# Searching for Cosmic Strings using data from the third LIGO-Virgo observing run

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# A brief introduction to Cosmic Strings

1. Cosmic strings are one-dimensional (line-like) objects, that could be left over after the early Universe went through a phase transition.

2. Such phase transitions may have occurred at grand unification, corresponding to an energy scale of about $10^{16}$ GeV.

3. Loops can shrink and finally decay due to gravitational wave emission.

4. Cosmic strings can produce both burst signal and stochastic gravitational wave background signal.

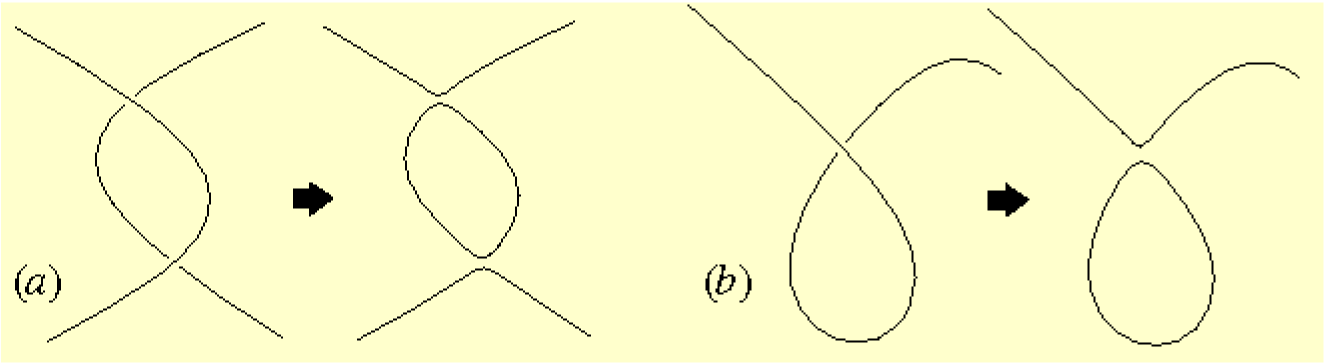


Fig.1 Cosmic string closed loops formation.

# Gravitational waves from cosmic string loops

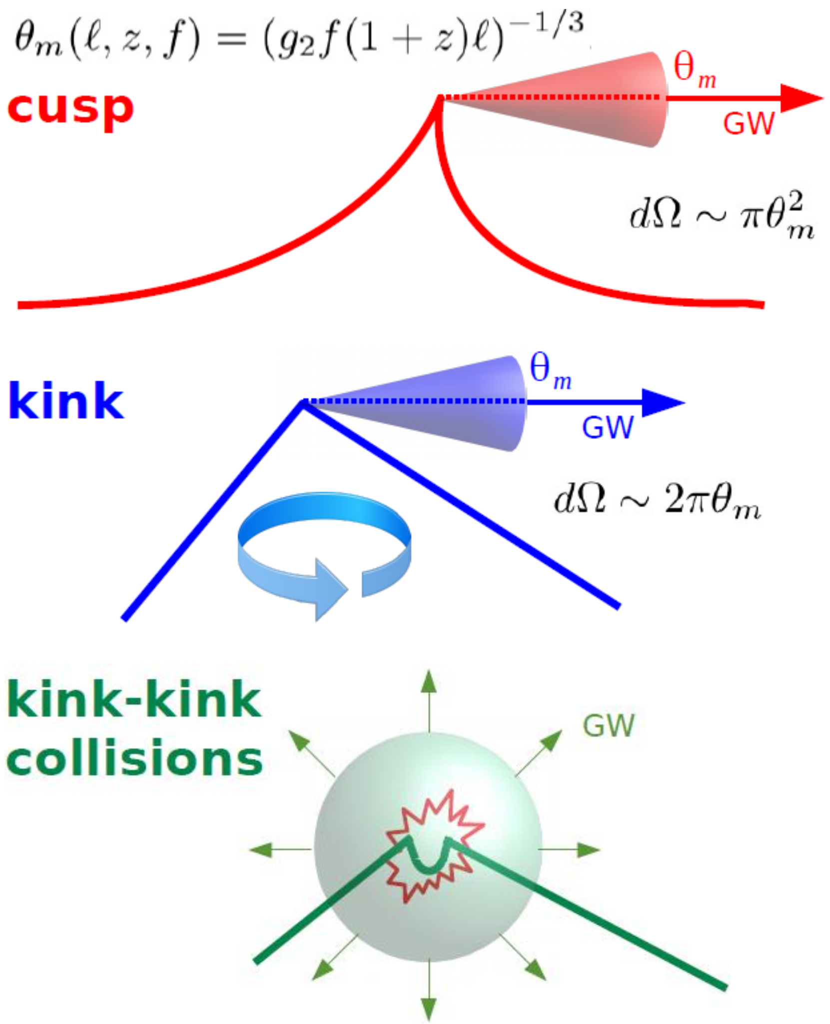



Fig. 2 Three types of gravitational wave burst signals from cosmic string loops. (Credits to Florent Robinet)

The power-law strain waveform produced by cusp, kink and kink-kink collision:

$$h_i(\ell, z, f) = A_i(\ell, z) f^{-q_i},$$

Source index $i = \{\mathrm{c}, \mathrm{k}, \mathrm{kk}\}$, $q_c = 4/3$, $q_k = 5/3$, $q_{kk} = 2$.

$$A_i(\ell, z) = g_{1,i} \frac{G\mu\ \ell^{2-q_i}}{(1+z)^{q_i-1} r(z)},$$

$G$: Gravitational constant
$\mu$: String linear mass density
$g_1$: O(1) number in the analysis
$r(z)$: Proper distance.

$G\mu$: string tension (dimensionless)

# Gravitational waves from cosmic string loops

$$\Omega_{\rm GW}(f) = \frac{4\pi^2}{3H_0^2} f^3 \sum_i \int {\rm d}z \int {\rm d}\ell \, h_i^2 \times \frac{{\rm d}^2 R_i}{{\rm d}z\,{\rm d}\ell}$$

$\int {\rm d}z$: consider whole history

$\int {\rm d}\ell$: consider all loop sizes

$\frac{{\rm d}^2 R_i}{{\rm d}z\,{\rm d}\ell}$: burst rate

Burst rate per unit loop size and per unit volume:

$$\frac{{\rm d}R_i}{{\rm d}\ell {\rm d}V} = \frac{2}{\ell} N_i \times n(\ell, t) \times \Delta_i \times (1+z)^{-1}$$

$N_i$: number of cusps, kinks or kink-kink collisions per loop oscillation

$n(\ell, t)$: loop distribution function

$\Delta_i$: observation fraction due to beaming angle of burst

1. Loop distribution function (LDF) is model dependent.
2. In our study, we consider two analytic models obtained from Nambu-Goto string simulations (labeled as A, B), plus agnostic Models C to interpolate between Model A and B.

Model **A** (Blanco-Pillado et al., PRD 89, 023512): One physical scale: gravitational decay scale $\gamma_d = \Gamma_{\rm d} G\mu$.
Model **B** (Lorentz et al., JCAP 10 (2010) 003): One additional physical scale: gravitational backreaction scale $\gamma_c$. ($\gamma_c < \gamma_d$)
Model **C** (Auclair et al., JCAP 06 (2019) 015): 2 variants: C-1 (respectively C-2) reproduces LDF of Model A (resp. B) in the radiation era and LDF of Model B (resp. A) in the matter era.

# Free parameter: Number of kink $N_k$

1. In previous O1 study, $N_c = N_\mathrm{k} = 1$ per loop oscillation.
2. It is the first time to consider the effect of varying $N_k$ on GW spectra from cosmic strings.
3. For $N_k \gg 1$, the kink-kink collision contribution becomes dominant, since $N_{kk} = \frac{N_k^2}{4}$
4. Decay rate of cosmic string loops due to GW emission has a new contribution:

$$\Gamma_\mathrm{d} \equiv \frac{P_\mathrm{gw}}{G\mu^2} = \sum_i \frac{P_{\mathrm{gw},i}}{G\mu^2}$$

$$= N_\mathrm{c} \frac{3\pi^2 g_{1,\mathrm{c}}^2}{(2\delta)^{1/3} g_2^{2/3}} + N_\mathrm{k} \frac{3\pi^2 g_{1,\mathrm{k}}^2}{(2\delta)^{2/3} g_2^{1/3}} + N_\mathrm{kk} 2\pi^2 g_{1,\mathrm{kk}}^2$$

New contribution from kink-kink collisions

contribution from cusps

contribution from kinks

# Gravitational wave power spectrum

Dominant contribution
from kink-kink collisions.

$N_c = 1$

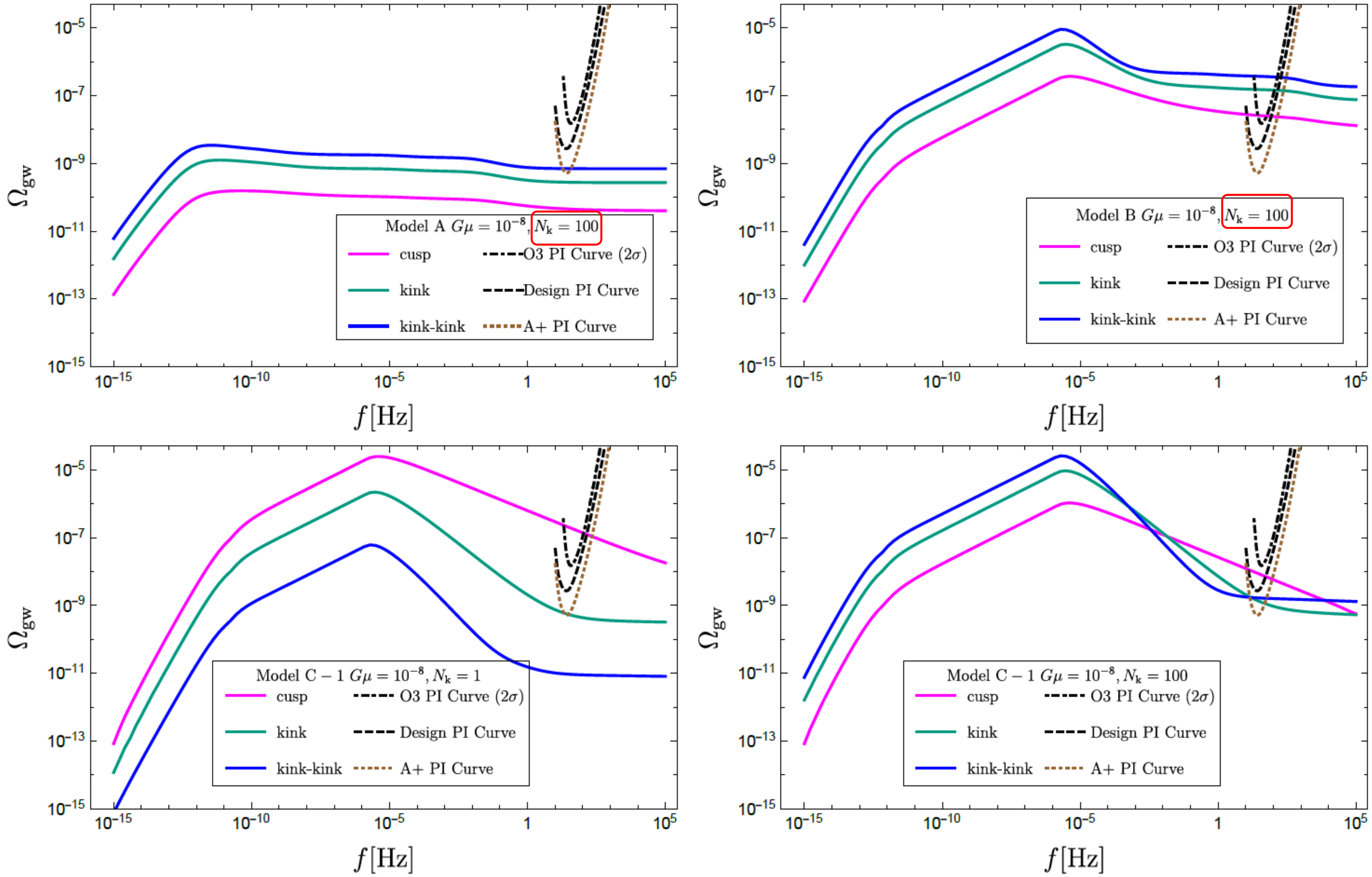



Fig. 3 Gravitational wave power spectra of Model A, B and C-1.

# Burst Search

The ten loudest events were carefully scrutinized. They all originate from a well-known category of transient noise.

1. Cosmic string burst signals in LIGO and Virgo data are searched using match-filtering techniques.
2. The background is estimated by time-shifting strain data $h(t)$ for each GW detector such that no real GW event can be found in coincidence.

⇒ No detection in O3 data

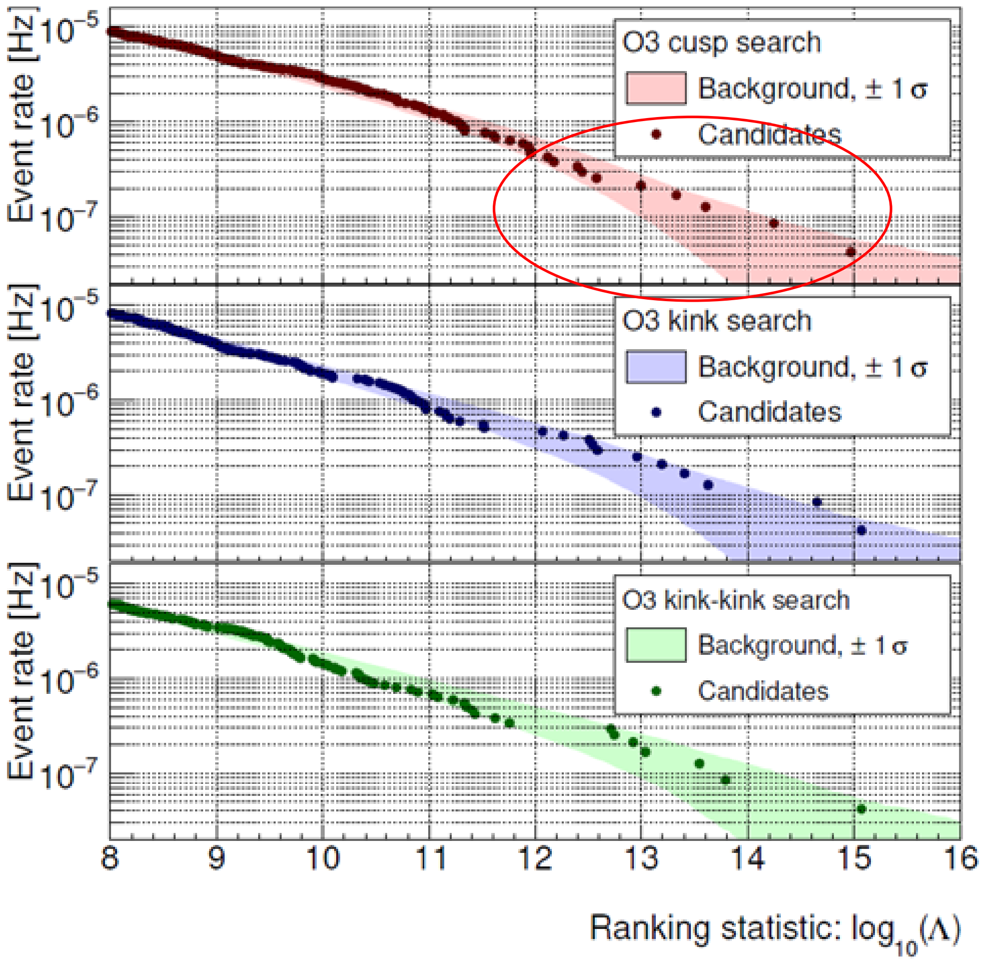



Fig. 4 The cumulative distribution of coincident O3 burst events as a function of the likelihood ratio Λ

# Burst Search

1. Obtain the sensitivities of the search to the three types of burst signals, by digitally adding simulated GW waveforms into time-shifted data.
2. The fraction of signals that were detected is obtained as a function of the amplitude $\epsilon_i(A_i)$.
3. The event rate as a function of $G\mu$ and $N_k$

$$R_i = \int \frac{\mathrm{d}R_i}{\mathrm{d}A_i}(A_i, f_*; G\mu, N_k)\varepsilon_i(A_i)\ \mathrm{d}A_i$$

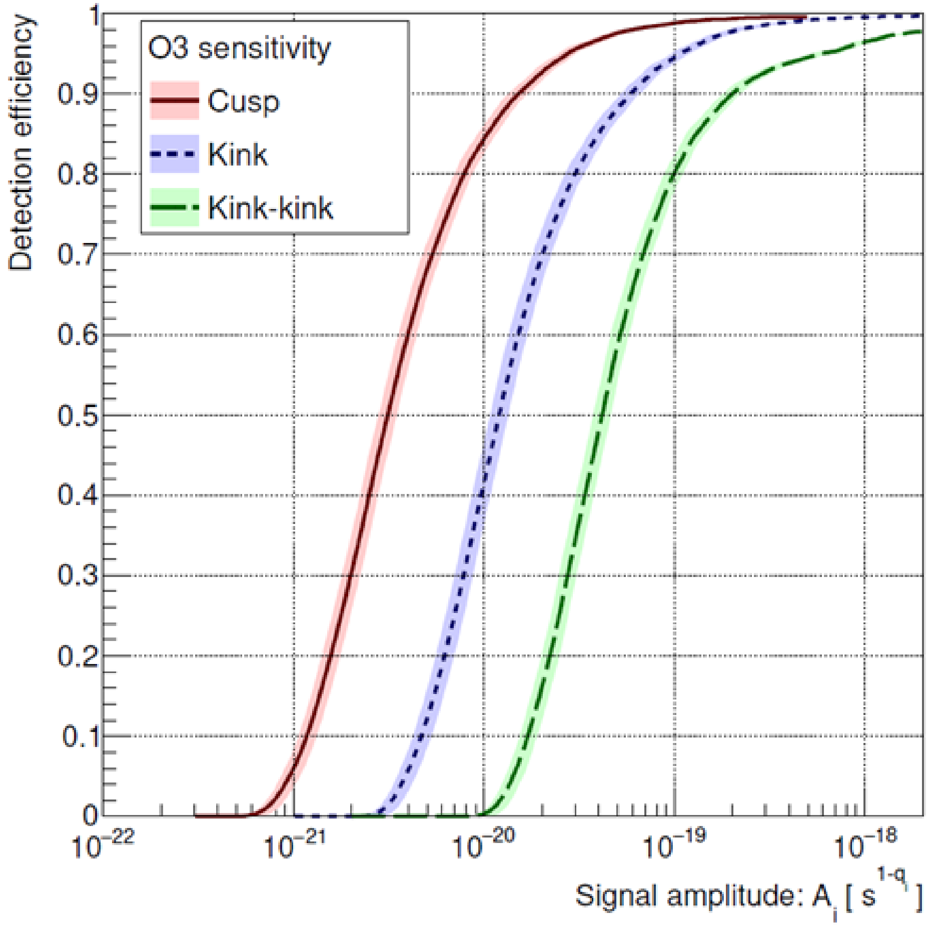



Fig. 5 The resulting efficiencies $\epsilon_i(A_i)$ as a function of the signal amplitude.

# Stochastic Search

$$\ln \mathcal{L}(\hat{C}_a^{IJ}|G\mu, N_k) = -\frac{1}{2}\sum_{IJ,a}\frac{(\hat{C}_a^{IJ} - \Omega_{\mathrm{GW}}^{(M)}(f_a; G\mu, N_k))^2}{\sigma_{IJ}^2(f_a)}$$

$I, J$: detector pair index

cross correlation estimator from two GW detectors

variance

1. Bayesian search using O1+O2+O3 observing run isotropic SGWB search.
2. The posterior for the string tension $G\mu$ is calculated according to Bayes' theorem with priors:
$G\mu$: $(10^{-18}, 10^{-6})$ uniform prior on the logarithmic scale,
$N_k$: (1, 200), $\delta$-function for each value.
3. 95% credible intervals for $G\mu$ given each $N_k$ is obtained:

$$\frac{1}{N}\int_{p\geqslant p_0} p(G\mu|N_k)\, d\ln G\mu = 0.95$$

posterior

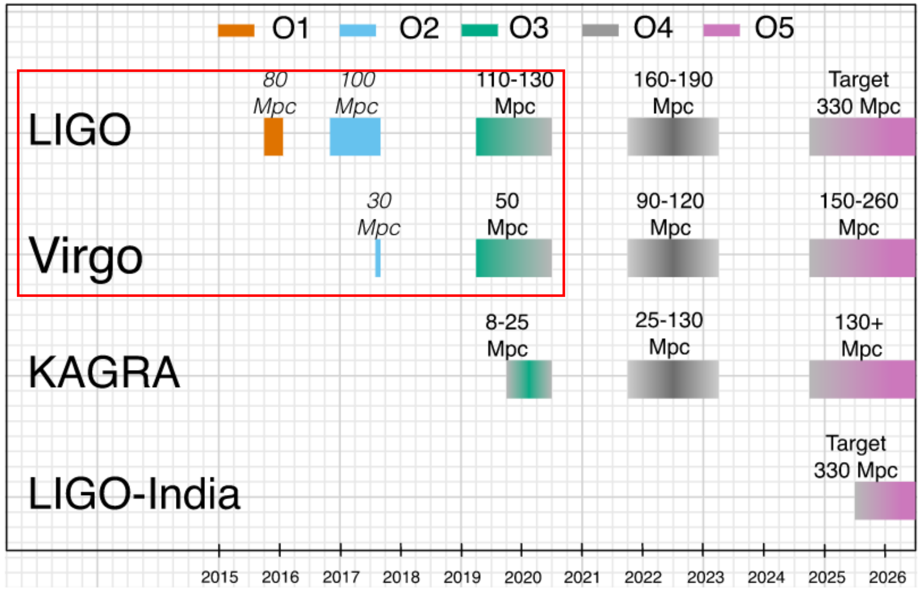
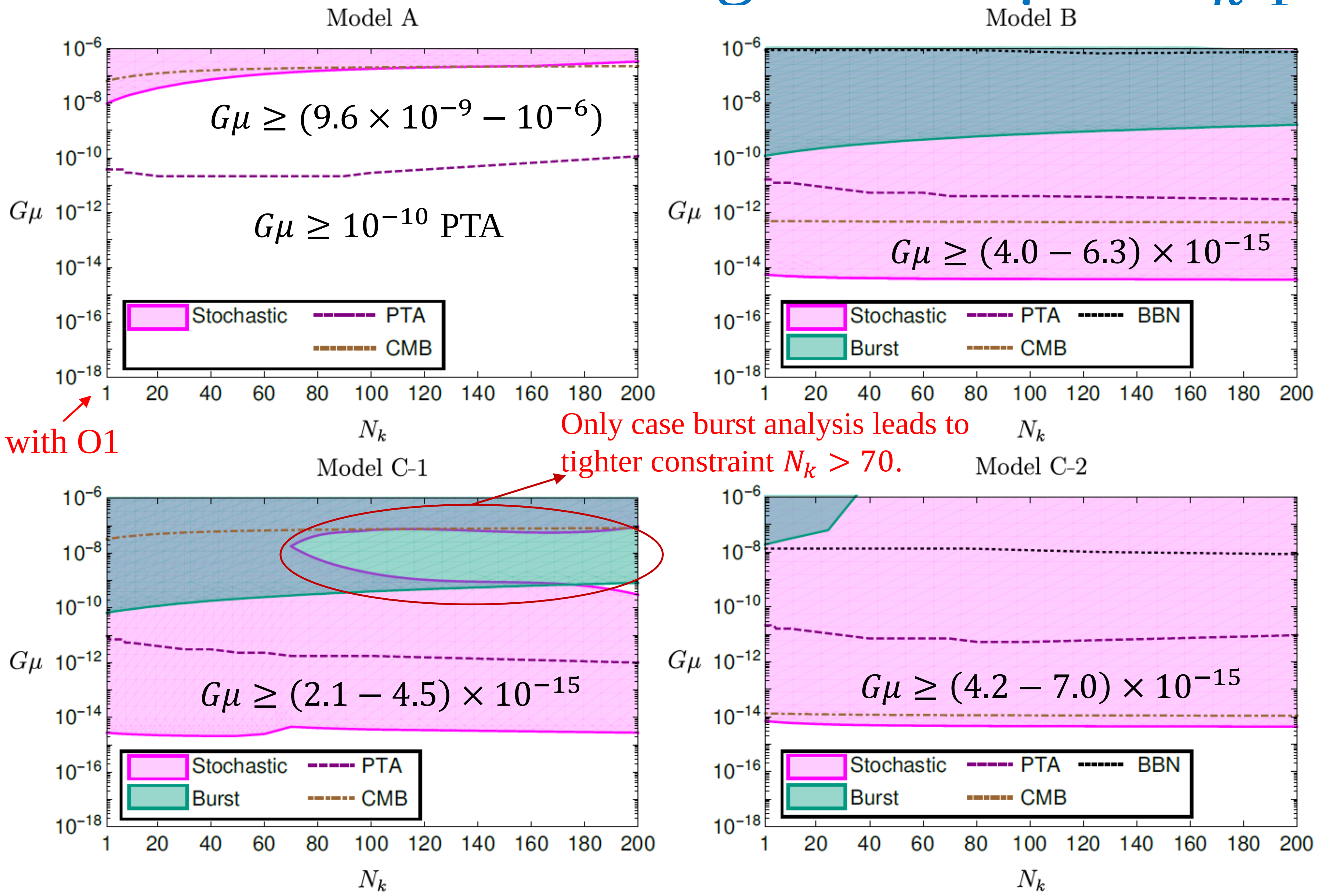



Fig. 6 Timeline of O1, O2 and O3 observing run

# 95% credible exclusion region on $G\mu - N_k$ plane

$N_c = 1$




Can compare with O1 results.

Fig. 7 Combining the constraints from burst search and stochastic search for four loop distributions

# Conclusion

1. LVK have performed a burst and a stochastic gravitational wave background search to constrain the tension of Nambu-Goto strings, as a function of the number of kinks per oscillation, for four loop distributions.
2. The current constraints on $G\mu$ are stronger by two and one orders of magnitude for models A and B respectively, when fixing $N_k = 1$. The agnostic models, labelled as C, are also studied to interpolate between models A and B.
3. For the first time, LVK have studied the effect of kink-kink interactions, which is relevant for large numbers of kinks.