# Probing particle physics and cosmology with **cosmic strings** and gravitational waves

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*[1] Constraints on Cosmic Strings Using Data from the Third Advanced LIGO–Virgo Observing Run, by LIGO, Virgo+Kagra collaborations, Phys.Rev.Lett. 126 (2021) 24, 241102,* arXiV: 2101.12248

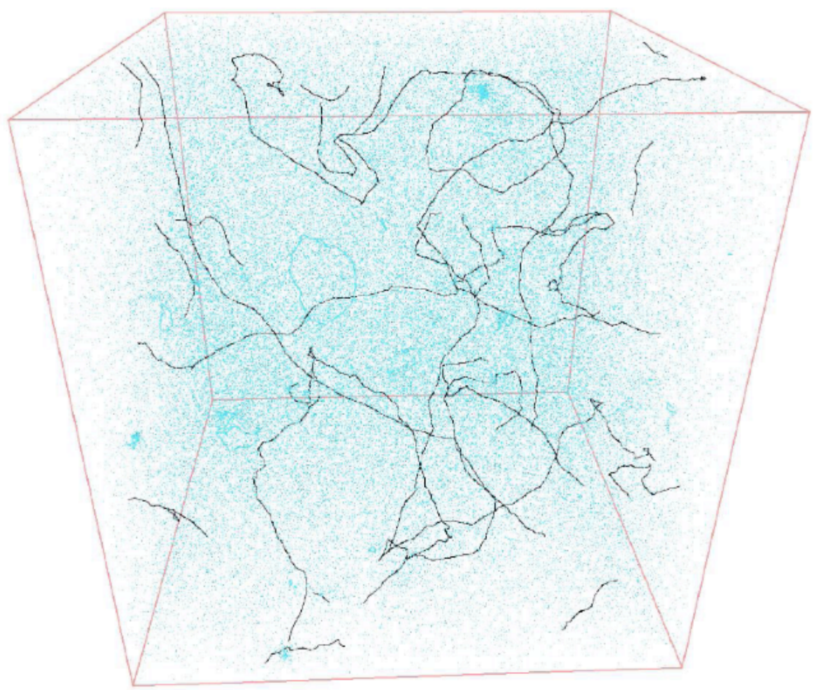
*[2] Probing the gravitational wave background from cosmic strings with LISA, P.Auclair, DAS et al, JCAP 04 (2020) 034,* arXiv: 1909.00819

*Beyond the standard models with cosmic strings, Y.Gouttenoire, G.Servant & P.Simakachorn, arXiv: 1912.02569*

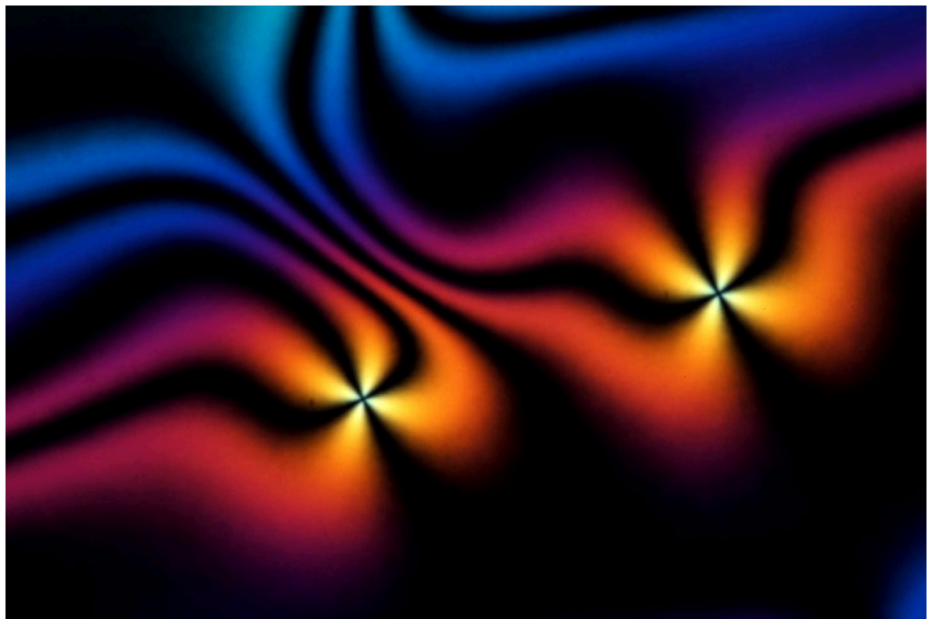
# Overview

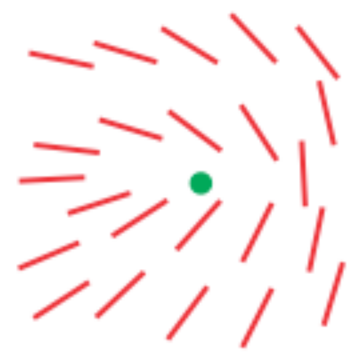
– line-like *topological defects (strings, vortices)* formed in a symmetry breaking phase transitions

– vortex loops in He4, He3, superconductors, strings in NLC.
– cosmic strings in cosmological phase transitions *[Kibble '76]*



Ringeval, Adv.Astron. 2010 (2010),380507





$G = SO(3), H = O(2) \Rightarrow \pi_1(\mathcal{M}) = \mathbf{Z}_2$

– Symmetry group G, unbroken symmetry subgroup H => manifold of degenerate vacua is M=G/H

– Strings form when M contains non-contractible loops, classified by $\Pi_1(G/H) = \Pi_1(\mathcal{M}) \neq 1$.

– Any theory with a spontaneous breaking of a U(1) symmetry has a string solution, since

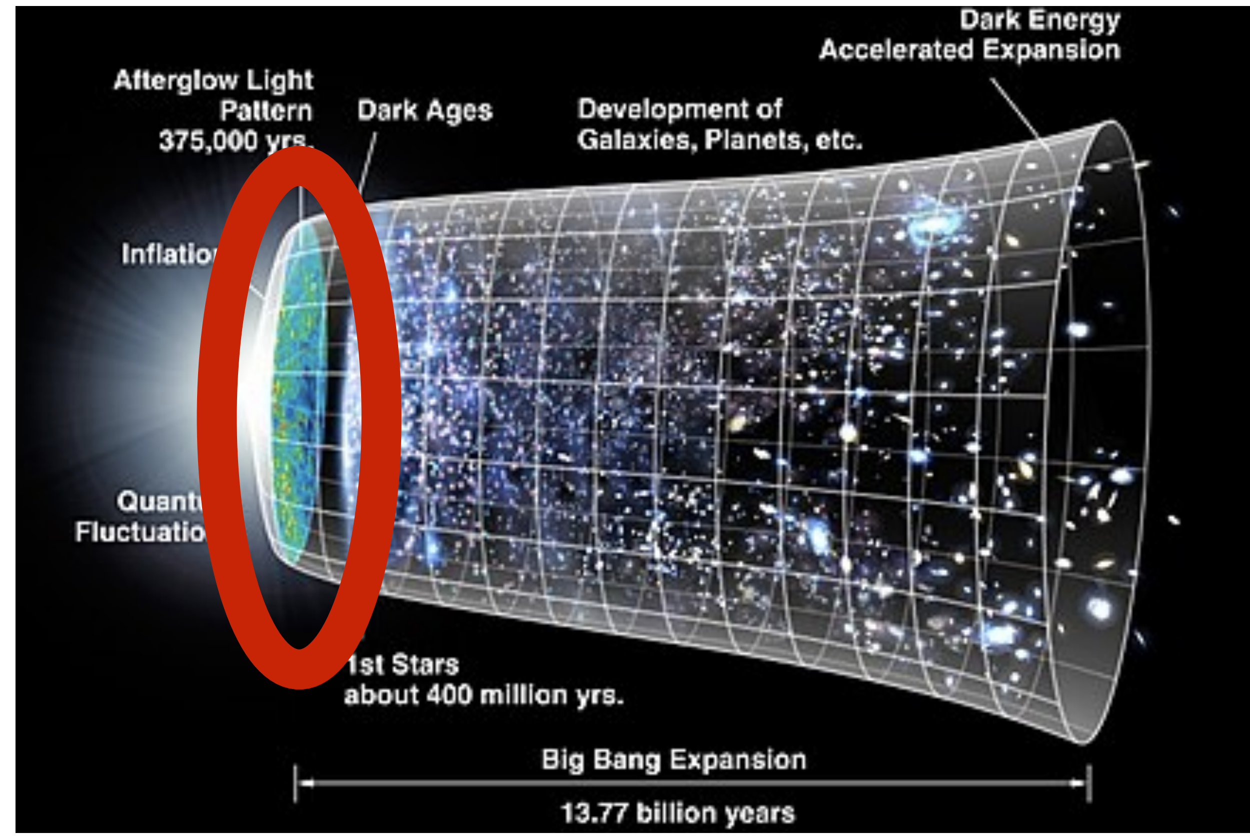
$$G = U(1) \qquad \mathcal{M} = S^1 \qquad \Pi_1(\mathcal{M}) = Z$$

– More complex vacuum manifolds with string solutions appear in various GUT theories.
Strings generically formed at the end of hybrid-like inflation, and in brane inflation (cosmic super-strings)

*[Jeannerot et al 03] [Jones et al, Sarangi and Tye]*

– Due to topological stability, if formed, the strings exist throughout the evolution of the universe (even today!), with multitude of possible observational effects

CMB anisotropies & B-modes;
lensing,
particle emission -> gamma-ray background
sources of dark matter
**Gravitational waves;**

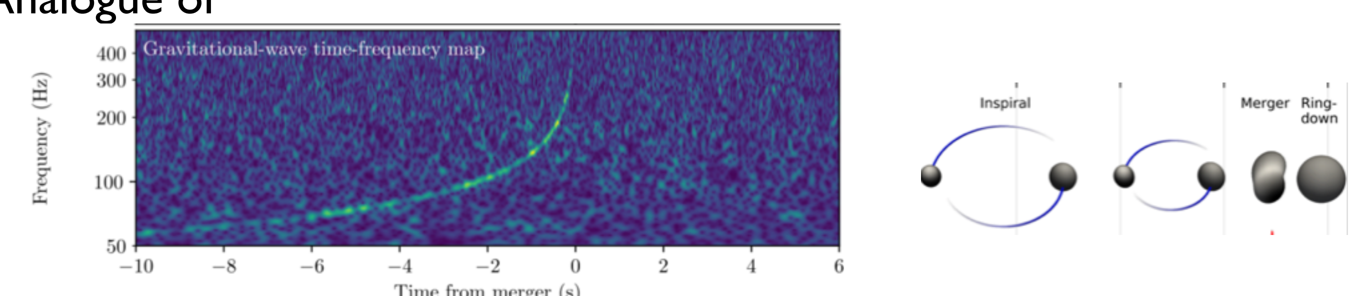



– Two types of signals that can be searched for at different frequencies (LIGO, LISA, PTA,etc):

- Stochastic GW background (superposition of GWs arriving at random times and from random directions, overlapping so much that individual waves not detectable)

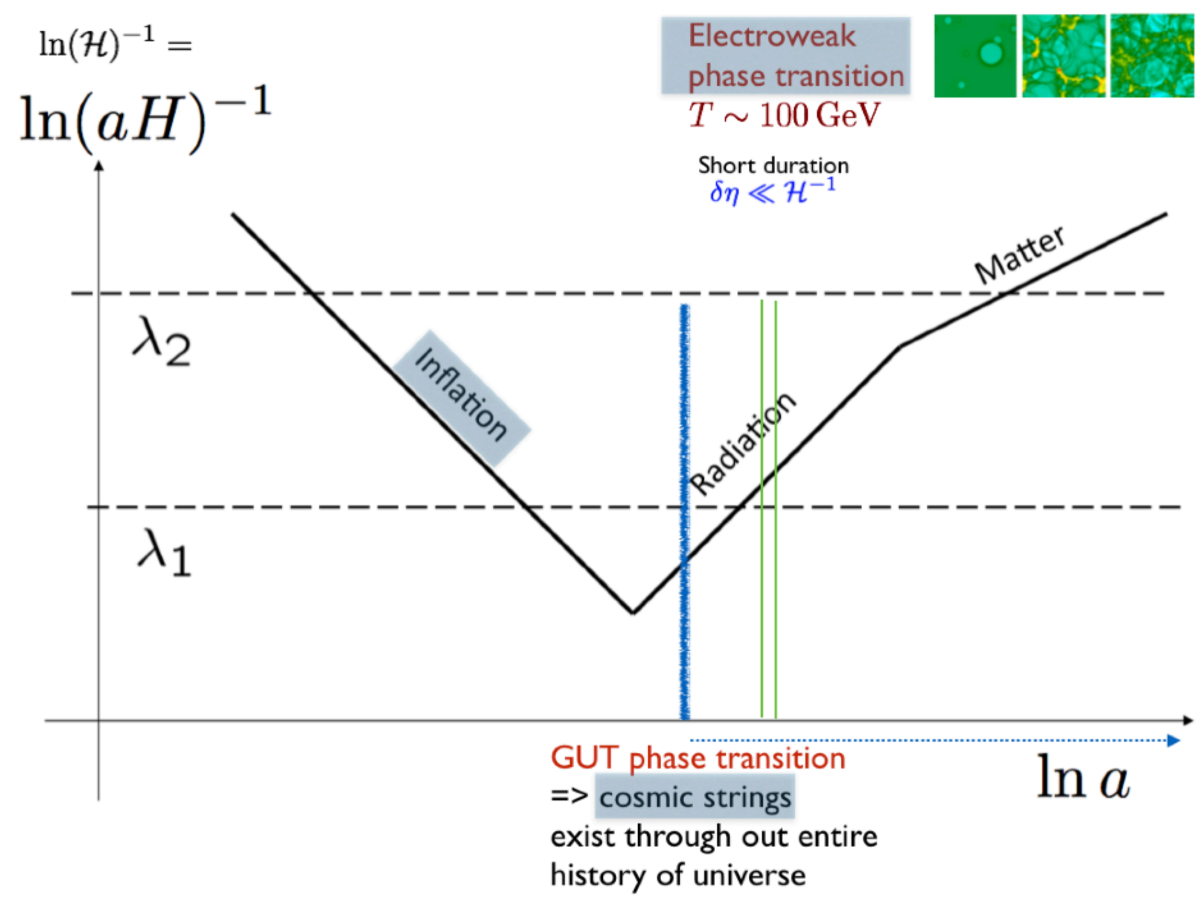
- Occasional sharp Individual bursts (resolved GW signals)

Analogue of



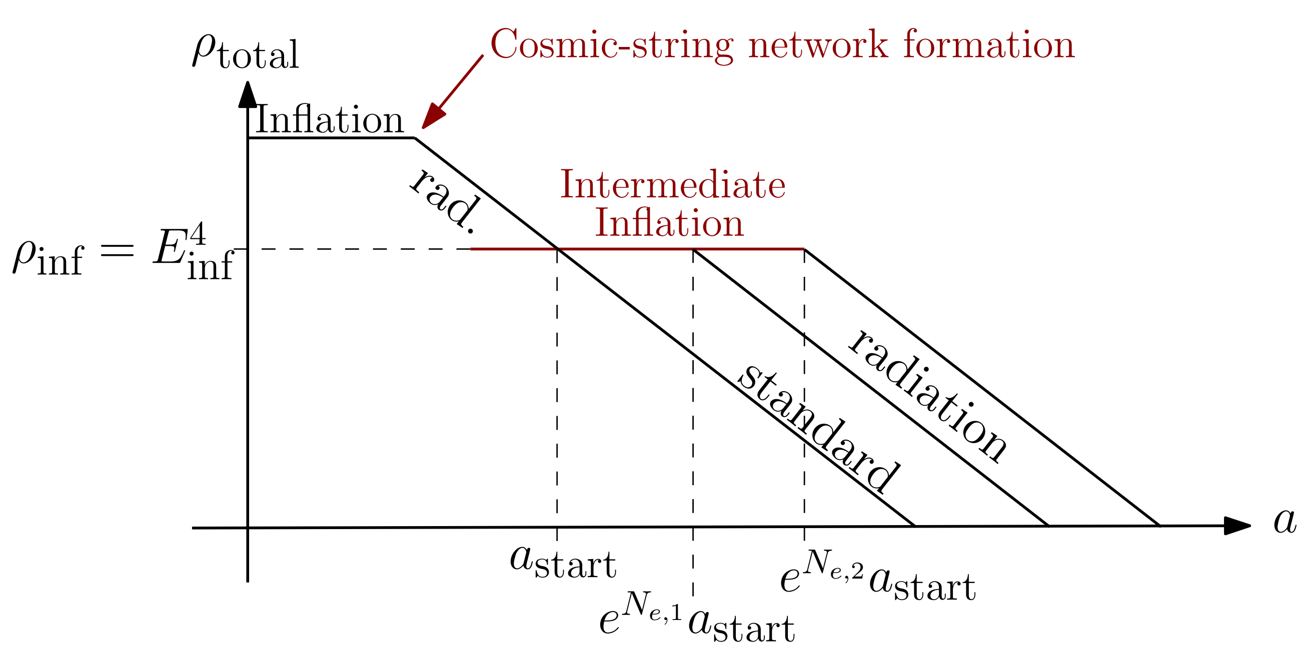

Since gravitons decoupled below Planck scale, cosmic strings can probe physics at these high scales

• Cosmic strings are one of a number interesting sources of primordial cosmological SGWB (indeed major science goals of LIGO-Virgo, LISA and other experiments)




• All observational their consequences depend on the **evolution of the network** from formation to today, and thus
(i) on the properties of the strings,
(ii) the expansion history of the universe.

• SGWB from strings encodes information on possible *deviations from standard cosmological model*




– Extensions to the standard model of particle physics often feature new d of f and new energy scales => impact expansion history in the early universe (essentially unconstrained at T> MeV)

e.g. • stage of early matter domination (induced by a heavy cold particle dominating universe and decaying before BBN)

e.g. • stage of early kination domination

e.g. • short inflationary period generated by highly supercooled phase transition (motivation: invoked to address the Higgs hierarchy problem)

# Plan

1) On string network evolution, burst waveform from loops *[apologies for incomplete citations]*

2) Constraints from LIGO-Virgo O3 run: SGWB and search for individual bursts; predictions for LISA and PTA (all assuming standard cosmology)

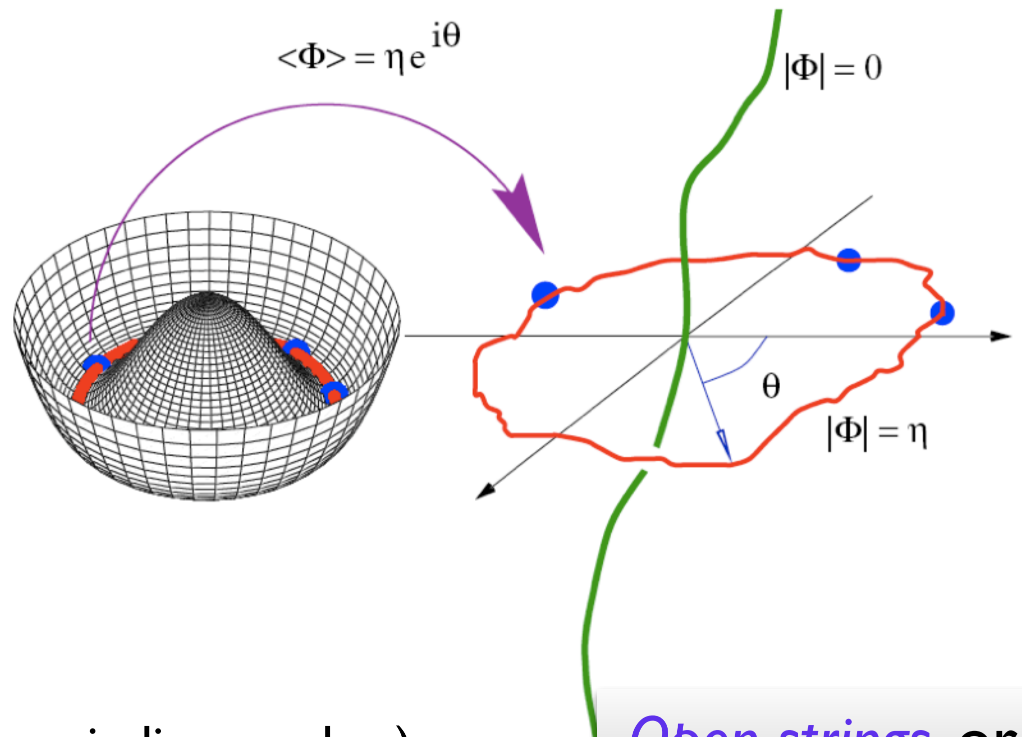
3) Beyond the standard picture: Effects of modified cosmology, emission channels, etc

4) Conclusions

# 1) Vanilla strings

– Abelian Higgs model

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\phi)^* D^\mu\phi - \frac{\lambda}{4}(|\phi|^2 - \eta^2)$$



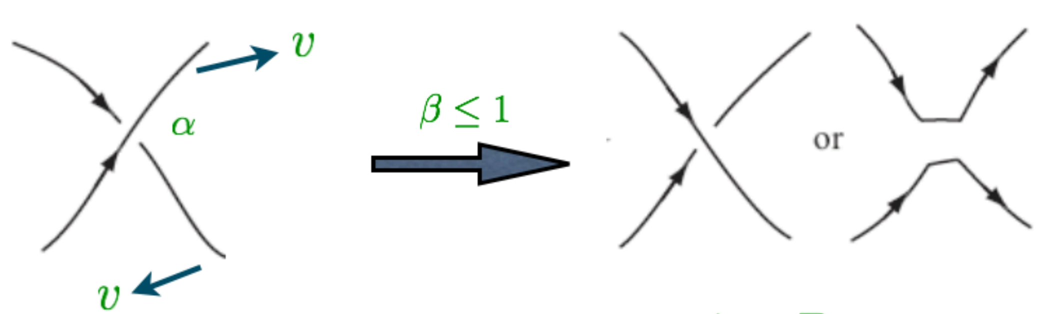

*Open strings*, or *closed loops*

- Degenerate vacuum/ground state with $\langle\phi\rangle = \eta e^{i\theta}$
- U(1) invariance $\phi \to \phi e^{i\theta}$ broken by choice of phase.
- String/vortex is a linear defect around which $\theta$ changes by $2\pi n$ ($n =$ winding number)

• Local strings with no long-range interactions, and energy localized in a core of **width** $w \sim \eta^{-1}$ and **energy/unit length**: $G\mu \sim 10^{-6}\left(\frac{\eta}{10^{16}\text{ GeV}}\right)^2$

e.g. for GUT strings $w \sim 10^{-32}\text{cm}$
$G\mu \sim 10^{-6}$,

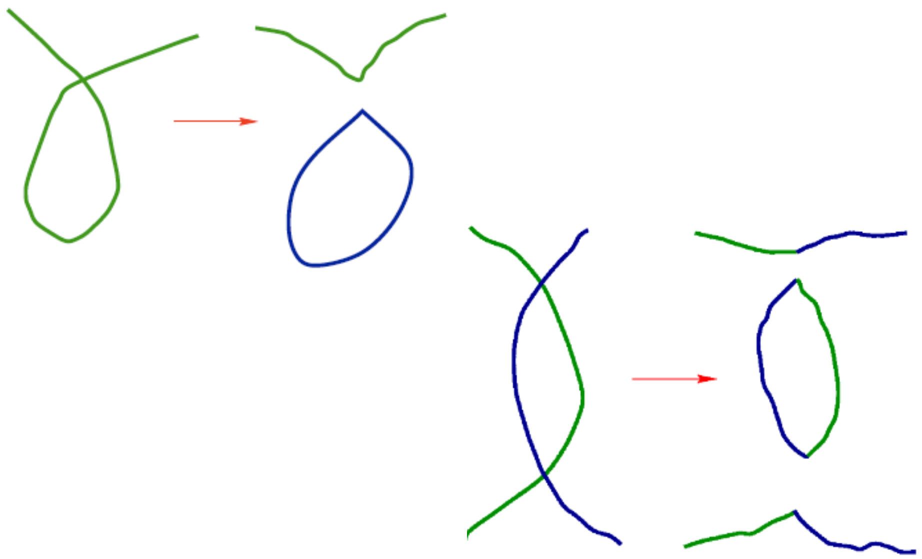
• Field theory simulations of AH strings show that they (nearly always) "intercommute"




prob $1-P$ prob $P$

$P = 1$

[Shellard et al,...]
[Achucarro and de Putter '06]



- Network of strings will contain (horizon-size and smaller) **loops** as well as **infinite strings**.

- number density of loops of length l at time t, $n(\ell, t)$

[Hindmarsh et al]

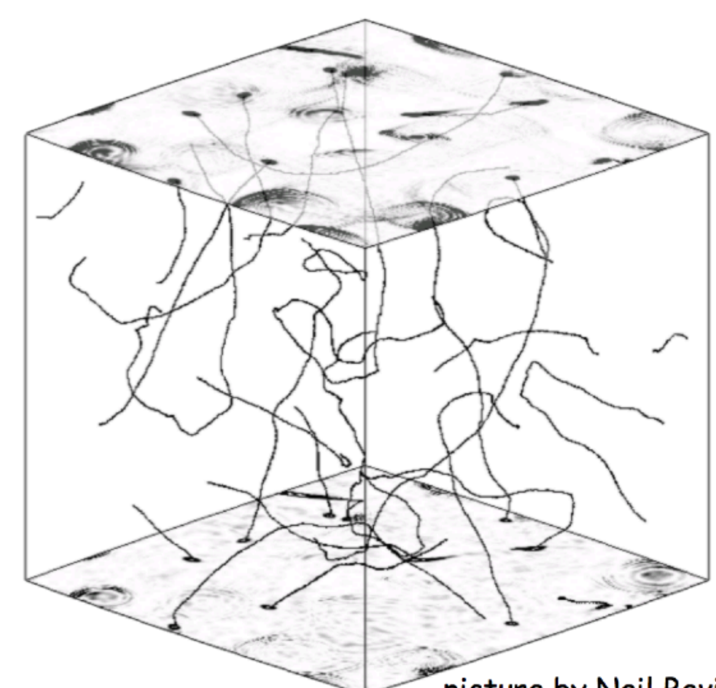
Large scale field theory simulations of a network of U(1) strings in an expanding universe show that
- loops are formed at all times, removing energy from the infinite string network.
- loops decay (in less than a Hubble time) into scalar and gauge radiation.
- Infinite strings reach an attractor "scaling solution" $\rho_\infty \propto t^{-2}$ (contrary to naive expectation $\rho_\infty \propto a^{-2}$ )

=> infinite string network has same equation of state as the main background cosmological fluid $\dfrac{\rho_\infty}{\rho_{\rm bkg}} \sim \dfrac{a^p}{t^2} \sim \text{const}$ $\qquad \rho_{\rm bkg} \sim a^{-p}, \; a = t^{2/p}$

Tricky simulations $w \sim 10^{-32}\text{cm} \ll H_0^{-1}$

High resolution field theory simulations of loops show loops longer lived

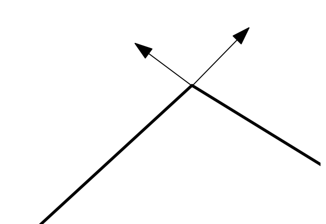
[Vachaspati et al, Martins et al]



picture by Neil Bevis

- All results presented here assume that strings can be modeled as infinitely thin

(+ rule of intercommutation —> build up of *kinks* on both loops and infinite strings)



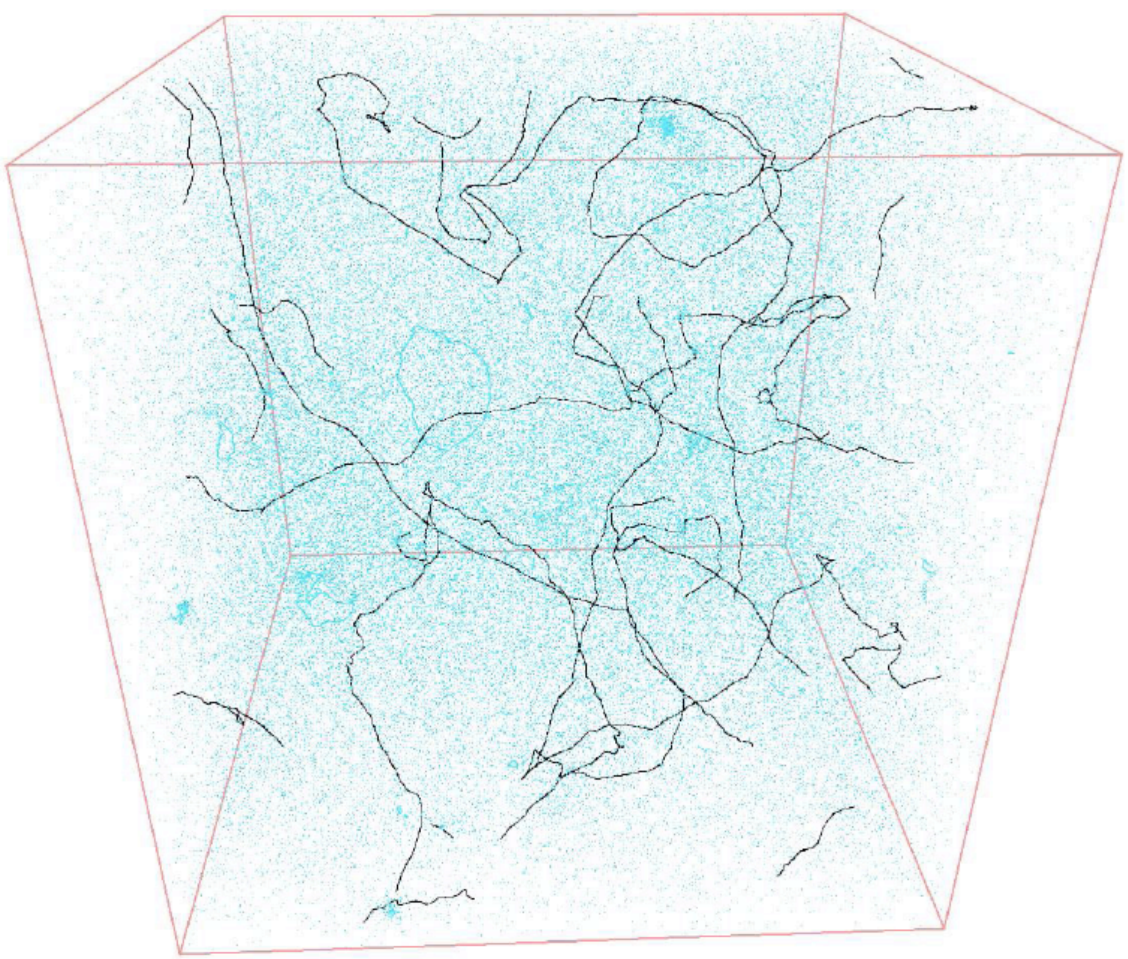
• Infinitely thin strings and assuming no d of f confined on string worldsheet, dynamics given by Nambu-Goto action

$$S_{NG} = -\mu \int d\sigma d\tau \sqrt{-\gamma}$$

$$\gamma_{ab} = \partial_a x^\mu \partial_b x^\nu g_{\mu\nu}(x^\alpha(\sigma,\tau))$$

String position $x^\mu(\sigma,\tau)$

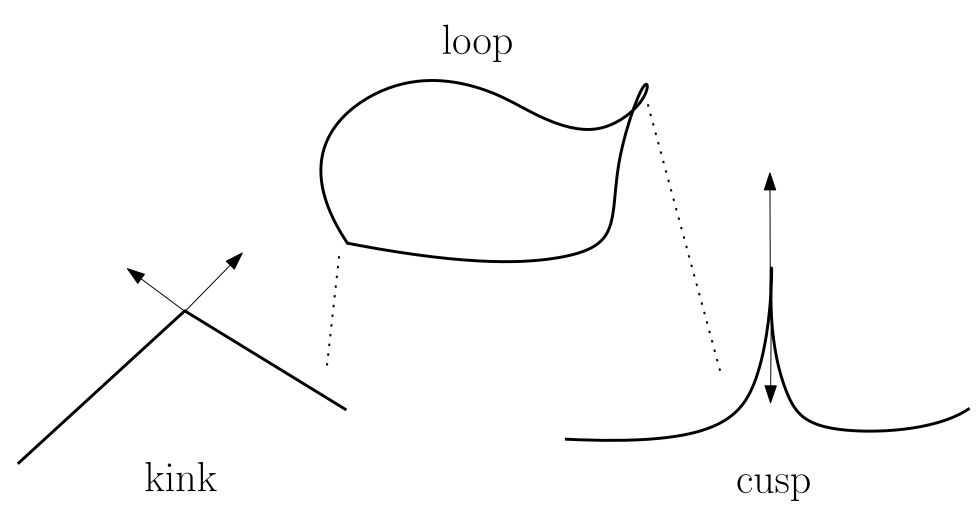
Minimise area swept out by worldsheet. Expect to break down when curvature ~ w



*Ringeval, Adv.Astron. 2010 (2010),380507*

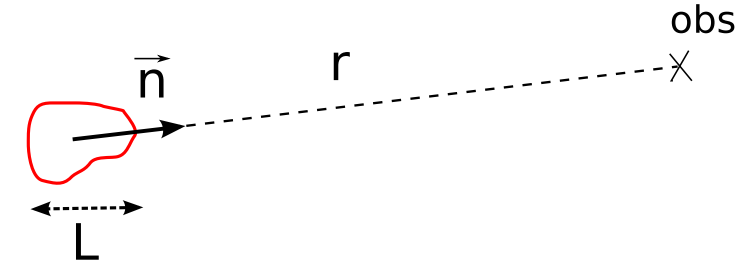
– Loops produced (from intercommutations) generally self-intersect before forming stable “daughter” loops.

– These evolve periodically in its CM frame, period $\ell/2$
*kinks* propagate along the string at c=1,
*cusps* (points at which the string $|\dot{\mathbf{x}}(\sigma_*, t_*)| = 1$)



– From stress energy tensor, using linearized theory, in wavezone $r \gg L\ ,\ r \gg L^2\omega \quad r \gg 1/\omega$

$$h_{ij}^{(TT)}(\mathbf{x},\omega) = \frac{4G}{r} e^{i\omega r} T_{ij}^{(TT)}(\omega\mathbf{n},\omega)$$




=>waveform of emitted GWs

(frequencies integer multiples of fundamental frequency $4\pi/\ell$ )

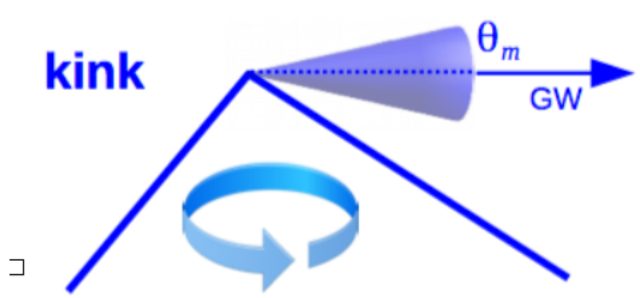
=>power emitted in GWs

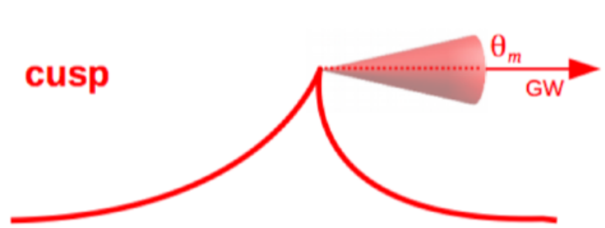
$$\dot{\ell} = -\Gamma G\mu$$

$$\Gamma = \sum_{n=1}^{\infty} P_n$$ independent of $\ell$ , but will depend on shape of the loop,

*[Vachaspati, Blanco-Pillado et al….]*

• power emitted decays exponentially with $f$ for $f\ell \gg 1$ , *except* at cusps and kinks and kink-kink collisions, which emit short bursts of radiation in certain special directions



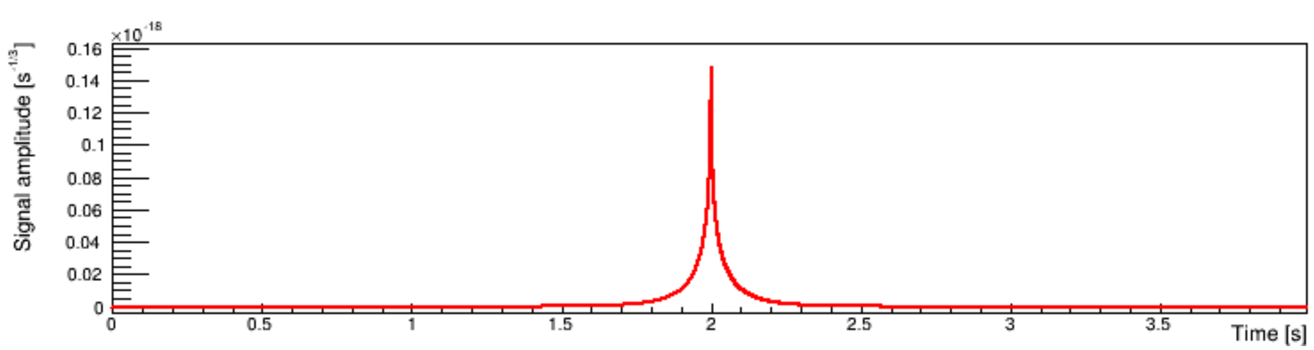

| | | |
|---|---|---|
| GW-form | | $h_i(\ell,z,f) = A_i(\ell,z) f^{-q_i}$ |
| Amplitude | | $A_i(\ell,z) = g_{1,i}\dfrac{G\mu\ell^{2-q_i}}{(1+z)^{q_i-1}r(z)}$ |

$i = \{c,k,kk\} \qquad q_c = 4/3, \quad q_k = 5/3 \quad q_{kk} = 2$

$\theta_m(\ell,z,f) = (g_2 f(1+z)\ell)^{-1/3}$

$\theta_m < 1$

*[Damour+Vilenkin; Siemens et al]*

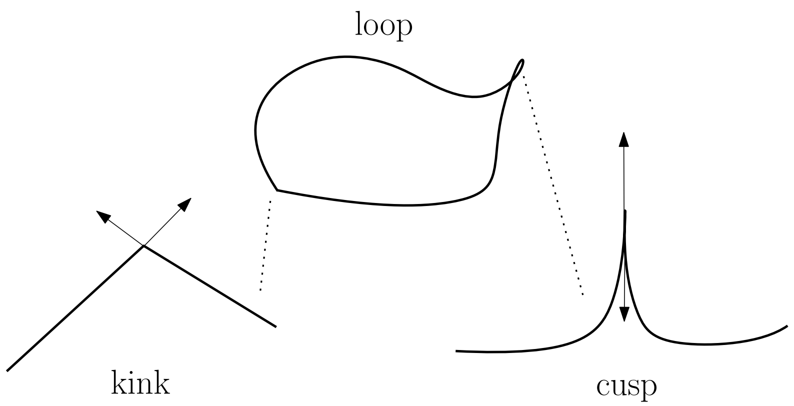



Predicted gravitational waveform produced by a cosmic string cusp.

• If an observer/experiment lies in one of those directions: stronger signal.

• To summarize:

$$\dot{\ell} = -\Gamma G\mu \quad \text{with} \quad \Gamma = \sum_{n=1}^{\infty} P_n$$




$$\Gamma \geq \Gamma_c + \Gamma_k + \Gamma_{kk}$$

$$\propto N_c \qquad N_k \qquad N_{kk} \sim N_k^2/4$$

average number of burst events/loop oscillation period $\ell/2$

and $P_{n_i} \propto n^{-q_i}$

$i = \{c, k, kk\} \quad q_c = 4/3, \quad q_k = 5/3 \quad q_{kk} = 2$

**LIGO-Virgo O3 burst search** sets $N_c = 1$
while leaving $N_k$ as free parameter, with $1 \leq N_k \leq 200$ (leading to $\Gamma \lesssim 50$ consistently with simulations)

– Loop lifetime: $\dot{\ell} = -\Gamma G\mu \quad \tau \sim \dfrac{\ell_0}{\Gamma G\mu} \gg H^{-1}$

# Loop distribution $n(\ell, t)$ ?

## Numerical NG simulations

*[Blanco-Pillado+Olum;Ringeval+Bouchet+, Shellard, Vachaspati Vilenkin, Albrecht….]*

NG equations of motion in an expanding universe given a representative initial condition + intercommutation. Radiation and matter era simulations. Limited in time and length scale. No GRad.

## Analytical modelling

*[Kibble, Martins+Shellard, Polchinski et al, Austin&Kibble&Copeland, ....]*

difficult because of non-linearities of problem, but not time limited. Include GR and attempts at gravitational back reaction

• All confirm, as in field-theory simulations, existence of an *attractor* scaling solution $\rho_\infty \propto \mu t^{-2}$ and (large) characteristic scales grow $\propto t$

• Occurs because of incessant formation of loops, characterized by a **loop production function** $\mathcal{P}(\ell, t)$ [Rate at which loops of length l (assumed non-self-intersecting), are chopped off the infinite string network at time t, per unit volume]

• Different numerical simulations find similar loop distributions on large scales

• Strings become very "wiggly" (kinks build up) down to smallest length scales, making it difficult on those scales to understand characteristic size of loops at formation. Furthermore GW emission from kinks may cause important back reaction effects on string dynamics.

Basic picture: Infinite string energy density:

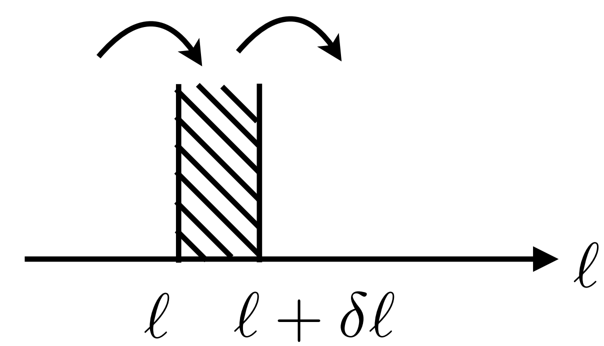
$$\frac{d\rho_\infty}{dt} = -2\frac{\dot{a}}{a}(1+\bar{v}^2)\rho_\infty - \mu \int_0^\infty l\mathcal{P}(l,t)dl\,,$$

Dilution of energy density in an expanding universe (cosmology dependent)

energy lost into non-self-intersecting loops

- Loop distribution obtained by solving a (modified) Boltzmann equation.

$$\left.\frac{\partial}{\partial t}\right|_\ell (a^3 n(t,\ell)) + \left.\frac{\partial}{\partial \ell}\right|_t \left(\frac{\mathrm{d}\ell}{\mathrm{d}t} a^3 n(t,\ell)\right) = a^3\mathcal{P}$$




scale factor (cosmology dependent)

rate at which loops loose energy

$\mathcal{P}(\ell, t)$ = loop production function

for GW emission $\dot{\ell} = -\Gamma G\mu$

including other forms of emission, $\dot{\ell}(\ell)$

# LIGO-Virgo O3 analysis considers three models:

**Model A**: LPF from simulations *[Olum Blanco-Pillado,]*

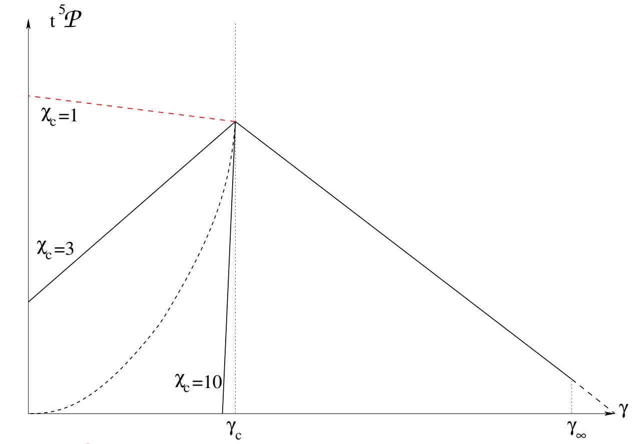
~ loops all formed with similar size at time t $t^5\mathcal{P}(\ell,t) = c\delta(\ell - \alpha t)$

*with parameters given* from simulations

Straightforward to solve the Boltzmann equation. In a given era the loop distribution scales

$$n(\ell,t) = t^{-4}\mathrm{n}(\gamma) \qquad \text{where} \qquad \gamma = \ell/t$$

e.g. in radiation era $$\mathrm{n}_r(x) = \frac{0.18}{(x+\Gamma G\mu)^{5/2}}\Theta(0.1-\gamma)$$




**Model B**: loops formed with a power-law distribution $t^5\mathcal{P}(\ell,t) = C\left(\frac{\ell}{t}\right)^{2\chi-3}\Theta(\alpha t-\ell)\Theta(\ell-\gamma_c t)$

up to a "backreaction scale" $\gamma_c = \ell_c/t \simeq 10(G\mu)^{1+2\chi} \ll \Gamma G\mu$

below which loop production assumed suppressed.

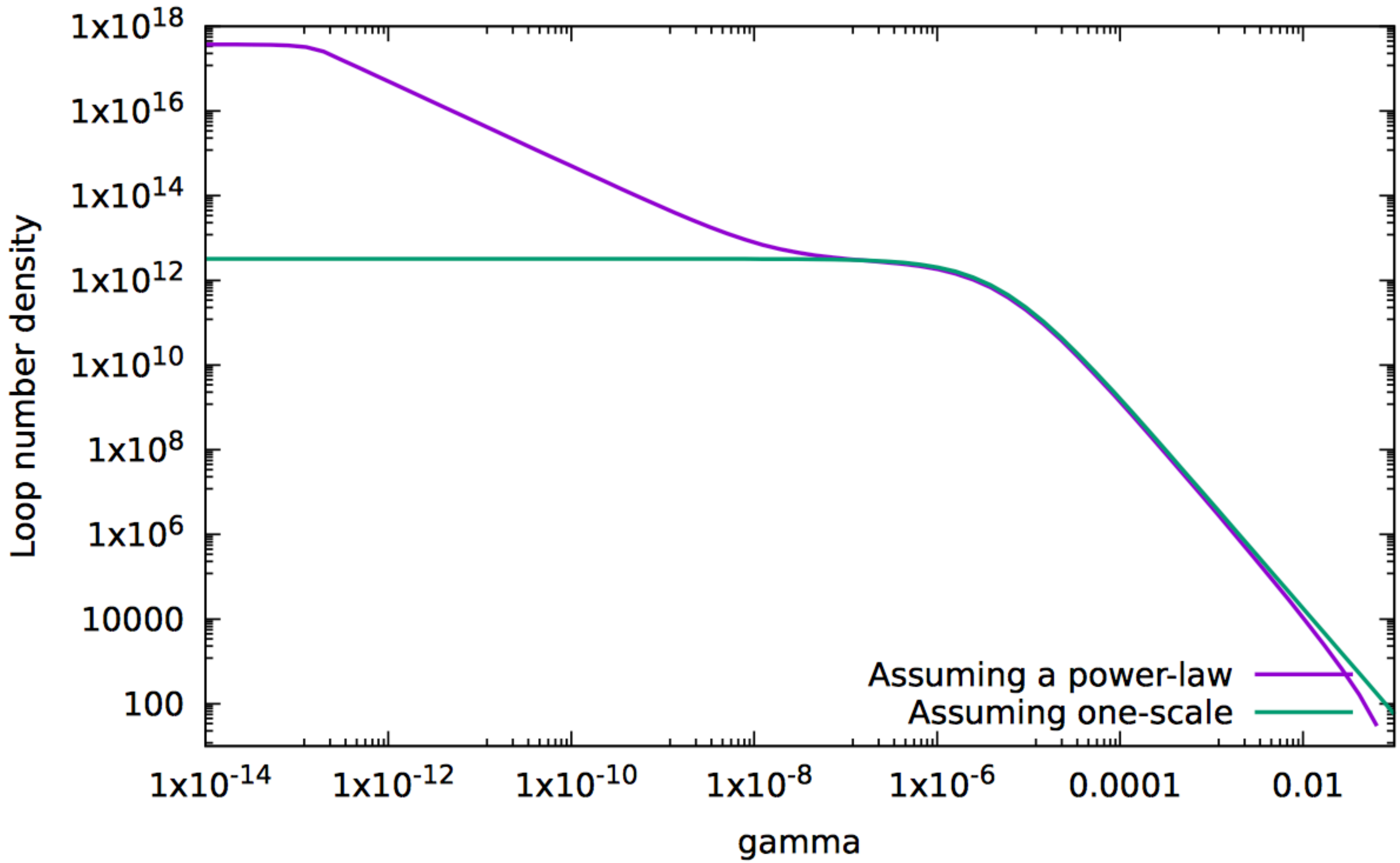
*[Polchinski Rocha, Ringeval, Lorenz, DAS, Auclair…]*

Solving Boltzmann equation gives the loop distribution, which on large scales is tuned to the loop distribution determined from the the numerical simulations *[Ringeval et al]*

**Models C**: interpolate between A and B *[Auclair 2020]*

(aim to help understand to what features burst + stochastic searches are sensitive)

Models A and B give the same loop distributions on large scales, but not on small scales where model B has many more loops. Expect contribute to SGWB at high frequencies.



# 2) Burst search from Third Advanced LIGO–Virgo Observing Run
# Phys.Rev.Lett. 126 (2021) 24, 241102, arXiV: 2101.12248

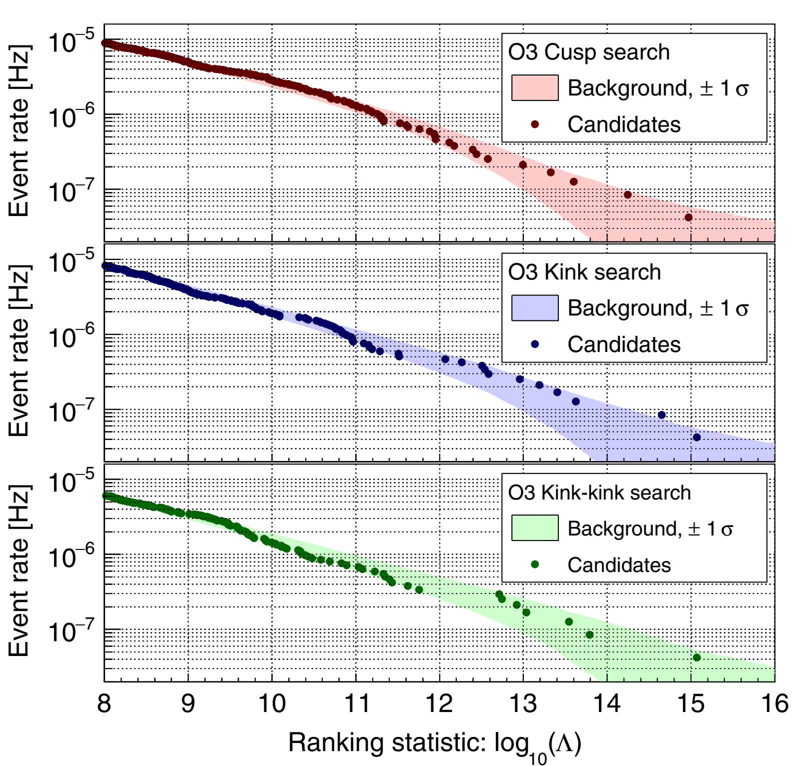
– Using burst waveforms from loops, carried out a matched-filter search in O3 data

– resulting candidates were filtered to retain only those detected in more than one detector within a time window accounting for the difference in the gravitational-wave arrival time between detectors.

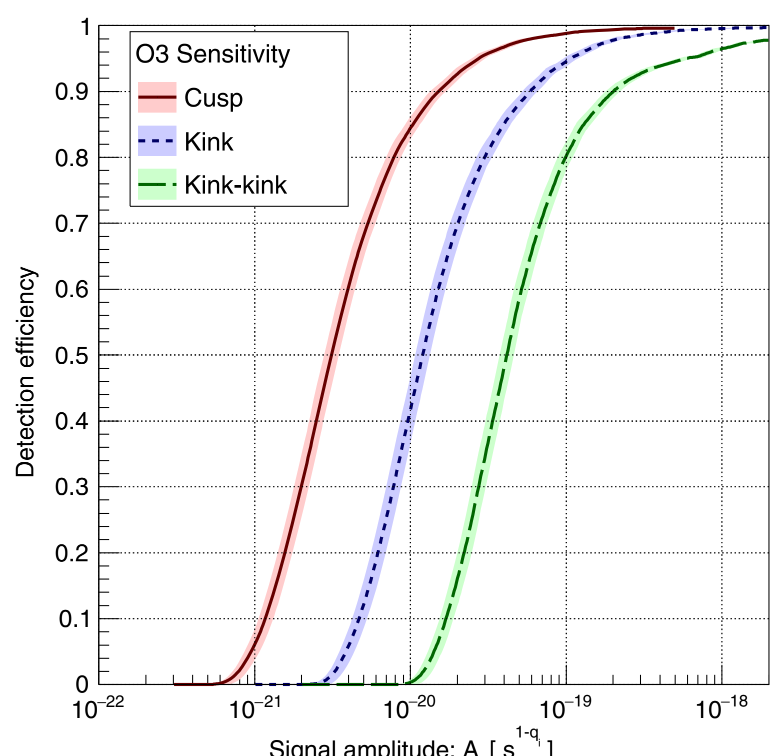
– procedure to discriminate true cosmic string signals from noise : no events seen!
(The ten loudest events originate from a well-known category of transient noise affecting all detectors that are broadband and very short-duration noise events of unknown instrumental origin)

– but burst rate depends on loop distribution and on number of kinks => for a given cosmology (here assumed flat Lambda-CDM, Planck 2018), non-observation gives constraint on $(G\mu, N_k)$

*background distribution of bursts from glitches*

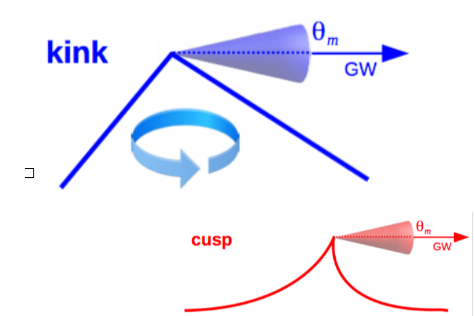



*Cosmic string burst search efficiency*




$$\frac{dR_i}{d\ell dV} = \frac{2}{\ell} N_i \times n(\ell, t) \times \Delta_i \times (1+z)^{-1}.$$

$$\Delta_i = (\theta_m/2)^{3(2-q_i)}$$




– expect *detection* burst rate is then

$$R_i = \int \frac{dR_i}{dA_i}(A_i, f_*; G\mu, N_k)\varepsilon_i(A_i)dA_i.$$

– Exclude parameters inconsistent with non-detection of bursts

$$R > 2.996/T_{\rm obs} \qquad T_{\rm obs} = 273.5 \rm days$$

# Stochastic search from Third Advanced LIGO–Virgo Observing Run

$$\boxed{\Omega_{\rm gw}(t_0,f) = \frac{8\pi G}{3H_0^2}\, f\, \frac{d\rho_{\rm gw}}{df}(t_0,f)}$$

Two complementary approaches used in the literature:

1) At a given frequency, add up GW emission from all the loops throughout entire history of the Universe that contribute to that frequency (infrequent bursts not treated separately):

*[Blanco-Pillado and Olum, Vilenkin, Hogan+Rees, Caldwell, Battye,…]*

$$\Omega_{\rm gw}(t_0,f) = \frac{8\pi G^2\mu^2 f}{3H_0^2}\sum_{n=1}^{\infty} C_n(f) P_n$$

$$C_n(f) = \frac{2n}{f^2}\int_0^\infty \frac{dz}{H(z)(1+z)^6}\, \mathrm{n}\left(\frac{2n}{(1+z)f}, t(z)\right)$$

average power emitted in harmonic mode n

$\Gamma = \sum_n P_n.$ e.g. $P_n = \frac{\Gamma}{\zeta(q)} n^{-q}$

*[see Blanco-Pillado, Olum, Wachter for modeling GBR]*

2) Sum of the incoherent superposition of many bursts from cusps, kinks and kink-kink collisions (removing infrequent bursts),

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

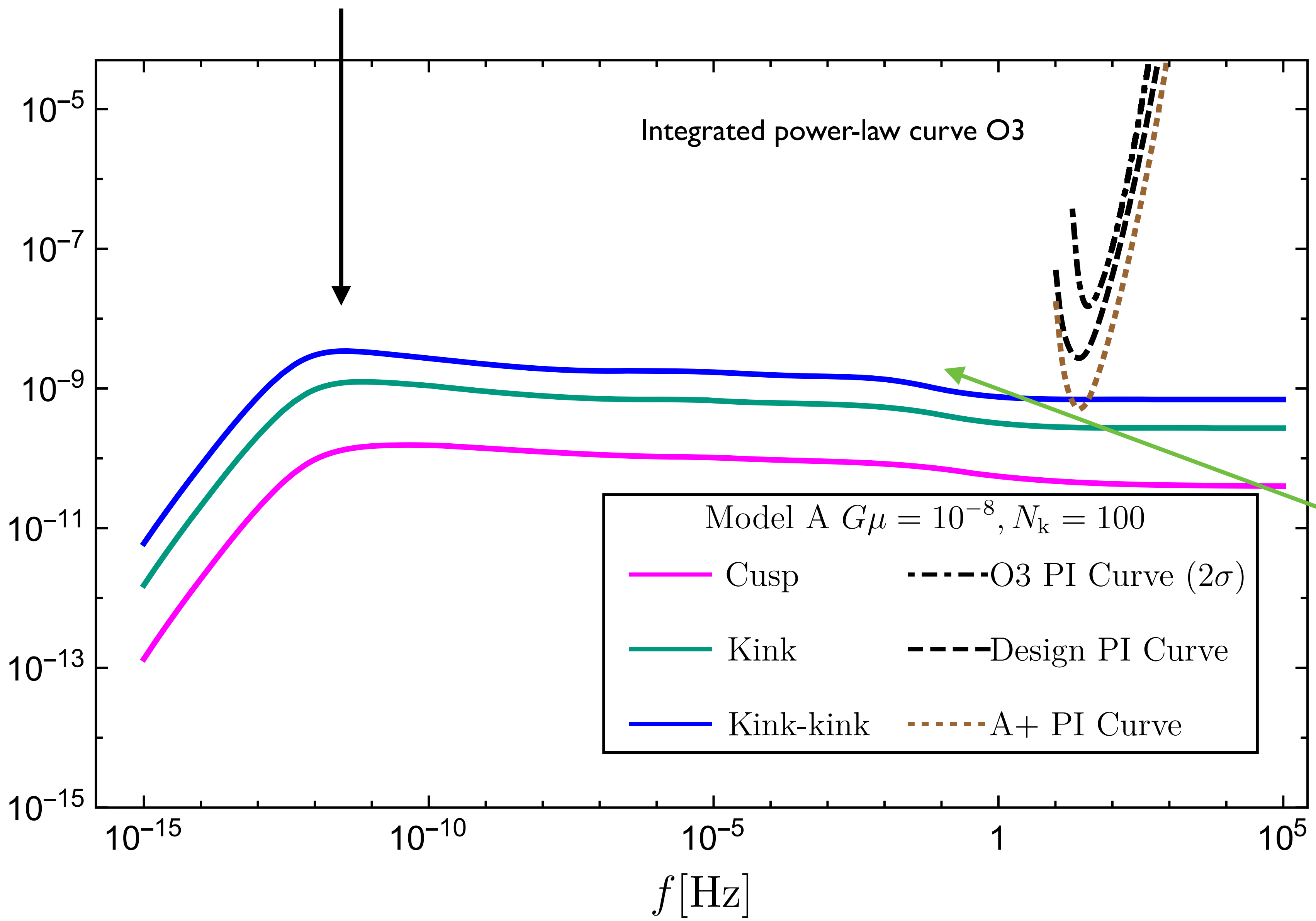
burst rate/redshift/length

strain from cusps/kinks/kk collisions.

*[Damour and Vilenkin, Olmes, Siemens et al…]*

# Generic shape
# (Model A, cusp emission)

$$f_{\rm peak} \sim H_m (\Gamma G\mu)^{-1}$$




emission in *radiation era* -> *flat spectrum* (exact compensation between redshifting of GW energy density, and loop production required for network to scale)

QCD phase transition T~100 GeV

emission in *matter era* (less loop production, redshifting of GW energy density "wins")

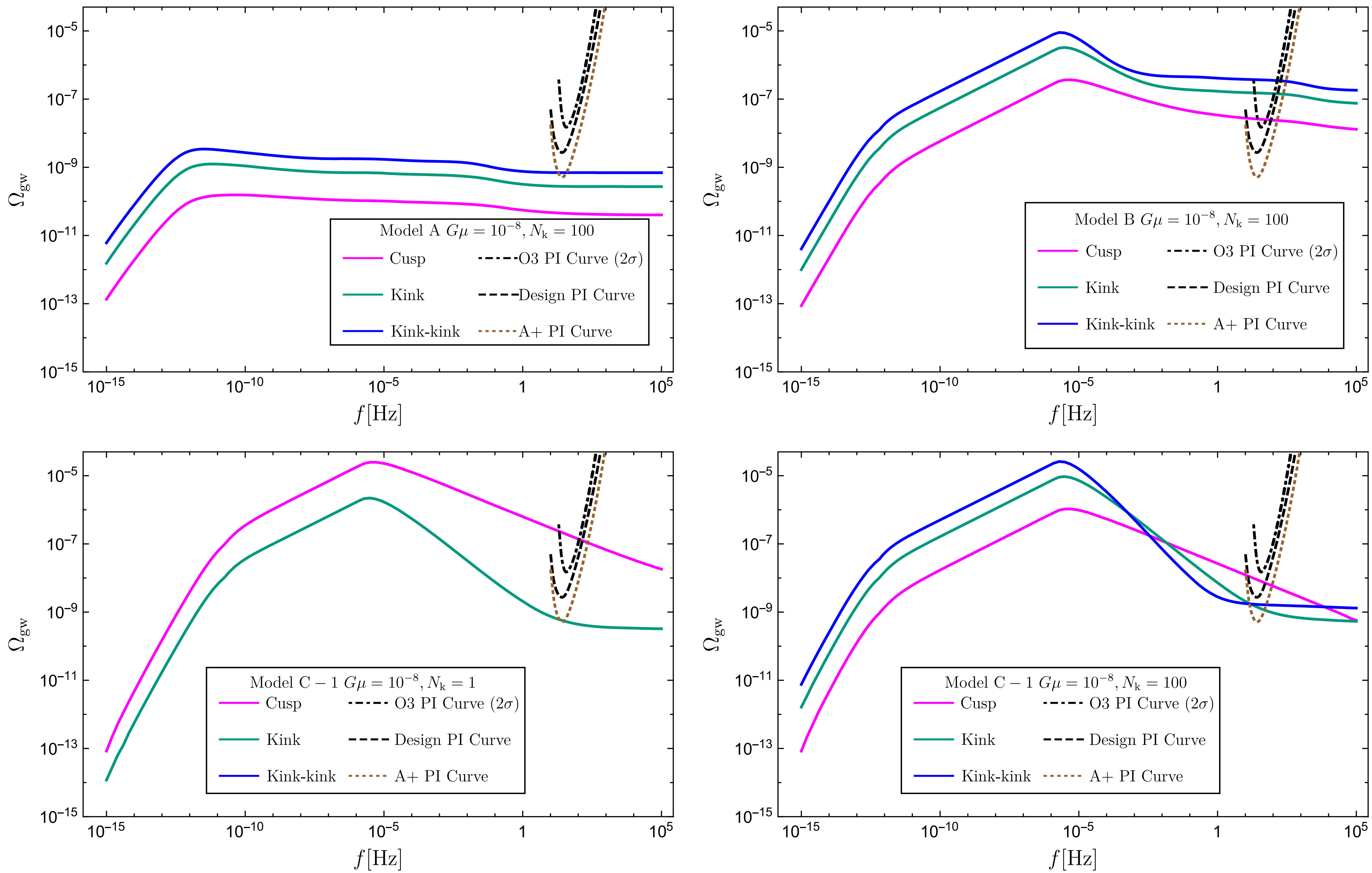
Flat LCDM

Standard Model numbers of degrees of freedom as given by microMEGAS

$$H(z) = H_0 \mathcal{H}(z)$$

$$\mathcal{H}(z) = \sqrt{\Omega_\Lambda + \Omega_{\rm mat}(1+z)^3 + \Omega_{\rm rad}\mathcal{G}(z)(1+z)^4}$$

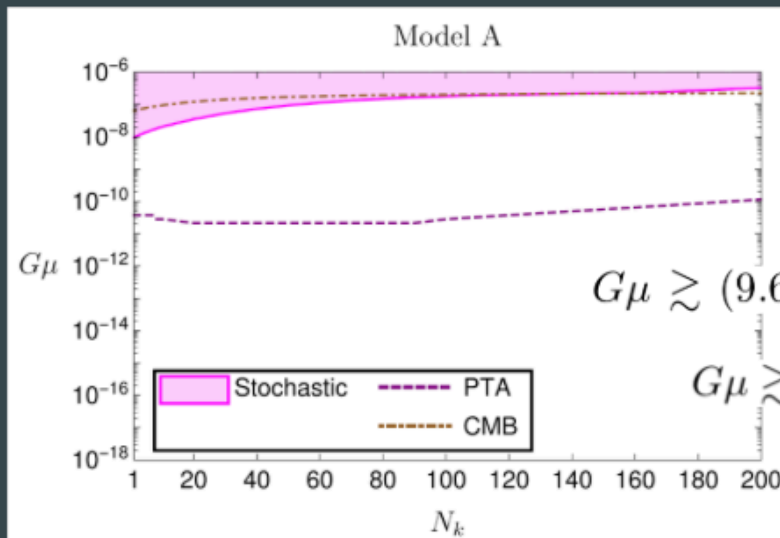
# Models A, B, C1 $\quad G\mu = 10^{-8}$




LPF of model B in matter era, of model A in radiation era

# Cosmic strings: exclusion plots

$N_c = 1$

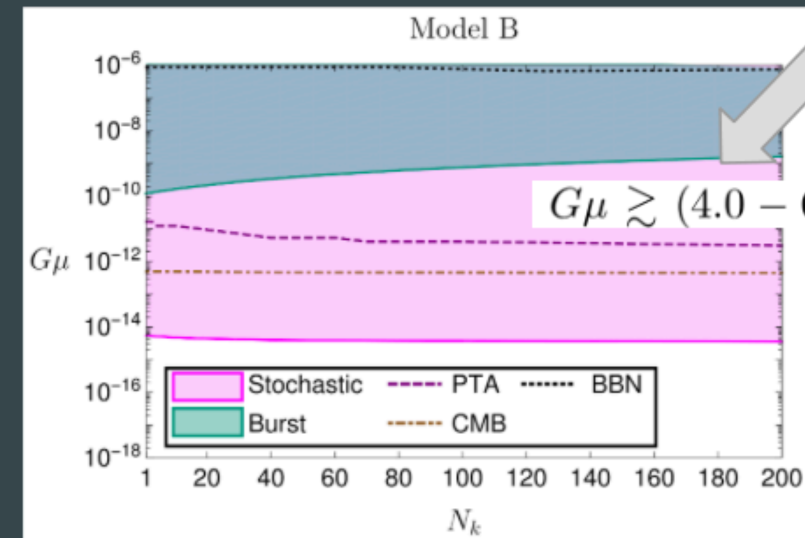



$G\mu \gtrsim (9.6 \times 10^{-9} - 10^{-6})$

$G\mu \gtrsim 10^{-10}$ PTA

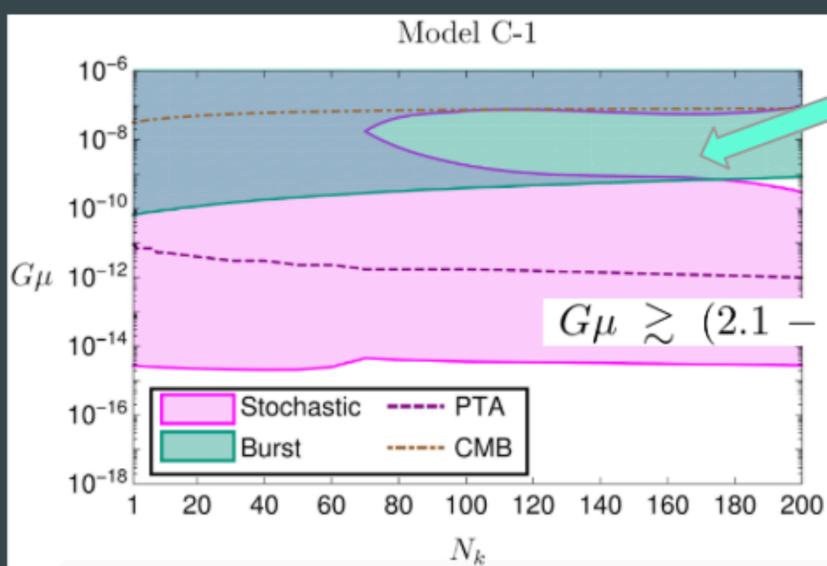
*Model A*: Blanco-Pillado, Olum, Shlaer, PRD 89, 023512(2014)

*Strongest constraint to date*




$G\mu \gtrsim (4.0 - 6.3) \times 10^{-15}$

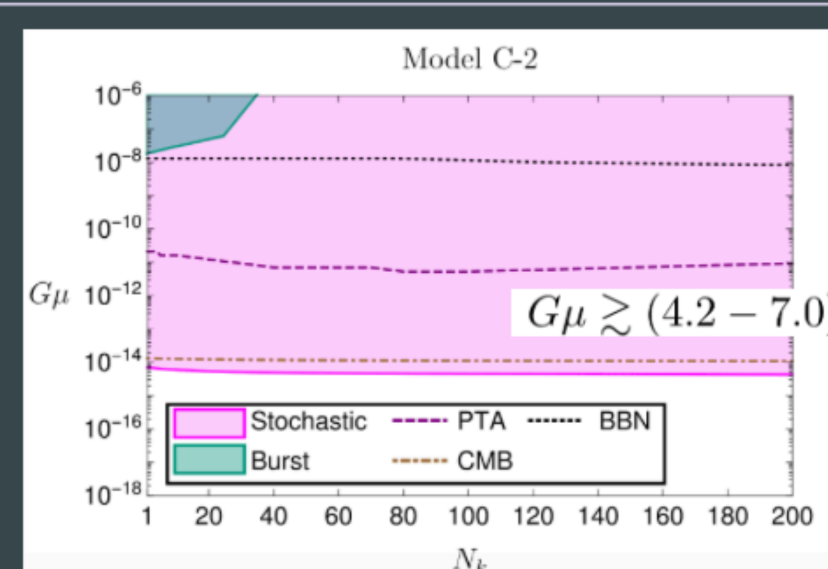
*Model B*: Lorenz, Ringeval, Sakellariadou, JCAP 1010, 003 (2010)




*Only case burst analysis leads to tighter constraint*

$N_k > 70$

$G\mu \gtrsim (2.1 - 4.5) \times 10^{-15}$




$G\mu \gtrsim (4.2 - 7.0) \times 10^{-15}$

*Model C*: Auclair, Ringeval, Sakellariadou, Steer, JCAP 06, 015 (2019)



*C1=LPF of model B in matter era, of model A in radiation era*

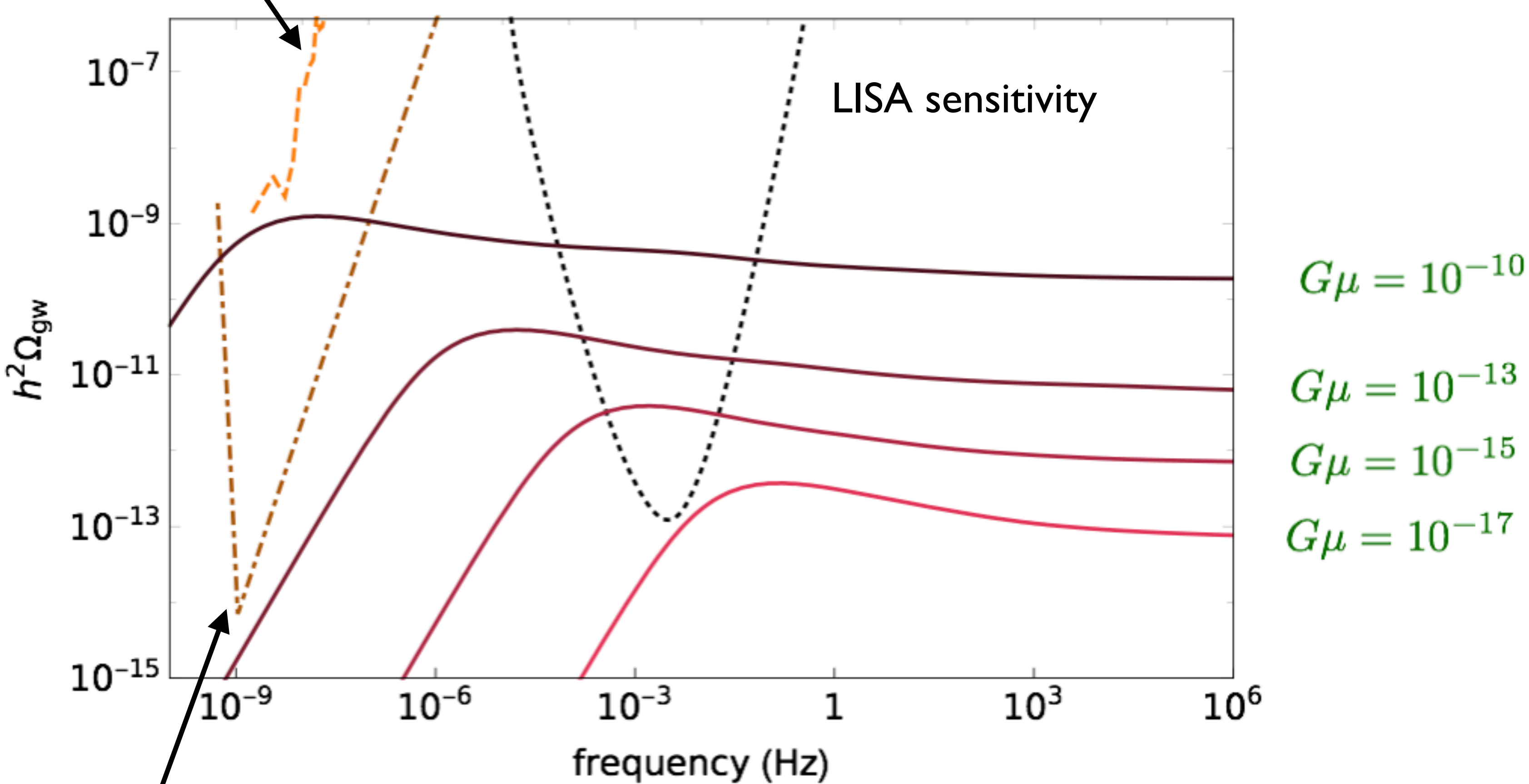
*C2=LPF of model A in matter era, of model B in radiation era*

Bound on integrated GW energy density generated before BBN, and before photon decoupling

- Relative to O1 and O2 analysis (Nk=1), constraints on Gmu stronger by 2 orders of magnitude for model A, and by 1 for model B

# PT and LISA bands, model A and B *[1909.00819]*

EPTA sensitivity



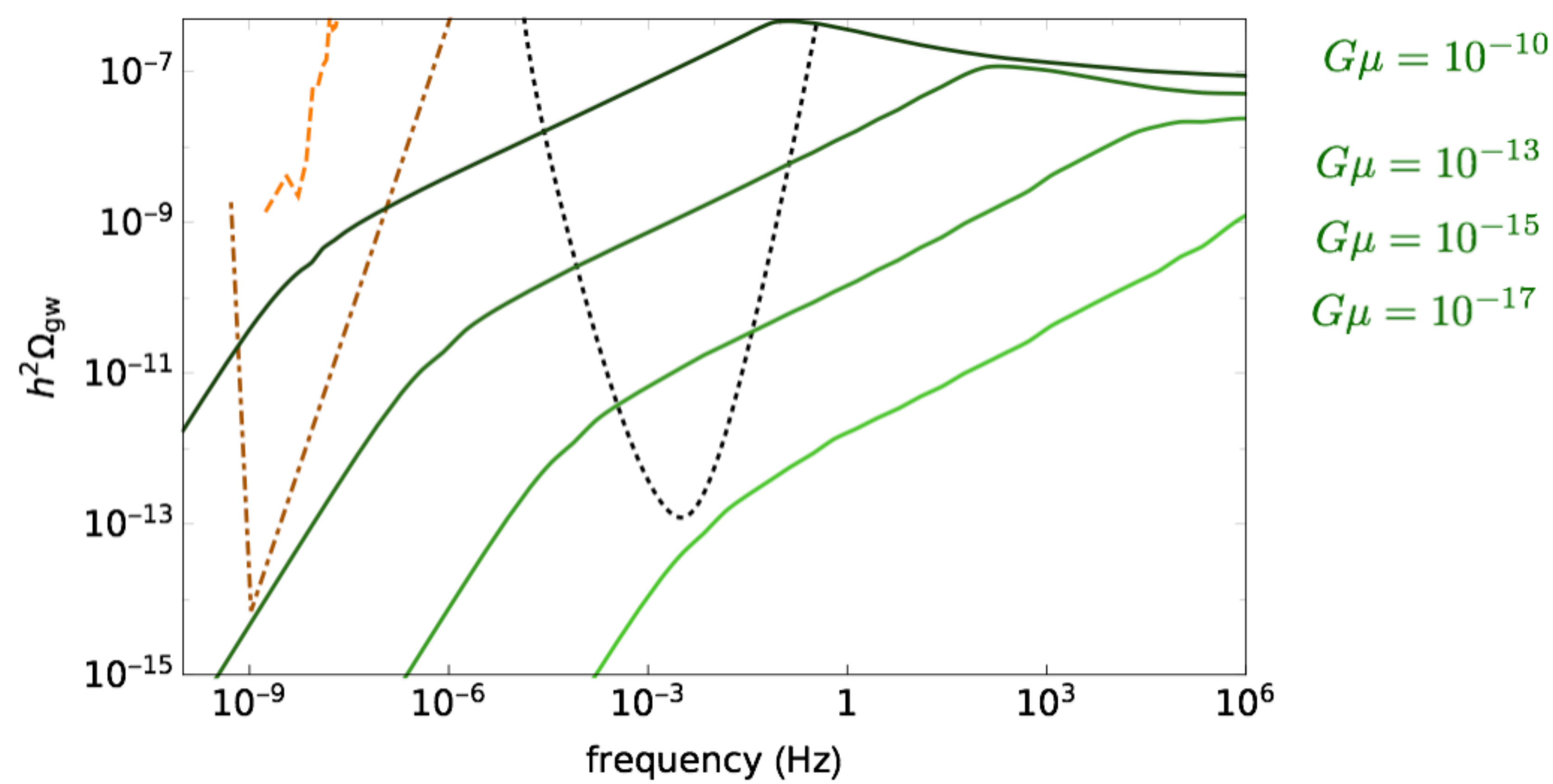

(projected) SKA sensitivity

*[2009.06555]*

NANOGrav PT data constraint, Model A:

$$G\mu \in (4\times 10^{-11}, 10^{-10})$$

Spectral shape => tightening of constraints not expected from low frequency experiments




LISA will be able to probe cosmic strings with tensions

$$G\mu \gtrsim \mathcal{O}(10^{-17})$$

# 3) Beyond the standard picture

## 1) Impact of varying the effective relativistic d of f. *[1909.00819]*

Standard Model numbers of degrees of freedom as given by microMEGAS

**Flat LCDM**

$$H(z) = H_0\mathcal{H}(z) \quad \text{with} \quad \mathcal{H}(z) = \sqrt{\Omega_\Lambda + \Omega_{\rm mat}(1+z)^3 + \Omega_{\rm rad}\mathcal{G}(z)(1+z)^4}$$

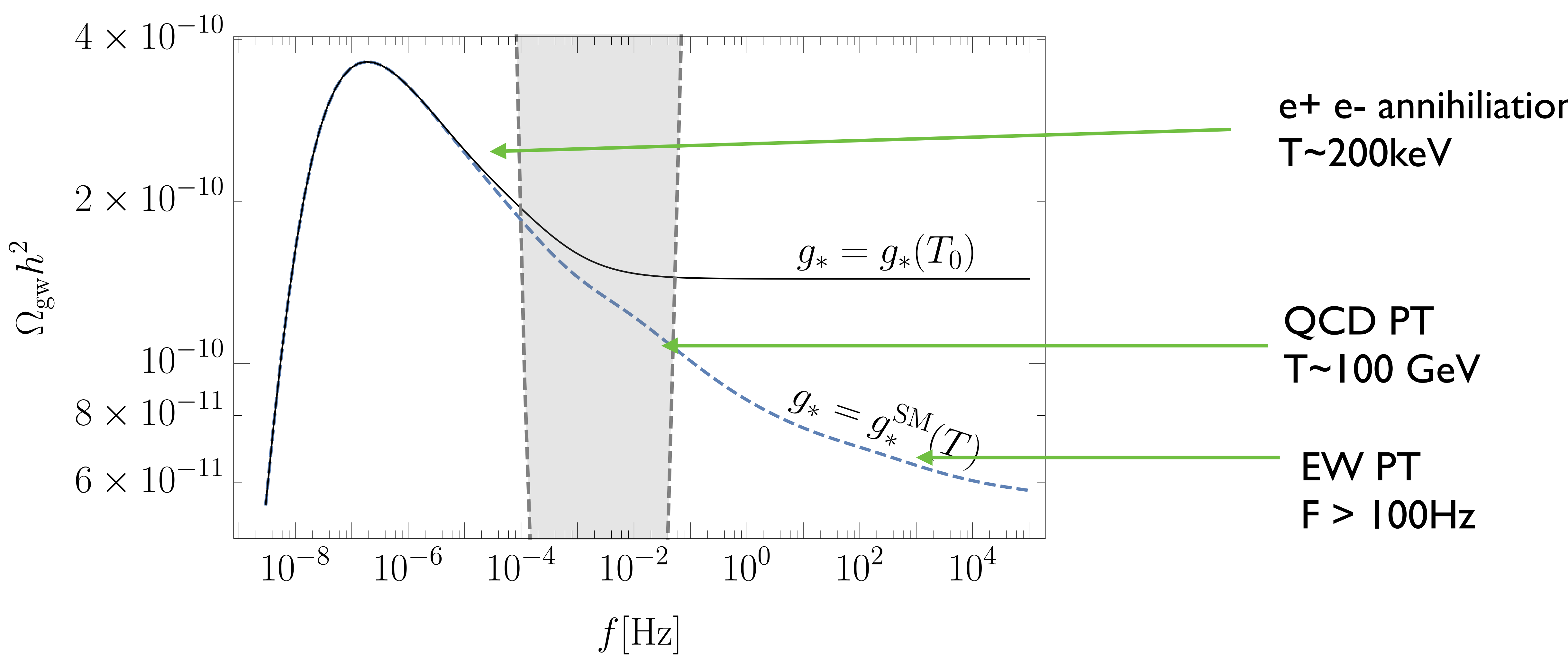



**Figure 4**. Examples of spectra with $G\mu = 10^{-11}$ assuming a constant number of degrees of freedom (black solid line) and standard cosmology with SM particle content (blue dashed line). The gray area indicates LISA sensitivity.

## 2) Impact of gravitational radiation *and* particle radiation.

– Recent results high resolution field theory simulation of Abelian-Higgs loops with **kinks** (in BPS limit) *[Matsunami et al, PRL 122 , 201301 (2019)]*

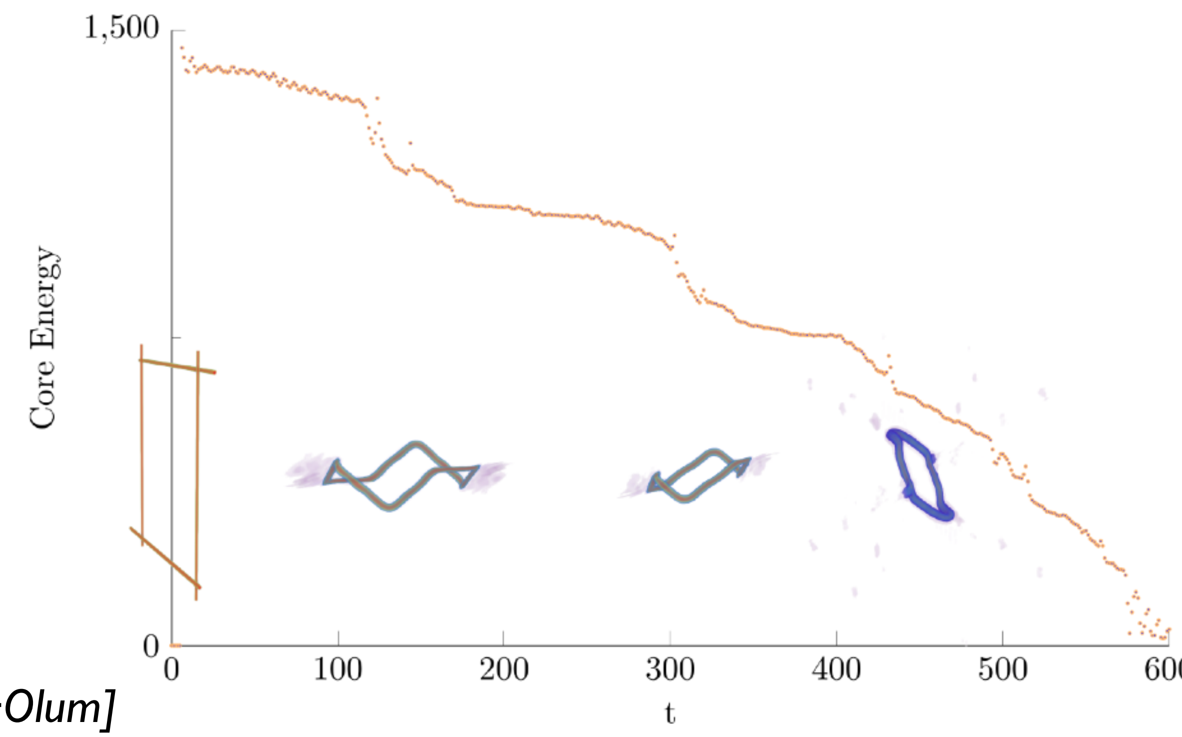
$$\boxed{\frac{d\ell}{dt} = \begin{cases} -\gamma_{\rm d}, & \ell \gg \ell_{\rm k} \\ -\gamma_{\rm d}\frac{\ell_{\rm k}}{\ell}, & \ell \ll \ell_{\rm k}, \end{cases}}$$

← *GW dominant decay mode* $(\gamma_{\rm d} \equiv \Gamma G\mu)$

← *Particle production primary decay channel*

- Standard NG strings, $\ell_{\rm k} \to 0$
- Particle radiation dominates $\ell_{\rm k} \to \infty$
- Find $\boxed{\ell_{\rm k} \sim \beta_{\rm k}\frac{w}{\gamma_{\rm d}}}$

string width $w \sim \mu^{-1/2}$, constant $\beta_{\rm k} \sim \mathcal{O}(1)$




- Other possible form: loop with **cusps** *[Blanco-Billado+Olum]*

$$\boxed{\frac{d\ell}{dt} = \begin{cases} -\gamma_{\rm d}, & \ell \gg \ell_{\rm c} \\ -\gamma_{\rm d}\sqrt{\frac{\ell_{\rm c}}{\ell}}, & \ell \ll \ell_{\rm c} \end{cases}}$$

$$\boxed{\ell_{\rm c} \sim \beta_{\rm k}\frac{w}{\gamma_{\rm d}^2}}$$

Equating the rates defines a characteristic timescale

$$t_k \equiv \frac{\ell_{\rm k}}{\gamma_{\rm d}} \qquad t_c \equiv \frac{\ell_{\rm c}}{\gamma_{\rm d}}$$

.

Solve the Boltzmann equation including this particle radiation, to determine effect on loop distribution, and hence SGWB. And also determine energy loss in particles

*[Auclair, DAS, Vachaspati, arXiV: 1911.12066]*

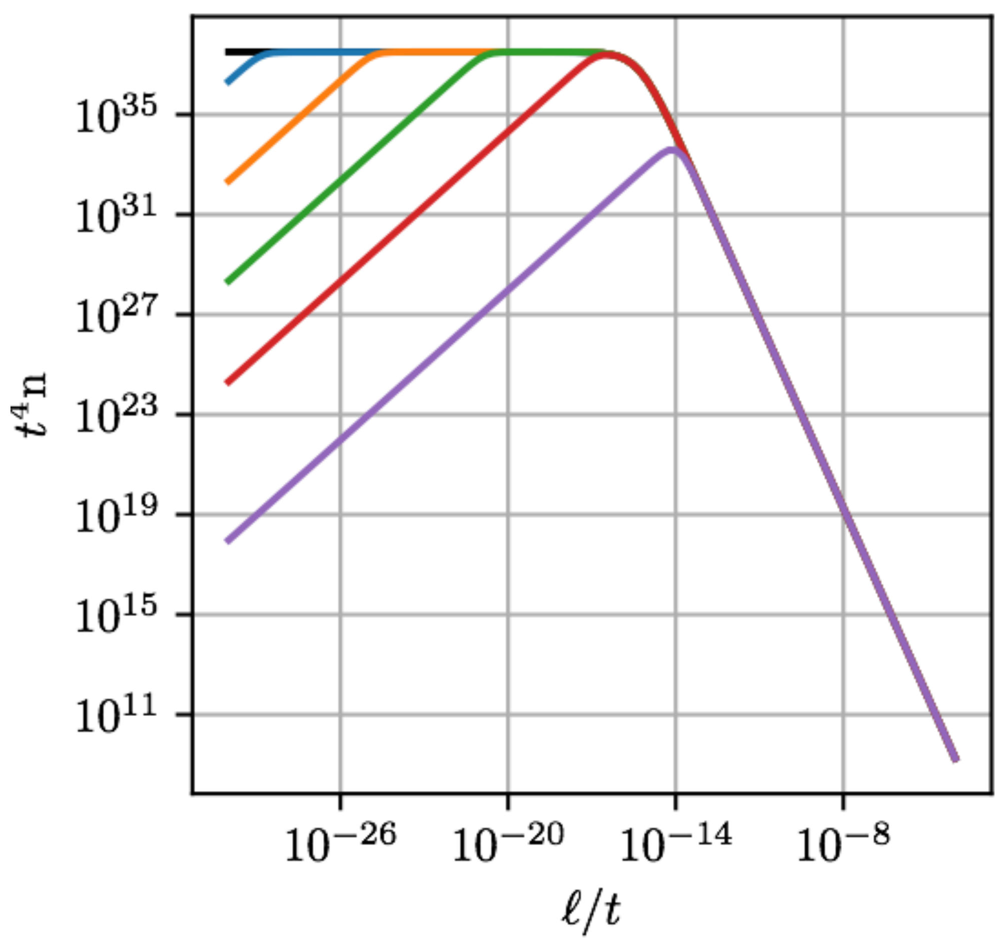
$$\left.\frac{\partial}{\partial t}\right|_{\ell}\left(a^3 n(t,\ell)\right) + \left.\frac{\partial}{\partial \ell}\right|_{t}\left(\frac{\mathrm{d}\ell}{\mathrm{d}t} a^3 n(t,\ell)\right) = a^3 \mathcal{P}$$

assumed delta (model A type)

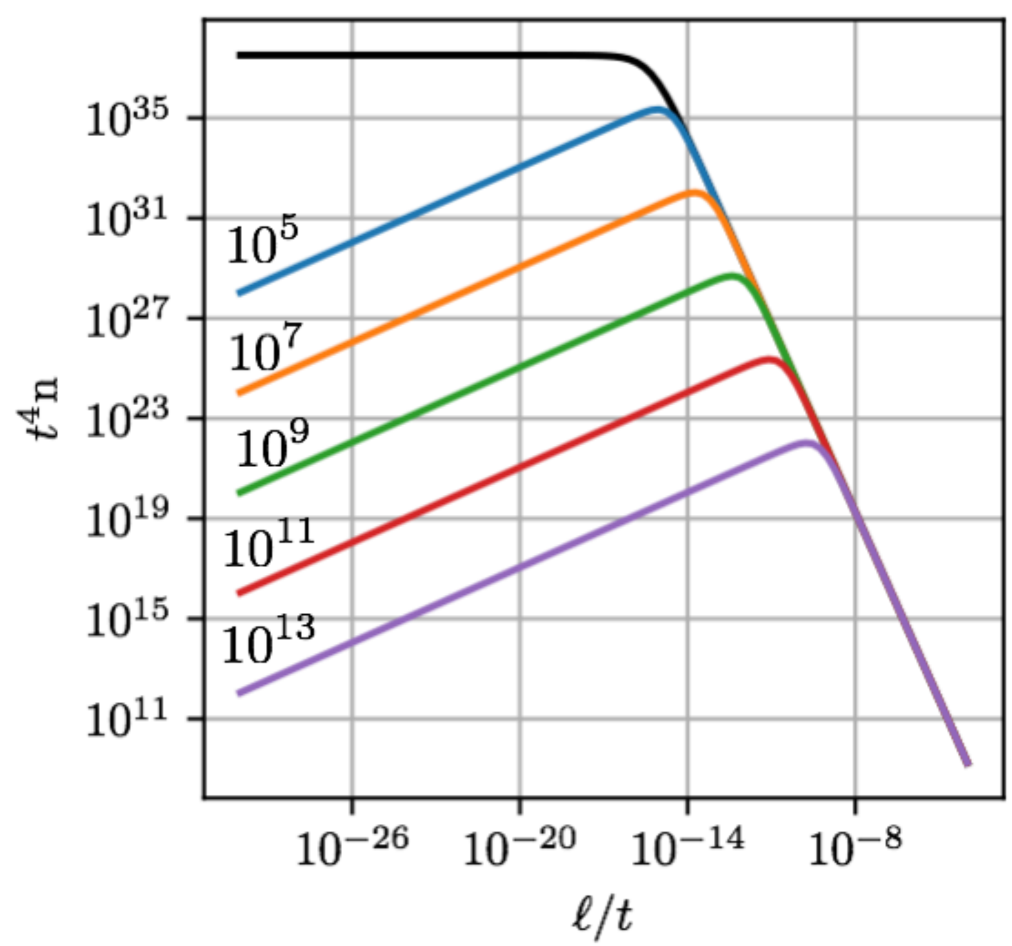
---

$z_k \sim 10^{12}$ $\boxed{G\mu = 10^{-17}}$ $z_c \sim 10^4$

Kinks




Cusps

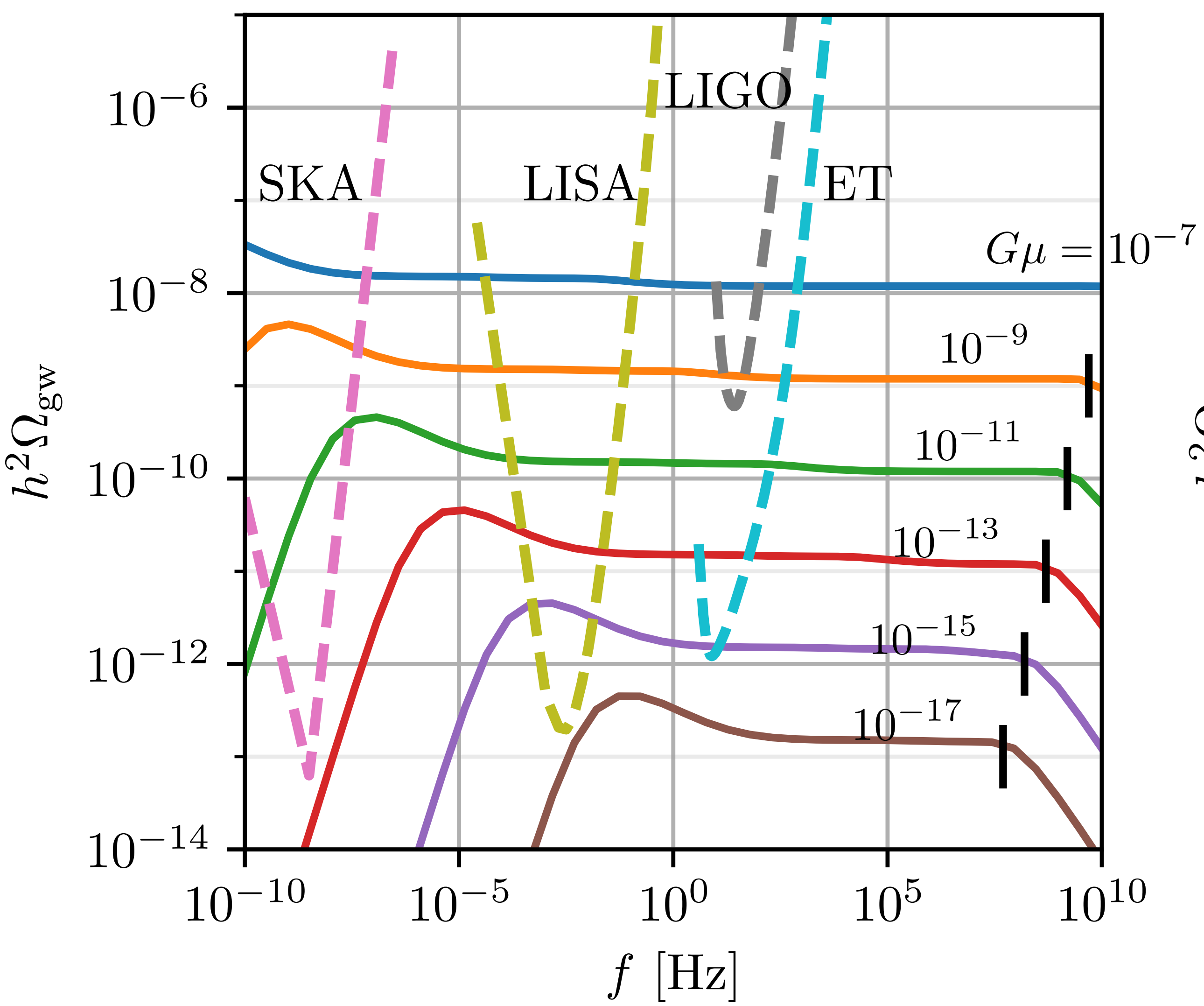



The loop distributions are supressed for $z \gg z_k$ or $z \gg z_c$

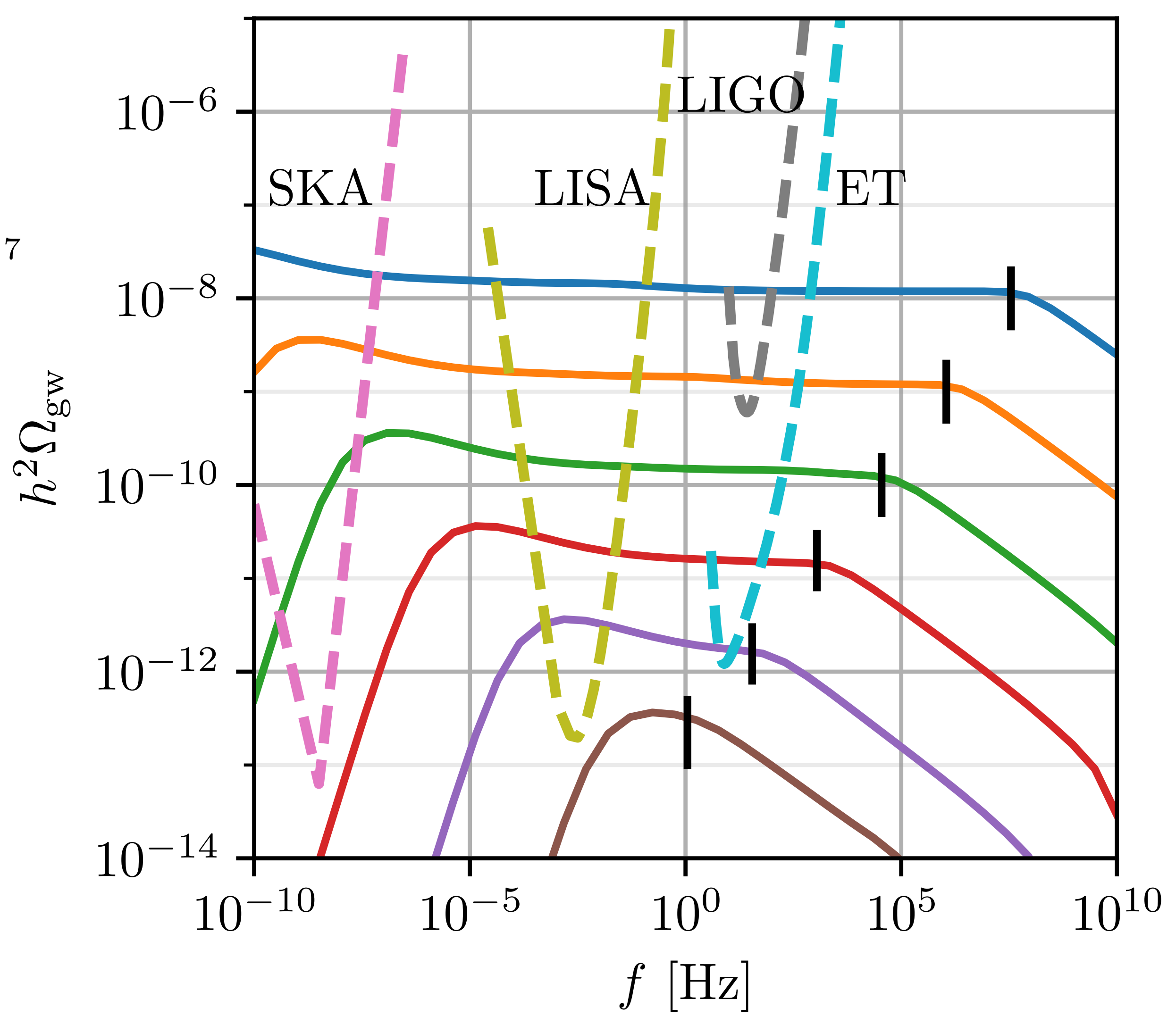
$(\beta_{\mathrm{k}}, \beta_{\mathrm{c}}) = 1$

# Stochastic GW background

Kinks




Cusps




Spectrum cutoff at high frequency $f > \left(\frac{8H_0\sqrt{\Omega_R}}{\ell_{\rm c,k}\gamma_{\rm d}}\right)^{1/2}$

$(\beta_{\rm k}, \beta_{\rm c}) = 1$

# Particle emission: Diffuse gamma-ray background

- loops radiate also into particles. For kinks $\dot{\ell}\Big|_{\mathrm{particle}} \sim -\gamma_{\mathrm{d}}\frac{\ell_{\mathrm{k}}}{\ell}$

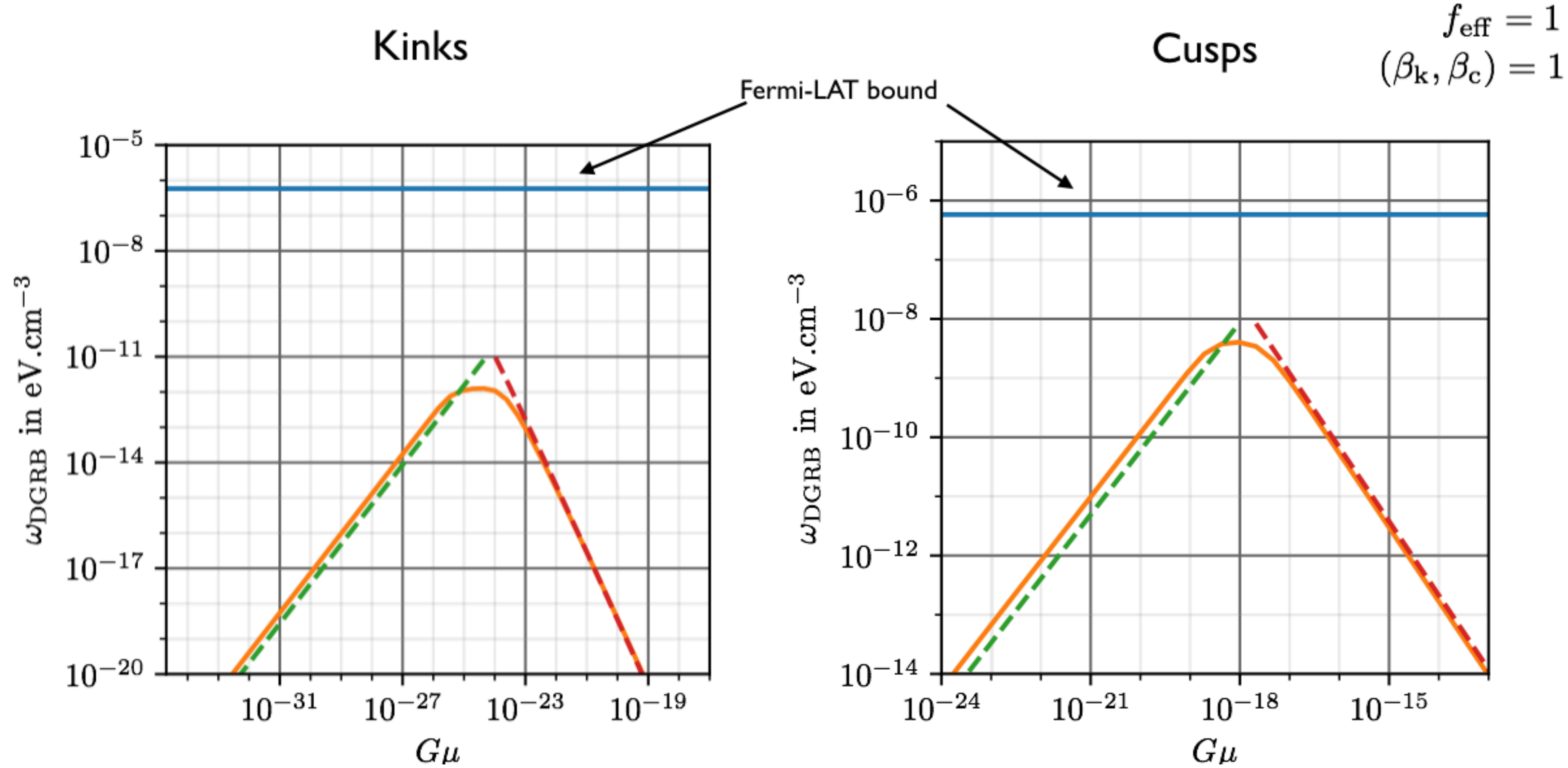
- Assume emitted particles decay into standard model Higgs particles, of which a fraction $f_{\mathrm{eff}}$ cascade down into gamma-rays, can calculate contribution from strings to the diffuse gamma-ray background:

$$\boxed{\omega_{\mathrm{DGRB}}^{\mathrm{strings}} = f_{\mathrm{eff}} \int_{t_\gamma}^{t_0} \frac{\Phi_{\mathrm{H}}(t)}{(1+z)^4}\mathrm{d}t}$$

Energy loss from strings /time/volume

$$\Phi_{\mathrm{H}}(t) = \mu\gamma_{\mathrm{d}}\ell_{\mathrm{k}} \int_0^{\alpha t} n(\ell,t)\frac{\mathrm{d}\ell}{\ell}$$

total EM energy injected since universe became transparent to GeV gamma-rays, at $t_\gamma \simeq 10^{15}\mathrm{s}$



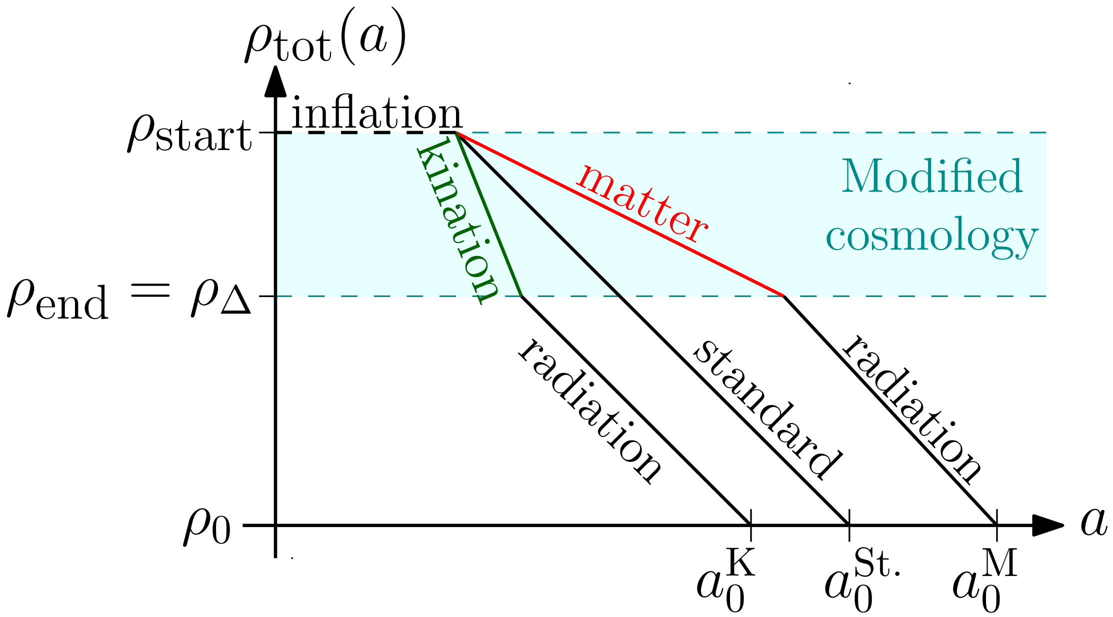

$$\boxed{\omega_{\mathrm{DGRB}}^{\mathrm{obs}} \lesssim 5.8\times 10^{-7}\ \mathrm{eVcm}^{-3}}$$

A. A. Abdo et al. (Fermi-LAT), Phys. Rev. Lett. **104**, 101101 (2010)

# 3) Impact of changing cosmological evolution

*[Gouttenoire, Servant & Simakachorn, 1912.02569]*

Non-standard cosmo. before rad. era

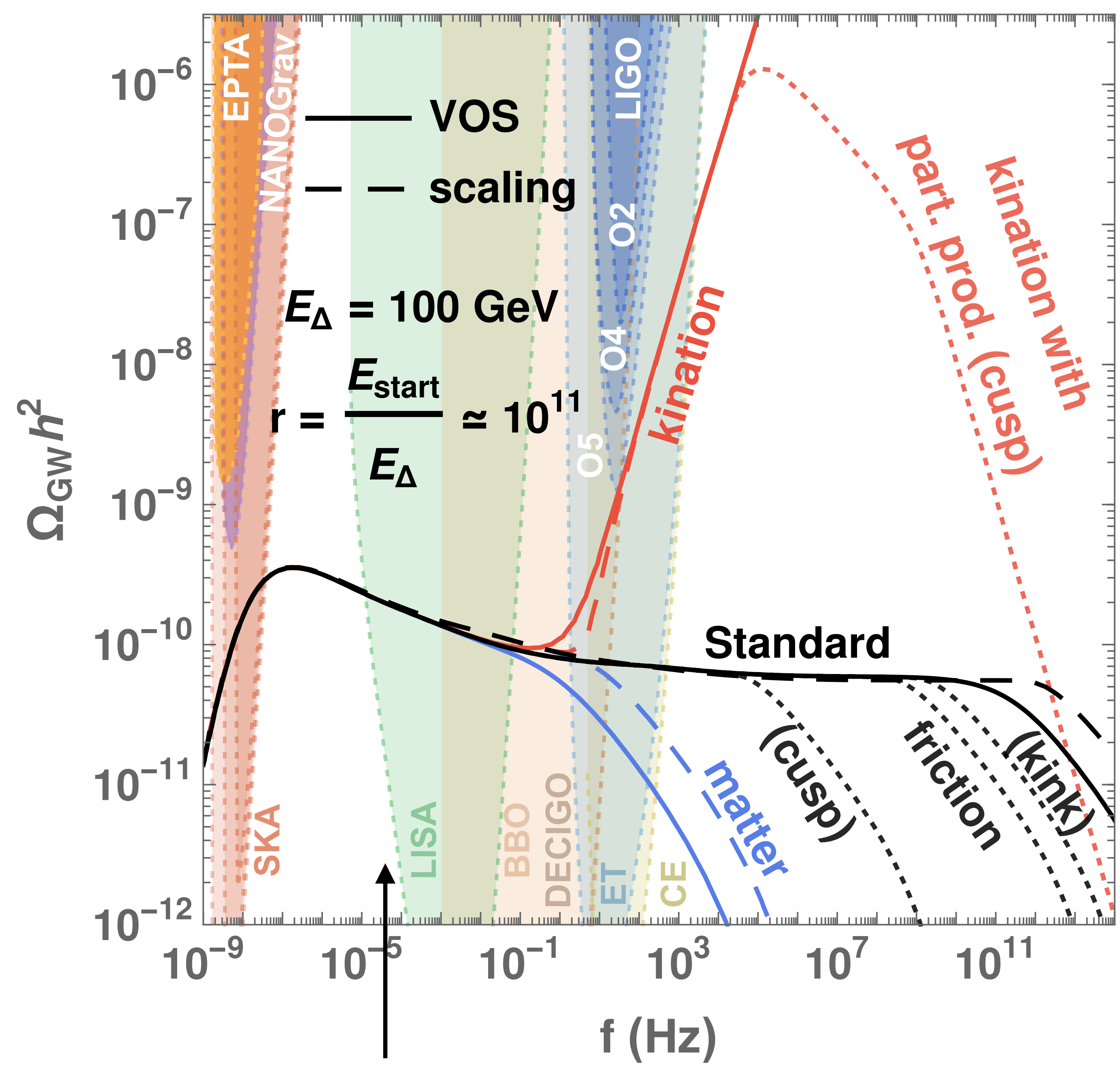



kinetically driven inflation typically followed by kination regime (rho dominated by kinetic energy density of a free scalar field)

$\rho \propto a^{-6}$
$a \sim t^{1/3}$

Slower expansion of universe -> more loop production

Non–standard cosmo. before rad. era
($G\mu = 10^{-11}$, $\Gamma = 50$, $\alpha = 0.1$)

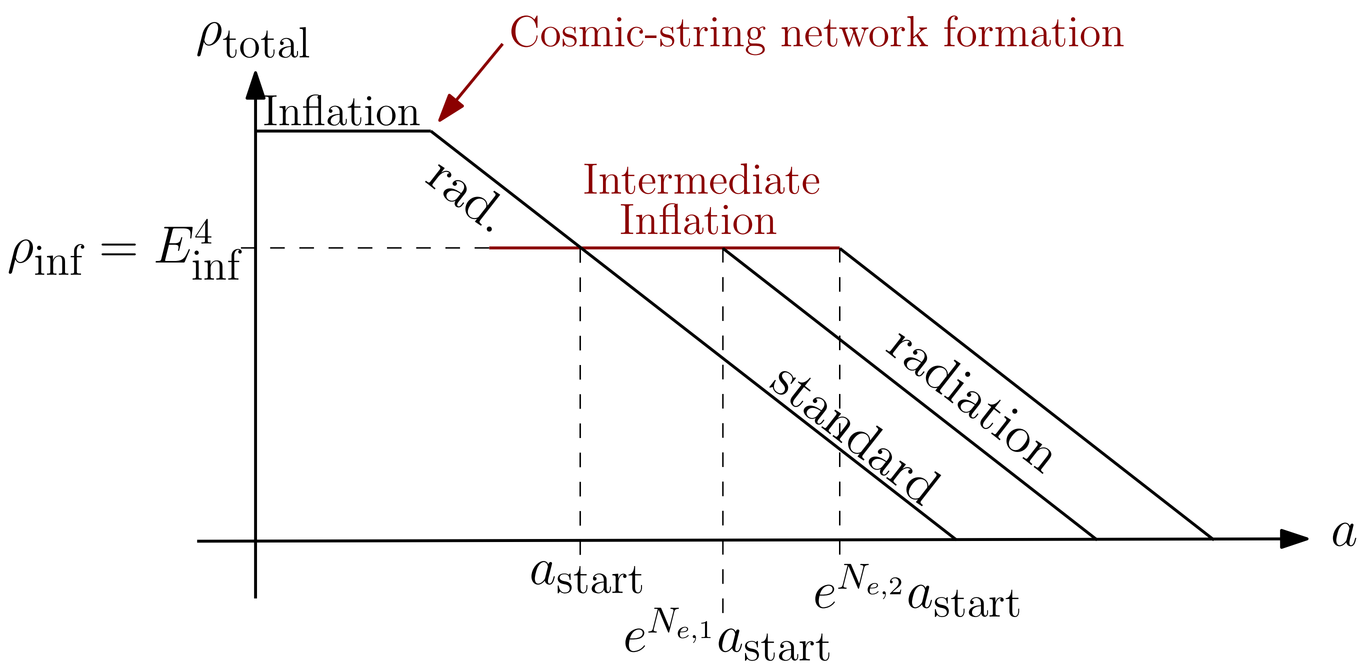


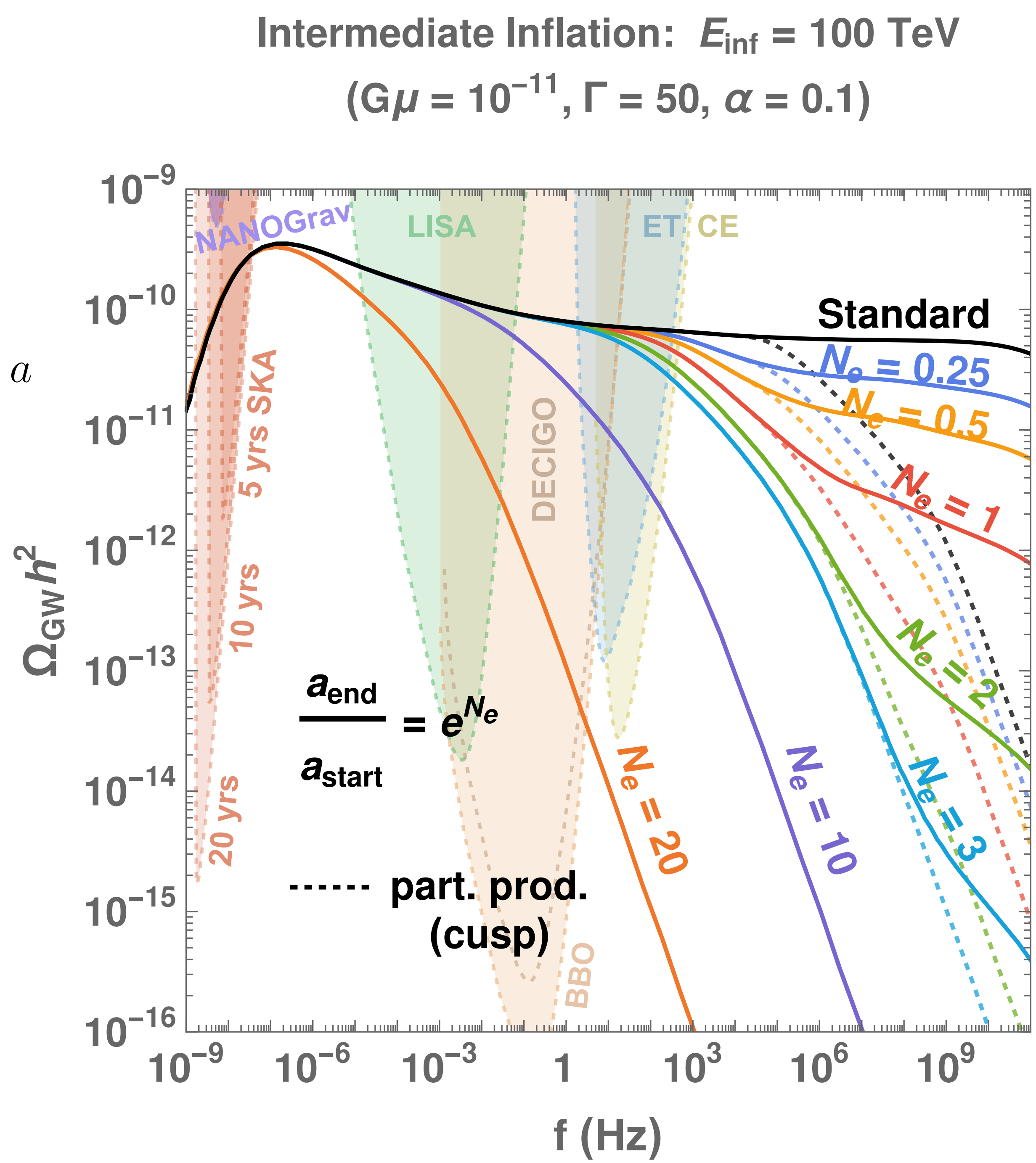

Integrated power-law sensitivity of future experiments

starting at $E_{\rm start} = m_{pl}\sqrt{G\mu}$ and ending at $E_{\rm end} = E_\Delta = 100$ GeV with duration $r \equiv \left(\frac{\rho_{\rm start}}{\rho_{\rm end}}\right)^{1/4} \equiv \left(\frac{E_{\rm start}}{E_\Delta}\right) \simeq 10^{11}$

# 3) Impact of changing cosmological evolution

*[Gouttenoire, Servant & Simakachorn, 1912.02569]*




e.g. due to a highly supercooled first order phase transition.

# 4) Impact of world-sheet degrees of freedom

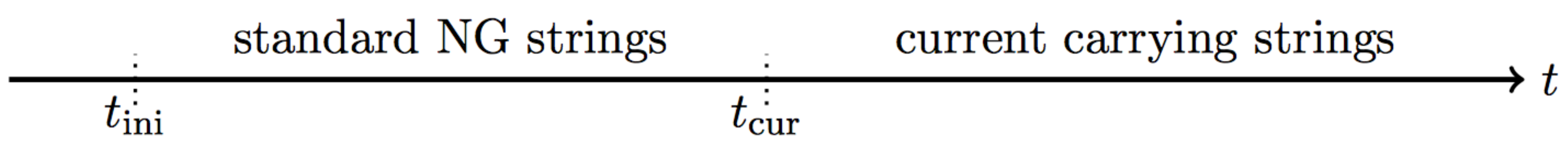
*[Auclair et al, 2010.04620]*

- If other fields couple to the Higgs forming the string, then they can condense in the string core, and subsequently propagate along the string : current carrying strings *[Witten]*

- The resulting strings behave like current carrying wires and are endowed with a much richer structure

- Loops radiate GWs and may stabilise into centrifugally supported configurations: **vortons**.

- On cosmological scales, these appear as point particles having different quantized charges and angular momenta, and can behave as dark matter.




- The total vorton abundance today should depend on $t_{cur}$ as well as $t_{ini.}$, and hence on the underlying particle physics model.

$$\mathcal{R} \equiv \lambda\sqrt{\mu} \simeq \frac{m_\phi}{m_\sigma} \gg 1$$

- Determining $\Omega_{tot}$, and using the current constraints on $\Omega_{dm}h^2 \simeq 0.12$ places constraints on the physics at work in the early Universe

- Solved Boltzmann equation to determine for first time vortons formed from initial conditions *as well as* those from loops chopped off infinite string network.

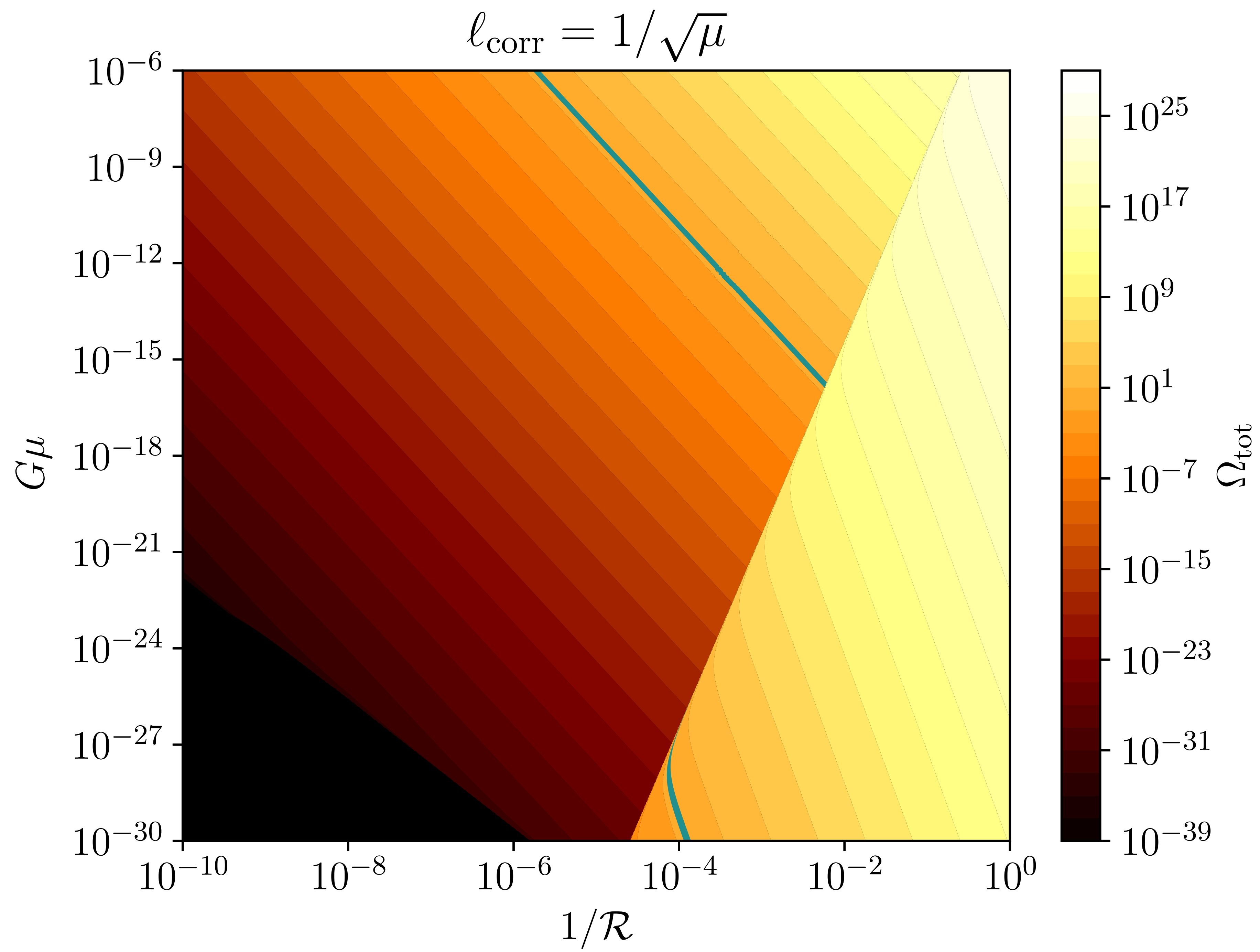



**Figure 5**: The total relic abundance of all vortons starting from a Vachaspati-Vilenkin initial loop distribution, with an initial thermal correlation length $\ell_{\rm corr} = 1/\sqrt{\mu}$, and a one-scale loop production function with $\alpha = 0.1$. The green line corresponds to the range of values $[0.2, 0.4]$. The different populations contribution is represented in figure 4.

# Conclusions

• Attempted to show that cosmic strings can be very good probes of cosmology, through SGWB

• Present latest LIGO-Virgo constraints on NG strings for different models, with Nk as a new free parameter, highlighting the assumptions and unknowns

• Discuss future possible constraints with other GW detectors, and how they depend on particle physics assumptions (particle emission for e.g.), and modified cosmology.

• We have not discussed global strings with long range forces (such as axion strings), which can also radiate Goldstones. Despite much work in similar directions, I think there are open questions remaining on the network evolution

• Interesting open questions: e.g. gravitational backreaction and PBH formation from loop collapse

**Cosmic String Loop Collapse in Full General Relativity**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[a] *Theoretical Particle Physics and Cosmology Group, Physics Department, Kings College London, Strand, London WC2R 2LS, United Kingdom*

• Fully general relativistic dynamical simulations of Abelian Higgs cosmic strings using 3+1D numerical relativity (GRChombo).

• Planar, circular cosmic string loops collapse due to their tension and either (i) unwind and disperse o (ii) form a black hole, depending on Gμ and initial radius

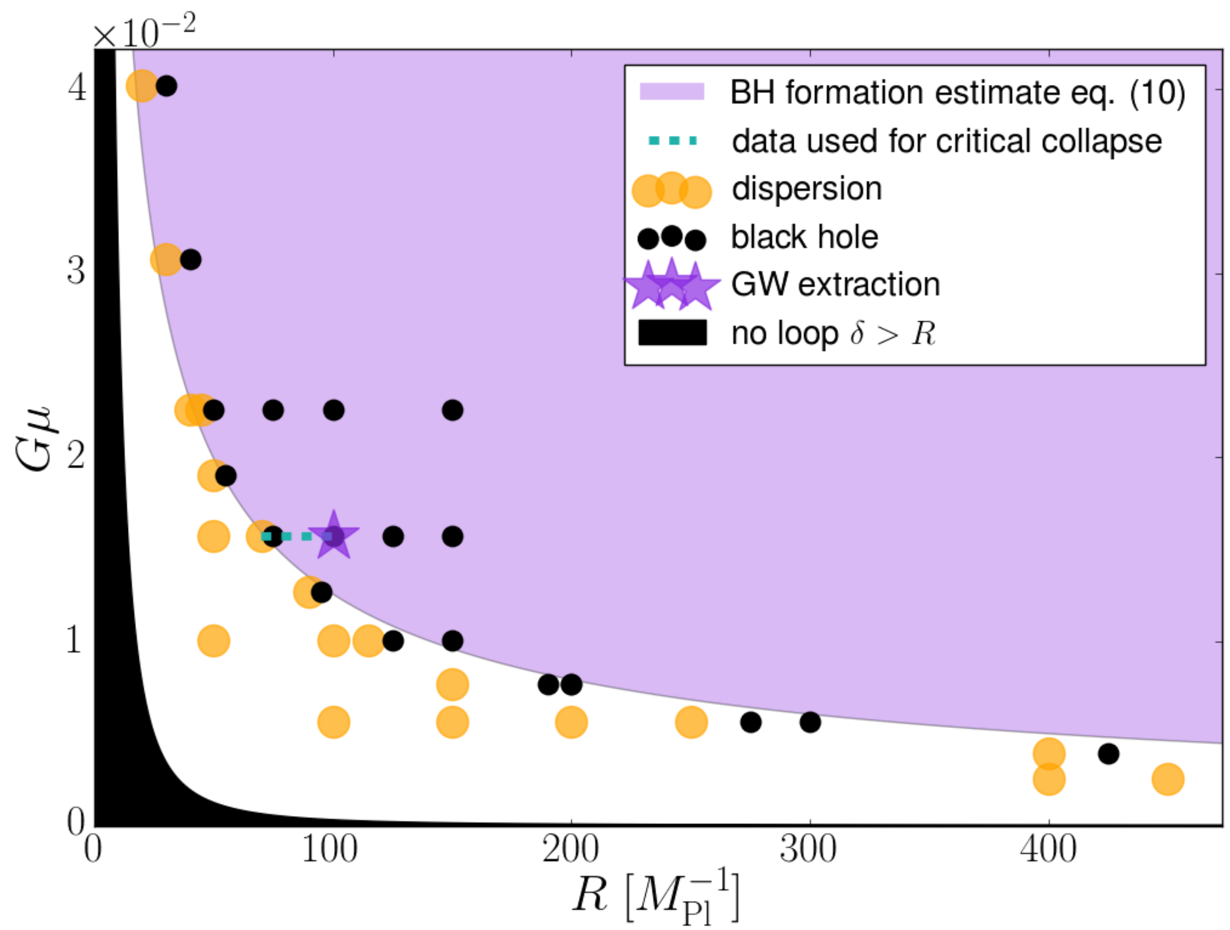


FIG. 2. **Overview of simulations :** The loop can either form a BH or unwind and radiate all its mass. The analytical expression derived from the hoop conjecture accurately predicts the outcome. Movie links for the evolution over time of the collapse are available for the dispersion [18] and black hole [19] cases.

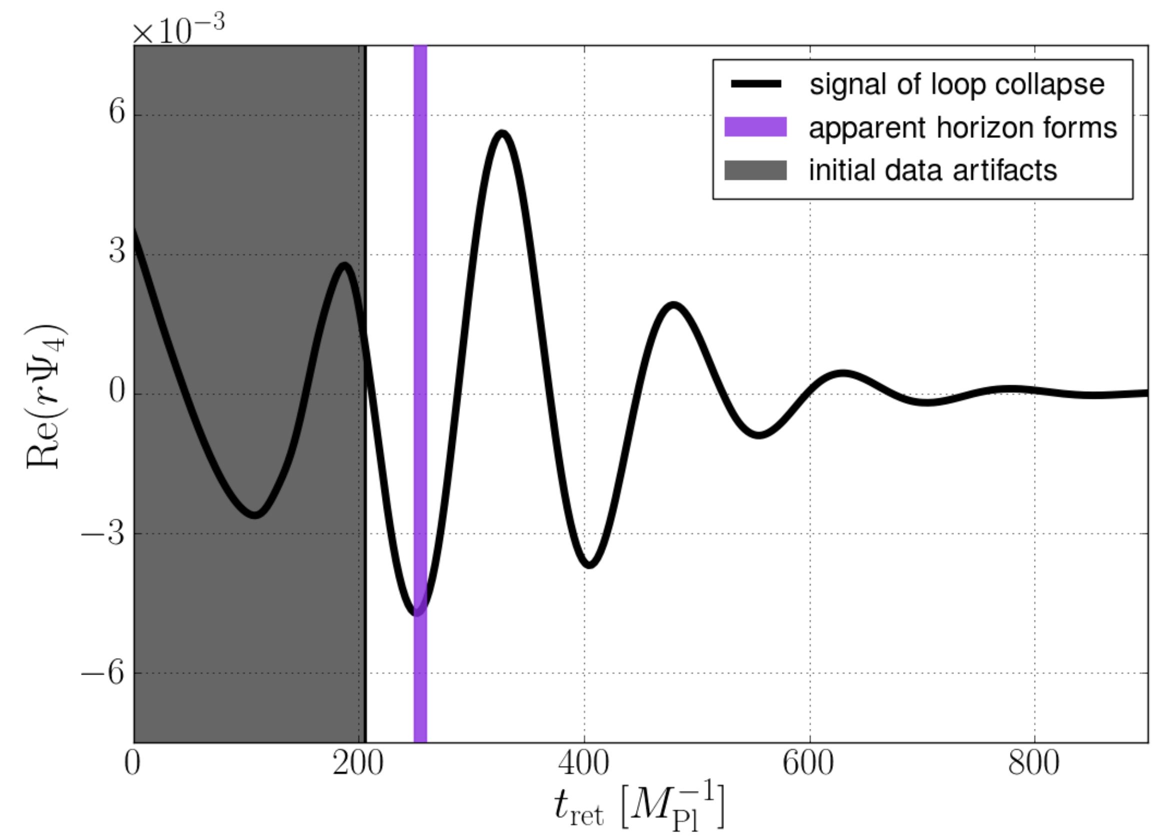


FIG. 1. **GW for a BH formed from circular cosmic string loop collapse:** We plot the real part of the dominant $l = 2$ $m = 0$ mode of $r\Psi_4$ over time. The loop has tension $G\mu = 1.6 \times 10^{-2}$ and an initial radius $R = 100\ M_{\rm Pl}^{-1}$. The grey shaded area of the plot are mixed with stray GWs that arise as artifacts of the initial data. The x-axis $t_{\rm ret} = t - r_{\rm ext}$ is the retarded time where $r_{\rm ext}$ is the extraction radius.