Gravitational Waves as a Probe of Super-Heavy Dark matter

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Research related to this presentation is supported by MSCA-Individual Fellowship IV FZU - CZ.02.2.69/0.0/0.0/20 079/0017754 and European Structural and Investment Fund and the Czech Ministry of Education, Youth and Sports.

PRAGUE, MARCH, 2022

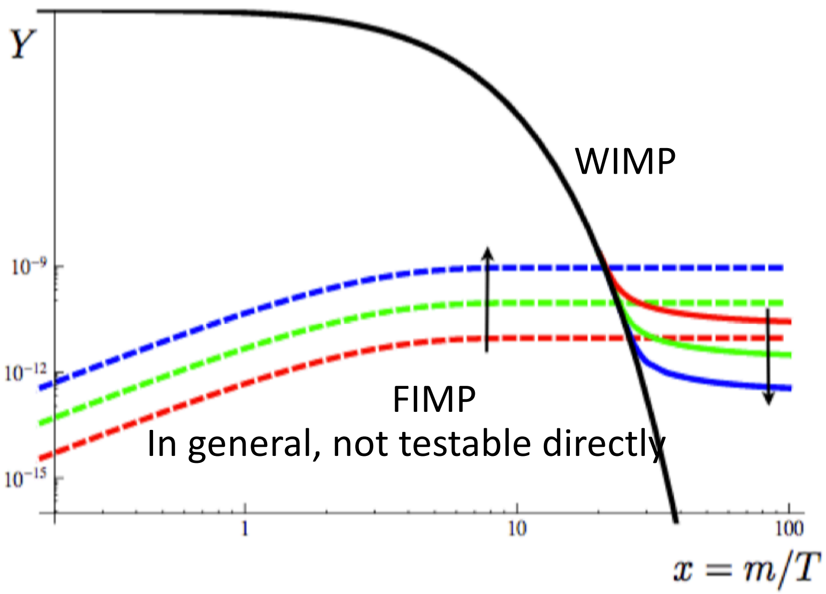
EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

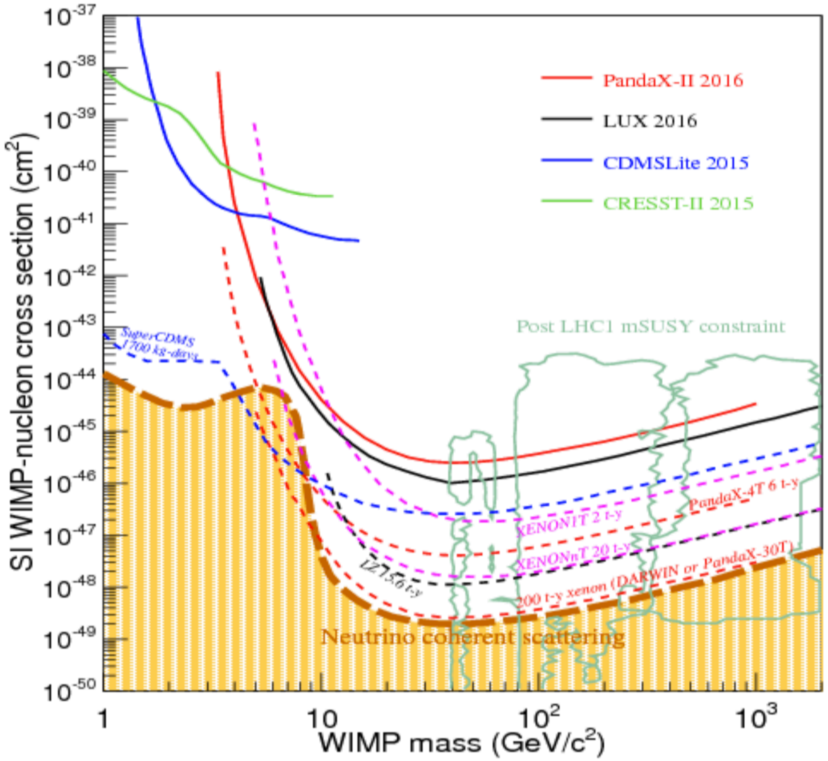
MINISTRY OF EDUCATION, YOUTH AND SPORTS

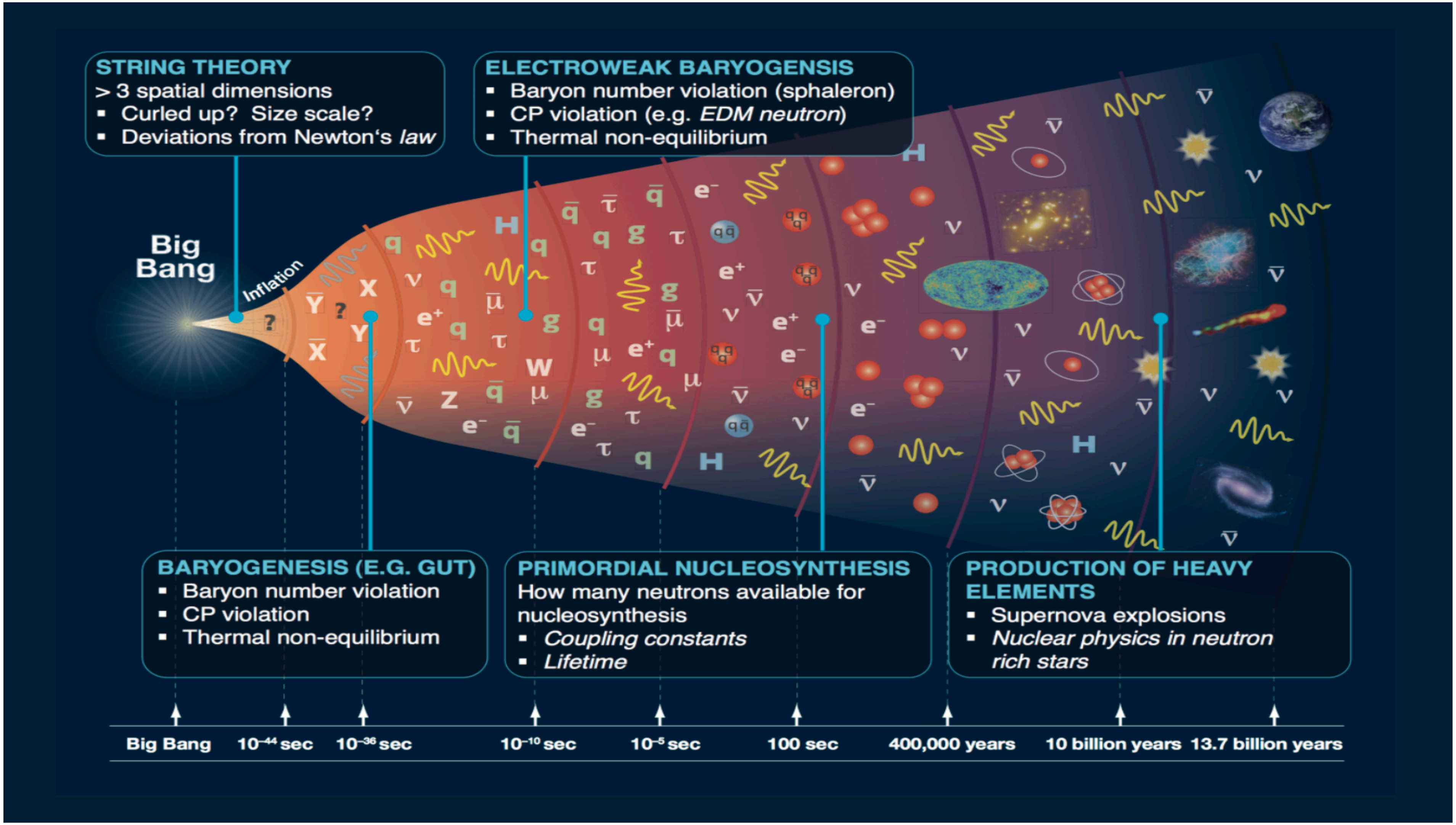
Collab: Federico Urban, CEICO based on 2112.04836

Dark Matter fact-file

Broadly two categories







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> 3 spatial dimensions
▪ Curled up? Size scale?
▪ Deviations from Newton's *law*
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▪ Baryon number violation (sphaleron)
▪ CP violation (e.g. *EDM neutron*)
▪ Thermal non-equilibrium
Big Bang
Inflation
BARYOGENESIS (E.G. GUT)
▪ Baryon number violation
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PRIMORDIAL NUCLEOSYNTHESIS
How many neutrons available for nucleosynthesis
▪ *Coupling constants*
▪ *Lifetime*
PRODUCTION OF HEAVY ELEMENTS
▪ Supernova explosions
▪ *Nuclear physics in neutron rich stars*
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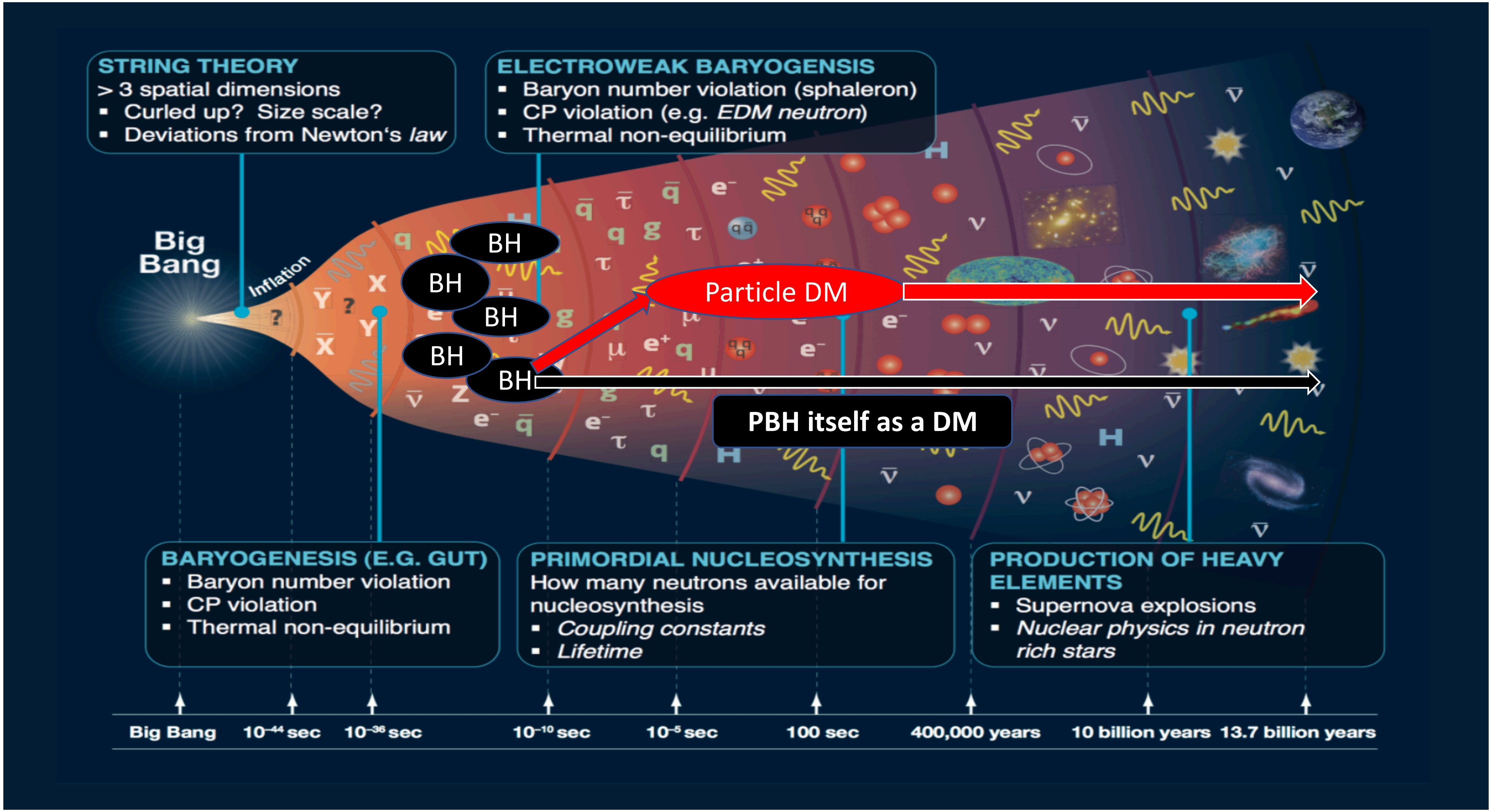
13.7 billion years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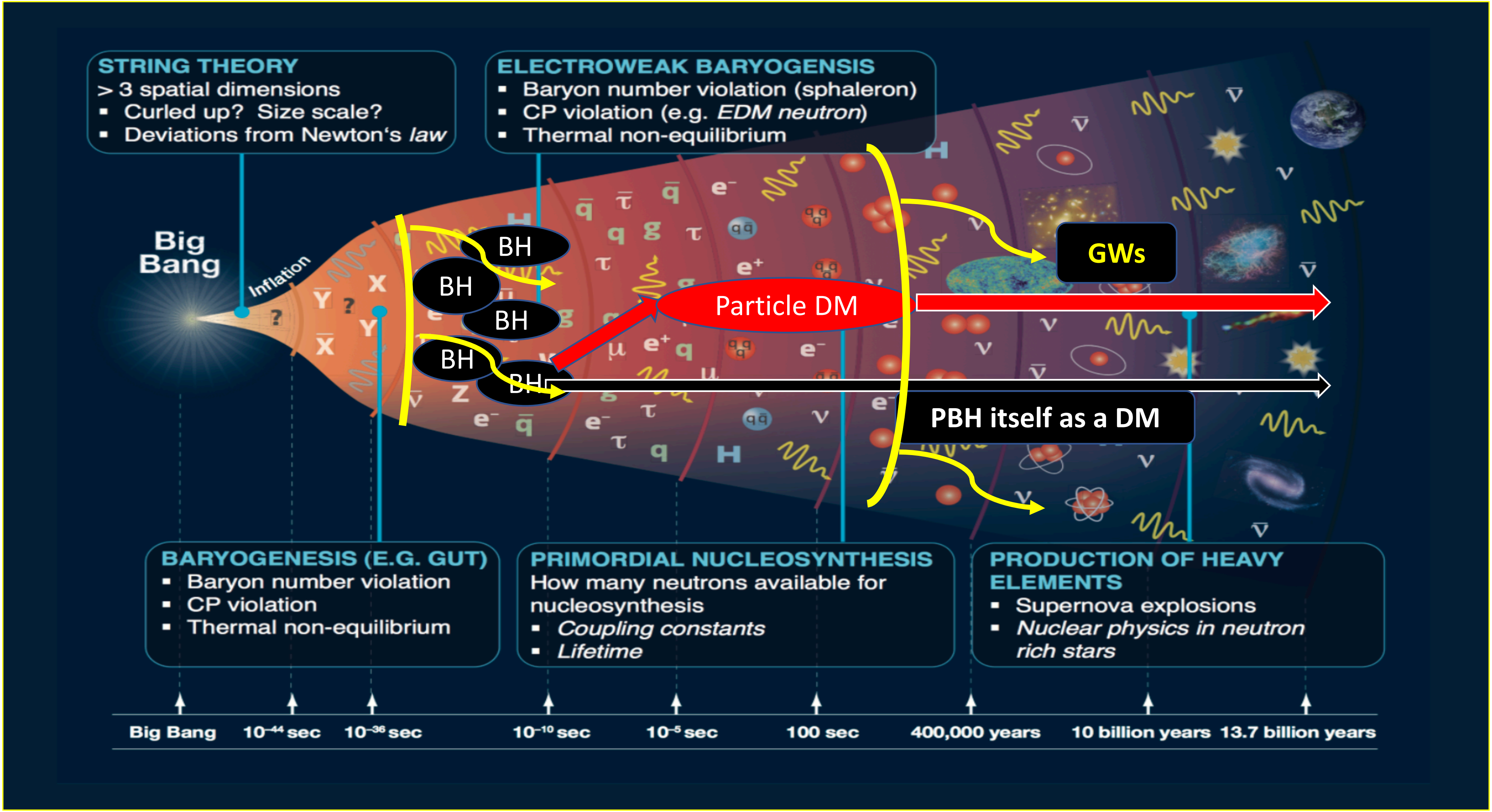
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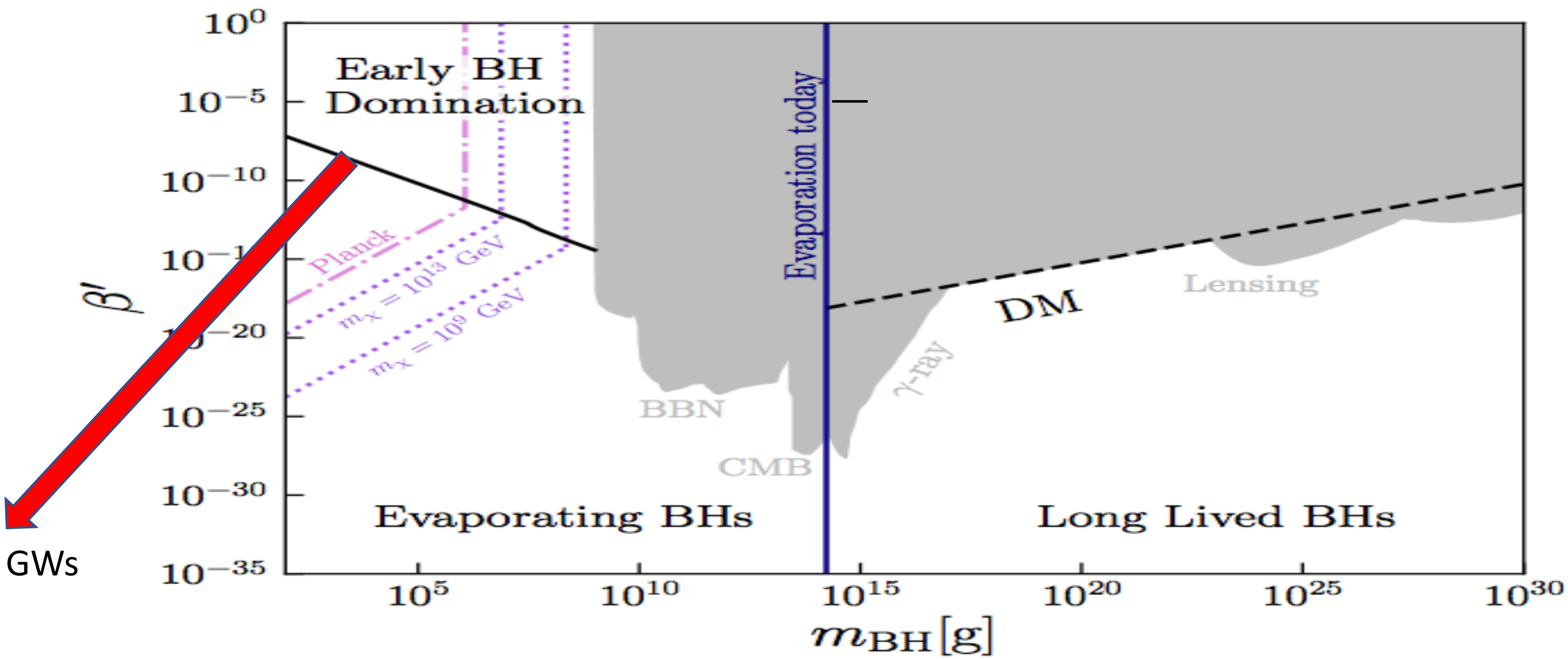
Constraints on black hole masses masses Free parameter: $\boldsymbol{\beta} = \boldsymbol{\rho}_{BH}/\boldsymbol{\rho}_{rad}$

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)

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

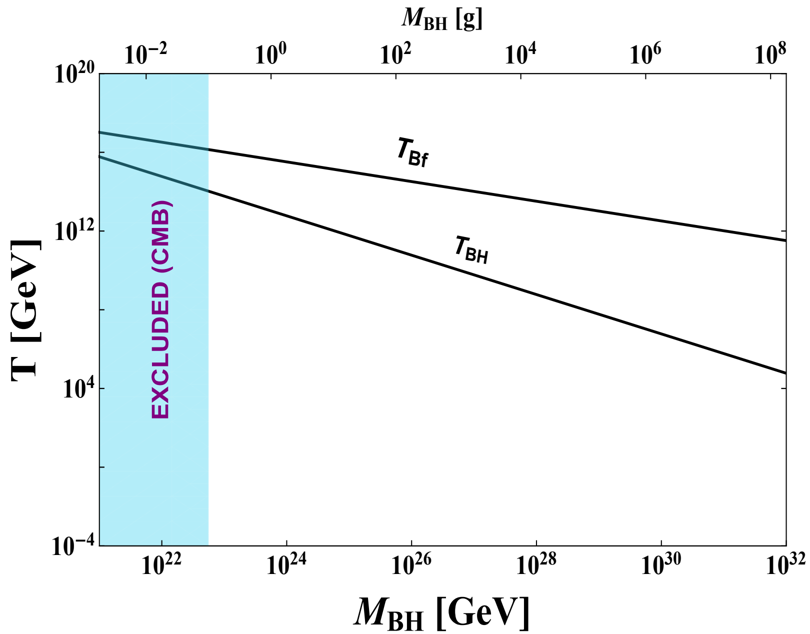
$$\frac{dM_{BH}}{dt} = -\frac{\mathcal{G} g_{*B}(T_{BH})}{30720\pi}\frac{M_{Pl}^4}{M_{BH}^2},$$

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

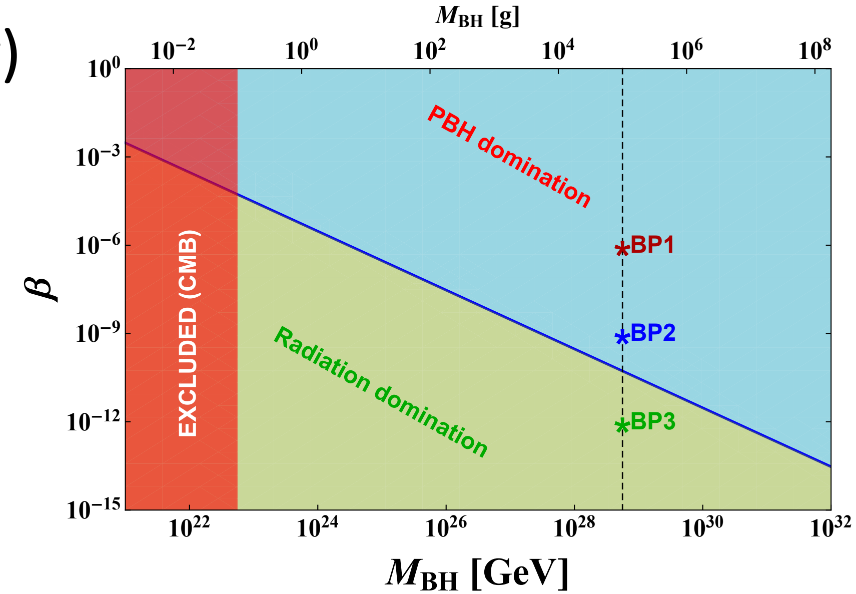
Formation temperature

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



Ultralight PBH dynamics (only non-rotating)

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

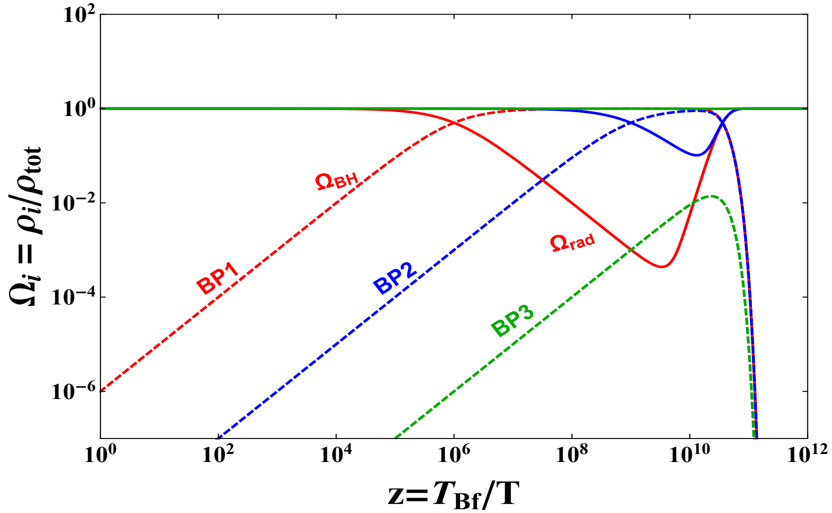


Kintetic equations:

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

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

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



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

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

T_{BH}: Hawking Temp ~ $1/M_{BH}$

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

Only viable solution for DM

Suppression

The `X' is DM

Super heavy Dark Matter (SHDM) from PBH

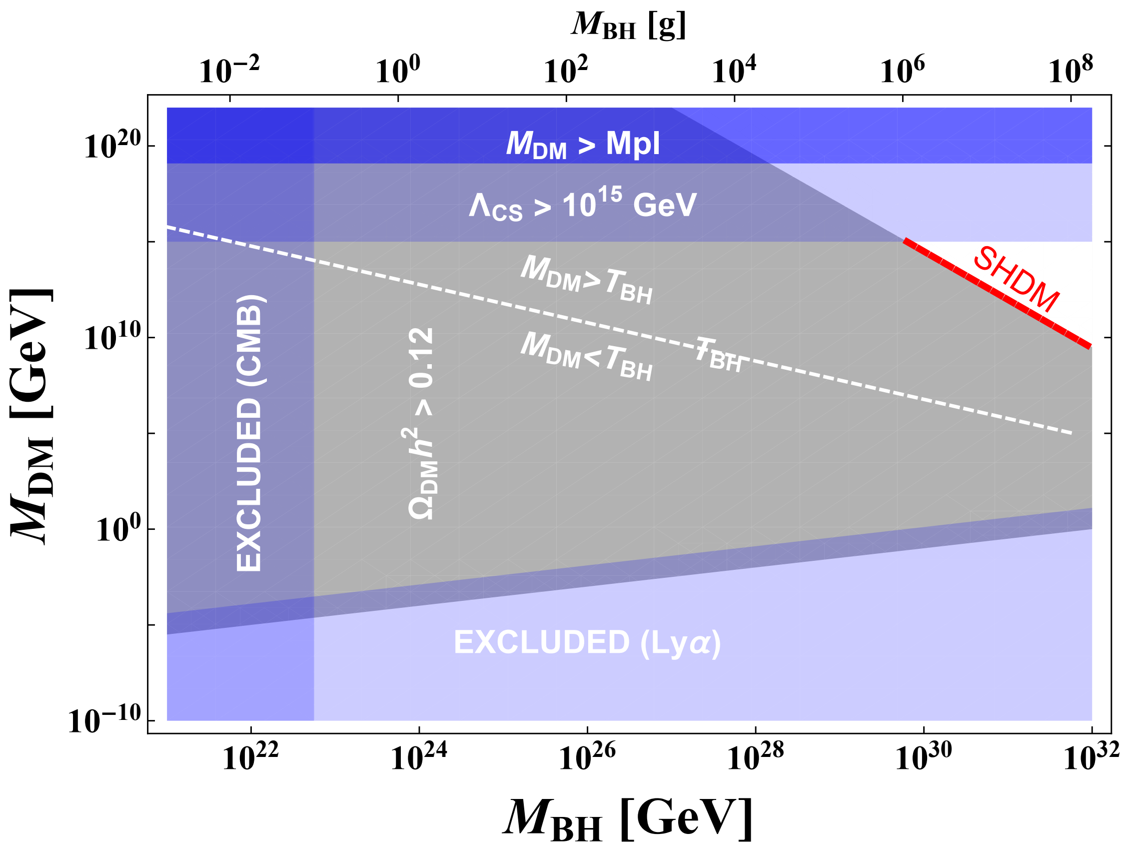
Can not save $M_{DM} < T_{BH}$

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 $z_{eq} > 2\times10^{-8}$

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



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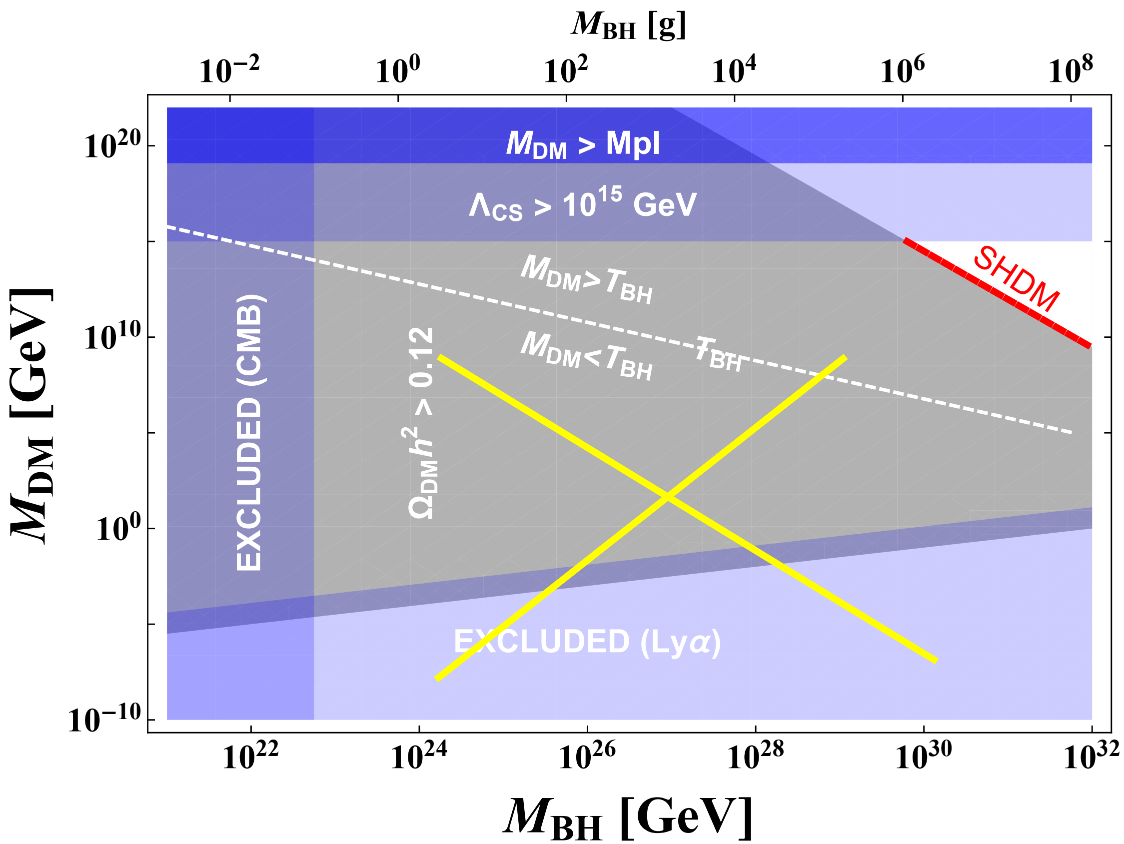

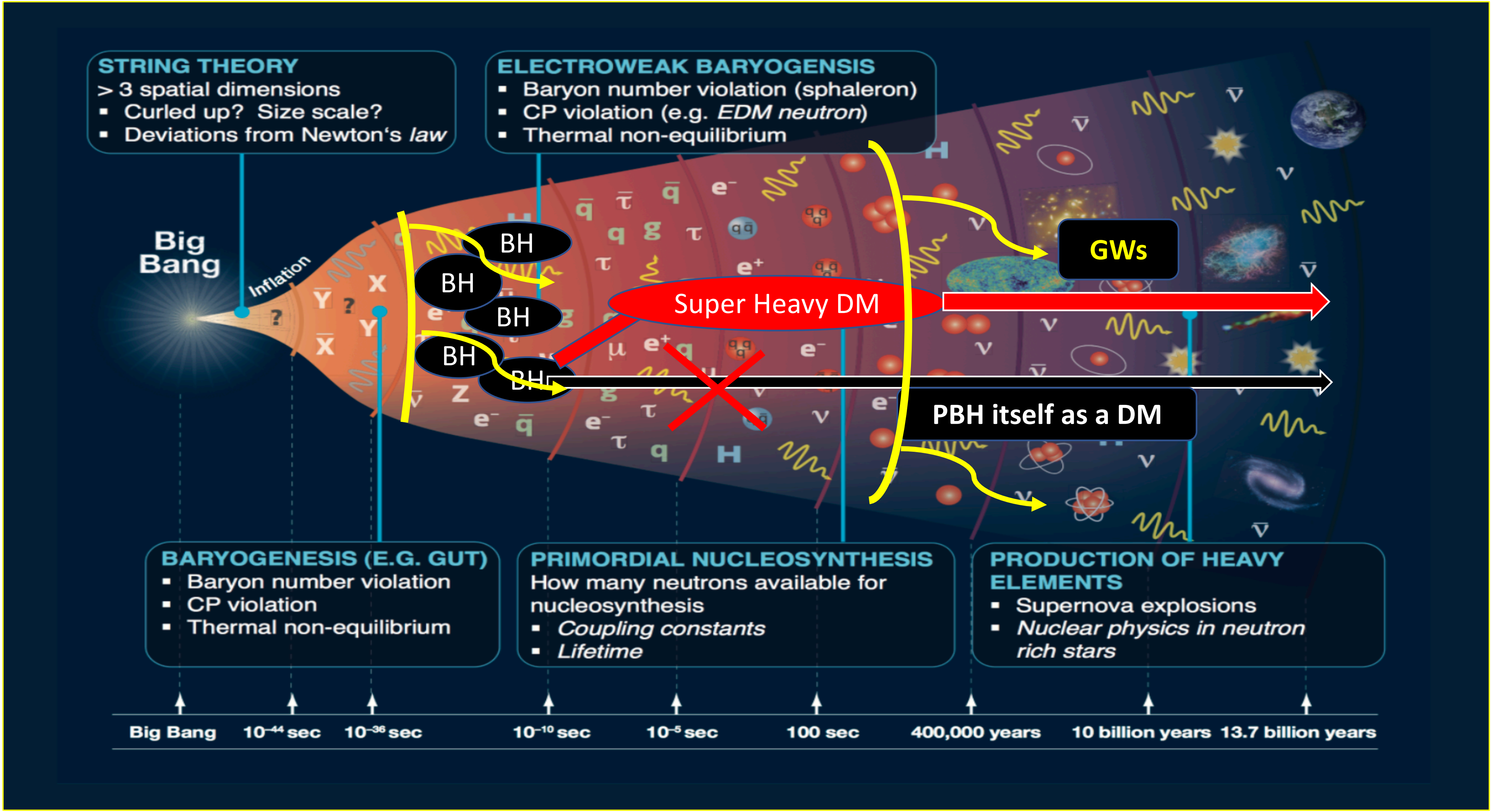
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Dark Matter generation from primordial black holes (PBHs)

Gravitational waves from DM sector

Dynamical origin of DM mass: Source of Gravitational waves

BSM Phase transition:

1) GWs from strong 1st order phase transition

2) Topological defects: Independent of order of phase transition. Examples: **Cosmic strings** and domain walls

We shall focus on

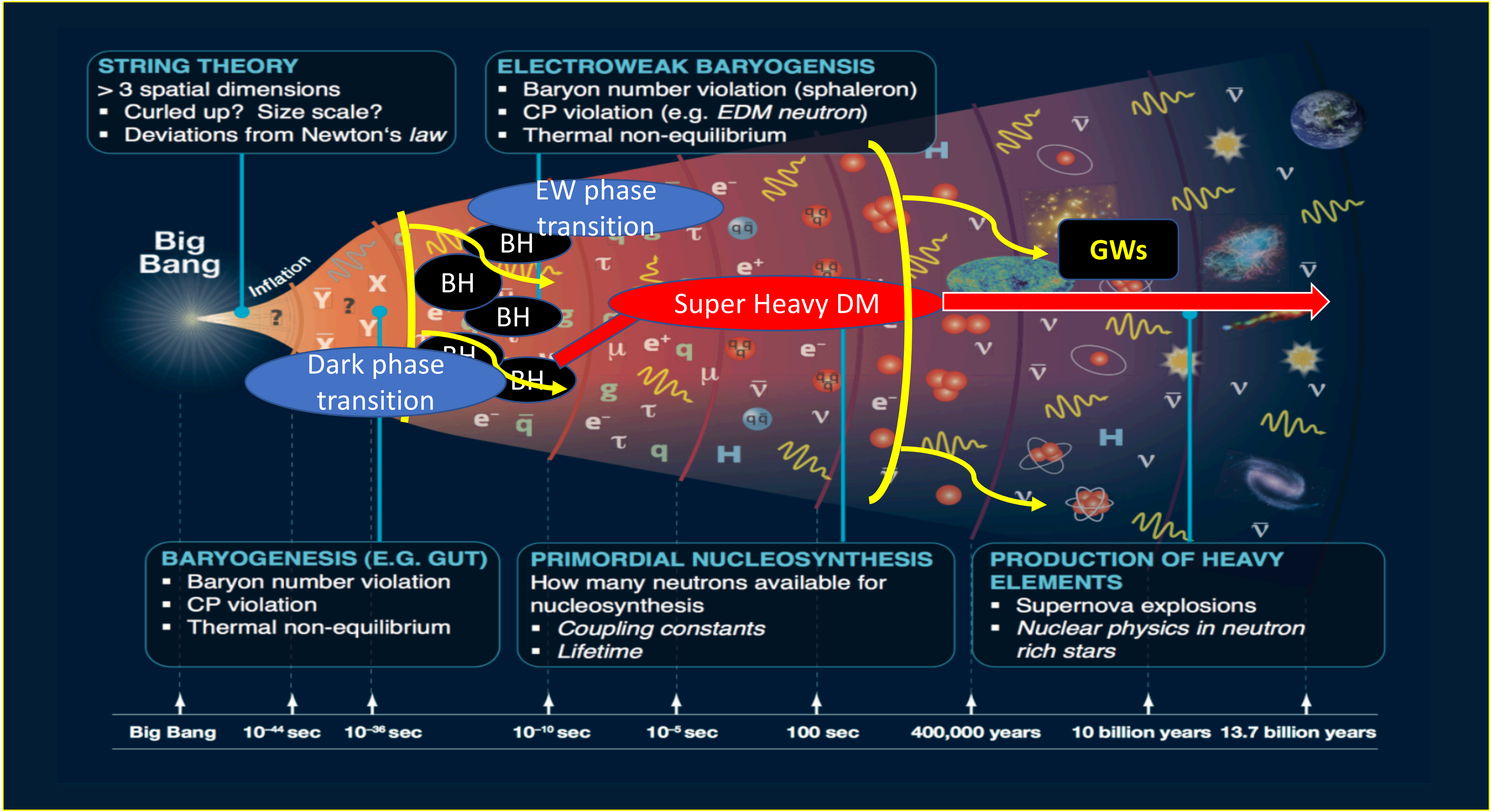
Gravitational waves from PBH sector

Production of PBHs: May be in the observed range

Distribution of PBHs: May be in the observed range

Radiation from PBHs: Very high frequency

Mergers of PBHs: Very high frequency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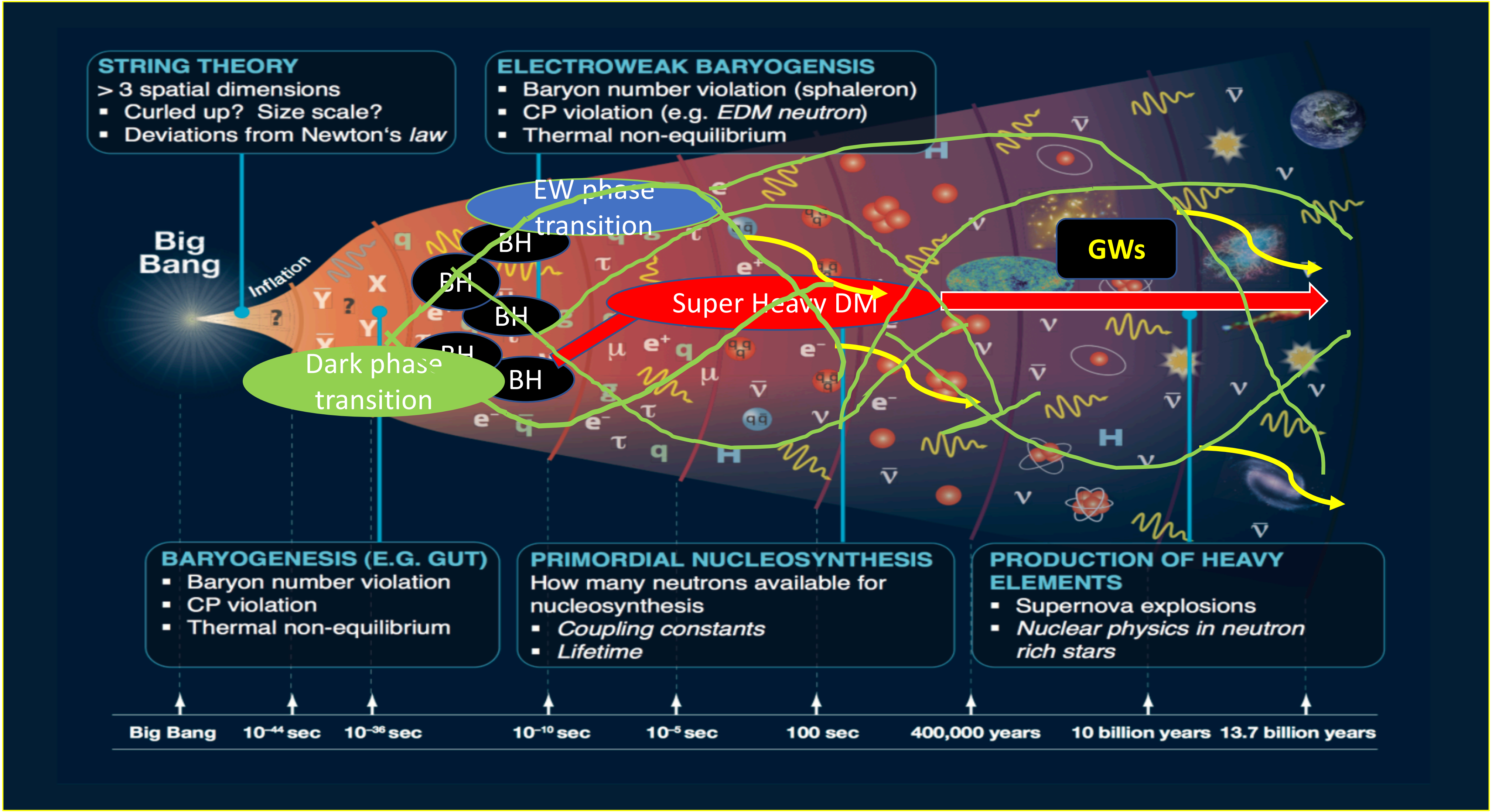

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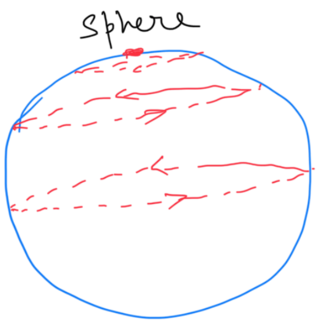
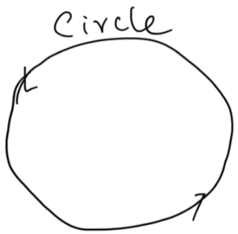
Cosmic strings originate when the vacuum manifold is not simply connected

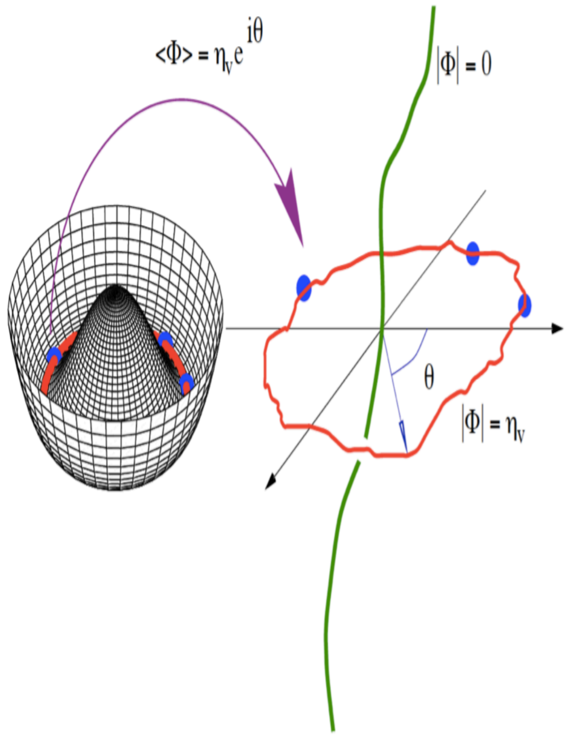


Simply connected.

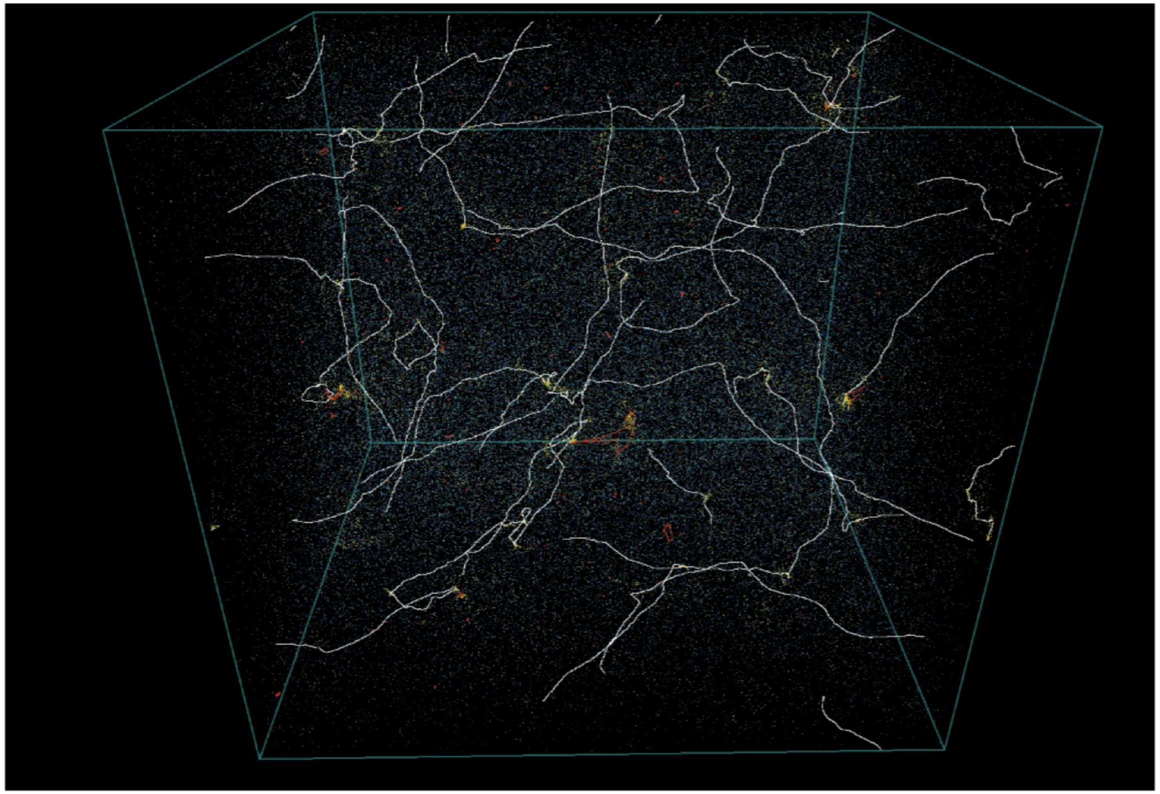


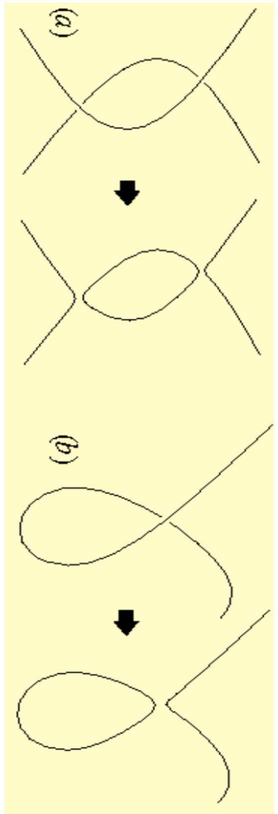
Not simply connected

U(1)-strings



String inter-commutation





These loops radiate to GWs

T. Vachaspati et al 1506.04039

String radiation: Particle production or GWs

Width of the strings: 1/V<< Horizon, V=> vacuum expectation value of the U(1) Scalar. **Known as Nambu - Goto strings**

String evolution extremely complicated: Needs numerical simulation for reliable conclusion

B.Pillado et al (Spain)
Phys. Rev. D 83, 083514 (2011)
GWs

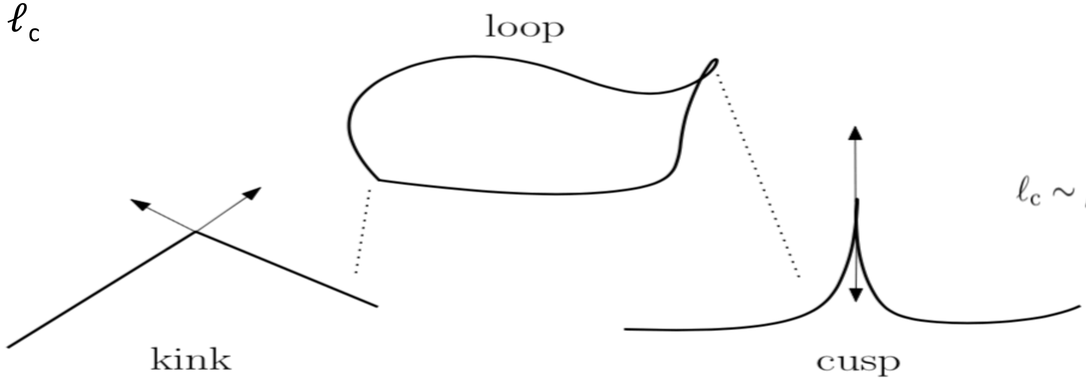
Hindmarsh et al (UK)
Phys. Rev. D96, 023525 (2017)
particle radiation

T. Vachaspati et al (US)
Phys.Rev.Lett.122,no.20,201301(2019).
Both: GWs and particle radiation !! **Cheers**

GWs from Cosmic strings

GWS => $\ell > \ell_k, \ell_c$

$$\ell_k \sim \beta_k \frac{w}{\Gamma G\mu}$$



$$\ell_c \sim \beta_c \frac{w}{(\Gamma G\mu)^2}$$

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)

The string parameter: **Gμ**

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

Cosmic string scaling

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

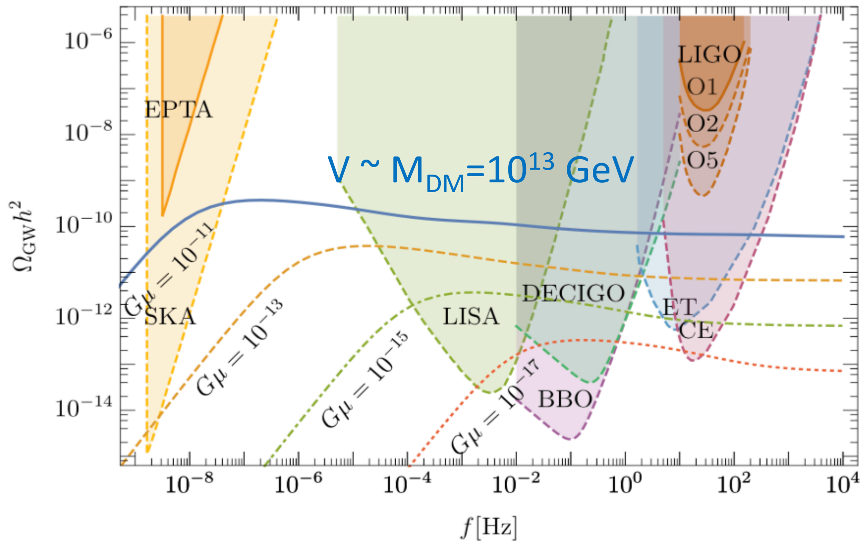
Long-string correlation length $L^2 = \boldsymbol{\mu}/\boldsymbol{\rho}_L$, $L \approx t$ => $\boldsymbol{\rho}_L \approx \boldsymbol{\mu}\, t^{-2}$

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

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

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

CS never dominates the energy density of the universe

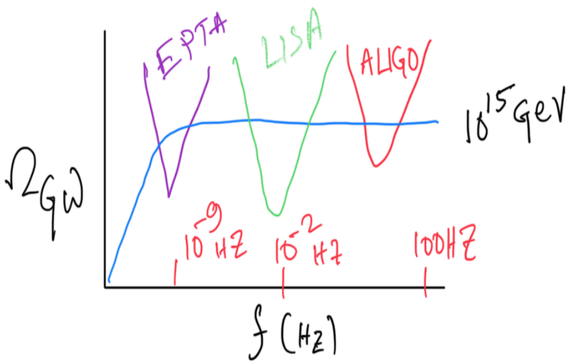


Cosmic archeology, GW spectral shapes

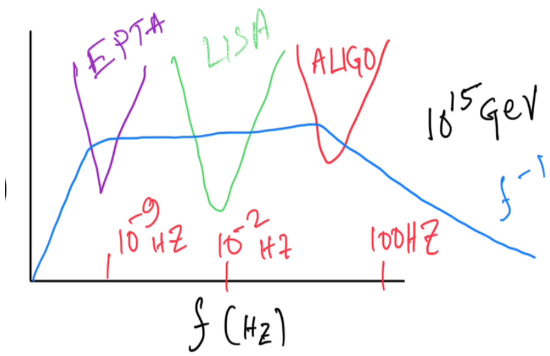
Amplitude sensitivity	Amplitude + spectral shape sensitivity	
Standard Cosmology (w=1/3)	Early Matter domination (w=0)	Kination (w=1)

A spectral break (f_*, T_*)

Fundamental mode (k=1):

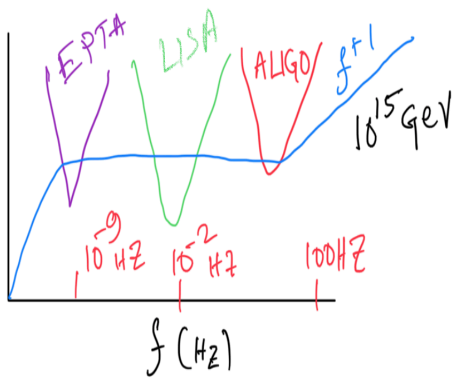


Standard cosmology



Black hole domination

Our attention

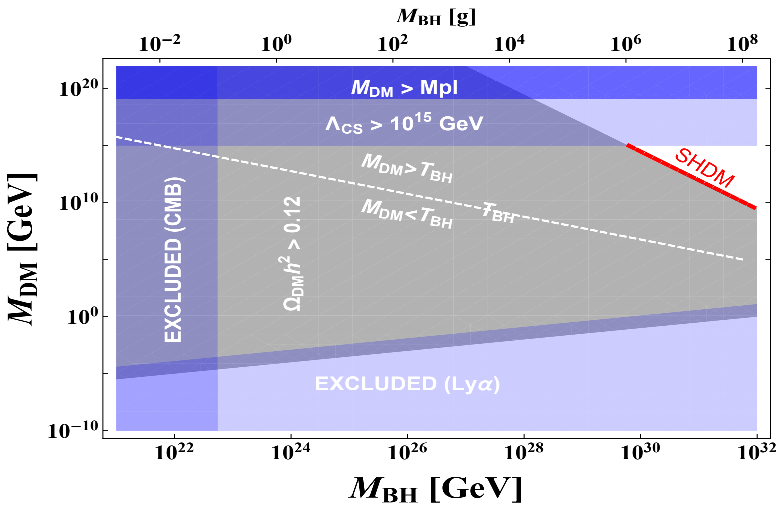


Kination

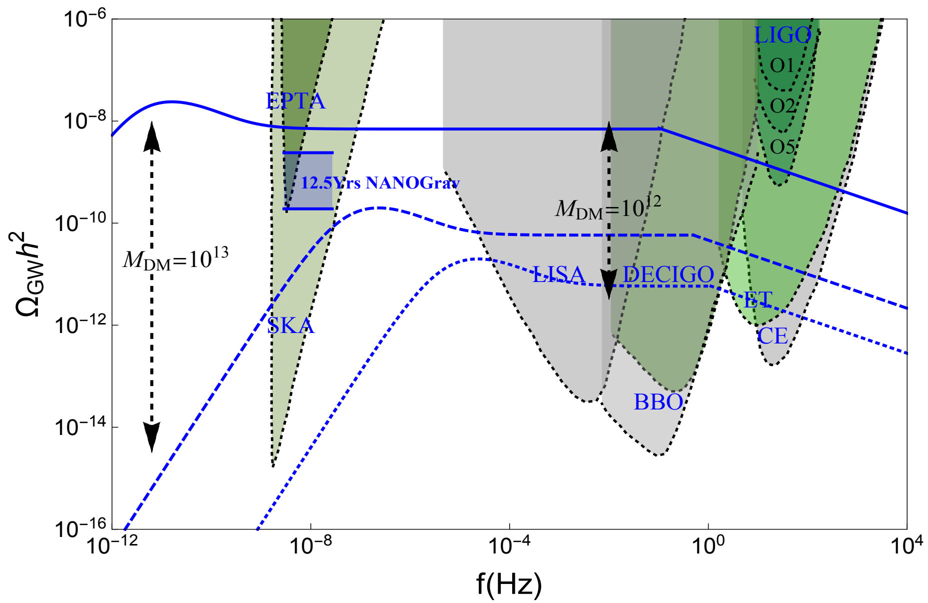
The turning point frequency

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

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



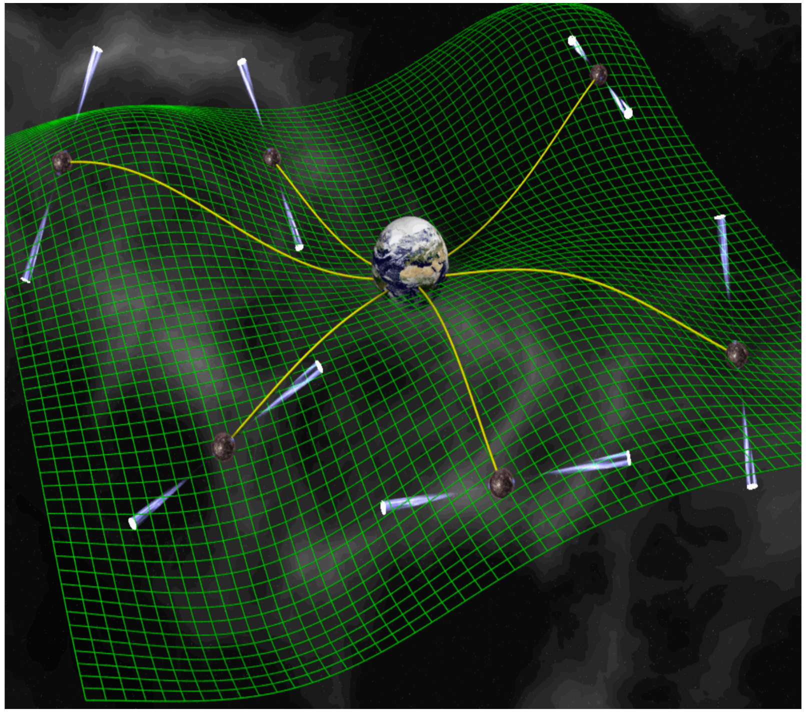
$$f_* \simeq 2.1 \times 10^{-8} \sqrt{\frac{50}{z_{eq} \alpha \Gamma G\mu}} \left(\frac{M_{DM}}{T_0} \right)^{3/5} T_0^{-2/5} t_0^{-1},$$



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.

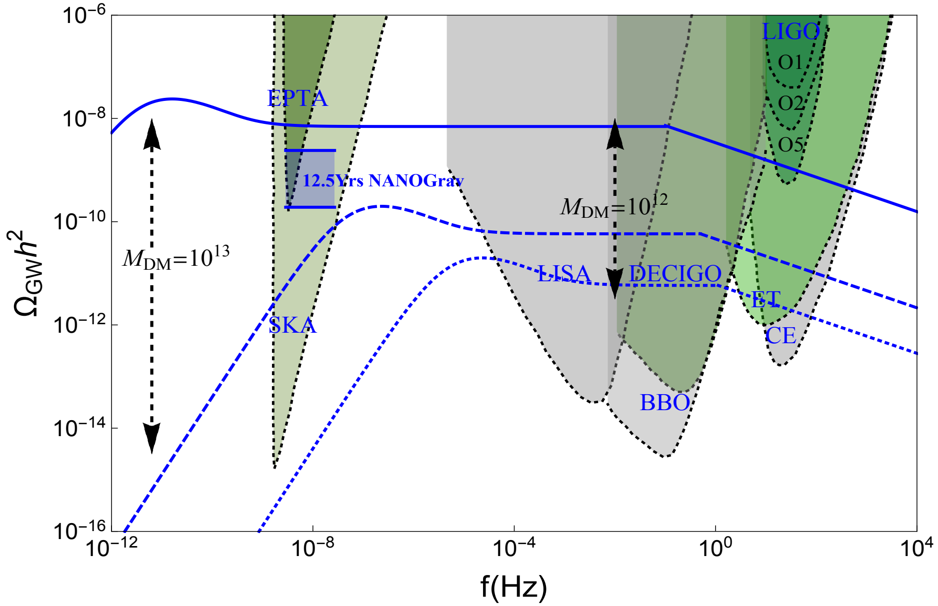


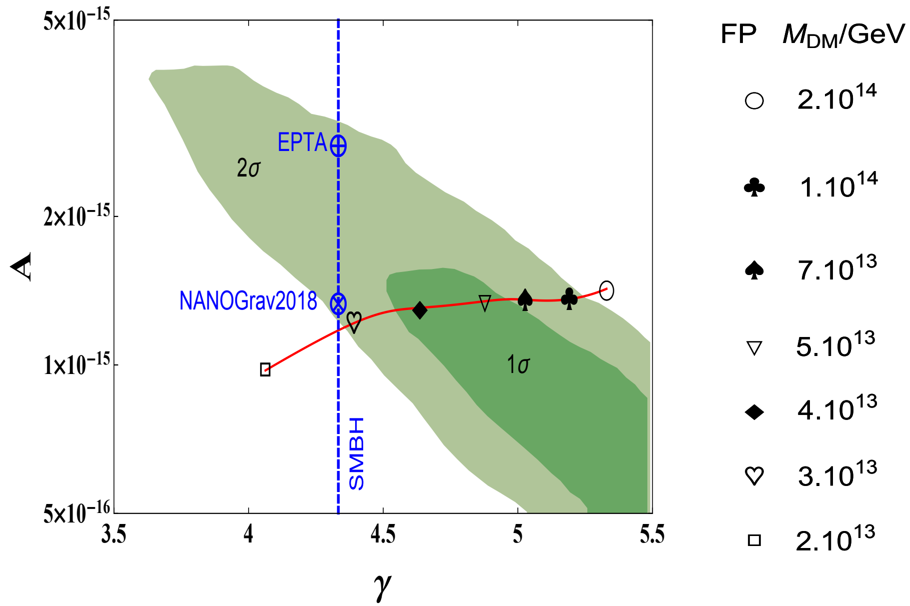
Time residual: $$R(t) = -\int_0^t \frac{\delta\nu}{\nu}\,\mathrm{d}t$$

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

NANOGrav-fit

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





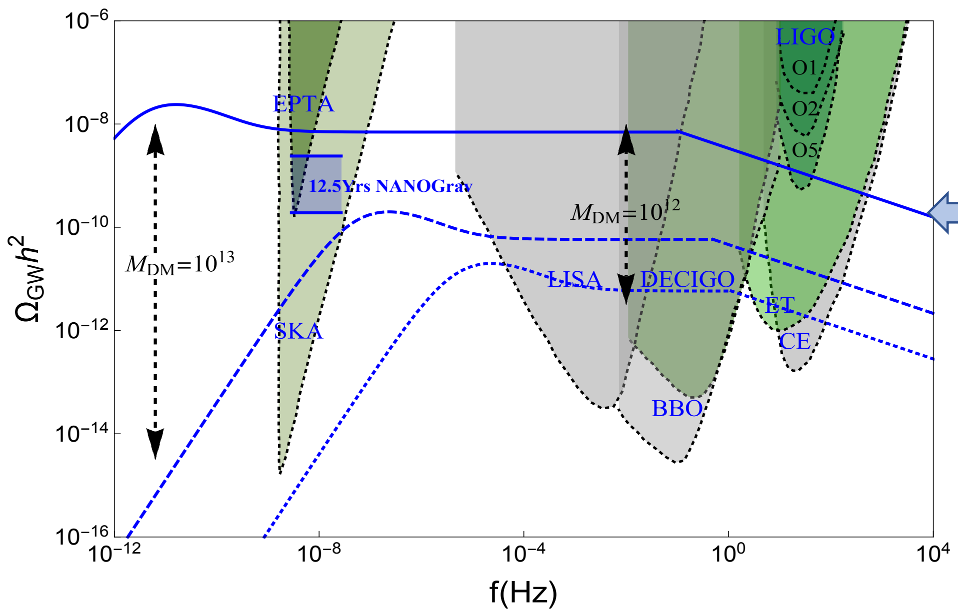
Potential of LISA to test Super heavy DM model

LISA
CosWG-19-03

PREPARED FOR SUBMISSION TO JHEP

Probing the gravitational wave background from cosmic strings with LISA

Pierre Auclair[a], Jose J. Blanco-Pillado[b,c], Daniel G. Figueroa[d,e,†], Alexander C. Jenkins[f], Marek Lewicki[f,g], Mairi Sakellariadou[f], Sotiris Sanidas[h], Lara Sousa[i,j], Danièle A. Steer[a], Jeremy M. Wachter[c], Sachiko Kuroyanagi[k]
For the LISA Cosmology Working Group



$M_{DM} = V_{CS}$

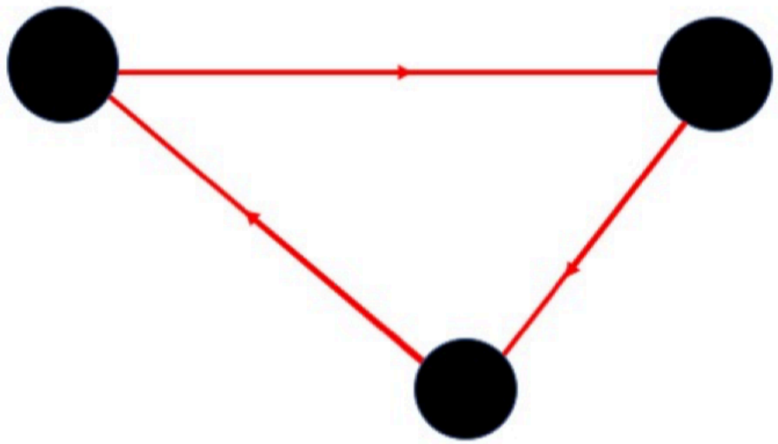
LISA: BROKEN POWER LAW

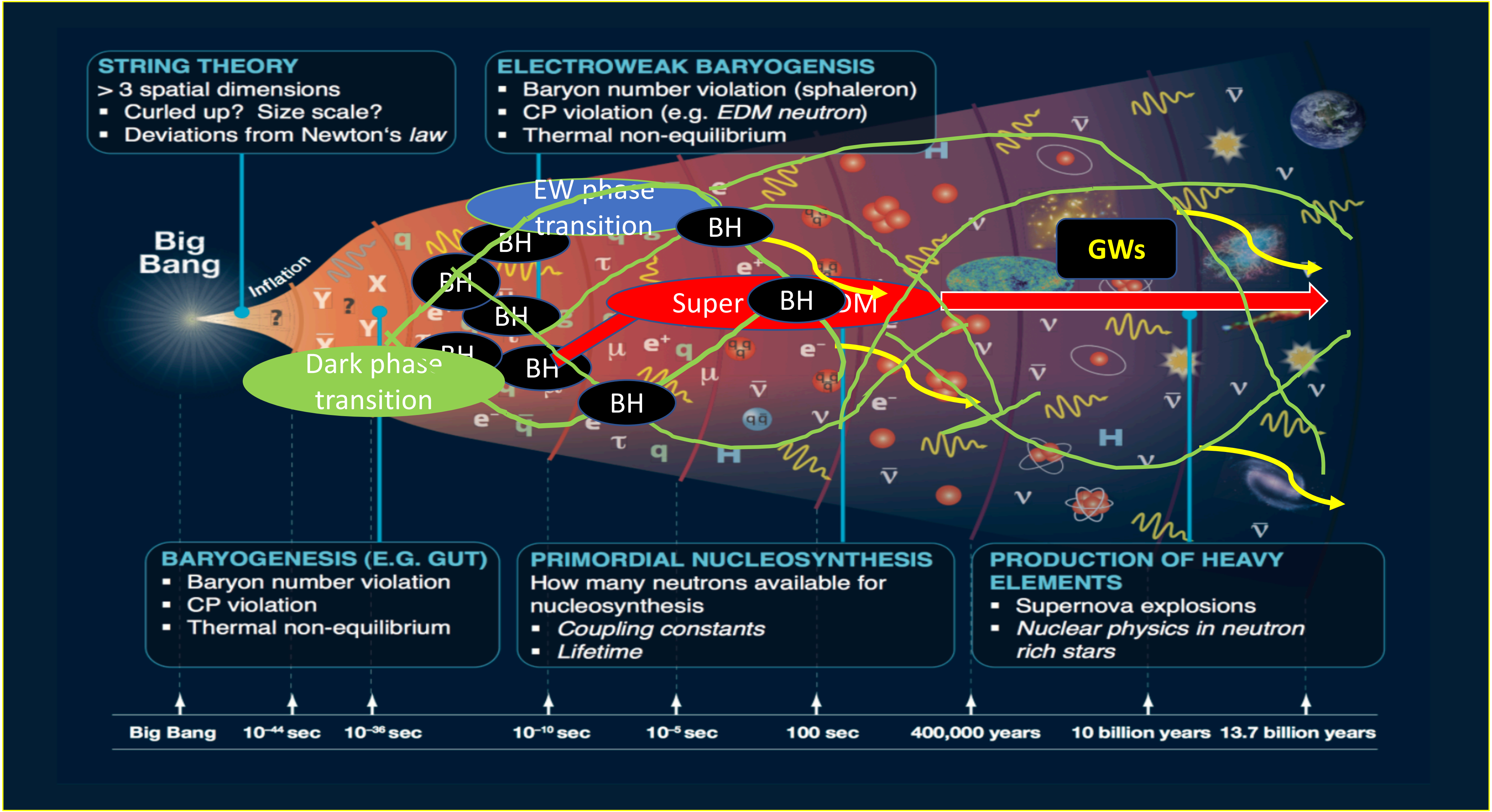
$M_{DM} < V_{CS}$

Needs theoretical improvement

Future improvement

We did not consider black hole-string network that could provide spectral distortion. (**Samanta** et al)





STRING THEORY
> 3 spatial dimensions
▪ Curled up? Size scale?
▪ Deviations from Newton's law
ELECTROWEAK BARYOGENSIS
▪ Baryon number violation (sphaleron)
▪ CP violation (e.g. EDM neutron)
▪ Thermal non-equilibrium
Big Bang
Inflation
EW phase transition
Dark phase transition
BH
Super
DM
GWs
BARYOGENESIS (E.G. GUT)
▪ Baryon number violation
▪ CP violation
▪ Thermal non-equilibrium
PRIMORDIAL NUCLEOSYNTHESIS
How many neutrons available for nucleosynthesis
▪ Coupling constants
▪ Lifetime
PRODUCTION OF HEAVY ELEMENTS
▪ Supernova explosions
▪ Nuclear physics in neutron rich stars
Big Bang
10⁻⁴⁴ sec
10⁻³⁶ sec
10⁻¹⁰ sec
10⁻⁵ sec
100 sec
400,000 years
10 billion years
13.7 billion years

Summary

Primordial black holes could be promising source of Dark matter

Particularly, super heavy Dark matter scenarios could be probed with GWs in this new cosmic frontier.

One can look for the amplitude as well as spectral shapes of the GWs as a probe.

Detectors like PTAs and LISA, DECIGO are suitable for very heavy Dark matter.