Gravitational wave spectrum from metastable cosmic string network and delayed scaling scenario

Based on: Yifan Hu (HIAS-UCAS), KK, JCAP04 (2025) 044,
arXiv: 2501.18380 [astro-ph.CO].

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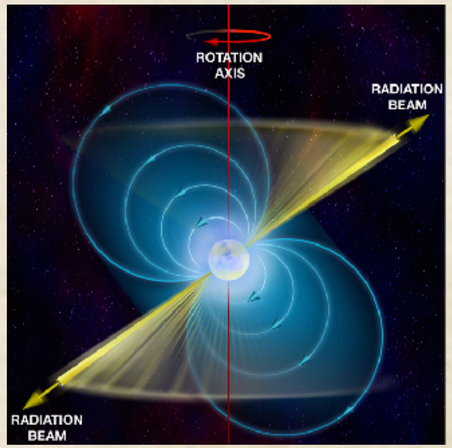
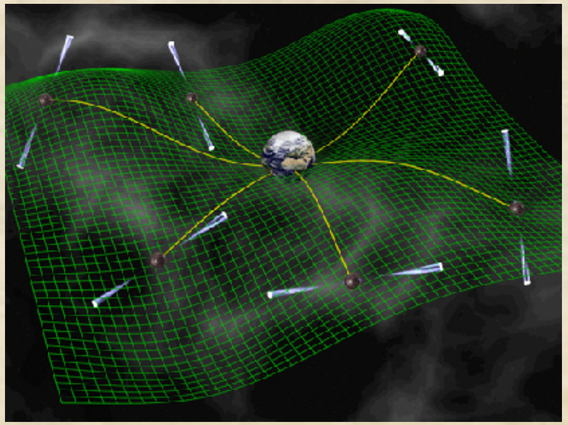
Xichang Qionghai Hotel, 28/08/2025

Pulsar Timing Arrays (PTAs) found an evidence of stochastic GWs?



(nrao.edu)



credit: David J. Champion

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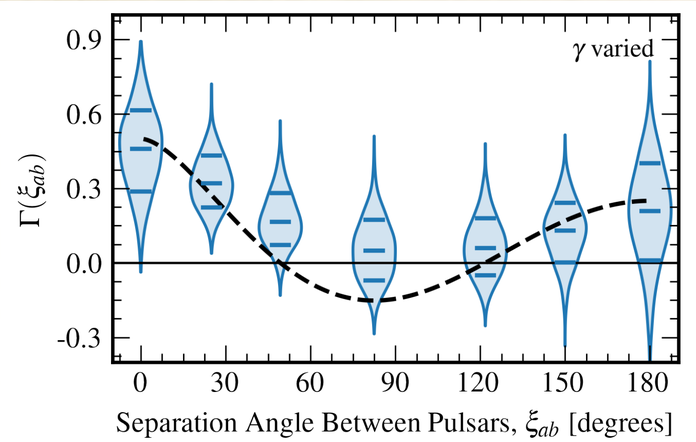
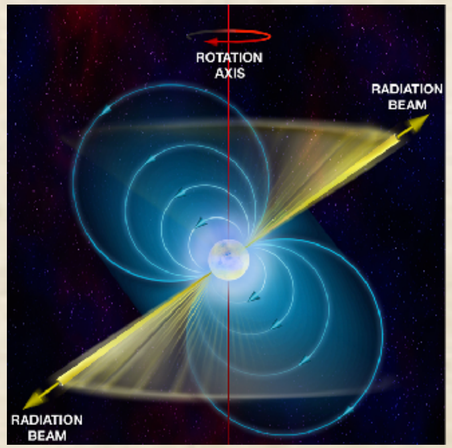
2306,16213: NANOGrav



68 pulsars, 16 yrs, 3~4 σ



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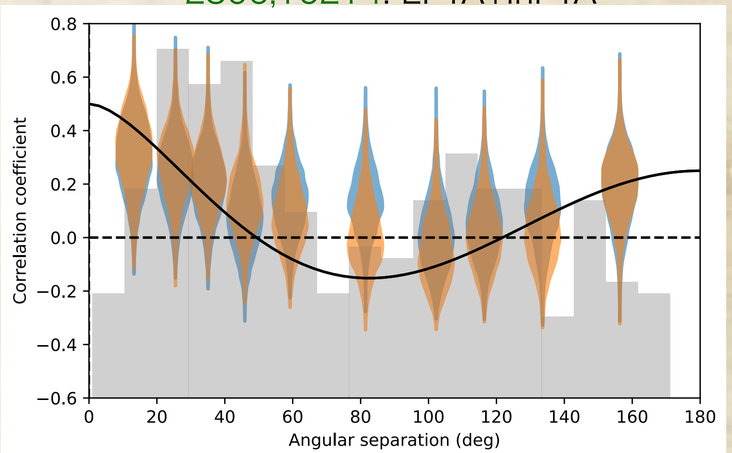
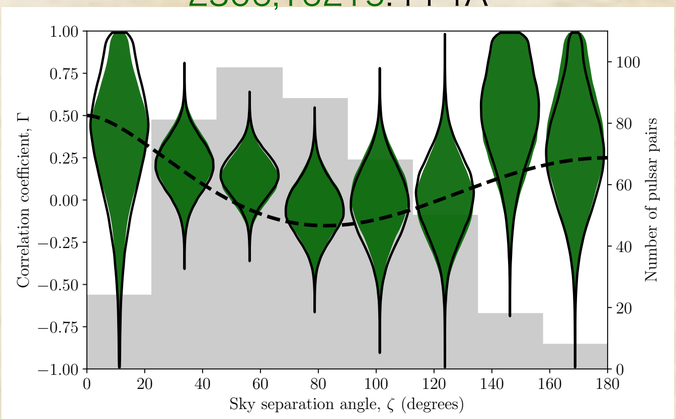
2306,16214: EPTA+InPTA

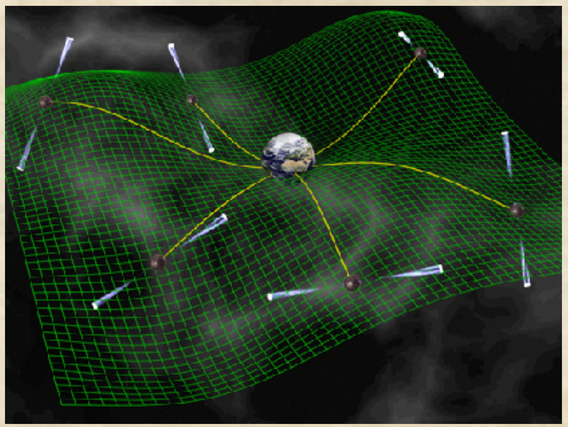


25 pulsars, 25 yrs, ~3 σ

2306,16215: PPTA

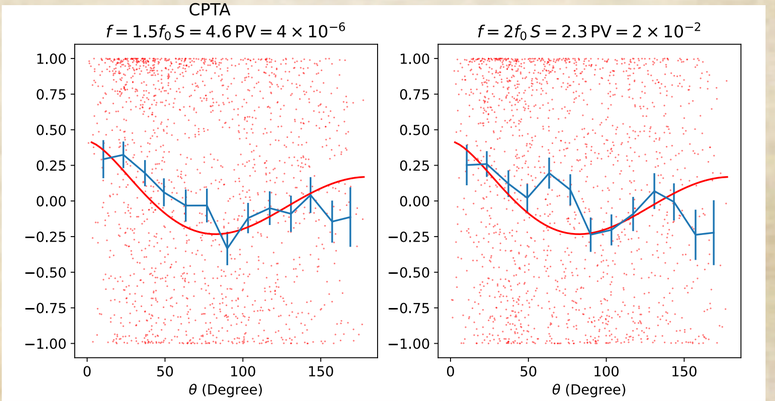


32 pulsars, 18 yrs, ~2 σ



credit: David J. Champion

2306,16216: CPTA



57 pulsars, 3.5 yrs, ~4.6 σ

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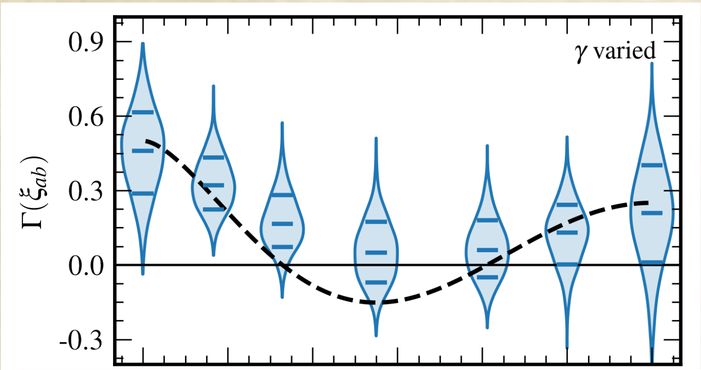

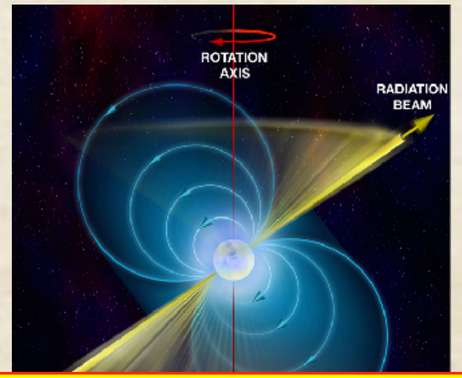

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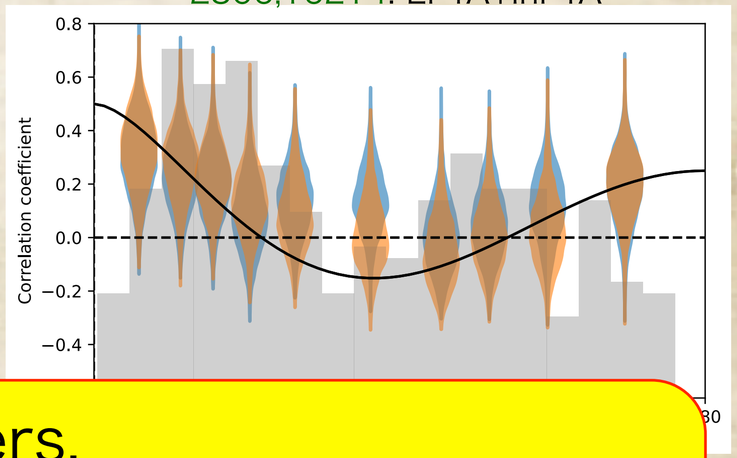
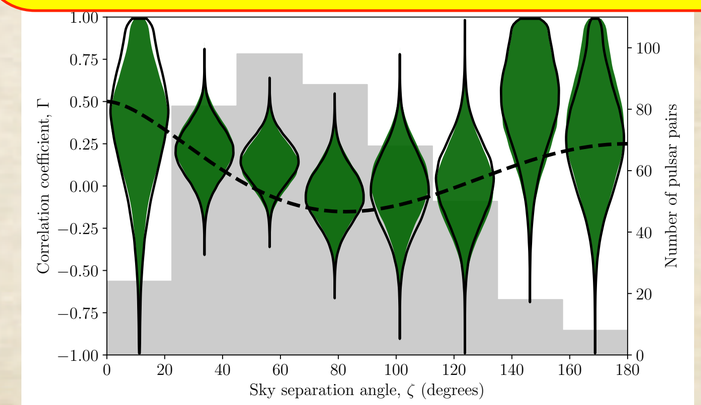


Can be explained supermassive blackhole mergers,
but may be sourced by new phenomena/physics in the early Universe?



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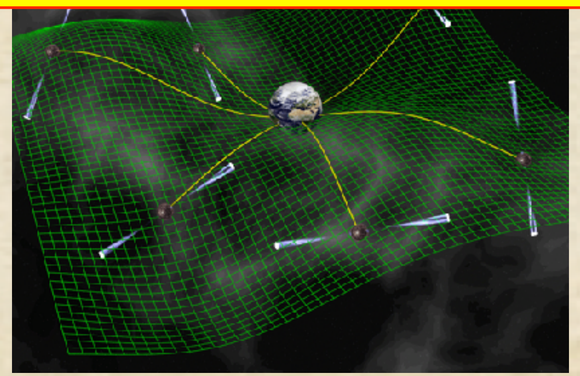

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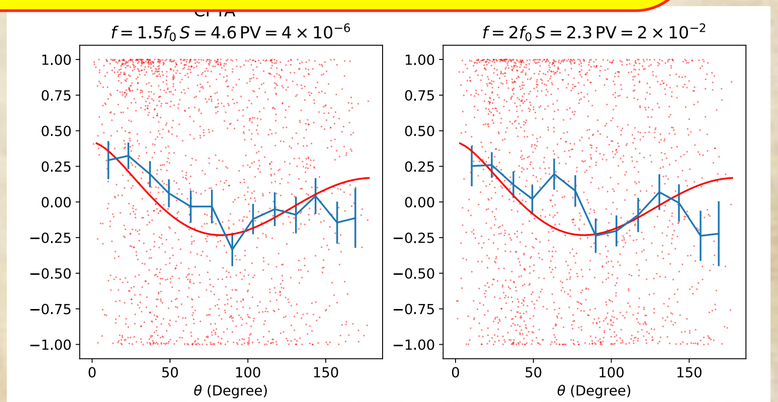

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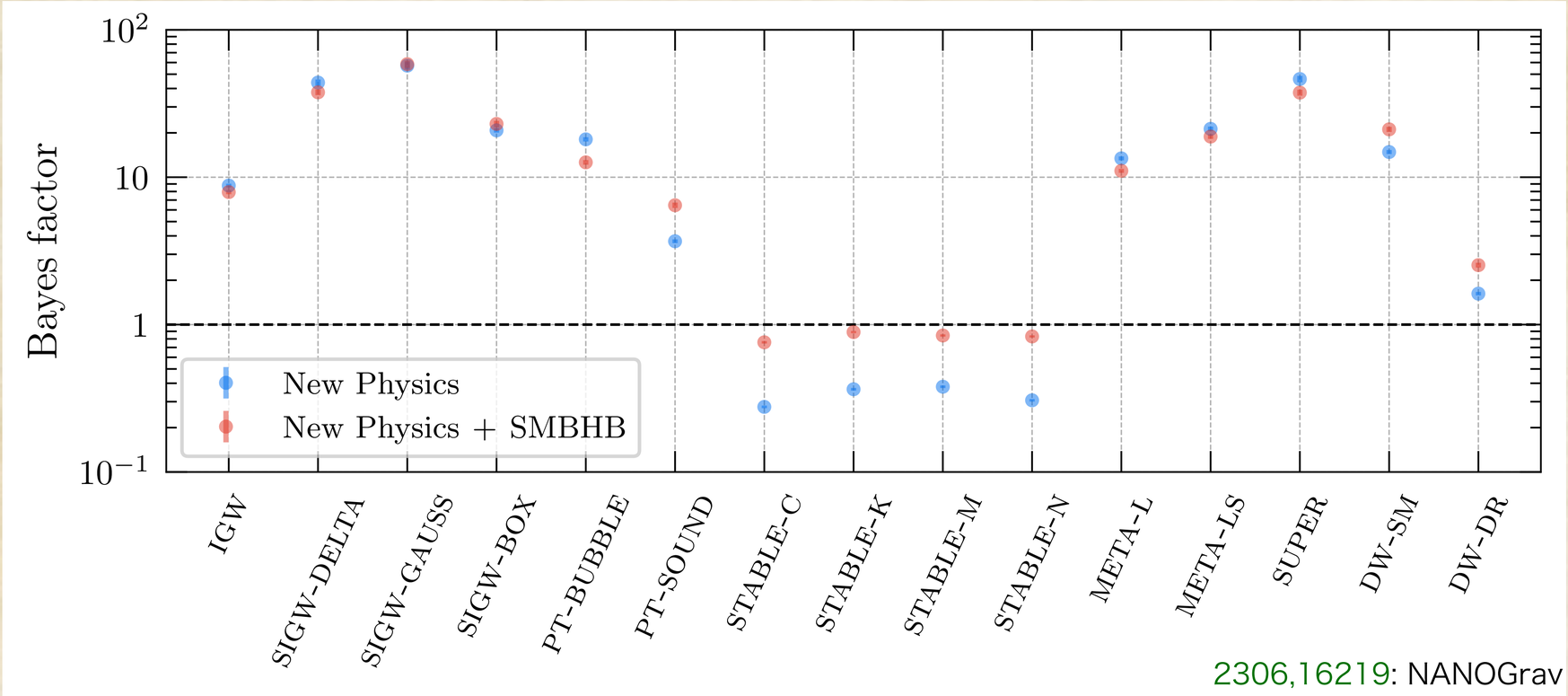
Bayesian model comparison for new physics



2306,16219: NANOGrav

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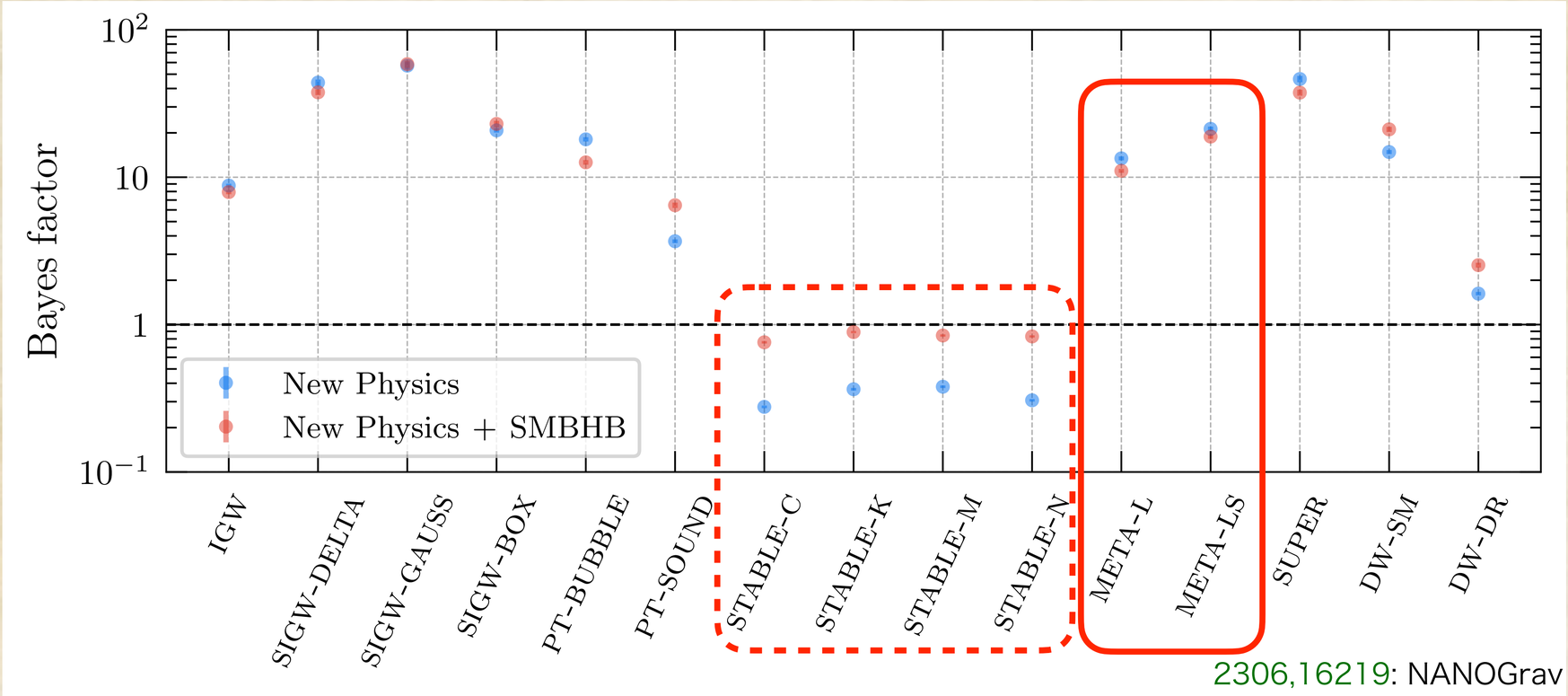


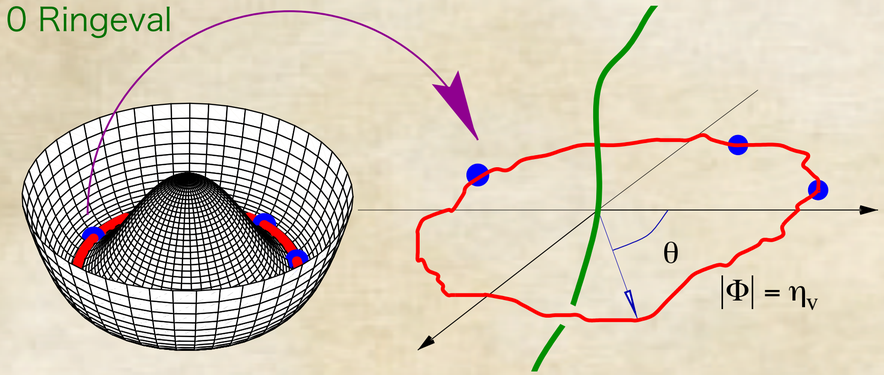
An interesting possibility: (meta-stable) cosmic strings

Slide Background Courtesy: H. Oide

Cosmic string: '76 Kibble

2-dimensional topological defect associated with U(1) symmetry breaking

'10 Ringeval



Field space

Real space

Cosmic string: ’76 Kibble

2-dimensional topological defect associated with U(1) symmetry breaking

Generated in the early Universe through phase transition, such as GUT breaking, to form a network of inifinite string and loops.

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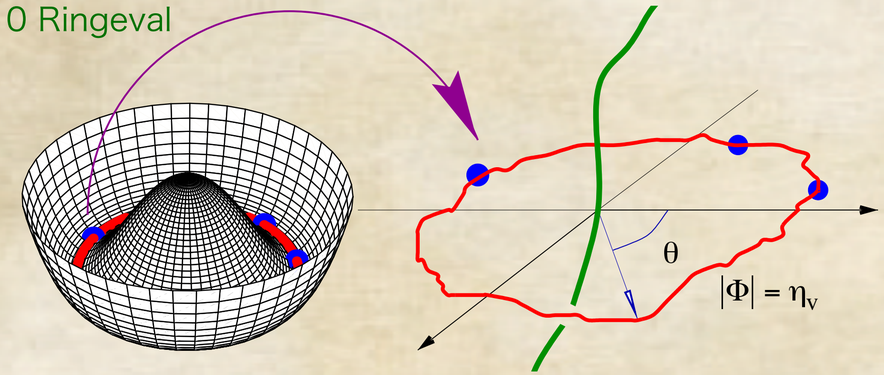

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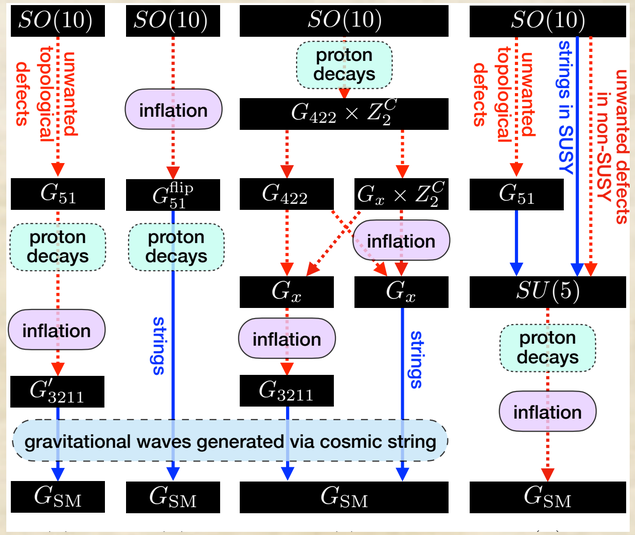
’21 King+



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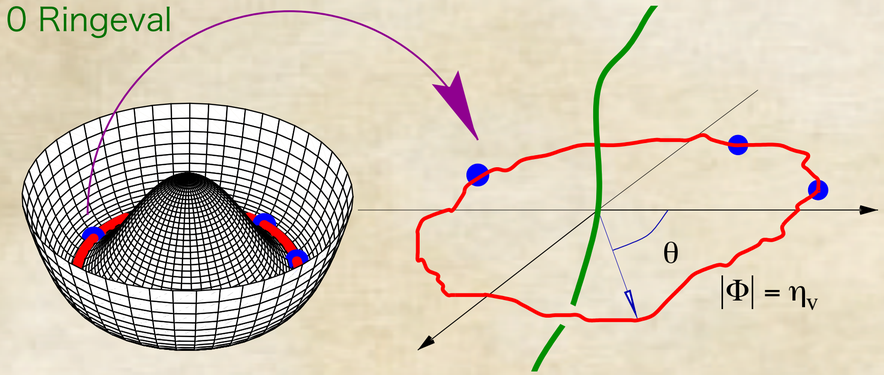

Field space Real space

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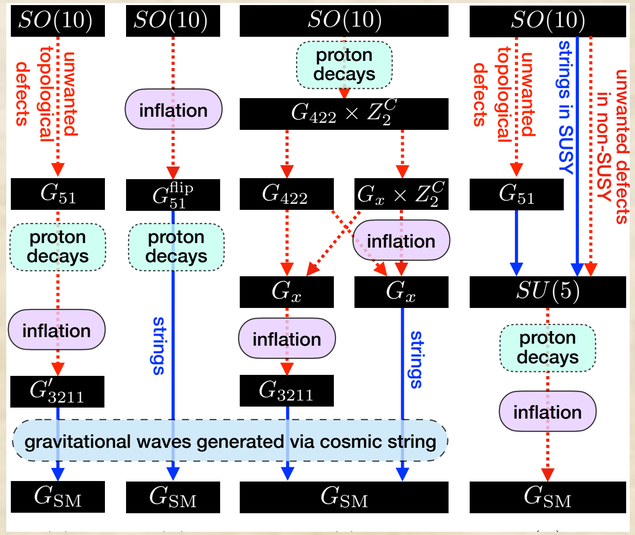
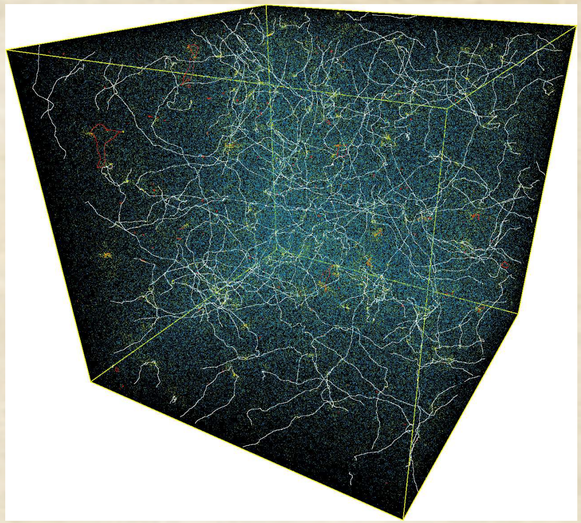


'22 da Cunha+



Network enters the "scaling regime" '85 Kibble, '89 Albrecht&Turok

The physical model parameter is only string tension, $\mu \sim 2\pi\eta_{\rm v}^2$

Slide Background Courtesy: H. Oide

GWs from cosmic strings:

If the underlying U(1) symmetry is a gauge symmetry,

loops in the string networks, continuously produced, shrink by emitting GWs.

'81 Vllenkin, '84 Hogan&Rees, '85 Vachaspati&Vilenkin

credit: Daniel Dominquez

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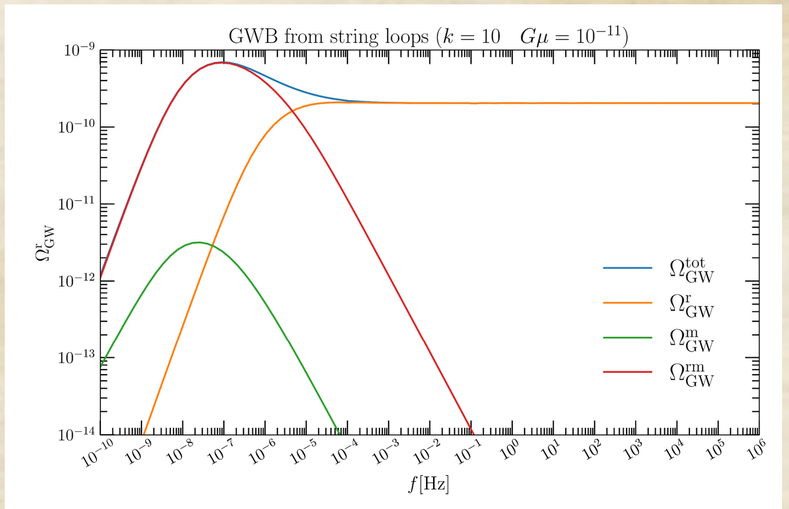
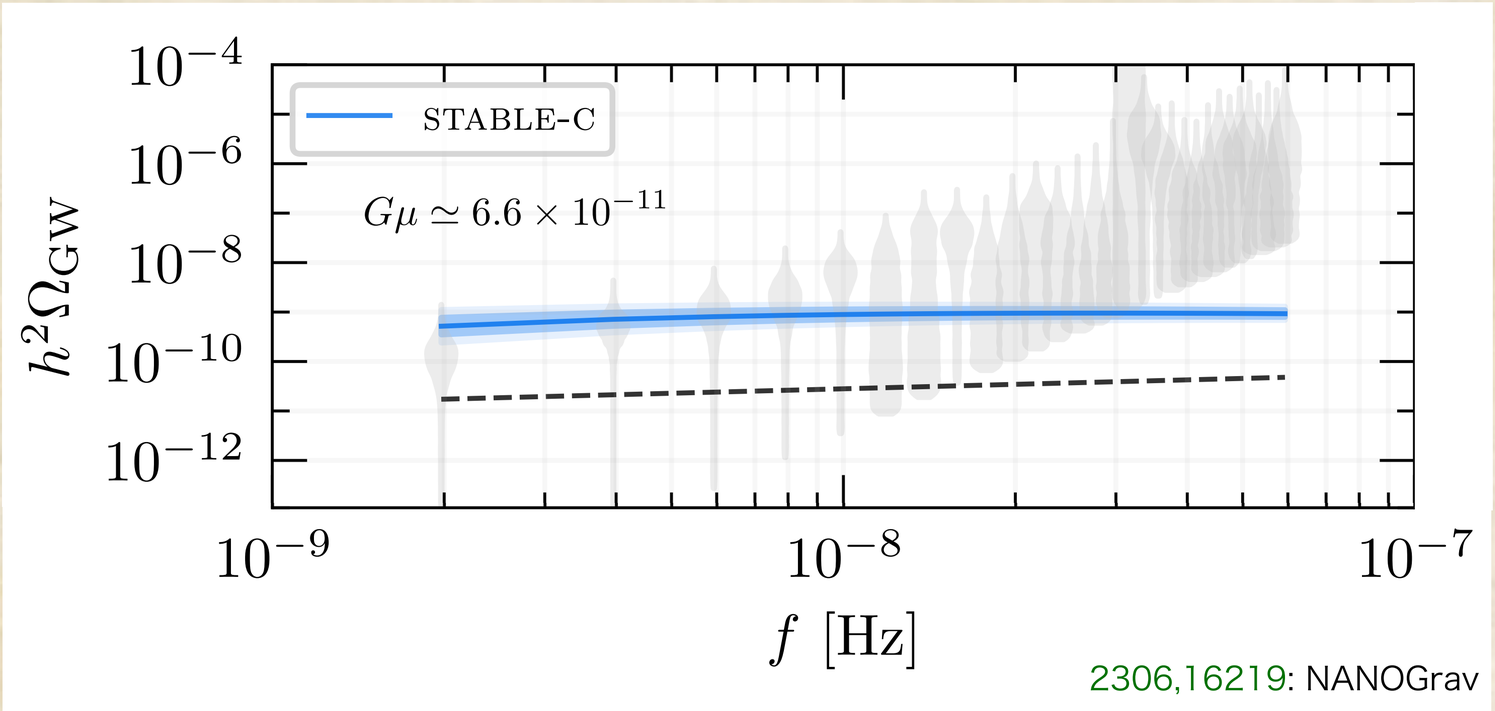


Predicts a broadband SGWB spectrum,
earlier loops produces high-frequency GWs today

Explaining PTA measurements?



2306,16219: NANOGrav

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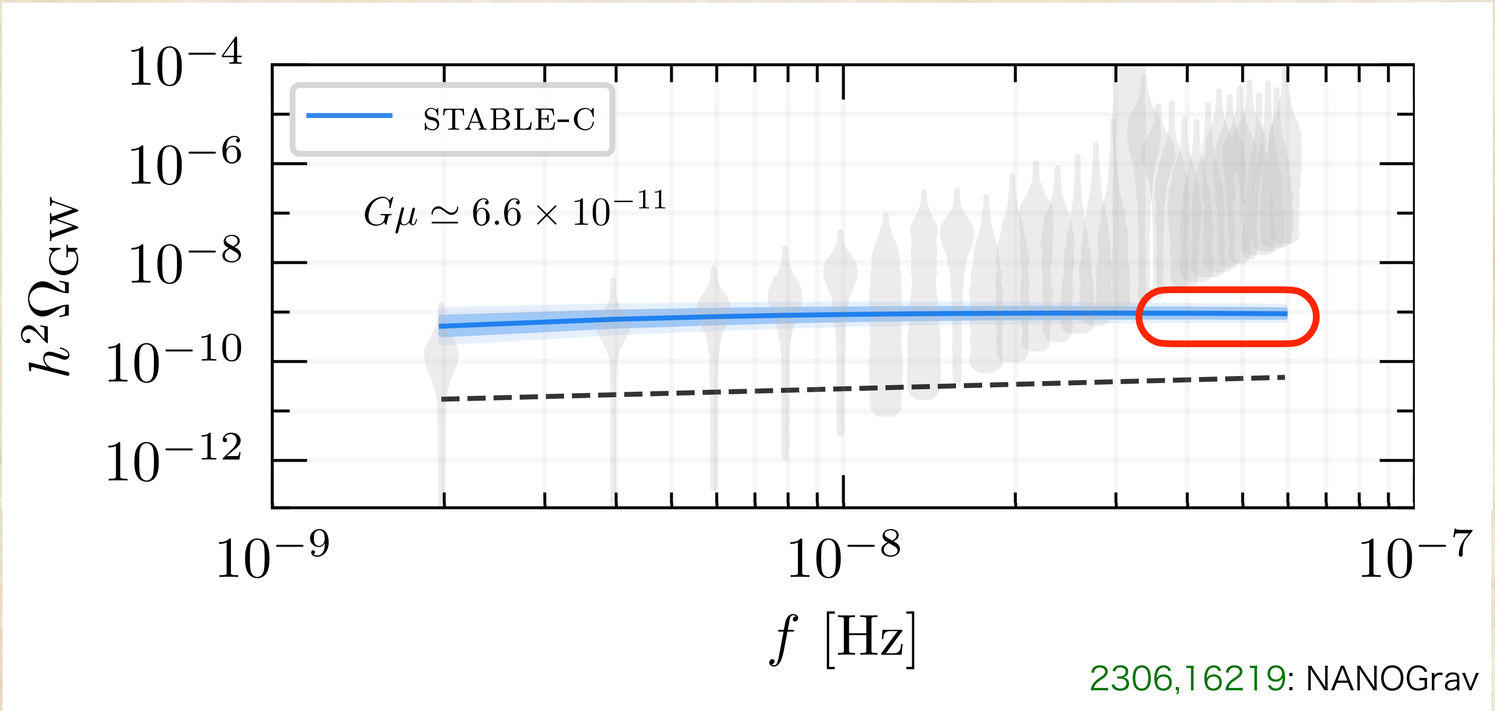

2306,16219: NANOGrav

The spectral index of the GW spectrum from stable cosmic string is too law to fit all the data.

Metastable cosmic strings!

If we can reduce the contribution at low-frequency GW,
we may explain the PTA measurements by cosmic strings.

Metastable cosmic strings!

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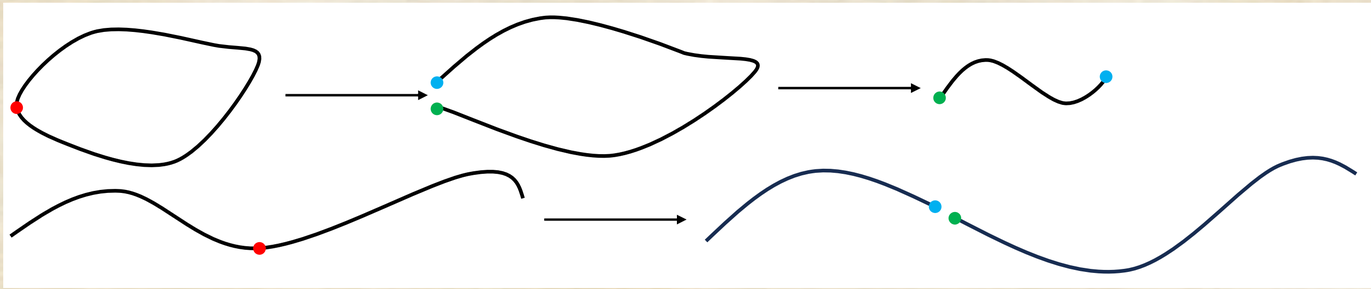
we may explain the PTA measurements by cosmic strings.

It is realized if cosmic strings are torn apart by the monopole-antimonopole pair production. ’82 Vilenkin, ’92 Preskil&Vilenkin, ’20, ’21, ’23 Buchmüller+



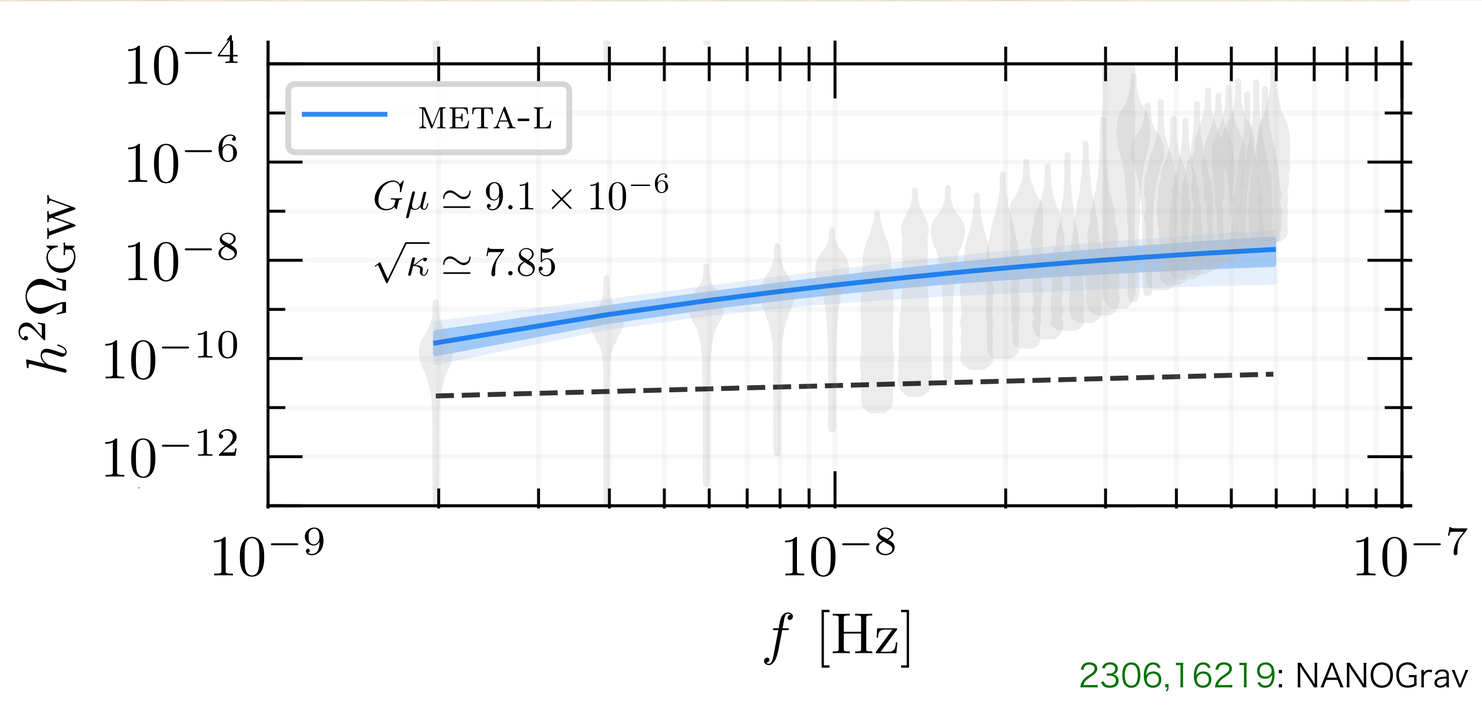
#Note that GUT often predicts such pair-creation like Schwinger effect.

Decay rate per unit length: $\Gamma = \dfrac{\mu}{2\pi}\exp[-\pi\kappa]$ $\kappa \simeq \dfrac{m^2_{\rm monopole}}{\mu}$

GW emission is suppressed after decay.

’92 Preskil&Vilenkin; see also ’24 Chitose+

Metastable cosmic strings



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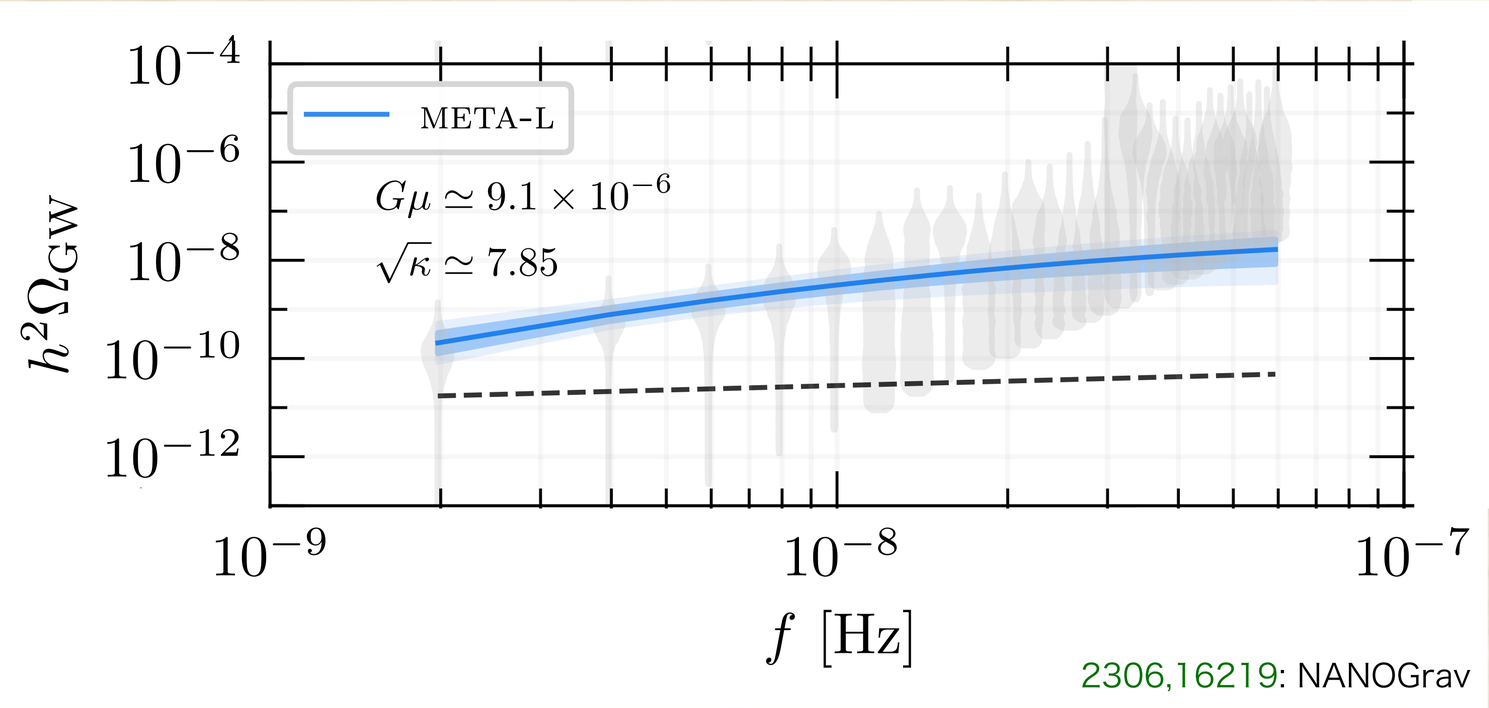

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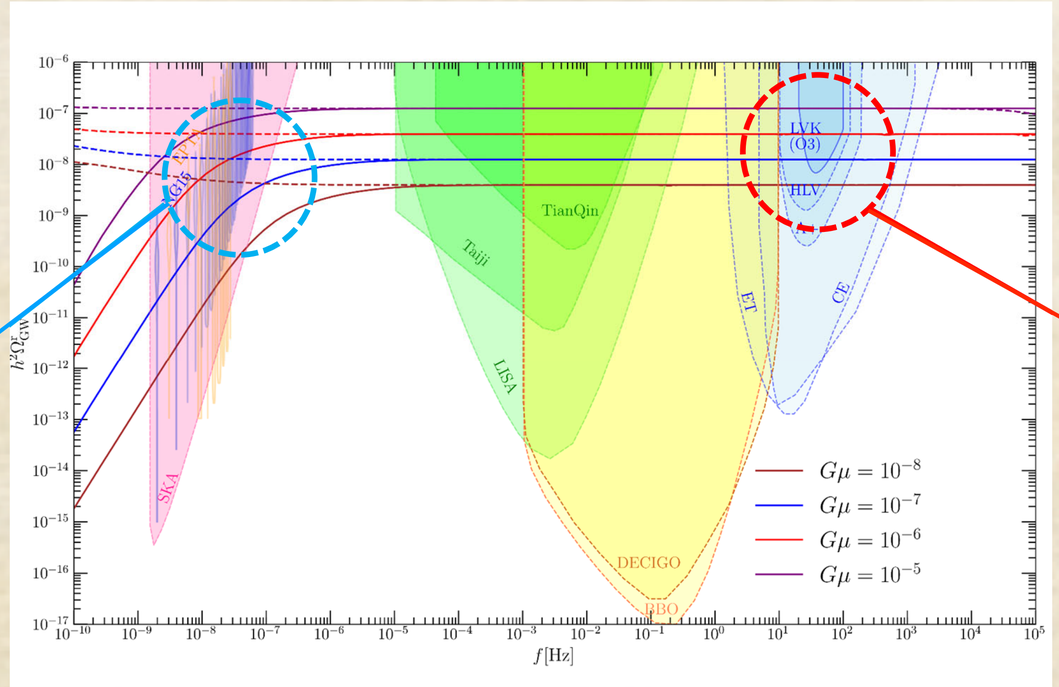
corresponds the case when string decays at around $z \sim 3 \times 10^9$

The low frequency spectrum is reduced to fit the spectral index, while the amplitude is fit by increasing the tension.

Problems in metastable cosmic strings in explaining PTA measurements

- Larger string tension $G\mu \sim 10^{-6}$ is favored, but it conflicts with non-observation of SGWB at LVK

Good to explain PTA



Constrained by LVK

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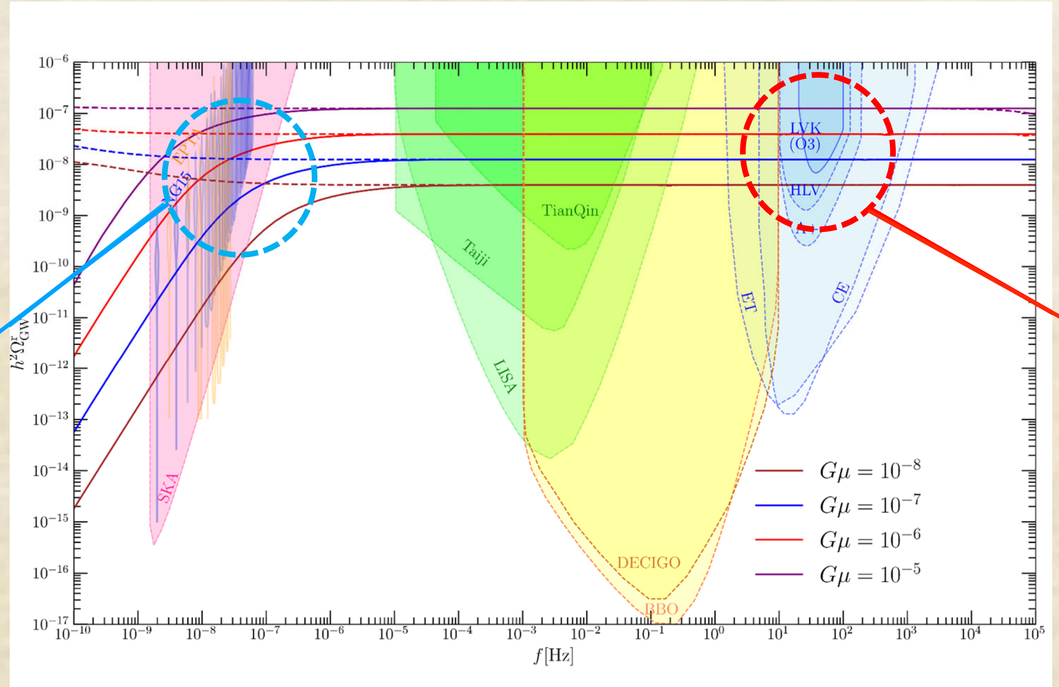


Constrained by LVK

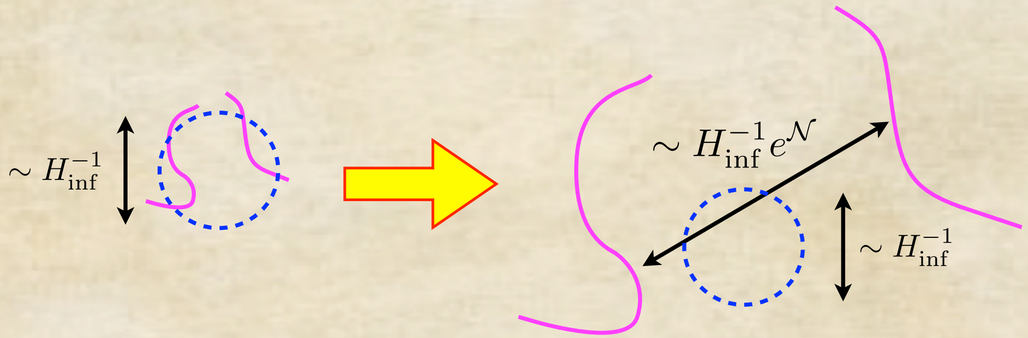
- Monopole producing SSB scale is close to the string forming SSB scale
  -> If the monopoles are also produced just before string formation, string network would not be formed, but monopoles are annihilated by strings.

Slide Background Courtesy: H. Oide

Delayed scaling scenario resolves these two issues.

'89 Yokoyama, '12 Kamada+, '20 Cui+

If the phase transitions take place during inflation, monopoles are first produced and sufficiently diluted, and long strings are then formed.
Long strings are also diluted to superhorizon scales until the end of inflation.



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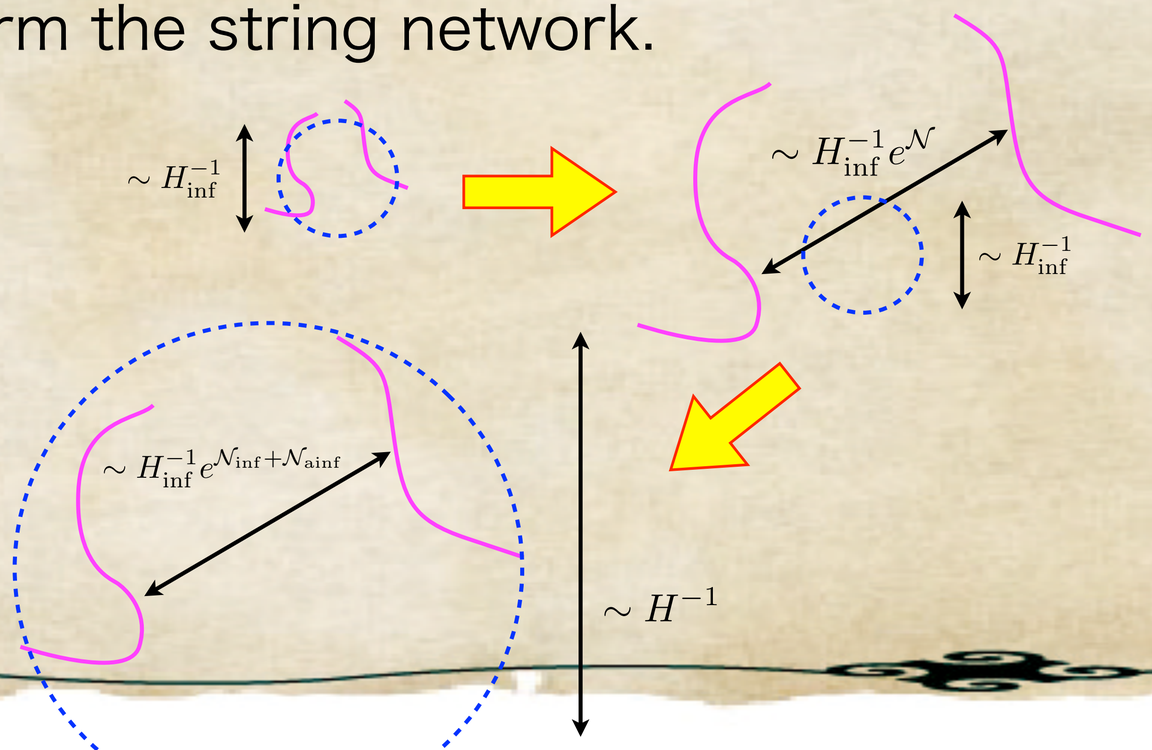
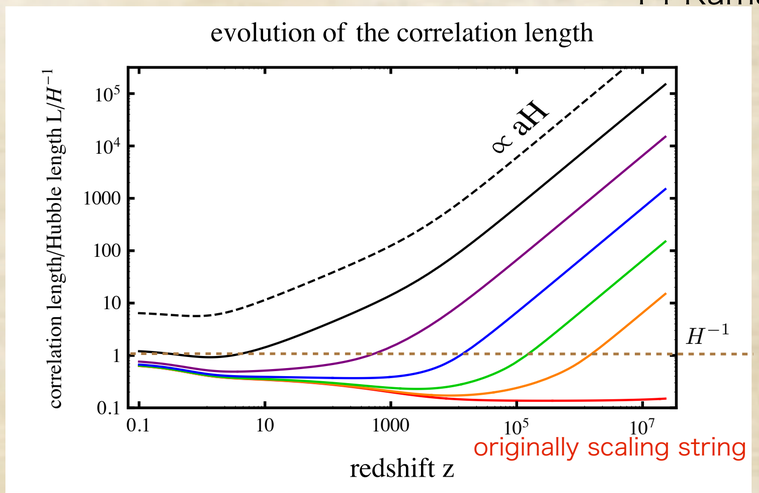
After inflation at relatively later time, they enter subhorizon scales,
to form the string network.



'14 Kamada+



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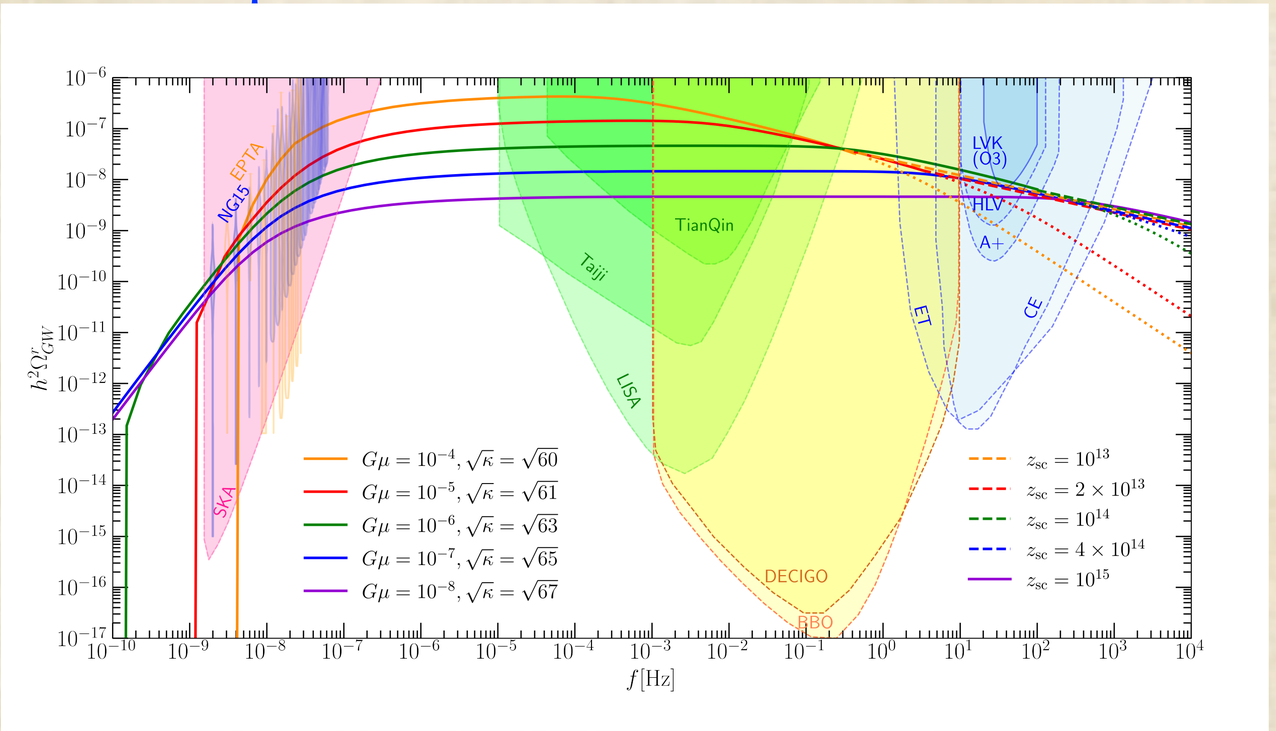
Representative SGWB spectrum



PTA and LVK can be consistently explained by cosmic strings with

$$G\mu \sim 10^{-5\sim7}, \quad \sqrt{\kappa} \sim 8, \quad z_{\rm sc} < 10^{14}$$

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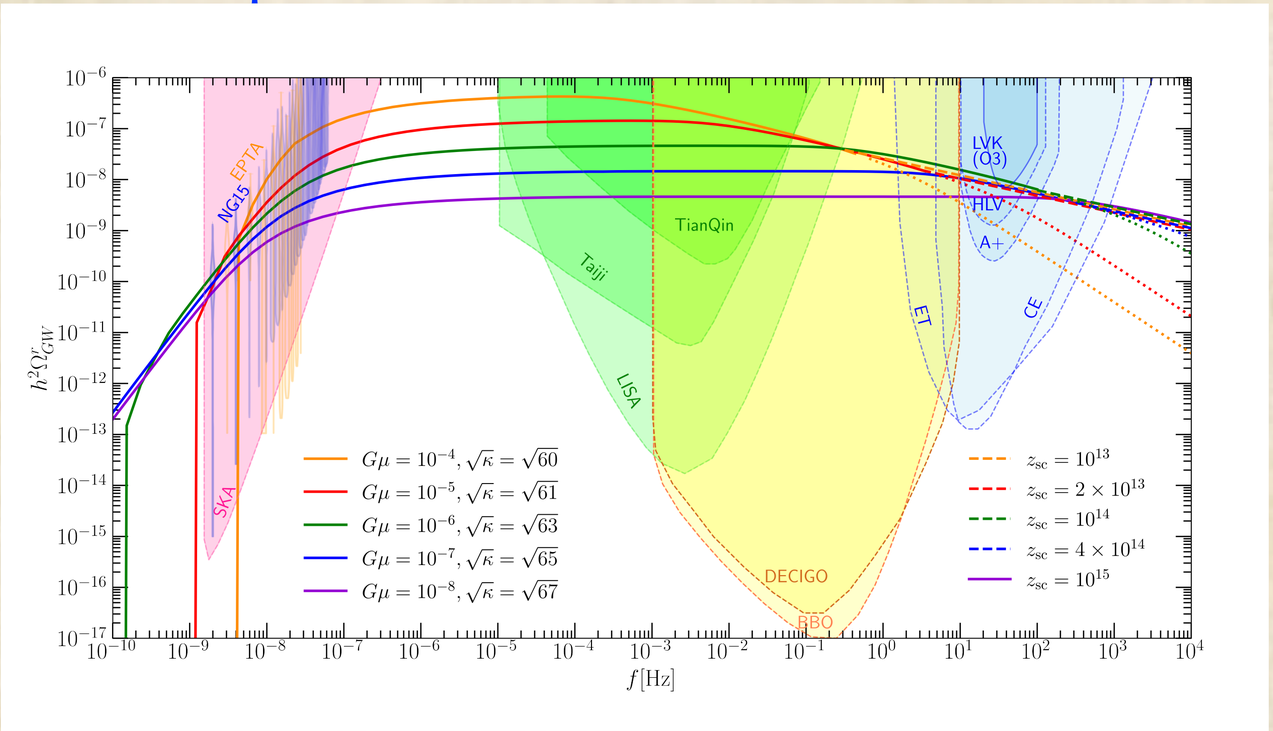

PTA and LVK can be consistently explained by cosmic strings with

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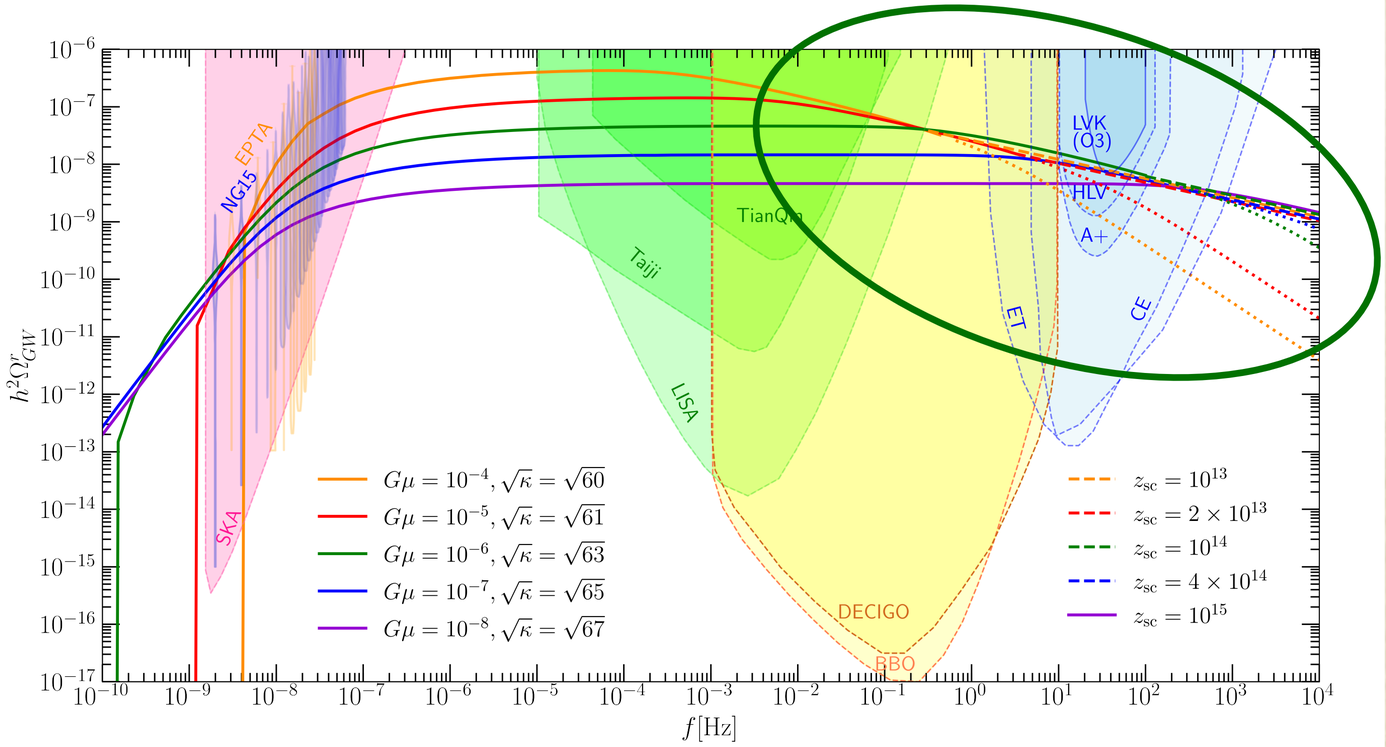
Can be tested at LISA, Taiji, TianQin, DECIGO, and BBO!

Slide Background Courtesy: H. Oide

Some technical issues



We identified that the high frequency tail should be

$$\Omega_{\rm GW} h^2 \propto f^{-1/3}$$

around the LVK scales, with analytical explanation of the numerically calculated SGWB spectrum from cosmic strings.

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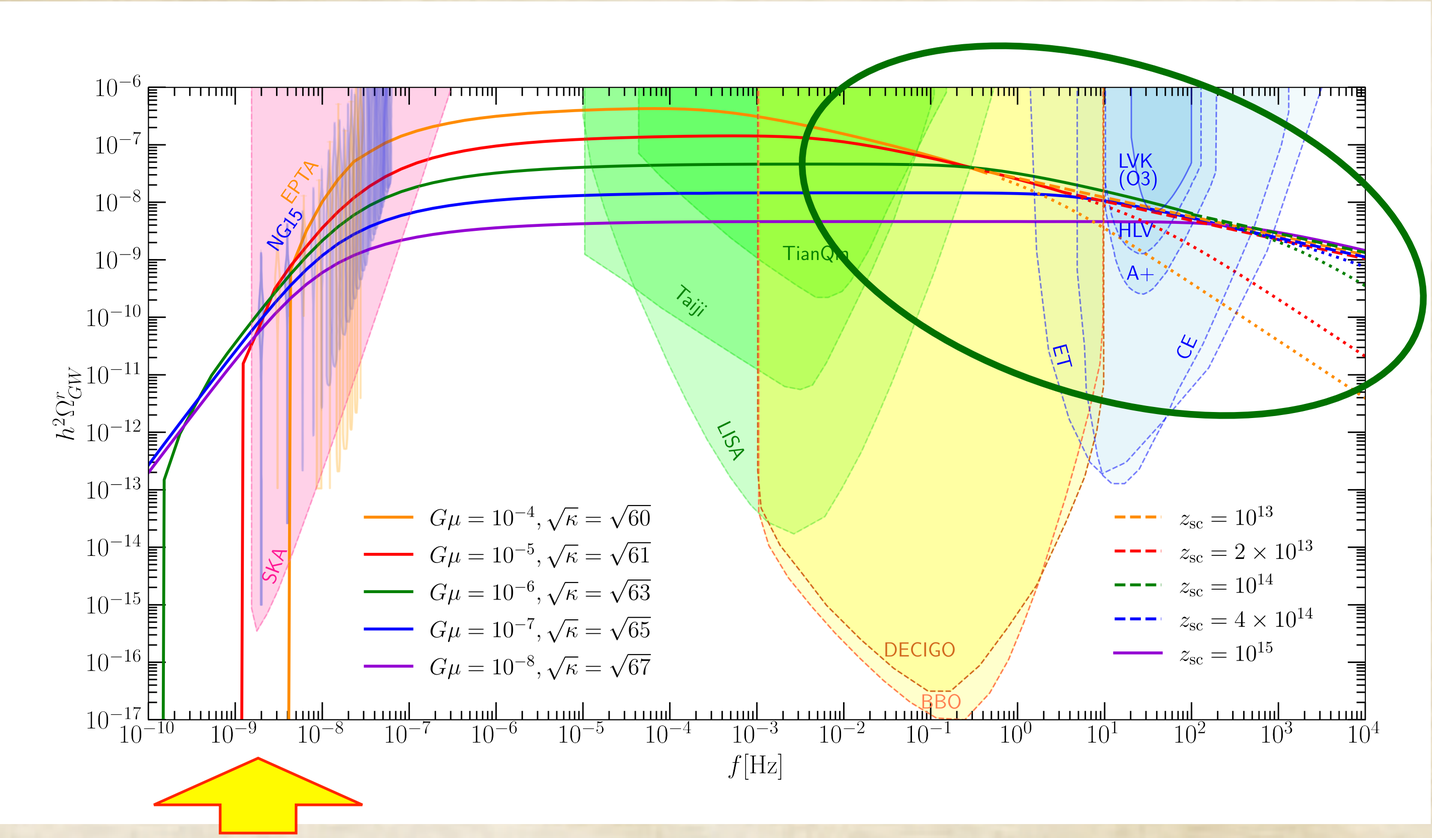

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Low frequency cutoff rules out $G\mu > 10^{-5}$, consistent with statement of NANOGrav collaboration.

Slide Background Courtesy: H. Oide

Summary

- Pulsar Timing Arrays might have discovered the stochastic GWBs, which can be a smoking gun of new physics in the early Universe, if ever.
- One of the most interesting possibilities is cosmic strings.
- If cosmic strings are metastable, PTA measurements can be explained well.
- The problems of too close monopole producing symmetry breaking scenario as well as non-detection of SGTB at LVK can be resolved by adopting the delayed scaling scenario, where the they are formed during inflation.
- Good target for LISA, Taiji, TianQin, DECIGO and BBO!

Appendix

Gravitational Wave Spectrum

T. Vachaspati and A. Vilenkin ‘85; J. J. Blanco-Pillado and K. D. Olum ‘17

- The power spectrum is

$$\Omega_{\rm gw}(t_0,f)=\frac{1}{\rho_{\rm c}}\frac{{\rm d}\ \rho_{\rm gw}(t_0,f)}{{\rm d}\ \ln f}$$

- The energy density of GW per unit logarithm frequency interval

$$\frac{{\rm d}\rho_{\rm gw}(t_0,f)}{{\rm d}\ln f}=G\mu^2 f\sum_{k=1}^{k_{\rm max}}C_k(t_0,f)p_k$$

Infinity?

- Coefficient $C_k(t_0,f)$ is given by

$$C_k(t_0,f)=\frac{2k}{f^2}\int_0^{z_{\rm sc}}\frac{{\rm d}z'}{H(z')(1+z')^6}n\left(\frac{2k}{(1+z')f},t(z')\right)$$

Redshift when string network reach a scaling regime

String Network Model for Metastable Cosmic String

- The number density of string loops before t_s, '82 Vilenkin, '92 Preskil&Vilenkin, '20, '21, '23 Buchmüller+

$$\mathring{n}^{\rm r}_{<}(l,t) = n^{\rm r}_{\rm stable}(l,t) e^{-\Gamma_d[l(t-l/\alpha)+\Gamma G\mu(t-l/\alpha)^2/2]}. \qquad \Gamma_d = \frac{\mu}{2\pi}\exp[-\pi\kappa]$$

- The number density of string loops after t_s but before $t_{\rm eq}$,

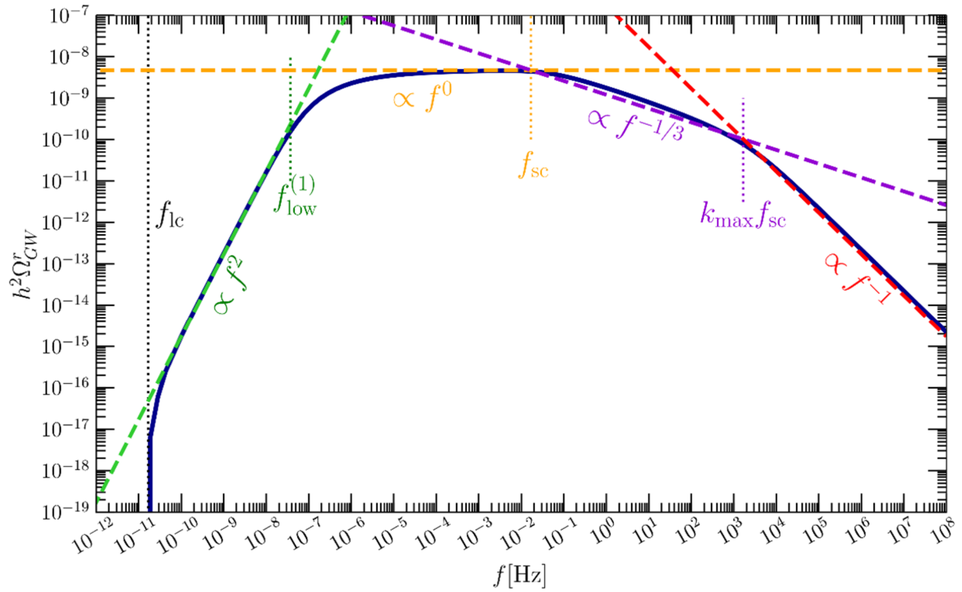
$$\mathring{n}^{\rm r}_{>}(l,t) = \frac{0.18}{t^{3/2}(l+\Gamma G\mu t)^{5/2}} e^{-\Gamma_d[l(t-t_s)+\Gamma G\mu(t-t_s)^2/2]} \Theta\left(\alpha t_s - \bar{l}(t_s;t,l)\right)\Theta(t_{\rm eq}-t).$$

- The number density of string loops created during radiation dominated but survival the matter dominated is

$$\mathring{n}^{\rm rm}_{>}(l,t) = \frac{0.18(2H_0\Omega_{\rm r}^{1/2})^{3/2}}{(l+\Gamma G\mu t)^{5/2}}(1+z(t))^3 e^{-\Gamma_d[l(t-t_s)+\Gamma G\mu(t-t_s)^2/2]} \Theta\left(\alpha t_s - \bar{l}(t_s;t,l)\right)\Theta(t-t_{\rm eq})$$

Slide Background Courtesy: H. Oide

Gravitational Wave Spectrum



- $f < f_{\rm lc}, \Omega_{\rm GW} = 0$
- $f_{\rm lc} < f < f_{\rm low}^{(1)}, \Omega_{\rm GW} \propto f^2$
- $f_{\rm low}^{(1)} < f < f_{\rm sc}, \Omega_{\rm GW} = \text{Constant}$
- $f_{\rm sc} < f < k_{\rm max} f_{\rm sc}, \Omega_{\rm GW} = f^{-1/3}$
- $f > k_{\rm max} f_{\rm sc}, \Omega_{\rm GW} = f^{-1}$

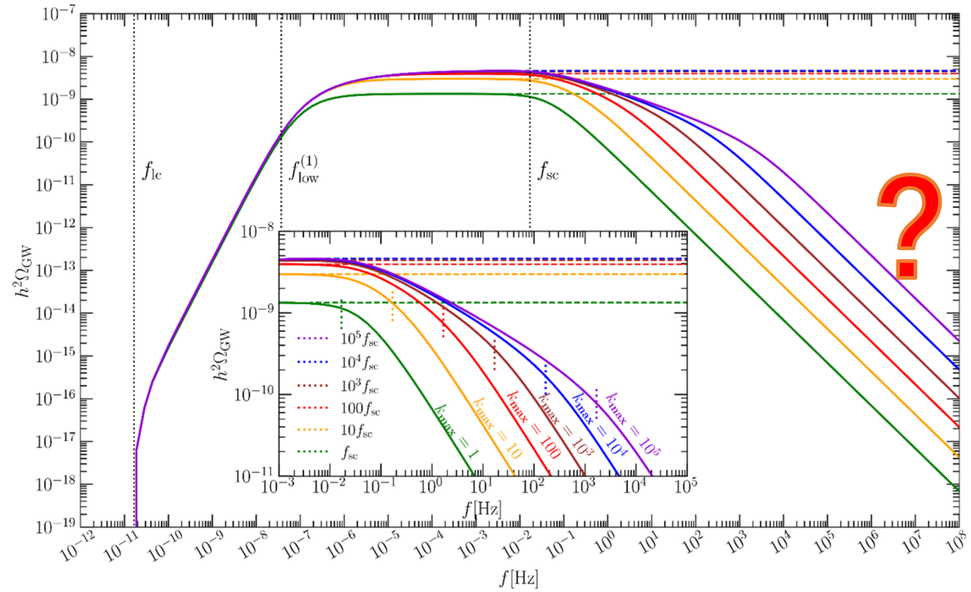
$$f_{\rm lc} = \frac{4(1+z_s)}{\alpha} H_r$$

$$f_{\rm low}^{(k)} \equiv 4 z_s k H_r \left(\frac{\Gamma G \mu}{2}\right)^{-3/4}$$

$$k f_{\rm sc} = f_{\rm high}^{(k)} = \frac{4 k H_r}{\Gamma G \mu} z_{\rm sc}$$

Slide Background Courtesy: H. Oide

Restriction for High Frequency Tail



- At physical time t, the loop length should be longer than wavelength of GW it emits and both of them are larger than string width

$$l(t) > \lambda_{\rm GW} > \delta$$

- The maximum value of harmoinc mode number is given by

$$k_{\rm max} = \frac{l(t)}{2\delta}$$

- The loop length is

$$l(t) = l' - \Gamma G\mu(t - t').$$

- The string width is

$$\delta \sim (\mu/2\pi)^{-1/2}$$

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