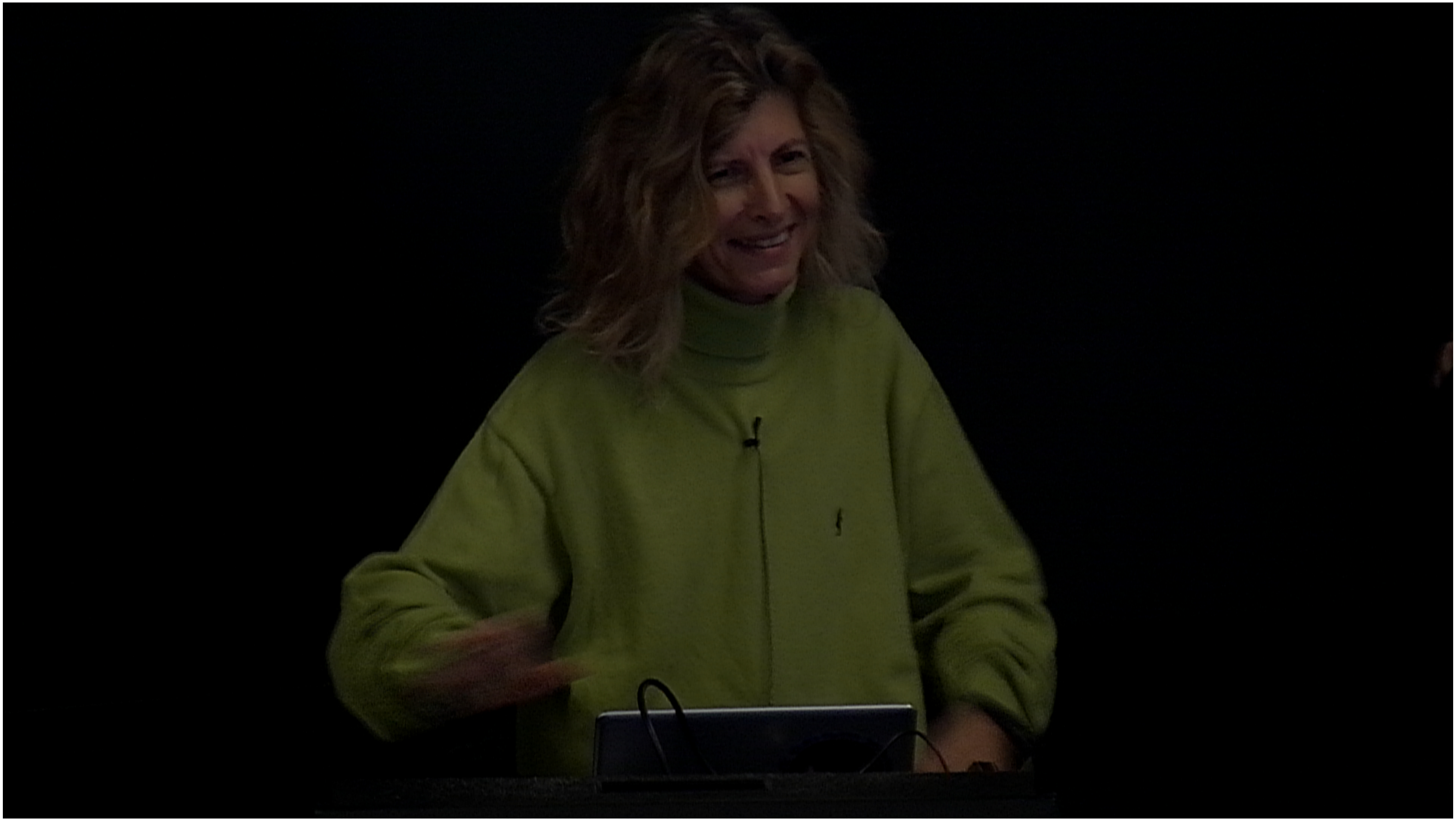
Title: Probing inflation with the space-based interferometer LISA

Date: Nov 29, 2016 11:00 AM

URL: http://pirsa.org/16110091

Abstract: <p class="gmailmsg">I will discuss the potential for the LISA space-based interferometer to detect the stochastic Gravitational Wave (GW) background produced from different mechanisms during inflation. In particular, I will present the GW contributions from particle production during inflation, inflationary spectator fields with varying speed of sound, effective field theories of inflation with specific patterns of symmetry breaking and models leading to the formation of primordial black holes. I will show that LISA is able to probe these inflationary scenarios beyond the irreducible vacuum tensor modes expected from any inflationary background.</p>



probing inflation with the space-based interferometer LISA

arXiv:1610.06481

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outline

- motivation
- GW background from inflation
- LISA sensitivity to a stochastic GW background
- particle production during inflation
- GW from inflationary spectator fields
- GW in the framework of broken spatial reparametrisations
- GW stochastic background from merging primordial black holes
- conclusions

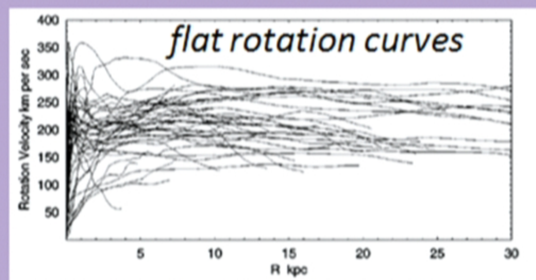
current cosmological model: **ΛCDM model**

- classical GR on a FLRW metric with $\Lambda > 0$

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G_{\mathrm{N}} T_{\mu\nu}$$

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\mathrm{d}\vec{x}^2$$

- CDM



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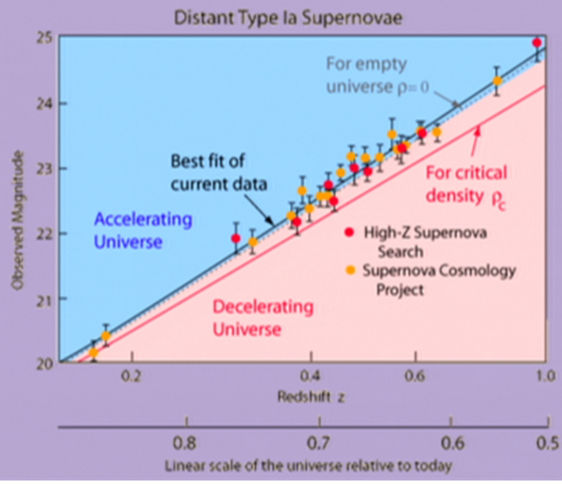
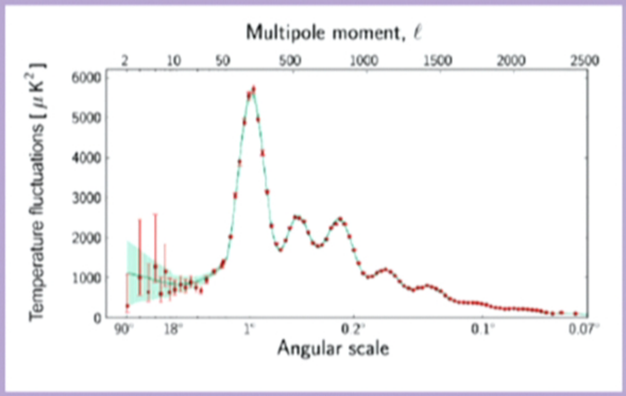
- $\Lambda > 0$

to explain the accelerated expansion of the universe





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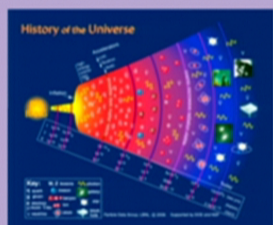
- early inflationary (accelerated expansion) era



$$\rho_{\mathrm{infl}} \simeq (10^{16}\ \mathrm{GeV})^4$$
$$\rho_{\mathrm{LHC}} \simeq (100\ \mathrm{GeV})^4$$
$$\rho_{\mathrm{now}} \simeq 10^{-47}\ (\mathrm{GeV})^4$$

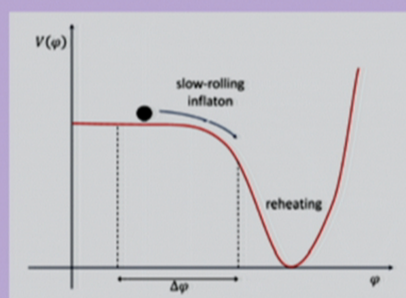
$$\rho = \frac{\dot{\phi}^2}{2} + V(\phi), \quad p = \frac{\dot{\phi}^2}{2} - V(\phi) \quad \Rightarrow \quad p \simeq -\rho$$

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + 3H(\rho + p) = 0 \simeq \frac{\mathrm{d}\rho}{\mathrm{d}t}$$

$$\Longrightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_{\mathrm{Pl}}^2}$$

inflation: the hubble parameter is almost constant

$$a(t) \sim \mathrm{e}^{Ht}$$



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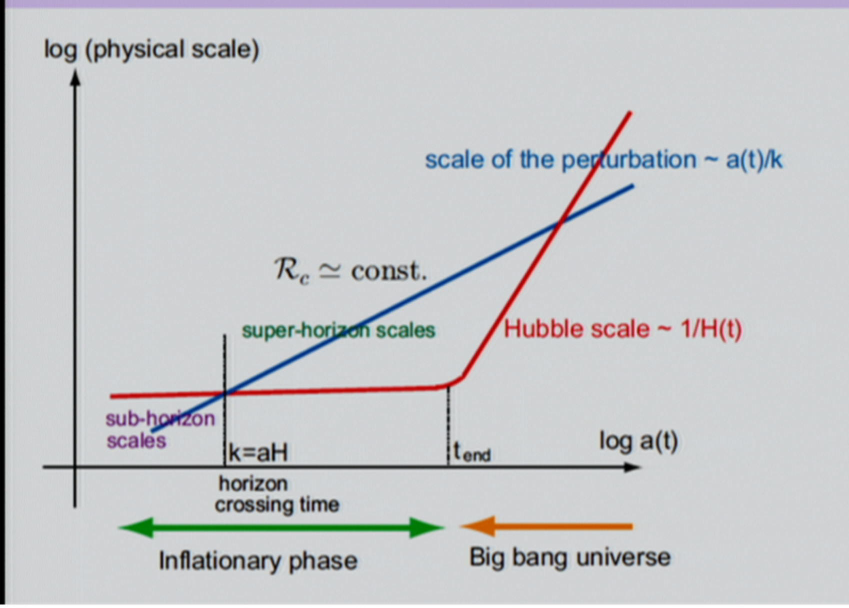
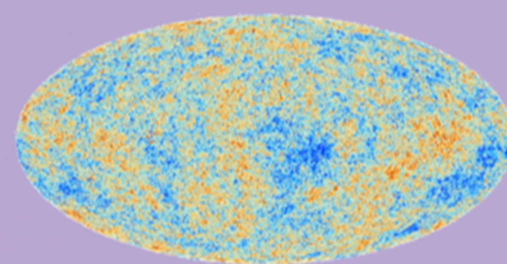
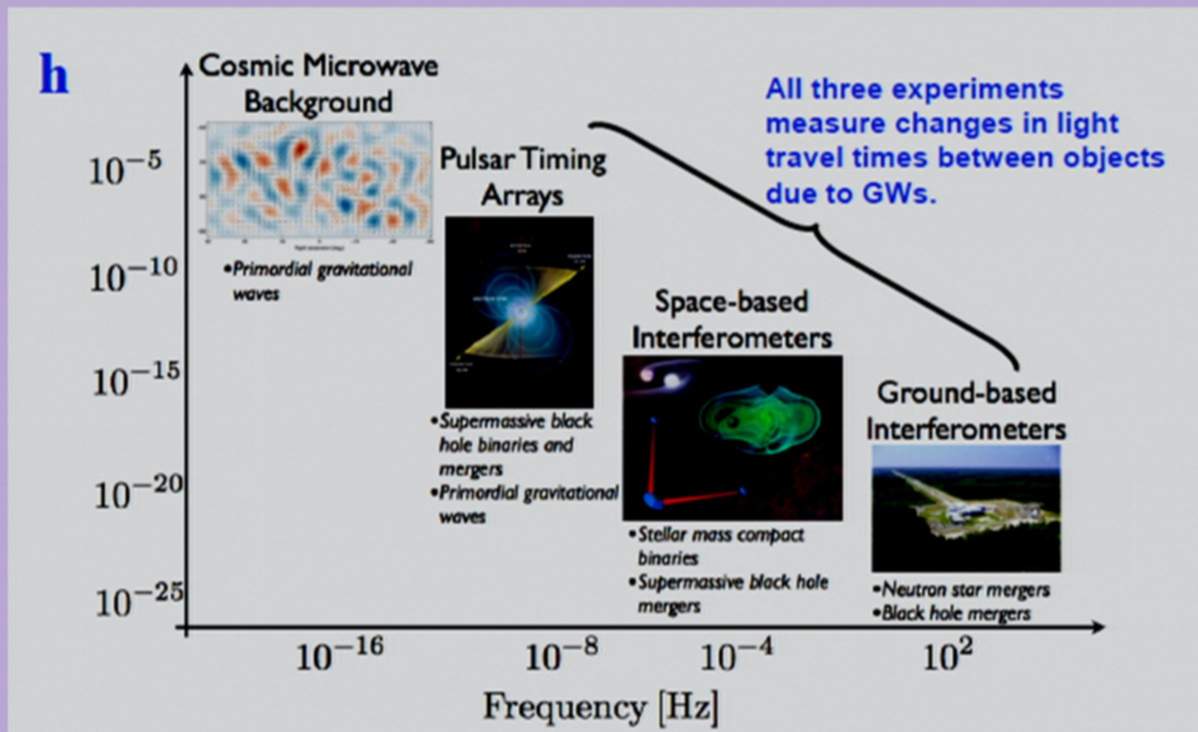


quantum fluctuations of the inflaton field as seeds of the measured CMB temperature anisotropies and the observed large scale structures



gravitational wave physics experiments



credit: x. siemens and NANOGrav collaboration tensor perturbation h_{ij} of FLRW background

$$ds^2 = -dt^2 + a^2(t)\,(\delta_{ij} + h_{ij})\,dx^i dx^j$$

transverse $\partial_i h^i_j = 0$ *traceless* $h^i_i = 0$ → *2 polarisations of GW*

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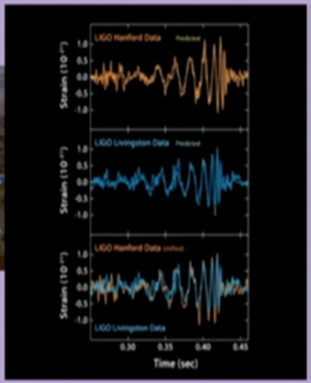
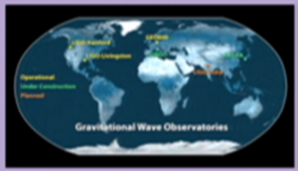
aLIGO, prl 116.241103



→ **a new window for exploring late and early stages of our universe**

advanced VIRGO

KAGRA



LIGO-india

einstein telescope (ET)

tensor perturbation h_{ij} of FLRW background

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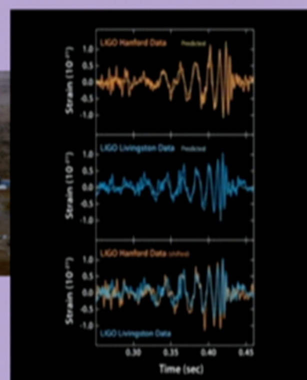
transverse $\partial_i h^i_j = 0$ *traceless* $h^i_i = 0$ ➡ *2 polarisations of GW*



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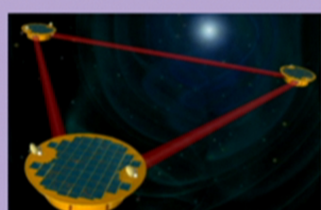
➡ **a new window for exploring late and early stages of our universe**



laser interferometer space antenna (LISA)

with the potential to detect, not only astrophysical sources, but also cosmological ones

e.g., GW background from EW phase transitions lies precisely in the LISA frequency window $f \sim (10^{-5} - 0.1)\ \mathrm{Hz}$

GW background from inflation

the irreducible background of GW from inflation

GW are generated by amplification of vacuum metric fluctuations

the irreducible background of GW from inflation

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scalar field minimally coupled to gravity

$$S=\int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}M_{\mathrm{pl}}^2R-\frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi-V(\varphi)\right]$$

perturbing at first order

action for tensor perturbations

$$S_{\mathrm{T}}^{(2)}=\frac{M_{\mathrm{pl}}^2}{8}\int \mathrm{d}^4x\,a^2(t)\left[\dot{h}_{ij}\dot{h}_{ij}-\frac{1}{a^2}\left(\nabla h_{ij}\right)^2\right]$$

varying w.r.t. h_{ij}
(symmetric, transverse and trace-free)

equation of motion

$$\nabla^2 h_{ij}-a^2\ddot{h}_{ij}-3a\dot{a}\dot{h}_{ij}=0$$

with solution

$$h_{ij}(\mathbf{x},t)=\sum_{\lambda=(+,\times)}h^{(\lambda)}(t)\,e_{ij}^{(\lambda)}(\mathbf{x})$$

the irreducible background of GW from inflation

GW are generated by amplification of vacuum metric fluctuations

parametrise the tensor power spectrum, as

$$P_{\rm T}(k) = A_{\rm T}\left(\frac{k}{k_*}\right)^{n_{\rm T}}$$

assuming no running of the tensor spectral index

null energy condition: $\rho + p \geq 0$ → $\dot{H} < 0$

$$\dot{H} = -4\pi G(\rho + p)$$

$$\epsilon \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V_\varphi}{V}\right)^2 = -\frac{\dot{H}}{H^2}$$

$n_{\rm T} < 0$

red tensor spectral index

almost scale-invariant

→ all GW produced, nearly frozen on super-horizon scales, have all the same amplitude

→ *the power spectrum* $P_{\rm T}(k) = \frac{k^3}{2\pi^2}\sum_\lambda \left|h_{\rm k}^{(\lambda)}\right|^2$ *on super-horizon scales is:*

$$P_{\rm T}(k) = \frac{8}{M_{\rm pl}^2}\left(\frac{H}{2\pi}\right)^2\left(\frac{k}{aH}\right)^{-2\epsilon}$$

the irreducible background of GW from inflation

GW are generated by amplification of vacuum metric fluctuations

$$\rho_{\rm gw} = \frac{1}{32\pi G a^2}\langle h'_{ij}(\mathbf{x},\tau)\, h'^{ij}(\mathbf{x},\tau)\rangle$$

$$\rho_c \equiv 3H^2/8\pi G$$

$$\Omega_{\rm GW}(k,\tau) \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm gw}}{{\rm d}\ln k}$$

$$n_{\rm T} < 0$$

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the irreducible background of GW from inflation

GW are generated by amplification of vacuum metric fluctuations

amplitude gives information about hubble parameter during inflation

standard single-field slow-roll inflation:
*almost **scale invariant** spectrum of tensor fluctuations, slightly **red-tilted***

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\ln f}$$

$$f_{\rm CMB} \sim 10^{-18} - 10^{-17}\ {\rm Hz}$$

amplitude of this irreducible background at frequencies corresponding to CMB scales :

$$h^2\Omega_{\rm GW}^{\rm CMB} \equiv h^2\Omega_{\rm GW}\left(f_{\rm CMB}\right) \approx 5\times10^{-16}\left(\frac{H}{H_{\rm max}}\right)^2$$

H: inflationary hubble rate evaluated at CMB scales

$$H_{\rm max} \approx 8.8\times10^{13}{\rm GeV}$$

GW energy-density spectrum at different frequencies: $\Omega_{\rm GW}(f) = \Omega_{\rm GW}^{CMB}\left(\frac{f}{f_{CMB}}\right)^{n_T}$

standard single-field slow-roll inflation: $n_T = -r/8$ *consistency relation* $r \equiv A_T/A_S$

$n_T < 0$ with $|n_T| \ll 1$ as current bounds from CMB indicate $r \lesssim 0.1$

the irreducible background of GW from inflation

important information about the early universe

precise imprint on CMB, resulting in a specific polarisation pattern of B-modes

BICEP

KECK

ACTPol

POLARBEAR

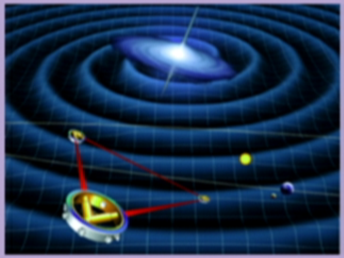
beyond the irreducible background of GW from inflation

the details of GWs produced during inflation change completely if any of the three happens:

- **additional d.o.f.** (besides the inflaton) are present during inflation
- **new symmetry** patterns in the inflationary sector
- large peaks in the inflationary scalar spectrum collapse into **PBH** after horizon re-entry

the obtained GW background can overtake the irreducible GW signal due to quantum fluctuations, leading to **a GW spectrum** that can be **large** and **blue-tilted**, or exhibit **a large amplitude-bump** at specific scales

attractive target for the upcoming first space-based GW observer, LISA



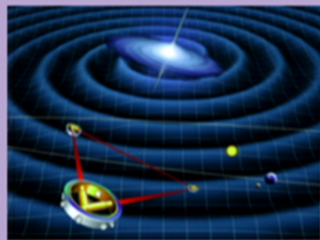
focus on the following (well-motivated) scenarios:

- *particle production during inflation*
  - inflaton ϕ sources gauge field via coupling $\phi F^{\mu\nu} \tilde{F}_{\mu\nu}$
  - the gauge field sources population of GWs with **blue spectrum**; this population (contrary to astrophysical backgrounds) has a net **chirality** and is highly **non-gaussian**

- *inflation with spectator fields*
  - amplitude and spectral index of such GW background is specified by sound speed of spectator field(s) and time-variation of the latter
  - the GW is expected to be **blue-tilted**

- *EFT of space-reparametrisation*
  - when space-reparametrisation invariance is broken, the graviton can acquire a mass
  - the tensor spectrum can be **blue** and **enhanced at small scales** due to the specific symmetry breaking patterns by the fields driving inflation

- *primordial black holes (PBHs)*
  - *in some models, large peaks in the power matter spectrum can collapse forming PBHs upon horizon re-entry at RDE*
  - *PBHs are clustered and merge, generating a stochastic background of GWs, probably detectable by LISA*

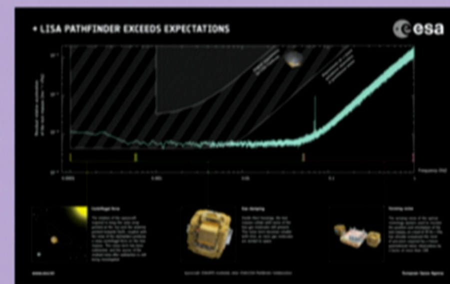


laser interferometer space antenna (LISA)

Name	A5M5	A5M2	A2M5	A2M2	A1M5	A1M2
Arm length [10^6 Km]	5	5	2	2	1	1
Duration [years]	5	2	5	2	5	2

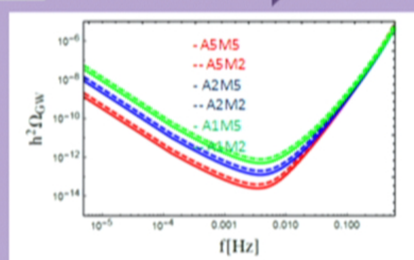
$(0.1\text{mHz} - 1\text{Hz})$

the performance of pathfinder satellite is 5 times better than what was expected, so we use the best low-frequency noise level (N2), and vary length of the arms (A1, A2, A5) and the mission duration (M2, M5)

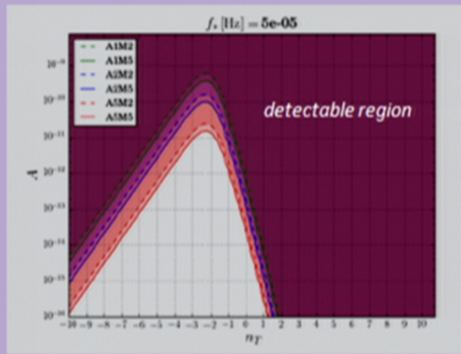


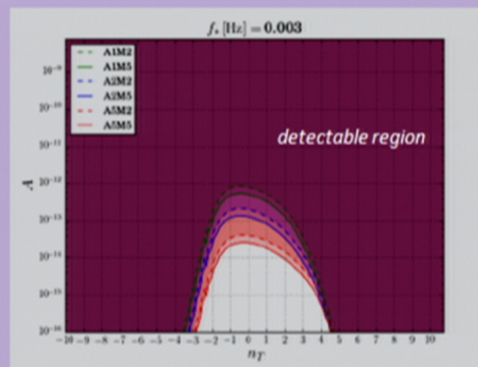
address the potential of several LISA configurations to detect a stochastic background of GW coming from inflation

the best 6-link configuration over 1 year can detect a white noise background at the level of $h^2\Omega_{\rm gw} = 10^{-13}$ → $\mathrm{SNR} = 10$ → ***every signal with $\mathrm{SNR} > 10$ must be visible by a 6-link LISA configuration***

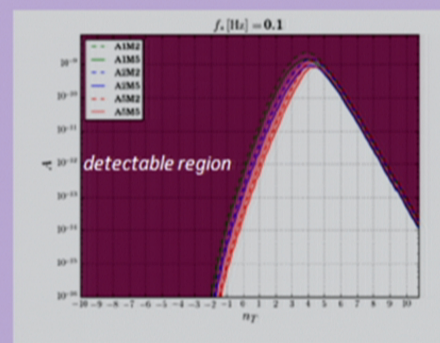


power law sensitivity curves for the 6 configurations *delectability by the 6 LISA configurations of a generic stochastic GW background parametrised by a single power law* $\Omega_{gw} = A(f/f_*)^{n_T}$





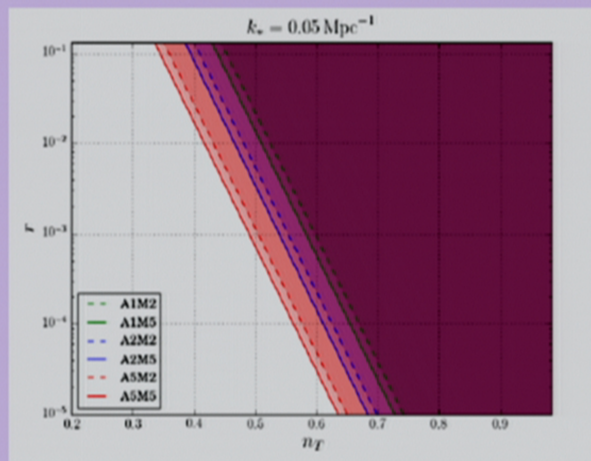
values of the spectral index close to zero are only visible for high enough amplitudes



assuming a power-law spectrum (relaxing the consistency relation) $\Omega_{\rm GW}(f) = \Omega_{\rm GW}^{CMB}\left(\frac{f}{f_{CMB}}\right)^{n_T}$ with arbitrary n_T

~~$n_{\rm T} = -r/8 < 0$~~

$f_* = f_{CMB} = 7.7 \times 10^{-17}$ Hz corresponding to $k_* = 0.05\,{\rm Mpc}^{-1}$



assuming the best LISA configuration A5M5, we can constrain the spectral index up to $n_T \lesssim 0.35$

initial LIGO O1: $n_T < 0.54$ at 95%C.L

⇓

test for deviations of consistency relation

⇒ any evidence of a blue tilt (necessary for a detection at the LISA frequencies) $n_{\rm T} > 0$ would be an indication of a deviation from single-field slow-roll inflation *particle production during inflation*

in general, quantum loops will contribute to the $V_{,\phi}, V_{,\phi\phi}, V_{,\phi\phi\phi}$

radiative corrections can disrupt the inflationary potential in 2 ways:
- affect the functional form of V(ϕ)
- affect the value of the parameters that appear in V(ϕ)

to make the radiative effects under control, one introduces symmetries:
- if a model has a symmetry, quantum effects cannot violate it (unless the symmetry is anomalous)
- if the symmetry is broken, quantum effects cannot make the breaking much larger (i.e., the breaking parameter is controllably small)

radiative stability of a scalar potential through shift symmetry: $\phi \to \phi + \phi_0$

constant

axionic coupling of inflaton (pseudo-scalar) ϕ to a U(1) gauge field

$$\Delta\mathcal{L} = -\frac{1}{4\,f}\,\phi\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}$$

1/f: coupling constant with dim of a length

generated in large class of inflationary models, leading to rich phenomenology e.o.m. of the $\pm$ 1-helicity modes $A_\pm(\mathbf{k}, \tau)$ of the gauge field in the presence of a time-dependent inflaton $\phi(t)$:

$$\frac{d^2 A_\pm(\mathbf{k}, \tau)}{d\tau^2} + \left[k^2 \pm 2\,\xi\,\frac{k}{\tau}\right] A_\pm(\mathbf{k}, \tau) = 0 \qquad \xi \equiv \frac{\dot\phi}{2\,f\,H}$$

for long wavelengths $-k\tau < 2\xi$ *only one of the two helicity modes (*A_+*) is exponentially amplified by* $\sim e^{\pi\xi}$ *for* $\xi \gtrsim \mathcal{O}(1)$

$\xi > 0$ ⇒ only positive helicity photons are amplified

reminiscent of parity-violating nature of operator $-\frac{1}{4f}\phi F_{\mu\nu}\tilde F^{\mu\nu}$ *in the presence of* $\dot\phi \neq 0$

A_+ source of scalar perturbations and of gravitational waves with non-gaussian statistics

$A + A \to \delta\phi$ $\qquad$ $A + A \to \delta g$

bispectrum of sourced scalar perturbations has an approximate equilateral shape

$$f_{NL}^{\rm equil} \simeq 7.1 \times 10^5\, \frac{H^6}{|\dot\phi|^3}\, \frac{e^{6\pi\xi}}{\xi^9}$$

⇓

the non-observation of scalar non-gaussianities by planck at cosmological scales (f $\sim 10^{-17}$ Hz***) implies a strong constraint*** $\xi \lesssim 2.5$ at 95% C.L. ***at those scales***

- for such small values of ξ the sourced GW are weak and unobservable
- but ξ is time-dependent so that it could grow to large values later ; ξ will increase for shorter scales (since $|\dot\phi|$ increases, H decreases at end of inflation)

study detectability of these GW by LISA

power spectrum of GW

for $\xi \gtrsim \mathcal{O}(1)$

$$P_{GW}(k) \equiv \frac{k^3}{2\pi^2}\sum_{i=\pm}|h_i(k)|^2$$
$$= P_{GW,vacuum}(k) + P_{GW,sourced}(k)$$
$$\simeq \frac{2H^2}{\pi^2 M_{Pl}^2} + 8.7\times10^{-8}\frac{H^4}{M_{Pl}^4}\frac{e^{4\pi\xi}}{\xi^6}.$$

$$\xi \equiv \frac{\dot{\phi}}{2fH}$$

$$\Omega_{GW}h^2 = \frac{\Omega_{R,0}h^2}{24}P_{GW}$$

statistically uncorrelated, so that there is no interference

power spectrum of GW

for $\xi \gtrsim \mathcal{O}(1)$

$$P_{\rm GW}(k) \equiv \frac{k^3}{2\pi^2}\sum_{i=\pm}|h_i(k)|^2 = P_{\rm GW,vacuum}(k) + P_{\rm GW,sourced}(k) \simeq \frac{2H^2}{\pi^2 M_{Pl}^2} + 8.7\times10^{-8}\frac{H^4}{M_{Pl}^4}\frac{e^{4\pi\xi}}{\xi^6}.$$

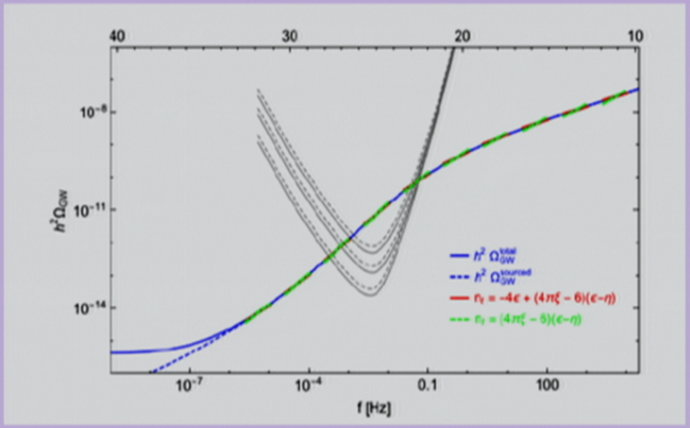
$$\xi \equiv \frac{\dot\phi}{2fH}$$

$$\Omega_{\rm GW}h^2 = \frac{\Omega_{R,0}h^2}{24}P_{\rm GW}$$

- large scales (f small) $f \lesssim 10^{-5}$ Hz :
  standard contribution from amplification of vacuum fluctuations of graviton dominates

- intermediate scales 10^{-5} Hz $\lesssim f \lesssim 1$:
  sourced GW dominate, but slow-roll equations determine time-dependence of ϕ and H

- smaller scales ($f \gtrsim 1$ Hz): $f = k/(2\pi)$
  flattening of $\Omega_{\rm GW}h^2$ as a function of frequency



power spectrum of GW

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$$\xi \equiv \frac{\dot\phi}{2fH}$$

additional distinctive properties of stochastic GW background:

- parity violation

difference in amplitude between spectra of left- and right-handed GW

$$P^{+}_{\rm GW,sourced} \simeq 8.7\times 10^{-8}\frac{H^4}{M_{Pl}^4}\frac{e^{4\pi\xi}}{\xi^6}, \qquad P^{-}_{\rm GW,sourced} \simeq 1.8\times 10^{-10}\frac{H^4}{M_{Pl}^4}\frac{e^{4\pi\xi}}{\xi^6}$$

→ **highly chiral stochastic GW background**

- non-gaussian statistics

$$k^6\langle \hat h_+(\mathbf{k}_1)\,\hat h_+(\mathbf{k}_2)\,\hat h_+(\mathbf{k}_3)\rangle_{\rm equil} \simeq 23 P_{\rm GW}^{3/2}$$

<u>power spectrum of GW</u>

$\xi \equiv \frac{\dot{\phi}}{2 f H}$

at large ξ the sourced GW dominate over vacuum ➡ $\Omega_{\rm GW} h^2 \simeq 1.5 \times 10^{-13} \frac{H^4}{M_{Pl}^4} \frac{e^{4\pi\xi}}{\xi^6} \quad , \quad \xi \gg 1$

relation between frequency and e-folds: $N \simeq 19.7 - \ln\left(\frac{f}{\rm Hz}\right) + \ln\left(\frac{H_N}{H_{60}}\right)$

power spectrum of GW

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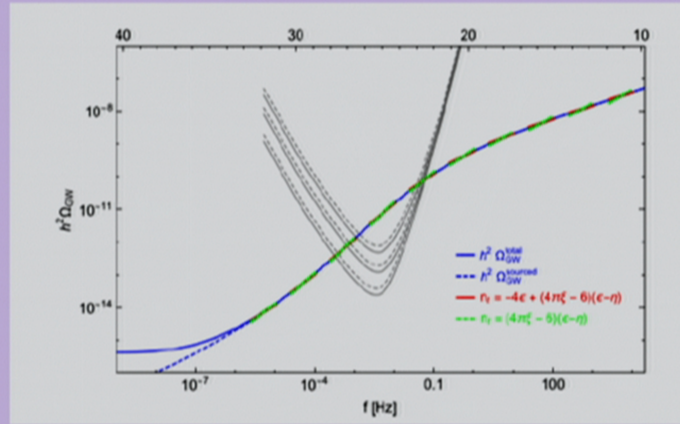


$\xi \equiv \frac{\dot{\phi}}{2 f H}$

at large ξ the sourced GW dominate over vacuum $\Rightarrow$ $\Omega_{\rm GW} h^2 \simeq 1.5 \times 10^{-13} \frac{H^4}{M_{Pl}^4} \frac{e^{4\pi\xi}}{\xi^6} \quad , \quad \xi \gg 1$

relation between frequency and e-folds: $N \simeq 19.7 - \ln\left(\frac{f}{\rm Hz}\right) + \ln\left(\frac{H_N}{H_{60}}\right)$

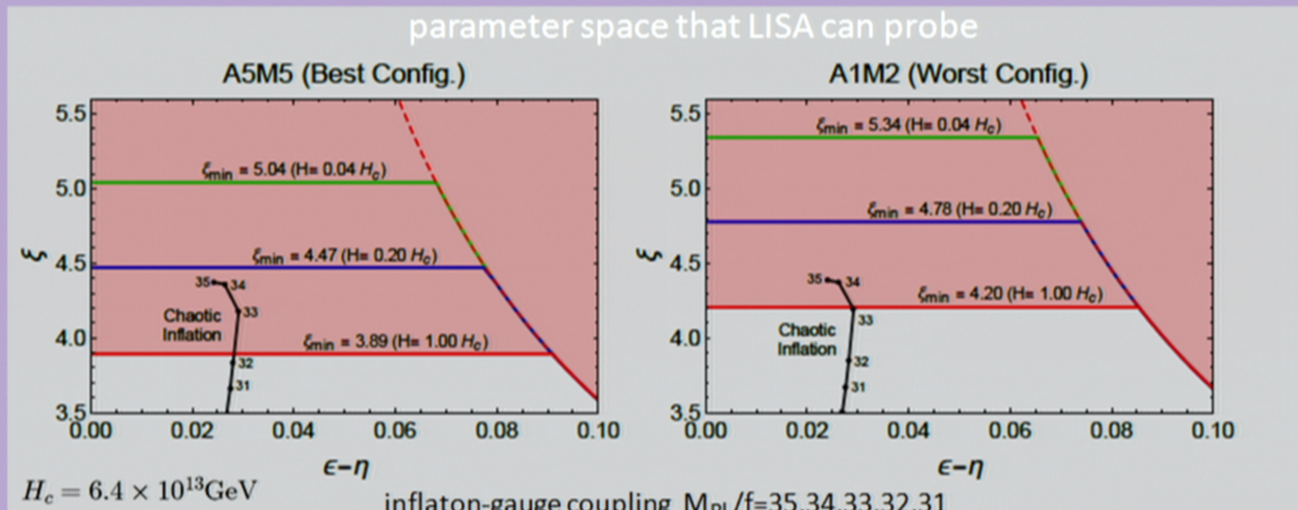
spectral tilt: $n_T(f) \equiv \frac{d \ln \Omega_{\rm GW} h^2}{d \ln f}$ $\Rightarrow$ $\Omega_{\rm GW} h^2 \propto f^{n_T}$

for constant spectral tilt

for LISA sensitivities $n_T \simeq (4\pi\xi - 6)(\epsilon - \eta)$

the GW signal depends only on $\{H_N, \xi, (\epsilon - \eta)\}$

compute minimum ξ required for a GW signal to be above minimum of sensitivity curve

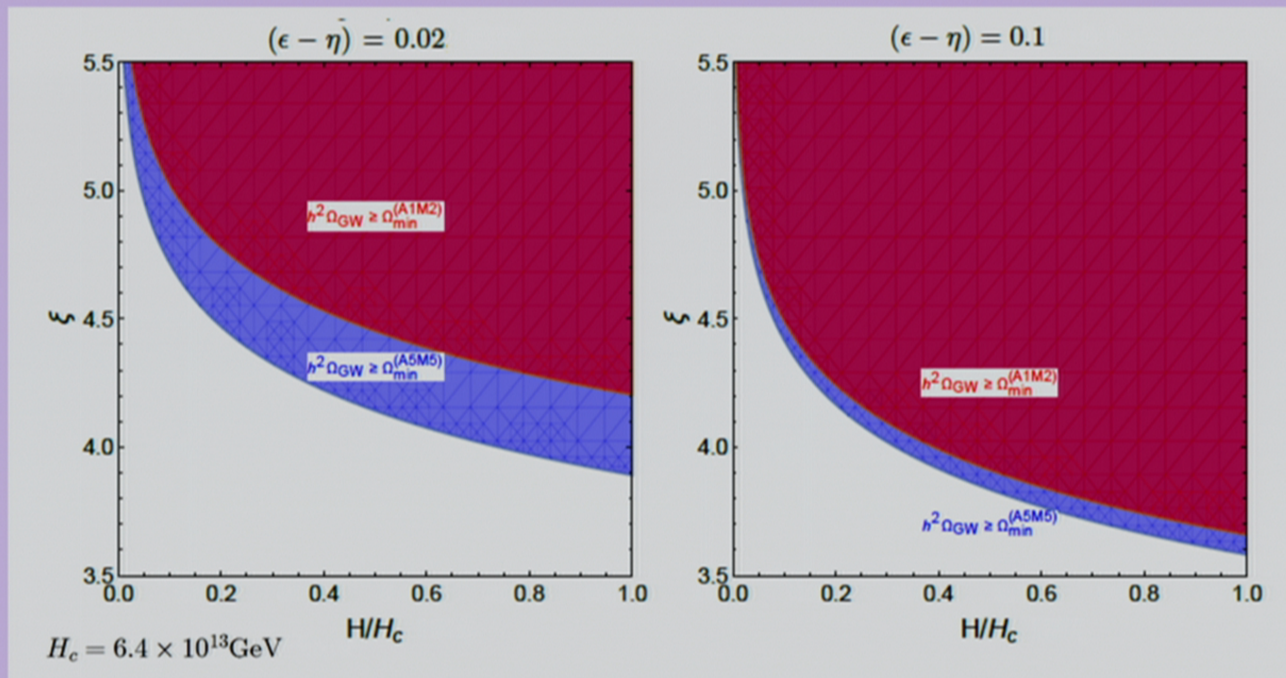


pivot scale: frequency of minimum of LISA sensitivity curve $f_*|_{A5M5} \simeq 0.00346\mathrm{Hz}$ and $f_*|_{A1M2} \simeq 0.00390$ Hz

horizontal lines: for small slow-roll parameters $(\epsilon-\eta) \ll 0.1$ the answer is independent of spectral tilt of signal, so independent of slow-roll parameters

LISA cannot probe any hubble rate smaller than $\sim \mathcal{O}(10^{-2})H_c$

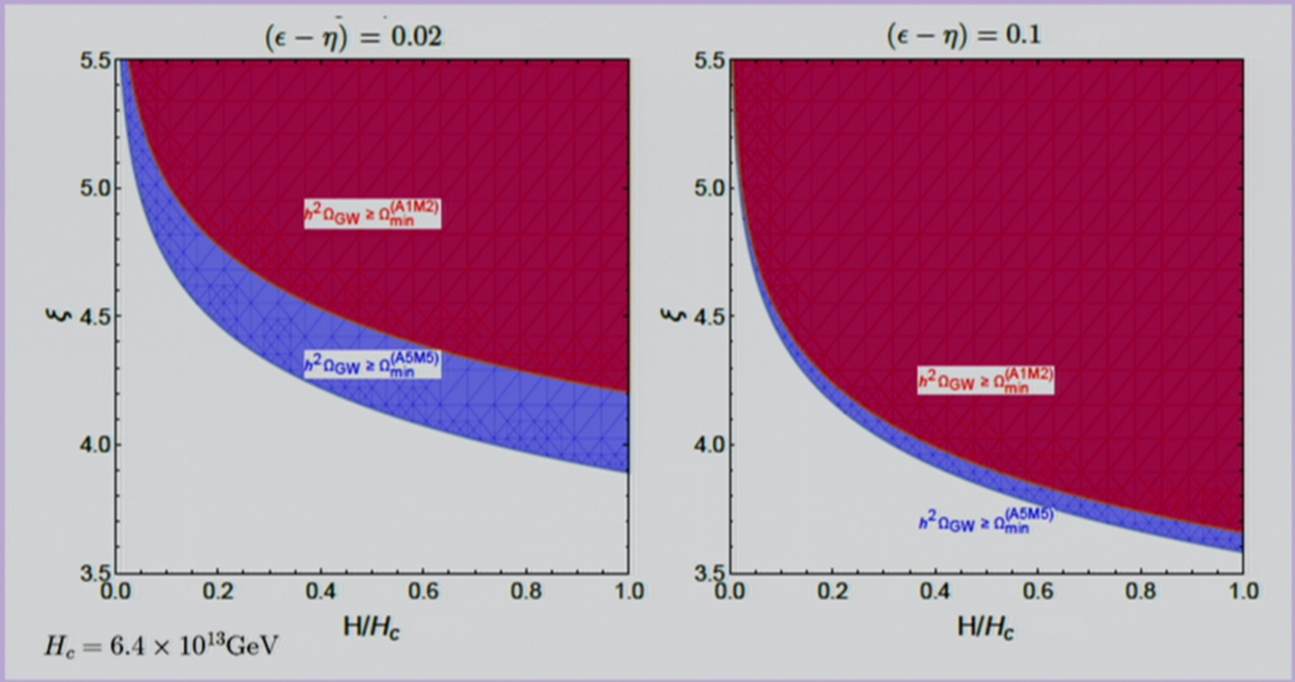
dashed curve: consider GW signal with amplitude smaller than LISA sensitivity curve at f_* and find minimum slow-roll parameter combination $(\varepsilon-\eta)_{min}$ required for the amplitude of signal to cross the LISA curve at a higher frequency



regions in (ξ-H) parameter space that LISA can probe for best (worst) configurations

Name	A5M5	A1M2
Arm length [10^6 Km]	5	1
Duration [years]	5	2

difference in ξ probed by the two configurations is $\Delta\xi \sim 0.31$
but $\Omega_{\rm GW} \propto e^{4\pi\xi}$ which translates into a GW boost factor of $\sim e^{3.9} \sim 10^2$!



degradation of LISA's ability to measure a signal for small inflationary hubble rates, as the minimum ξ required for a detection grows exponentially fast as the hubble rate decreases

<u>particular inflationary models</u>

up to now, we were agnostic about the inflation potential; let us specify it now

single-field inflation,
described by ansatz $\epsilon_V = \frac{1}{2}\left(\frac{V_{,\phi}}{V}\right)^2 = \frac{\beta}{N^p}$

$$a = a_{\text{final}} \exp(-N)$$

a_{final} when $\frac{\rho+p}{p} \simeq \mathcal{O}(1)$

the spectrum of fluctuations observed in CNB corresponds to $N \simeq (50-60)$

assume that during this rather short range of N the change of the equation of state is monotonic and smooth and use that

$\frac{\rho+p}{\rho} \simeq \mathcal{O}(1)$ *at* $N = 0$

$$\Longrightarrow \quad 1 + \frac{p}{\rho} = \frac{\beta}{(N+1)^p}$$

particular inflationary models

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single-field inflation, described by ansatz $\epsilon_V = \frac{1}{2}\left(\frac{V_{,\phi}}{V}\right)^2 = \frac{\beta}{N^p}$

$$\text{chaotic } (p=1): \quad V(\phi) = V_0 \phi^\gamma \quad \rightarrow \quad \beta = \gamma/4\,,$$
$$\text{Starobinsky } (p=2): \quad V(\phi) = V_0(1-e^{-\gamma\phi})^2 \quad \rightarrow \quad \beta = 1/(2\gamma^2)$$

remaining parameter space (f, γ, V_0): one parameter eliminated by COBE normalisation

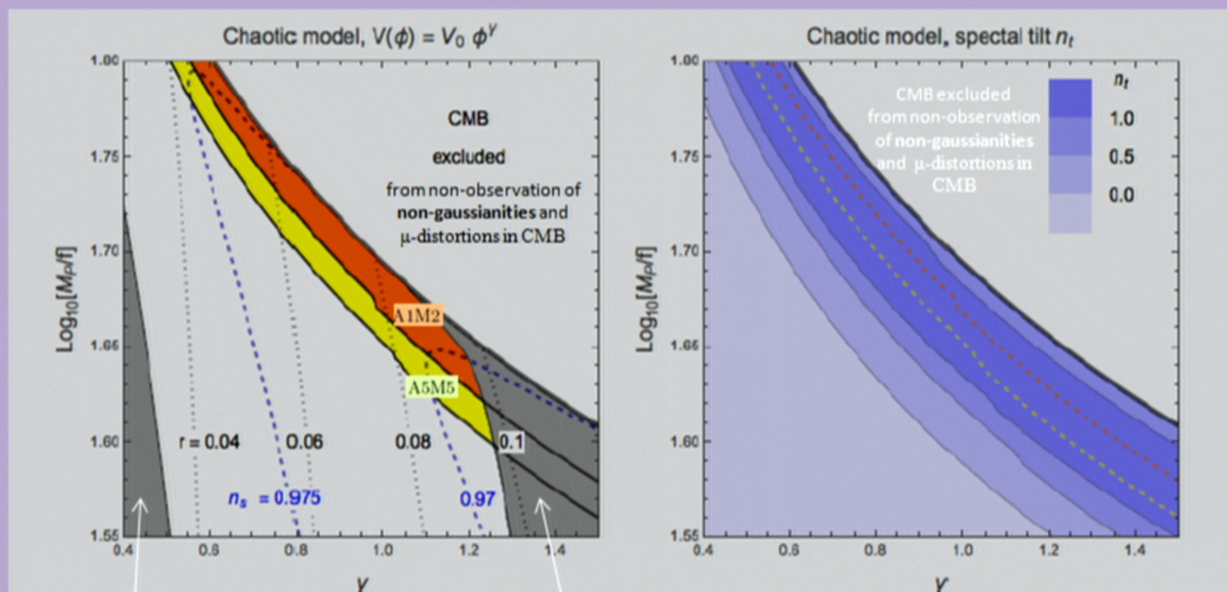
CMB observables: scalar amplitude A_s, spectral tilt n_s, tensor-to-scalar ration r, equilateral non-gaussianity parameter f_{NL}^{equil}, level of μ-distortion in CMB black body spectrum

$\mu < 6 \times 10^{-8}$

GW amplitude and tilt are evaluated at peak of LISA sensitivity $f \sim 4 \times 10^{-3}$ Hz

complementarily between CMB experiments and direct GW detectors

correlation between GW amplitude
and tilt of GW in the LISA band



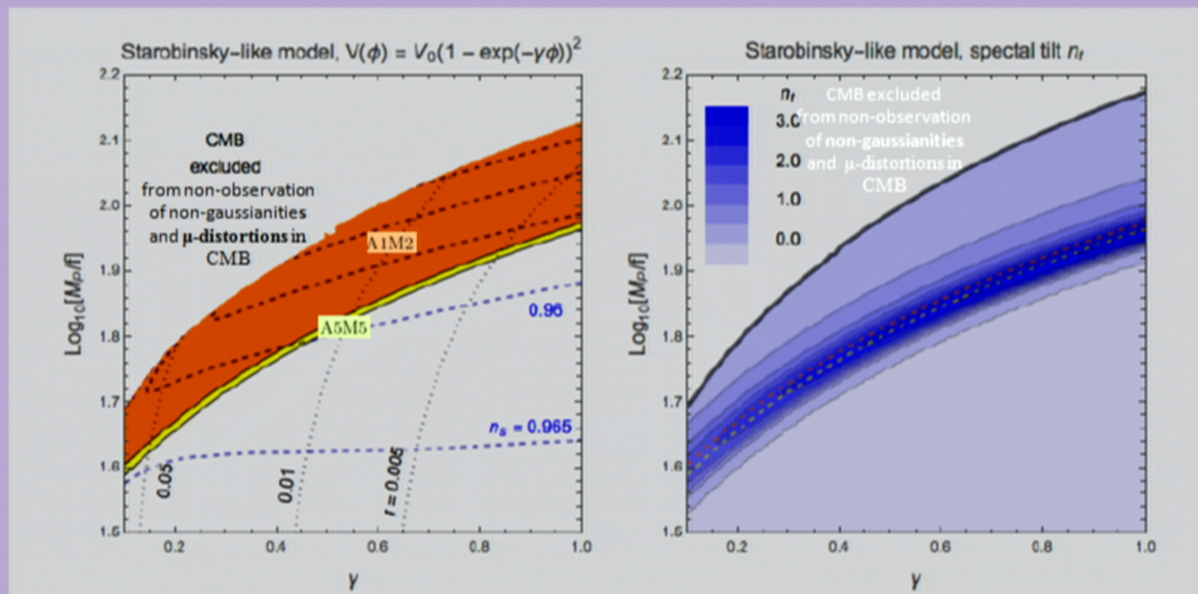
CMB constraints and LISA sensitivity *tilt of tensor power spectrum*

excluded by CMB
constraints on n_s

excluded by CMB
constraints on r

at γ=1.0, for a GW amplitude marginally
detectable by best (worst) LISA configuration,
prediction: $n_T \simeq 1.21\ (1.20)$
while for a GW just below non-gaussianity bound:
$n_T \simeq 0.8$

due to larger value of p, the growth of GW is steeper, hence the maximal spectral index is larger



CMB constraints and LISA sensitivity *tilt of tensor power spectrum*

at γ=**0.5**, for a GW amplitude marginally detectable by best (worst) LISA configuration, prediction: $n_T \simeq 3.2\ (2.8)$

while for a GW just below non-gaussianity bound: $n_T \simeq 0.2$

focus on the following (well-motivated) scenarios:

- *particle production during inflation*
  - inflaton ϕ sources gauge field via coupling $\phi F^{\mu\nu} \tilde{F}_{\mu\nu}$
  - the gauge field sources population of GWs with **blue spectrum**; this population (contrary to astrophysical backgrounds) has a net **chirality** and is highly **non-gaussian**

- *inflation with spectator fields*
  - amplitude and spectral index of such GW background is specified by sound speed of spectator field(s) and time-variation of the latter
  - the GW is expected to be **blue-tilted**

- *EFT of space-reparametrisation*
  - when space-reparametrisation invariance is broken, the graviton can acquire a mass
  - the tensor spectrum can be **blue** and **enhanced at small scales** due to the specific symmetry breaking patterns by the fields driving inflation

- *primordial black holes (PBHs)*
  - *in some models, large peaks in the power matter spectrum can collapse forming PBHs upon horizon re-entry at RDE*
  - *PBHs are clustered and merge, generating a stochastic background of GWs, probably detectable by LISA*

spectator field: besides the inflaton field, there may be another scalar field which does not influence the inflationary dynamics of the background

particular example:

$$\mathcal{L} = \frac{1}{2}M_{Pl}^2 R + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + P(X,\sigma)$$

$X = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma$

inflaton (ϕ), *generic function* (P), *spectator* (σ)

inflaton: drives accelerated expansion and generates scalar perturbations

spectator: does not influence background dynamics but induces scalar and tensor perturbations with propagations speed $c_s \equiv P_X / \left(P_X + P_{XX}\dot{\sigma}_0^2\right)$, which can vary during inflation

spectator field: besides the inflaton field, there may be another scalar field which does not influence the inflationary dynamics of the background

particular example:

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tensor power spectrum

$$P_{\rm GW}(k) \simeq \frac{2H^2}{M_{Pl}^2}\left(\frac{k}{k_*}\right)^{n_T^{(v)}} + \frac{8}{15\pi c_s^3}\frac{H^4}{M_{Pl}^4}\left(\frac{k}{k_*}\right)^{n_T^{(\sigma)}}$$

$n_T^{(\sigma)} = -4\epsilon - 3s$

$n_S^{(\sigma)} - 1 = -4\epsilon - 7s$

$s \equiv \dot{c}_s/Hc_s \neq 0.$

$\epsilon \equiv -\dot{H}/H^2$

scalar power spectrum

$$P_S(k) \simeq \frac{H^2}{4\epsilon M_{Pl}^2}\left(\frac{k}{k_*}\right)^{n_S^{(v)}-1} + \frac{1}{32\pi c_s^7}\frac{H^4}{M_{Pl}^4}\left(\frac{k}{k_*}\right)^{n_S^{(\sigma)}-1}$$

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contribution from vacuum fluctuations of the gravitational field

induced by the presence of the spectator field

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contribution from vacuum fluctuations of the inflaton field

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contribution from vacuum fluctuations of the gravitational field

$A_T^{(\sigma)}$ *amplitude of sourced tensor contribution*

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for c_s sufficiently small and $s<0$ with large absolute value, there is an enhancement of GW amplitude on small scales, in principle detectable by LISA

present-time GW spectral energy density

$$h^2\Omega_{\rm GW}(k,\tau_0) = \frac{k^2}{12a_0^2H_0^2}P_{\rm GW}(k)T^2(k,\tau_0)$$

$$T(k,\tau_0) = \frac{3\Omega_m j_1(k\tau_0)}{k\tau_0}\sqrt{1.0+1.36\left(\frac{k}{k_{eq}}\right)+2.50\left(\frac{k}{k_{eq}}\right)^2}$$

described by energy scale of inflation H, slow-roll parameter ε, and the quantities c_s and s

$$s \equiv \dot{c}_s/Hc_s \neq 0$$

$$k_* = 0.05\mathrm{Mpc}^{-1}$$

$$H = 10^{12}\ \mathrm{GeV}$$

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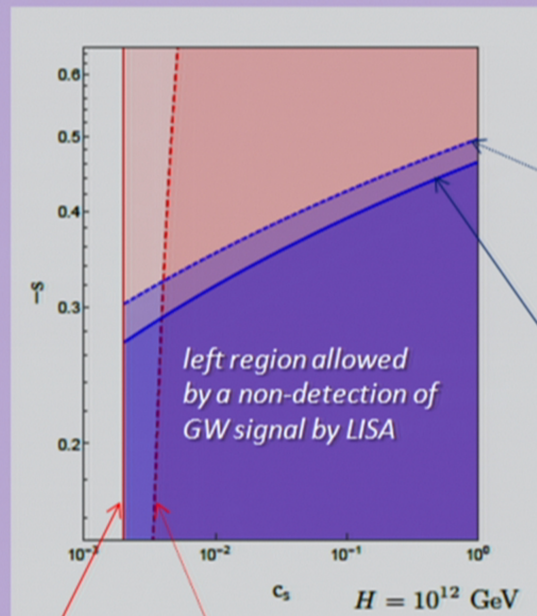

discriminant power of LISA for A1M2

discriminant power of LISA for A5M5

lower limit from contribution to scalar perturbations due to spectator field (CMB)

$$\epsilon < 0.0068$$

lower limit from total amplitude of scalar power spectrum (CMB)

present-time GW spectral energy density

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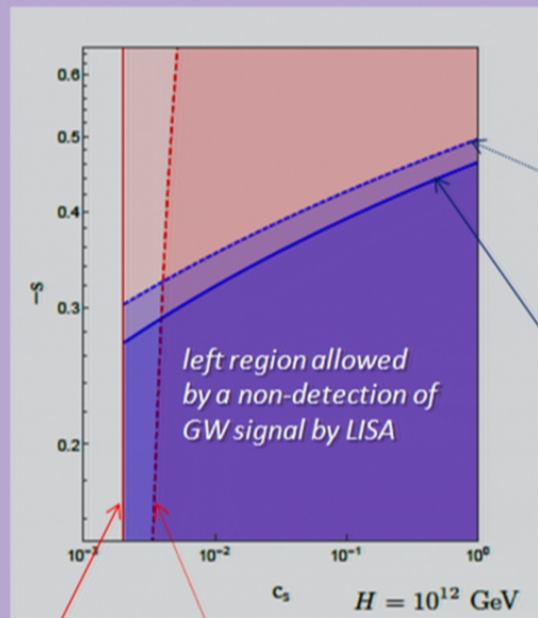


discriminant power of LISA for A1M2

discriminant power of LISA for A5M5

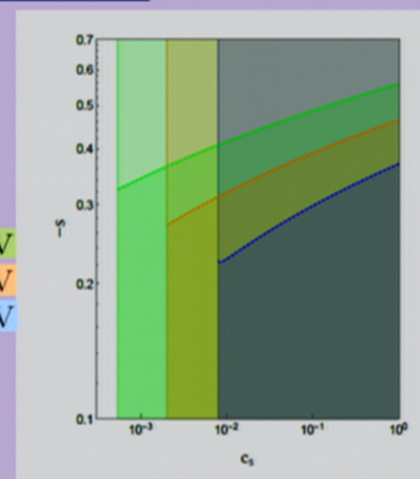
lower limit from contribution to scalar perturbations due to spectator field (CMB) (ε must be >0)

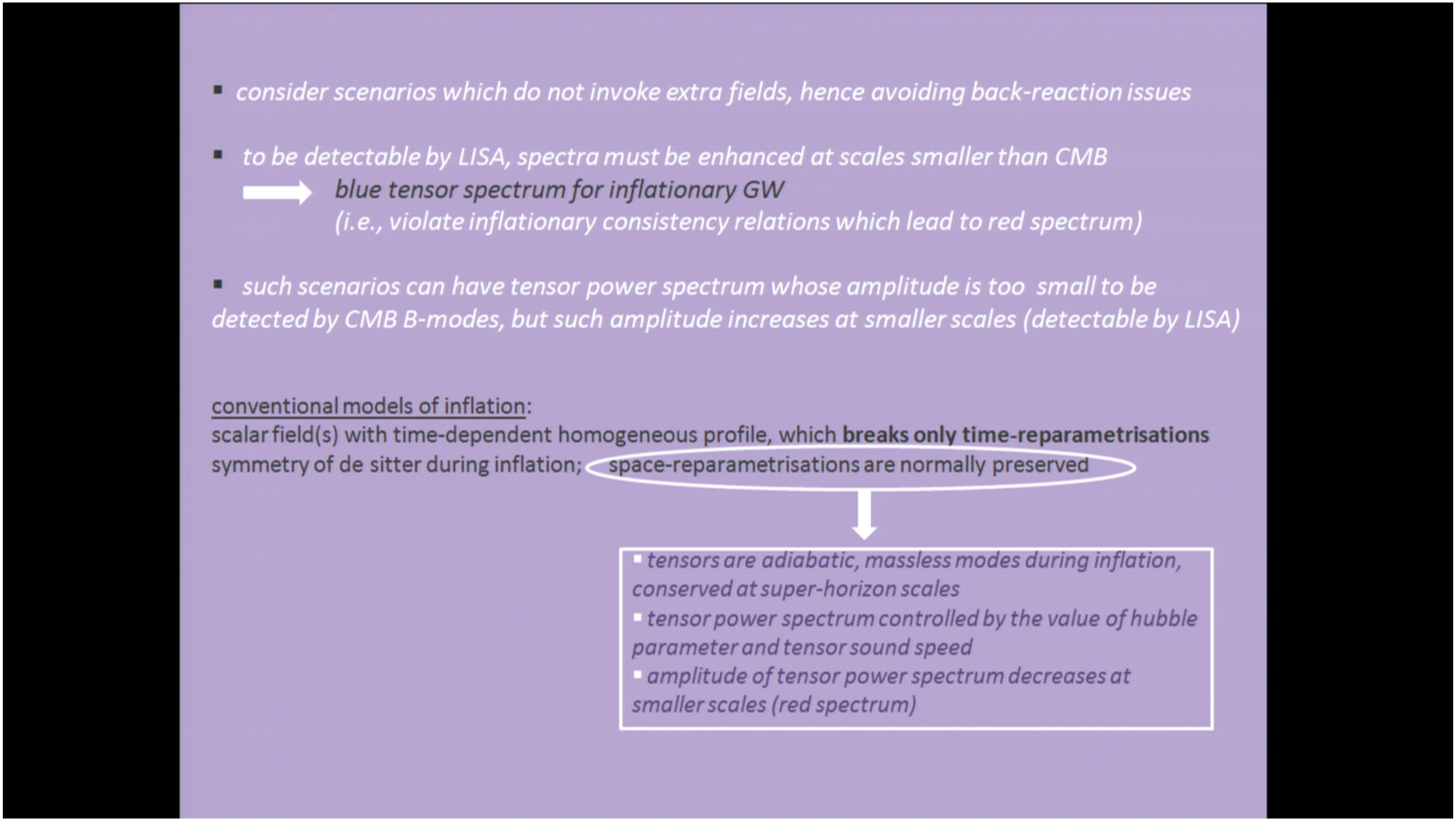
lower limit from total amplitude of scalar power spectrum (CMB)

10^{11}GeV

10^{12}GeV

10^{13}GeV




consider scenarios which do not invoke extra fields, hence avoiding back-reaction issues
to be detectable by LISA, spectra must be enhanced at scales smaller than CMB
blue tensor spectrum for inflationary GW
(i.e., violate inflationary consistency relations which lead to red spectrum)
such scenarios can have tensor power spectrum whose amplitude is too small to be detected by CMB B-modes, but such amplitude increases at smaller scales (detectable by LISA)
conventional models of inflation:
scalar field(s) with time-dependent homogeneous profile, which breaks only time-reparametrisations symmetry of de sitter during inflation;
space-reparametrisations are normally preserved
tensors are adiabatic, massless modes during inflation, conserved at super-horizon scales
tensor power spectrum controlled by the value of hubble parameter and tensor sound speed
amplitude of tensor power spectrum decreases at smaller scales (red spectrum)

- *consider scenarios which do not invoke extra fields, hence avoiding back-reaction issues*
- *to be detectable by LISA, spectra must be enhanced at scales smaller than CMB*
  → *blue tensor spectrum for inflationary GW*
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<u>conventional models of inflation</u>:
scalar field(s) with time-dependent homogeneous profile, which **breaks only time-reparametrisations** symmetry of de sitter during inflation; space-reparametrisations are normally preserved

breaking space-reparametrisation, inflationary tensor modes can be massive

if graviton mass is sufficiently large → blue GW spectrum with enhanced power at scales << CMB

end of inflation: inflaton can recover space-reparametrisation symmetry → graviton mass = 0

most general form for second order action for tensor fluctuations:

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

tensor sound speed $c_T \neq 1$

graviton squared mass $m_h^2 > 0$ *or* $m_h^2 < 0$

consider pure de sitter $H = \text{const.}$ and c_T, m_h constants, setting $n = 1$

for small graviton mass $|m_h/H| \ll 1$

power spectrum

$$\mathcal{P}_h = \frac{H^2}{2\pi^2 M_{Pl}^2 c_T^3} \left(\frac{k}{k_*} \right)^{n_T}$$

with $n_T = \frac{2}{3} \frac{m_h^2}{H^2}$

a blue spectrum, $n_T > 0$, requires $m_h^2 > 0$

interesting case: it enhances the tensor spectrum at small scales and can lead to a signal detectable with LISA

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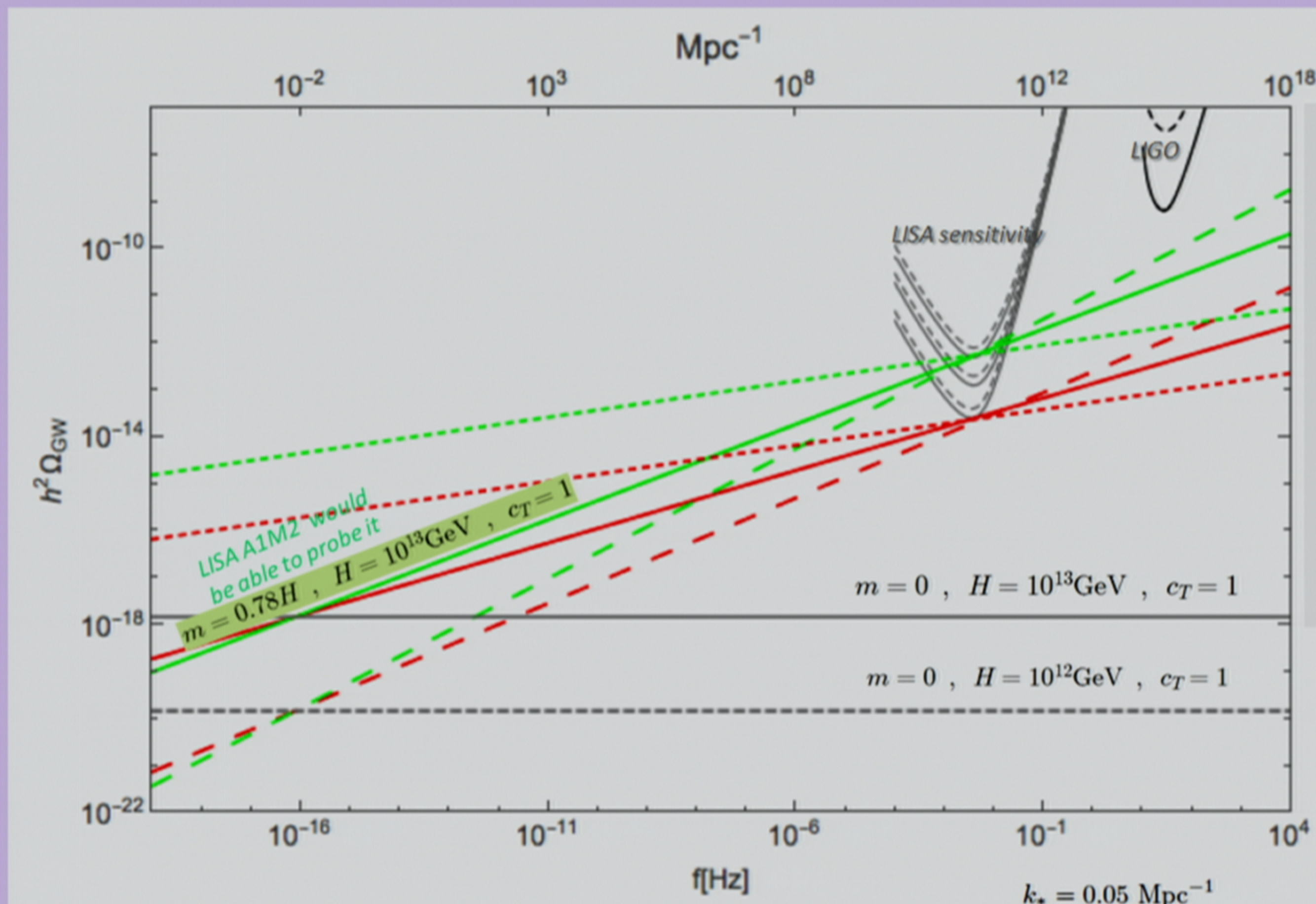
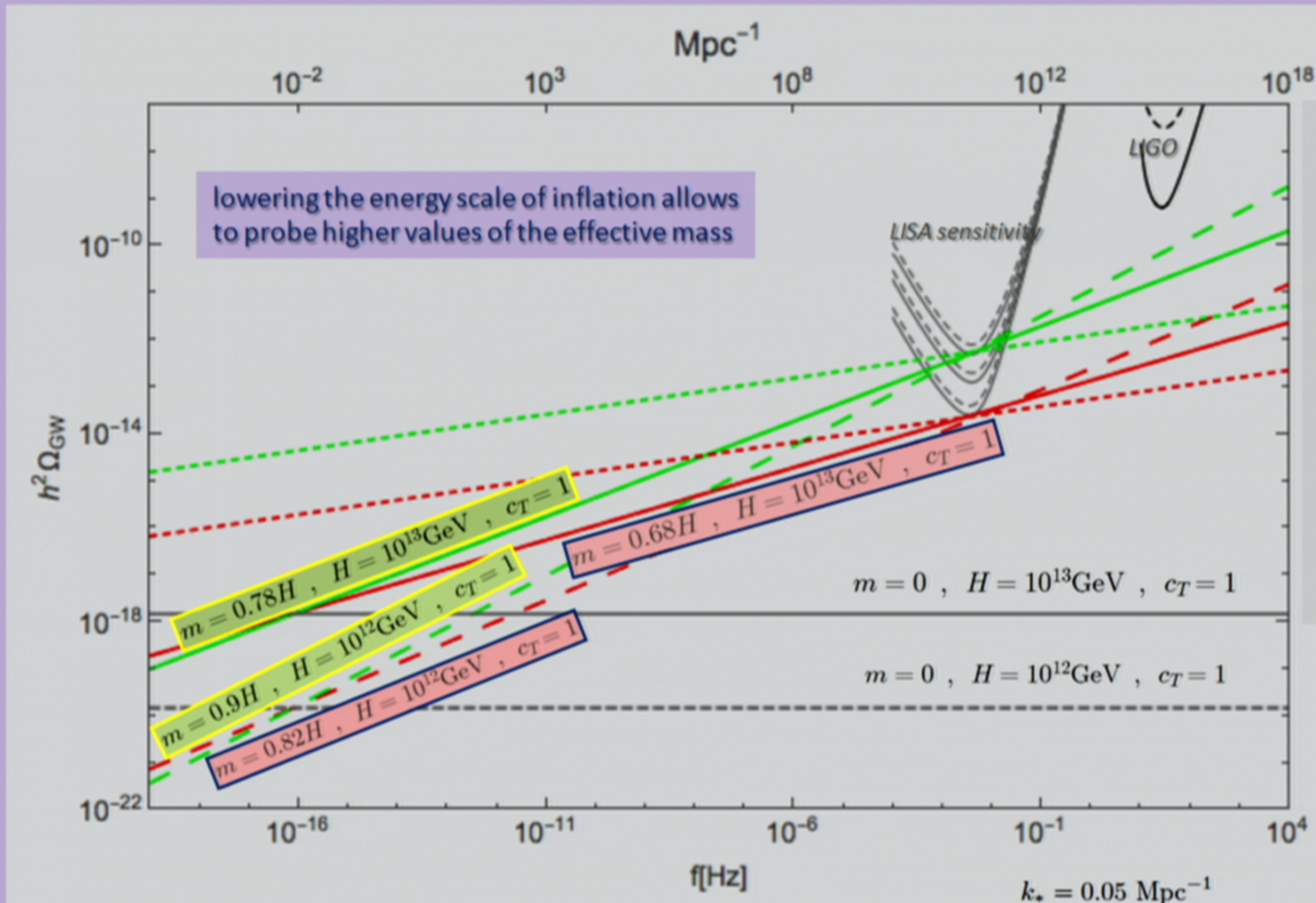


assuming tensor sound speed and graviton mass time-independent



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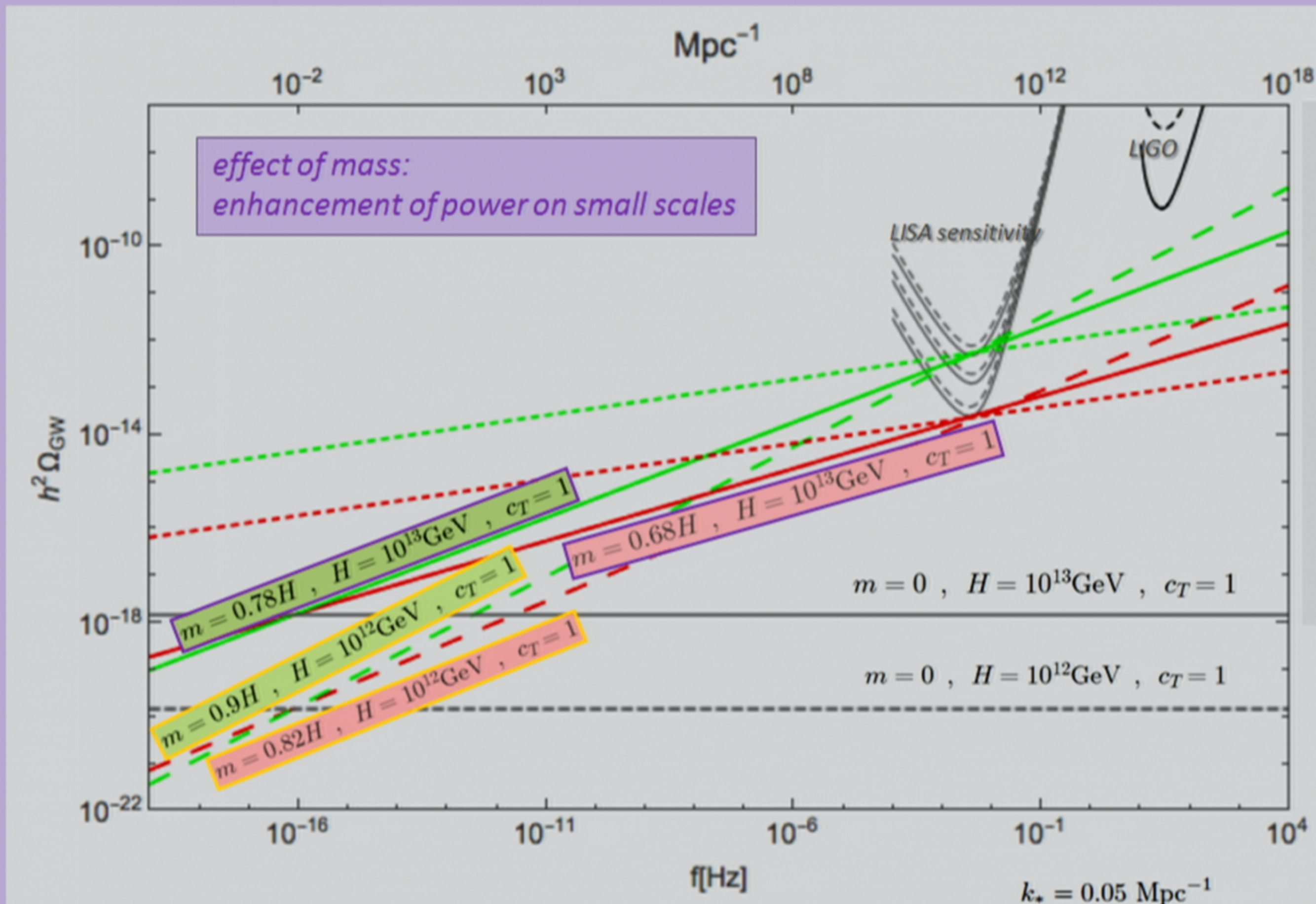

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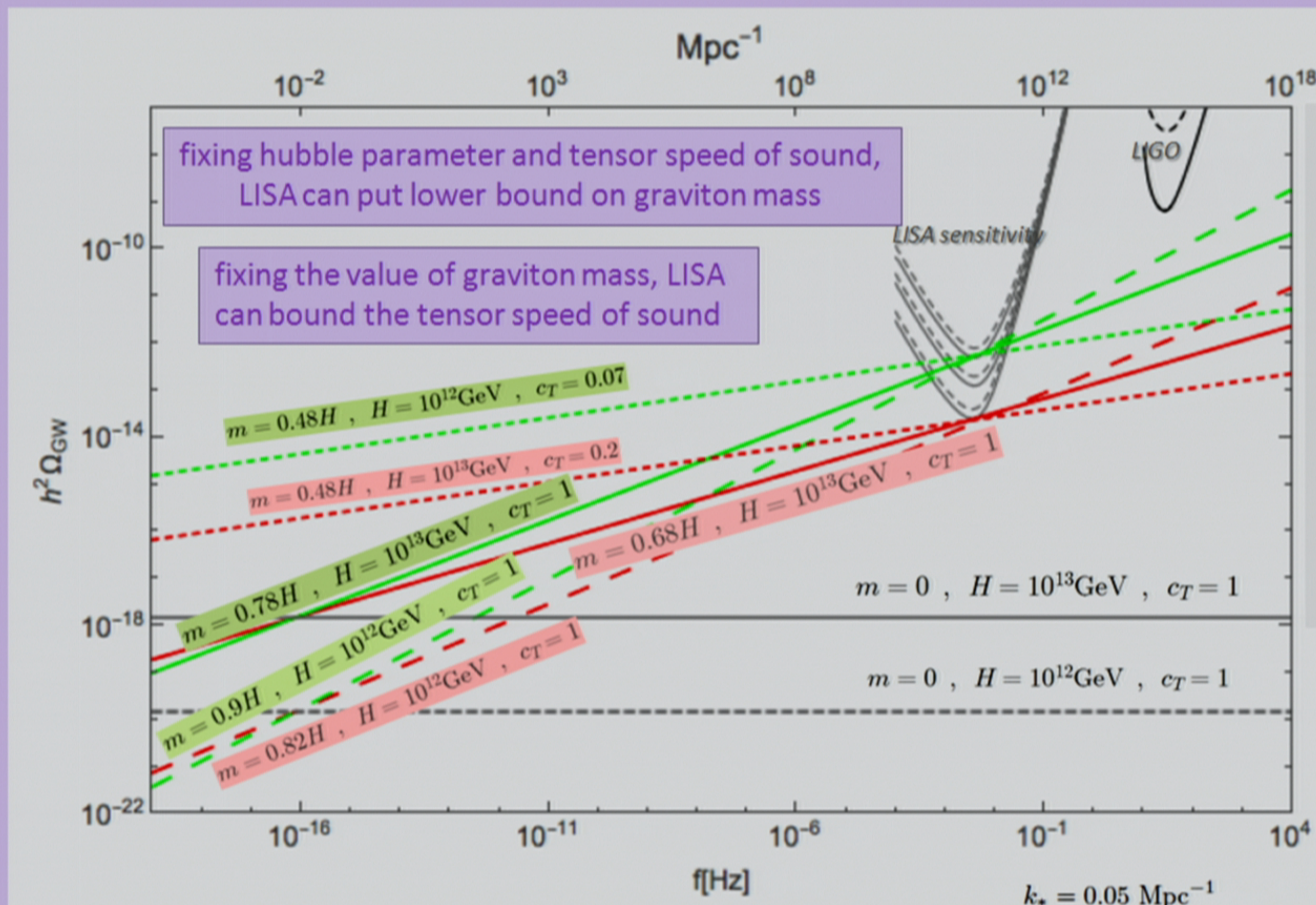

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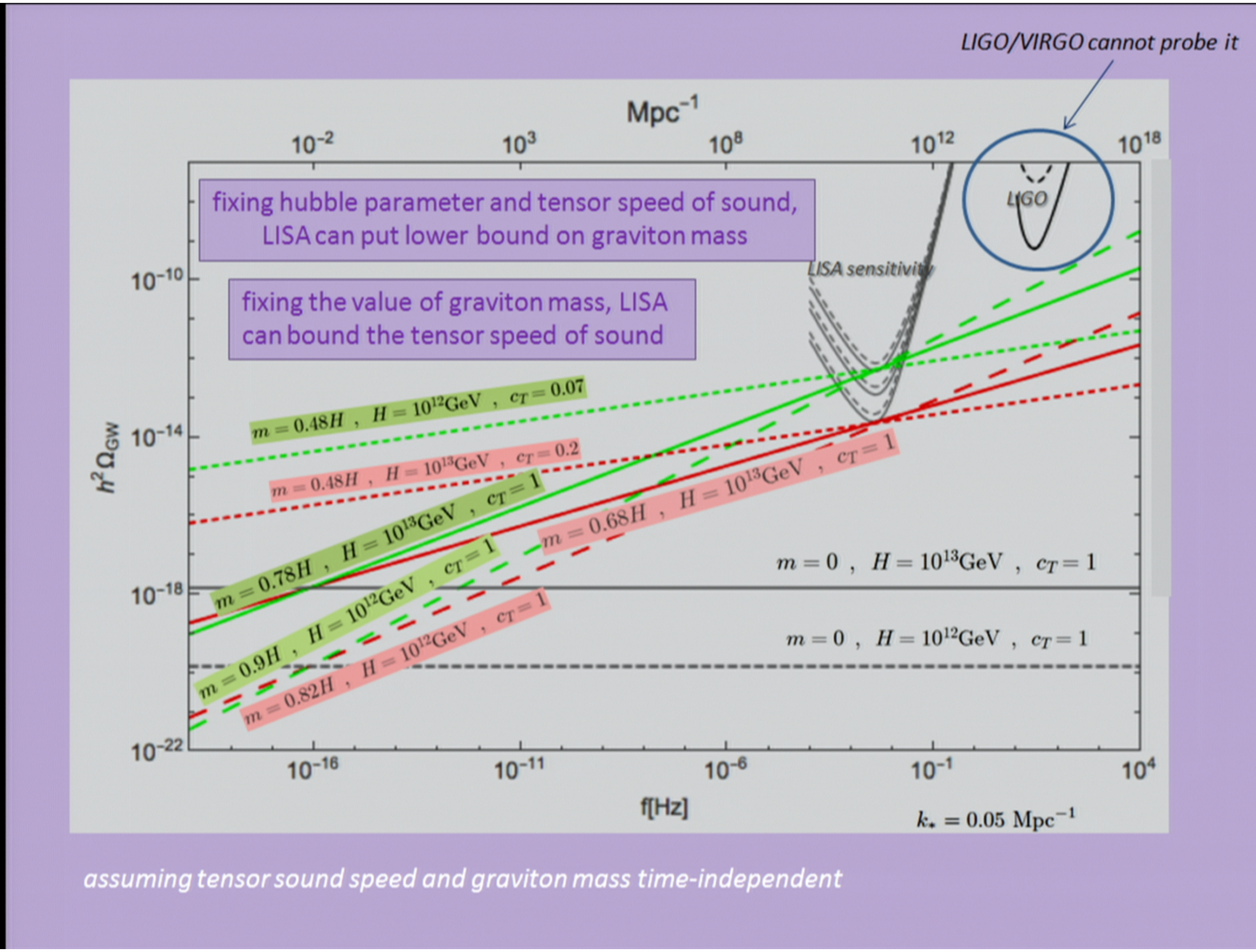
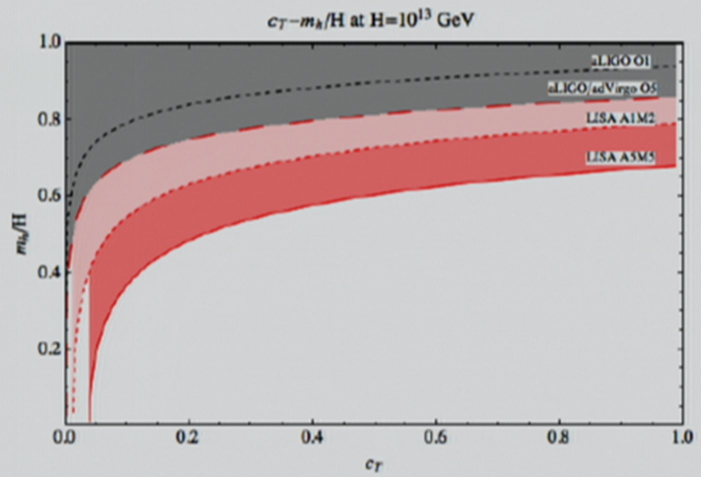
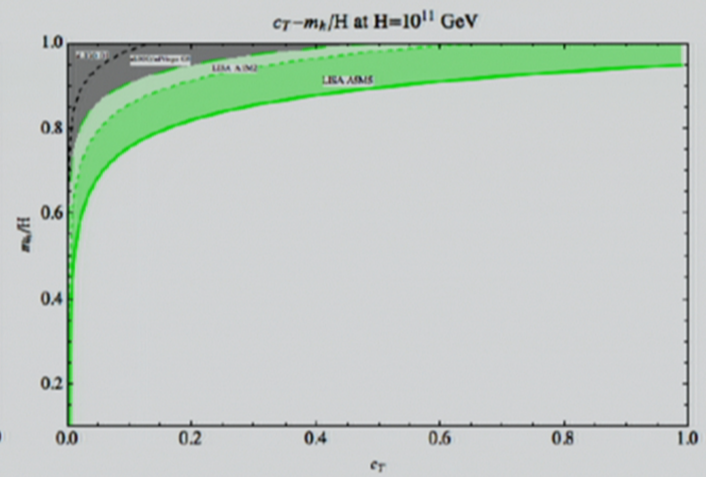
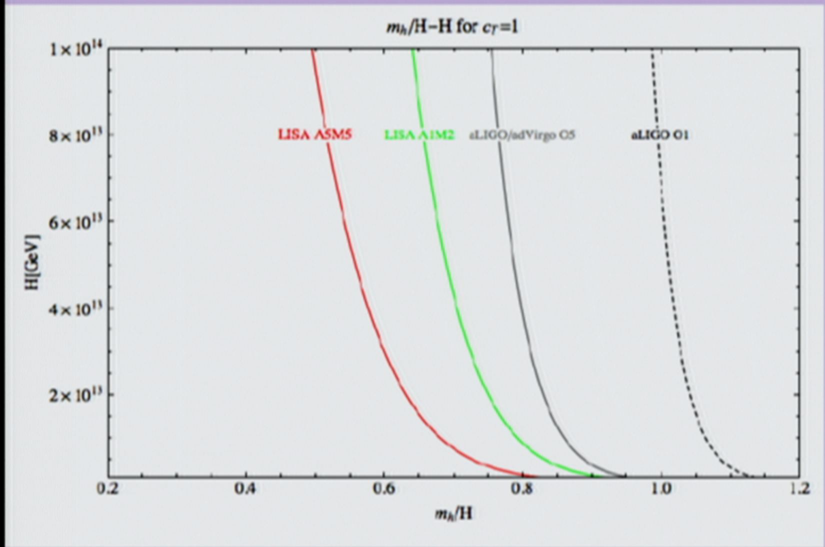


LIGO/VIRGO cannot probe it
Mpc^-1
10^-2
10^3
10^8
10^12
10^18
LIGO
fixing hubble parameter and tensor speed of sound, LISA can put lower bound on graviton mass
fixing the value of graviton mass, LISA can bound the tensor speed of sound
LISA sensitivity
10^-10
10^-14
10^-18
10^-22
h^2 Ω_GW
m = 0.48H , H = 10^12GeV , c_T = 0.07
m = 0.48H , H = 10^13GeV , c_T = 0.2
m = 0.78H , H = 10^13GeV , c_T = 1
m = 0.68H , H = 10^13GeV , c_T = 1
m = 0 , H = 10^13GeV , c_T = 1
m = 0.9H , H = 10^12GeV , c_T = 1
m = 0.82H , H = 10^12GeV , c_T = 1
m = 0 , H = 10^12GeV , c_T = 1
10^-16
10^-11
10^-6
10^-1
10^4
f[Hz]
k_* = 0.05 Mpc^-1
assuming tensor sound speed and graviton mass time-independent

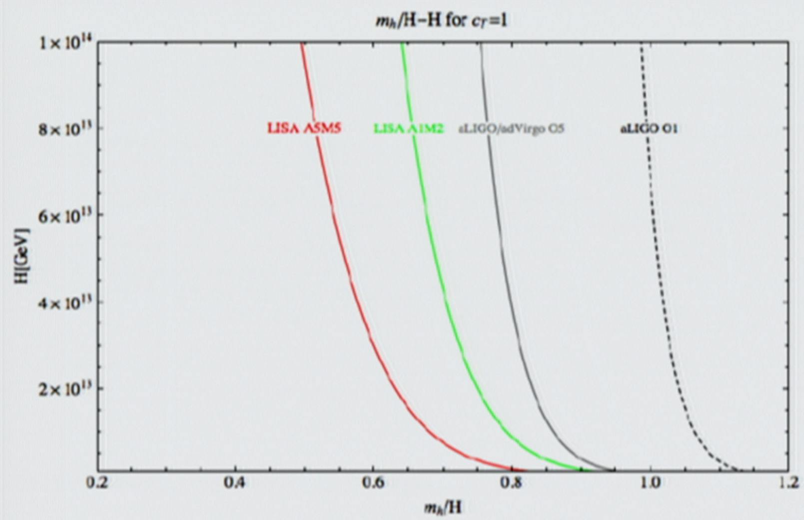
upper bounds on graviton mass and sound speed of tensor perturbations during inflation, from a non-detection of such GW signal

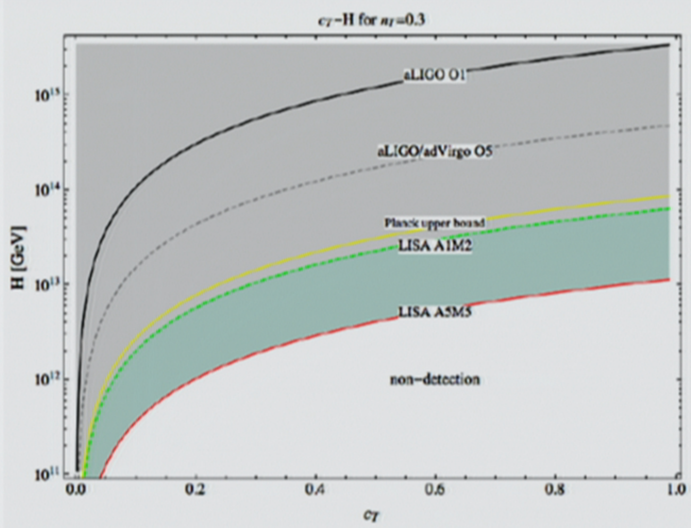






assuming standard case of graviton travelling at the speed of light, read the lower masses of graviton to which LISA and LIGO are sensitive





assuming standard case of graviton travelling at the speed of light, read the lower masses of graviton to which LISA and LIGO are sensitive

choosing $n_T = 0.3$(in the range of LISA possibilities), see that LISA A5M5 can be sensitive to energy scales of inflation around $10^{12}\mathrm{GeV}$

a higher value of spectral tilt, or a tensor sound speed lower than the speed of light, would allow to reach lower inflationary energy scales

focus on the following (well-motivated) scenarios:

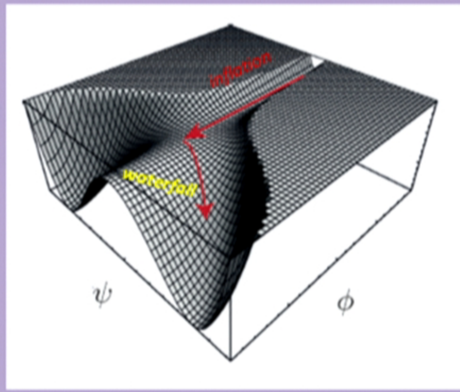
- *particle production during inflation*
  - inflaton ϕ sources gauge field via coupling $\phi F^{\mu\nu} \tilde{F}_{\mu\nu}$
  - the gauge field sources population of GWs with **blue spectrum**; this population (contrary to astrophysical backgrounds) has a net **chirality** and is highly **non-gaussian**

- *inflation with spectator fields*
  - amplitude and spectral index of such GW background is specified by sound speed of spectator field(s) and time-variation of the latter
  - the GW is expected to be **blue-tilted**

- *EFT of space-reparametrisation*
  - when space-reparametrisation invariance is broken, the graviton can acquire a mass
  - the tensor spectrum can be **blue** and **enhanced at small scales** due to the specific symmetry breaking patterns by the fields driving inflation

- *primordial black holes (PBHs)*
  - *in some models, large peaks in the power matter spectrum can collapse forming PBHs upon horizon re-entry at RDE*
  - *PBHs are clustered and merge, generating a stochastic background of GWs, probably detectable by LISA*

hybrid inflation models end inflation when a symmetry breaking field ψ triggers a quantum phase transition while the inflaton field ϕ is still in slow-roll



$$V(\phi,\psi)=\Lambda\left[\left(1-\frac{\psi^2}{v^2}\right)^2+\frac{(\phi-\phi_c)}{\mu_1}-\frac{(\phi-\phi_c)^2}{\mu_2^2}+\frac{2\phi^2\psi^2}{\phi_c^2v^2}\right]$$

- initially, inflation takes place along the valley ψ=0
- below the critical value ϕ_c, this potential develops a tachyonic instability, forcing the field trajectories to reach one of the global minima, at $\phi = 0\ ,\ \ \psi = \pm\, v$

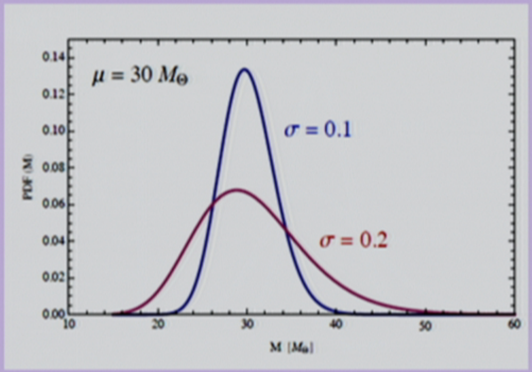
in hybrid inflation models with long-lasting waterfall regimes, large and broad peaks may arise in the matter power spectrum (through exponential expansion of topological defects formed at the phase transition) scenario:

large and broad peaks in the matter power spectrum can give rise to PBHs with masses a few solar masses, when those scales re-enter the horizon during RDE

such PBHs can arise in clusters, e.g., within hybrid inflation, and merge during the MDE, creating a stochastic GW background, that for $M_{\rm PBH} \sim 10^2 - 10^4 M_\odot$ is within LISA sensitivity

assume a lognormal distribution of PBHs, coming from peaks in the power spectrum produced during inflation

$$PDF(m) = \frac{1}{m\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\log^2(m/\mu)}{2\sigma^2}\right)$$



$$\Omega_{\rm GW}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln f}$$

GW background from inspariling BH obtained form GW emission of binary systems

where

$$\frac{d\rho_{\rm GW}}{d\ln f} = \int_0^\infty \frac{dz}{1+z}\frac{dn}{dz}\frac{\pi^{2/3}}{3c^2}\mathcal{M}_c^{5/3}(G f_r)^{2/3}$$

$$\mathcal{M}_c^{5/3} = m_1 m_2 (m_1 + m_2)^{-1/3}$$ *chirp mass*

$$f_r = f(1+z)$$ *rest-mass frequency at the source*

$$\frac{dn}{dz} = \tau_{\rm merger}\frac{dt}{dz} = \frac{\tau_{\rm merger}}{H(z)(1+z)}$$ *number density of GW events within red-shift interval*

$$H^2(z) = H_0^2\left[\Omega_{\rm M}(1+z)^3 + \Omega_\Lambda\right].$$ *considering ΛCDM*

$$h_c(f) = 1.14\times 10^{-25}\,\tau_{\rm merger}^{1/2}\left(\frac{f}{\rm Hz}\right)^{-2/3}\left(\frac{\mathcal{M}_c}{M_\odot}\right)^{5/6}$$

mass distribution

$$PDF(m) = \frac{1}{m\sqrt{2\pi\sigma^2}}\exp\left(-\frac{\log^2(m/\mu)}{2\sigma^2}\right)$$

$$h^2\,\Omega_{\rm GW}(f) = 8.15\times 10^{-15}\,\tau_{\rm merger}\left(\frac{f}{\rm Hz}\right)^{2/3}\left(\frac{\mu}{M_\odot}\right)^{5/3} R(\sigma)$$

numerical function of σ

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degeneracy between merger rate and mean mass $\tau_{\rm merger} \times \mu^{5/3}(M_\odot) = {\rm const.}$

mass distribution

$$PDF(m) = \frac{1}{m\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\log^2(m/\mu)}{2\sigma^2}\right)$$

assume a fixed merger rate of 50 events per year and Gpc

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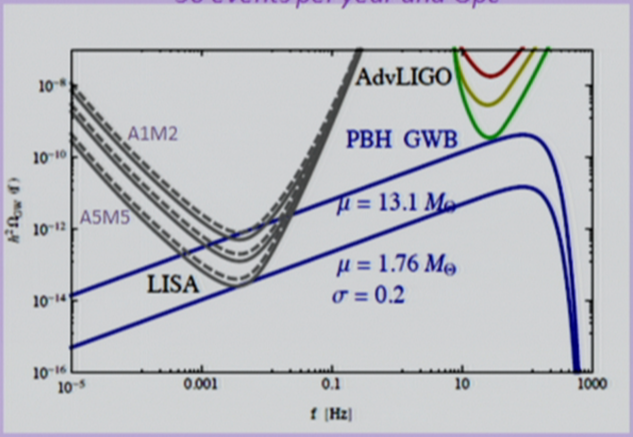

the amplitude depends on mass distribution of PBHs, mainly through the mean and the width of the distribution

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stochastic GW bckgd from insparilling PBHs after recombination

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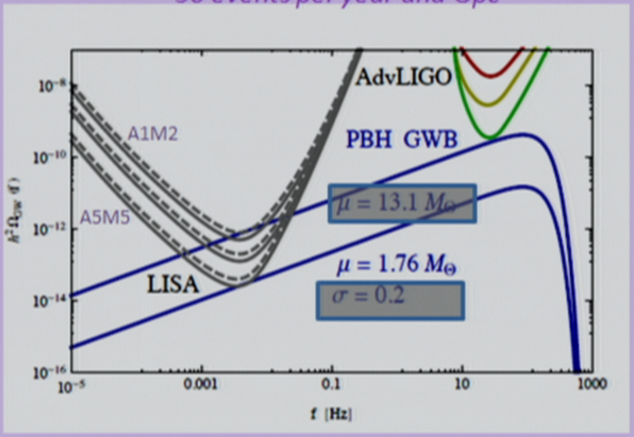
concrete case of stochastic GW background from PBHs with $\mu = 13.1\, M_\odot$ and $\sigma = 0.2$ which could easily be detected by LISA

assume a fixed merger rate of 50 events per year and Gpc



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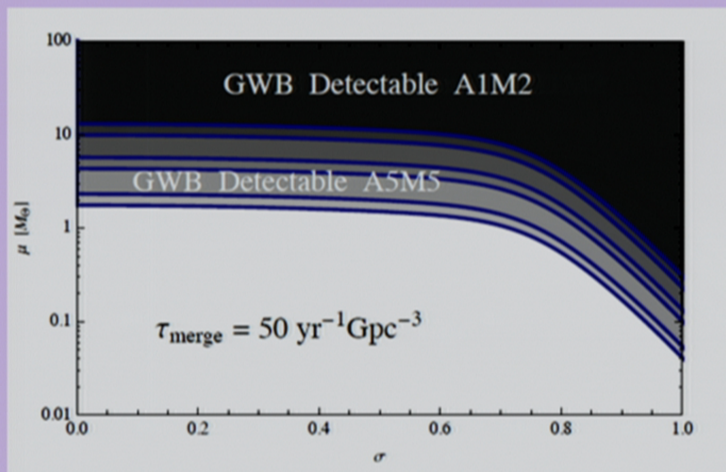
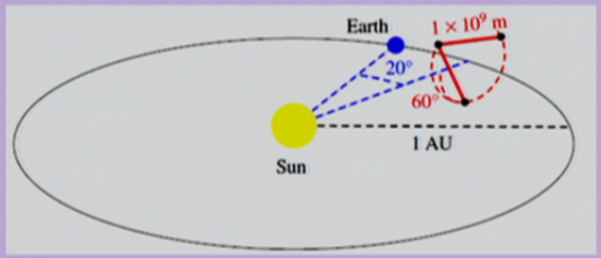


this particular GWB from inspiraling PBHs, with $n_T = 2/3$ can be detectable by LISA in a very wide range of parameters of the model

$$h^2\,\Omega_{GW}(f) = 8.15 \times 10^{-15}\,\tau_{merger} \left(\frac{f}{\mathrm{Hz}}\right)^{2/3} \left(\frac{\mu}{M_\odot}\right)^{5/3} R(\sigma)$$

numerical function of σ

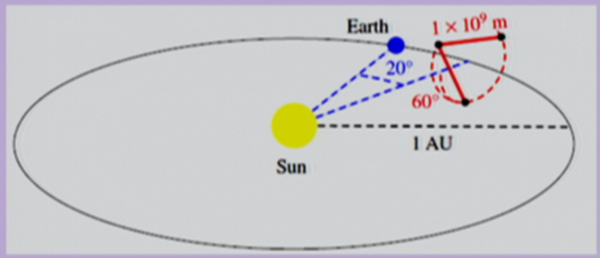


LISA will survey for first time the low-frequency GW band $f \sim (10^{-5} - 0.1)$ Hz with sufficient sensitivity to detect individual astrophysical sources out to z=15

scientific goals:

- explore stellar-mass close binaries in the milky way
- study evolution of BH population
- study nearby galactic nuclei, exploring regions that are invisible to electromagnetic techniques
- probe GR in the strong-field limit (coalescence of massive BH binaries moving at speeds near c)
- probe new physics and cosmology and search for unforeseen sources of GW

  LISA will be able to probe bulk motions at times about $3 \times 10^{-18} - 3 \times 10^{-10}$ sec after the big bang



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*LISA will be able to detect the stochastic GW background produced by **strong first-order cosmological phase transitions**, testing scenarios beyond the standard model of particle physics*

arXiv:1512.06239

*LISA, using standard sirens, has the potential to provide a complementary and calibration-free way **to test the expansion of the universe** (and in particular H_0) with entirely different systematics than present probes (e.g. SNIa), which rely on electromagnetic observations only*

arXiv:1601.07112

▪ particle production during inflation:
broad class of inflation models, where the inflaton is coupled to gauge fields
amplification of vacuum fluctuations of gauge field which source ***GWs of parity-violating*** *and* ***highly non-gaussian*** *nature (smoking gun of this mechanism)*

▪ inflationary spectator fields during inflation:
amplitude and spectral index of such GW background is specified by sound speed of spectator fields and time variation of the latter
the spectrum is ***blue tilted*** *& LISA can provide constraints complementary to those by current CMB*

▪ space-reparametrisation is spontaneously broken during inflation
GW spectrum with a **blue tilt**, **enhanced** and detectable at LISA frequency scales

▪ models of inflation (e.g., mild-waterfall hybrid model) with large peaks in the matter power spectrum
stochastic background *of GW, generated by mergers of PBHs, detectable by LISA*

LISA will be able to

- **test the latest stages of the inflationary period**
- **probe the couplings of the inflaton to other d.o.f., or simply the presence of extra fields besides the inflaton**
- **probe the degree of violation of the inflationary consistency relation**