Cosmic String Interpretation of NANOGrav Pulsar Timing Data and its impact on Cosmic Archaeology with Gravitational Waves

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University of Warsaw

TU Dresden, 20 V 2021

Based on:

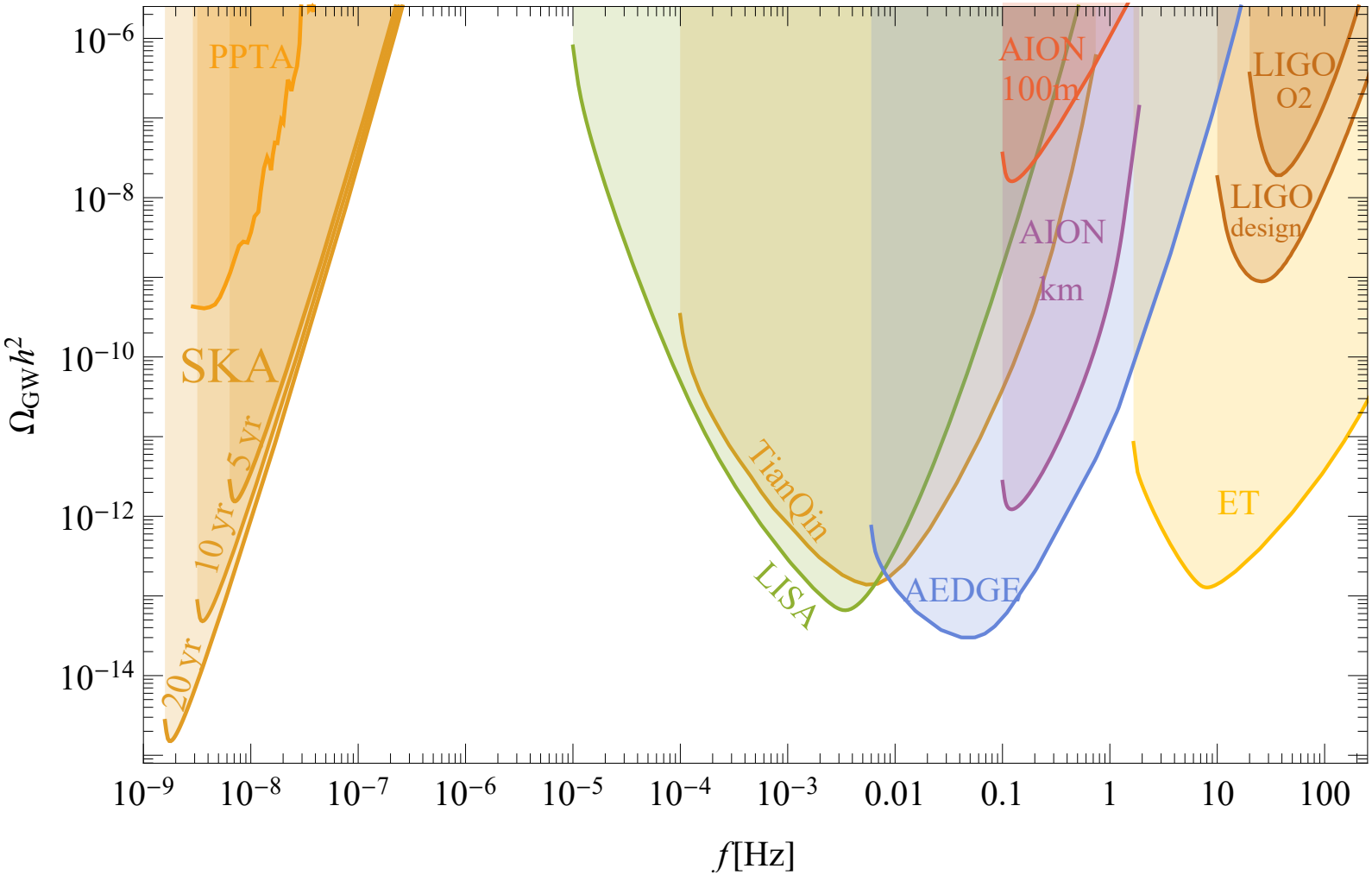
J. Ellis, ML arXiv: 2009.06555

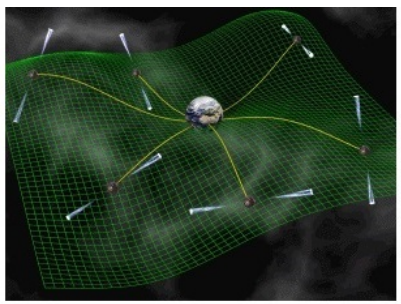
Y. Cui, D. Morrissey and ML arXiv: 1912.08832

Y. Cui, D. Morrissey, ML and J. D. Wells arXiv: 1711.03104, 1808.08968

Plan

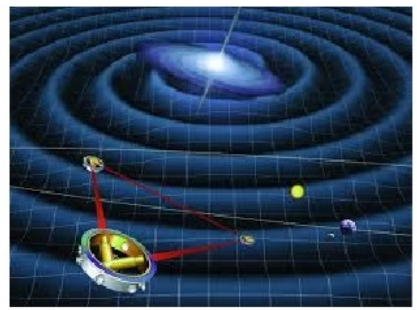
- Introduction: Stochastic GW background from Cosmic Strings
- Cosmic String Interpretation of NANOGrav Pulsar Timing Data
- Cosmic Archaeology
  - Probing the expansion history of the Universe with cosmic strings
  - Strings diluted by inflation
- Conclusions





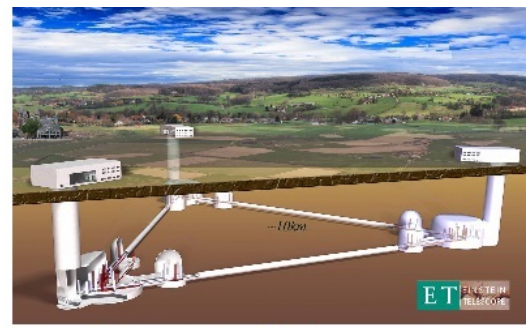
Pulsar Timing

[David Champion/NASA/JPL]



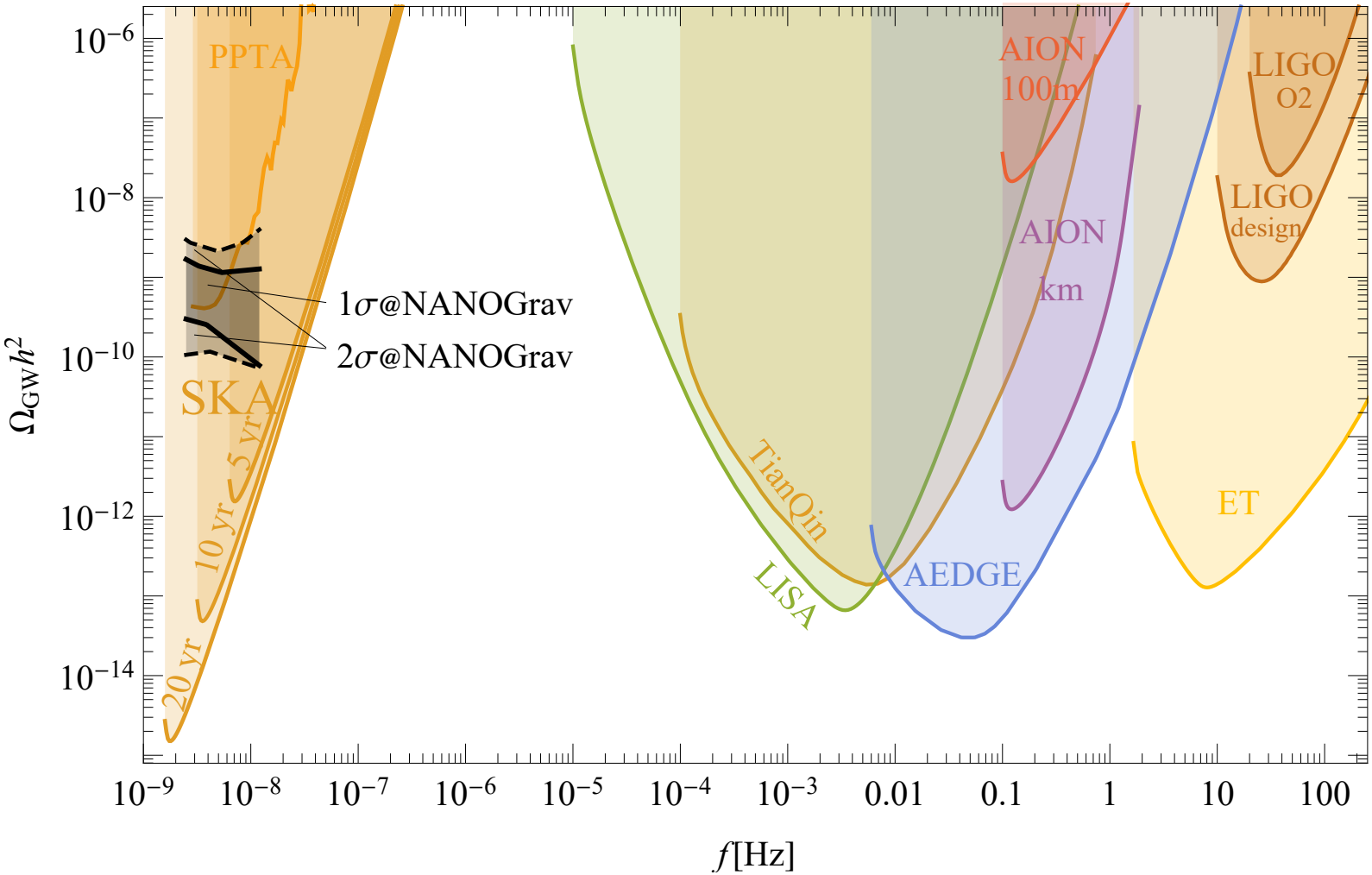
LISA

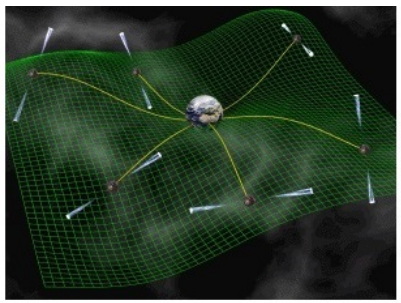
wiki/Laser_Interferometer_Space_Antenna



Einstein Telescope

www.et-gw.eu





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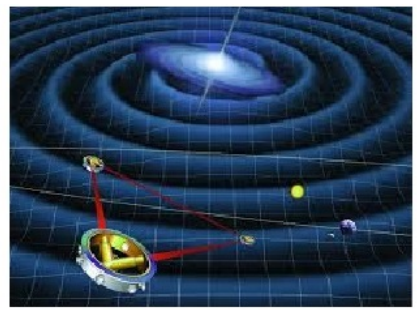

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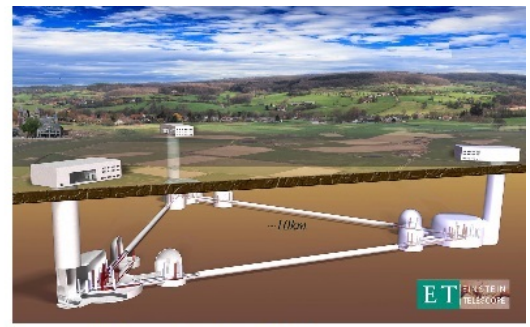

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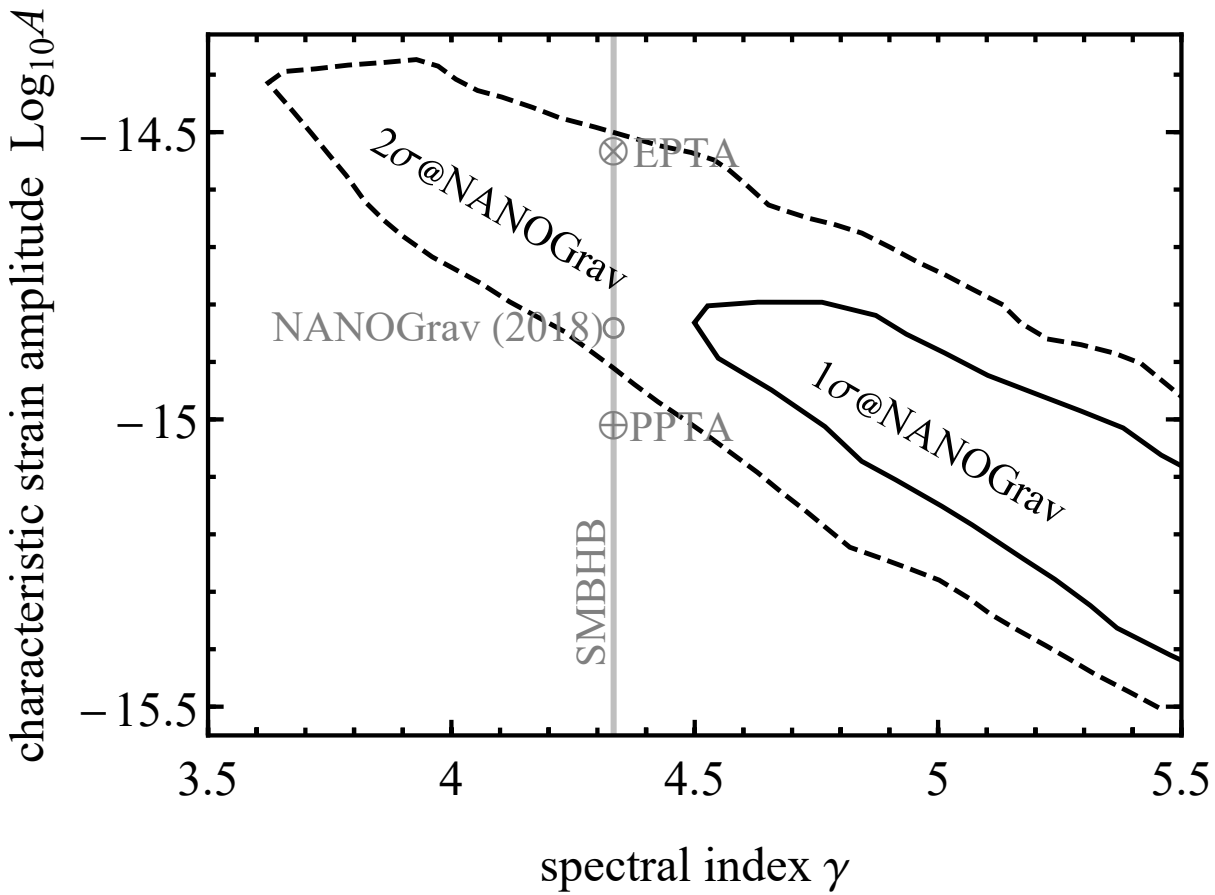
NANOGrav 12.5 yr data



- power-law fit to the data

$$\Omega(f) = \frac{2\pi^2}{3H_0^2} A^2 f_{yr}^2 \left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma}$$

The NANOGrav Collaboration 2009.04496

Cosmic String

- **What are cosmic strings?**
  - → Stable one-dimensional topological defects
- **The origins of cosmic strings:**
  - → Prediction from Superstring theory:
    (F-) string, D-string
  - → Vortex-like solutions in field theory
    e.g. from spontaneously broken U(1) symmetry

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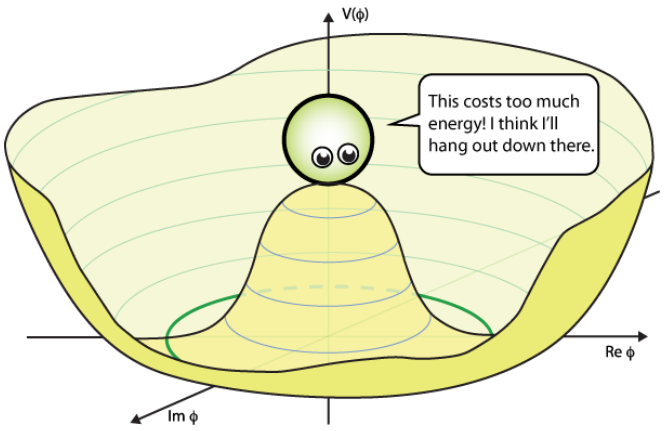
- Charged complex scalar field

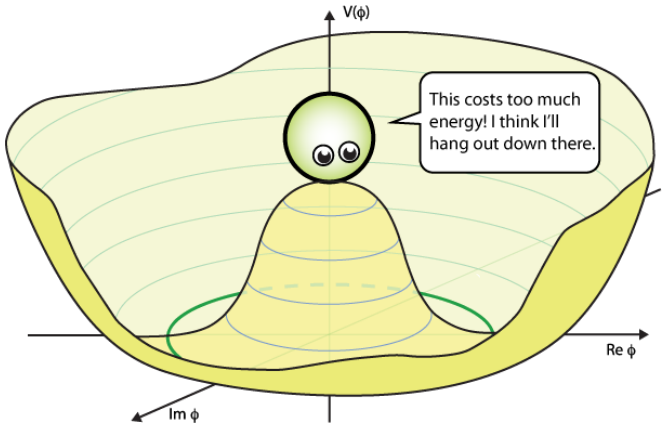
$$V = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$



Cosmic String formation (Kibble mechanism)

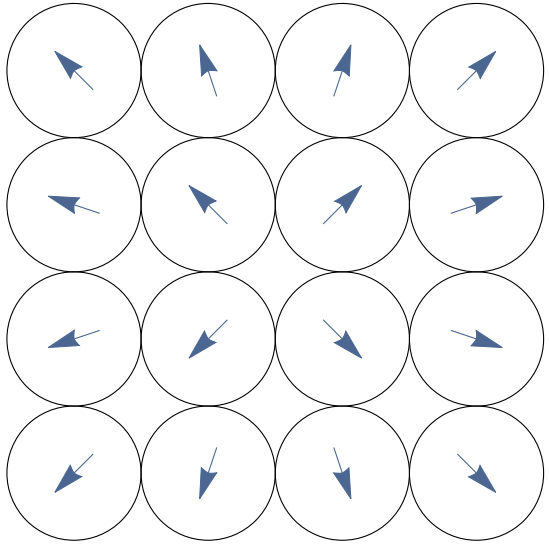
- Charged complex scalar field

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



- Horizon size at early time (high temperature)
  $d_H \propto M_p/T^2$
- we need a solution:

$$\Phi \xrightarrow{r\to\infty} \frac{v}{\sqrt{2}} e^{i\theta}$$



Cosmic String solution

- In the Abelian Higgs model

$$\mathcal{L} = D_\mu \Phi D^\mu \Phi^\dagger - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$

- approximate solution

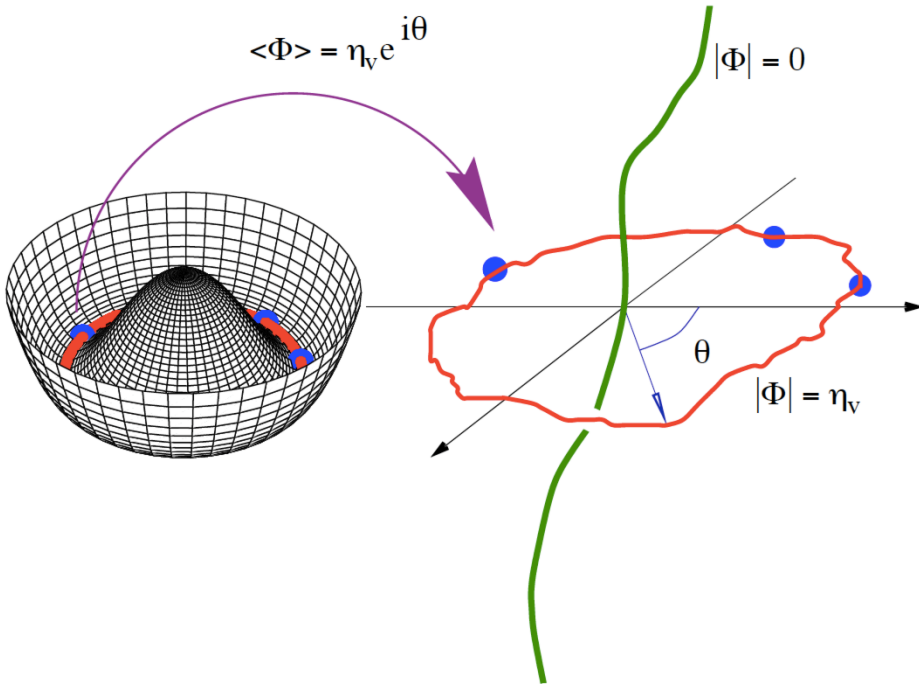
$$\Phi = \frac{v}{\sqrt{2}} \left(1 - \exp(-r/r_1)\right) \exp(-i\theta)$$

$$A_\theta = \frac{1}{er} \left(1 - \exp(-r/r_2)\right)^2$$

$\langle \Phi \rangle = 0$ at the origin

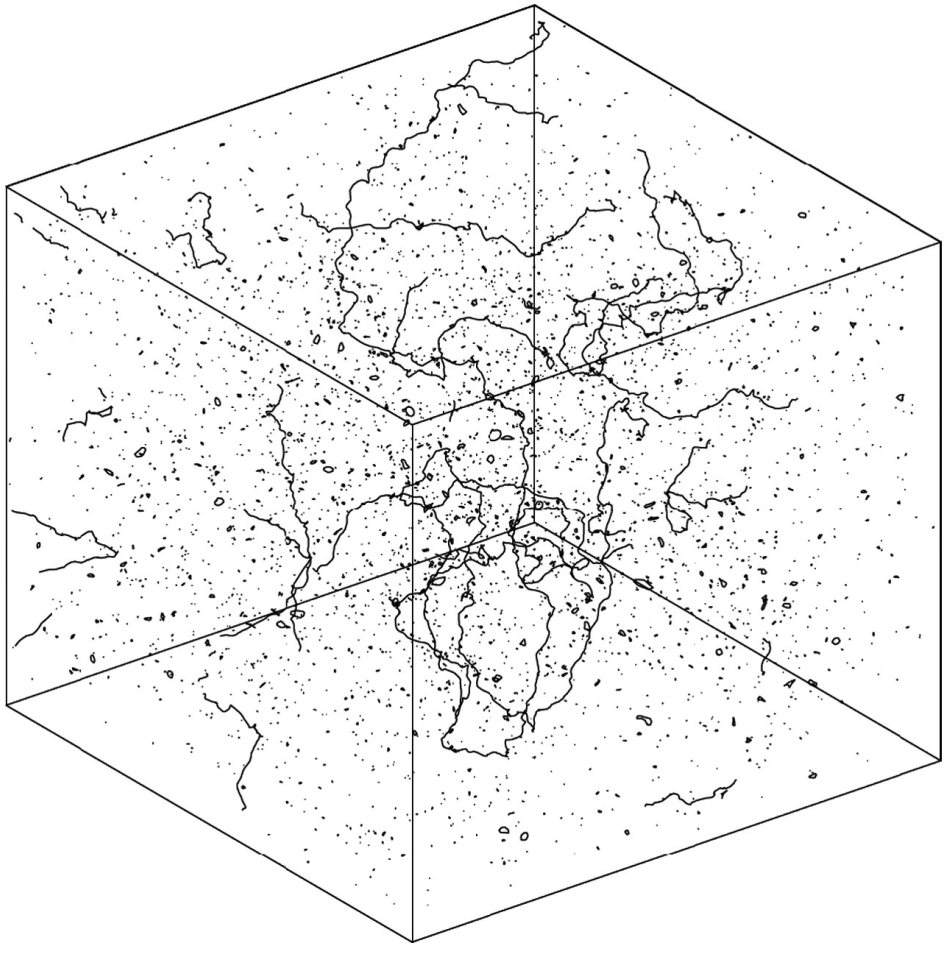
$$r_1, r_2 \propto v^{-1}$$

- tension of the string
(energy per unit length)
$\mu \propto v^2$



Christophe Ringeval (Adv.Astron. 2010)

Cosmic Strings



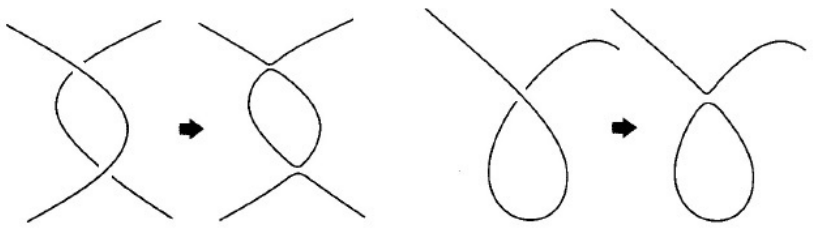
Vilenkin and Shellard 94'

Cosmic String network

- 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

$$\frac{\rho_\infty}{\rho_{\rm tot}} \propto G\mu$$

Stochastic GW background from Cosmic String loops

- After its creation each loop radiates energy at a constant rate

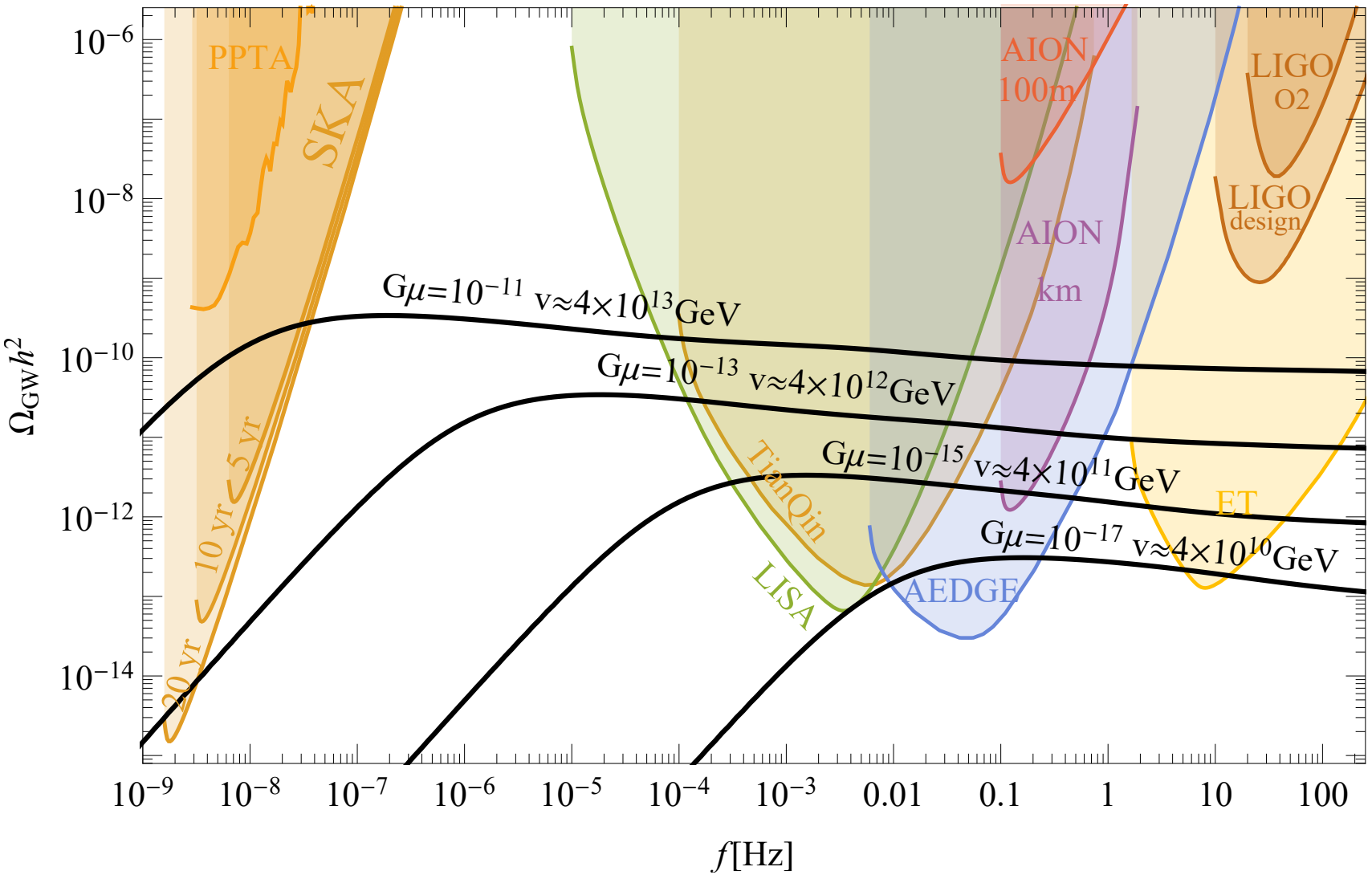
$$l(t) = \alpha t_i - \Gamma G\mu (t - t_i), \quad \alpha \approx 0.1\,,\ \Gamma \approx 50$$

Blanco-Pillado '13 '17 Lorenz '10

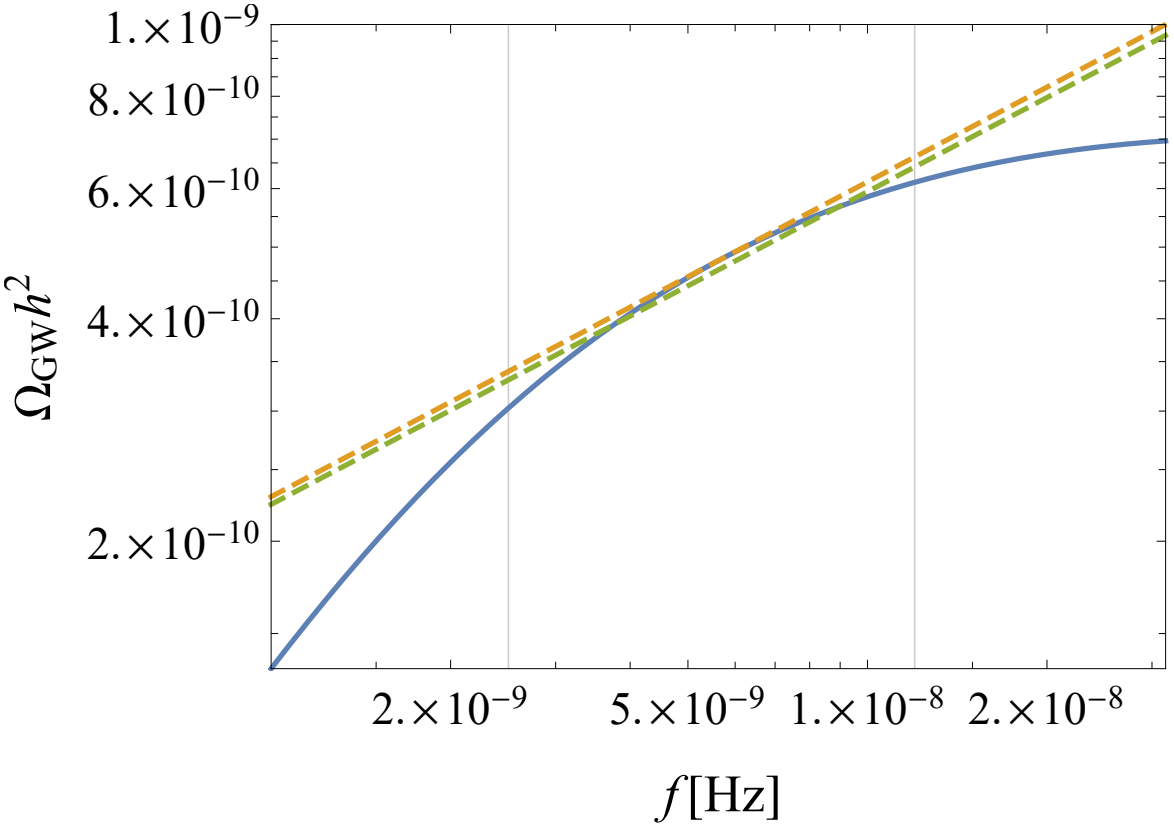
- The final estimate for GW density today, reads

$$\Omega_{\rm GW}(f)h^2 = h^2 \frac{16\pi}{3f} \frac{\Gamma (G\mu)^2}{H_0^2 \alpha\,(\alpha + \Gamma G\mu)} \int_{t_F}^{t_0} d\tilde{t} \frac{C_{\rm eff}(t_i)}{t_i^4} \left(\frac{a(\tilde{t})}{a(t_0)}\right)^5 \left(\frac{a(t_i)}{a(\tilde{t})}\right)^3 \Theta\,(t_i - t_F)$$

Stochastic GW background from Cosmic Strings



power-law fit to Cosmic String spectrum

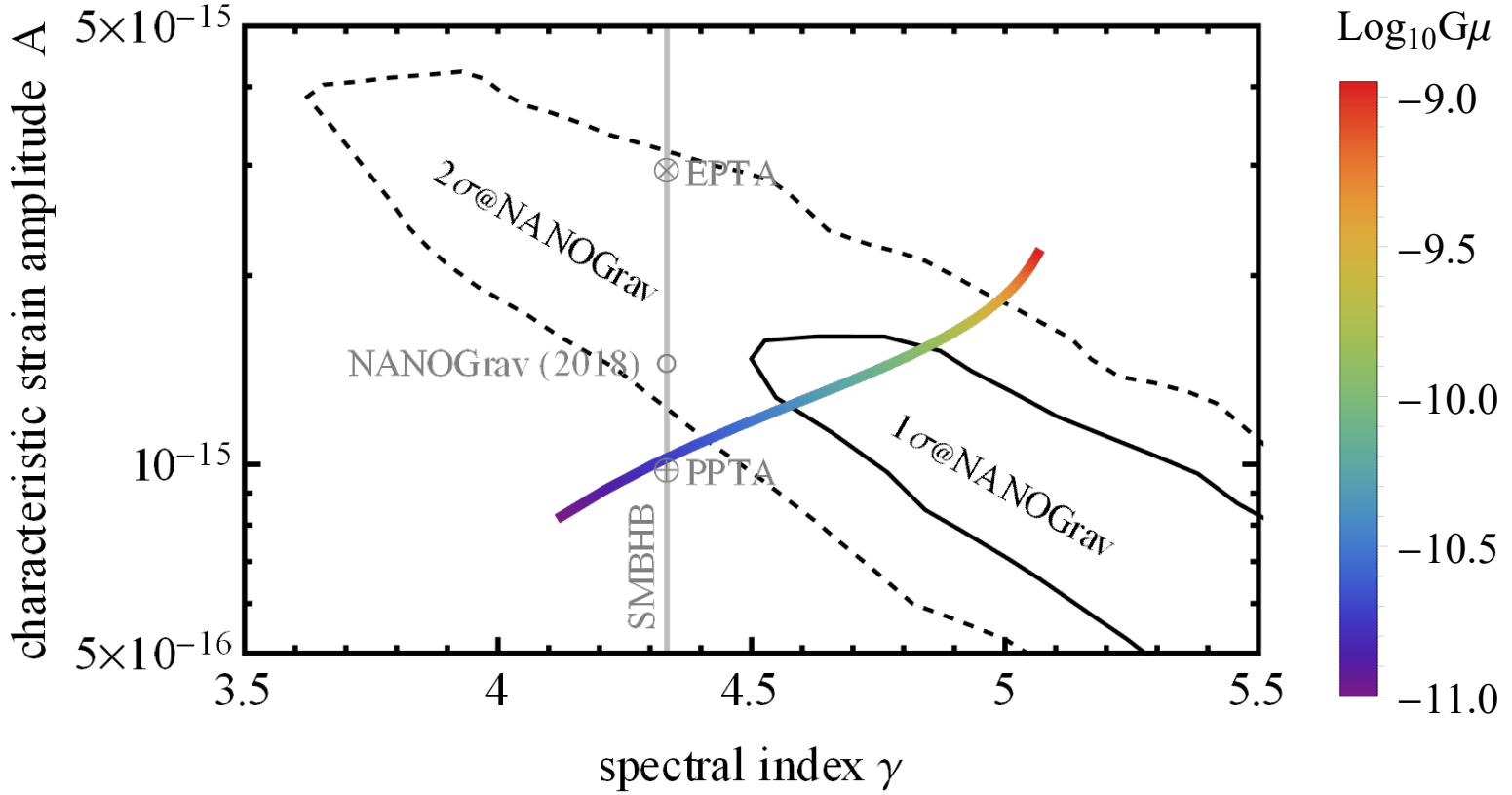


- power-law fit to string spectra

$$\gamma = 5 - \left.\frac{d\log\Omega_{GW}^{CS}(f)}{d\log f}\right|_{f=f_*}, \qquad A = \sqrt{\frac{3H_0^2}{2\pi^2}\,\frac{\Omega_{GW}^{CS}(f_*)(f_{\rm yr}/f_*)^{5-\gamma}}{f_{\rm yr}^2}}$$

at the reference frequency $f_* \approx 5.6 \times 10^{-9}$ Hz.

Cosmic String fit to NANOGrav data



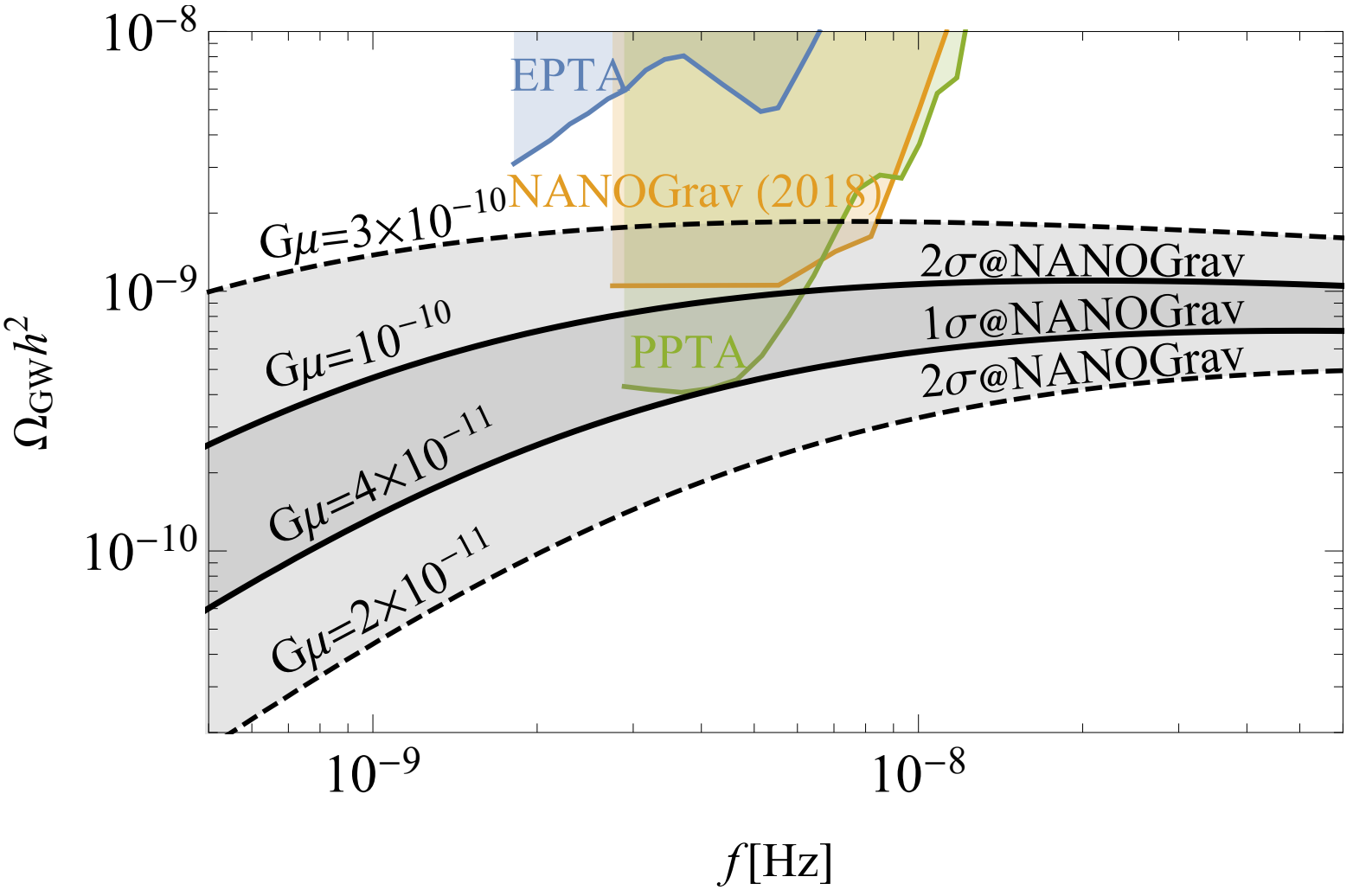
- results within the 68% CL

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

- results within the 95% CL

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

Cosmic String fit to NANOGrav data



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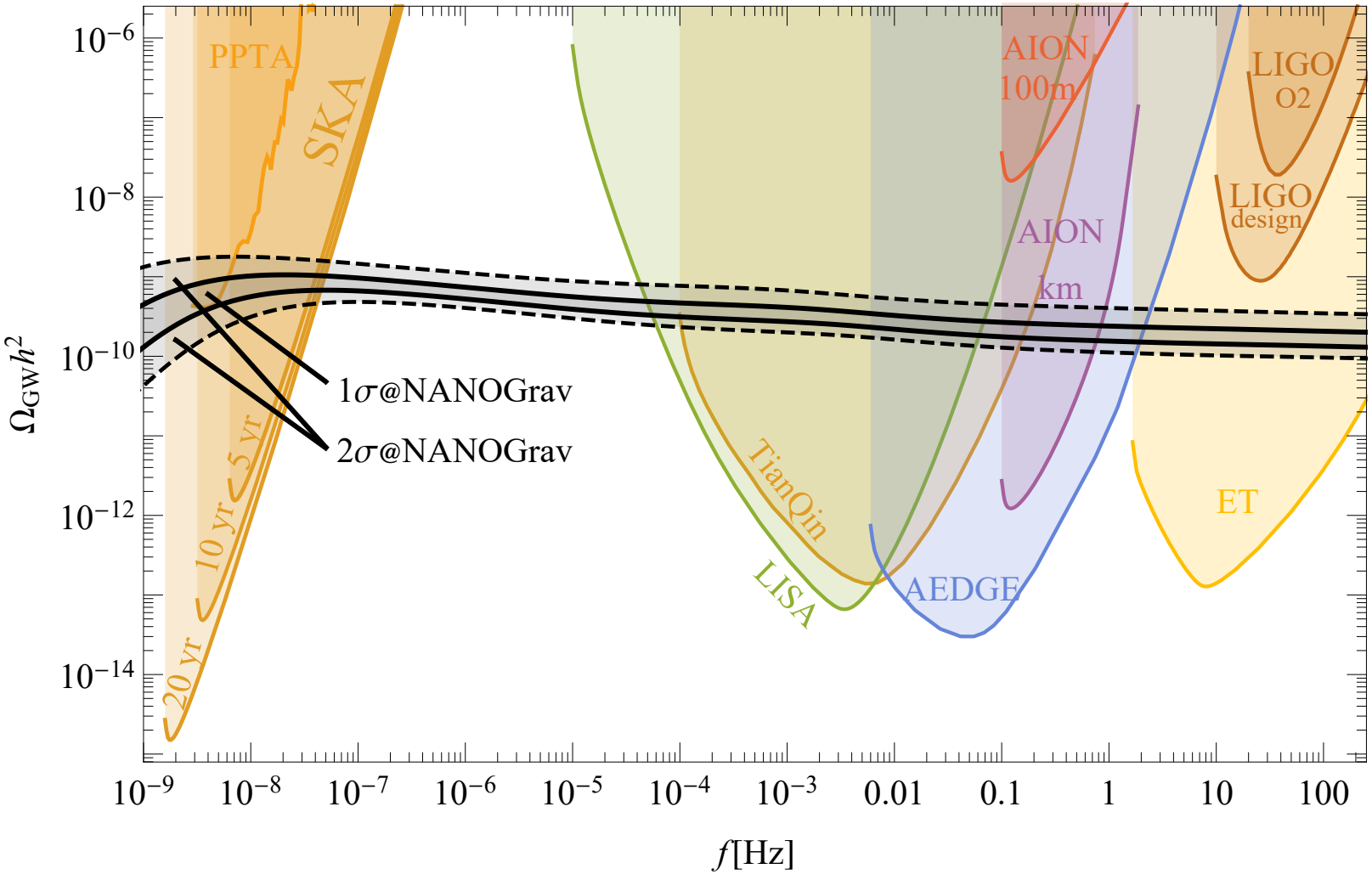
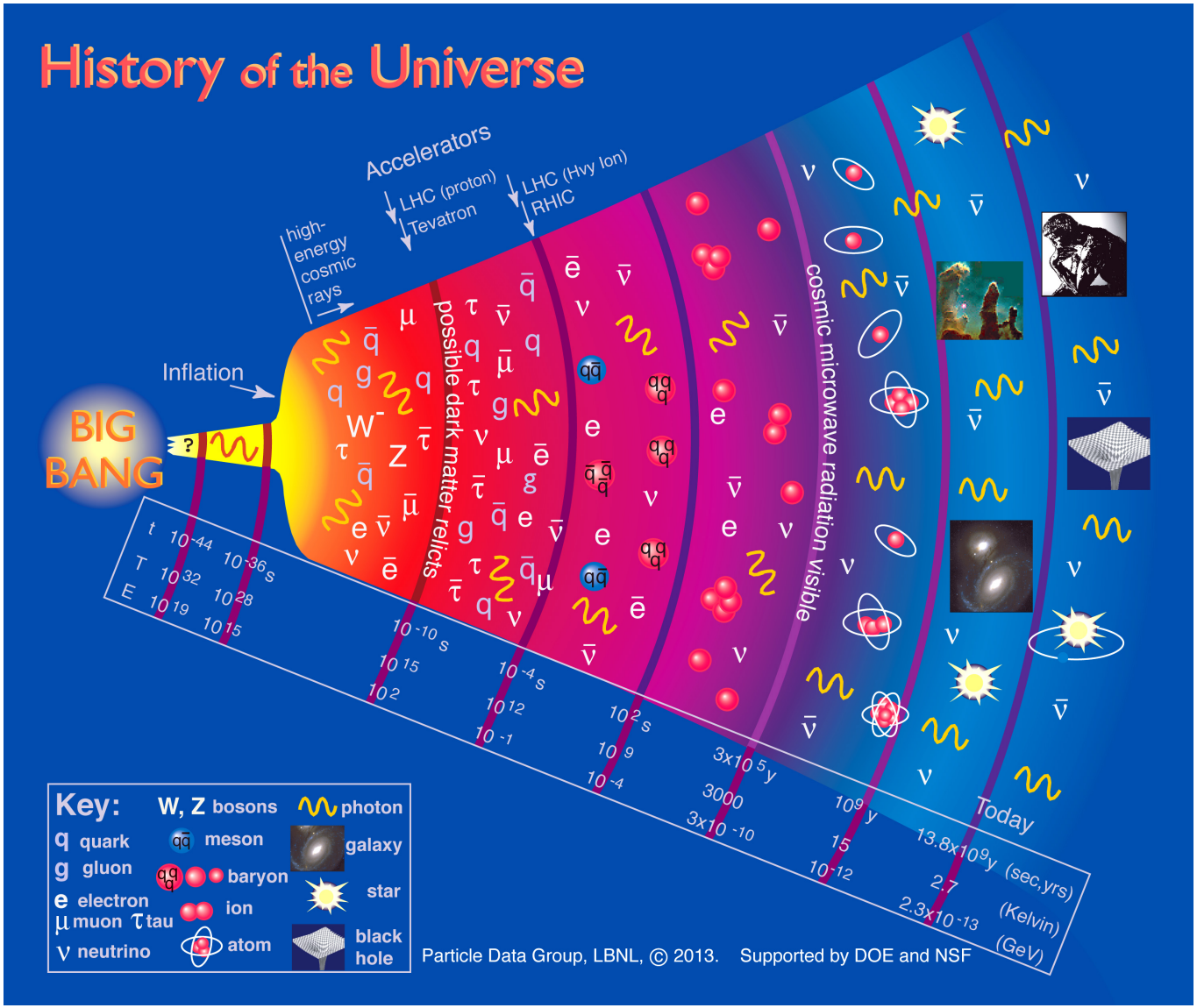


Part 2: Cosmic Archaeology



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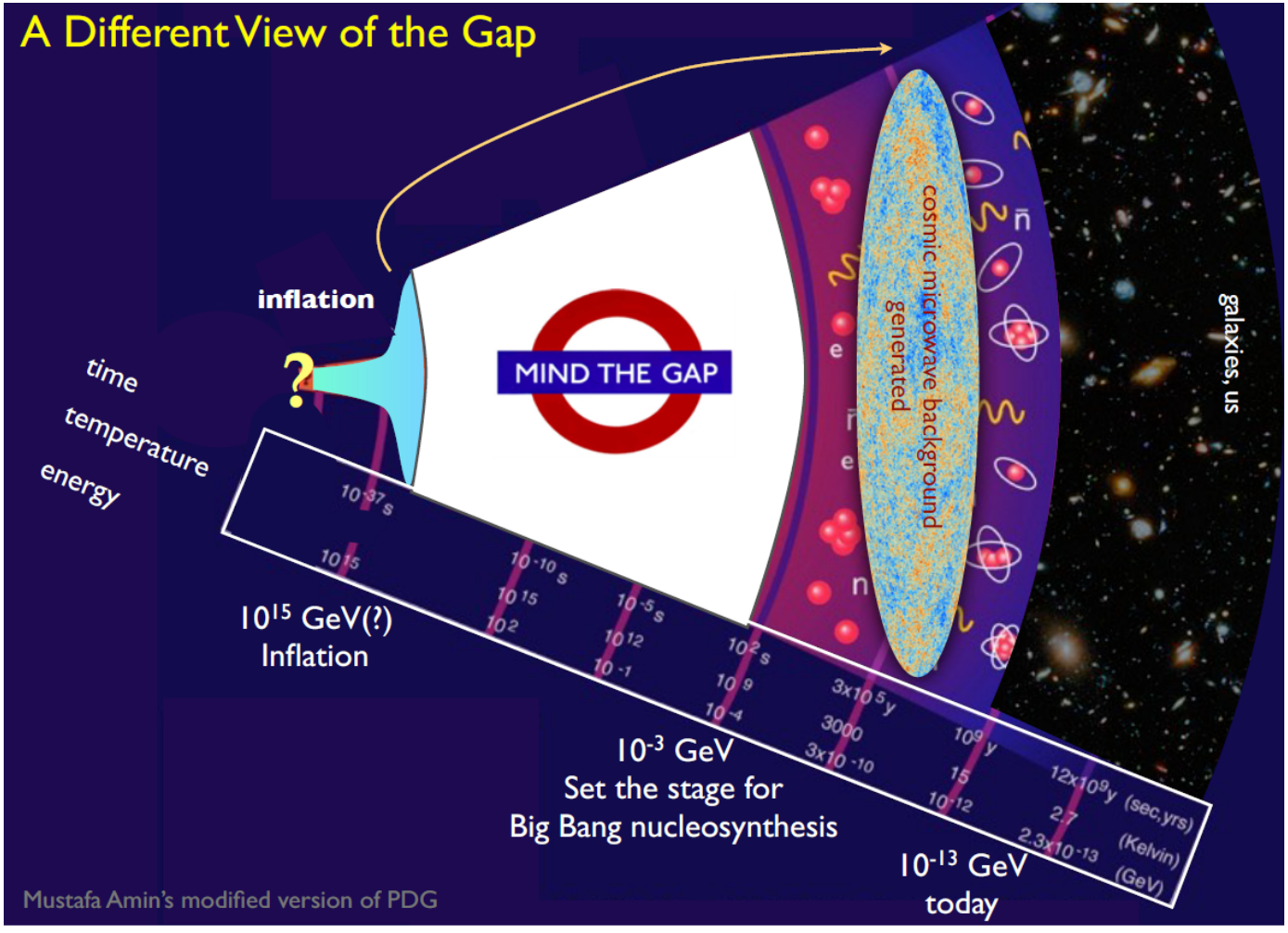
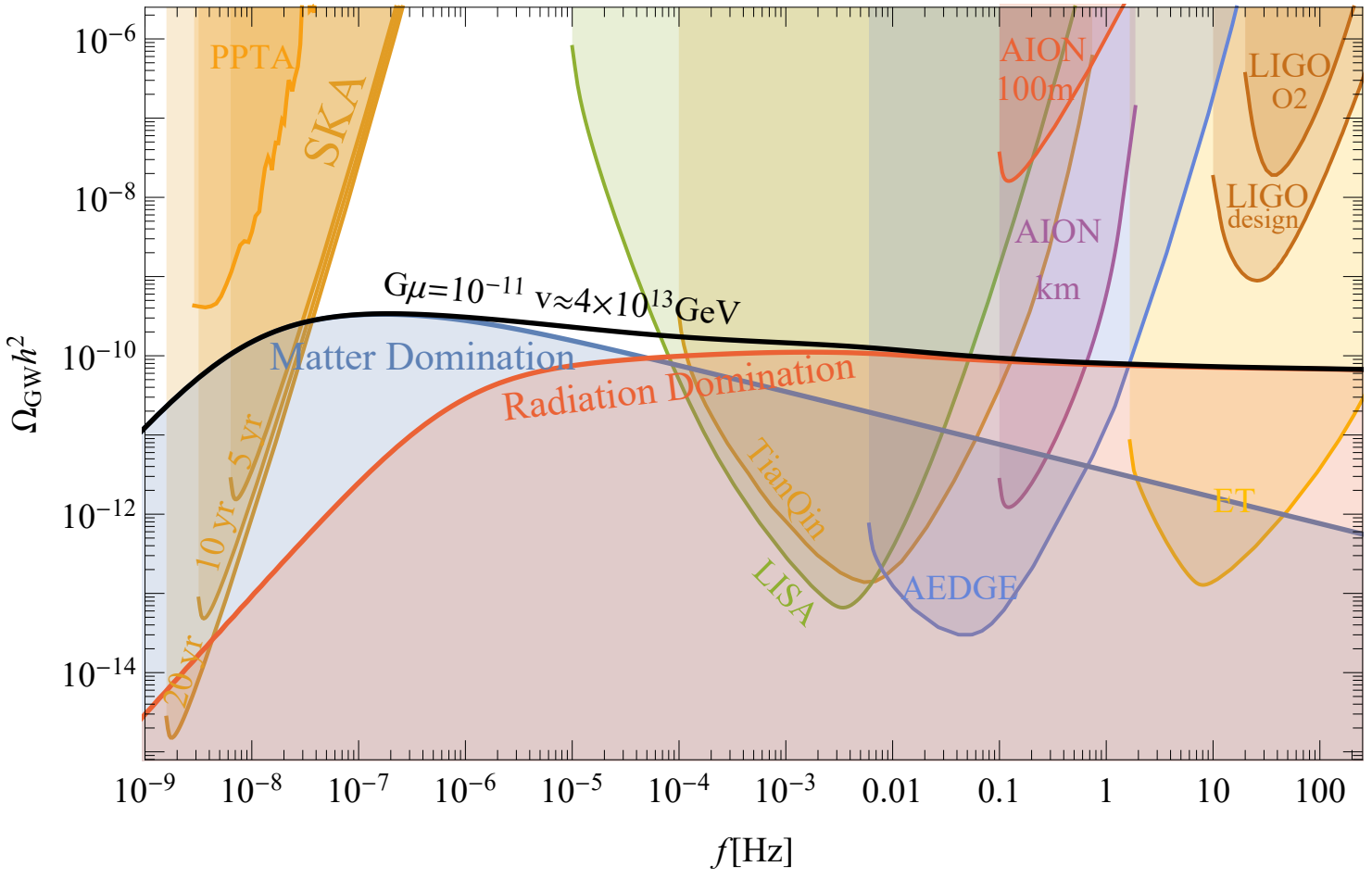


Stochastic GW background from Cosmic Strings



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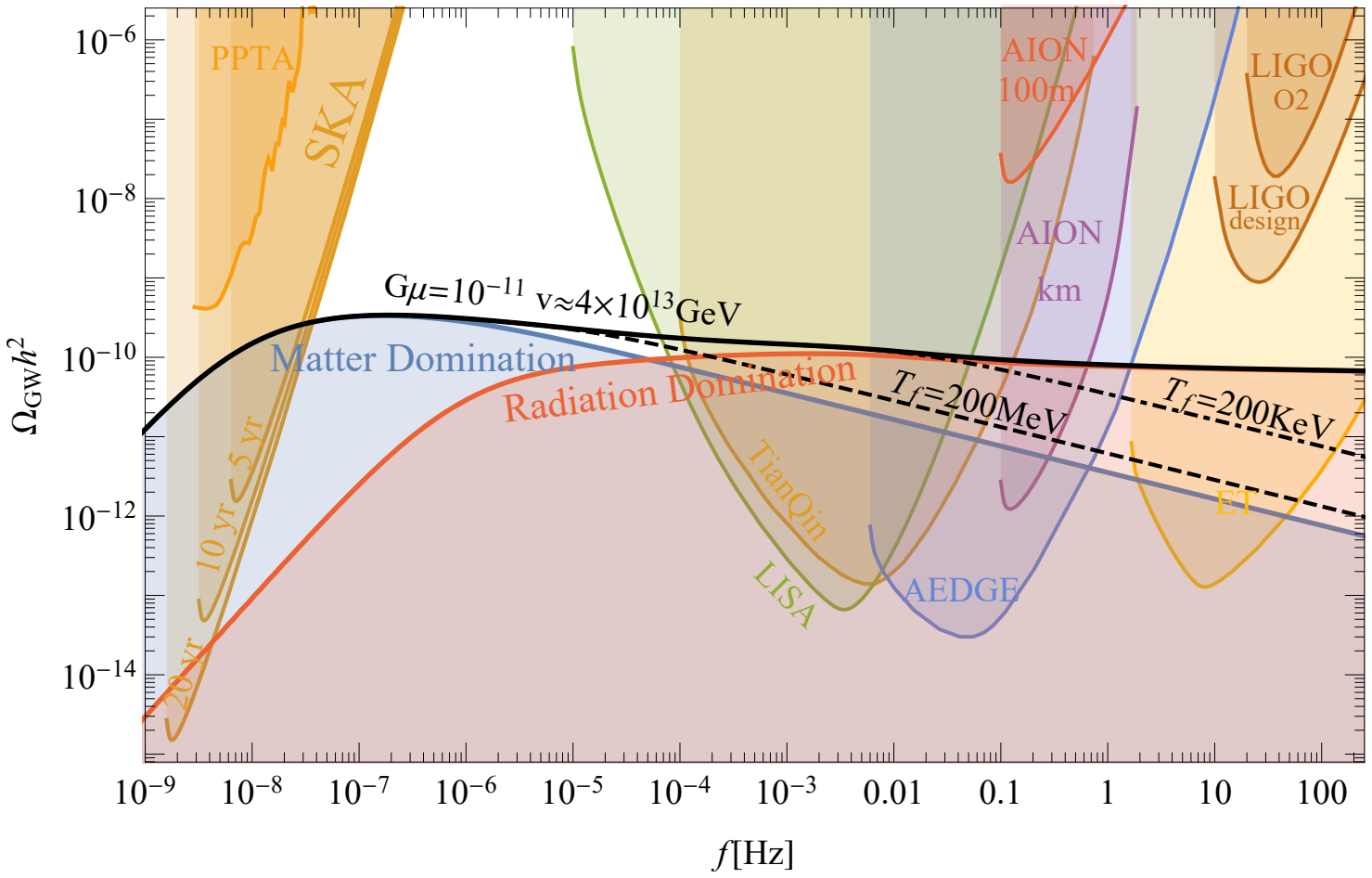

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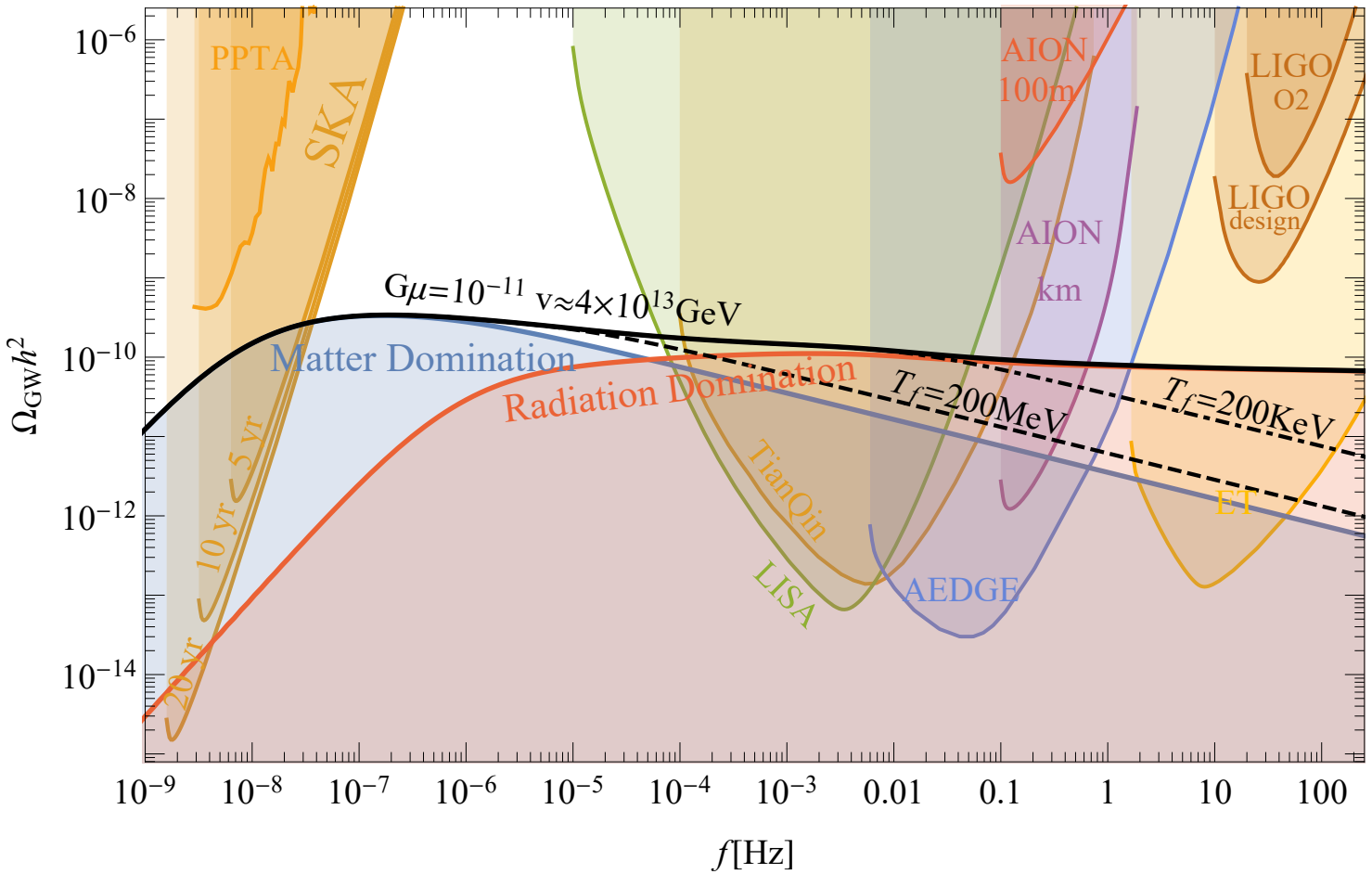
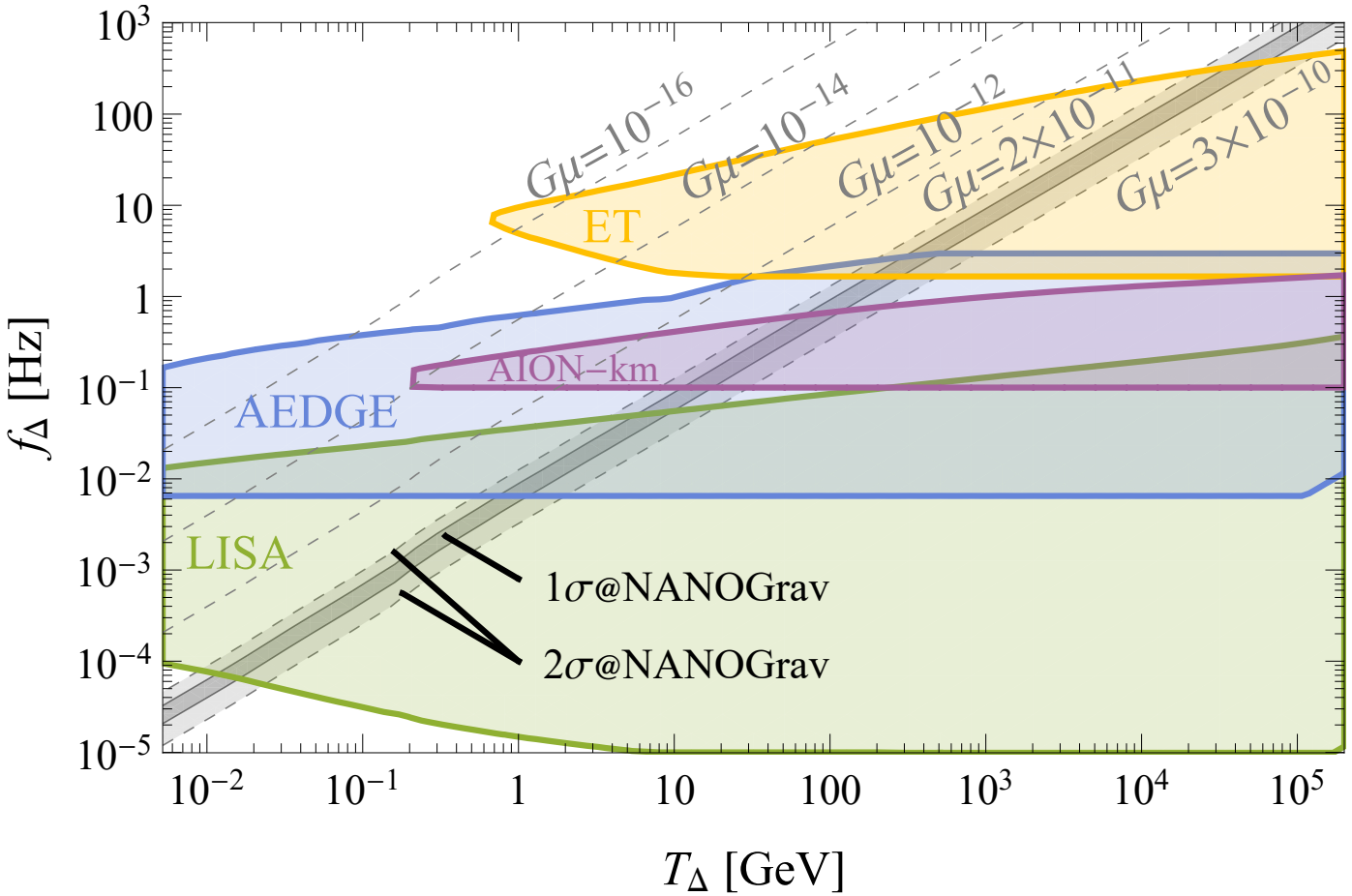


- GW frequency $\leftrightarrow$ temperature

$$f_\Delta \propto \frac{T_\Delta}{\sqrt{G\mu\,\alpha}}$$

Detection capabilities



- slightly better numerical result

$$f_\Delta = (8.67\times10^{-9}\,\mathrm{Hz})\,\frac{T_\Delta/\mathrm{GeV}}{\sqrt{\alpha\,G\mu}}\left(\frac{g_*(T_\Delta)}{g_*(T_0)}\right)^{\frac{8}{6}}\left(\frac{g_S(T_0)}{g_S(T_\Delta)}\right)^{-\frac{7}{6}}$$

Extra DOF

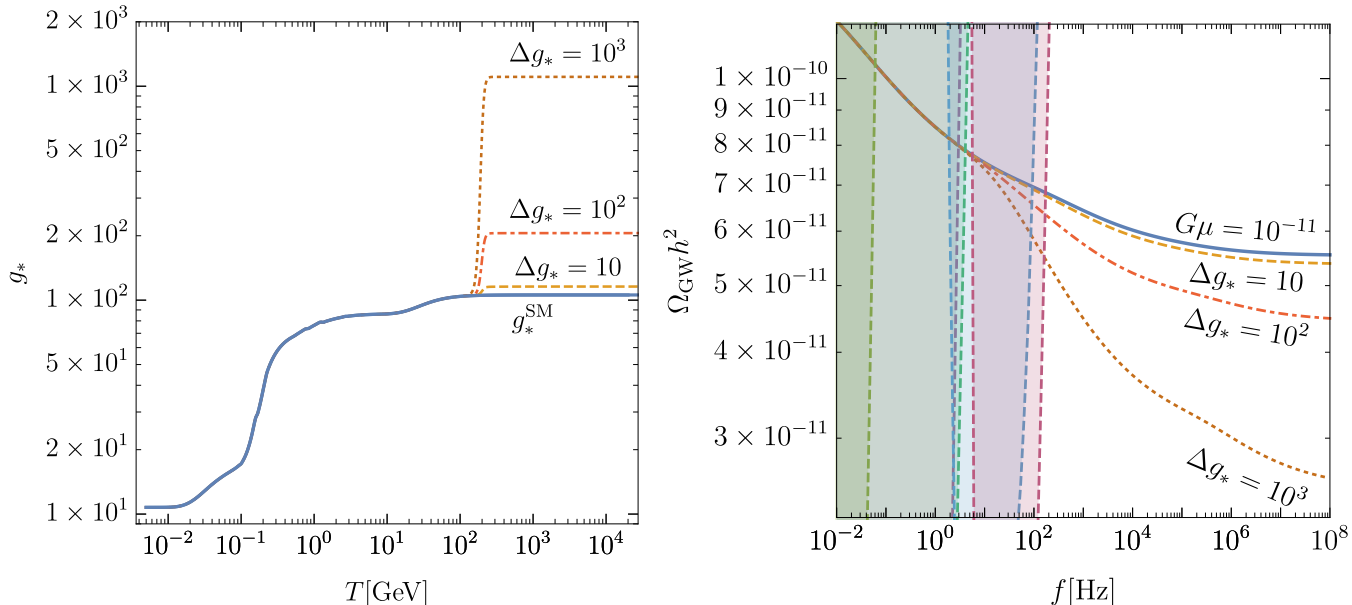
- We add Δg_* new degrees of freedom at T_Δ

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

- The GW abundance changes as

$$\Omega_{\rm GW}(f >> f_\Delta) \approx \Omega_{\rm GW}^{\rm SM}(f) \left(\frac{g_*^{\rm SM}}{g_*^{\rm SM} + \Delta g_*} \right)^{\frac{1}{3}}$$

- An example with $T_\Delta = 200\,\text{GeV}$ and $G\mu = 10^{-11}$



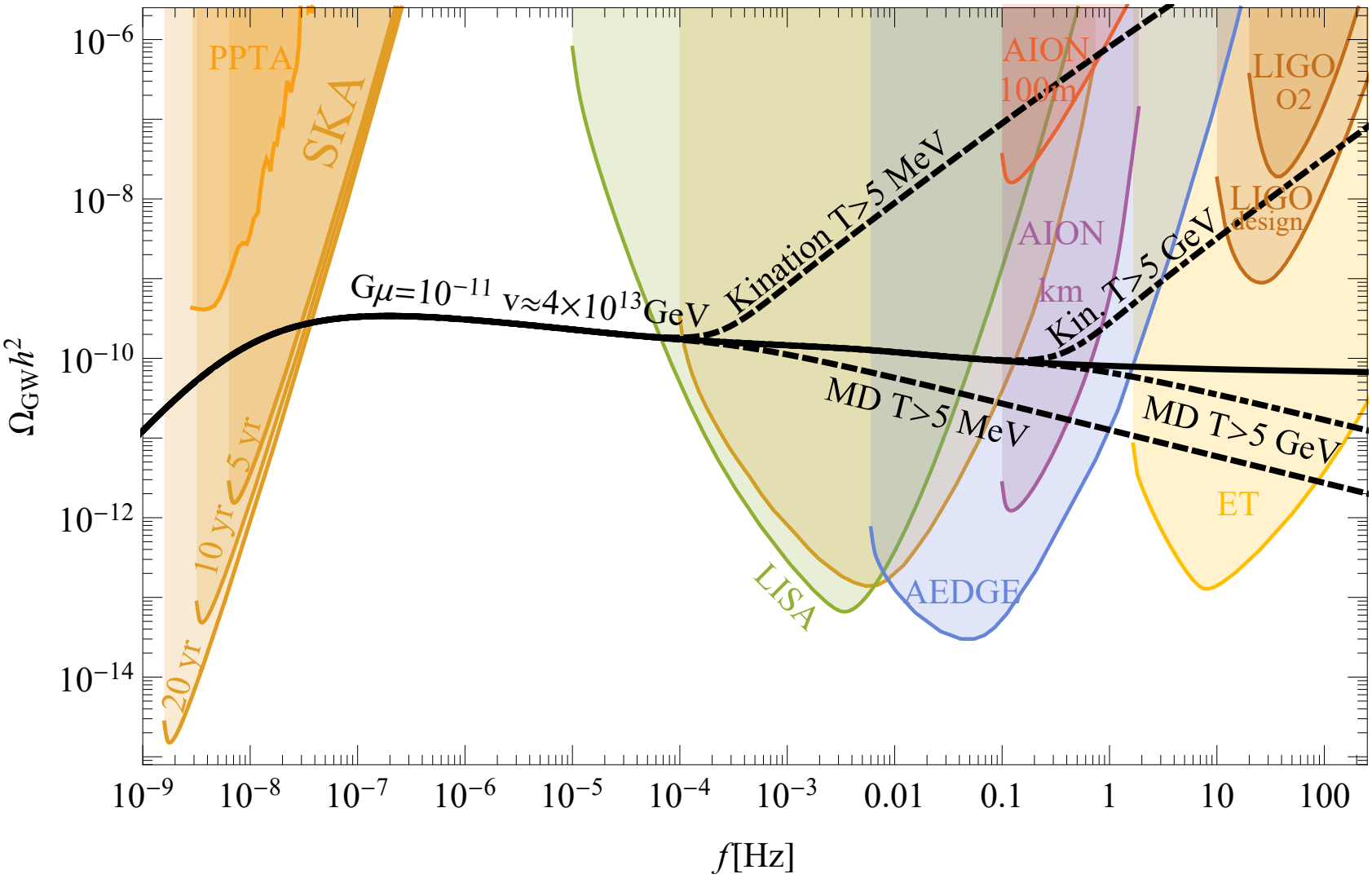
Non standard cosmologies

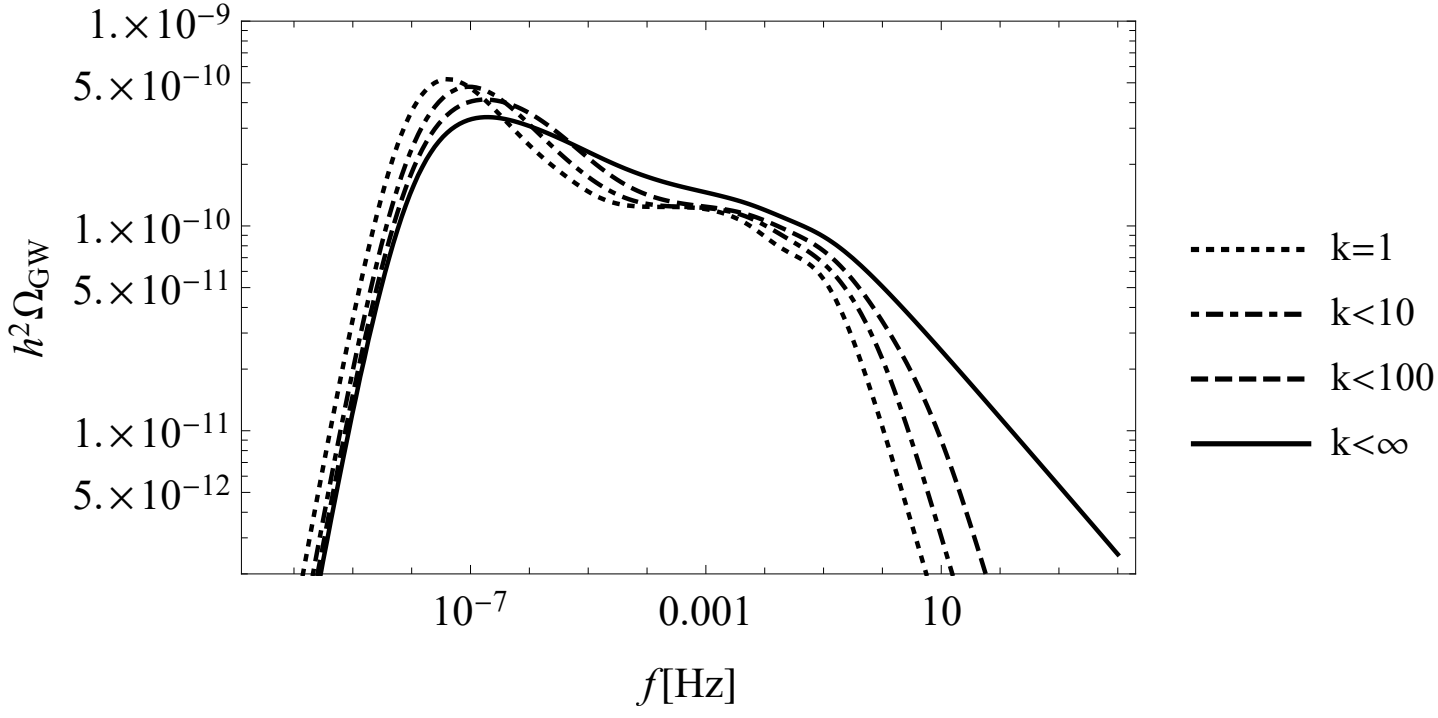
- We will model the energy budget of the universe as

$$\rho(t) = \begin{cases} \rho_{st}(t) & ; t \geq t_\Delta \\ \rho_{st}(t_\Delta) \left[\frac{a(t_\Delta)}{a(t)}\right]^n & ; t < t_\Delta \end{cases}$$

- examples:
  1. standard radiation domination ($n = 4$)
  2. early matter domination ($n = 3$)
  3. oscillating scalar field (for non-renormalisable potential $n \to 6$)
  4. ...
- experimental bounds: RD during BBN $\Rightarrow T_\Delta \gtrsim 5$ MeV

Non standard cosmologies





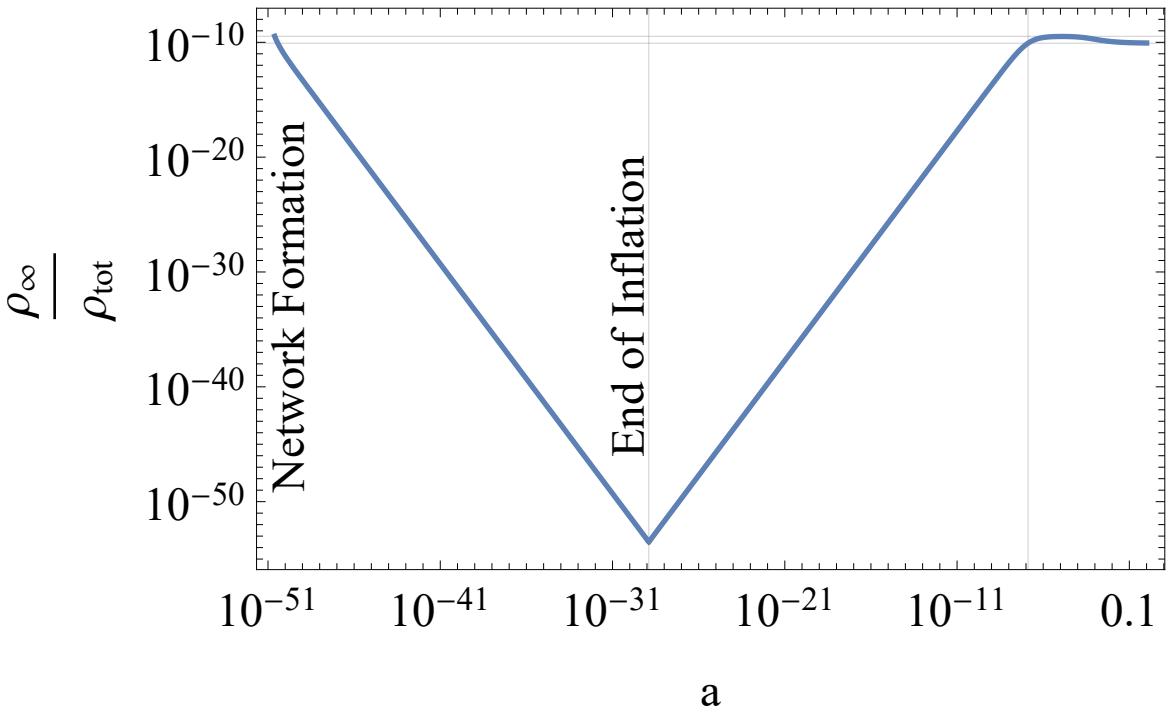
- sum over emission modes

$$\Omega_{\rm GW}(f) = \sum_{k=1}^{\infty} \Omega_{\rm GW}^{(k)}(f) = \sum_{k=1}^{\infty} k^{-\frac{4}{3}} \Omega_{\rm GW}^{(1)}(f/k)$$

- useful approximation

$$\Omega_{\rm GW}(f) = \sum_{k=1}^{\infty} \Omega_{\rm GW}^{(k)}(f) \approx \sum_{k=1}^{N} \Omega_{\rm GW}^{(k)}(f) + \int_{k=N+1}^{\infty} \Omega_{\rm GW}^{(k)}(f)$$

Strings diluted by inflation



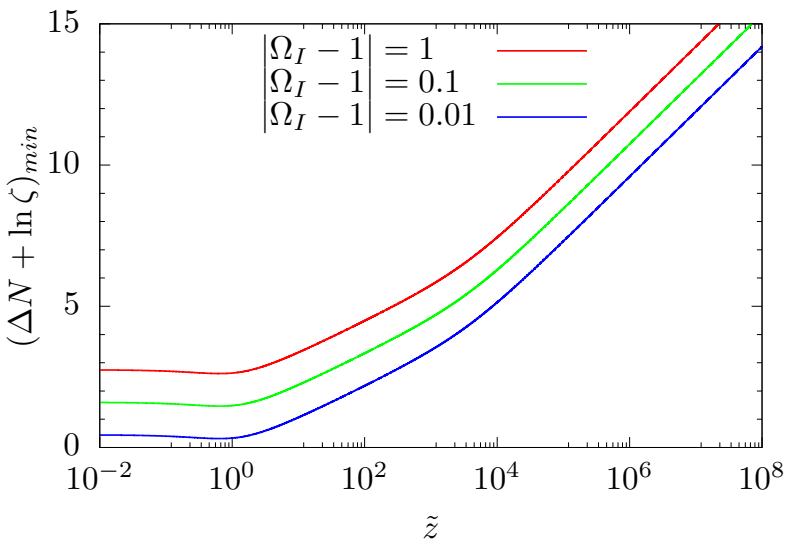
- When loop production is inefficient energy density network scales as

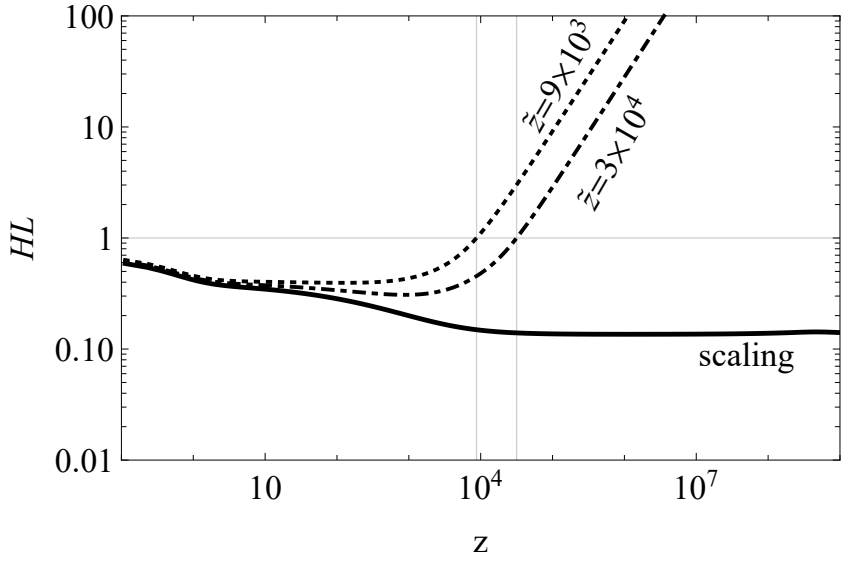
$$\rho_\infty \propto a^{-2}$$

- How many efolds of dilution ?

$$\Delta N \;\geq\; 2.7 + \frac{1}{2}\ln(|\Omega_I - 1|) + \frac{1}{2}\ln\left[\Omega_\Lambda(1+\tilde{z})^{-2} + \Omega_m(1+\tilde{z}) + \Omega_r(1+\tilde{z})^2\right]$$

Strings diluted by inflation





- Initial overdensity has a similar effect

$$L_f = \frac{1}{\zeta H_I} \rightarrow \rho_\infty \propto \zeta^2$$

- How many efolds of dilution or initial overdensity ?

$$\Delta N + \ln\zeta \geq 2.7 + \frac{1}{2}\ln(|\Omega_I - 1|) + \frac{1}{2}\ln\left[\Omega_\Lambda(1+\tilde{z})^{-2} + \Omega_m(1+\tilde{z}) + \Omega_r(1+\tilde{z})^2\right]$$

Strings diluted by inflation

- Stochastic background as sum of bursts

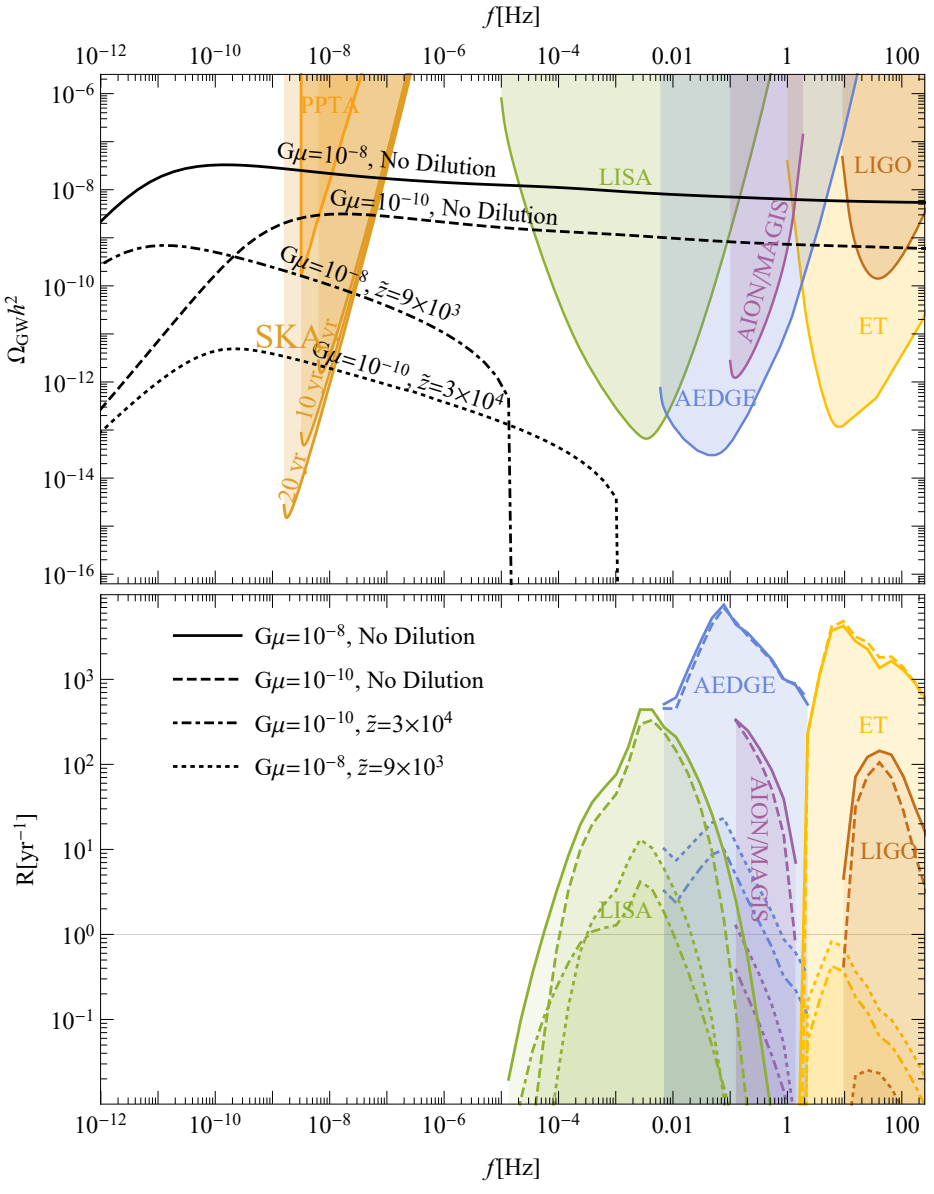
$$\Omega_{\rm GW}(f) = \frac{4\pi^2 f^3}{3H_0^2} \int_{z_*}^{\infty} dz \int_{h_{\rm min}}^{h_{\rm max}} dh\, h^2\, \frac{d^2R}{dz\, dh}(h, z, f)$$

- With individually observable bursts excluded

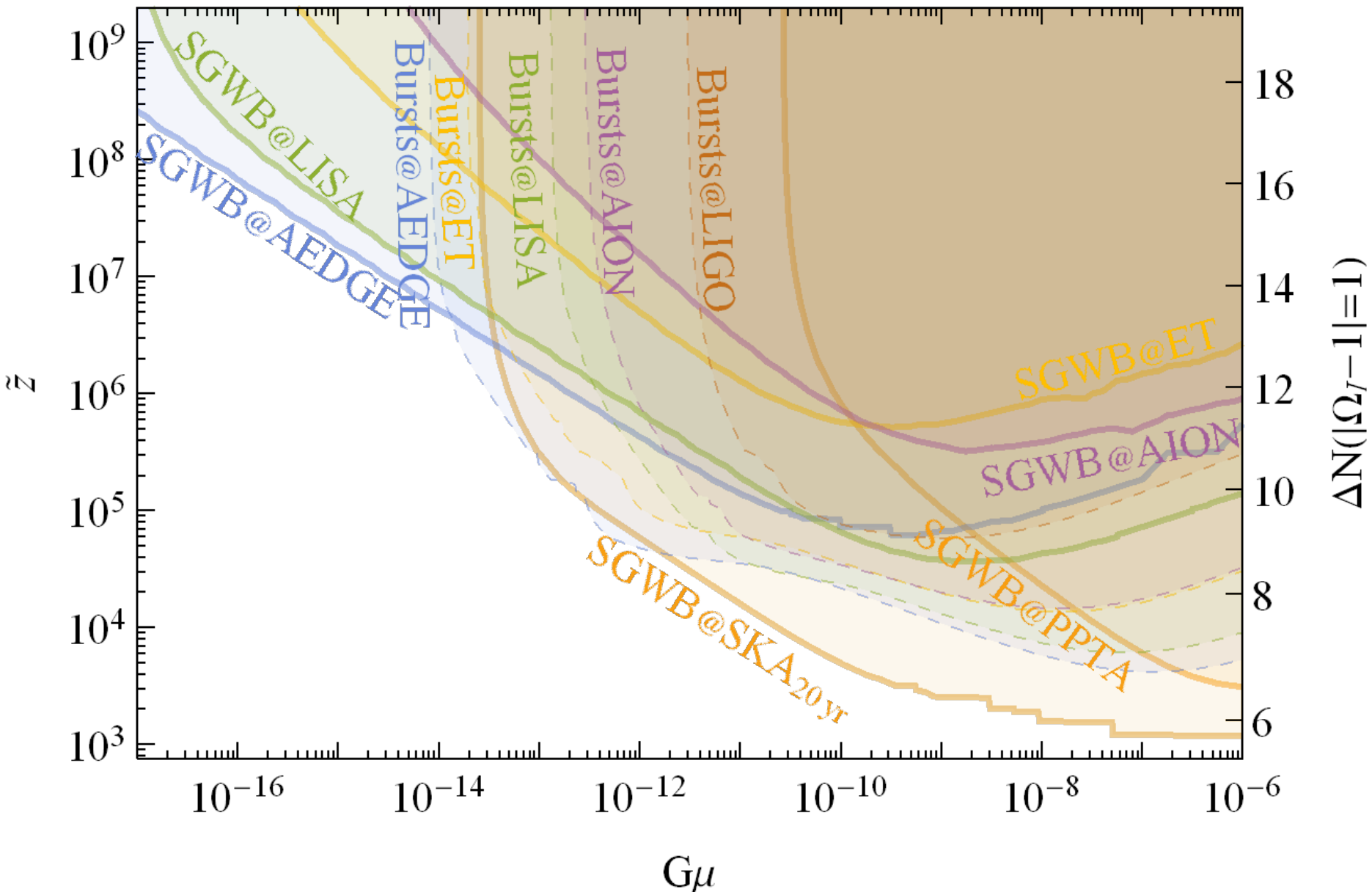
$$f = \int_0^{z_*} dz \int_{h_{\rm min}}^{h_{\rm max}} dh\, \frac{d^2R}{dz\, dh}(h, z, f)\,.$$

- Rate of individually observable bursts

$$R_{\rm exp}(f) = \int_0^{z_*} dz \int_{\max(h_{\rm min}, h_{\rm exp})}^{h_{\rm max}} dh\, \frac{d^2R}{dz\, dh}(h, z, f)$$



Strings diluted by inflation parameter space



Conclusions

- Cosmic Strings are a very good candidate to fit the new NANOGrav data
- All next-generation GW detectors (SKA, LISA, TianQin, AEDGE, AION and ET) will be able to probe the cosmic string spectra that fit the current data.
- If the NANOGrav signal is caused by cosmic strings it would also provide a powerful tool allowing us to probe the expansion history up to $T \approx 10^5\,\mathrm{GeV}$.
- Cosmic string networks diluted by inflation can be observable through GWs with a smoking gun signal of strong rare burst without typical accompanying the stochastic background.