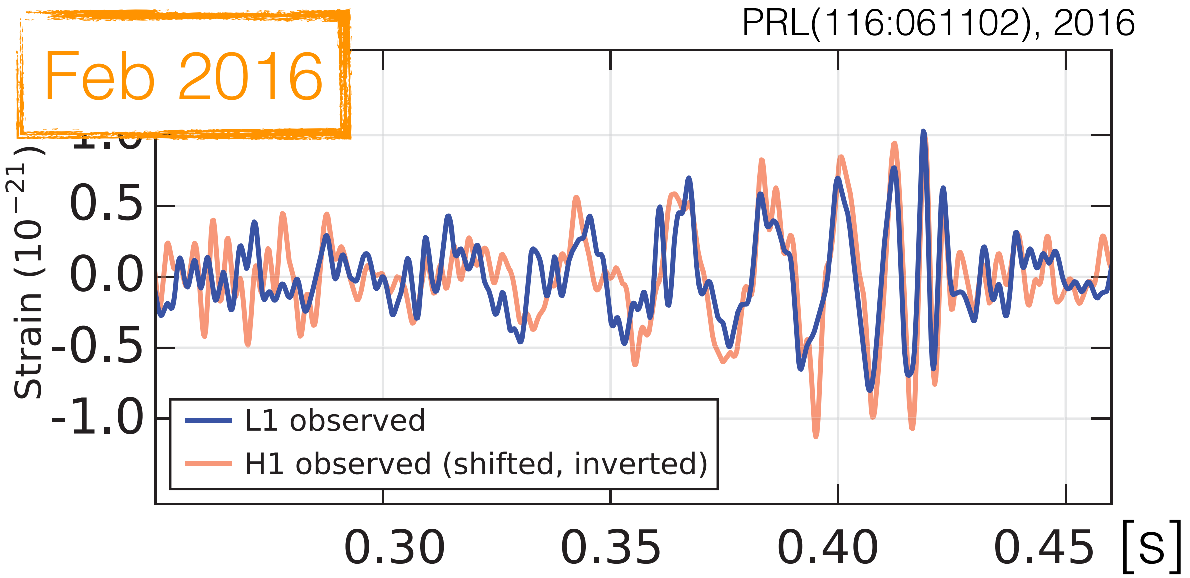
BH - BH merger,

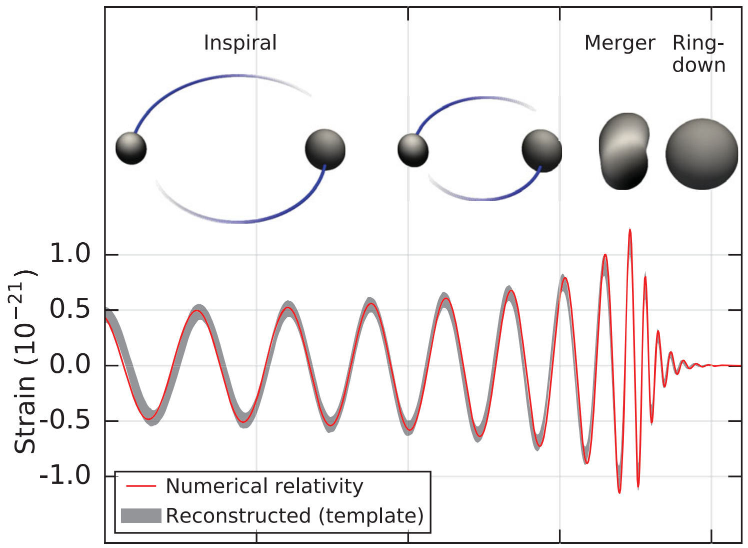
GW150914



GWs in 2016

Feb 2016





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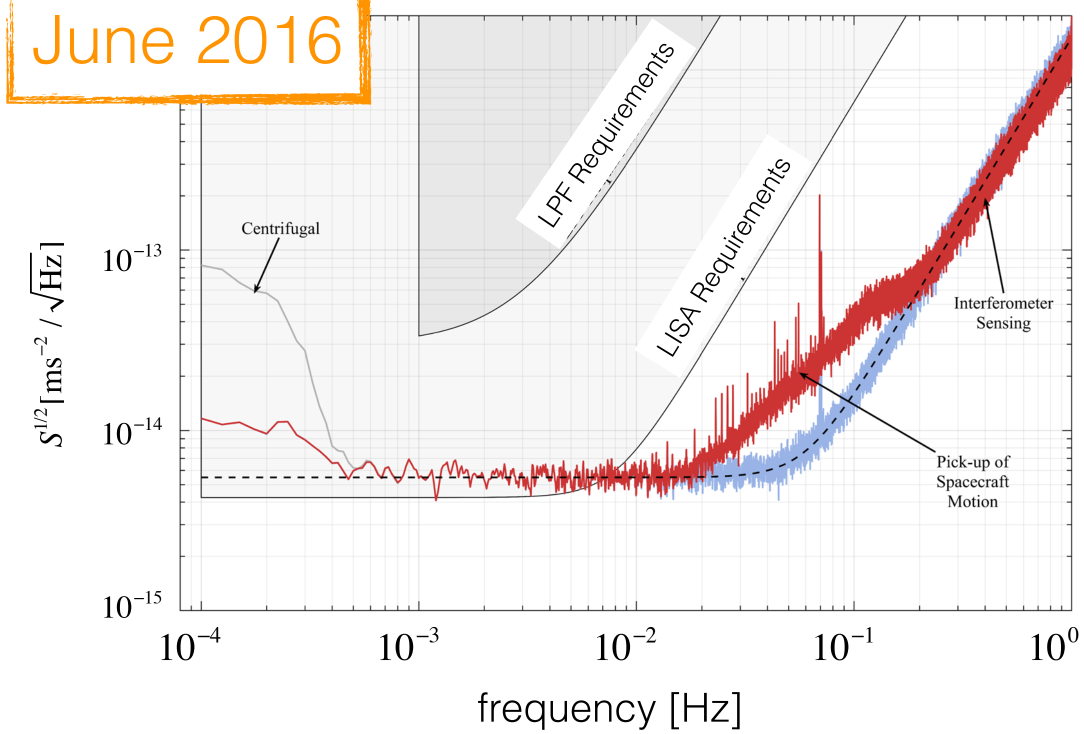
June 2016



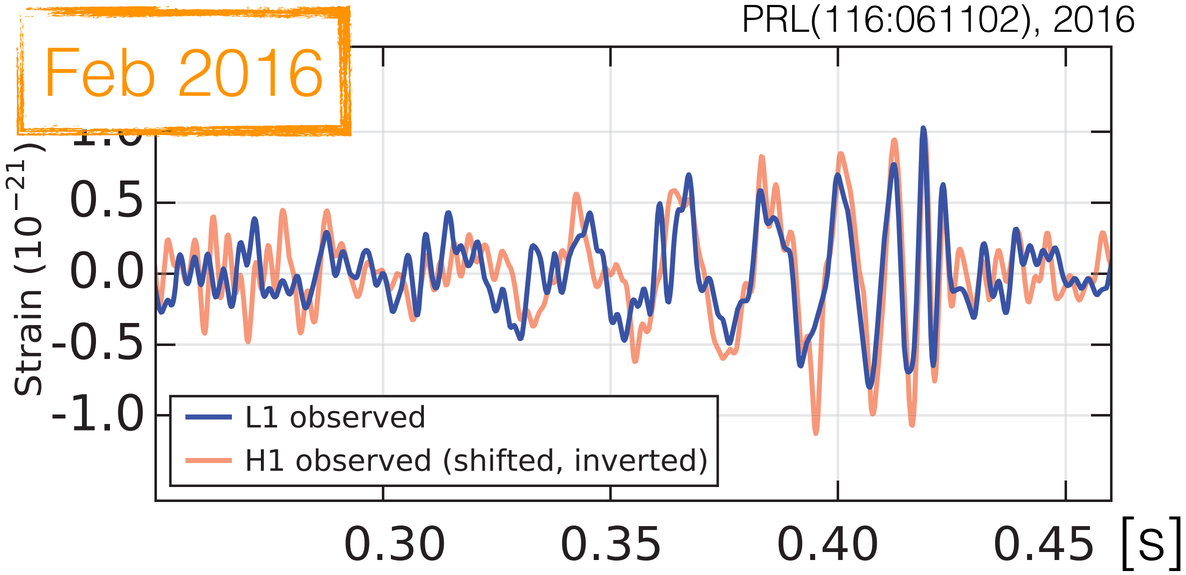
LISA Pathfinder, noise levels

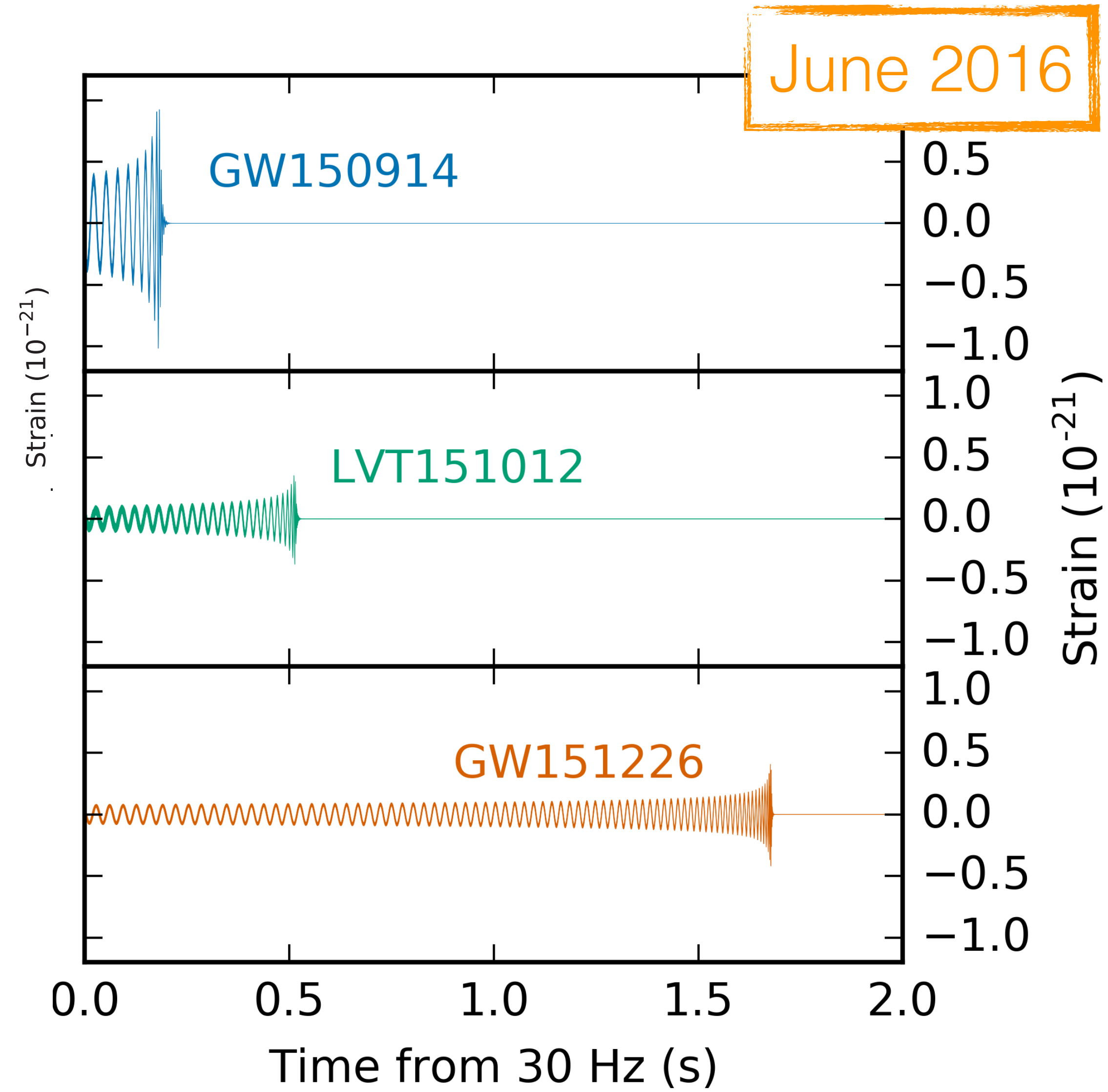
- ESA mission, launch ~ 2034 (?)
- Interferometer(s) with free falling test masses in 3 satellites

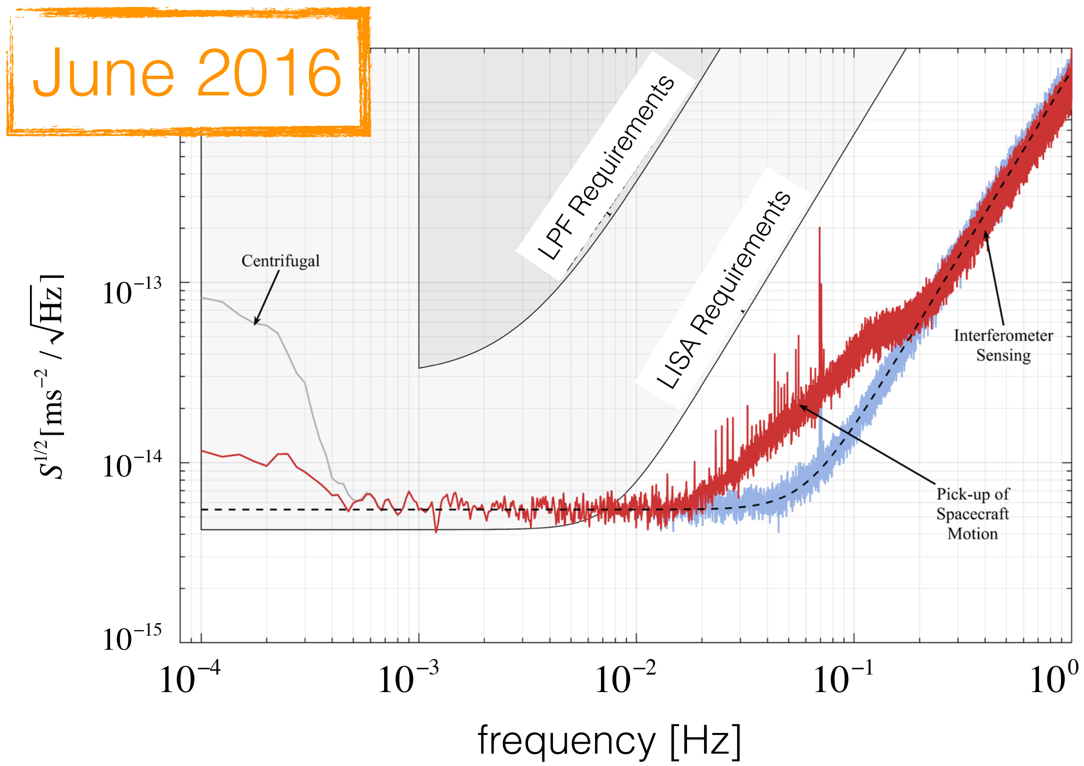
PRL(116:231101), 2016

GWs in 2016

PRL(116:061102), 2016







PRL(116:231101), 2016

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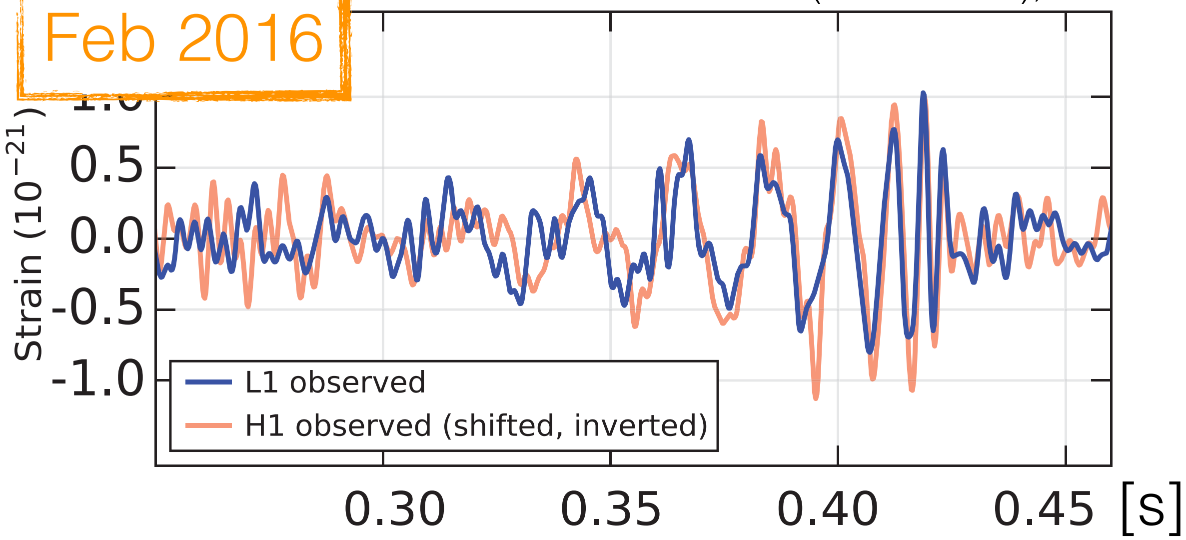
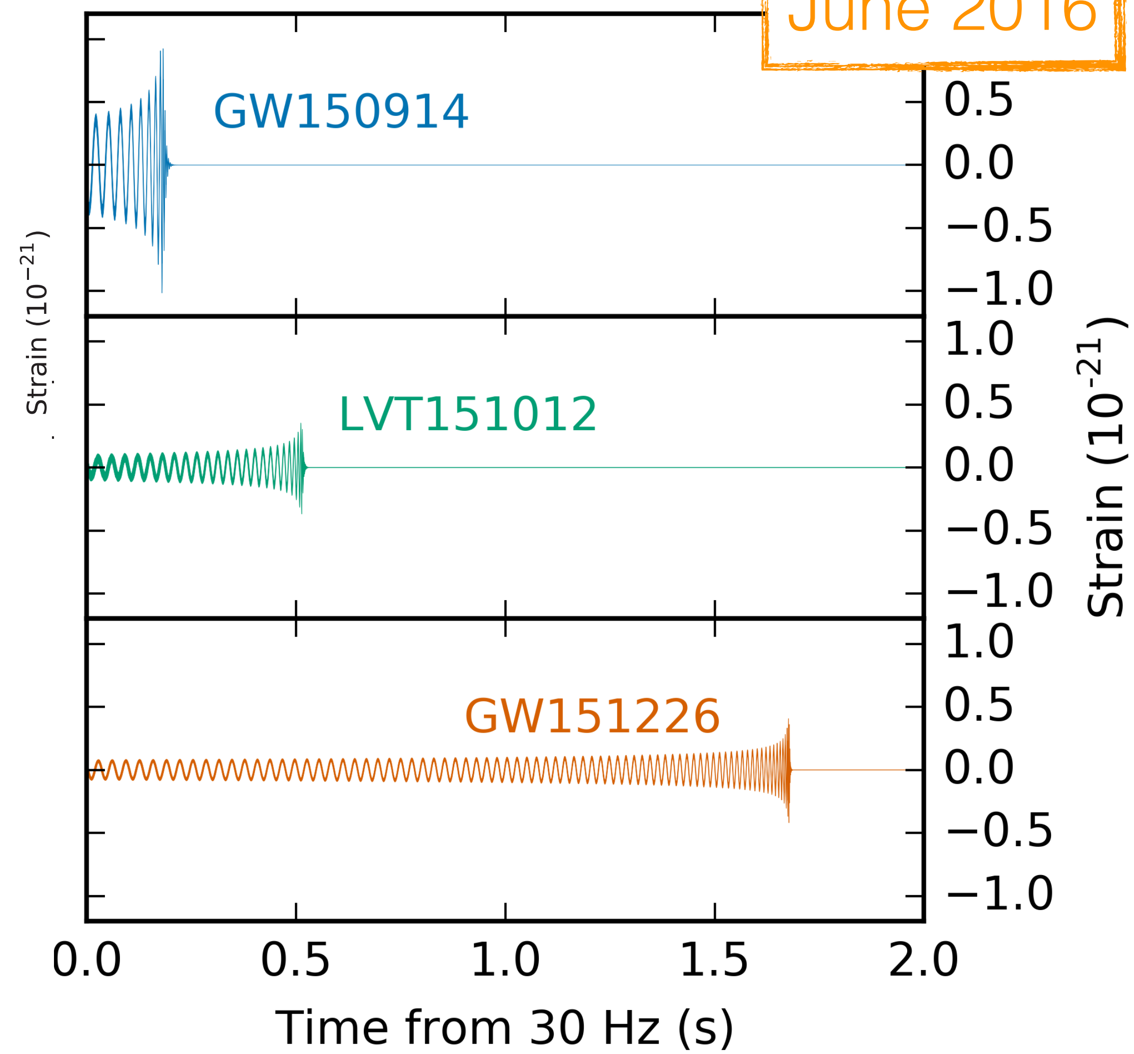
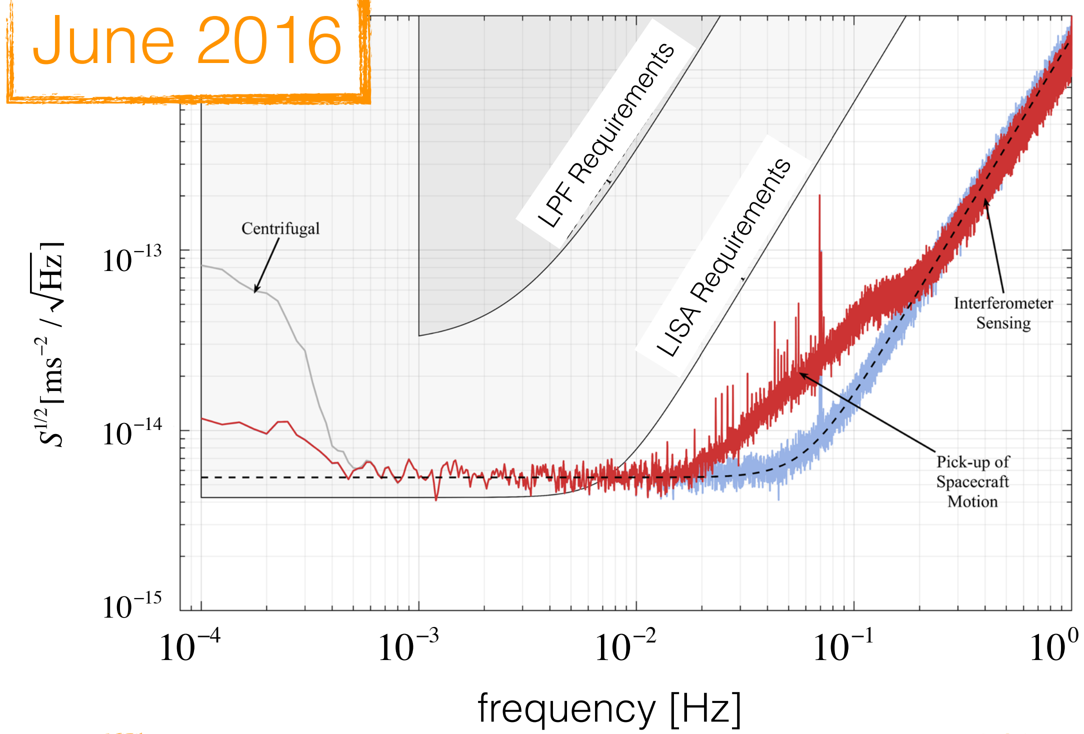


June 2016



PRL(116:231101), 2016

June 2016



March 2016 LIGO India funded

October 2016 eLISA -> LISA (full 3 - arm mission)

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

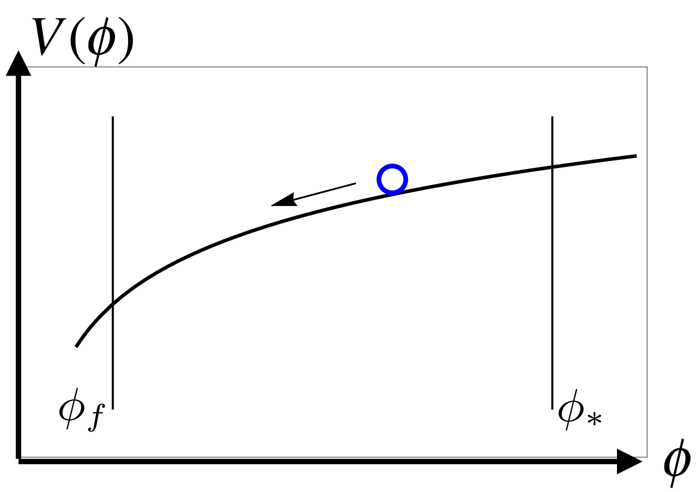
- An enhanced GW background ?

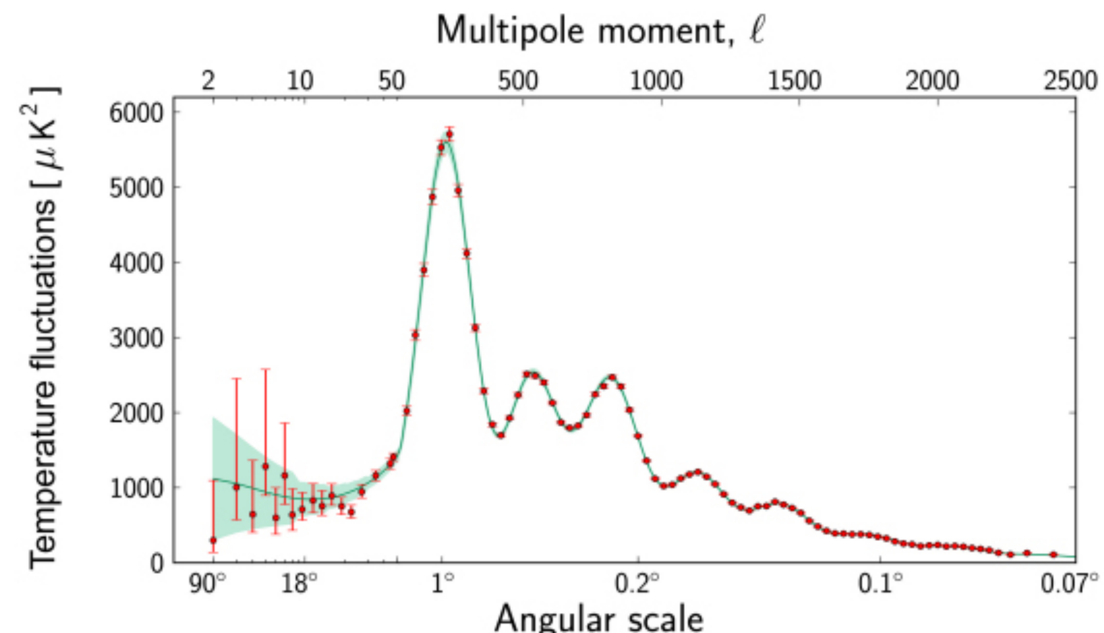
……..axion inflation

……..reduced symmetry during inflation

……..stiff equation of state after inflation

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

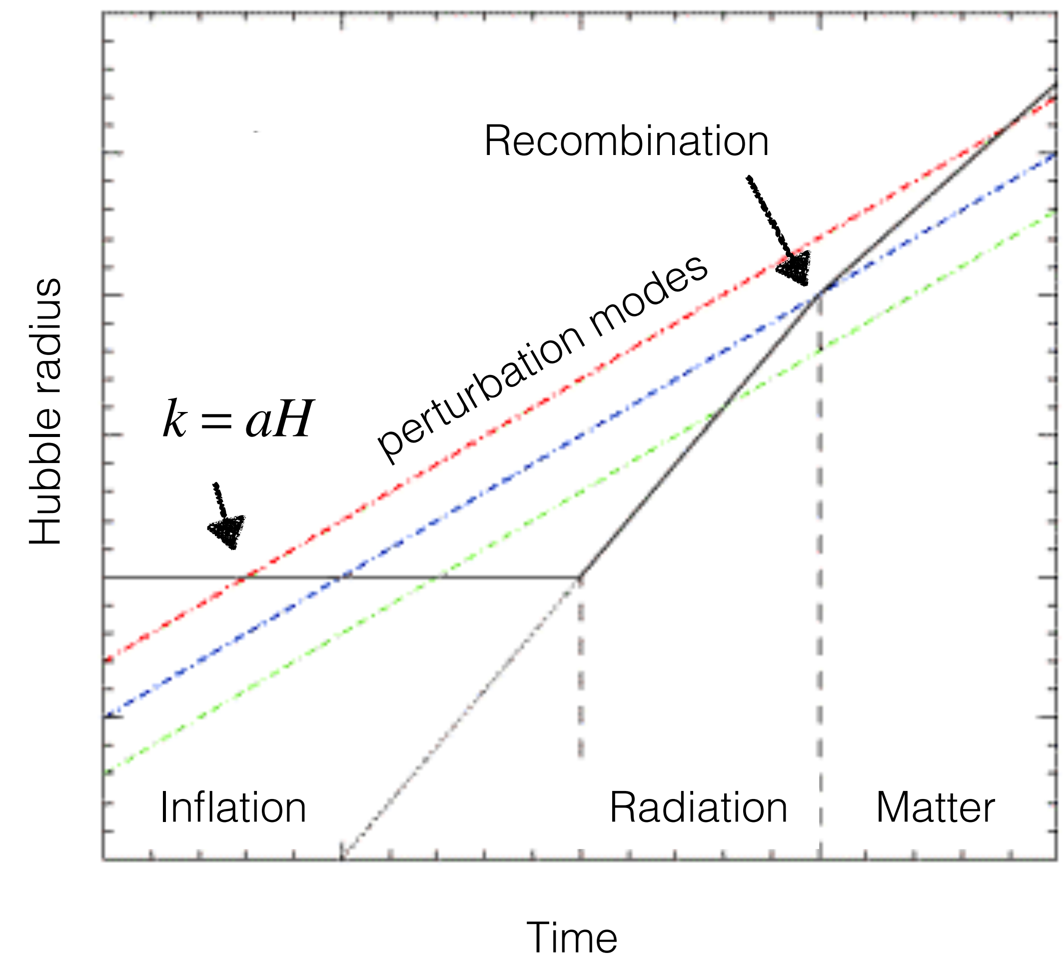
co-moving perturbation modes
leave Hubble horizon during inflation,
re-enter after inflation

↓

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

↓

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



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

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

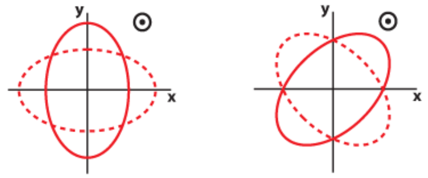
$$\tilde{h}''_{ij}(\boldsymbol{k},\tau) + \Bigg(k^2 - \underbrace{\frac{a''}{a}}_{\sim a^2 H^2}\Bigg)\tilde{h}_{ij}(\boldsymbol{k},\tau) = \underbrace{16\pi\, G\, a\, \Pi_{ij}(\boldsymbol{k},\tau)}_{\text{source term from } \delta T_{\mu\nu}}$$

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

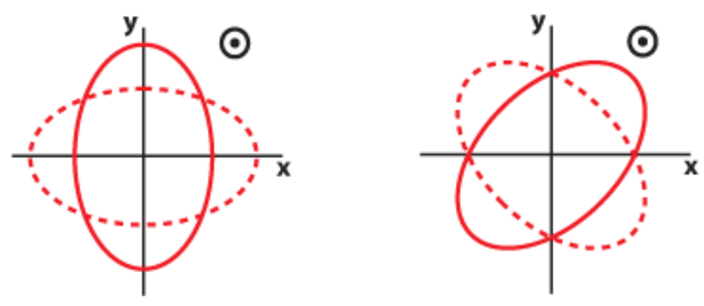
transfer function, expansion coefficients, polarization tensor $P = +,\times$



observational quantity in direct detection

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

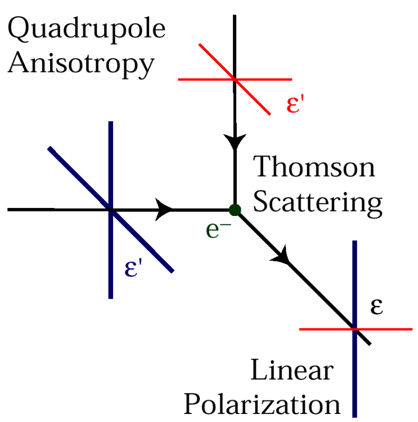
Hunting for primordial GWs



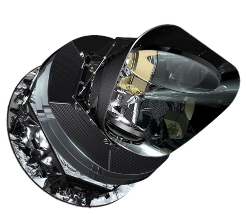
CMB

tensor anisotropies
on last scattering surface

polarization of CMB photons
through Thomson scattering



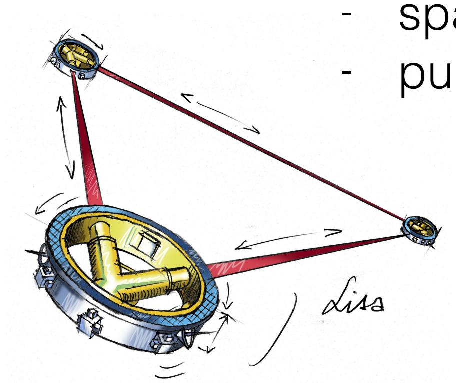
- Lensing: T -> E
- dust contaminates primordial signal
- B - modes most sensitive



direct

GW travels freely until today

distortion of space as GW
passes detector

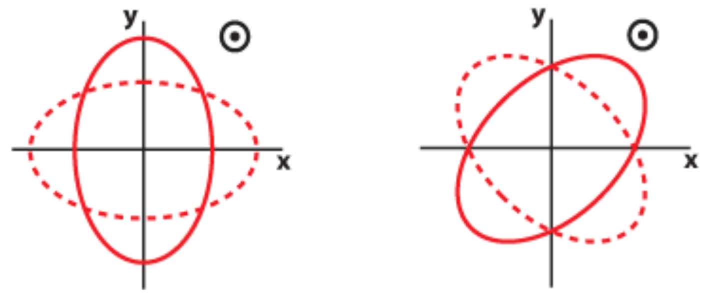


- ground-based interferometers
- space-based interferometers
- pulsar timing arrays

Hunting for primordial GWs

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

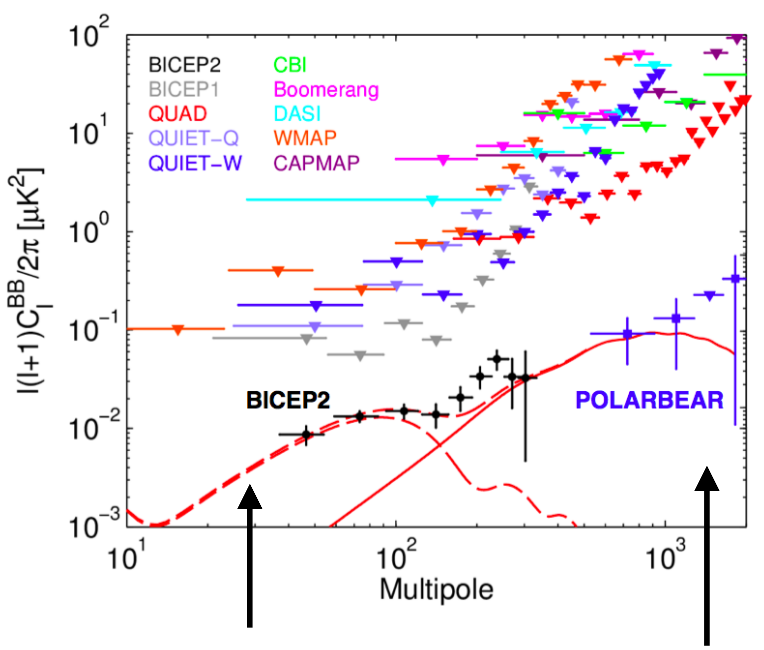
CMB



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

direct

BICEP2 '14



hypothetical primordial contribution with r ~ 0.17

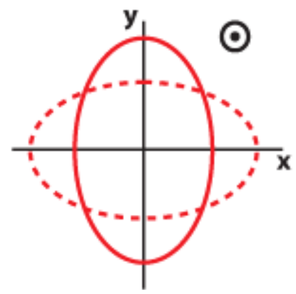
Lensing

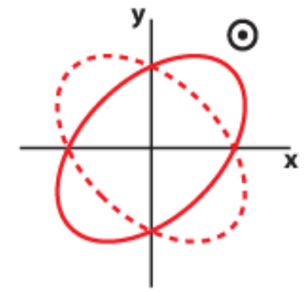
sensitive to CMB scales

Hunting for primordial GWs

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

CMB





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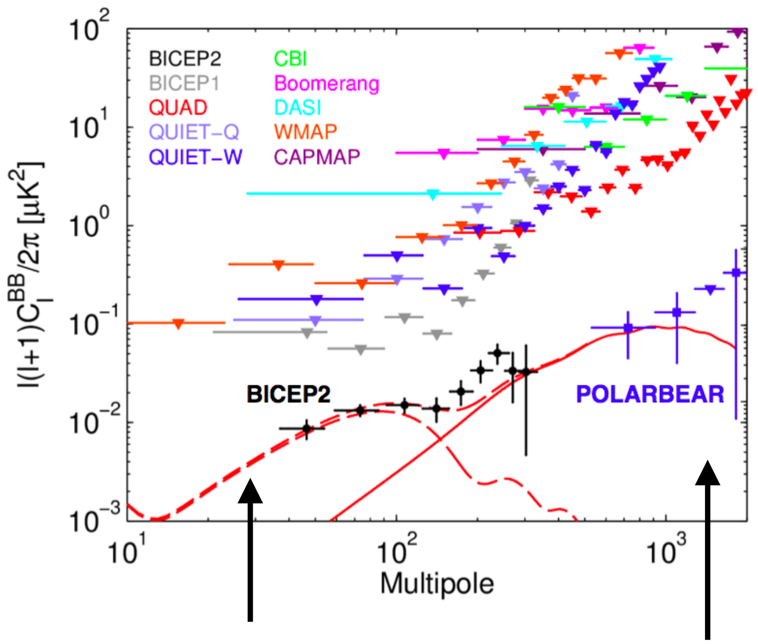

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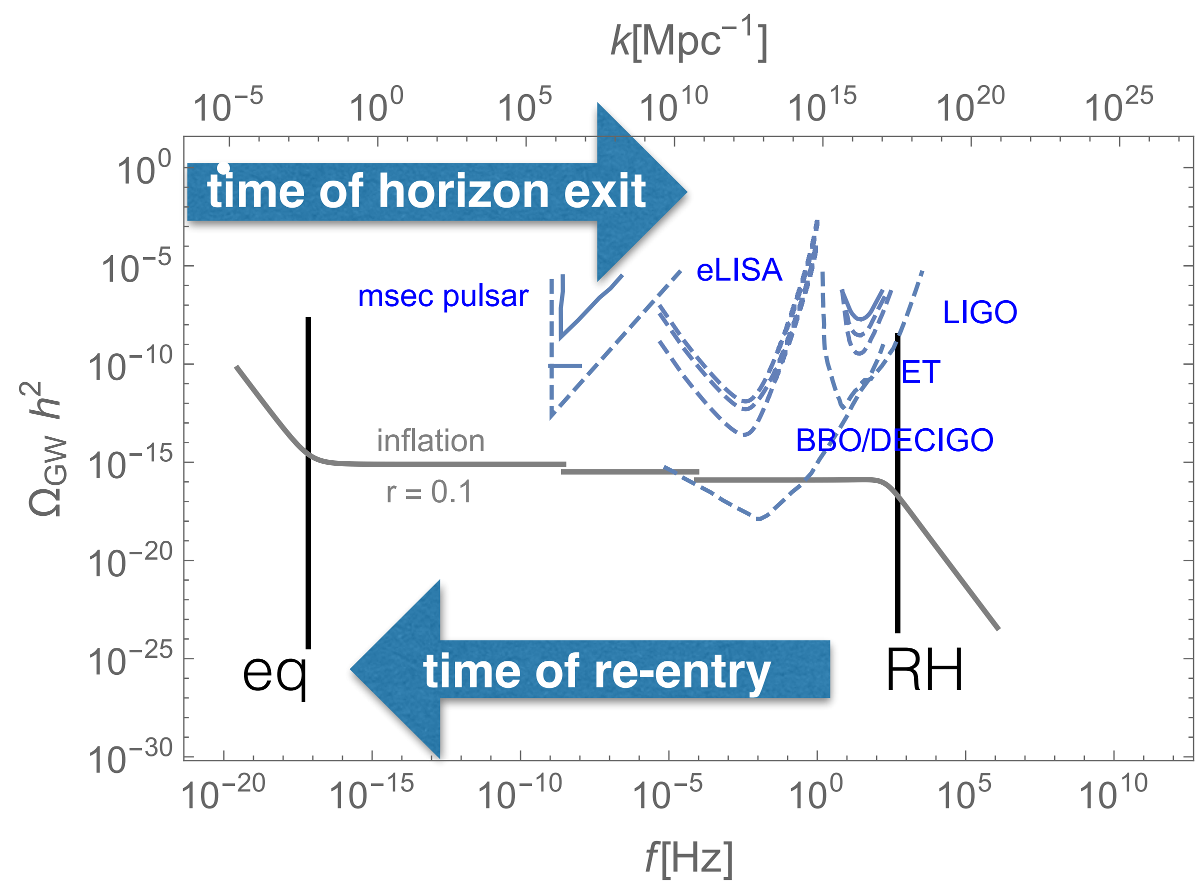
Lensing



sensitive to CMB scales

with suitable detectors, probe 30 orders of magnitude

Any hope of detection?

consistency relation of single-field slow-roll inflation: $n_T = -r/8 < 0$

Is this the end of the story ?

Any hope of detection?

consistency relation of single-field slow-roll inflation: $n_T = -r/8 < 0$

violated in slow-roll inflation if:

- extra dofs/sources during inflation
  → additional classical source of GWs

  Cook, Sorbo '12 — particle production during inflation

  Fujita et al '15 — spectator fields with $c_s < 1$

- broken spatial homogeneity during inflation

  Endlich et al '13, Dimastro-giovanni et al '16 — eg solid inflation, chromo-natural inflation

- second order GW production from large scalar perturbations
  Assadulahi, Wands '09

evaded in non-standard cosmology:

- non-standard equation of state during reheating

  kination domination (w = 1)

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

- alternatives to inflation

  bouncing cosmology
  Gasperini, Veneziano '02

- ….

See also: Figueroa, Ricciardone et al '16

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See also: Figueroa, Ricciardone et al '16

Axion inflation

a generic coupling for a pseudoscalar inflaton:

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

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:

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

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

- tachyonic instability for the gauge field, controlled by $\boxed{\xi \propto \sqrt{\epsilon} = \dot{\phi}/(\sqrt{2}H)}$
- 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

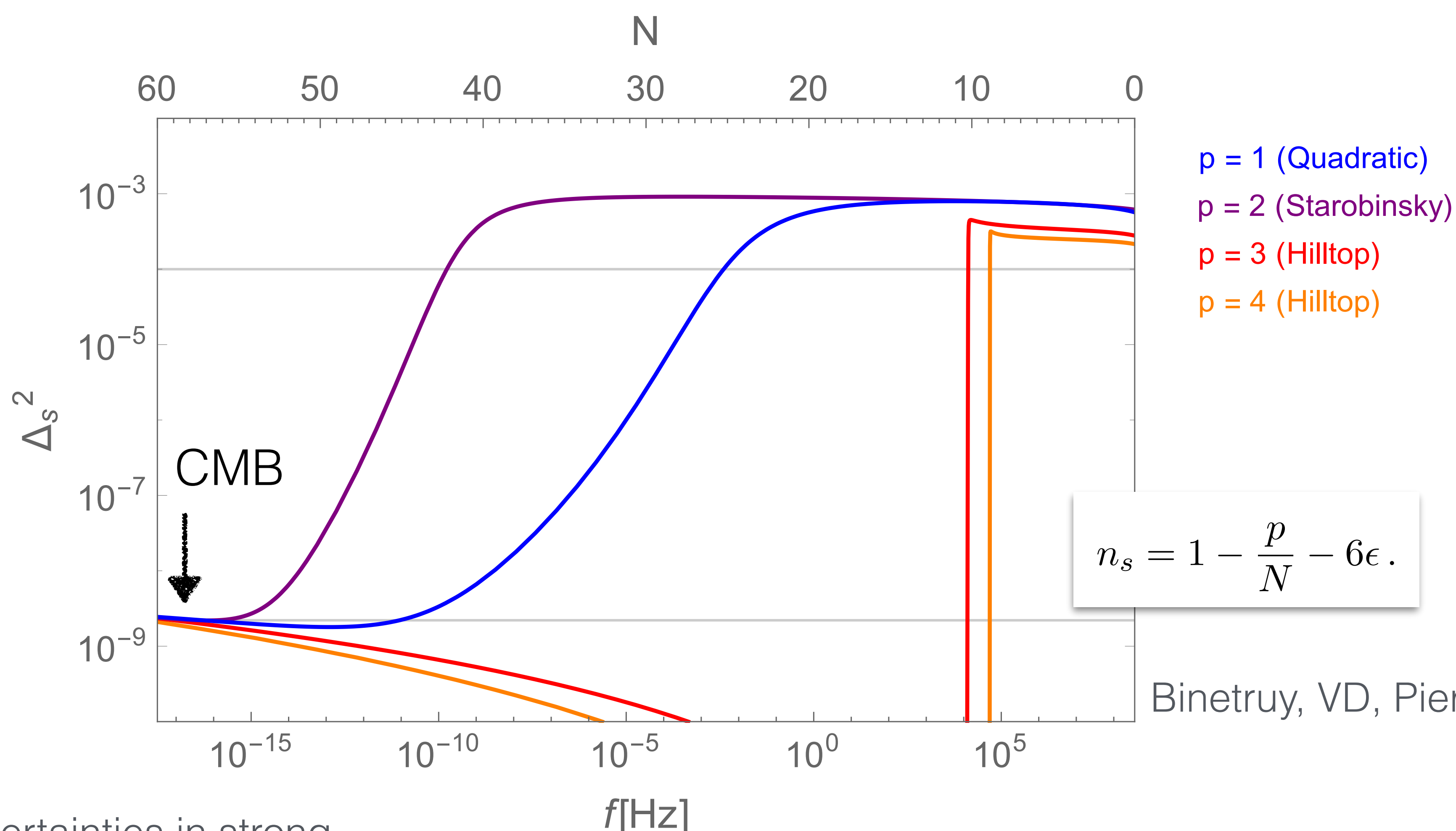
Scalar power spectrum

vacuum + sourced contribution:

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

$$b = 1 - 2\pi\xi\frac{\alpha\langle\vec{E}\vec{B}\rangle}{3\Lambda H\dot\phi},$$

$$\langle\vec{E}\vec{B}\rangle \simeq \mathcal{N}\cdot 2.4\cdot 10^{-4}\frac{H^4}{\xi^4}e^{2\pi\xi}$$



$$n_s = 1 - \frac{p}{N} - 6\epsilon\,.$$

Binetruy, VD, Pieroni '16

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

a simple parametrization of the scalar potential:

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

Mukhanov '13

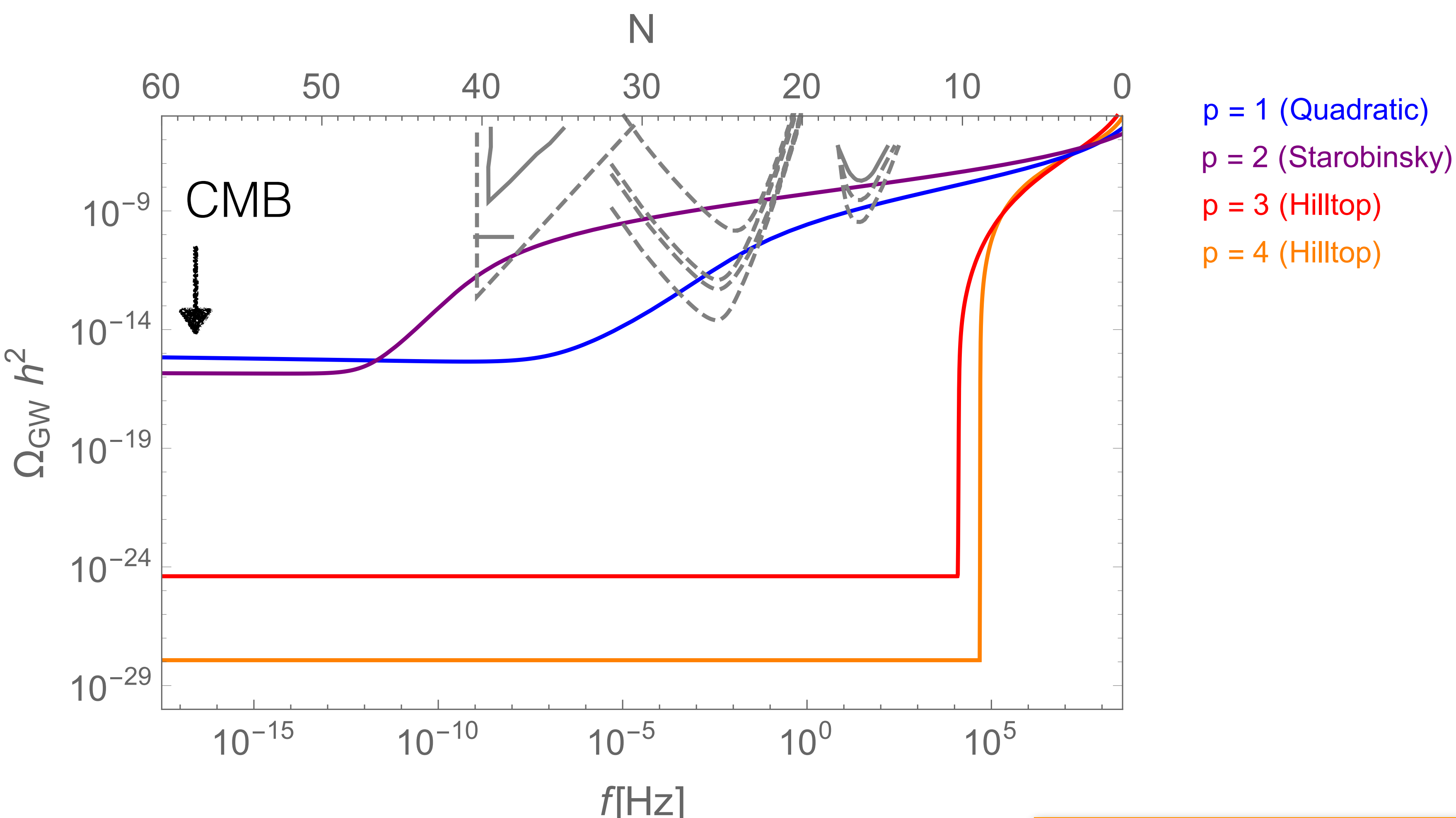
→ $\boxed{\text{3 parameters: } \alpha, \beta, p}$

strong, quasi-universal enhancement at small scales

Tensor power spectrum

vacuum + sourced contribution:

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



Binetruy, VD, Pieroni ’16

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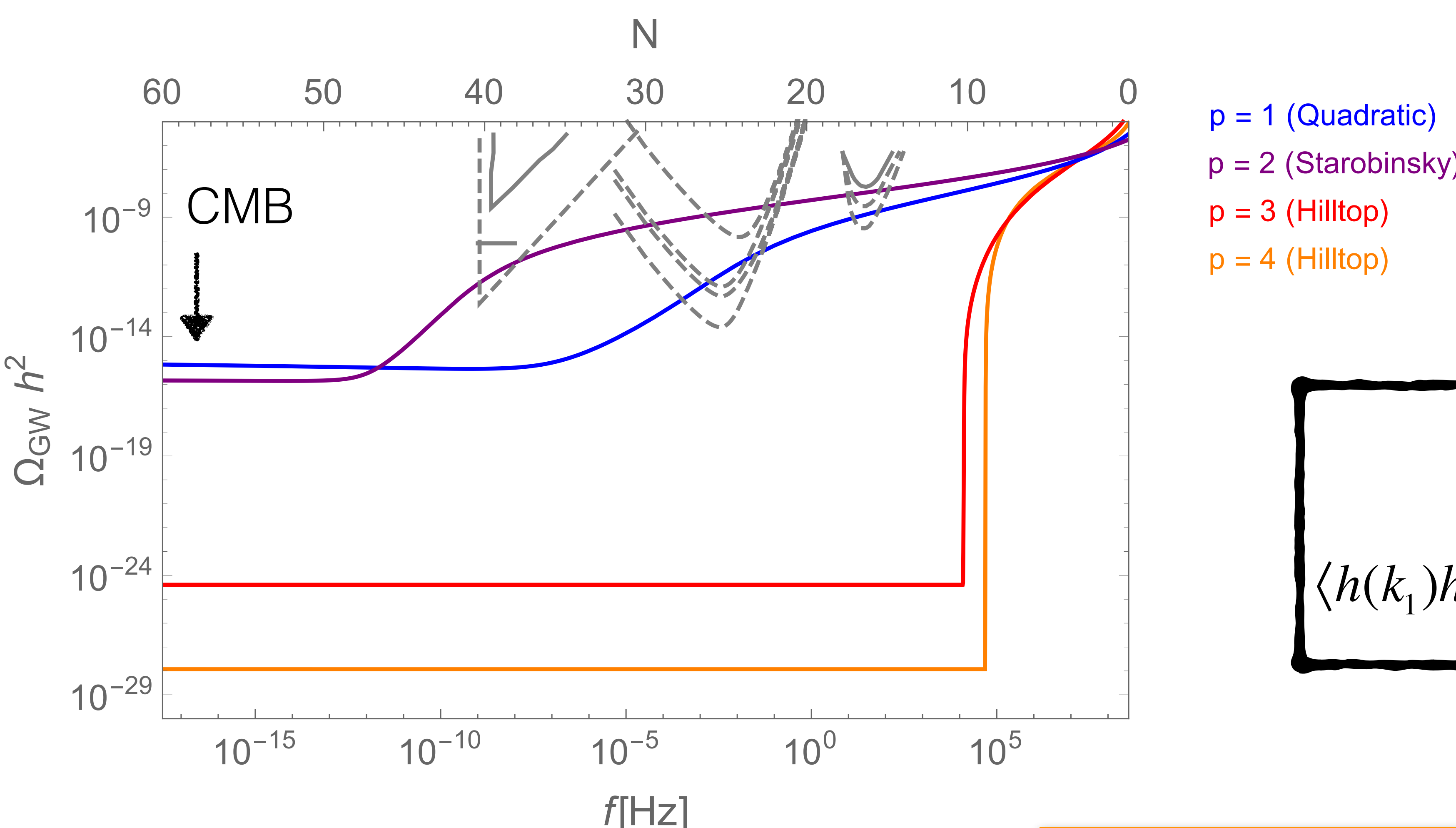


Binetruy, VD, Pieroni '16

polarized

non-gaussian

$$\langle h(k_1)h(k_2)h(k_3)\rangle_{\rm equil} \propto \Omega_{\rm GW}(k)^{3/2}$$

strong enhancement on small scales

Observables & scales

60	50	40	30	20	10	0	N

10^{-15}	10^{-10}	10^{-5}	10^{0}	10^{5}	$f[\mathrm{Hz}]$
10^{0}	10^{5}	10^{10}	10^{15}	10^{22}	$k[\mathrm{Mpc}^{-1}]$

CMB: $A_s, n_s, f_{\rm NL}, r$

PTA $\Omega_{\rm GW}, n_t$

LIGO $\Omega_{\rm GW}, n_t$

scalar

tensor

CMB + : $\mu-$distortion

LISA $\Omega_{\rm GW}, n_t$

constraints dominated by small scales (to be taken with grain of salt):

PBHs $b \sim \int P(\xi) d\xi$

CMB $N_{\rm eff} \sim \int \Omega_{\rm GW}\, df$

BBN $N_{\rm eff} \sim \int \Omega_{\rm GW}\, df$

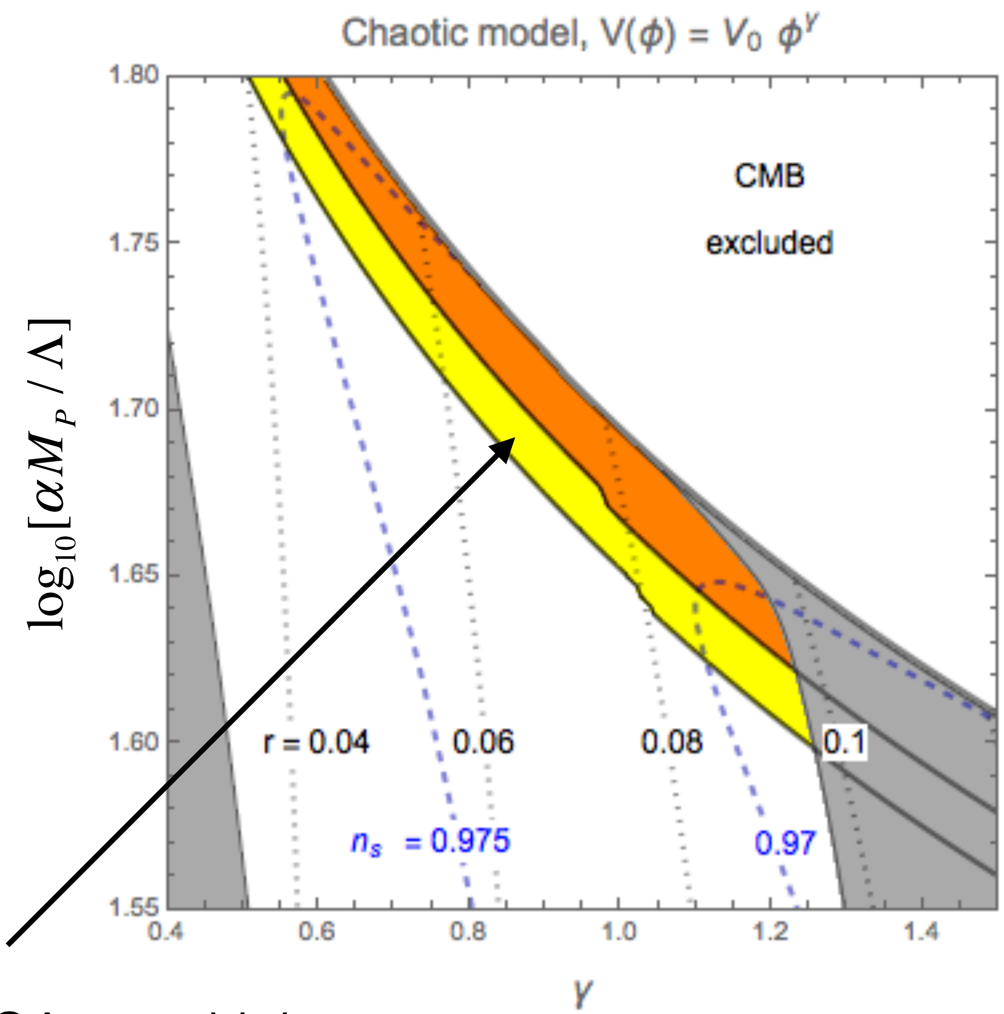
Chaotic model

Binetruy, VD, Pieroni ’16; Figueroa, Ricciardone et al ‘16

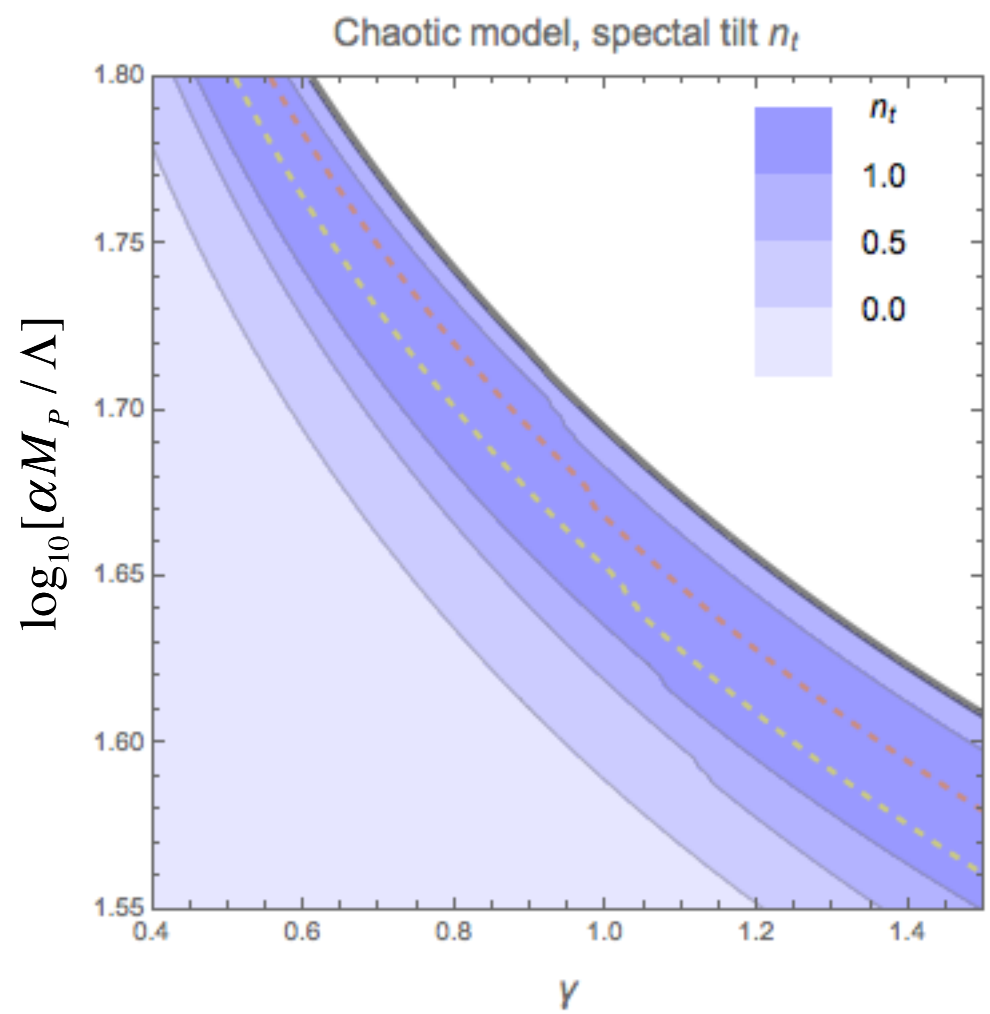
3 parameters: $\alpha / \Lambda, \beta, p$

$$V(\phi) = V_0 \phi^\gamma$$

$\rightarrow$ $p = 1,$ vary $\beta = \gamma / 4$ and α



LISA sensitivity



Remarkable complementarity between CMB and direct GW searches

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

- An enhanced GW background ?

……..axion inflation

……..reduced symmetry during inflation

……..stiff equation of state after inflation

Broken spatial reparametrization invariance

standard picture: inflaton is time-dependent, but homogeneous

what if this space-reparametrization invariance is broken?

tensor modes may acquire mass m_h

consistency relation $n_T = -r/8 < 0$ evaded

explicit examples: chromo-natural inflation, solid inflation

Adshead, Wyman '12
Maleknejad, Sheikh-Jabbari '13
Endlich, Horn, Nicolis, Wang '14

general effective field theory description:
(preserving isotropy and homogeneity)

Cannone, Tasinato, Wands '15

$$S_{(2)} = \frac{M_P^2}{8}\int dt\, d^3x\, a^3(t) n(t) \left[\dot{h}_{ij} - \frac{c_T^2(t)}{a^2}(\partial_l h_{ij})^2 - m_h^2(t) h_{ij}^2 \right]$$

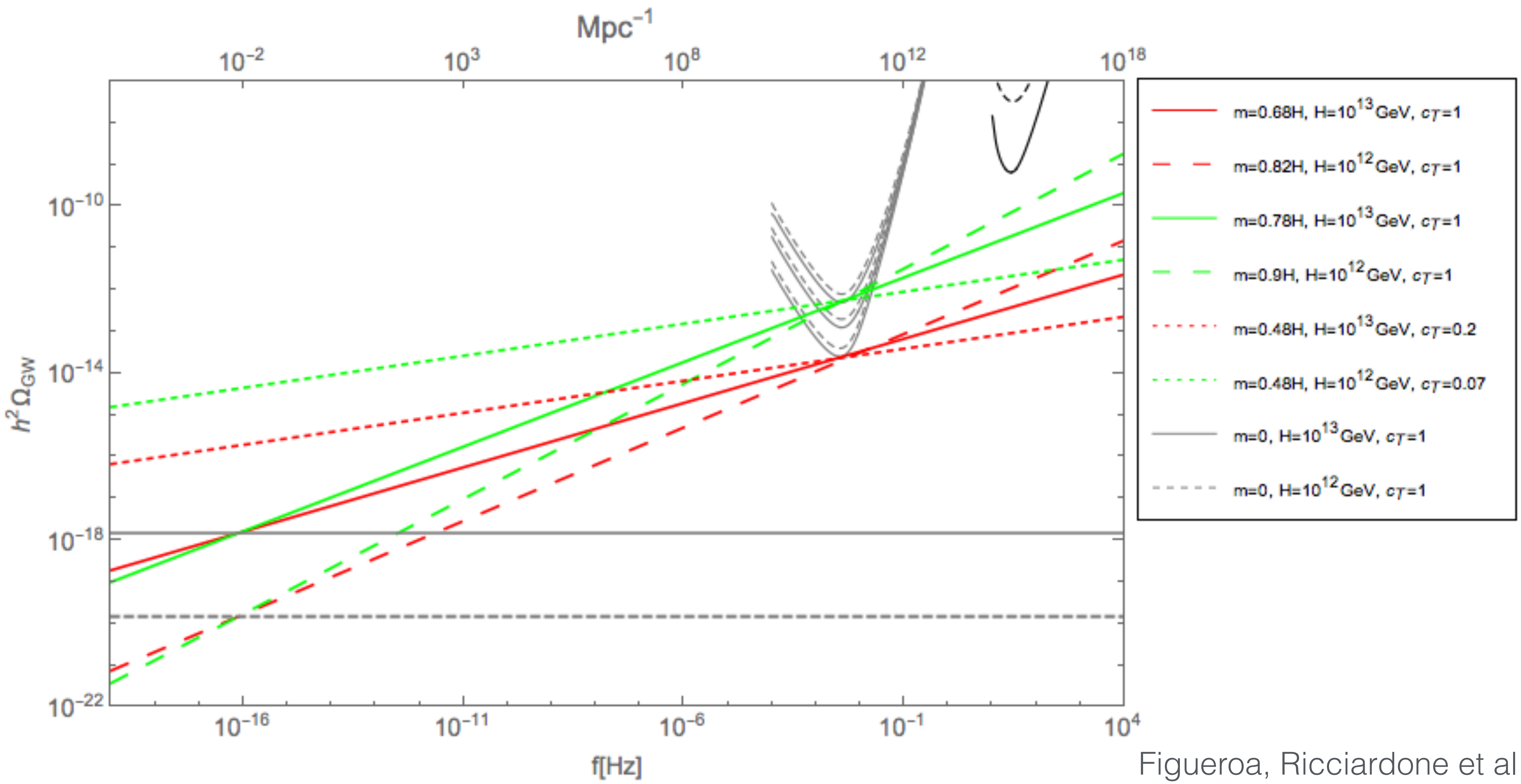
renormalization of Planck mass — tensor sound speed — mass for tensor modes

simplified setup: $n(t) \to 1$ $\quad c_T(t) \to c_T$ $\quad m_h(t) \to m_h$

Broken spatial reparametrization invariance

effective field theory description with time-independent m_h and c_T:

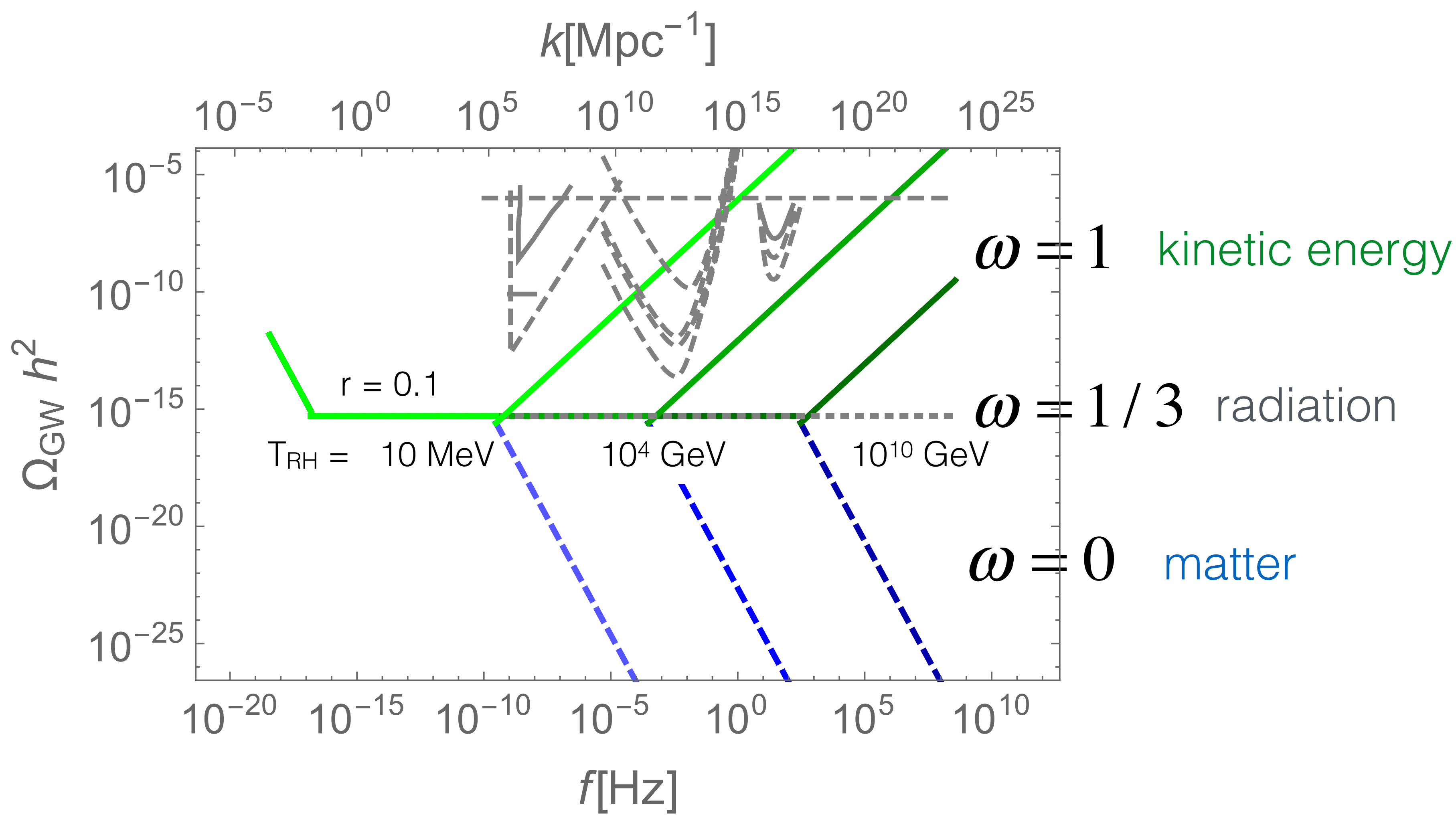
3 parameters: H, m_h, c_T



Figueroa, Ricciardone et al '16

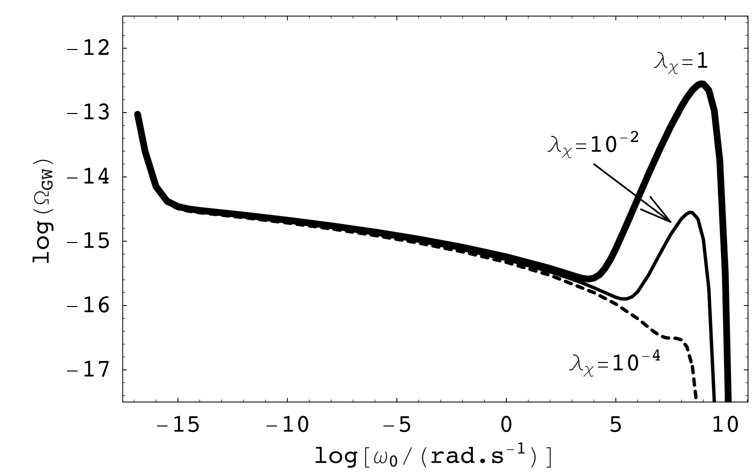
Non-standard equation of state after inflation

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



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

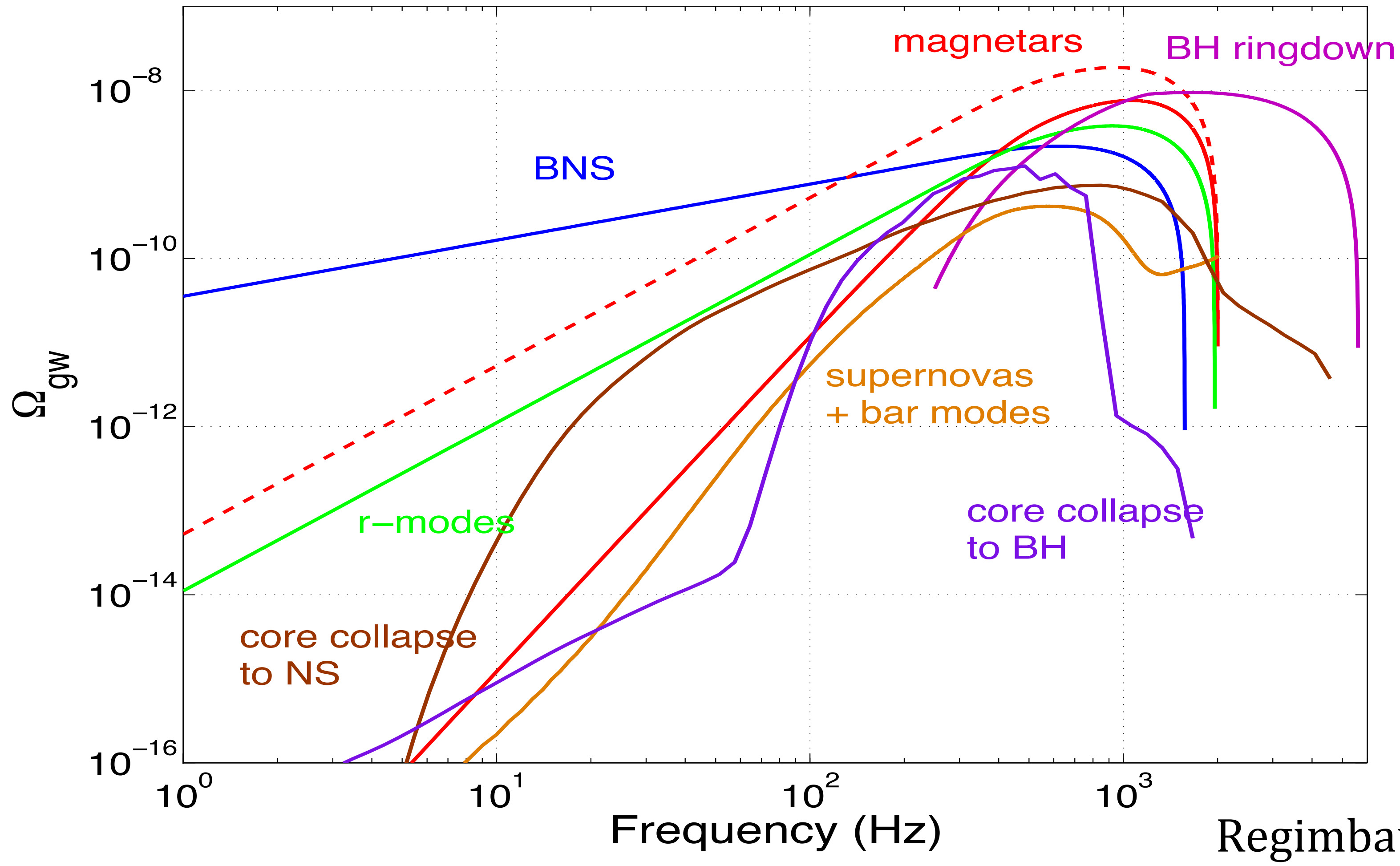
GW production in
(hybrid) quintessential models:
Giovannini ’99; Sa, Henriques ‘10



stiff equation of state during reheating can enhance primordial GW signal

A note of caution...

astrophysical SGWBs



Regimbau, arXiv:1101.2762

LIGO events suggest large astrophysical backgrounds, possibly substractable due to 'popcorn' nature

Conclusion and Outlook

- 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 standard primordial tensor vacuum fluctuations are too small to be detectable with in the near future, but an enhancement by many orders of magnitude is possible in well-motivated models
- If the inflaton is a pseudoscalar, both scalar and tensor spectrum are strongly enhanced towards the end of inflation - at the small frequencies of LISA and LIGO
- The complementarity of CMB and direct GW measurements provides a powerful probe of the physics of cosmic inflation.

Conclusion and Outlook

- 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 standard primordial tensor vacuum fluctuations are too small to be detectable with in the near future, but an enhancement by many orders of magnitude is possible in well-motivated models
- If the inflaton is a pseudoscalar, both scalar and tensor spectrum are strongly enhanced towards the end of inflation - at the small frequencies of LISA and LIGO
- The complementarity of CMB and direct GW measurements provides a powerful probe of the physics of cosmic inflation.

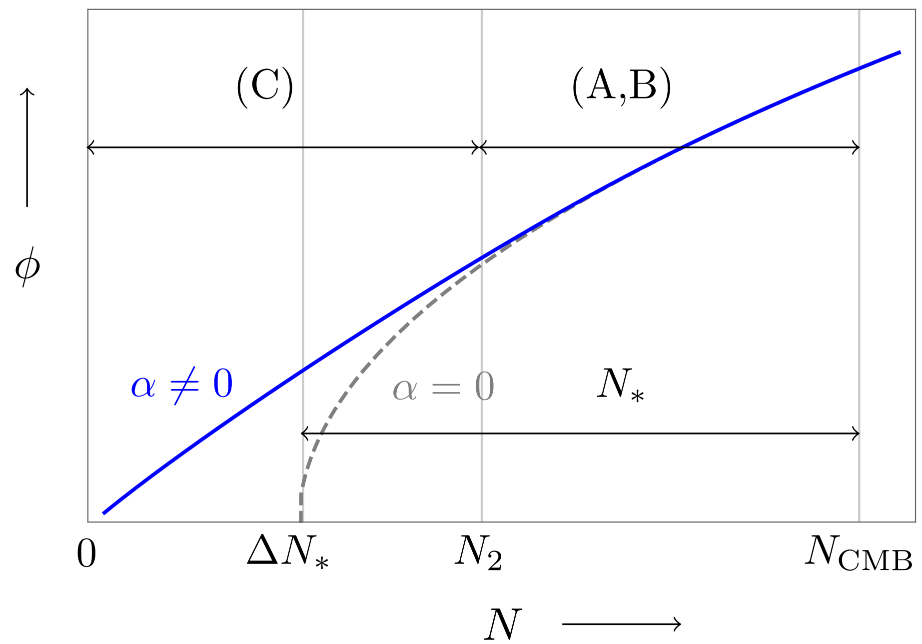
Thank you!

backup slides

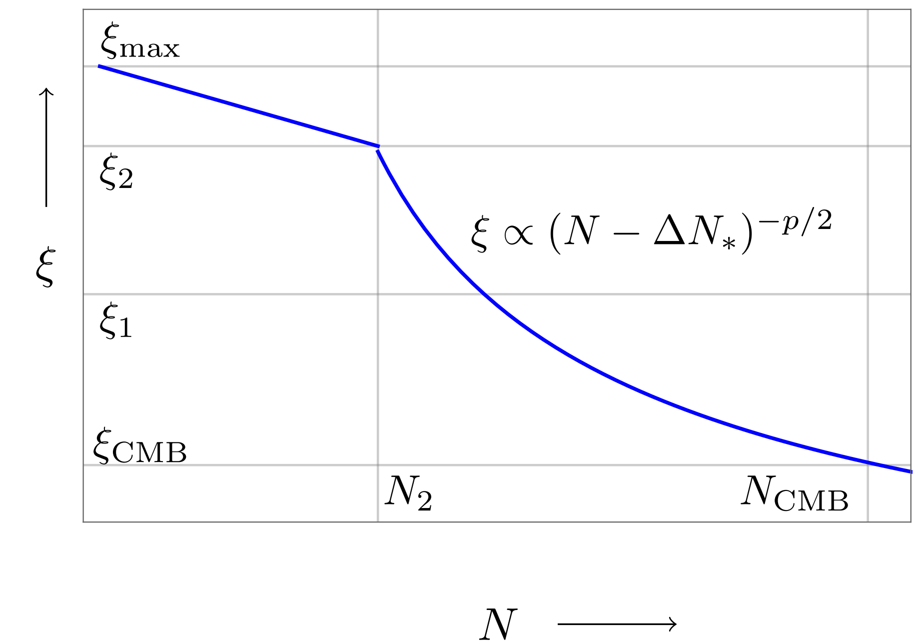
pseudoscalar inflation background dynamics

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



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



- 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

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

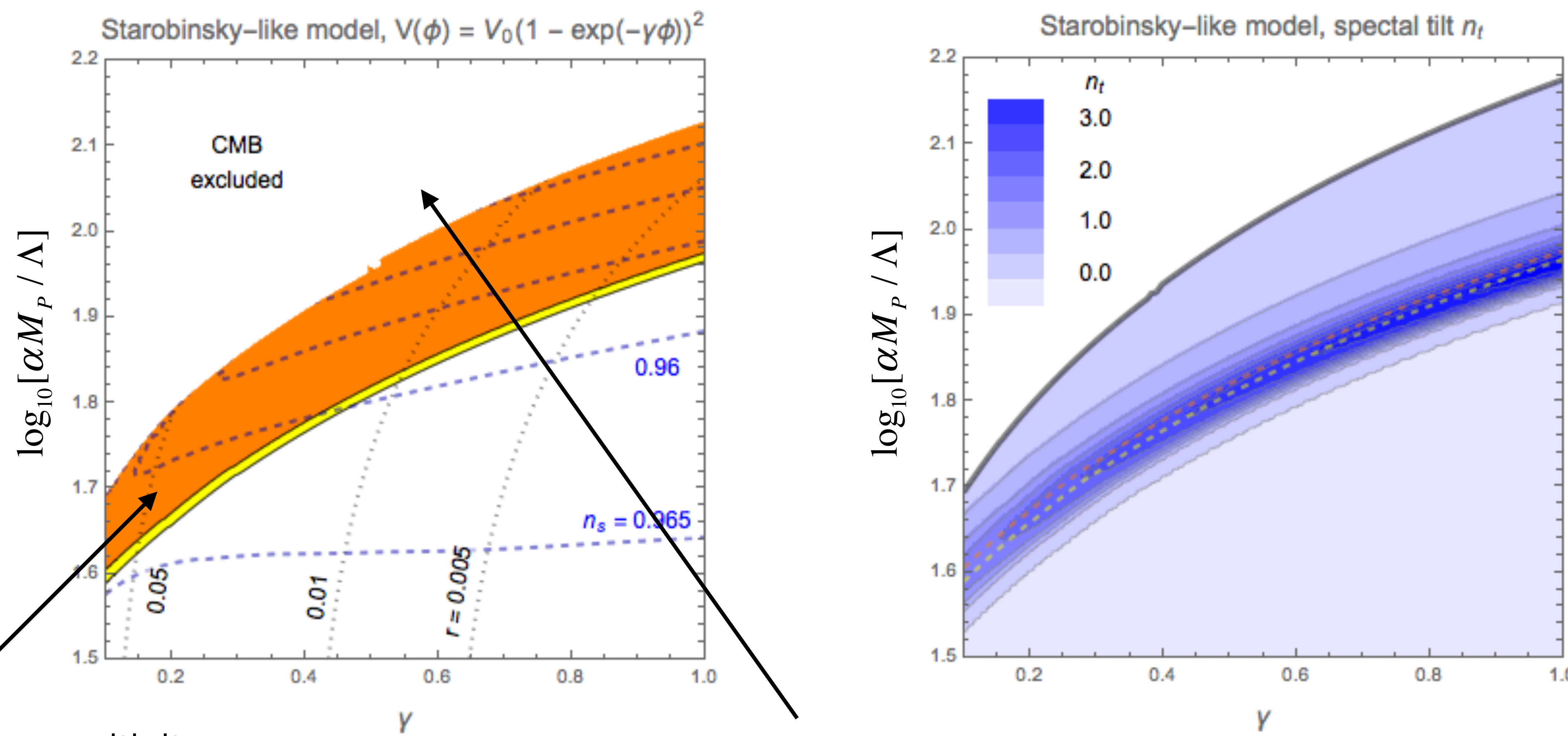
large gauge field effects at the end of inflation, in particular for large p (small r !)

Starobinsky-type model

Binetruy, VD, Pieroni ’16; Figueroa, Ricciardone et al ‘16

$\boxed{\begin{array}{c}\text{3 parameters:}\\ \alpha/\Lambda, \beta, p\end{array}}$

$$V(\phi) = V_0(1 - e^{-\gamma\phi})^2 \quad \dashrightarrow \quad p = 2, \text{ vary } \beta = 1/(2\gamma^2) \text{ and } \alpha$$

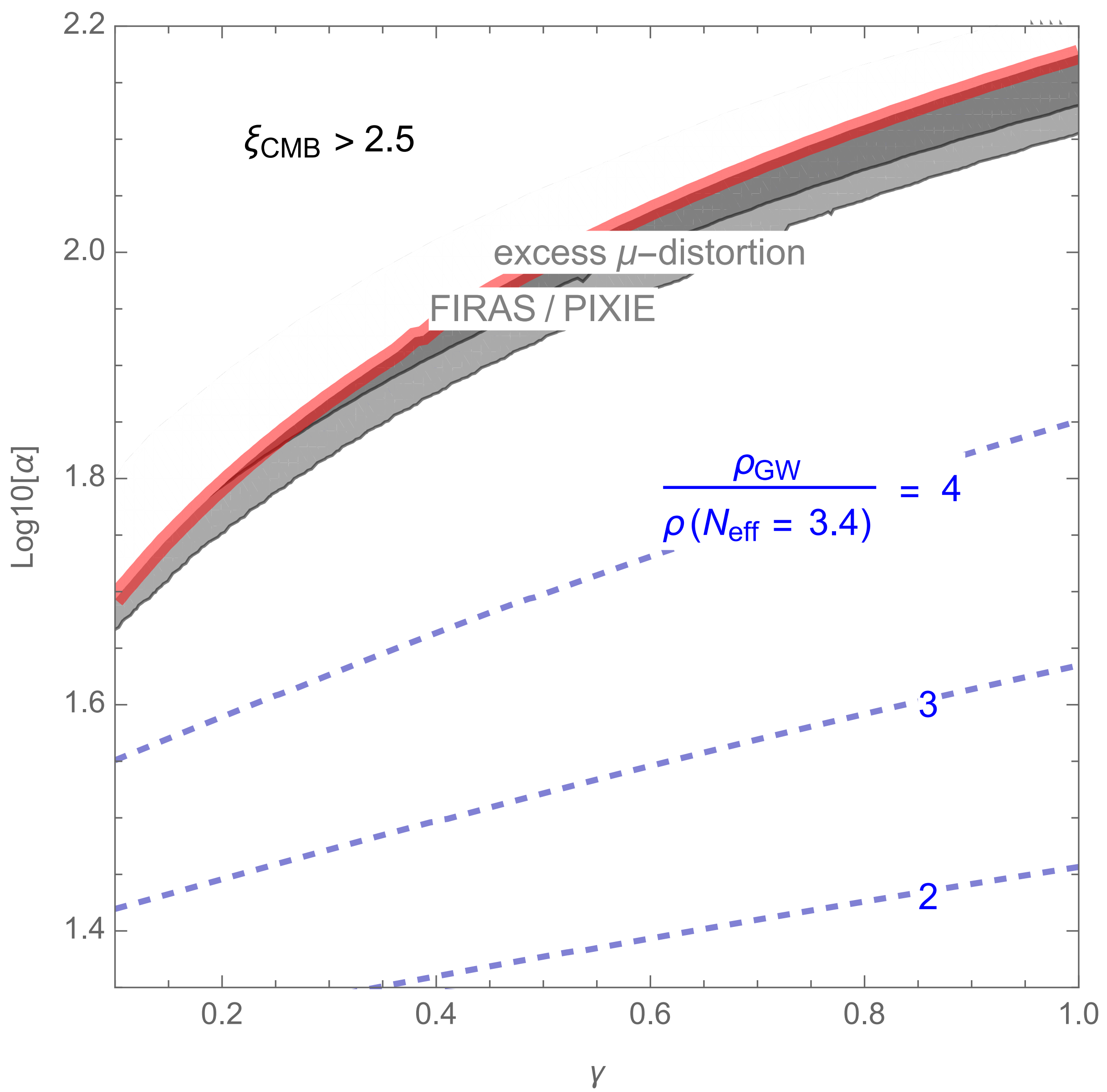


LISA sensitivity

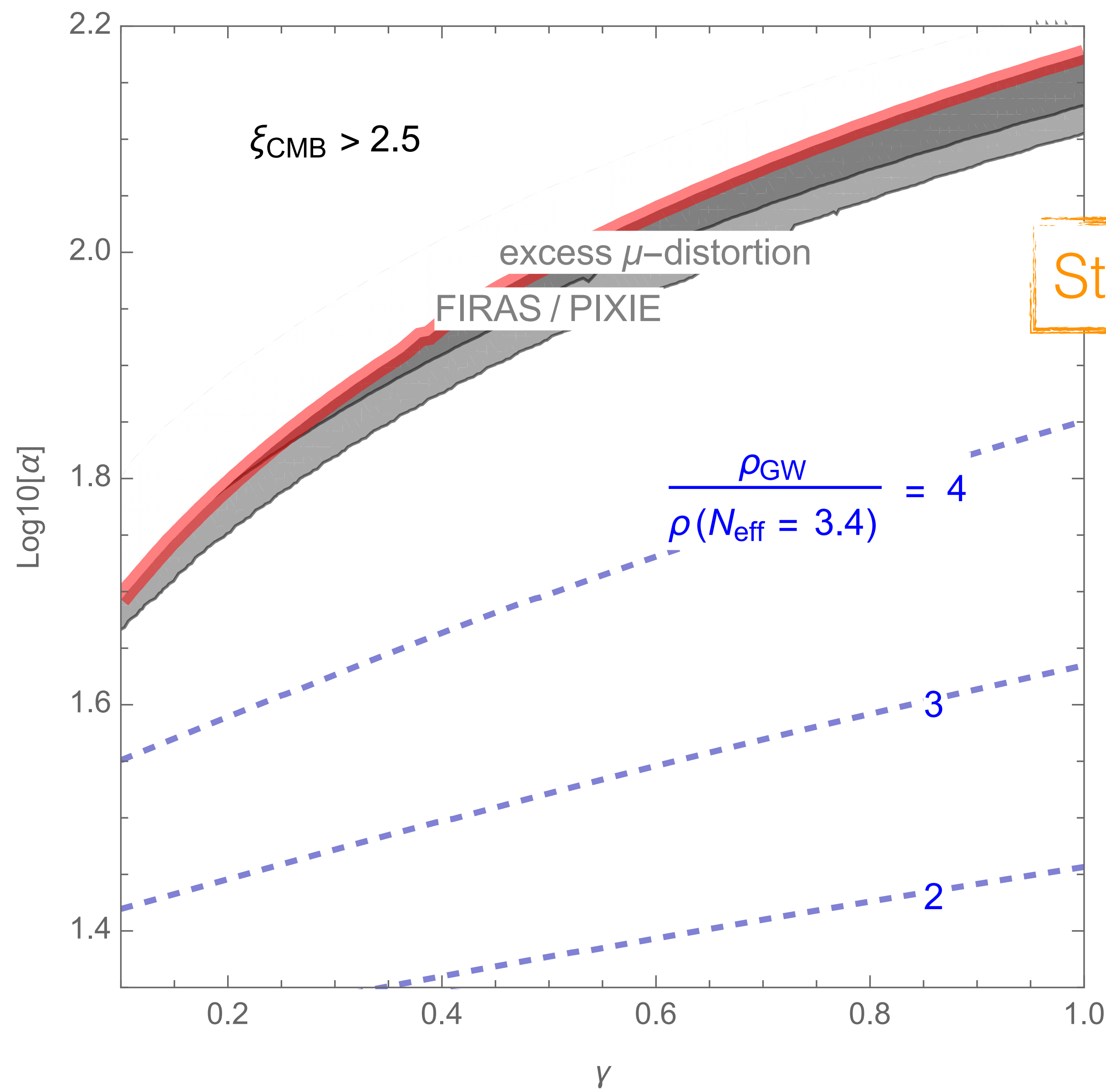
non-gaussianities, mu-distortions (+ LIGO)

complementarily between CMB and direct GW observations

pseudoscalar inflation mu - distortion and N_eff



pseudoscalar inflation
mu - distortion and N_eff



Starobinsky-like model

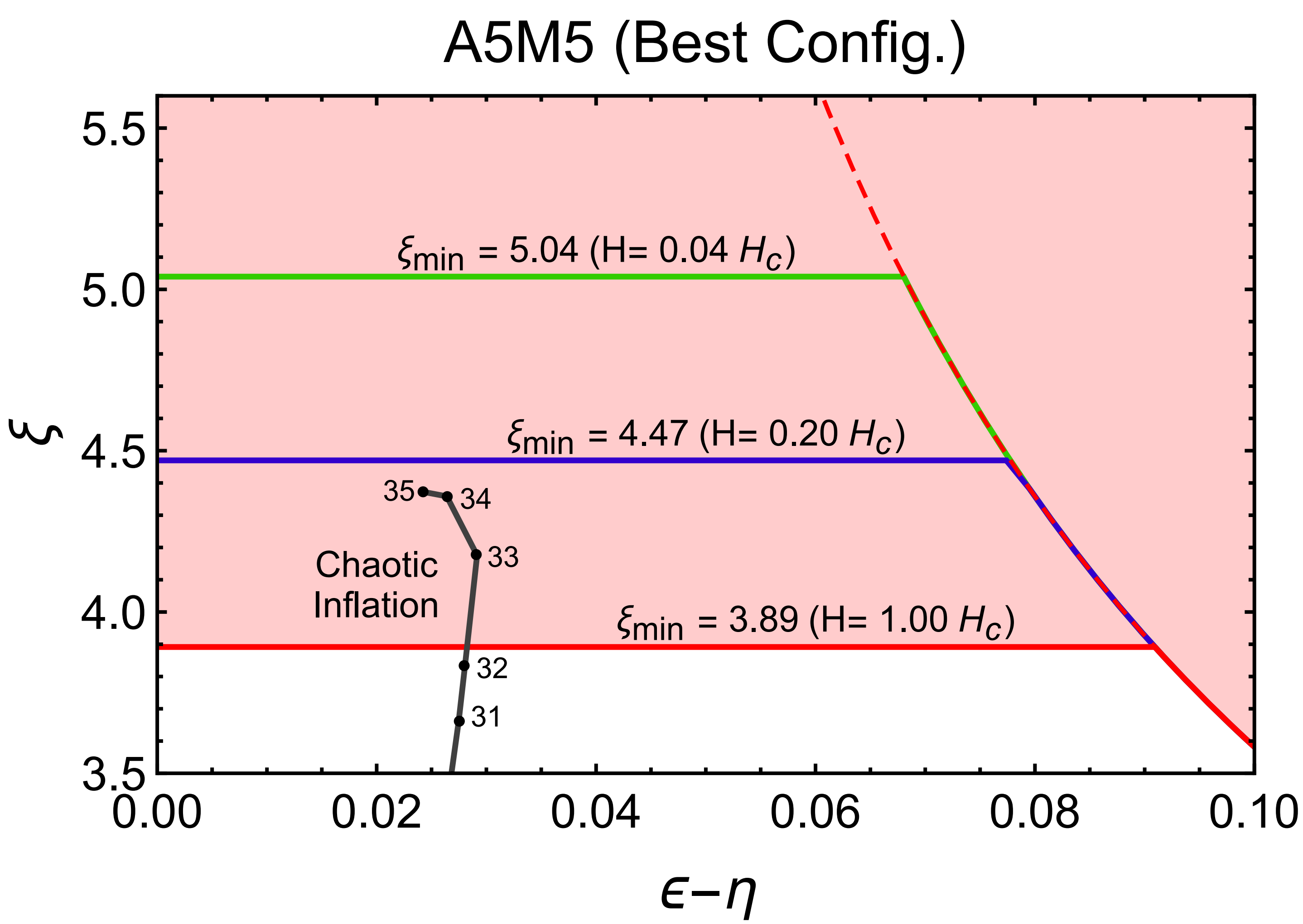
model independent parametrization:

Figueroa, Ricciardone et al '16

local parametrization: $$\Omega_{\rm GW} h^2 \propto \left(\frac{f}{f_*}\right)^n_t, \quad \epsilon_H = -\frac{\dot{H}}{H^2}, \quad \eta = -\frac{\ddot{\phi}}{H\dot{\phi}}:$$

$$\rightarrow \quad \Omega_{\rm GW} h^2 \simeq 1.5 \cdot 10^{-13} \frac{H^4}{M_P^4} \frac{e^{4\pi\xi}}{\xi^6}, \quad n_t \simeq (4\pi\xi - 6)(\epsilon_H - \eta)$$

3 parameters: $H, \xi, \epsilon_H - \eta$



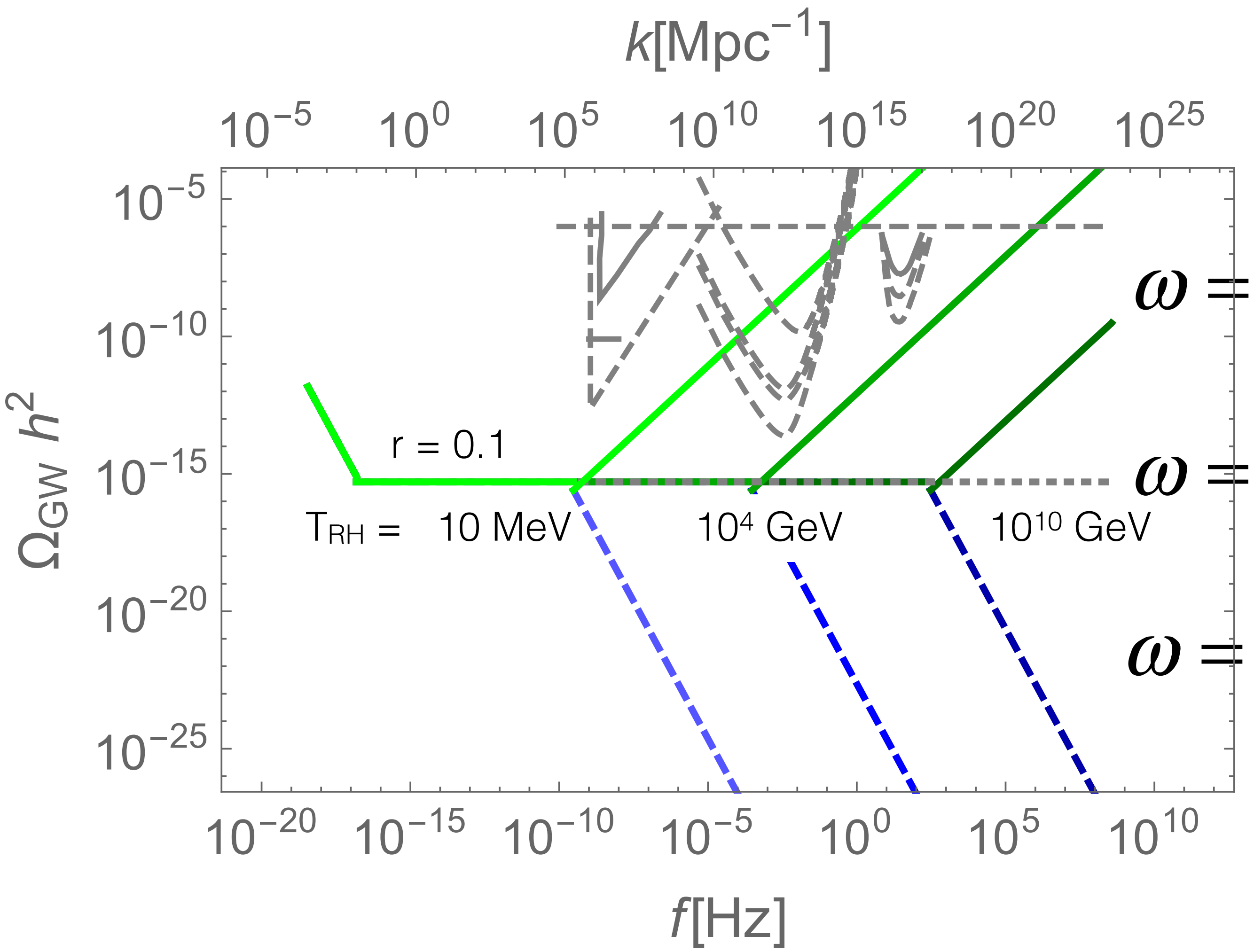
Significant part of parameter space can be probed

Amplitude and spectral tilt could determine 2 out of 3 parameters

Tensor non-gaussianites: consistency relation

non-standard equation of state after inflation

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



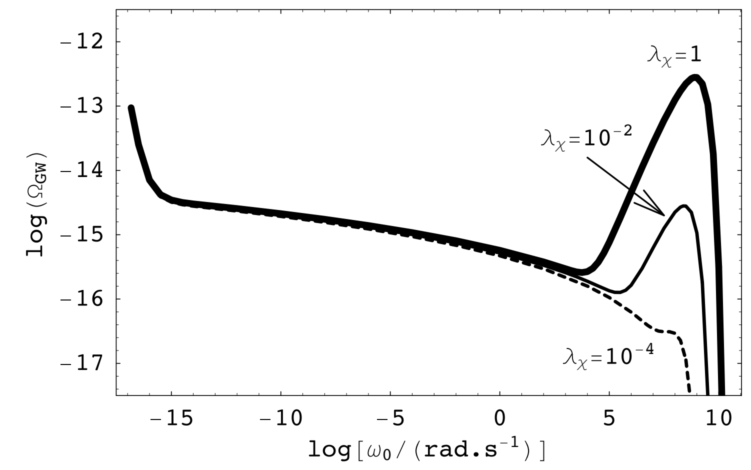
$\omega = 1$ kinetic energy

$\omega = 1/3$ 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

second order GW production

Large scalar perturbations re-entering the horizon after inflation

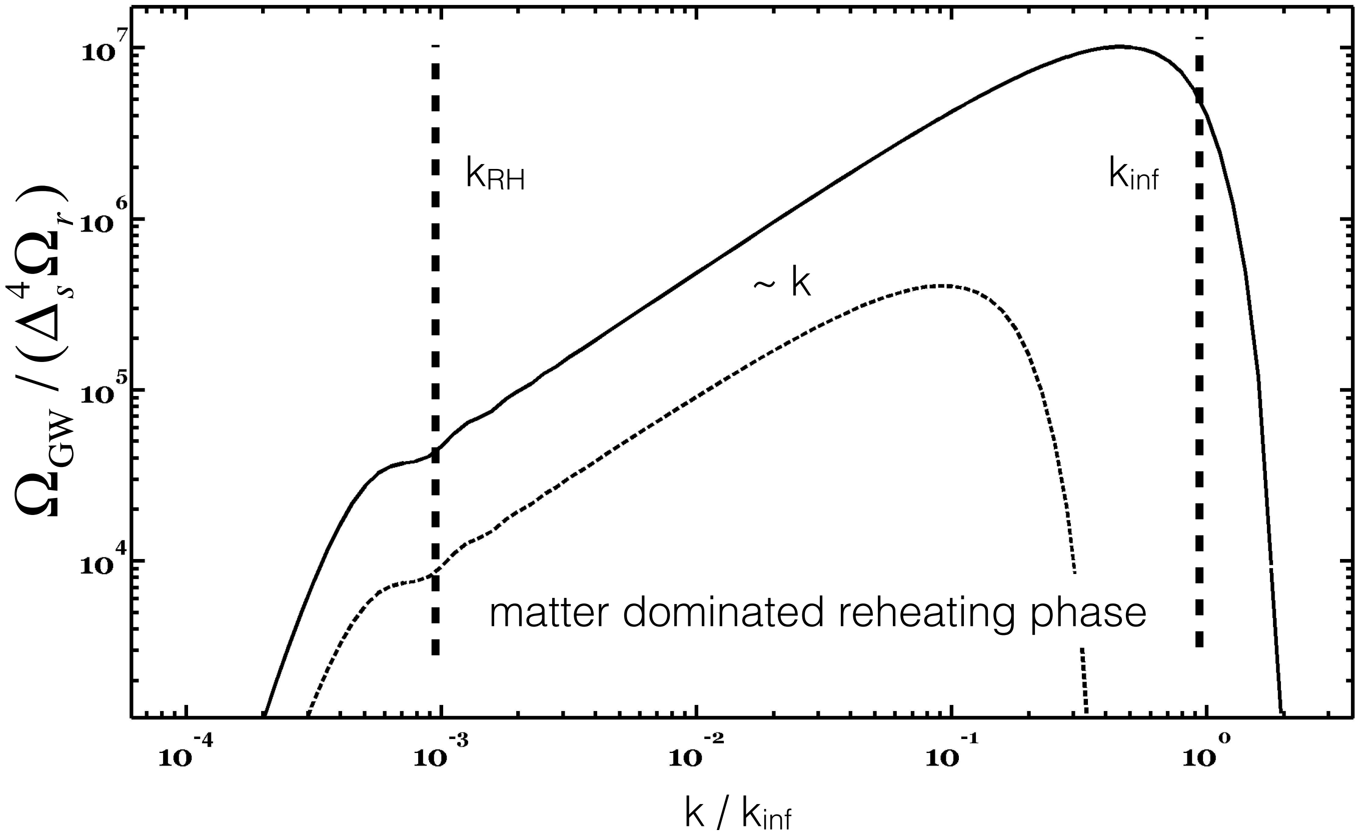
Tomita '67, ……

Assadulahi, Wands '09

grow in a matter-dominated reheating phase

source second order tensor perturbations

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



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

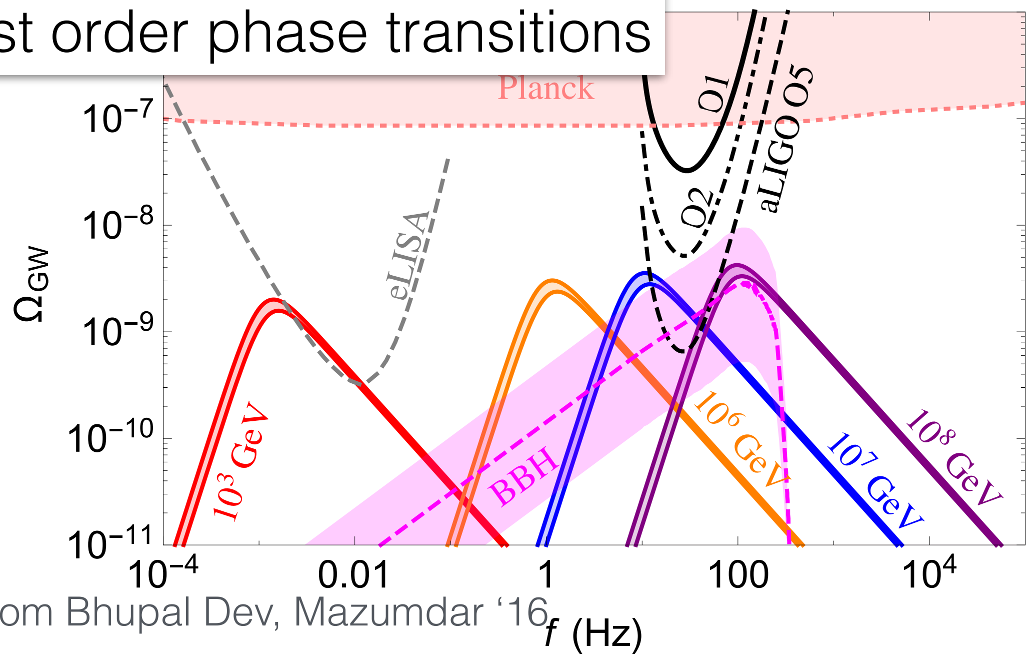
$$(\Delta_s^2)_{\text{small scales}} \gg (\Delta_s^2)_{\text{CMB}}$$

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.

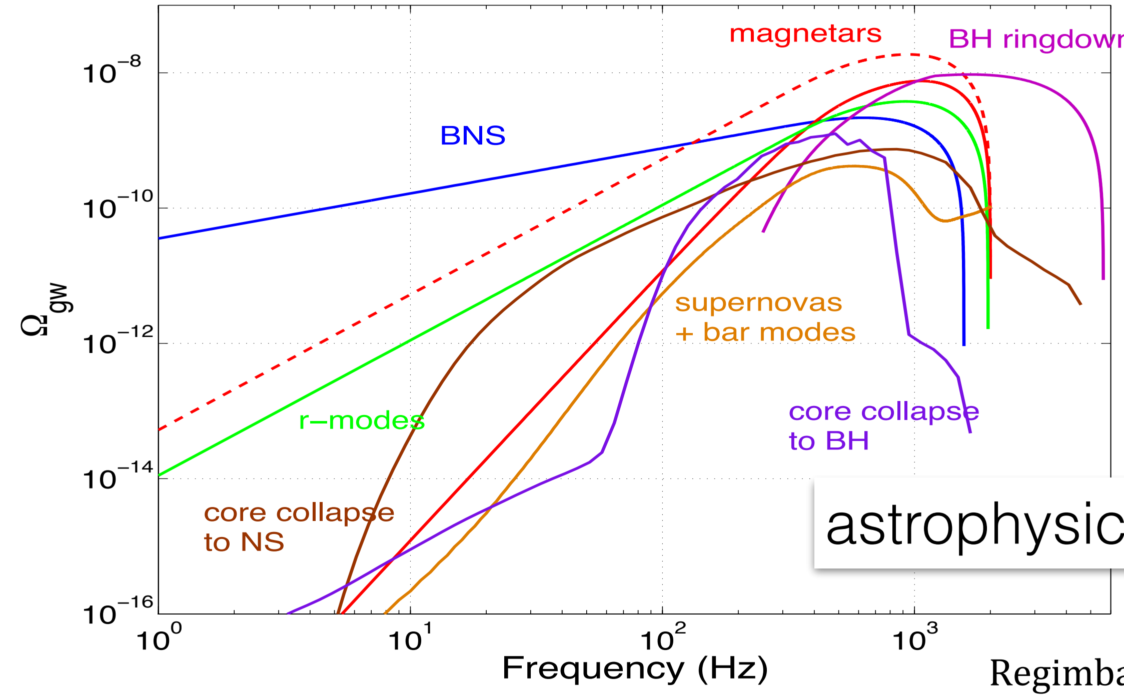
primordial scalar fluctuations can source gravitational waves after inflation

Other (cosmological) sources

first order phase transitions

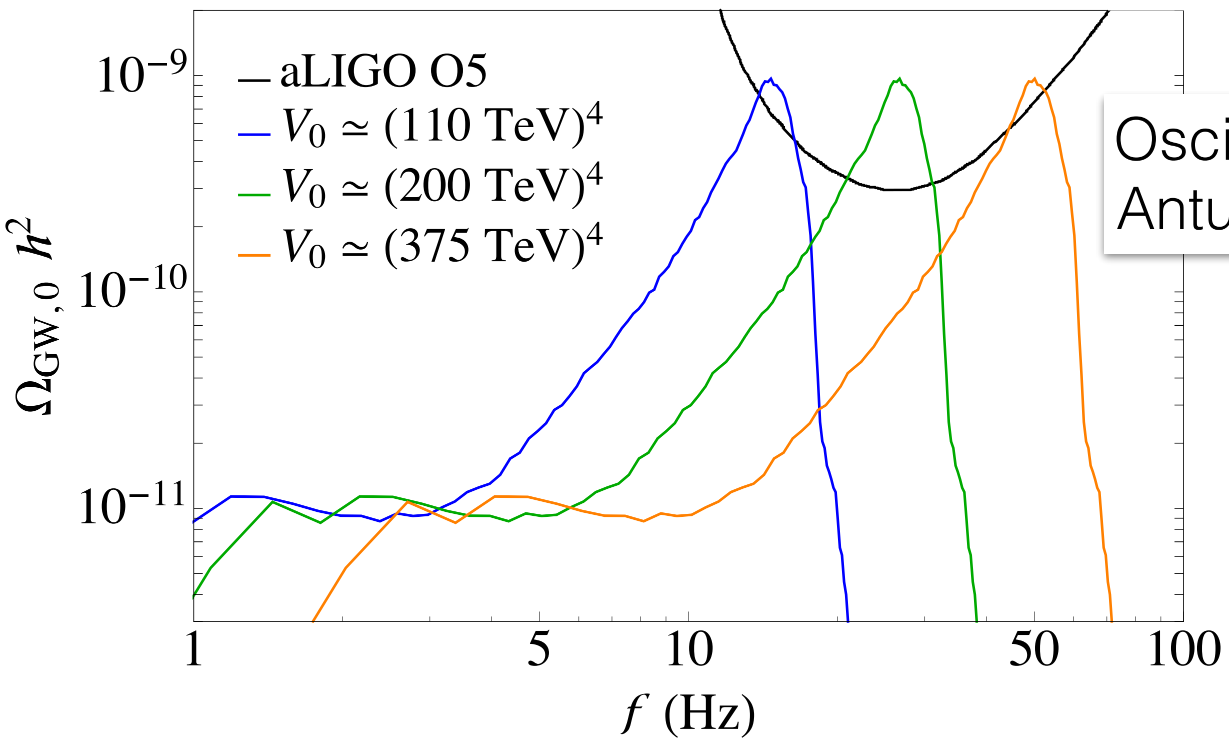


plot from Bhupal Dev, Mazumdar '16



astrophysical SGWBs

Regimbau, arXiv:1101.2762



Oscillons
Antusch, Orani, Cefala '16

Cosmic strings, preheating, ….