Gravitational-wave signal from cosmological phase transitions

Tommi Alanne

MPIK

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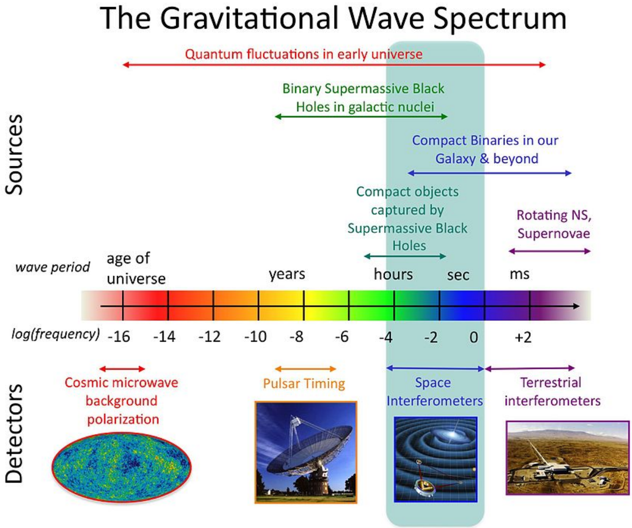
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

With Thomas Hugle, Moritz Platscher, and Kai Schmitz
JHEP 03 (2020) 004

I

Background

The big picture

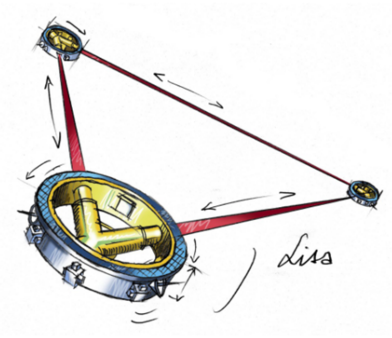


NASA, http://science.gsfc.nasa.gov/663/research/index.html

Gravitational-wave astronomy 2.0

Space-based missions: GWs produced in the early Universe

- LISA (*Laser Interferometer Space Antenna*)
    - launch: 2034
    - 3 satellites
    - $2.5 \cdot 10^6$ km arms

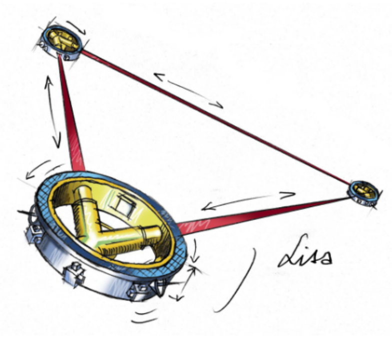


https://sci.esa.int/s/8k0LjeA

Gravitational-wave astronomy 2.0

Space-based missions: GWs produced in the early Universe

- LISA (*Laser Interferometer Space Antenna*)
- DECIGO (*Deci-Hertz Interferometer Gravitational-Wave Observatory*)
    - launch: 2027 (?)
    - 3 satellites (?)
    - 1000 km arms



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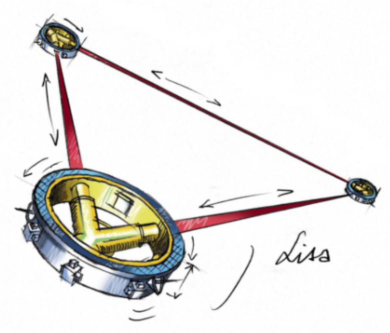
Gravitational-wave astronomy 2.0

Space-based missions: GWs produced in the early Universe

- LISA (*Laser Interferometer Space Antenna*)
- DECIGO (*Deci-Hertz Interferometer Gravitational-Wave Observatory*)
- BBO (*Big-Bang Observer*)
  - post-LISA idea
  - 3+3 satellites
  - $5 \cdot 10^4$ km arms



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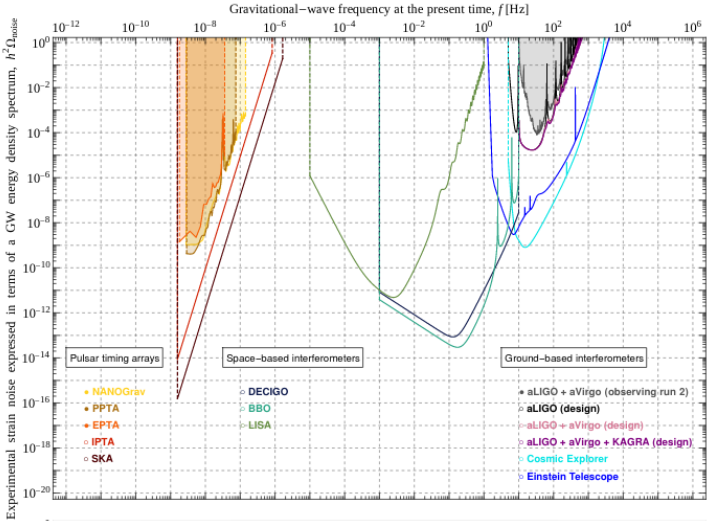
Gravitational-wave astronomy 2.0



Schmitz, 2002.04615

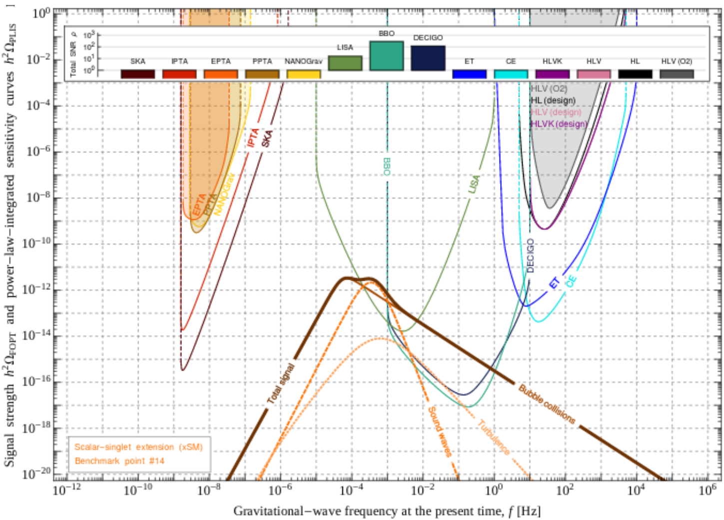
Probe on the early Universe

- Direct searches (colliders, DM, ...) of new physics so far discouraging
- On the other hand studying the cosmic background radiation has turned out very fruitful
    - Could stochastic GW backgroung turn out equally rewarding?

Probe on the early Universe

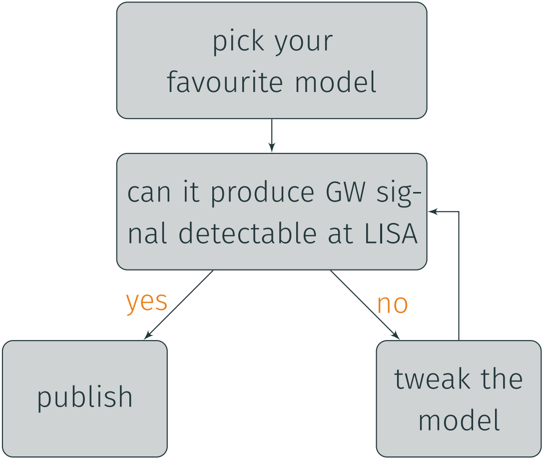
- Direct searches (colliders, DM, ...) of new physics so far discouraging
- On the other hand studying the cosmic background radiation has turned out very fruitful
    - Could stochastic GW backgroung turn out equally rewarding?
- Potential beyond the reach of current colliders
- Direct probe on beyond-SM physics
    - Strong first-oder phase transitions
    - Cosmic strings Blasi, Brdar & Schmitz, 2004.02889
    - Inflaton...

GWs from first-order phase transitions

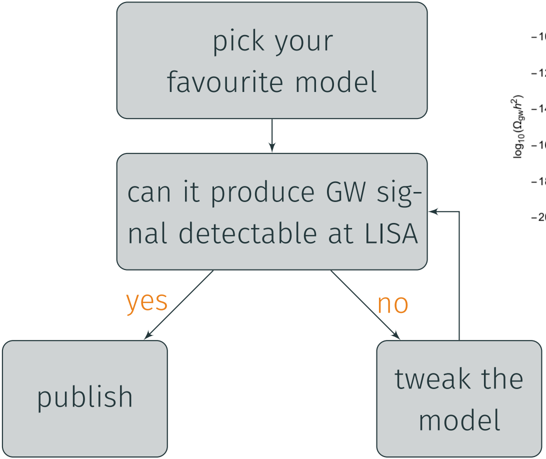


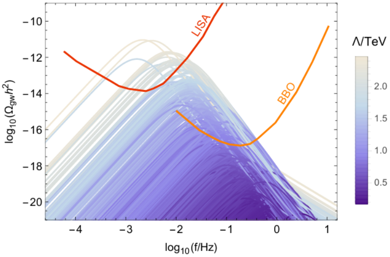
Schmitz, 2002.04615

State of the art



State of the art





Vaskonen, 1611.02073

- Importantly, many potentially interesting scenarios producing detectable GWs have been found!

Open questions

Q_1: What if a signal is detected?

- Can different models / classes of models be distinguished or at least (dis)favoured?
- Systematic study lacking

Q_2: How to get a better handle on the micro-macro connection?

- How to predict the fluid dynamics from the model parameters accurately enough?

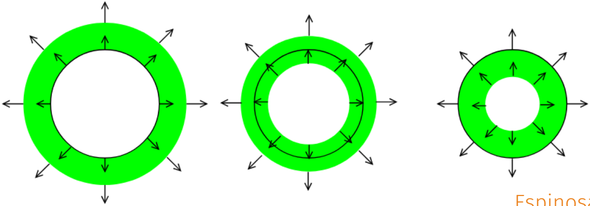
Q_3: What are the actual multi-messenger prospects?

II

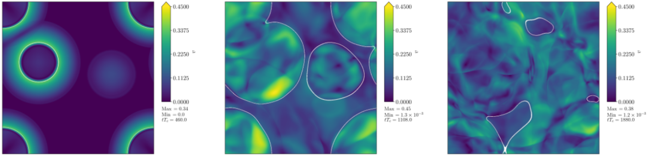
Peak-Integrated Sensitivity Curves

What happens in the plasma during SFOPT?

- Three types of transitions:
  deflagrations ($v_w < c_s$), hybrid ($v_w > c_s$), detonations ($v_w > c_s$)
  - In fluid rest frame, green: non-zero fluid velocity



Espinosa et al., 1004.4187



Cutting, Hindmarsh, Weir, 1906.00480

GW spectra from SFOPTs

- Sources
  - bubble collisions (b)
  - sound waves in the bulk plasma (s)
  - turbulence in the plasma (t)
- The corresponding spectra can be approximately computed and written in terms of peak amplitudes, Ω_i^{peak} and spectral shapes, $\mathcal{S}_i$

$$h^2\Omega_i\,(f) = h^2\Omega_i^{\text{peak}}\,(\alpha, \beta/H_*, T_*, v_w, \kappa_i)\;\mathcal{S}_i(f, f_i)$$

Peak amplitudes

The peak amplitudes have fit formulas

$$h^2\Omega_{\mathrm{b}}^{\mathrm{peak}} = 1.67 \cdot 10^{-5} \left(\frac{1}{\beta/H_*}\right)^2 \left(\frac{100}{g_*(T_*)}\right)^{\frac{1}{3}} \left(\frac{\kappa_{\mathrm{b}}\, \alpha}{1+\alpha}\right)^2 \left(\frac{0.11 v_w^3}{0.42 + v_w^2}\right)$$

$$h^2\Omega_{\mathrm{s}}^{\mathrm{peak}} = 2.65 \cdot 10^{-6} \left(\frac{v_w}{\beta/H_*}\right) \left(\frac{100}{g_*(T_*)}\right)^{\frac{1}{3}} (1-\varepsilon) \left(\frac{\kappa_v\, \alpha}{1+\alpha}\right)^2$$

$$h^2\Omega_{\mathrm{t}}^{\mathrm{peak}} = 3.35 \cdot 10^{-4} \left(\frac{v_w}{\beta/H_*}\right)^2 \left(\frac{100}{g_*(T_*)}\right)^{\frac{1}{3}} \varepsilon \left(\frac{\kappa_v\, \alpha}{1+\alpha}\right)^{\frac{3}{2}}$$

Spectral-shape functions

And likewise the spectral-shape functions

$$S_{\mathrm{b}}(f, f_{\mathrm{b}}) = \frac{3.8\,(f/f_{\mathrm{b}})^{2.8}}{1 + 2.8\,(f/f_{\mathrm{b}})^{3.8}}$$

$$S_{\mathrm{s}}(f, f_{\mathrm{s}}) = \frac{(f/f_{\mathrm{s}})^{3}}{[4/7 + 3/7\,(f/f_{\mathrm{s}})^{2}]^{\frac{7}{2}}}$$

$$S_{\mathrm{t}}(f, f_{\mathrm{t}}, h_*) = \frac{(f/f_{\mathrm{t}})^{3}}{(1 + 8\pi f/h_*)[1 + (f/f_{\mathrm{t}})]^{\frac{11}{3}}}$$

with the peak frequencies

$$f_{\mathrm{b}} = 1.6 \cdot 10^{-5}\,\mathrm{Hz} \left(\frac{g_*(T_*)}{100}\right)^{\frac{1}{6}} \left(\frac{T_*}{100\,\mathrm{GeV}}\right) \left(\frac{0.62\,\beta/H_*}{1.8 - 0.1\,v_w + v_w^2}\right)$$

$$f_{\mathrm{s}} = 1.9 \cdot 10^{-5}\,\mathrm{Hz} \left(\frac{g_*(T_*)}{100}\right)^{\frac{1}{6}} \left(\frac{T_*}{100\,\mathrm{GeV}}\right) \left(\frac{\beta/H_*}{v_w}\right)$$

$$f_{\mathrm{t}} = 2.7 \cdot 10^{-5}\,\mathrm{Hz} \left(\frac{g_*(T_*)}{100}\right)^{\frac{1}{6}} \left(\frac{T_*}{100\,\mathrm{GeV}}\right) \left(\frac{\beta/H_*}{v_w}\right)$$

Signal-to-noise ratio

- SNR defined by

$$\rho = \left[n_{\mathrm{det}} \frac{t_{\mathrm{obs}}}{s} \int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} \frac{\mathrm{d}f}{\mathrm{Hz}} \left(\frac{h^2 \Omega_{\mathrm{signal}}(f)}{h^2 \Omega_{\mathrm{noise}}(f)} \right)^2 \right]^{1/2} .$$

  - $n_{\mathrm{det}} = 1$ for LISA (auto-correlation), $n_{\mathrm{det}} = 2$ for DECIGO (?) and BBO (cross-correlation)

SNR rewritten

- SNR can be rewritten as

$$\frac{\rho^2}{t_{\mathrm{obs}}/\mathrm{yr}} = \left(\frac{h^2\Omega_{\mathrm{b}}^{\mathrm{peak}}}{h^2\Omega_{\mathrm{PIS}}^{\mathrm{b}}}\right)^2 + \left(\frac{h^2\Omega_{\mathrm{s}}^{\mathrm{peak}}}{h^2\Omega_{\mathrm{PIS}}^{\mathrm{s}}}\right)^2 + \left(\frac{h^2\Omega_{\mathrm{t}}^{\mathrm{peak}}}{h^2\Omega_{\mathrm{PIS}}^{\mathrm{t}}}\right)^2 + \left(\frac{h^2\Omega_{\mathrm{b/s}}^{\mathrm{peak}}}{h^2\Omega_{\mathrm{PIS}}^{\mathrm{b/s}}}\right)^2 + \left(\frac{h^2\Omega_{\mathrm{s/t}}^{\mathrm{peak}}}{h^2\Omega_{\mathrm{PIS}}^{\mathrm{s/t}}}\right)^2 + \left(\frac{h^2\Omega_{\mathrm{b/t}}^{\mathrm{peak}}}{h^2\Omega_{\mathrm{PIS}}^{\mathrm{b/t}}}\right)^2$$

- The integration over the frequency range has already been carried out implicitly

$$h^2\Omega_{\mathrm{PIS}}^{i/j} \equiv \left[(2-\delta_{ij})\, n_{\mathrm{det}}\, 1\,\mathrm{yr} \int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} \mathrm{d}f\, \frac{S_i(f)\, S_j(f)}{\left(h^2\Omega_{\mathrm{noise}}(f)\right)^2}\right]^{-1/2}$$

- The mixed peak amplitudes are defined as the respective geometric means, $h^2\Omega_{i/j}^{\mathrm{peak}} = \left(h^2\Omega_i^{\mathrm{peak}}\, h^2\Omega_j^{\mathrm{peak}}\right)^{1/2}$

III

Benchmark data

Singlet extension of the SM

- Add a real singlet scalar to the SM

$$V_{\mathrm{tree}} = \left(\mu_H^2 + \mu_{HS} S + \frac{1}{2}\lambda_{HS} S^2\right) |H|^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{3}\mu_3 S^3 + \lambda_H |H|^4 + \frac{1}{4}\lambda_S S^4$$

- Theoretical constraints
    - Boundedness from below & vacuum stability
    - Perturbative unitarity
- Complementary experimental constraints
    - Higgs couplings
    - EW precision

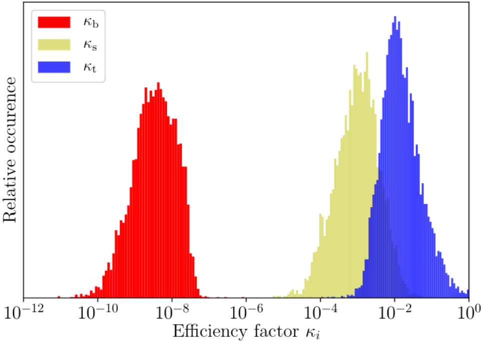
Sample of Benchmark parameters

- We generate a sample of ~ 6000 characteristic points

$$
\begin{aligned}
v_s &\in [-2\,v_h,\; 2\,v_h] \\
m_s &\in [1\,\text{GeV},\; 10\,\text{TeV}] \\
\theta &\in [-0.5,\; 0.5] \\
\mu_3 &\in [-10\,v_h,\; 10\,v_h] \\
\lambda_S &\in [0.001,\; 5]
\end{aligned}
$$

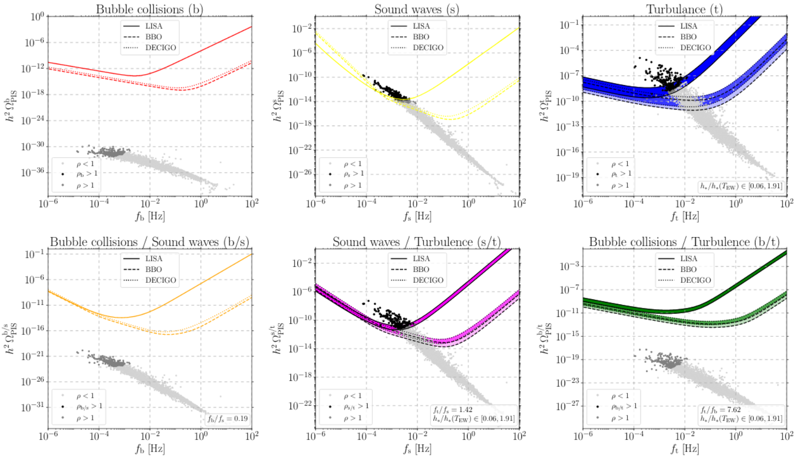
- We fix $v_w = 0.9$, $\rho_{\text{thr}} = 1$, $t_{\text{obs}} = 1$ yr
- Goal here is not to exhaustively study the parameter space, but rather illustrate the method

Efficiencies for energy conversion



- We use the upper limit for the turbulence factor from
  Ellis et al., 1903.09642
  - This likely overestimates the turbulence fraction, but this is an open question
  - However, shows that the turbulence can be very relevant
- $v_w = 0.9$ to increase the GW signal
  - Most transitions detonation types
  - For lower wall velocities, especially deflagrations, sound wave contribution can be significantly suppressed
    Cutting, Hindmarsh, Weir, 1906.00480

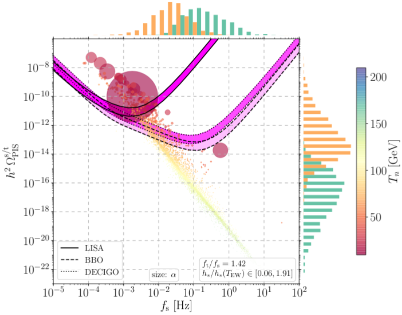
PISC

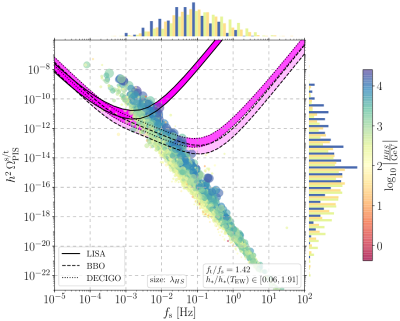


- black: detectable in this channel, dark gray: combined SNR above the threshold, light gray: undetectable

Parameter space

- Signal region for the most restrictive channel (s/t)



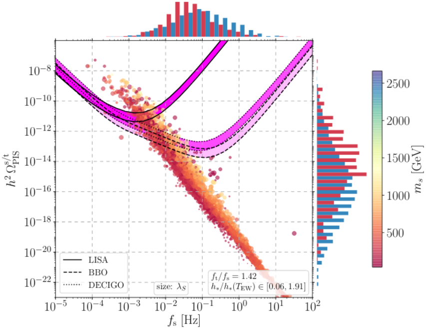


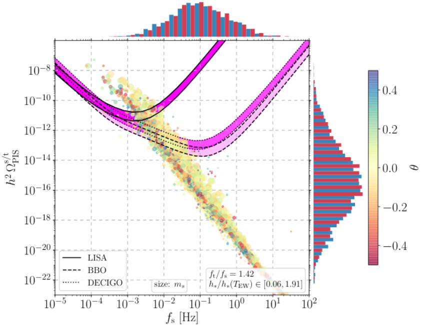
orange: $T_n < 100$ GeV
green: $T_n > 100$ GeV
size: α

blue: $\mu_{HS} > 5$ TeV
green: 500 GeV$< \mu_{HS} < 5$ TeV
orange: $\mu_{HS} < 500$ GeV

size: λ_{HS}

Parameter space





blue: $m_s > 200$ GeV
red: $m_s < 200$ GeV

size: λ_S

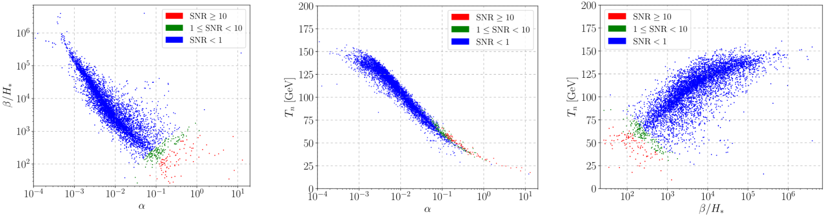
blue: $\theta > 0$
red: $\theta < 0$

size: m_s

IV

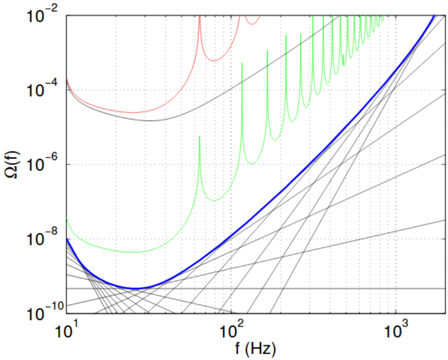
Comparison with existing approaches

α, β & T_n



- Cross check: agrees with previous studies Alves et al., 1812.09333
- Some level of degeneracy wrt SNR
- Studying the model parameter space less straightforward

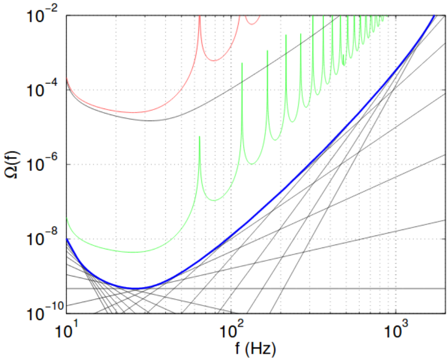
Power-law integrated sensitivity curves



Thrane & Romano, 1310.5300

- black: single-detector sensitivity
  red: H-L detector pair
  green: one-year integrated

Power-law integrated sensitivity curves



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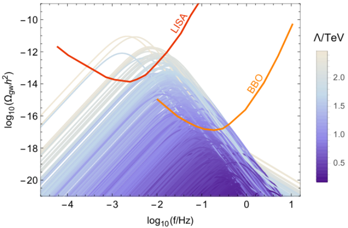

Vaskonen, 1611.02073

- black: single-detector sensitivity
  red: H-L detector pair
  green: one-year integrated

Comparison with existing approaches

- PISCs only depend on the experimental noise spectra and spectral shape functions
  - They represent truly *experimental* quantities that are insensitive to uncertainties on the theory side
  - Does not depend, e.g., on how we compute the parameters α, β/H_*, and T_n
- Varying $\rho_{\rm thr}$ easy: just Δy in the PICS plots
- Straightforward to generalize to other signal shapes
  - The GW signal from inflation or cosmic strings can be described by a large range of different shapes, depending on the underlying model $\Rightarrow$ Not possible to construct a universally applicable sensitivity curve.
  - However, possible if restricted to a more model-dependent analysis

Comparison with existing approaches

- Allows for an easy comparison of the six different signal channels (s, b, t, s/b, s/t, b/t)
    - Illustrate the relative importance of these six channels
    - Allows to study study the impact of change in one component at a time
- To generate traditional SNR plots, one has to compute the frequency integral for every parameter point in every model
    - Computationally expensive and unnecessary
    - Instead, it suffices to restrict oneself to the peak amplitudes and peak frequencies which then need to be evaluated for each point in the data set

Conclusions

- The next-generation space-based GW missions have an intriguing potential to probe new physics beyond the reach of the current colliders
- To use this potential, one needs also next-generation research
    - Discriminating power, fluid dynamics, multi-messenger probes
    - Systematic studies on different classes of models needed
- We proposed a novel way to illustrate the GW signal region
    - Scatter plots in the plane of peak frequencies and peak amplitudes similar to those seen in DM direct-detection experiments
    - The spectral shape of the signal integrated out
    - Allows to study the model parameter space easily on the GW signal region