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

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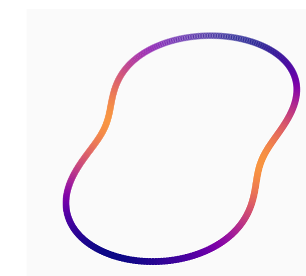
1) <u>GW emission is the dominant decay mode</u>: $\dot{\ell} = -\Gamma G\mu$

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]

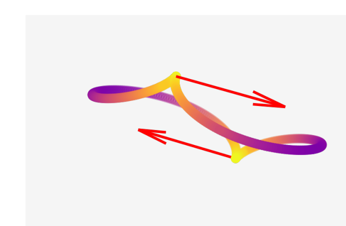
$\frac{\mathrm{d}\ell}{\mathrm{d}t}$ = rate at which a cosmic string loop of loses energy



2) <u>other decay channels, into both GWs and particles</u>

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]

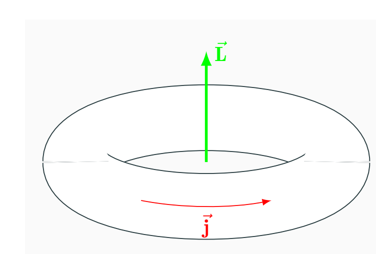


cusps, kinks

3) <u>subsequent phase transition leads to current carrying strings</u>

Stabilised loops or “vortons”: dark matter?

[Irreducible cosmic production of relic vortons, P.Auclair, P.Peter, C.Ringeval, DAS, JCAP 03 (2021) 098, arXiv: 2010.04620]

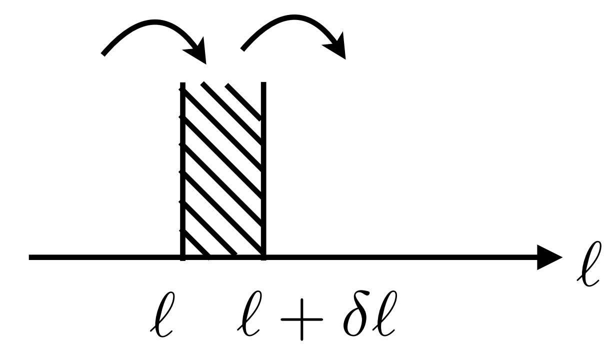


vorton

- Feeds directly into the loop distribution $n(\ell, t)$

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

– Loop distribution satisfies a (modified) Boltzmann equation.
Taking into account flux of loops in ℓ-space



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

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]

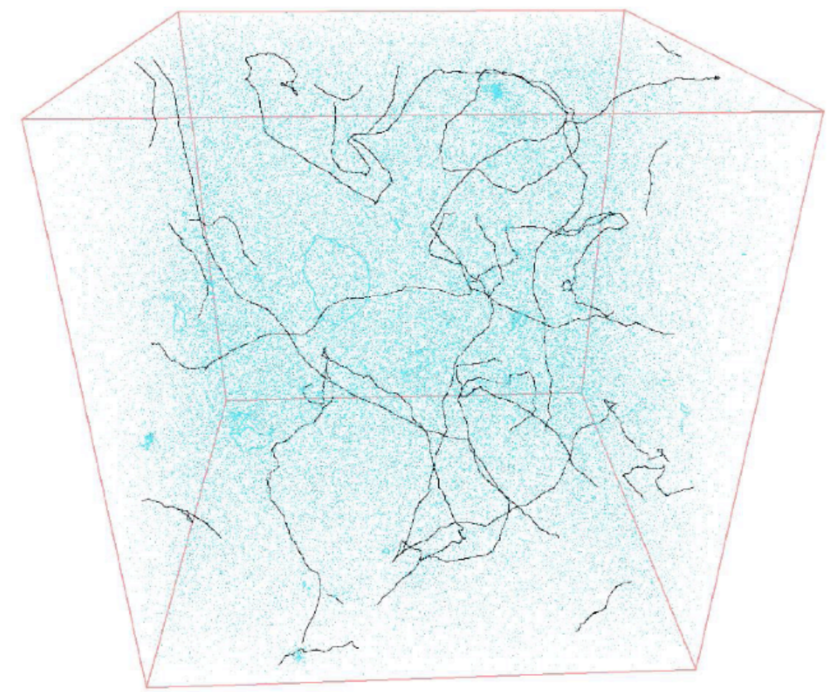
– given $\frac{\mathrm{d}\ell}{\mathrm{d}t}$, with clever changes of variables this can be integrated, given some LPF.

– Final step is to specify the LPF (different models)

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 $\frac{\rho_\infty}{\rho_{\rm bkg}} \sim \frac{a^p}{t^2} \sim {\rm const}$ $\quad \rho_{\rm bkg} \sim a^{-p},\ a = t^{2/p}$



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

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 initial condition + intercommutation. Radiation and matter era simulations. Limited in time and length scale. Smallest scale physical processes not included: grav radiation and backreaction, possible particle emission

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

- Assume scaling of infinite string network: $\mathcal{P}(\ell, t) = C t^{-5} f(\ell/t)$ $\qquad \gamma \equiv \frac{\ell}{t}$

=> determine the loop distribution, and different observables

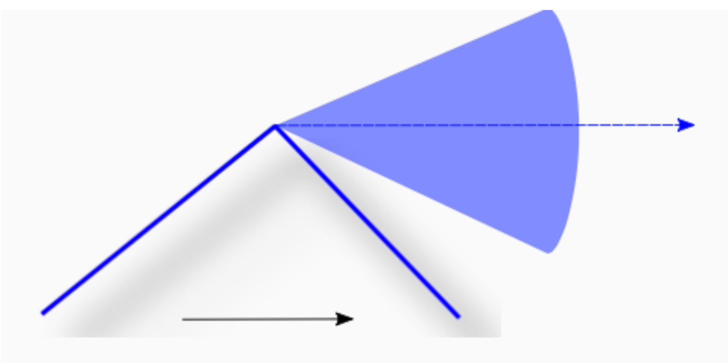
– Regarding GWs, two types of signals that can be searched for at different frequencies (LIGO, LISA, PTA,etc):

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

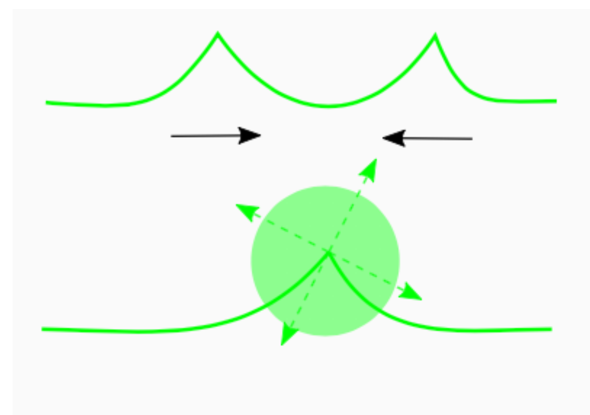
$$\Omega_{\mathrm{GW}}(\ln f) = \frac{1}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}\ln f}$$

- Occasional sharp **individual bursts** (resolved GW signals)

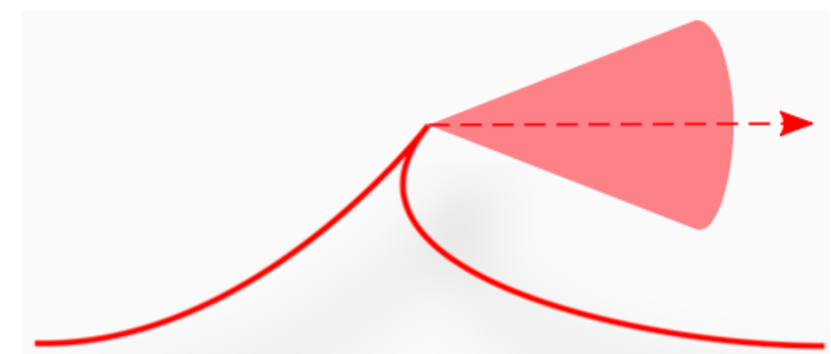
  – kinks



  – kink-kink collisions



  – cusps

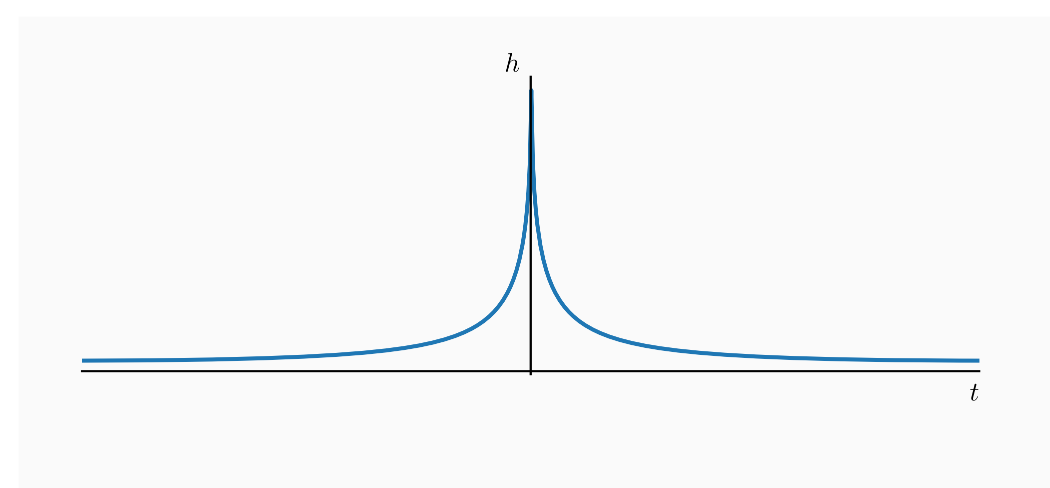


GW-form	$h_i(\ell, z, f) = A_i(\ell, z) f^{-q_i}$
Amplitude	$A_i(\ell, z) = g_{1,i} \dfrac{G\mu \ell^{2-q_i}}{(1+z)^{q_i - 1} r(z)}$

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

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

$\theta_m < 1$



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

Plan

1) GW emission is the dominant decay mode: $\dot{\ell} = -\Gamma G\mu \equiv \gamma_d$

Constraints from LIGO-Virgo O3 run: SGWB and search for individual GW bursts for different models (i.e. different loop production functions).

[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) Decay of loops into both GWs and Particles: $\dot{\ell}(\ell)$

Observable effects on both SGWB and diffuse gamma-ray background

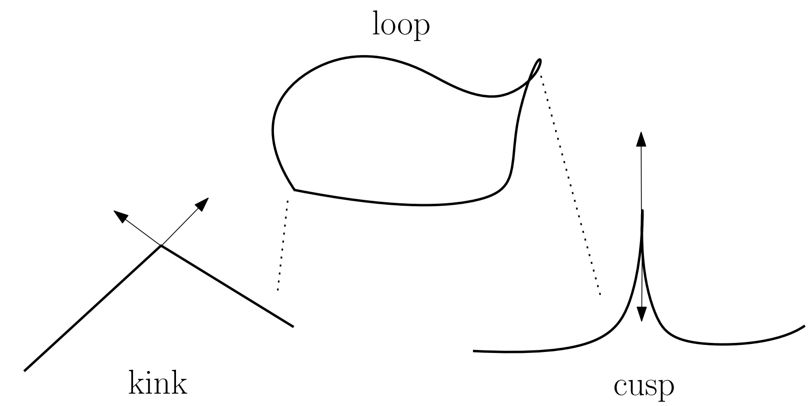
[Particle emission and gravitational radiation from cosmic strings: observational constraints, P.Auclair, D.A.S, T.Vachaspati, Phys.Rev.D 101 (2020) 8, 083511, arXiv 1911.12066]

3) Current carrying strings: vortons as dark matter?

[Irreducible cosmic production of relic vortons, P.Auclair, P.Peter, C.Ringeval, DAS, JCAP 03 (2021) 098, arXiv: 2010.04620]

4) Conclusions, and comments on beyond standard cosmology

Stochastic search from Third Advanced LIGO–Virgo Observing Run



- GW emission is the dominant decay mode: $\dot{\ell} = -\Gamma G\mu \equiv \gamma_d$

$$\Gamma = \frac{P_{\rm GW}}{G\mu^2} \simeq \Gamma_c + \Gamma_k + \Gamma_{kk}$$

$\propto N_c$ $\quad N_k \quad$ $N_{kk} \sim N_k^2/4$ average number of burst events/loop oscillation period $\ell/2$

- Set $N_c = 1$ while leaving N_k as free parameter, with $1 \leq N_k \leq 200$ (leading to $\Gamma \lesssim 50$ consistently with simulations)

[Blanco-Pillado et al, Allen et al]

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

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

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

strain from cusps/kinks/kk collisions.

- Flat LCDM

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

- different semi-analytical loop-production function models

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

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

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

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

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" $\gamma\equiv\dfrac{\ell}{t}>\gamma_{\mathrm{c}}$

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

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

Models C: interpolates between A and B

[Auclair et al, Auclair 2019,2020]

(aims to help understand features to which burst + stochastic searches are sensitive)

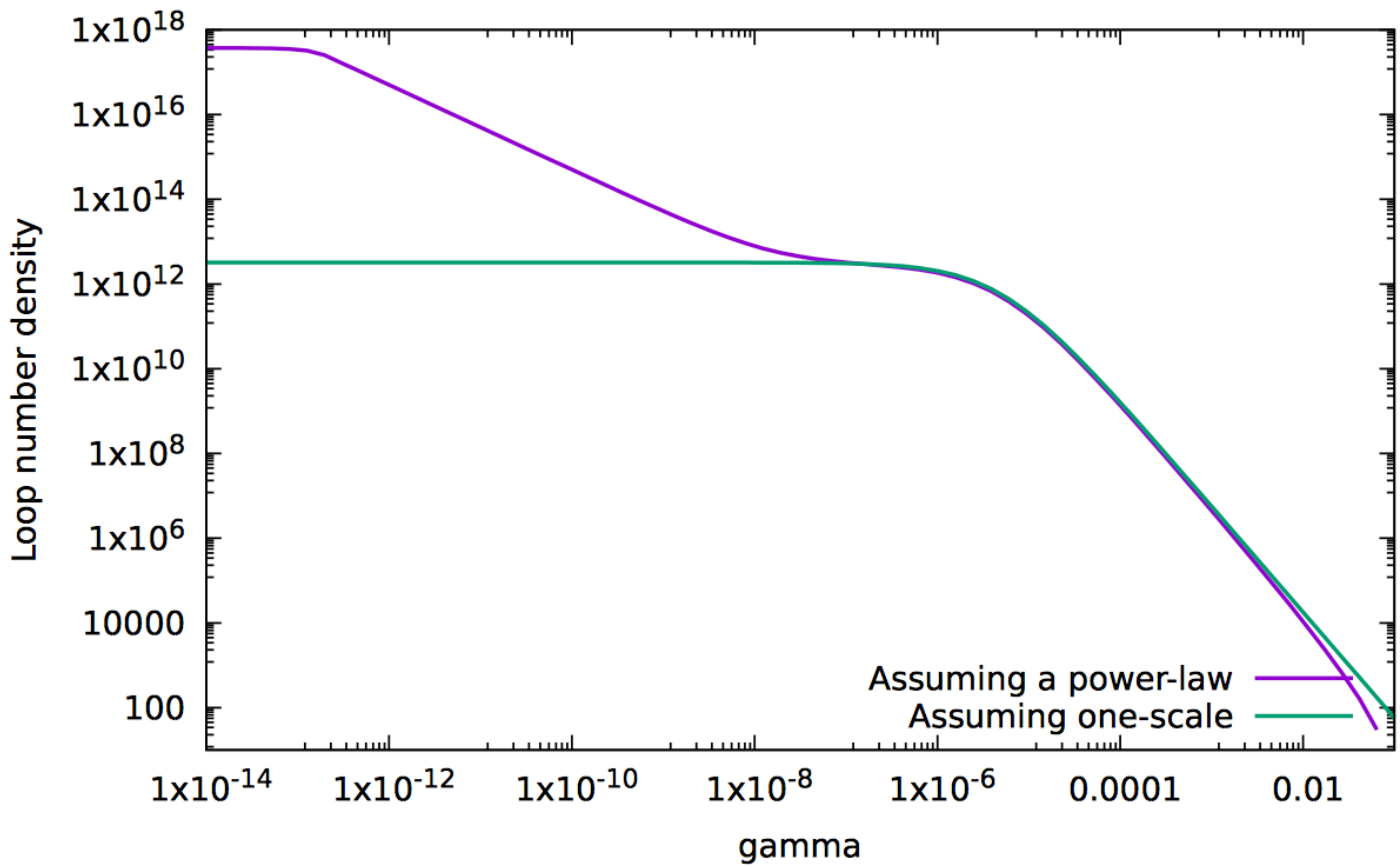
Models A and B :

– similar loop distributions on large scales,

– differences small scales where model B has many more loops.

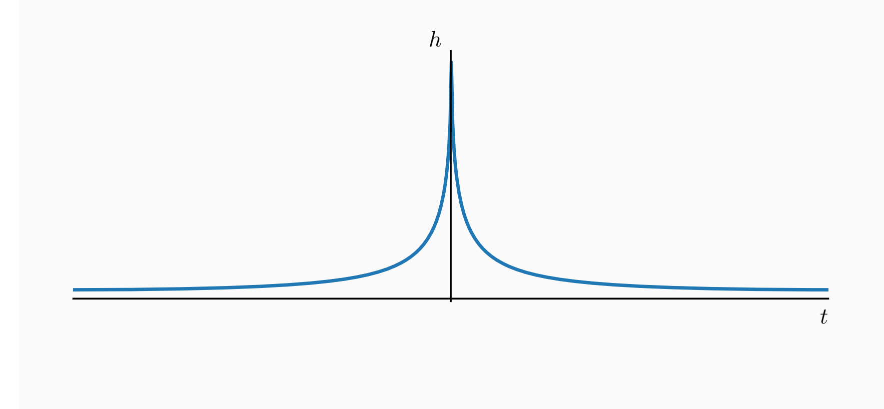
Expect these contribute to SGWB at high frequencies.

[Auclair et al, Auclair 2019,2020]



γ_c γ_d

Burst search



– Using burst waveforms from cusps, kinks and kink-kink collisions, carried out a matched-filter search in O3 data

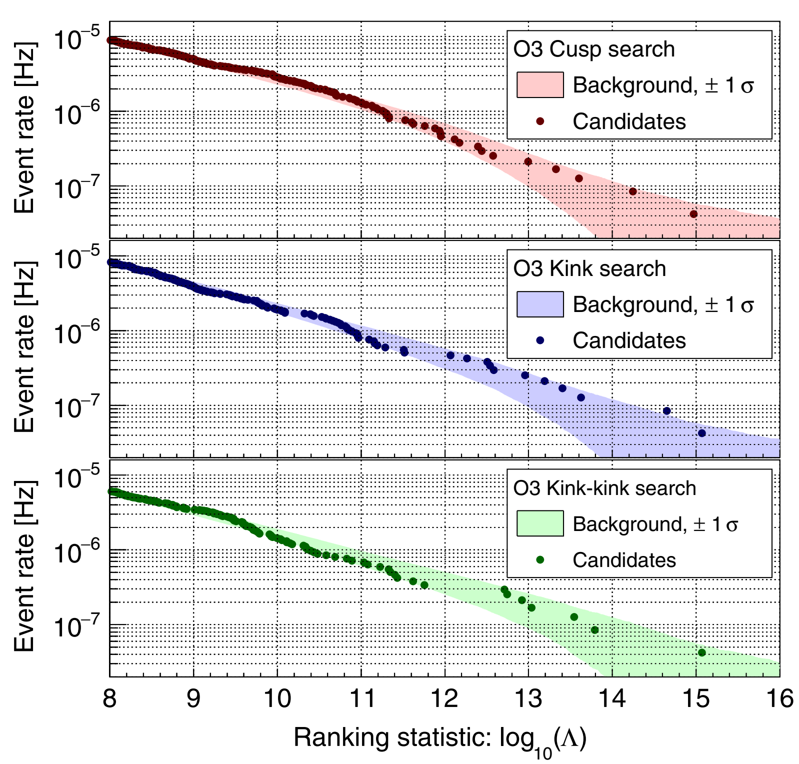
– resulting candidates filtered to retain only those detected in more than one detector within a time window accounting for the difference in the gravitational-wave arrival time between detectors.

– 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)

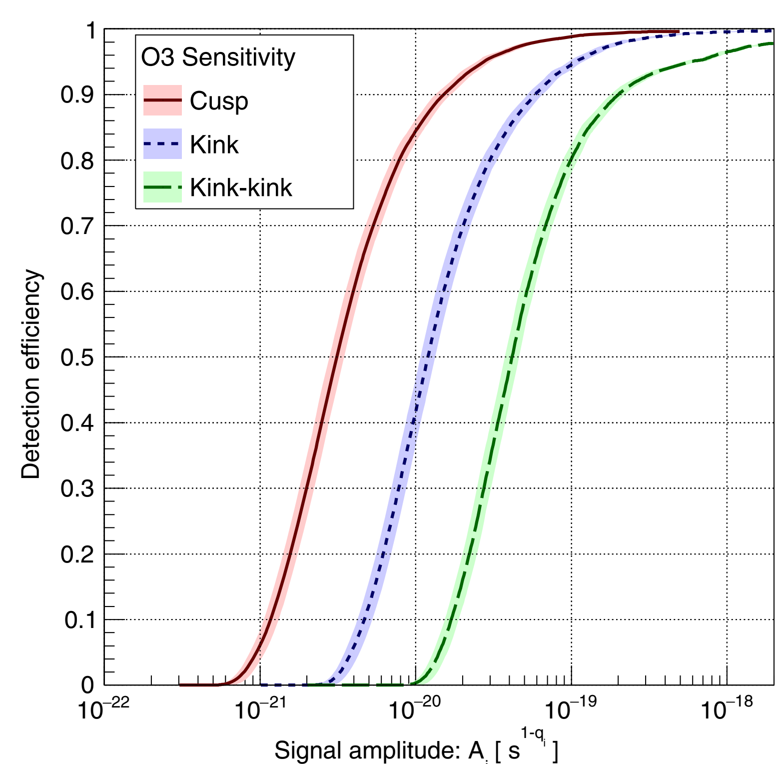
– burst rate depends on loop distribution and on number of kinks => non-observation gives constraint on

$$(G\mu, N_k)$$

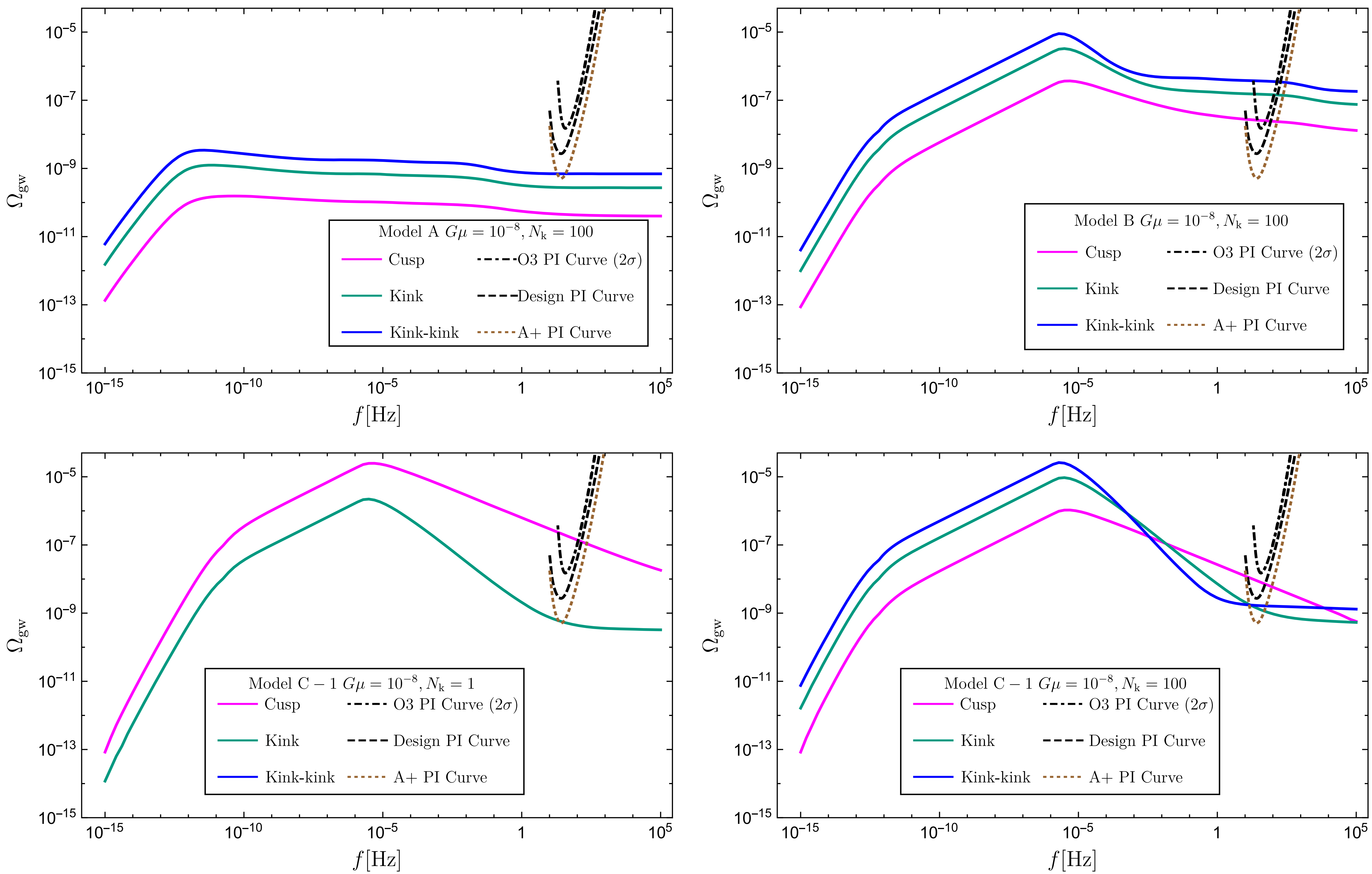
background distribution of bursts from glitches



Cosmic string burst search efficiency

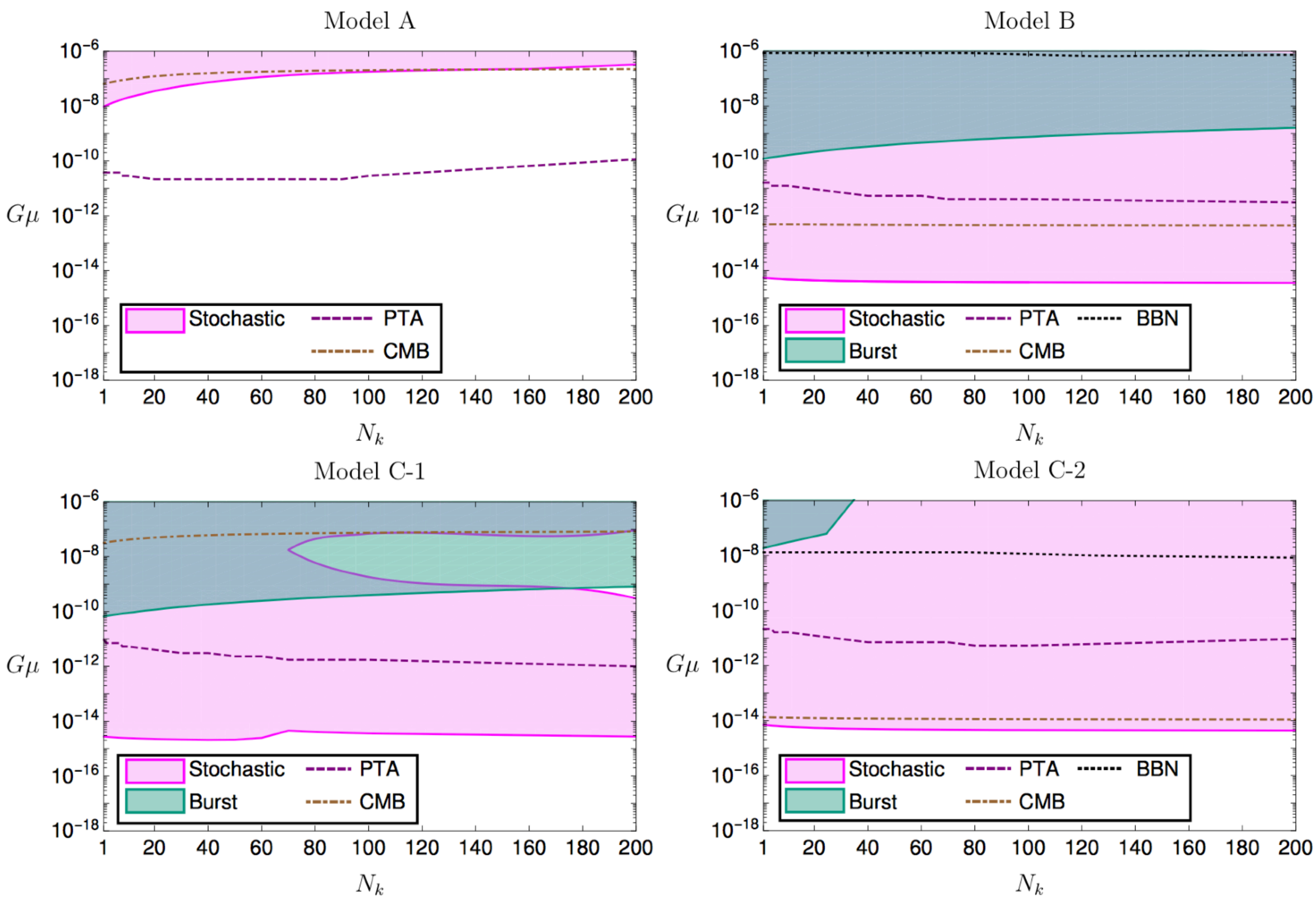


Models A, B, C1 $G\mu = 10^{-8}$



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

Exclusion plots



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

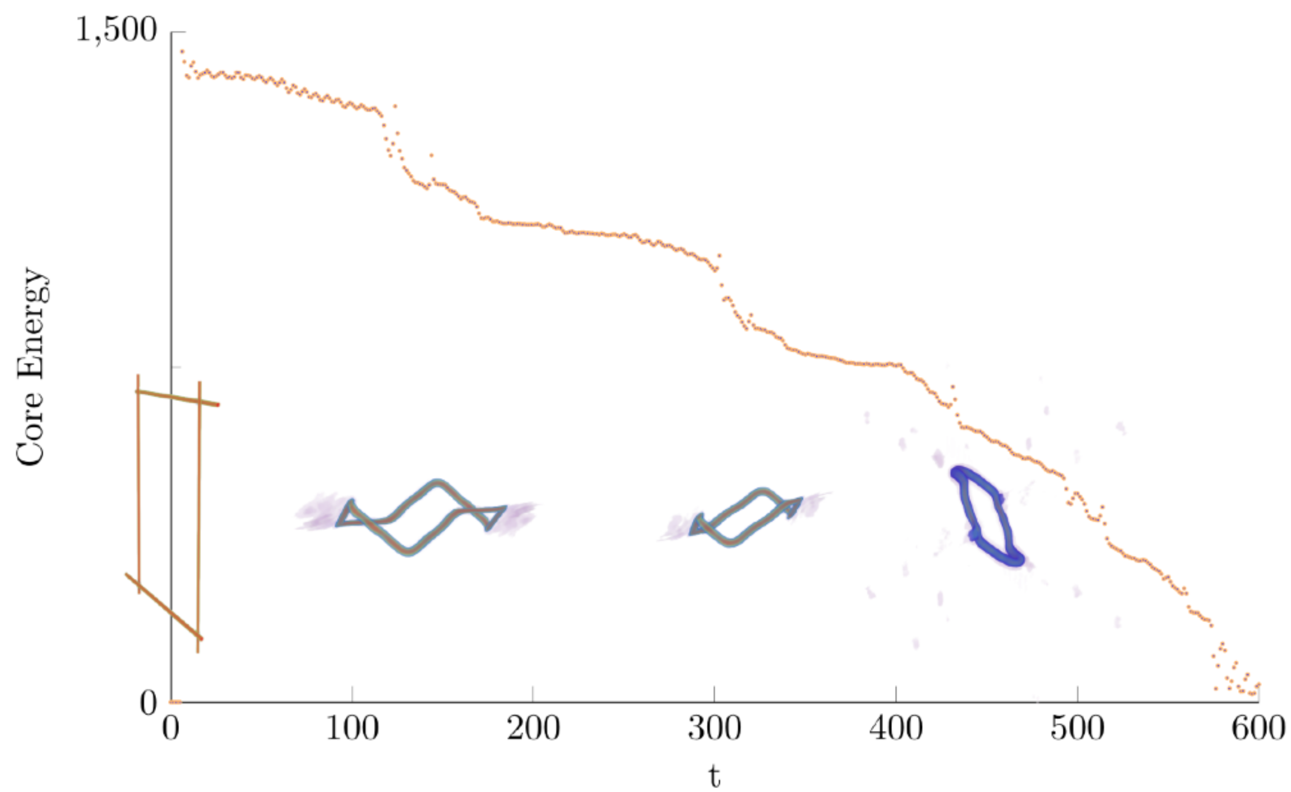
C1=LPF of model B in matter era, of model A in radiation era

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

- 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

2) 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)]*



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

← *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 $\ell_{\rm k} \to \infty$

Non-scaling loop distribution!

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

2) Gravitational radiation *and* particle radiation.

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

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

← *Particle production primary decay channel*

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

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

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

– More generally, can solve the Boltzmann equation for $\boxed{\frac{{\rm d}\ell}{{\rm d}t} = -\gamma_{\rm d}\mathcal{J}(\ell)}$

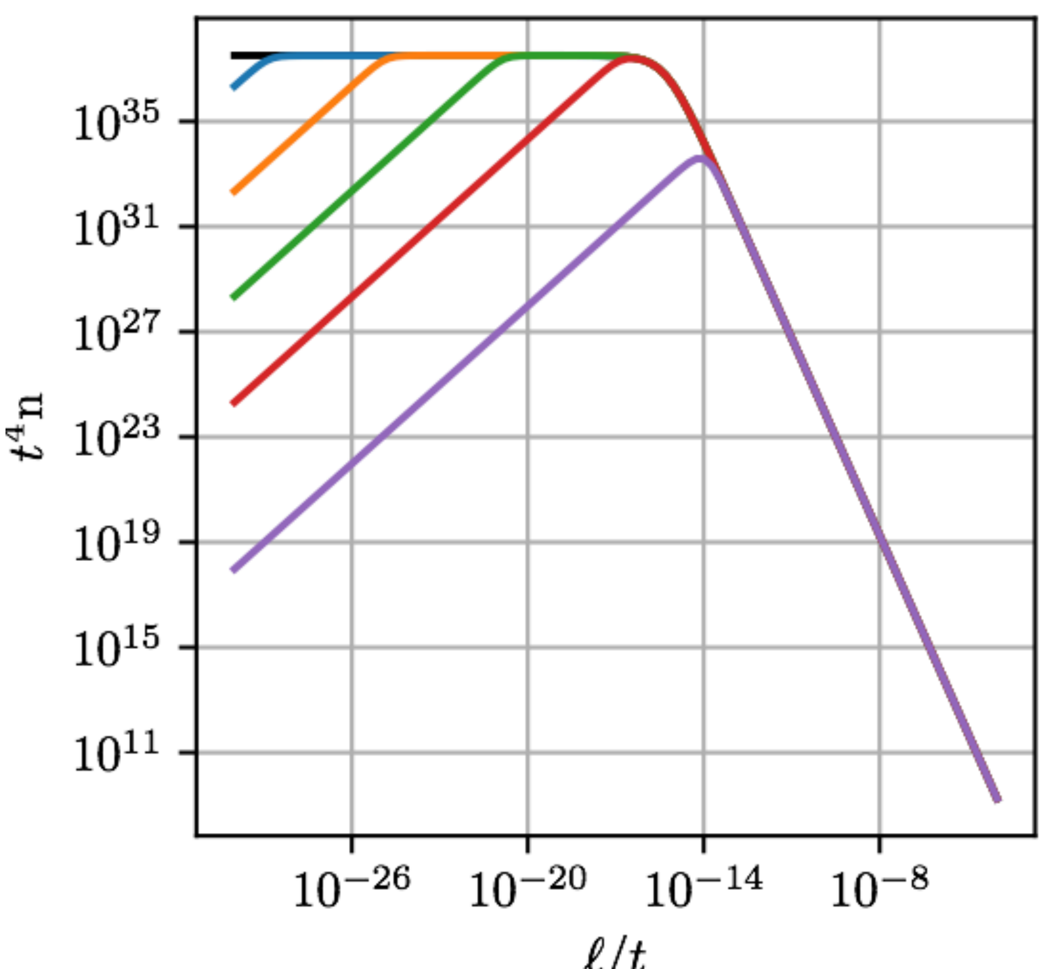
– assuming $t^5\mathcal{P} = C\delta_{\rm D}(\ell/t-\alpha)$

$$t^4\mathbf{n} = \frac{C}{\mathcal{J}(\ell)}\frac{\mathcal{J}(\alpha t_\star)}{\alpha+\Gamma G\mu\mathcal{J}(\alpha t_\star)}\left(\frac{t_\star}{t}\right)^{-4}\left(\frac{a(t_\star)}{a(t)}\right)^3$$

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

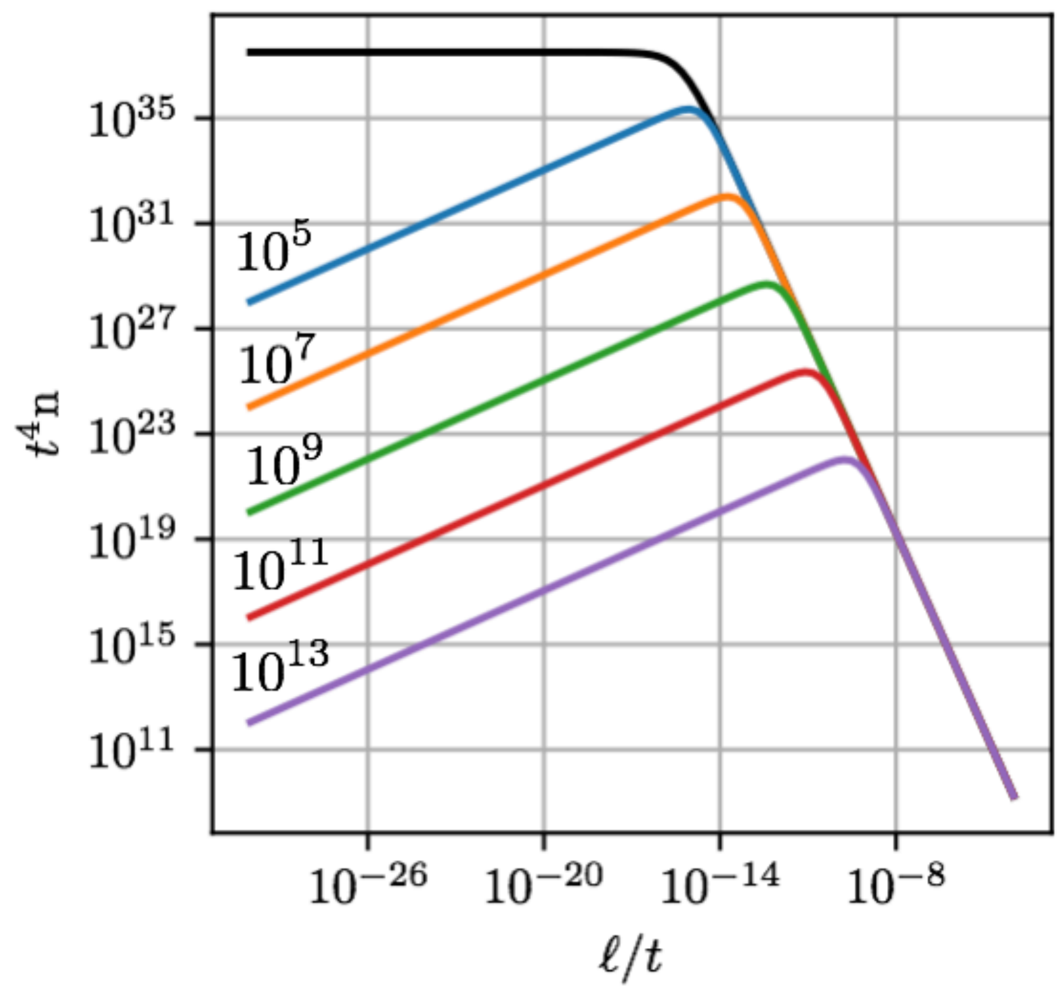
$z_k \sim 10^{12}$

Kinks



$z_c \sim 10^4$

Cusps

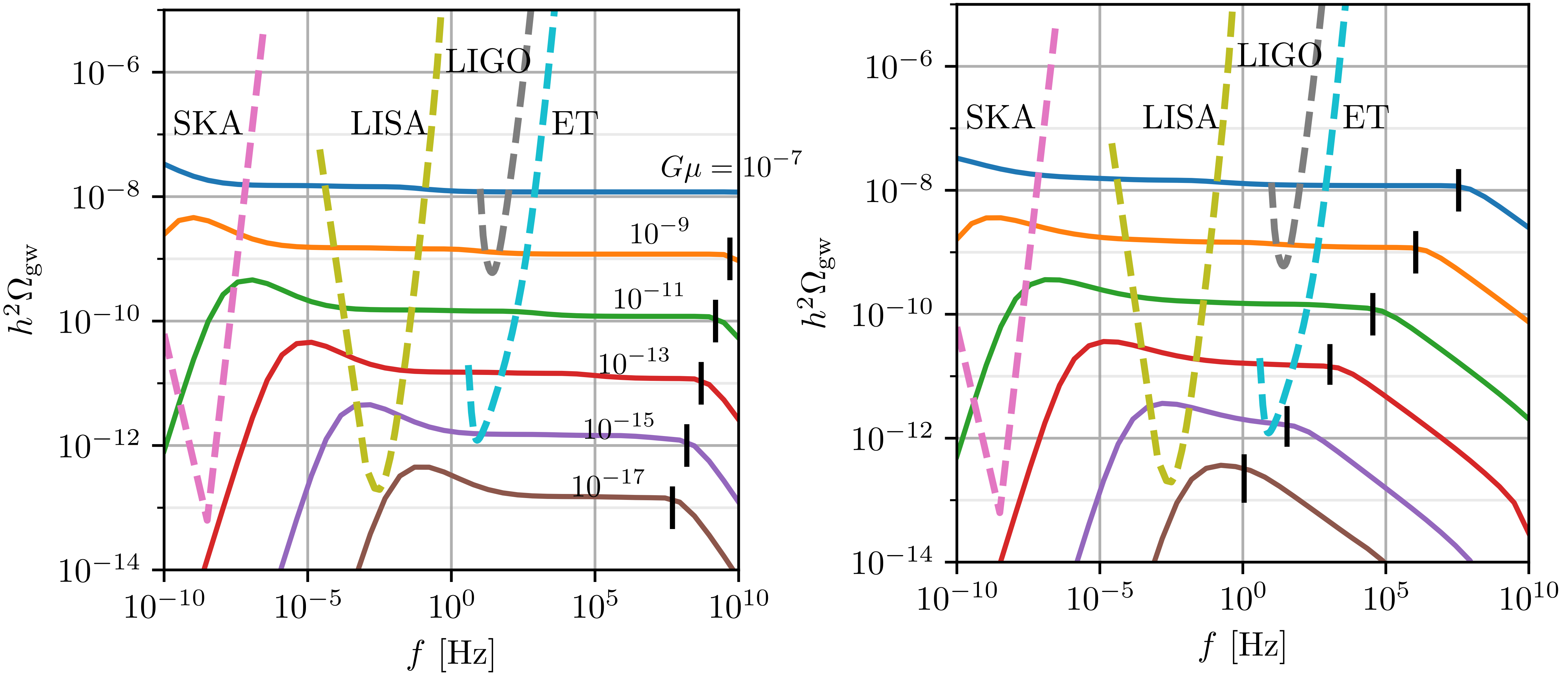


The loop distributions are supressed for $z \gg z_k$ or $z \gg z_c$

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

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 $\left.\dot{\ell}\right|_{\mathrm{particle}} \sim -\gamma_{\mathrm{d}} \frac{\ell_{\mathrm{k}}}{\ell}$

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

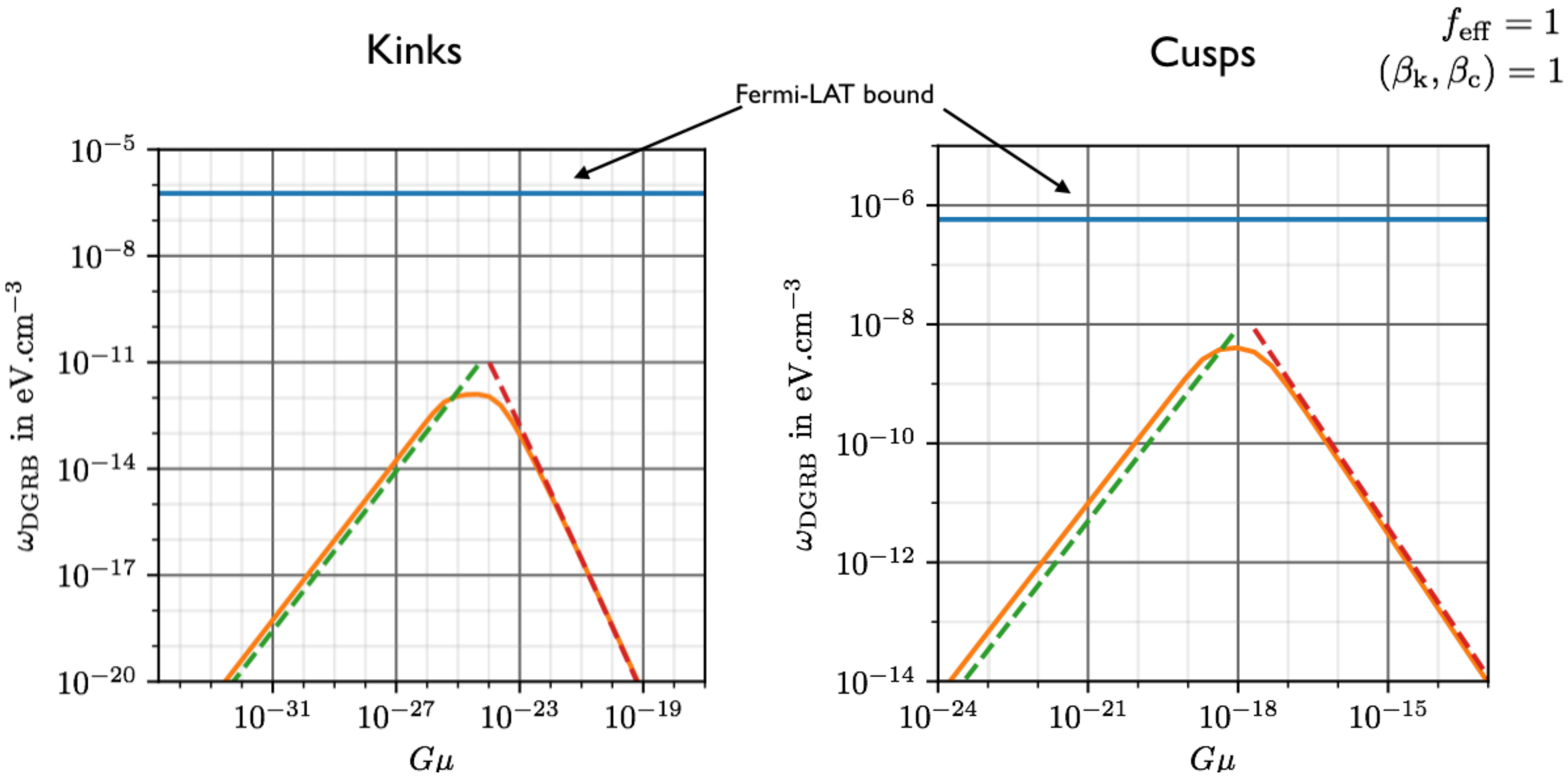
$$\boxed{\omega_{\mathrm{DGRB}}^{\mathrm{strings}} = f_{\mathrm{eff}} \int_{t_\gamma}^{t_0} \frac{\Phi_{\mathrm{H}}(t)}{(1+z)^4} \mathrm{d}t}$$

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

$$t_\gamma \simeq 10^{15}\mathrm{s}$$



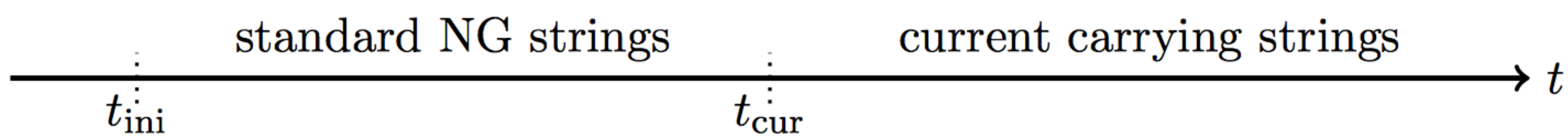
$$\boxed{\omega_{\mathrm{DGRB}}^{\mathrm{obs}} \lesssim 5.8 \times 10^{-7}\ \mathrm{eVcm}^{-3}}$$

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

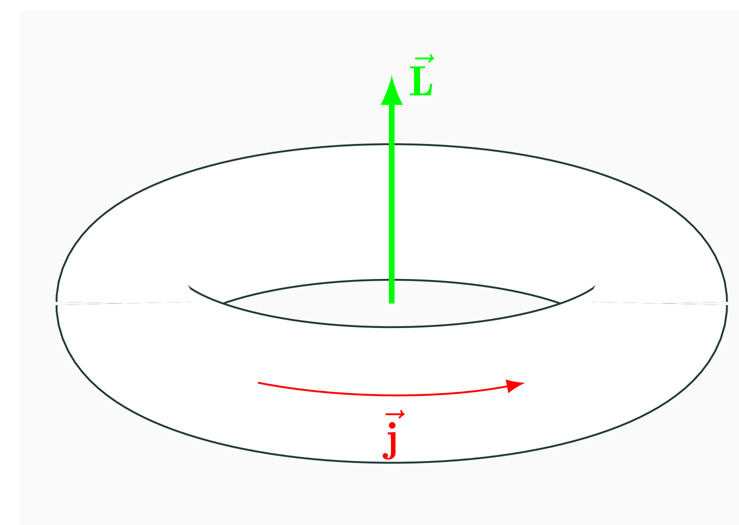
3) Current carrying strings: vortons as dark matter?

[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]*



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



- Loops radiate GWs and may stabilise into centrifugally supported configurations, **vortons**, at scale $\ell_0(N)$

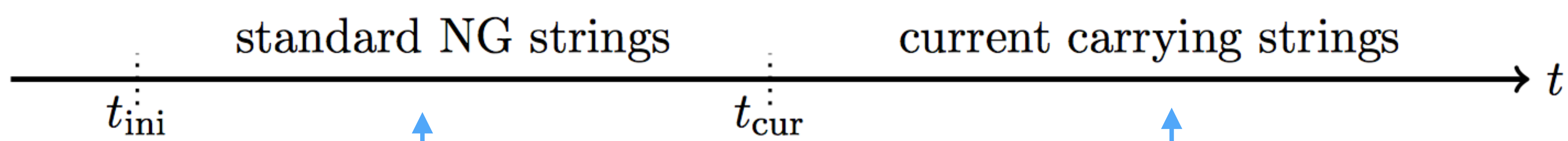
- N = conserved charge $N|_{\mathrm{prod}} \simeq \sqrt{\dfrac{\ell}{\lambda}}$

- Loop distribution $n(\ell, t, N)$

- can model physics of vortons with $\left(\begin{array}{l} \dfrac{\mathrm{d}\ell}{\mathrm{d}t} = -\Gamma G\mu \mathcal{J}(\ell, N), \\ \dfrac{\mathrm{d}N}{\mathrm{d}t} = 0, \end{array}\right.$ and $\mathcal{J}(\ell, N) = \Theta[\ell - \ell_0(N)]$

- Calculate distribution of loops

$$\frac{\partial}{\partial t}\left[a^3\frac{\mathrm{d}^2\mathcal{N}}{\mathrm{d}\ell\mathrm{d}N}(\ell,t,N)\right]-\Gamma G\mu\frac{\partial}{\partial \ell}\left[a^3\mathcal{J}(\ell,N)\frac{\mathrm{d}^2\mathcal{N}}{\mathrm{d}\ell\mathrm{d}N}(\ell,t,N)\right]=a^3\mathcal{P}(\ell,t,N).$$



$$\mathcal{P}(\ell,t)=Ct^{-5}\delta\left(\frac{\ell}{t}-\alpha\right)$$

$$\mathcal{P}(\ell,t,N)=Ct^{-5}\delta\left(\frac{\ell}{t}-\alpha\right)\delta\left(N-\sqrt{\frac{\ell}{\lambda}}\right)\Theta(t-t_{\mathrm{cur}})$$

Assume Vachaspati-Vilenkin initial distrubution (random walk on length scale ℓ_{corr})

1. *Doomed loops*: these loops have an initial size which is too small to support a current, and hence they decay through gravitational radiation never becoming vortons. They are characterised by quantum numbers $N<\mathcal{R}$.

2. *Proto-vortons*: these are loops which are initially large enough to be stabilised by a current (thus $N>\mathcal{R}$), but have not yet reached the vorton size ℓ_0.

3. *Vortons*: these are all those proto-vortons which have decayed by gravitational radiation to become vortons. Hence vortons have $N>\mathcal{R}$

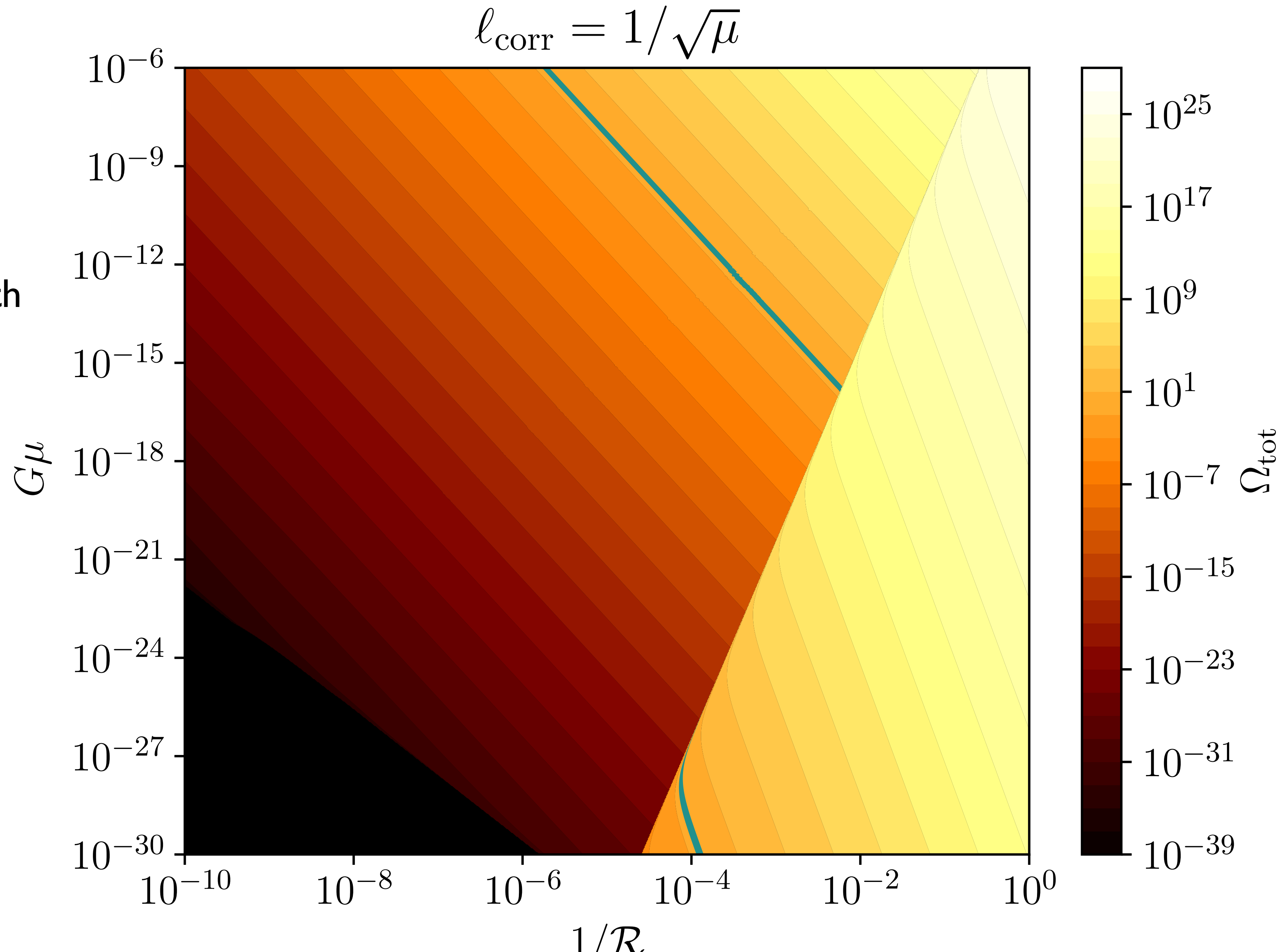
• Thus determine vortons formed from initial conditions *as well as* (for first time) those from loops chopped off infinite string network.

• Density parameter of relic vortons today $$\Omega \equiv \frac{8\pi G\mu}{3H_0^2}\int_0^\infty \ell n_{\mathrm{vortons}}(\ell, t_0)d\ell$$

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

The total relic abundance of all vortons starting from a VV initial loop distribution with $\ell_{\mathrm{corr}} = 1/\sqrt{\mu}$ $\alpha = 0.1$

green line = density parameter values in range $[0.2, 0.4]$



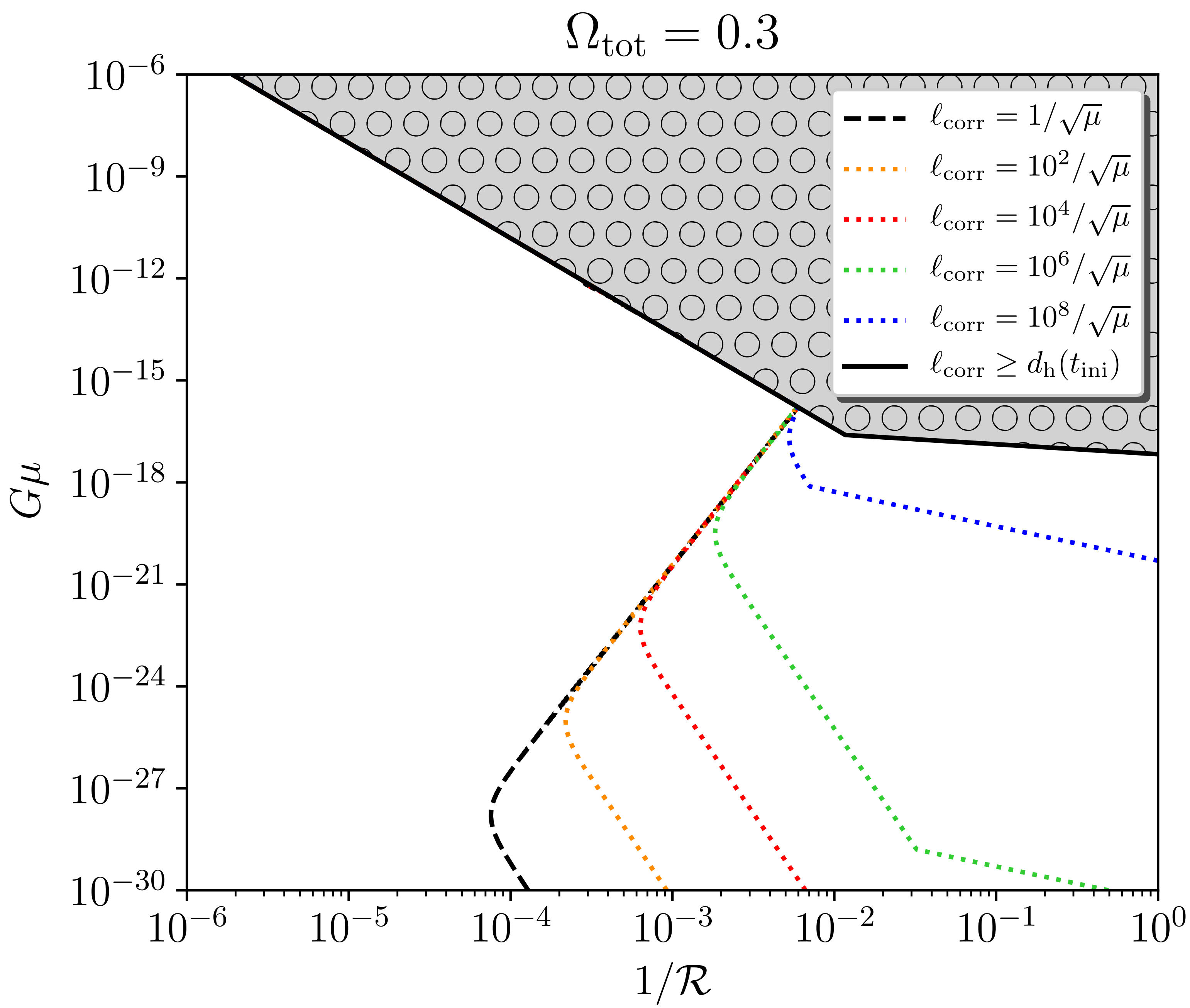


Figure 6: The total relic abundance of all vortons starting from a Vachaspati-Vilenkin initial loop distribution with various correlation length $\ell_{\rm corr}$ ranging from the thermal one $1/\sqrt{\mu}$ to the Kibble one $\mathrm{d_h}(t_{\rm ini})$. Each curve represents the value $\Omega_{\rm tot} = 0.3$. Domains right of this curve lead to vortons overclosing the Universe, domains on the left are compatible with current cosmological constraints. The upper hatched region corresponds to the irreducible relaxed and produced vortons not affected by the initial conditions.

Conclusions

• Presented latest LIGO-Virgo O3 constraints on NG strings for different models, with Nk as a new free parameter, highlighting the assumptions and unknowns

• Cosmic strings beyond the standard NG picture: particle particle emission, currents

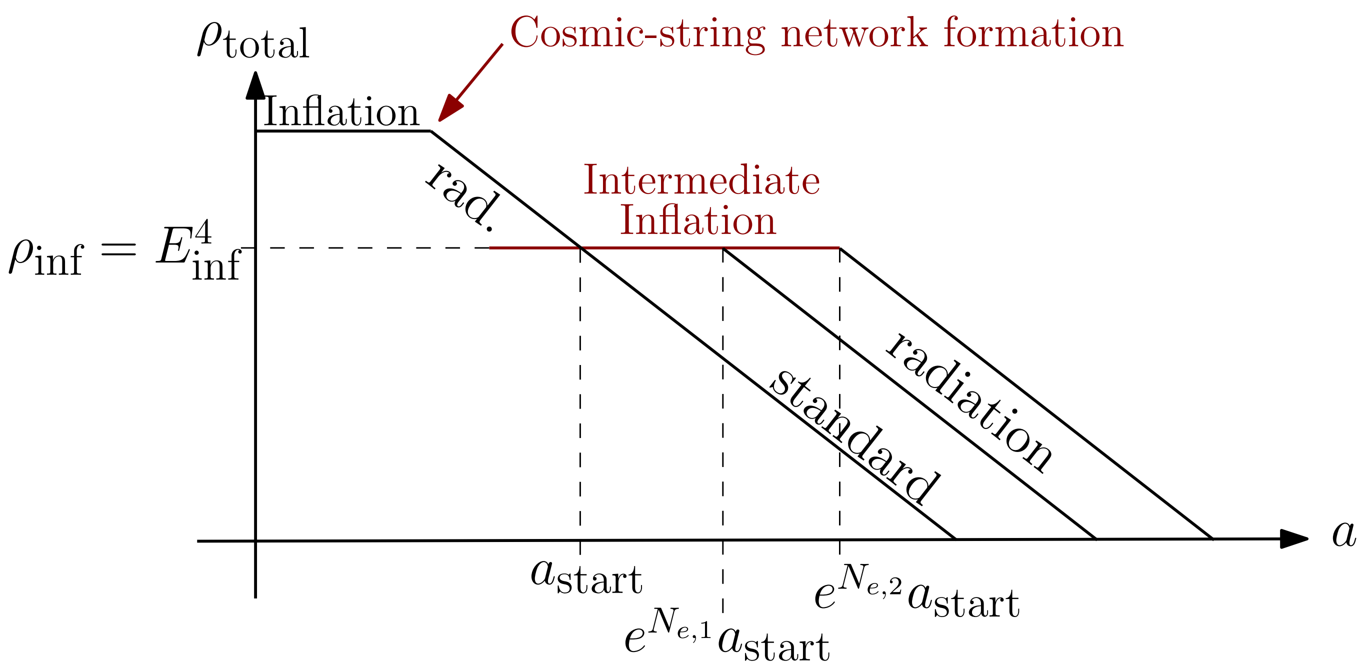
• Effects of modified cosmology *[Many authors, including Gouttenoire, Servant & Simakachorn, 1912.02569]*

• 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]*. See also next talk!

Impact of changing cosmological evolution

[Gouttenoire, Servant & Simakachorn, 1912.02569]



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