Cosmic Archaeology with *Gravitational Waves* from (Axion) Cosmic Strings

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University of California, Riverside

arxiv: 1711.03104 (PRD), 1808.08968 (JHEP)

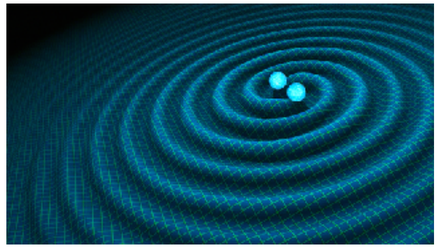
YC with Marek Lewicki, David Morrissey and James Wells

arxiv: 1912.08832 (PRL),YC with Marek Lewicki and David Morrissey

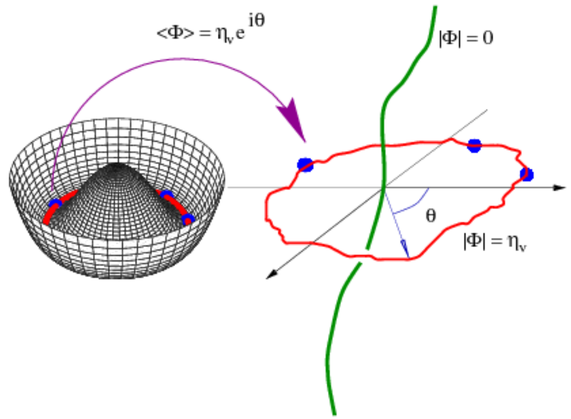
arXiv:1910.04781 (PDU), 2106.09746 (JHEP), YC with Chia-Feng Chang

Work in prep with Chia-Feng Chang

Cambridge High Energy Workshop, Aug 3 2022



GWs from Cosmic Strings



- **Cosmic strings:**

  A network of 1-dim topological defects: a few long strings +more loops per horizon size; strong motivations (U(1)' breaking, superstring theory, axion…)

- A leading cosmological/BSM source of GWs (SGWB, bursts), potentially strong signal, primary targets of LIGO, LISA

  — *General/basic aspects on cosmic strings see earlier talks by David, Kai, + later by Sungwoo, Seth…*

  — *Resonates with Anson's talk yesterday*

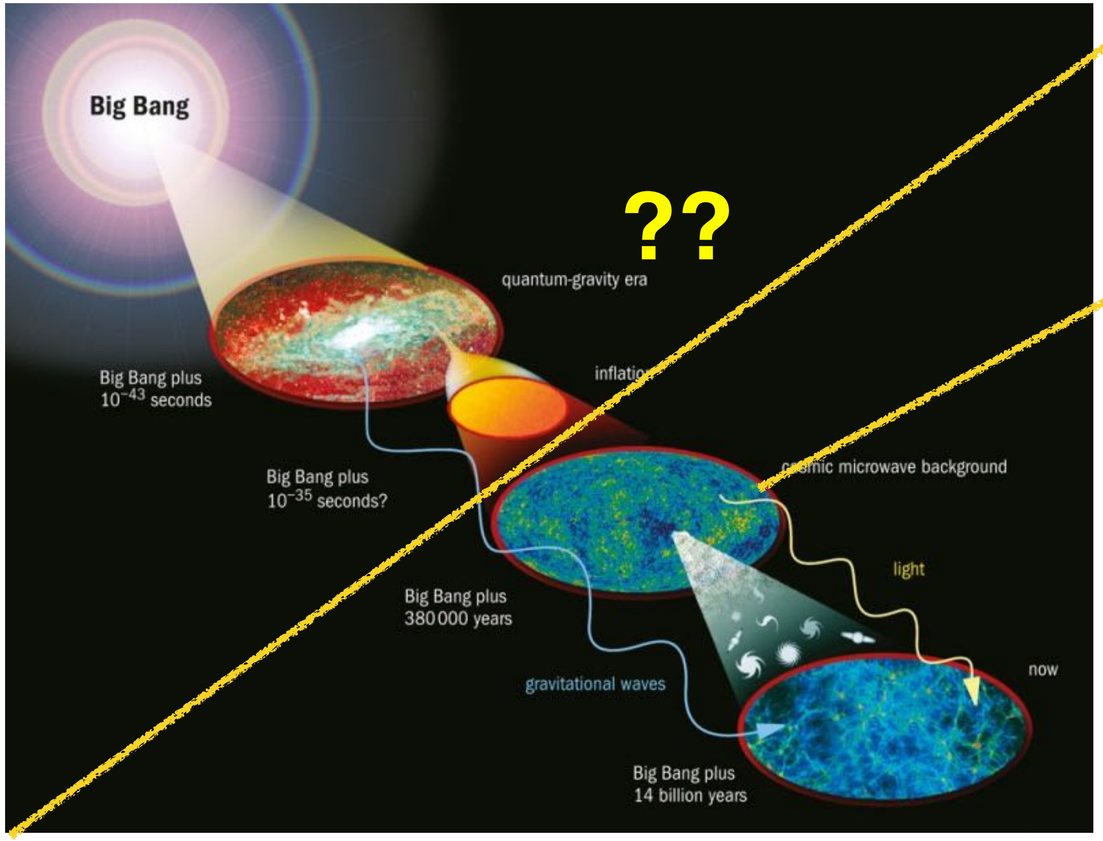
Outline

- Cosmic archaeology with GWs from (NG) cosmic strings:
  - Probe pre-BBN Hubble expansion history with f-spectrum of SGWB from cosmic strings: test the standard model of cosmology/particle physics, e.g. new eq. of state, new d.o.f
  - GW bursts as signals of cosmic strings diluted by inflation
- Probe ALP DM models with GWs from global (axion) strings
- Conclusion/Outlook

I. Cosmic archaeology with GWs from (NG) cosmic strings

Pre-BBN Cosmology

-what we do not "know"



- **The horizon of confidence**: BBN *(~1s-3 min after Big Bang)*
- CMB light: a direct window back to *~400k yrs after the Big Bang*

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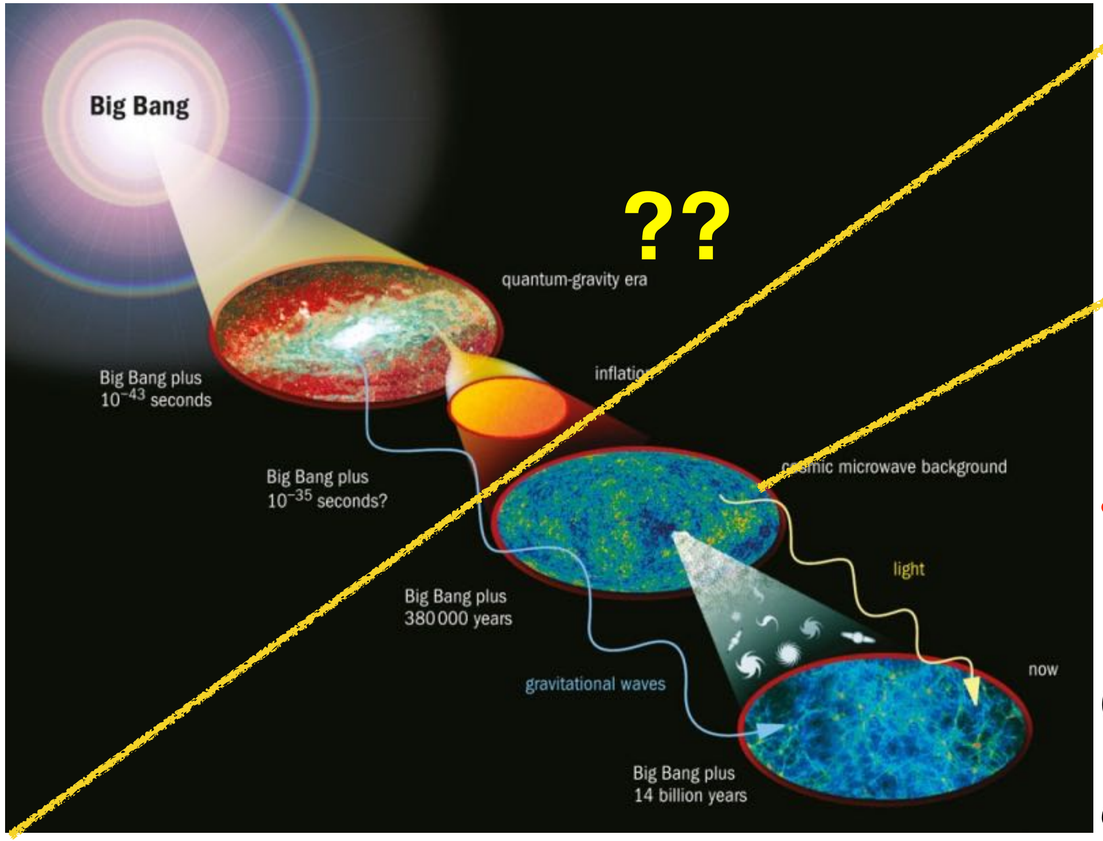

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- **What happened before BBN?**
  Standard cosmology theory: **assumptions to be tested, many unknowns!**
  (scale of inflation/reheating?
  early matter domination/kination?
  early phase transitions? new d.o.f?…)

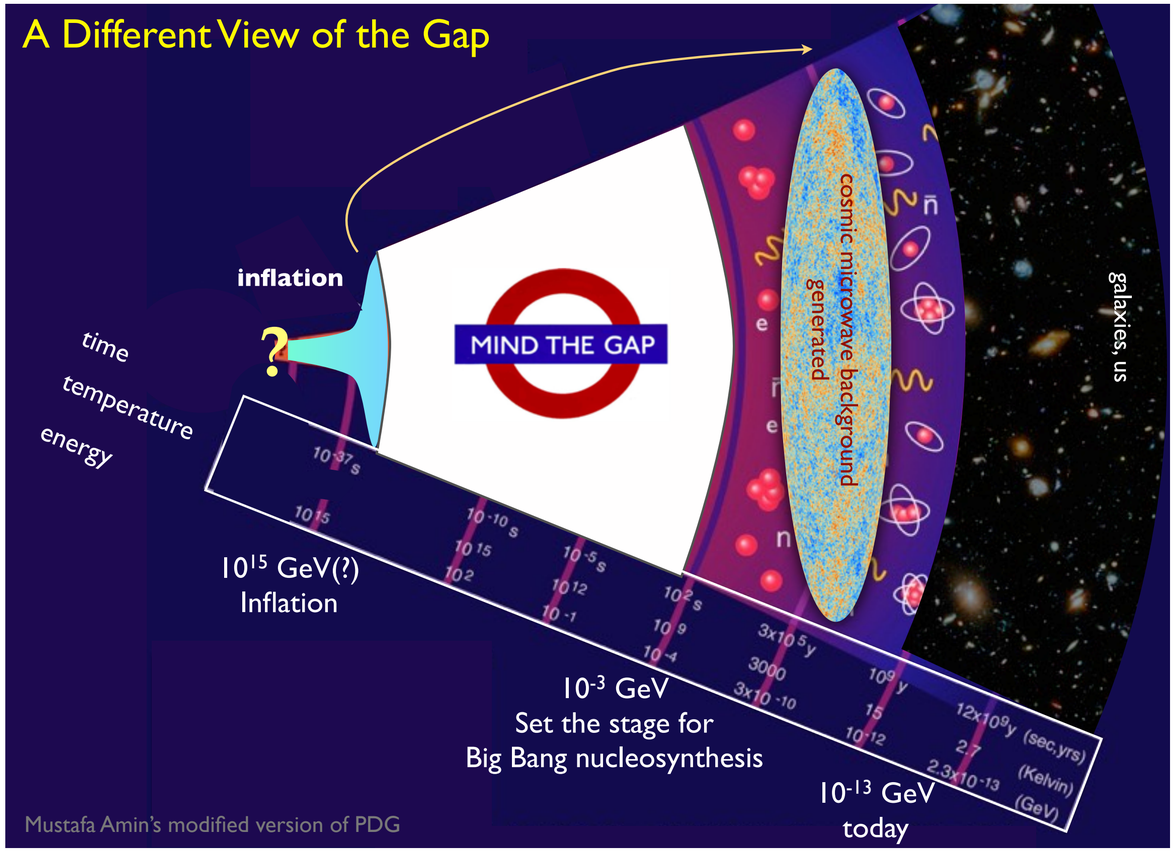
Pre-BBN Cosmology?

— *the Primordial Dark Age*

(Boyle and Steinhardt 2005, Boyle and Buonanno 2007)

What happened within the first ~1 sec?

The gap amplified on Log scale of temperature T ($\propto a^{-1}$)! ☞



The Universe is RD with SM content from T_{eq} all the way back to the end of inflation: *up to 24 orders of magnitudes on T scale!* — **IS IT??**

Pre-BBN Cosmology

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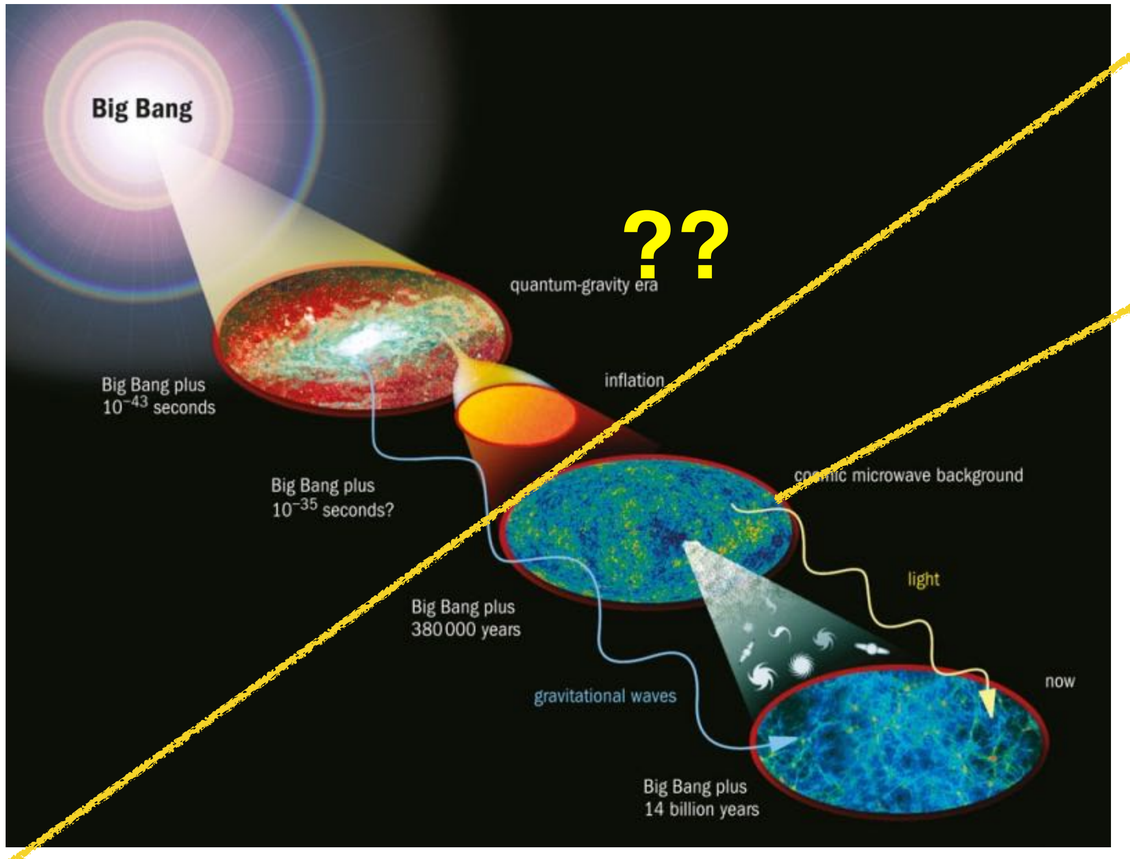

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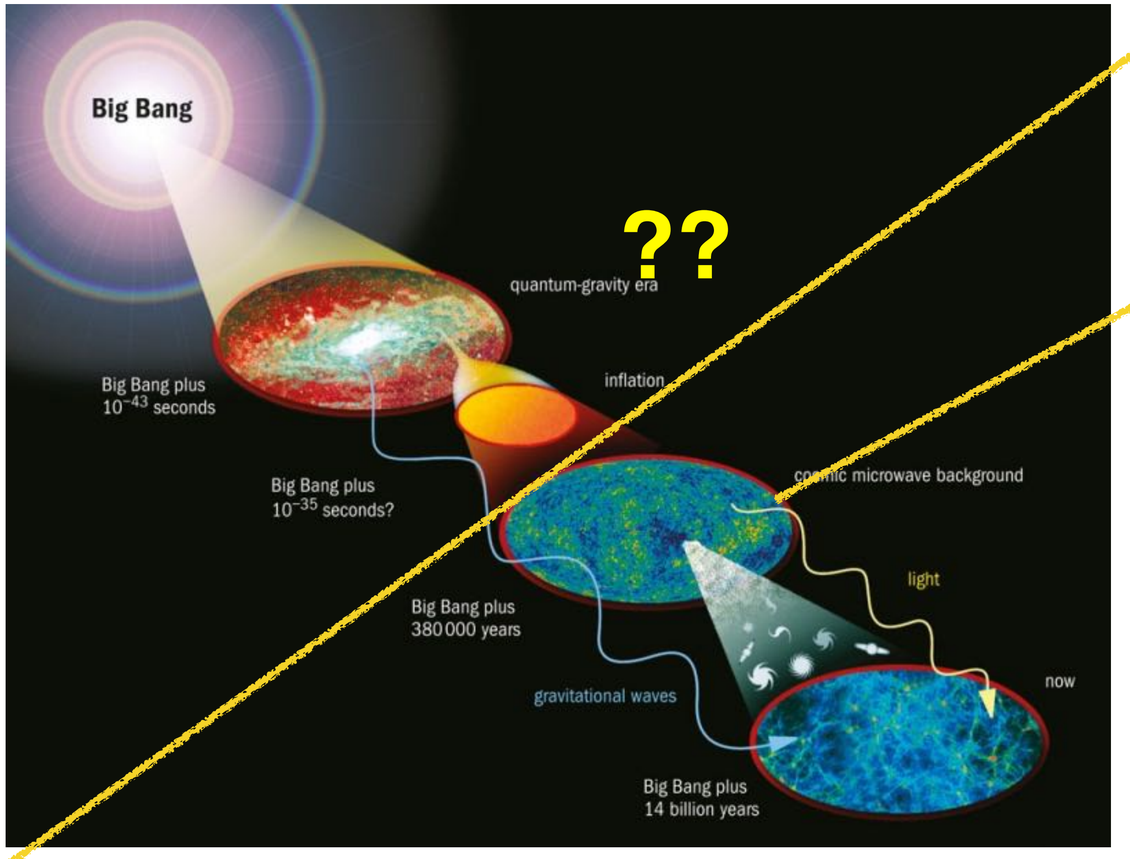

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- **Direct observational probe?**
  inflation + post-inflationary thermal history
  (Impact on Ω_{DM}, DM halo structure/detection!)

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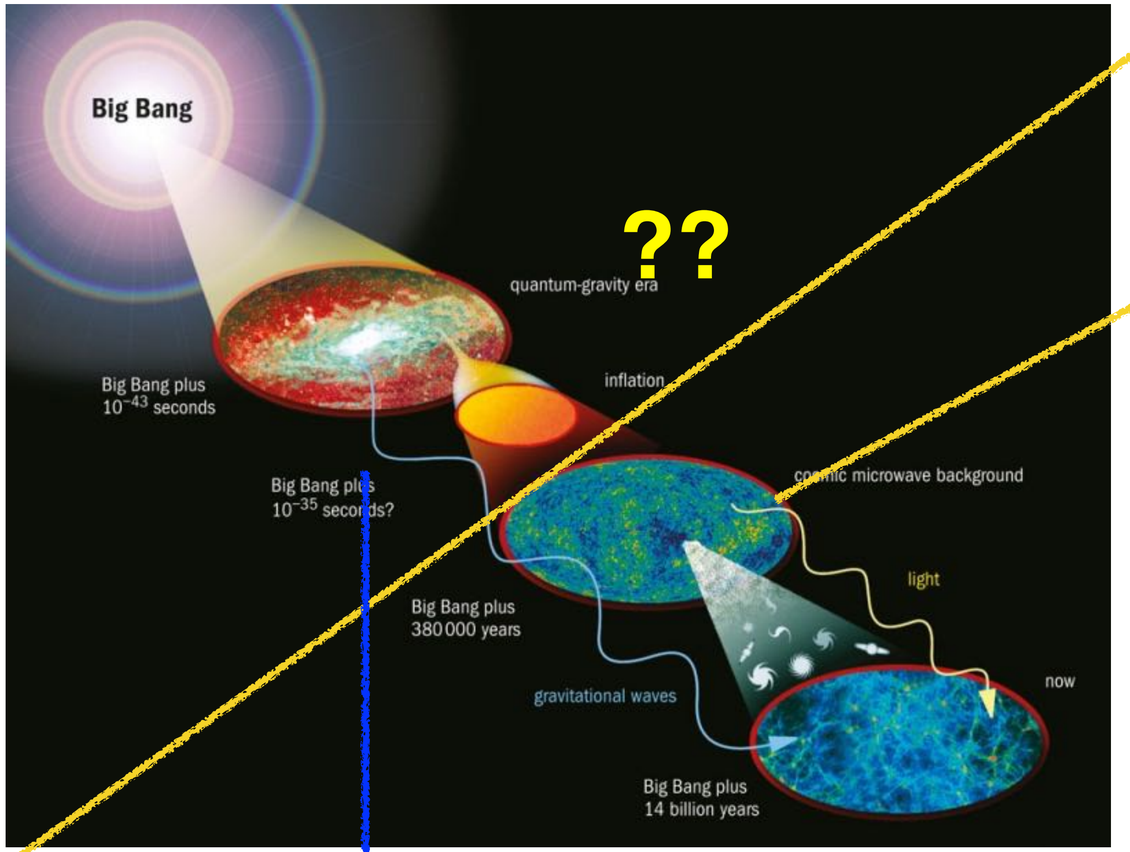

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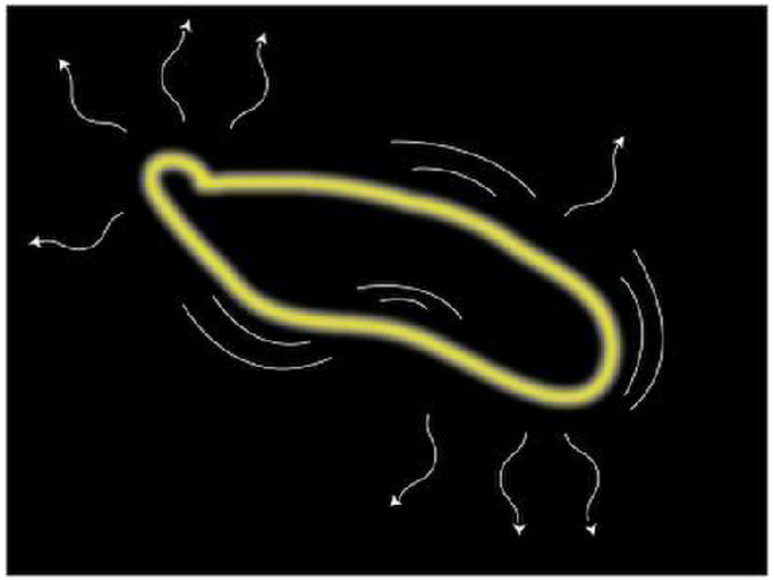
GW: the window of hope?

- **Direct observational probe?**
  inflation + post-inflationary thermal history
  (Impact on Ω_{DM}, DM halo structure/detection!)

GW Signatures from Cosmic Strings

- **Gravitational waves emitted from oscillating string loops**

  ➜ Relic stochastic GW background: continuous emission throughout the string network history ★ *(c.f. 1st order PT)*



Credit: Matt DePies/UW.

⟹ SGWB spectrum spanning a wide frequency range

Stochastic GW Background from Cosmic Strings

arxiv: 1711.03104, 1808.08968, YC with Lewicki, Morrissey and Wells

- We use a simplified loop size distribution (at formation) justified by recent simulation results (*e.g. Blanco-Pillado and Olum 2017*) :

$$l_i = \alpha t_i, \quad \alpha \approx 0.1$$

- The loop formation rate per unit V per unit time (t):

$$n(l,t) = \frac{C_{\rm eff}(t_i)}{\alpha^2 t_i^4} \frac{a^3(t_i)}{a^3(t)}$$

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

$$\frac{dE}{dt} = -\Gamma G\mu^2, \quad \Gamma \approx 50$$

Stochastic GW Background from Cosmic Strings

- Consequently, the loop size decreases as

$$l = \alpha t_i - \Gamma G\mu \left(t - t_i\right)$$

- The observed GW frequency today from a loop of size l

$$f = \frac{a(\tilde{t})}{a(t_0)} \frac{2k}{l}$$

k: oscillation mode

Stochastic GW Background from Cosmic Strings

Putting things together:

- **GW density per unit frequency seen today:**

$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df} = \sum_k \Omega_{GW}^{(k)}(f)$$

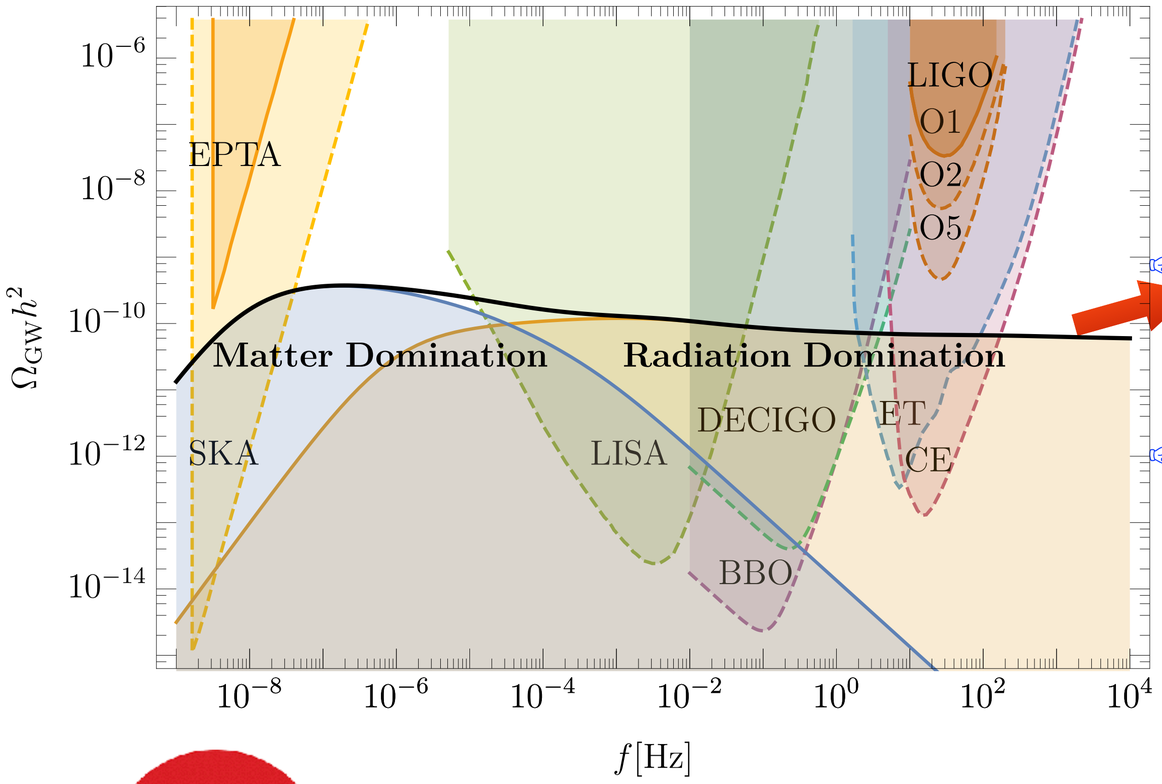
$$\Omega_{GW}^{(k)}(f) = \frac{1}{\rho_c}\frac{2k}{f}\frac{(0.1)\,\Gamma_k G\mu^2}{\alpha(\alpha+\Gamma G\mu)} \times \int_{t_F}^{t_0} d\tilde{t}\ \frac{C_{eff}(t_i)}{t_i^4}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5\left[\frac{a(t_i)}{a(\tilde{t})}\right]^3 \Theta(t_i - t_F)$$

expansion parameter

-Cosmic expansion history $H(t) \equiv \dot{a}/a$ is encoded ($a(\tilde{t})$)!

Testing Standard Cosmology w/GW Spectrum from Cosmic Strings

- An example: $G\mu = 2\times10^{-11}$, α=0.1 (in standard cosmology)



<u>Features of the GW spectrum</u>:

- A long (nearly) flat plateau: emission during RD epoch, *deviation could be easy to see!*
- GW with a given *f* was dominantly contributed by loops formed at a certain *t/T* (higher *f* ↔ earlier time)

(next slide…)

Looking back in time!

The GW Frequency-Time (Temperature) Correspondence

arxiv: 1711.03104, 1808.08968, YC with Lewicki, Morrissey and Wells

- Quantify/utilize the *f*-*T* correspondence

$$\text{GW frequency} \leftrightarrow \text{temperature}$$

GW with a given *f* was dominantly contributed by loops formed at a certain t/T

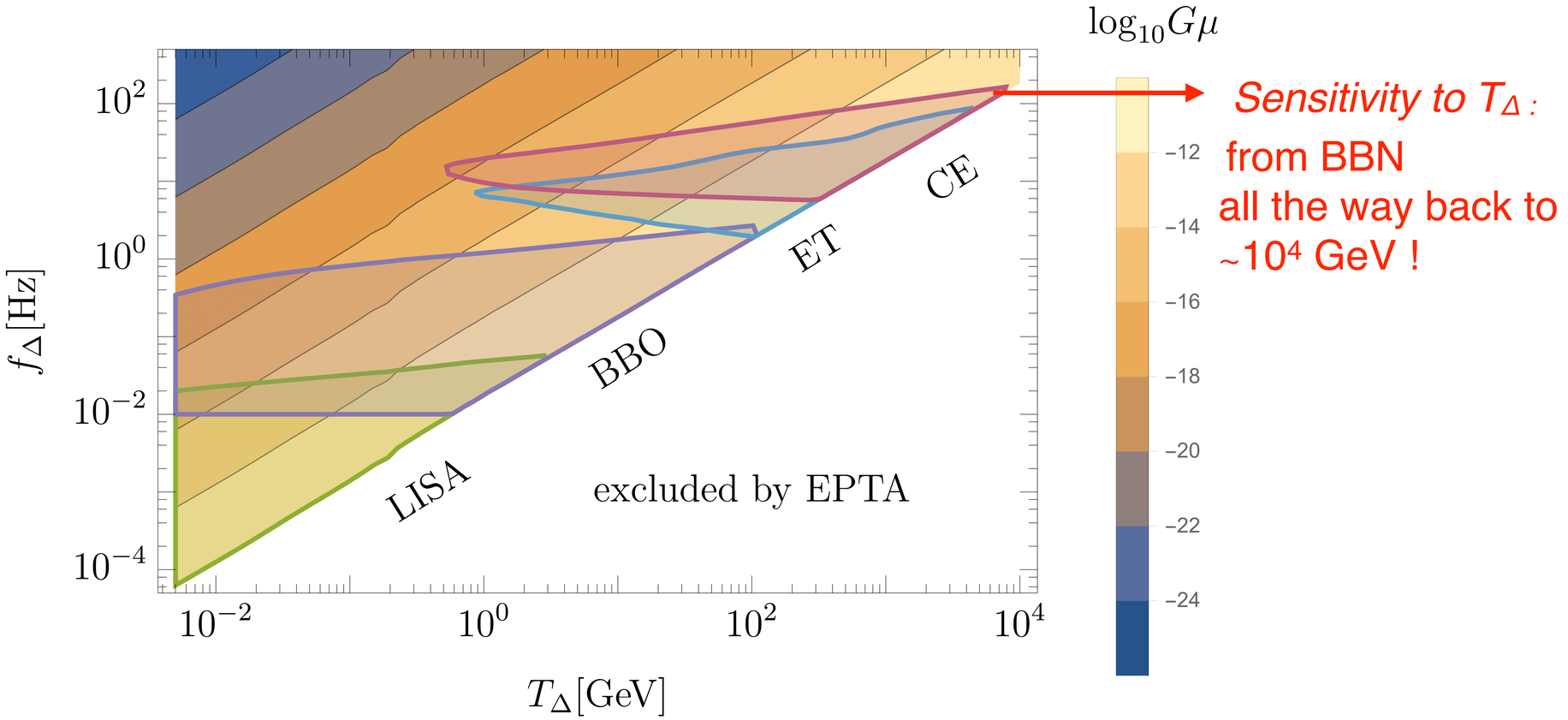
$$f_\Delta \simeq \sqrt{\frac{8}{z_{\rm eq}\alpha\,\Gamma G\mu}}\left[\frac{g_*(T_\Delta)}{g_*(T_0)}\right]^{1/4}\left(\frac{T_\Delta}{T_0}\right)t_0^{-1}$$

Numerical fit:

$$f_\Delta = (8.67\times10^{-3}\,\text{Hz})\left(\frac{T_\Delta}{\text{GeV}}\right)\left(\frac{0.1\times50\times10^{-11}}{\alpha\,\Gamma\,G\mu}\right)^{1/2}\left(\frac{g_*(T_\Delta)}{g_*(T_0)}\right)^{\frac{8}{6}}\left(\frac{g_{*S}(T_0)}{g_{*S}(T_\Delta)}\right)^{-\frac{7}{6}}$$

Experimental Detection Prospects

(f-T correspondence)



Sensitivity to T_Δ :
from BBN
all the way back to
~10^4 GeV !

- Fig.: f_Δ required to test the standard cosmology up to radiation T_Δ for a range of Gμ, α=0.1. Shaded regions: signal within detection sensitivity by the corresponding GW detector.

Probing New Phases (Equation of States) in Cosmological Evolution

Non-standard cosmology (new e.o.s) well-motivated, e.g.

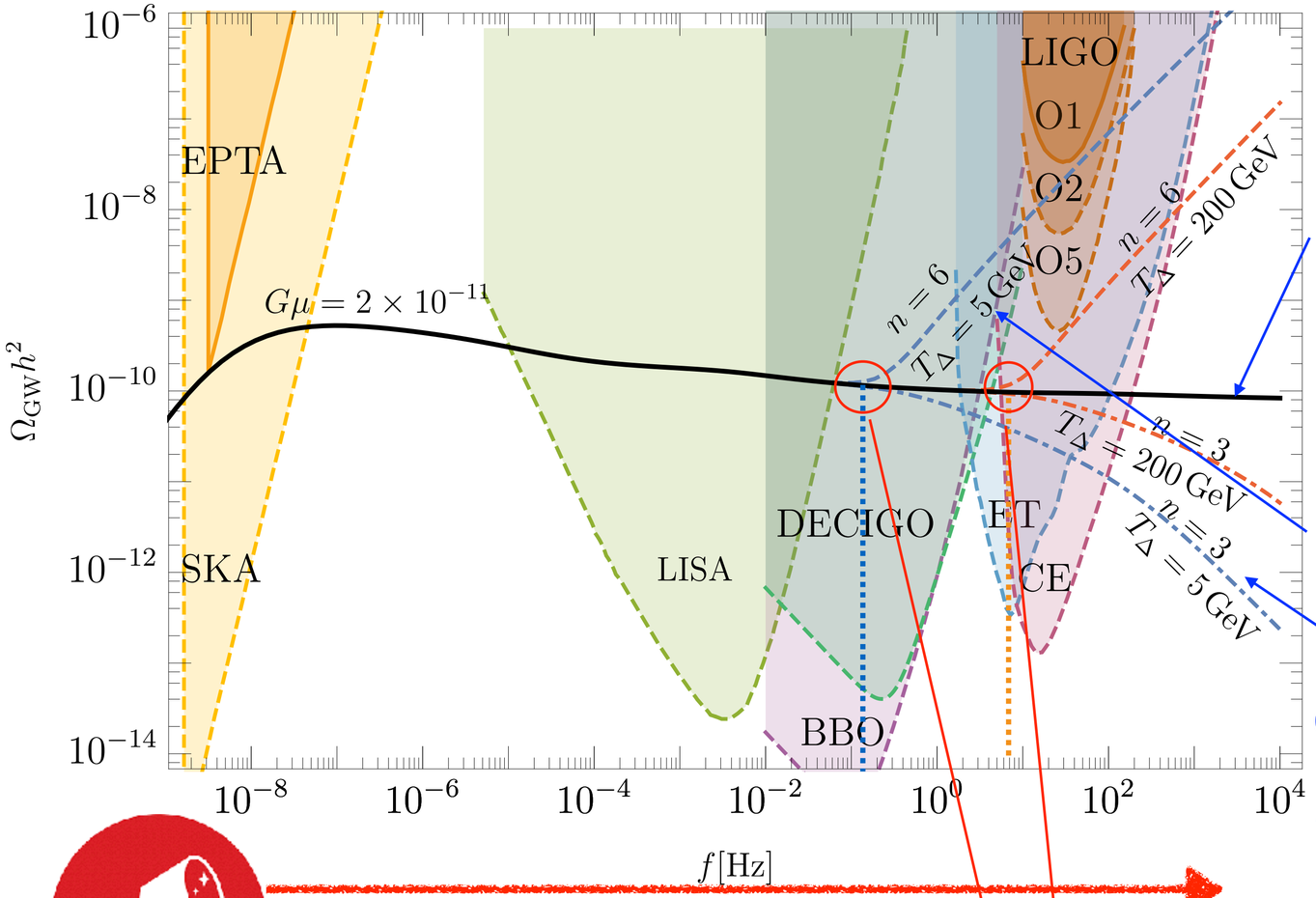
- Early matter domination ($\rho \propto a^{-3}$): baryogenesis, moduli…
- Kination ($\rho \propto a^{-6}$): DE, axion, inflation…

— **Take a break from the "boring" RD era ($\rho \propto a^{-4}$) !**

Impact on SGWB spectrum from cosmic strings:

$$H^2 = \frac{8\pi}{3}\rho,\ H^2 \propto a^{-n}$$

Probing New Phases in Cosmic History with Cosmic String GWs



$\alpha = 10^{-1}$

- n=4: RD (standard, flat)

Assume a transition at T_Δ = 5, 200 GeV:

- n=6: kination (rise)
- n=3: early MD (fall)

☞*Dramatic departure from RD flatness!*

Looking back in time!

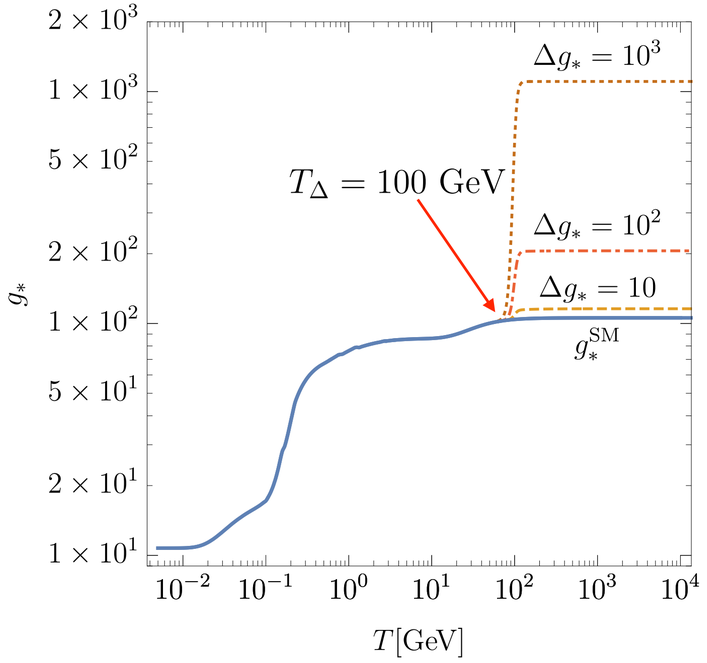
$$f_\Delta \propto T_\Delta \alpha^{-\frac{1}{2}} (G\mu)^{-\frac{1}{2}}$$

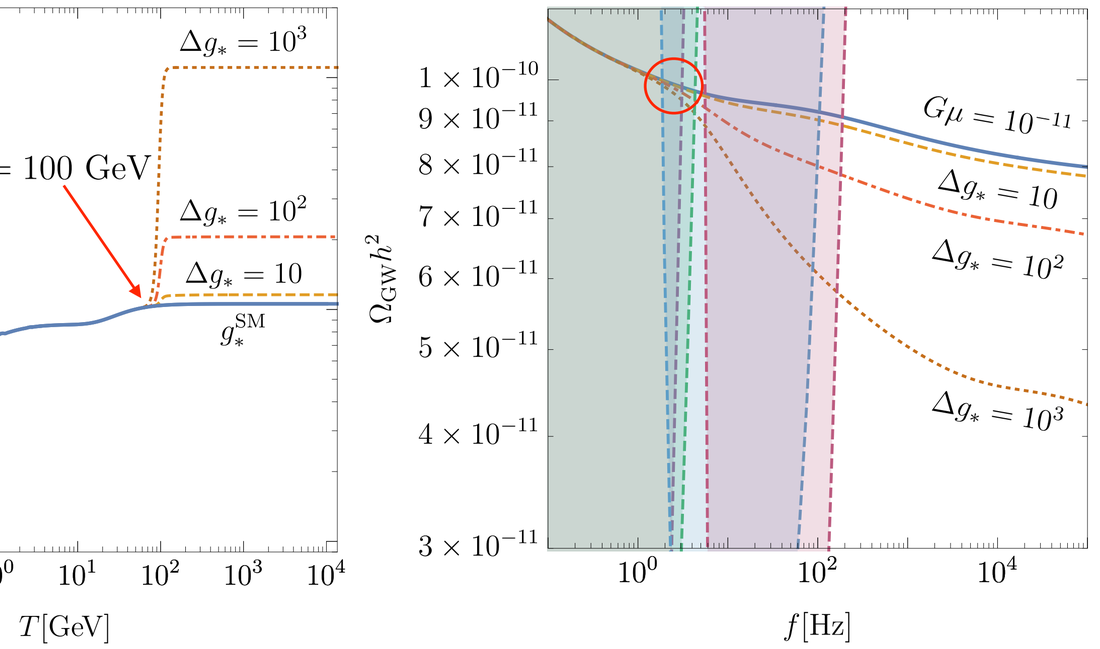
Probing New (Massive) Degrees of Freedom

Cosmological Probe for (Massive) BSM Degrees of Freedom

- Additional d.o.f's: ubiquitous in BSM theories, maybe hundreds of them! *(GUT, DM, SUSY, RS, hidden valley, twin Higgs, NNaturalness…)*
- Massive d.o.f's: radiation in the early Universe (g_*), later freezeout/decay☞can't be traced by CMB ΔN_{eff} (unlike massless d.o.f)

— GW spectrum may provide a way! $(H^2 \propto g_* T^4)$





Gravitational Wave Bursts as Harbingers of Cosmic Strings Diluted by Inflation

(arxiv: 1912.08832 PRL, YC with Marek Lewicki and David Morrissey)

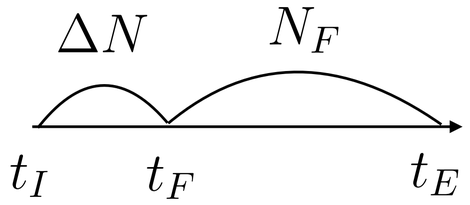
Inflation buries all relics before it (or shortly after it starts)?

A counter-example!

Inflation and Cosmic String Regrowth

- **How is it possible?**

L: correlation length $\rho_\infty \equiv \dfrac{\mu}{L^2}$



During inflation: $L(t) = L_F\, e^{H_I(t-t_F)}$

$$L(t_F) \equiv L_F = \frac{1}{\zeta\, H_I}$$

After inflation: $L \propto a,\ \rho_\infty \propto a^{-2}$

Slower than the growth of horizon size H^{-1}*!*

RD: $H^{-1} \propto a^{2}$, $\rho_r \propto a^{-4}$

MD: $H^{-1} \propto a^{3/2}$, $\rho_m \propto a^{-3}$

☞ *Strings may grow back into horizon after inflation!* $(\text{after } \tilde{z}\ LH \lesssim 1)$

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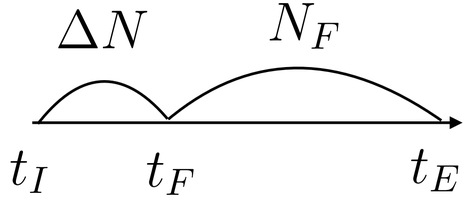

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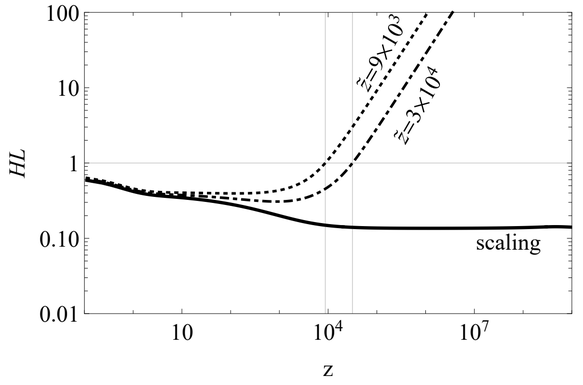
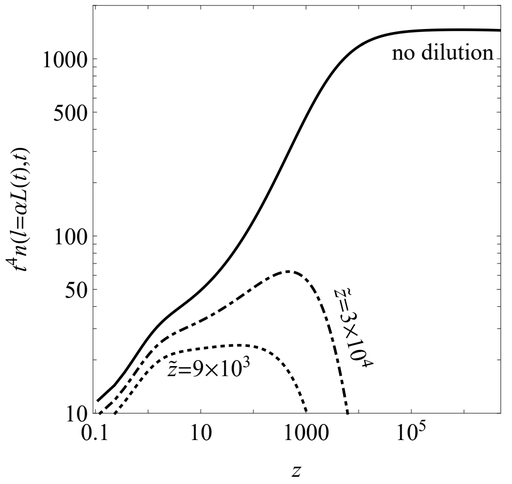
☞ *Strings may grow back into horizon after inflation!* $(\text{after } \tilde{z}\ LH \lesssim 1)$

Solve for string network evolution with VOS model:

$$\frac{dL}{dt} = (1 + \bar{v}^2)\, HL + \frac{\tilde{c}\bar{v}}{2}$$

$$\frac{d\bar{v}}{dt} = (1 - \bar{v}^2) \left[\frac{k(\bar{v})}{L} - 2H\, \bar{v} \right]$$



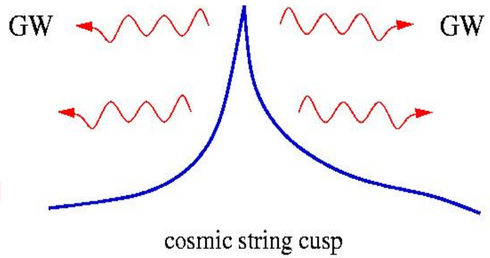


Gravitational Wave Bursts as Harbingers of Cosmic Strings Diluted by Inflation

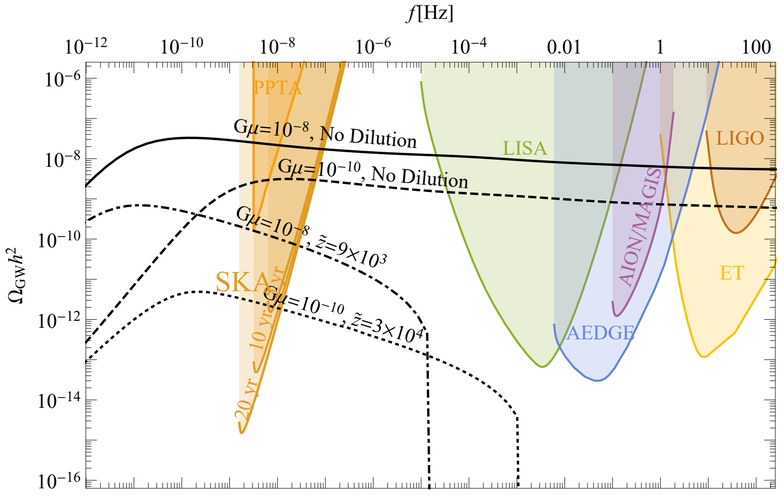
*(arxiv: 1912.08832 **PRL**, YC with Marek Lewicki and David Morrissey)*

Distinct GW signals from a diluted then regrown cosmic string network

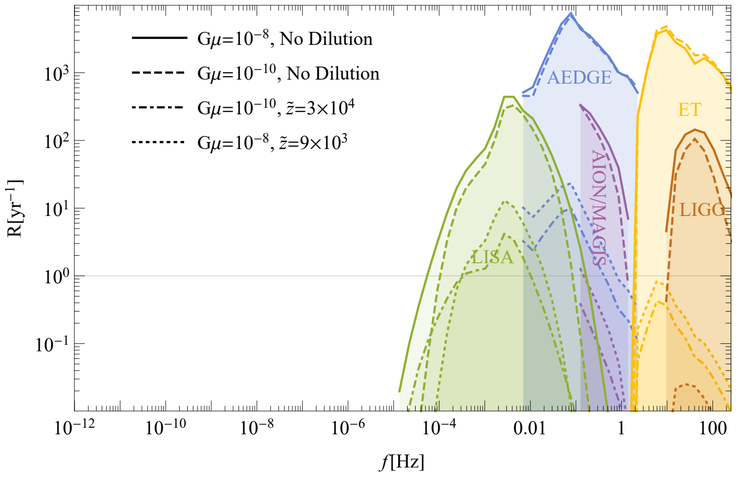
- **Stochastic GW background:** suppressed esp. at higher f, strong constraints on $G\mu$ based on SGWB alleviated (PPTA, LIGO…)
- **GW bursts:** transient resolvable, late time/nearby events due to cusps/kinks on strings; subdominant signal channel to SGWB for standard strings, but can be the leading discovery channel now!



★ **SGWB:** *Standard vs. diluted*



★**GW bursts:** detectable rates



II. Novel Probes of ALP DM Models with GWs from Axion Topological Defects

— An interesting twist/application when switch gear to a global U(1)…

Novel Probes of Axion-like Dark Matter Models with GWs from Axion Topological Defects

(arXiv:1910.04781 (PDU), 2106.09746 YC (JHEP) with Chia-Feng Chang)

- Axion-like particle (ALP) DM: ultra-light (pseudo-)goldstone boson from a global $U(1)_{PQ}$ breaking, leading alternative to WIMP paradigm, a lot of interest/effort recently; QCD axion, generic (hidden) ALPs also motivated *(e.g. string axiverse)*

- **A relatively under-developed aspect of ALP studies:** implication of ALP topological defects ☞ ALP cosmic strings/domain walls: indispensable companion of ALP particles for $U(1)_{PQ}$ breaking after inflation

  — *potentially significant impact on axion DM physics and detection methods;*

  Rapidly increasing interest in the past few years (simulations, analytical studies, signals…)

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GW signature from axion cosmic strings?

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Our focus: GW signature from global/axion cosmic strings? 

— An overlooked, yet potentially discovery channel

Why Overlooked? "too small" by naive estimate, some earlier literature (few) suggested non-detectability

- Difference from gauge/local/NG strings #1: GW radiation subdominant to Goldstone emission

Radiation power: $P_{\rm GW} \sim \Gamma G\mu^2 \ll P_g \sim \Gamma_g \eta^2,$

- Difference from gauge/local strings #2: Log-divergent, time-dependent string tension:

$$\mu \sim \eta^2 \log\left(L/\delta\right) \quad \text{correlation length: } L \sim H^{-1}, \text{string core width: } \delta \sim \eta^{-1}$$

$N \equiv \log(L/\delta)$ —time-dependent parameter (later…)

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- **Key motivation:** rare decay mode can be discovery mode! (e.g. Higgs discovery, axion/goldstone search strategy model dependent…) + GW signal universal, GW detector sensitivity keep improving…

Novel Probes of ALP DM Models with GWs from Axion Topological Defects

(arXiv:1910.04781, 2106.09746 YC with Chia-Feng Chang)

- **Challenges:**
  - Limited literature (compared to NG/gauge strings)
  - Rapid recent development of global string simulation: not converging, non-scaling, more to investigate (*challenge*: cover hierarchical scales)
  - More complex for axion strings: cosmic strings + domain walls

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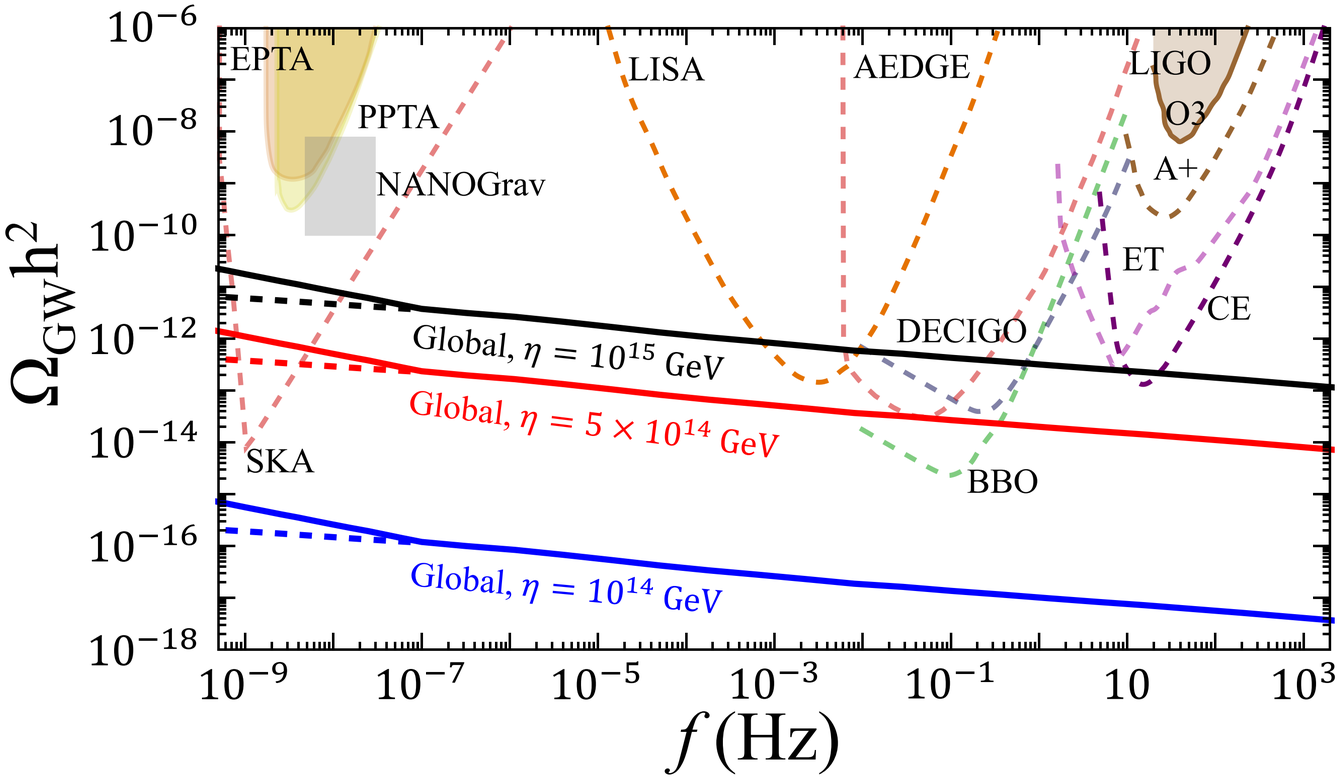
  - More complex for axion strings: cosmic strings + domain walls
- **Our approach:**
  - Start with the simple case: SGWB signal from global strings (massless goldstone) (→QCD axion→ALPs)
  - Semi-analytical: VOS model (including Goldstone emission) calibrated with simulation results (low *N)*
  - Complement simulations: simple extrapolation of low *N* data to late time evolution vs. solving evolution equation with essential physics encoded

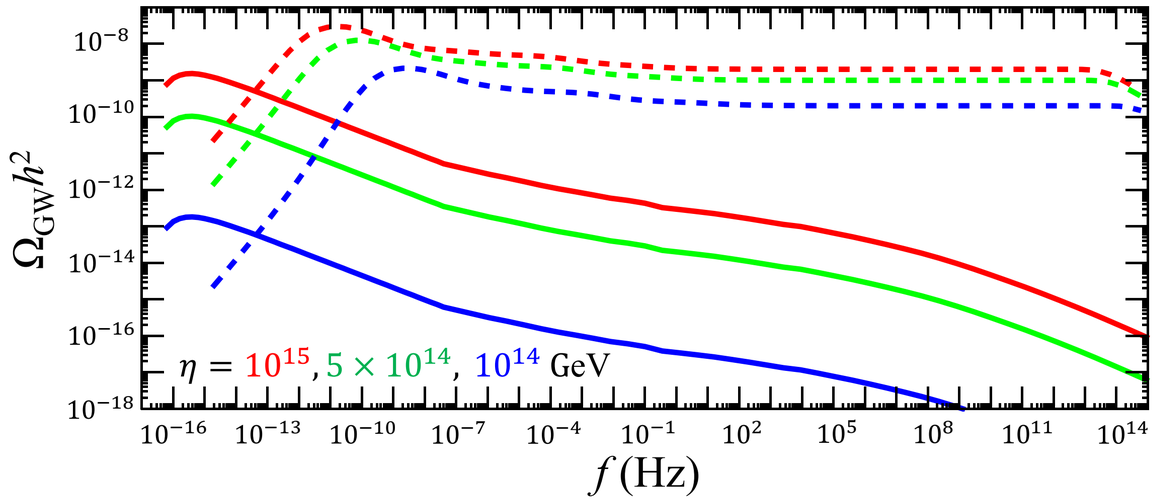
SGWB Spectrum from Global Cosmic Strings

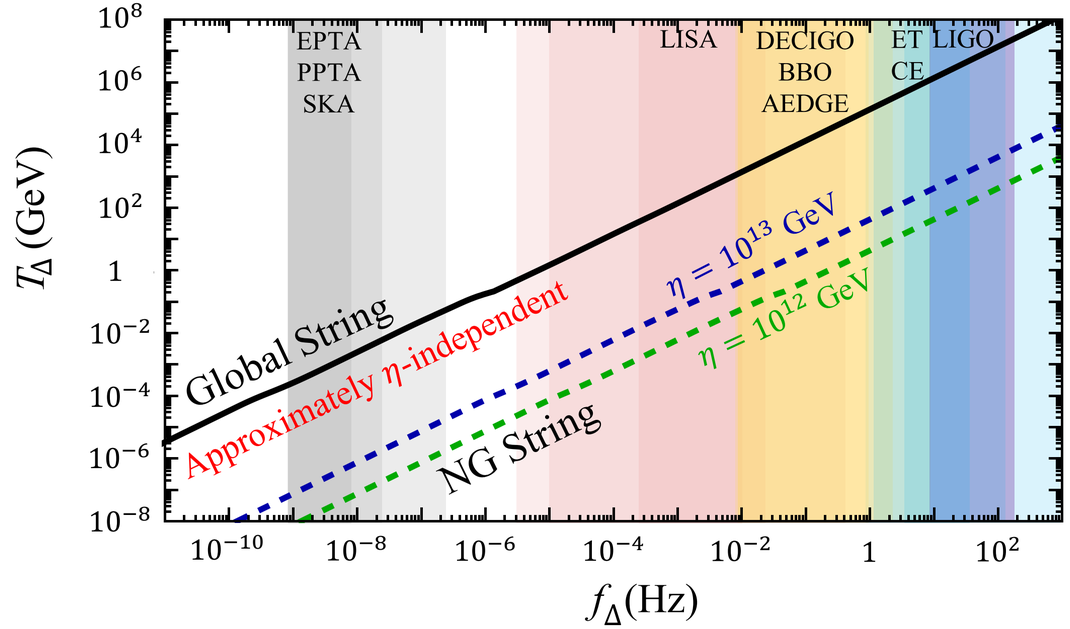
With standard cosmology *(YC and Chang 2019, updated in 2021):*



- Detectable with upcoming GW experiments! Supported by recent simulation findings (details differ) *(Gorghetto, Hardy and Nicholaescu 2021; Figueroa, Hindmarsh, Lizarraga and Urrestilla 2020)*

Comparison with NG strings, *f-T* Correspondence





- Global strings (solid) vs. NG strings (dashed): Overall smaller amplitude, spectrum redshifted, logarithmically declining tail
- Explanation: Goldstone emission dominance, short-lived loops, log factor in μ

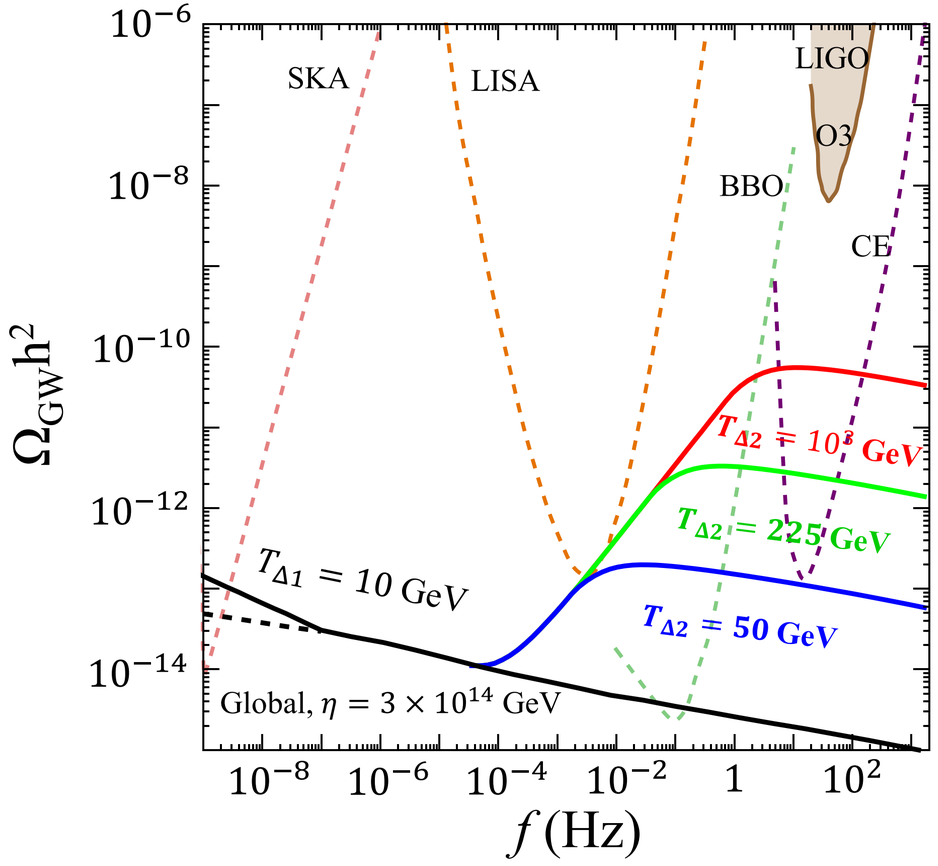
- f-T correspondence: very different from NG, Insensitive to η , the same *f* corresponds to higher *T*→probe up to $T \sim 10^8\ GeV$! *(short-lived loops)*

$$f_\Delta \simeq \frac{2}{\ell(\tilde{t})}\frac{a(t_\Delta)}{a(t_0)} = \frac{2}{\alpha z_{\rm eq} t_{\rm eq} T_{\rm eq}}\left[\frac{g_*(T_\Delta)}{g_*(T_{\rm eq})}\right]^{1/4} T_\Delta$$

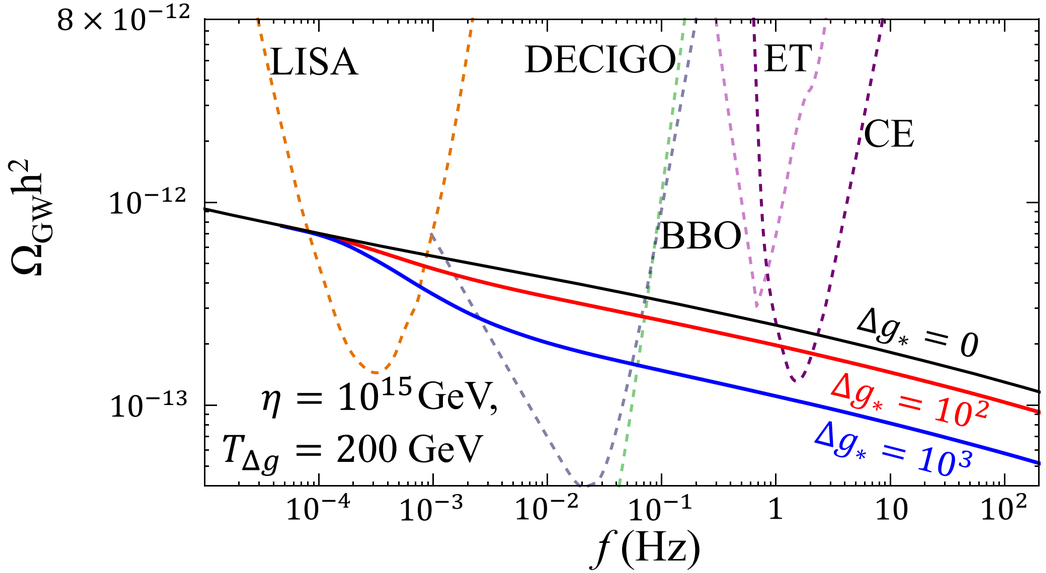
$$\simeq (3.02\times10^{-6}\,{\rm Hz})\left(\frac{T_\Delta}{1\,{\rm GeV}}\right)\left(\frac{\alpha}{0.1}\right)^{-1}\left[\frac{g_*(T_\Delta)}{g_*(T_{\rm eq})}\right]^{1/4}$$

Cosmic archaeology with GWs from global strings

- SGWB with non-standard cosmology (early MD, kination):



- SGWB with new particle species in the early Universe:



Conclusion/Outlook

- **Cosmic strings:** a potentially strong, well-studied source of SGWB that can serve as a "standard candle" for probing very early Universe — a unique and powerful tool for **reconstructing a timeline for pre-BBN cosmic history** *(the f-T correspondence)* **+ finding new particle species!**

- Cosmic strings may regrow back into horizon despite inflationary dilution and leave an imprint: GW bursts + suppressed SGWB, clues for (pre-)inflationary epoch?

- GWs from (global) axion strings/domain walls may be the **smoking gun** for dark matter; work in prep (w/CF Chang): better understanding of evolution/dynamics of axion DW (towards DM axion)

- Welcome follow-up discussion (reach out to me by email)!

Thank you!