TRIUMF

Looking Back in Time with Gravitational Waves from Cosmic Strings

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with
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1711.03104 (PRD97, 123505)
1808.08968 (JHEP1901, 081)
1912.08832

Reheating Meets Particles, KITP UCSB, Feb.4, 2020

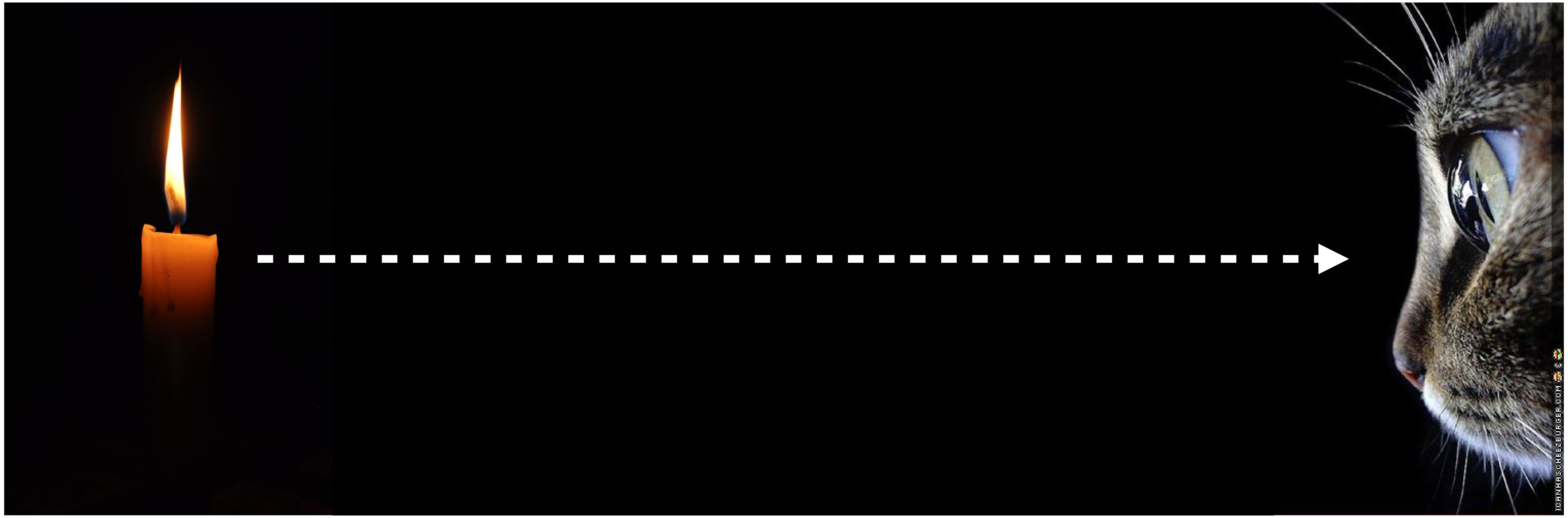
[Symmetry Magazine 2015]

Chumash Peoples

Some related works:

- Vachaspati, Vilenkin, PRD31, 3052
- Allen [gr-qc/9604033]
- Binétruy, Bohé, Caprini, Dufaux, JCAP1206, 027
- Guedes, Avelino, Sousa, PRD98 123505 [astro-ph.CO/1809.10802]
- Caldwell, Smith, Walker, PRD100, 043513 [astro-ph.CO/1812.07577]
- Figueroa, Tanin, JCAP1908, 011 [astro-ph.CO/1905.11960]
- Gouttenoire, Servant, Simakachorn [hep-ph/1912.02569, 1912.03245]

Cosmic Learnings



Standard-ish Source → **Cosmological Expansion** → **Precision Detector**

Cosmic Scrambling

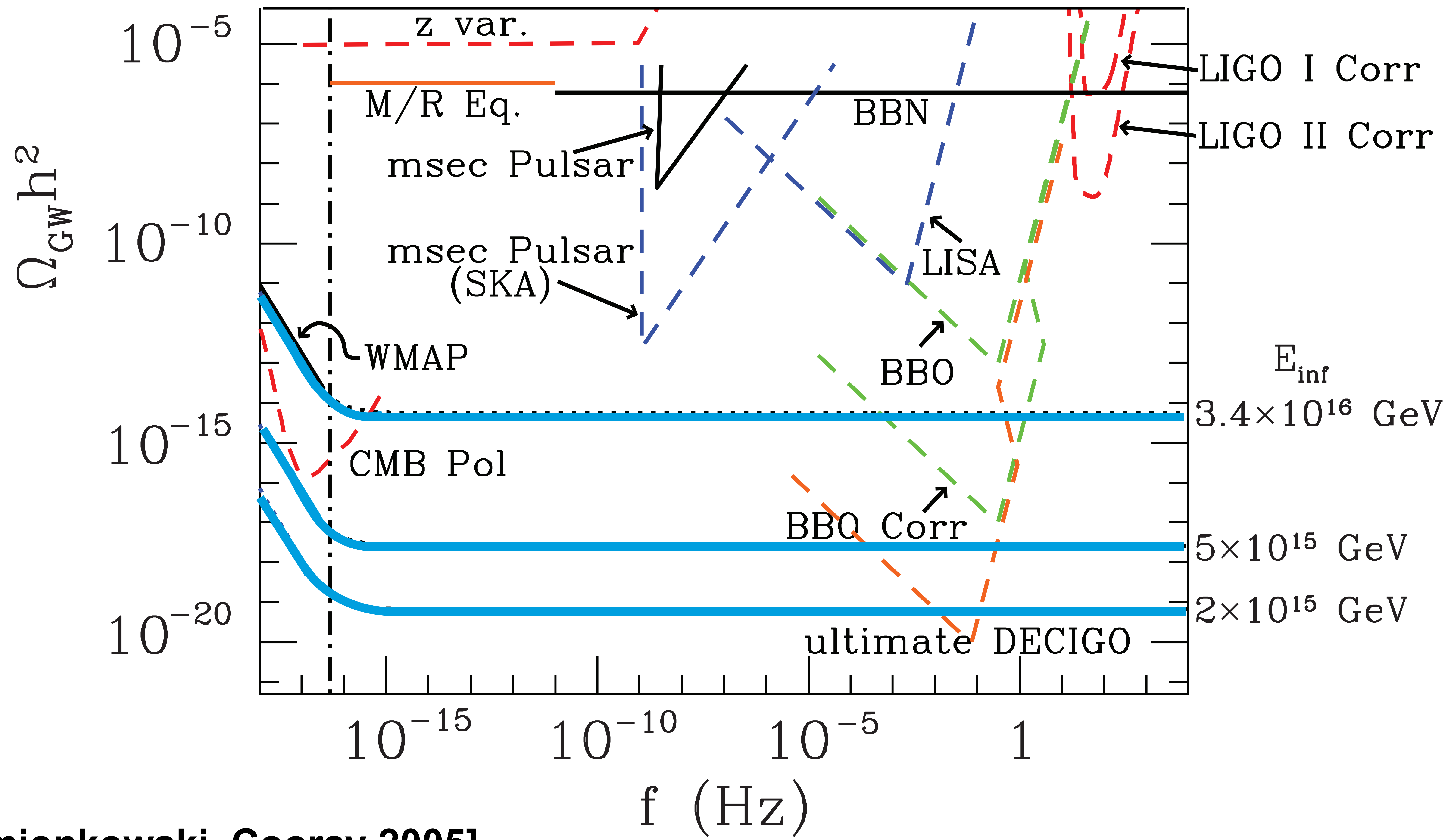
- CMB+BBN:
  $\Lambda\mathrm{CDM}$ cosmology with $N_{eff} \simeq 3$ up to $T \simeq 5\,\mathrm{MeV}$

- Thermalization scrambles (most) direct probes from earlier than this.

Gravitational Waves

- No scrambling (to a good approximation)!
- Cosmological sources?
- Inflation:

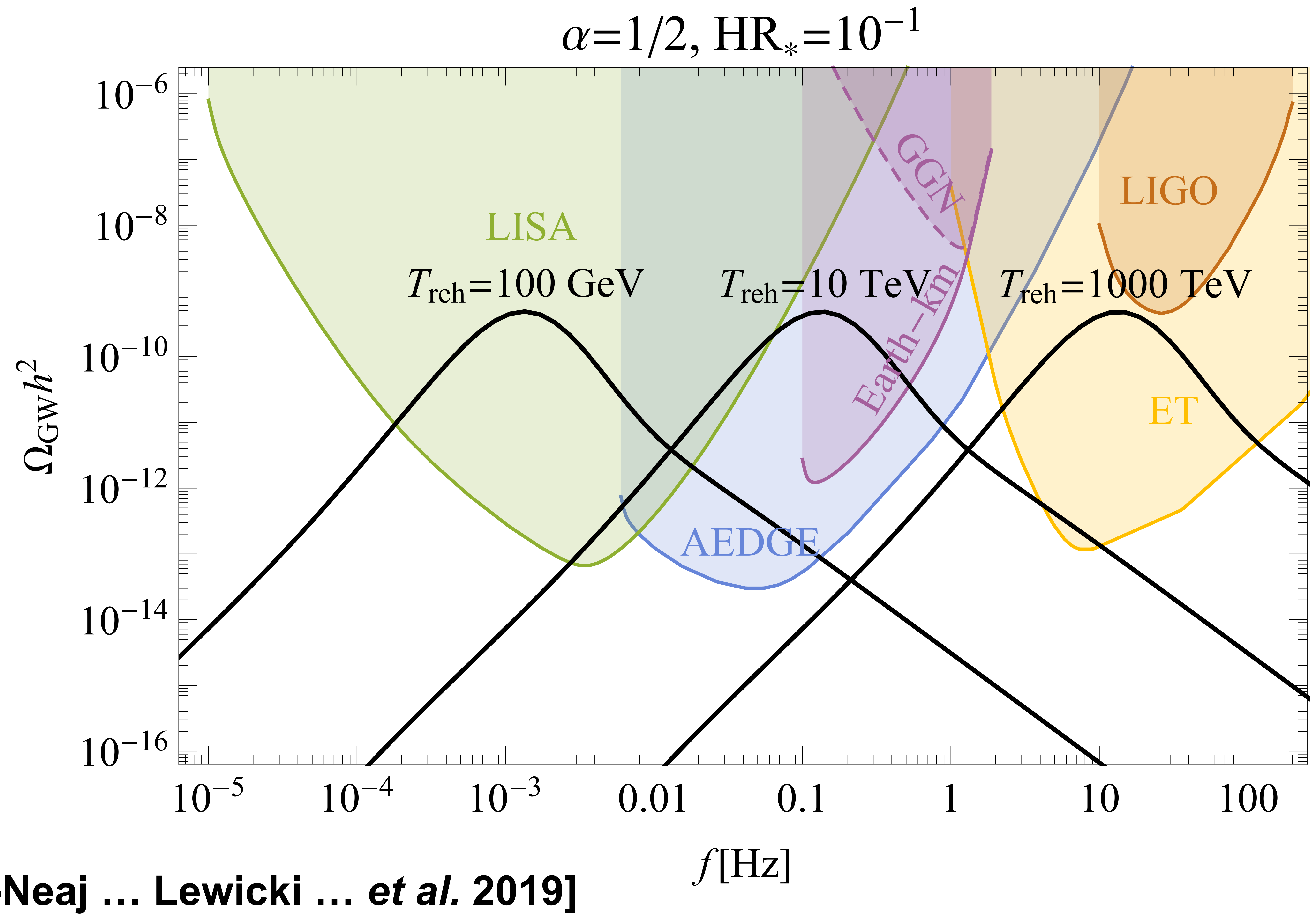
(But may be enhanced at high frequencies in some cases!)



[Smith, Kamionkowski, Cooray 2005]

Gravitational Waves

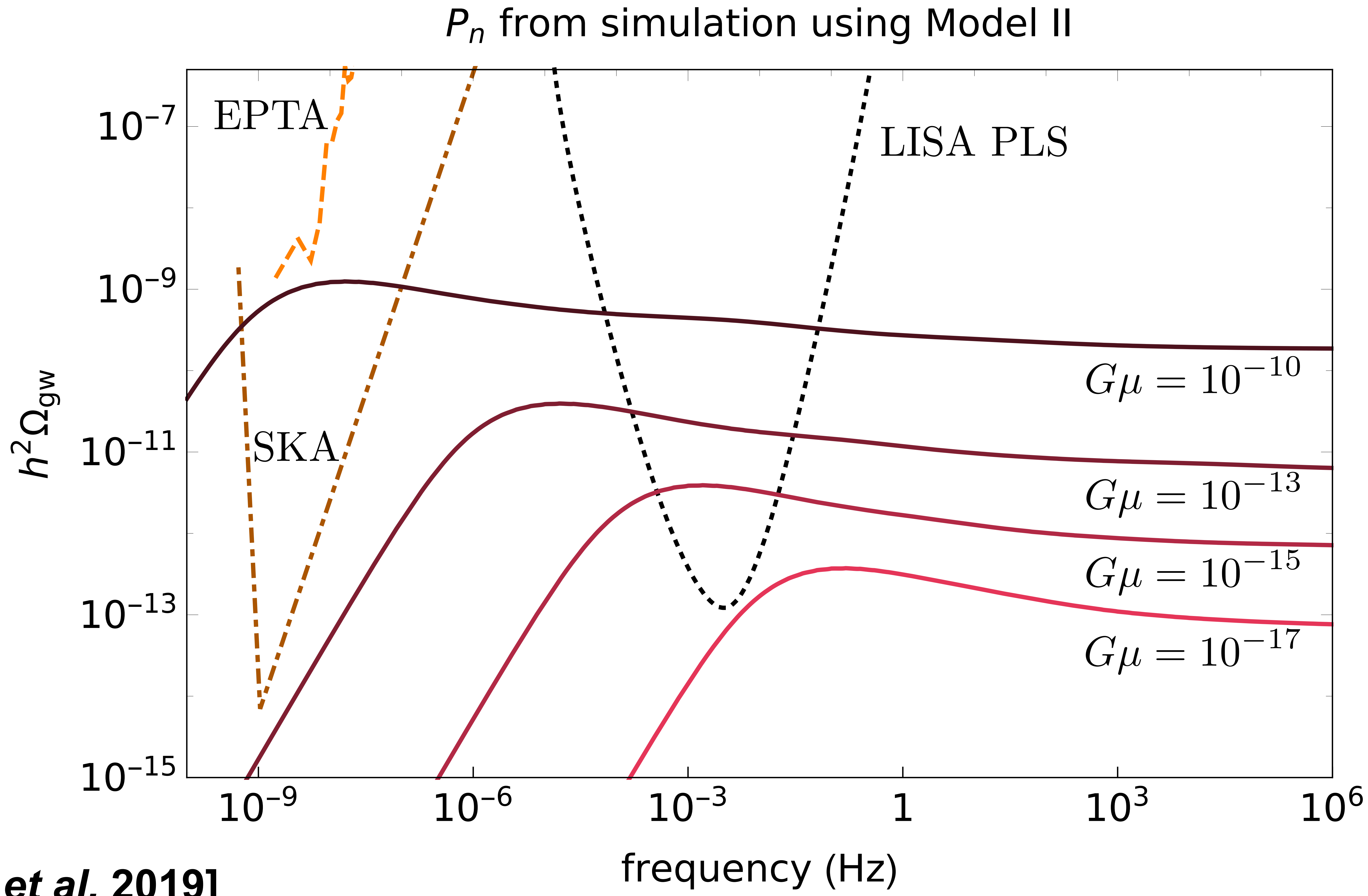
- No scrambling (to a good approximation)!
- Cosmological sources?
- Phase Transitions:



[AEDGE: Abou El-Neaj … Lewicki … *et al.* 2019]

Gravitational Waves

- No scrambling (to a good approximation)!
- Cosmological sources?
- Cosmic Strings:



[LISA: Auclair *et al.* 2019]

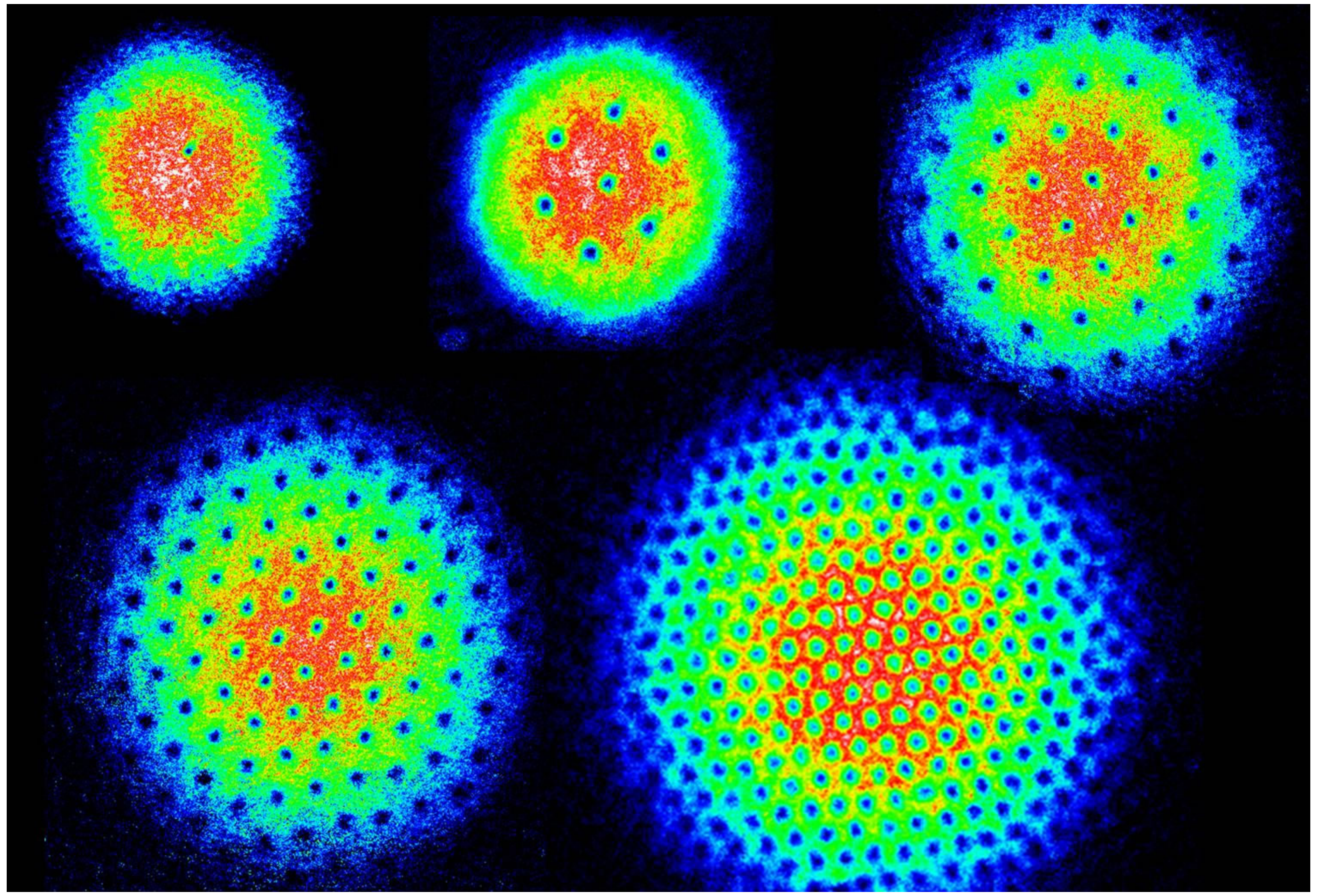
Cosmic Strings

- One-dimensional objects with tension = energy/length = μ

- Can arise from spontaneous $U(1)$ breaking **[Nielsen-Olesen, Kibble]**, or semi-fundamental objects in string theory **[Copeland, Myers, Polchinski]**.

- Can be created cosmologically in a phase transition or during reheating.

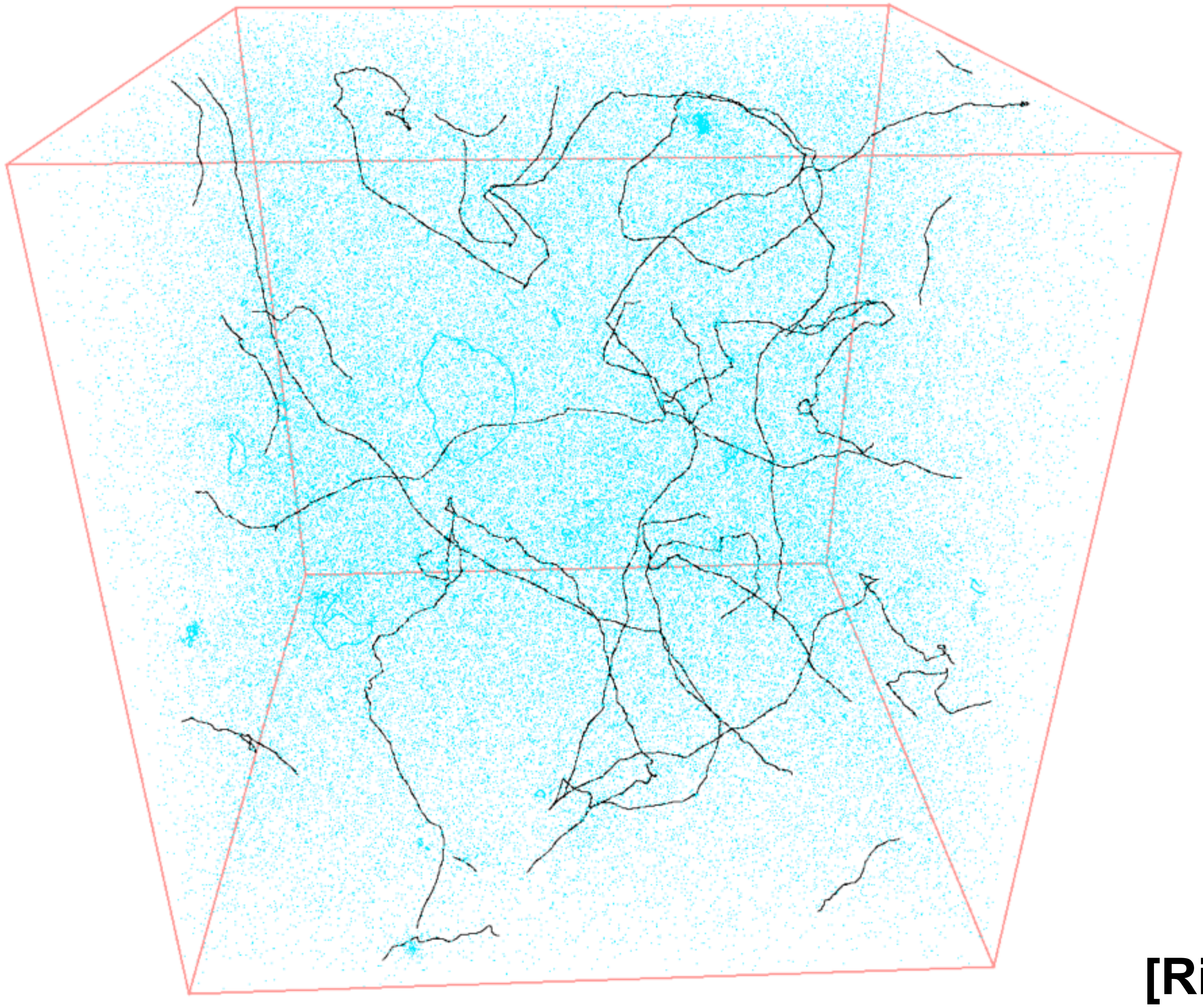
- Analogs of vortices seen in CM systems. *e.g.* vortex lattice in superfluid BEC →



[E.Cornell Group, JILA]

Cosmic Strings in Cosmology

- Formation mechanisms (*e.g.* Kibble-Zurek) usually produce ***closed loops*** and a few horizon-length ***long strings***.



[Ringeval 2010]

Cosmic Strings in Cosmology

- Formation mechanisms (*e.g.* Kibble-Zurek) usually produce ***closed loops*** and a few horizon-length ***long strings***.

- Without interactions:

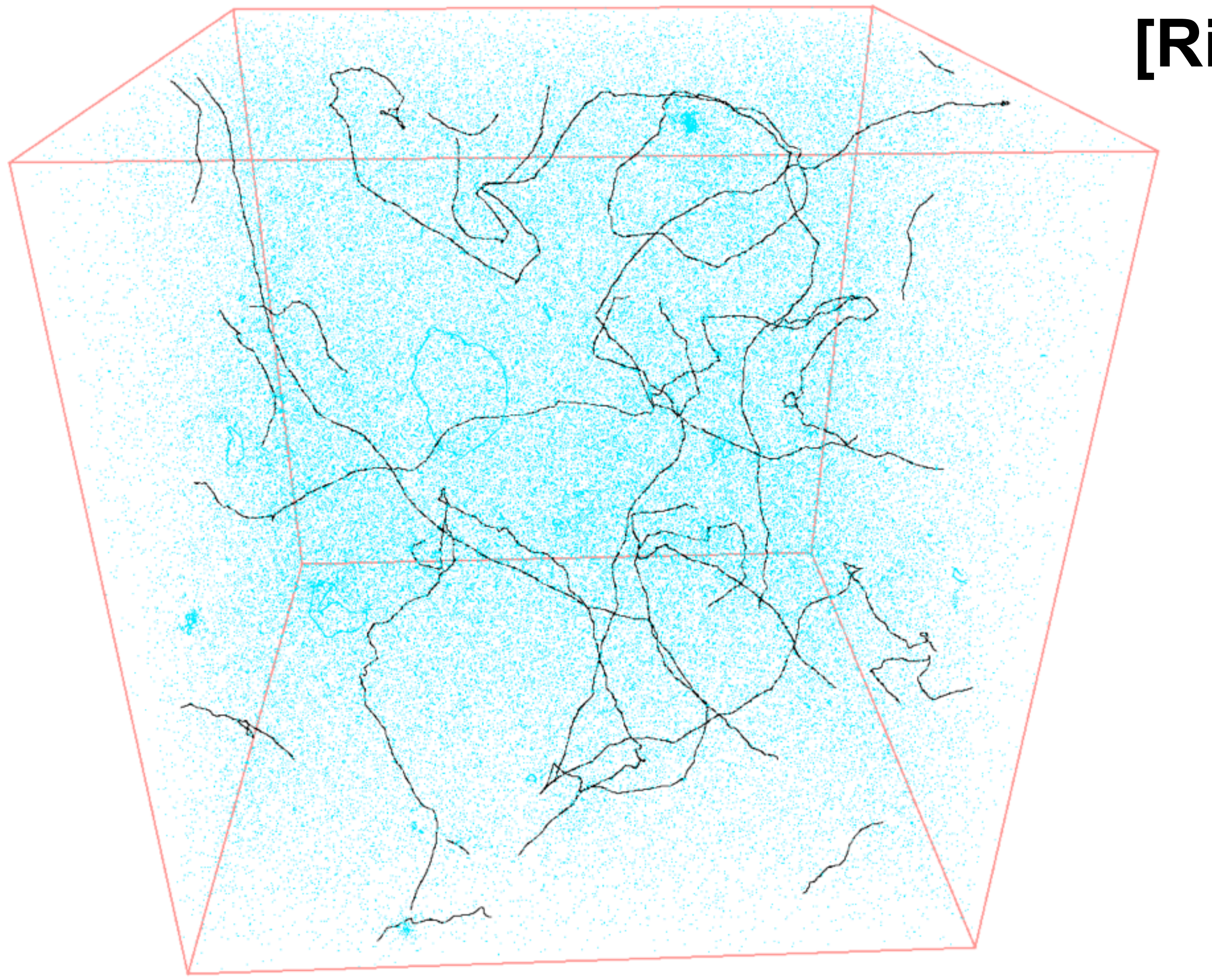
$$\rho_{long} \propto a^{-2}$$
$$\rho_{loop} \propto a^{-3}$$

- But:
  - string self-interactions allow long strings to form loops.
  - loops oscillate and lose energy to radiation.

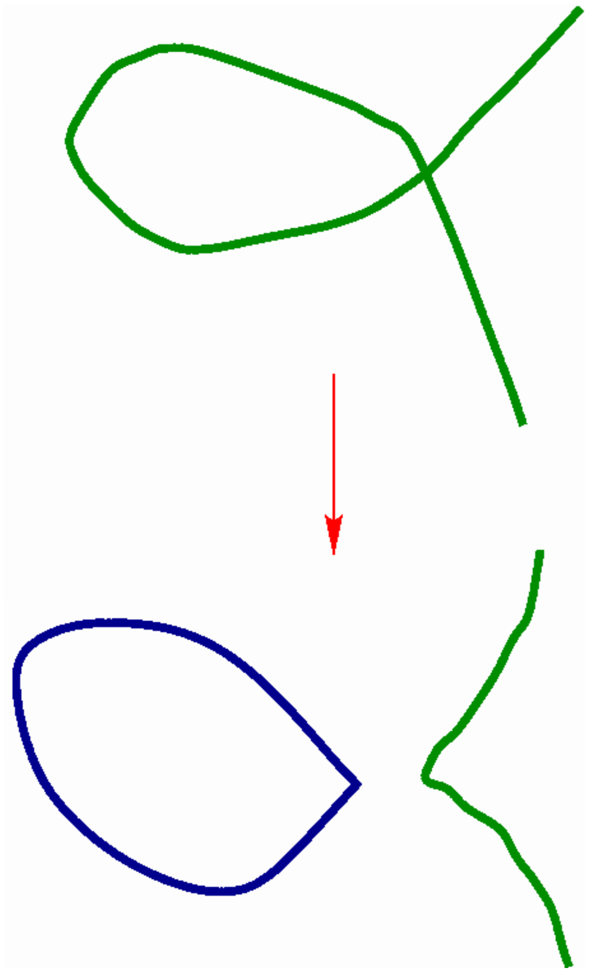
Cosmic Strings in Cosmology

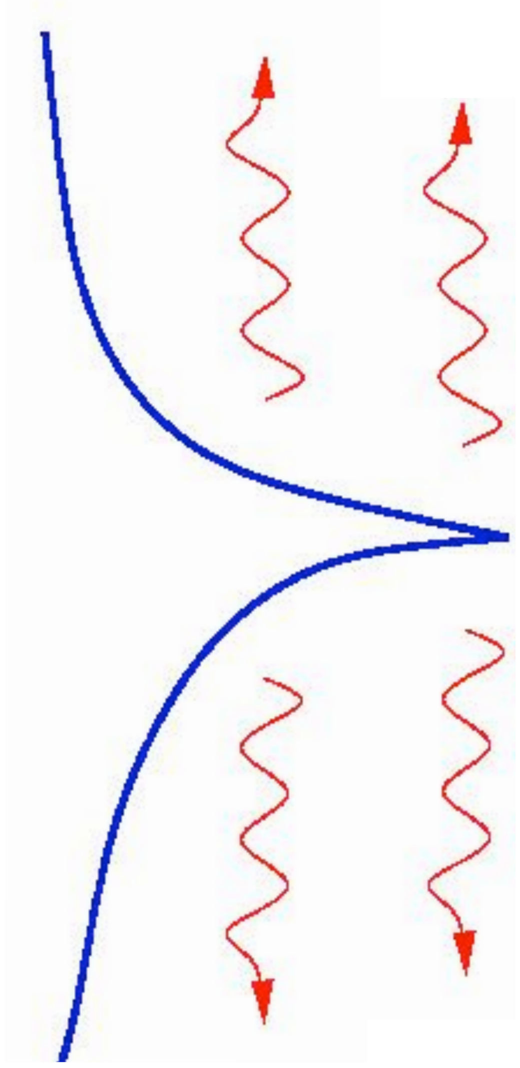
- Loop formation transfers energy from long strings to closed loops.

- Closed loop oscillations transfer energy to (gravitational) radiation.



[Ringeval 2010]





[Jeong, Smoot 2016]

- **Cosmic String Scaling**: $\rho_{long} \simeq G\mu\,\rho_{tot}$ ← !!!

Cosmic String Scaling

- Long string expansion, loop formation, and radiation reach a steady state.

- **Scaling**: long string energy density tracks the total cosmological density.

$$\rho_{long} \simeq G\mu\, \rho_{tot}$$

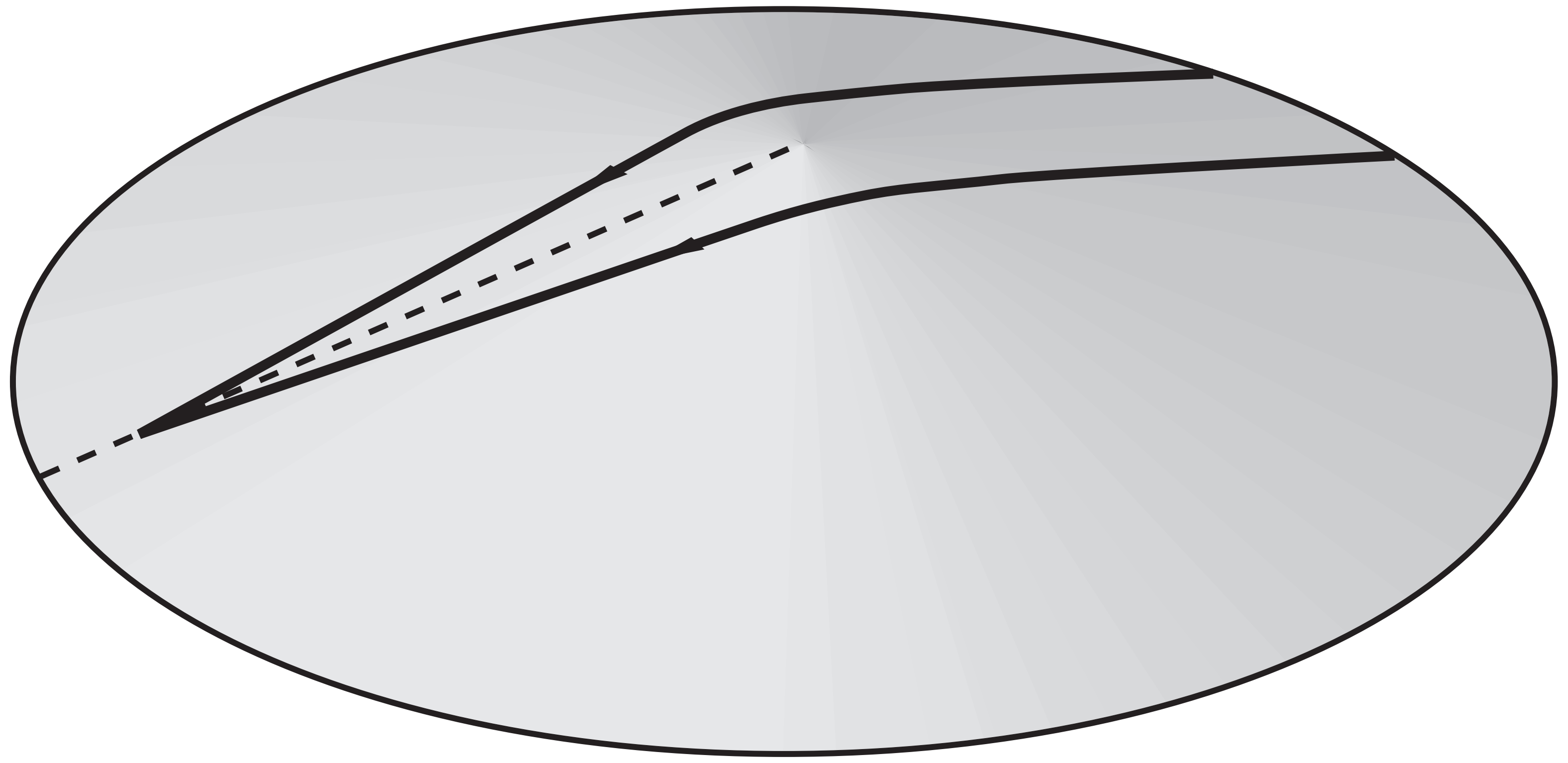
[Albrecht, Turok 1985; Bennett, Bouchet 1988; Allen, Shellard 1990;…]

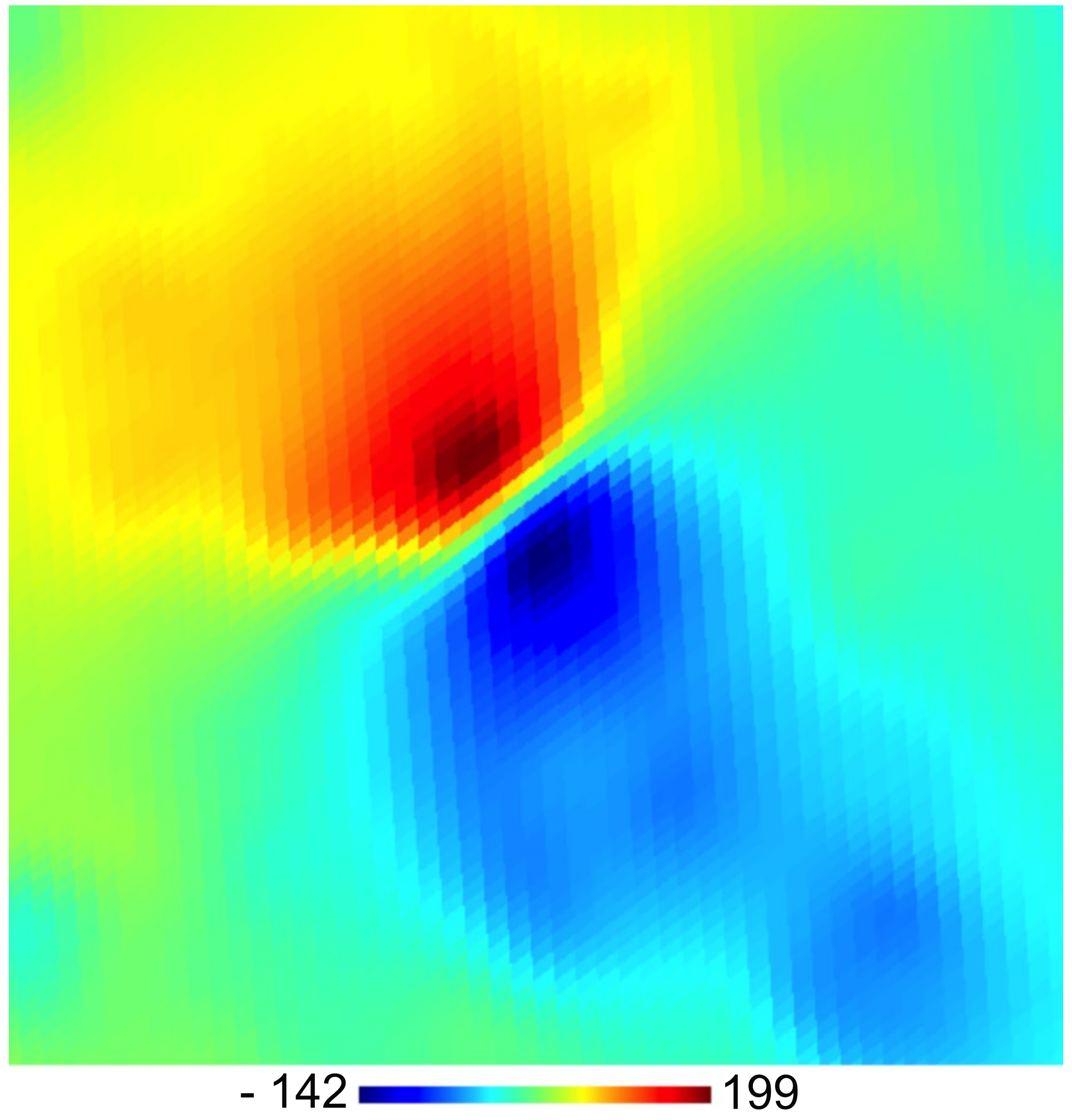
- Strong attractor solution provided $\rho_{tot} \propto a^{-n}\,, \quad n > 2\,.$

- Cosmic strings are “safe” cosmic defects!

Direct Bounds on Cosmic Strings

- Cosmic strings induce gravitational lensing, seed perturbations, and distort the CMB.





[Planck 2013]

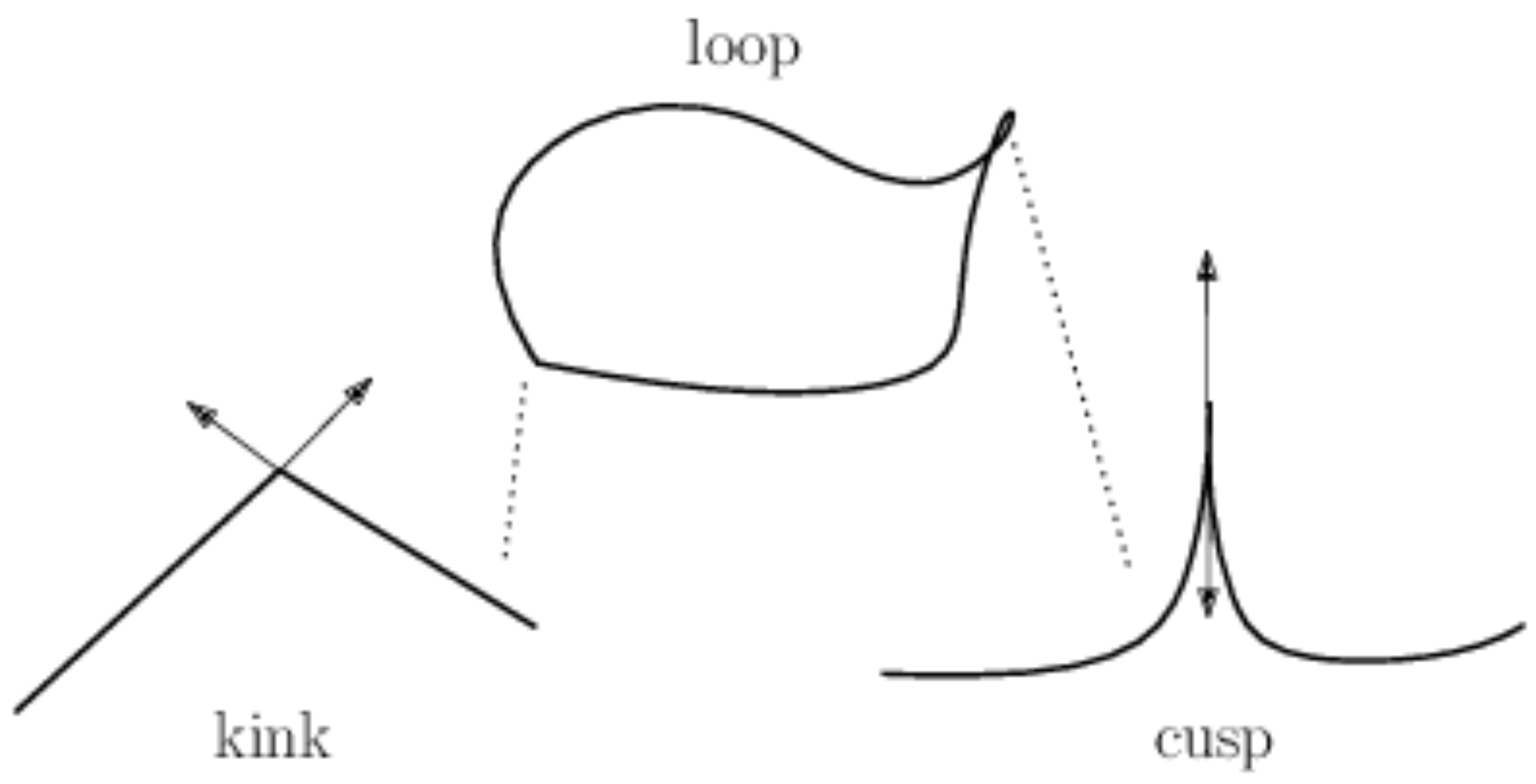
$$G\mu \ \leq \ 1.1 \times 10^{-7}$$

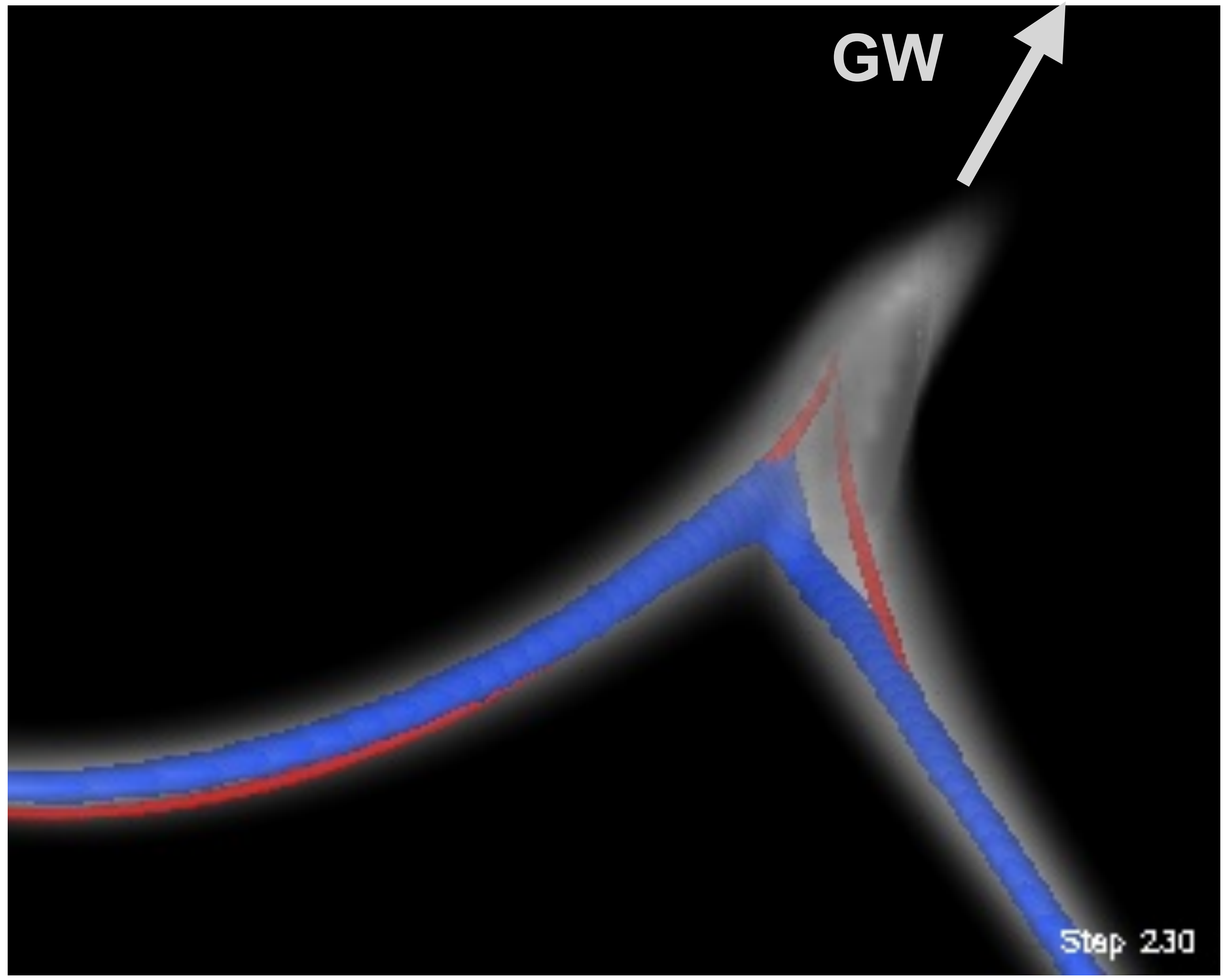
[Charnock *et al.* 2016]

Gravitational Waves from Cosmic Strings

- Loops oscillate and radiate - GWs can dominate if no other light modes.

- GW emission is dominated by cusps, about one per loop oscillation:





[Gouttenoire, Servant, Simakachorn 2019]

[K. Olum]

Gravitational Waves from Cosmic Strings

- GW emission is dominated by cusps.

- Total emission rate of GW from a loop:

$$\left(\frac{dE}{dt}\right)_{loop} = \Gamma G\mu^2$$

- Averaged emission can be treated as a sum of normal mode oscillations:

$$\Gamma = \sum_{n=1}^{\infty} \Gamma_n \simeq 50$$

$$\Gamma_n = \left(\frac{\Gamma}{3.36}\right) n^{-4/3}$$

[Vilenkin 1981; Turok 1984]

Gravitational Waves from Cosmic Strings

- Unresolved GW emission from loops creates a stochastic GW background:

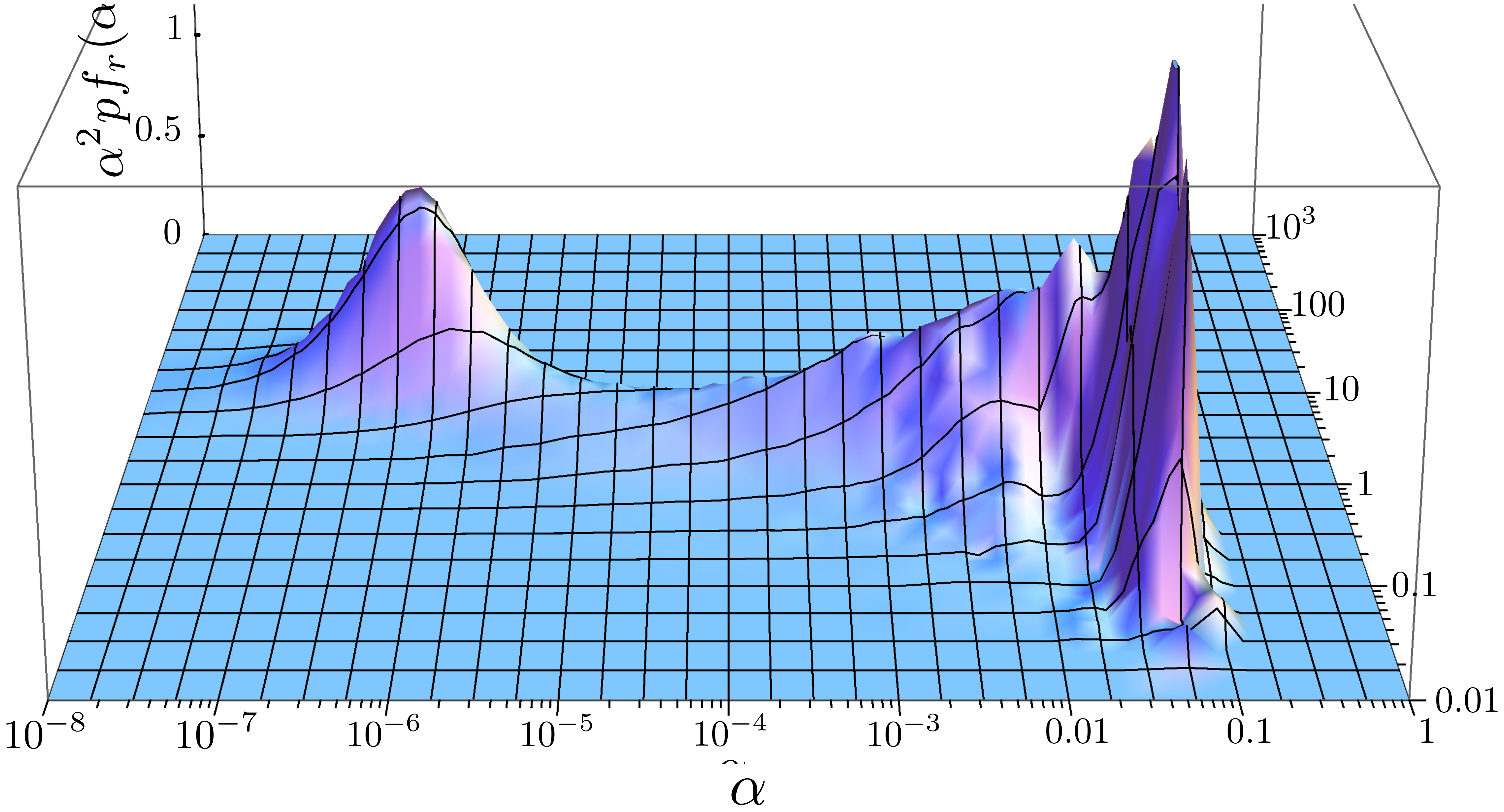
$$\Omega_{GW} \equiv \frac{f}{\rho_c} \frac{d\rho_{GW}}{df}$$

- To compute it we need:
  - loop production rate (during cosmic string scaling)
  - loop evolution and emission
  - sum on loop emissions with redshifting

- Recent cusps can produce resolvable “burst” signal but usually harder to detect.

Loop Production

- Cosmic string scaling fixes the total rate of energy transfer to loops.
- (Some) recent string simulations find:
  - 10% of energy goes to slow, large loops with $l(t_i) = \alpha\, t_i \;, \quad \alpha \simeq 0.1$
  - rest goes to relativistic loops that lose most of their energy to redshifting



$p = v/\sqrt{1-v^2}$

[Blanco-Pillado, Olum, Shlaer 2013]

Loop Evolution and Emission

- Assume monochromatic loop formation with length

$$l(t_i) = \alpha\, t_i \ , \quad \alpha \simeq 0.1$$

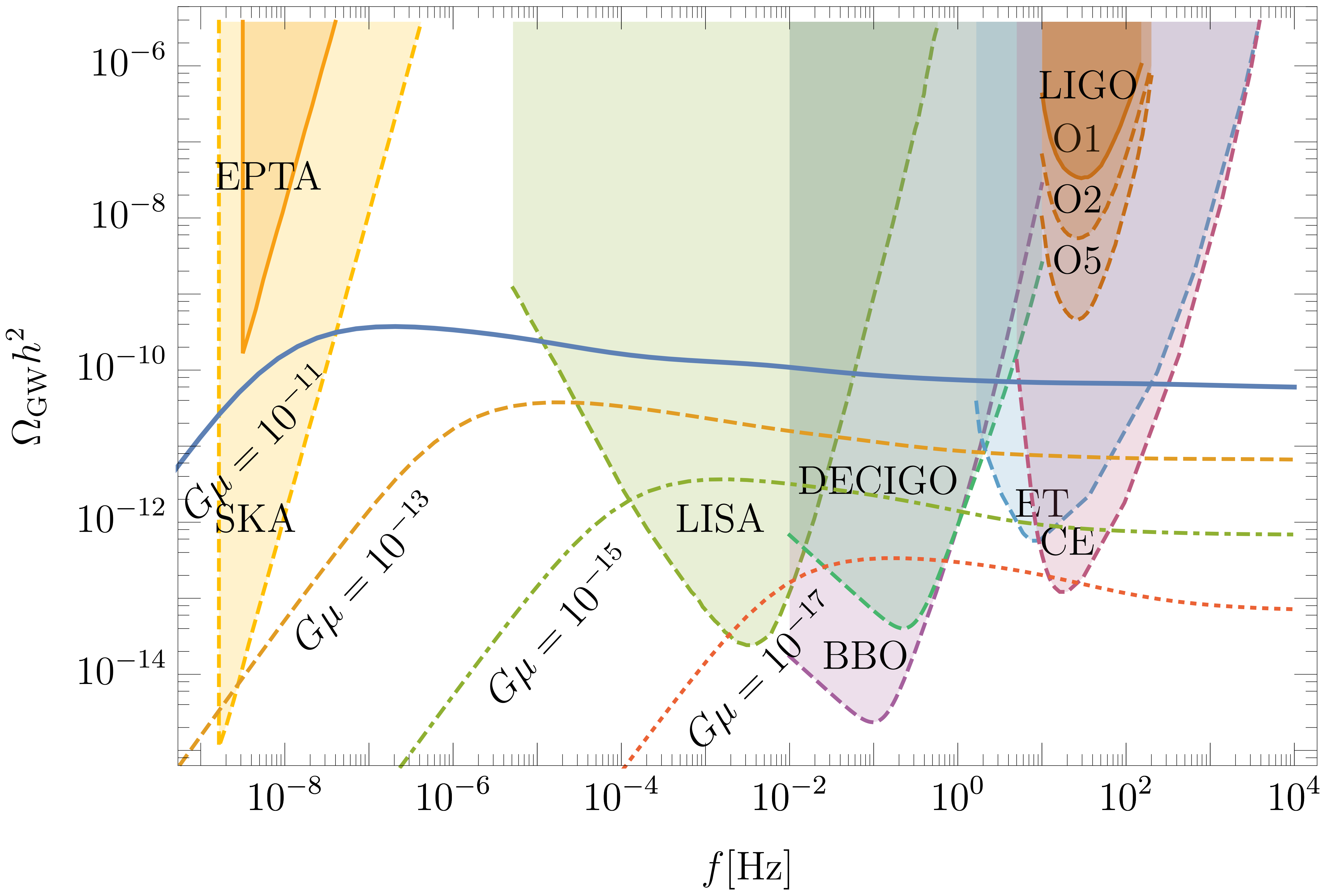
- Loops oscillate, radiate, and shrink:

$$l(t; t_i) = l(t_i) - \Gamma G\mu(t - t_i)$$

- Frequency seen today from mode n emitted by loop $l(t; t_i)$:

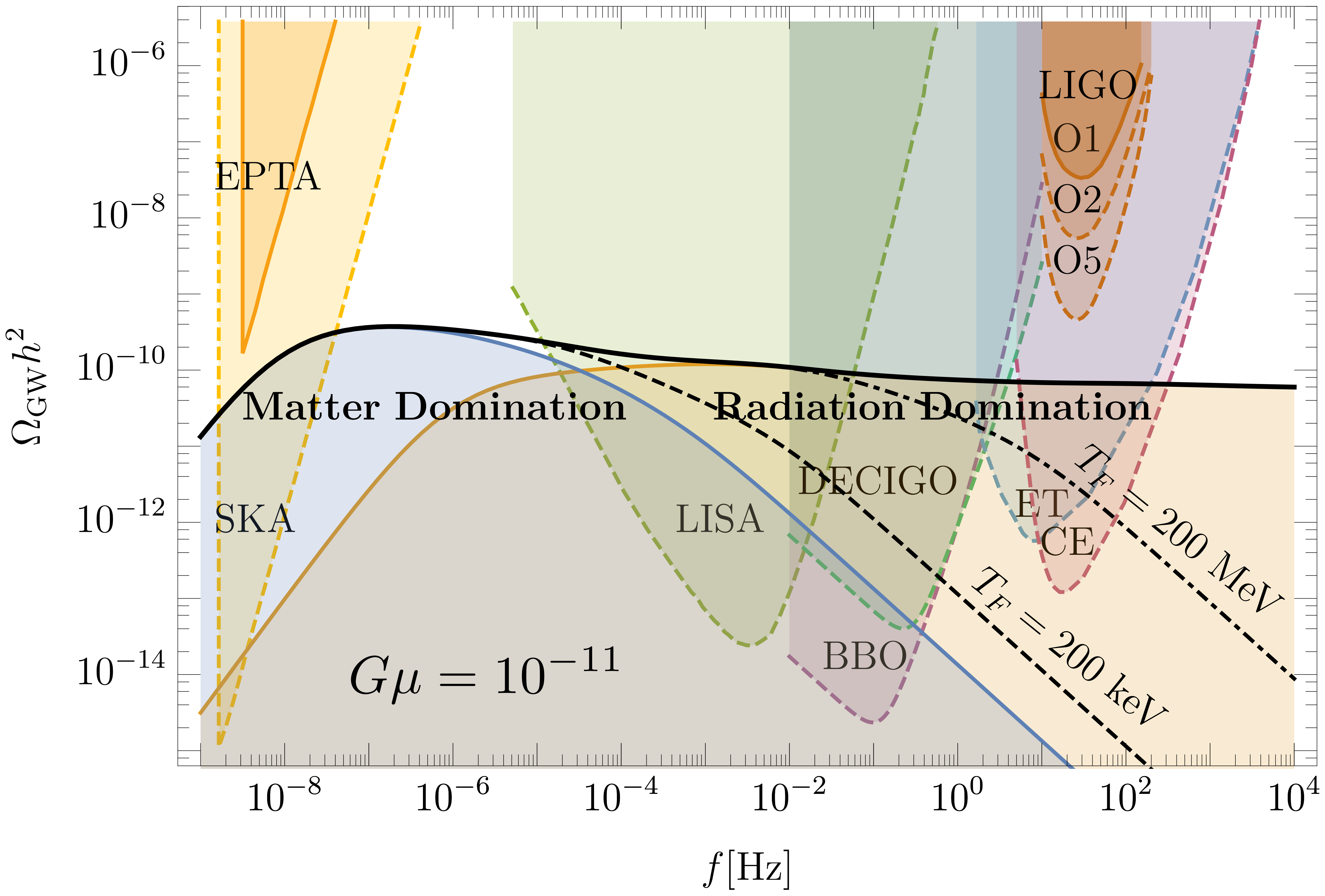
$$f = \left(\frac{a}{a_0}\right) \frac{2\pi n}{l(t; t_i)}$$

Gravitational Waves from Cosmic Strings



- Sum over loops and add redshift to get the total stochastic GW spectrum.
- Each frequency band is dominated by loops emitting at a specific time.

Gravitational Waves from Cosmic Strings



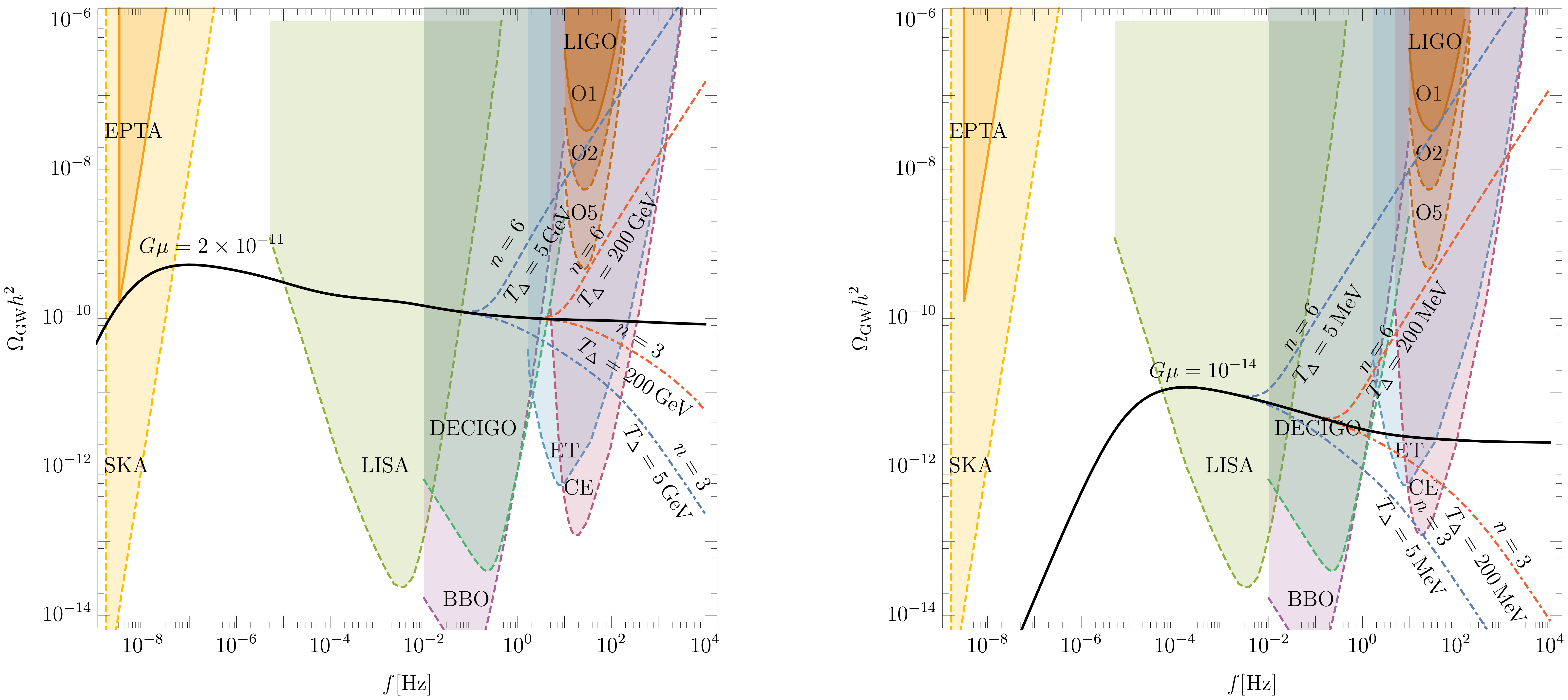
- Sum over loops and add redshift to get the total stochastic GW spectrum.
- Each frequency band is dominated by loops emitting at a specific time.

Cosmic String GWs as a Probe

- Suppose the most recent era of (Standard Model) radiation domination extended back to time t_Δ and temperature T_Δ .
- Possibilities for physics earlier than this:
  - new dominant energy source redshifting as $\rho \propto a^{-n} \;, \quad n \neq 4$
  - new degrees of freedom
  - inflation and (late) reheating
  - …
- These would all modify the GW spectrum from cosmic strings!

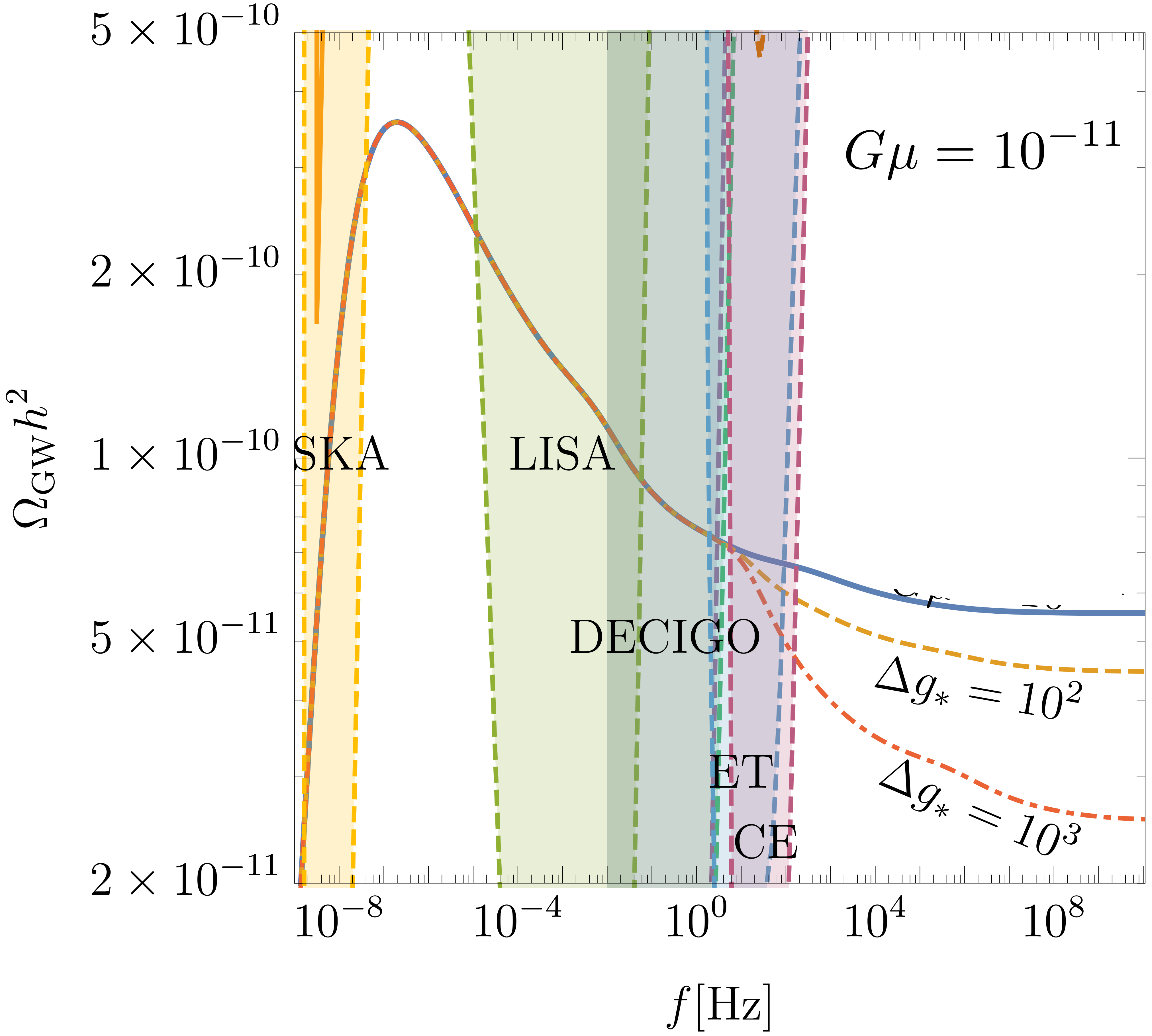
Cosmic String GWs as a Probe

- Non-standard early cosmology ($n = \{3, 6\};\ T_\Delta = \{5, 200\}\,\mathrm{GeV}$):



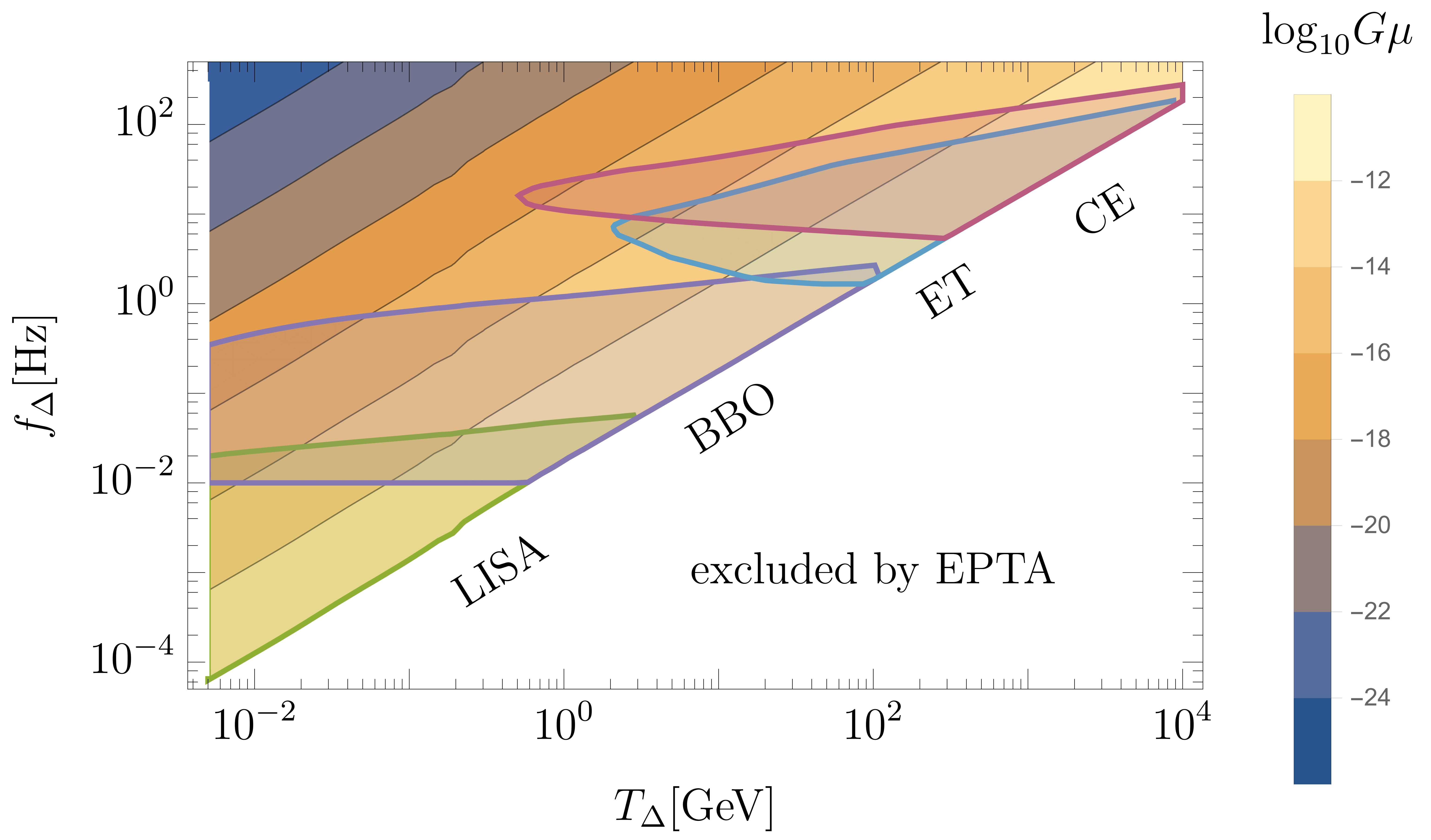
Cosmic String GWs as a Probe

- New degrees of freedom ($\Delta g_* = \{10^2, 10^3\};\ T_\Delta = 200\,\mathrm{GeV}$):



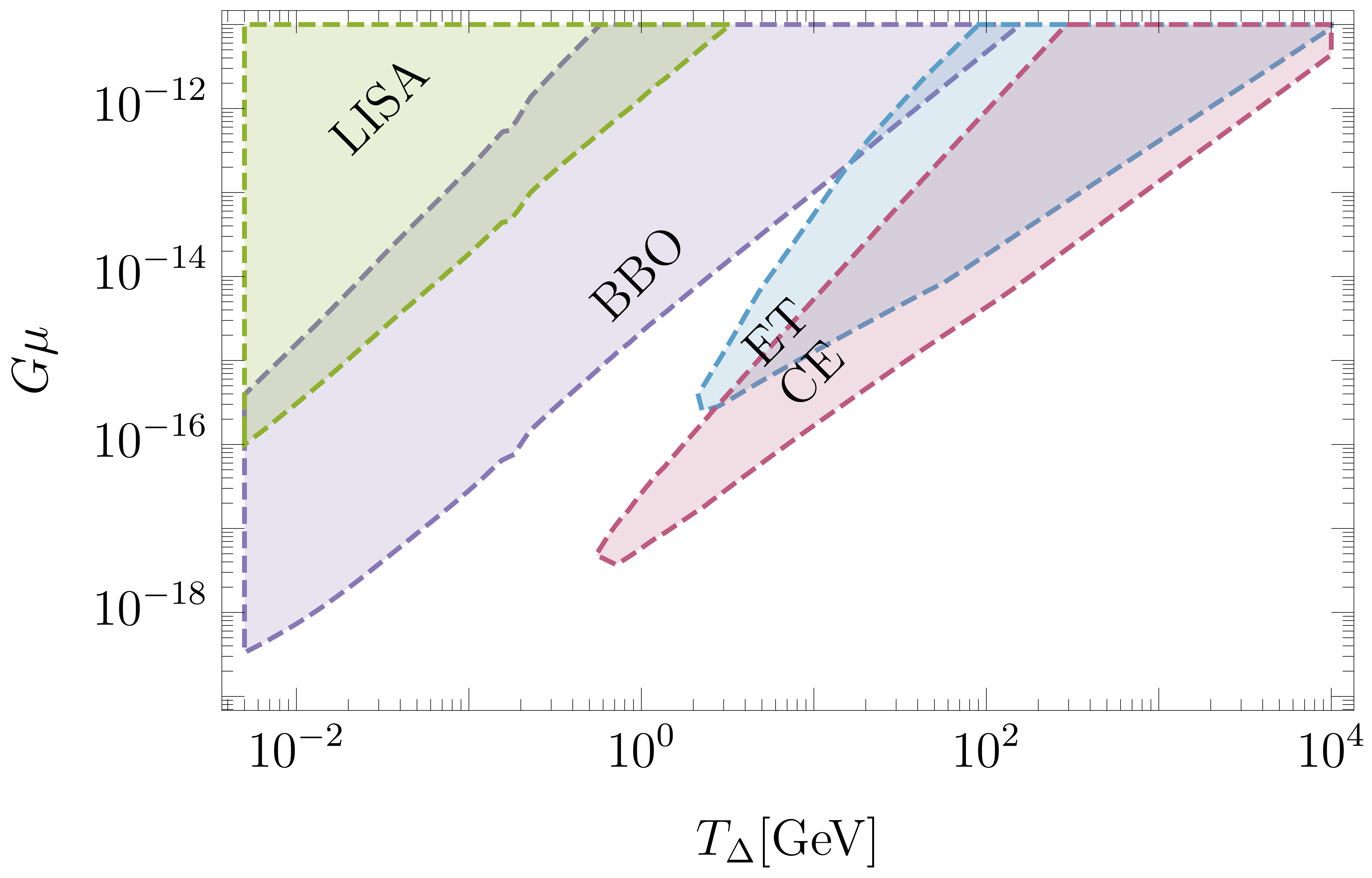
Potential Reach Back in Time

- Direct correspondence between f_Δ and T_Δ for given $G\mu$.



Potential Reach Back in Time

- For moderate $G\mu$, planned experiments can probe back to $T_\Delta \gg 5\,\mathrm{MeV}$



Some Caveats…

- Cosmic strings might not exist.

- They may be more complicated than the simple Nambu-Goto picture.
  e.g. multiple types, internal structure, low reconnection probability …

- Not everybody agrees on dominant GW emission for gauge theory strings.
  e.g. **[Figueroa, Hindmarsh, Urrestilla 2013]** — emission to massive modes
  e.g. **[Matsunami *et al.* 2019]** — emission mostly to GW above cutoff

- Not everybody agrees on the distribution of loop sizes at production.
  e.g. **[Blanco-Pillado, Olum, Shlaer 2013]** *vs.* **[Lorenz, Ringeval, Sakellariadou 2010]**

Some Caveats…

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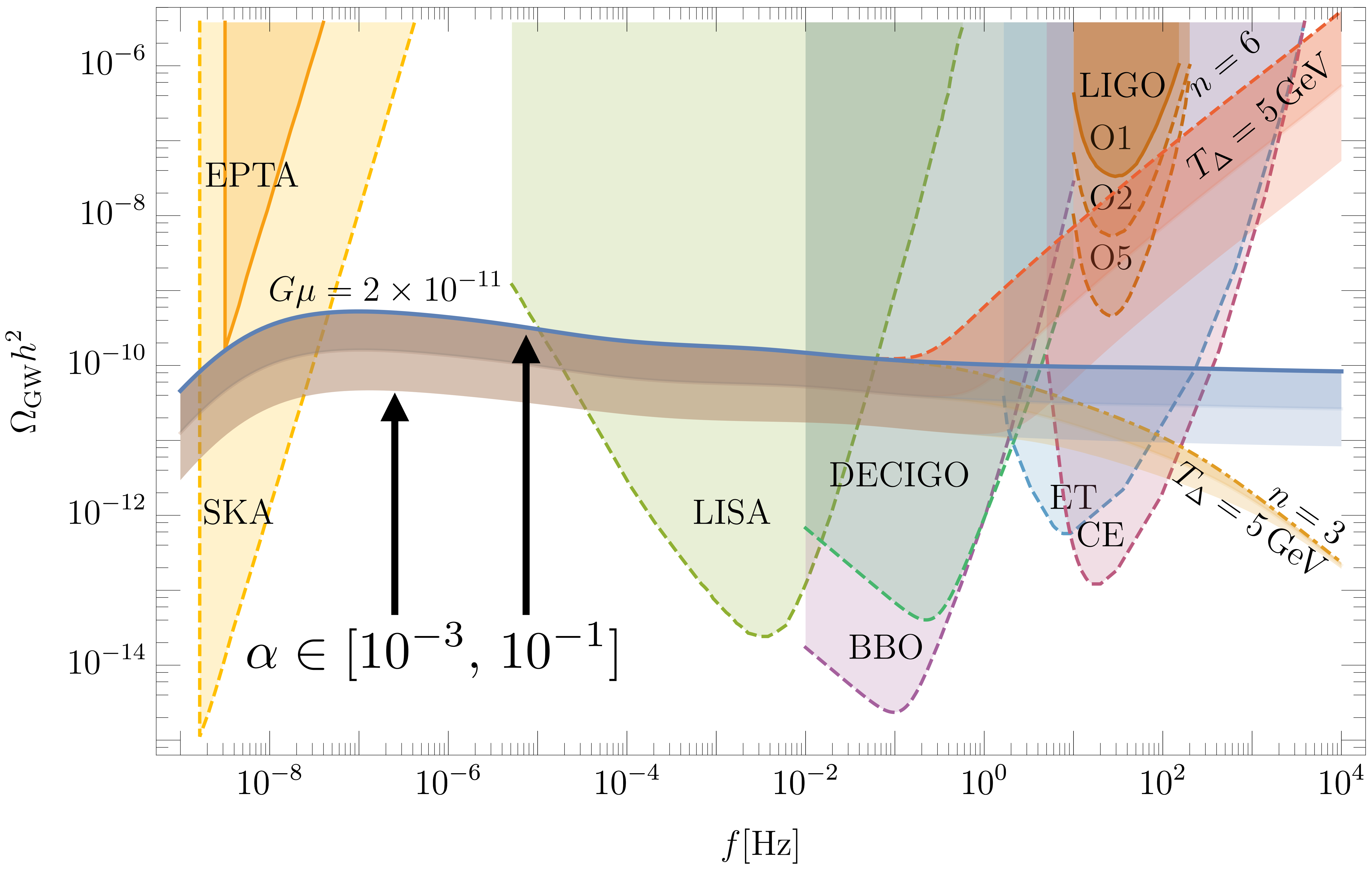


Strings from Before/During Inflation?

- Suppose the CS network is formed before or at the start of inflation.
- No scaling! Long strings are diluted as

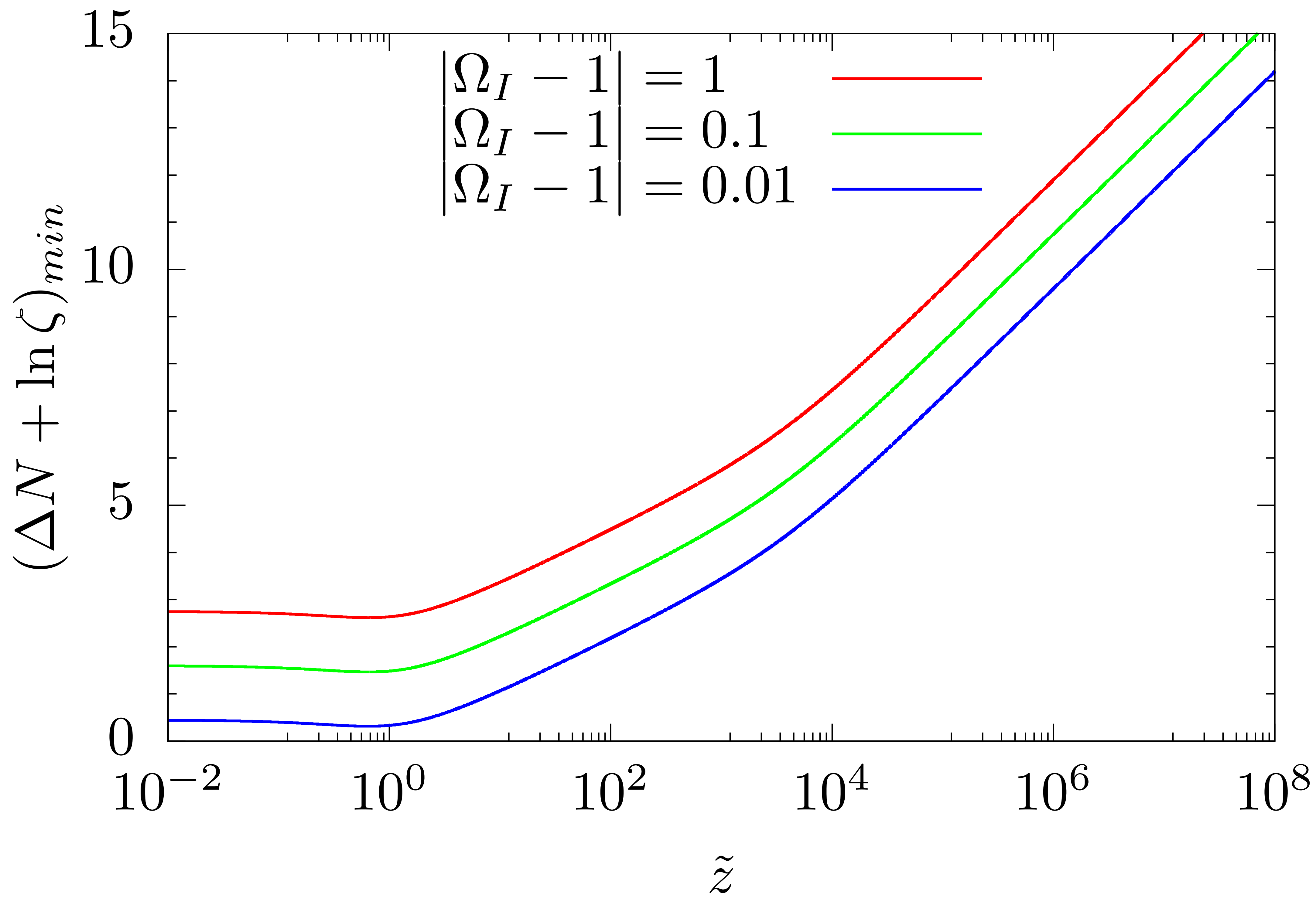
$$\rho_{long} \propto a^{-2} \rightarrow e^{-2(N_{tot} - \Delta N)}$$

- Long strings regrow after inflation as a^{-2} until they start to self-interact.
- Could such strings be observable?

Cosmic String Regrowth

- String dilution and regrowth depends on the amount of inflation.

- Compare to curvature bound: $|\Omega - 1| = 0.007 \pm 0.0037$ [Planck 2018]



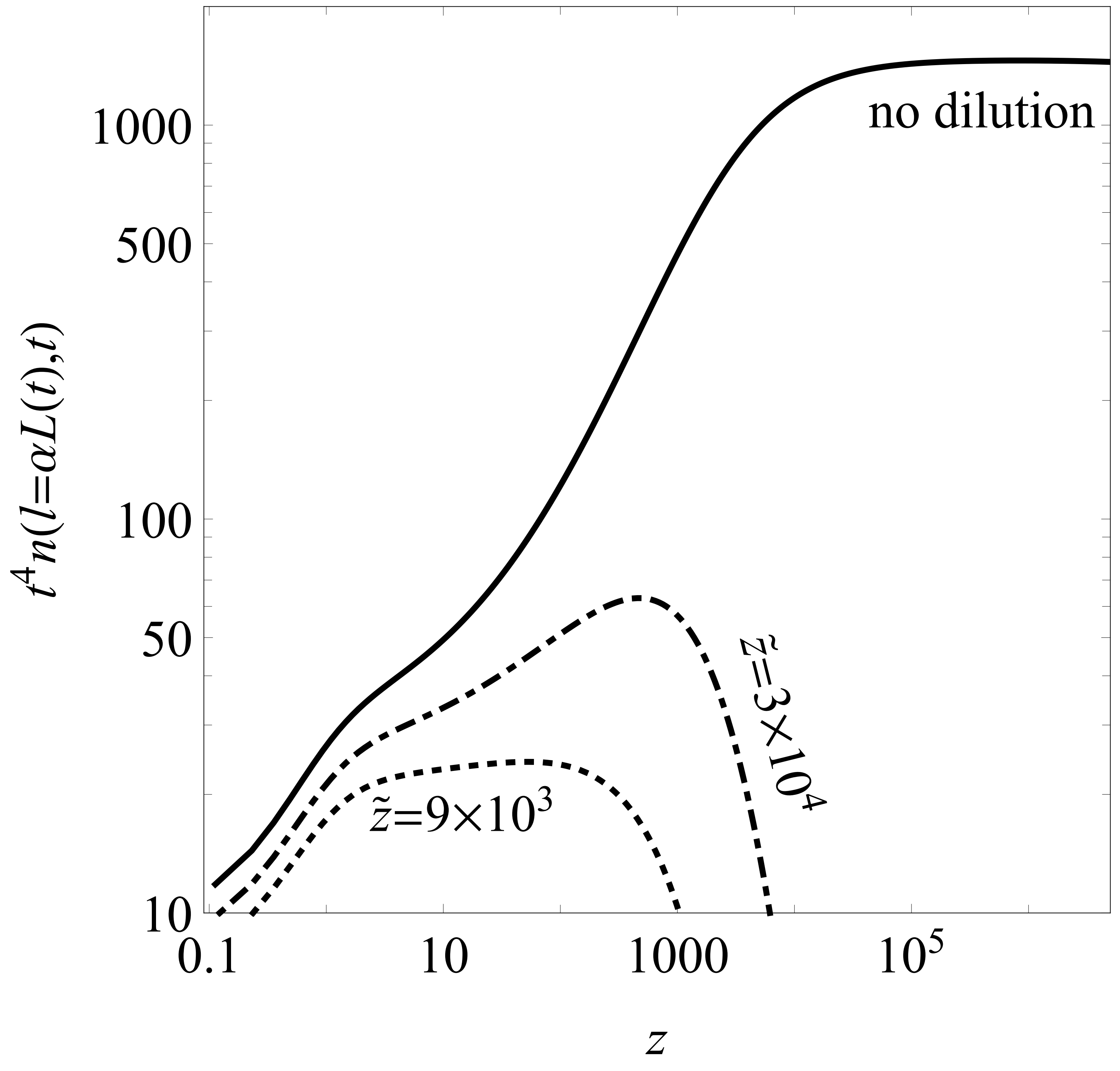
$\Delta N \geq 0$: # e-folds strings formed after the start of inflation

$\zeta^2 =$ initial number of long strings

$\tilde{z} =$ redshift when long strings start to interact

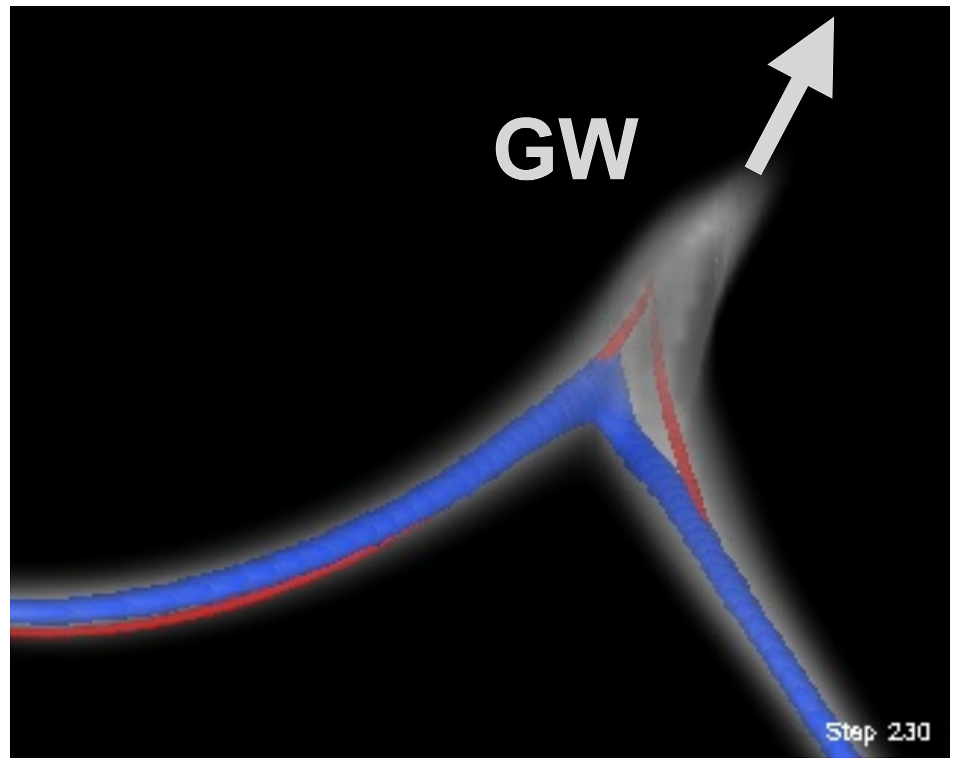
Cosmic String Regrowth

- String dilution and regrowth depends on the amount of inflation.
- Input $\tilde{z}$ as redshift when long strings start to interact.



Cosmic String Bursts

[K. Olum]



- GW emission is dominated by bursts from loop cusps.
- Unresolved emission dominates the stochastic signal.
- Recent bursts can be resolved individually, but usually harder to observe.

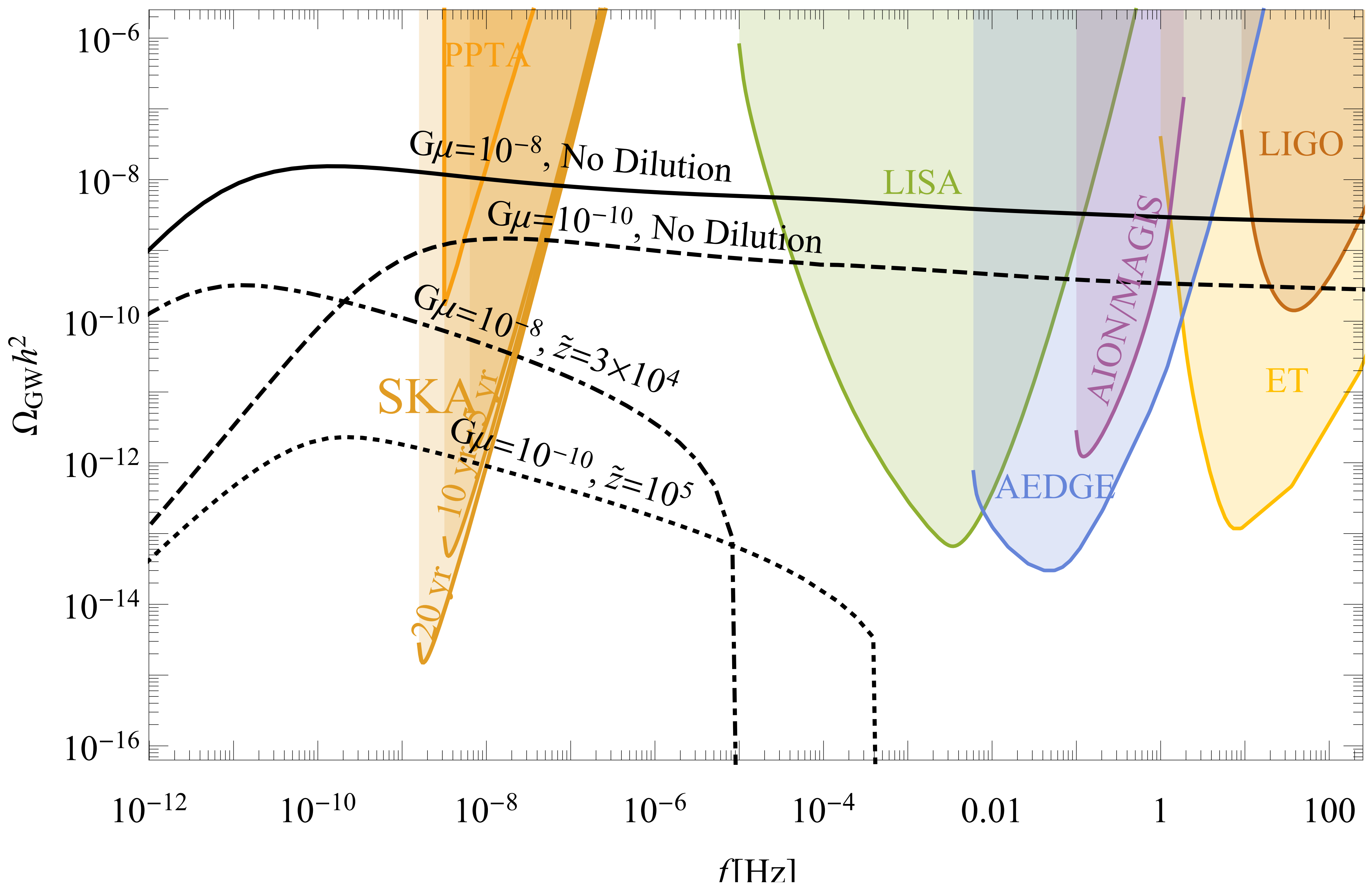
[Damour, Vilenkin 2000]

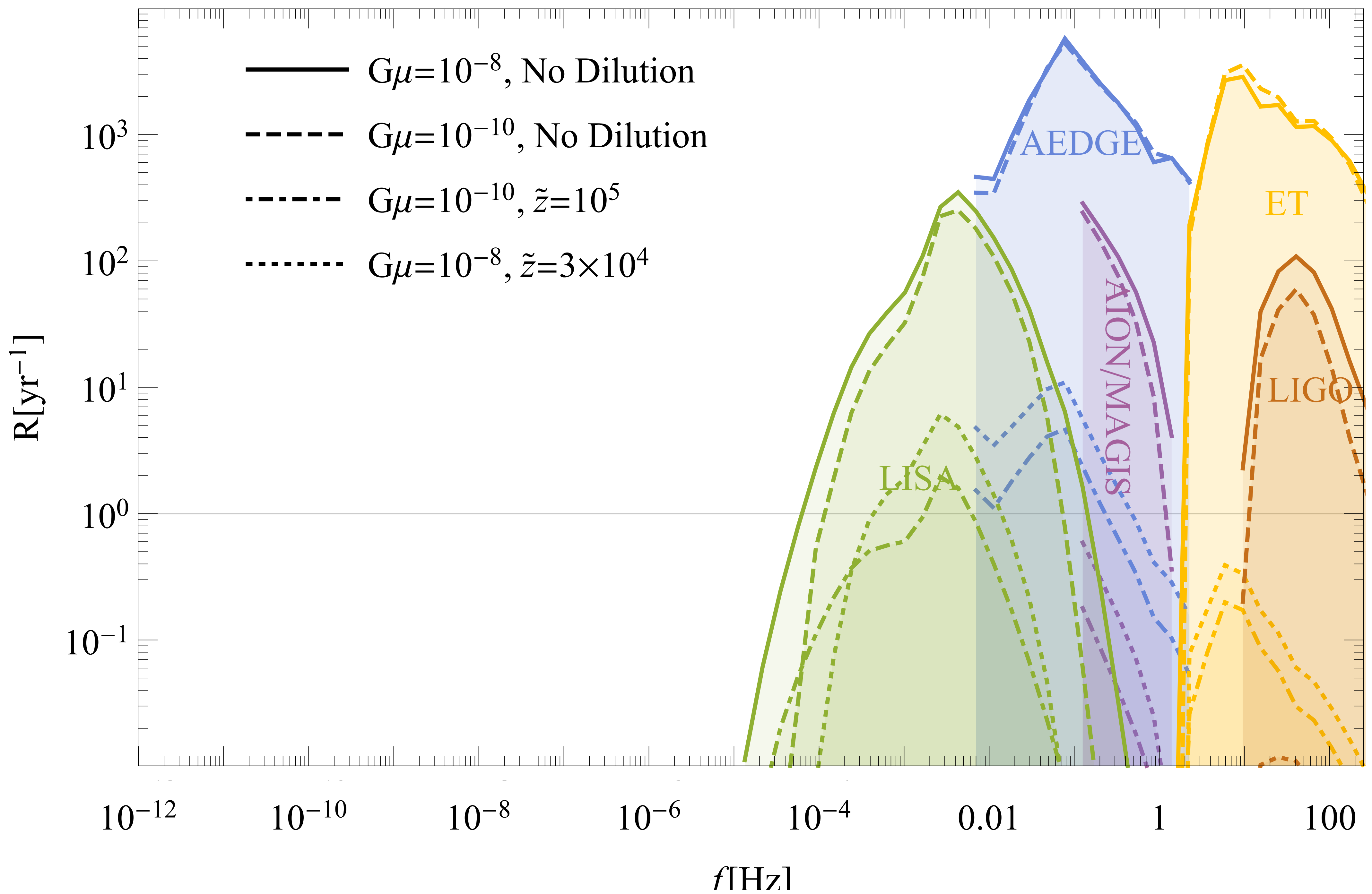
- Late string scaling reduces the stochastic signal, not bursts.
- Bursts are beamed within angle θ_m with distinctive waveform h:

$$\theta_m = \left[(1+z)fl\right]^{-1/3} \qquad h = \frac{f^{-4/3}l^{2/3}}{(1+z)^{1/3}}\frac{G\mu}{r(z)}$$

Cosmic String Regrowth Signals

- Strings can come back, start to interact, approach scaling, make GWs.
- Stochastic GW signal is suppressed, but recent bursts could be seen!





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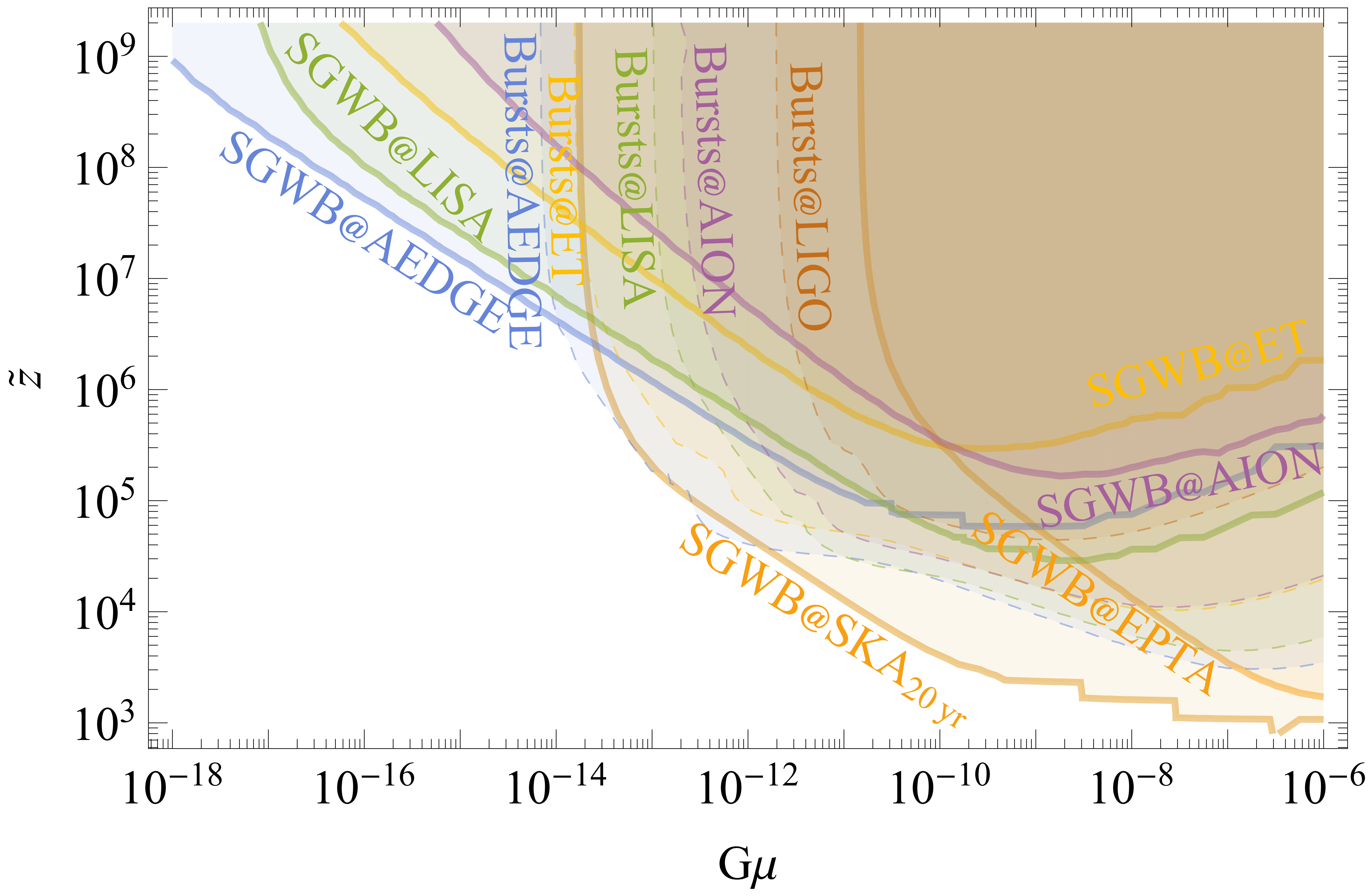

Summary

- Gravitational waves avoid thermal scrambling.
- An early source of GWs could teach us about the very early universe.
- Cosmic strings are a motivated and understood GW source.
- GWs from a cosmic string network could be observed in future detectors.
- Their frequency spectrum would reflect the expansion history of the cosmos.

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Thank you
Merci

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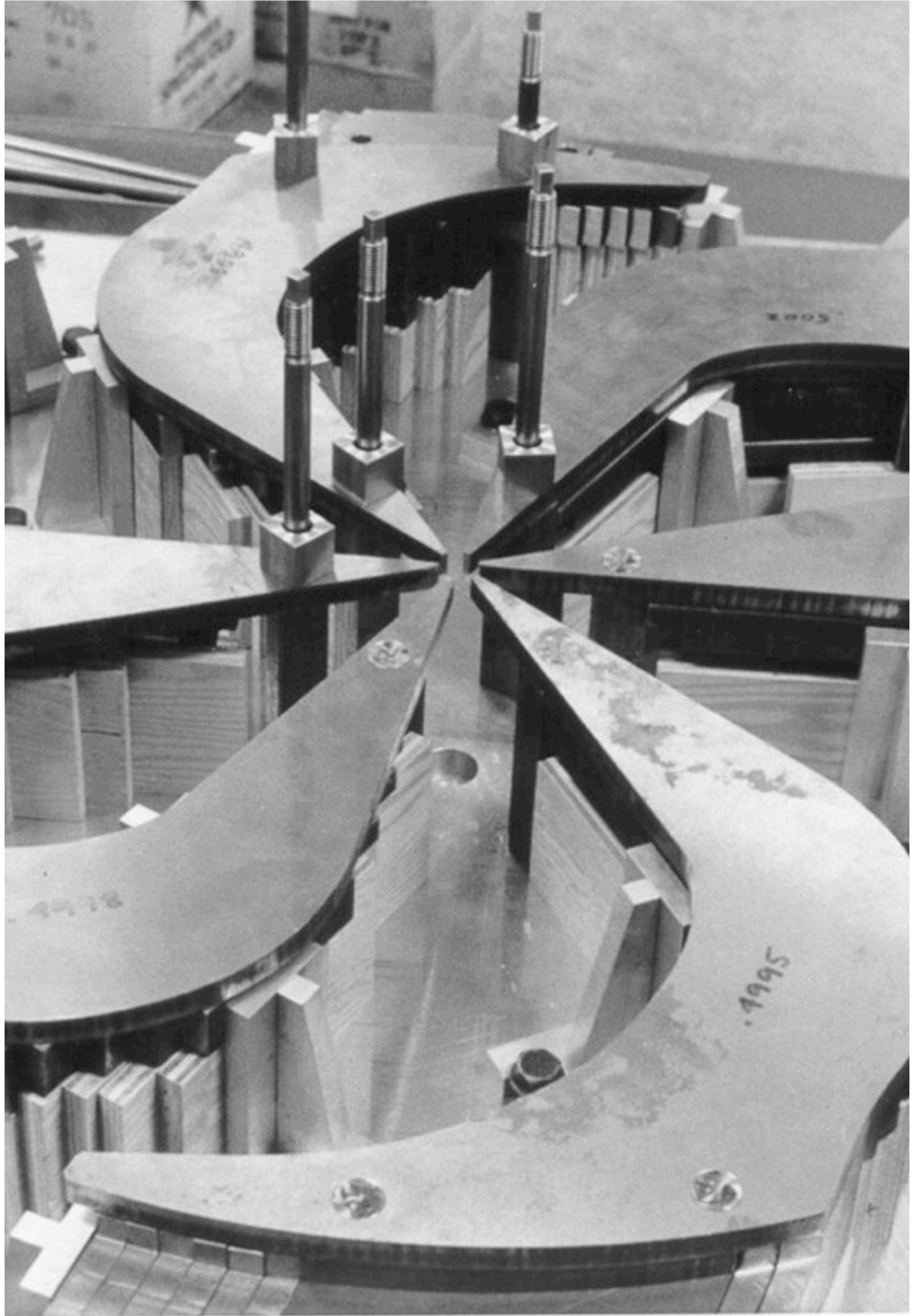

Discovery,
accelerated

Extra Slides

Scaling and the VOS Model

- VOS = velocity-dependent one-scale model
  → describes (long) cosmic string scaling and the approach to it

- L = length parameter, $\bar{v}$ = velocity parameter

[Martins, Shellard 1995]

$$\rho_{long} = \frac{\mu}{L^2}$$

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

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

Scaling and the VOS Model

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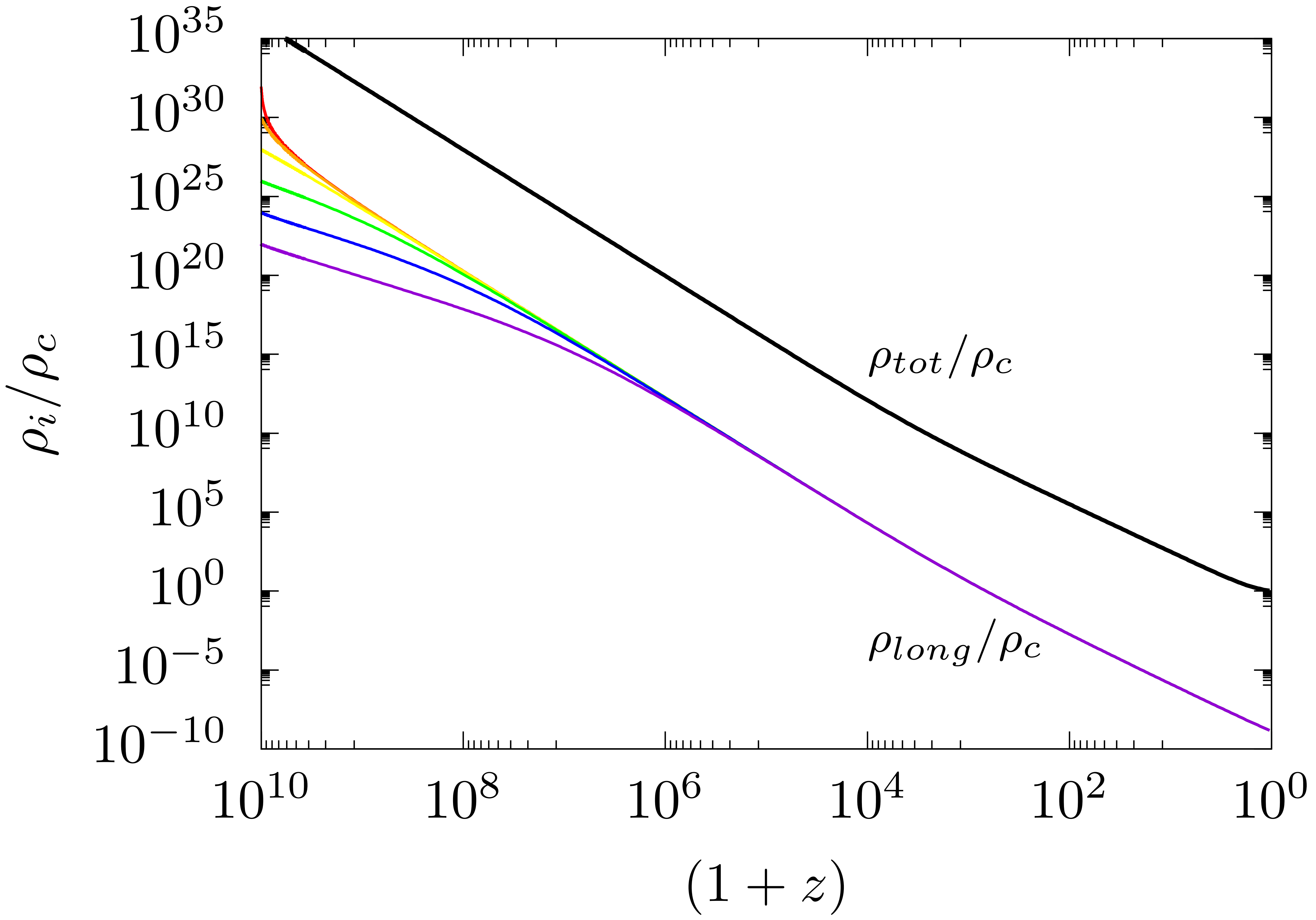


Loop Production Rate

- Energy loss to loops in the VOS model:

$$\left(\frac{d\rho}{dt}\right)_{long} = -\tilde{c}\,\bar{v}\,\frac{\rho_{loop}}{L}$$

- Production rate for large loops with length $l_i = \alpha\, t_i$, boost γ, fraction $\mathcal{F}$:

$$\frac{dn}{dt_i} = \mathcal{F}\,\frac{\tilde{c}\,\bar{v}}{\gamma}\,\frac{\rho_{loop}}{L}\,\frac{1}{\mu\,\alpha\,t_i} \propto t_i^{-4}$$

Loop Emission Rate

- GW emission is dominated by cusps.

- Total emission rate of GW from a loop:

$$\left(\frac{dE}{dt}\right)_{loop} = \Gamma G\mu^2$$

- Averaged emission can be treated as a sum of normal mode oscillations:

$$\Gamma = \sum_{n=1}^{\infty} \Gamma_n \ , \quad \Gamma_n = \left(\frac{\Gamma}{3.36}\right) n^{-4/3}$$

$$f = \frac{2n}{l(t)}$$

Cosmic String Stochastic GW Signal

- Sum over loop emissions:

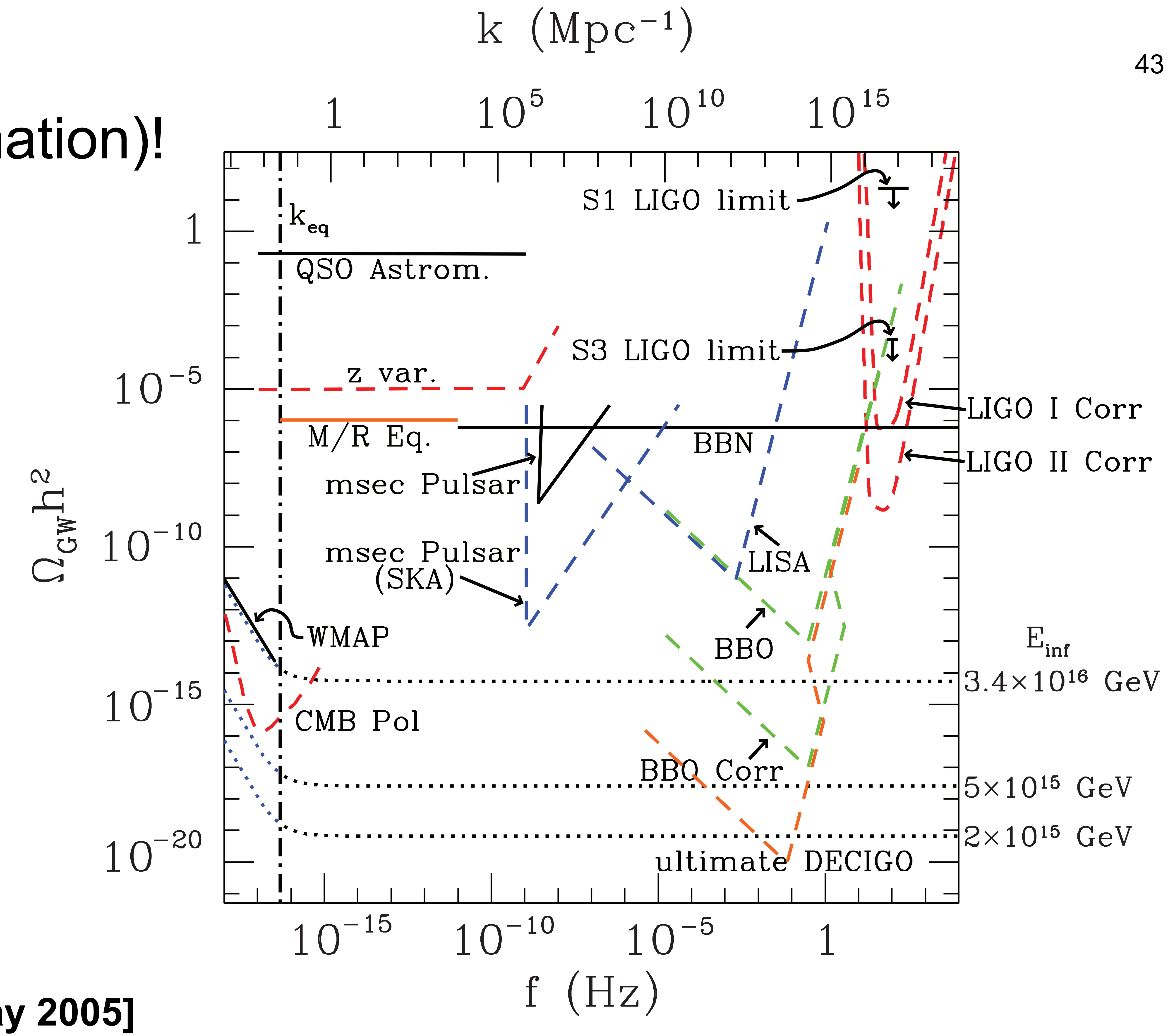
$$\Omega_{GW}(f) = \sum_n \Omega_{GW}^{(n)}(f)$$

$$\Omega_{GW}^{(n)}(f) = \frac{1}{\rho_c}\frac{2n}{f}\frac{\Gamma_n G\mu^2}{(\alpha+\Gamma G\mu)}\int dt\,\frac{dn}{dt_i}\left[\frac{a(t)}{a(t_0)}\right]^5\left[\frac{a(t_i)}{a(t_0)}\right]^3$$

$$t_i = \frac{1}{\alpha+\Gamma G\mu}\left[\frac{2n}{f}\frac{a(t)}{a(t_0)} + \Gamma G\mu t\right]$$

Gravitational Waves

- No scrambling (to a good approximation)!
- Cosmological sources?
- Inflation:



[Smith, Kamionkowski, Cooray 2005]