Origin of matter in a black hole-cosmic string landscape

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CEICO, Institute of Physics of the Czech Academy of Sciences, CZ

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Presentation take away

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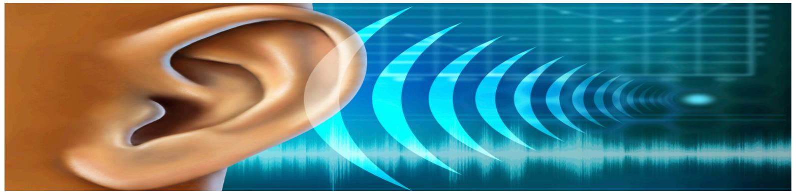
2. If **the recent finding by the pulsar timing arrays** corresponds to an existence of super heavy dark matter, high frequency detectors like LISA, DECIGO should be able to find a break in the GW spectrum.

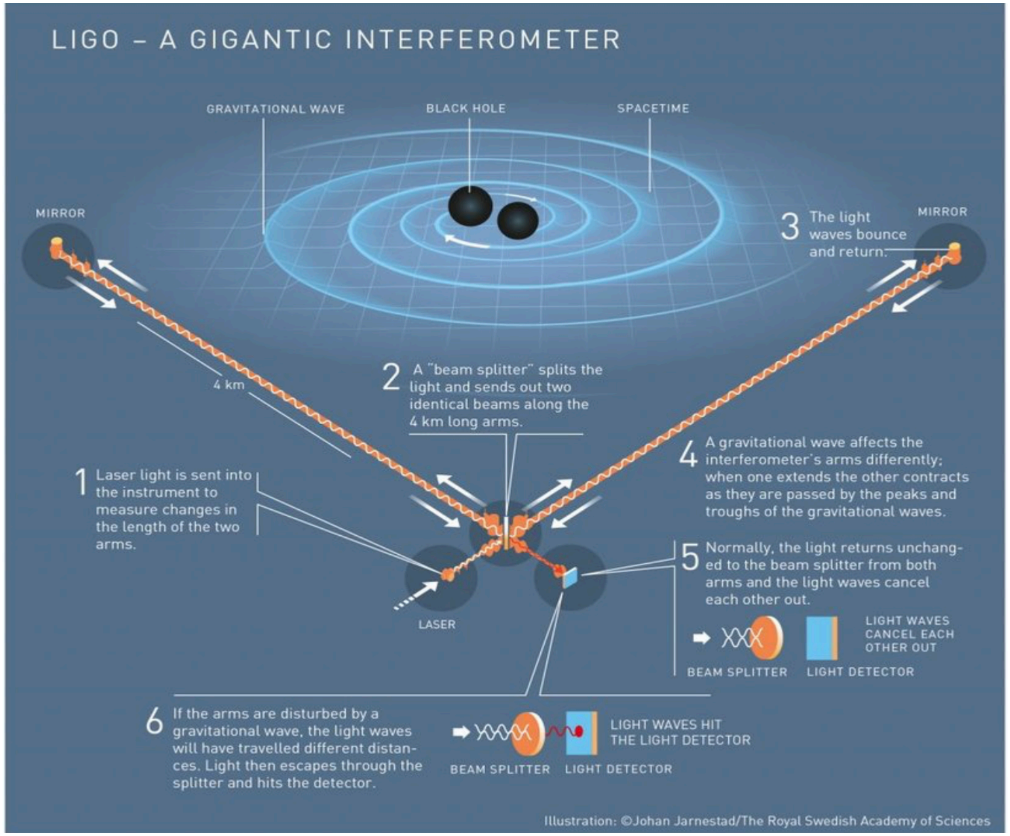
3. **When implemented in seesaw**, one of the right-handed neutrinos could be super heavy dark matter and other two lead to thermal leptogenesis.

References

- R. Samanta and F. Urban, JCAP**(2022)***.
- R. Samanta, D. Borah, S.Das, A Saha, 2202.10474
- R. Samanta and F. Urban, to appear soon.

Hearing from the early universe





1 Laser light is sent into the instrument to measure changes in the length of the two arms.

2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.

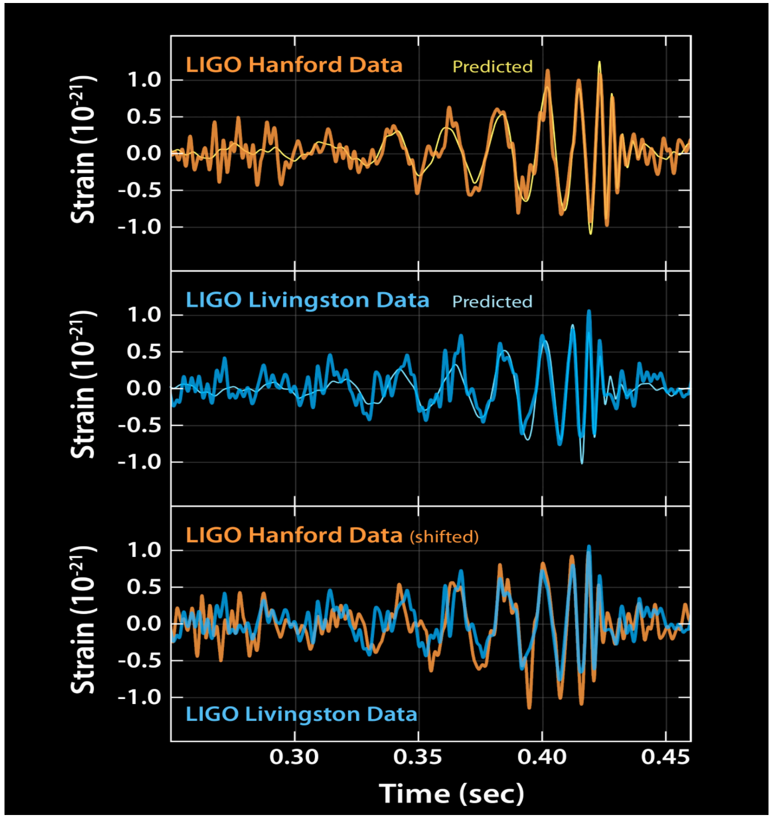
3 The light waves bounce and return.

4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.

5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.

6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.

Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences



CREDIT: https://phys.org/news/2019-05-ligo-virgo-neutron-star-smash-ups.html

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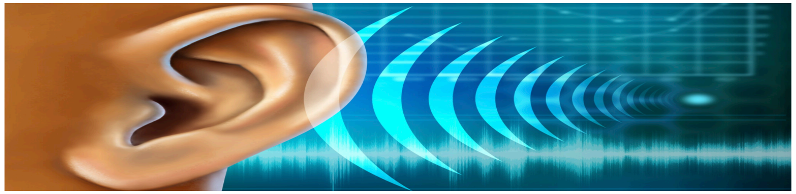

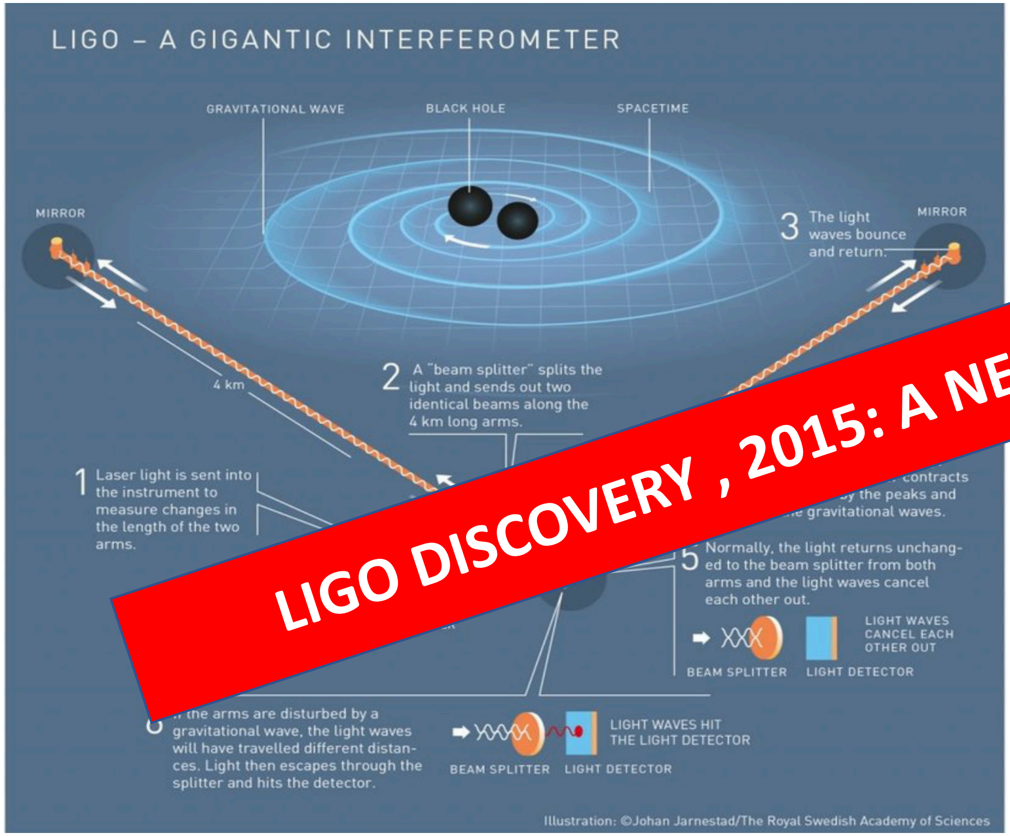

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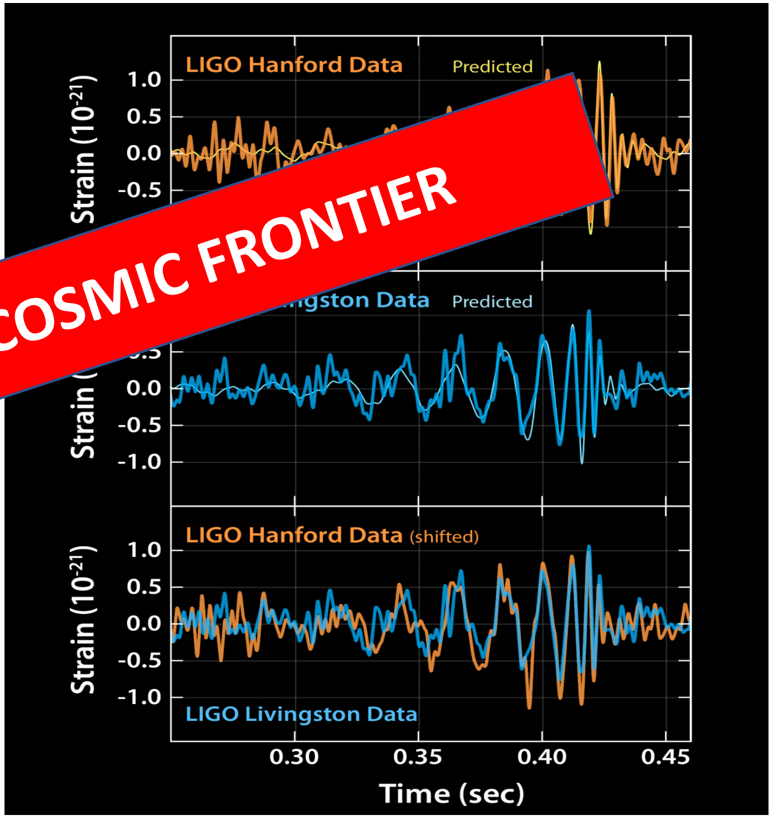

LIGO DISCOVERY , 2015: A NEW COSMIC FRONTIER

CREDIT: https://phys.org/news/2019-05-ligo-virgo-neutron-star-smash-ups.html

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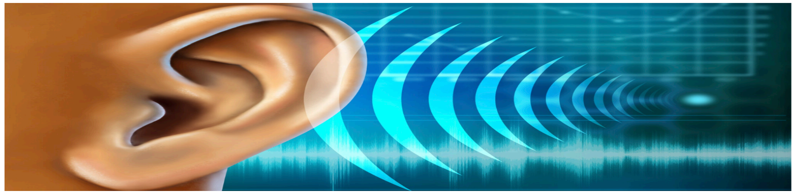

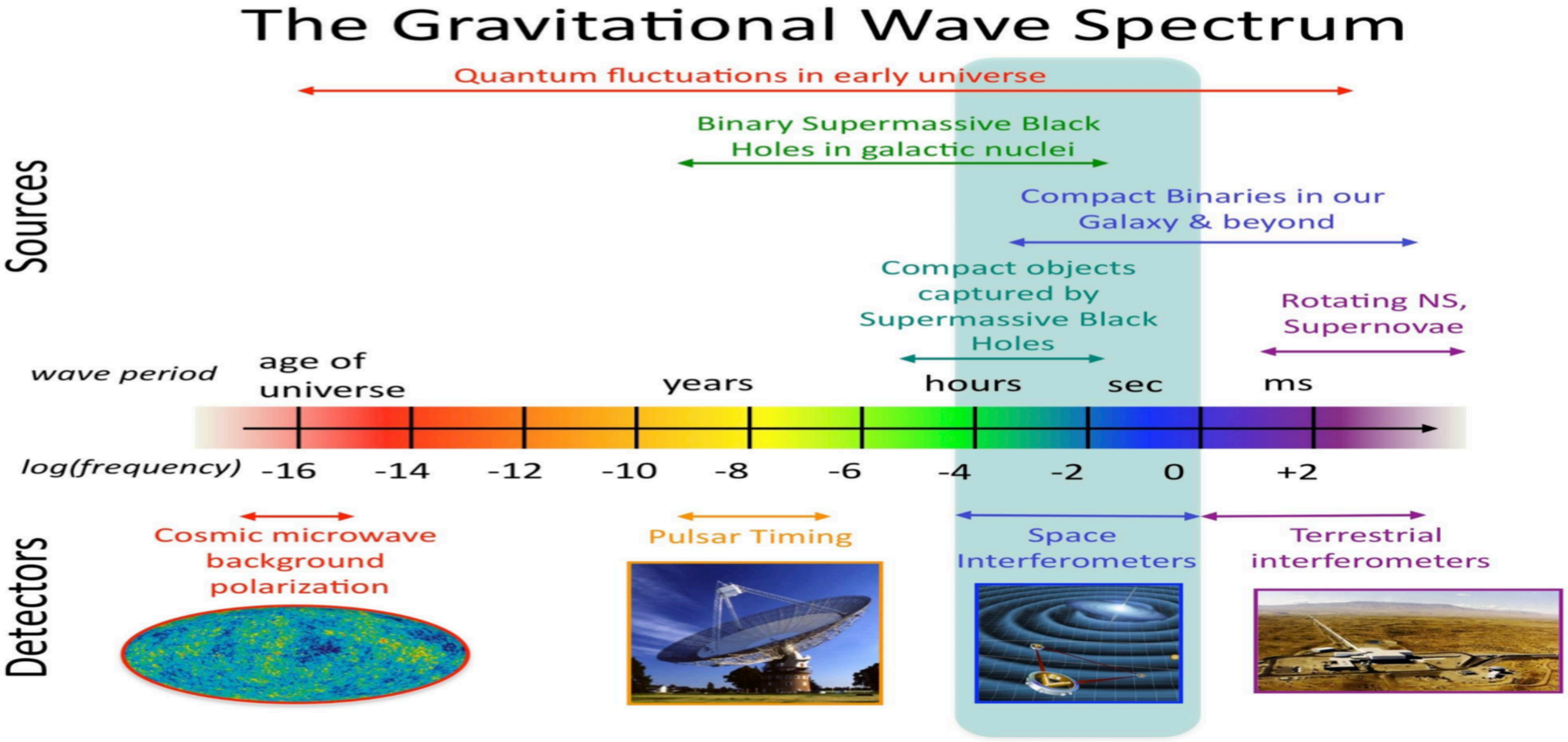

Credit: NASA Goddard Space Flight Center

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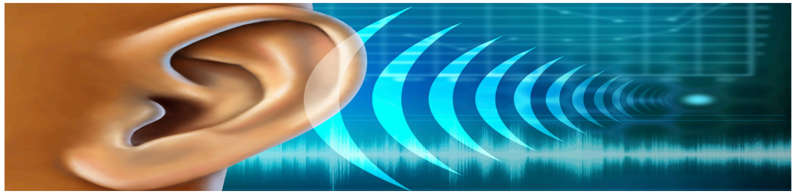

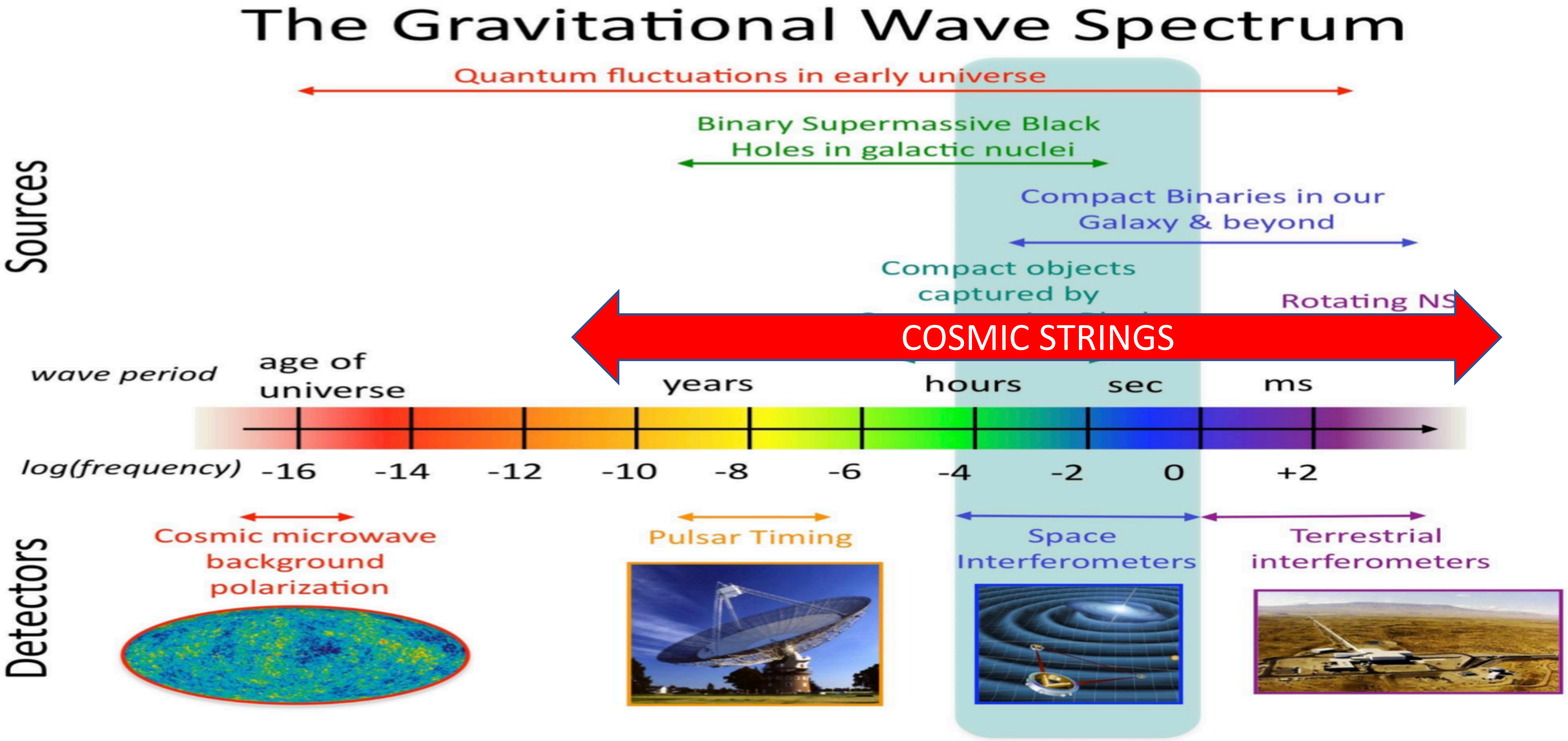

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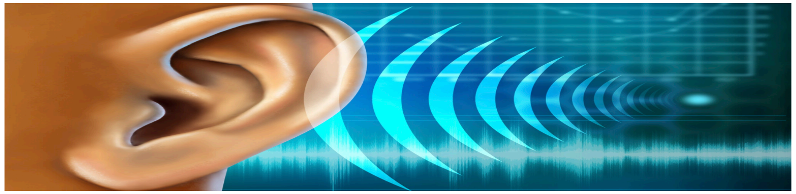
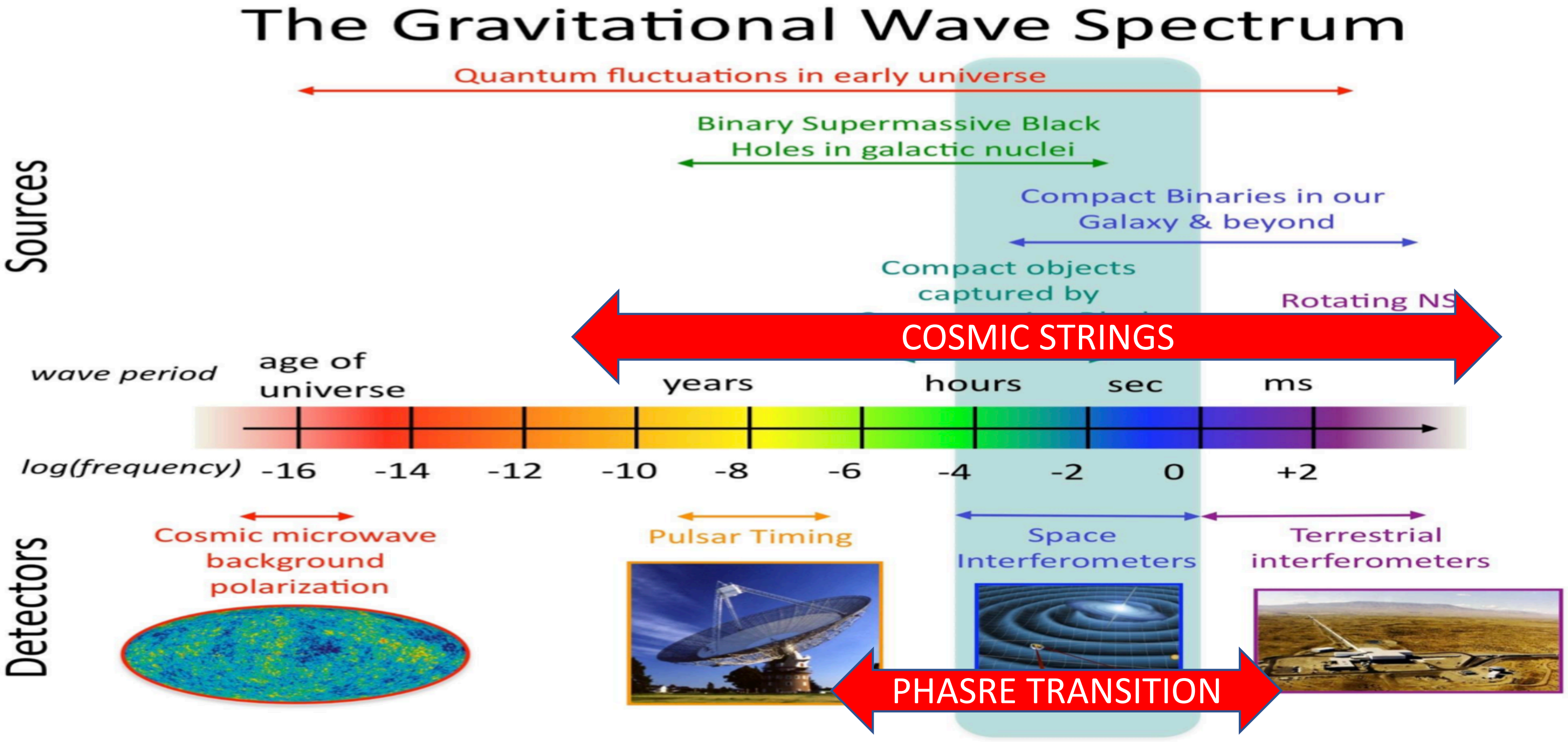




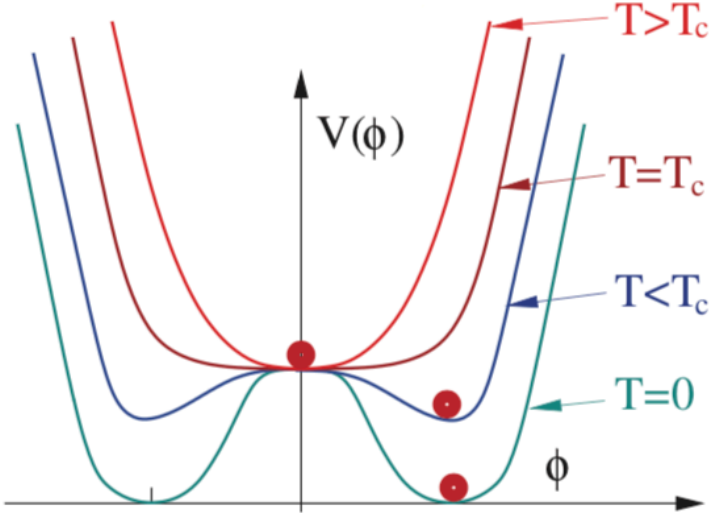
COSMIC STRINGS

PHASRE TRANSITION

Credit: NASA Goddard Space Flight Center

Dynamics of phase transition

Second order Transition



Rolling of the field

$$V(\Phi,0) = -\frac{\mu^2}{2}\Phi^2 + \frac{\lambda}{4}\Phi^4$$

$$V(\Phi,T) = V(\Phi,0) + D(T^2 - T_0^2)\Phi^2 - ET\Phi^3$$

$$D = \frac{3g^2+4\lambda}{24}, \quad E = \frac{3g^3+g\lambda+3\lambda^{3/2}}{24\pi} \quad \text{and} \quad T_0 = \frac{\sqrt{12\lambda}v_\Phi}{\sqrt{3g^2+4\lambda}}.$$

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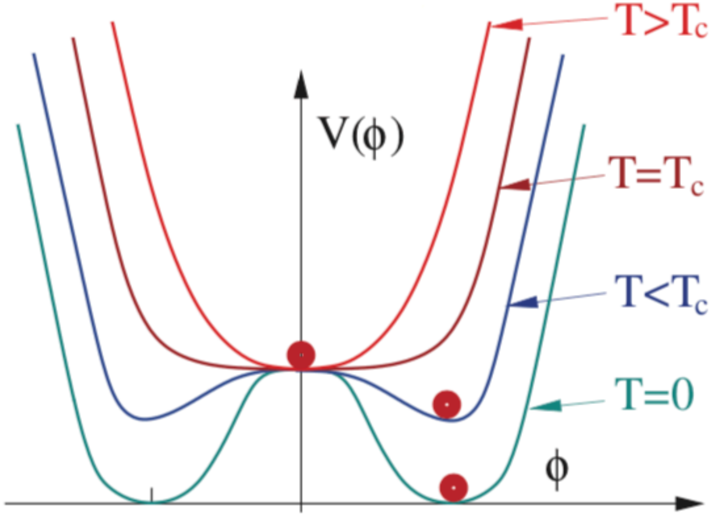

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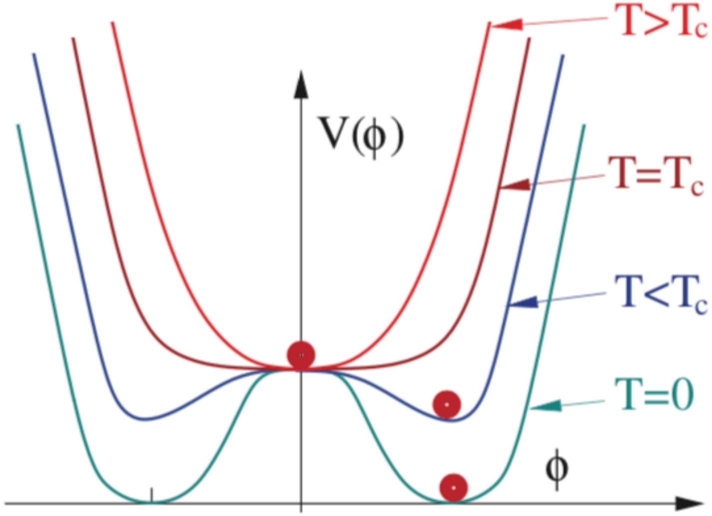

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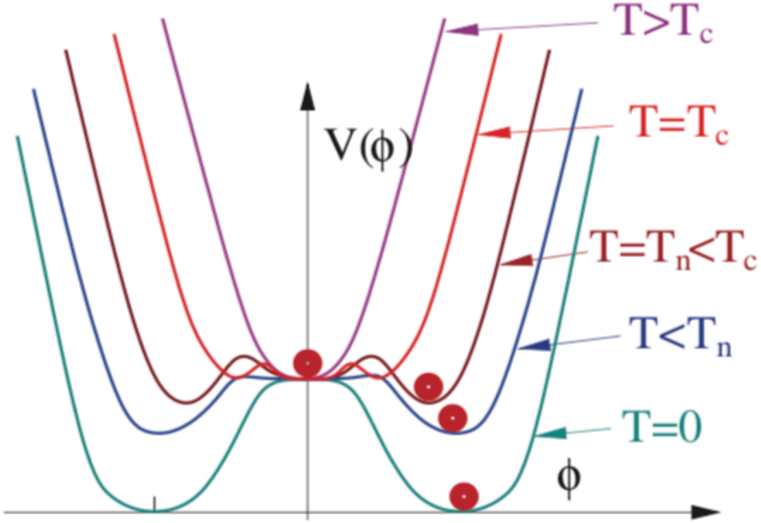

Tunneling

$$V(\Phi,T) = V(\Phi,0) + D(T^2 - T_0^2)\Phi^2 - ET\Phi^3,$$

Dynamics of phase transition

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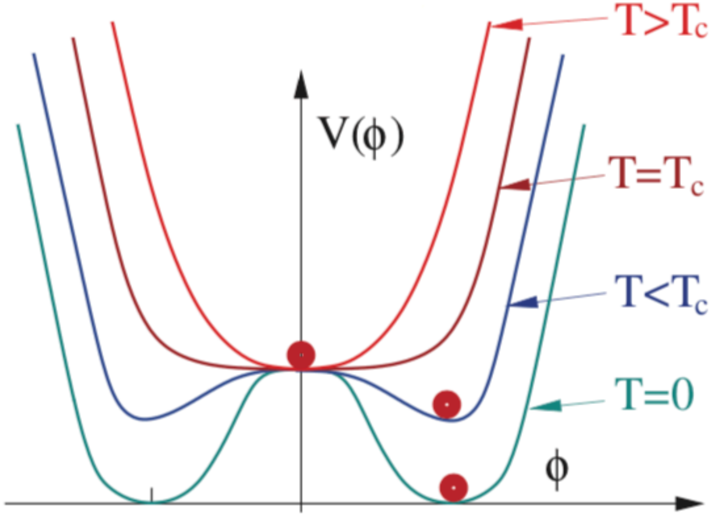

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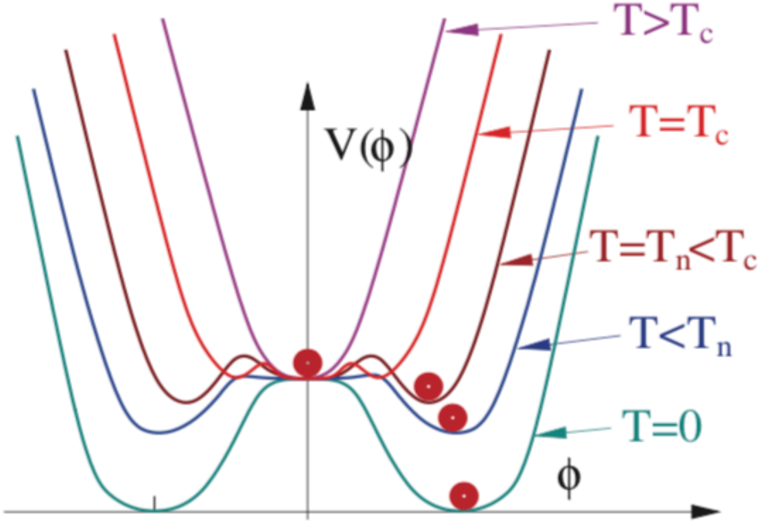

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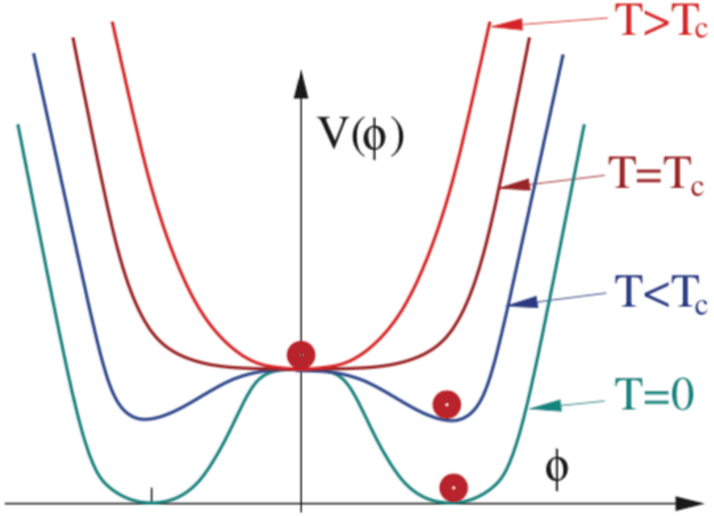

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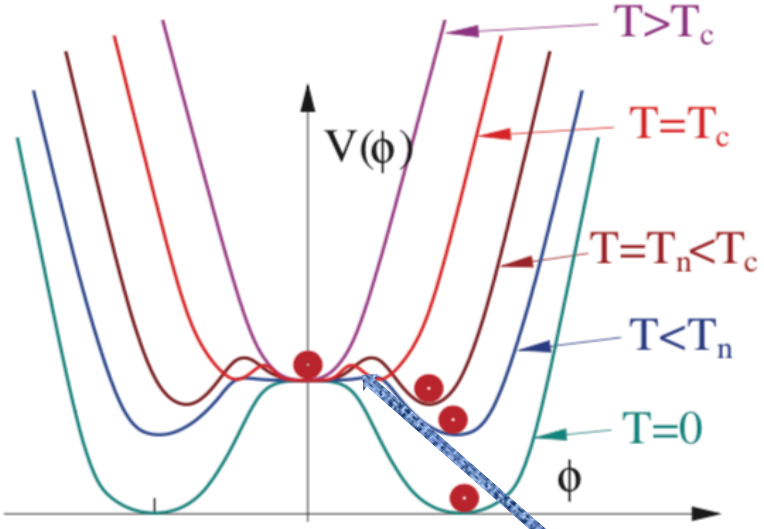

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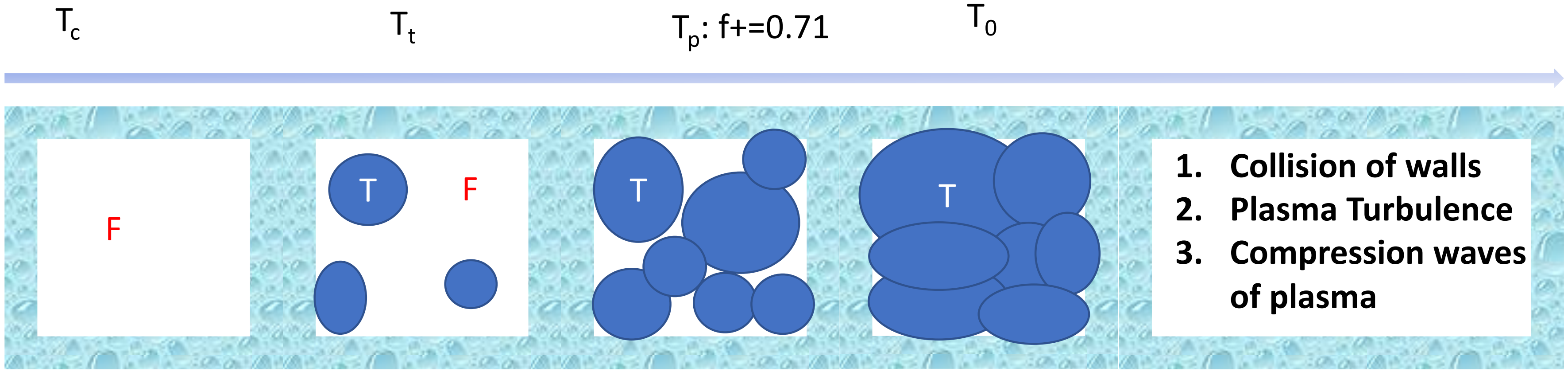
Gravitational waves

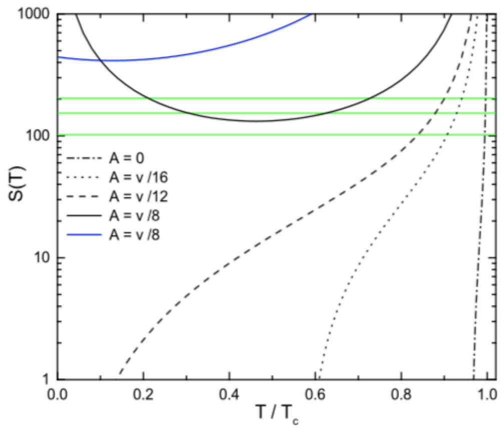
E.g., Hindmarsh et al, SciPost (2021)

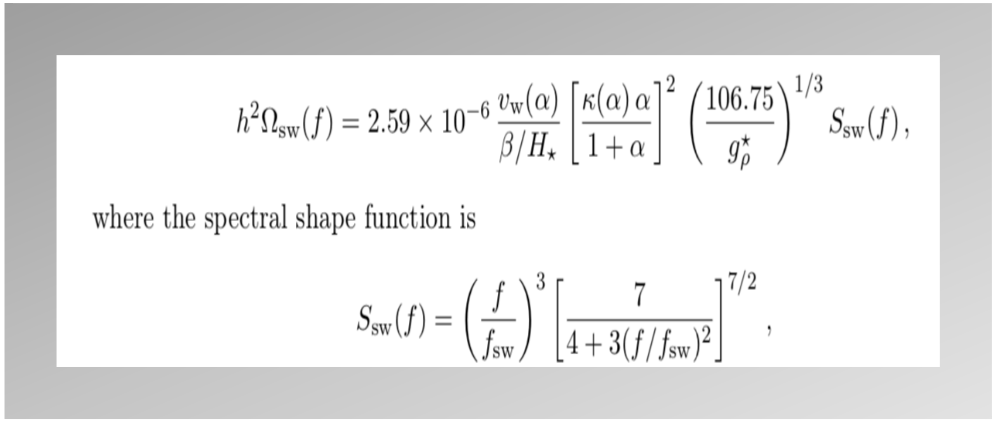
First order Transition → direct contribution (Dynamics of vacuum bubbles)



1. **Collision of walls**
2. **Plasma Turbulence**
3. **Compression waves of plasma**

$$\frac{\beta}{H_*} = \left[T \frac{\mathrm{d}}{\mathrm{d}T} \left(\frac{S_3(T)}{T} \right) \right] \Bigg|_{T=T_*}$$





$$h^2\Omega_{\rm sw}(f) = 2.59 \times 10^{-6} \frac{v_{\rm w}(\alpha)}{\beta/H_\star} \left[\frac{\kappa(\alpha)\,\alpha}{1+\alpha}\right]^2 \left(\frac{106.75}{g_\rho^\star}\right)^{1/3} S_{\rm sw}(f),$$

where the spectral shape function is

$$S_{\rm sw}(f) = \left(\frac{f}{f_{\rm sw}}\right)^3 \left[\frac{7}{4+3(f/f_{\rm sw})^2}\right]^{7/2},$$

Gravitational waves

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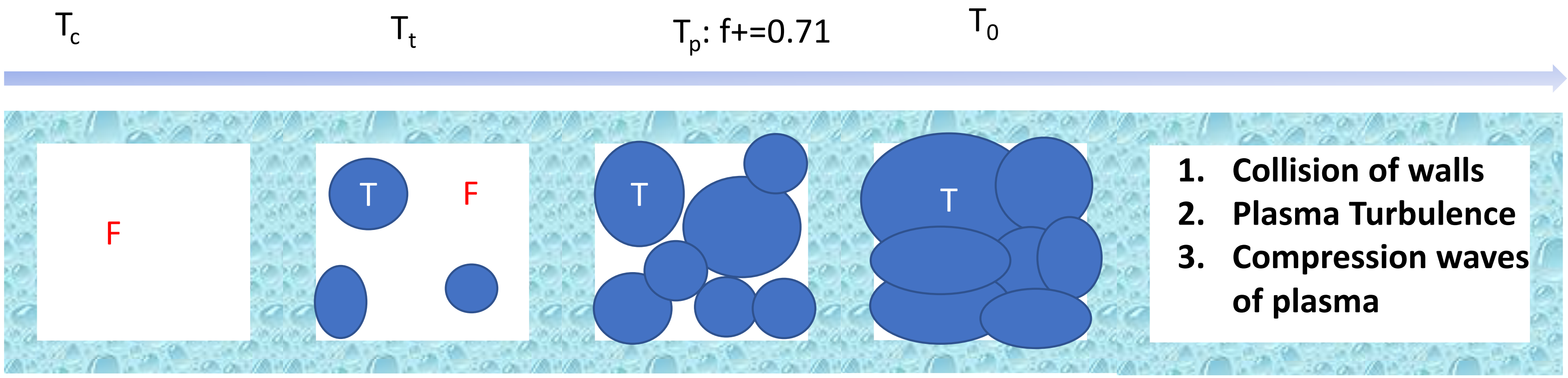

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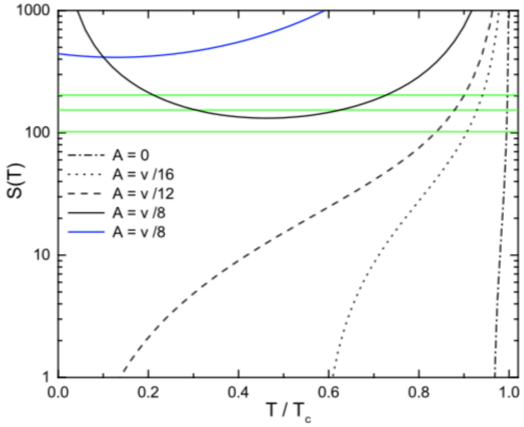
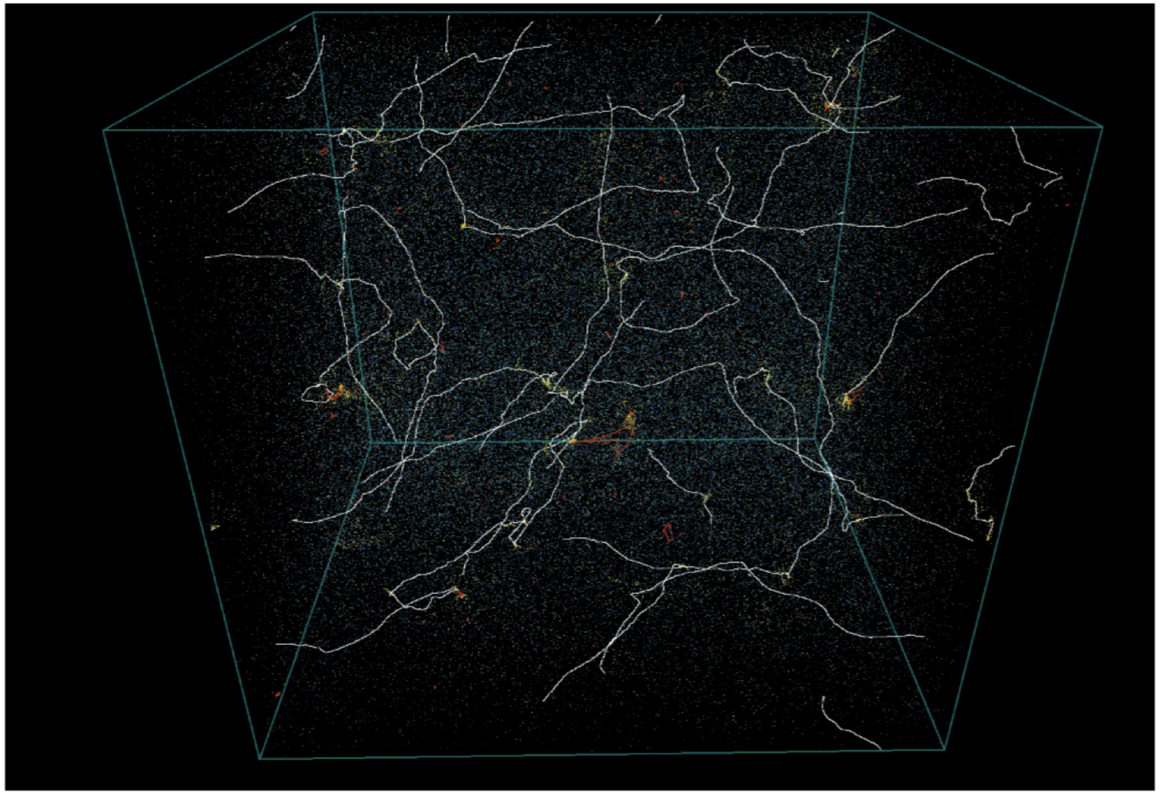


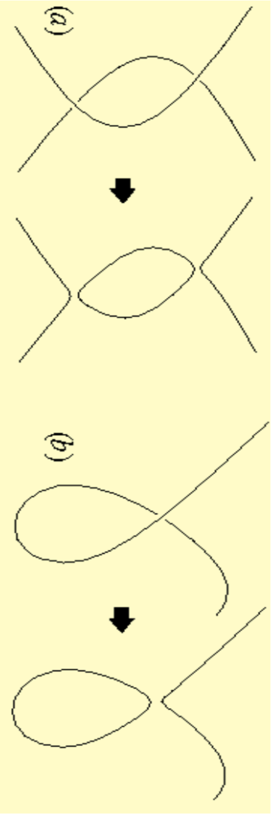
$$f_{\rm sw} = 1.92\times 10^{-2}\,{\rm mHz}\,\frac{1}{v_{\rm w}}\,\frac{\beta}{H_\star}\,\frac{T_\star}{100\,{\rm GeV}}\left(\frac{g_\rho^\star}{106.75}\right)^{1/6}$$

String inter-commutation

U(1) theory



T. Vachaspati et al 1506.04039



These loops radiate to GWs

Cosmic string scaling

Long strings evolution is a random walk problem in the early universe (**velocity-dependent-one-scale model**)

$$\boxed{\boldsymbol{\mu} = V(\text{vev})^2}$$

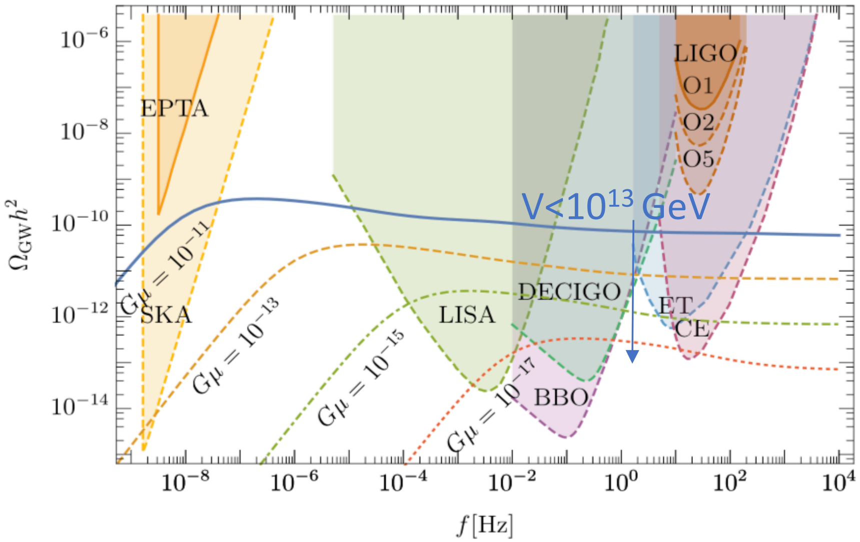
Long-string correlation length $L^2 = \boldsymbol{\mu}/\boldsymbol{\rho}_L$, $L \approx t \Rightarrow \boldsymbol{\rho}_L \approx \boldsymbol{\mu}\, t^{-2}$

Friedmann equation: $t^{-2} G^{-1} \approx \boldsymbol{\rho}_{bg}$

$$\boxed{\boldsymbol{\rho}_L \approx \boldsymbol{\rho}_{bg} G\boldsymbol{\mu}}$$

$V = 10^{15} \Rightarrow \boldsymbol{\mu} = 10^{30}, \Rightarrow G\boldsymbol{\mu} \approx 10^{-8}$

CS never dominates the energy density of the universe



$V < 10^{13}$ GeV

Gravitational waves power spectrum and loop number density

Amplitude/energy density

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

Summing over all the modes

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:

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

Analytical

$$n(l, t) = \frac{A_\beta C_\beta(\alpha)}{t^{3\beta}\left(l + \Gamma G\mu t\right)^{4-3\beta}},$$

Cosmic archeology, GW spectral shapes and Leptogenesis

Amplitude sensitivity

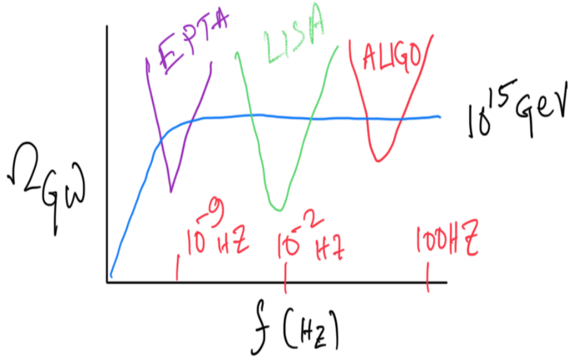
Amplitude + spectral shape sensitivity

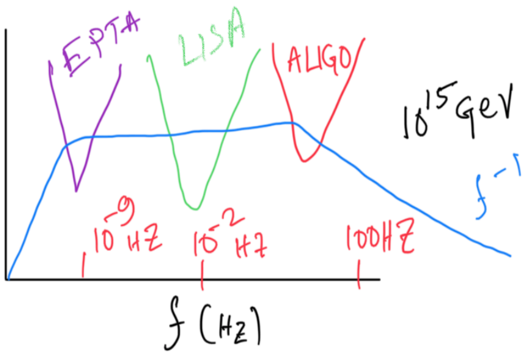
Standard Cosmology (w=1/3)

Early Matter domination (w=0)

A spectral break

Fundamental mode (k=1):





Turning point frequency

$$f_\Delta = \sqrt{\frac{8}{z_{\rm eq}\alpha\Gamma G\mu}}\left[\frac{g_*(T_\Delta)}{g_*(T_0)}\right]^{1/4}\left(\frac{T_\Delta}{T_0}\right)t_0^{-1},$$

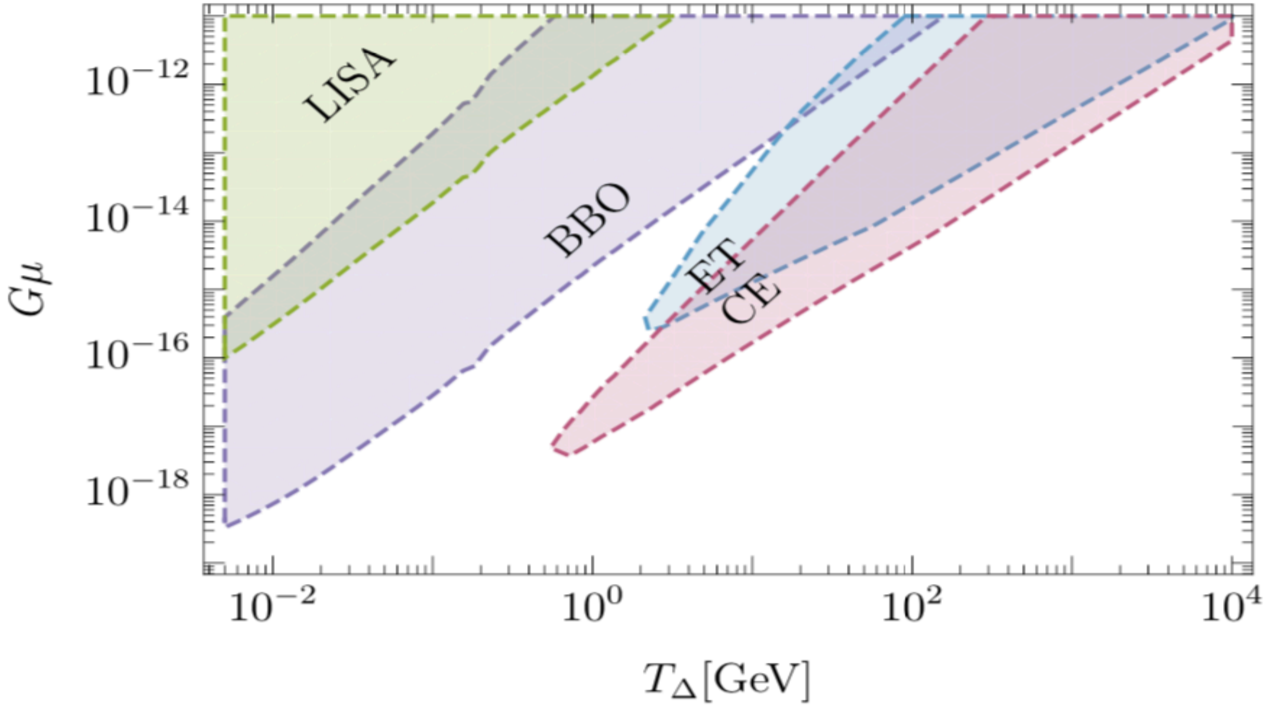
Standard cosmology

Murayama et al PRL(2020)
Samanta et al JHEP(2020)

Matter/Black holes dominated universe

Samanta et al JCAP(2021)

Sensitivity

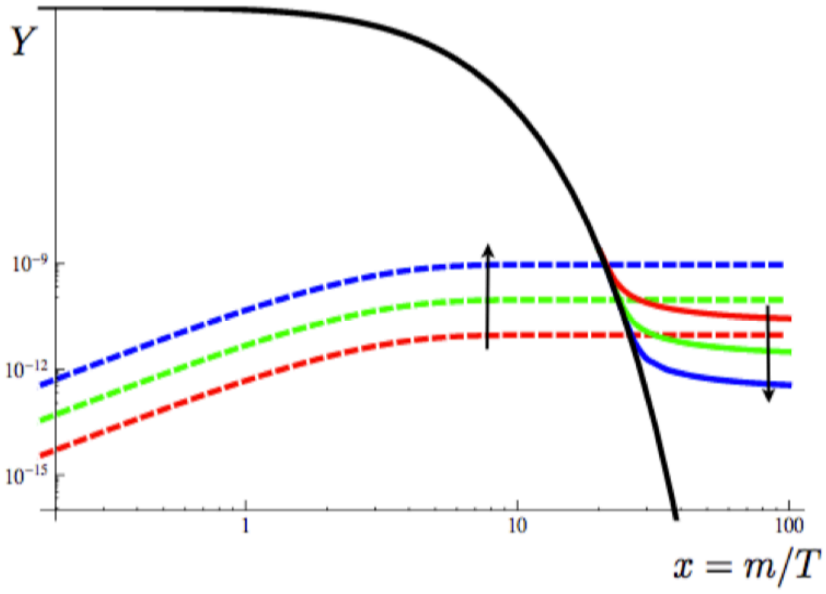


e.g, Y. Cui et al, JHEP (2020)

Miracle-less WIMP: A new class of DM

Samanta et al, 2202.10474

DM has u(1) charge



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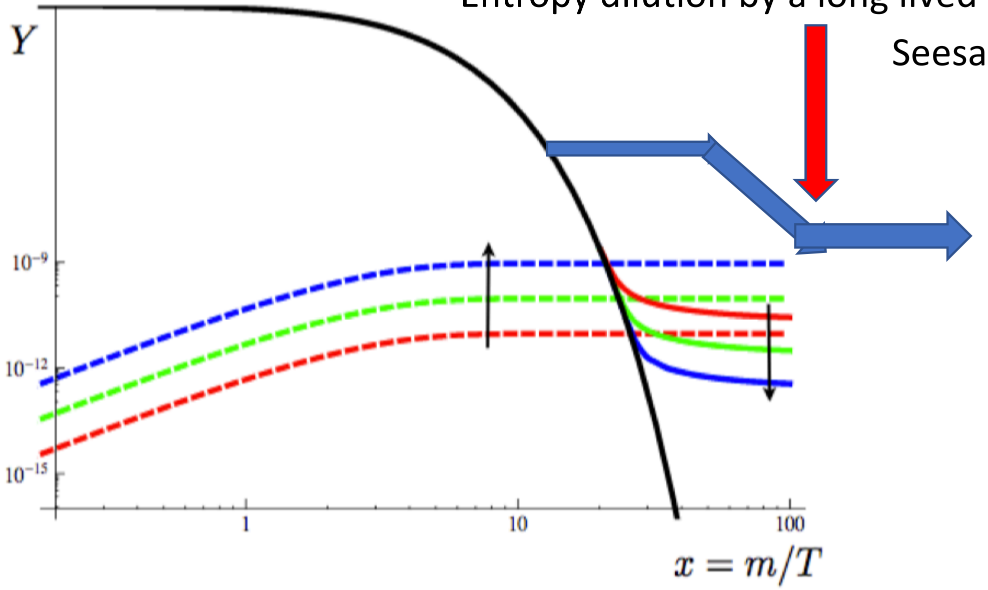

Entropy dilution by a long lived particle

Seesaw: N_1

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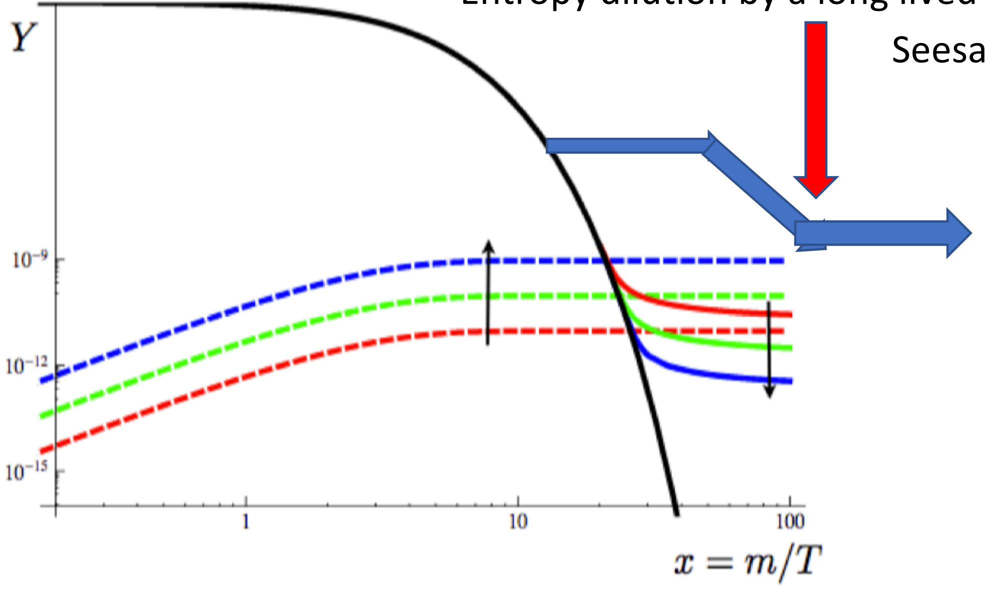
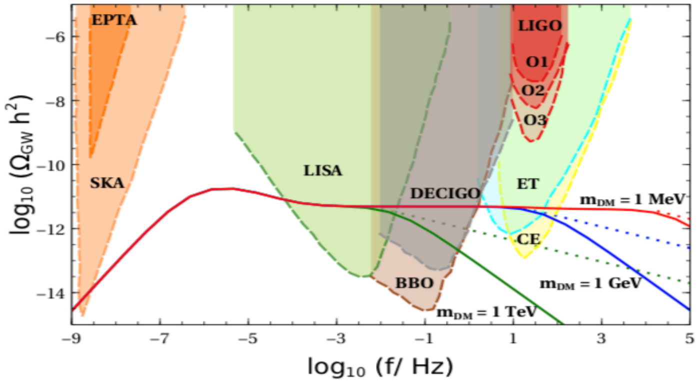
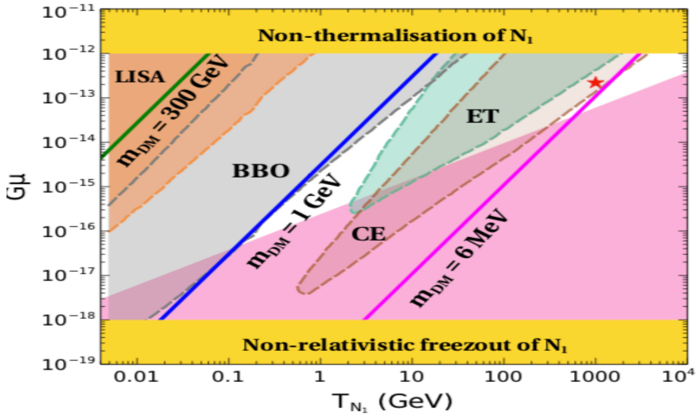






$M_{DM} < 8$ TeV

Otherwise Diluter mess with BBN predictions

Ultralight primordial black holes as diluters

Ultralight primordial black holes as diluters

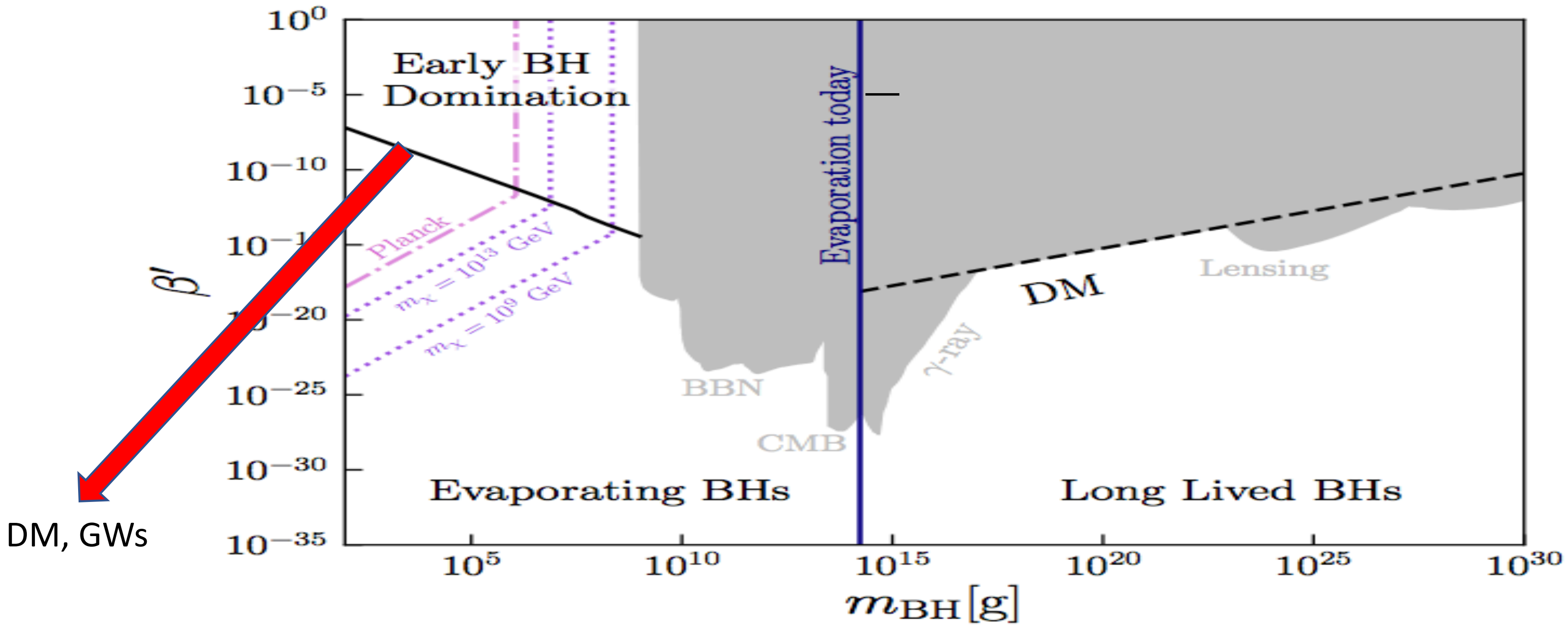
Constraints on black hole masses masses Free parameter: $\boldsymbol{\beta} = \boldsymbol{\rho}_{BH}/\boldsymbol{\rho}_{rad}$

PBH Mass

< 0.1 g (CMB) produce Dark matter

>10^9 g (constrained by BBN T~5MeV)

> 10^{15} g (it self Dark matter)

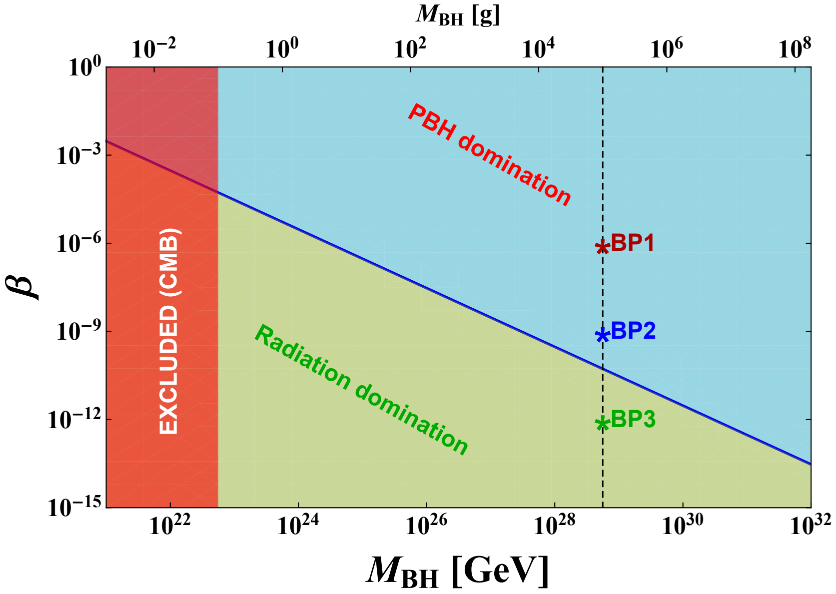


DM, GWs

Ultralight PBH dynamics (only non-rotating)

e.g., Samanta, Datta JCAP (2021)

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



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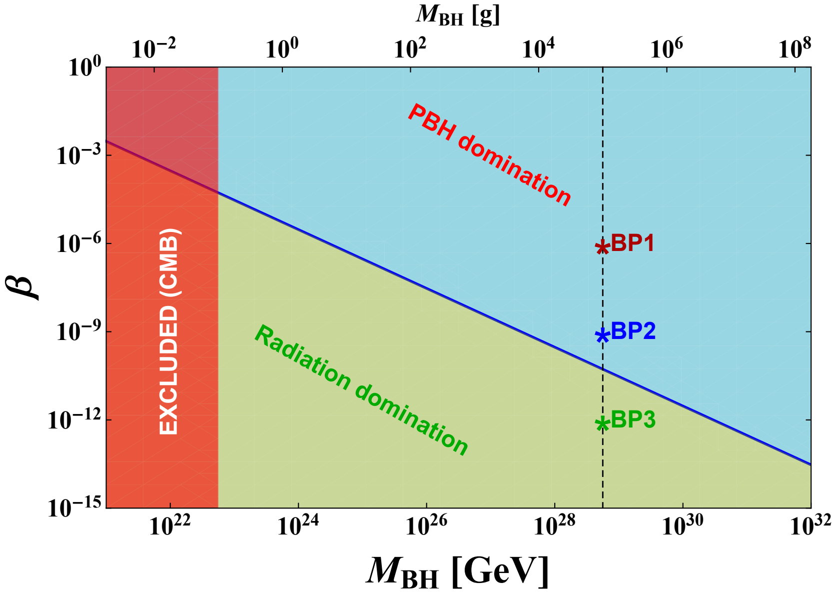

Kintetic equations:

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

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

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

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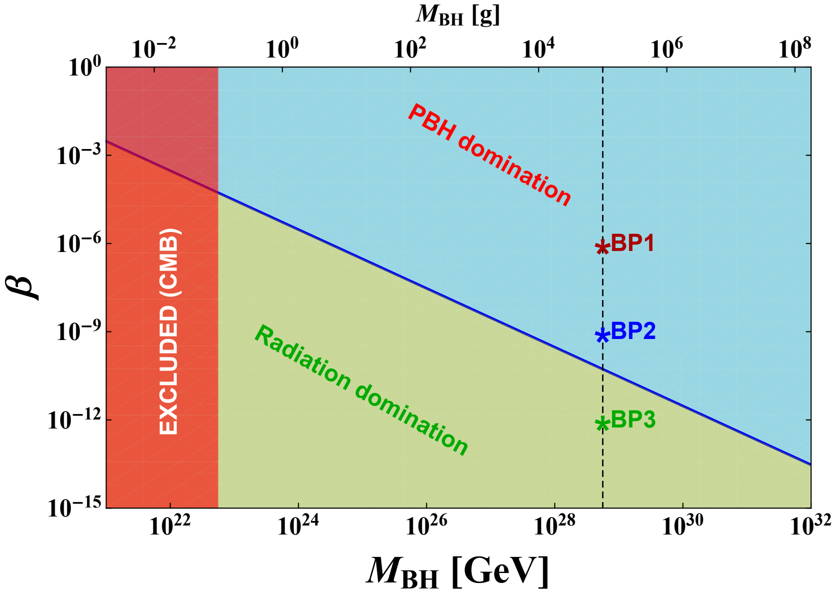

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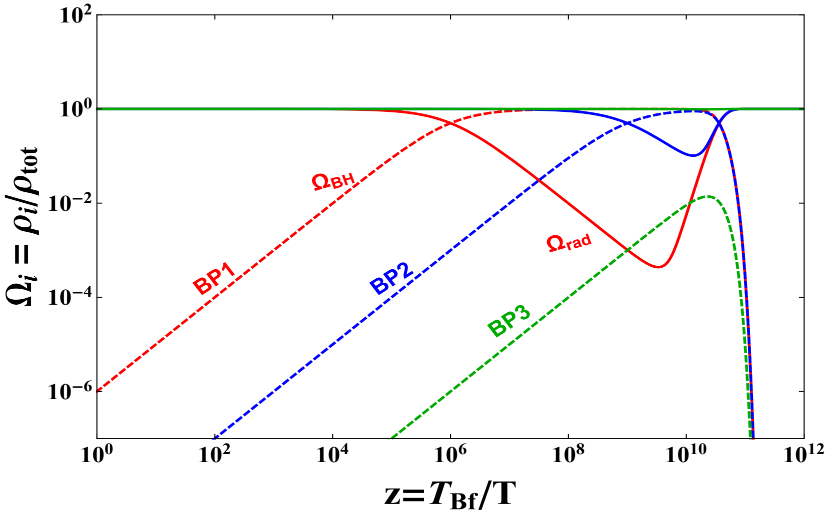

Ultralight PBH dynamics (only non-rotating)

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:

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

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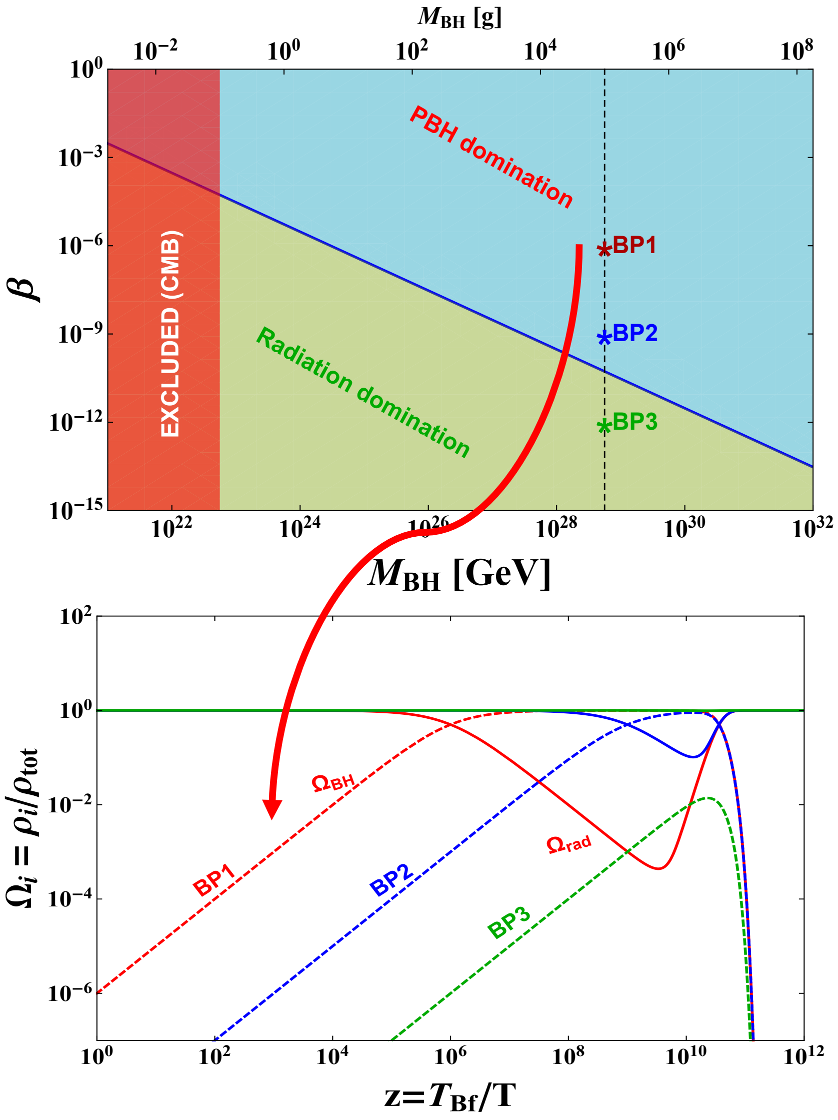

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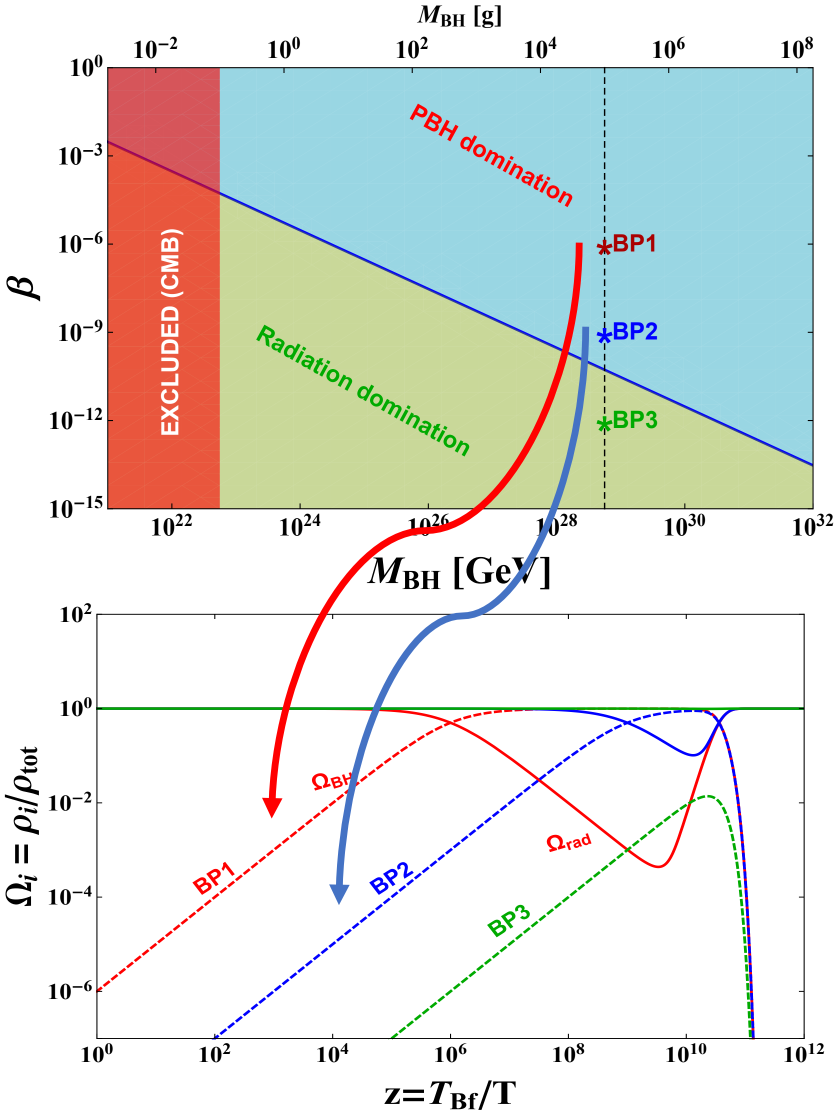

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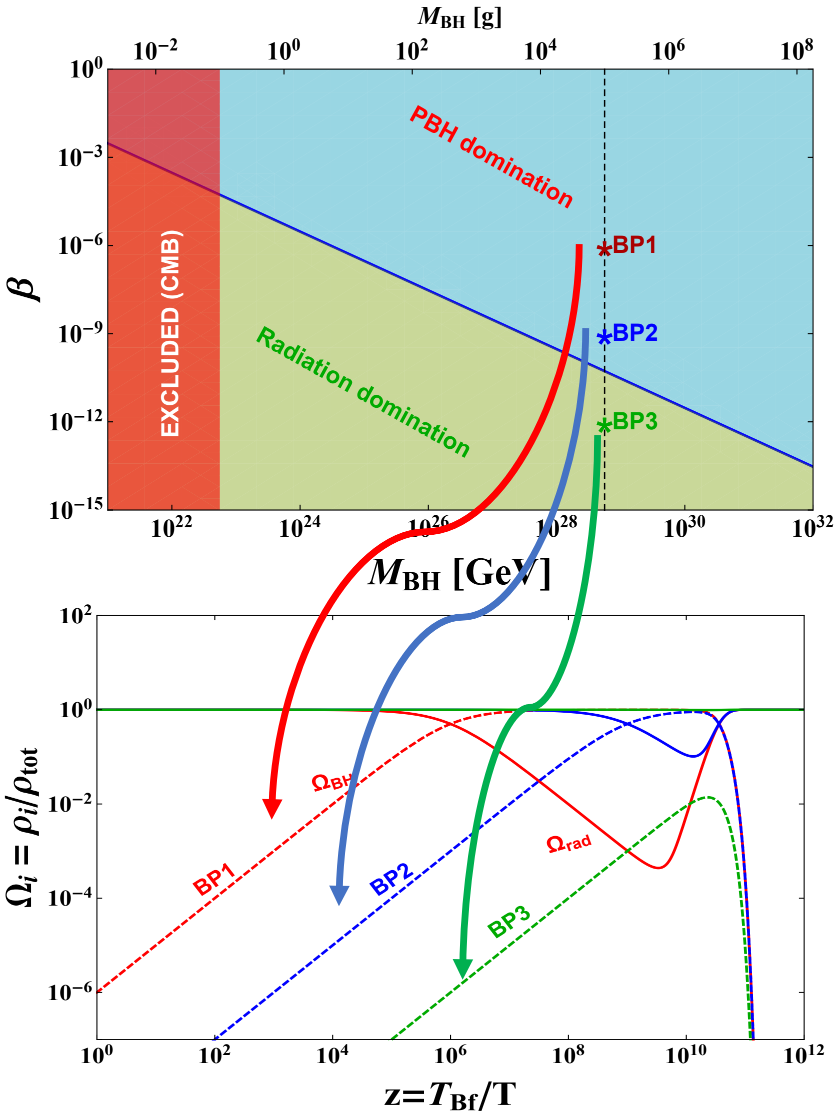


Ultralight PBH dynamics (only non-rotating)

Consider formation in the radiation domination

Mass:

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

Mass loss:

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

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

Life-time:

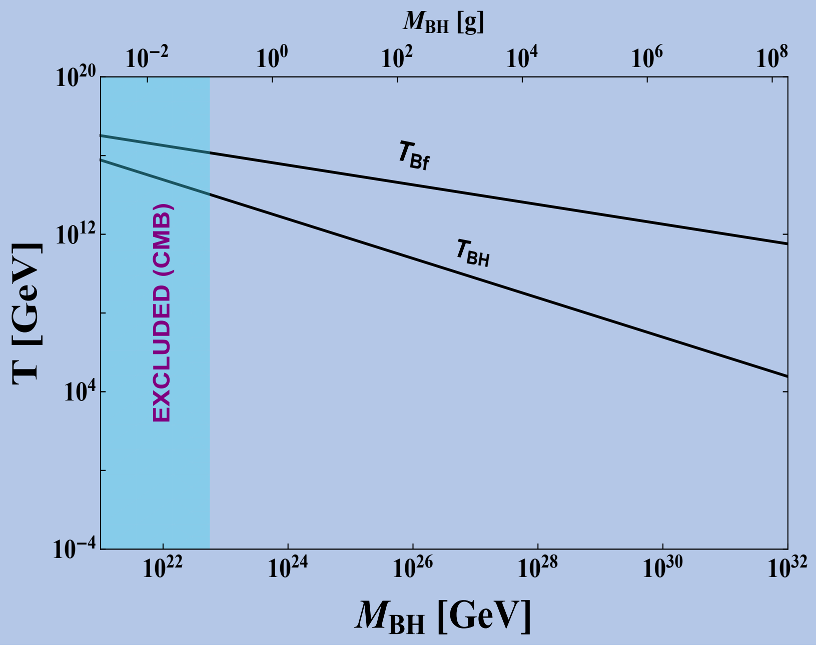
$$\tau = \int_{t_{Bf}}^{t_{ev}} dt = -\int_{M_{BH}}^{0} dM_{BH}\frac{30720\pi M_{BH}^2}{\mathcal{G}\, g_{*B}(T_{BH}) M_{Pl}^4} = \frac{10240\pi M_{BH}^3}{\mathcal{G}\, g_{*B}(T_{BH}) M_{Pl}^4}.$$

Evaporation

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

Formation temperature

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



Super heavy Dark Matter (SHDM) from PBH

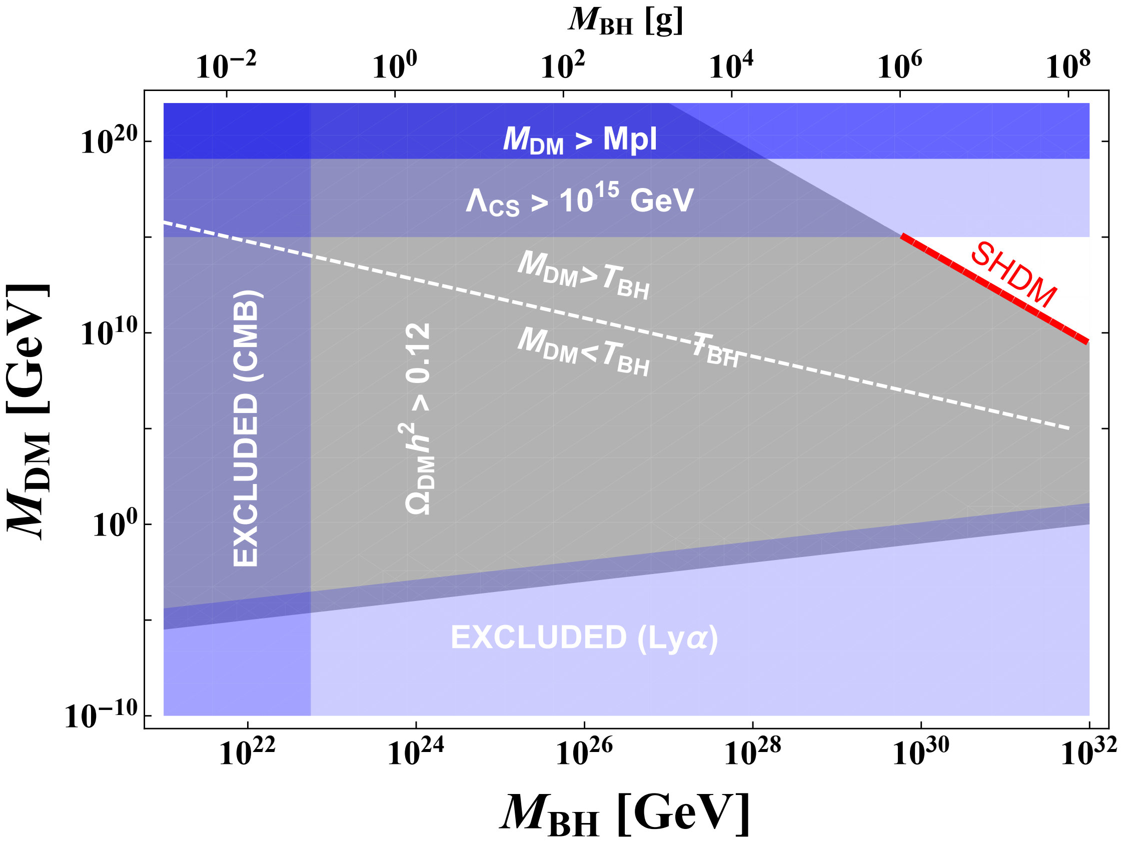
Can not Save $M_{DM} < T_{BH}$

free streaming length

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

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

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



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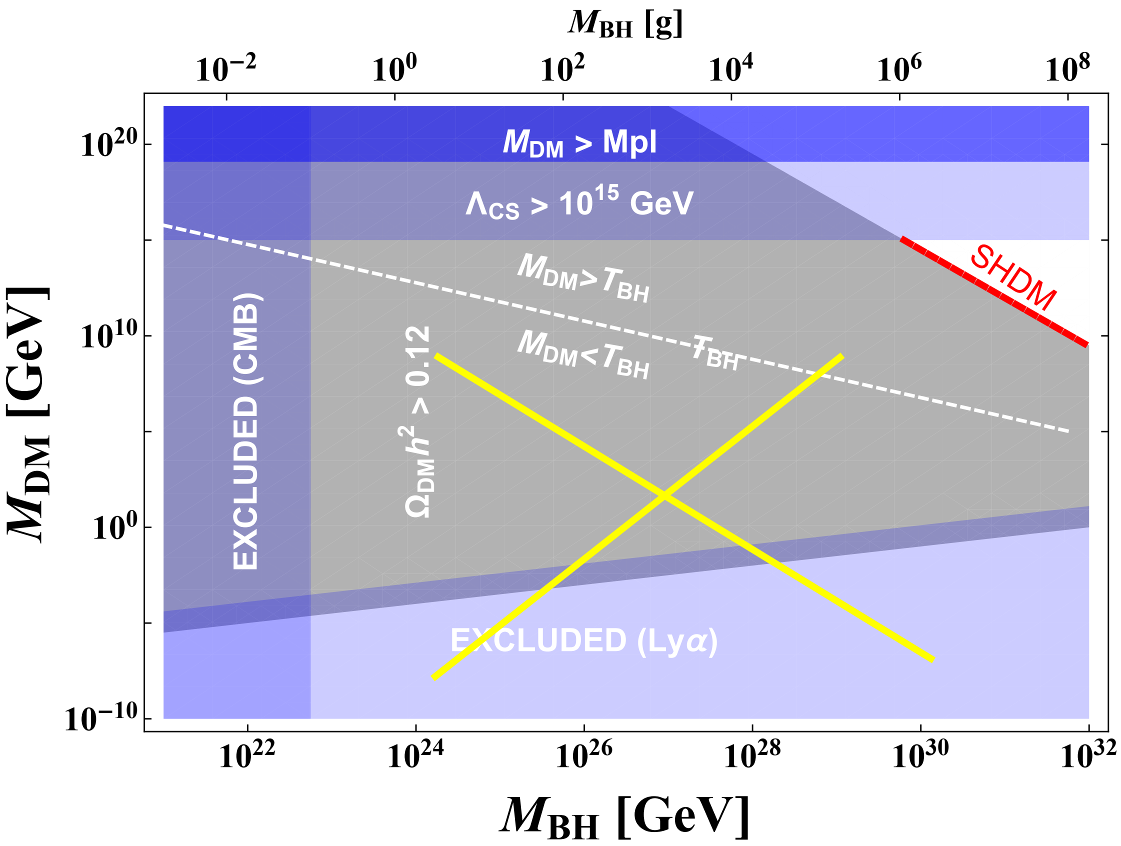


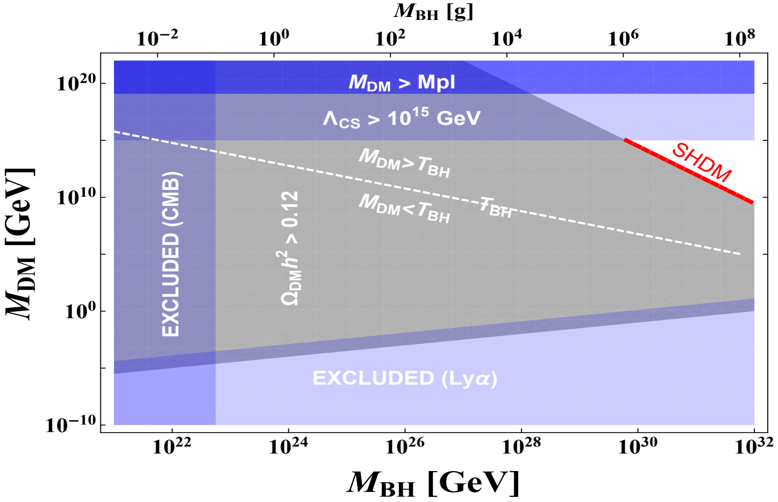
The turning point frequency

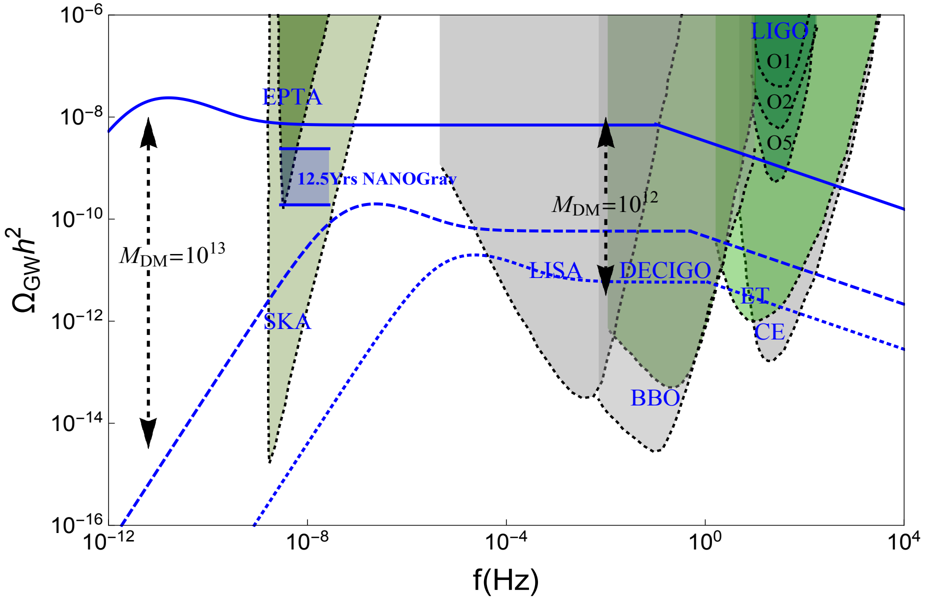
Samanta, Urban JCAP(2022)

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

$$f_* \simeq 2.1 \times 10^{-8} \sqrt{\frac{50}{z_{\rm eq} \alpha \Gamma G\mu}} \left(\frac{M_{DM}}{T_0} \right)^{3/5} T_0^{-2/5} t_0^{-1},$$

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



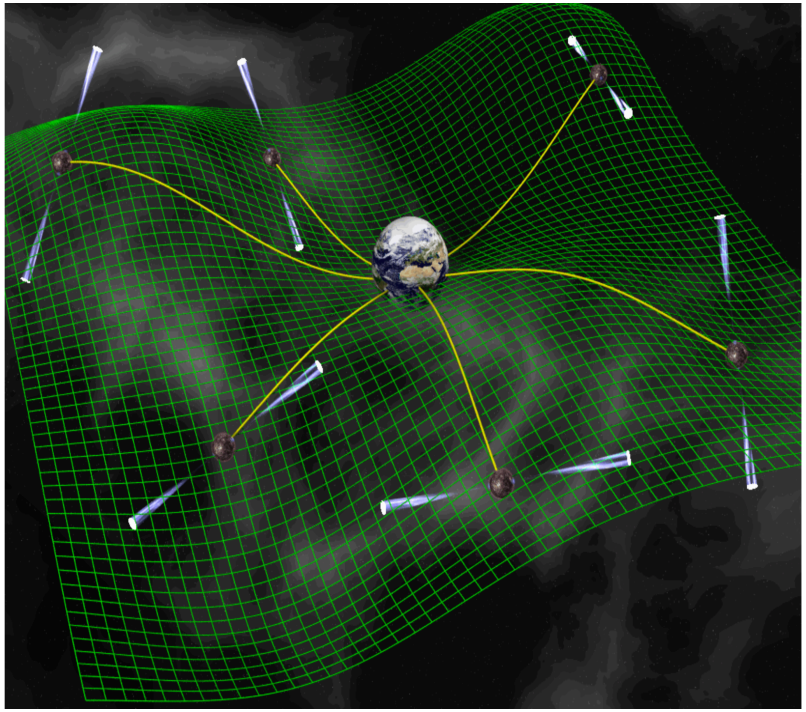


Why strong amplitude GWs are of interest? PTAs and LIGO

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

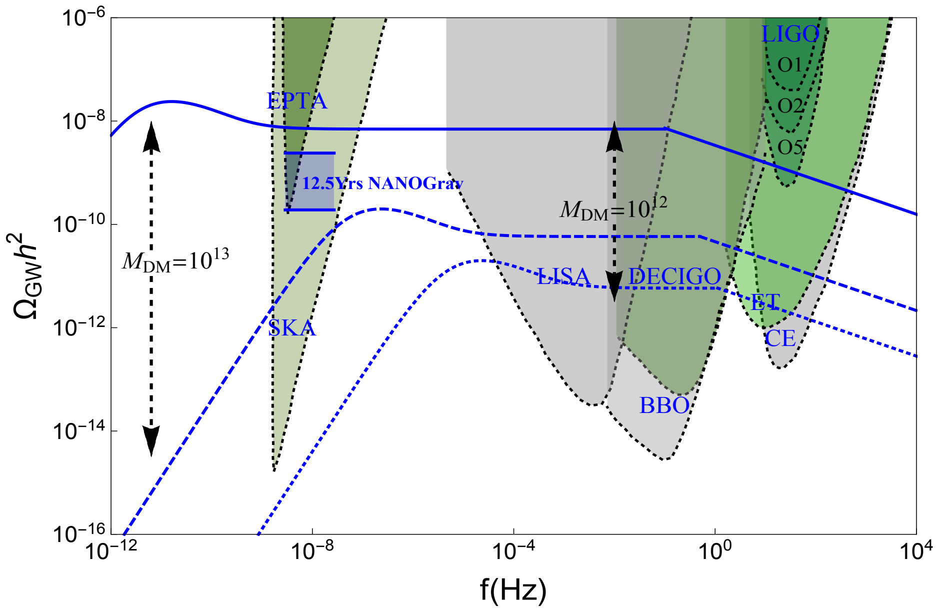


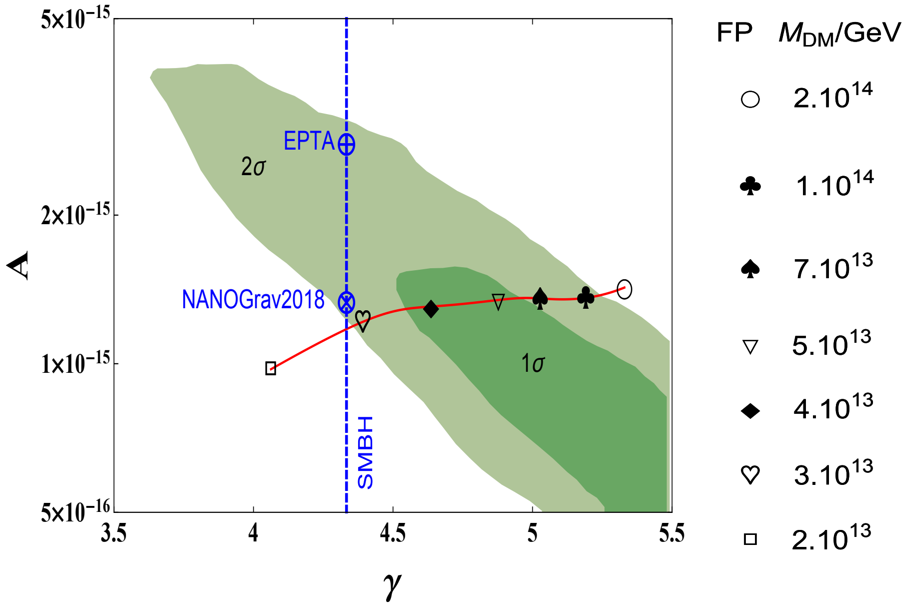
Pulsar-Timing-Arrays typically work with high amplitude GWs => Could be a Detector of High Scale Symmetry breaking theories

PTA results (2020)

NANOGrav-fit

$$\Omega_{GW}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c(f)^2 = \Omega_{yr}\left(\frac{f}{f_{yr}}\right)^{5-\gamma}, \quad \text{with} \quad \Omega_{yr} = \frac{2\pi^2}{3H_0^2} A^2 f_{yr}^2.$$





Samanta, Urban JCAP (2022)

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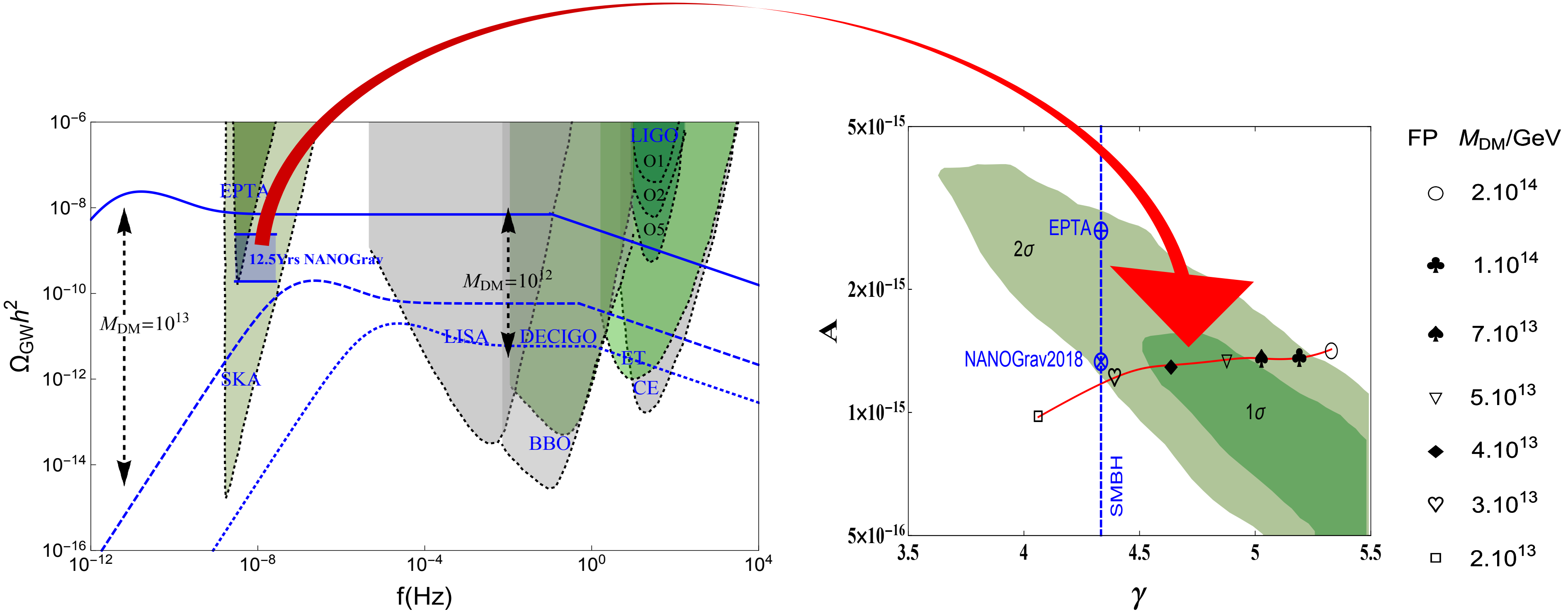

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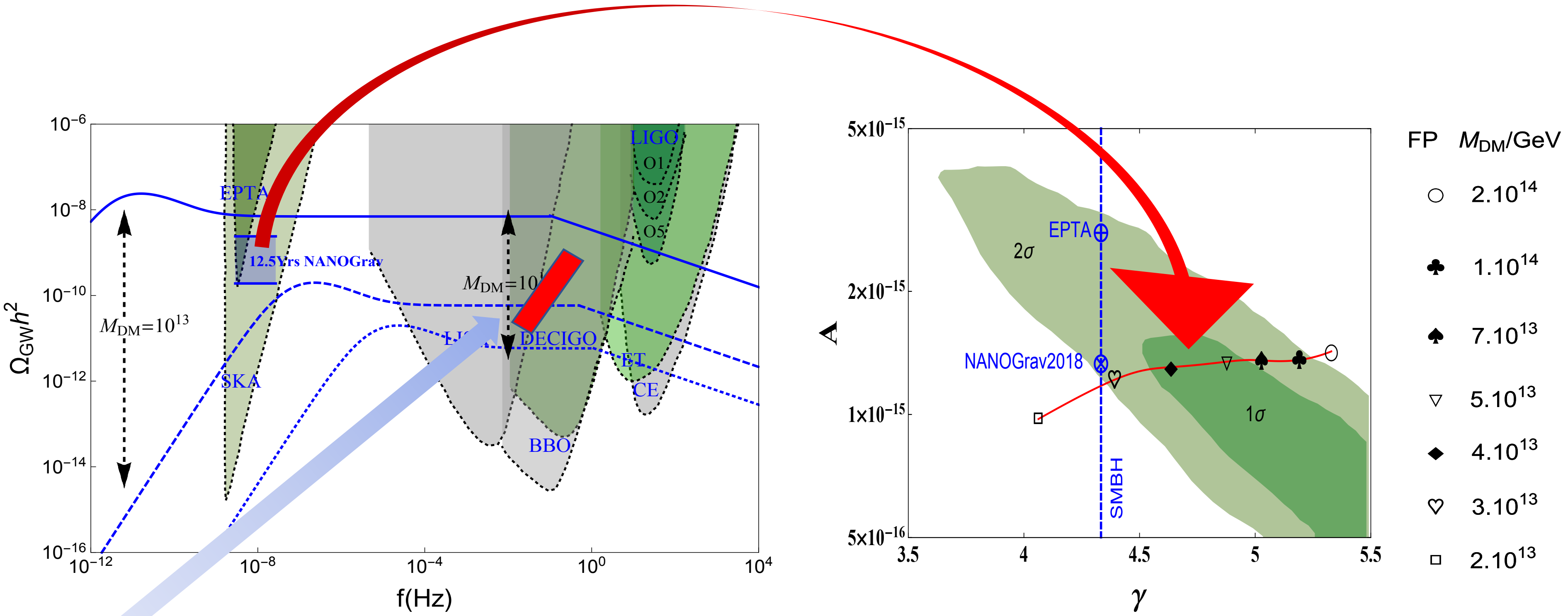
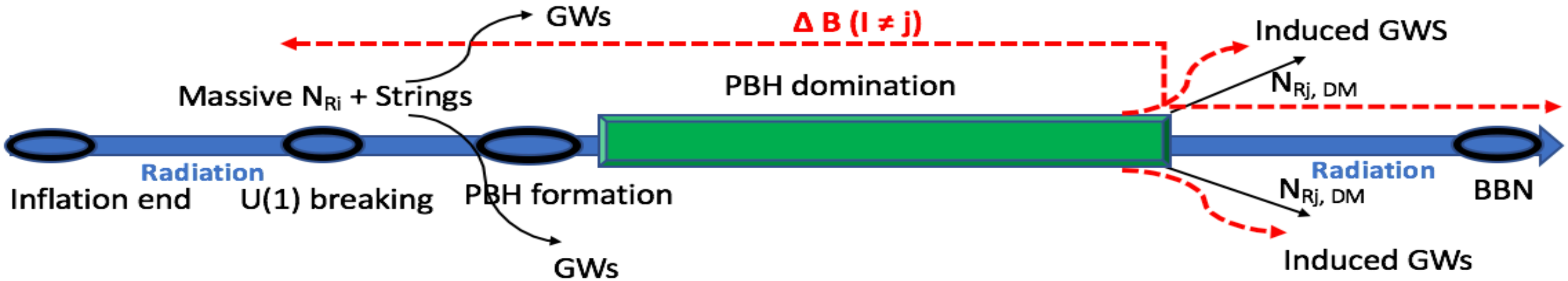


Turning point freq.

Samanta, Urban JCAP (2022)

Implementing in seesaw



GWs

Δ B (I ≠ j)

Induced GWS

Massive N_{Ri} + Strings

PBH domination

$N_{Rj,\ DM}$

Radiation

Inflation end

U(1) breaking

PBH formation

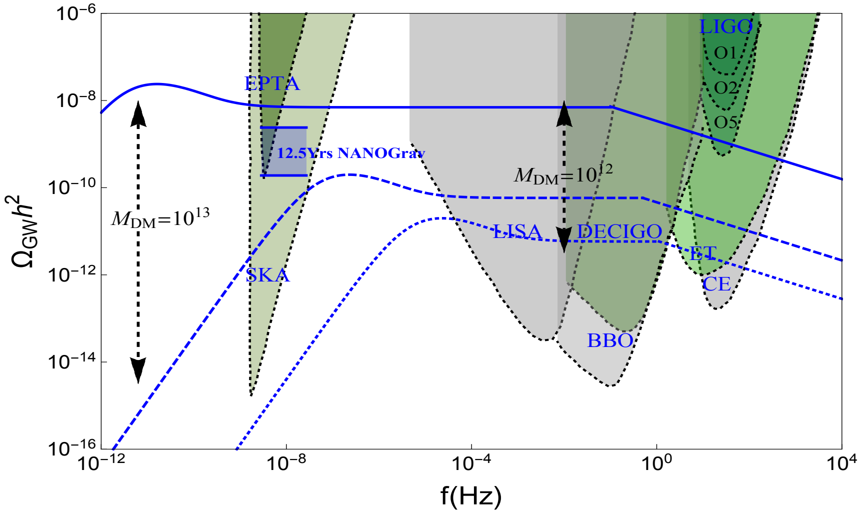
Radiation

$N_{Rj,\ DM}$

BBN

GWs

Induced GWs



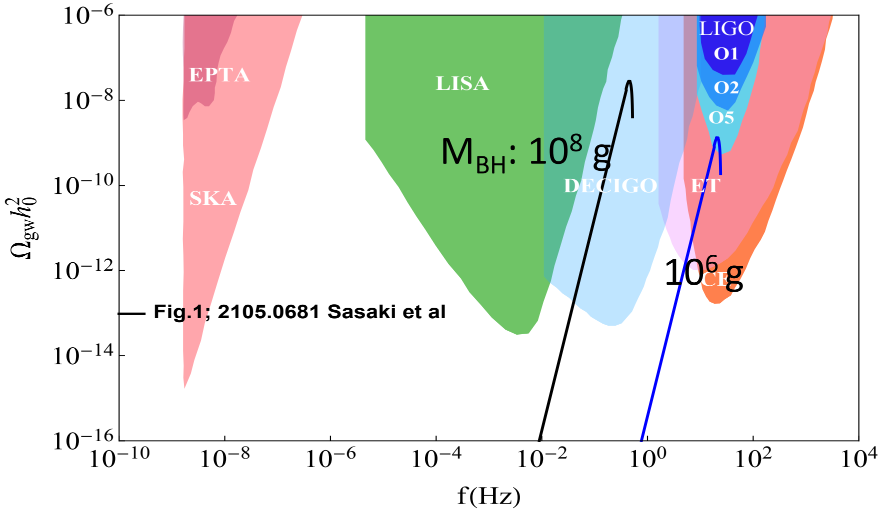
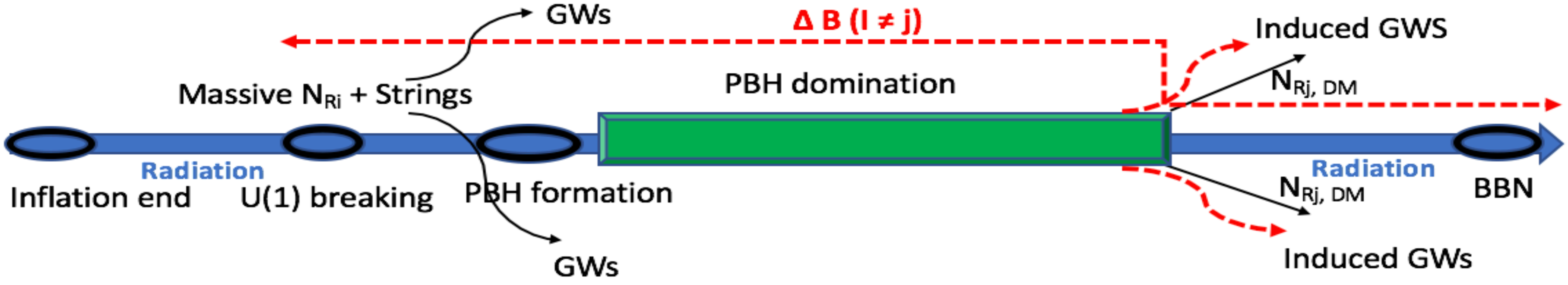


Fig.1; 2105.0681 Sasaki et al

$$\Omega_{GW}^{\rm peak} \simeq 2\times 10^{-6}\left(\frac{\beta}{10^{-8}}\right)^{16/3}\left(\frac{M_{BH}}{10^{7}{\rm g}}\right)^{34/9}$$

Implementing in seesaw



GWs

$\Delta B\ (l \neq j)$

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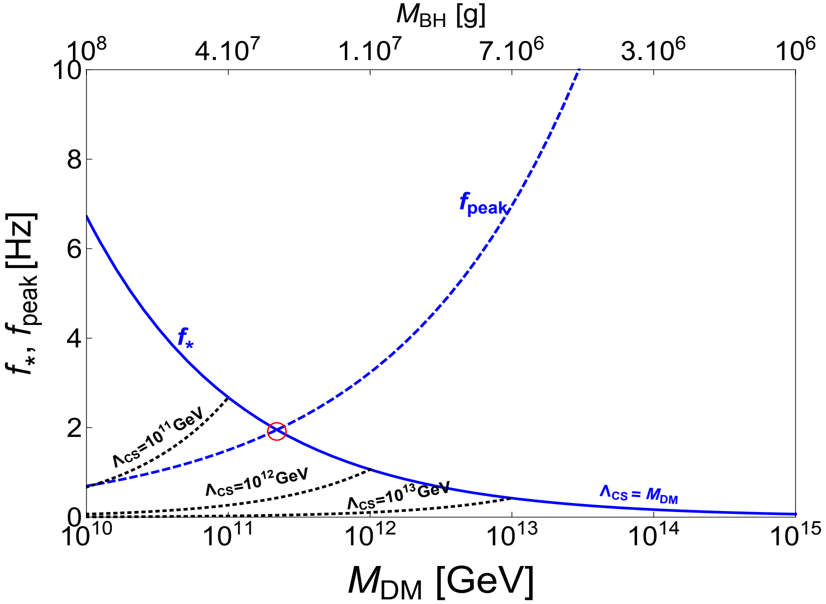

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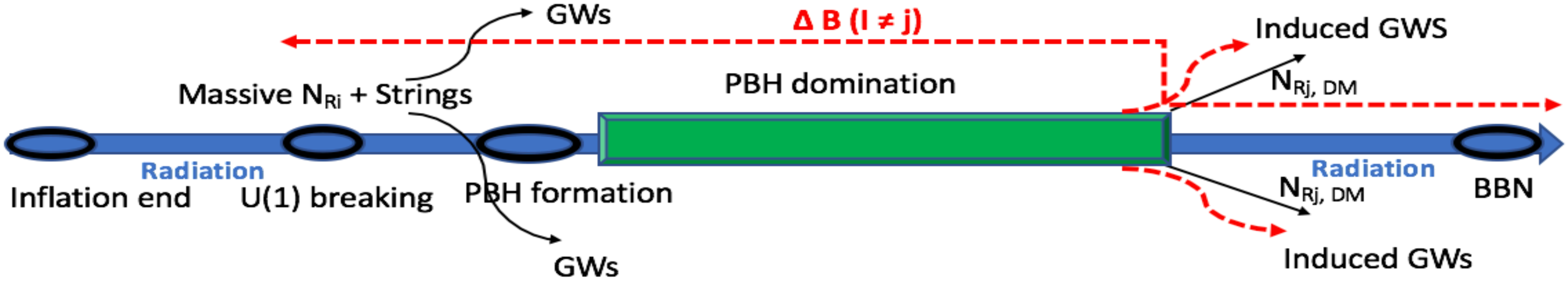

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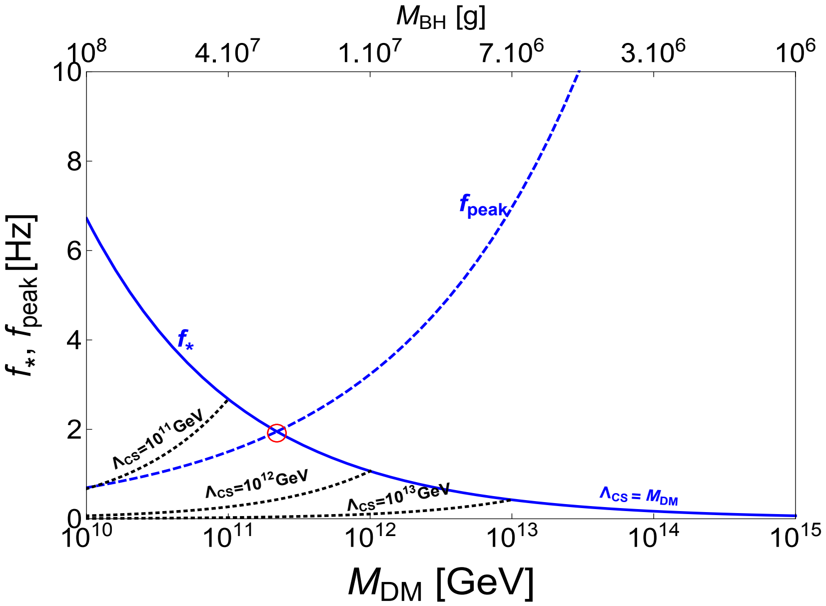

Seesaw: all the N_i s are super heavy ~ M~ $M_{DM} > 10^9$ GeV

Presentation take away

1. Ultralight primordial black hole can produce super heavy dark matter. **If the dark matter gets its mass with a gauged U(1)-breaking**, gravitational waves and their spectral features could be a unique way to probe dark matter above 10^9 GeV.

2. If **the recent finding by the pulsar timing arrays** corresponds to an existence of super heavy dark matter, high frequency detectors like LISA, DECIGO should be able to find a break in the GW spectrum.

3. **When implemented in seesaw**, one of the right-handed neutrinos could be super heavy dark matter and other two lead to thermal leptogenesis.

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2. If **the recent** ence of super heavy
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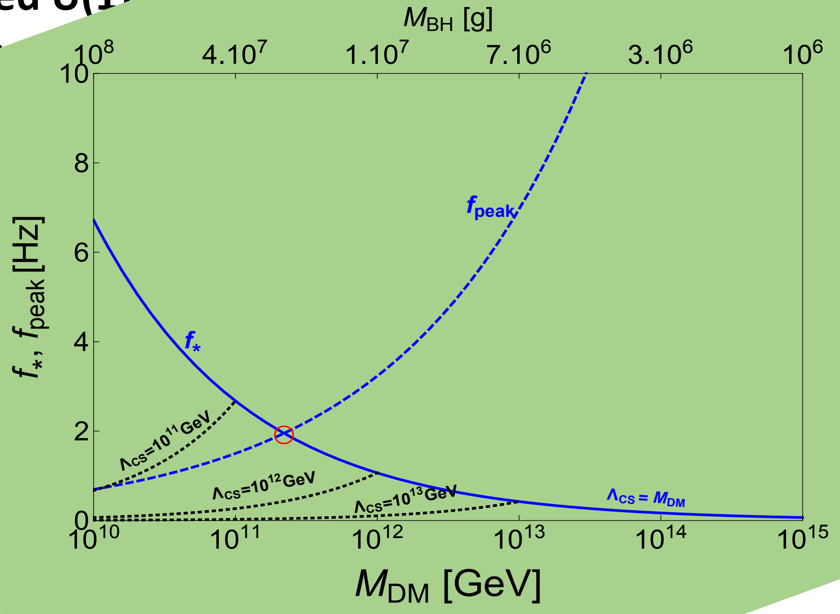

U(1) saga

S.F King, S Pascoli, J. Turner, YL Zhou, PRL (2021)