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

Yanou Cui

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, YC with Chia-Feng Chang

arxiv: 2012.07874 (PRD), YC with Barry Barish and Simeon Bird

International workshop on GW probes for BSM physics, Jul 12, 2021

GWs from Cosmic Strings

- Cosmic strings: 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 see earlier talks in this session*

Outline of This Talk

Other new physics imprints in GWs from cosmic strings?

- 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

How to distinguish SGWB from cosmic strings (or other cosmo sources) vs. astro SGWB?

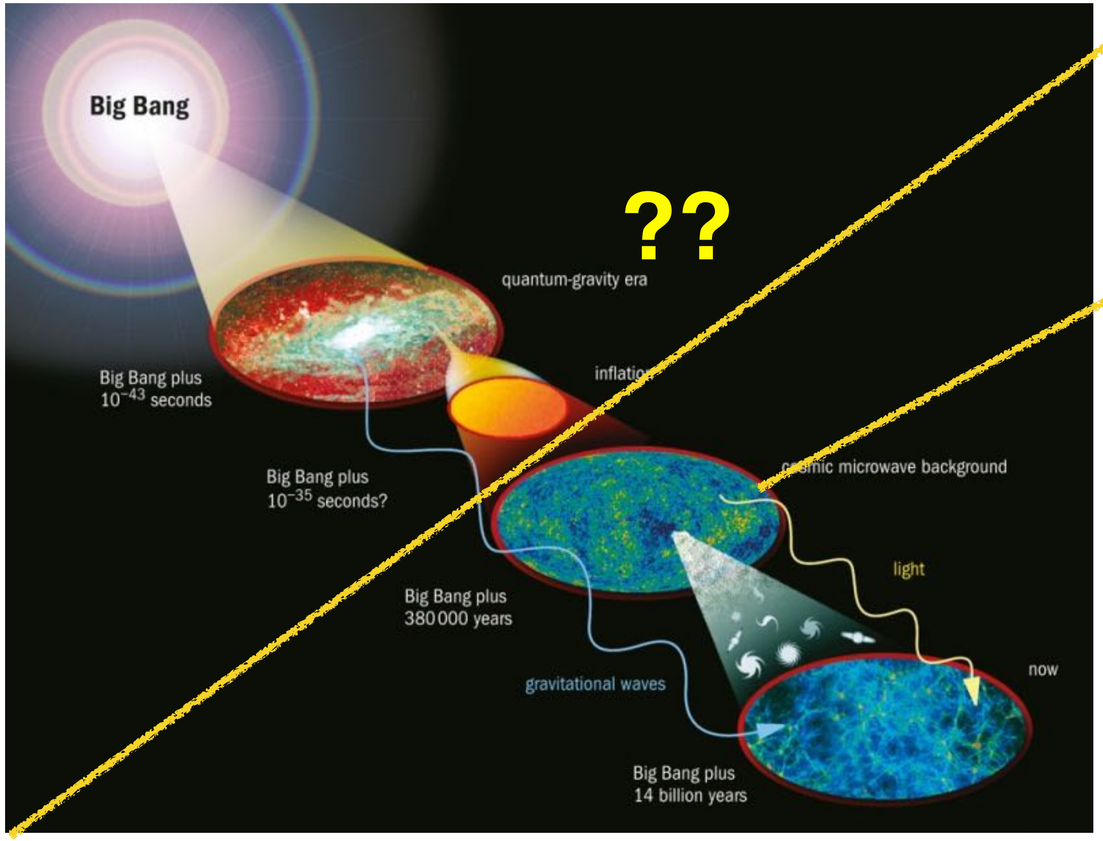
- Use frequency domain information, e.g. with a midband GW experiment

(Also see Barry's keynote talk on Friday)

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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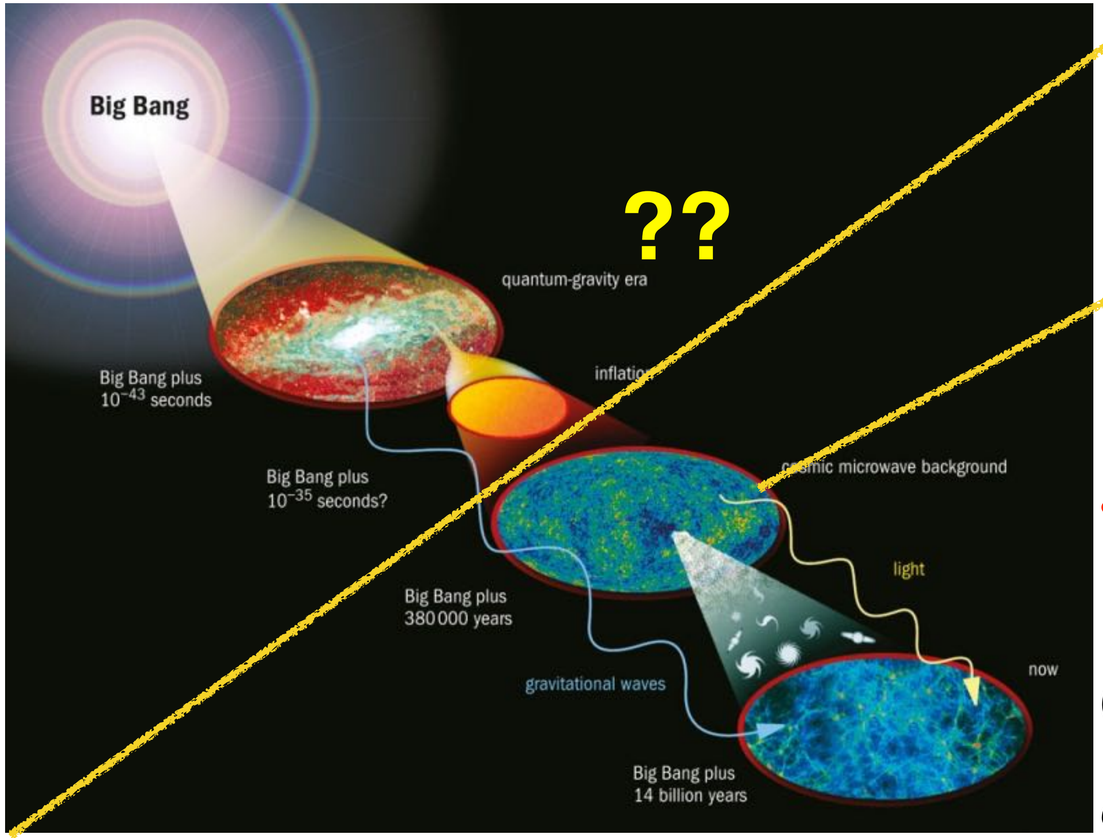

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- **What happened before BBN?**
  Standard cosmology theory: **assumptions to be tested, many unknowns!**
  (scale of inflation/reheating?
  early matter domination/kination?
  early phase transitions? new d.o.f?…)

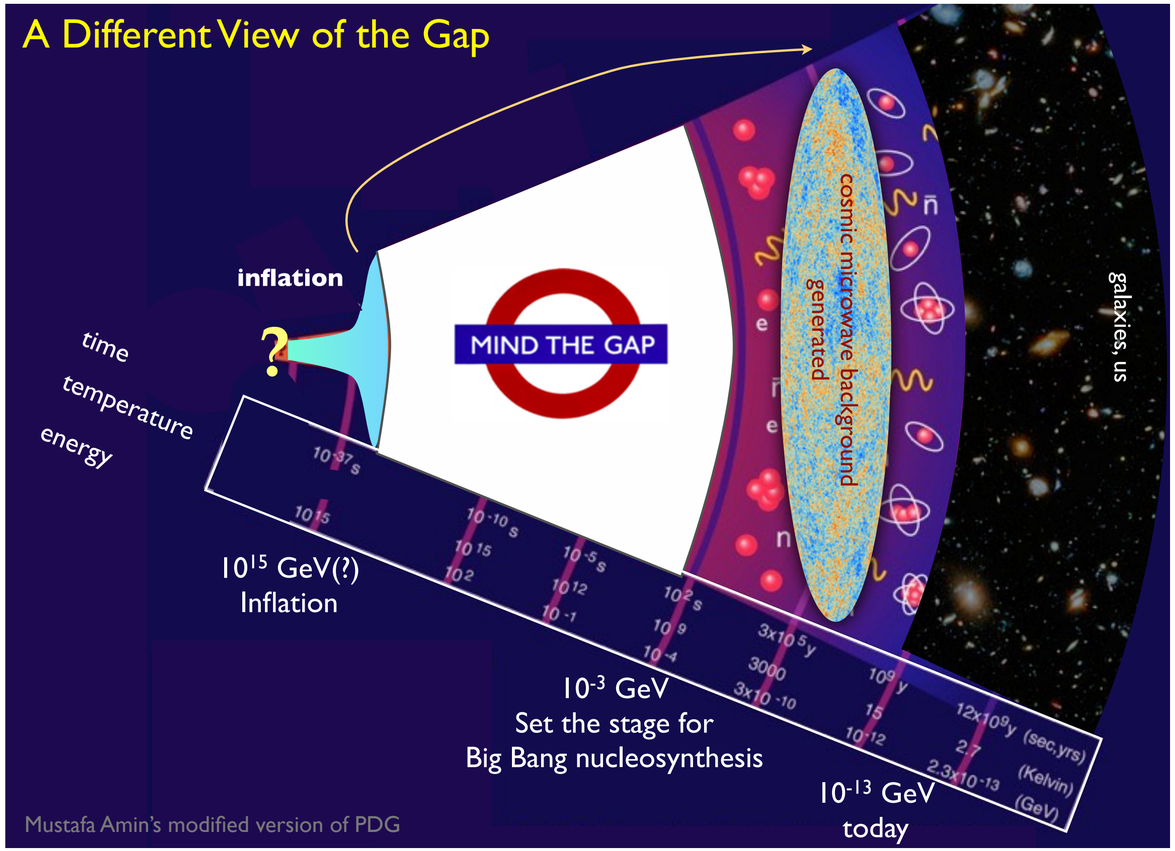
Pre-BBN Cosmology?

— *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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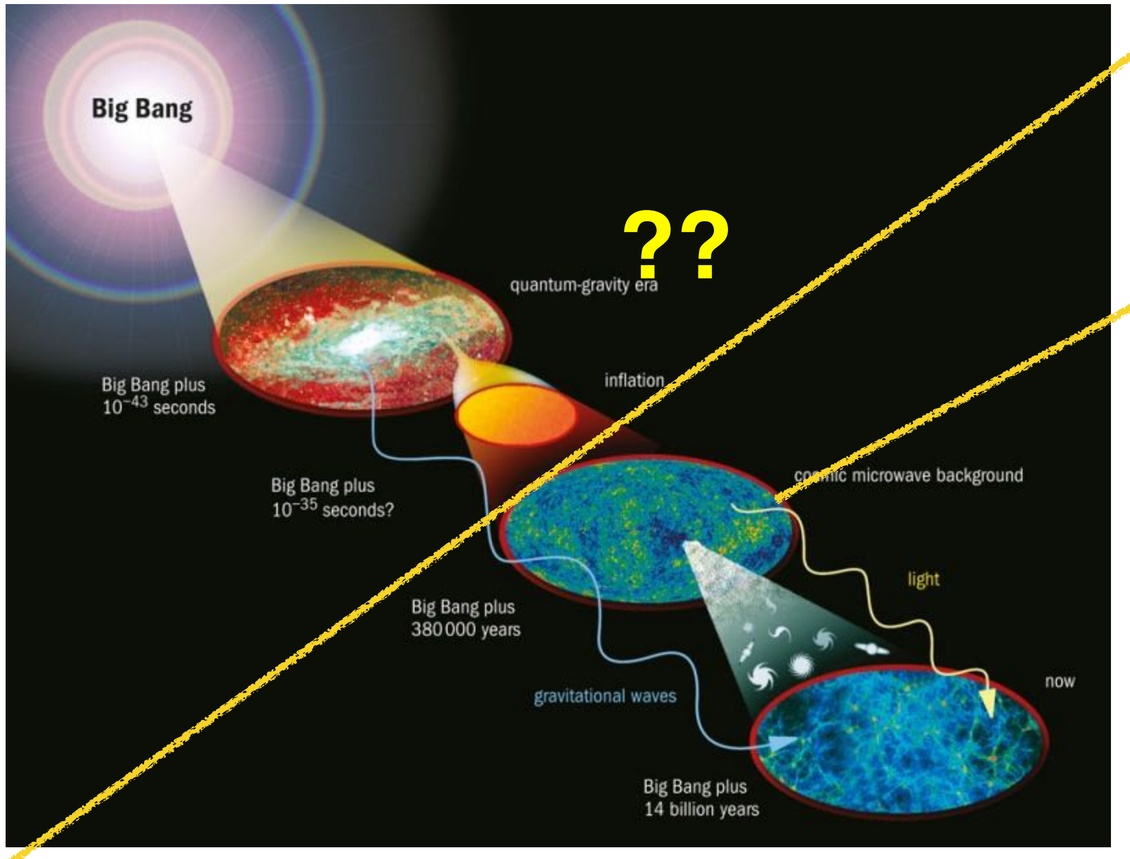

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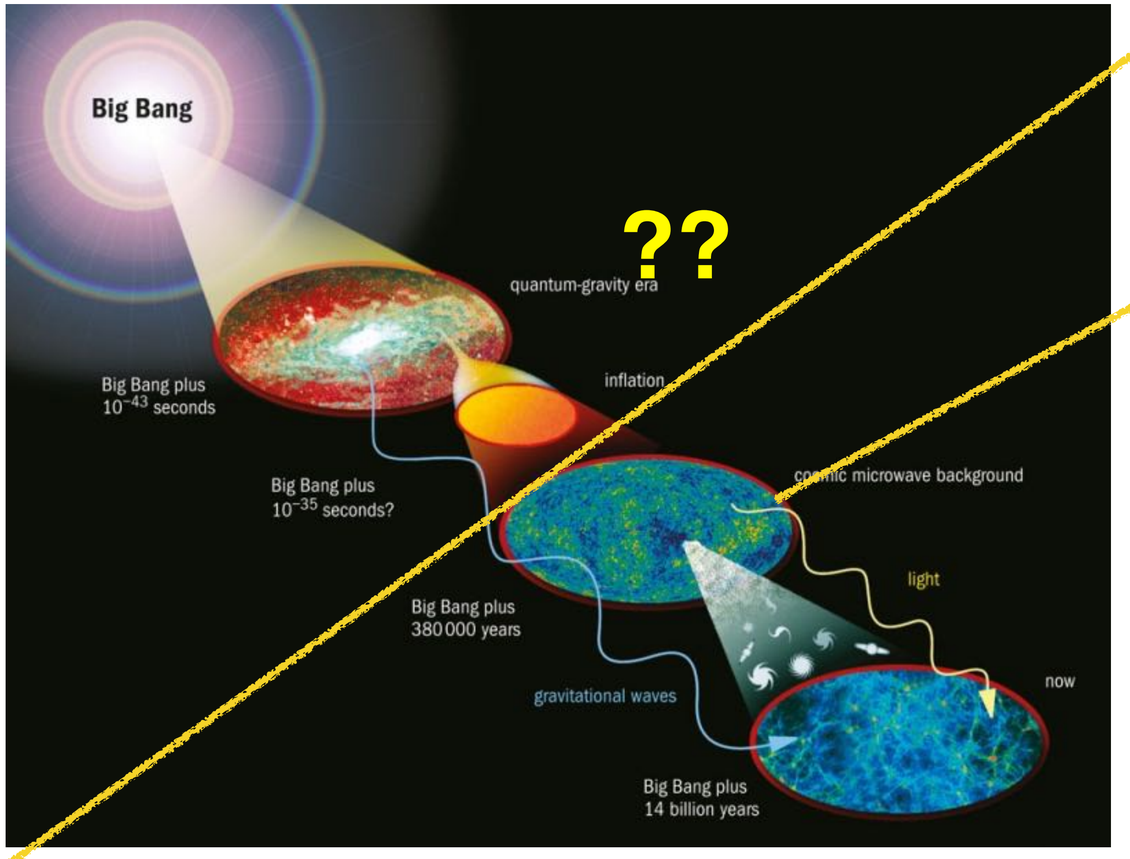

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  inflation + post-inflationary thermal history
  (Impact on Ω_{DM}, DM halo structure/detection!)

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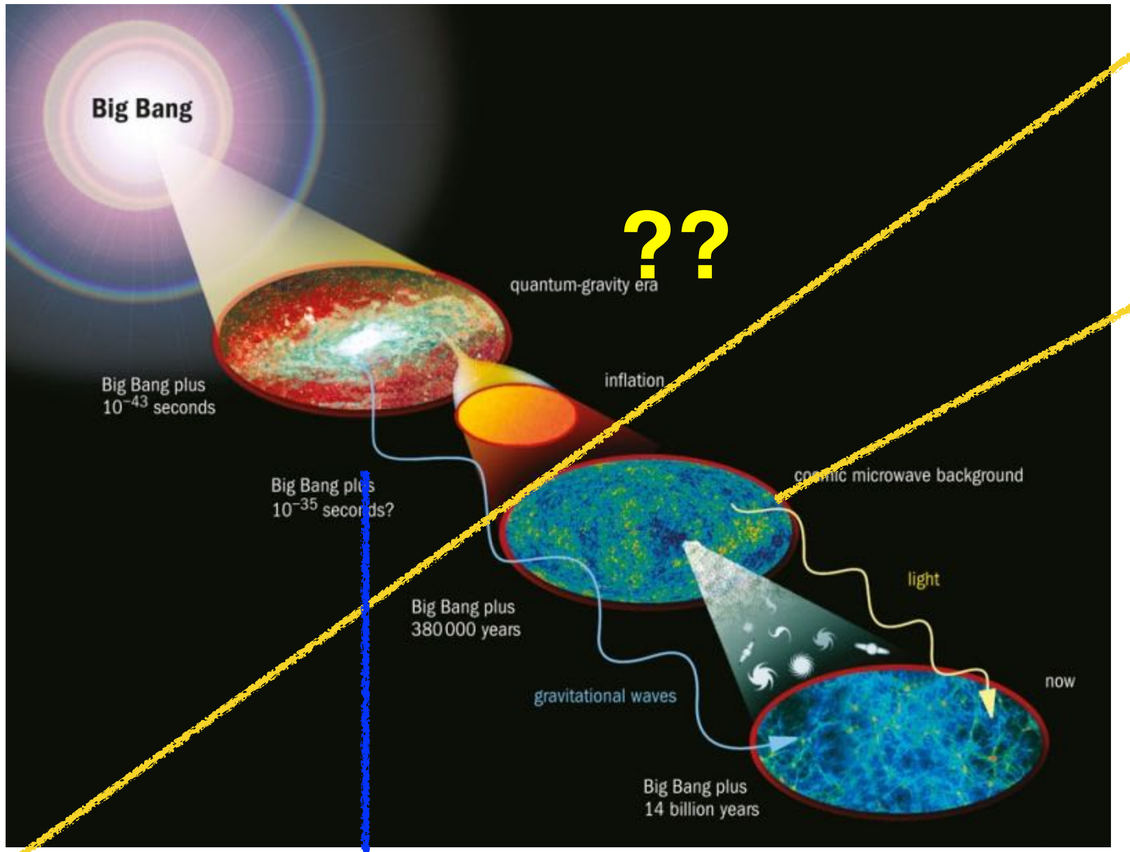

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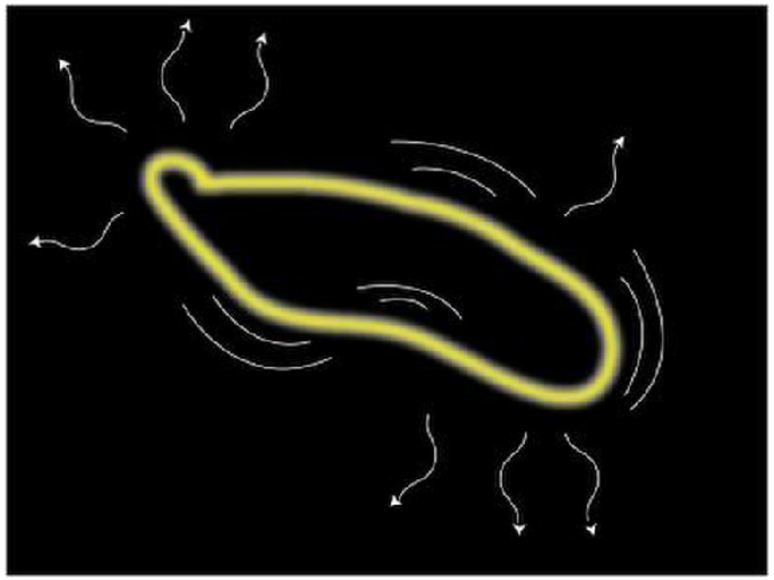
GW: the window of hope?

- **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

- 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 dominates

Stochastic GW Background from Cosmic Strings

Putting things together:

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

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

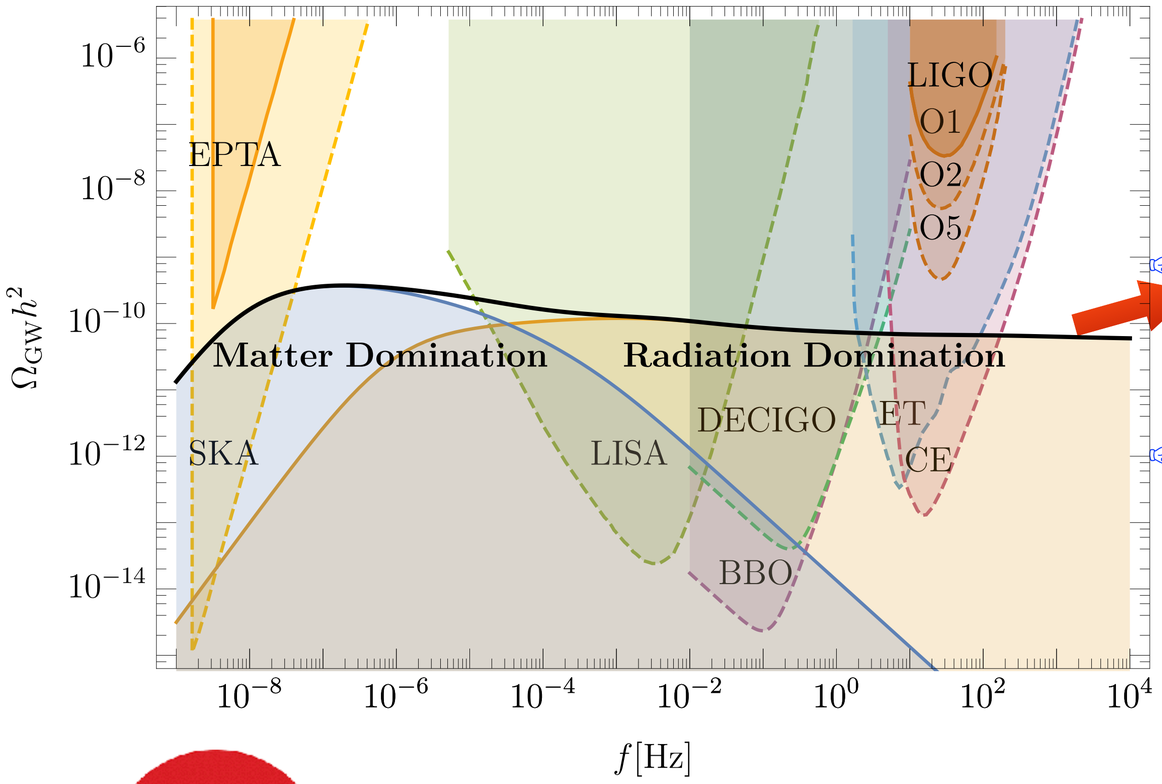
$$\Omega_{GW}^{(k)}(f) = \frac{1}{\rho_c}\frac{2k}{f}\frac{(0.1)\,\Gamma_k G\mu^2}{\alpha(\alpha+\Gamma G\mu)} \times \int_{t_F}^{t_0} d\tilde{t}\ \frac{C_{eff}(t_i)}{t_i^4}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5\left[\frac{a(t_i)}{a(\tilde{t})}\right]^3 \Theta(t_i - t_F)$$

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

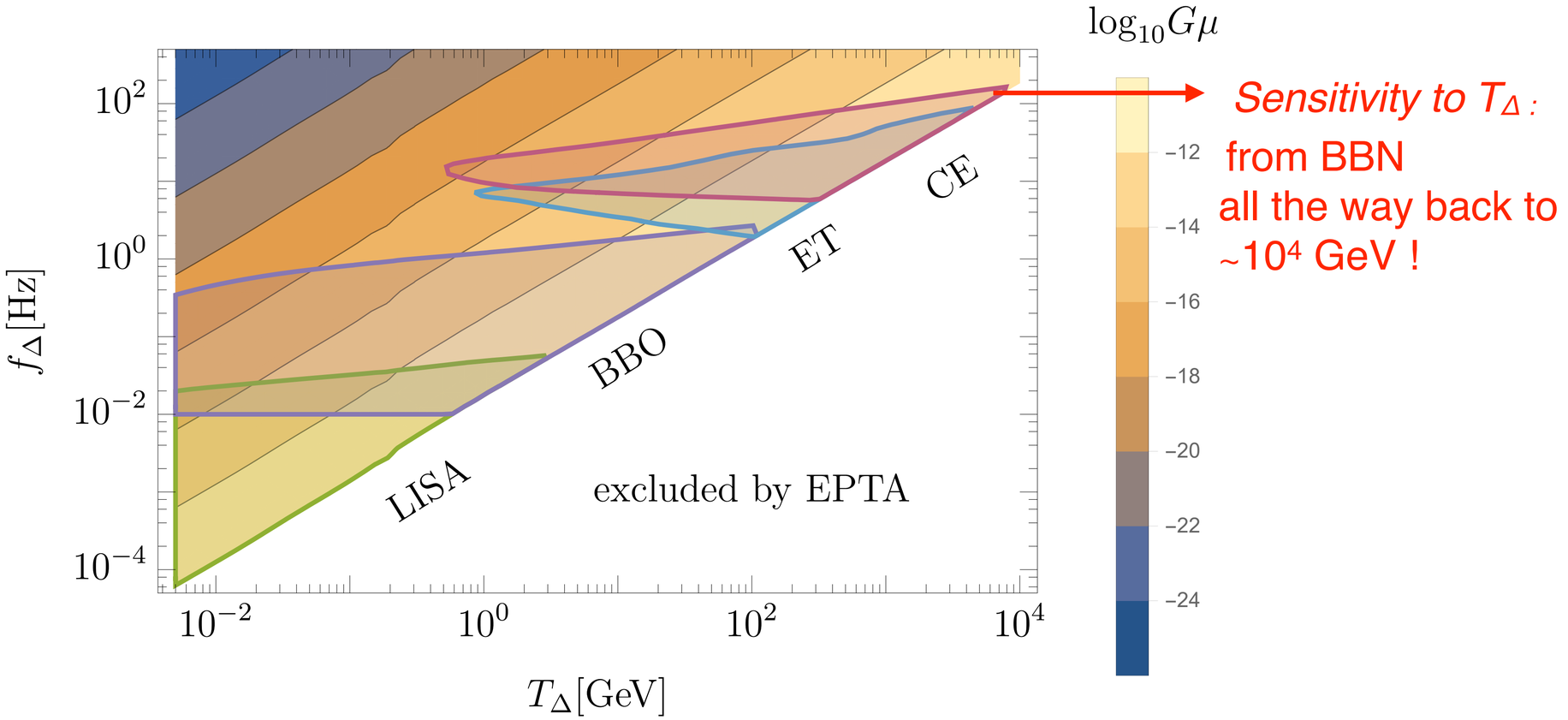
$$f_\Delta \simeq \sqrt{\frac{8}{z_{\rm eq}\alpha\,\Gamma G\mu}}\left[\frac{g_*(T_\Delta)}{g_*(T_0)}\right]^{1/4}\left(\frac{T_\Delta}{T_0}\right)t_0^{-1}$$

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)



- 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

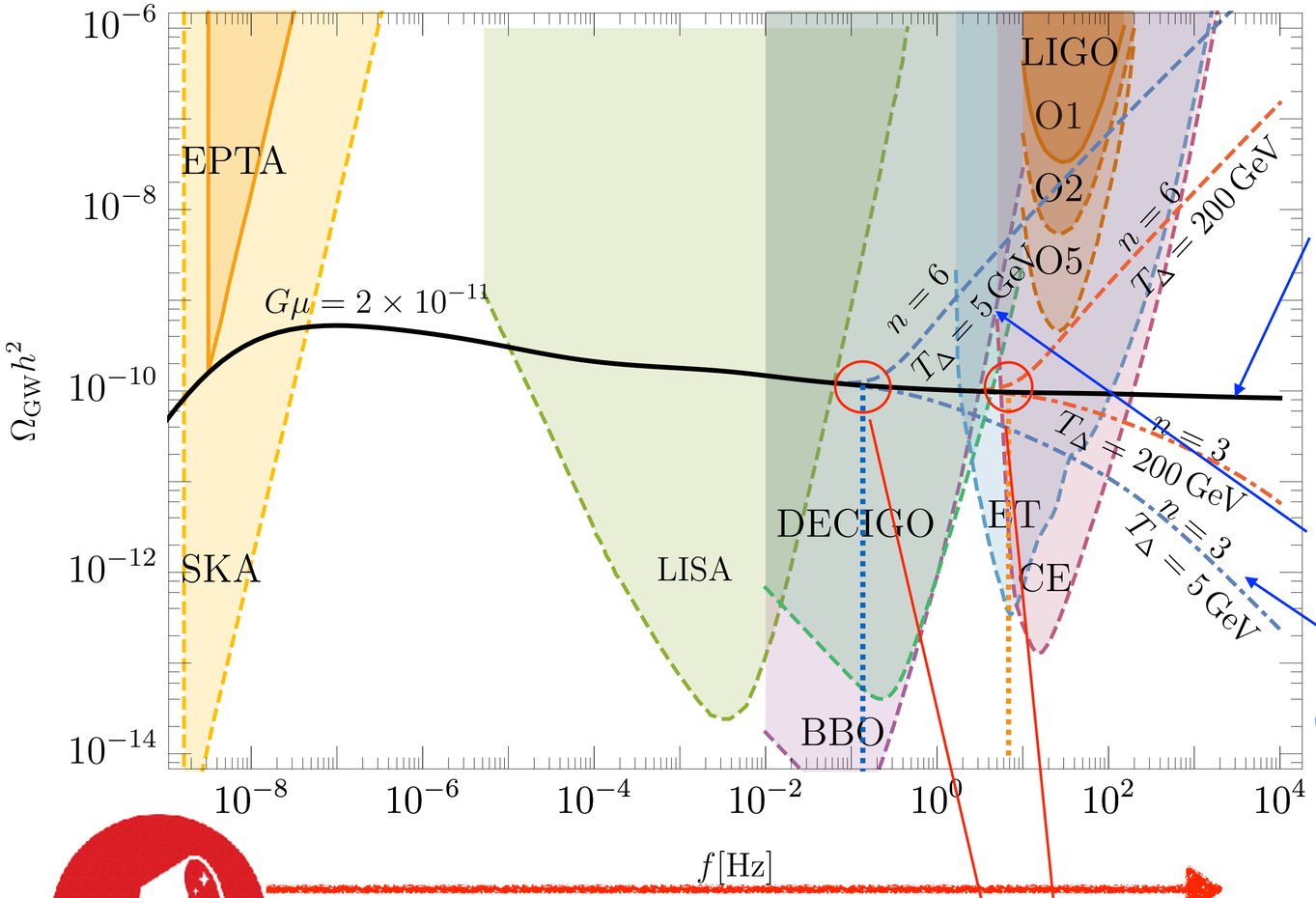
Non-standard cosmology (new e.o.s) well-motivated, e.g.

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

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!

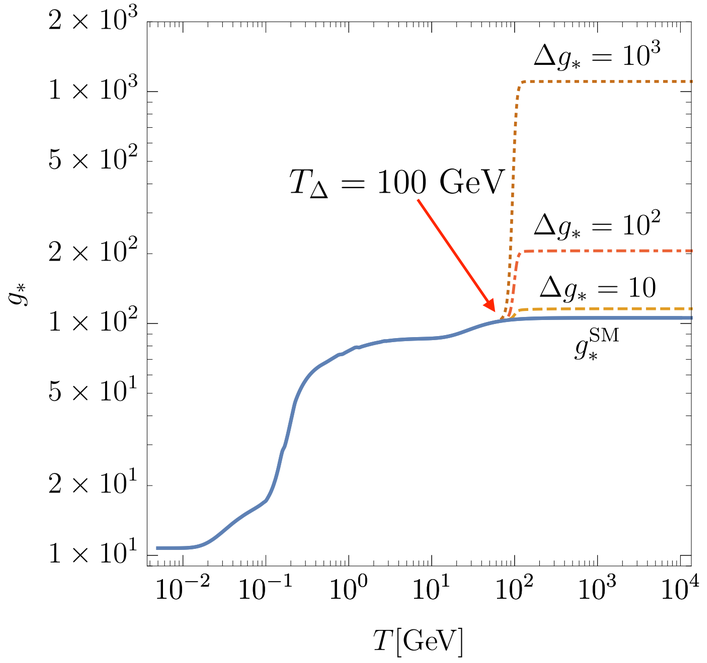
$$f_\Delta \propto T_\Delta \alpha^{-\frac{1}{2}} (G\mu)^{-\frac{1}{2}}$$

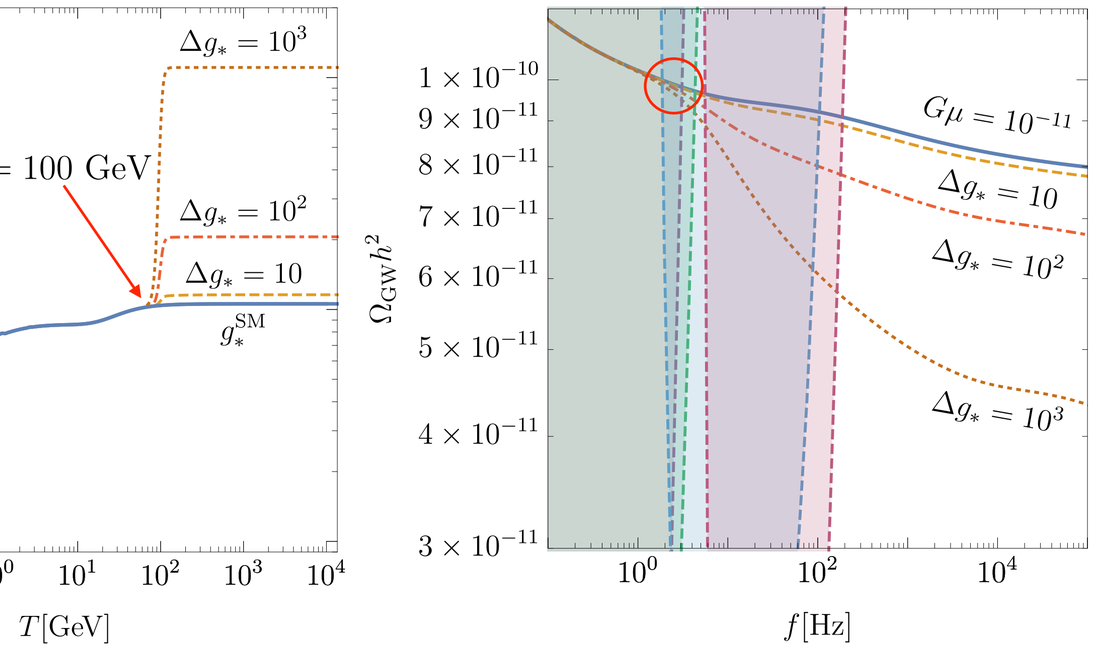
Probing New (Massive) Degrees of Freedom

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)

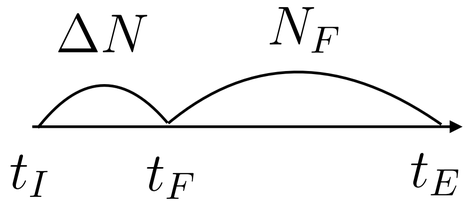
Inflation buries all relics before it (or shortly after it starts)?

A counter-example!

Inflation and Cosmic String Regrowth

- **Why is it possible?**

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



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

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

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

Compare:

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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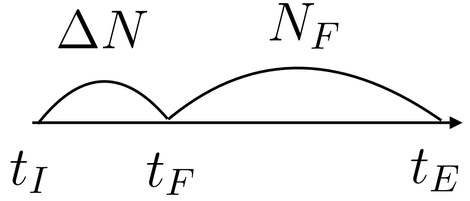

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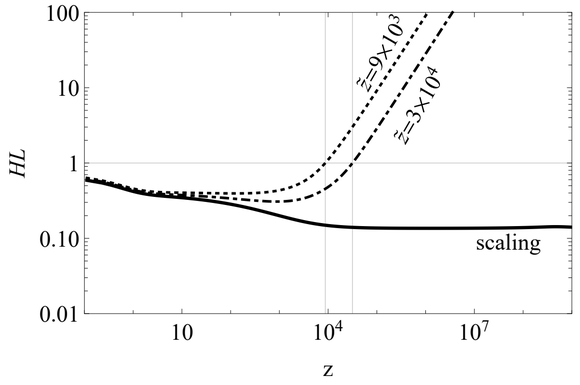
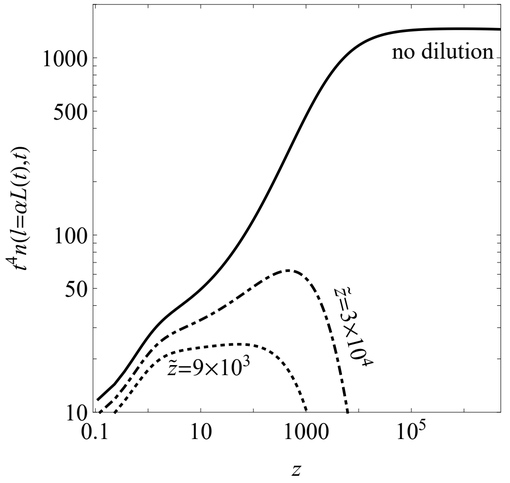
Solve for string network evolution with VOS model:

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

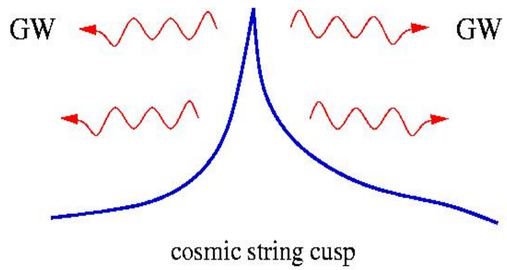
$$\frac{d\bar{v}}{dt} = (1-\bar{v}^2)\left[\frac{k(\bar{v})}{L} - 2H\,\bar{v}\right]$$





GW Signatures of Cosmic Strings Diluted by Inflation

- **Stochastic GW background:** suppressed esp. at higher f (intuition: recall f-T correspondence)
- **GW bursts:** transient resolvable low z events due to cusps/kinks; subdominant to SGWB for standard strings, but can be leading signal now!



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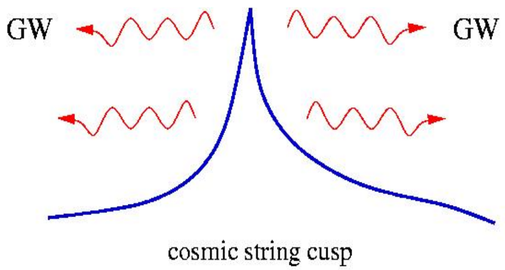


Beaming angle: $\theta_m(l,z,f) = [(1+z)fl]^{-\frac{1}{3}} < 1$

Strain/waveform: $h(l,z,f) = \dfrac{f^{-q}\, l^{2-q}}{(1+z)^{q-1}} \dfrac{G\mu}{r(z)} \qquad q = 4/3\,(5/3)$ for cusps (kinks)

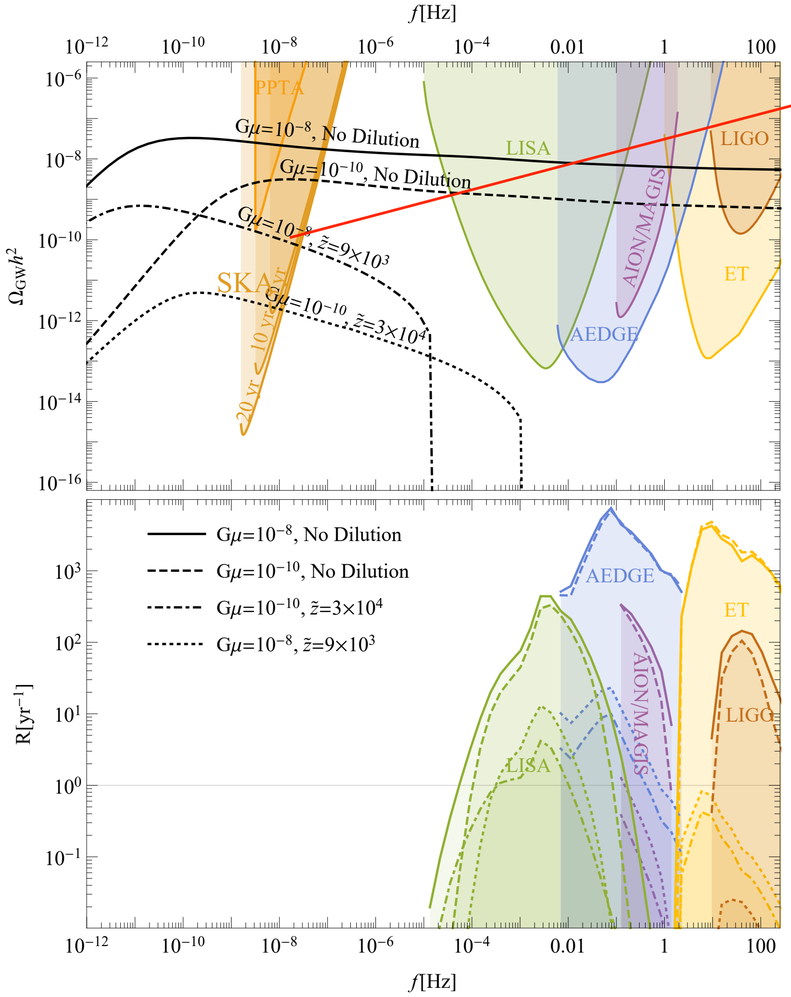
Burst event rate: $\dfrac{d^2R}{dV\,dl}(l,a,f) = \dfrac{\nu(l,z)}{(1+z)} \left(\dfrac{\theta_m(l,z,f)}{2}\right)^{3(2-q)} \Theta(1-\theta_m)$

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

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

GW Signatures of Cosmic Strings Diluted by Inflation

SGWB vs. GW burst signals (standard vs. diluted):



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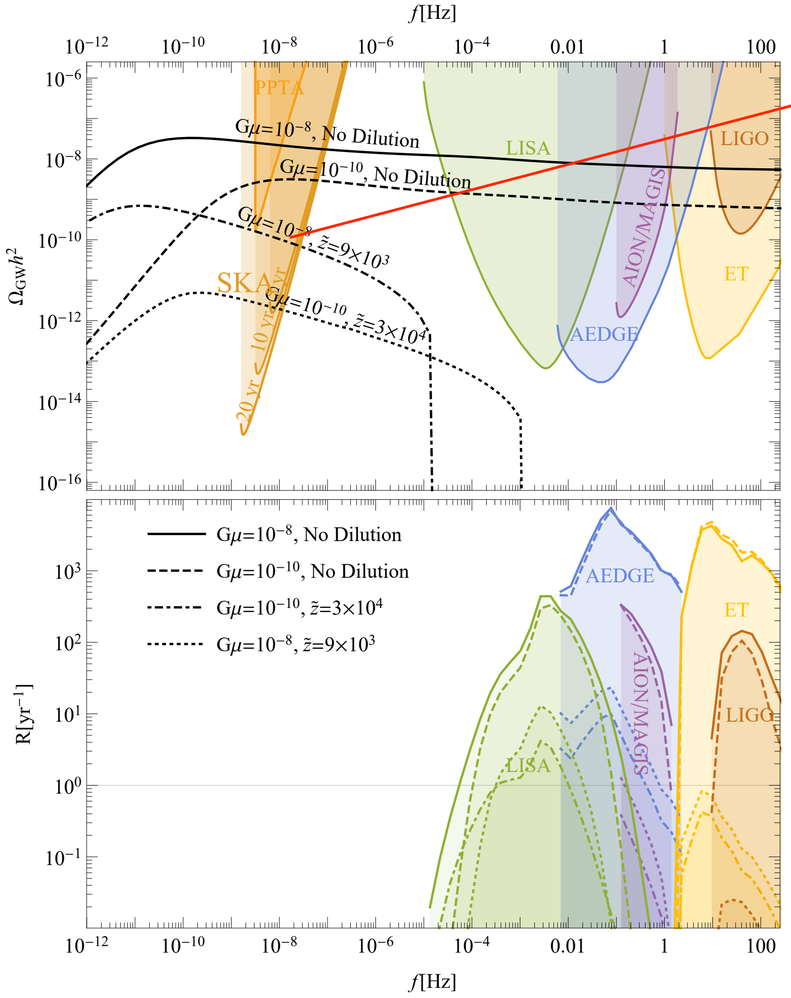
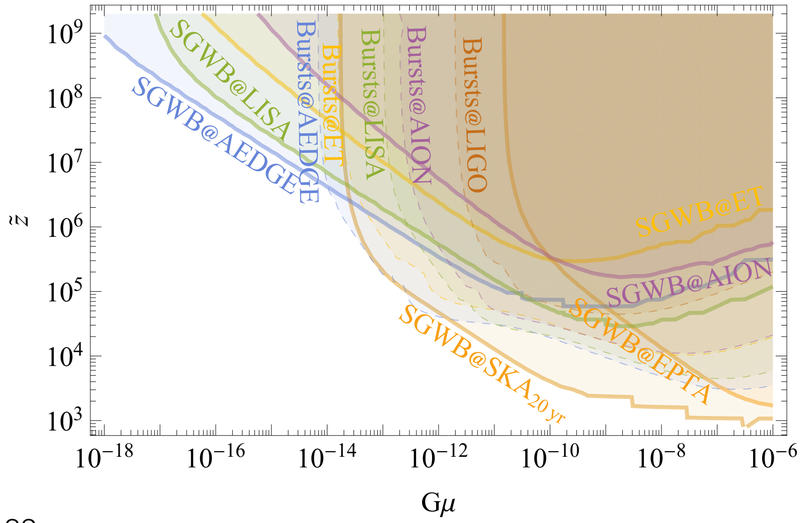


- Strong constraints on $G\mu$ based on SGWB alleviated (PPTA, LIGO…)
  - GW bursts important for low $\tilde{z}$
  - For very low $\tilde{z} \lesssim 10^3$ CMB bound alleviated as well, astrophysical signals (lensing, structure formation) as smoking-gun



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)…

GWs from Axion Topological Defects
Novel Probes of ALP DM Models

- 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, potentially significant effects:

  ALP cosmic strings/domain walls: indispensable companion of ALP particles for $U(1)_{PQ}$ breaking after inflation

  (Rapidly increasing interest in the past few years)

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GW signature from axion cosmic strings?

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

- GW signature from global/axion cosmic strings: an overlooked, yet potentially important discovery channel

— *Why Overlooked? "too small" by naive estimate*

Sub-dominant relative to goldstone emission:

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

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

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

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- BUT: 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, many to investigate (*challenge*: cover hierarchical scales)
  - More complex for axion strings: cosmic strings + domain walls

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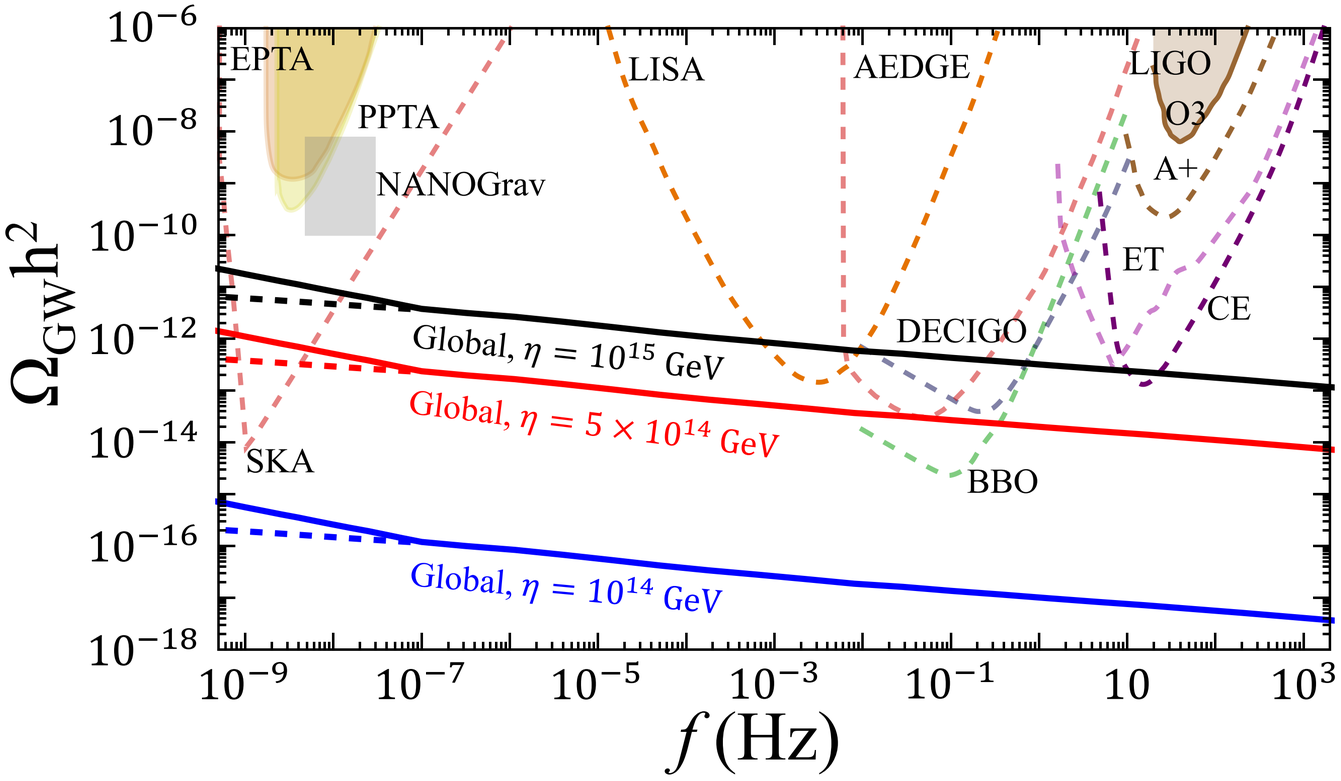
  - More complex for axion strings: cosmic strings + domain walls
- **Our approach:**
  - Start with the simple case: SGWB signal from global strings (massless goldstone) (→QCD axion→ALPs)
  - Semi-analytical: VOS model (including Goldstone emission) calibrated with simulation results (low *N)*
  - Complement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

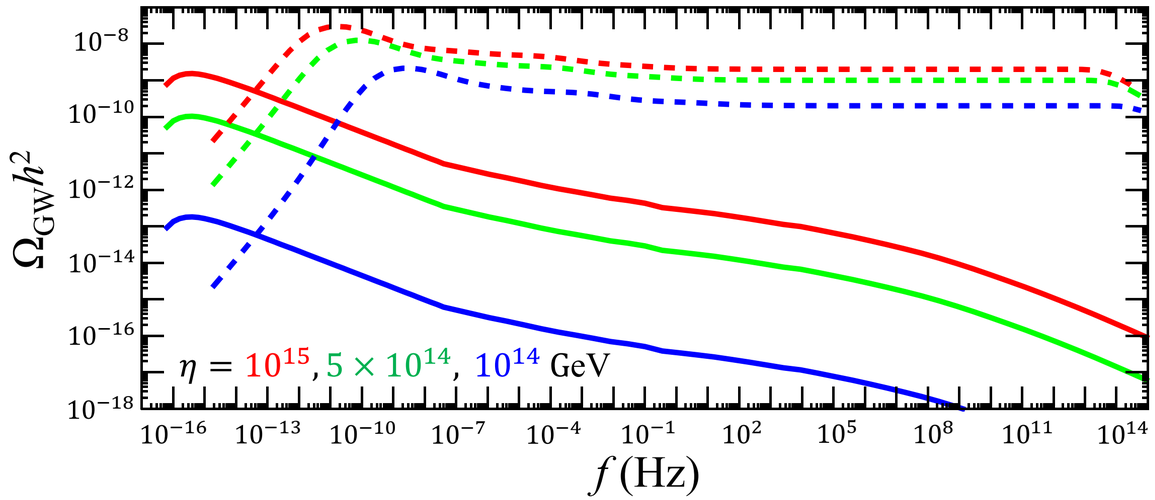
SGWB Spectrum from Global Cosmic Strings

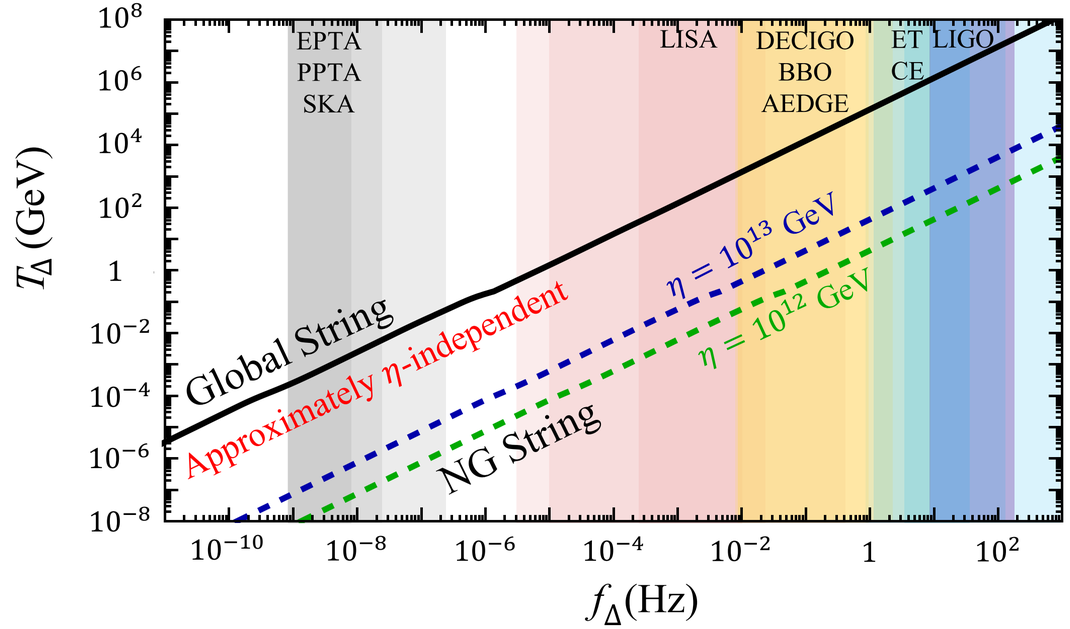
With standard cosmology *(YC and Chang 2019, updated in 2021):*



- 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

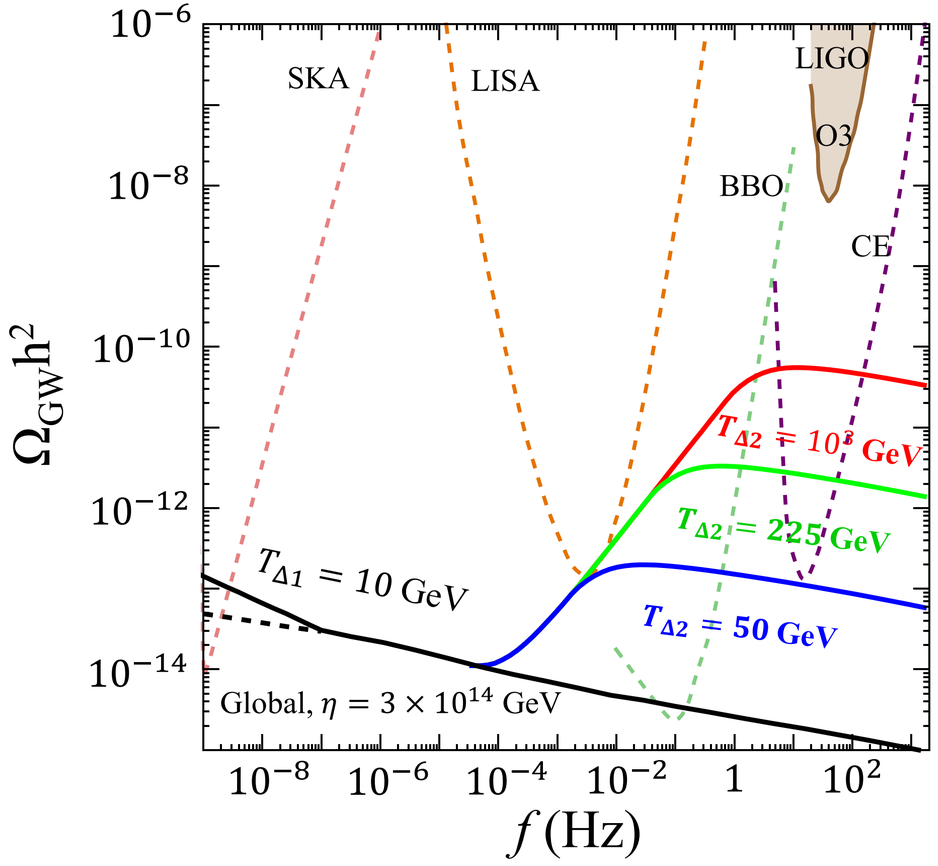
- f-T correspondence: very different from NG, Insensitive to η , the same *f* corresponds to higher *T*→probe up to $T \sim 10^8\ GeV$! *(short-lived loops)*

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

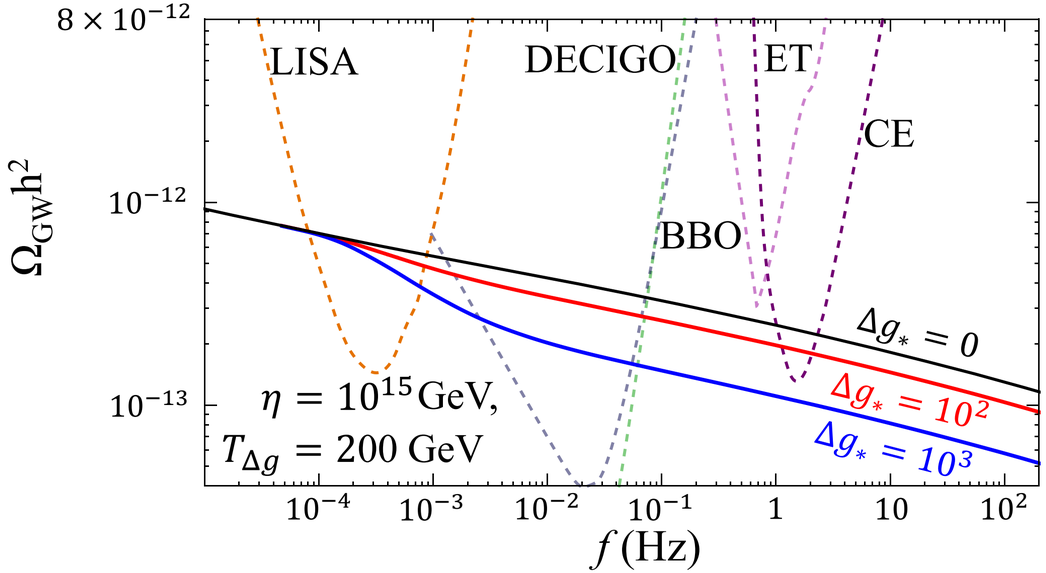
$$\simeq (3.02\times10^{-6}\,{\rm Hz})\left(\frac{T_\Delta}{1\,{\rm GeV}}\right)\left(\frac{\alpha}{0.1}\right)^{-1}\left[\frac{g_*(T_\Delta)}{g_*(T_{\rm eq})}\right]^{1/4}$$

Cosmic archaeology with GWs from global strings

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



- SGWB with new particle species in the early Universe:



III. Distinguish SGWB from cosmic strings (or other cosmo sources) from astro SGWB with frequency domain info

E.g. with a midband GW experiment: AEDGE, TianGo, Tianjin, DECIGO, BBO…

The Practical Challenge for Probing BSM: Astrophysical Sources of SGWB

- SGWB can also originate from astrophysics!

  e.g. With modeling assumptions LIGO/Virgo expect to detect stochastic GW bkg from unresolved binary BH/NS mergers, possibly overwhelms/confuses with cosmogenic signals in the LIGO f range…

- **Possible solutions** (developing!):
  - Optimize statistical analysis in time domain: identify fine patterns, e.g. Gaussianity *arXiv:1712.00688*
  - Resolve the “unresolved”: subtract astro bkg by identifying them with future observations/detectors (e.g. + LISA, ET/CE, BBO) *e.g. arXiv: 1611.08943*

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  - **Utilize information in frequency domain:** astro and cosmo SGWB generally have different shapes in frequency spectrum

    e.g. binary mergers $f^{2/3}$ *with a cutoff* $\sim 10^3 Hz$, *cosmic strings* f^0 *at high* f, PT split power-law with a peak at characteristic f…

The Impact of a Midband Gravitational Wave Experiment On Detectability of Cosmological Stochastic Gravitational Wave Backgrounds

arxiv: 2012.07874 YC with Barry Barish and Simeon Bird (also see Barry's Fri. Talk)

- Midband: $10^{-2} - 10\ Hz$, cover the gap between LIGO and LISA, many proposals: (B-)DECIGO, TianGo, TianQin, MAGIS, AEDGE/AION, BBO…

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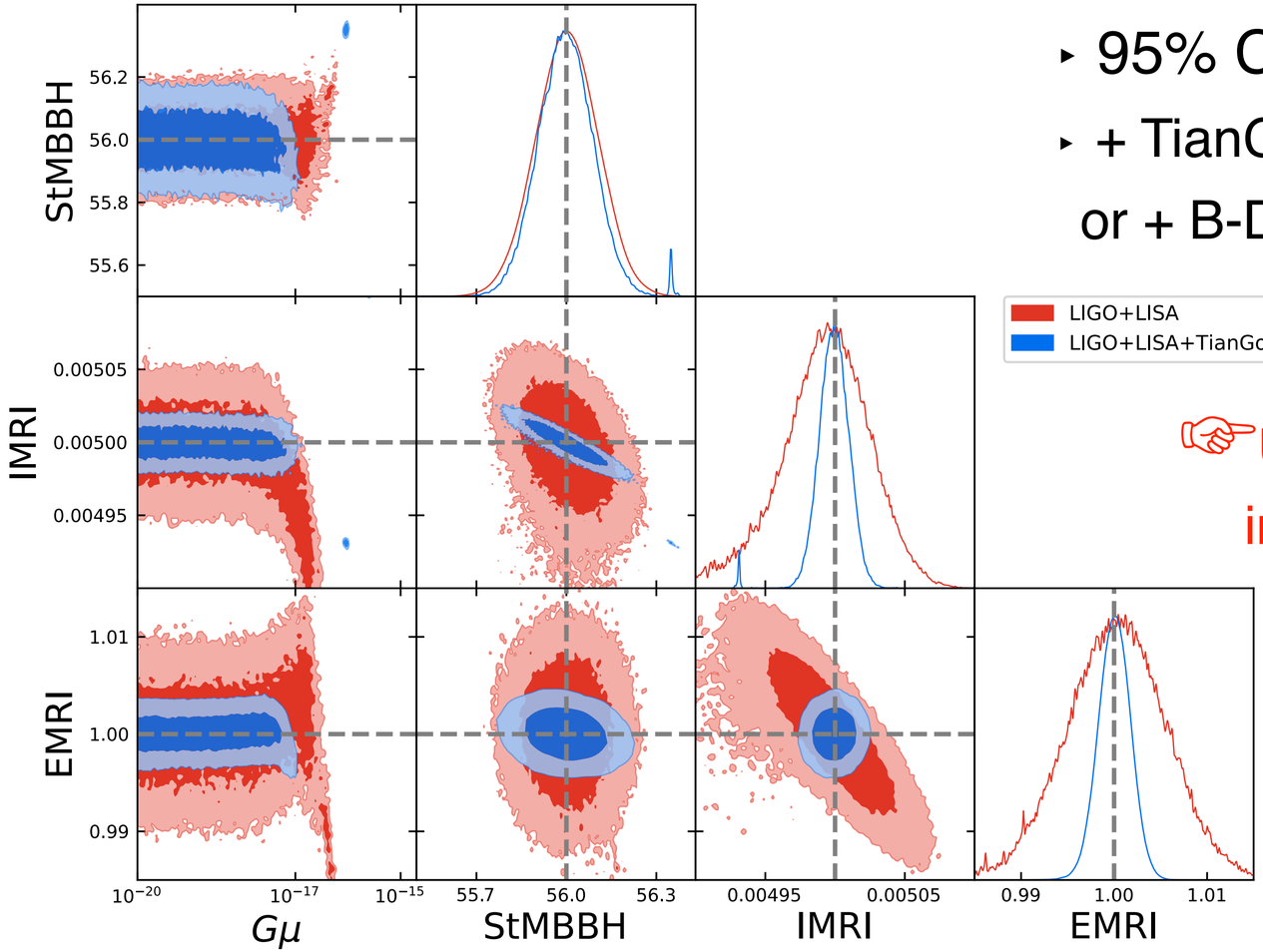
Our goals

- Dedicated quantitative study (explicit modeling of astro and cosmo sources): how a future midband GW experiment complements LIGO + LISA (continuous coverage over a wide f range) for improving sensitivity to cosmo SGWB and separation from astro SGWB
- Help boost the science case for midband GW experiments from HEP/cosmo motivation

Results from likelihood analysis: Cosmic Strings

- **Constraints**: mock data with astro sources only

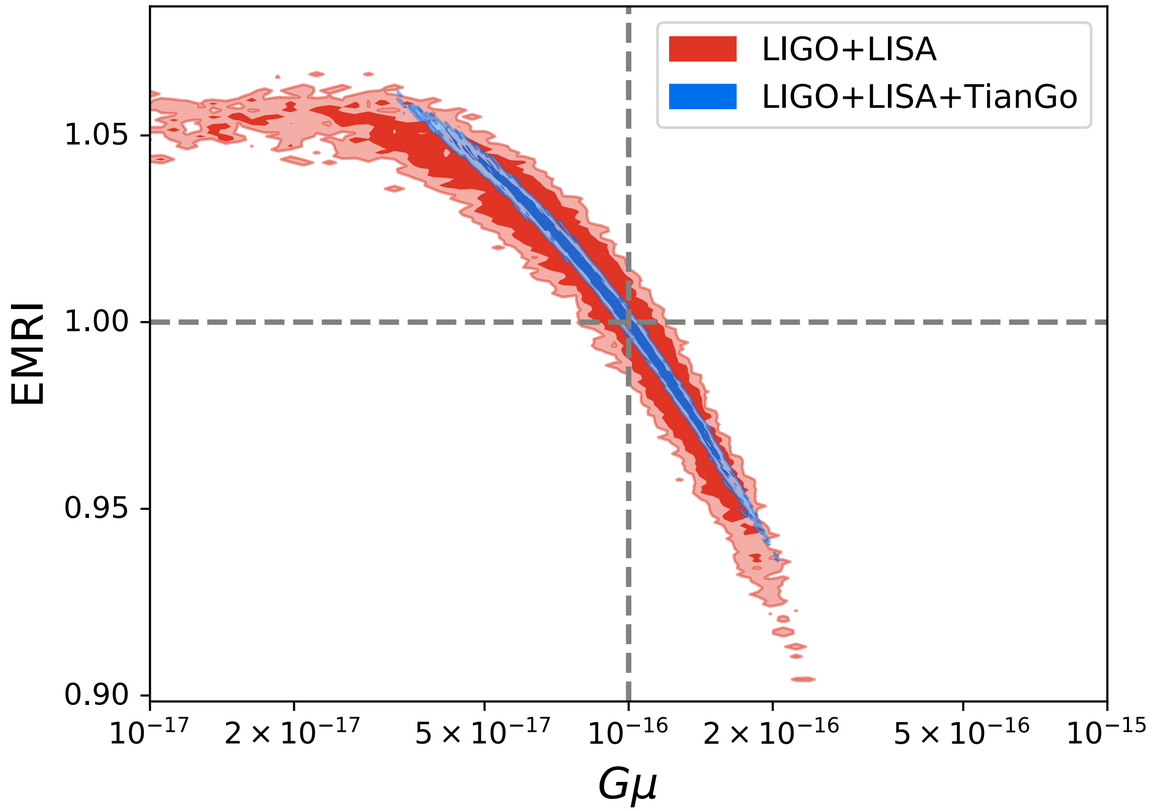


- 95% C.L. with LIGO+LISA only: $G\mu < 2.7 \times 10^{-17}$
- + TianGo: $G\mu < 9 \times 10^{-18}$,
  or + B-DECIGO: $G\mu < 2.5 \times 10^{-18}$

☞Up to an order of magnitude improvement in $G\mu$ sensitivity!

Results from likelihood analysis: Cosmic Strings

- **Discovery**: mock data adding cosmo source with $G\mu = 10^{-16}$ (near LISA threshold)



- Strong curving degeneracy between string signal and EMRI
- LISA alone not able to correctly separate cosmo vs. astro SGWB
- Extra info from midband: greatly improves separation

+ TianGo: $G\mu = 4\times10^{-17} - 1.7\times10^{-16}$
+ B-DECIGO: $G\mu = 6\times10^{-17} - 1.65\times10^{-16}$

Conclusion

- **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)*
- 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…
- A midband GW experiment may have a significant impact for improving the sensitivity to SGWB from cosmic strings or other cosmological sources

Thank you!