Early Universe filled with ultra-light primordial black holes

Rome Samanta, MSCA-IF, FZU
CEICO, Institute of Physics of the Czech Academy of Sciences, CZ

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Subject of this talk:

Primordial black holes with mass < 10^9 g evaporates before BBN via Hawking radiation

Features:

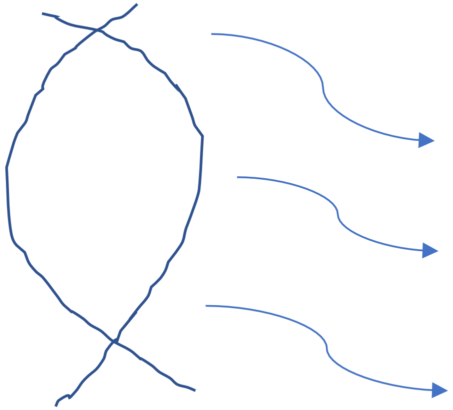
1) The initial energy density at formation is not constrained unlike the PBH as Dark matter.
2) Can produce Dark matter, Dark radiation and heavy particle responsible for baryogenesis.
3) At the same time opens up a pathway to probe very Early Universe Physics with Gravitational waves

   broadly in two ways

   A) Either generating gravitational waves from their own dynamics or

   B) Affect the spectrum of GWs from other external sources

Cosmic string loop



Gravitational waves, Amplitude ~ $[\mathrm{VEV}_{U(1)}]^2$

Scenario: $\mathbf{T_b^{formation} < VEV_{U(1)}}$

Opens up the possibilities to probe very High scale physics at GW detectors

State-of-the-art constraint on PBH masses

Free parameter: $\boldsymbol{\beta} = \boldsymbol{\rho}_{BH}/\boldsymbol{\rho}_{rad}$

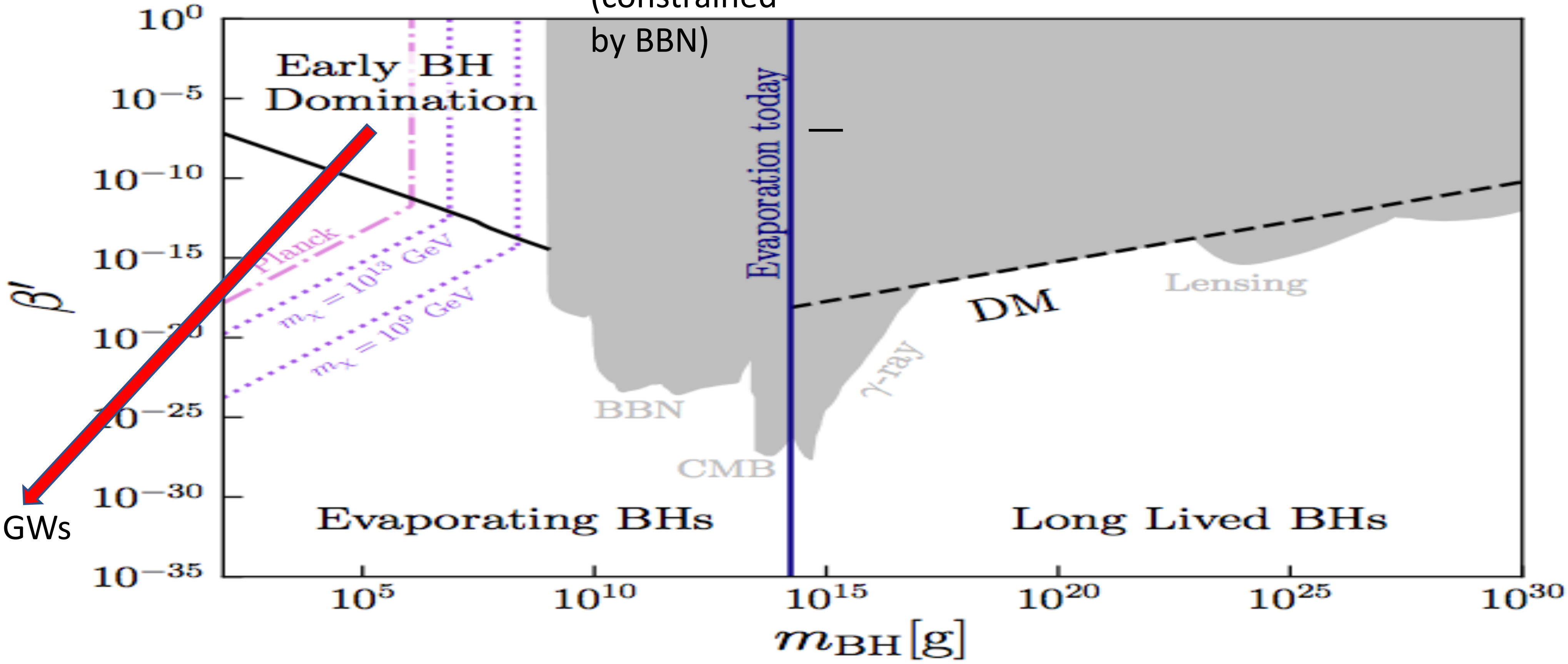
PBH Mass

< 0.1 g (CMB)

Dark matter

$>10^8$ g (constrained by BBN)

$>10^{15}$ g (Dark matter)



DM, GWs

Ultralight PBH dynamics (only non-rotating)

Consider formation in the radiation domination

Mass: $$M_{BH} = \gamma \frac{4}{3}\pi (H_{Bf}^{-1})^3 \rho_{Bf} \text{ with } \rho_{Bf} = \frac{3H_{Bf}^2 M_{Pl}^2}{8\pi}, \quad H_{Bf} = \frac{1}{2t_{Bf}}.$$

Mass loss: $$-\frac{dM_{BH}}{dt} = f_{ev}(4\pi r_{BH}^2)\frac{dE}{dt},$$

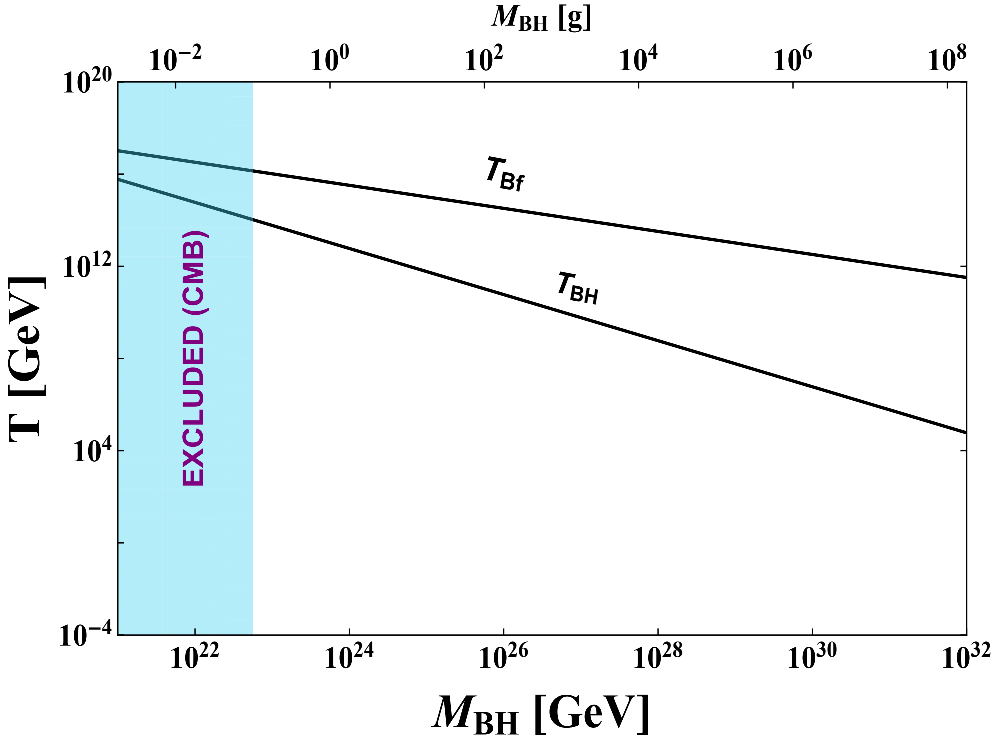
$$\frac{dM_{BH}}{dt} = -\frac{\mathcal{G} g_{*B}(T_{BH})}{30720\pi}\frac{M_{Pl}^4}{M_{BH}^2},$$

Life-time: $$\tau = \int_{t_{Bf}}^{t_{ev}} dt = -\int_{M_{BH}}^{0} dM_{BH} \frac{30720\pi M_{BH}^2}{\mathcal{G} g_{*B}(T_{BH}) M_{Pl}^4} = \frac{10240\pi M_{BH}^3}{\mathcal{G} g_{*B}(T_{BH}) M_{Pl}^4}.$$

Evaporation $$T_{ev} = \left(\frac{45 M_{Pl}^2}{16\pi^3 g_*(T_{ev})\tau^2}\right)^{1/4}.$$

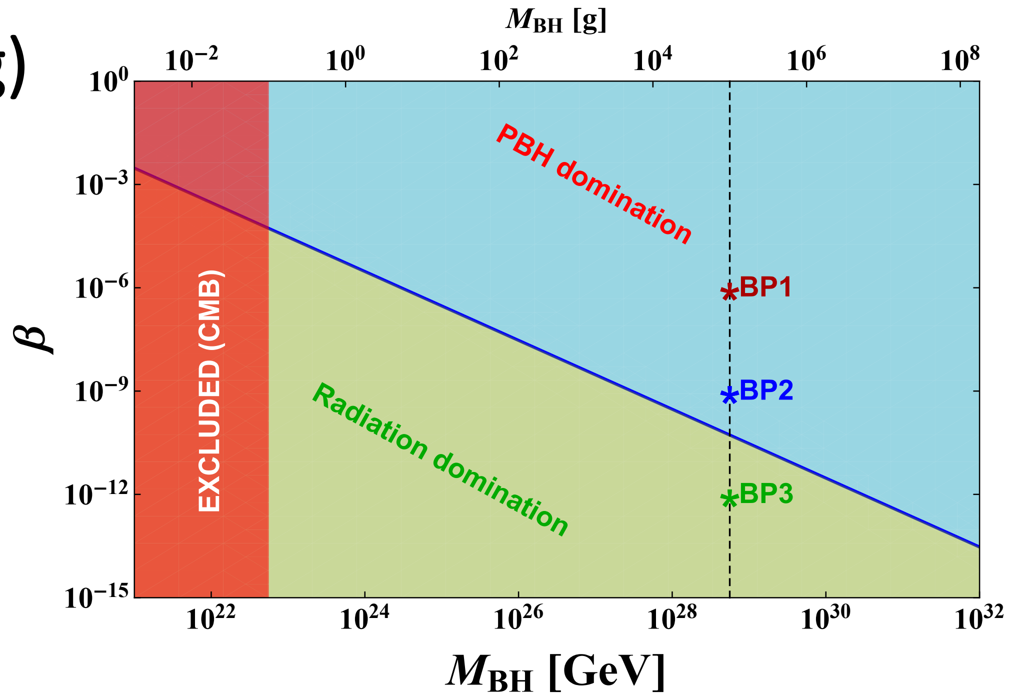
Formation temperature

$$T_{Bf} = \left(\frac{45\gamma^2}{16\pi^3 g_*(T_{Bf})}\right)^{1/4}\left(\frac{M_{Pl}}{M_{BH}}\right)^{1/2} M_{Pl}.$$



Ultralight PBH dynamics (only non-rotating)

Black holes not to dominate: $$\beta < \gamma^{-1/2} \left(\frac{\mathcal{G} g_{*B}(T_{BH})}{10240\pi} \right)^{1/2} \frac{M_{Pl}}{M_{BH}}.$$

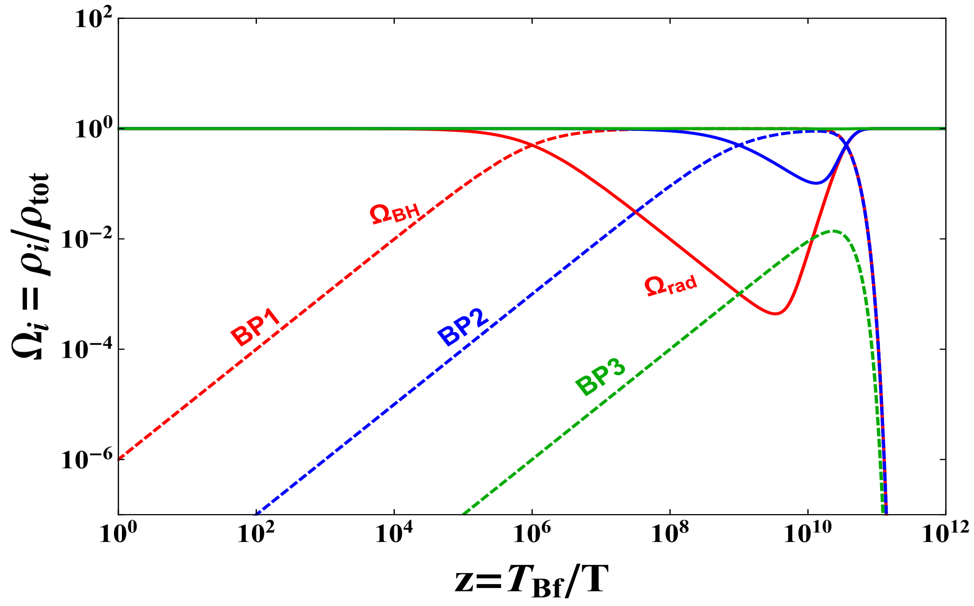


Kintetic equations:

$$\frac{d\rho_R}{dt} + 4H\rho_R = -\frac{\dot{M}_{BH}}{M_{BH}}\rho_{BH},$$

$$\frac{d\rho_{BH}}{dt} + 3H\rho_{BH} = +\frac{\dot{M}_{BH}}{M_{BH}}\rho_{BH},$$

$$\frac{ds}{dt} + 3Hs = -\frac{\dot{M}_{BH}}{M_{BH}}\frac{\rho_{BH}}{T},$$



Particle production

Differential number of particles

$$dN = dE/3T_{BH} = \frac{M_{Pl}^2}{24\pi}\frac{1}{T_{BH}^3}dT_{BH},$$

Where ,

$$dE \equiv -d(M_{BH}) = \frac{M_{Pl}^2}{8\pi}\frac{dT_{BH}}{T_{BH}^2}$$

Number of `X' particle by a black hole

$$N_X = \frac{g_X}{g_{*B}}\int_{T_{BH}}^{\infty} dN = \frac{4\pi}{3}\frac{g_X}{g_{*B}}\left(\frac{M_{BH}}{M_{Pl}}\right)^2 \quad \text{for} \quad T_{BH} > M_X,$$

$$N_X = \frac{g_X}{g_{*B}}\int_{M_X}^{\infty} dN = \frac{1}{48\pi}\frac{g_X}{g_{*B}}\left(\frac{M_{Pl}}{M_X}\right)^2 \quad \text{for} \quad T_{BH} < M_X.$$

Only viable solution for DM

Suppression

The `X' could be a DM

Dark Matter production

Observed Dark Matter relic: $\Omega_{DM}h^2=0.12 \approx n_{BH}\times N_{DM} \times M_{DM}/\boldsymbol{\rho}c$

$$n_{BH} = \frac{\rho_{BH}}{M_{BH}}(T_{ev}) = \frac{M_{Pl}^2}{6\pi T^2 M_{BH}}$$

For $M_{DM} < T_{BH}$

one gets $M_{DM} \leq 3\times 10^{-7}\left(\frac{M_{BH}}{M_{Pl}}\right)^{1/2}$

For $M_{DM} > T_{BH}$

one gets $M_{DM} \geq 4.5\times 10^{-3}\left(\frac{M_{Pl}}{M_{BH}}\right)^{5/2} M_{Pl}^2$

The equality sign $\Rightarrow \Omega_{DM}h^2 = 0.12$

Super heavy Dark Matter (SHDM) from PBH

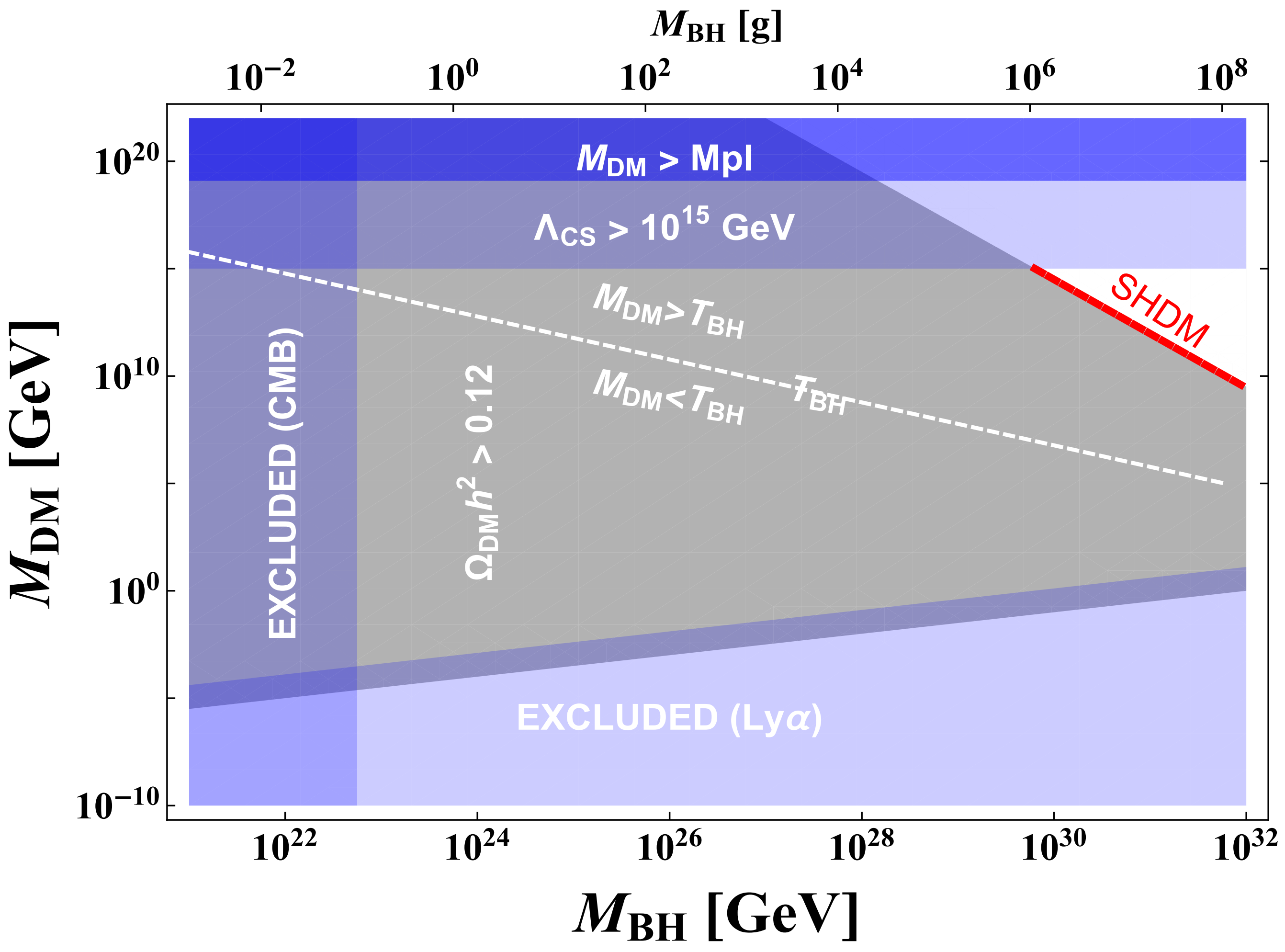
Can not Save $M_{DM} < T_{BH}$

free streaming length

$$\lambda_{FS} = \int_{t_i}^{t_{eq}} \frac{v(t)}{a(t)} dt \lesssim 0.1\,\mathrm{Mpc}$$

$\Rightarrow V_{DM}$ at $t_{eq} > 2\times10^{-8}$

$\Rightarrow M_{DM} > 2\times10^{-3} \left(M_{BH}\right)^{1/2}$



An idea to probe SHDM with GW

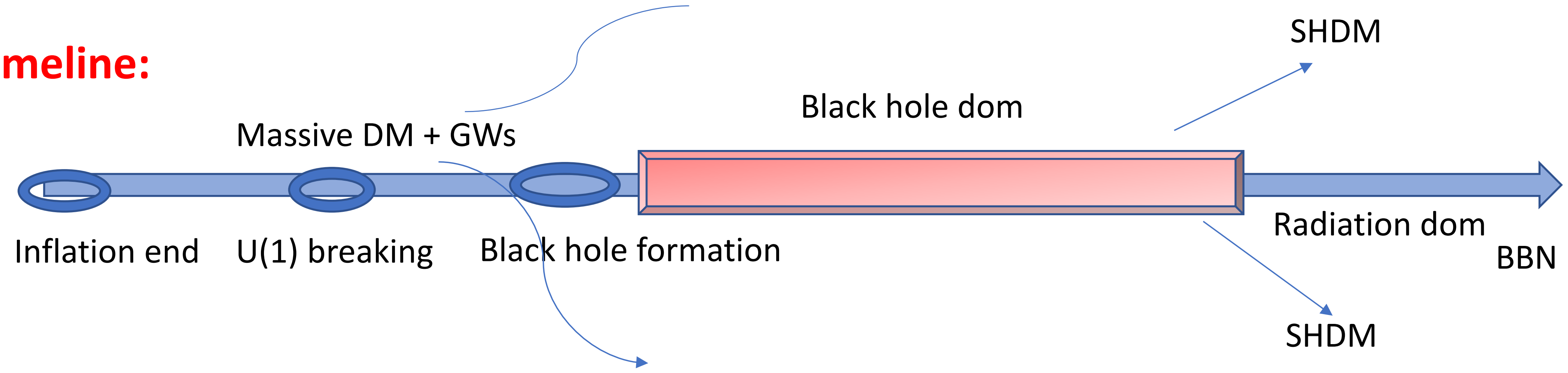
Samanta & Urban, upcoming

Keep in mind that we are dealing with a particle DM candidate

This probably motivates: The mass MDM is generated by a symmetry breaking mechanism ! Consider a simple gauge symmetry is U(1) that protects vanishing DM mass.

U(1) breaking=> DM mass + cosmic strings (gravitational)

Timeline:



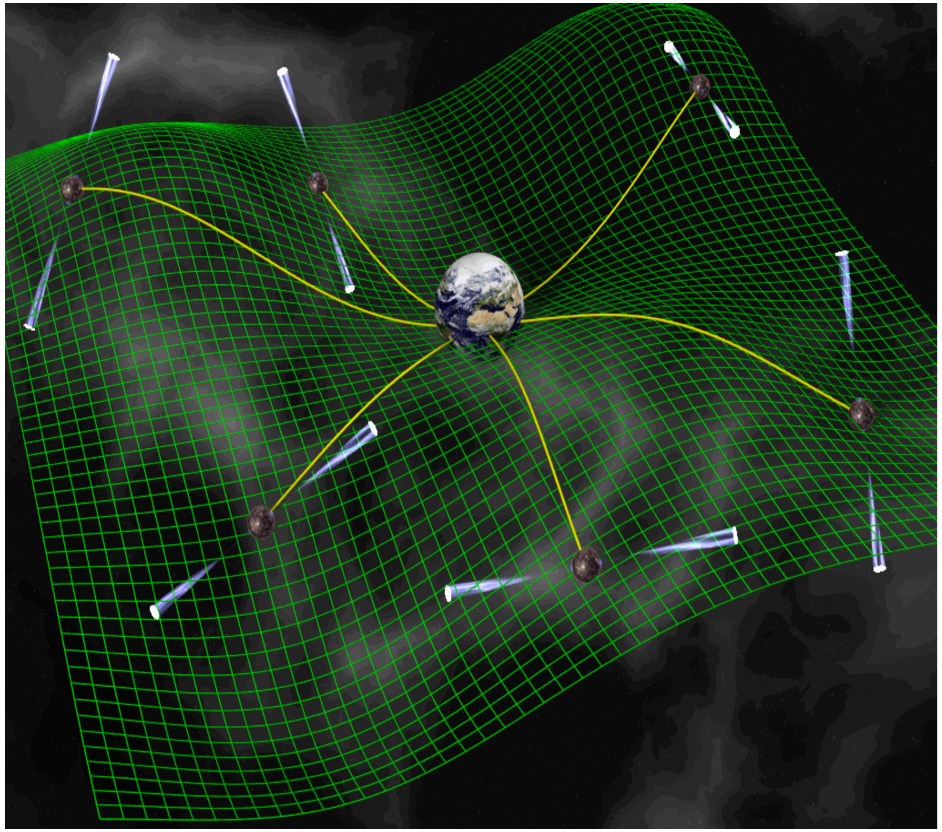
High scale physics: Motivation for cosmic strings, e.g., PTAS

Millisecond pulsars (spins ~100 times a second) produce most stable pulses and are used by the PTAs

When a gravitational wave (a disturbance) passes between the earth and pulsar system, the time of arrival of the signal from the pulsars changes. This induces a change in frequency due to the gravitational wave.

Time residual: $$R(t) = -\int_0^t \frac{\delta\nu}{\nu}\,\mathrm{d}t$$

Pulsar-Timing-Arrays typically work with high amplitude GWs => Could be a Detector of High Scale Symmetry breaking theories



Recent report of SGWB at NANOGrav

Cosmic strings

Cosmological phase transition leads to spontaneous breaking of abelian symmetry
This is associated with topological defect like cosmic strings (CS). (T. Kibble, J. Phys. A 9 (1976)).

They can form close loop and shrink via GW emission.

Still there are debates whether they loose energy via particle radiation or GW emission.

Recent numerical simulation based Nambu-Goto action shows that the dominant emission is GW if the broken symmetry is a local gauge symmetry. (Pillado et al, **PRD 2011**, T. Vachaspati et al ,**PRD**, C. Ringeval et al **JCAP**).

Radiate energy at constant rate $$\frac{dE}{dt} = -\Gamma G\mu^2,$$

Length dynamics $$l(t) = \alpha t_i - \Gamma G\mu(t - t_i)$$

G: Newton constant , $\boldsymbol{\mu}$: string tension (~**Square of symmetry breaking scale**), $\boldsymbol{\alpha}$: loop size (max: 0.1)

Gravitational waves power spectrum and loop number density

Amplitude/energy density

$$\Omega_{GW}(t_0, f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df} = \sum_k \Omega_{GW}^{(k)}(t_0, f).$$

Differential energy density

$$\frac{d\rho_{GW}^{(k)}}{df} = \int_{t_F}^{t_0}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^4 P_{GW}(\tilde{t}, f_k)\frac{dF}{df}d\tilde{t},$$

Power spectrum

$$P_{GW}(\tilde{t}, f_k) = \frac{2kG\mu^2\Gamma_k}{f_k^2}n(\tilde{t}, f_k) = \frac{2kG\mu^2\Gamma_k}{f^2\left[\frac{a(t_0)}{a(\tilde{t})}\right]^2}n\left(\tilde{t}, \frac{2k}{f}\left[\frac{a(\tilde{t})}{a(t_0)}\right]\right).$$

μ^2/M_{pl}

Amplitude/energy density

$$\Omega_{GW}^{(k)}(t_0, f) = \frac{2kG\mu^2\Gamma_k}{f\rho_c}\int_{t_{osc}}^{t_0}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5 n\left(\tilde{t}, \frac{2k}{f}\left[\frac{a(\tilde{t})}{a(t_0)}\right]\right)d\tilde{t}.$$

Loop number density

Numerical simulation:

$$n(\tilde{t}, l_k(\tilde{t})) = \frac{0.18}{\left[l_k(\tilde{t}) + \Gamma G\mu\tilde{t}\right]^{5/2}\tilde{t}^{3/2}}.$$

Cosmic archeology, GW spectral shapes

Amplitude sensitivity

Amplitude + spectral shape sensitivity

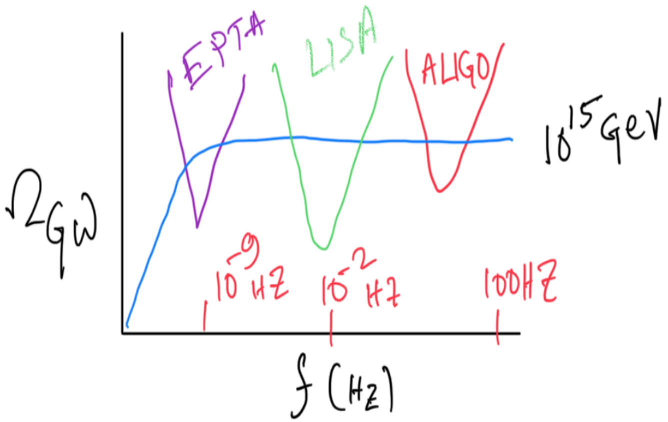
Standard Cosmology (w=1/3)

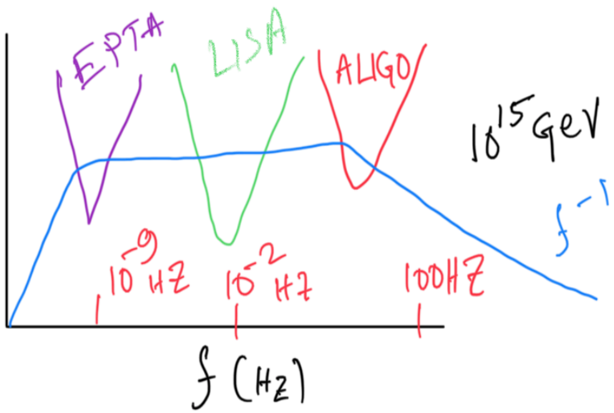
Early Matter domination (w=0)

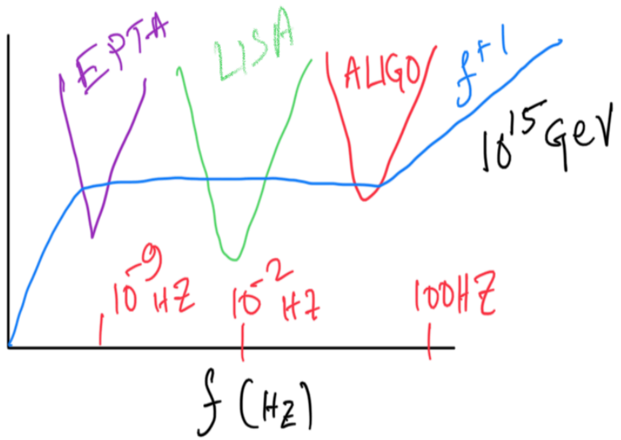
Kination (w=1)

A spectral break (f_*,T_*)

Fundamental mode (k=1):







Standard cosmology

Black hole domination

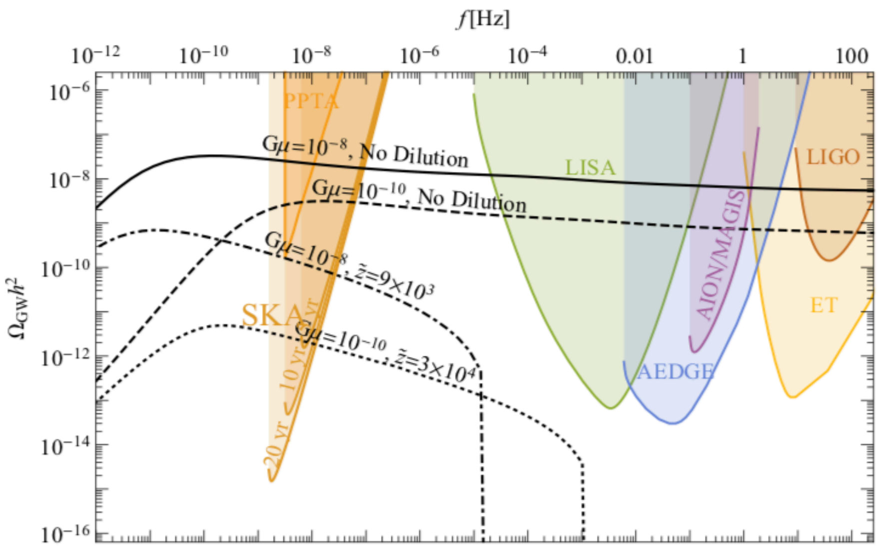
Kination

Our attention

Some non-standard spectrums

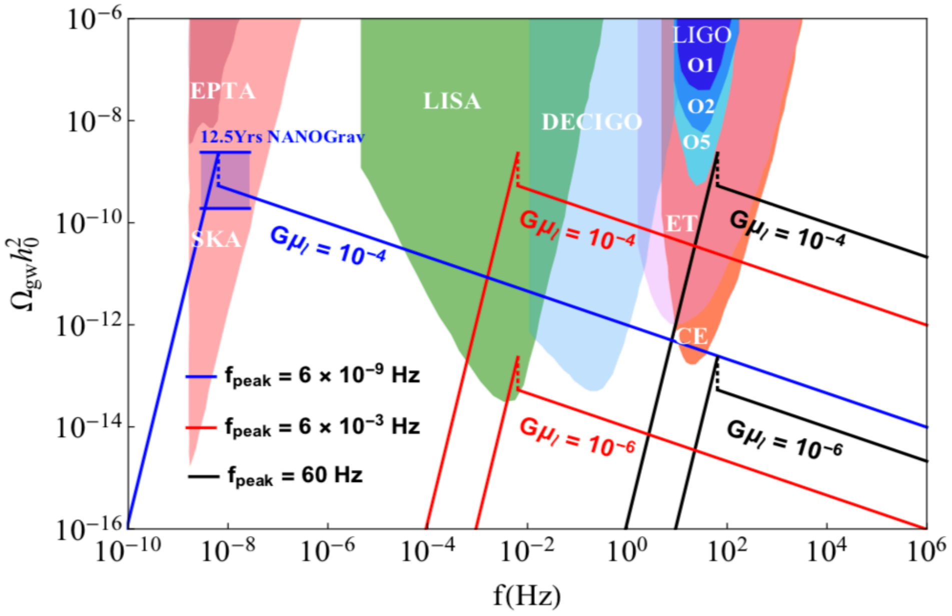
Cosmic strings with inflation dilution

Cui, Lewicki, Morrissey, PRL, 2020



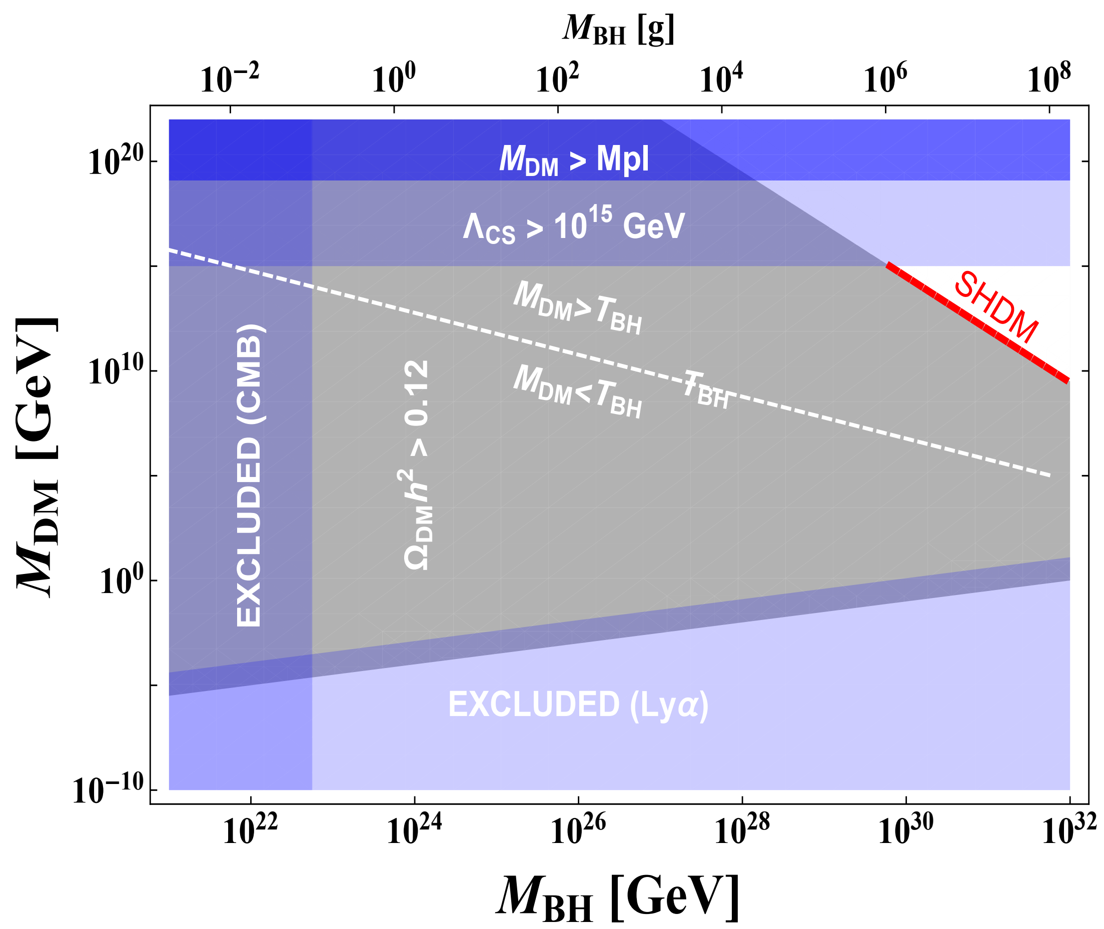
Melting cosmic strings

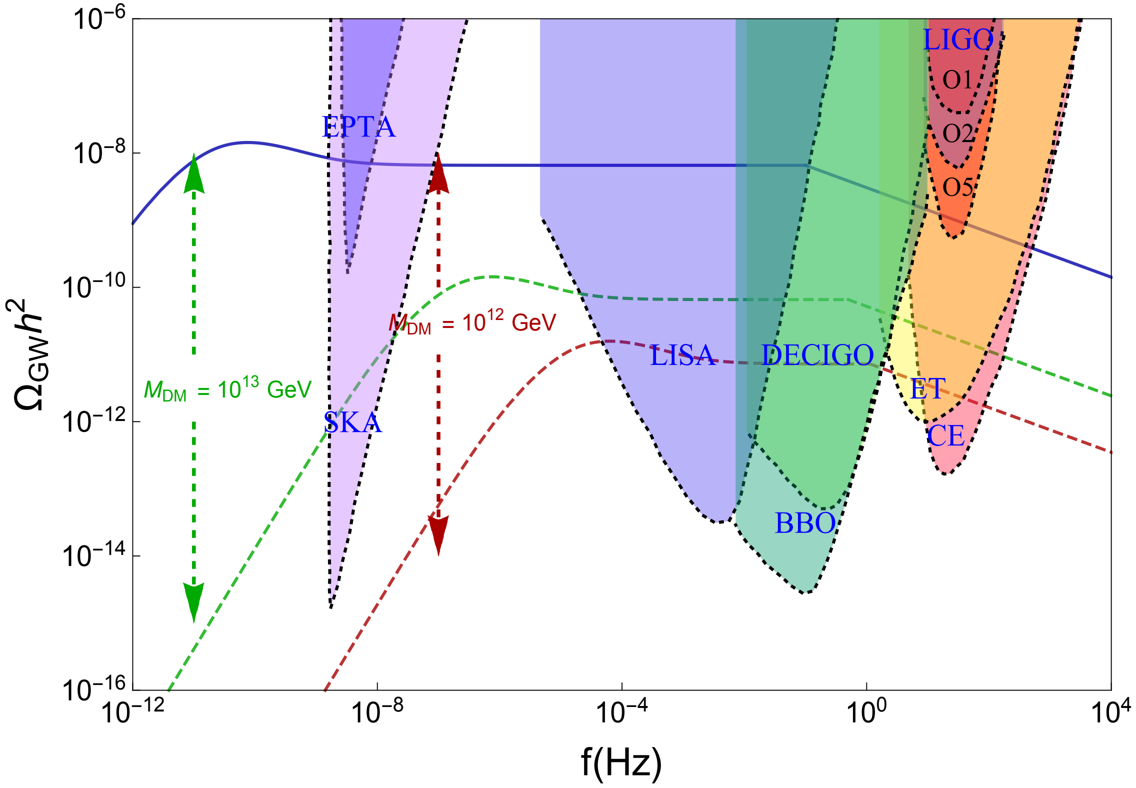
Emond, Ramazanov, Samanta (2108.05377)



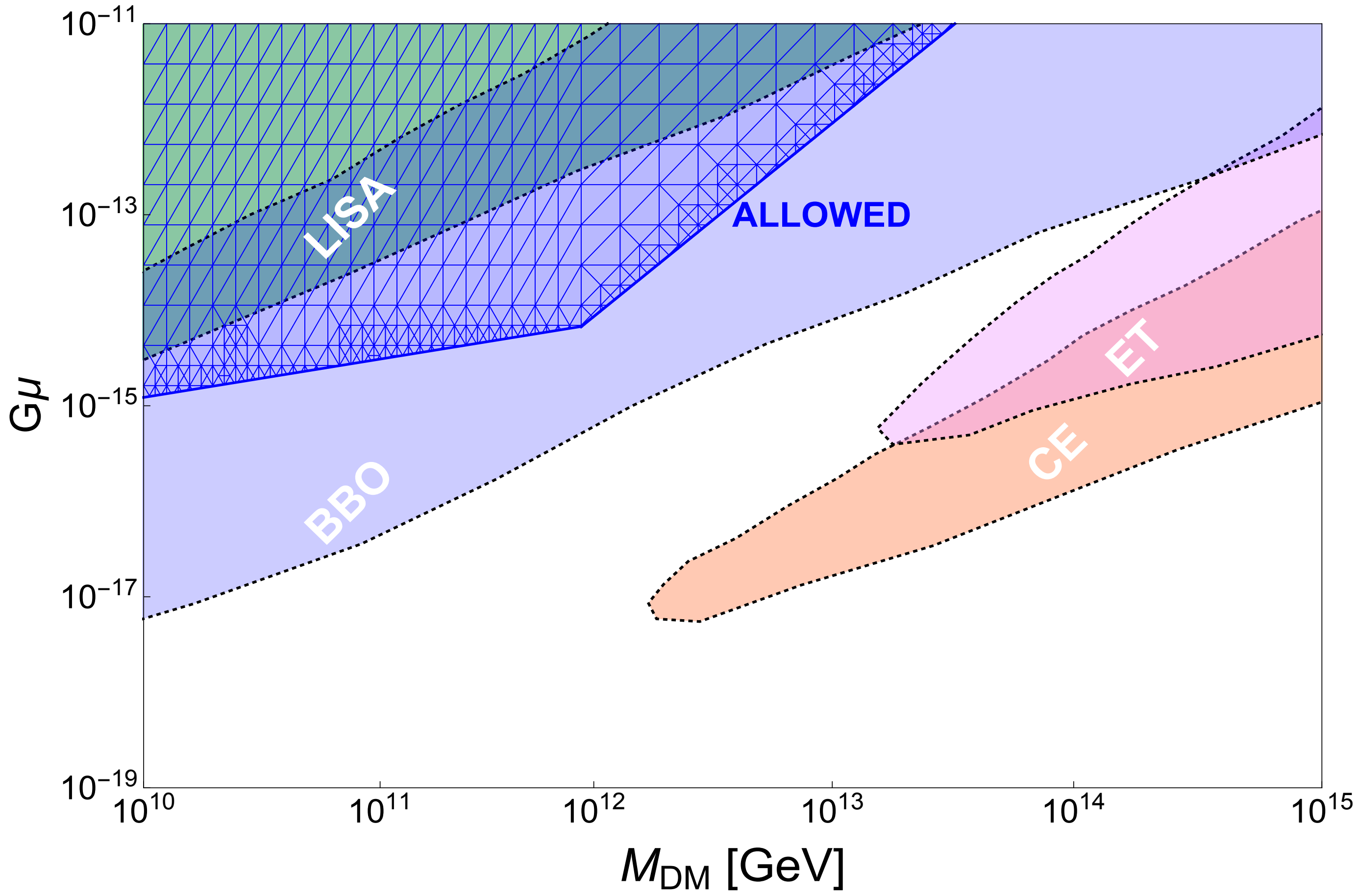
GW spectral features as a probe of SHDM

$$f_* = \sqrt{\frac{8}{z_{eq}\,\alpha\, T\, G M}}\left[\frac{g_*(T_{ev})}{g_*(T_0)}\right]^{1/4}\left(\frac{T_{ev}}{T_0}\right) f_0^{-1}$$





A more rigorous parameter space



Towards a testable theory of matter

Samanta & Urban, upcoming

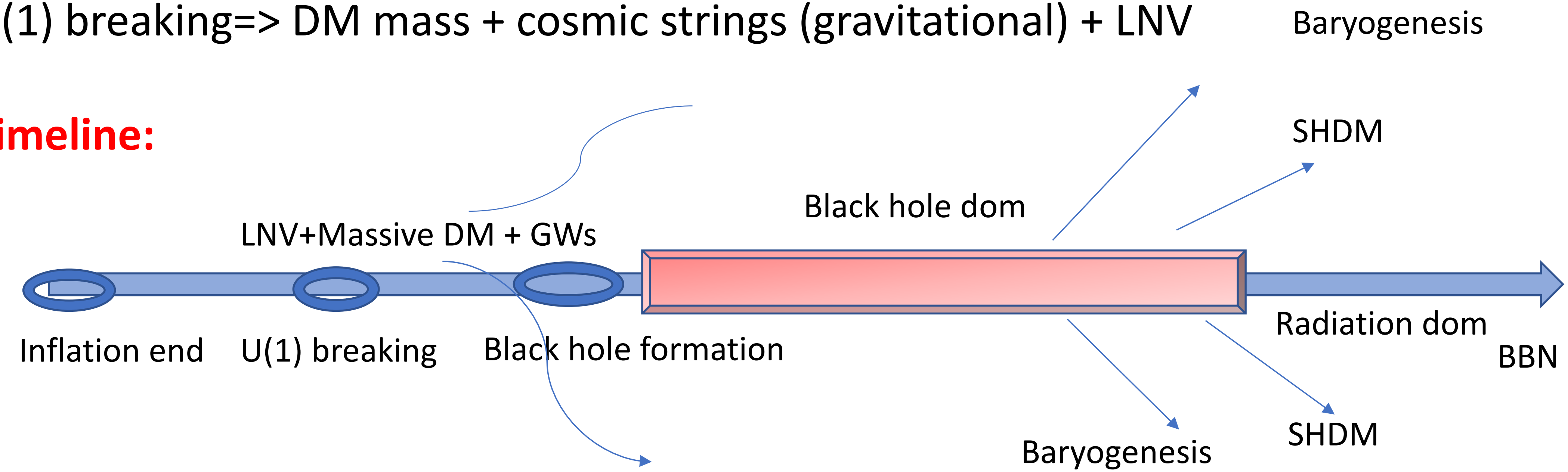
Keep in mind that we are dealing with a particle DM candidate

A simple sterile **three (like any other fermion generation)** Majorana fermion extension of the SM models solves three problems 1) N1-> DM matter 2) N2, N3 baryogenesis via leptogenesis.

Lepton number violation at a high scale, $\mathrm{VEV}_{U(1)}$

U(1) breaking=> DM mass + cosmic strings (gravitational) + LNV

Timeline:



Future improvement

1) We did not consider black hole-string network that could provide spectral distortion. (Vilenkin et al , 2018)

2) Potential GWs from black hole density perturbation (Papanikolaou, 2020)

Summary

Gravitational Waves could be potential probe of High scale physics which otherwise cannot be probed e.g., in colliders.

I discussed a way to probe Super heavy Dark Matter with GWs

A characteristic spectral features along with bounded GW amplitudes Could be a smoking gun signal of SHDM.

We are now constructing a more general scenario where GW detectors will confront the origin of the matter content of universe.