Recent developments on topological defects in cosmology

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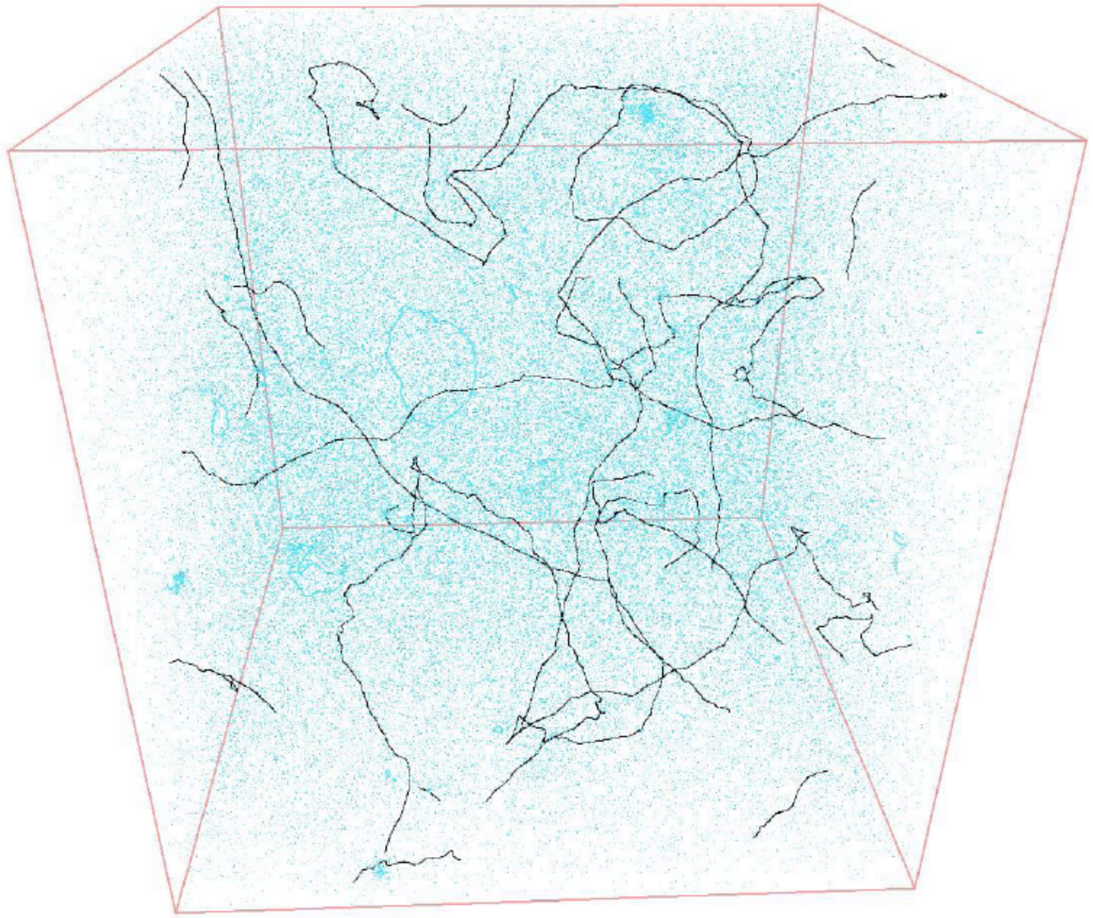
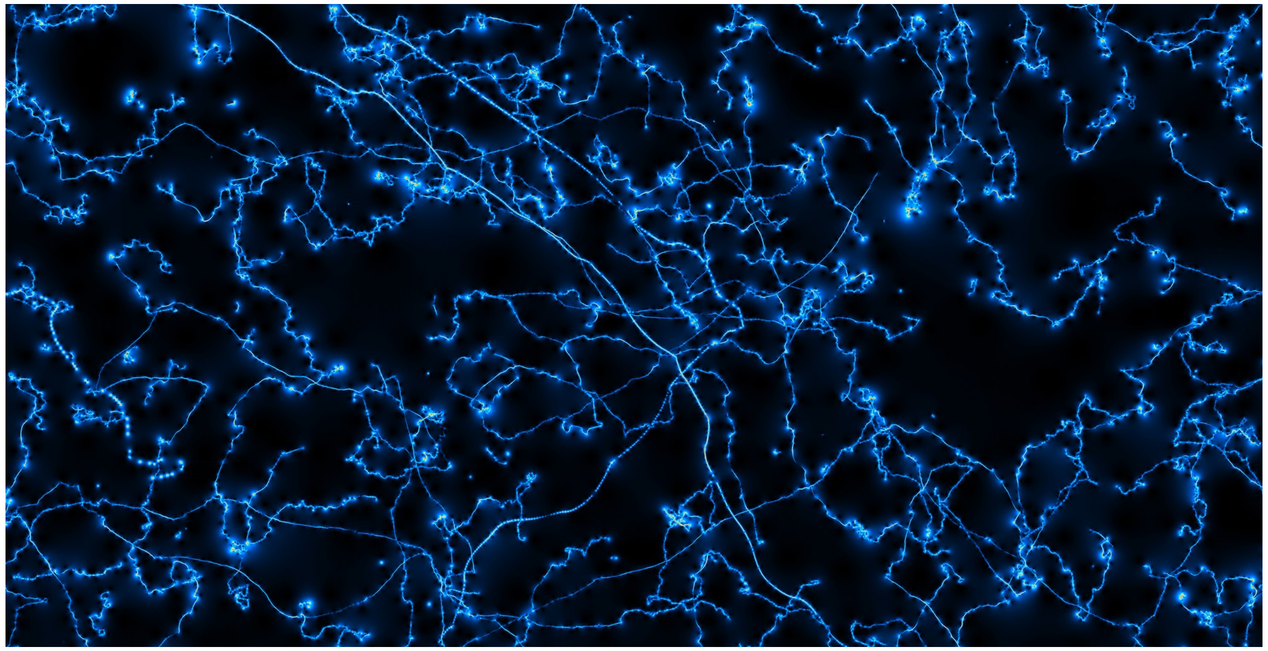
Cosmic strings

1) Modeling
2) GW constraints (LIGO-Virgo-Kagra O3; NanoGrav; predictions for LISA)
3) Constraints from the diffuse gamma-ray background



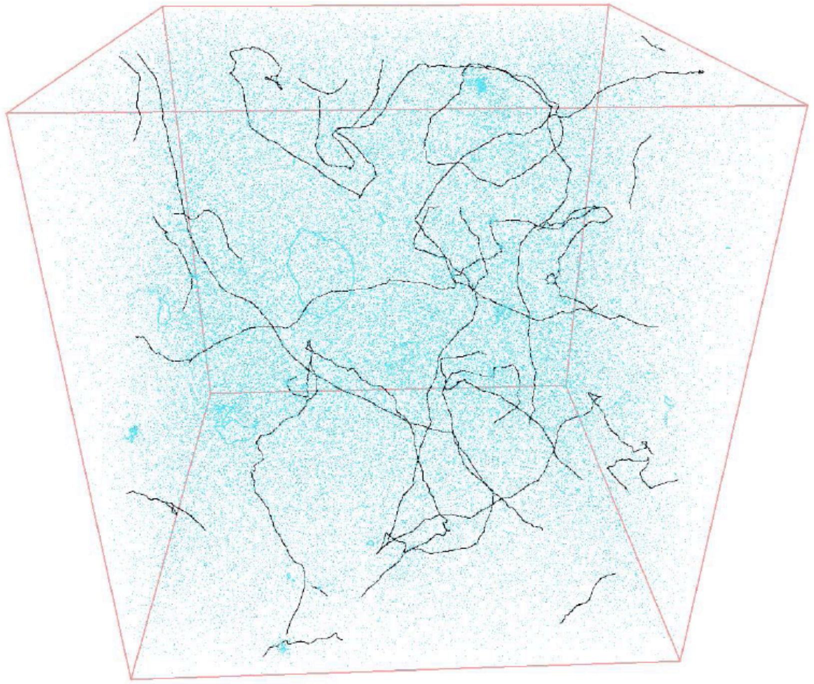


Ringeval, Adv.Astron. 2010 (2010),380507

Cosmic strings

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

- – vortex loops in He4, He3, superconductors, strings in nematic liquid crystals.
- – cosmic strings in cosmological phase transitions *[Kibble ’76]*



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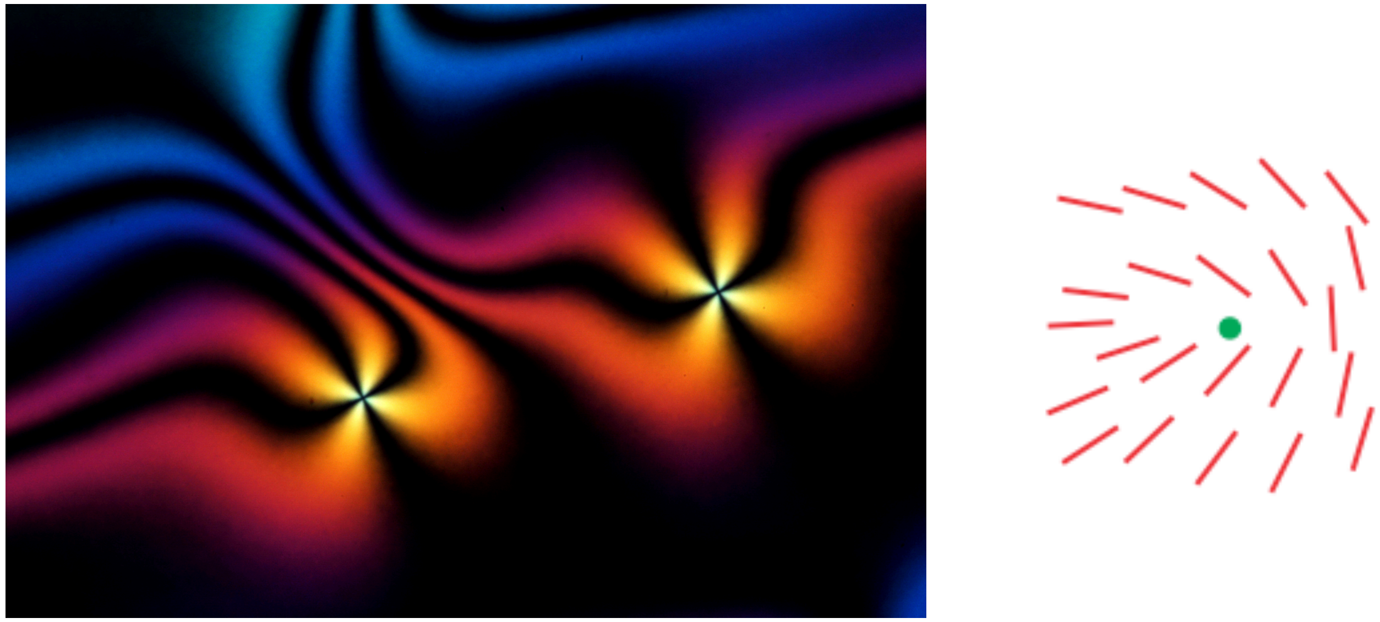


$G = SO(3), H = O(2) \Rightarrow \pi_1(\mathcal{M}) = \mathbf{Z}_2$

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

– Strings form when $\Pi_1(G/H) = \Pi_1(\mathcal{M}) \neq 1$

– Any spontaneous breaking of a U(1) has string solution, since $G = U(1)$ $\mathcal{M} = S^1$ $\Pi_1(\mathcal{M}) = Z$

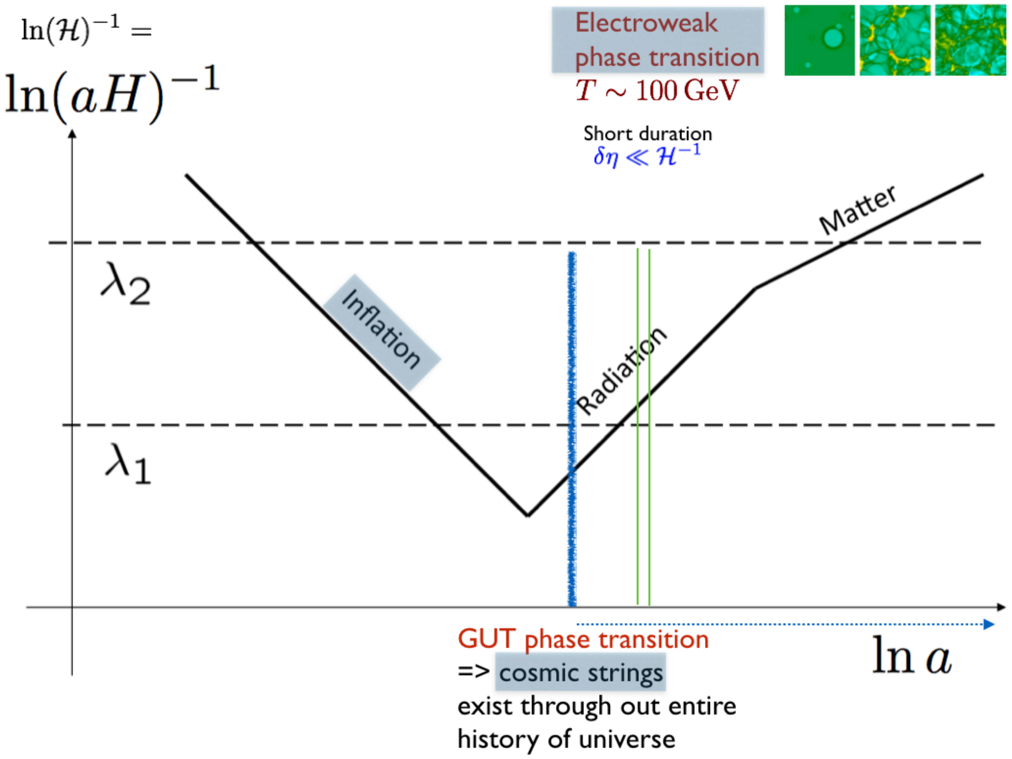
– More complex vacuum manifolds with string solutions appear in various GUT theories.

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

Cosmic strings in cosmology

– If formed, cosmic strings exist throughout the evolution of the universe. Possible observational effects

CMB anisotropies & B-modes;
lensing,…
particle emission -> gamma-ray background
Gravitational waves;

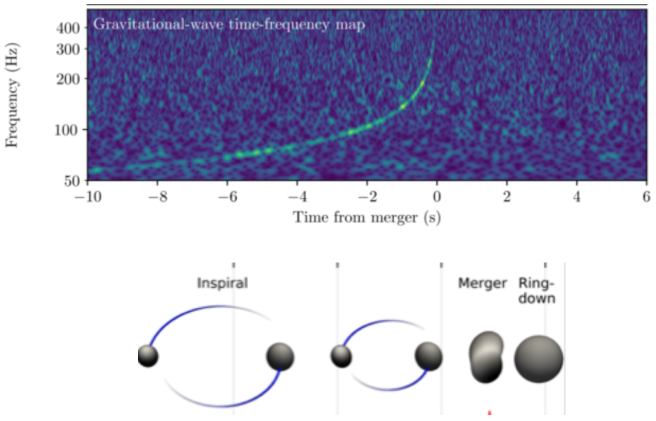


GUT phase transition
=> cosmic strings
exist through out entire
history of universe

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

- Occasional sharp Individual bursts (resolved GW signals)

Analogue of



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

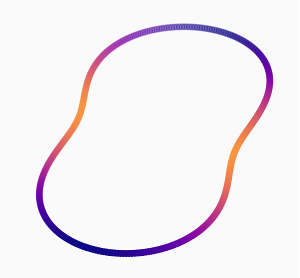
$$\Omega_{\mathrm{GW}}(\ln f) = \frac{1}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}\ln f}$$

Constraints string tension

$$\boxed{G\mu \sim 10^{-6}\left(\frac{\eta}{10^{16}\ \mathrm{GeV}}\right)^{2}}$$

1) Modeling

$$\frac{\mathrm{d}\ell}{\mathrm{d}t}$$ = rate at which a cosmic string loop of loses energy



1) GW emission is the dominant decay mode:

Constraints from LIGO-Virgo O3 run: SGWB and search for individual GW bursts

[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 *]*

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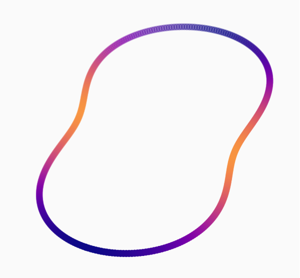

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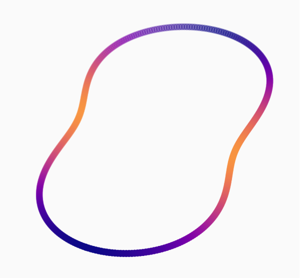
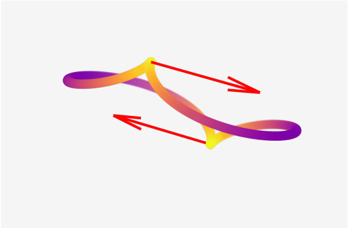


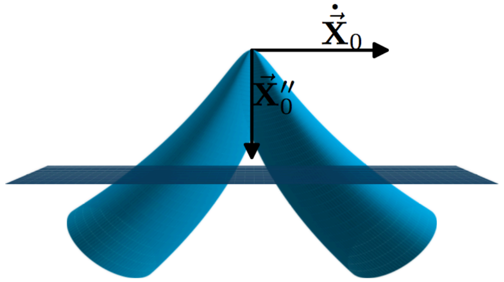
2) other decay channels, into both GWs and particles

Observable effects on both SGWB and diffuse gamma-ray background

[Particle emission and gravitational radiation from cosmic strings: observational constraints , P.Auclair, D.A.S, T.Vachaspati, Phys.Rev.D 101 (2020) 8, 083511, arXiv 1911.12066 ; P.Auclair, K.Leyde and DAS, in preparation]



cusps, kinks

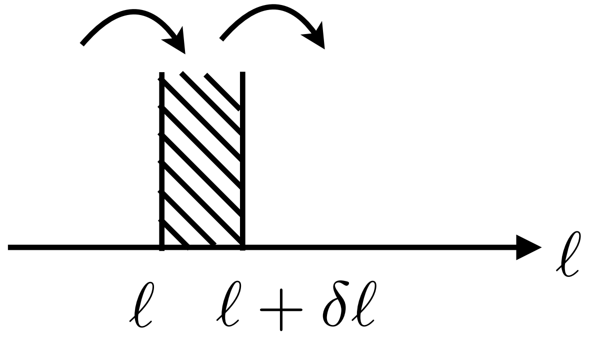


Loop distribution

[$n(\ell,t)\mathrm{d}\ell$ =number of loops/unit volume with length between ℓ & $\ell+\mathrm{d}\ell$ at time t]

– Satisfies a Boltzmann equation:

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



scale factor

rate at which loops loose energy

loop production function (LPF)

= Rate at which loops of length l (assumed non-self-intersecting), are chopped off the infinite string network at time t, per unit volume]

– given $\frac{\mathrm{d}\ell}{\mathrm{d}t}$, can be integrated, given the LPF (thus defining different models).

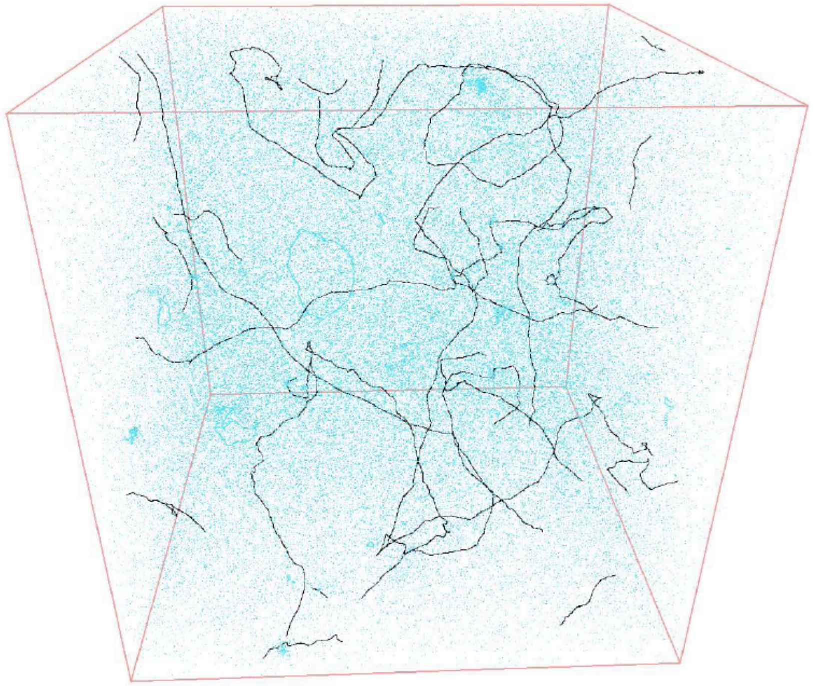
– Assume scaling of infinite string network: $\mathcal{P}(\ell,t) = Ct^{-5}f(\ell/t)$

$$\gamma \equiv \frac{\ell}{t}$$

Broad-brush picture:

- loops are formed at all times, removing energy from the infinite string network.
- loops decay into GWs and possibly other 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 $\frac{\rho_\infty}{\rho_{\rm bkg}} \sim \frac{a^p}{t^2} \sim {\rm const}$ $\rho_{\rm bkg} \sim a^{-p},\ a = t^{2/p}$



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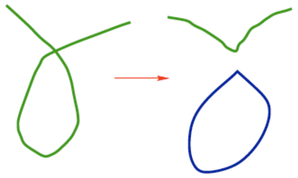


Numerical simulations *[Blanco-Pillado, Olum &Wachter; Ringeval&Bouchet&Sakellariadou;Allen+Shellard, Hindmarsh et al….]*
NG or field theory equations of motion in an expanding universe given a representative network initial conditions + intercommutation. Radiation and matter era simulations. Limited in time and length scale. Smallest scale physical processes not included: grav radiation and backreaction, (and in NG simulations, particle emission). Further simulations to study some of these effects on loops.

Analytical modelling *[Kibble, Martins&Shellard, Polchinski et al, Austin&Kibble&Copeland, ...]*
difficult because of non-linearities of problem, but not time limited and can probe different cosmological backgrounds. Include grav radiation and attempts at gravitational back reaction.

- different semi-analytical loop-production function models. All agree with numerical simulations on the scales on which these are valid.

Model A: *[Blanco-Pillado, Olum and Shlaer, 2014]*

$$t^5\mathcal{P}(\ell,t) = C\delta_{\rm D}\left(\frac{\ell}{t}-\alpha\right)$$

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

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

Model B: *[Lorentz, Ringeval + Sakellariadou, 2010]*

$$t^5\mathcal{P}(\ell,t) = C\left(\frac{\ell}{t}\right)^{2\chi-3}$$

[Polchinski, Rocha et al]

loops produced up to a "backreaction scale" $\gamma \equiv \dfrac{\ell}{t} > \gamma_c$

$$\gamma_c = \ell_c/t \simeq 10(G\mu)^{1+2\chi} \ll \Gamma G\mu$$

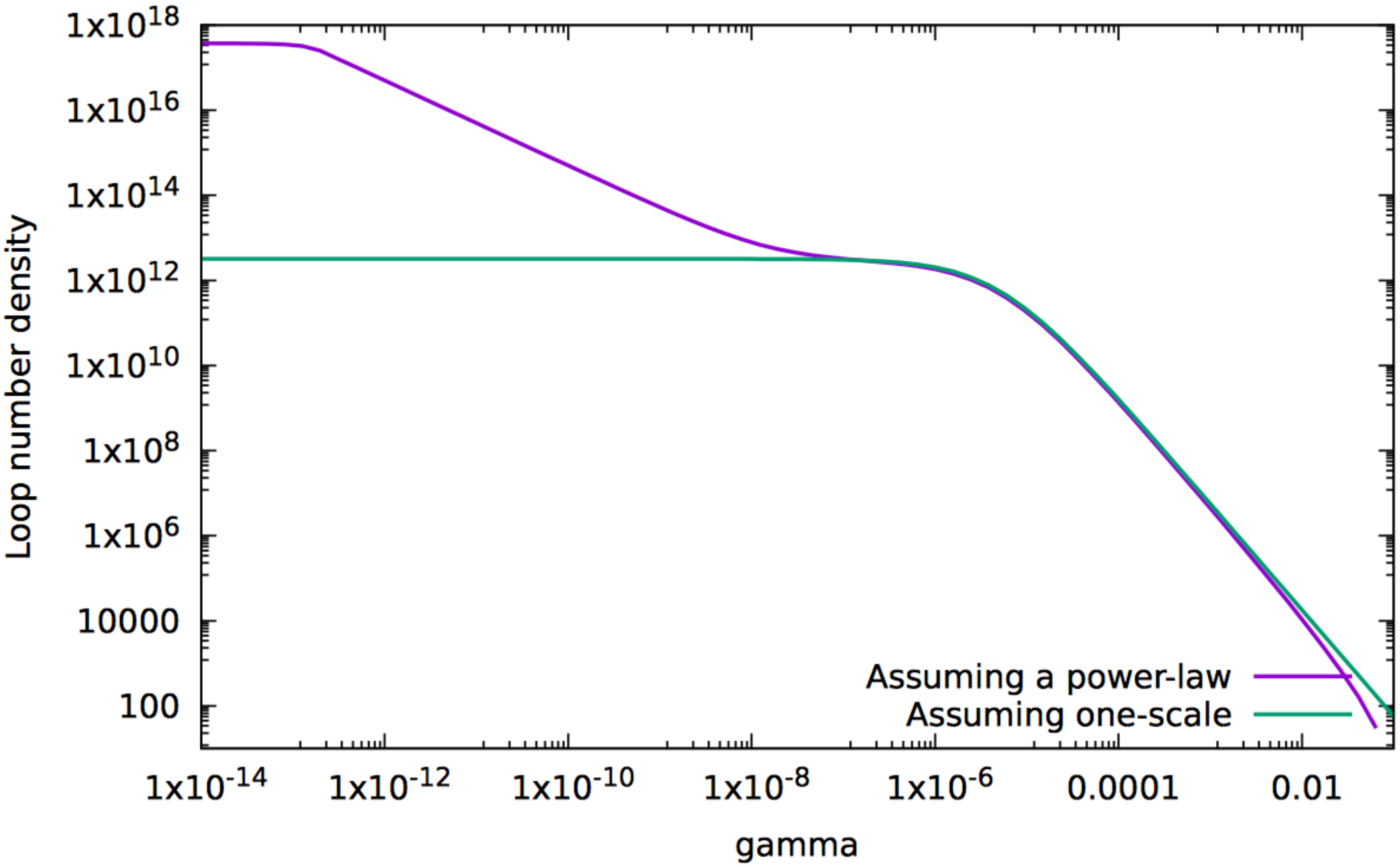
Solution of Boltzmann equation calibrated to simulations of Ringeval et al on large scales

Models C: interpolates between A and B

(aims to help understand features to which burst + stochastic searches are sensitive) *[Auclair et al, Auclair 2019,2020]*

Models A and B :
– similar loop distributions on large scales,
– differences small scales where model B has many more loops.
Expect these contribute to SGWB at high frequencies.

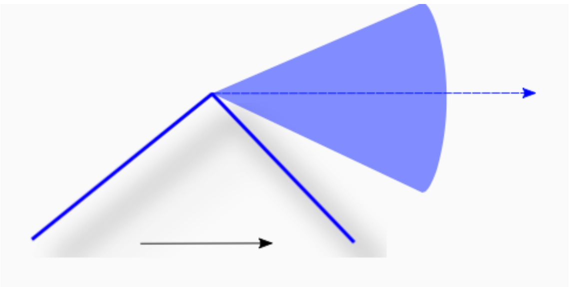
[Auclair et al, Auclair 2019,2020]

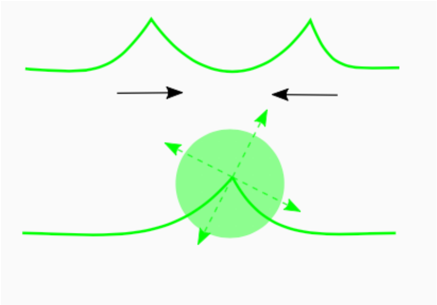


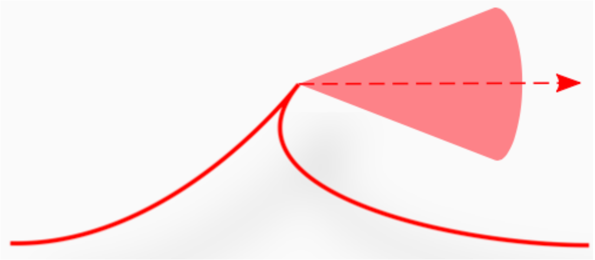
γ_c γ_d

I) Constraints from GWs (LIGO-Virgo O3 run)

- Occasional sharp **individual bursts** (resolved GW signals)
  - – kinks
  - – kink-kink collisions
  - – cusps



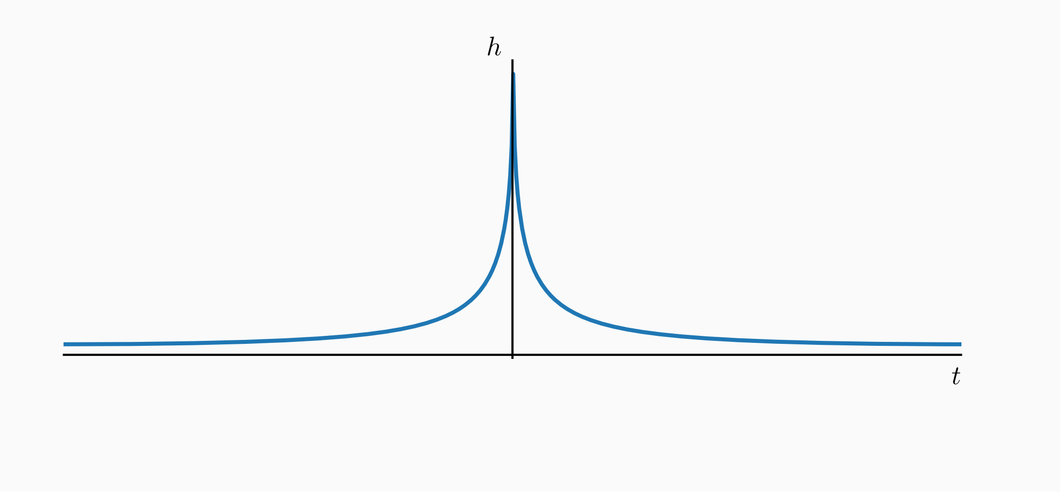




GW-form	$h_i(\ell, z, f) = A_i(\ell, z) f^{-q_i}$
Amplitude	$A_i(\ell, z) = g_{1,i} \dfrac{G\mu \ell^{2-q_i}}{(1+z)^{q_i-1} r(z)}$

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

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



[Vachaspati+Vilenkin, Damour+Vilenkin; Siemens et al]

- & SGWB [sum of the incoherent superposition of many bursts from cusps, kinks and kink-kink collisions (removing infrequent bursts)]

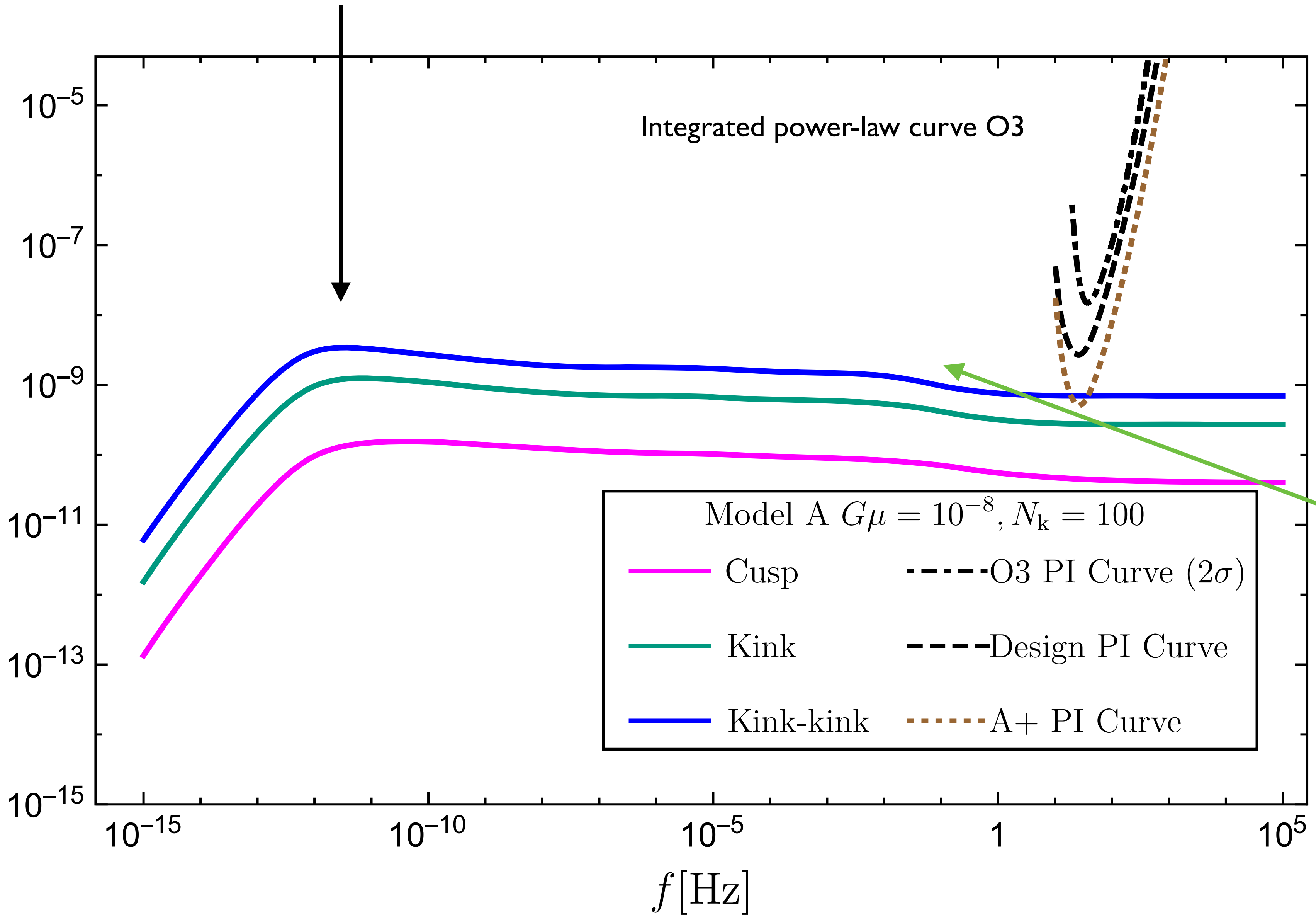
$$\Omega_{\rm GW}(f) = \frac{4\pi^2}{3H_0^2} f^3 \sum_i \int dz \int d\ell \, h_i^2 \times \frac{d^2 R_i}{dz\, d\ell}.$$

← burst rate/redshift/length *[Damour and Vilenkin, Siemens et al…]*

↑ strain from cusps/kinks/kk collisions.

Generic shape
(Model A)

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



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")

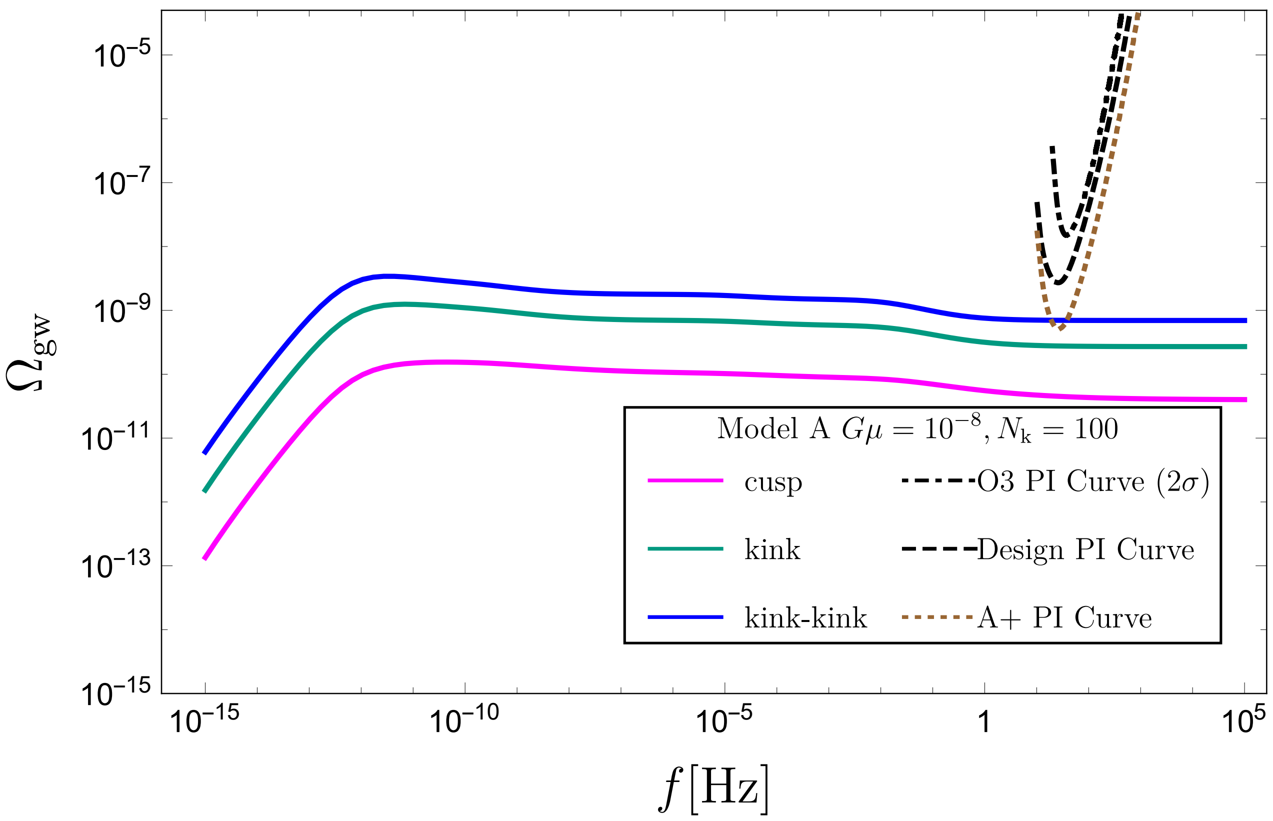
Flat LCDM

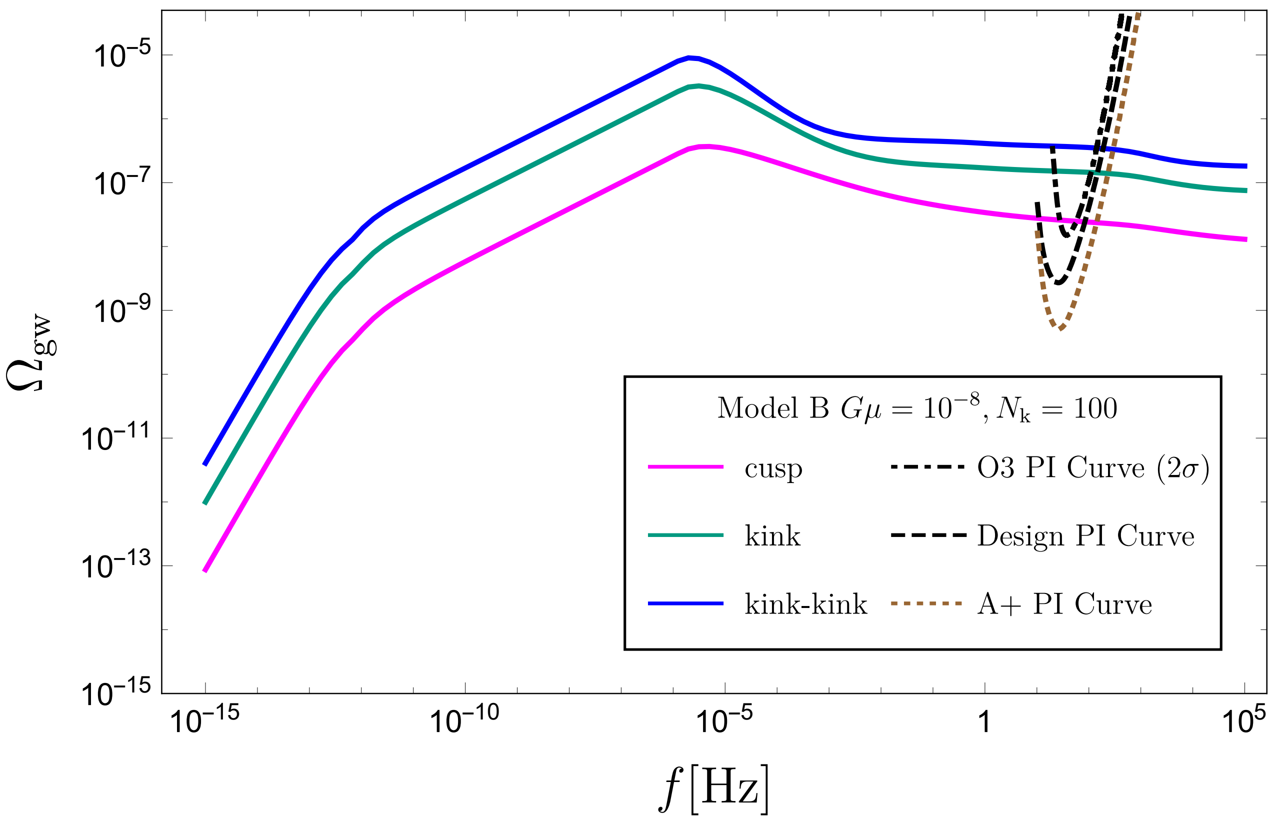
Standard Model numbers of degrees of freedom as given by microMEGAS

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

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

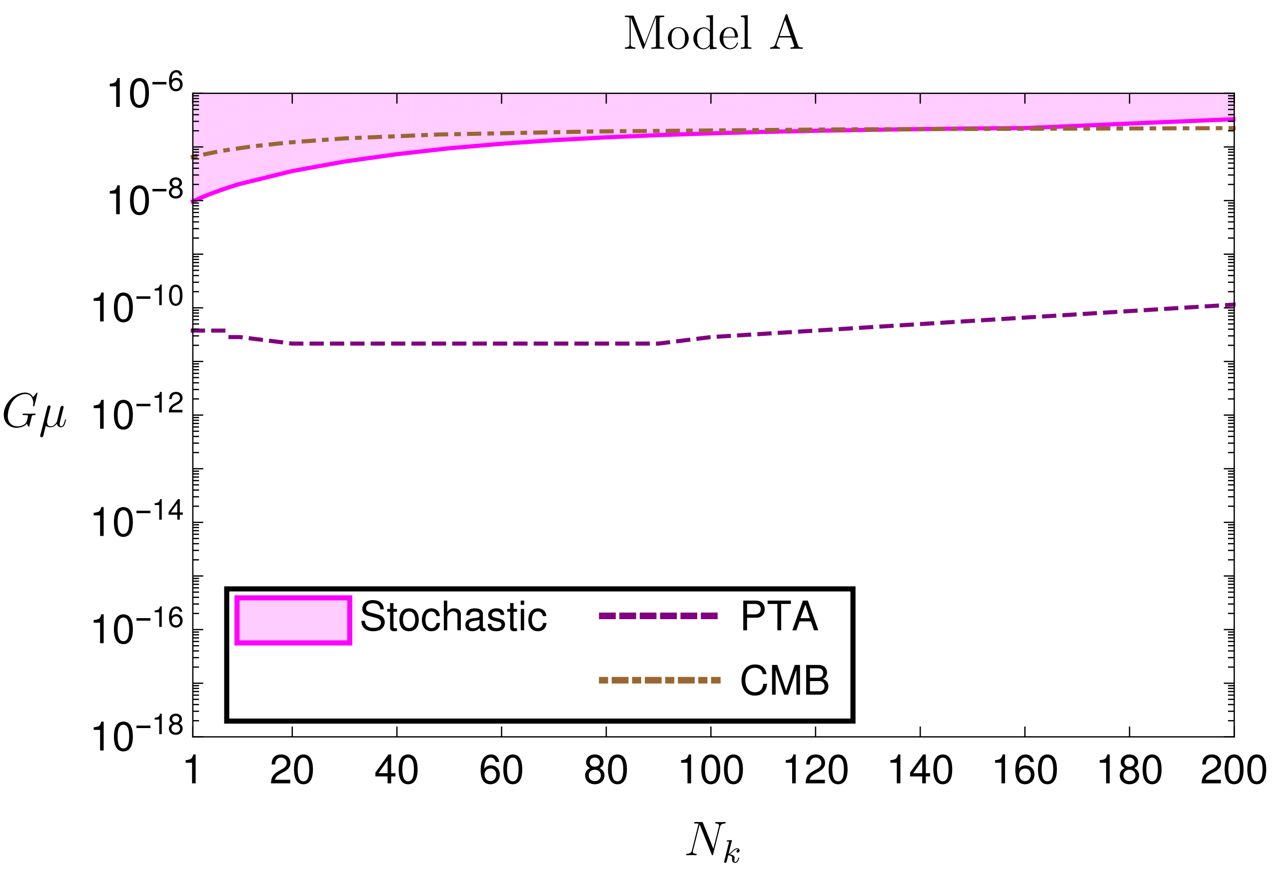
Models A, B $G\mu = 10^{-8}$

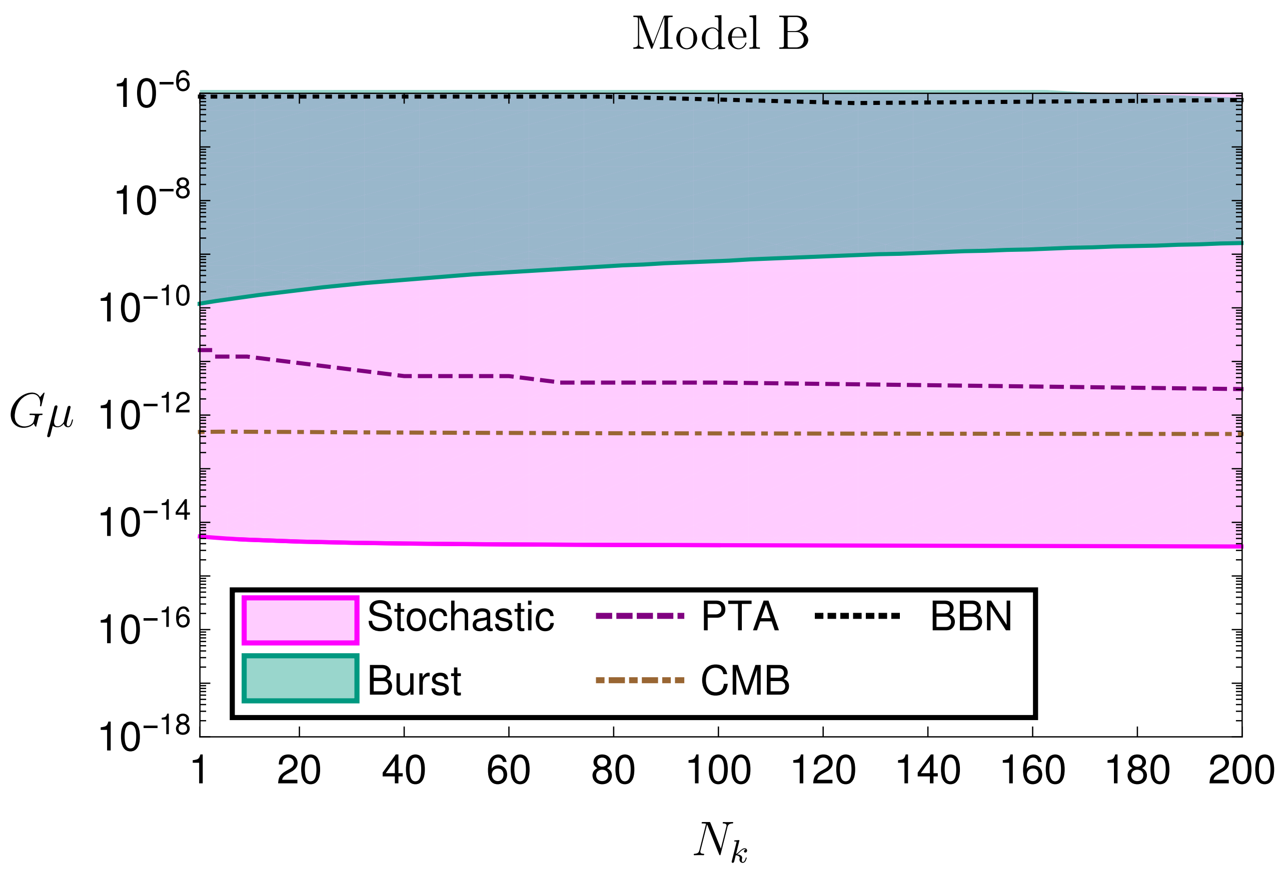




Exclusion plots

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





Excluded:

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

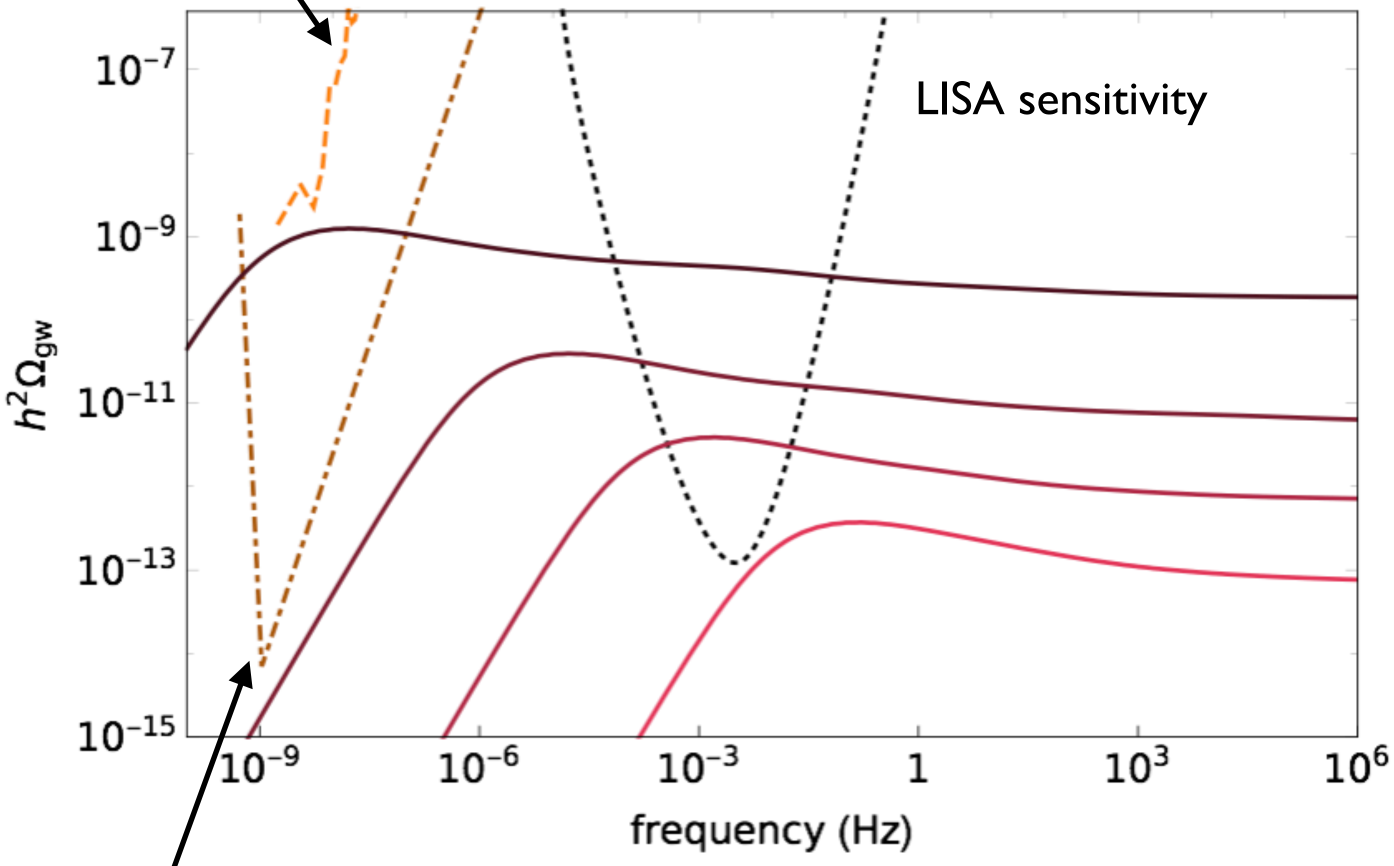
Excluded:

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

- Relative to O1&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



$G\mu = 10^{-10}$

$G\mu = 10^{-13}$

$G\mu = 10^{-15}$

$G\mu = 10^{-17}$

(projected) SKA sensitivity

[2009.06555]

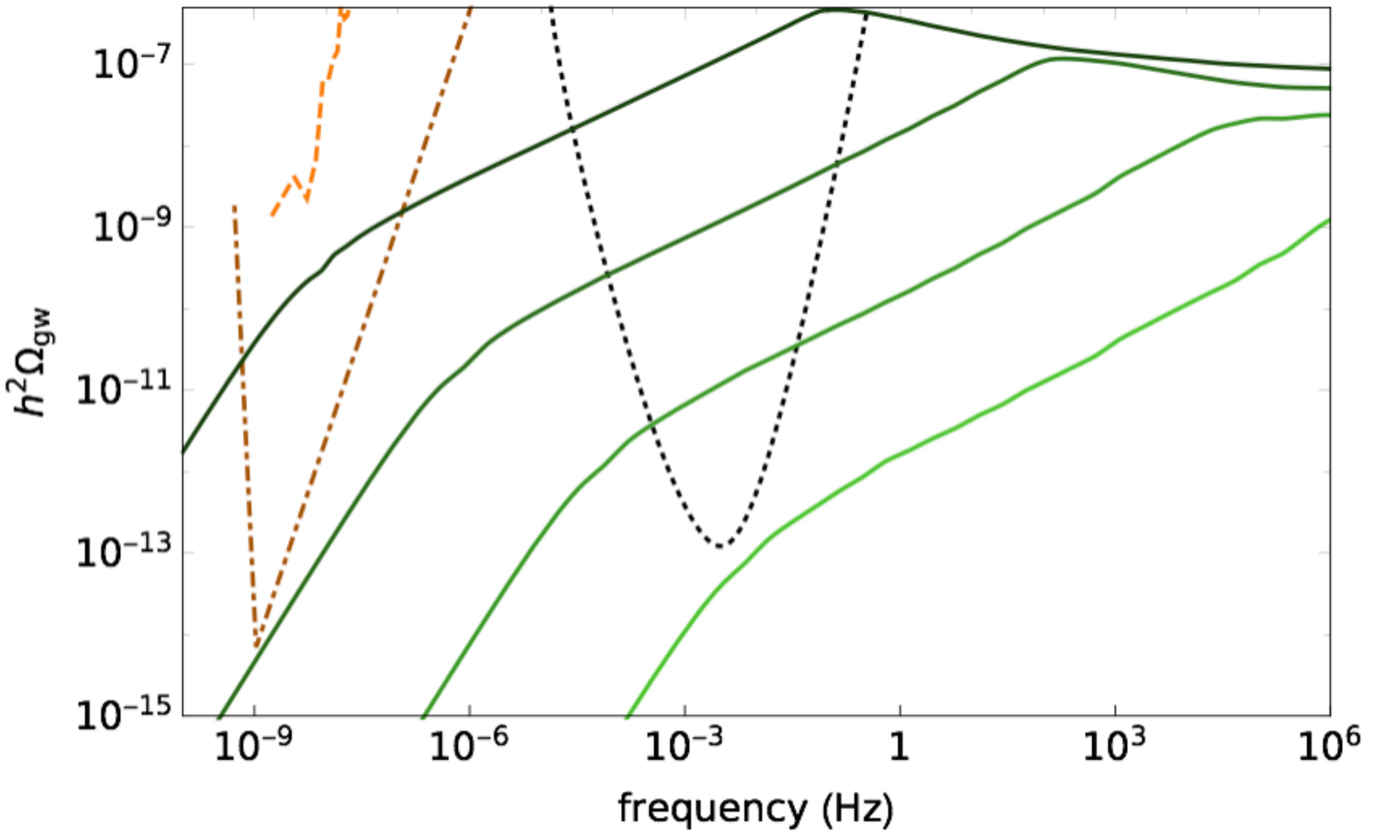
NANOGrav PT data constraint, Model A:

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

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

LISA will be able to probe cosmic strings with tensions

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



$G\mu = 10^{-10}$

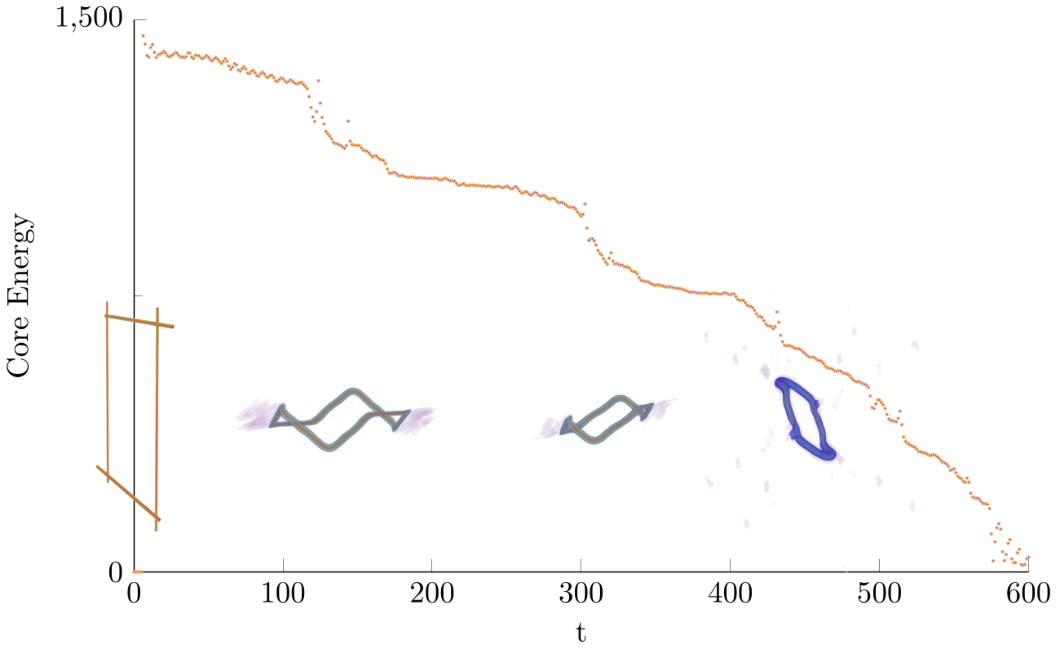
$G\mu = 10^{-13}$

$G\mu = 10^{-15}$

$G\mu = 10^{-17}$

3) Particle production + GWs

– 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*

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

Cusps
[Blanco-Billado+Olum]

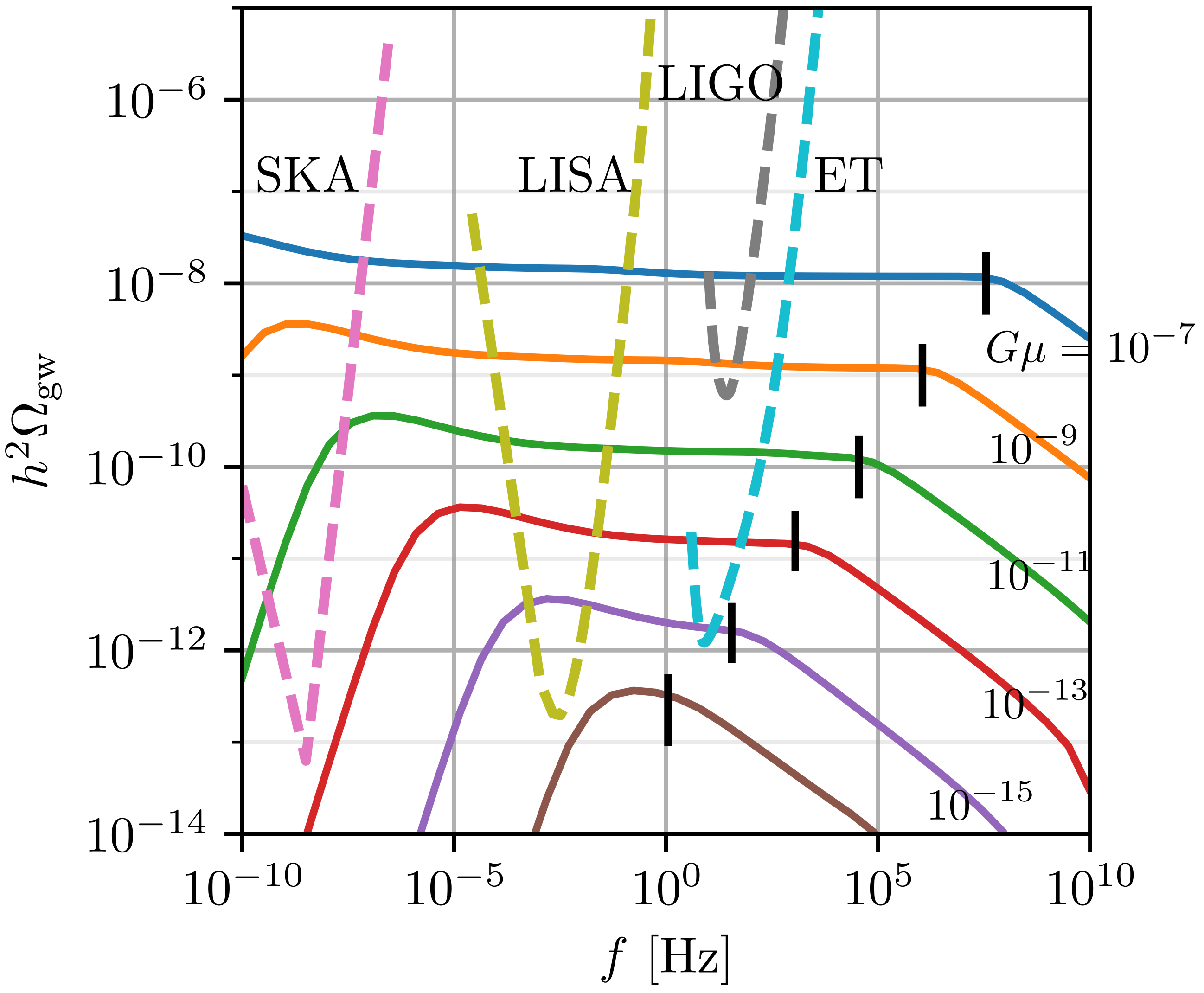
string width $w \sim \mu^{-1/2}$

- Loop distribution obtained by solving a Boltzmann equation.

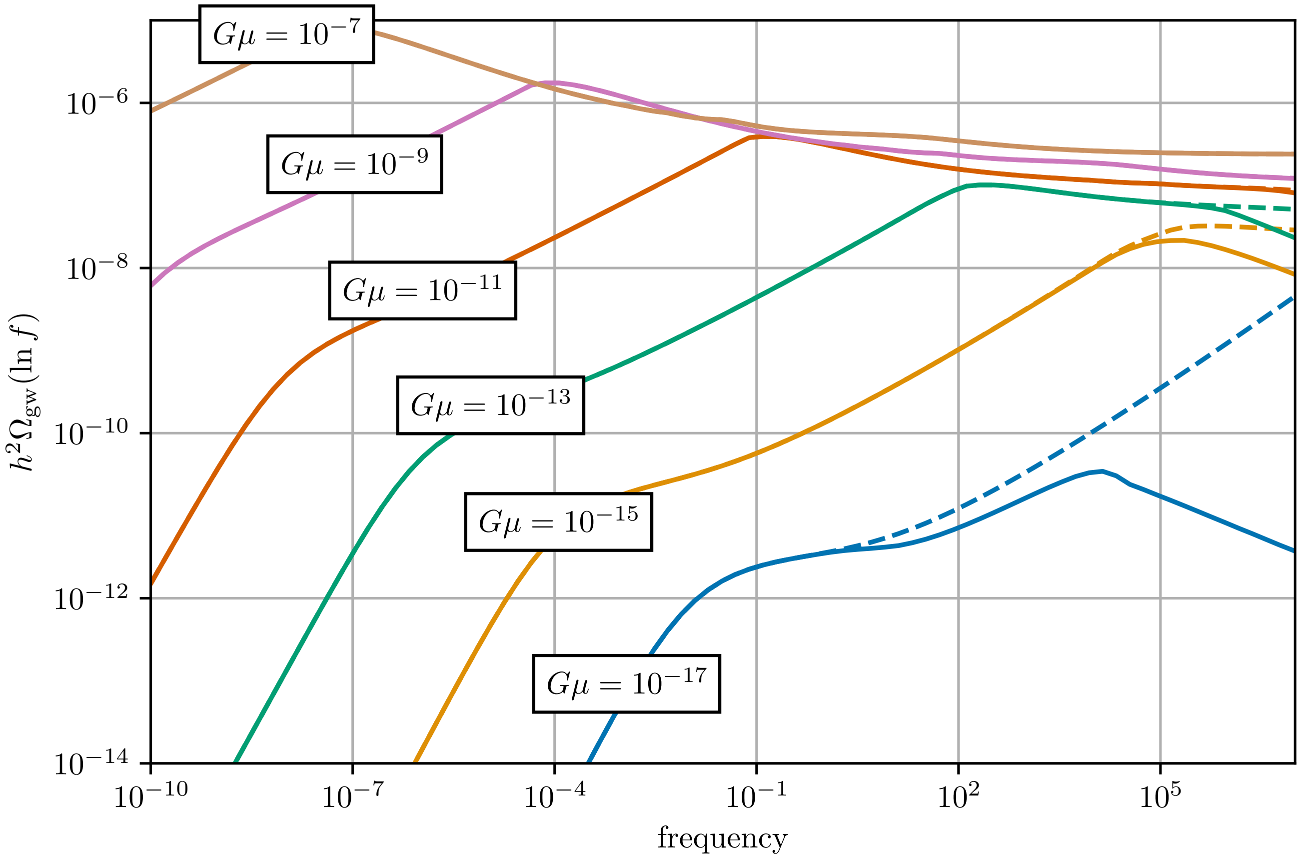
$$\frac{\partial}{\partial t}\bigg|_{\ell}\left(a^3 n(t,\ell)\right) + \frac{\partial}{\partial \ell}\bigg|_{t}\left(\frac{\mathrm{d}\ell}{\mathrm{d}t}a^3 n(t,\ell)\right) = a^3\mathcal{P}(t,\ell)$$

Stochastic GW background

Cusps, Model A



Cusps, Model B



Spectra cutoff at high frequency, beyond range of GW detectors: previous bounds unchanged

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

Particle emission: Diffuse gamma-ray background

- loops radiate also into particles. Assume decay into standard model Higgs particles, of which fraction $f_{\rm eff}$ cascade down into gamma-rays. Contribution from strings to the diffuse gamma-ray background:

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

Energy loss from strings /time/volume

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

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

$$\boxed{\omega_{\rm DGRB}^{\rm obs} \lesssim 5.8 \times 10^{-7} \ {\rm eV cm}^{-3}}$$

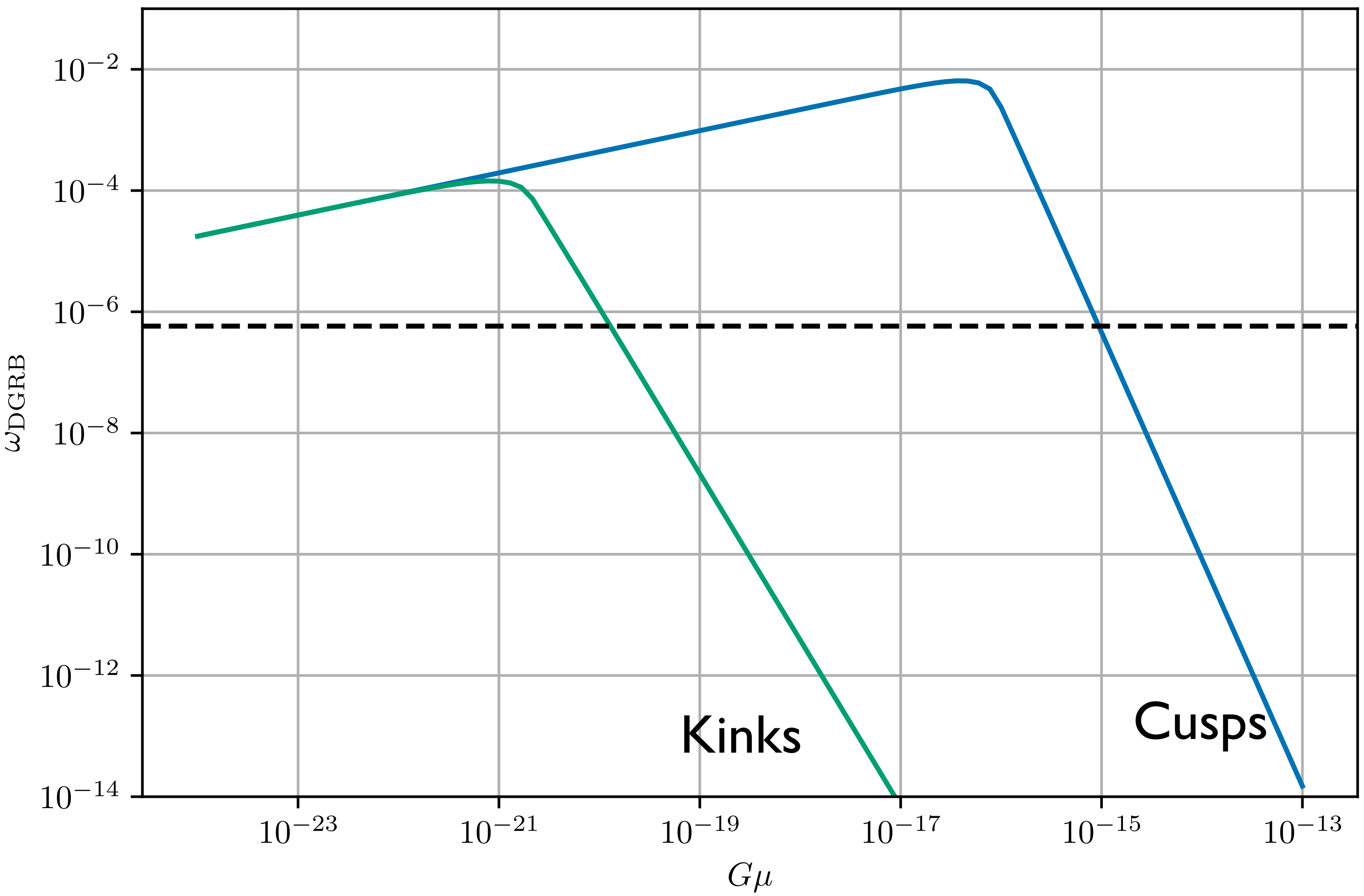
A. A. Abdo et al. (Fermi-LAT), Phys. Rev. Lett. **104**, 101101 (2010)

- Model A: no further constraints

[Particle emission and gravitational radiation from cosmic strings: observational constraints , P.Auclair, D.A.S, T.Vachaspati, Phys.Rev.D 101 (2020) 8, 083511, arXiv 1911.12066 ;

[P.Auclair, K.Leyde and DAS, in preparation]

- Model B, and assuming $f_{\rm eff} = 1$



$\omega^{\rm obs}_{\rm DGRB} \lesssim 5.8 \times 10^{-7}$ eVcm^{-3}

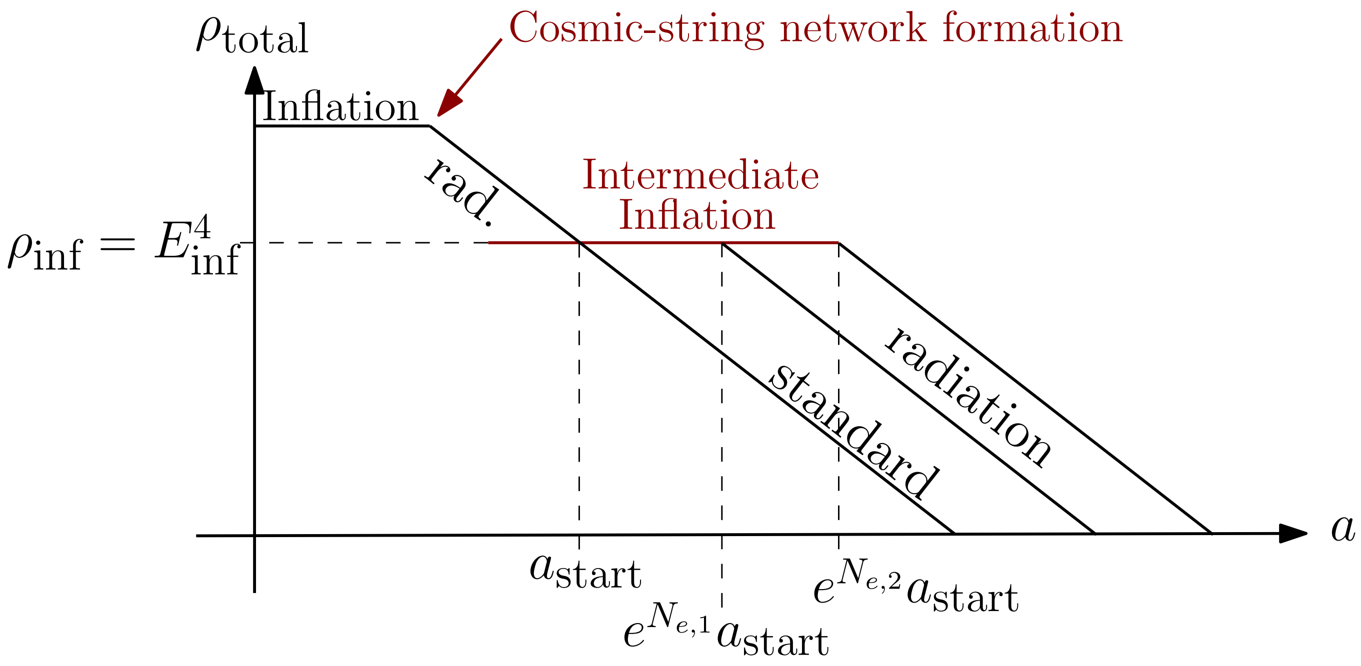
A. A. Abdo et al. (Fermi-LAT), Phys. Rev. Lett. **104**, 101101 (2010)

GW constraints + gamma-ray: this model is squeezed!

$$10^{-15} \lesssim (G\mu)_{\rm cusps} \lesssim 4.0 \times 10^{-15}$$

Impact of changing cosmological evolution

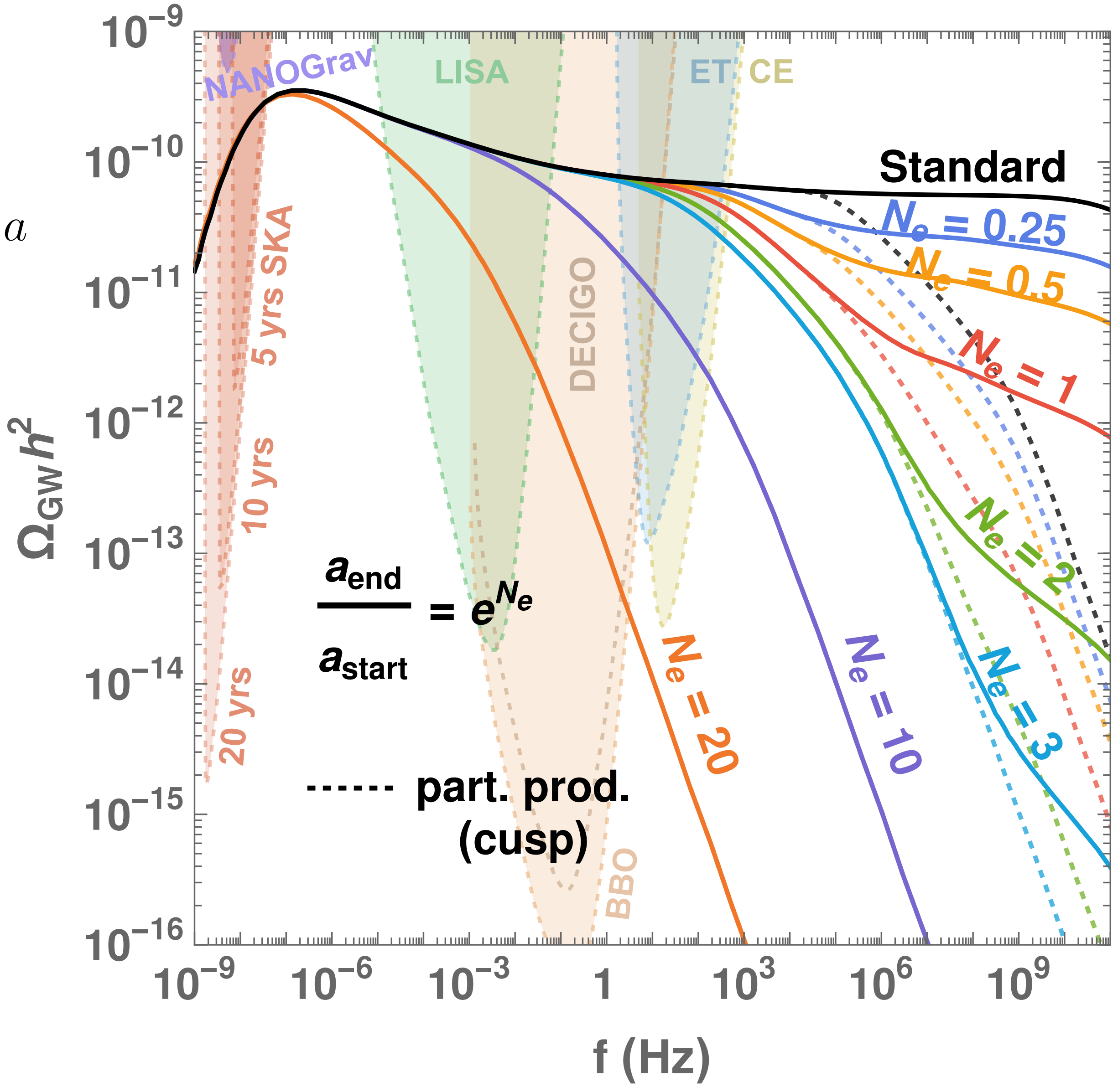
[Gouttenoire, Servant & Simakachorn, 1912.02569]



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

Intermediate Inflation: $E_{\rm inf}$ = 100 TeV

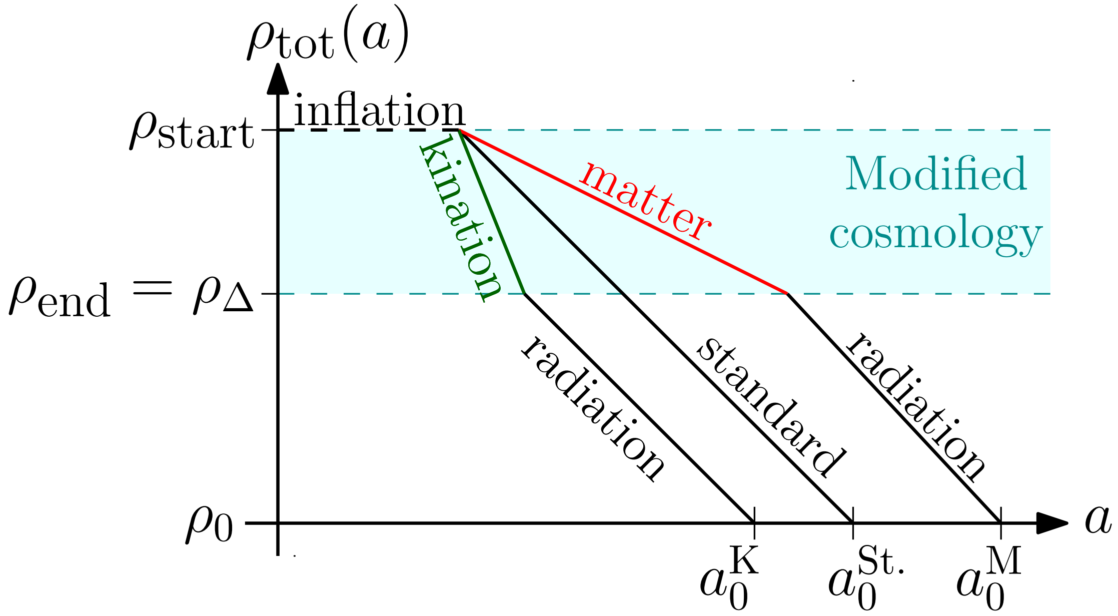
($G\mu = 10^{-11}$, $\Gamma = 50$, $\alpha = 0.1$)



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)

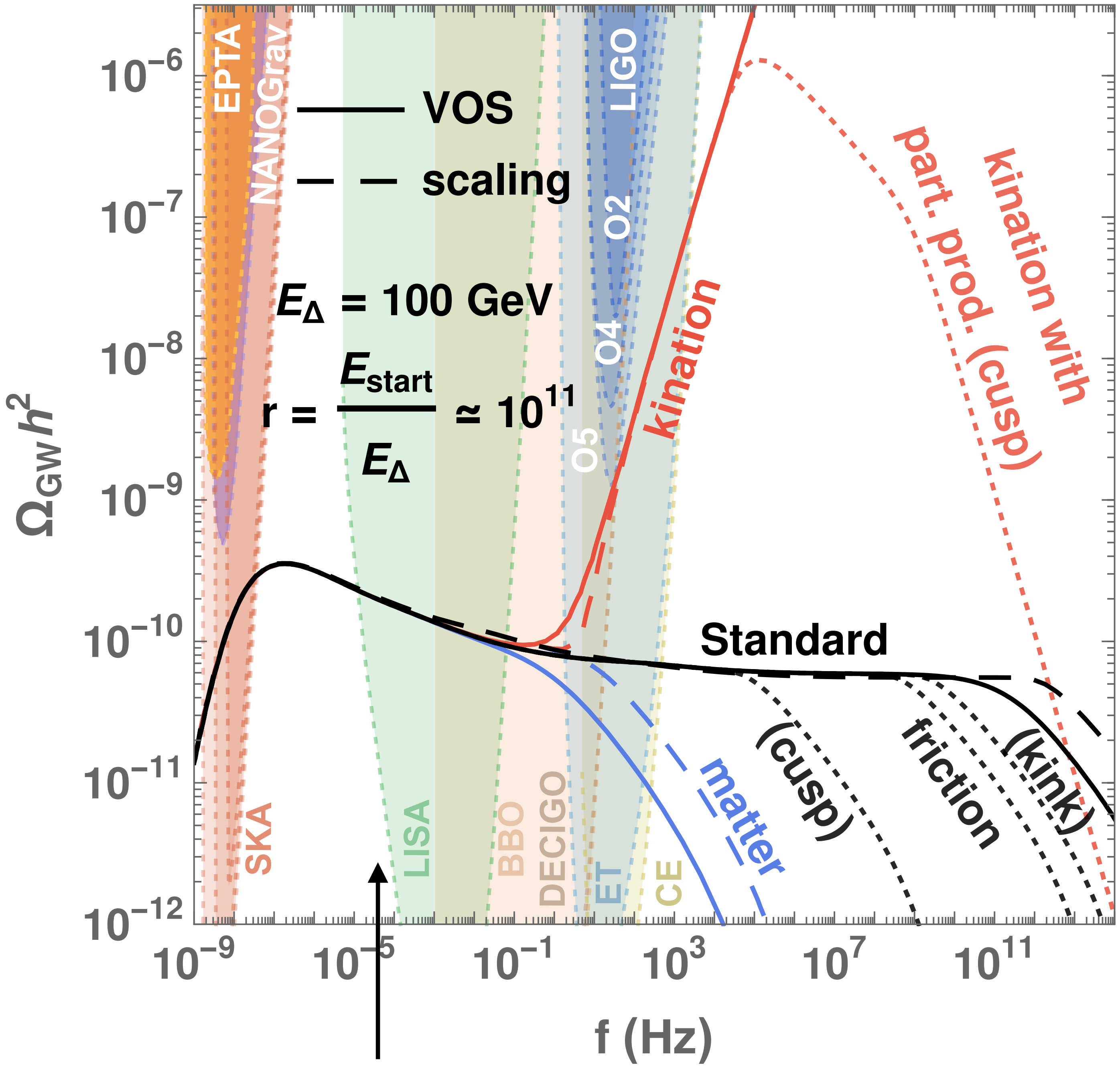
$\rho \propto a^{-6}$

$a \sim t^{1/3}$

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 $r \equiv \left(\frac{\rho_{\rm start}}{\rho_{\rm end}}\right)^{1/4} \equiv \left(\frac{E_{\rm start}}{E_\Delta}\right) \simeq 10^{11}$

Conclusions

- Cosmic strings can be very good probes of cosmology, through SGWB

- Presented latest LIGO-Virgo O3 constraints on NG strings for different models, (Nk as a new free parameter); predictions for LISA

- Cosmic strings beyond the standard picture: particle particle emission.

- Effects of modified cosmology *[Many authors, including Gouttenoire, Servant & Simakachorn, 1912.02569]*

- Have not discussed global strings with long range forces (such as axion strings), which can also radiate Goldstones.

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

  Fully general relativistic dynamical simulations of Abelian Higgs cosmic strings using 3+1D numerical relativity (GRChombo) *[Helfer, Aurrekoetxea & Lim, 1808.06678]*.

Cosmic String Loop Collapse in Full General Relativity

Thomas Helfer[a],[*] Josu C. Aurrekoetxea [a],[†] and Eugene A. Lim[a‡]
[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

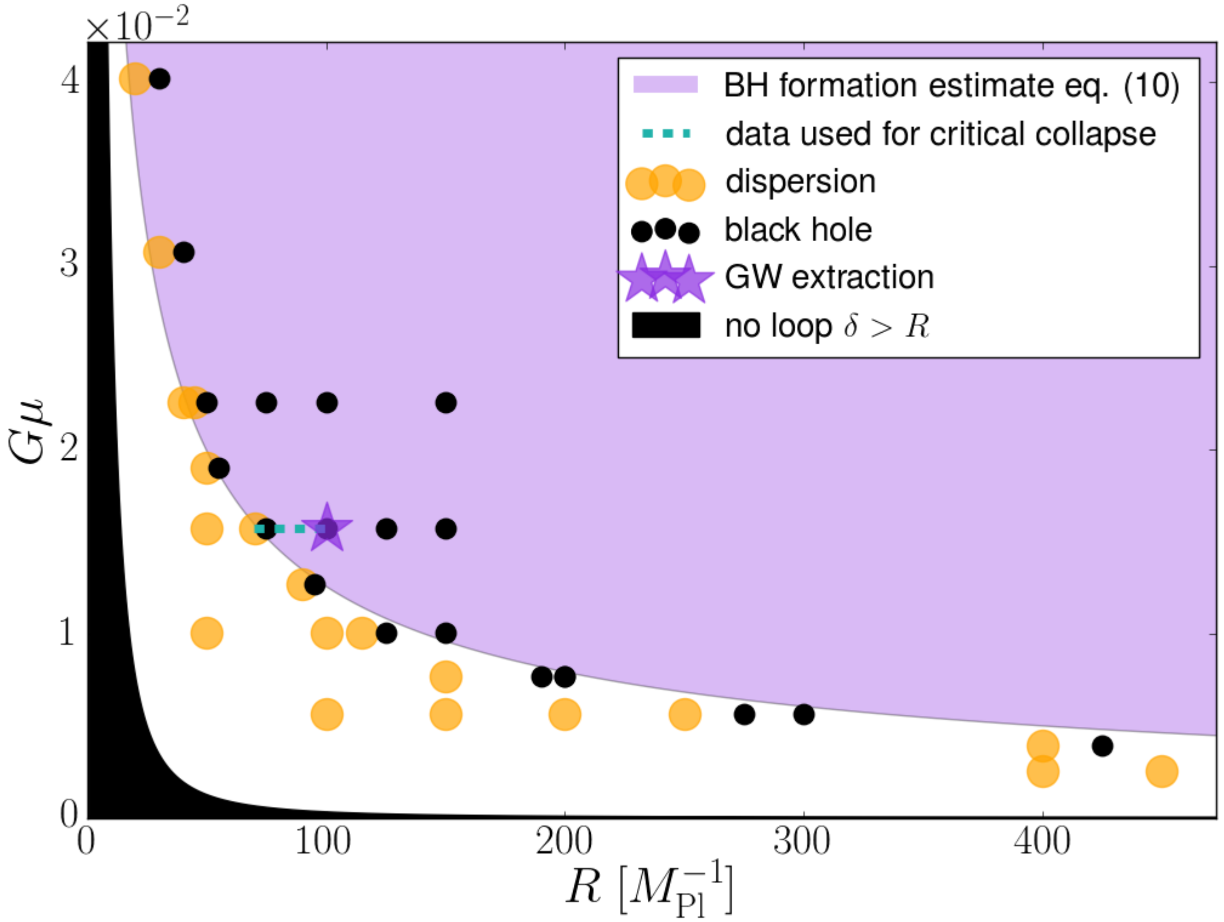


FIG. 2. **Overview of simulations :** The loop can either form a BH or unwind and radiate all its mass. The analytical expression derived from the hoop conjecture accurately predicts the outcome. Movie links for the evolution over time of the collapse are available for the dispersion [18] and black hole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

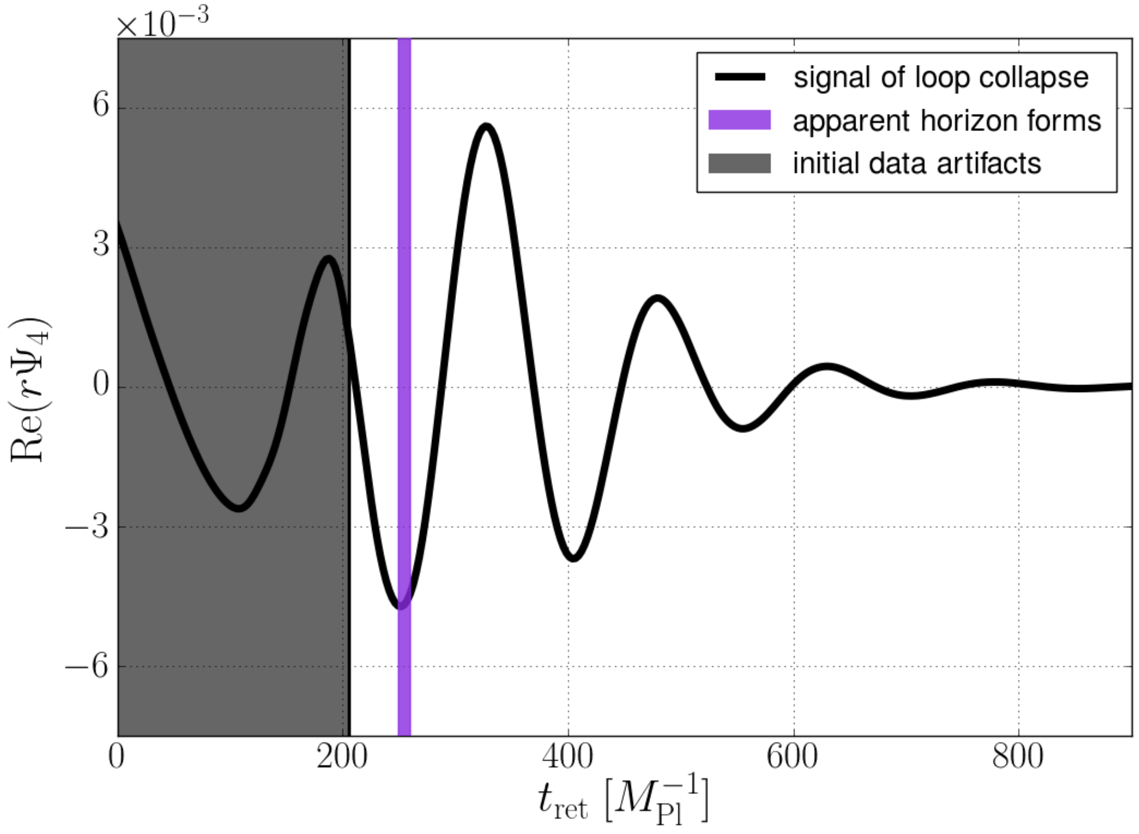


FIG. 1. **GW for a BH formed from circular cosmic string loop collapse:** We plot the real part of the dominant $l = 2$ $m = 0$ mode of $r\Psi_4$ over time. The loop has tension $G\mu = 1.6 \times 10^{-2}$ and an initial radius $R = 100\ M_{\rm Pl}^{-1}$. The grey shaded area of the plot are mixed with 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.

Impact of world-sheet degrees of freedom

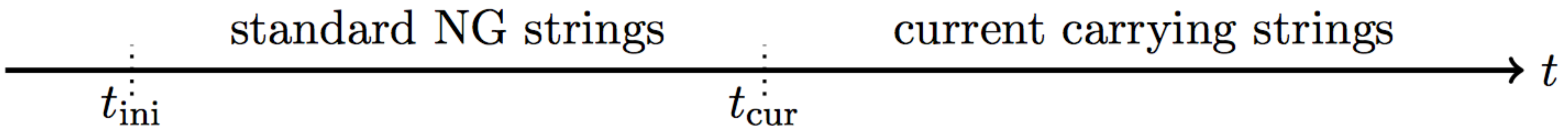
[Auclair et al, 2010.04620]

- 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.



standard NG strings

current carrying strings

t_{ini}

t_{cur}

t

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

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

- Determining Ω_{tot}, and using the current constraints on $\Omega_{\text{dm}}h^2 \simeq 0.12$ 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.

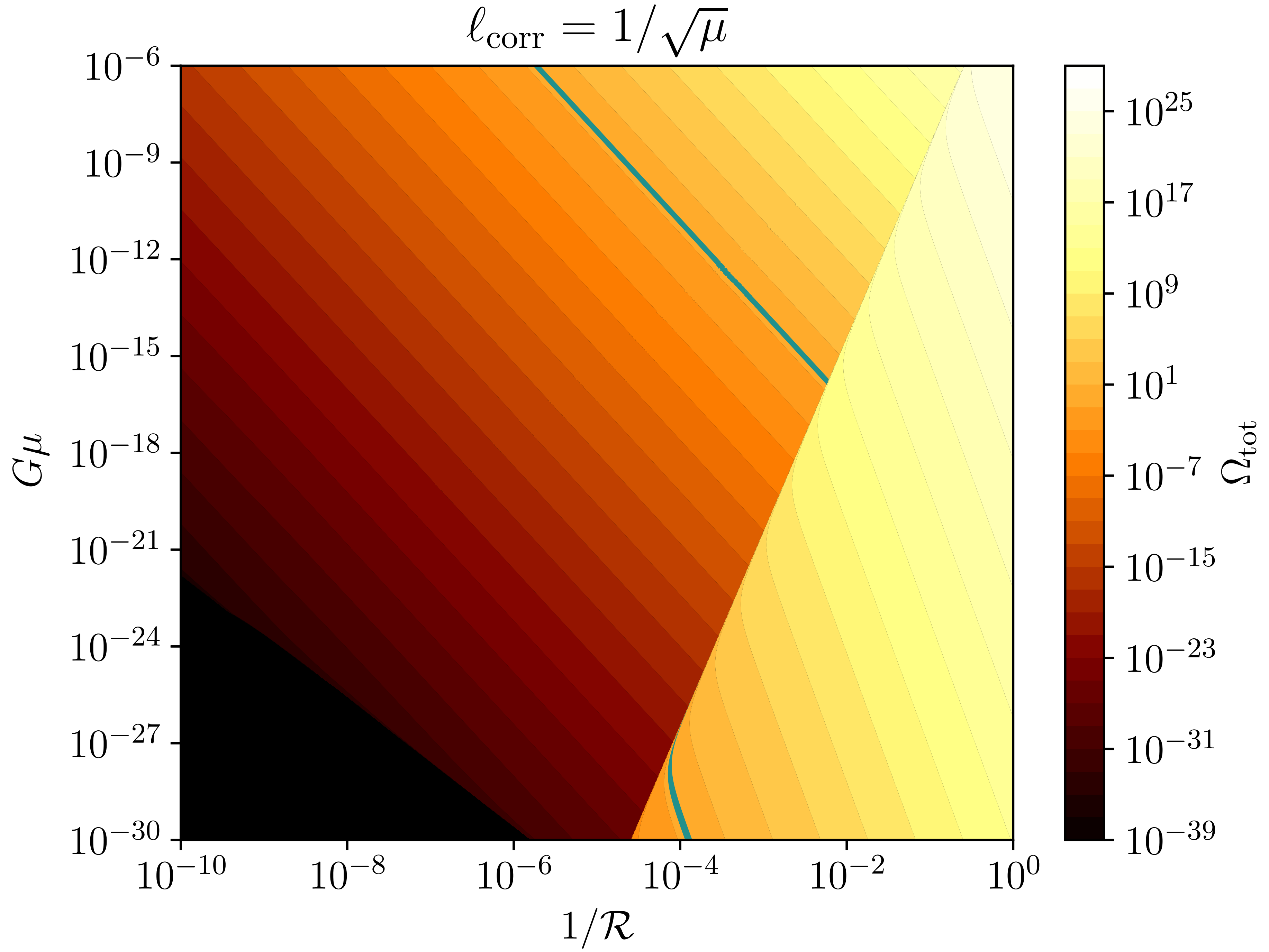


Figure 5: The total relic abundance of all vortons starting from a Vachaspati-Vilenkin initial loop distribution, with an initial thermal correlation length $\ell_{\rm corr} = 1/\sqrt{\mu}$, and a one-scale loop production function with $\alpha = 0.1$. The green line corresponds to the range of values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