

Gravitational Wave Signals

Marek Lewicki

University of Warsaw

Terrestrial Very-Long-Baseline Atom Interferometry Workshop,
CERN, 13 III 2023

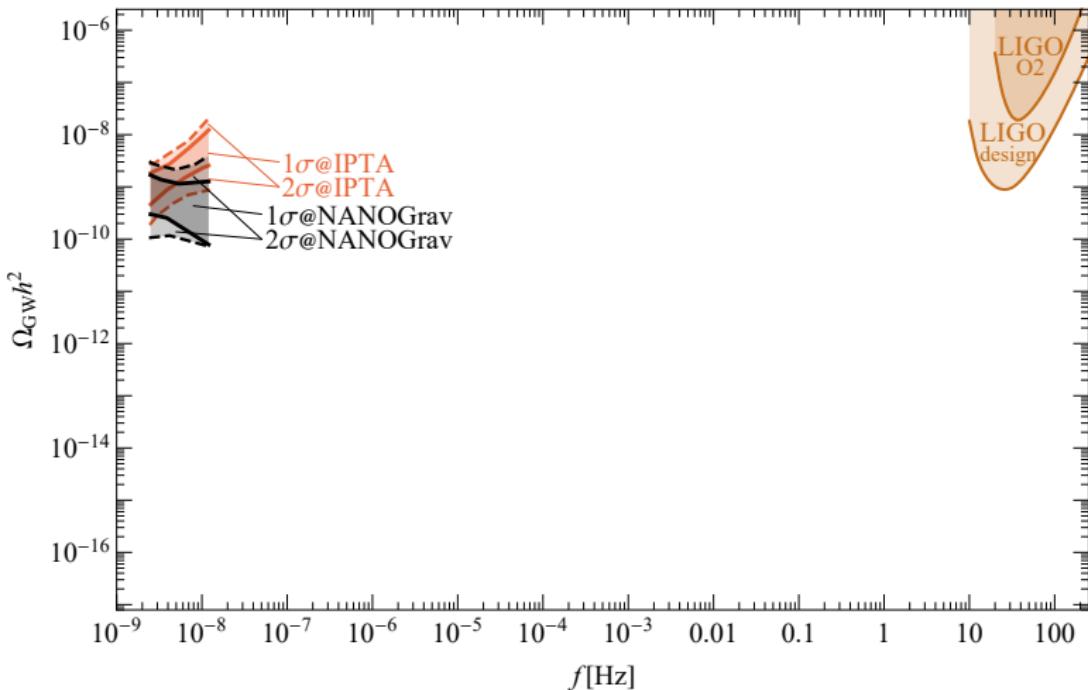
POLSKIE POWROTY
POLISH RETURNS

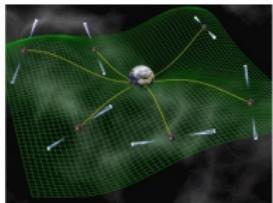
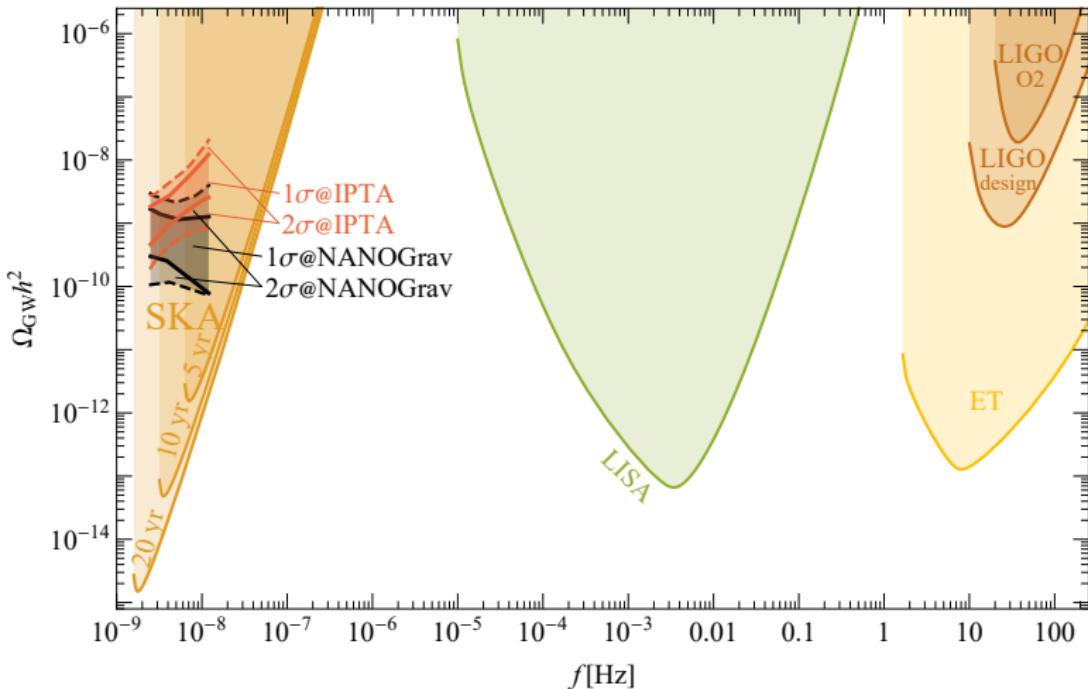


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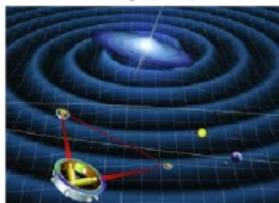
National
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Poland





Pulsar Timing

[David Champion/NASA/JPL]



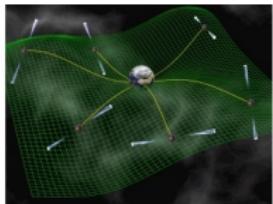
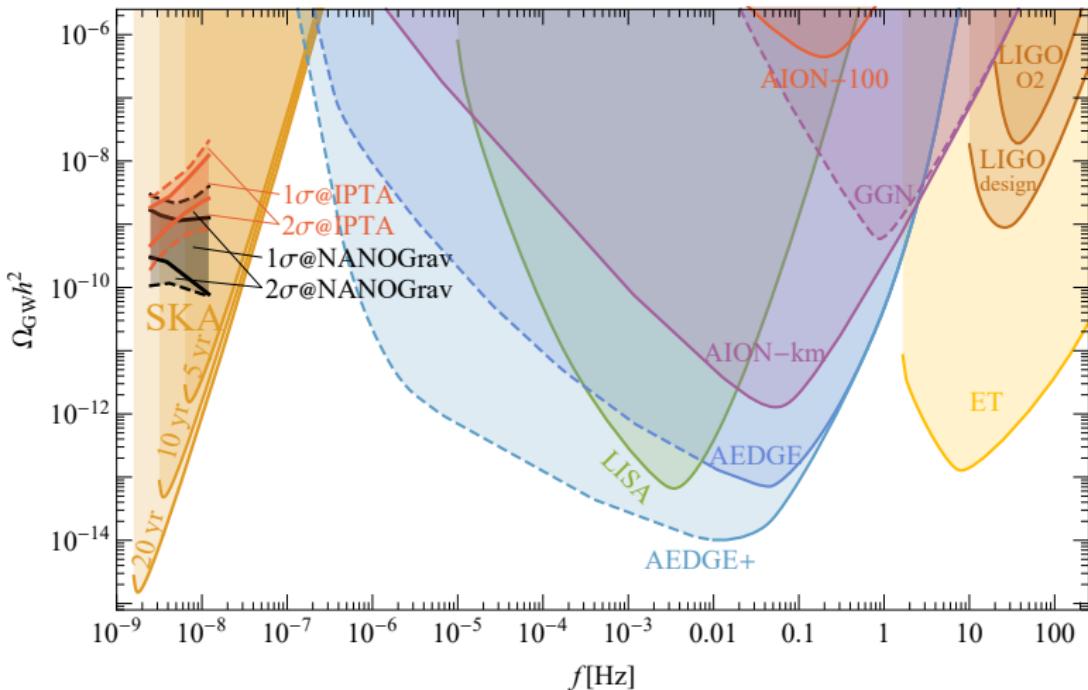
LISA

[wiki/Laser_Interferometer_Space_Antenna](https://en.wikipedia.org/wiki/Laser_Interferometer_Space_Antenna)



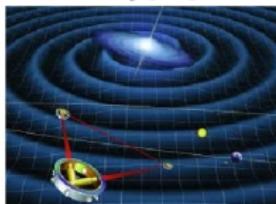
Einstein Telescope

www.et-gw.eu

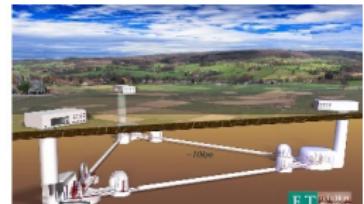


Pulsar Timing

[David Champion/NASA/JPL]



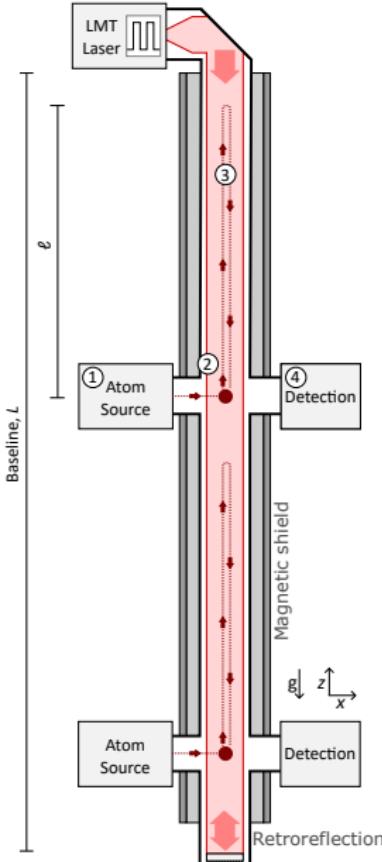
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Einstein Telescope
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- The presence of a gravitational wave modulates the separation distance L , giving rise to time variations in phase shift between the interferometers.
- Sensitivity scales with number of interferometers

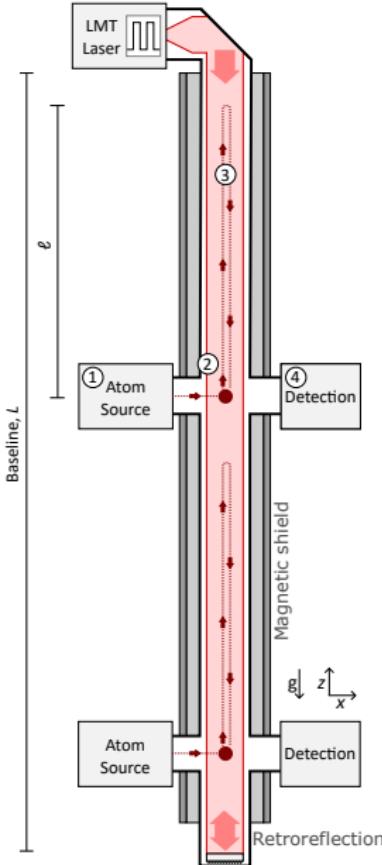
$$h \propto \frac{1}{\sqrt{N}}, \quad \Omega_{\text{GW}} \propto \frac{1}{N}$$



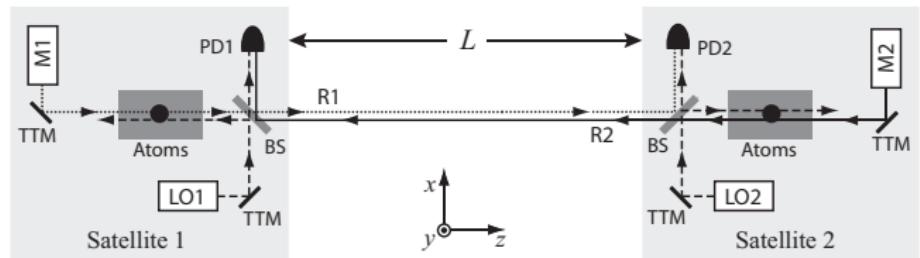
Sensitivity Scenario	L [m]	T [sec]	$\delta\phi_{\text{noise}}$ [$1/\sqrt{\text{Hz}}$]	LMT [number n]
AION-10	10	1.4	10^{-4}	1000
AION-100	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000

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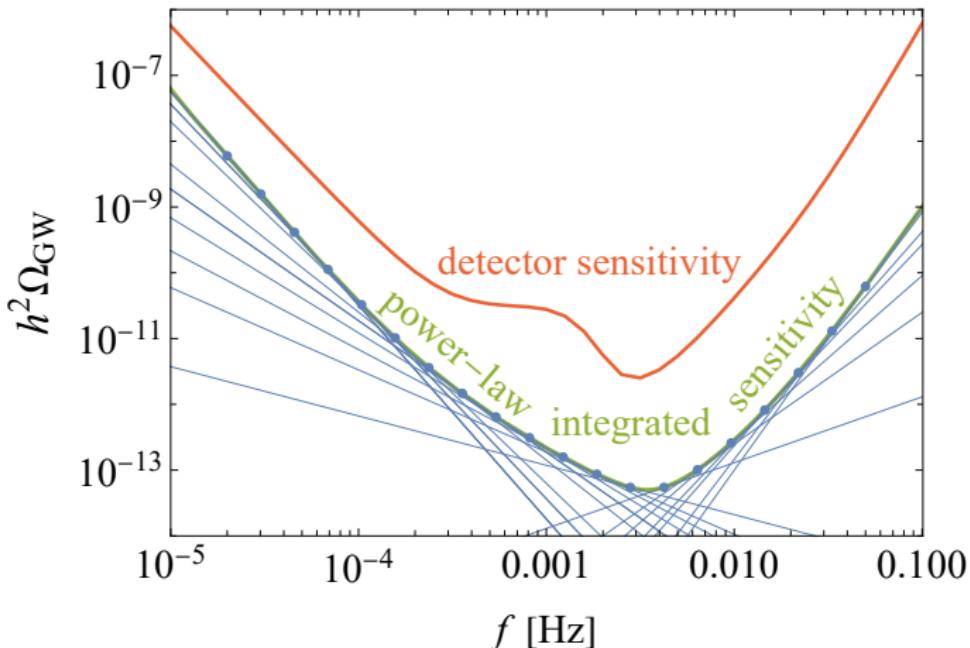


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AEDGE	4.4×10^7	300	10^{-5}	1000

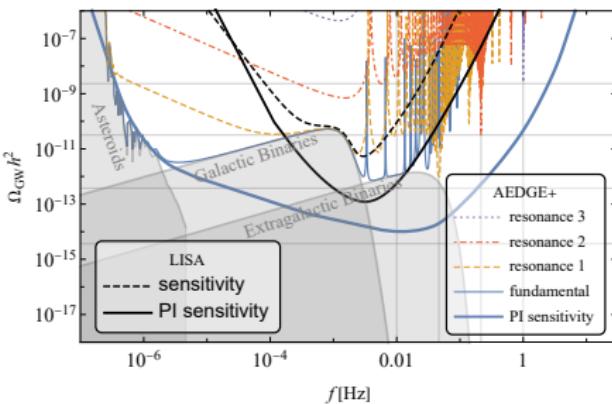
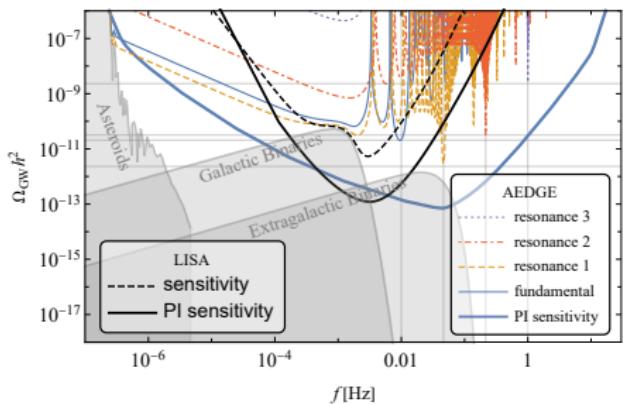


Power-law integrated sensitivity

$$\Omega_{\text{GW}}^{\text{noise}} = \frac{2\pi}{3} \frac{f^3 h_c^2}{H_0^2}, \quad \text{SNR} = \sqrt{\mathcal{T} \int df \left(\frac{\Omega_{\text{GW}}^{\text{signal}}}{\Omega_{\text{GW}}^{\text{noise}}} \right)^2}, \quad \Omega_{\text{GW}}^{\text{signal}} = \Omega \left(\frac{f}{f_{\text{ref}}} \right)^\alpha$$

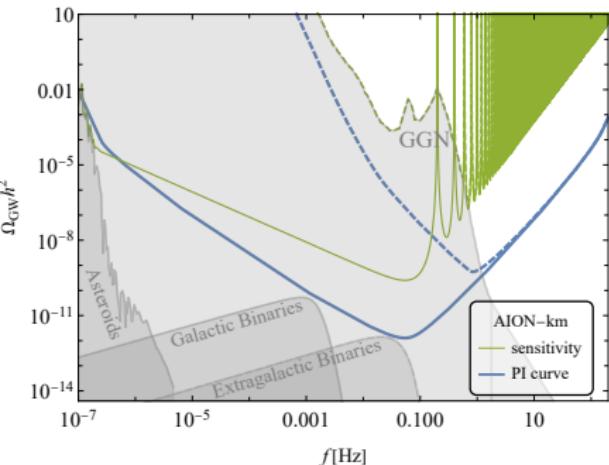
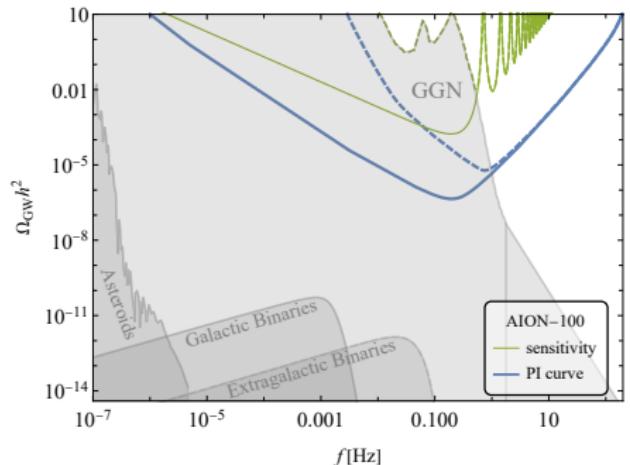


AEDGE noise sources



- Thin lines: instantaneous sensitivity of operation modes
- Thick lines: Power-Law integrated sensitivities

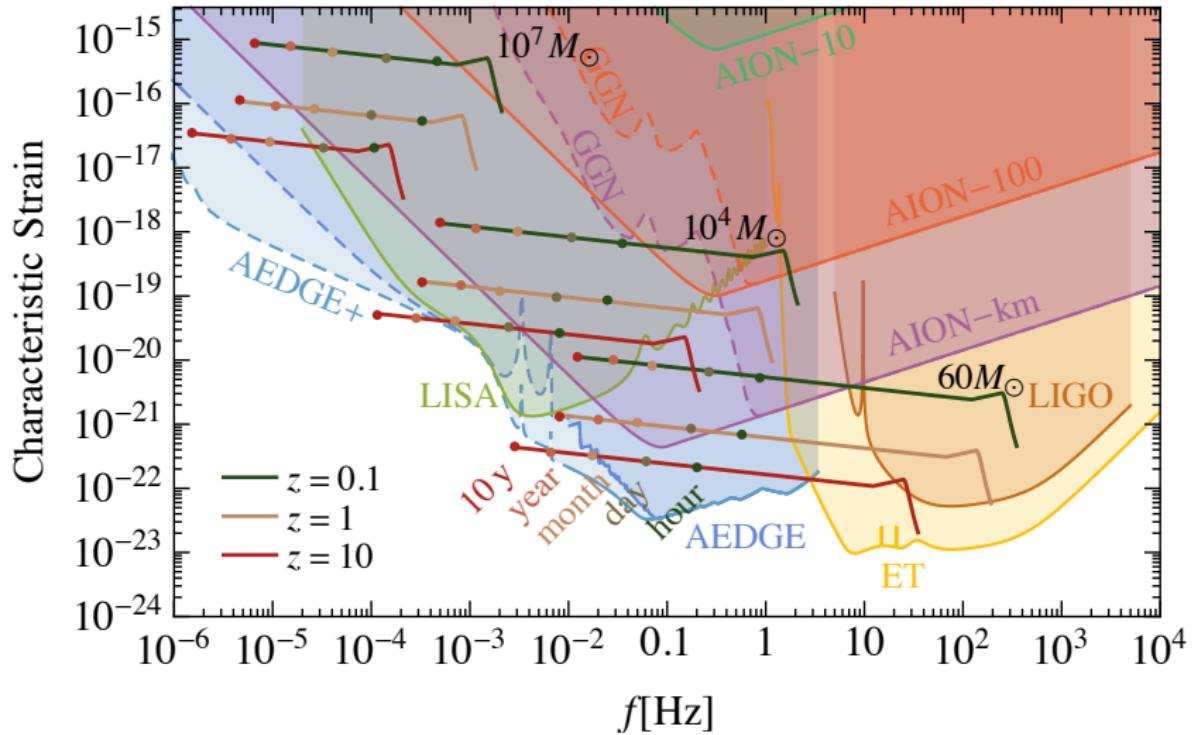
AION noise sources



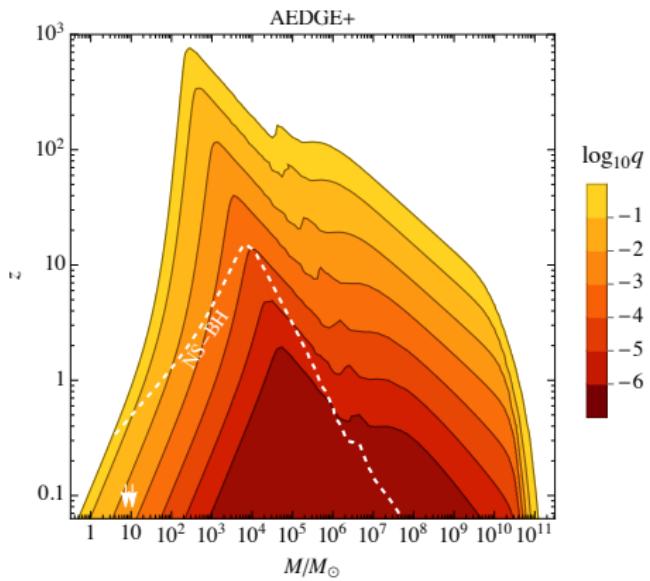
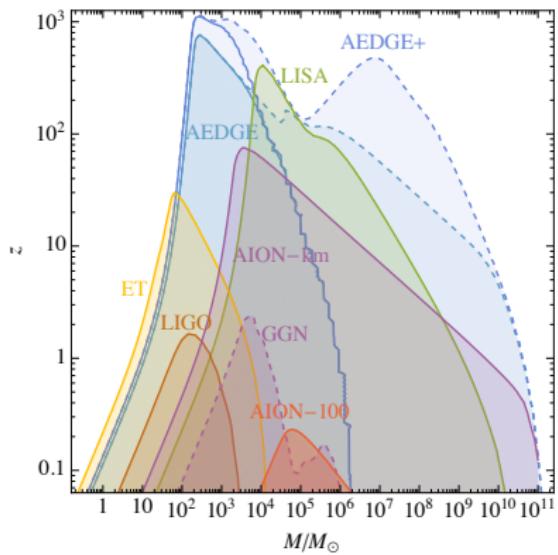
- Solid lines: sensitivity of the detector from amplitude of the phase shift
- Dashed lines: amplitude of the GGN noise from NLNM

$$S_{h\text{GGN}} \propto 1/(\sqrt{NL})$$

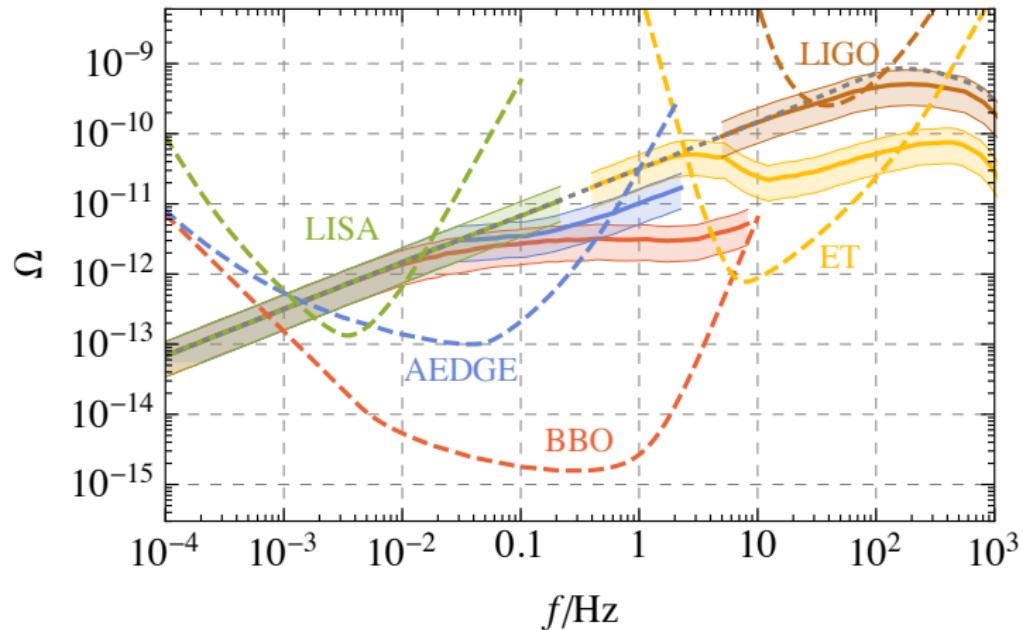
Sensitivity to binary mergers



Sensitivity to binary mergers



Foreground from LIGO-Virgo binaries

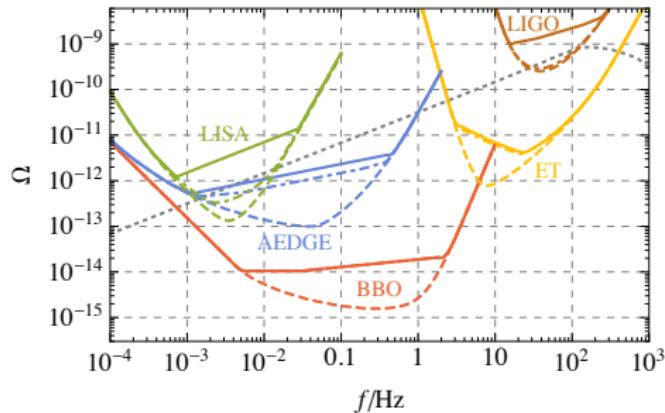


- Dashed gray line: total foreground from LIGO-Virgo binaries
- Thick lines: foreground without individually observable binaries

Improved sensitivities from Fisher analysis

- assuming power-law signal as in PI sensitivity

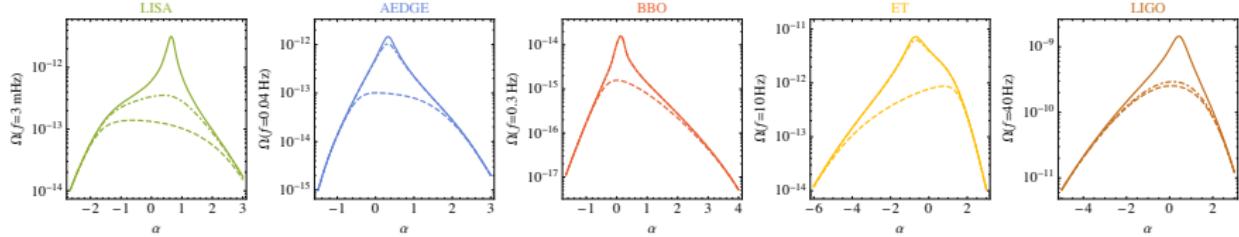
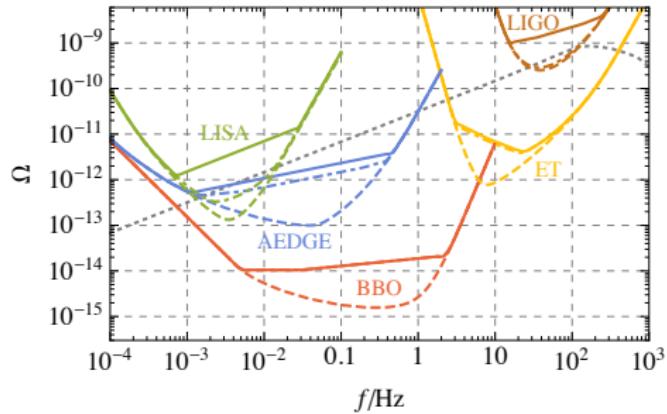
$$\Omega_{\text{GW}}(f) = \Omega \left(\frac{f}{f_{\text{ref}}} \right)^{\alpha} + A \langle \Omega_{\text{BBH}}(f) \rangle + \Omega_{\text{BWD}}(f) + \Omega_{\text{instr}}(f)$$



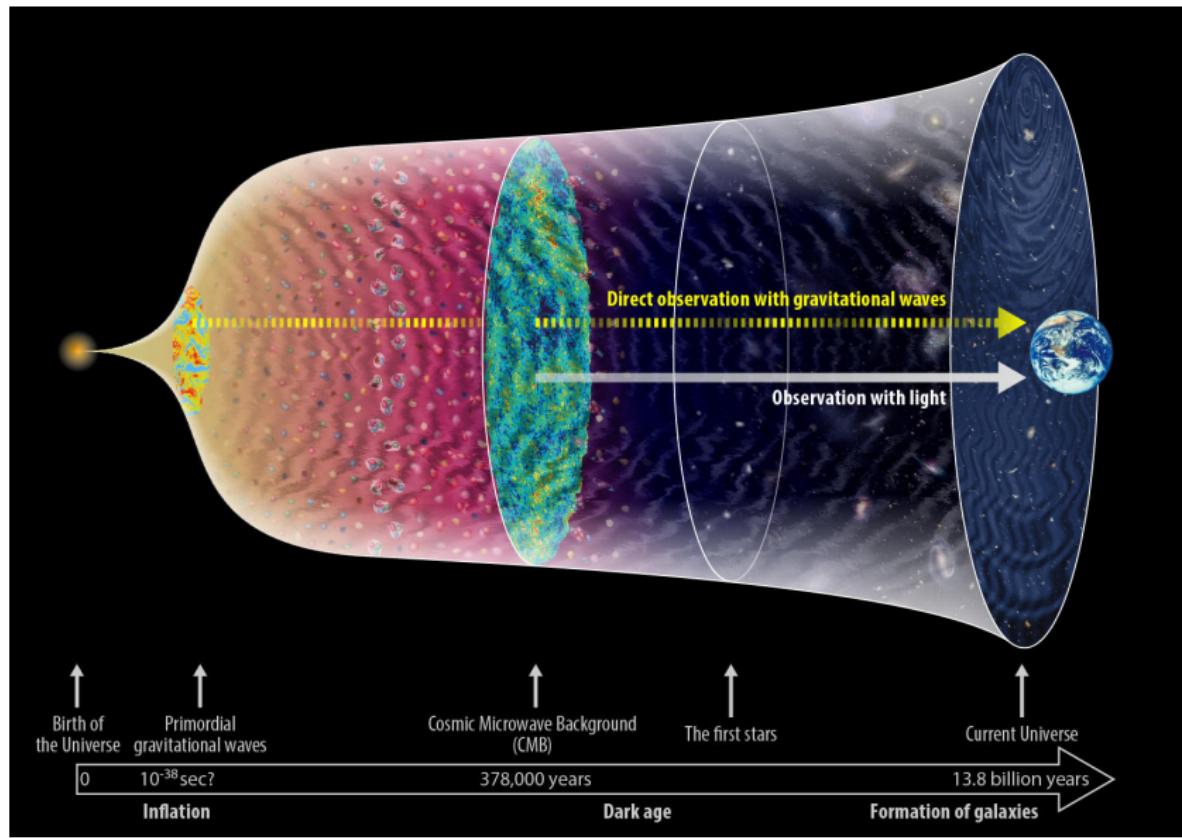
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Early Universe Sources

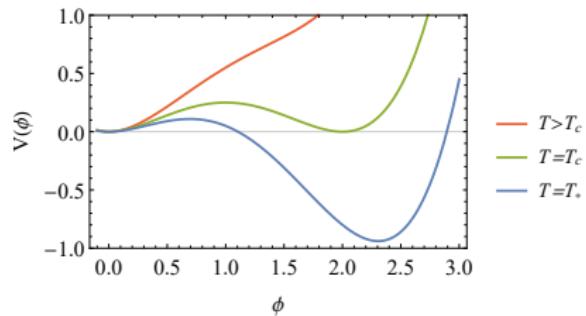


plot credit:<https://gwpo.nao.ac.jp/en/gallery>

First Order Phase Transition

- Simple high temperature expansion

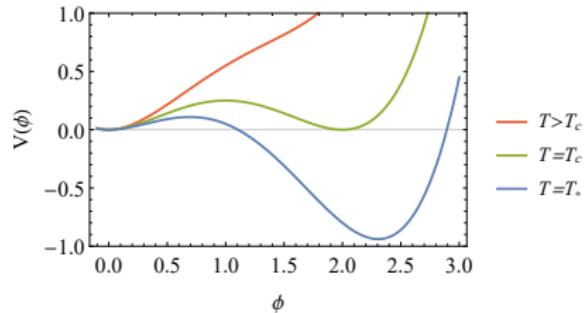
$$V(\phi, T) = \frac{g_m^2}{24} (T^2 - T_0^2) \phi^2 - \frac{g_m}{12\pi} T \phi^3 + \lambda \phi^4, \quad T_0^2 > 0$$



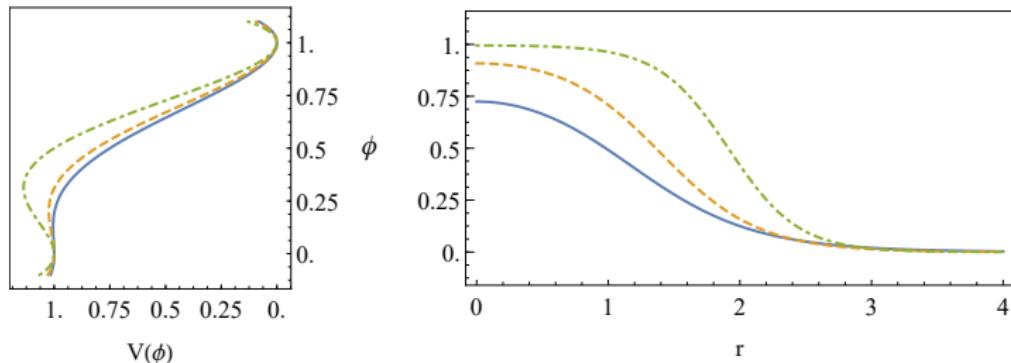
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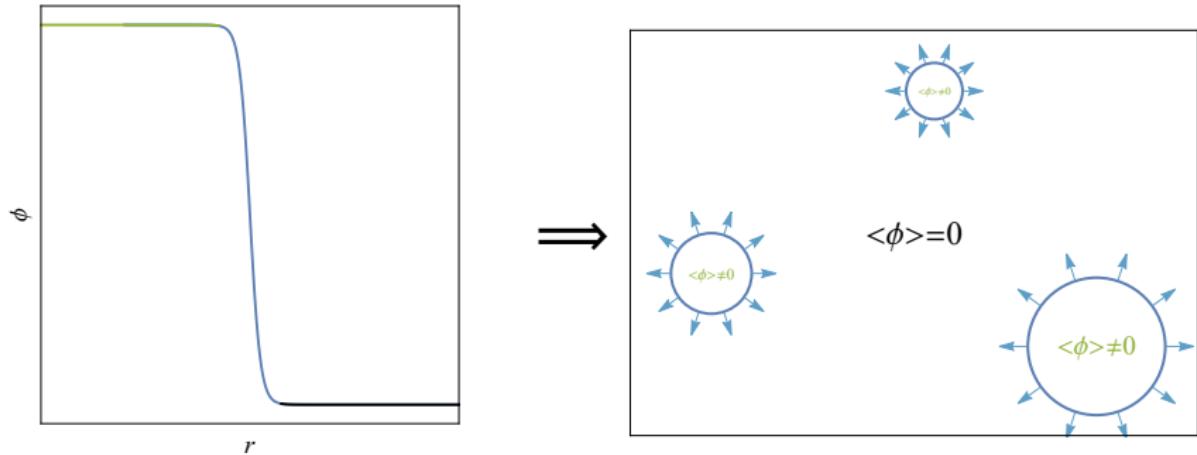
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- Eventually the barrier becomes small enough that bubbles can nucleate



First Order Phase Transition



- Strength of the transition

$$\alpha \approx \left. \frac{\Delta V}{\rho R} \right|_{T=T_*}, \quad \Delta V = V_f - V_t$$

- Characteristic scale

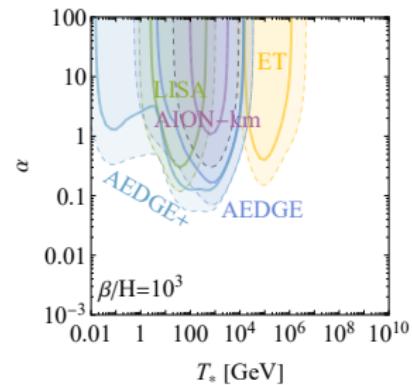
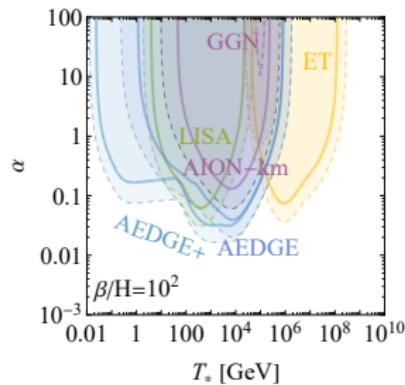
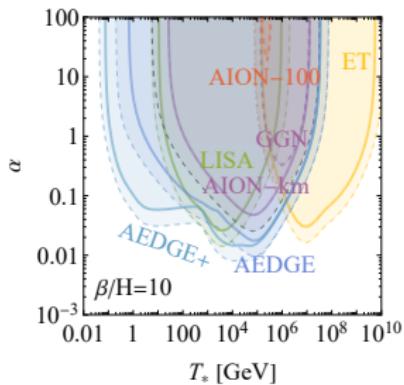
$$HR_* = (8\pi)^{\frac{1}{3}} \left(\frac{\beta}{H} \right)^{-1}$$

Reach of upcoming experiments

- Position of the peak

$$\Omega_{\text{peak}} \propto \left(\frac{\alpha}{\alpha + 1} \right)^2 (HR_*)^2, \quad f_{\text{peak}} \propto T_* (HR_*)^{-1}$$

- Detectability assuming plasma related sources

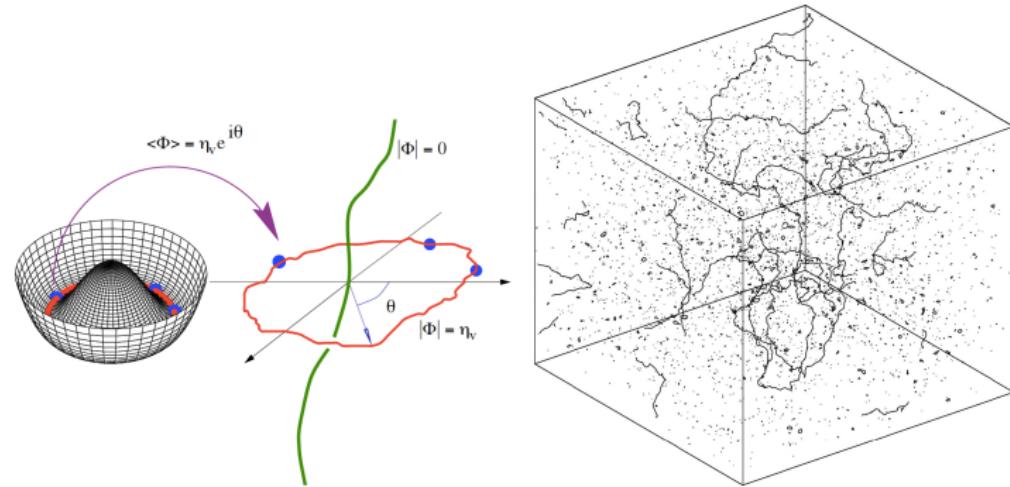


Cosmic Strings

- Charged complex scalar field

$$V = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$

- Horizon size at early time (high temperature) $d_H \propto M_p/T^2$

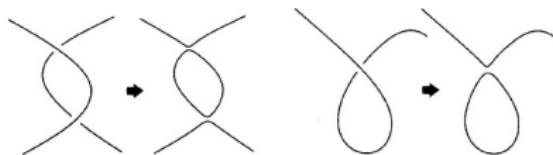


Cosmic String network evolution

- Static string network would red-shift as

$$\rho_\infty \propto a^{-2}$$

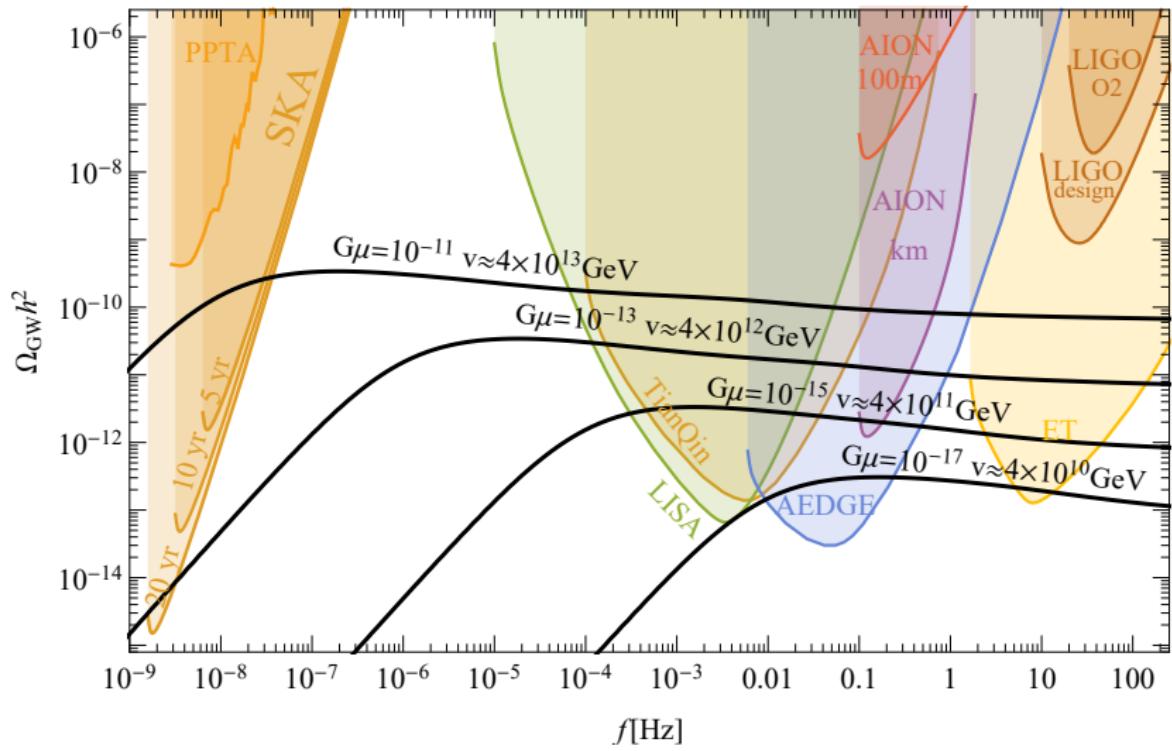
- strings intercommute on collision



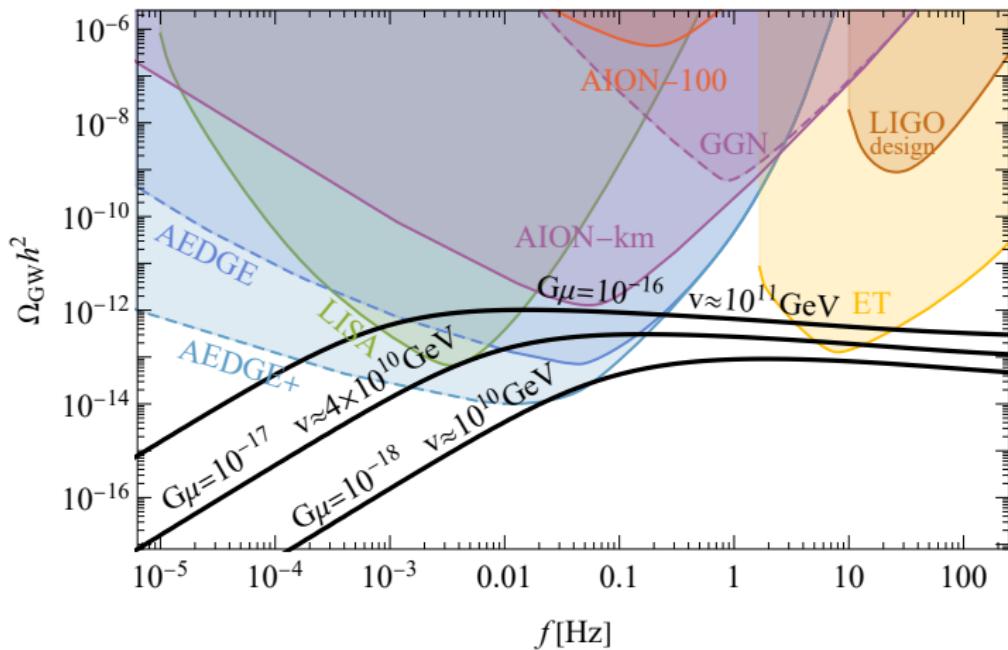
- overall energy density of the network scales with total energy density

$$\frac{\rho_\infty}{\rho_{\text{tot}}} \propto G\mu \propto \frac{v^2}{M_p^2}$$

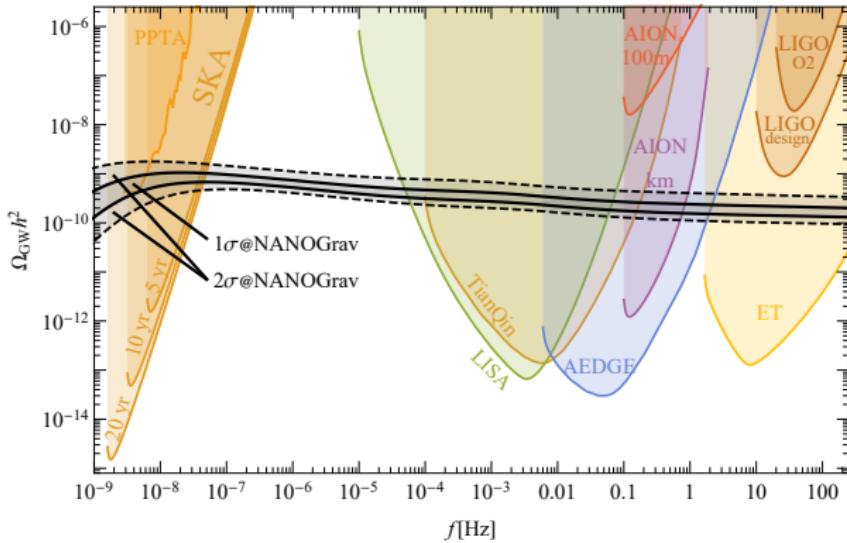
Stochastic GW background from Cosmic Strings



Stochastic GW background from Cosmic Strings



Cosmic String fit to NANOGrav data



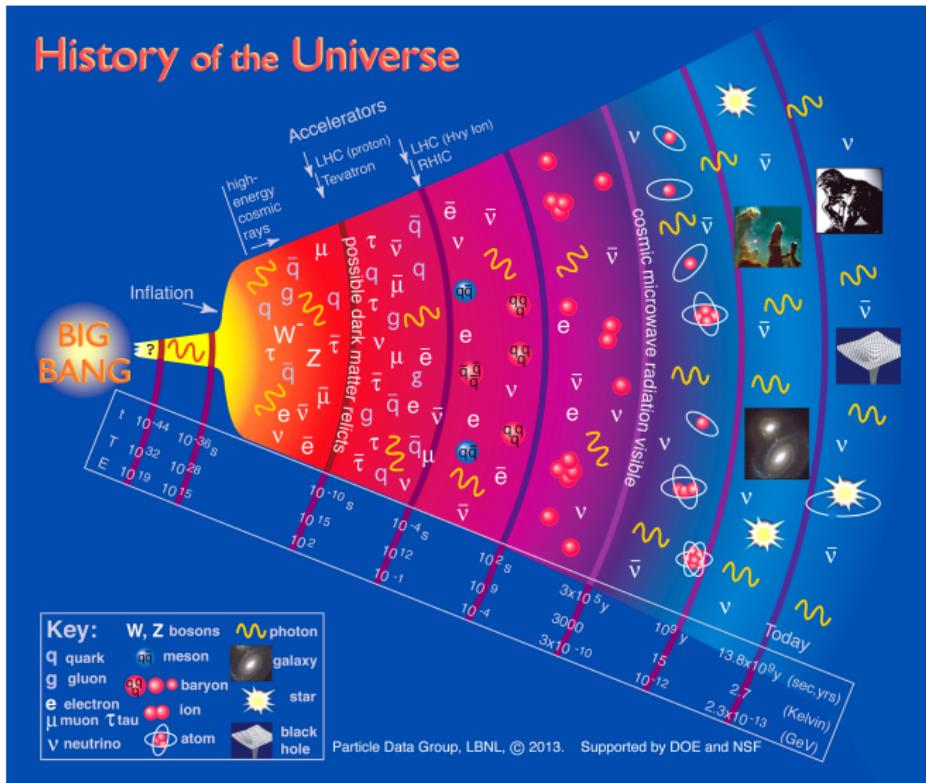
- results within the 68% CL

$$G\mu \in (4 \times 10^{-11}, 10^{-10})$$

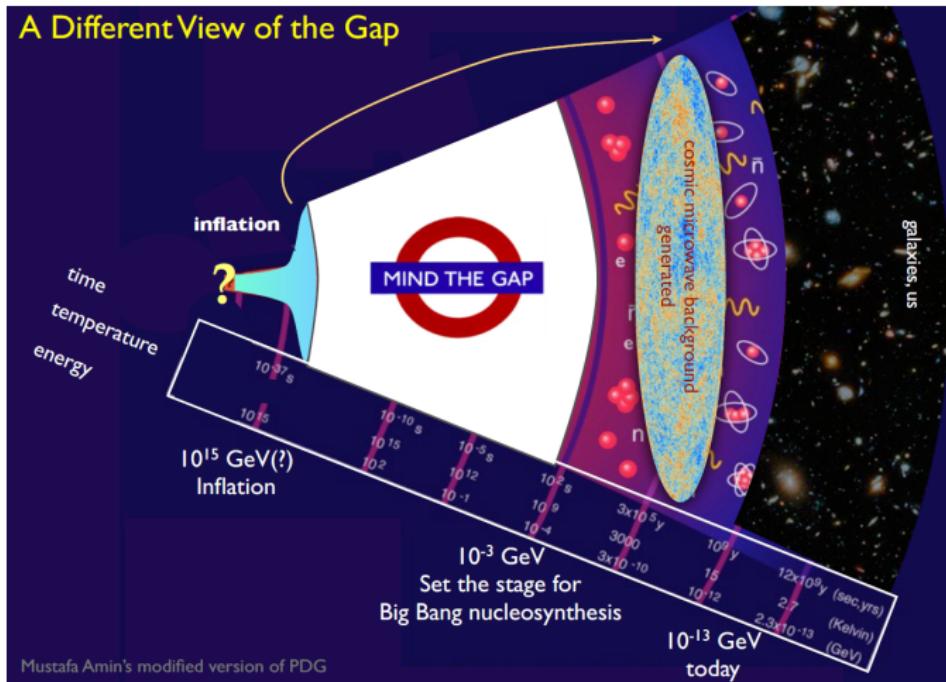
- results within the 95% CL

$$G\mu \in (2 \times 10^{-11}, 3 \times 10^{-10})$$

Cosmic Archaeology



Cosmic Archaeology

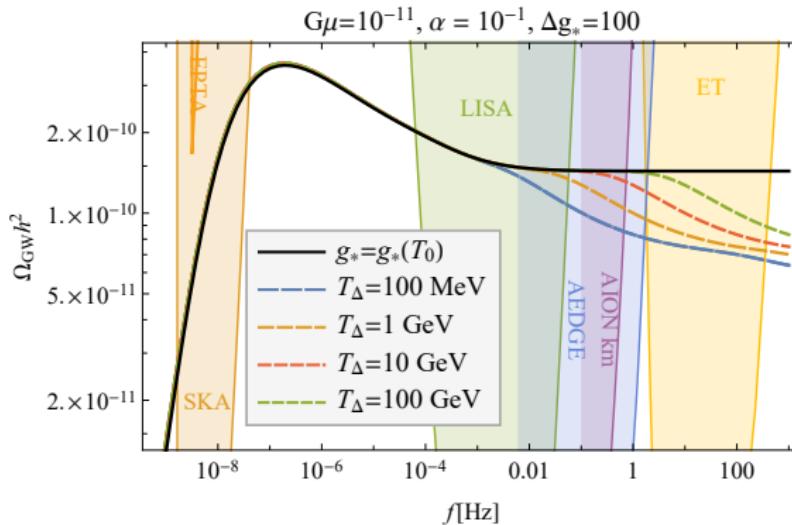


Cosmic Strings GW signal and expansion history

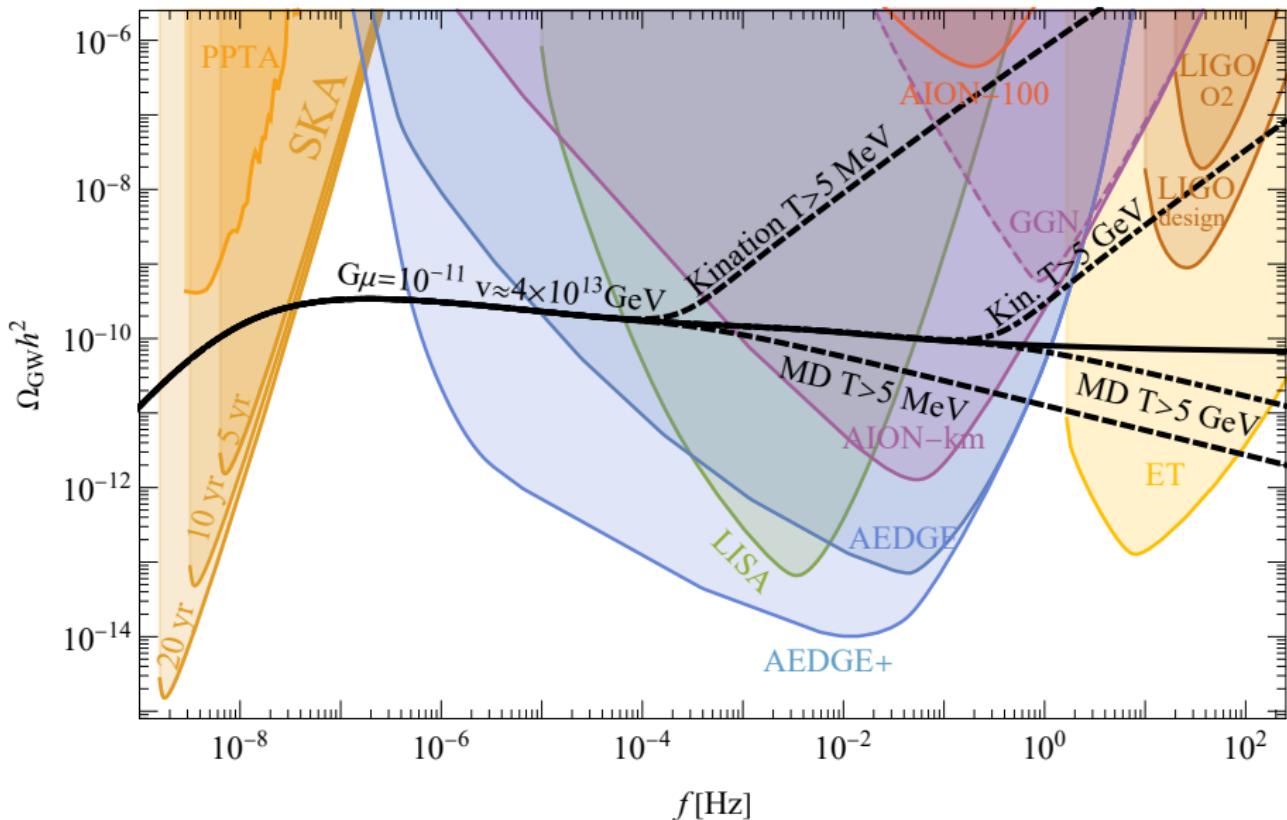
- We add Δg_* new degrees of freedom at T_Δ

$$g_*(T) = \begin{cases} g_*(T_0) & \text{for } T < T_\Delta \\ g_*(T_0) + \Delta g_* & \text{for } T > T_\Delta \end{cases}$$

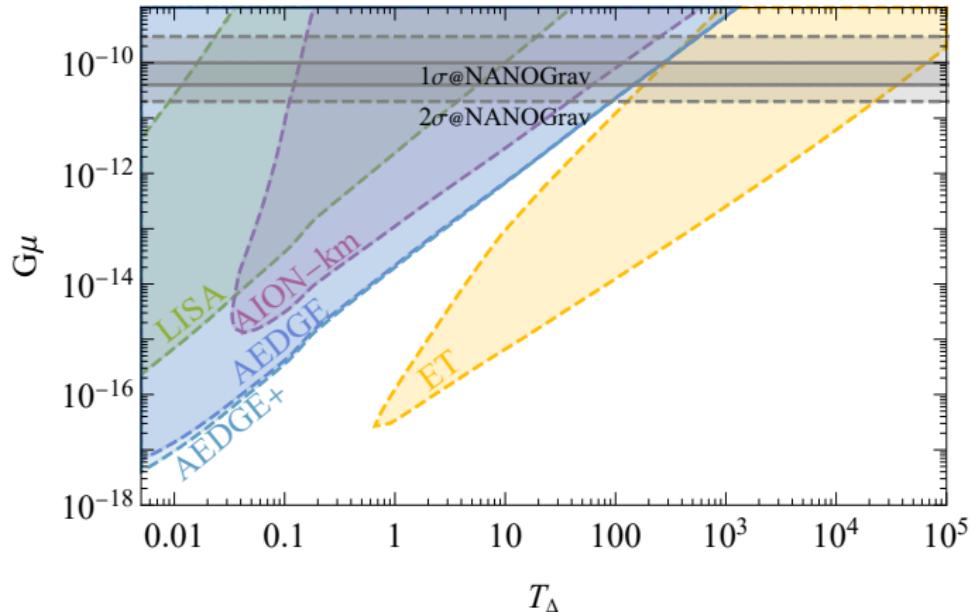
- An example with $\Delta g_* = 100$



Cosmic Strings GW signal and expansion history



Detection capabilities



- frequency of the modification

$$f_\Delta = (8.67 \times 10^{-9} \text{ Hz}) \frac{T_\Delta/\text{GeV}}{\sqrt{\alpha G\mu}} \left(\frac{g_*(T_\Delta)}{g_*(T_0)} \right)^{\frac{8}{6}} \left(\frac{g_S(T_0)}{g_S(T_\Delta)} \right)^{-\frac{7}{6}}$$

Conclusions

- Probing the mid frequency band is optimal for probing collisions of black holes with masses between those detected by LIGO and super massive black holes that may be observed by LISA, as well as earlier evolution of LIGO binaries paving the way to multi messenger astronomy.
- AION and AEDGE would be optimal in searching for phase transitions occurring at $T_* \approx 10^4$ GeV.
- Wide coverage in frequencies is crucial for probing the evolution of the Universe via GW signals from cosmic strings.