

Gravitational probes of the Early Universe

Yann Gouttenoire

2th October 2025



New Physics from Galaxy Clustering at GGI

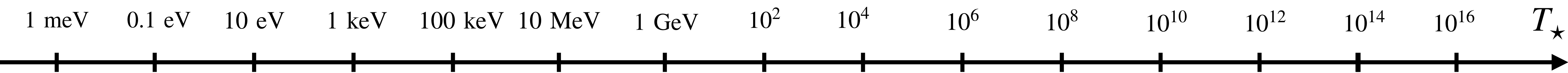
The Galileo Galilei Institute For Theoretical Physics

Centro Nazionale di Studi Avanzati dell'Istituto Nazionale di Fisica Nucleare

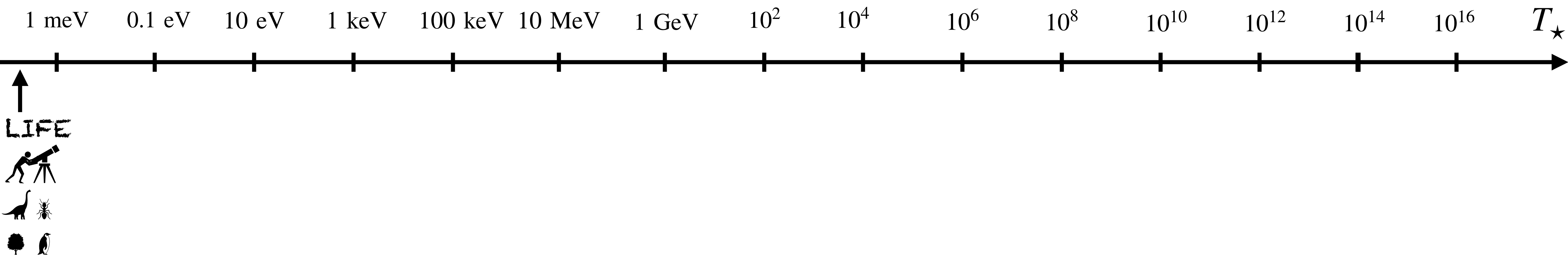
February 2026



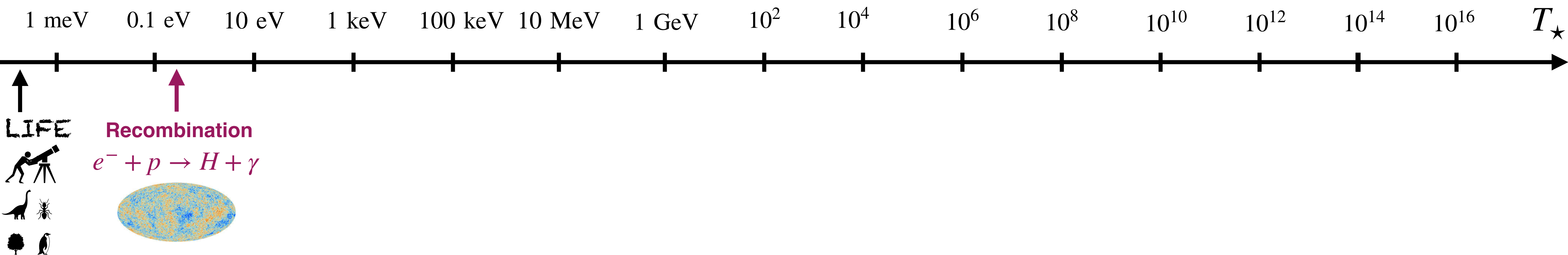
Institute of Astrophysics in Paris



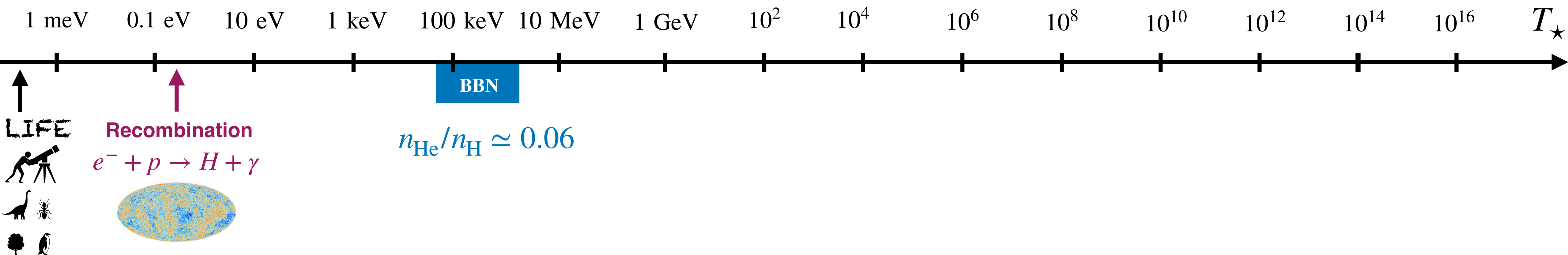
What we do know about the
History of our Universe



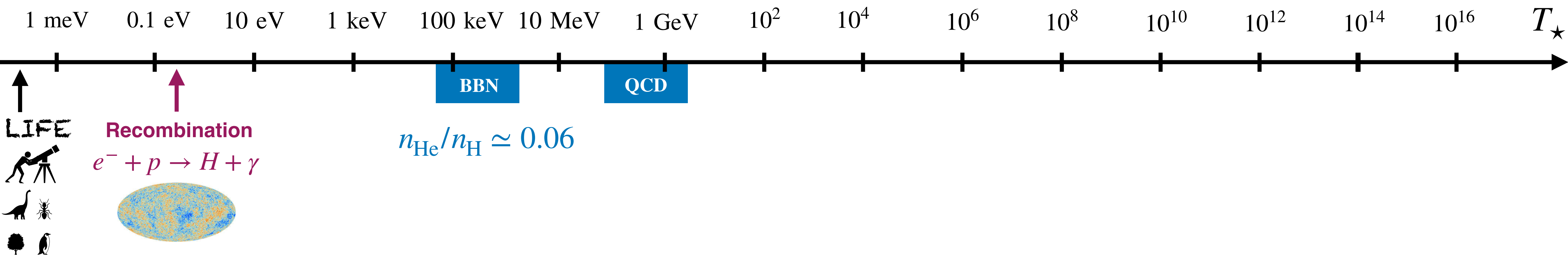
What we do know about the
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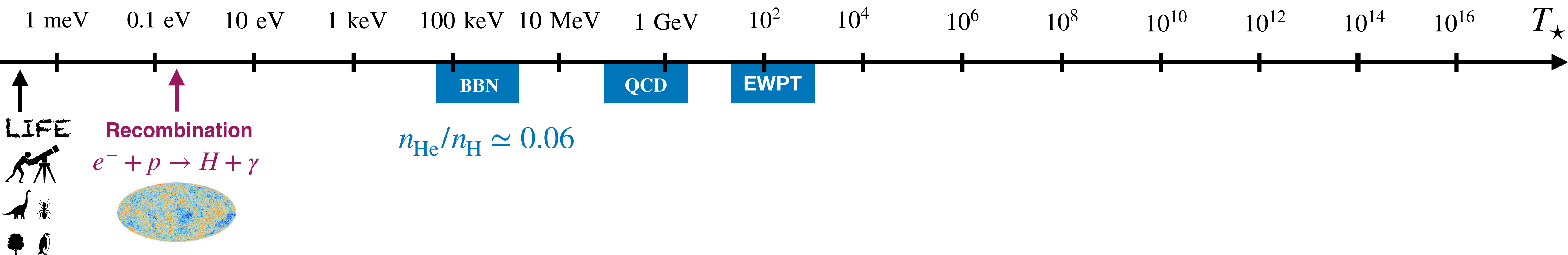
What we do know about the
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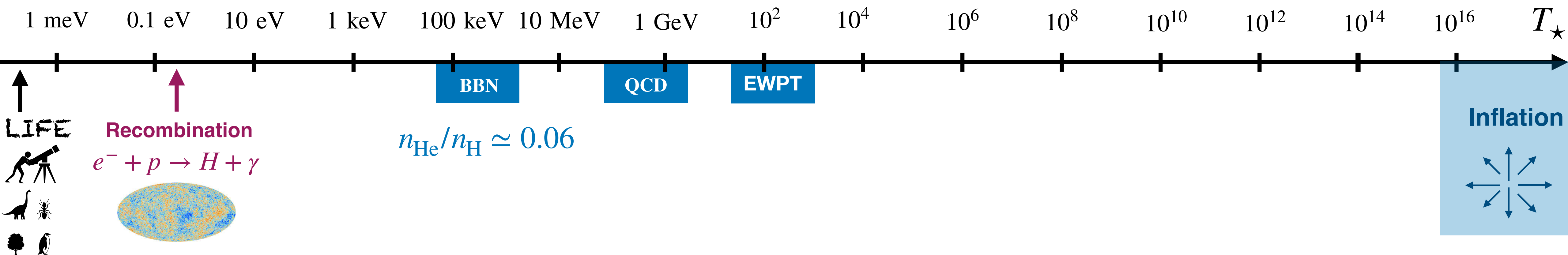
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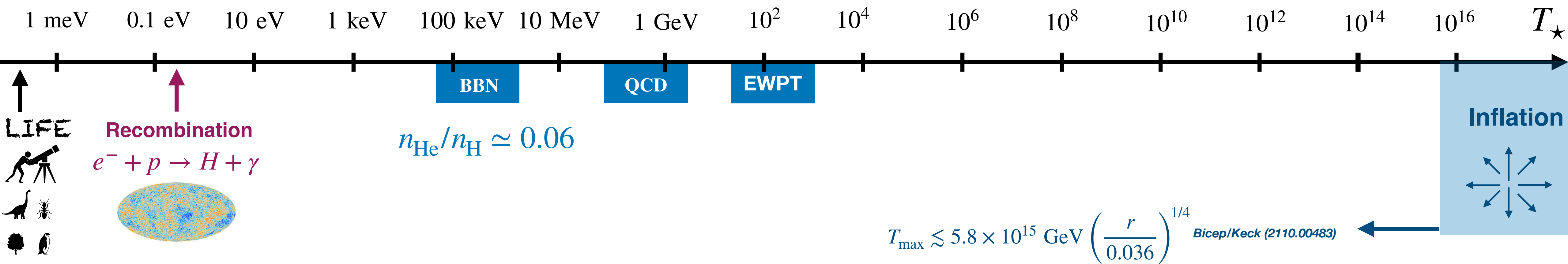
What we do know about the
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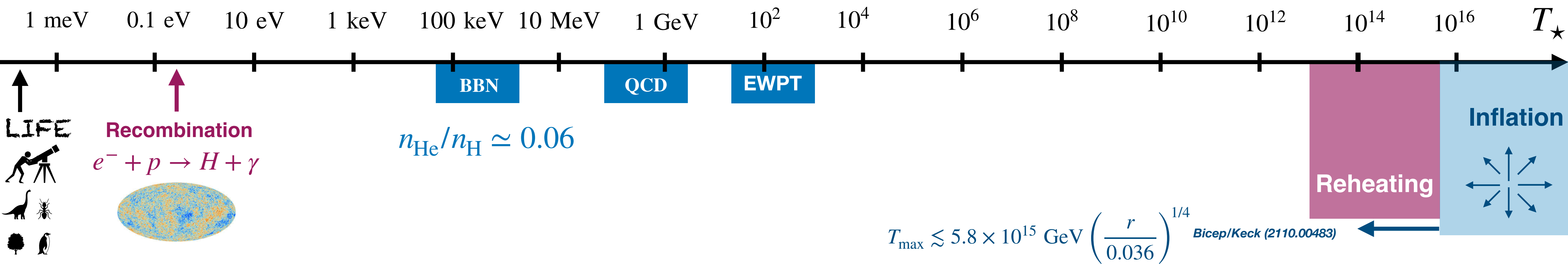
What we do know about the
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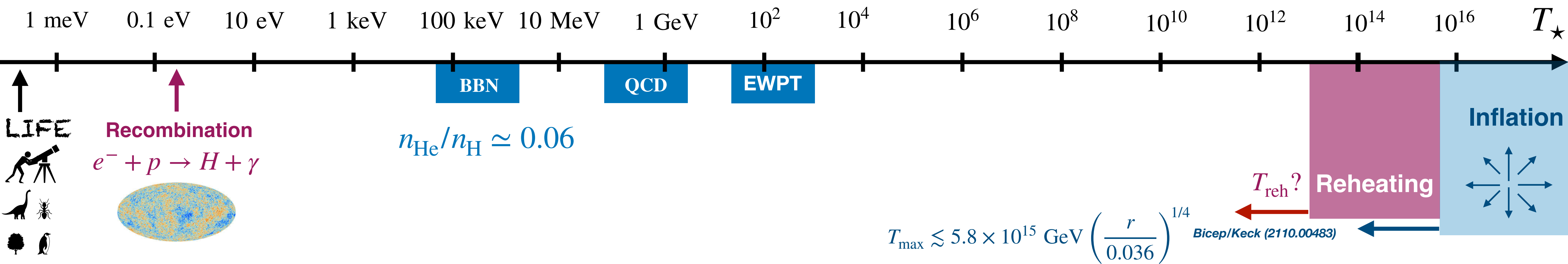
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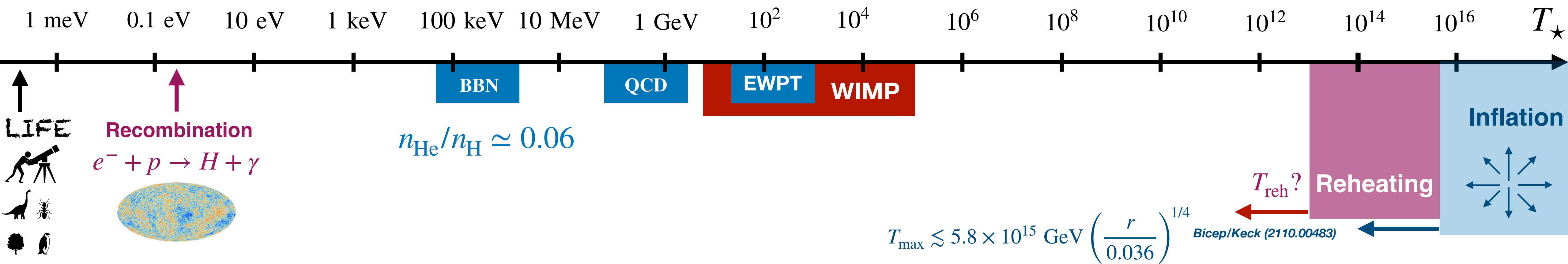
What we do know about the
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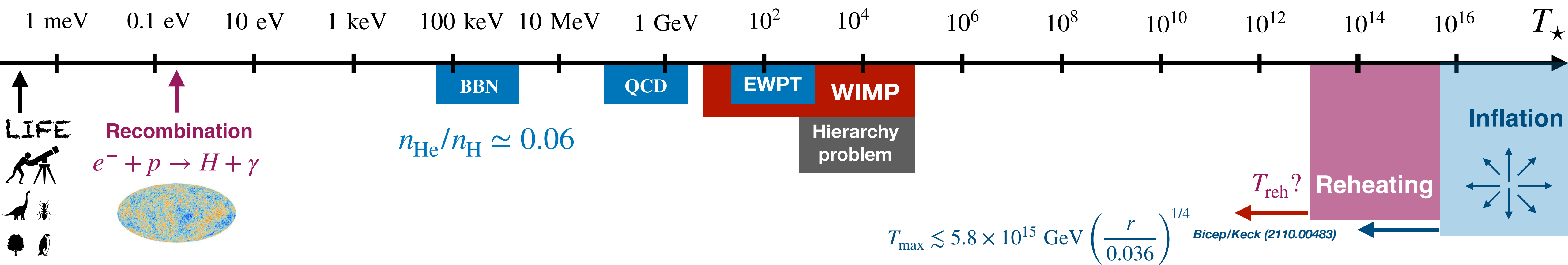
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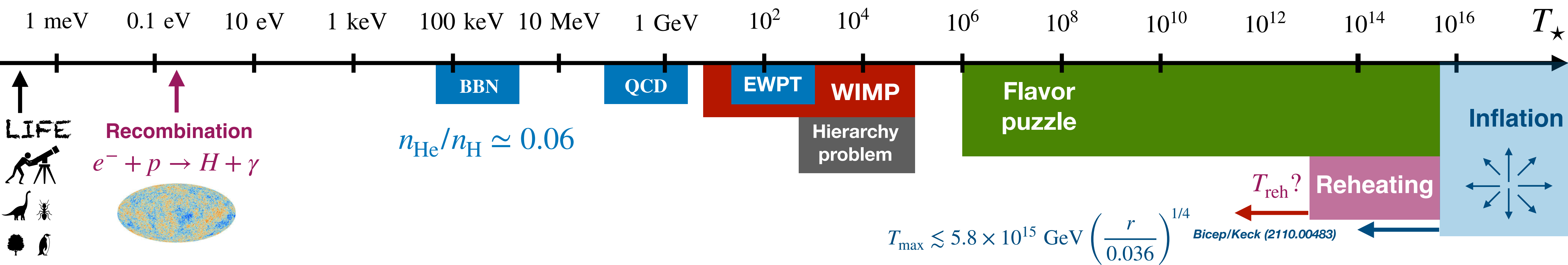
What we **don't** know about the
History of our Universe



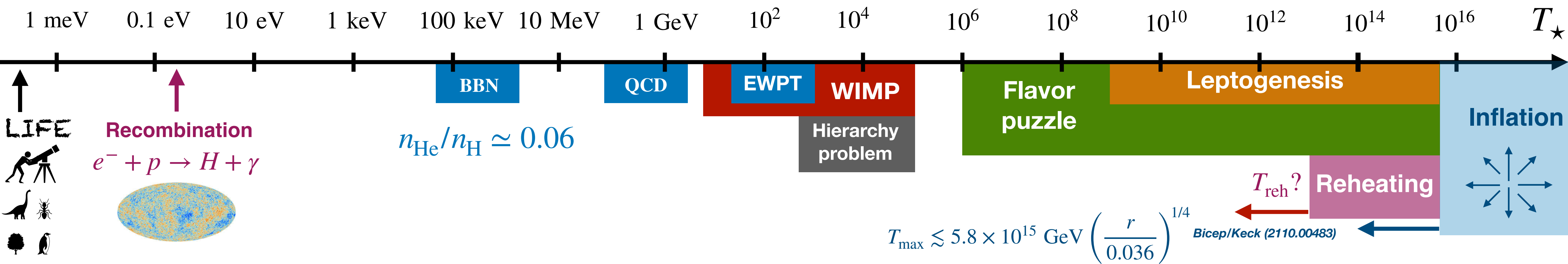
What we **don't** know about the History of our Universe



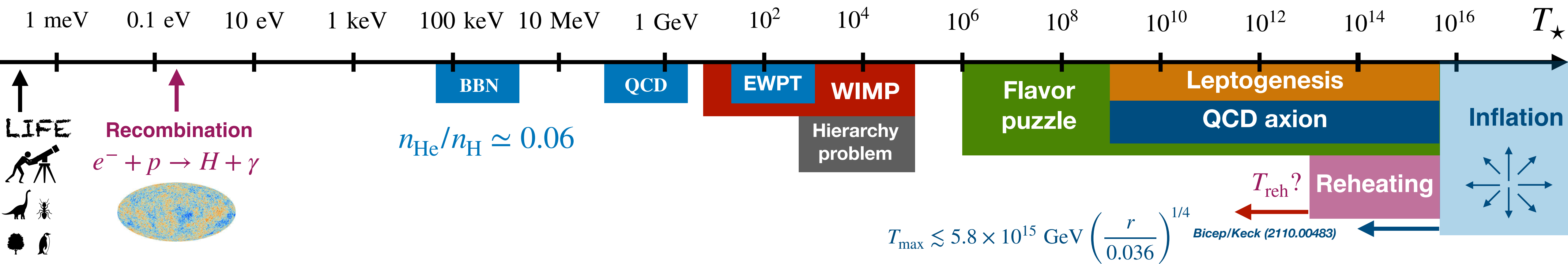
What we **don't** know about the
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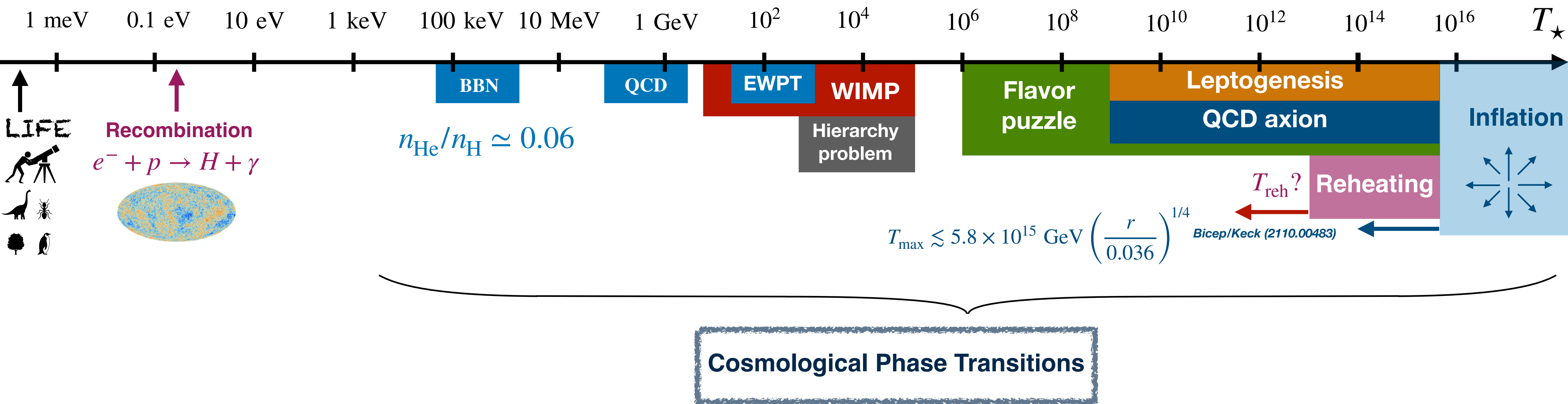
What we **don't** know about the
History of our Universe

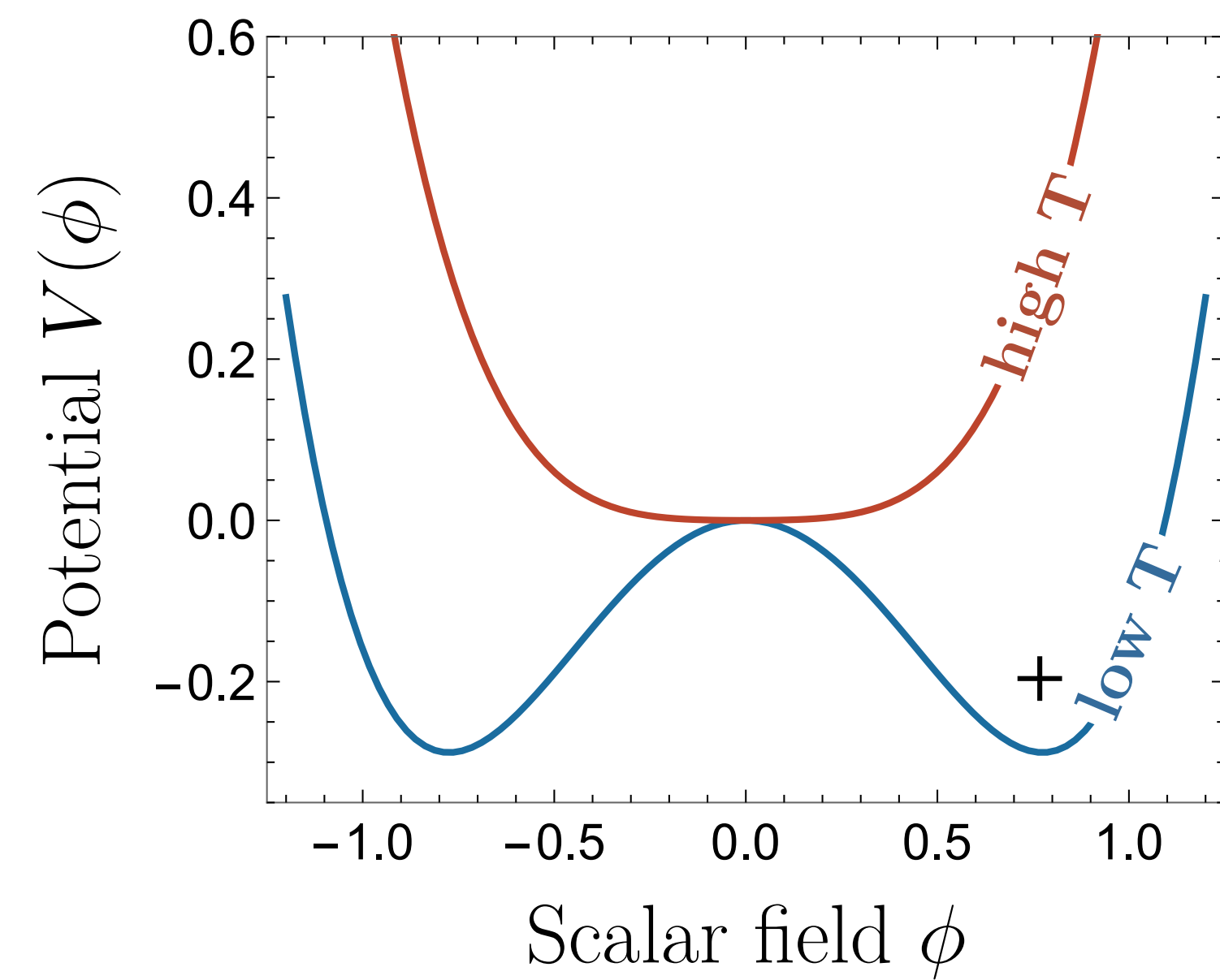
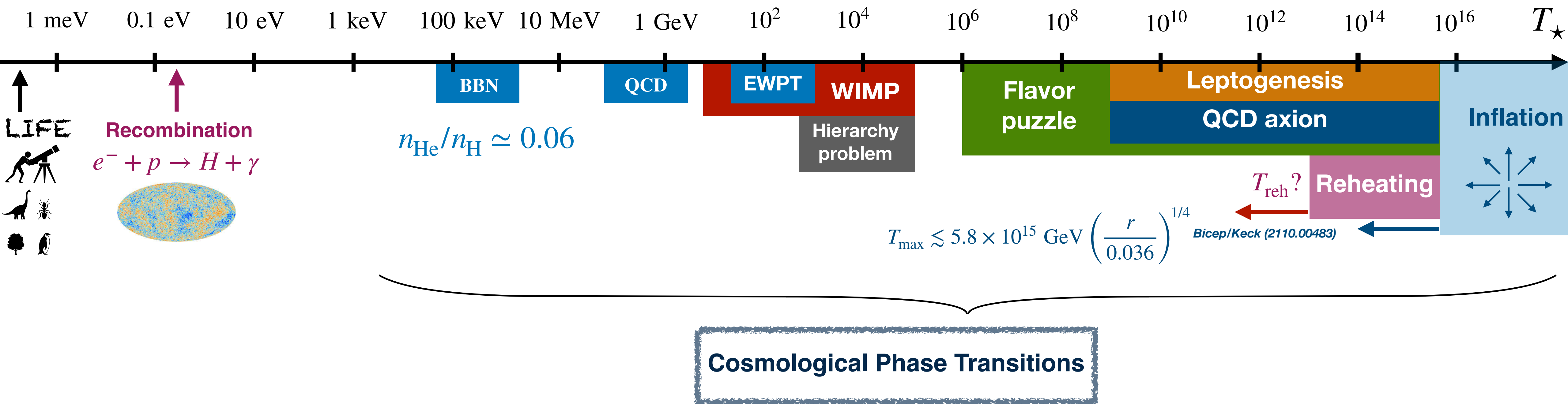


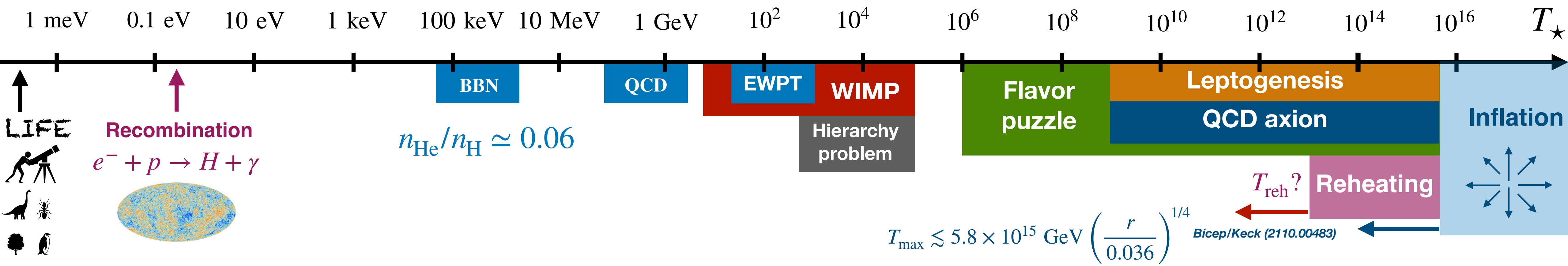
What we **don't** know about the History of our Universe



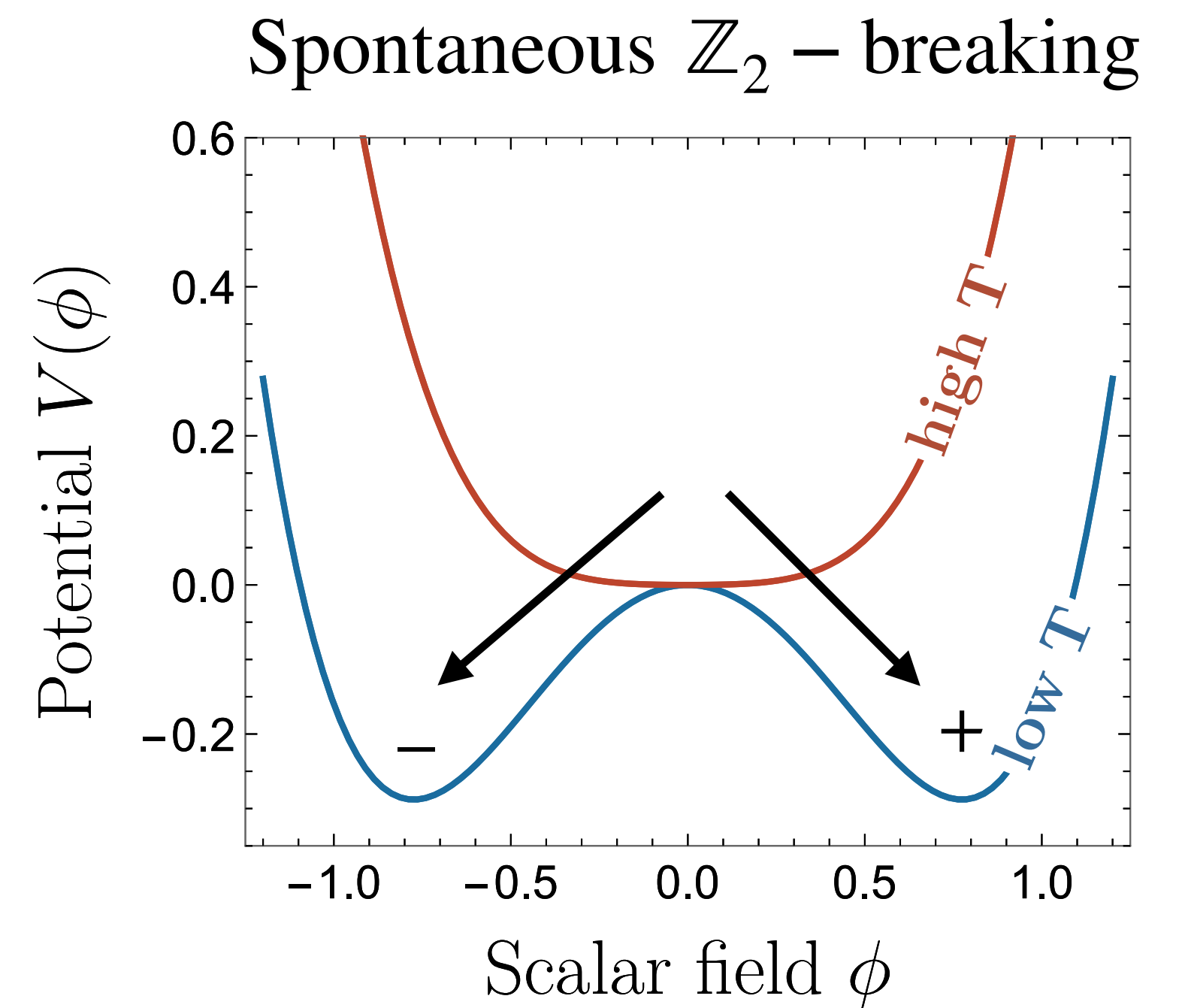
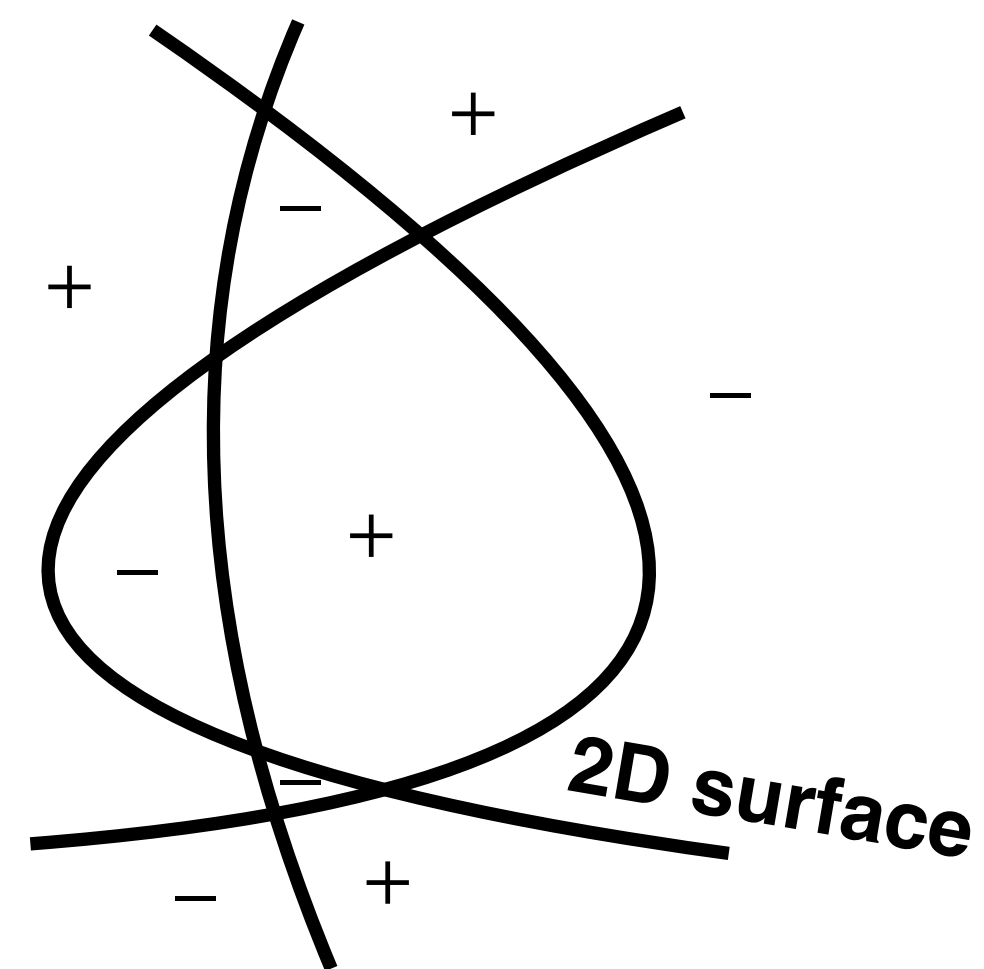
What we **don't** know about the History of our Universe

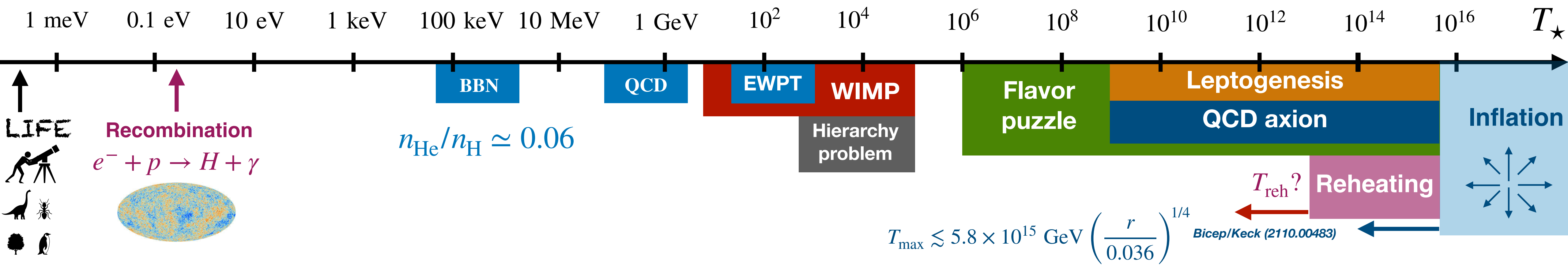




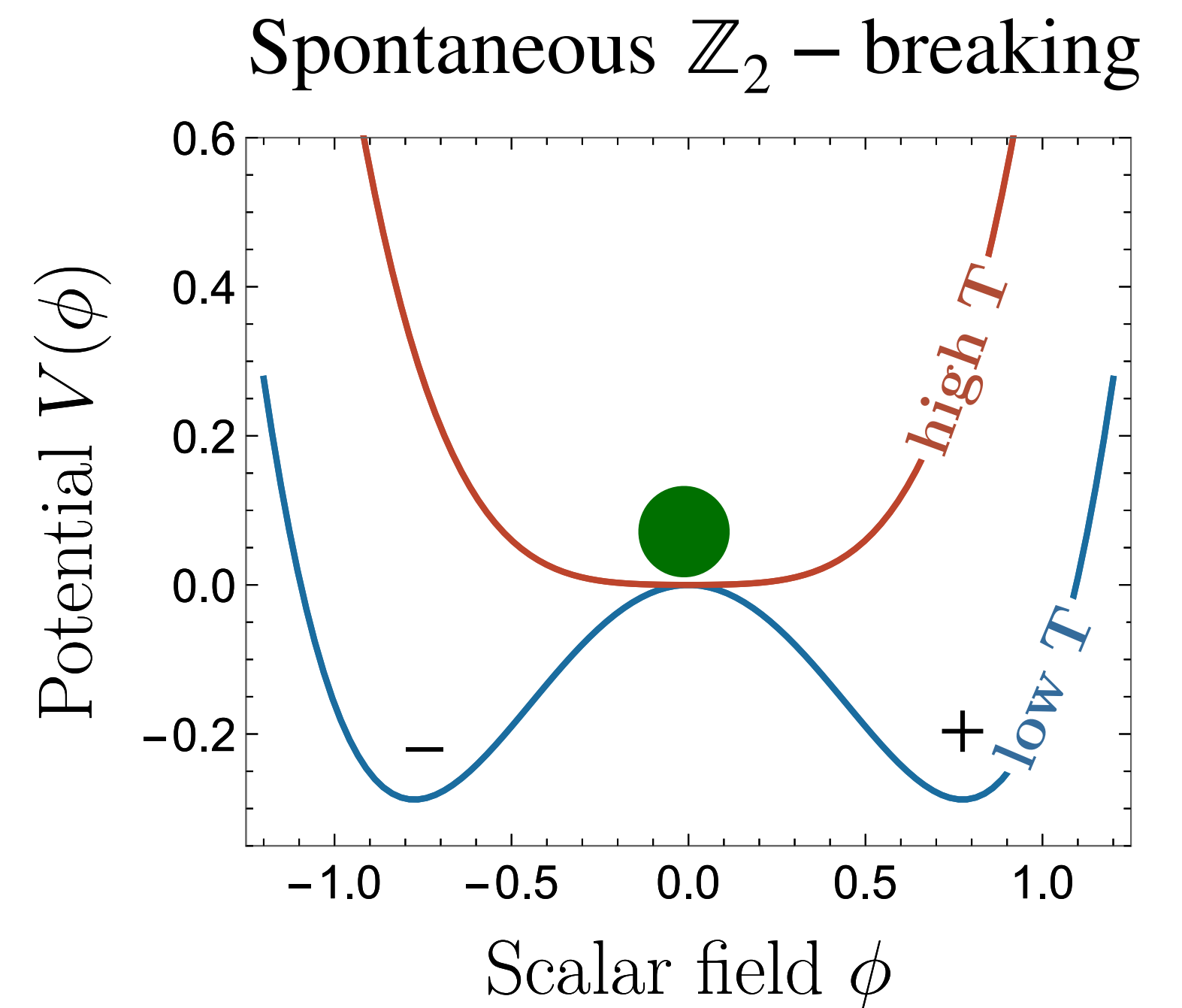
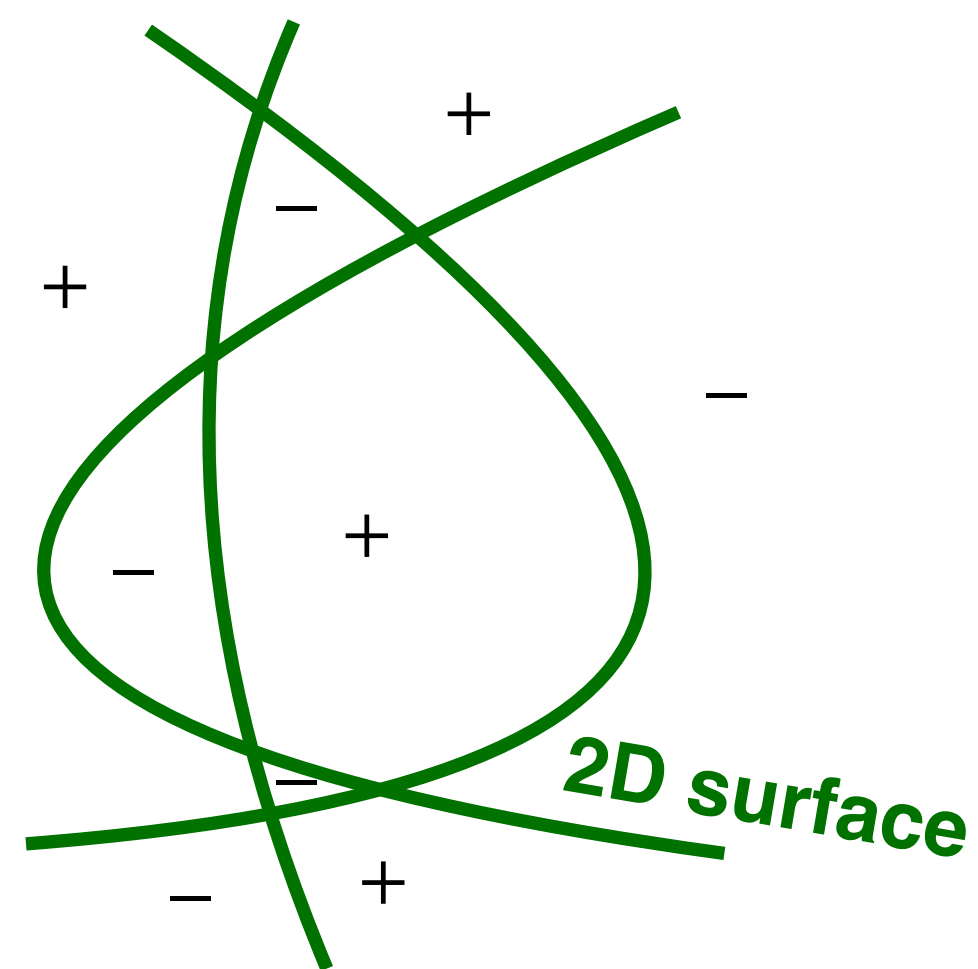


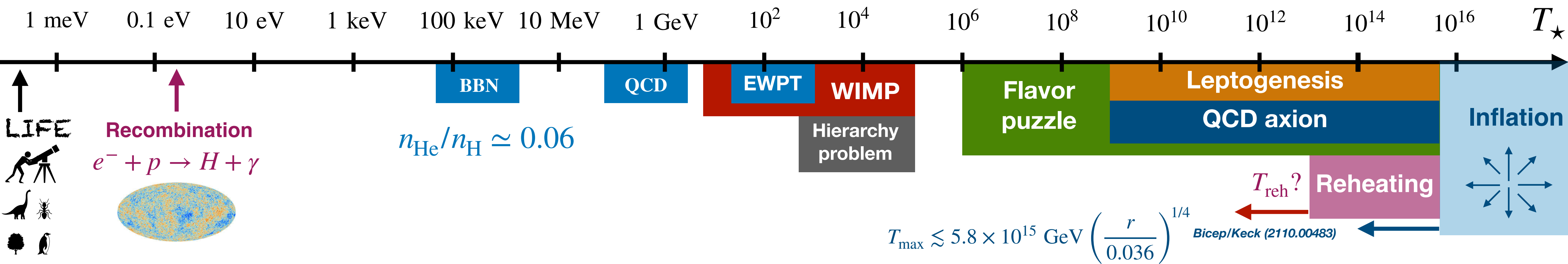
Cosmological Phase Transitions



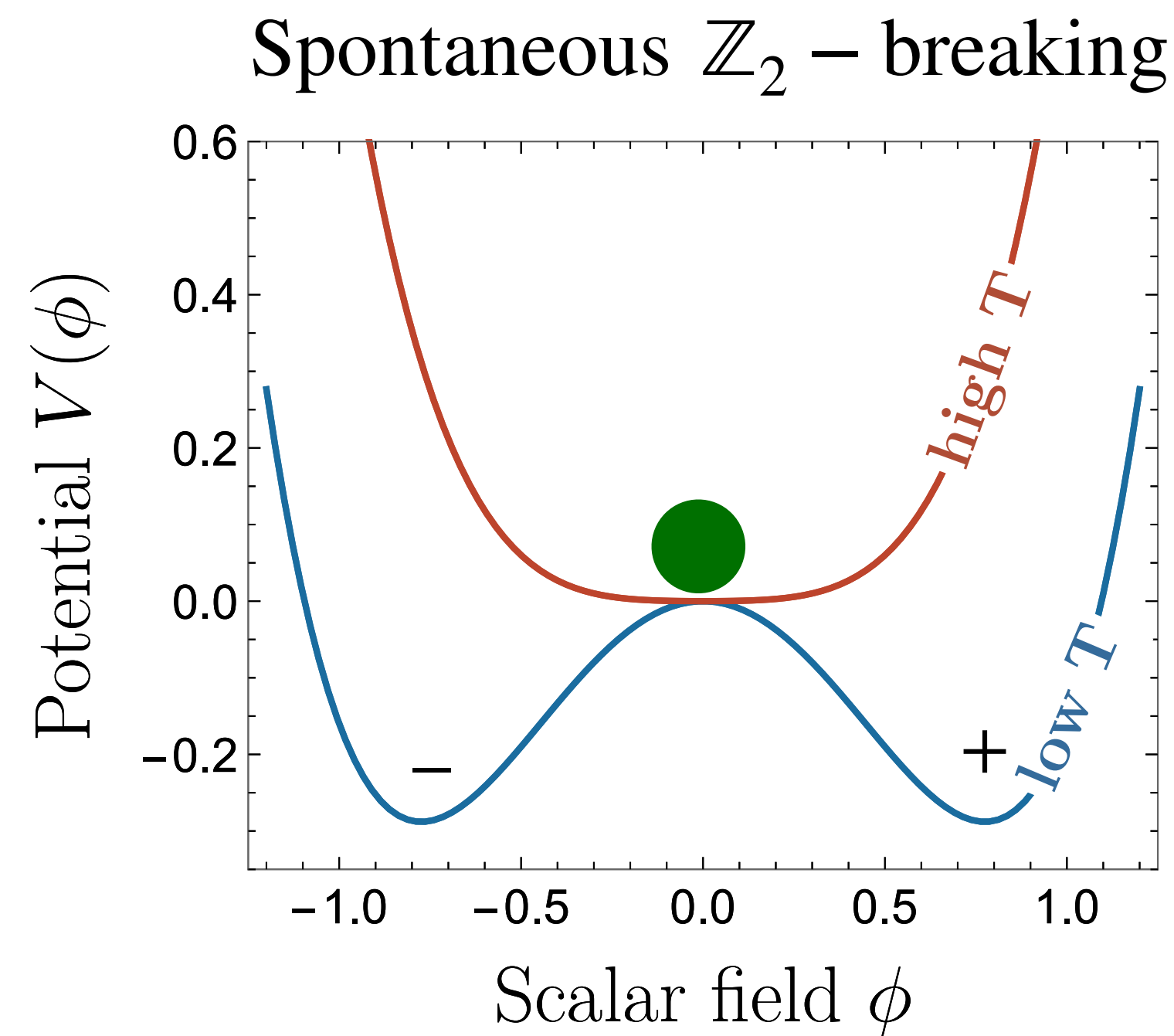
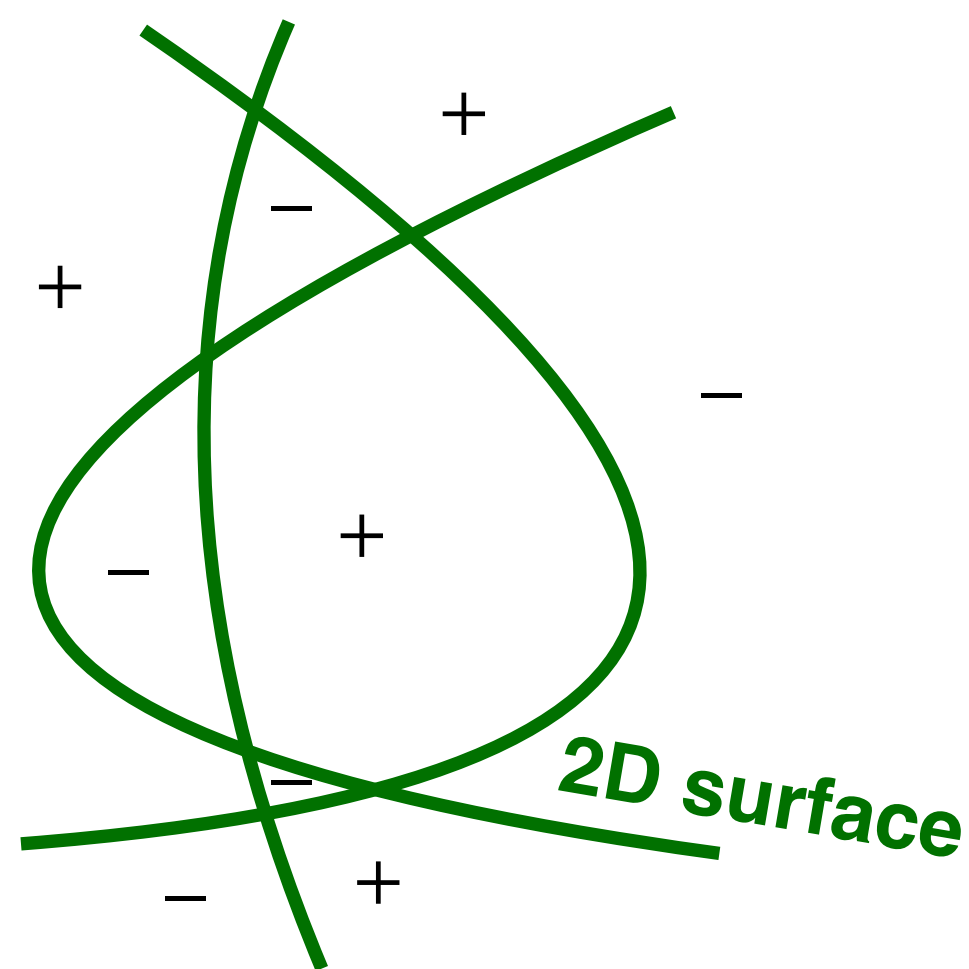


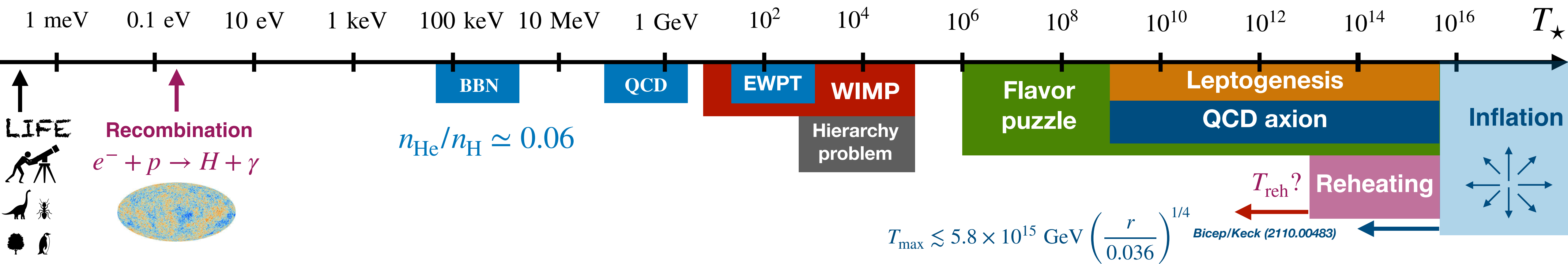
Cosmological Phase Transitions



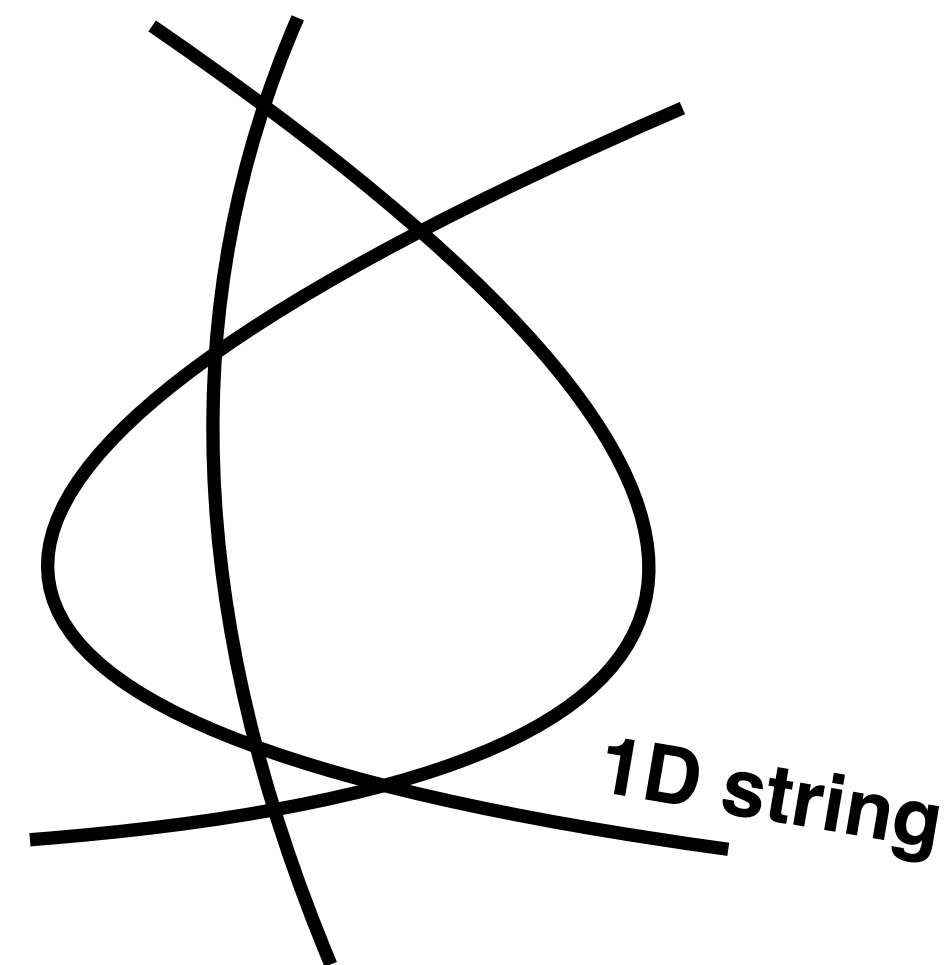


Cosmological Phase Transitions

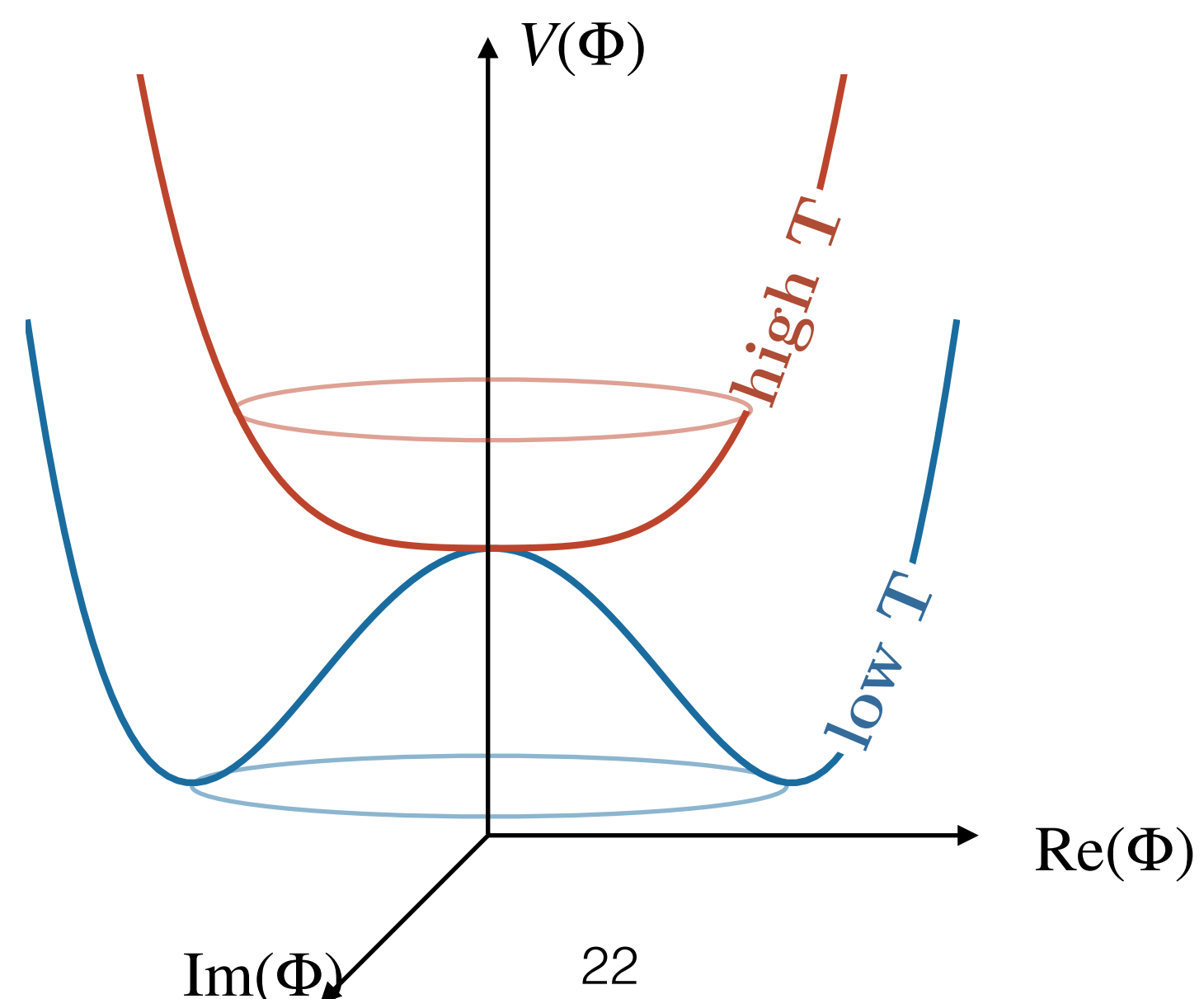


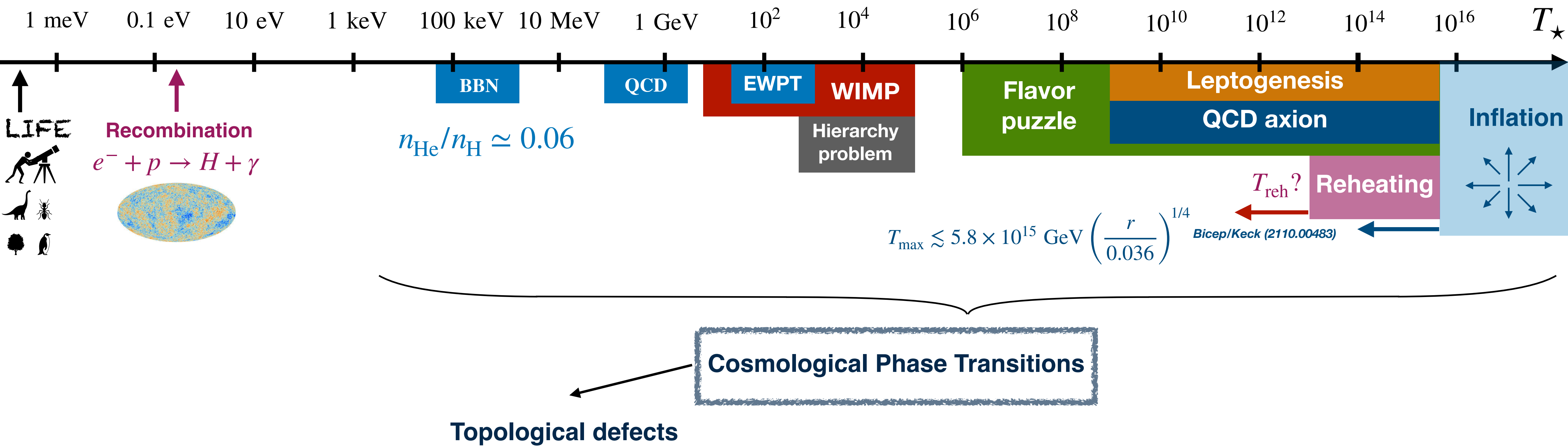


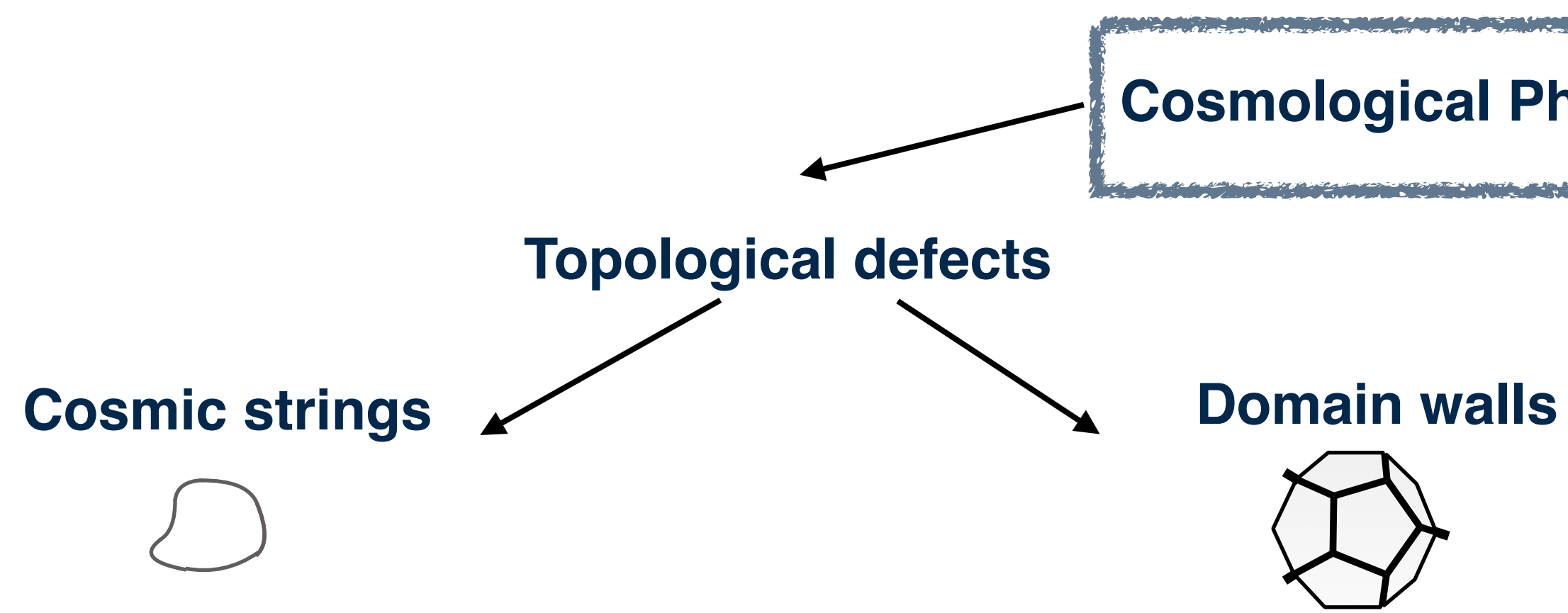
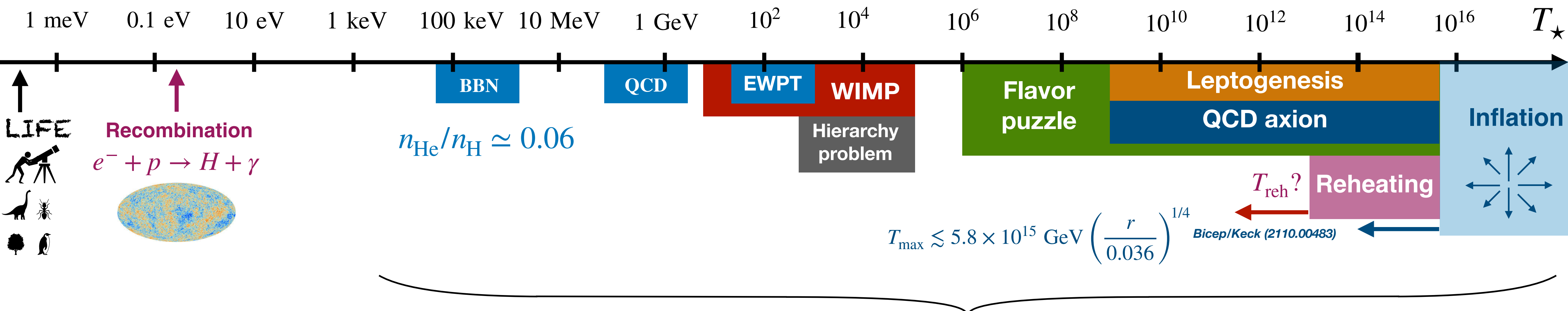
Cosmological Phase Transitions

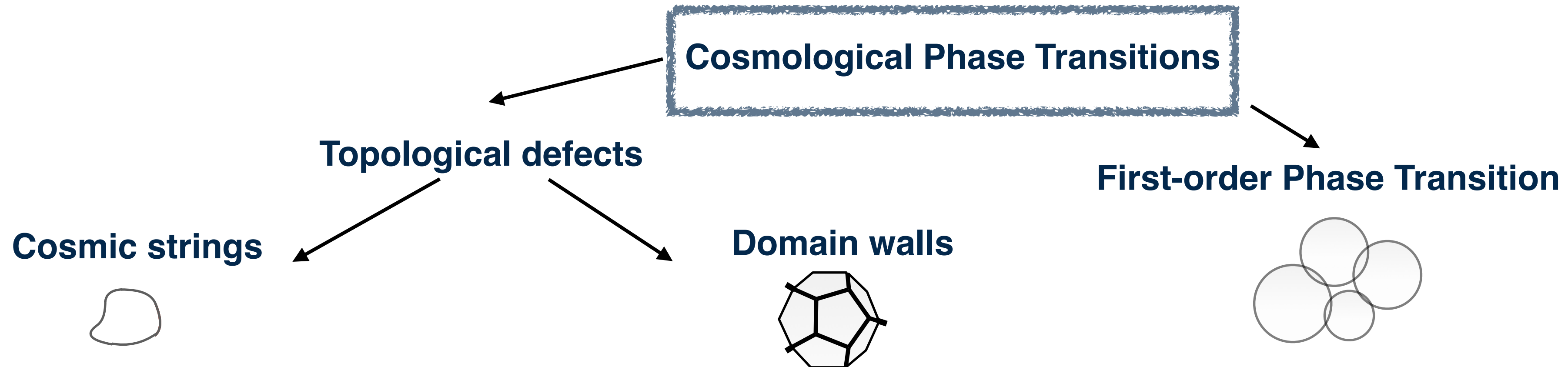
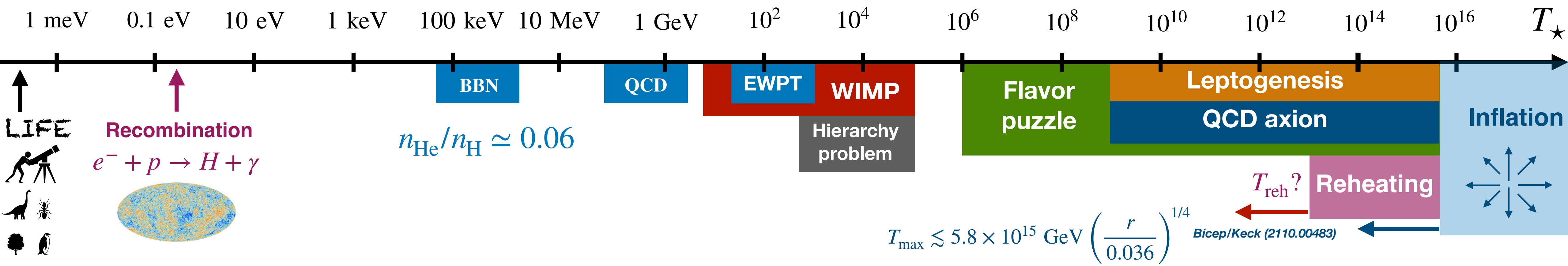


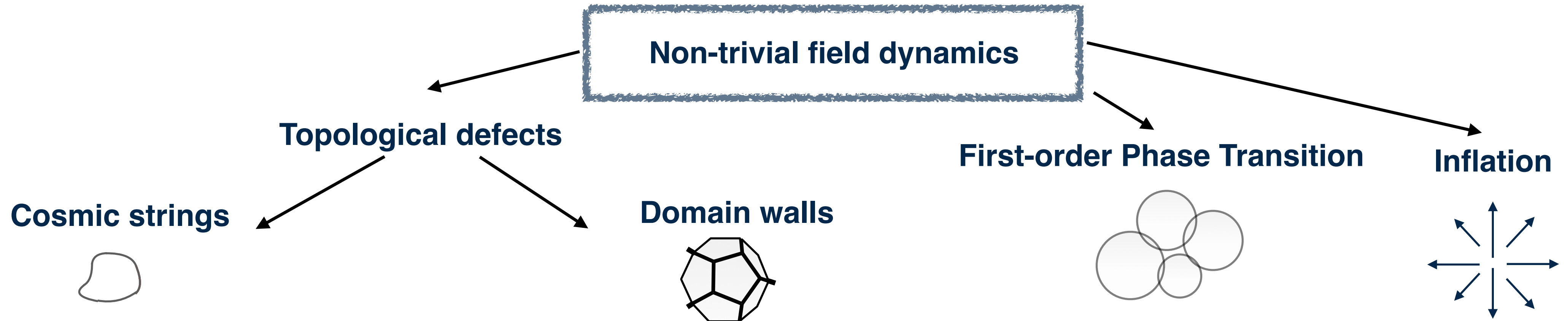
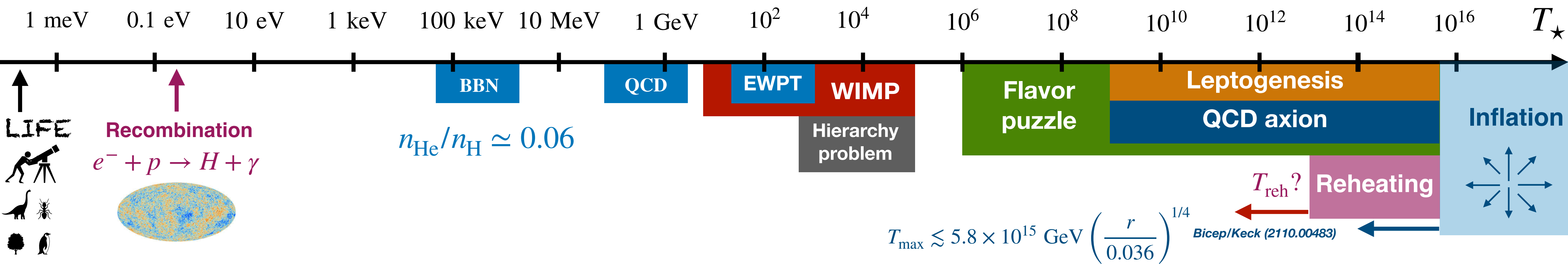
Spontaneous U(1) – breaking

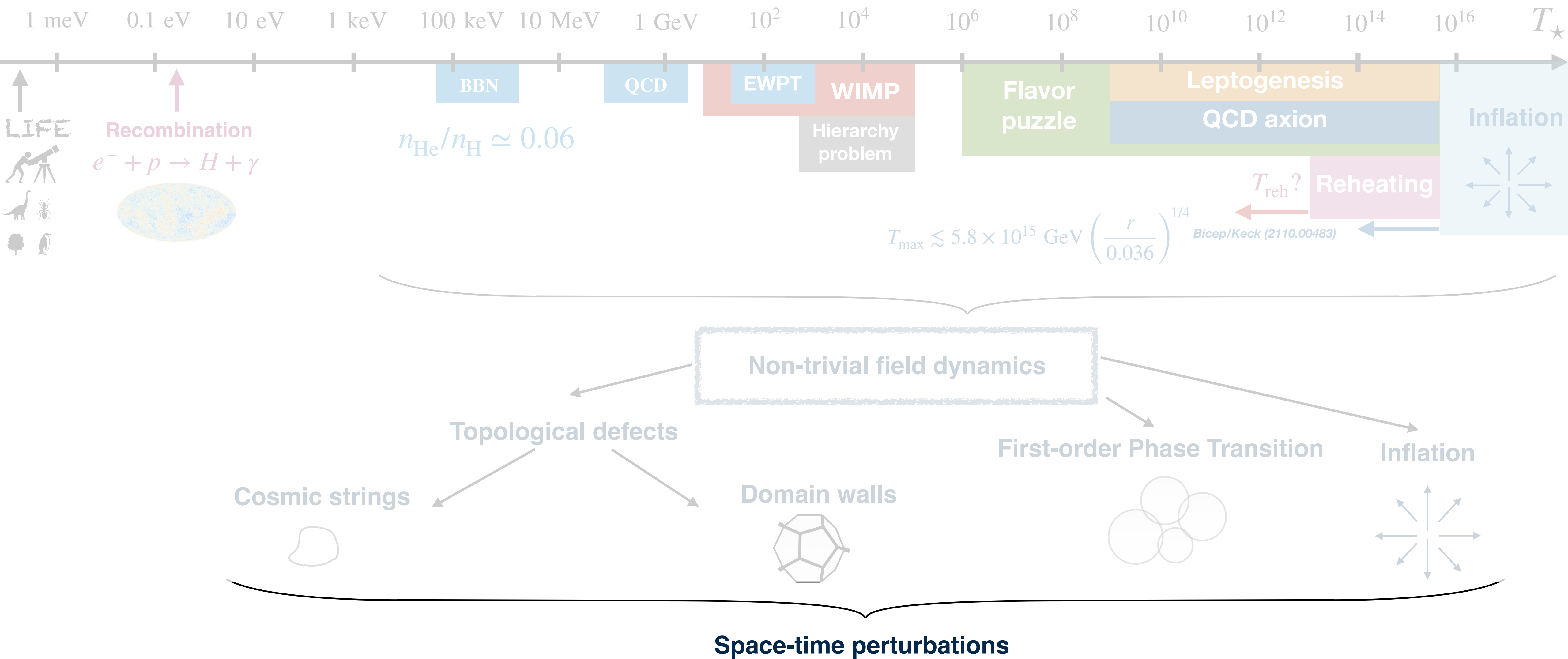


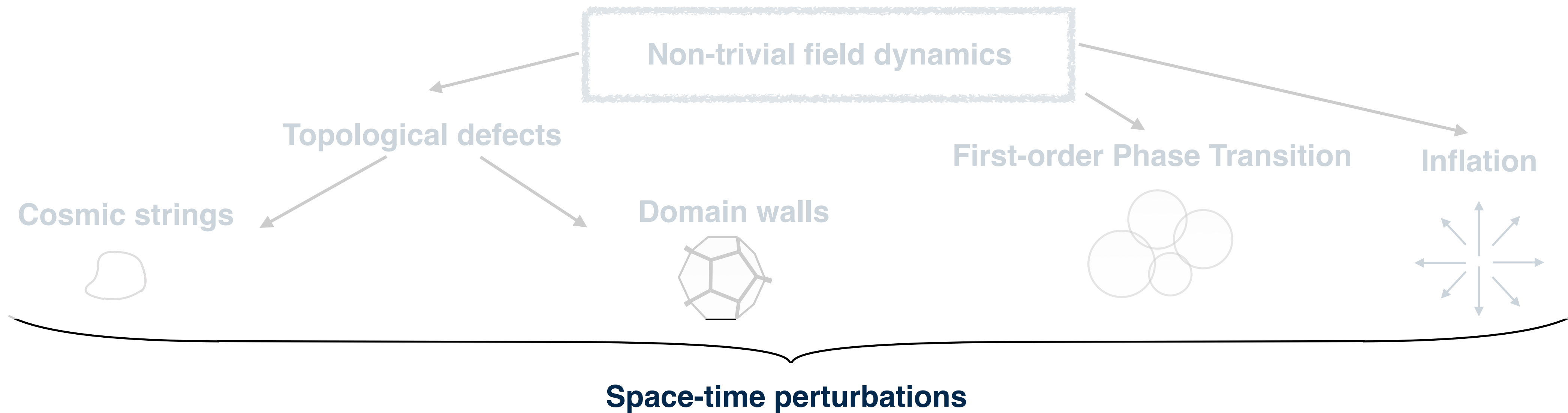
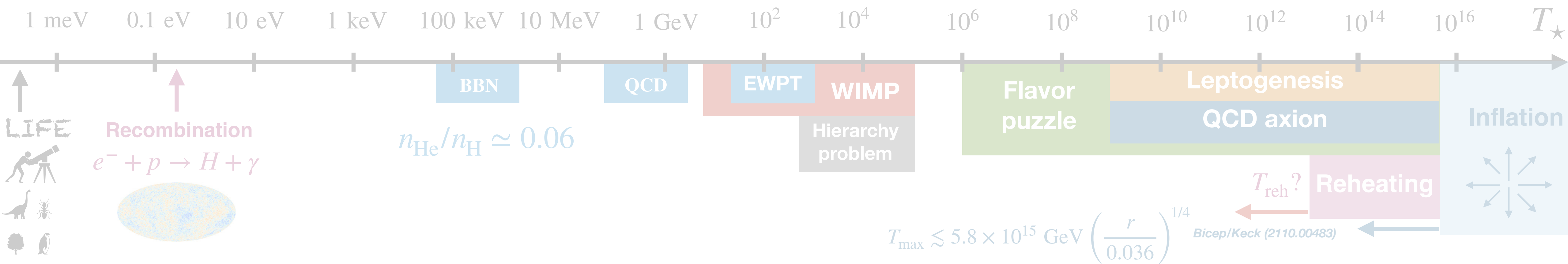








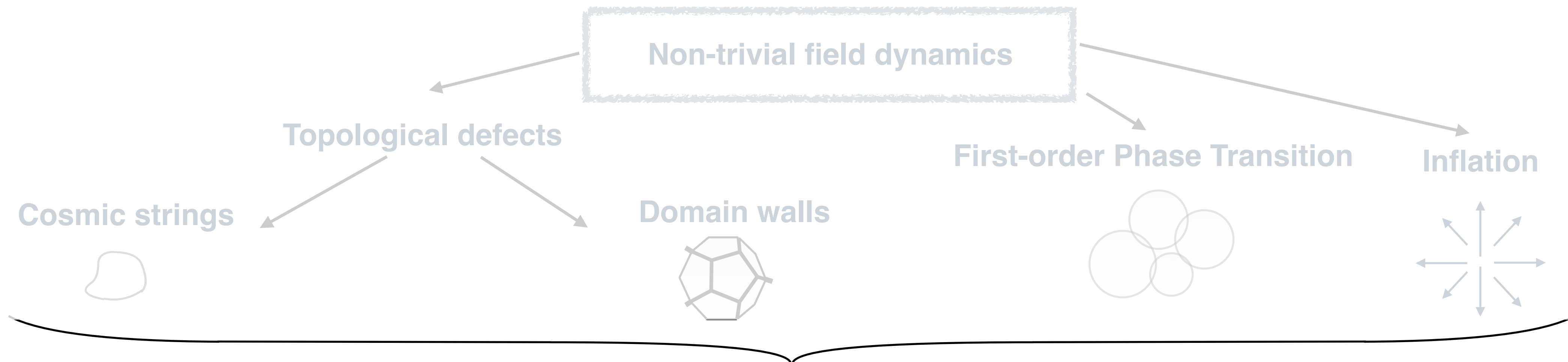
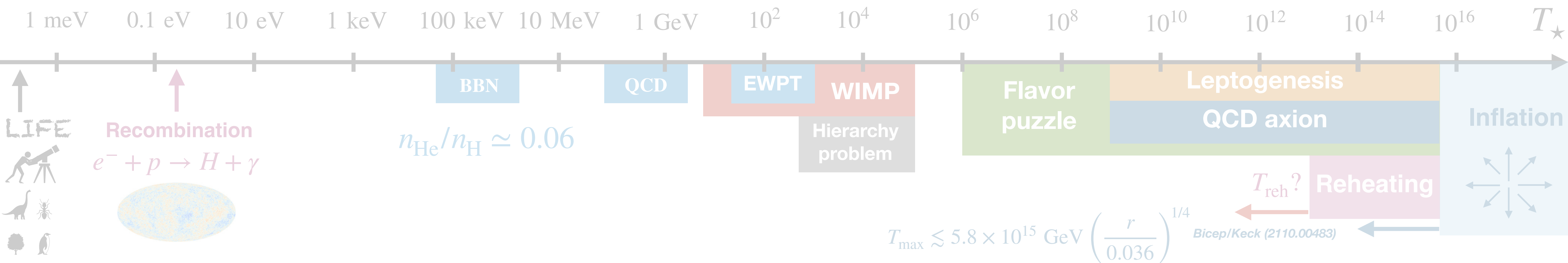




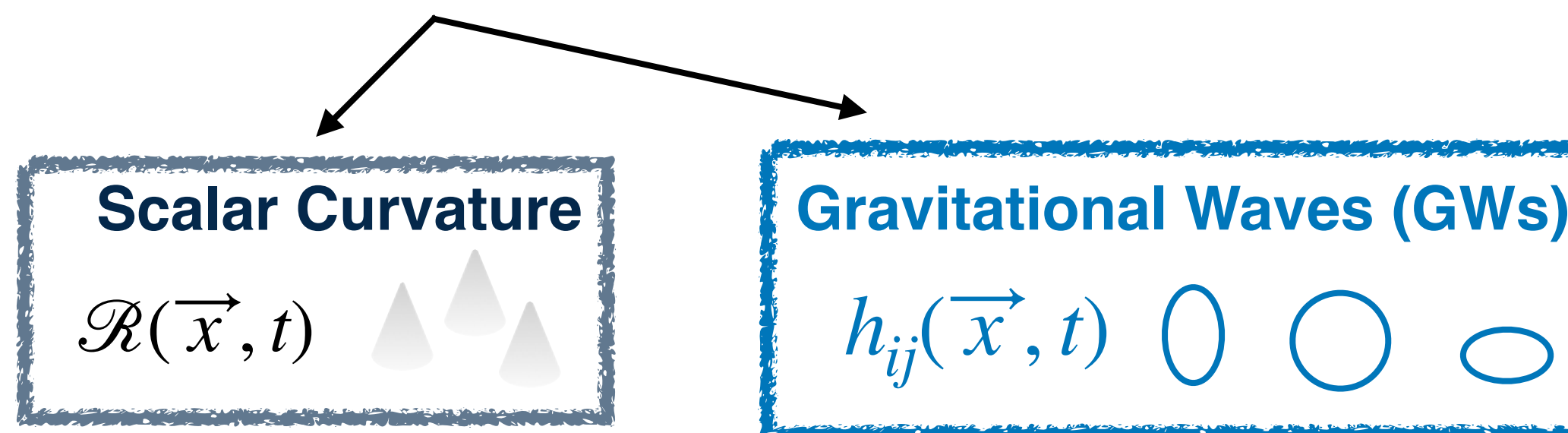
Gravitational Waves (GWs)

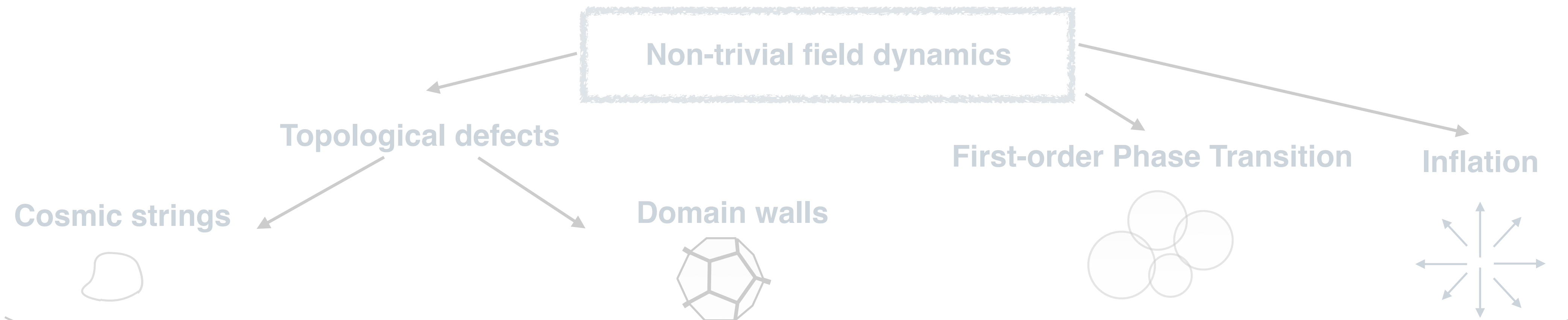
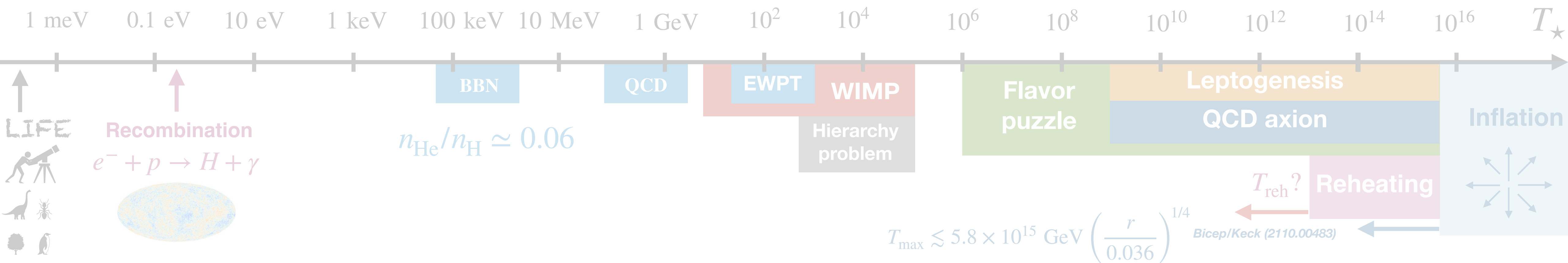
$h_{ij}(\vec{x}, t)$

(represented by three concentric ellipses)



Space-time perturbations





Primordial Black Holes (PBHs)

(Shibata & Sasaki 1999)

if $\langle \mathcal{R} \rangle_H \gtrsim 0.1$

Space-time perturbations

Scalar Curvature

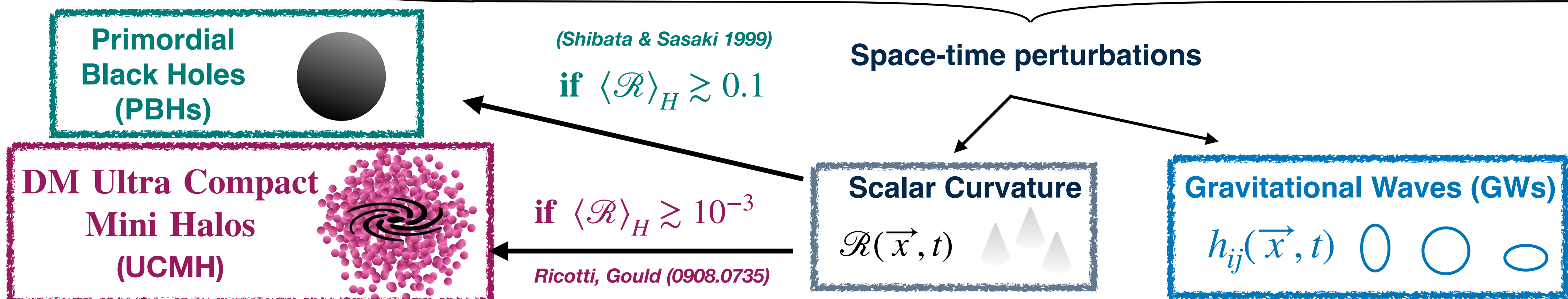
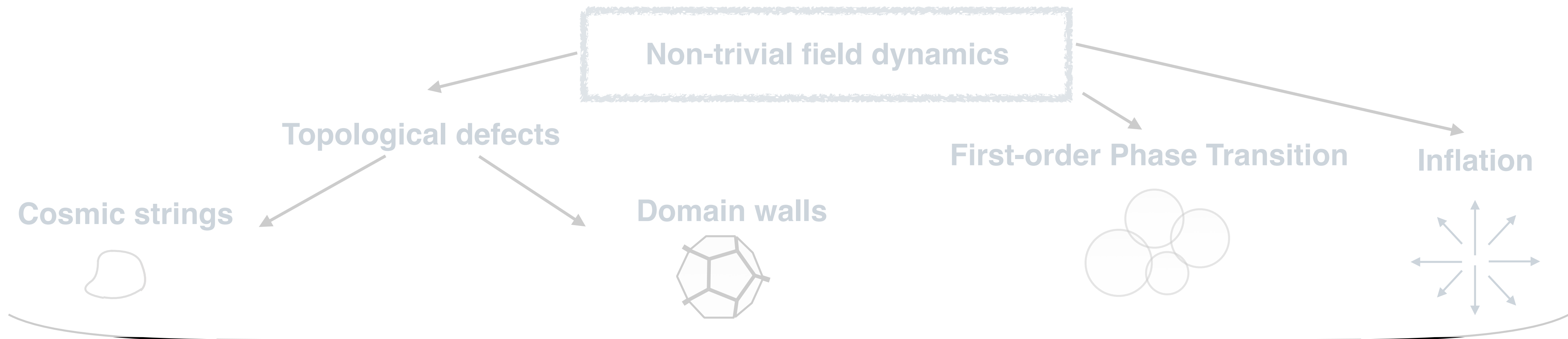
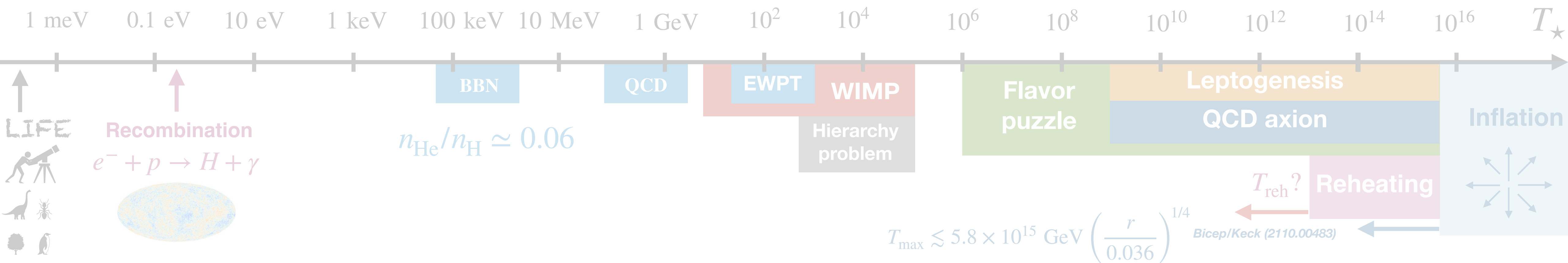
$\mathcal{R}(\vec{x}, t)$



Gravitational Waves (GWs)

$h_{ij}(\vec{x}, t)$





Plan of the talk

Plan of the talk

1)

Gravitational Waves (GWs)

$$h_{ij}(\vec{x}, t)$$

Plan of the talk

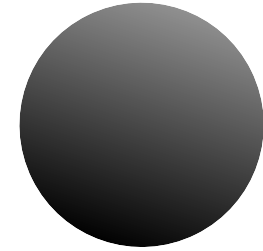
1)

Gravitational Waves (GWs)

$$h_{ij}(\vec{x}, t)$$

2)

Primordial
Black Holes
(PBHs)



Plan of the talk

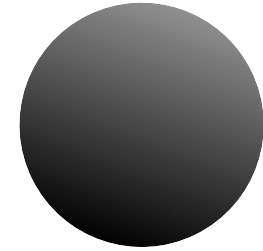
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Gravitational Waves (GWs)

$$h_{ij}(\vec{x}, t)$$

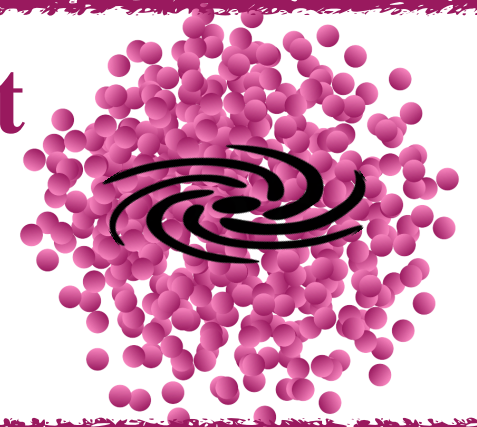
2)

Primordial
Black Holes
(PBHs)



3)

DM Ultra Compact
Mini Halos
(UCMH)



Plan of the talk

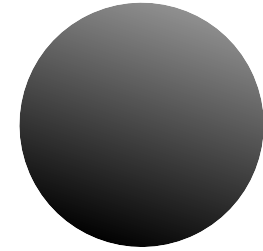
1)

Gravitational Waves (GWs)

$$h_{ij}(\vec{x}, t)$$

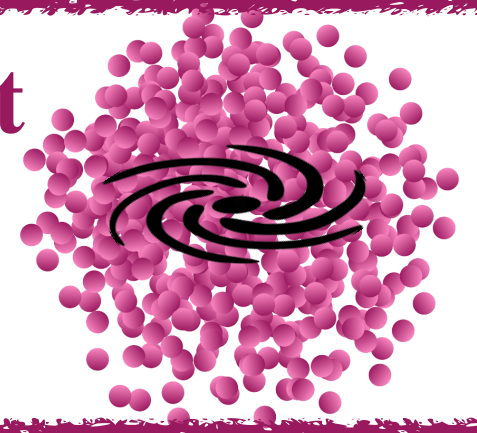
2)

Primordial
Black Holes
(PBHs)



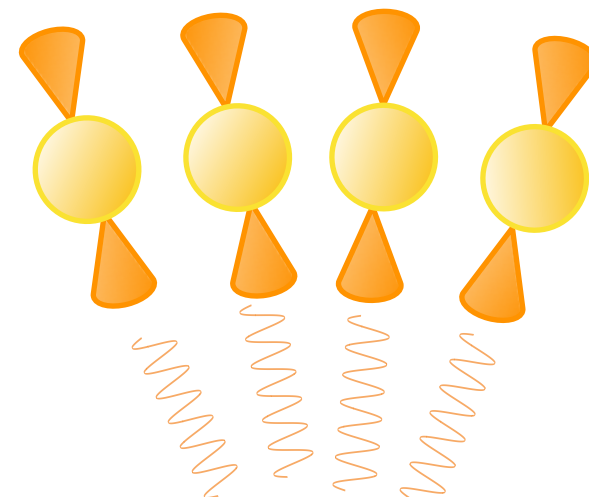
3)

DM Ultra Compact
Mini Halos
(UCMH)



4)

What is the PTA
signal ?



Plan of the talk

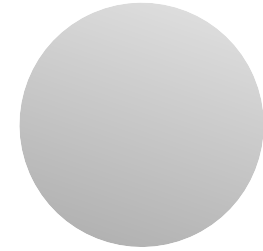
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Gravitational Waves (GWs)

$$h_{ij}(\vec{x}, t)$$

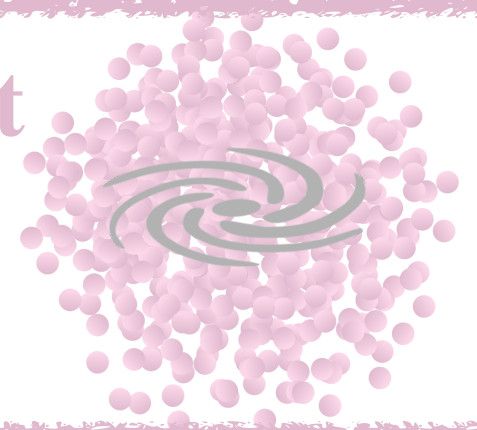
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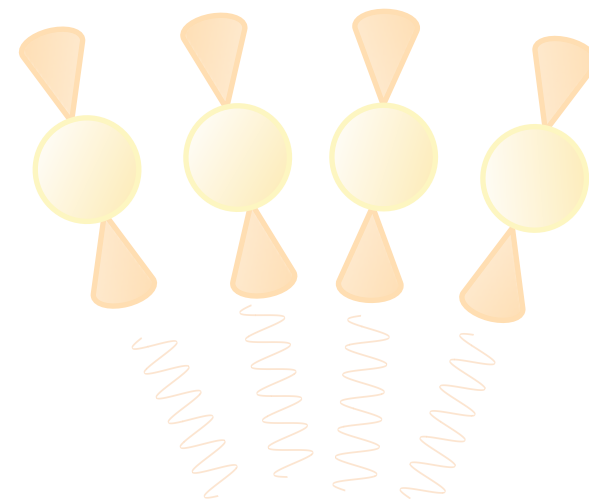
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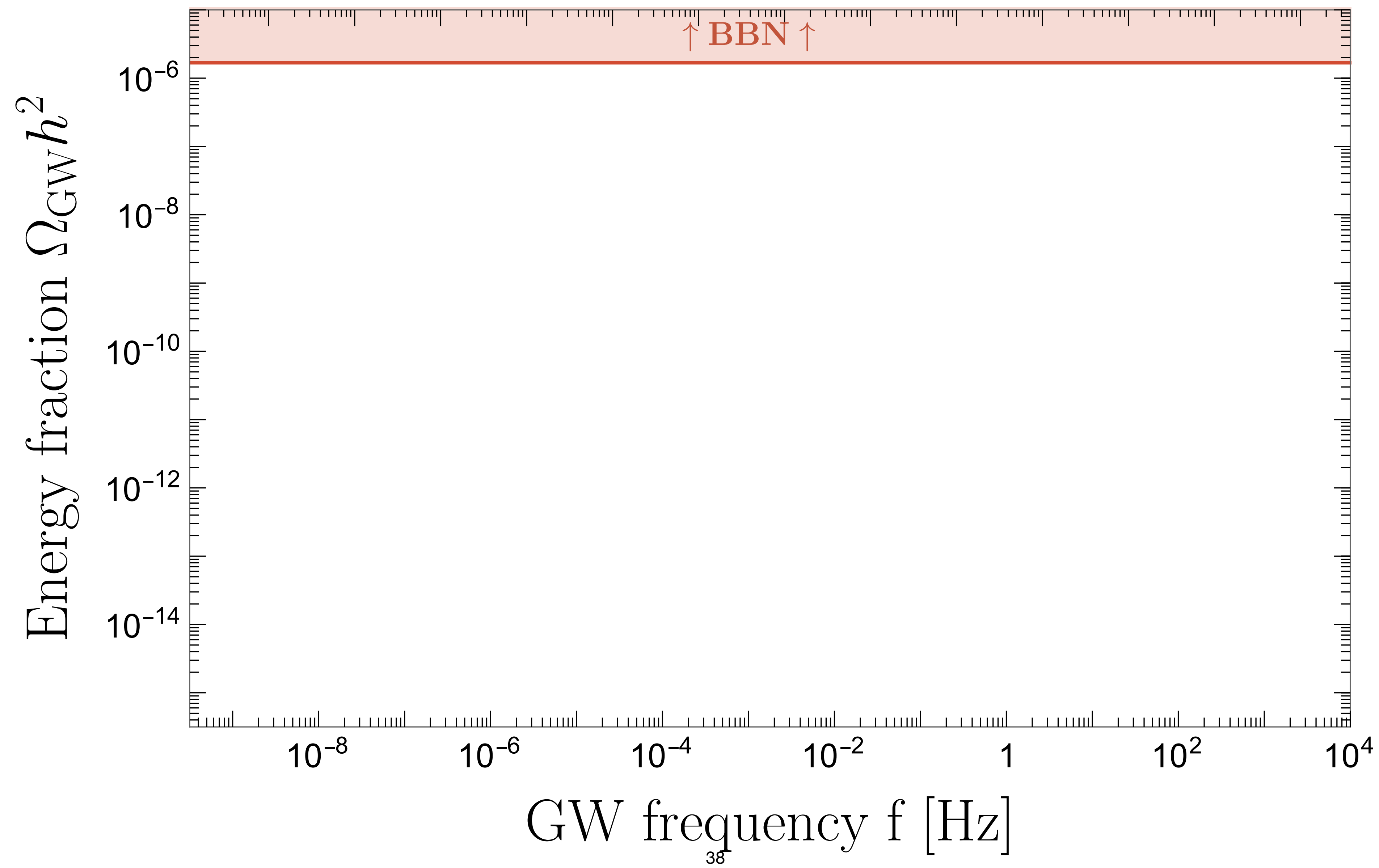
DM Ultra Compact
Mini Halos
(UCMH)

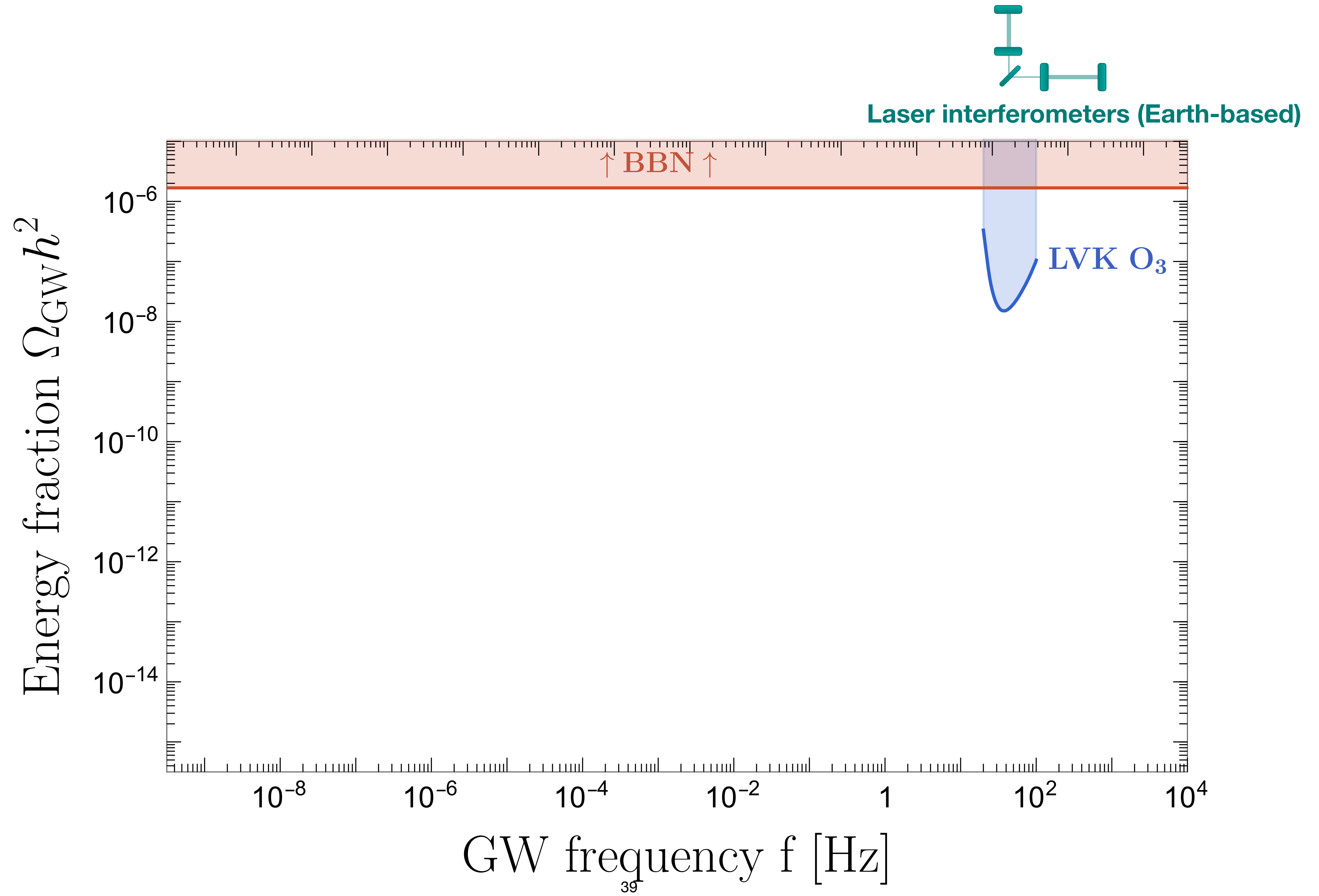


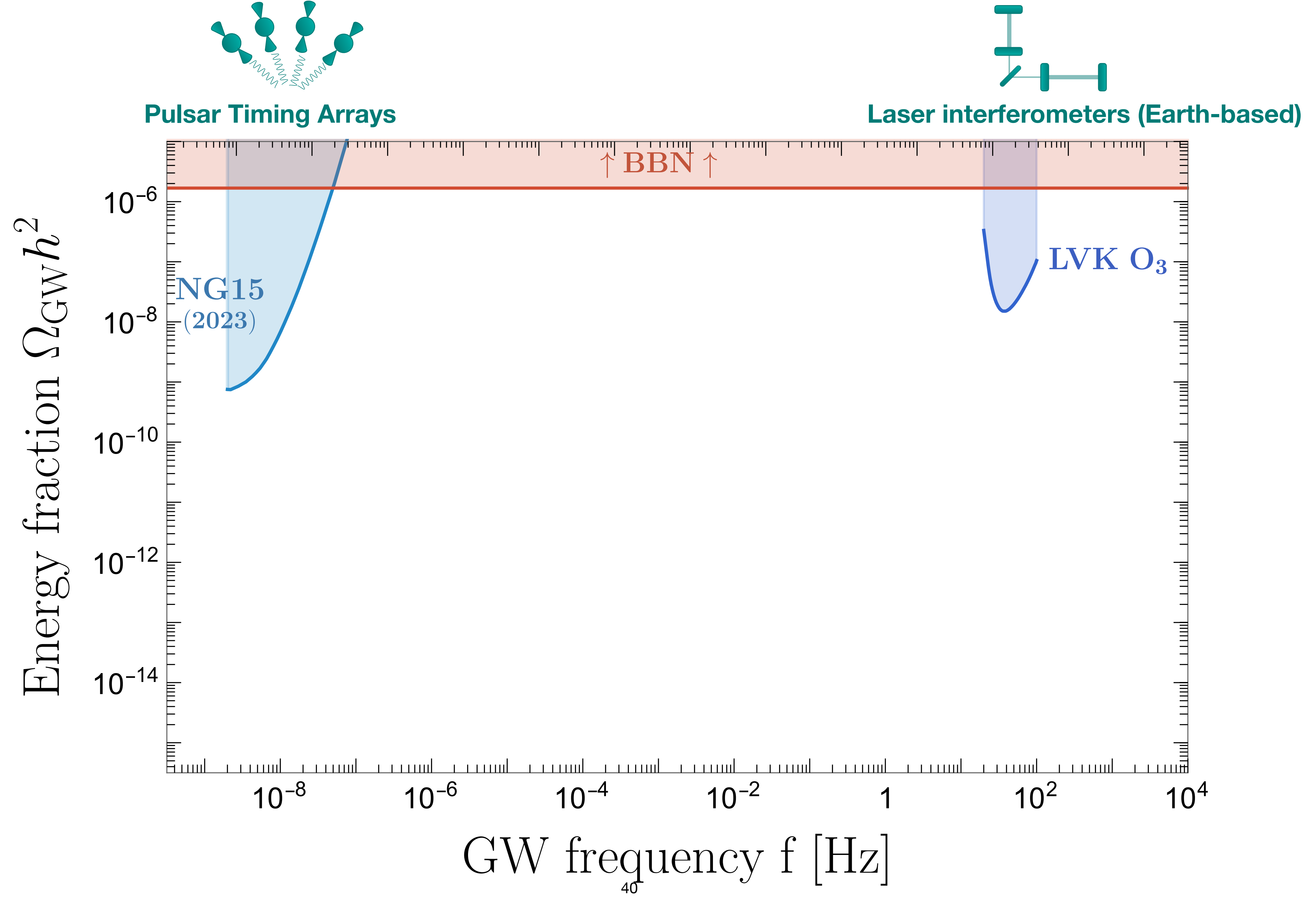
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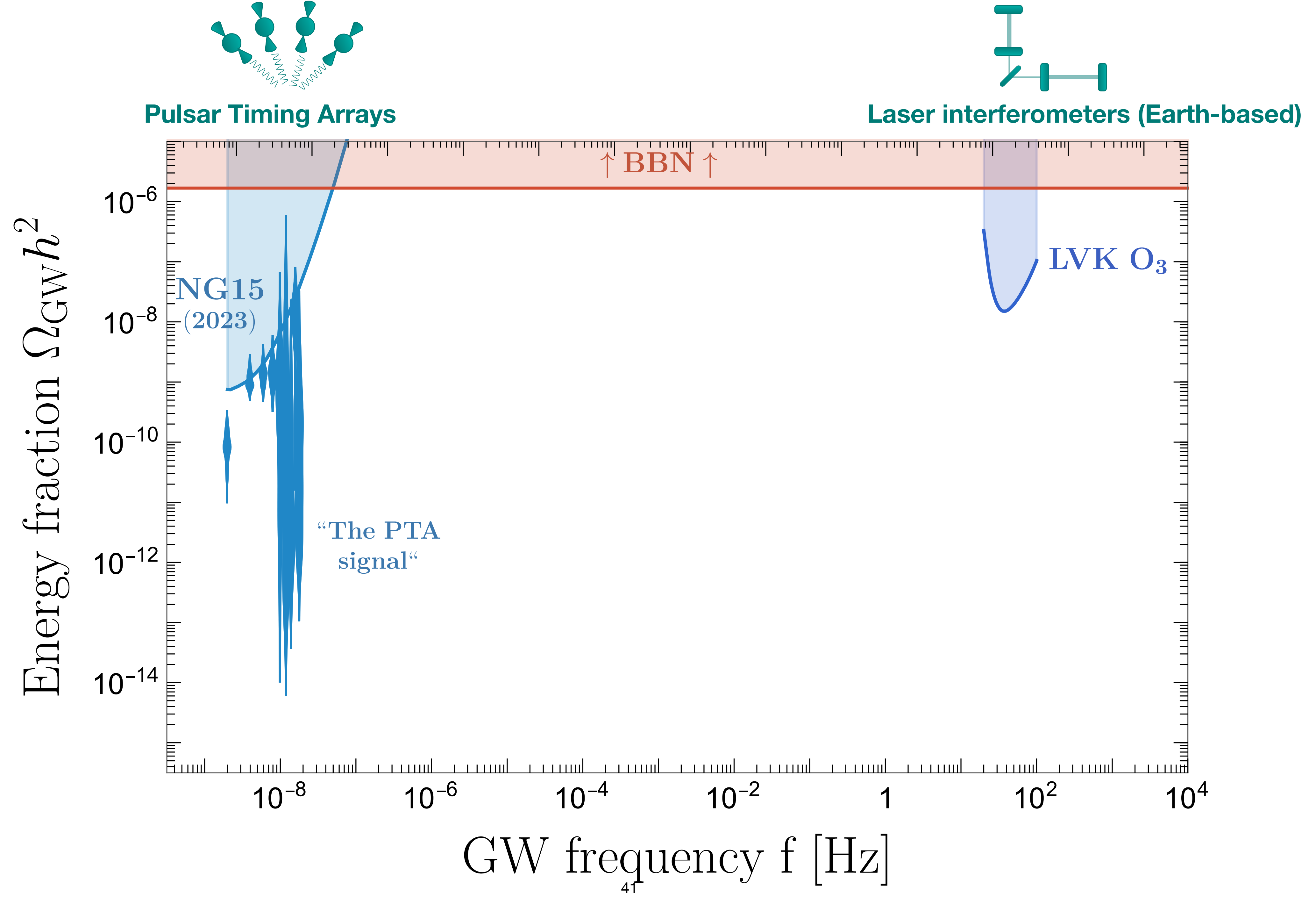
What is the PTA
signal ?

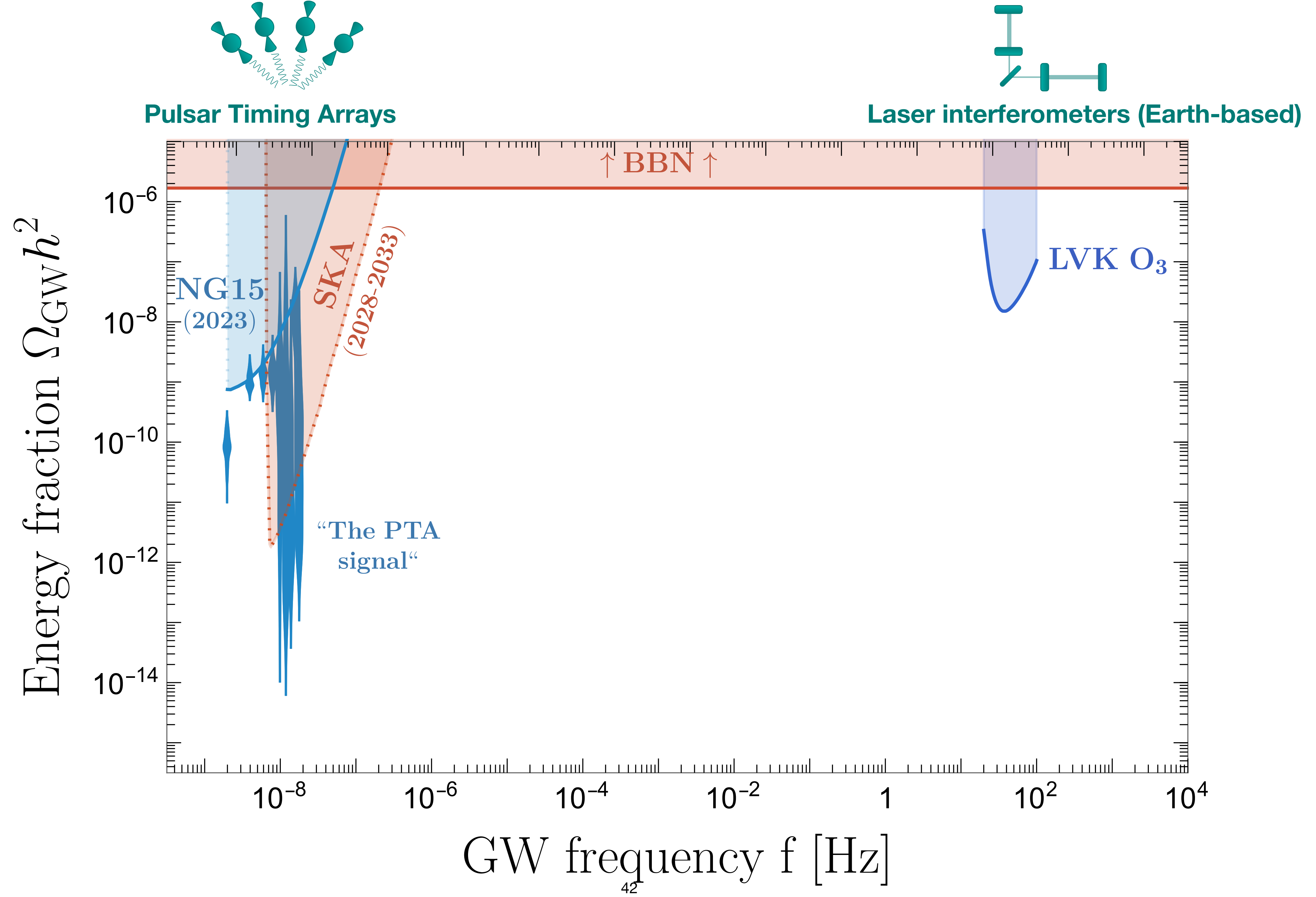


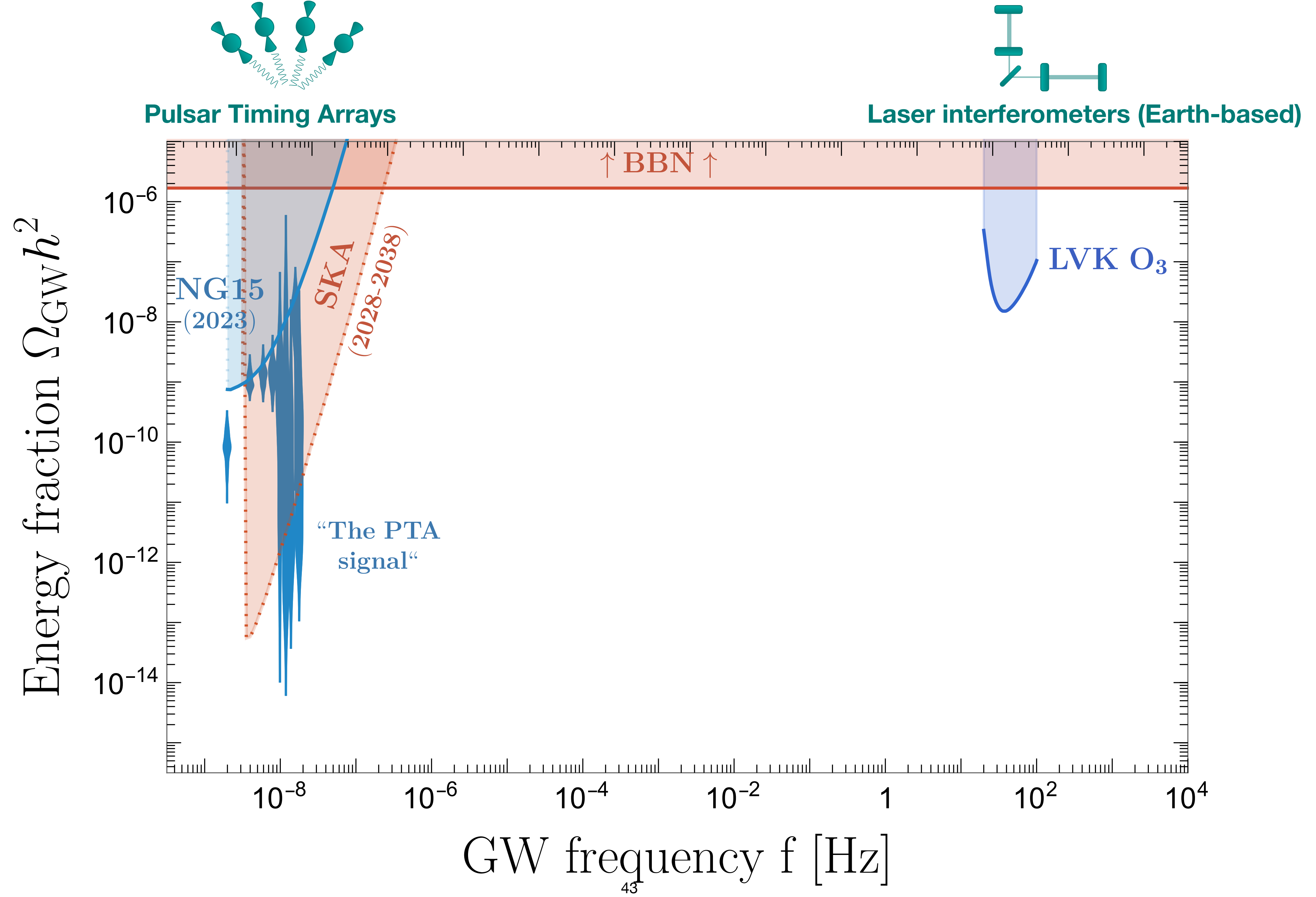


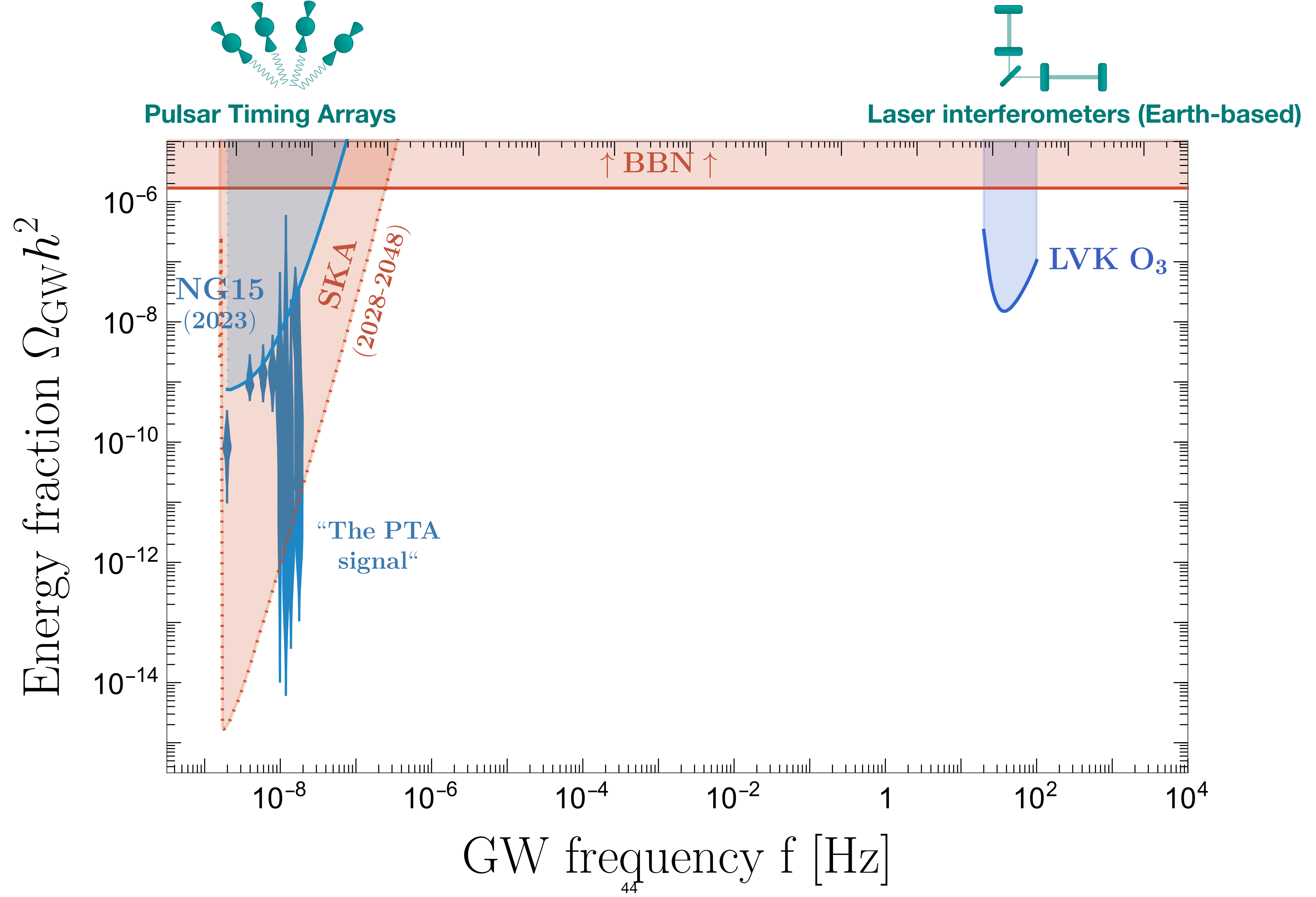


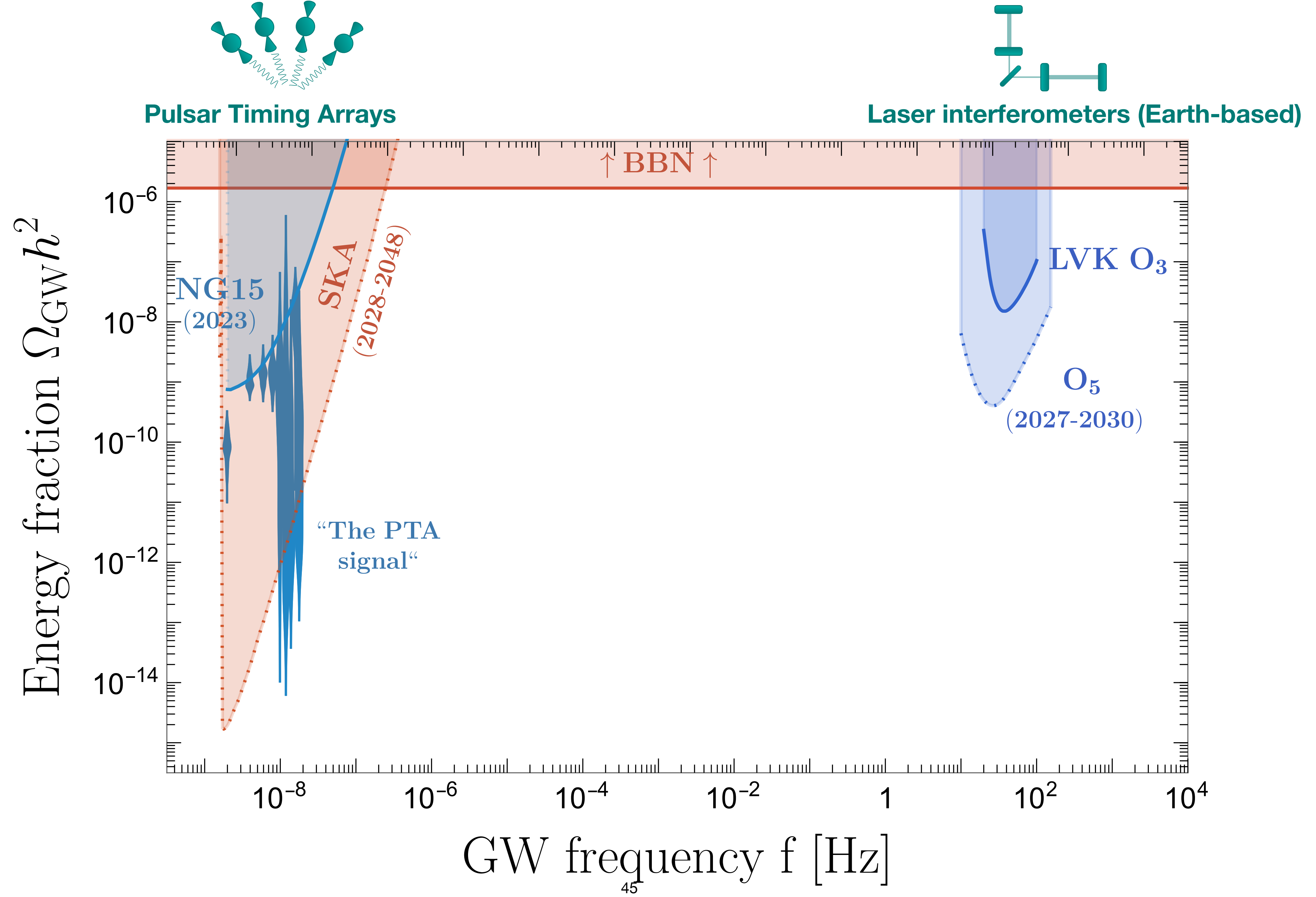


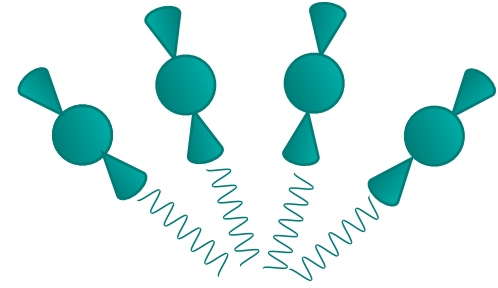




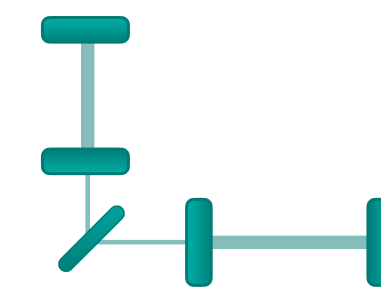




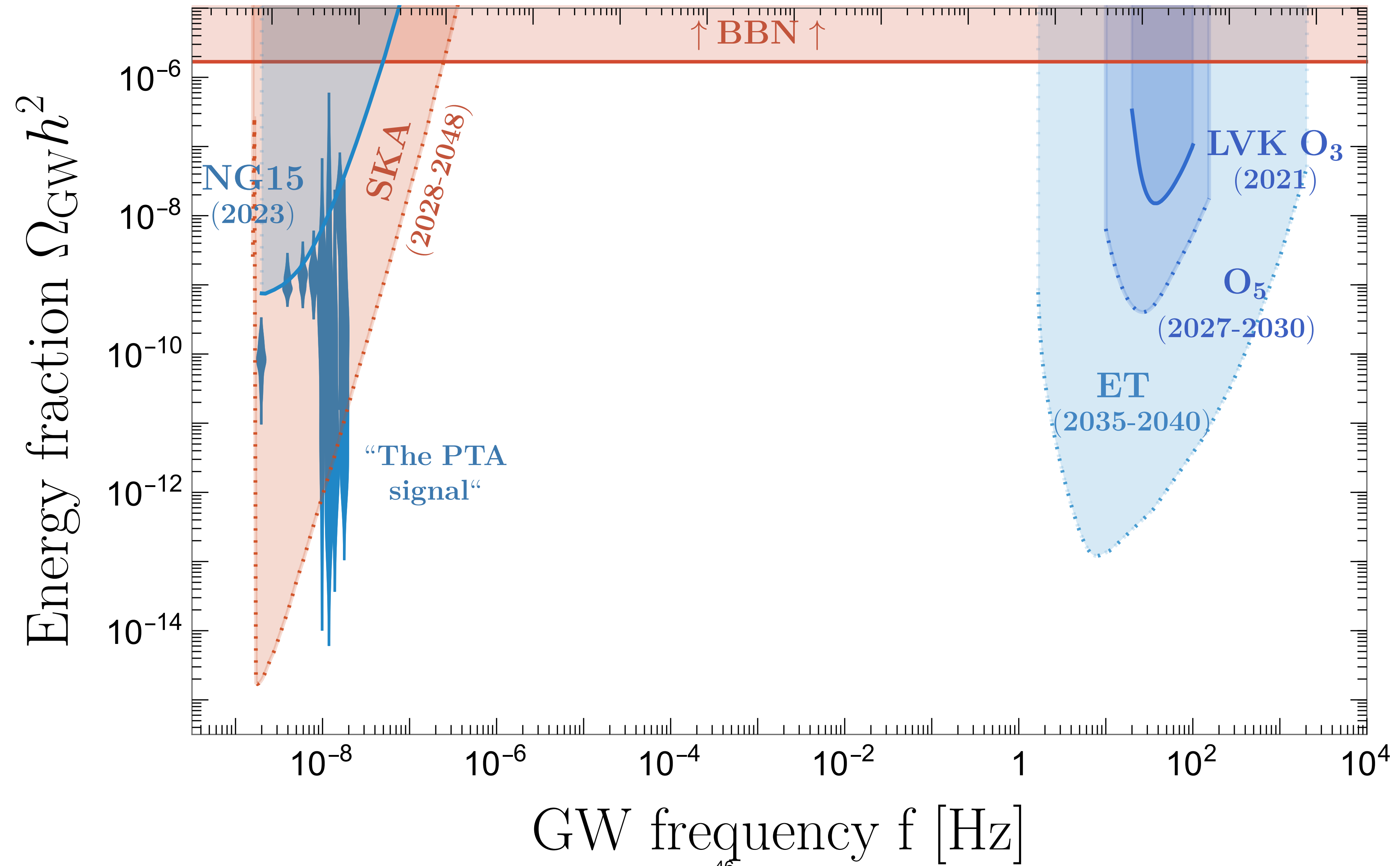


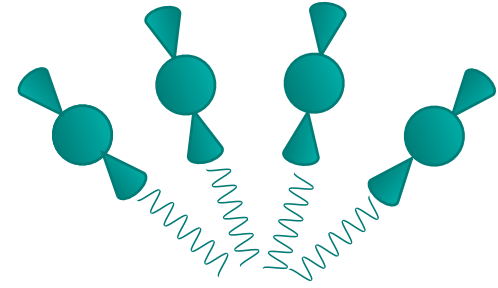


Pulsar Timing Arrays

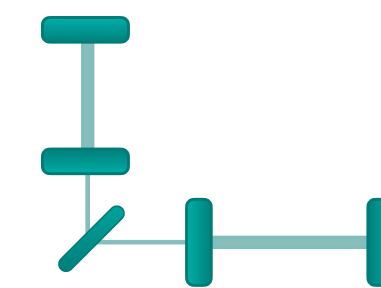


Laser interferometers (Earth-based)

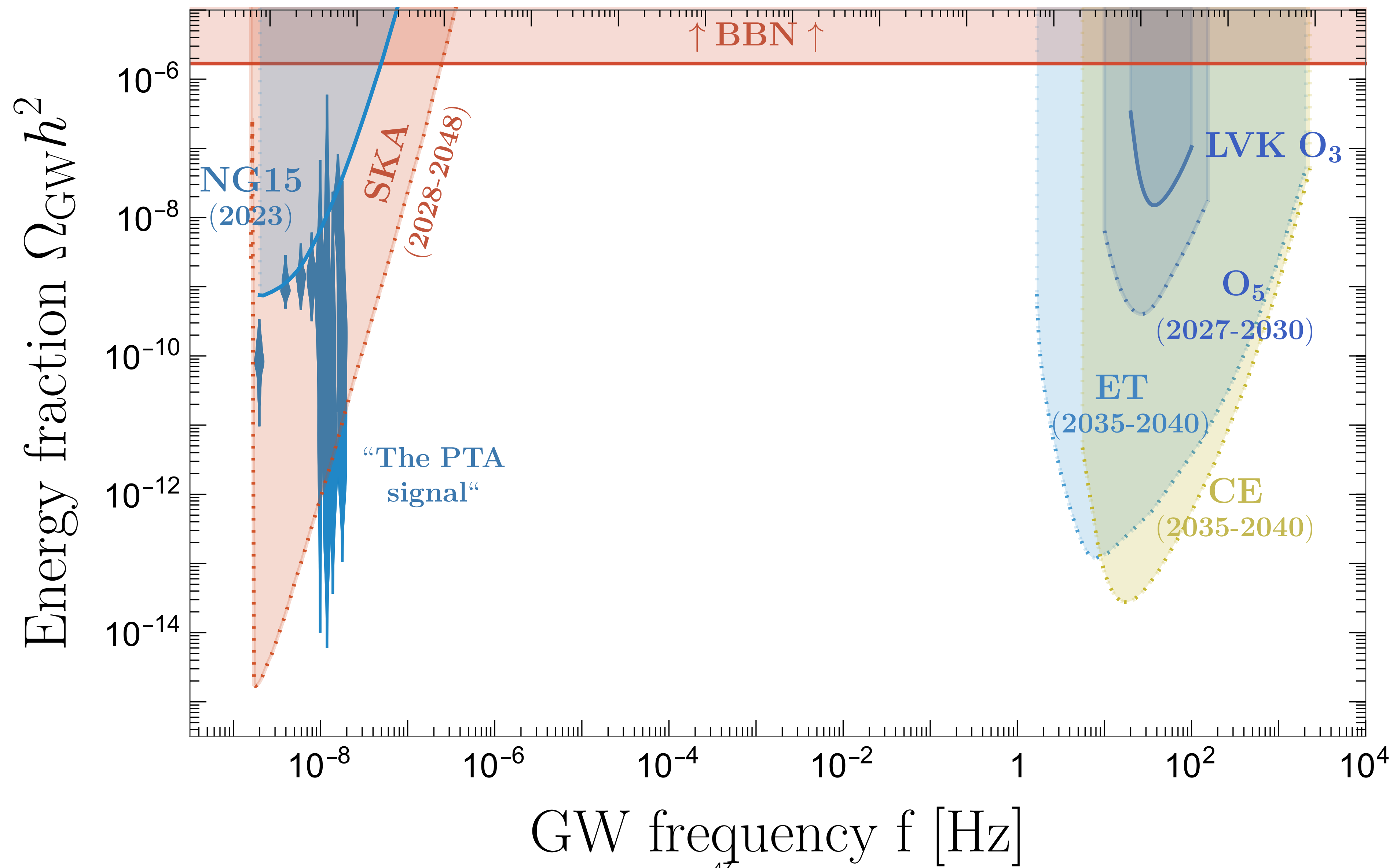


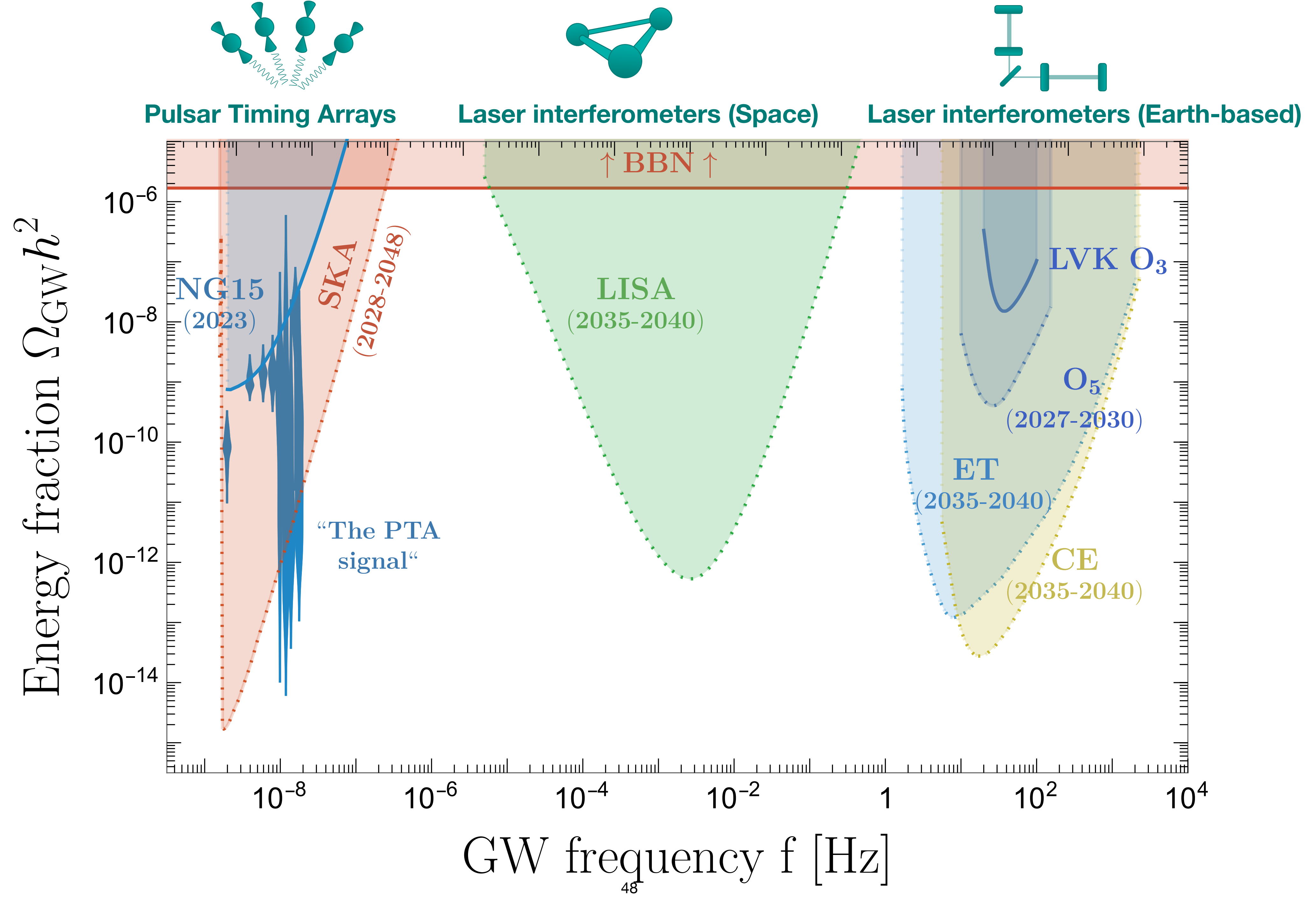


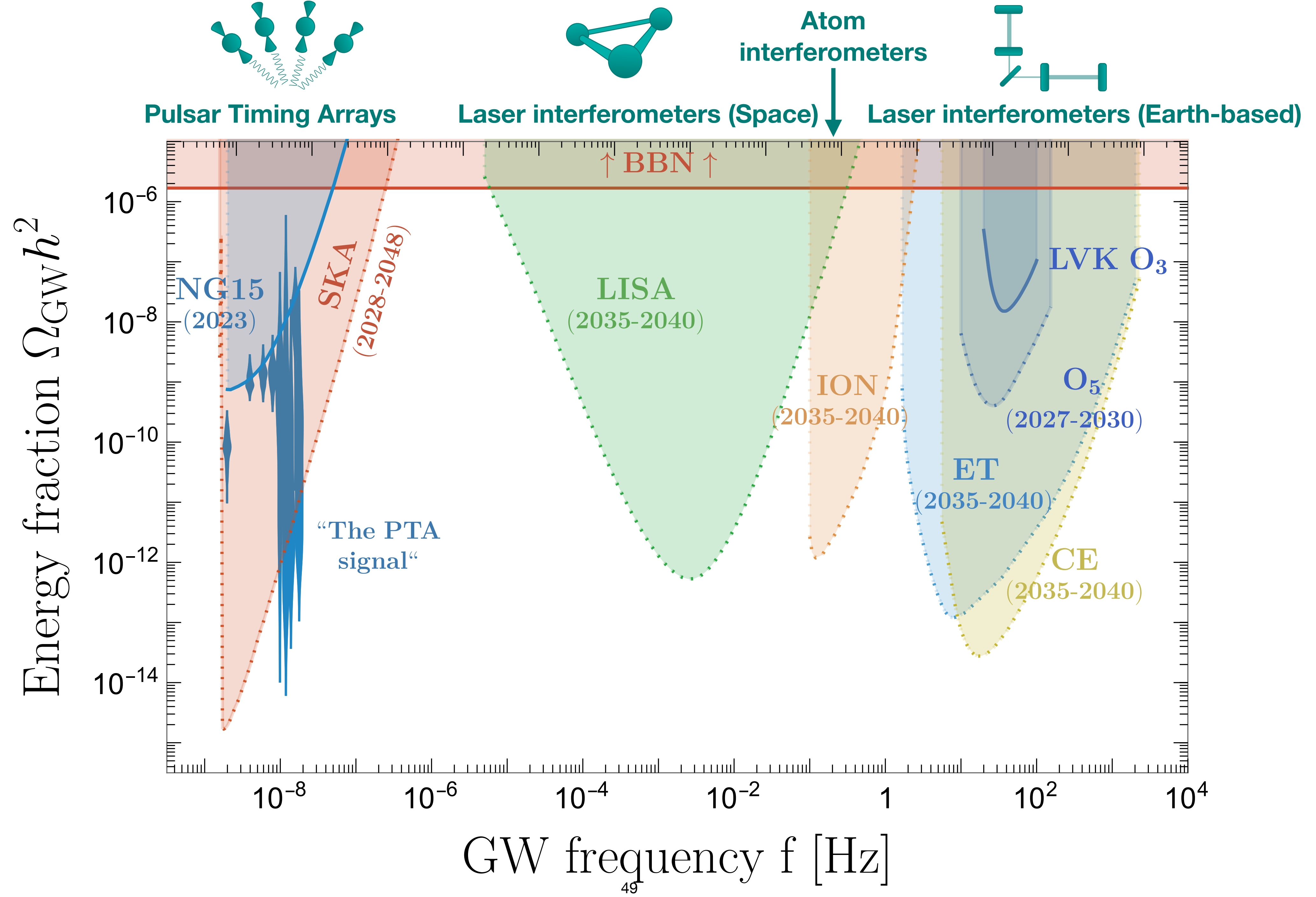
Pulsar Timing Arrays

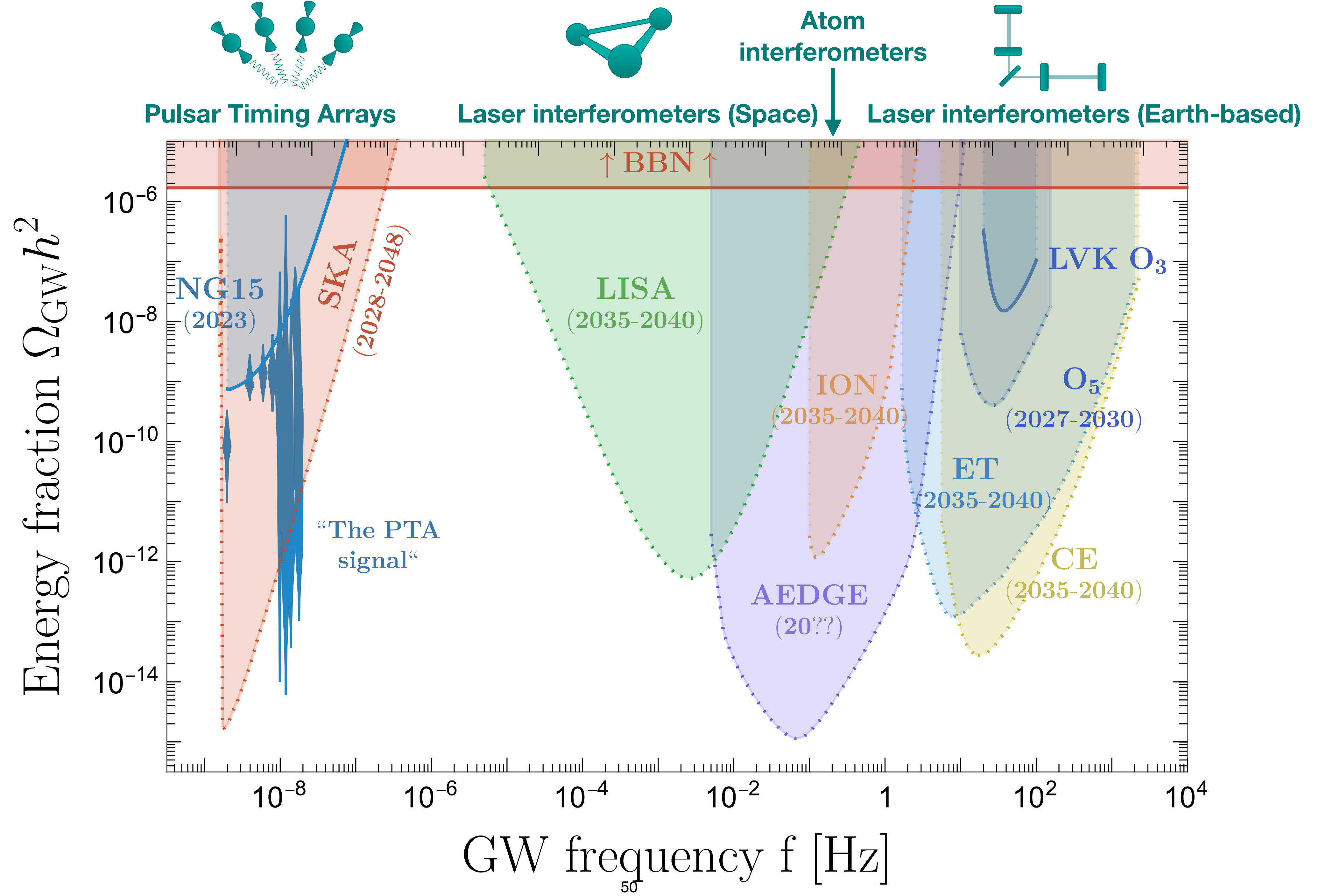


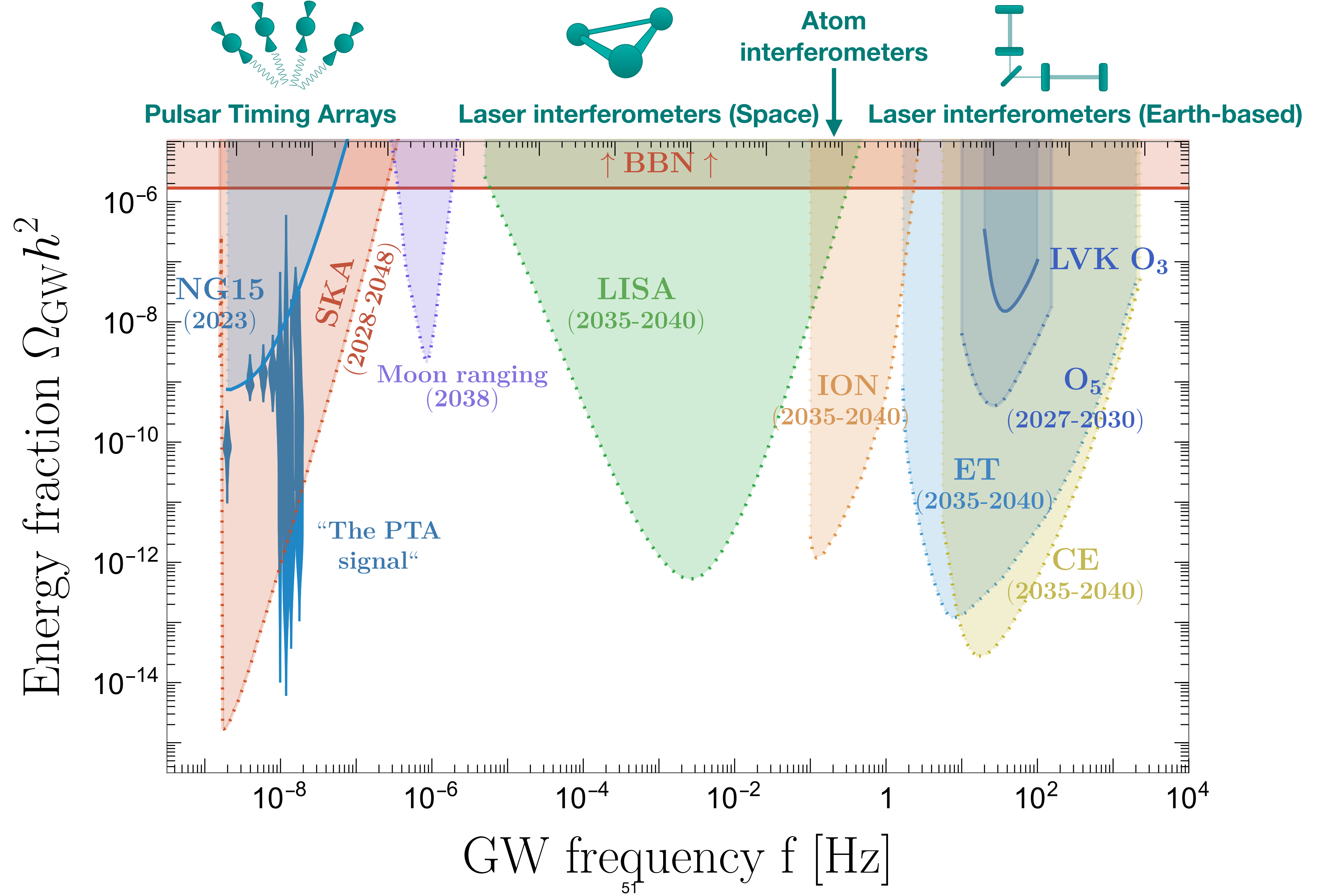
Laser interferometers (Earth-based)

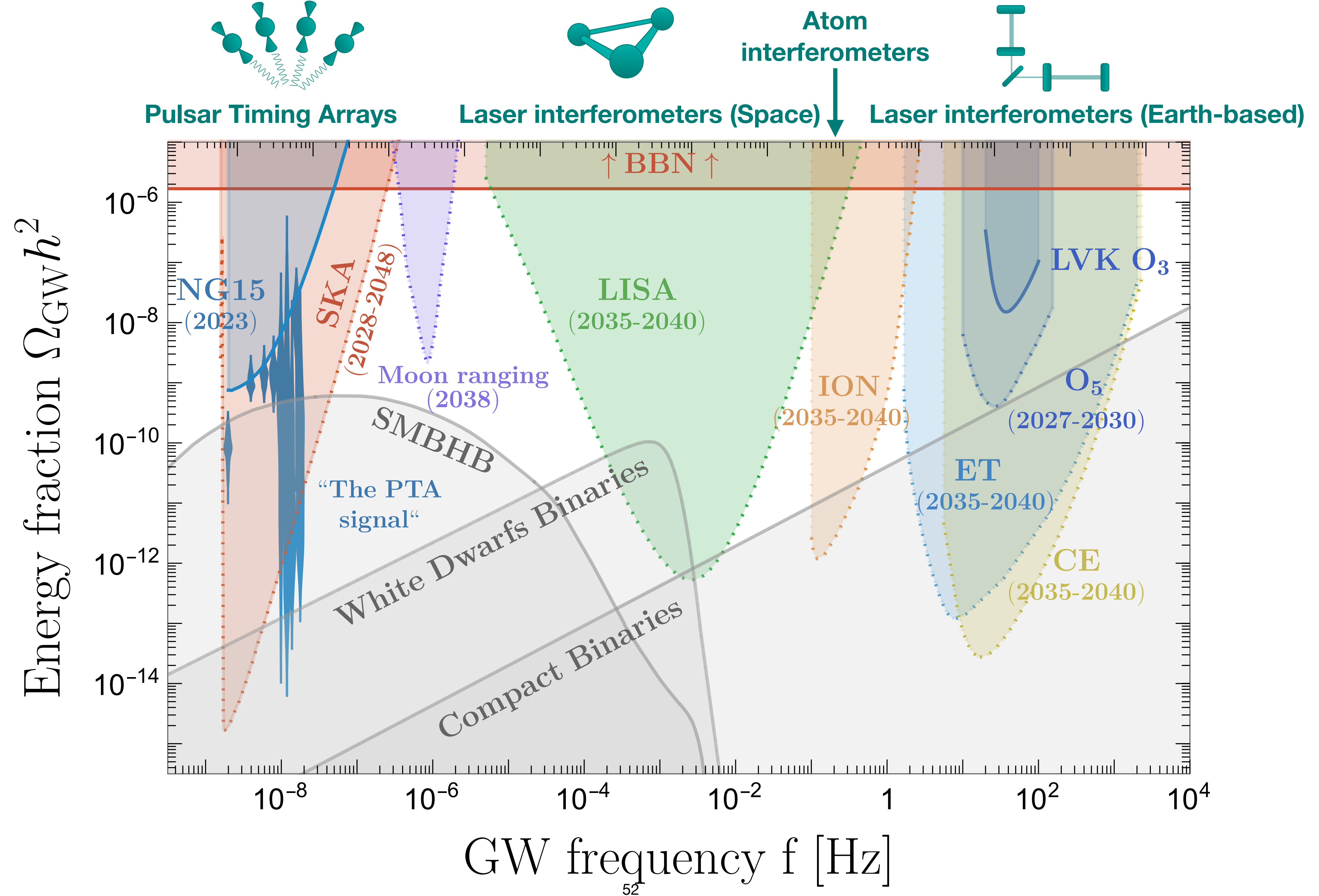




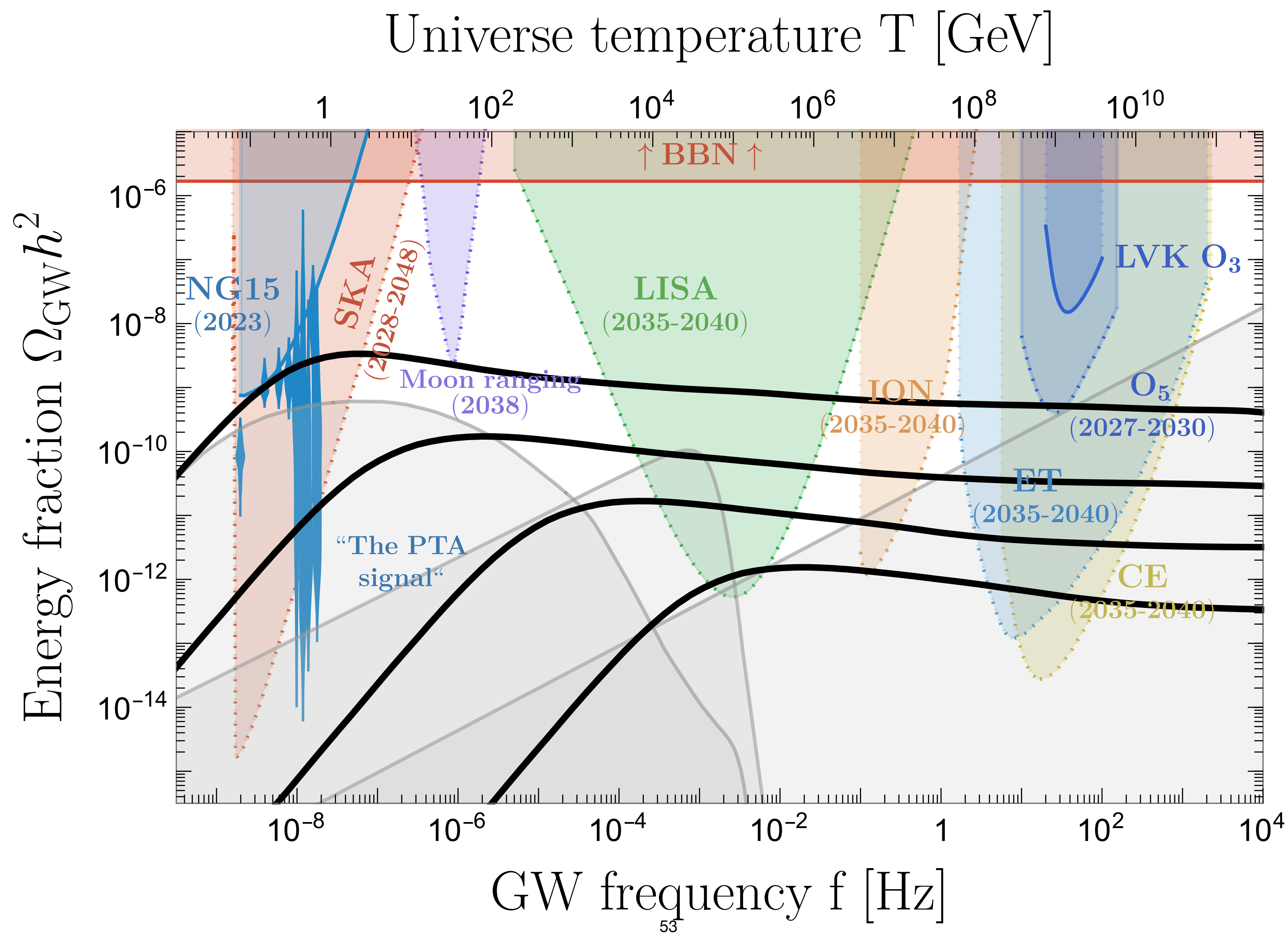
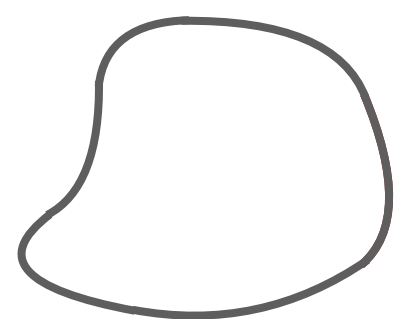




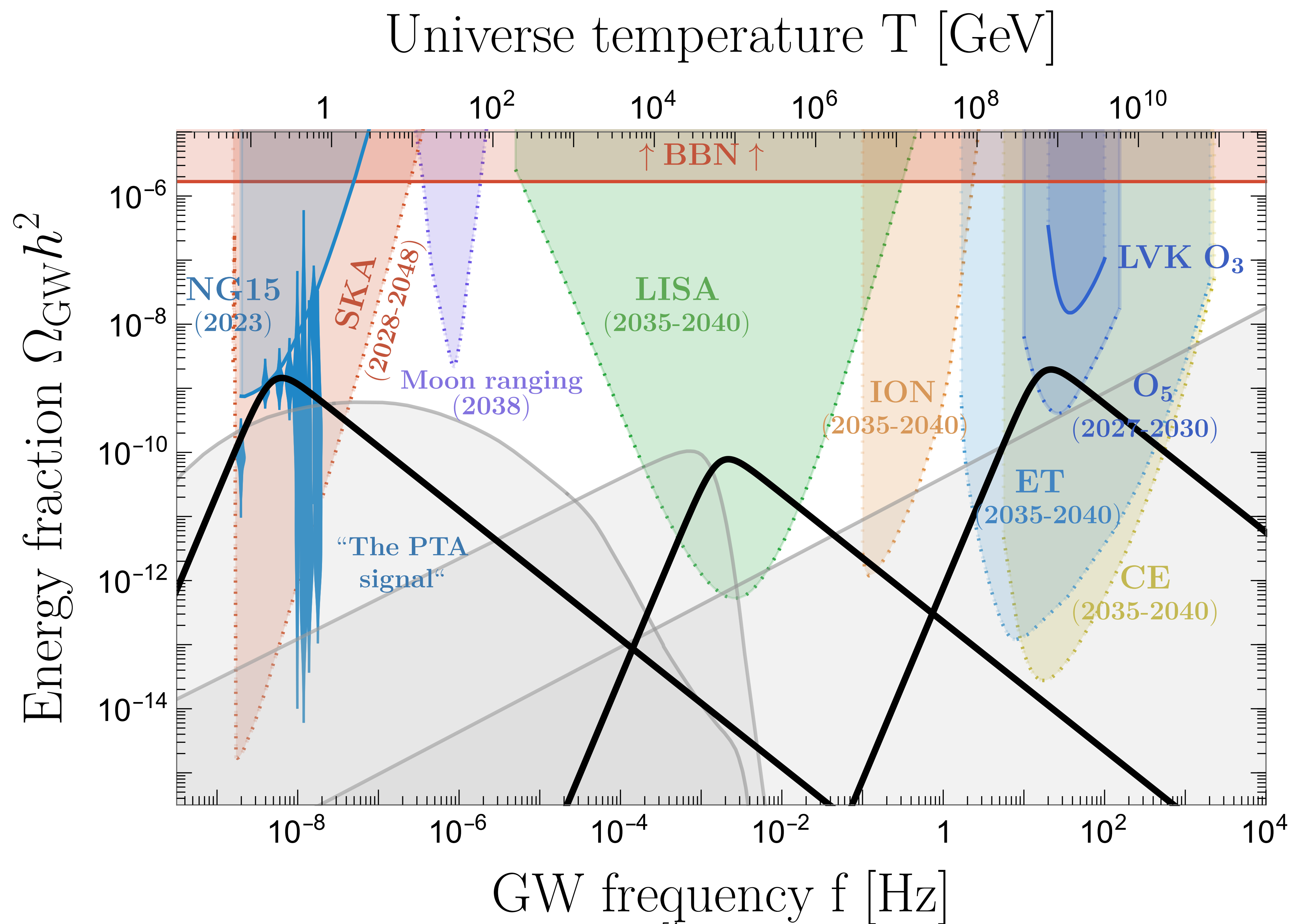
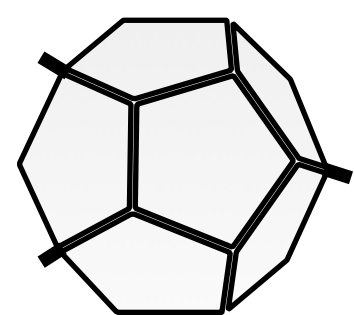




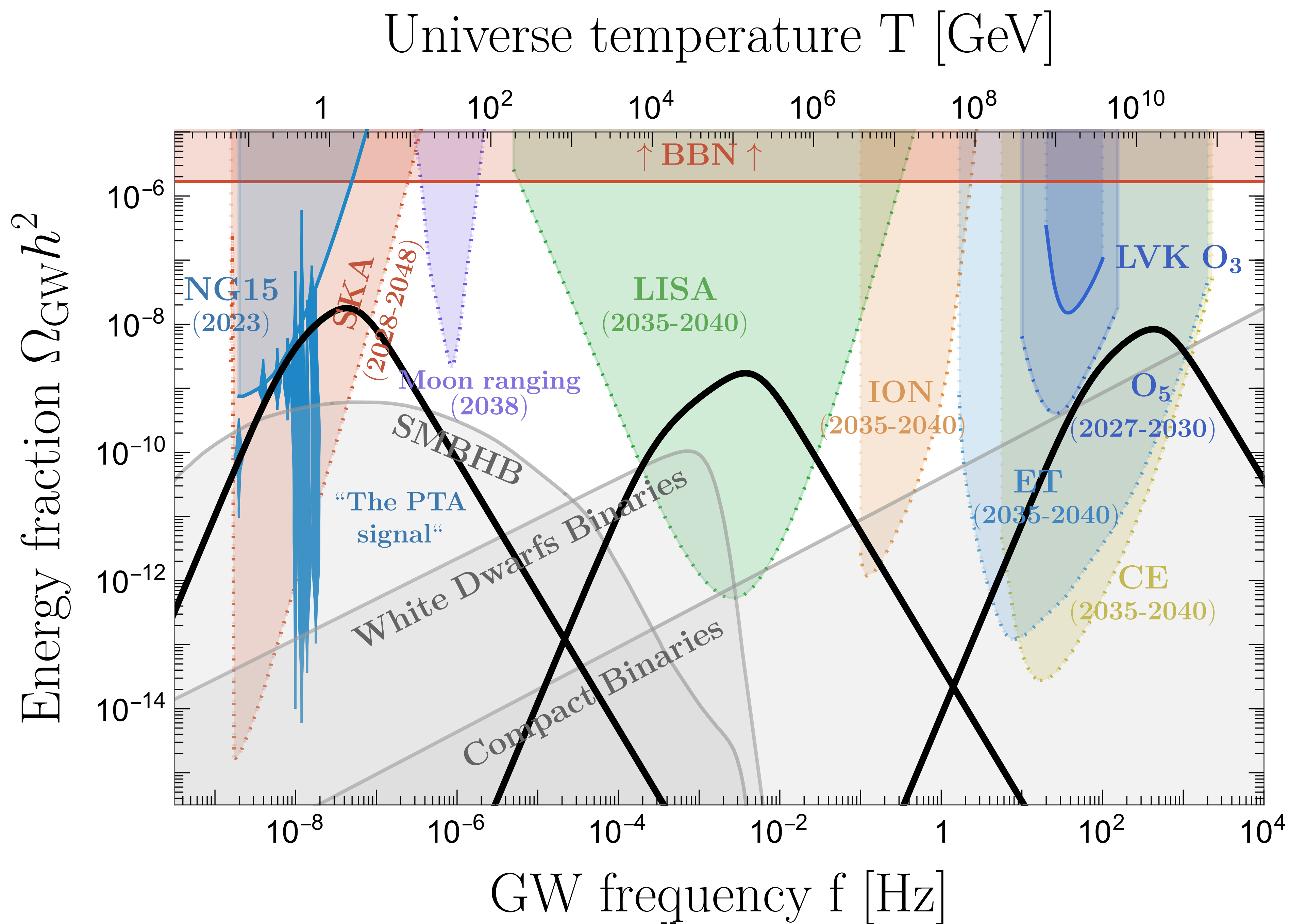
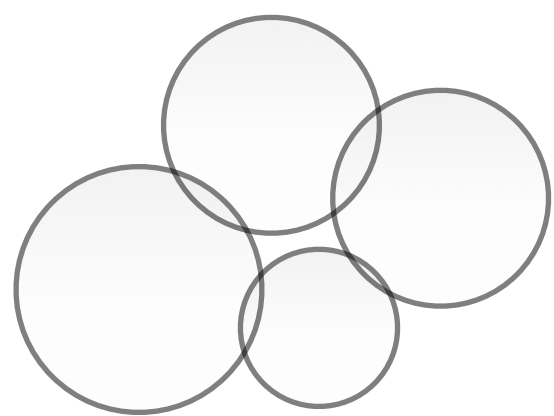
Cosmic strings

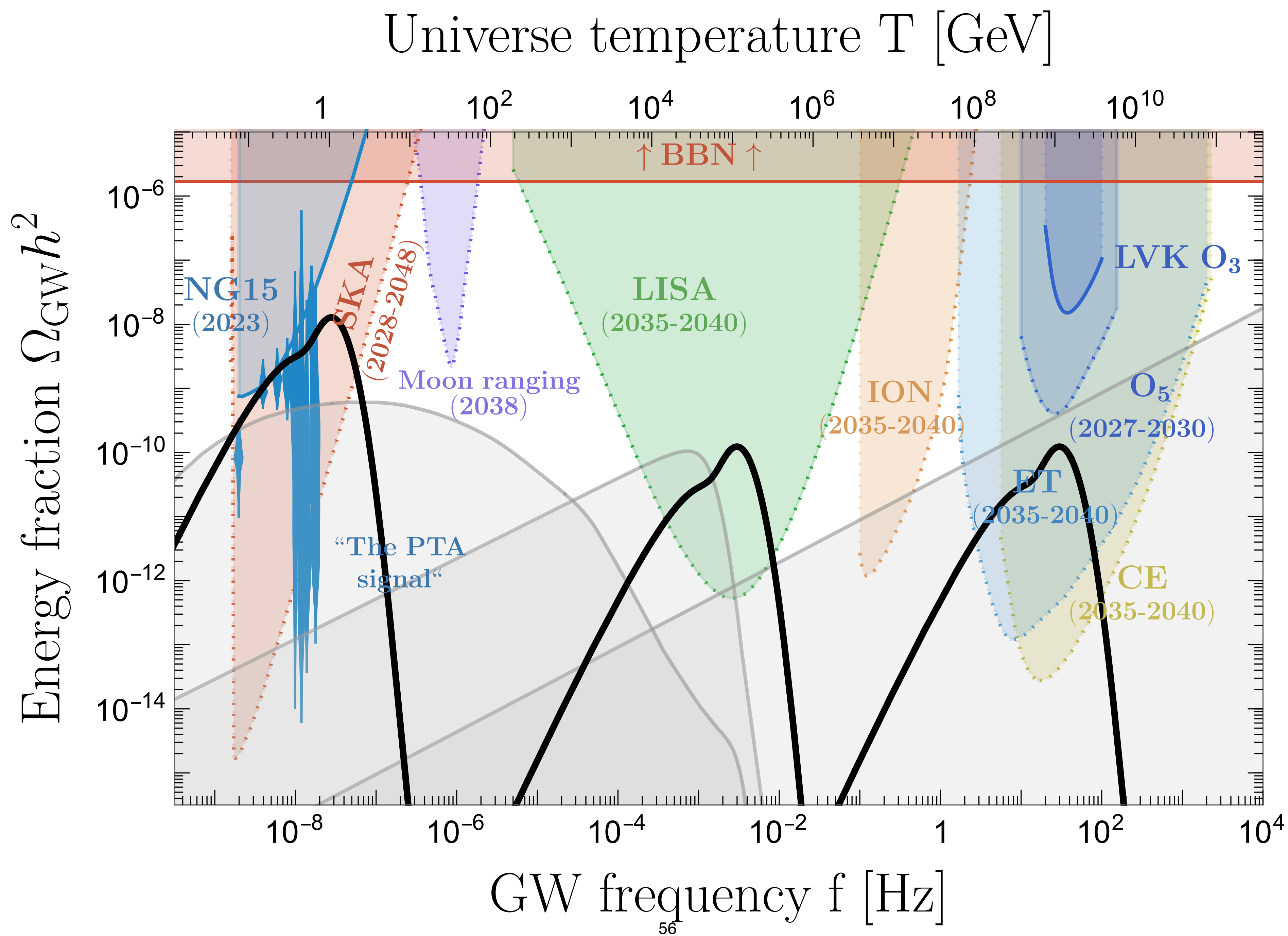


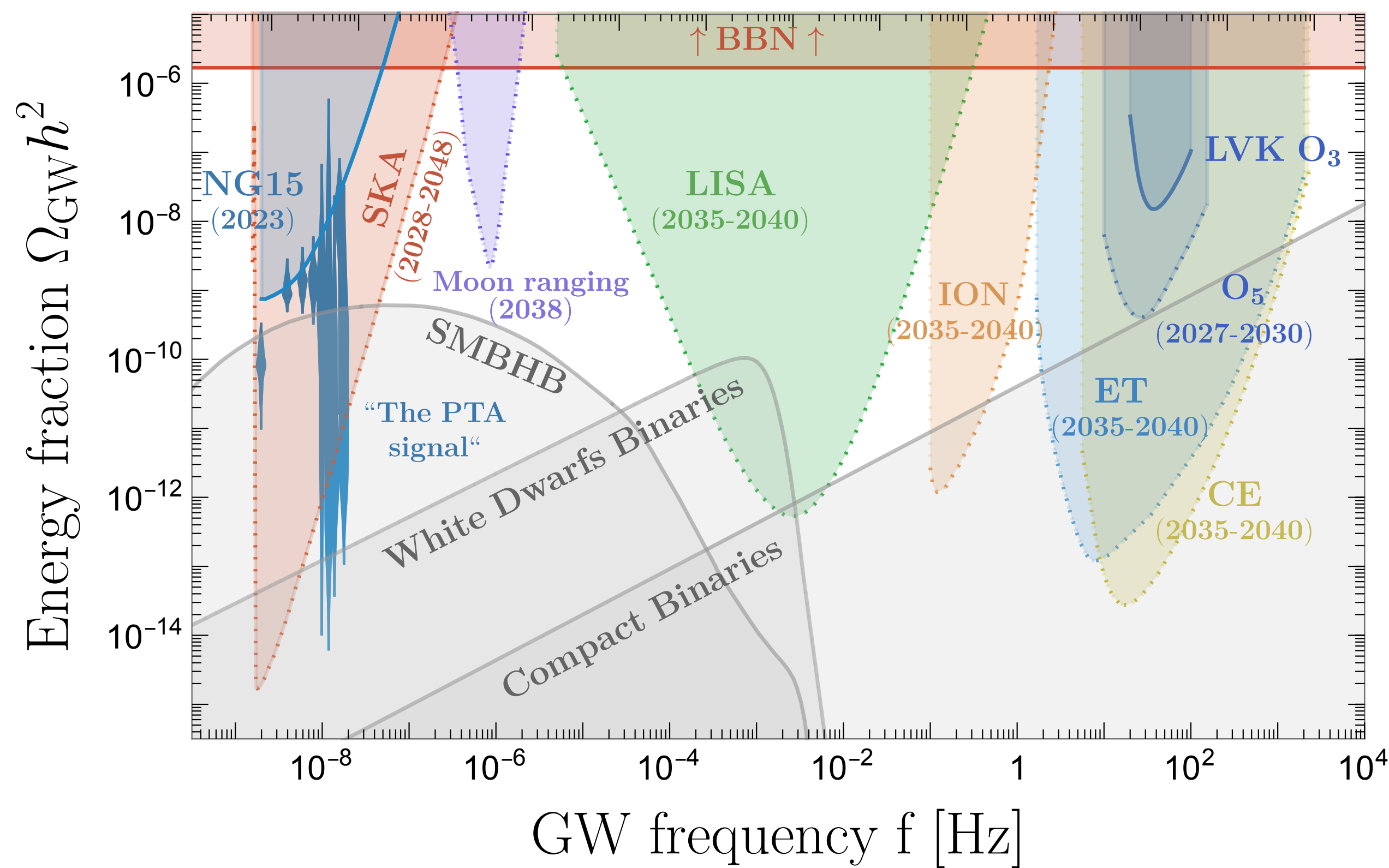
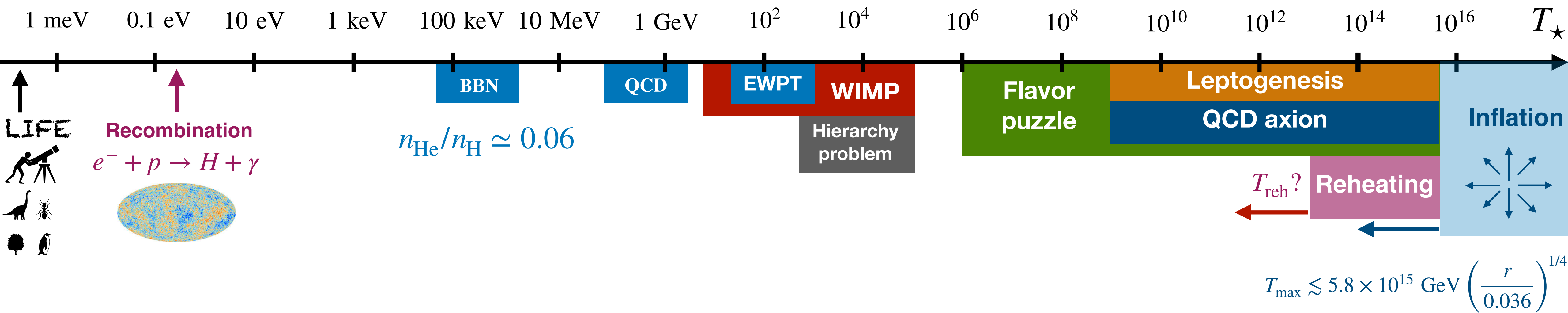
Domain walls

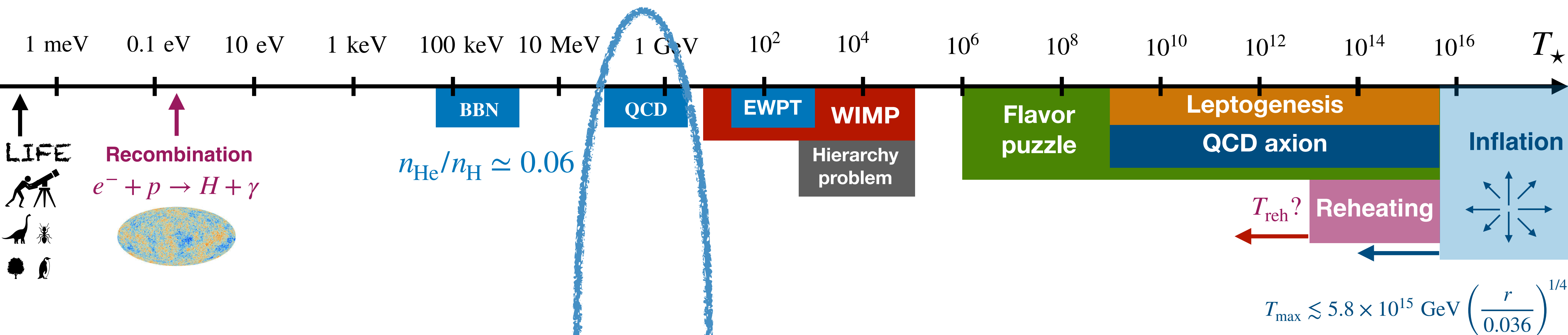


**First-order
phase transition**

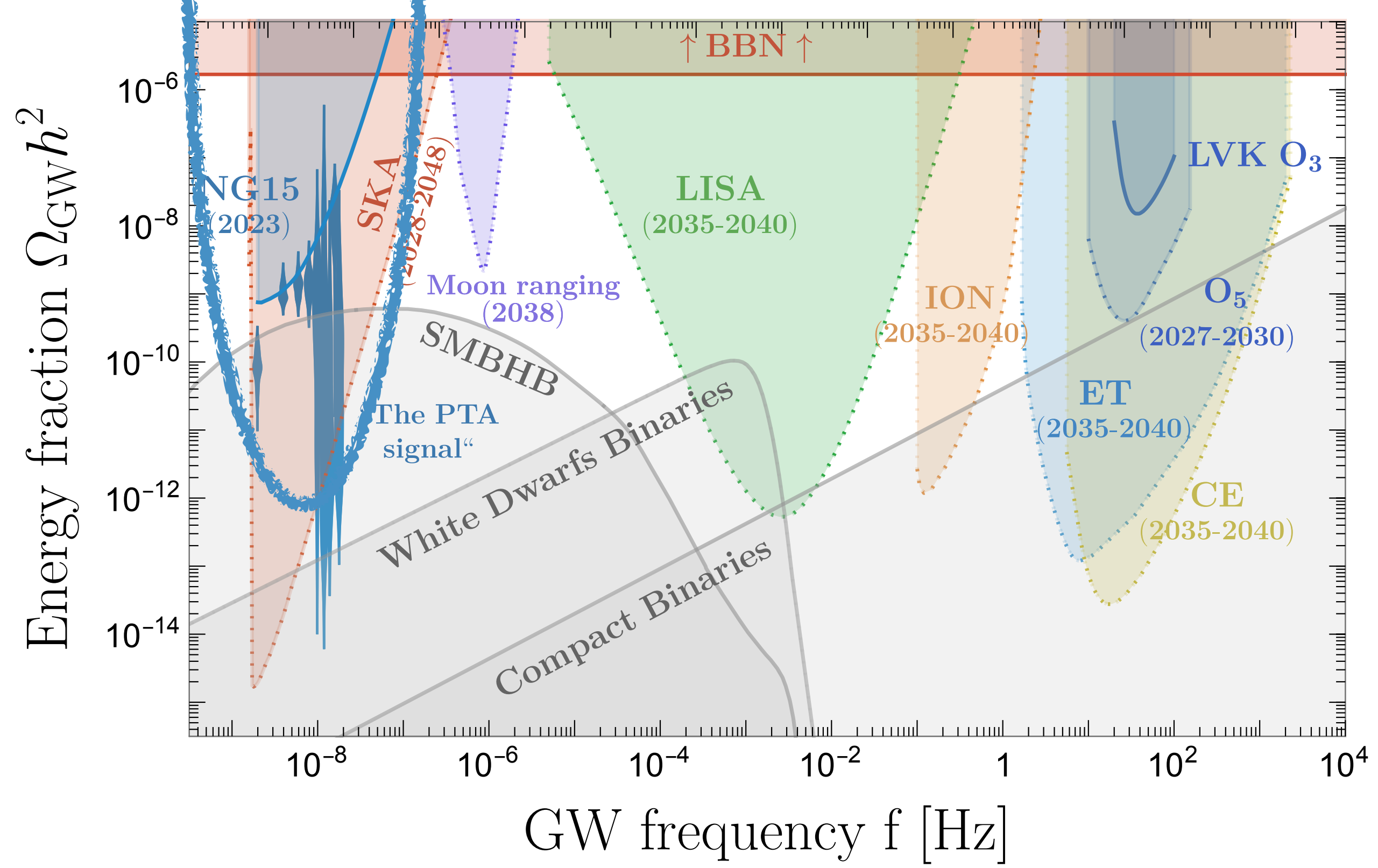


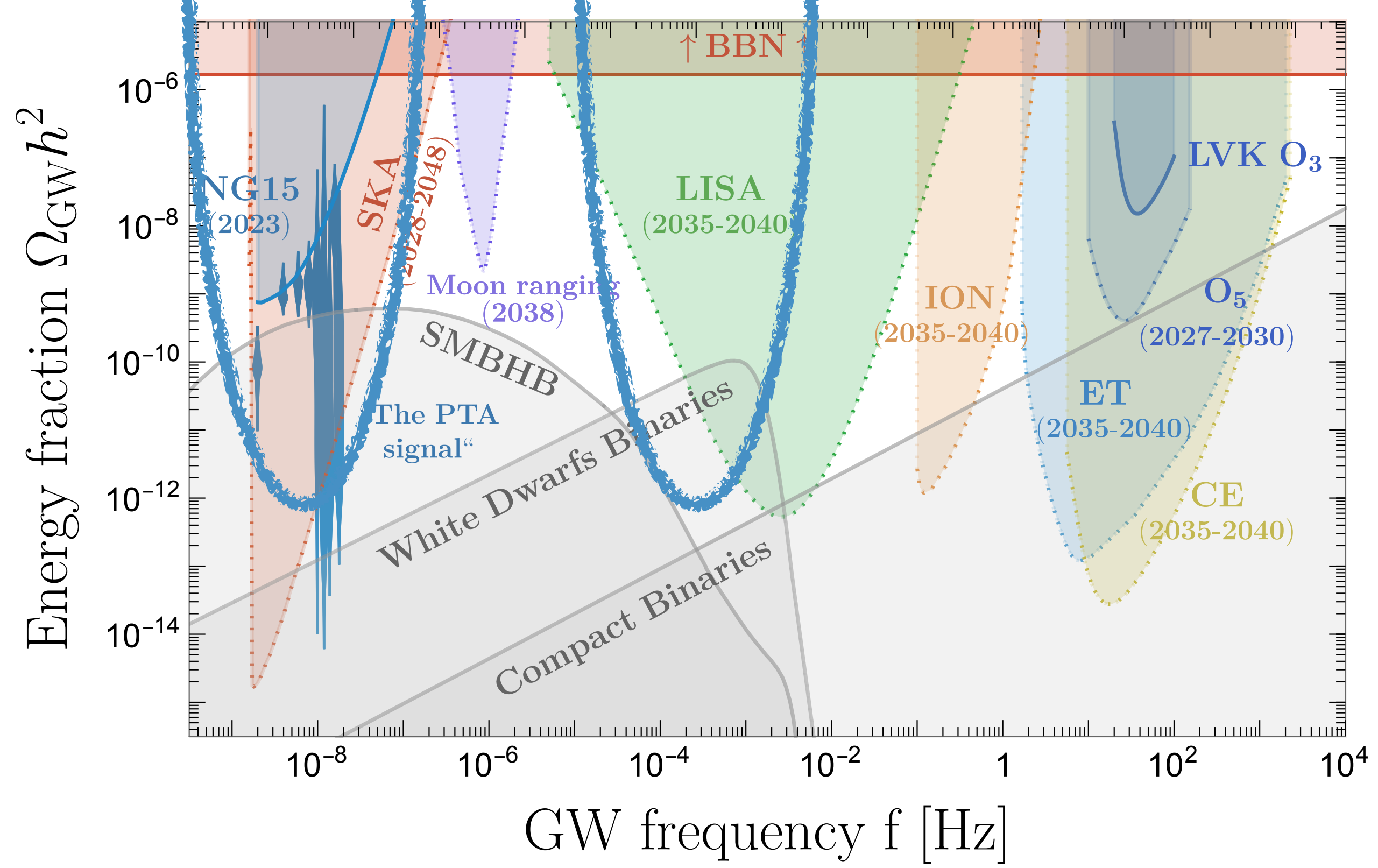
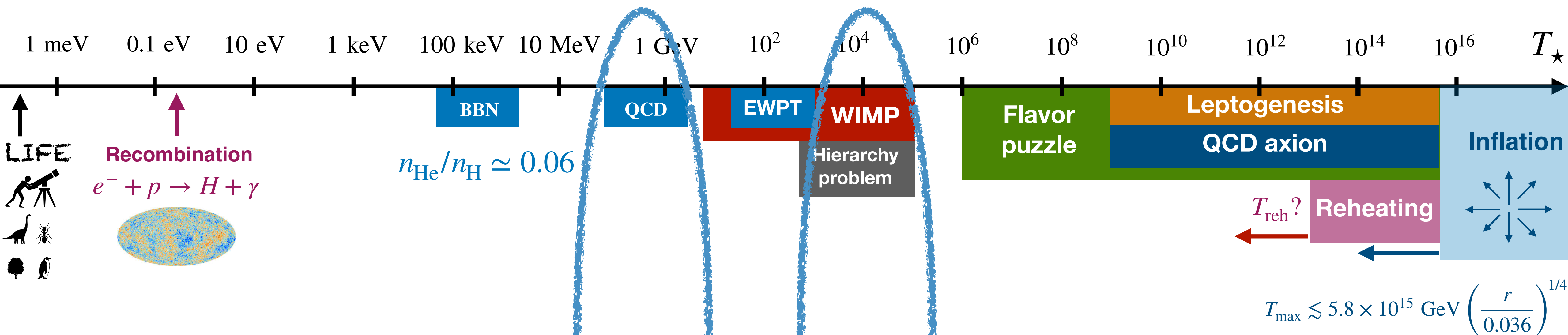
GW frequency f [Hz]

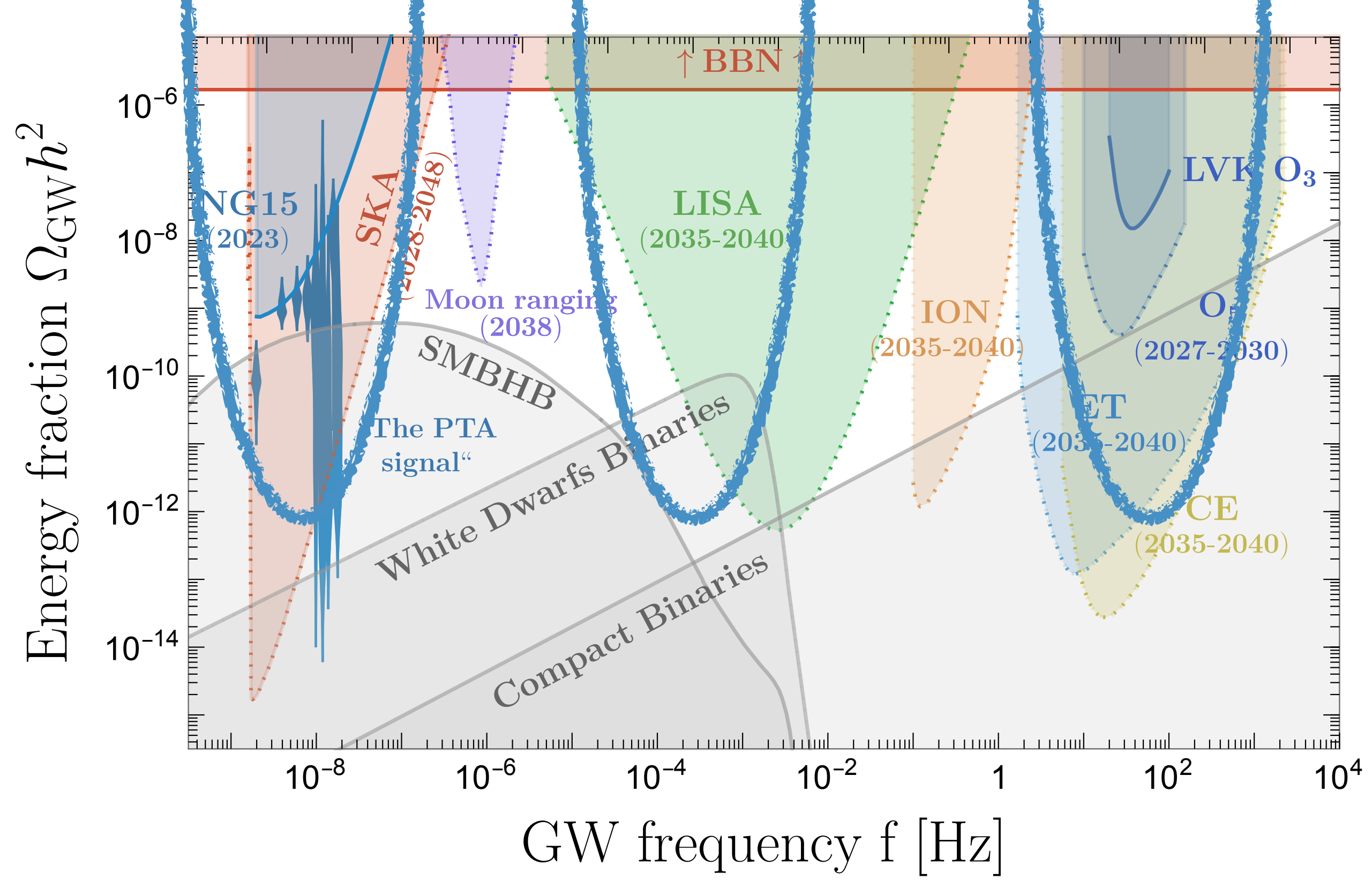
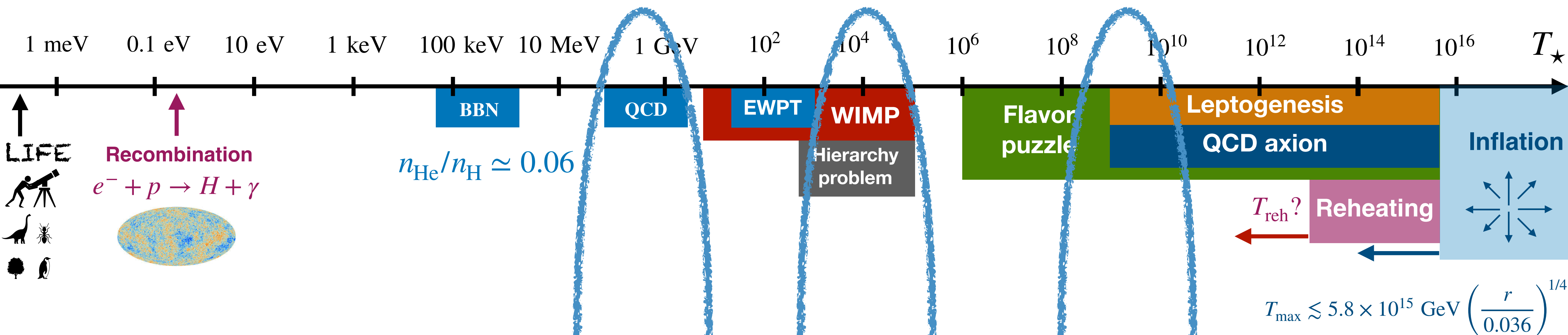




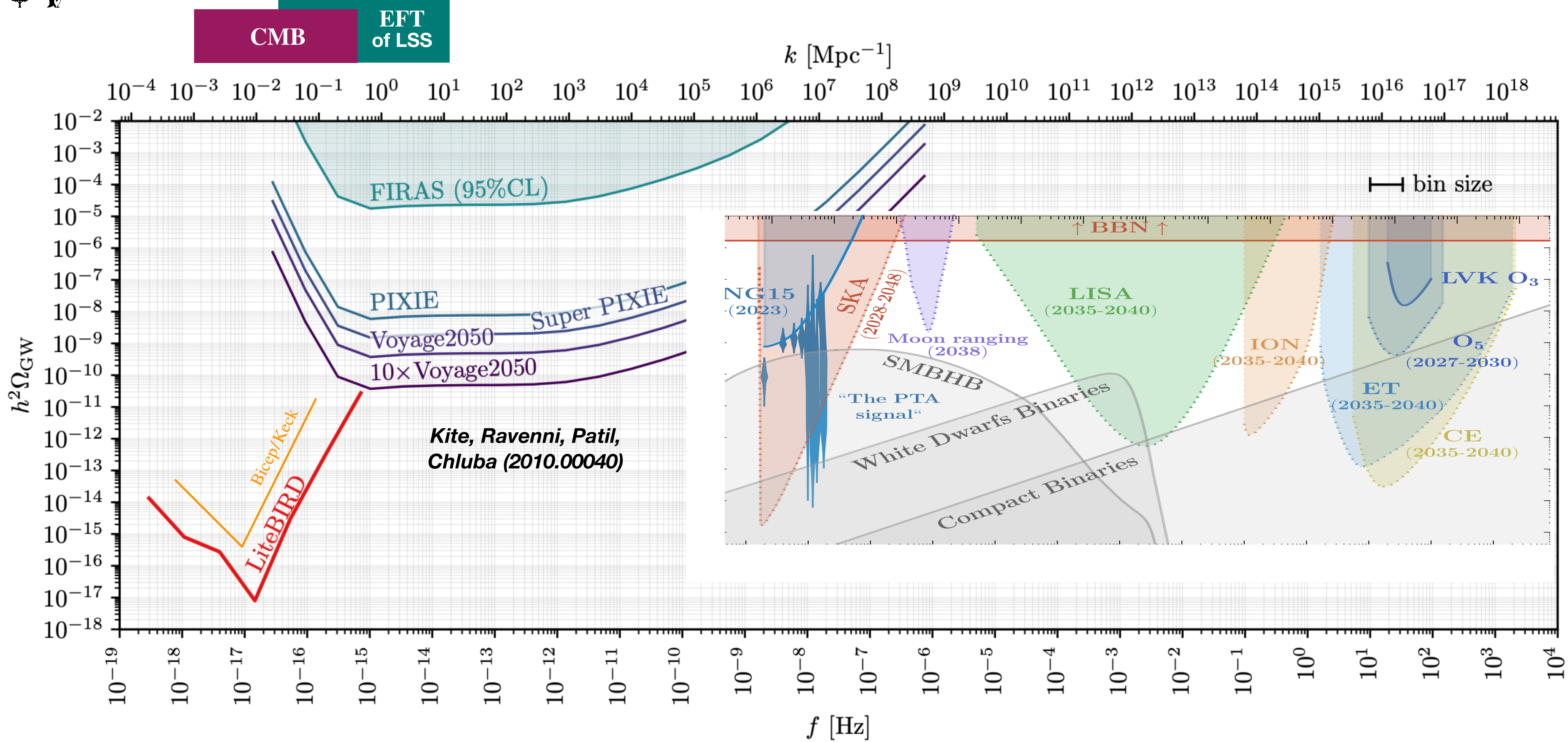
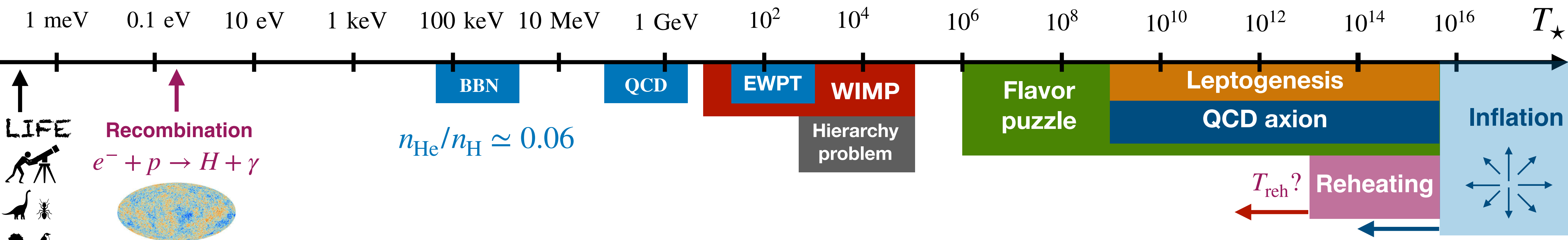
Bicep/Keck (2110.00483)





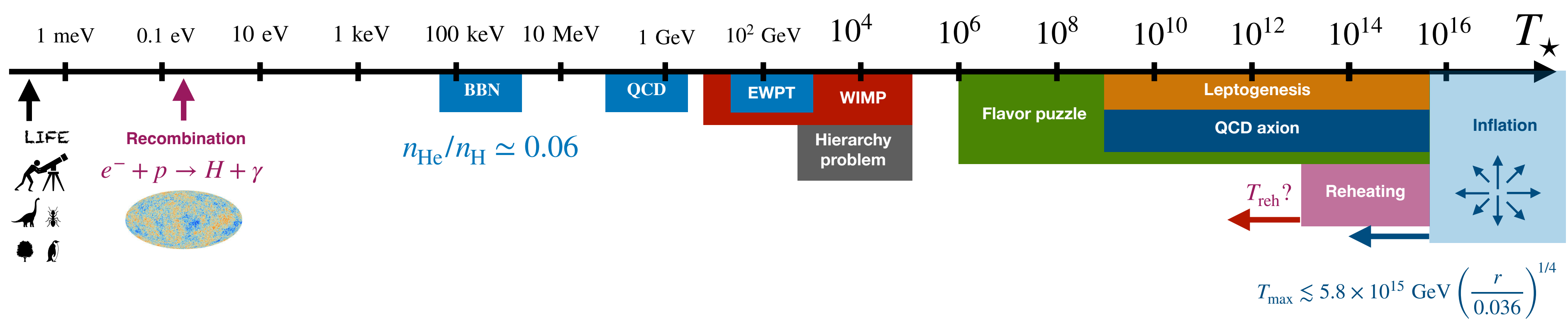


Bicep/Keck (2110.00483)



$$T_{\text{max}} \lesssim 5.8 \times 10^{15} \text{ GeV} \left(\frac{r}{0.036} \right)^{1/4}$$

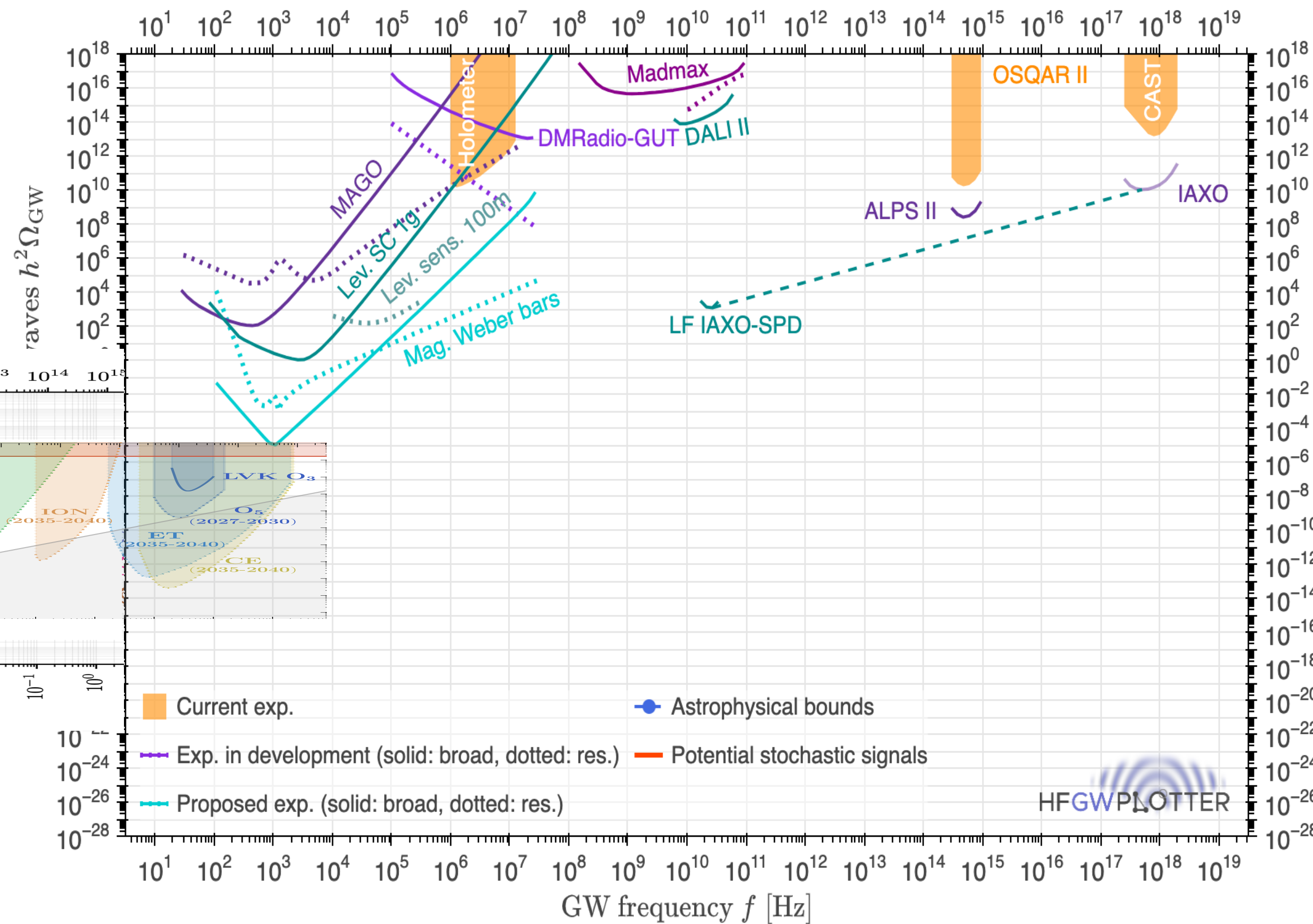
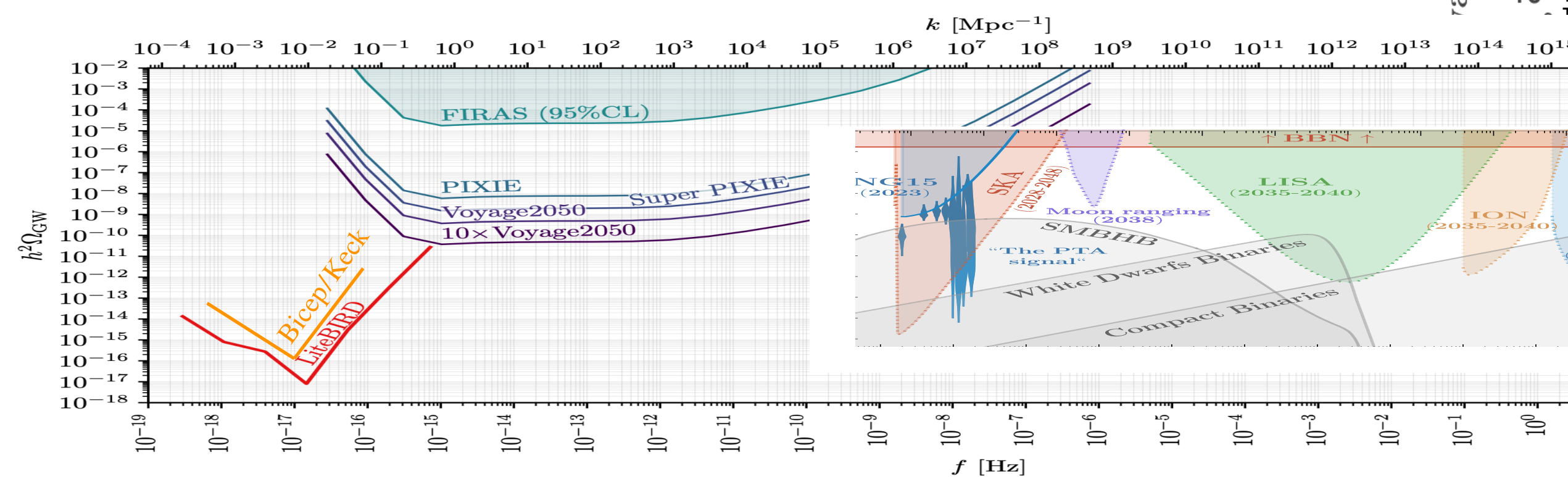
Bicep/Keck (2110.00483)



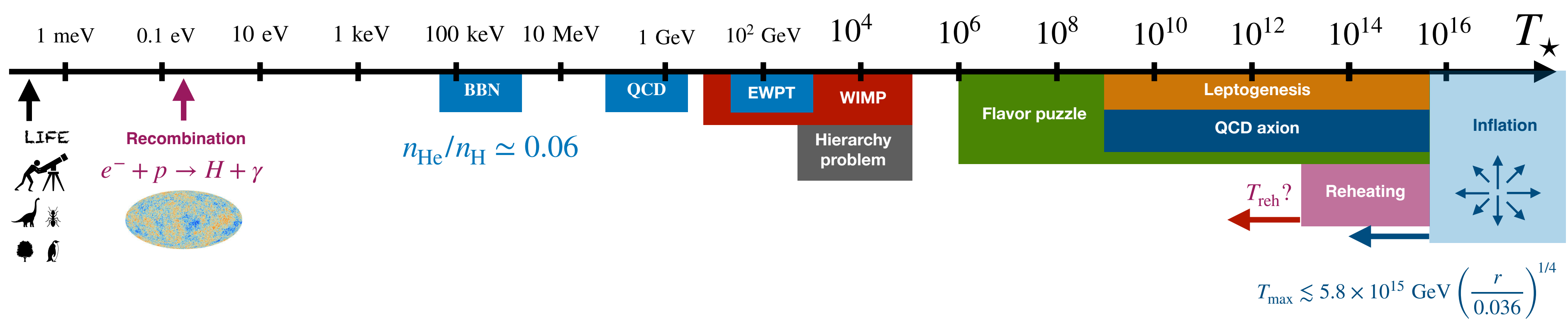
Bicep/Keck (2110.00483)

GWPlotter: Muia, Ringwald, Tamarit (2501.11723)

Kite, Ravenni, Patil, Chluba (2010.00040)



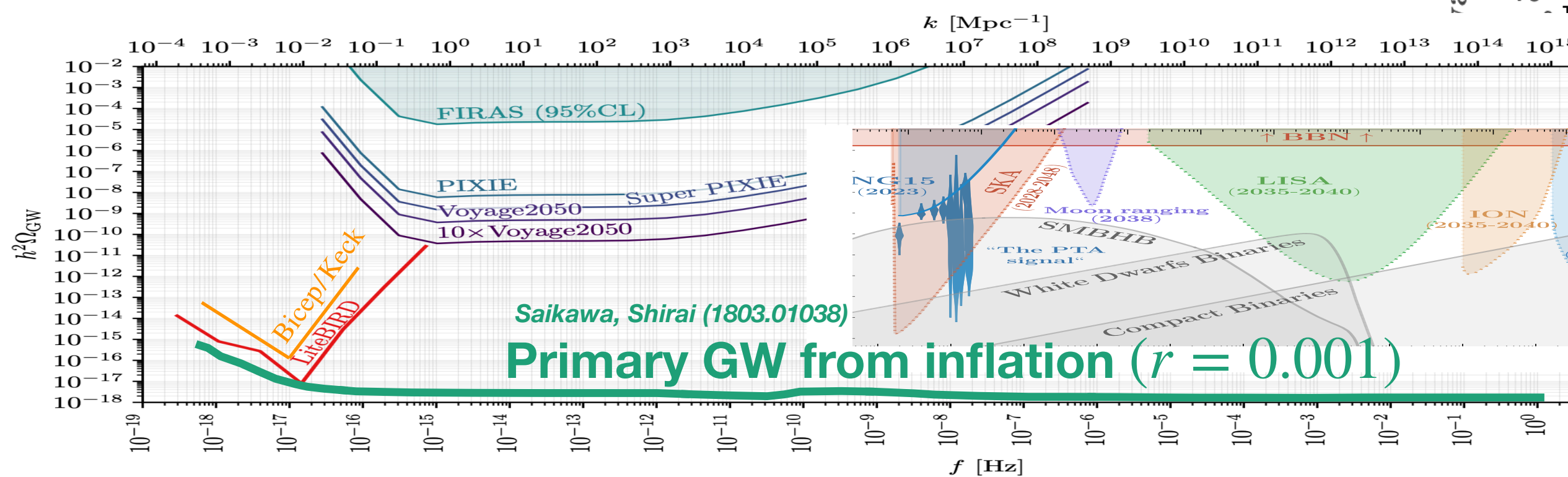
HFGWPLOTTER



Bicep/Keck (2110.00483)

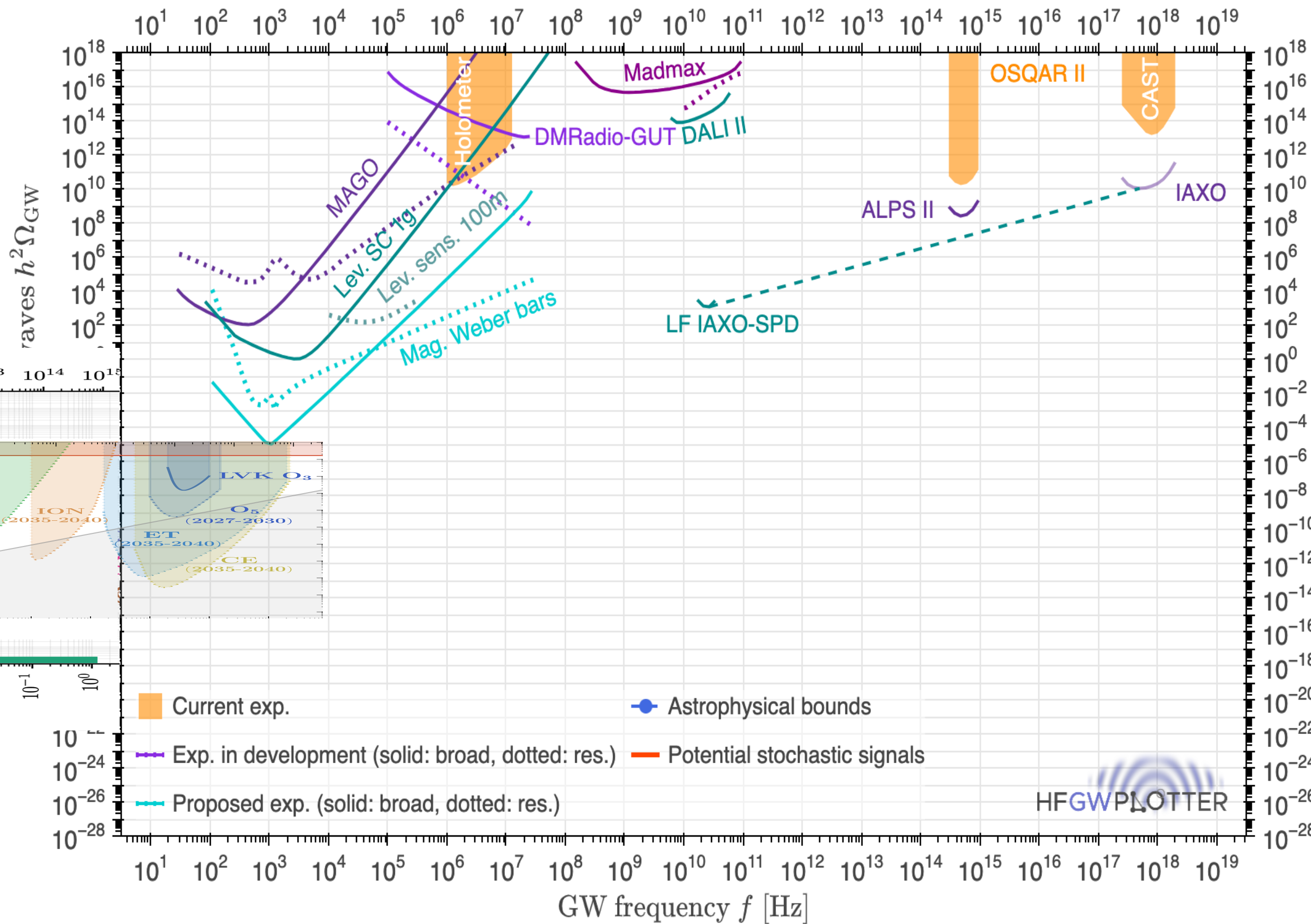
GWPlotter: Muia, Ringwald, Tamarit (2501.11723)

Kite, Ravenni, Patil, Chluba (2010.00040)

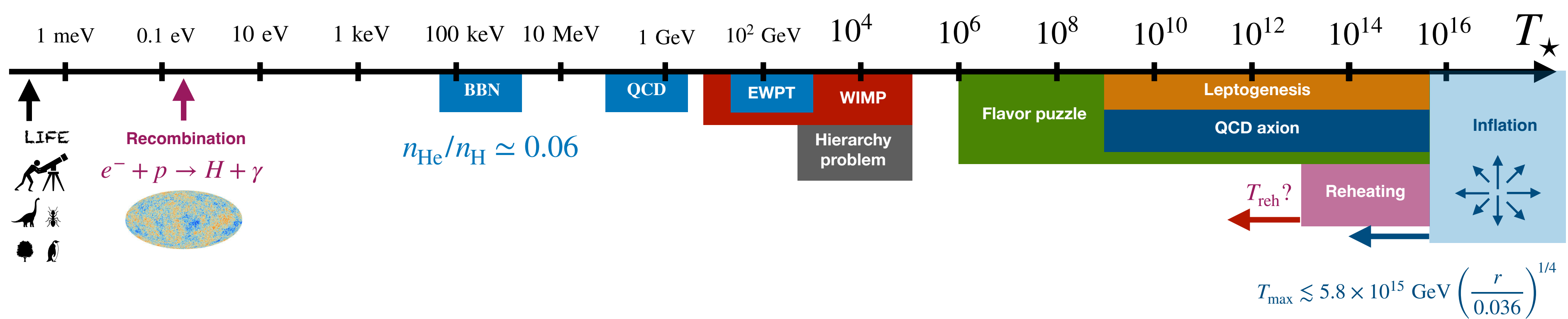


Saikawa, Shirai (1803.01038)

Primary GW from inflation ($r = 0.001$)



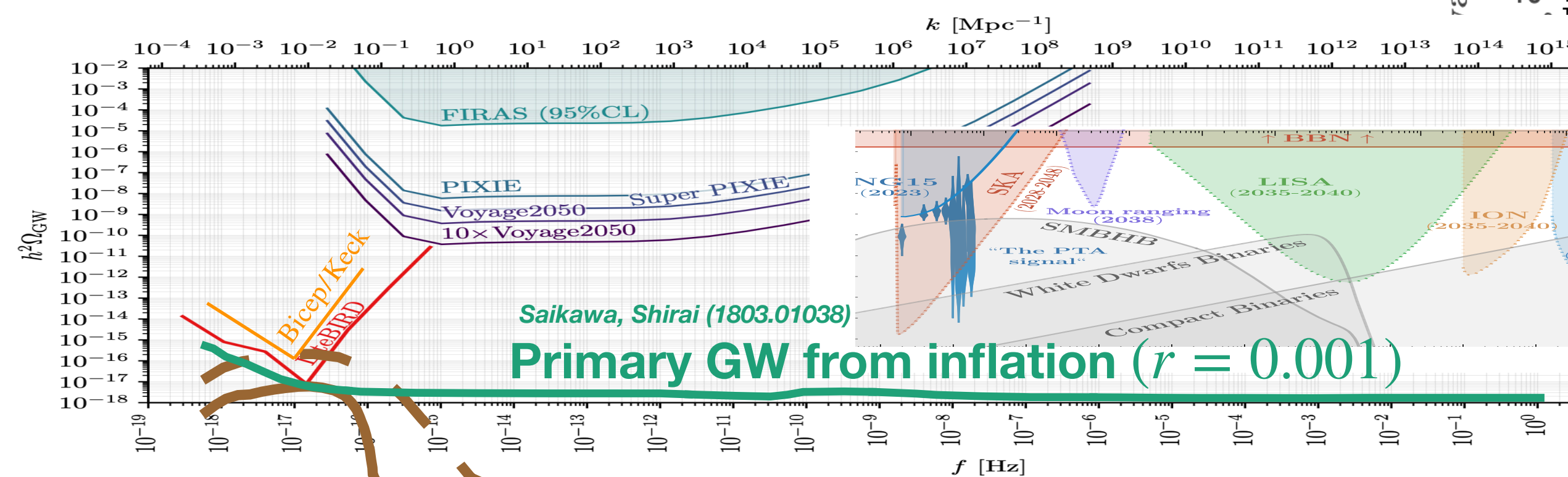
HFGWPLOTTER



Bicep/Keck (2110.00483)

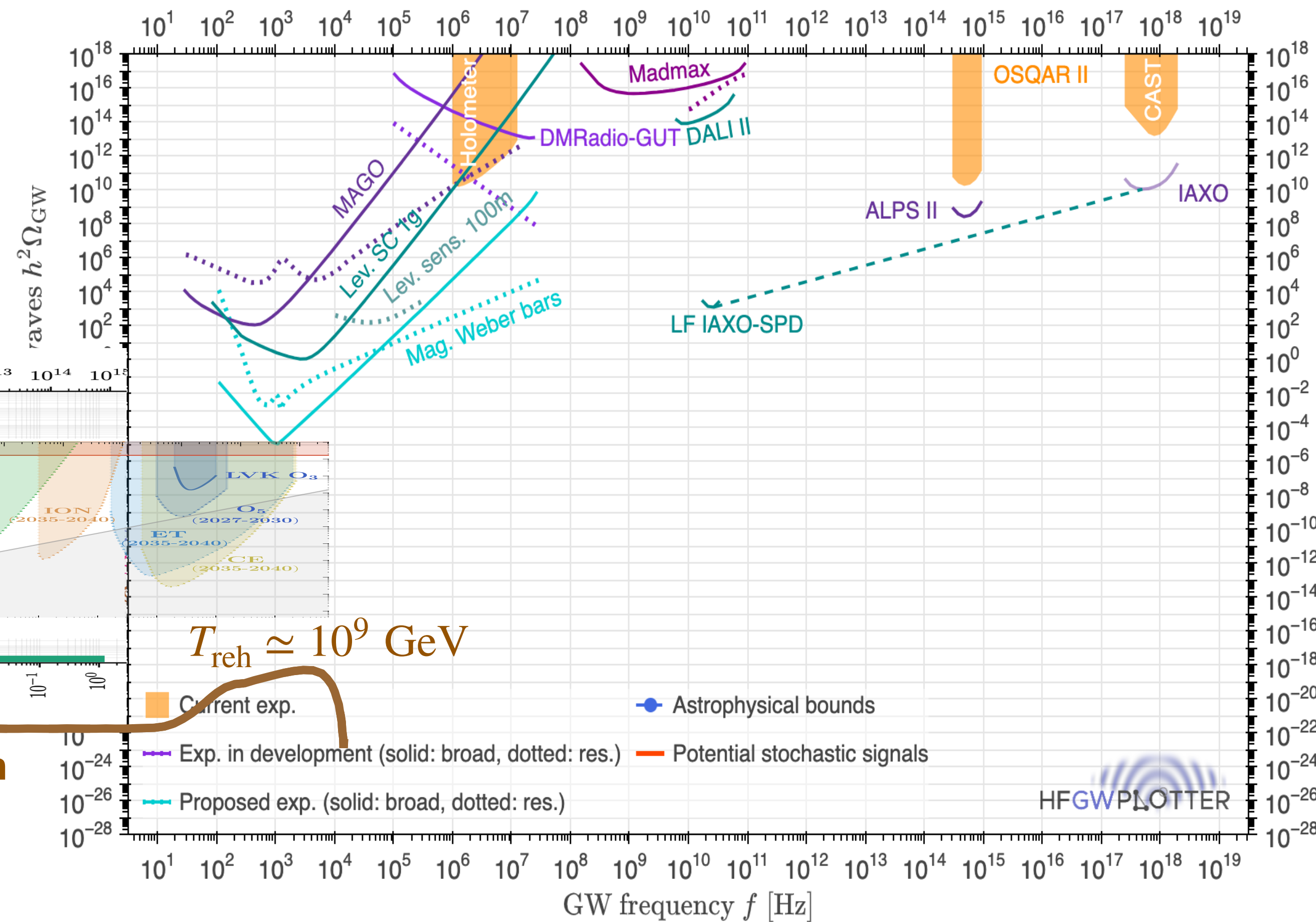
GWPlotter: Muia, Ringwald, Tamarit (2501.11723)

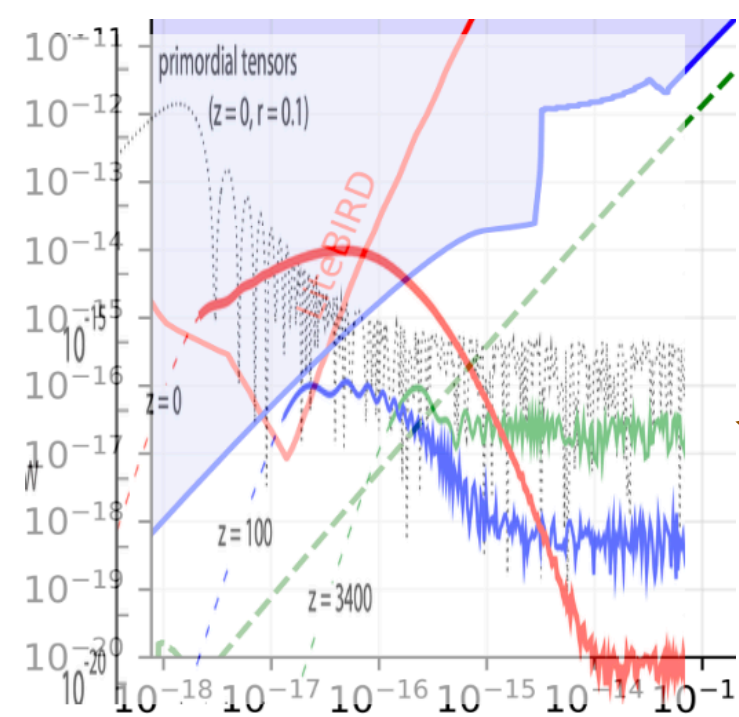
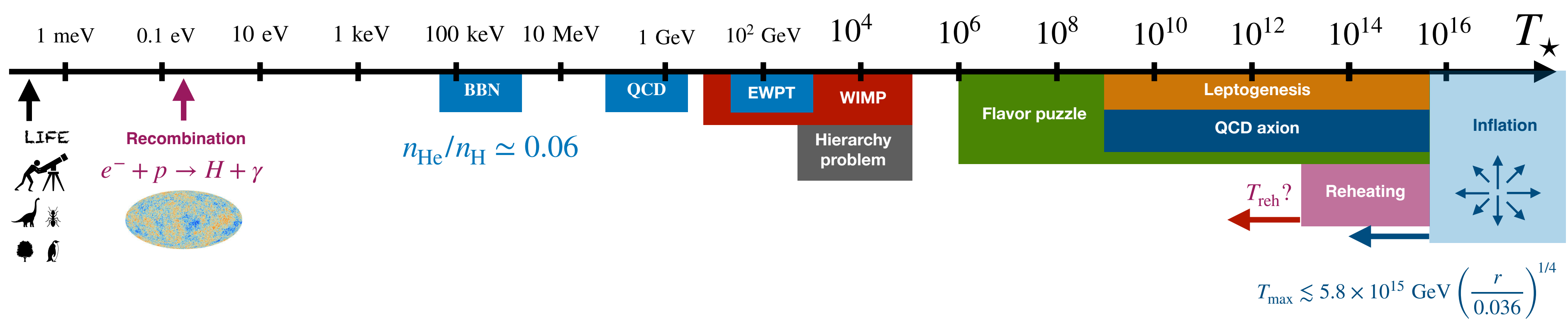
Kite, Ravenni, Patil, Chluba (2010.00040)



Irreducible secondary GW from inflation
(Only depend on $\mathcal{A}_{\mathcal{R}} \simeq 2.1 \times 10^{-9}$ and is independent of r)

Kohri & Terada (1804.08577)

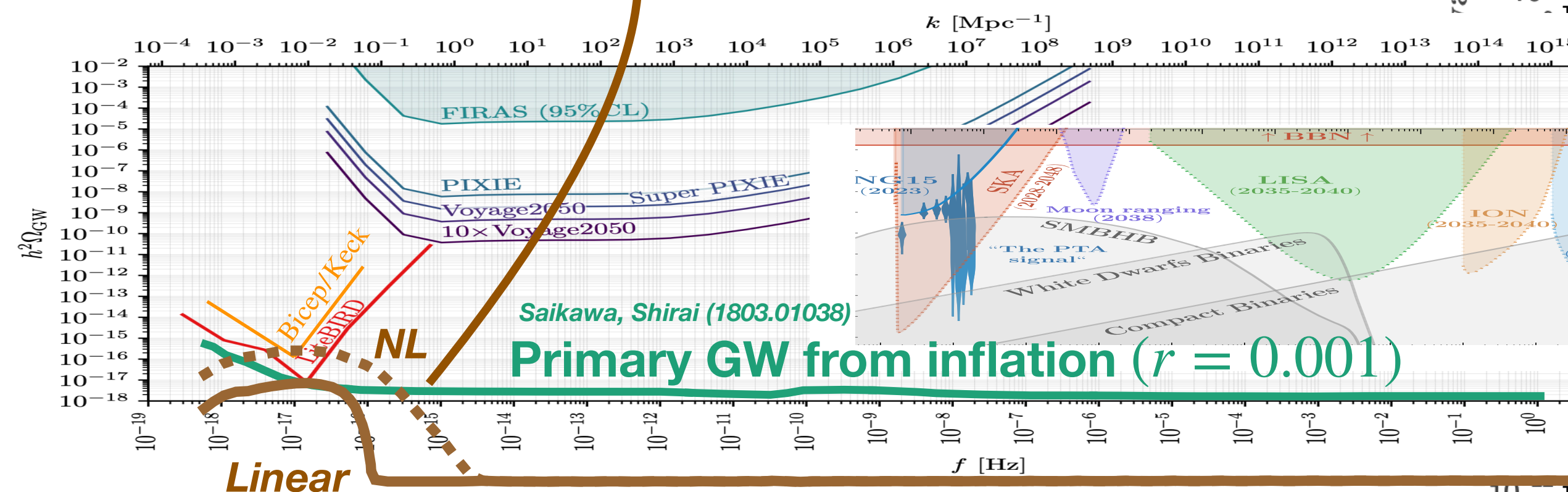




Baumann, Steinhardt, Takahashi, Ichiki (0703290)

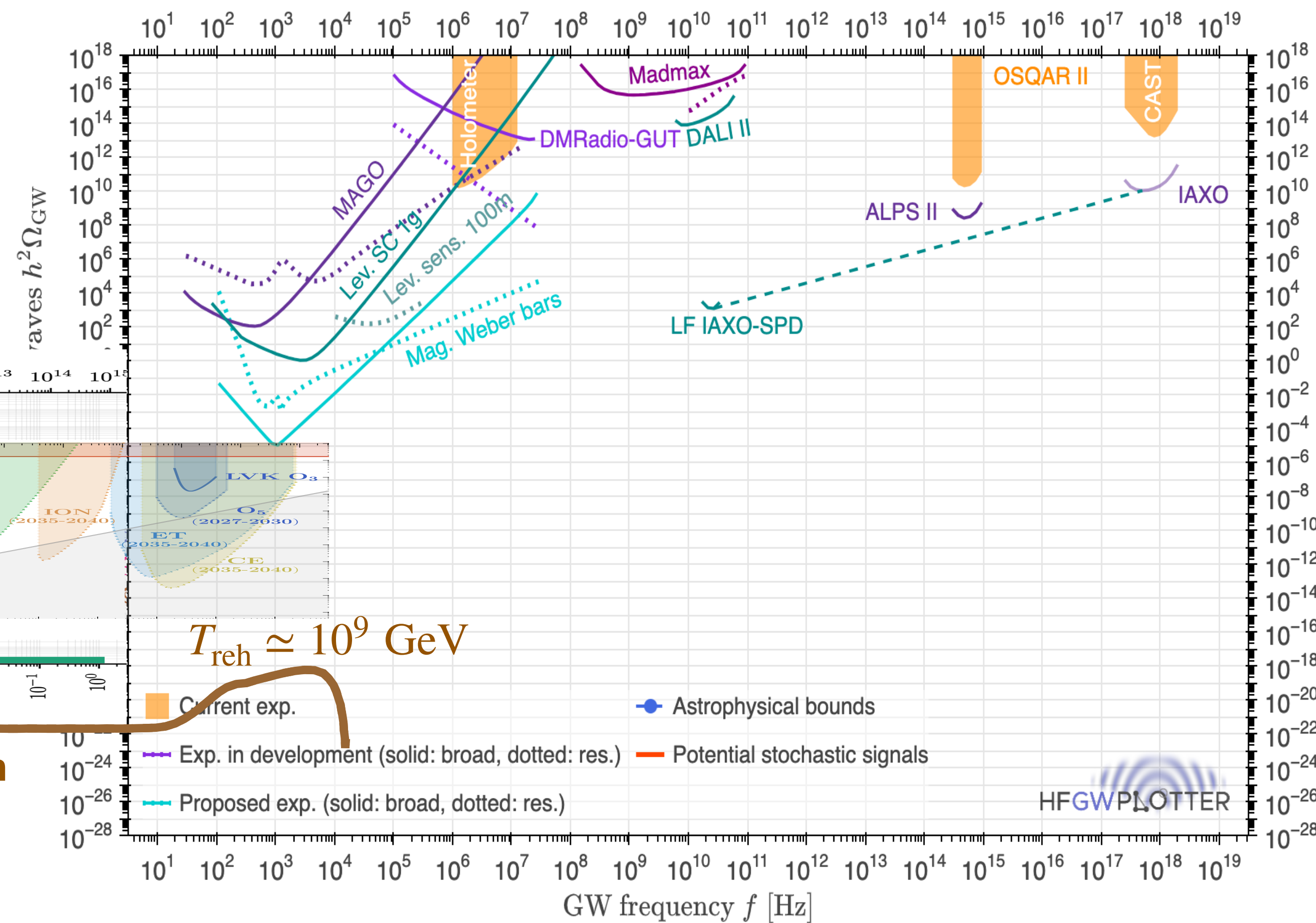
Redshift dependence !

Kite, Ravenni, Patil, Chluba (2010.00040)



Irreducible secondary GW from inflation
(Only depend on $\mathcal{A}_{\mathcal{R}} \simeq 2.1 \times 10^{-9}$ and is independent of r)

Kohri & Terada (1804.08577)



$T_{\text{reh}} \simeq 10^9 \text{ GeV}$

HFGWPLOTTER

Plan of the talk

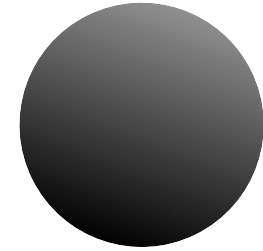
1)

Gravitational Waves (GWs)

$$h_{ij}(\vec{x}, t)$$

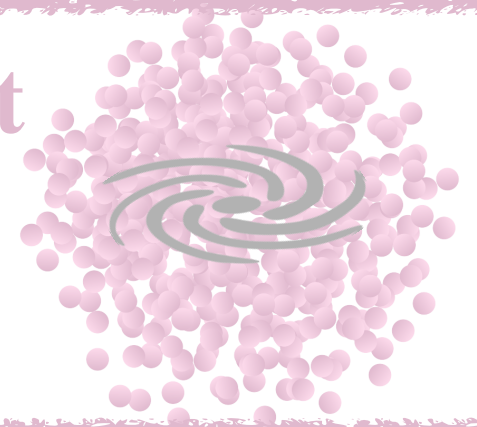
2)

Primordial
Black Holes
(PBHs)



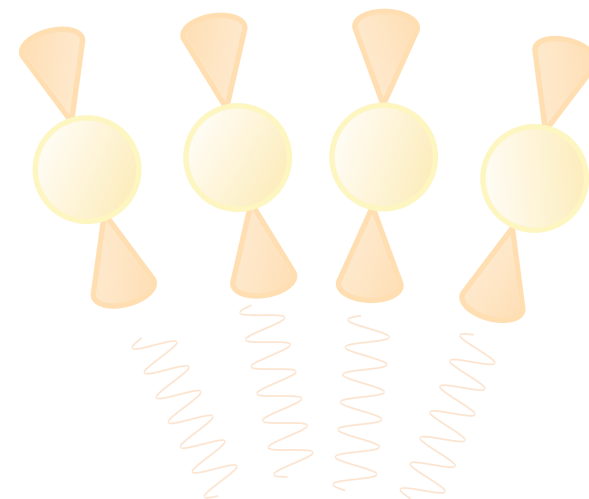
3)

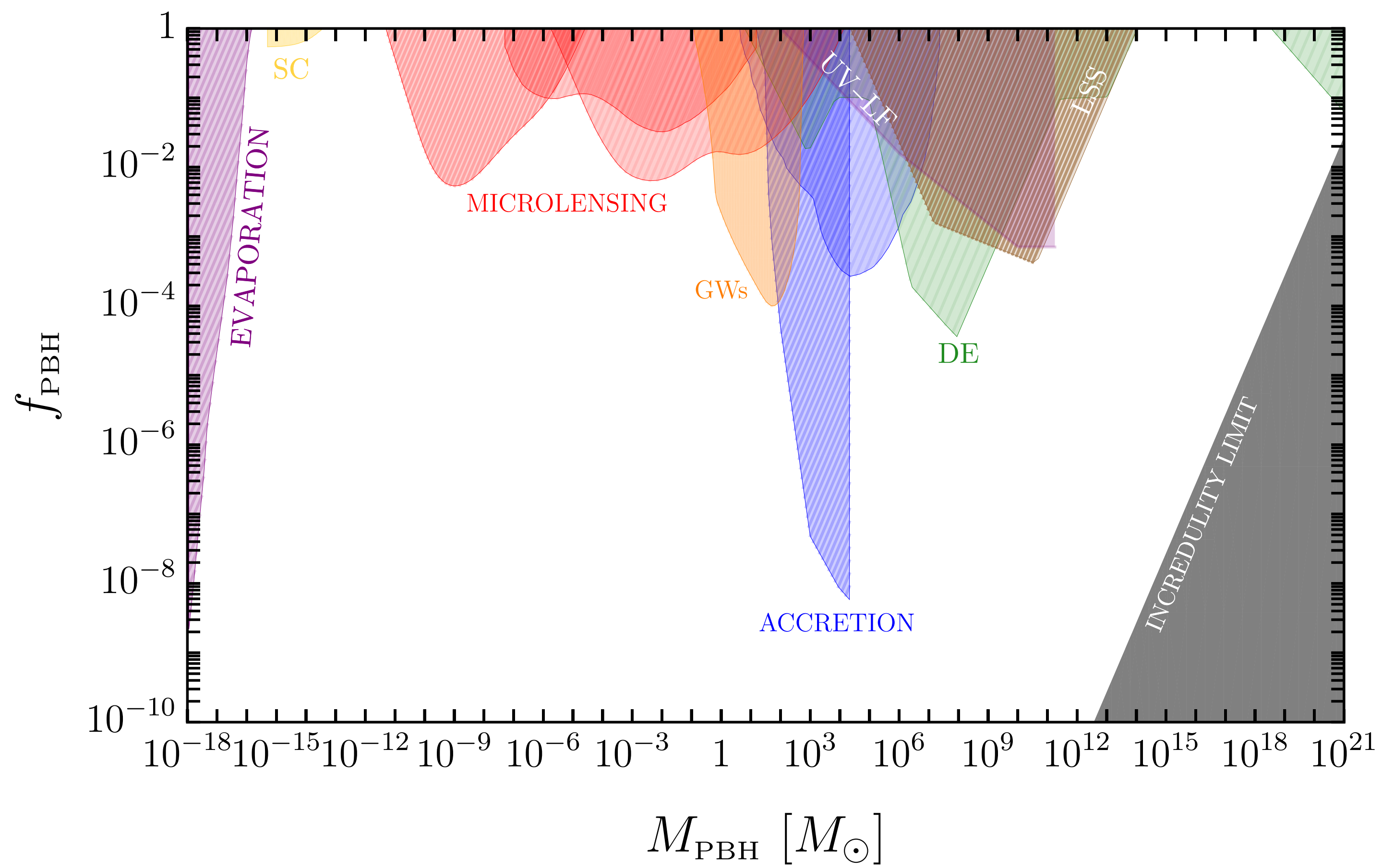
DM Ultra Compact
Mini Halos
(UCMH)

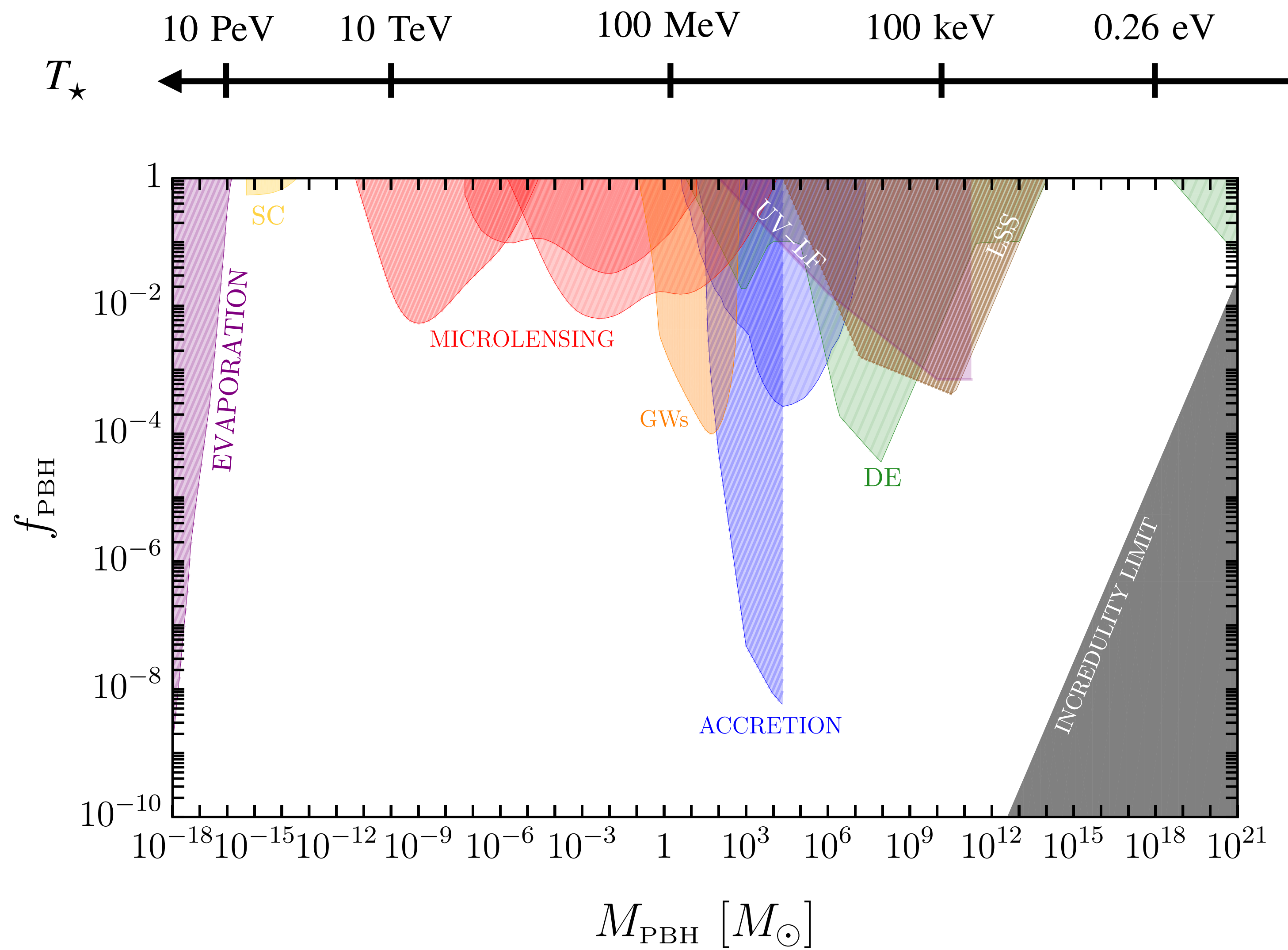


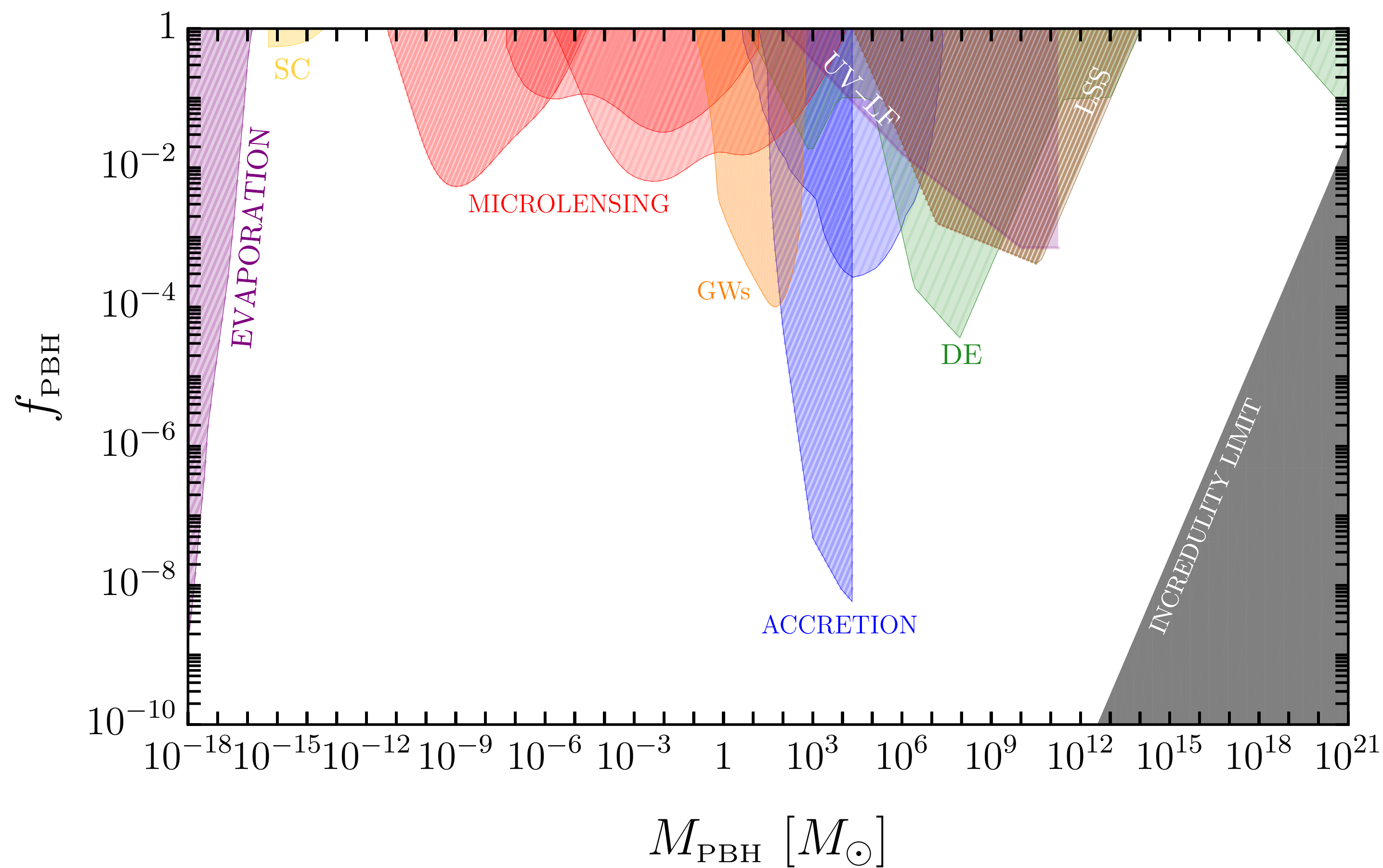
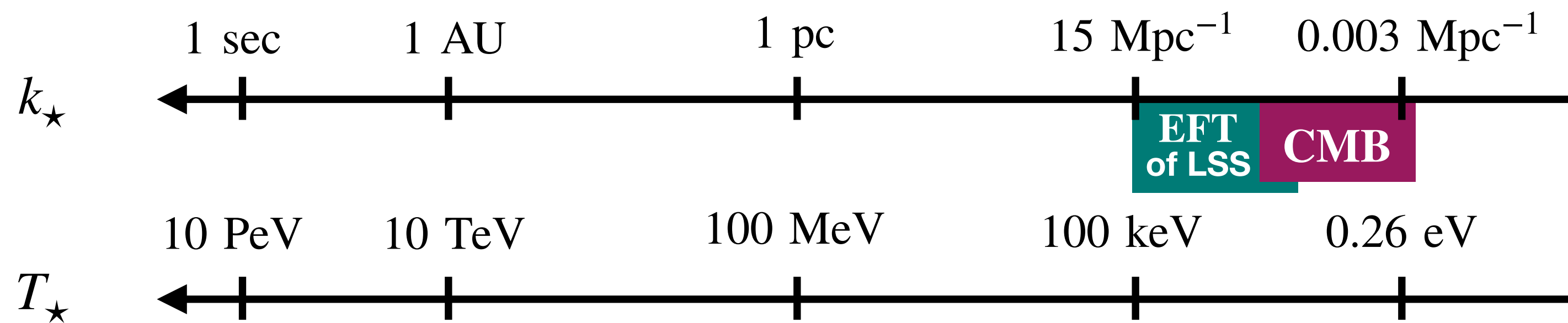
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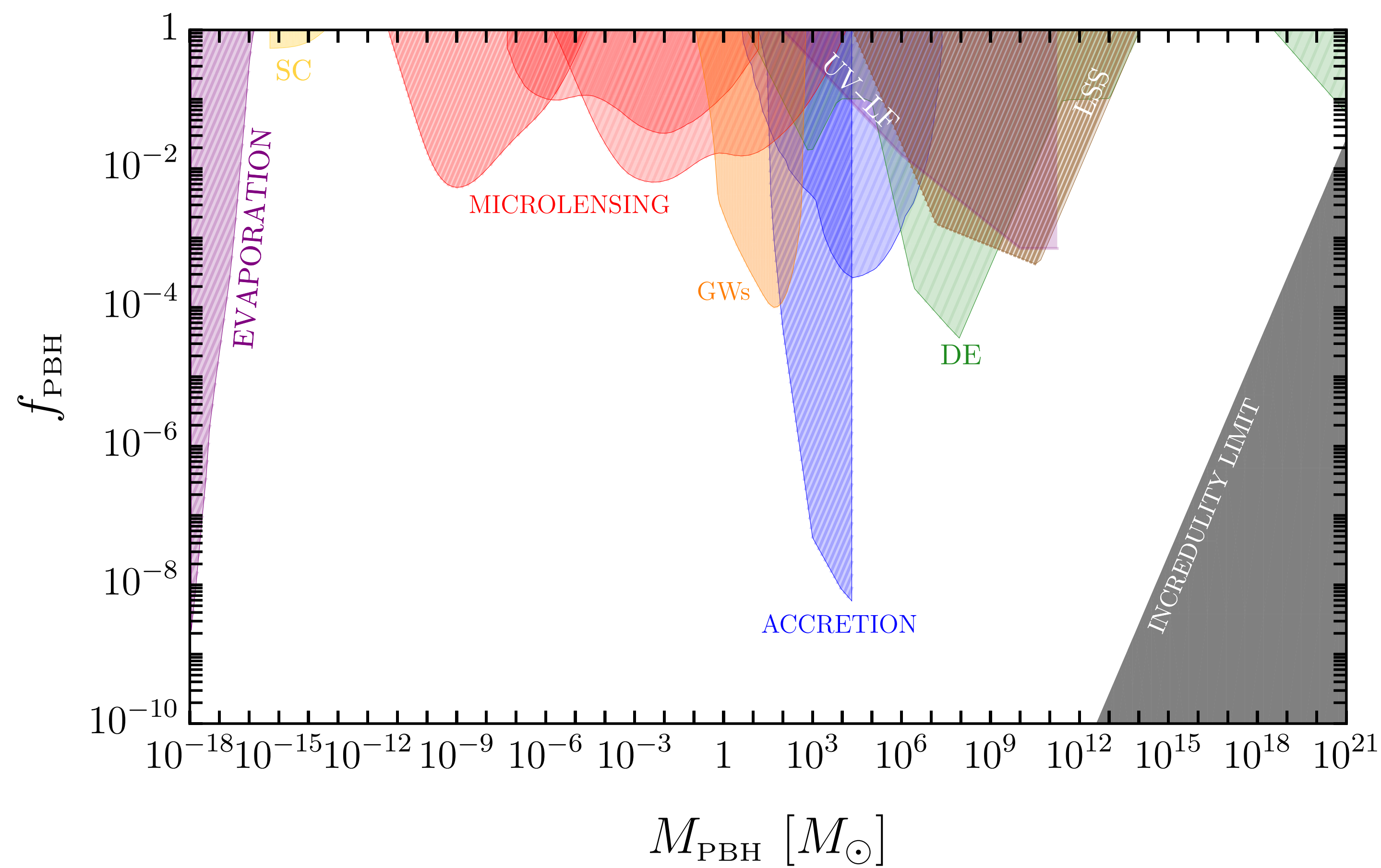
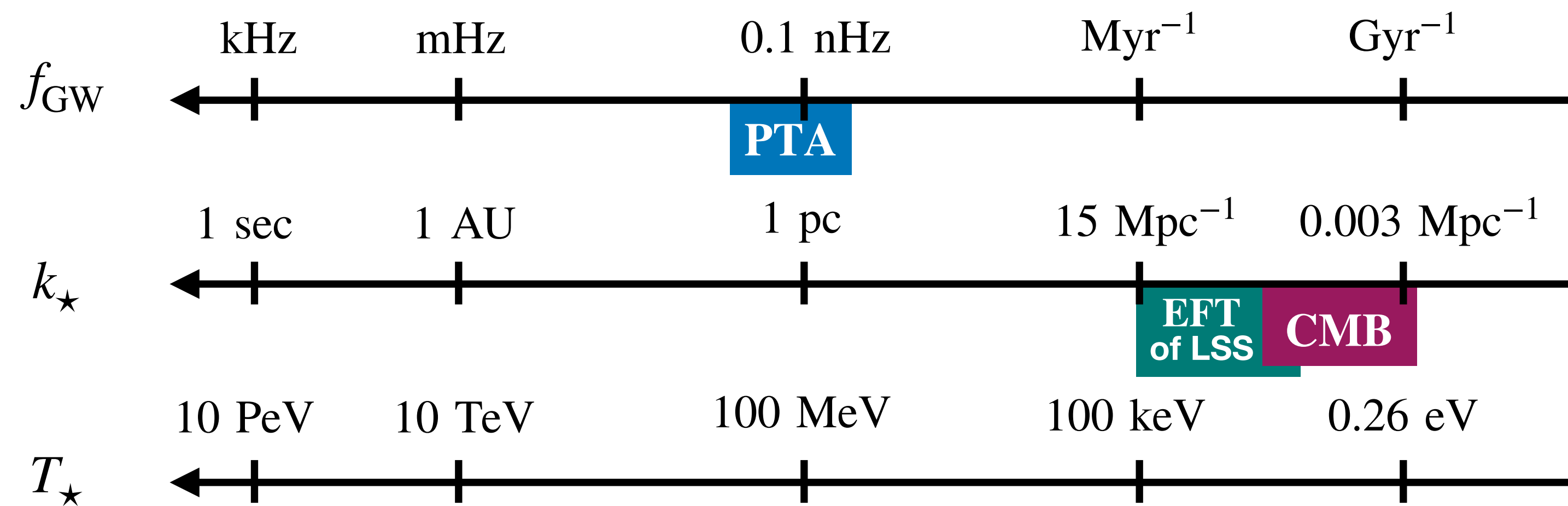
What is the PTA
signal ?











Lyman – α

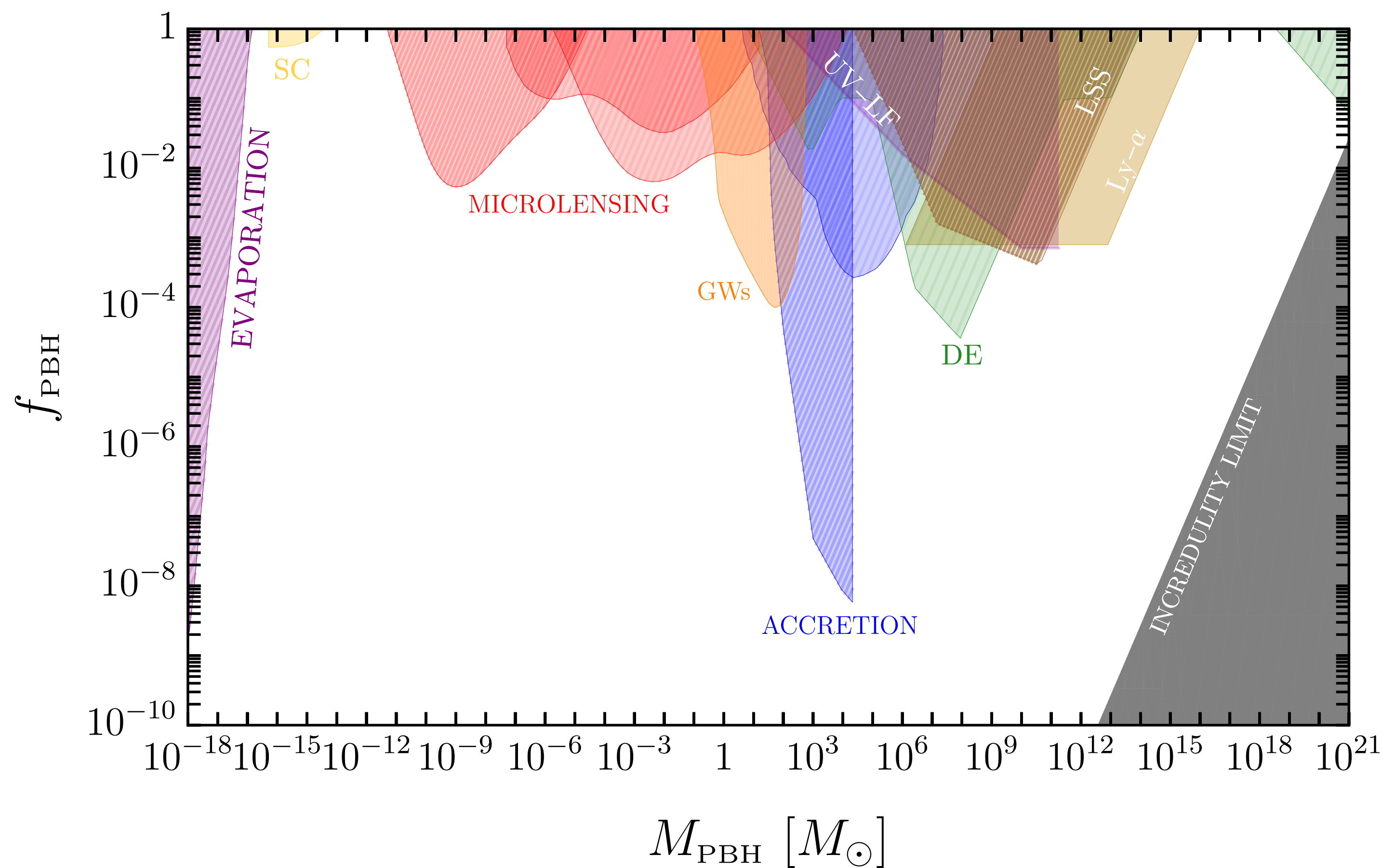
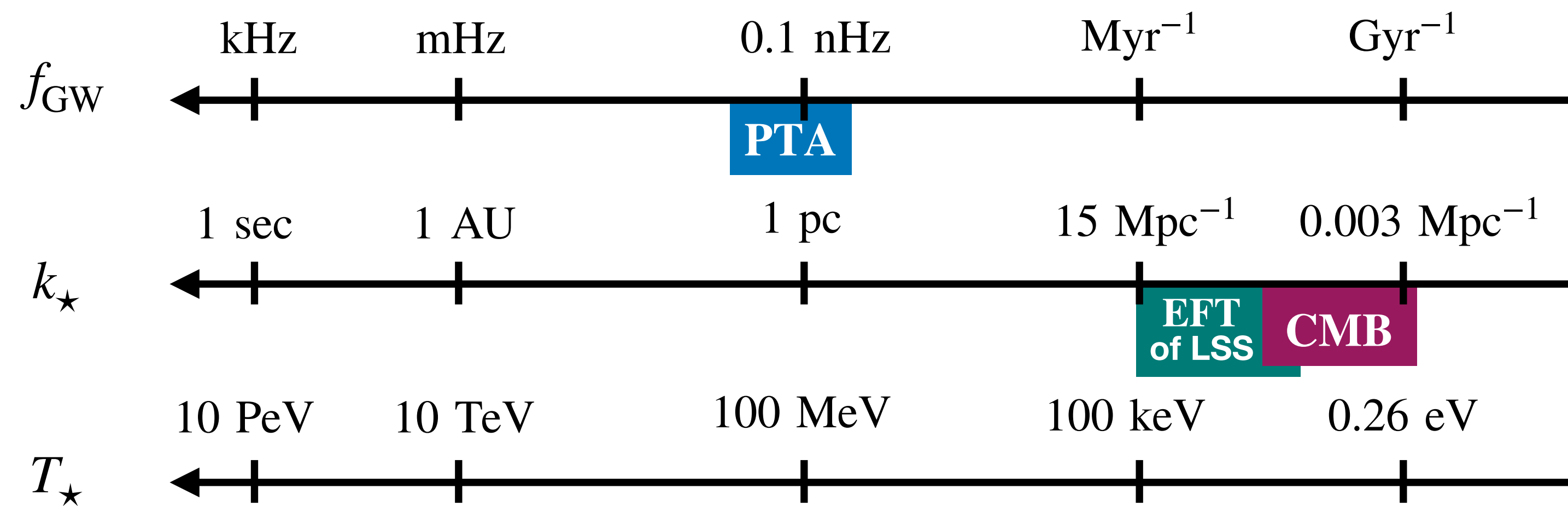
Effective Field Theory Constraints on Primordial Black Holes from the High-Redshift Lyman- α Forest

Mikhail M. Ivanov^{1,*} and Sokratis Trifinopoulos^{1,2,3,†}

¹Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

²Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland

³Physik-Institut, Universität Zürich, 8057 Zürich, Switzerland



Lyman α

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CMB + BAO

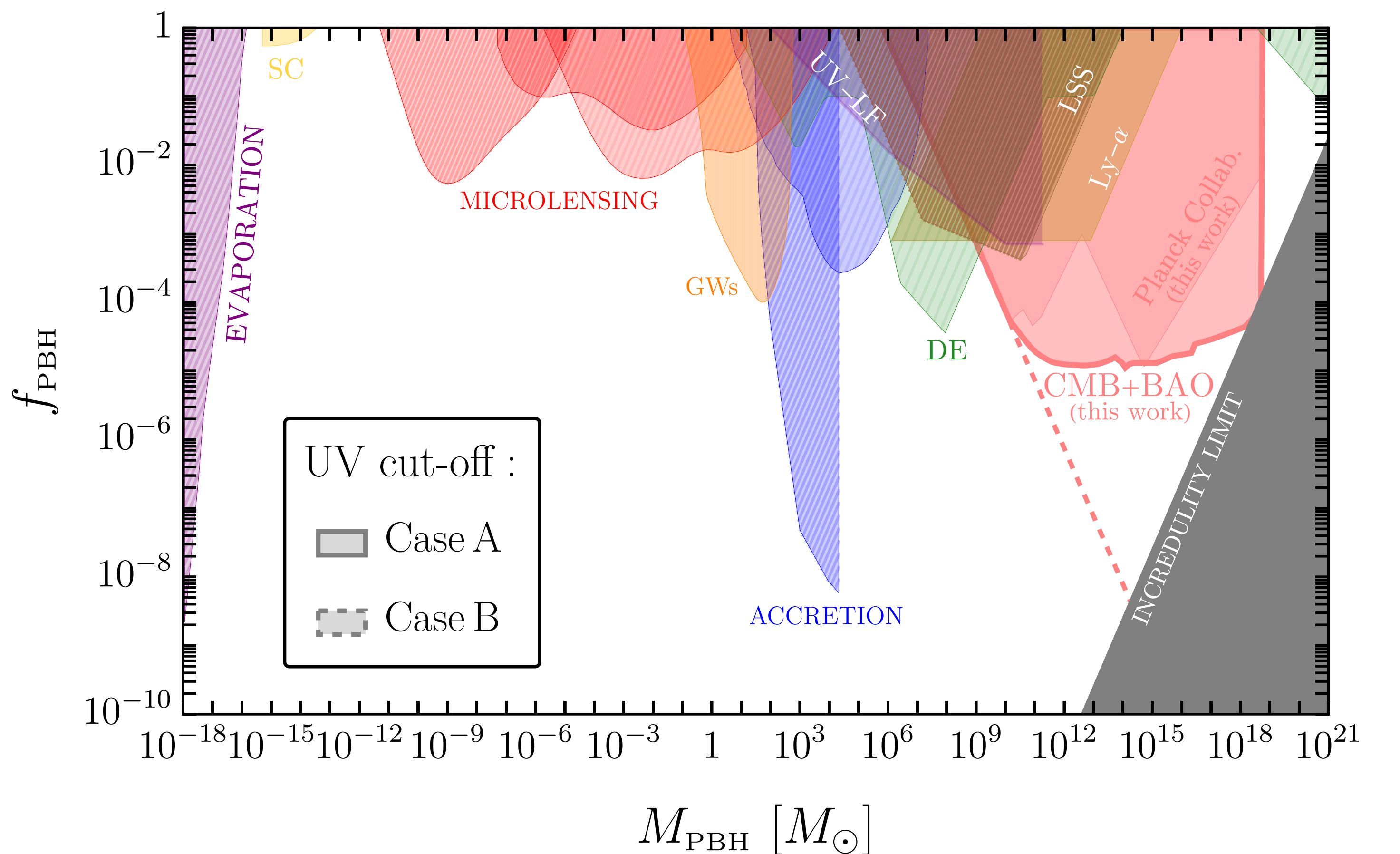
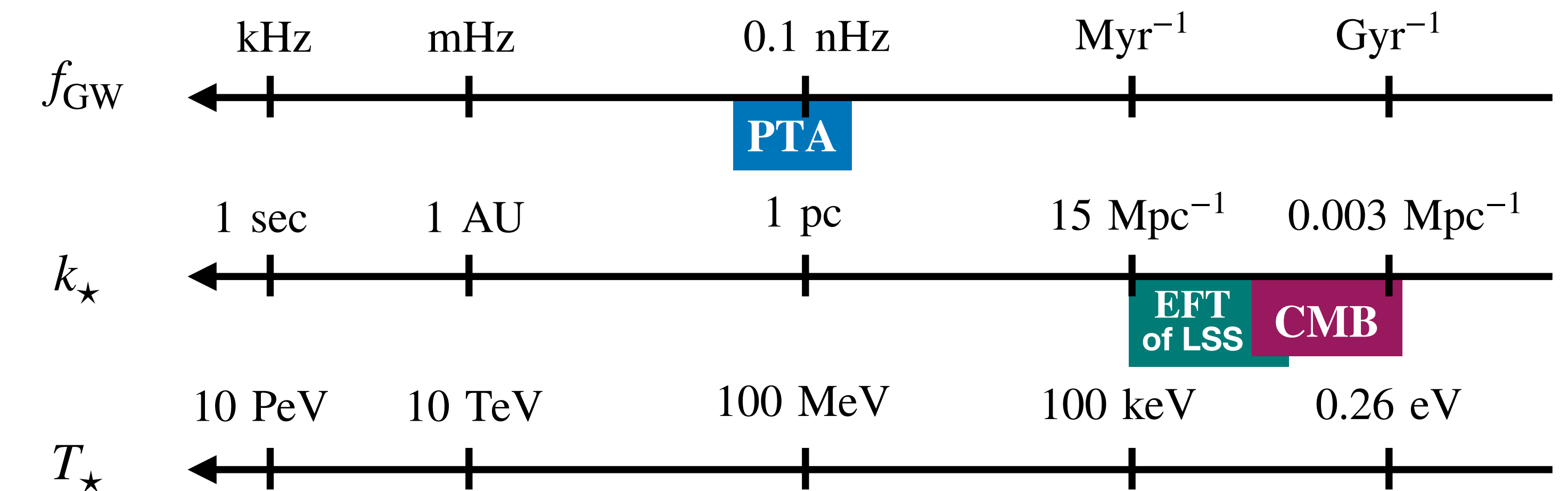
Closing the Mass Window for Stupendously Large Black Holes

Christopher Gerlach^{ⓧ,1,*} Yann Gouttenoire^{ⓧ,1,†} Antonio J. Iovino^{ⓧ,2,3,‡} and Nicholas Leister^{ⓧ,1,§}

¹*PRISMA⁺ Cluster of Excellence & Mainz Institute for Theoretical Physics,
Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*

²*New York University, Abu Dhabi, PO Box 129188 Saadiyat Island, Abu Dhabi, UAE*

³*Department of Theoretical Physics and Gravitational Wave Science Center,
24 quai E. Ansermet, CH-1211 Geneva 4, Switzerland*



Lyman α

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CMB + BAO

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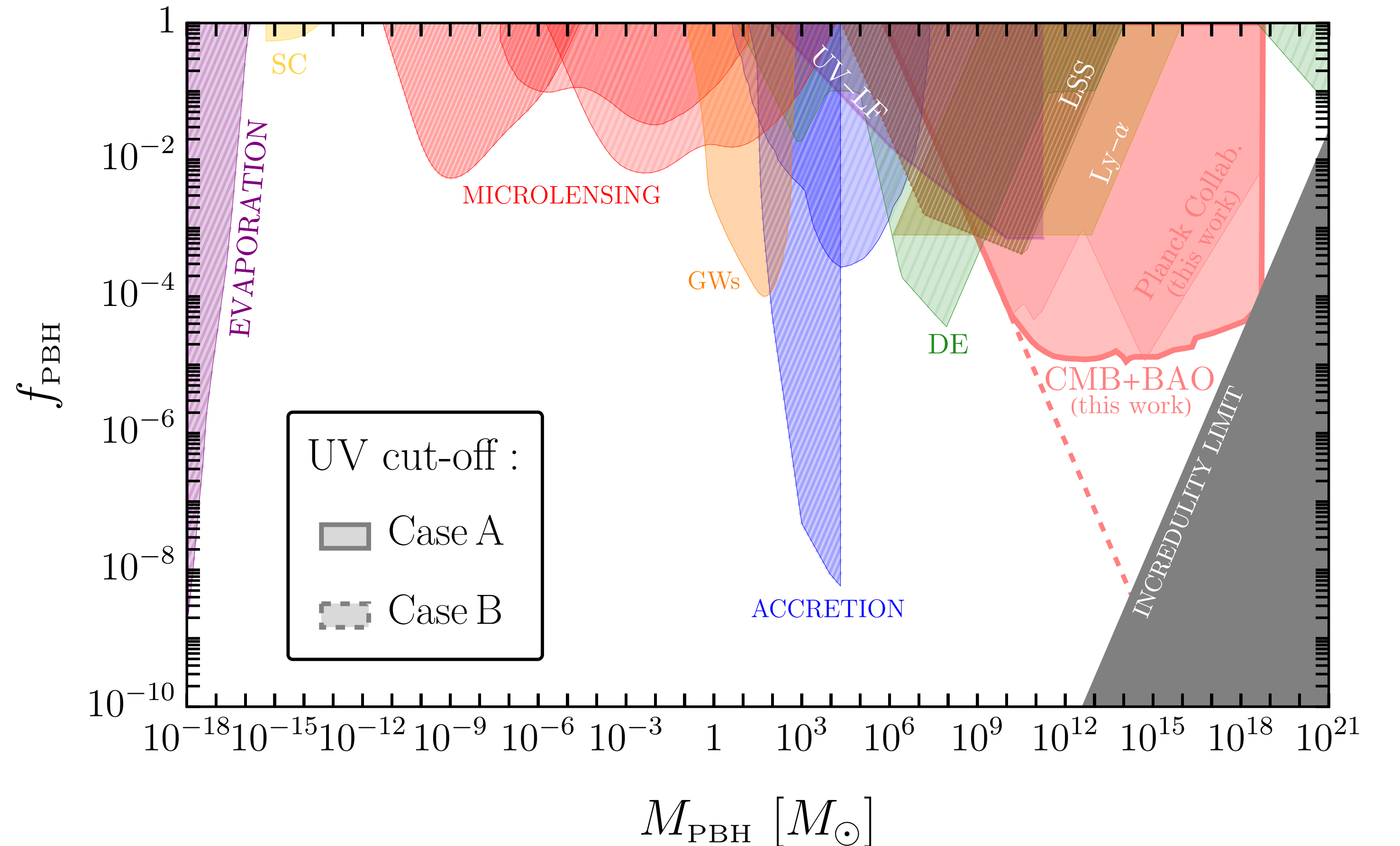
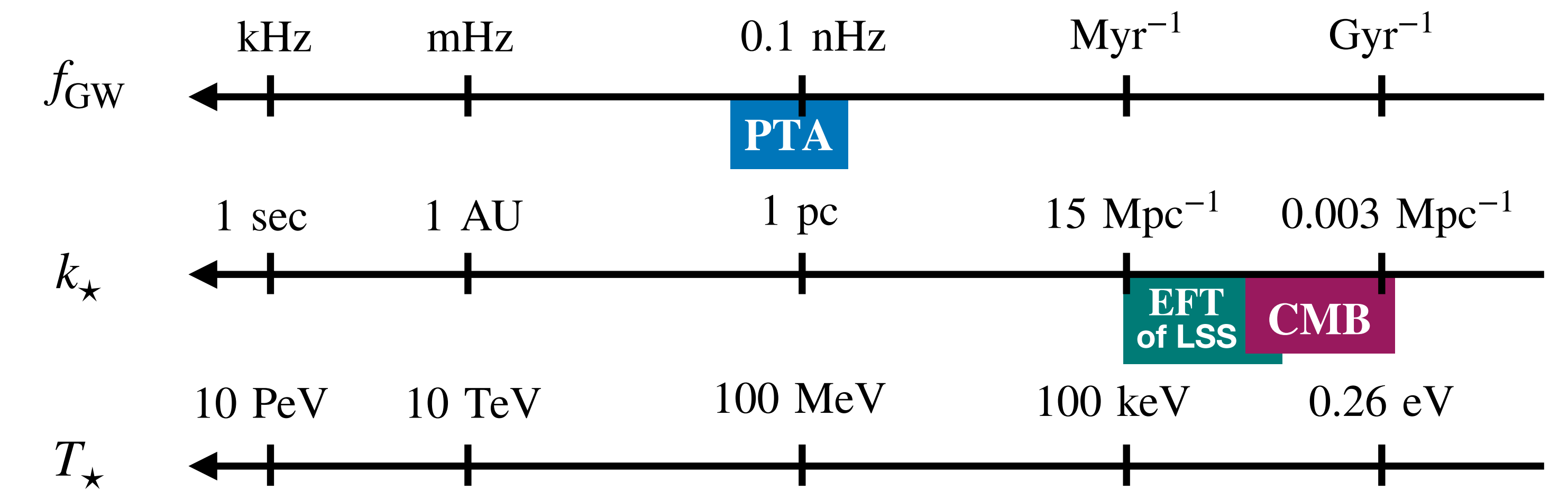
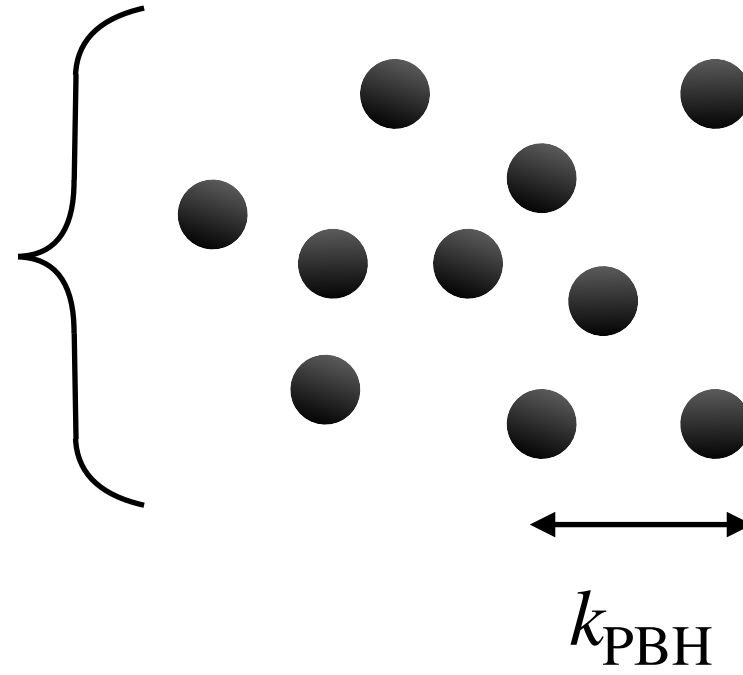
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Gas of PBHs



Lyman – α

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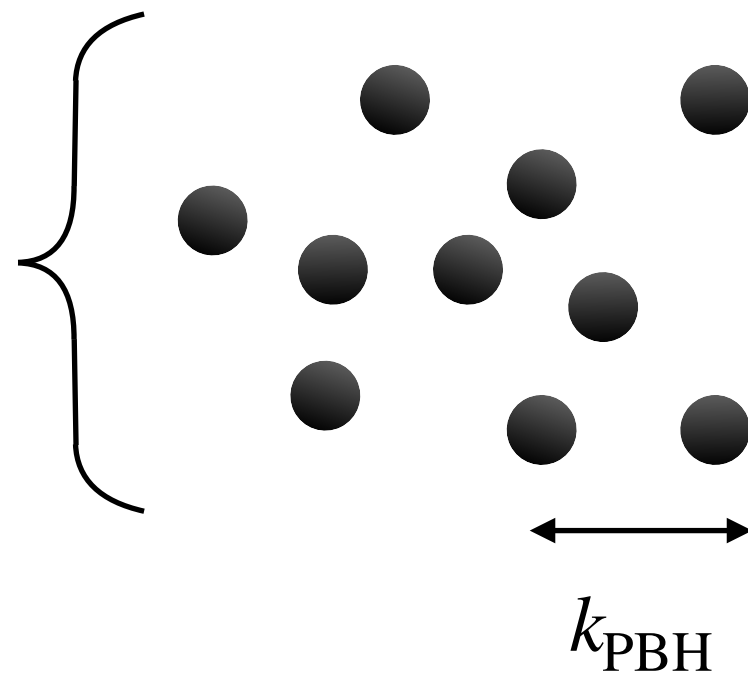
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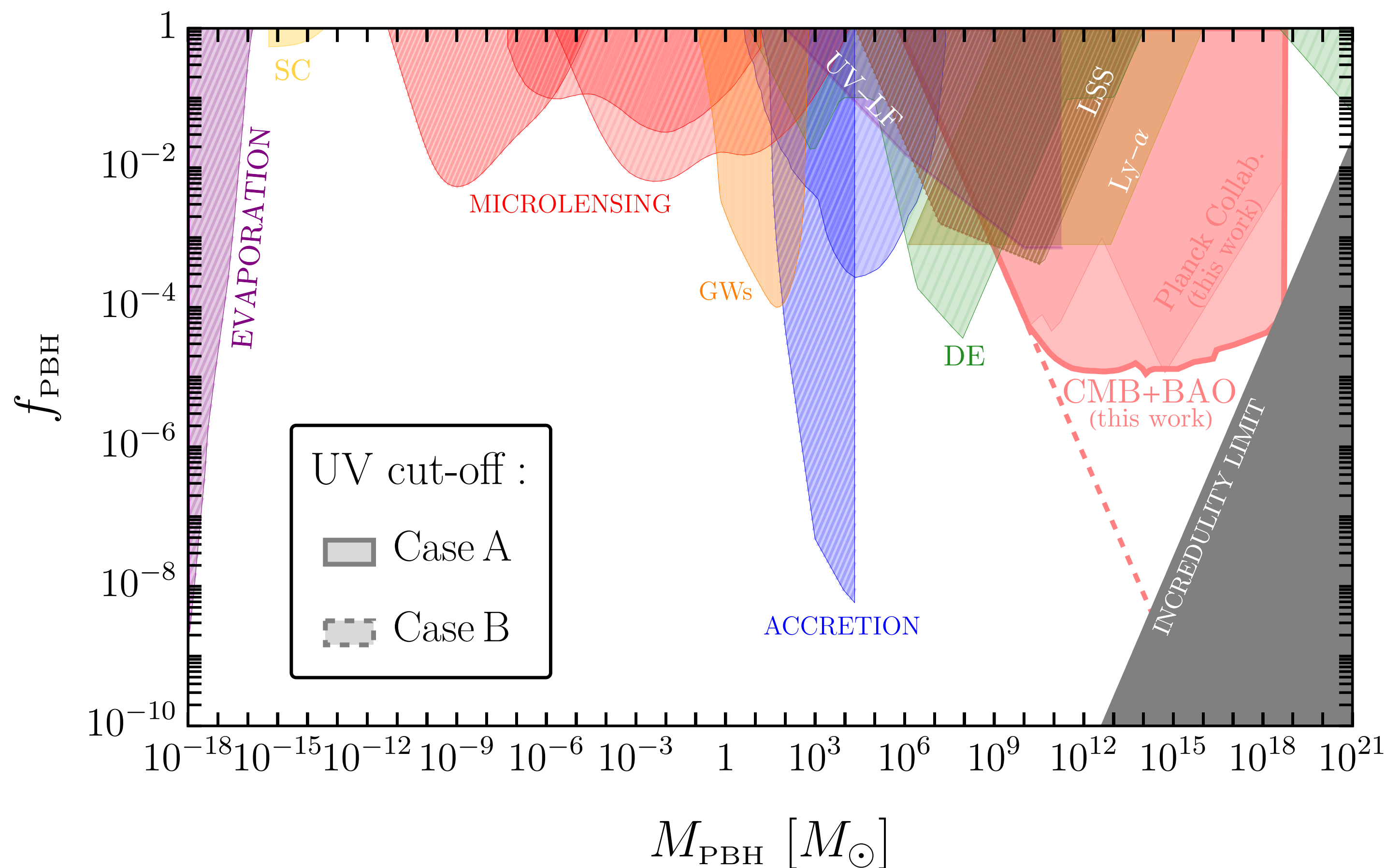
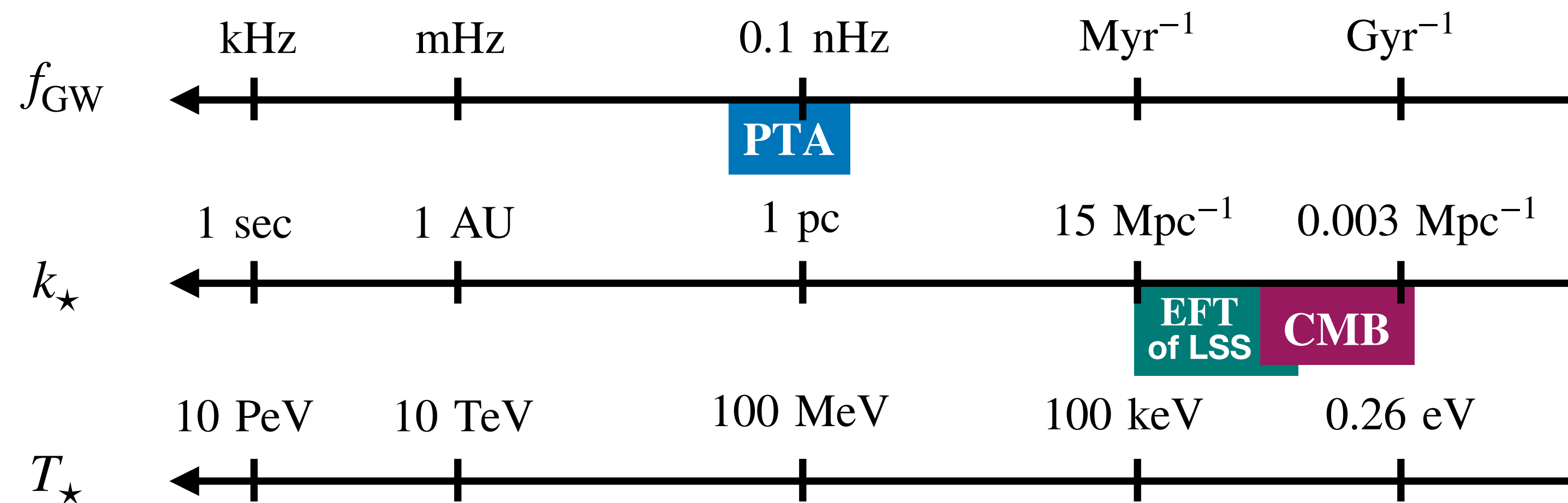
³*Department of Theoretical Physics and Gravitational Wave Science Center,
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Gas of PBHs



Poisson noise :

$$\mathcal{P}_\delta = f_{\text{PBH}}^2 \left(\frac{k}{k_{\text{PBH}}} \right)^3 \Theta(k_{\text{PBH}} - k)$$



Lyman – α

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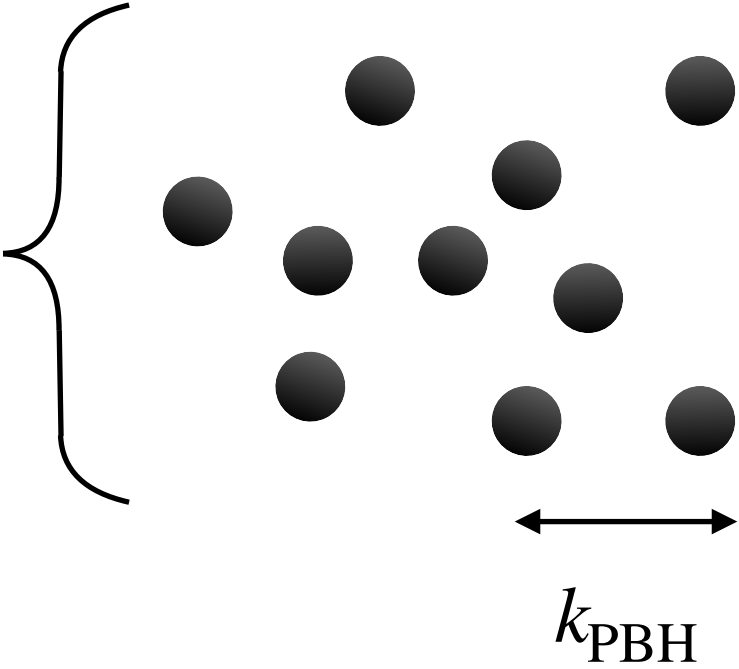
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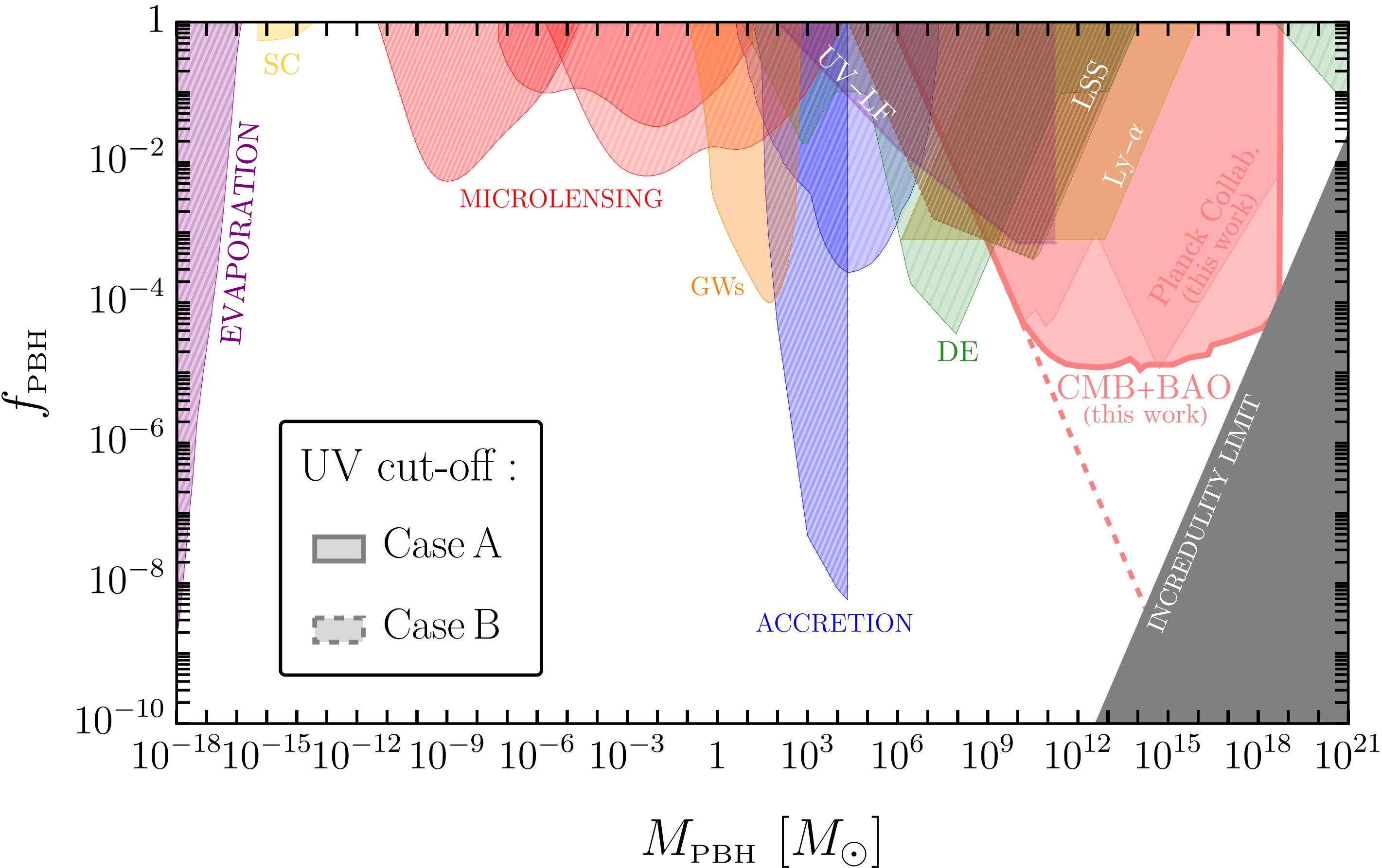
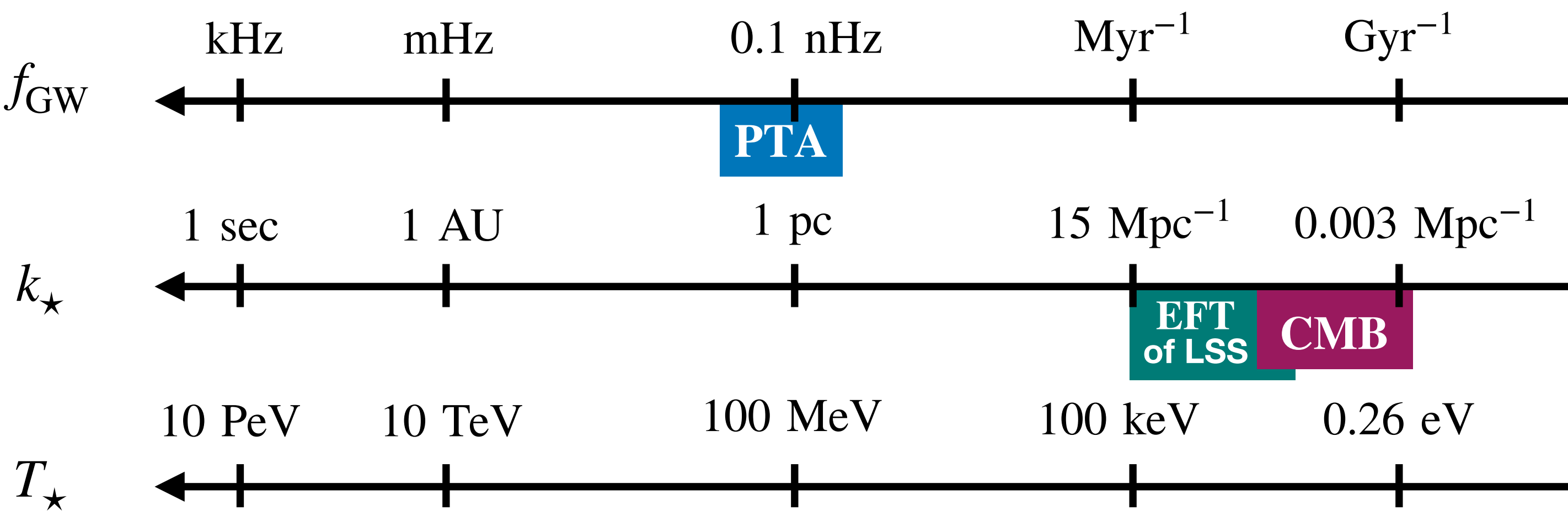
Gas of PBHs



Poisson noise :

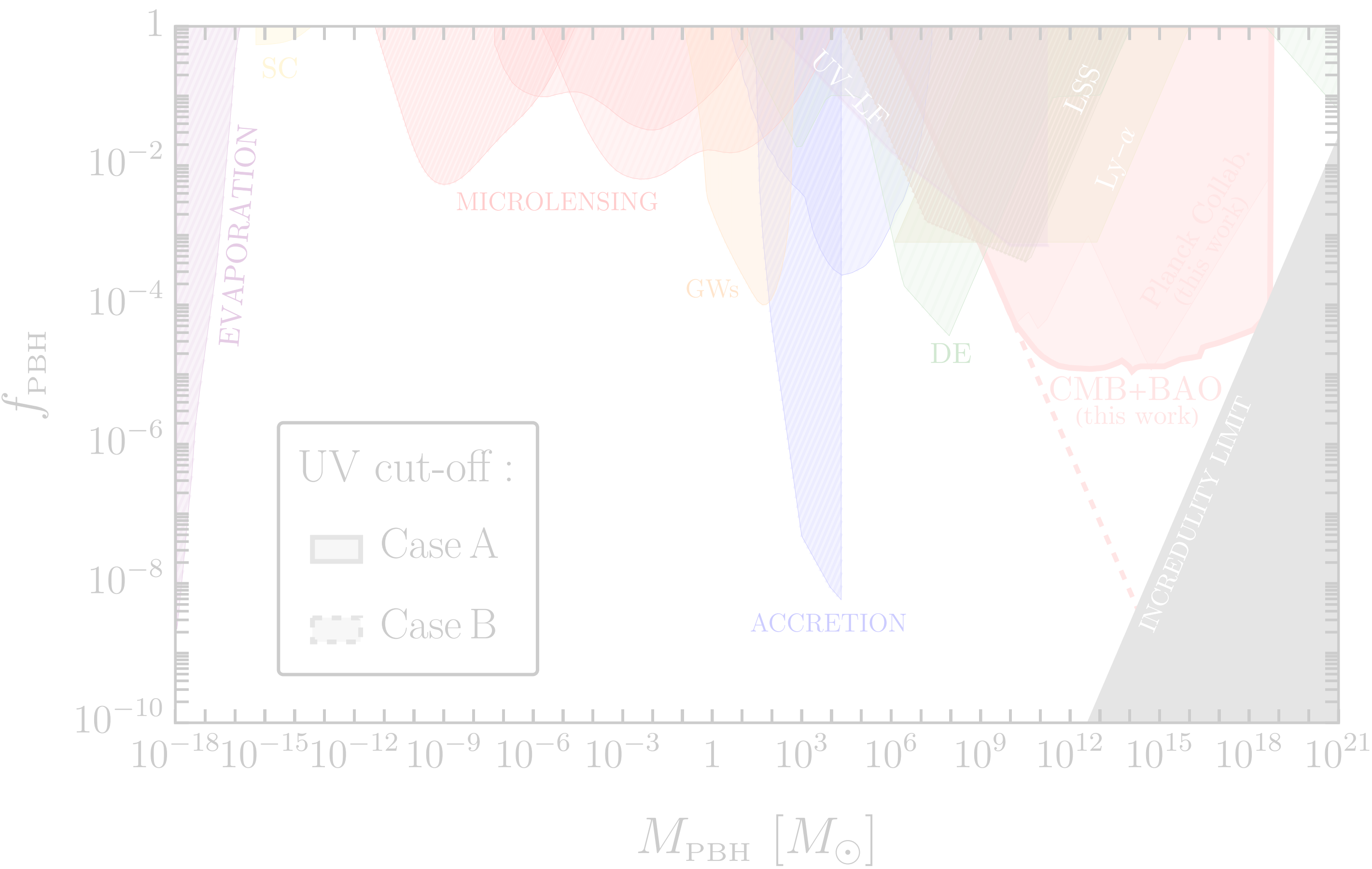
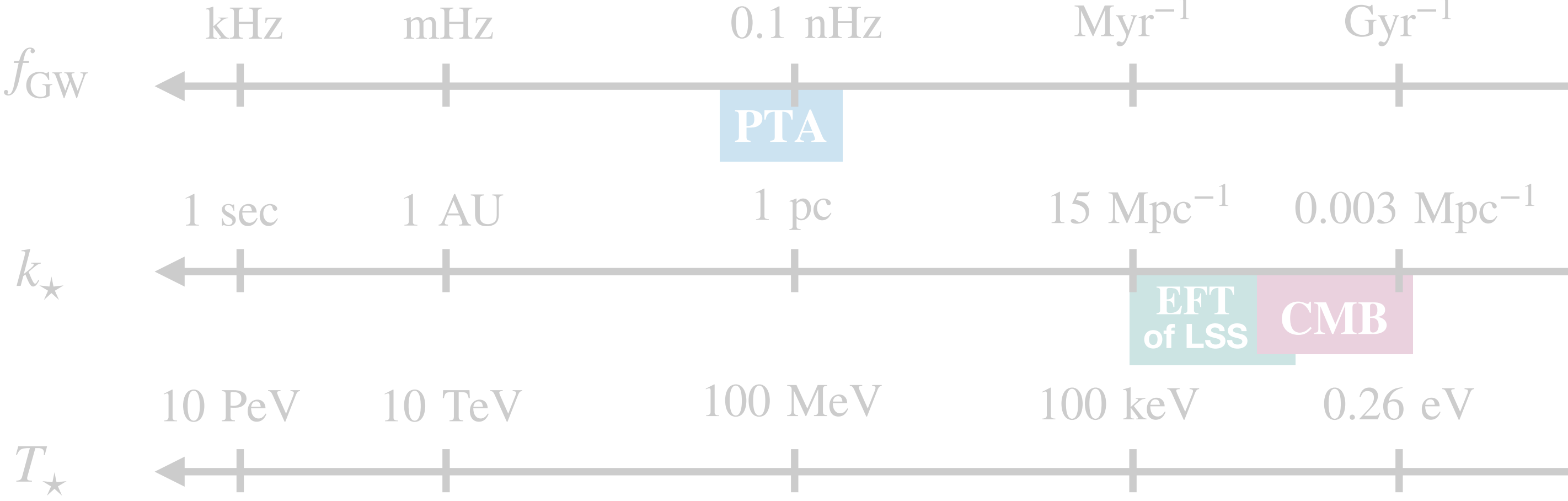
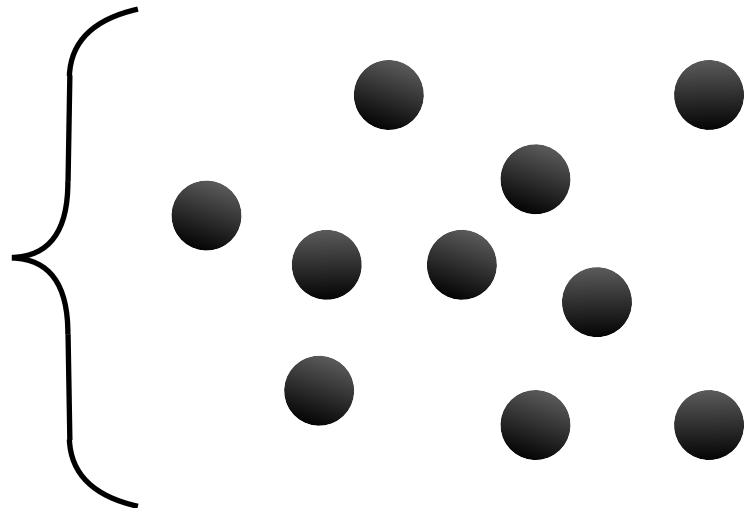
$$\mathcal{P}_\delta = f_{\text{PBH}}^2 \left(\frac{k}{k_{\text{PBH}}} \right)^3 \Theta(k_{\text{PBH}} - k)$$

⇒ source isocurvatures



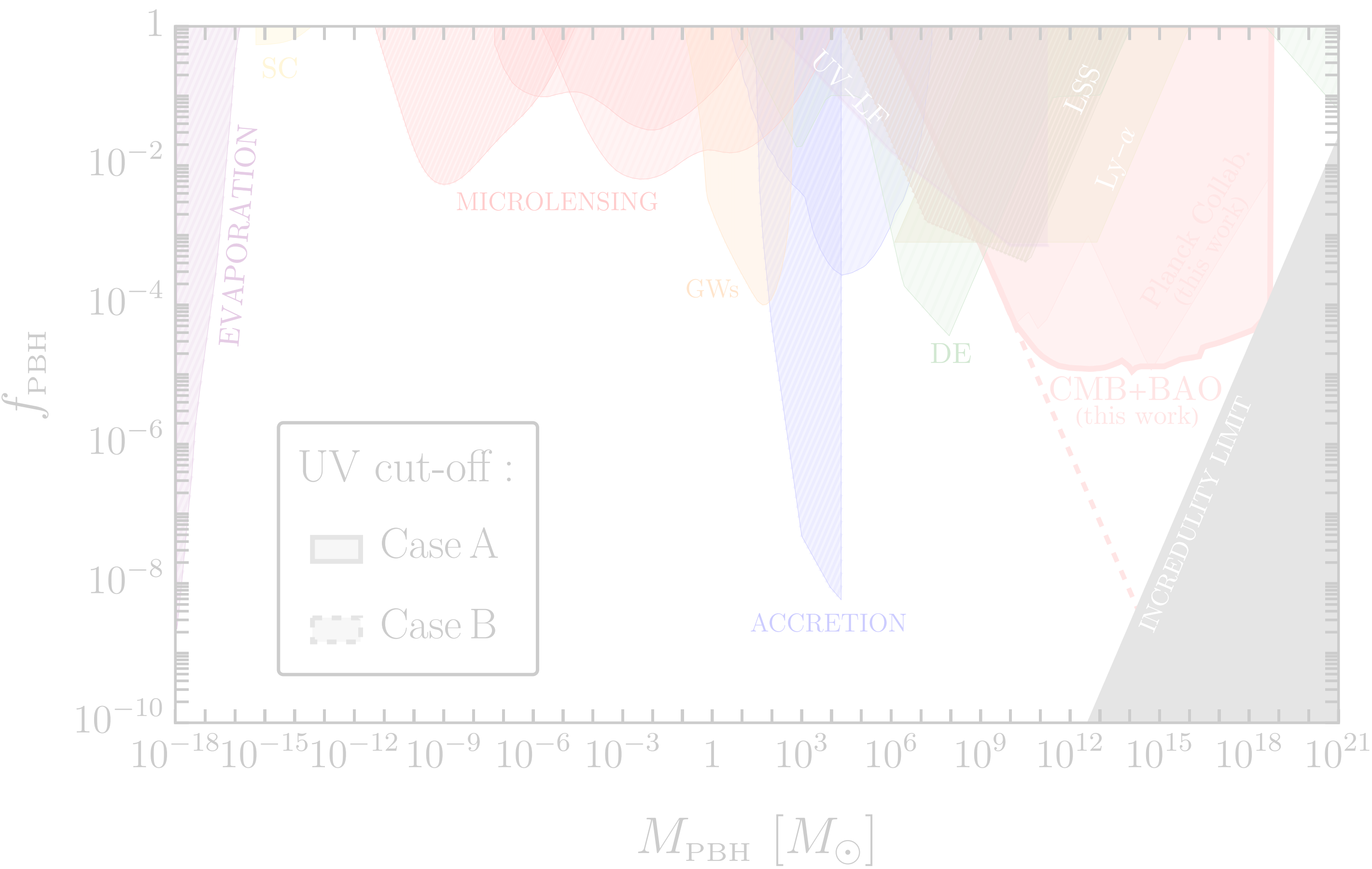
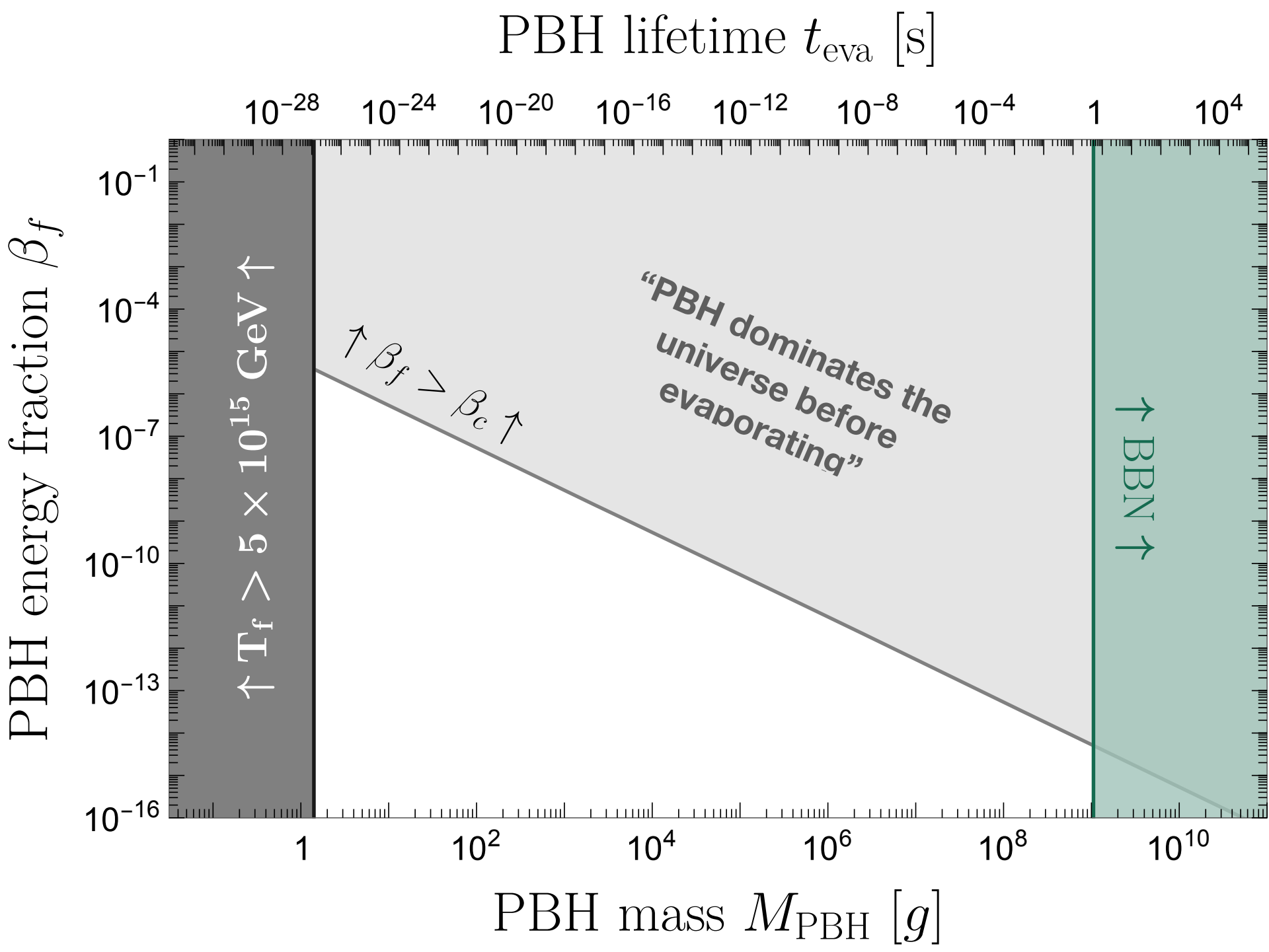
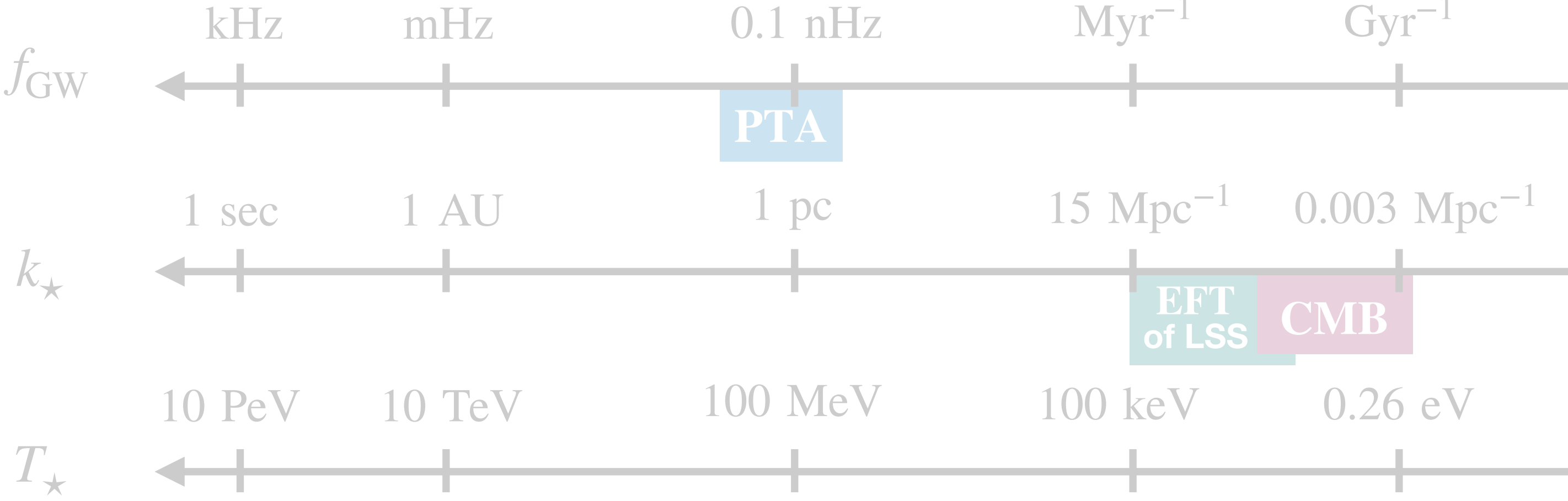
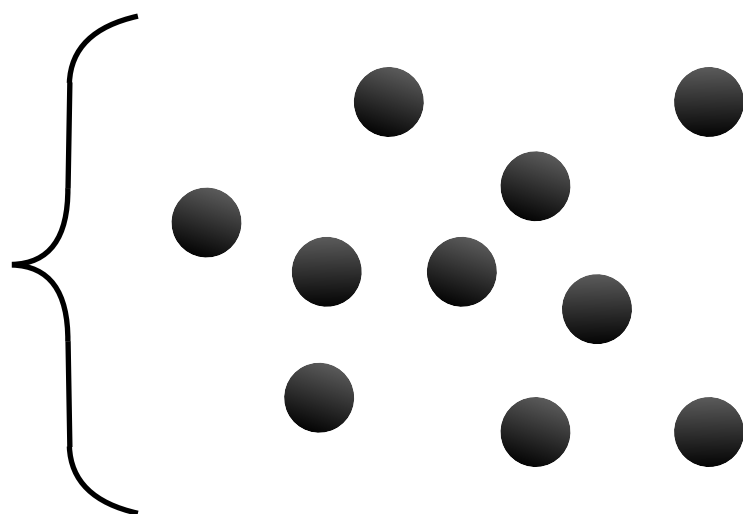
Ultra-light PBHs

Gas of
evaporating PBHs



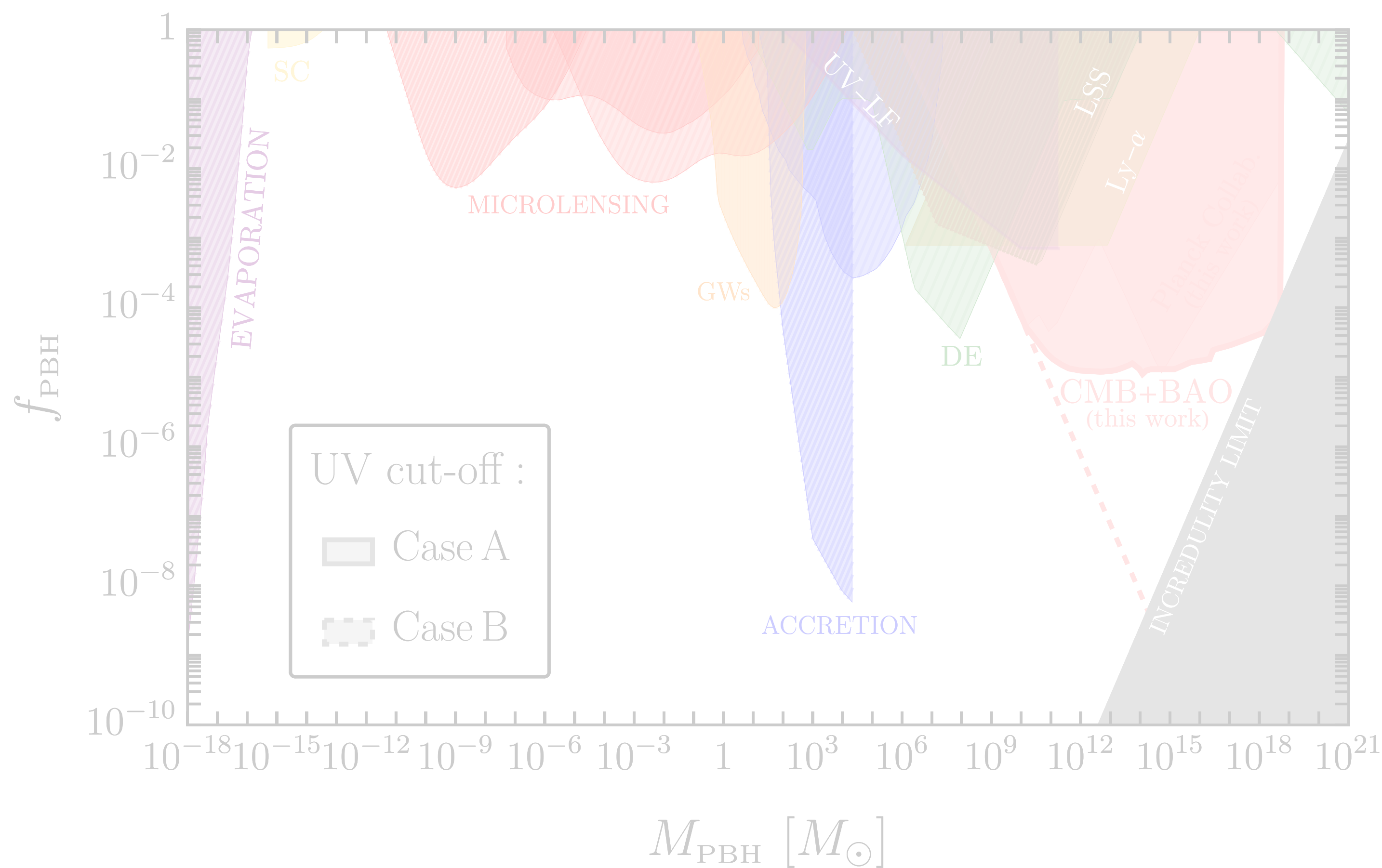
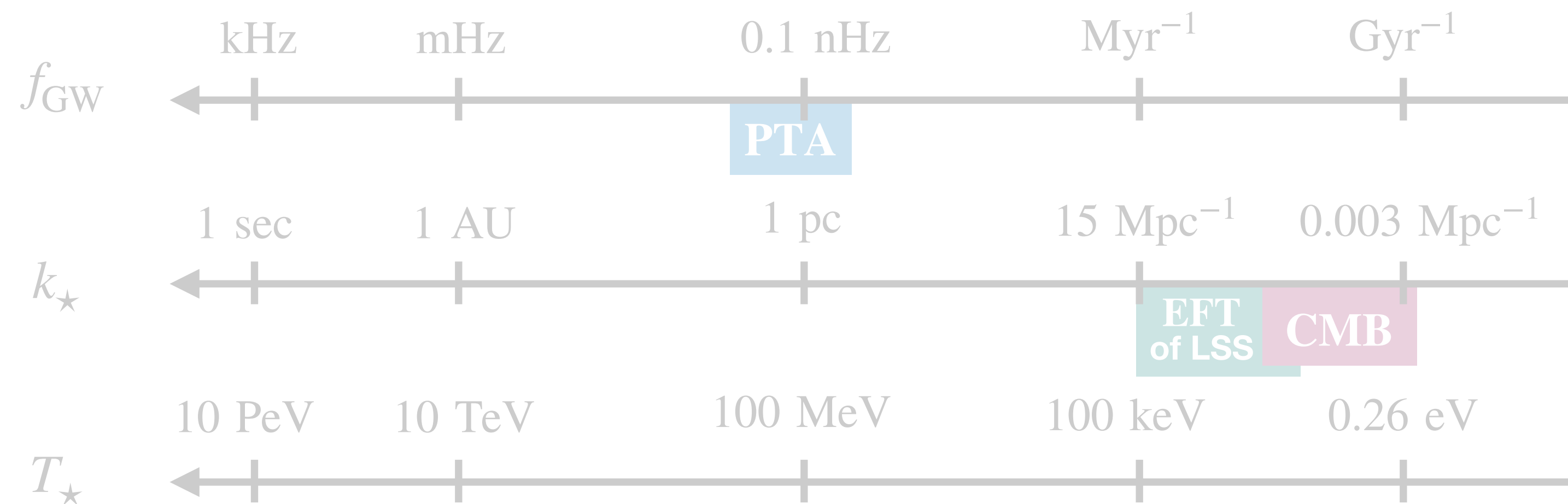
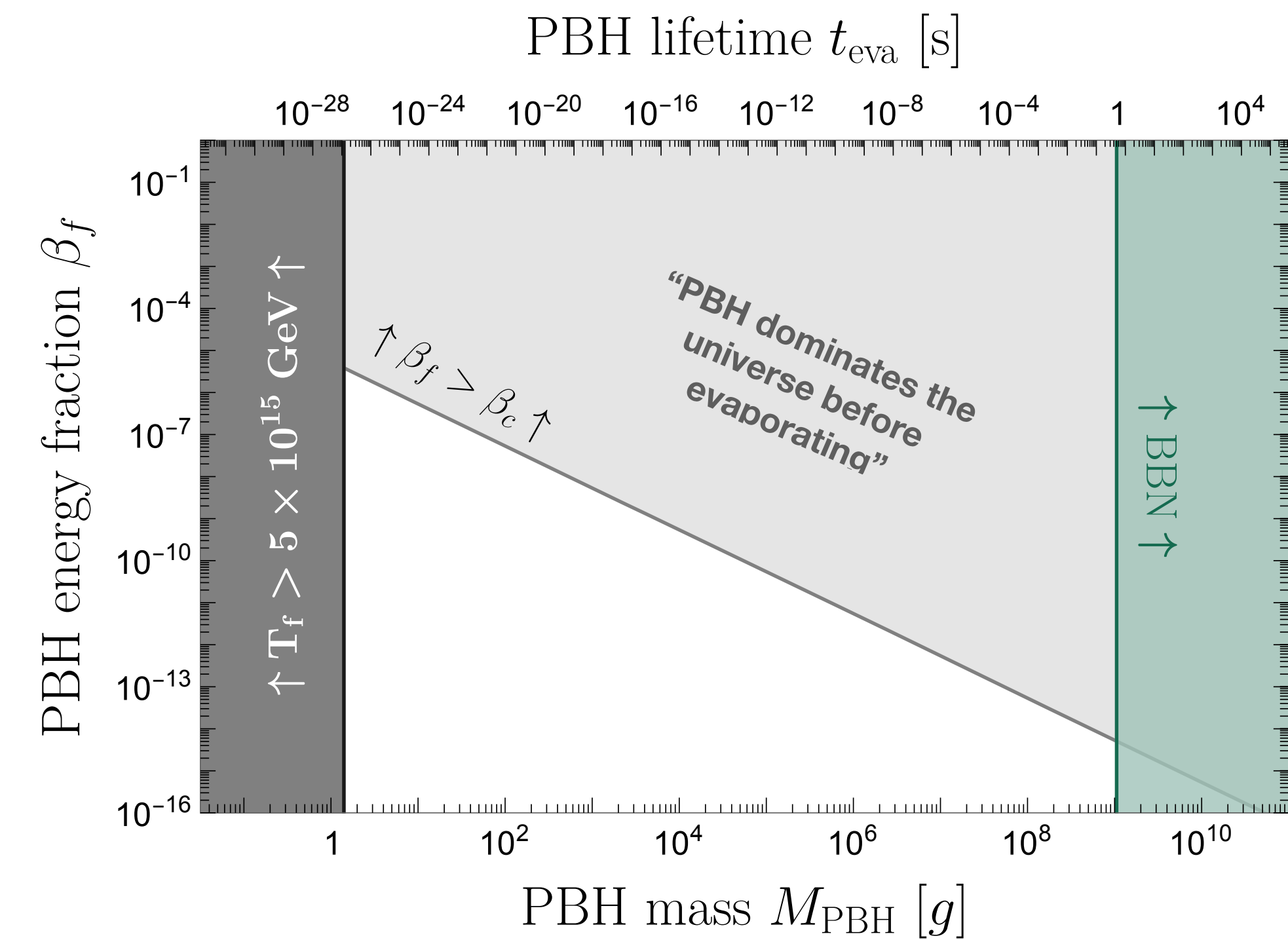
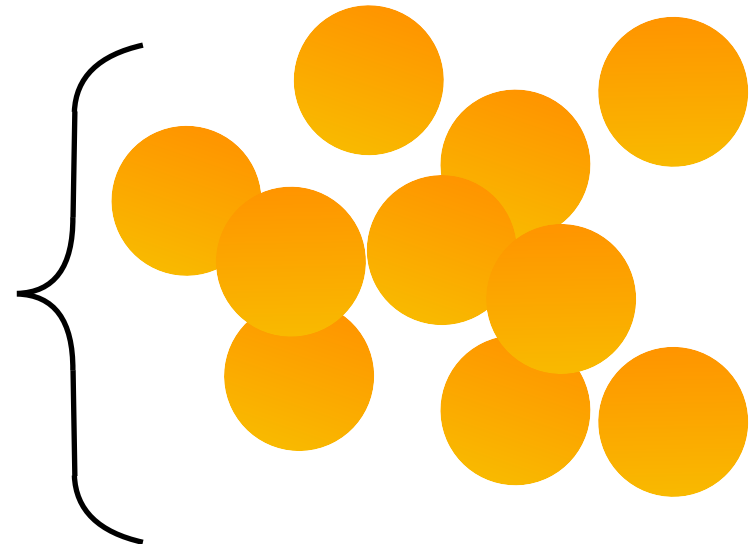
Ultra-light PBHs

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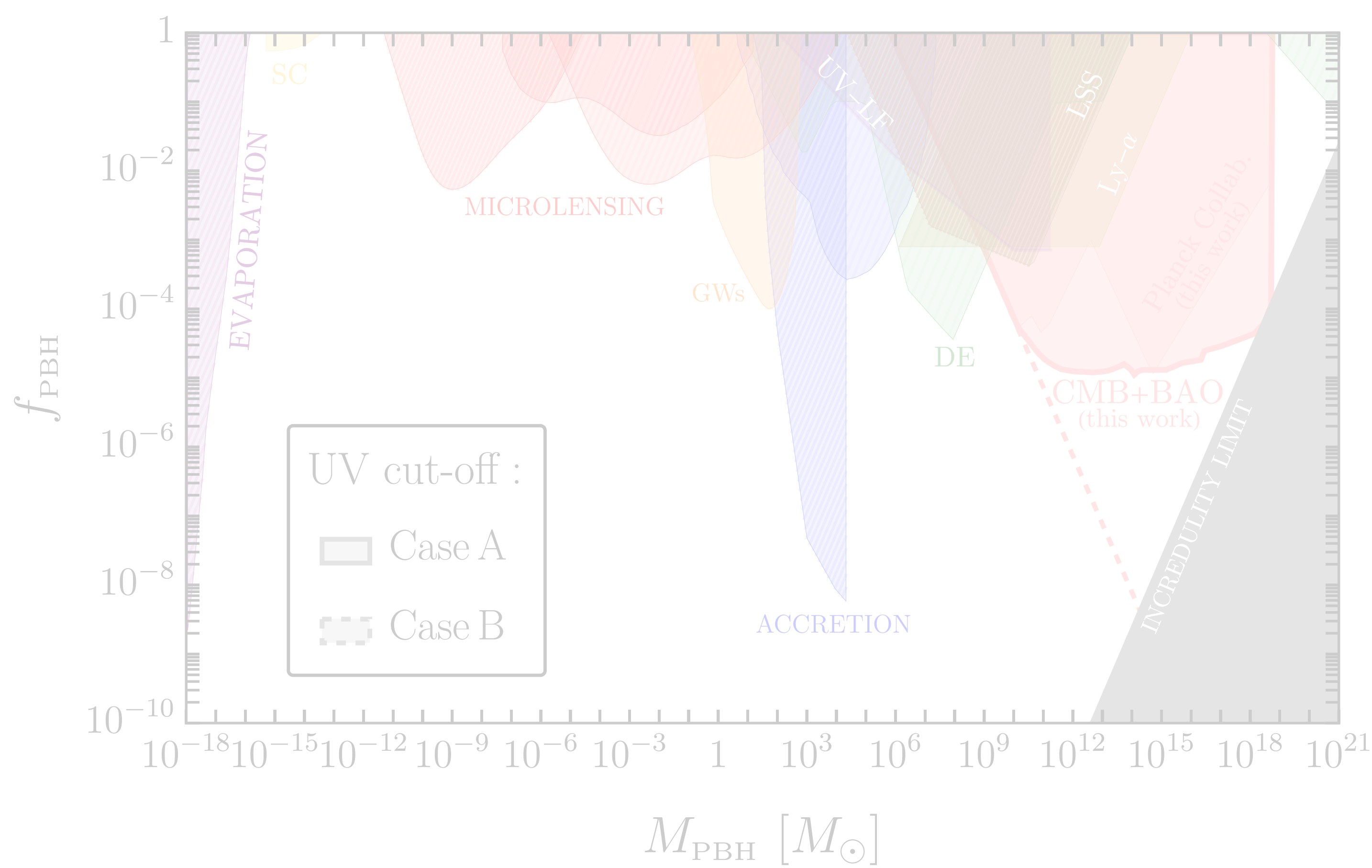
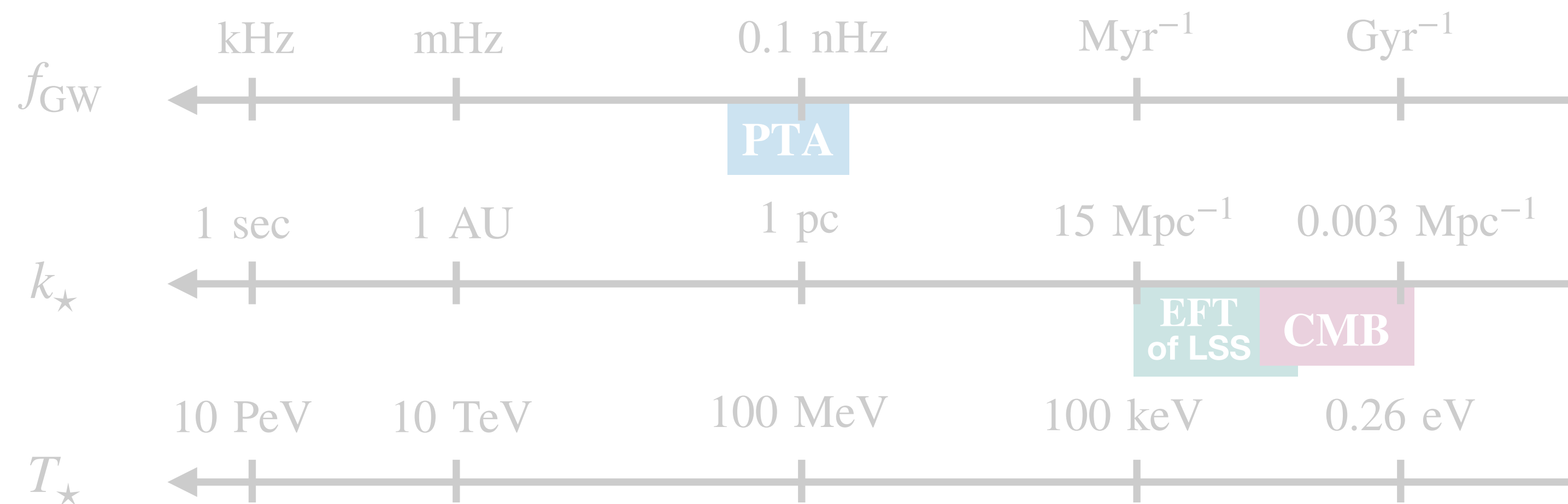
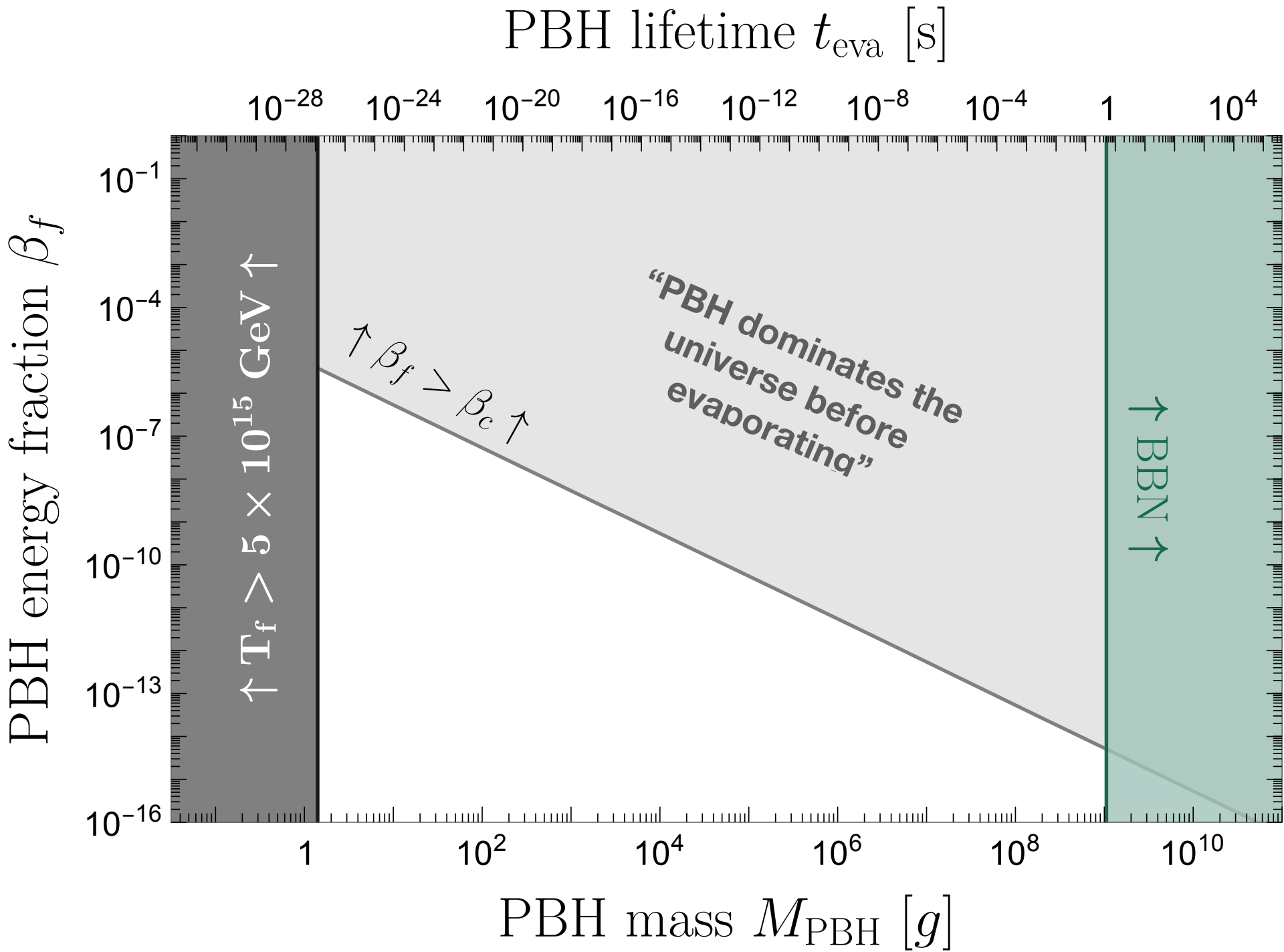
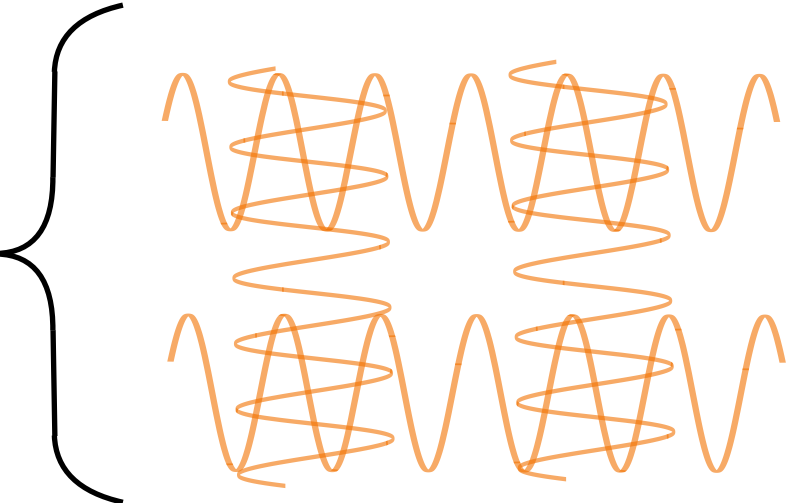
**Gas of
evaporating PBHs**

Evaporation



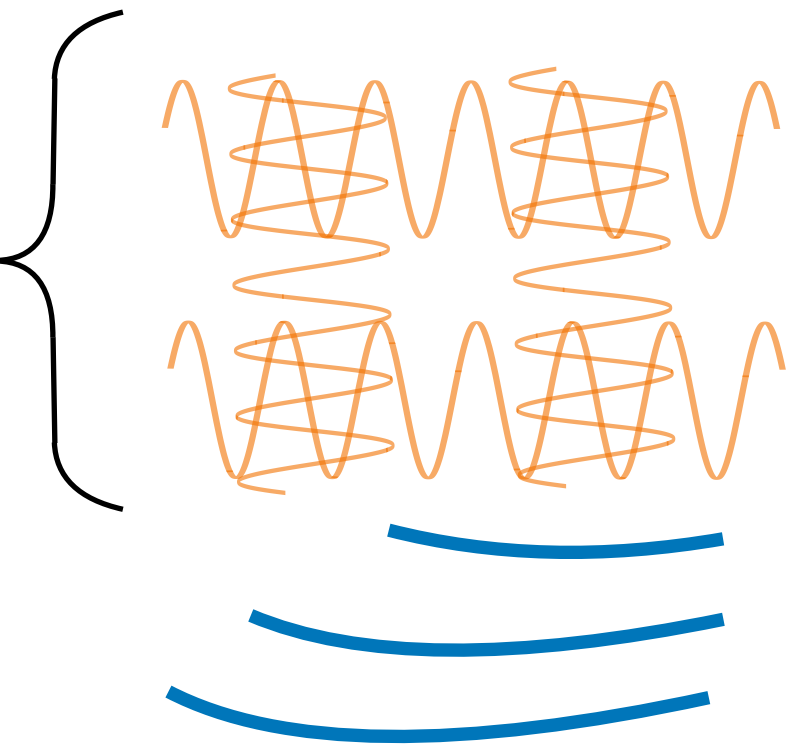
Evaporation $\Rightarrow$ Sound waves

Gas of
evaporating PBHs



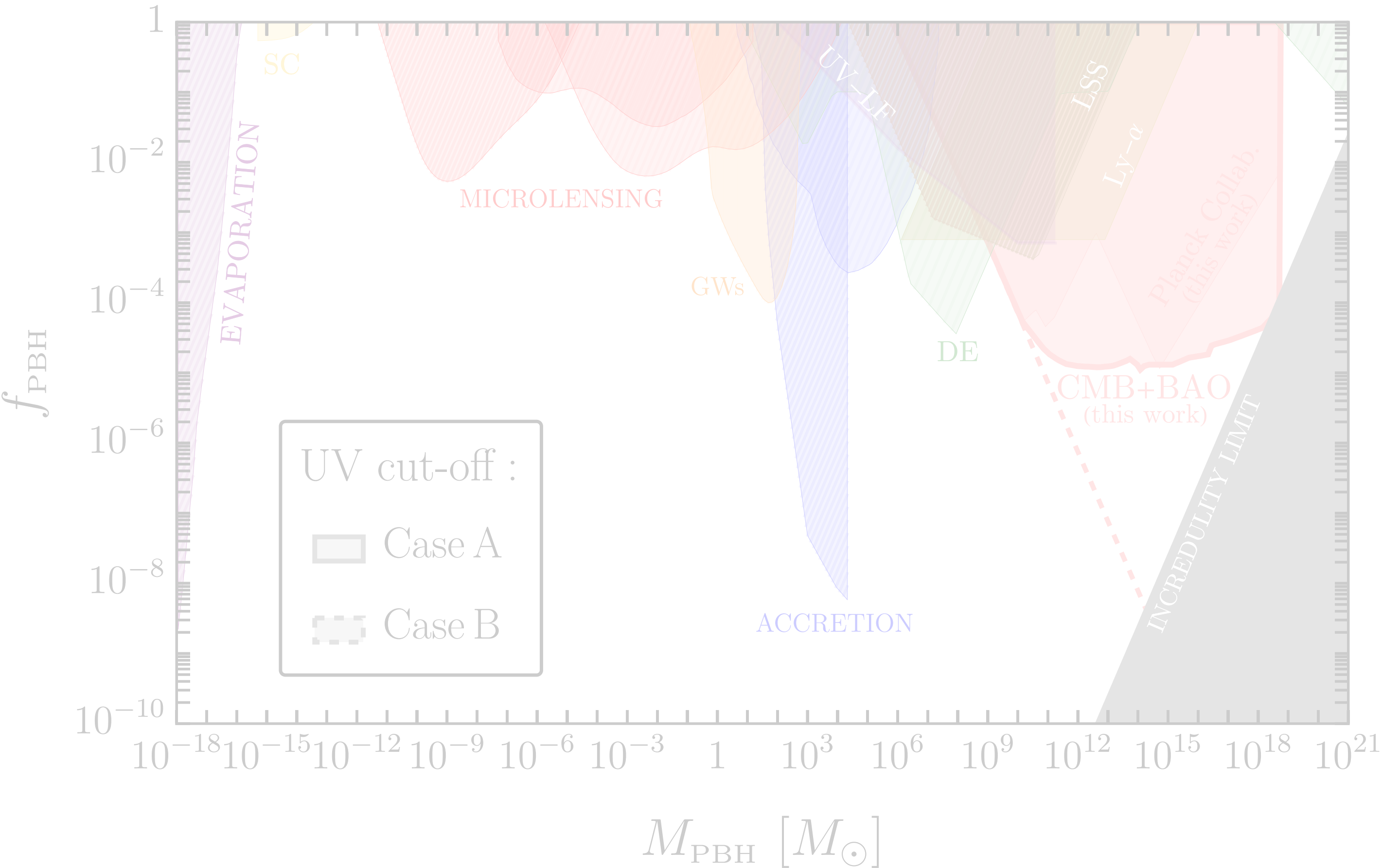
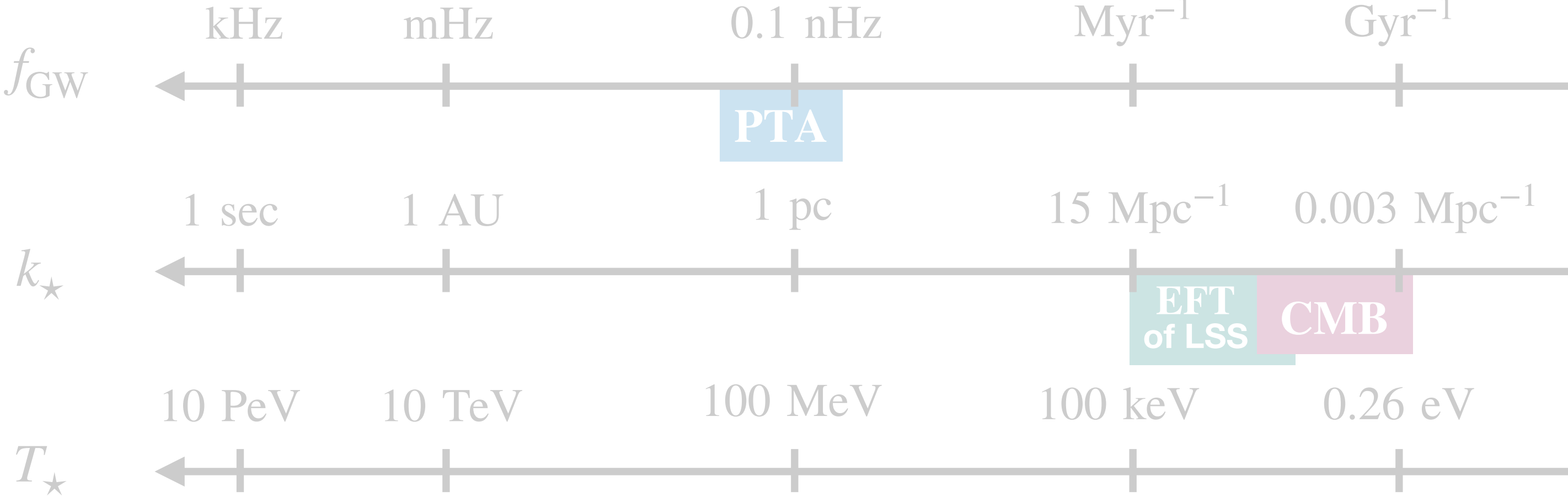
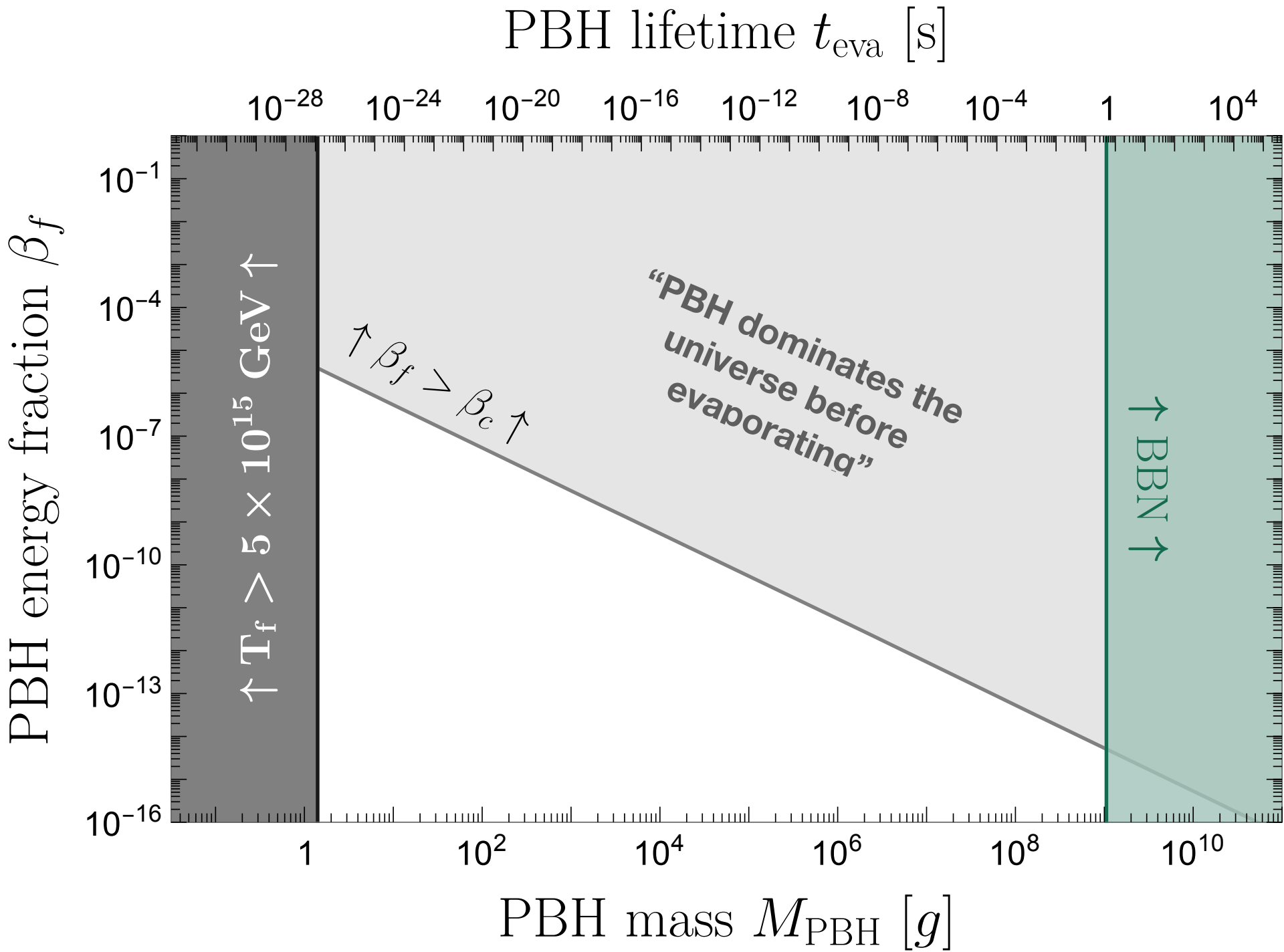
Evaporation $\Rightarrow$ Sound waves

Gas of
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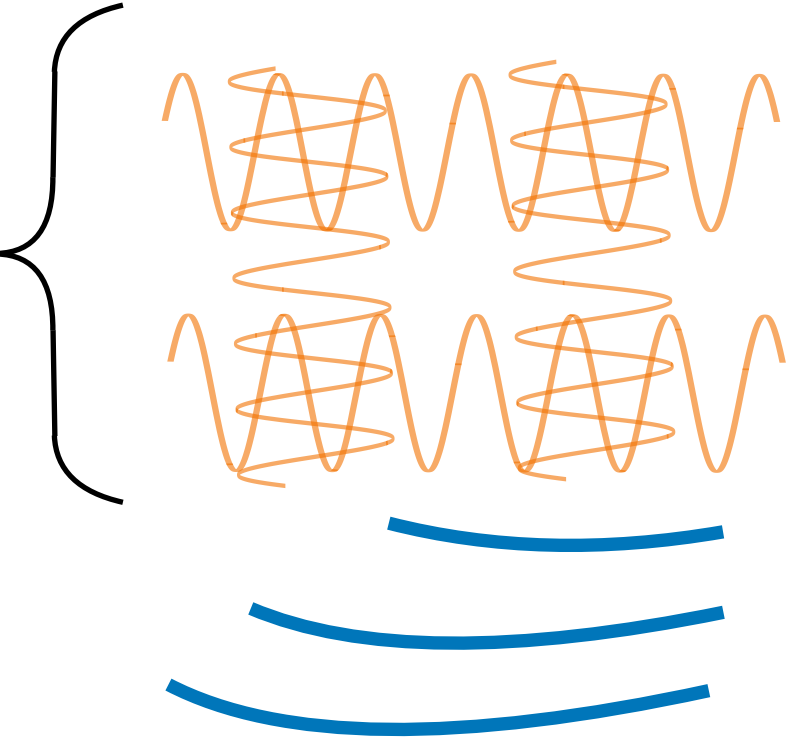
Poltergeist GWs

Inomata, Kawasaki,
Mukaida, Terada, Yanagida
(2003.10455)



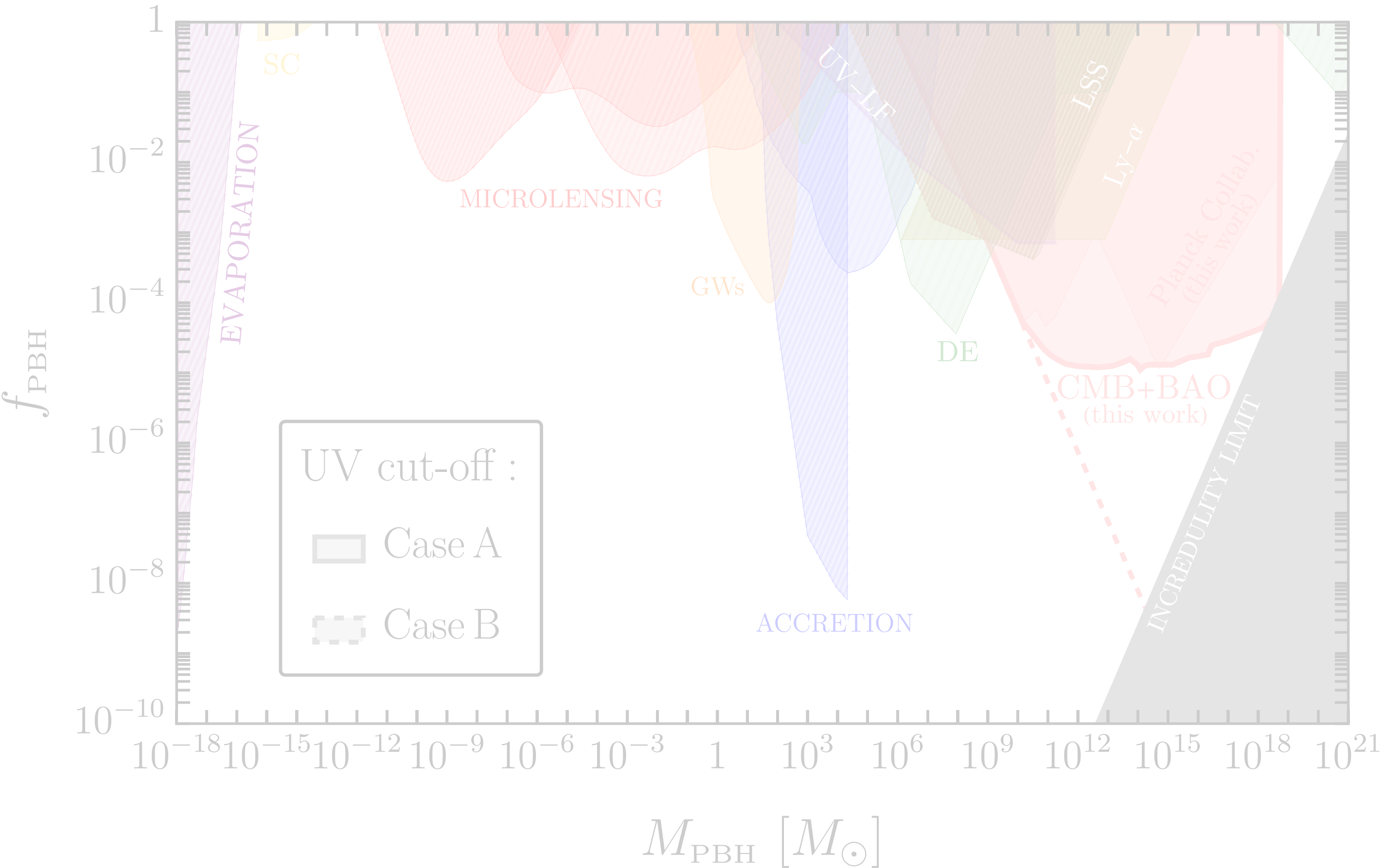
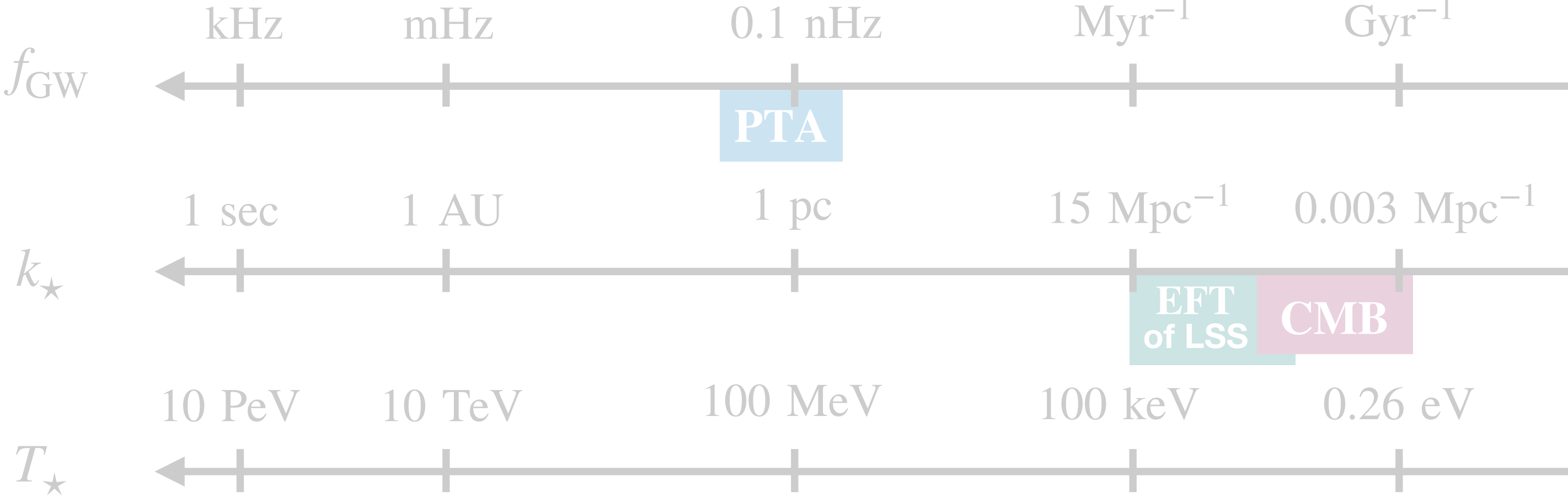
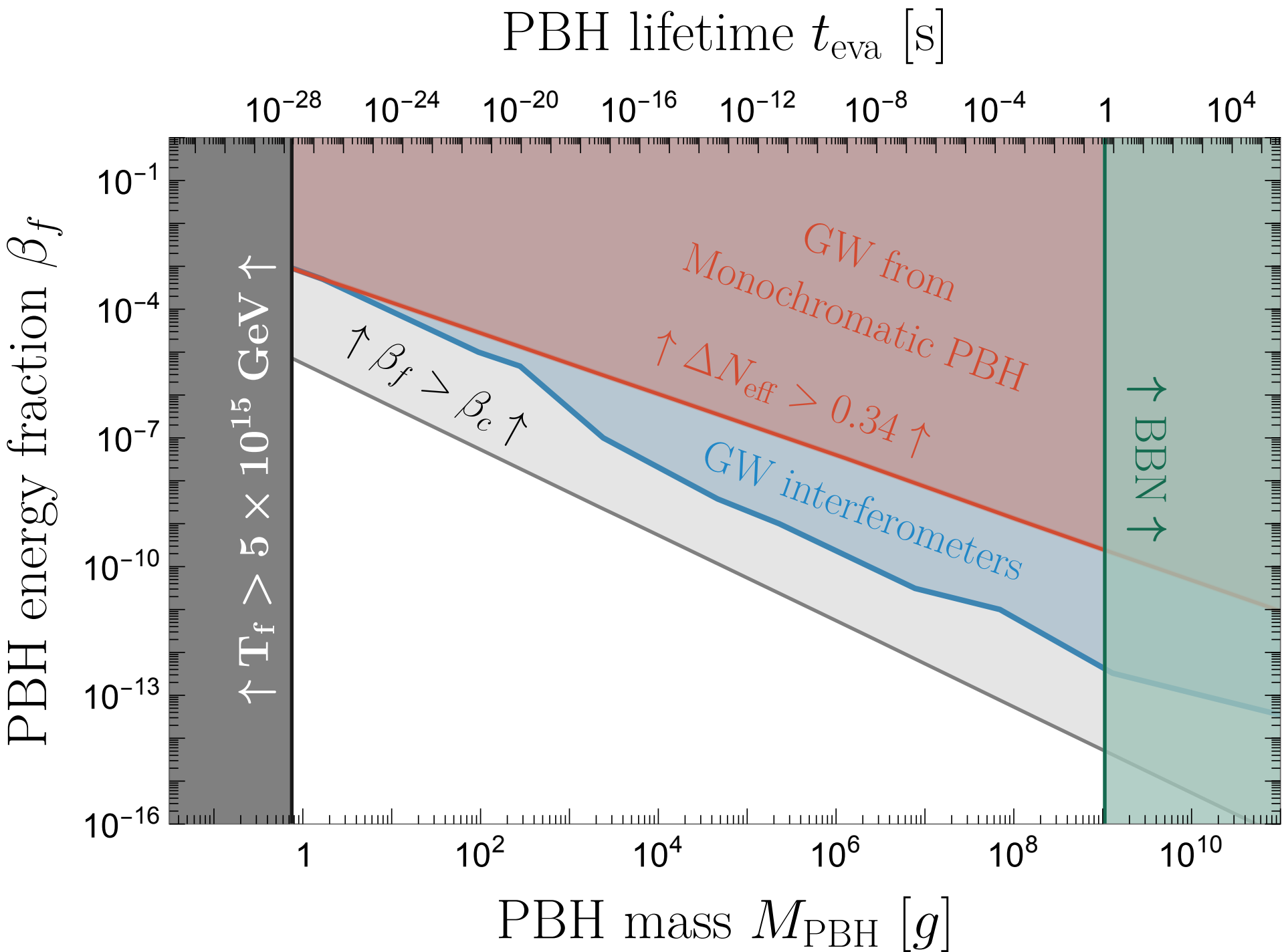
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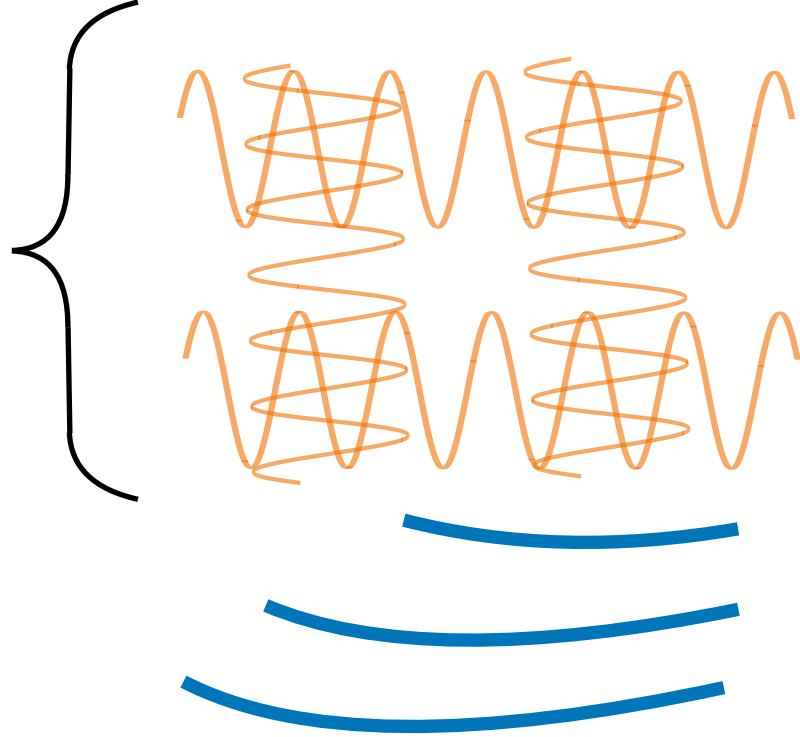
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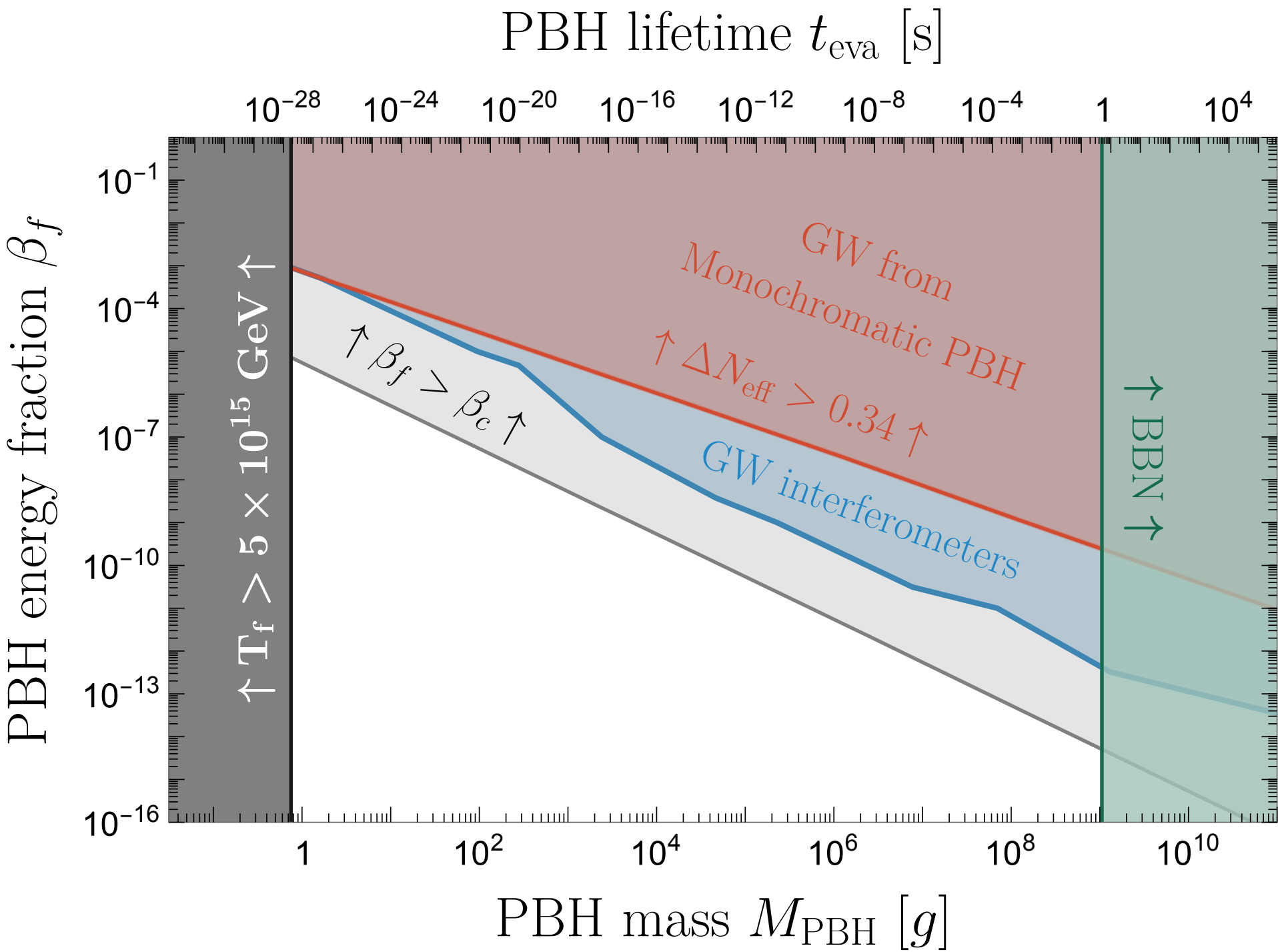
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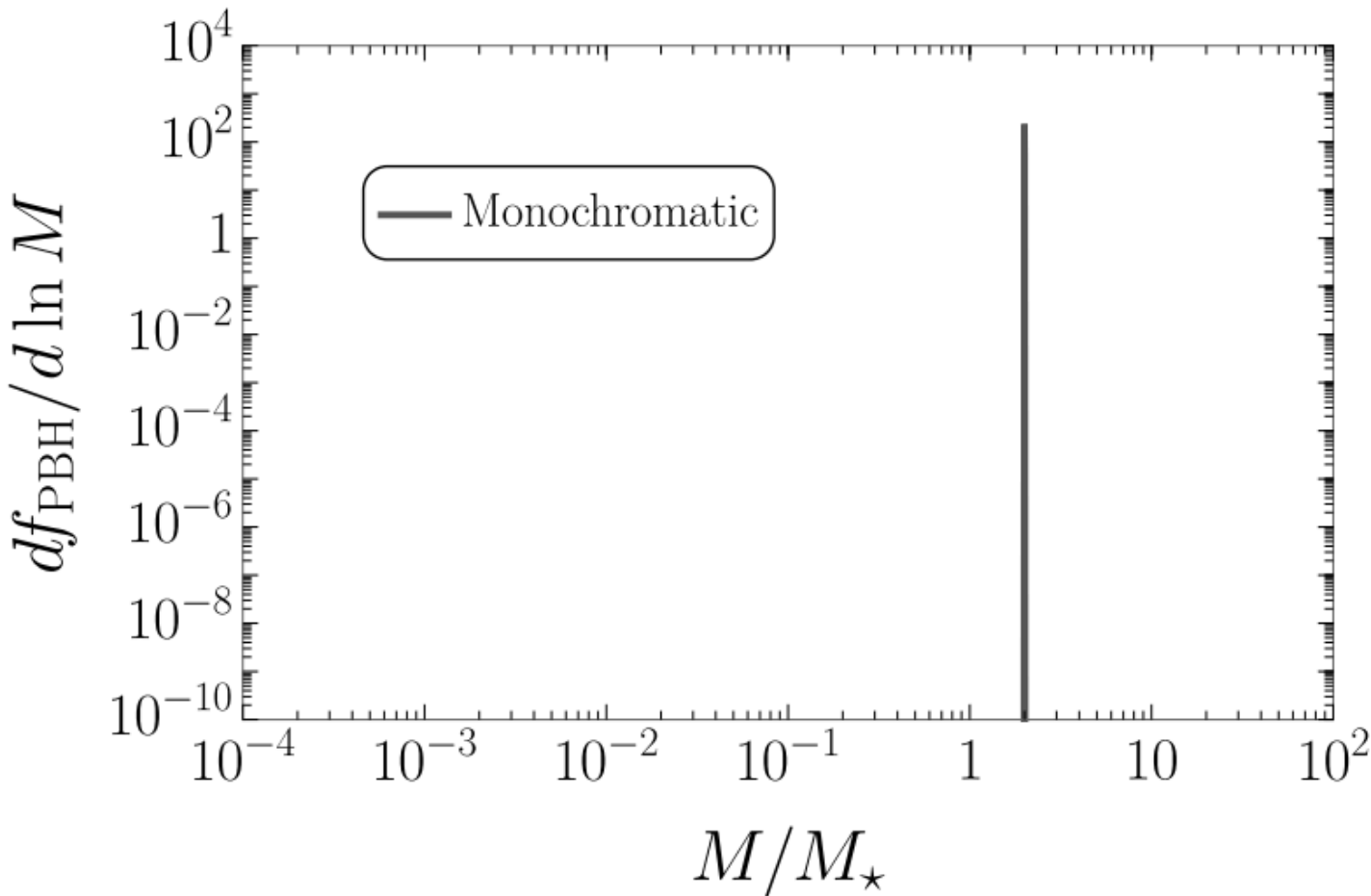


Opening the Window for Ultra-Light Primordial
Black Holes

In preparation (25XX.XXXX)

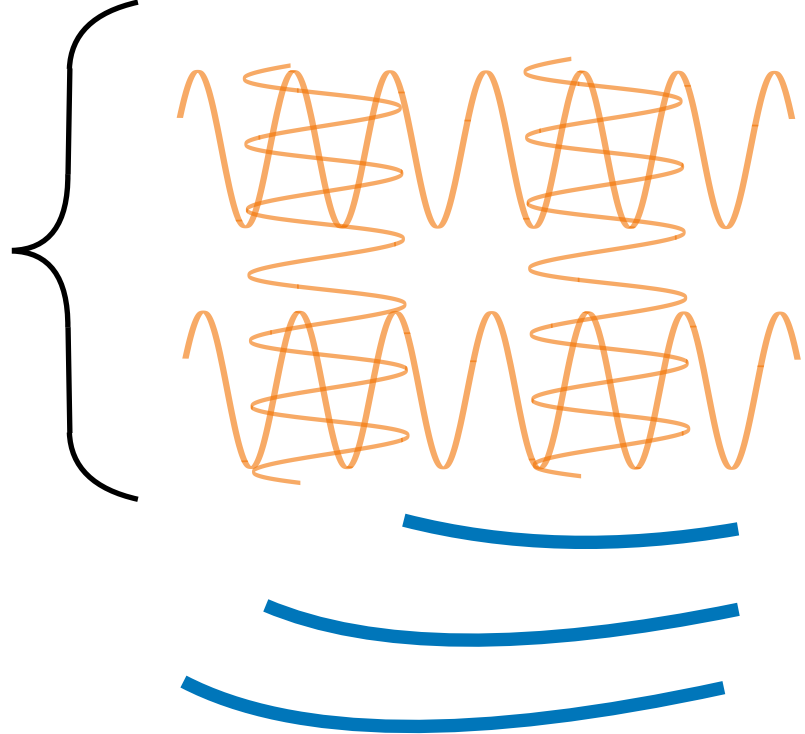
Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany



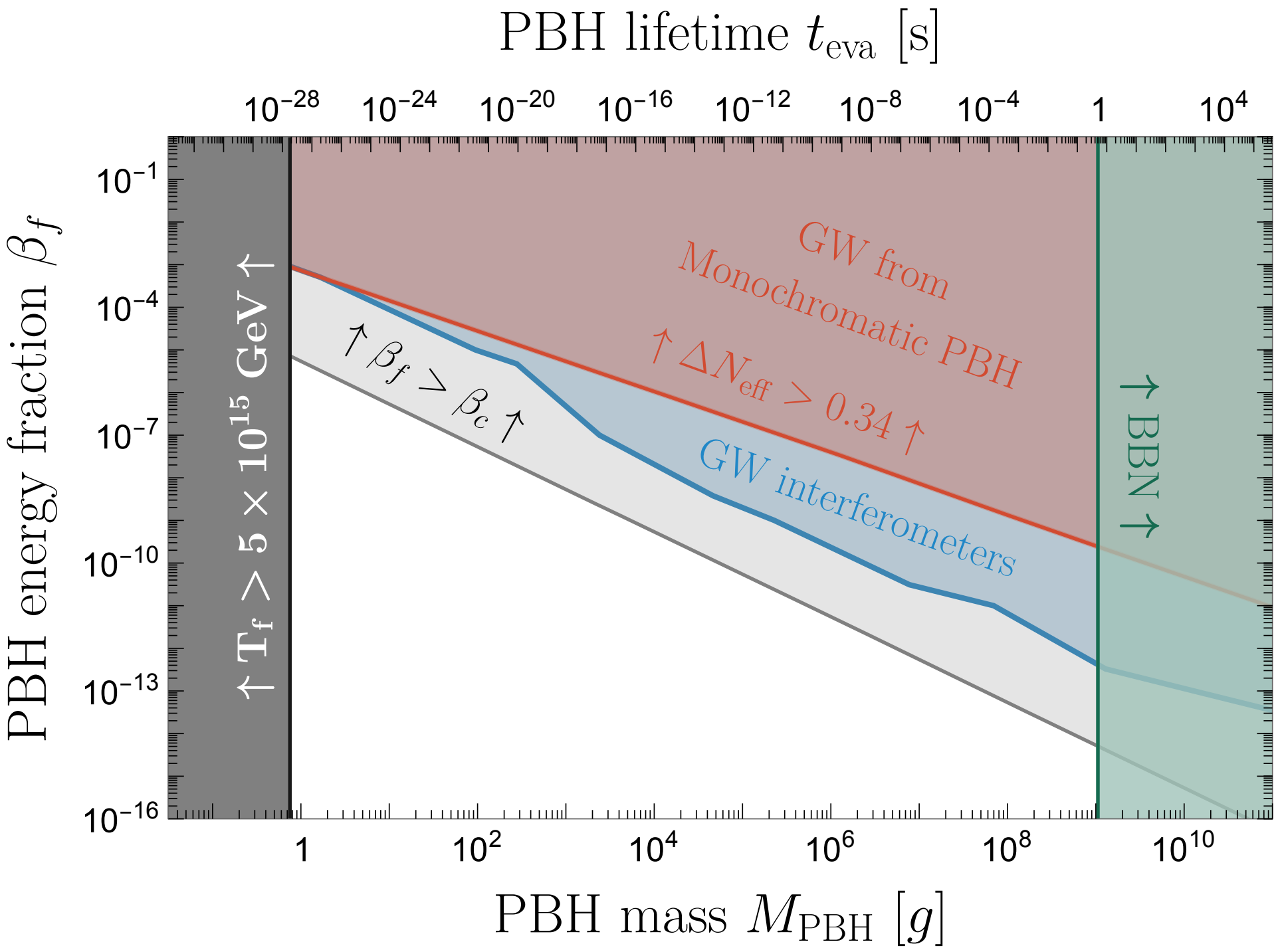
Evaporation $\Rightarrow$ Sound waves

Gas of
evaporating PBHs



Poltergeist GWs

Inomata, Kawasaki,
Mukaida, Terada, Yanagida
(2003.10455)

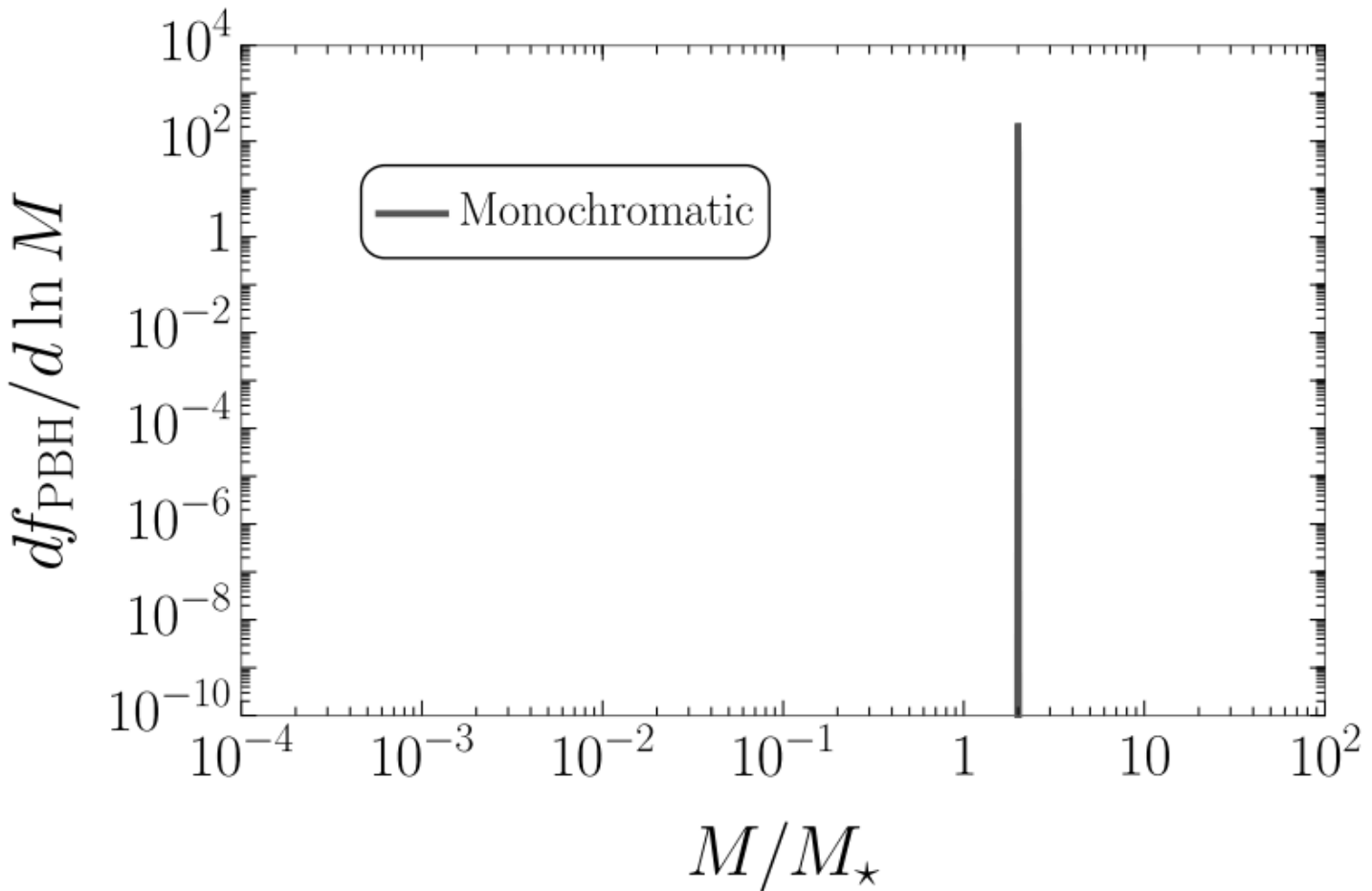
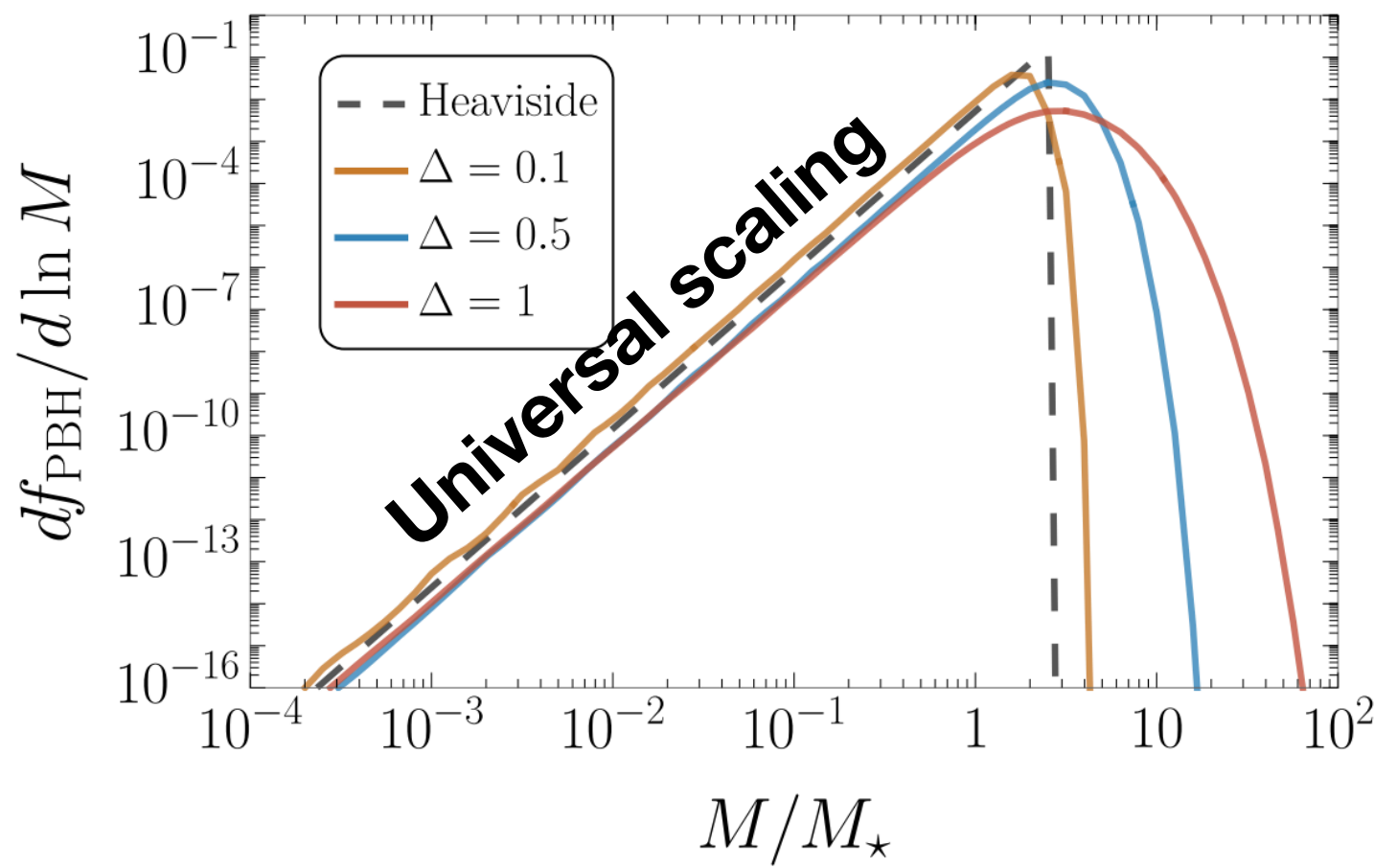


Opening the Window for Ultra-Light Primordial Black Holes

In preparation (25XX.XXXX)

Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany



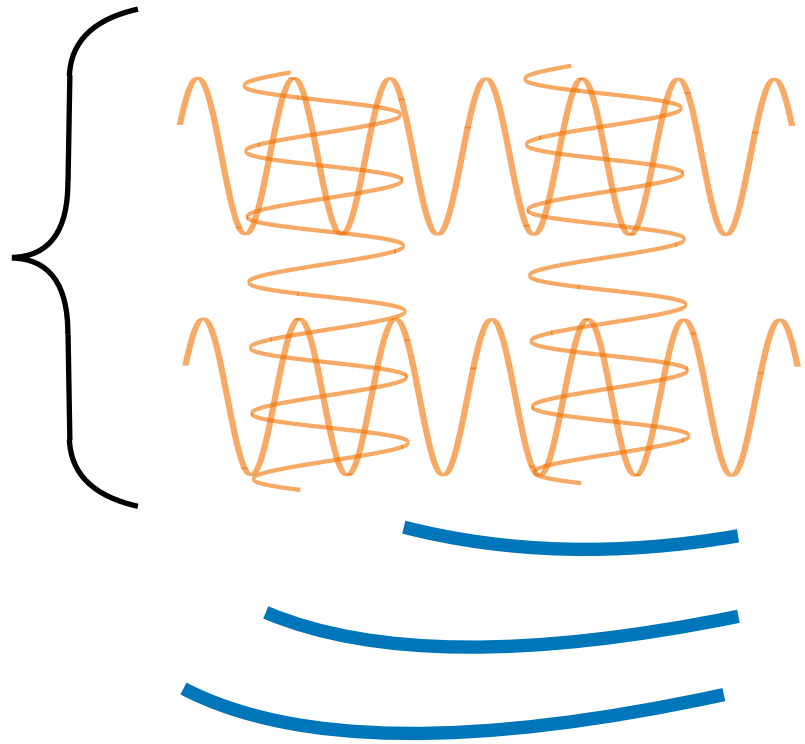
$$\frac{df_{\text{PBH}}}{d \log M} \propto M^{1+1/\gamma}$$

$\gamma \simeq 0.36$

Choptuik's law
(Choptuik 93')

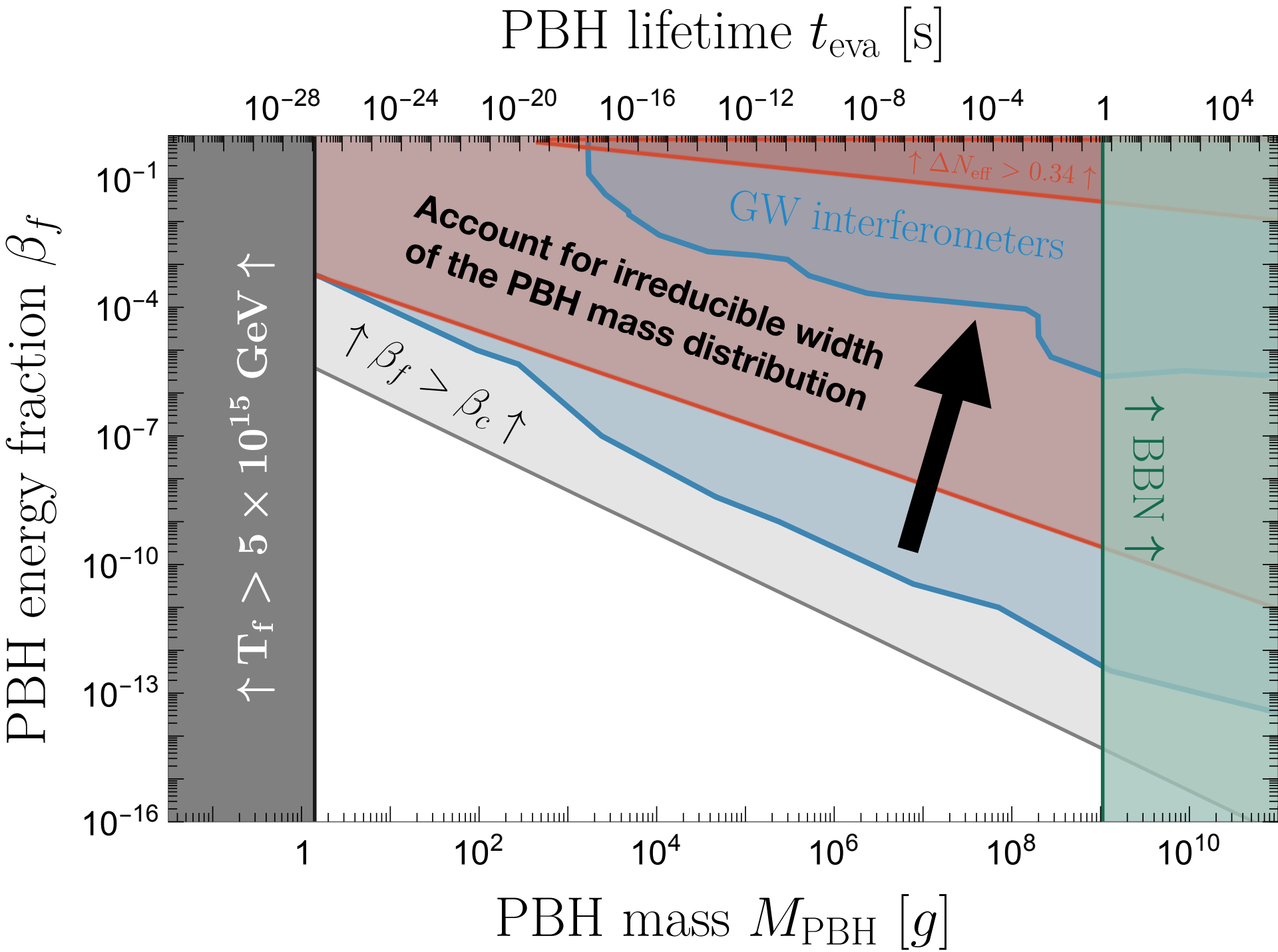
Evaporation $\Rightarrow$ Sound waves

Gas of
evaporating PBHs



Poltergeist GWs

Inomata, Kawasaki,
Mukaida, Terada, Yanagida
(2003.10455)

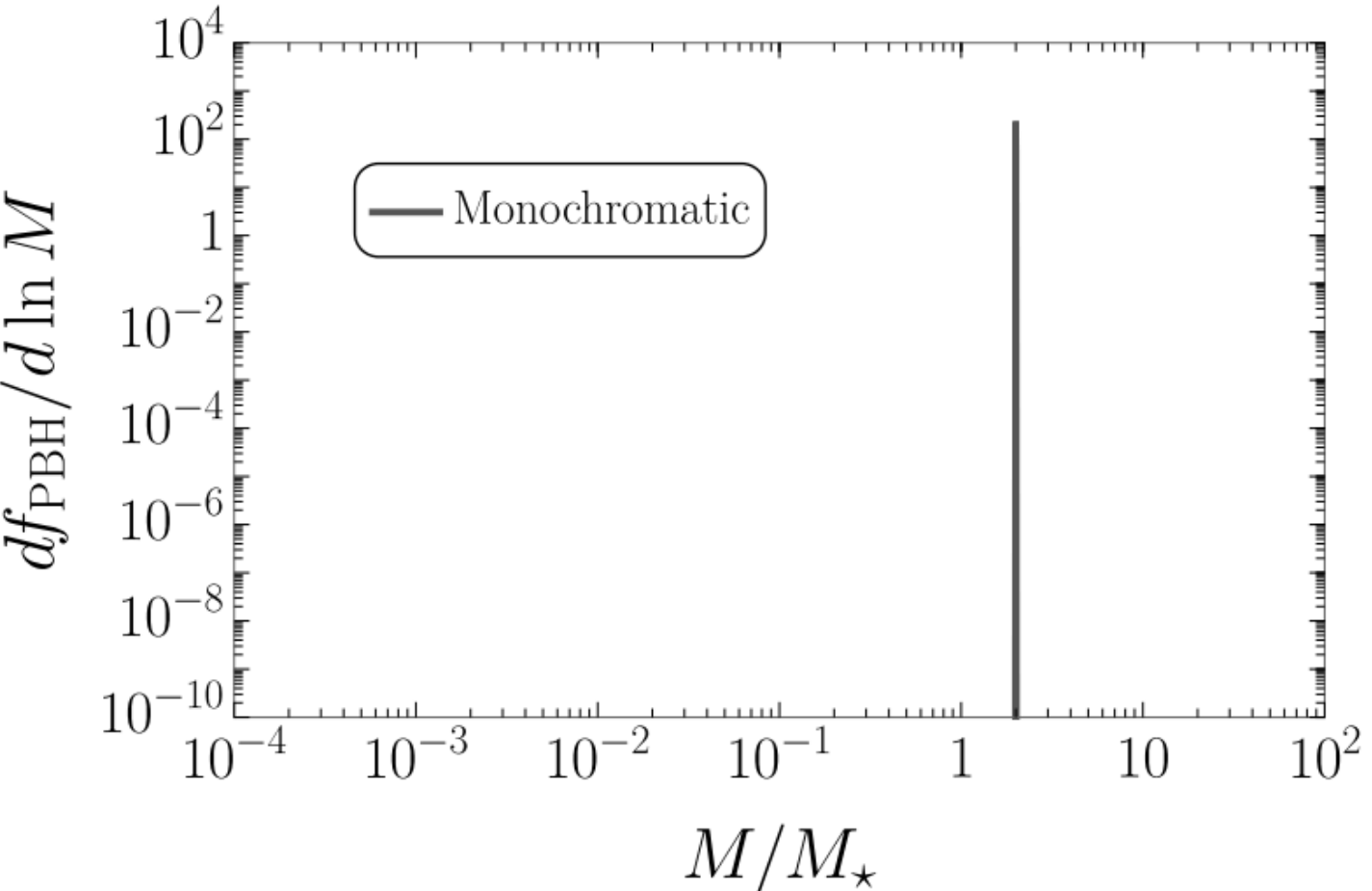
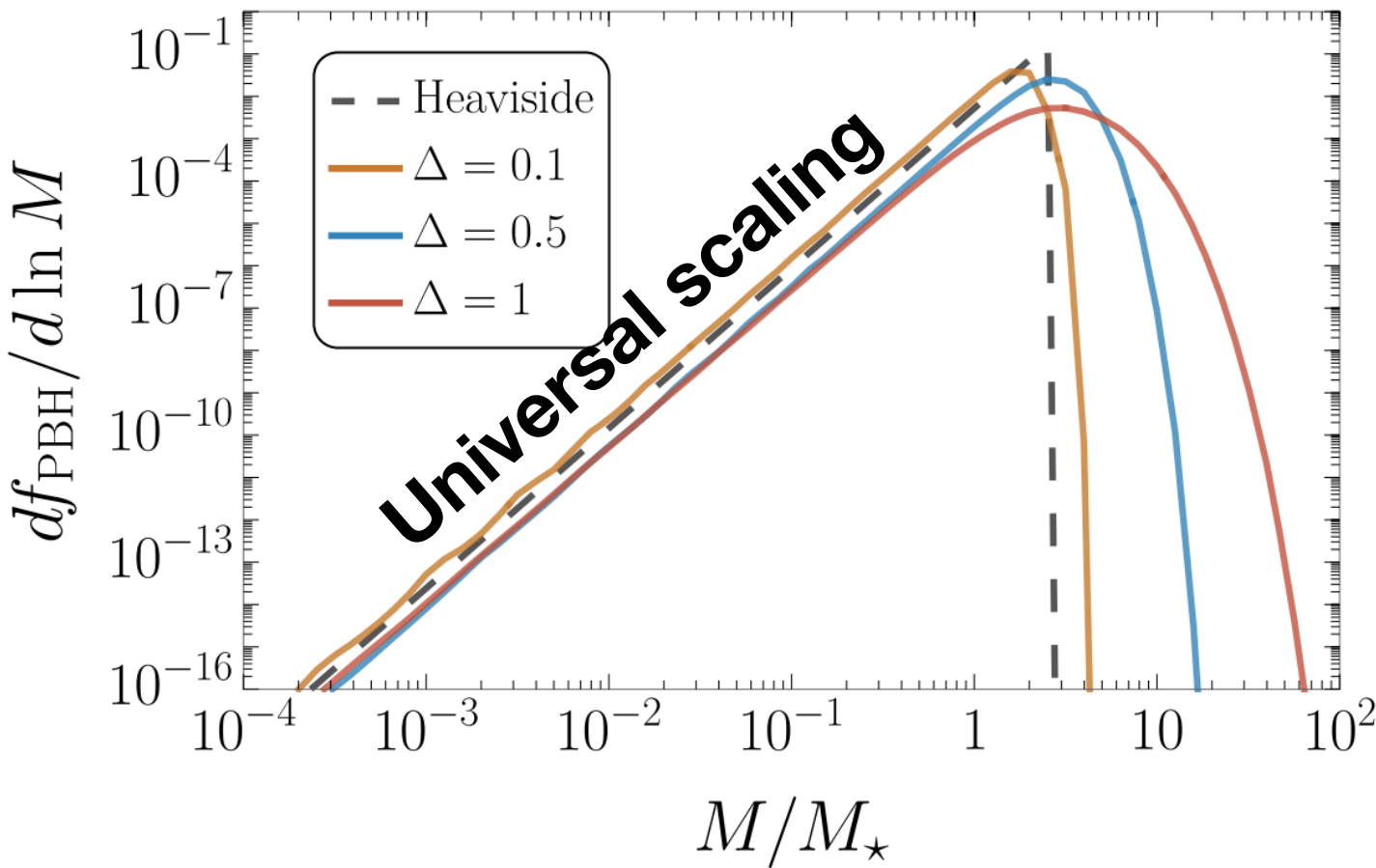


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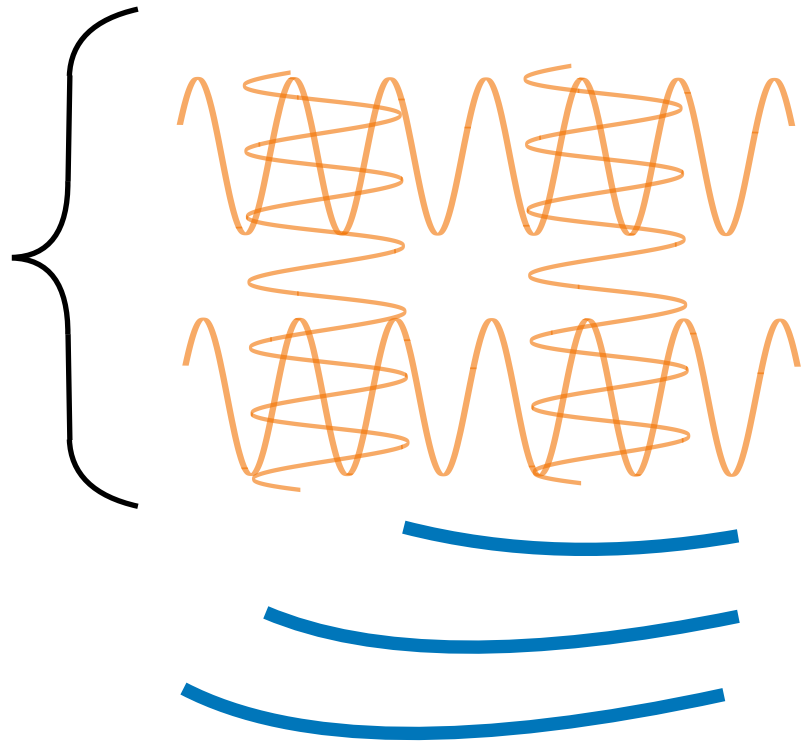
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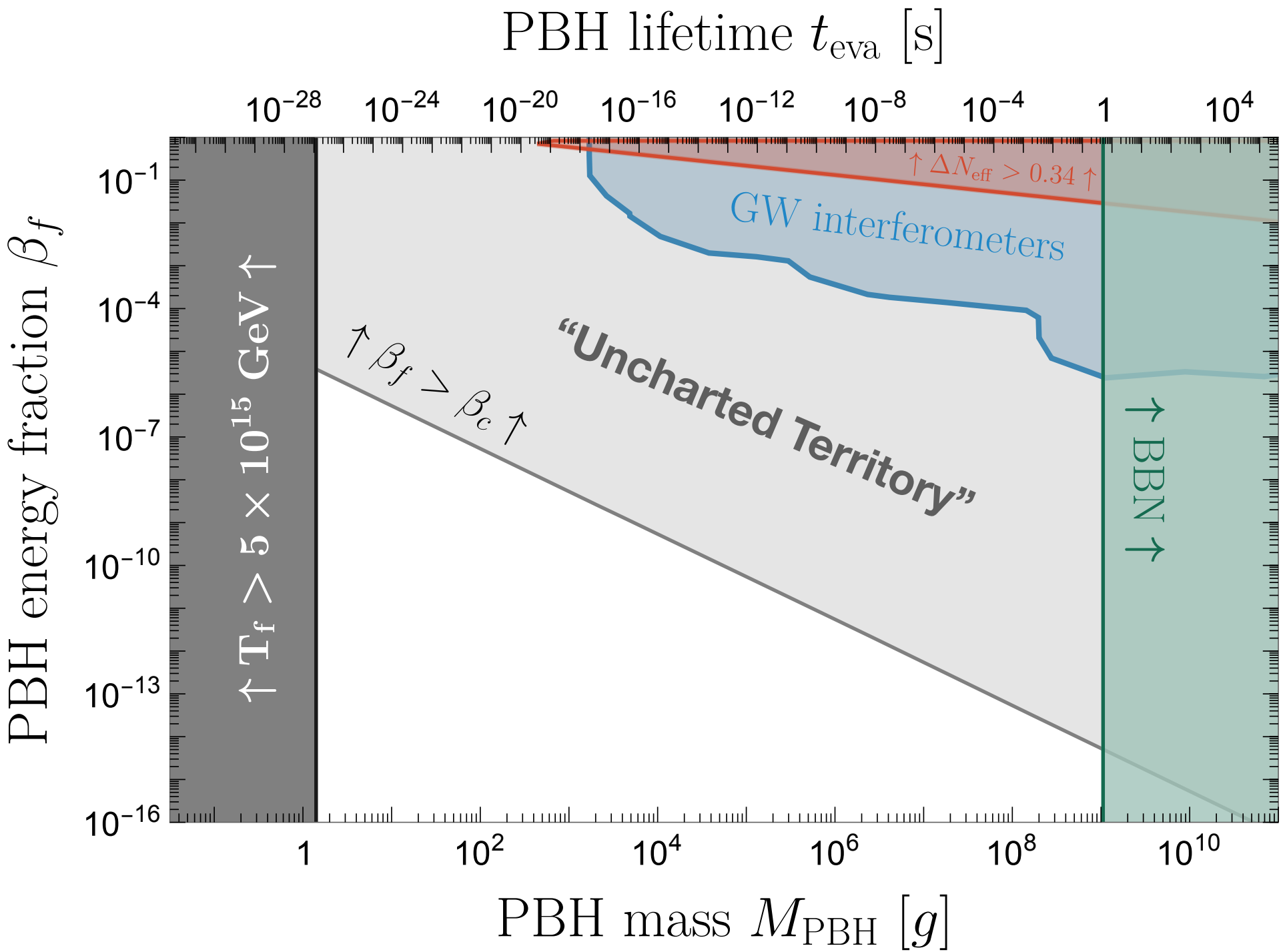
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Poltergeist GWs

Inomata, Kawasaki,
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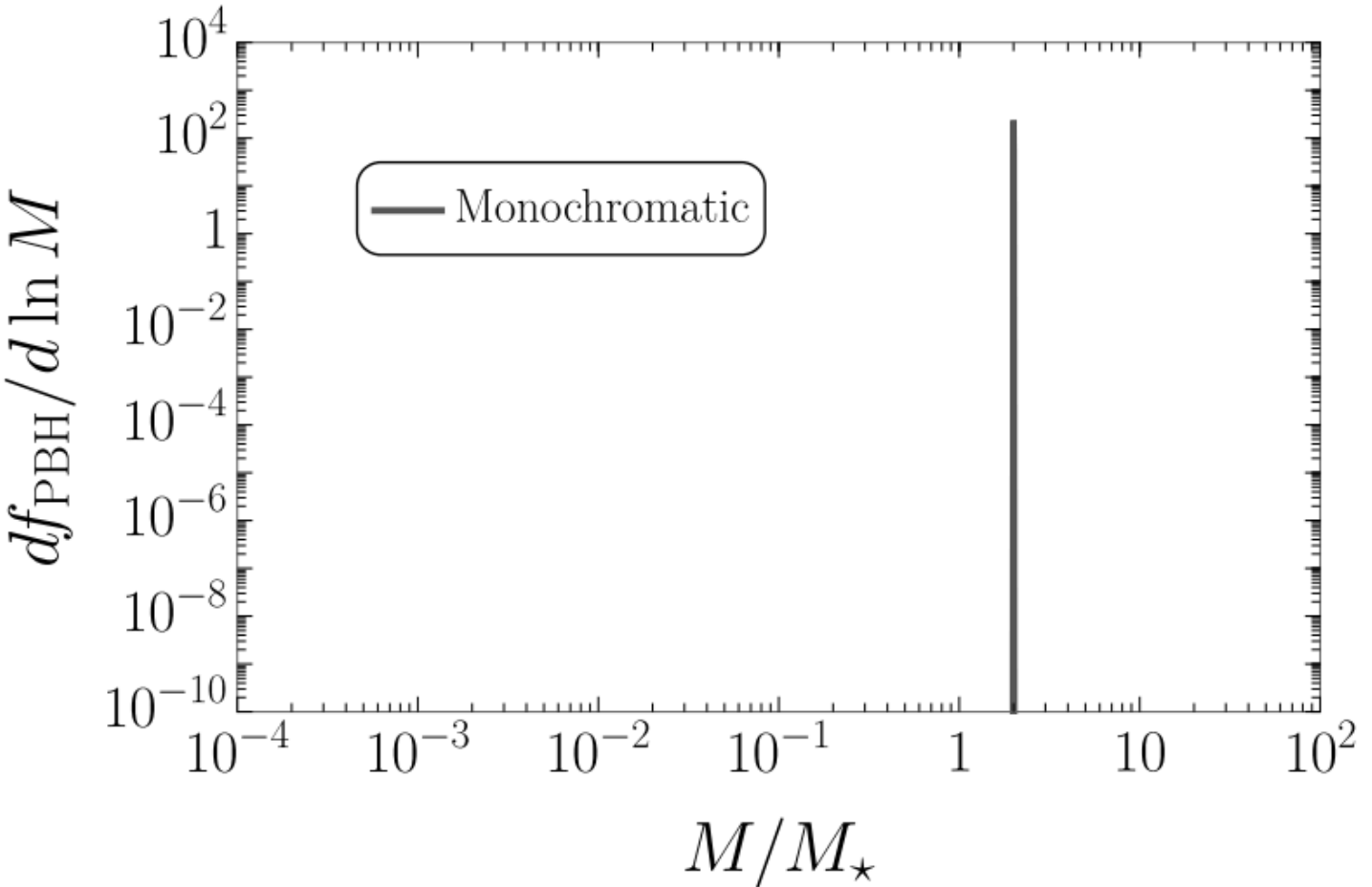
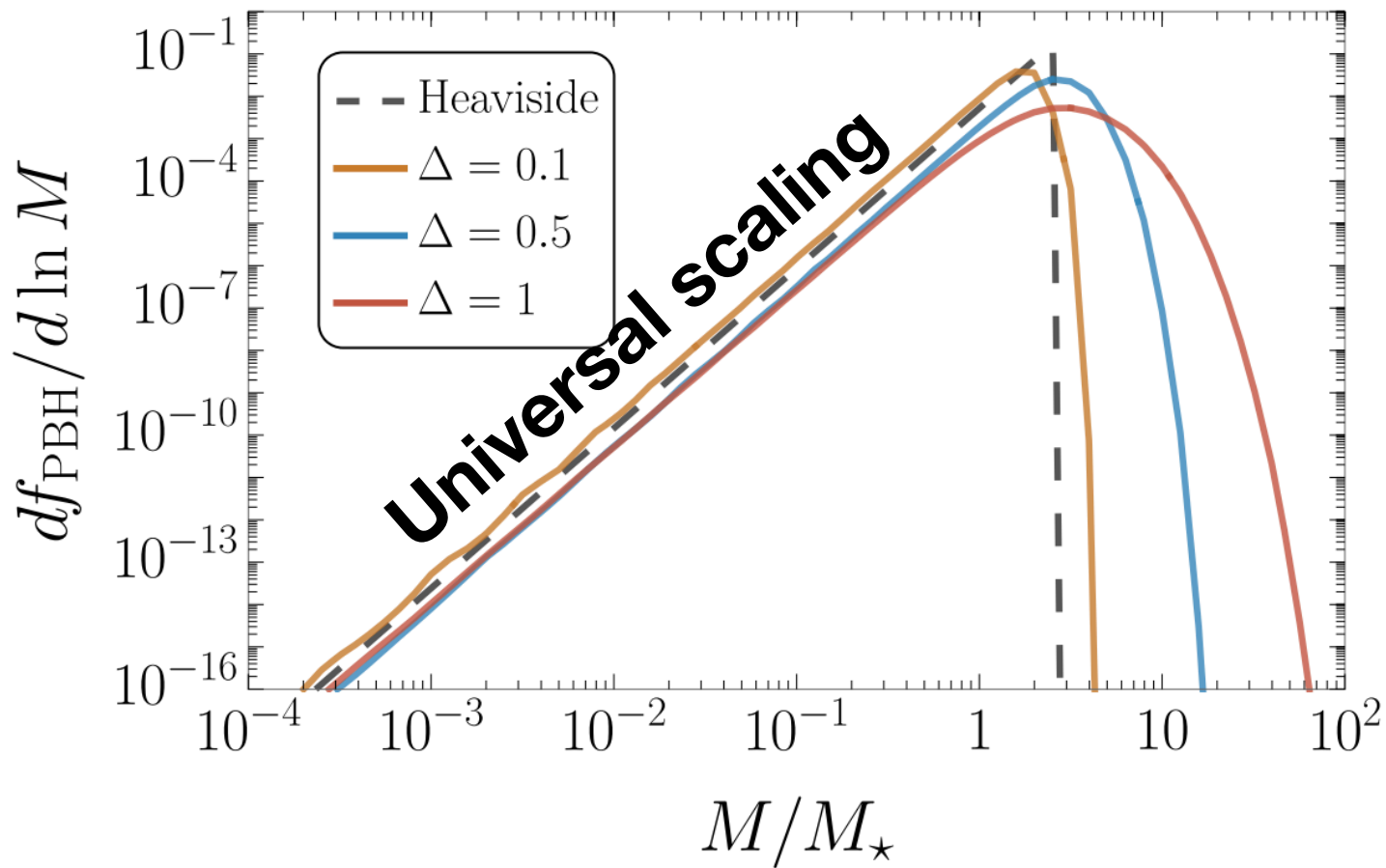


Opening the Window for Ultra-Light Primordial
Black Holes

In preparation (25XX.XXXX)

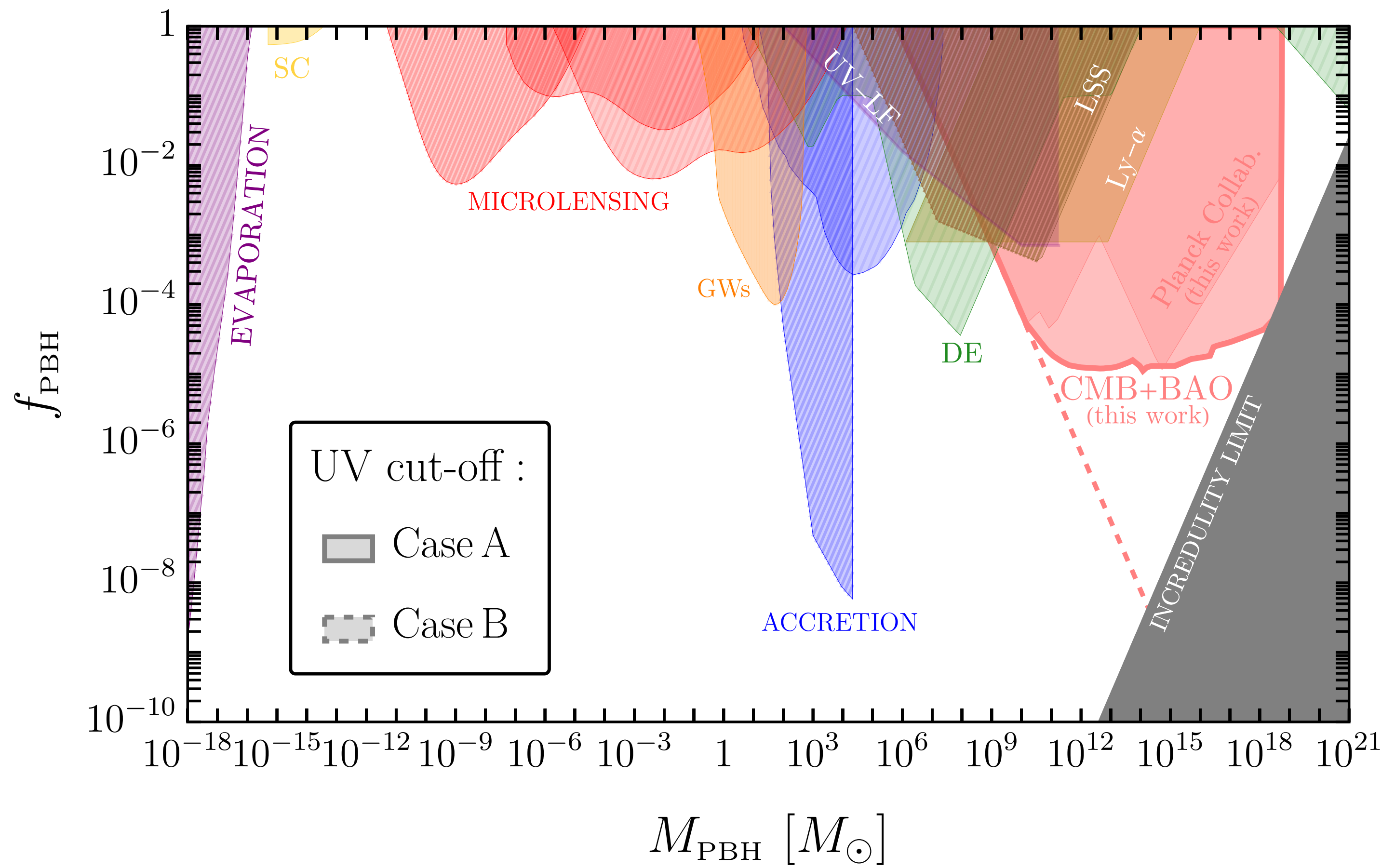
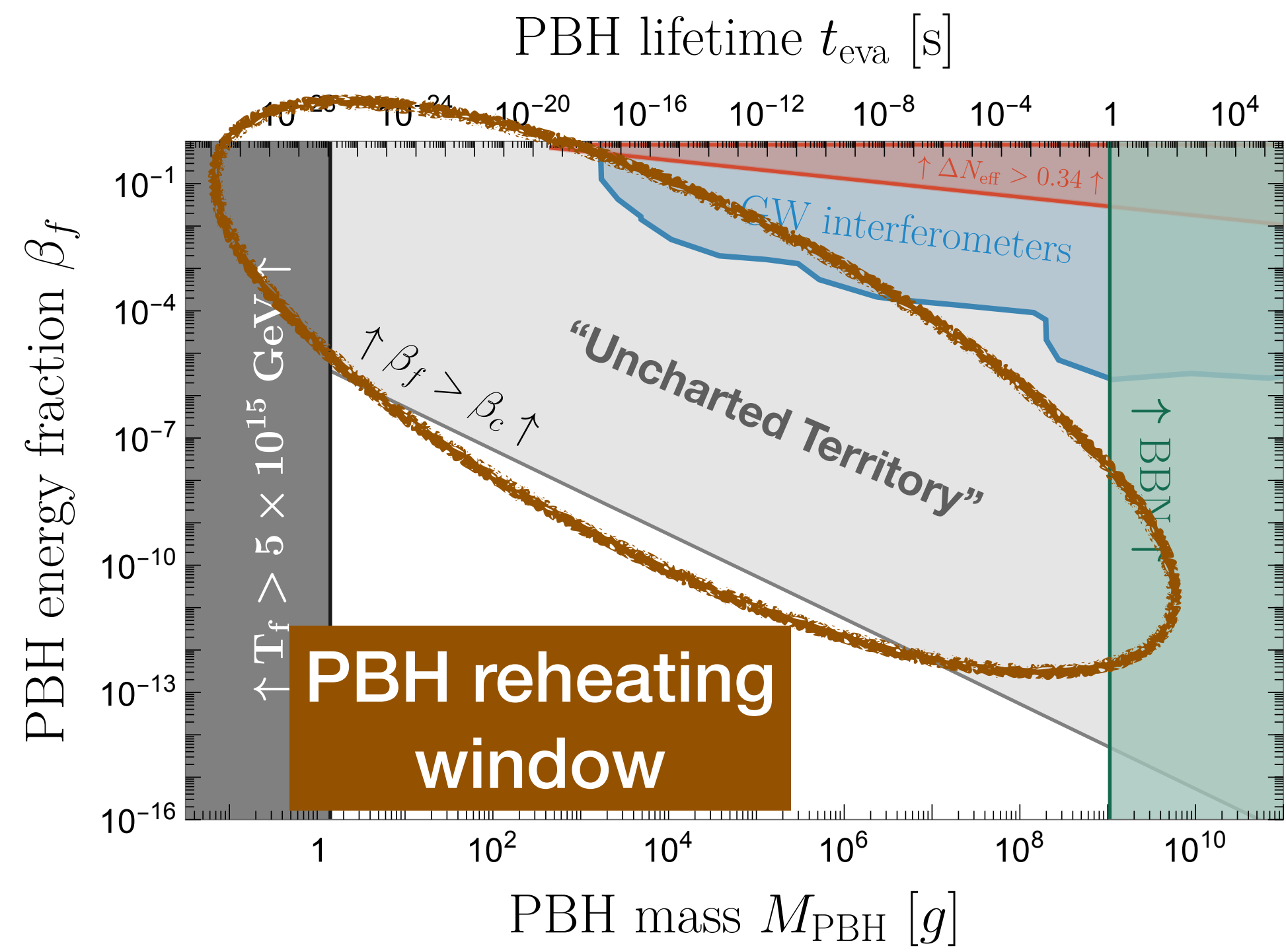
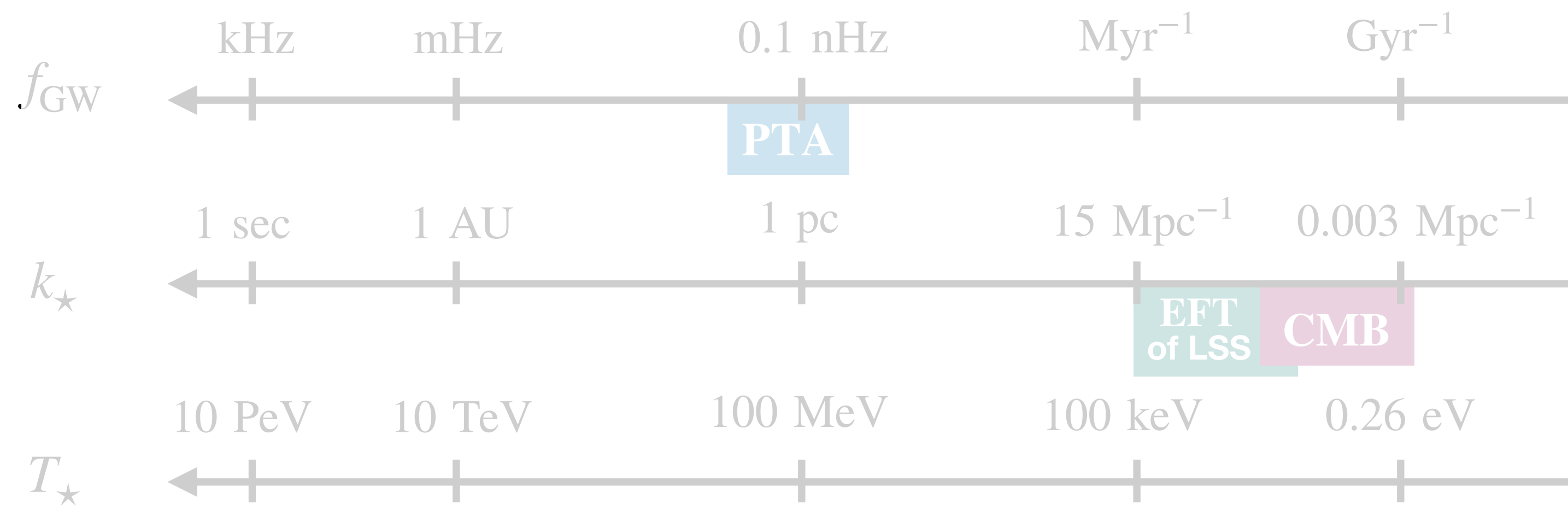
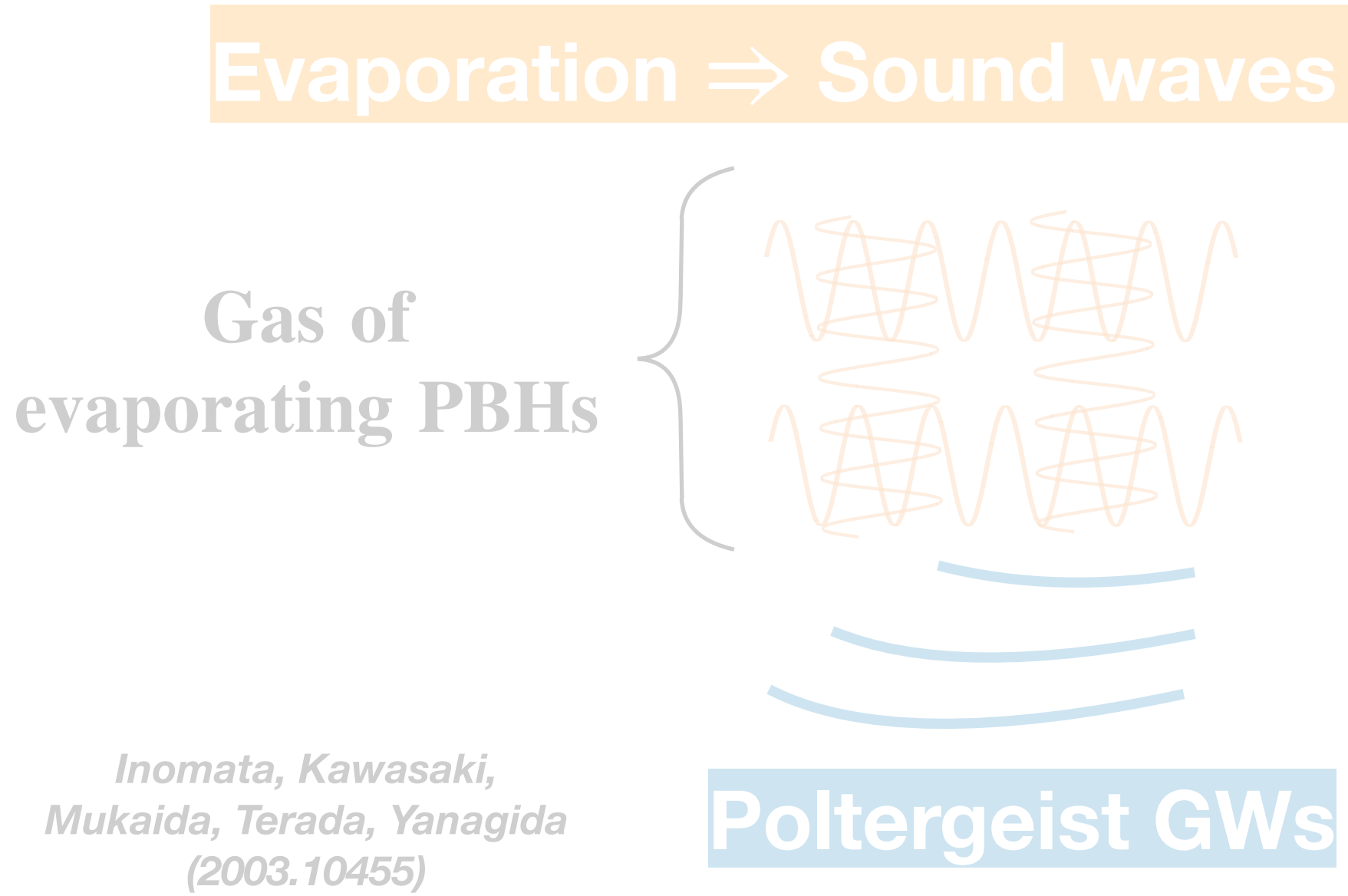
Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

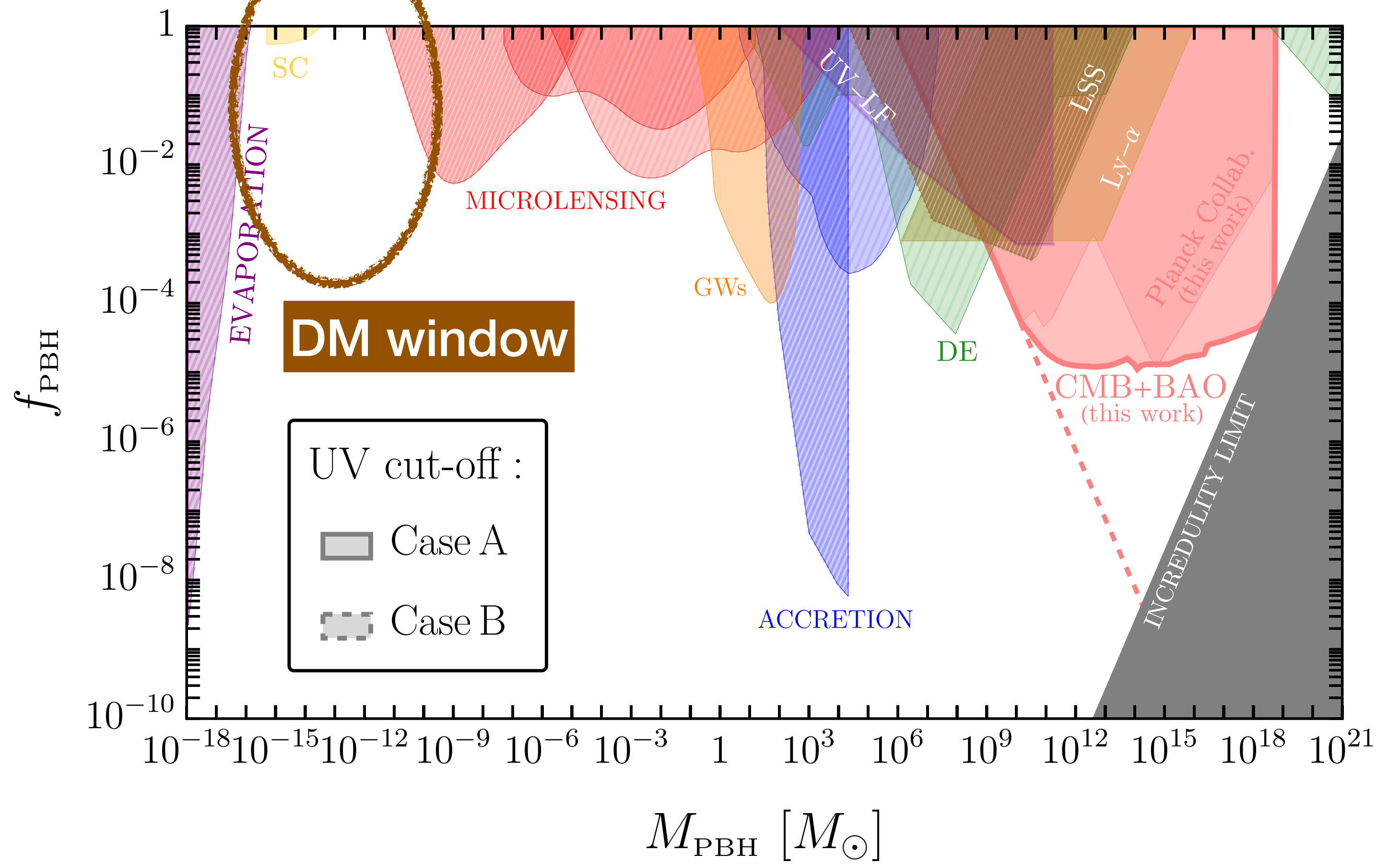
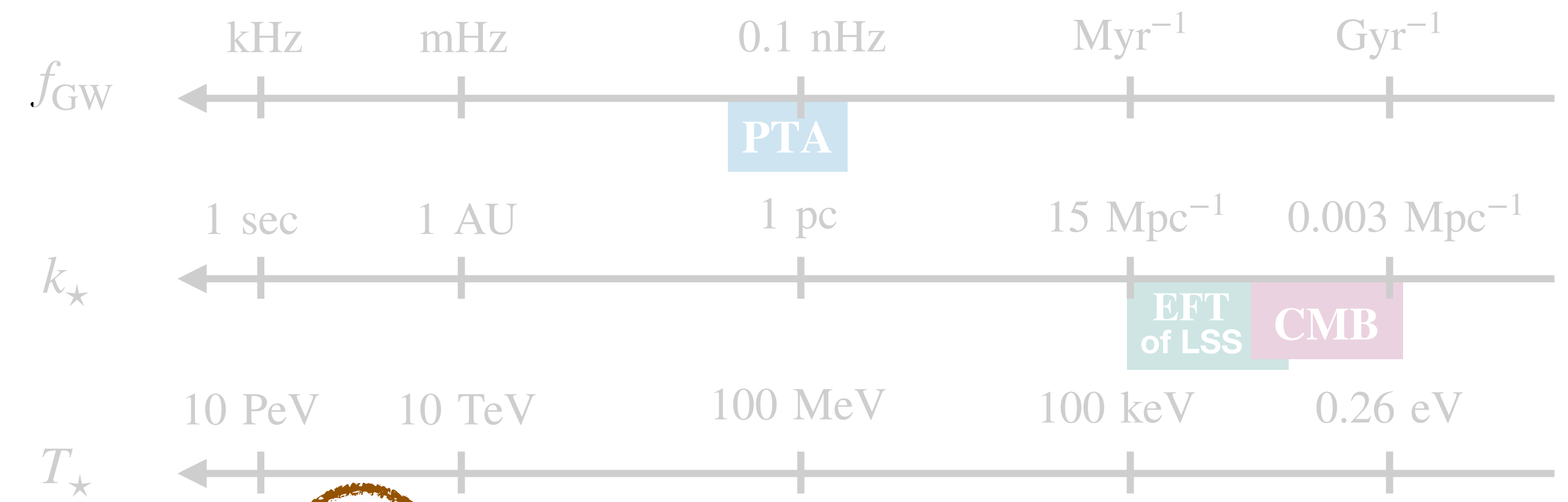
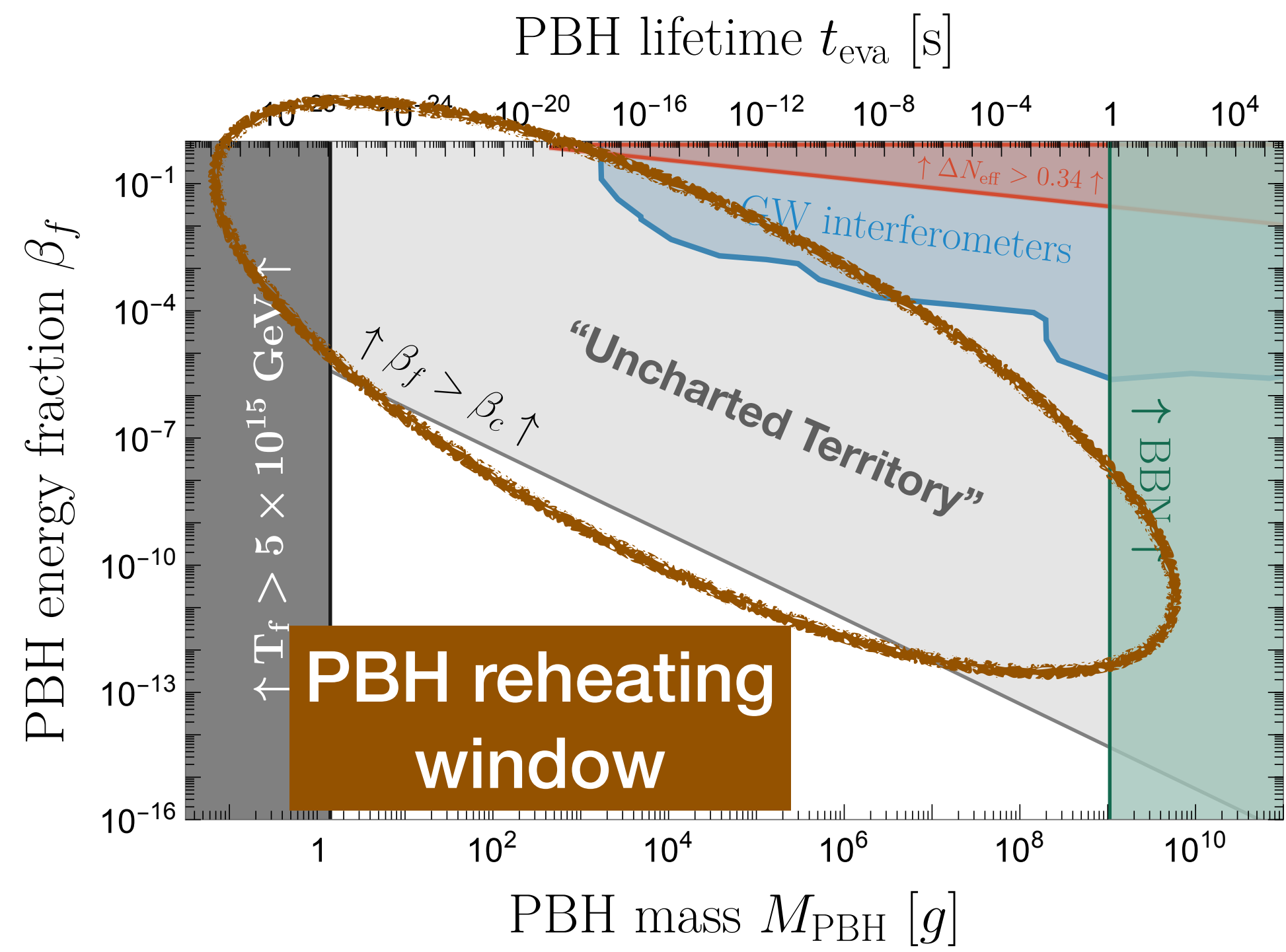
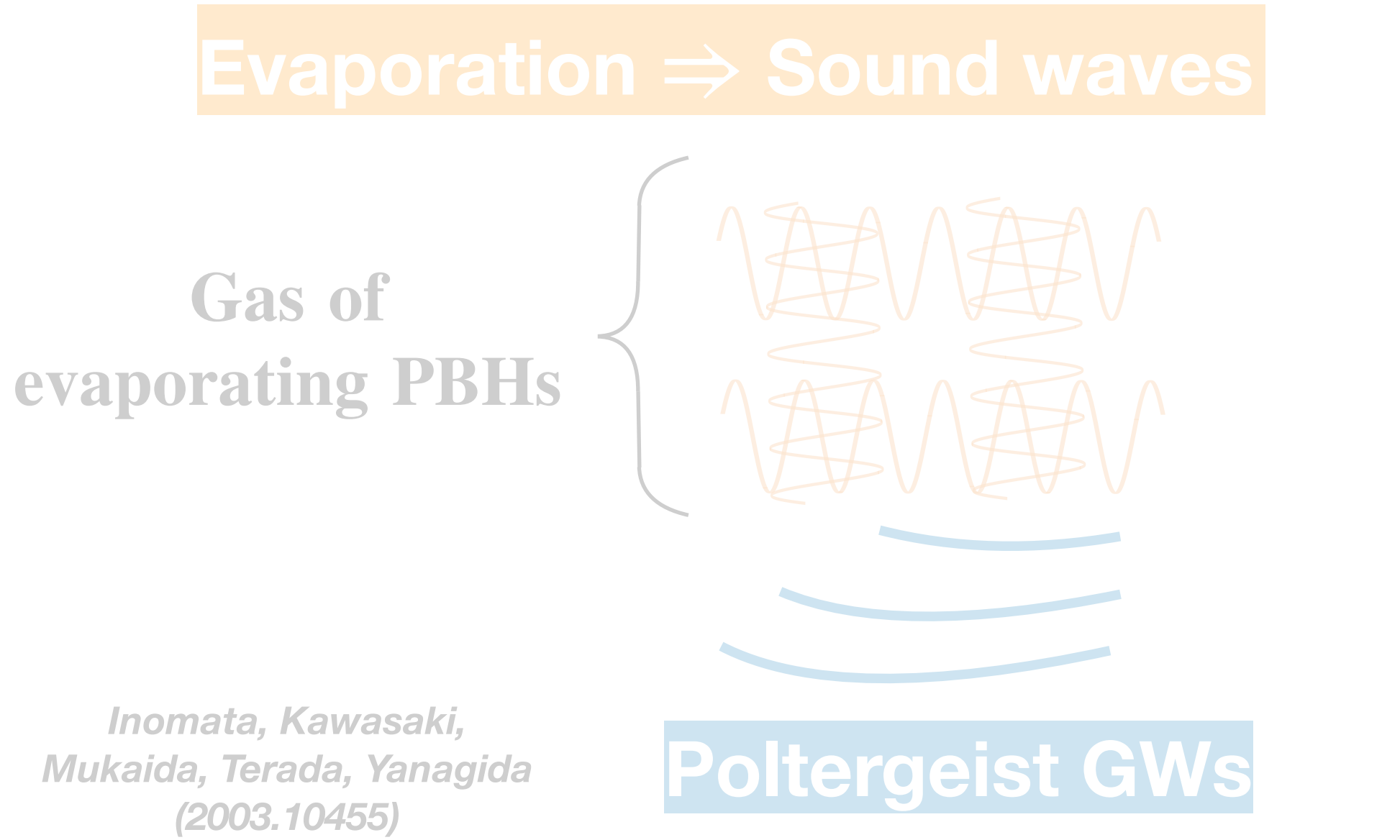
PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany

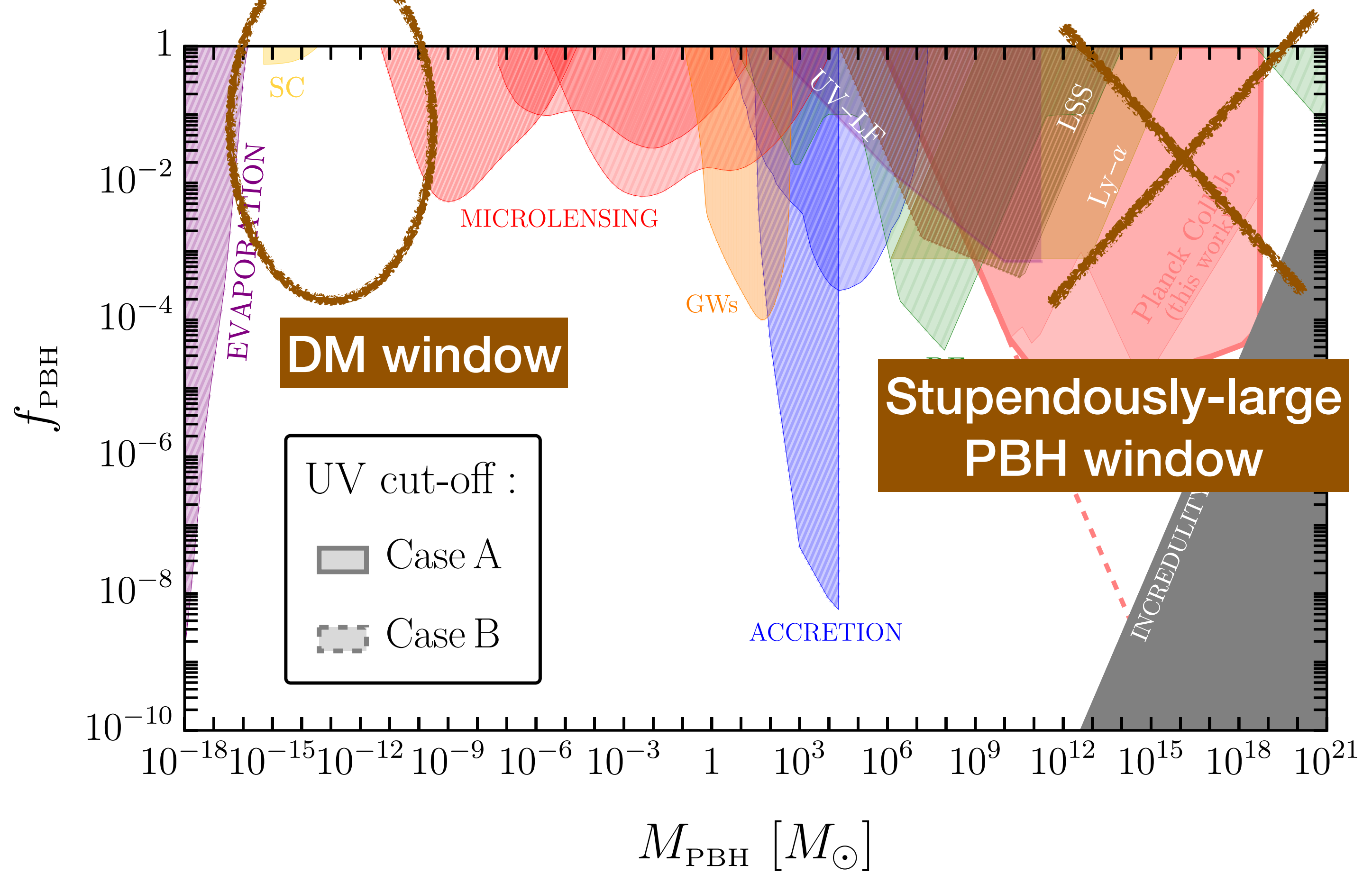
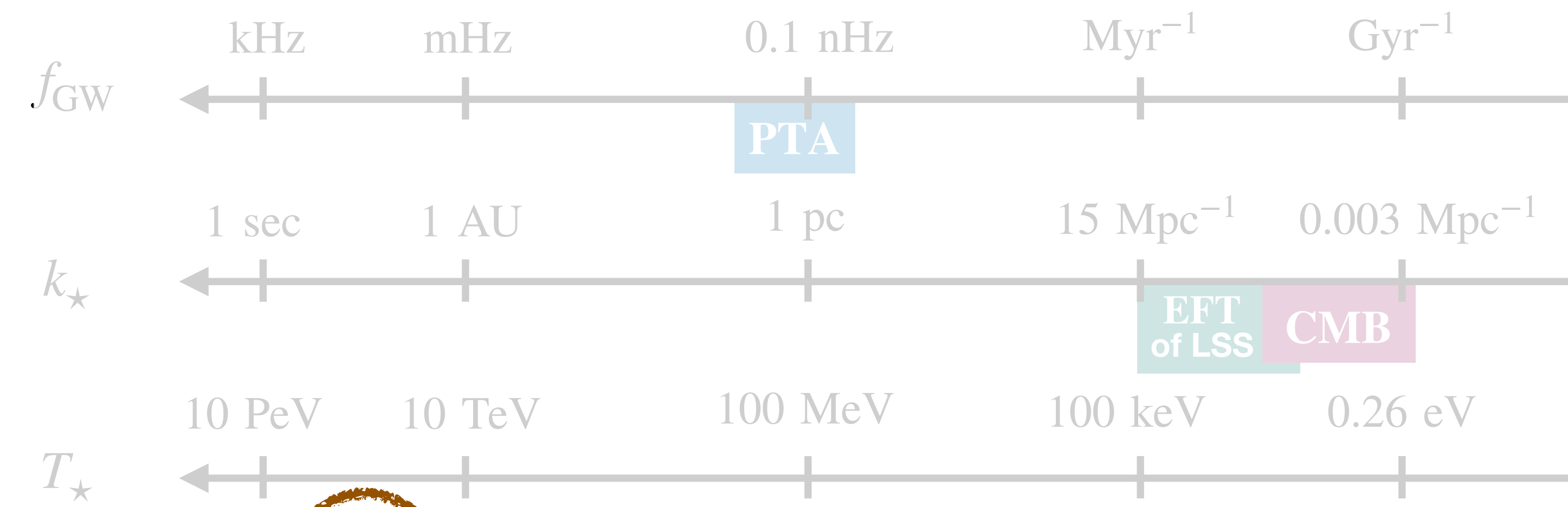
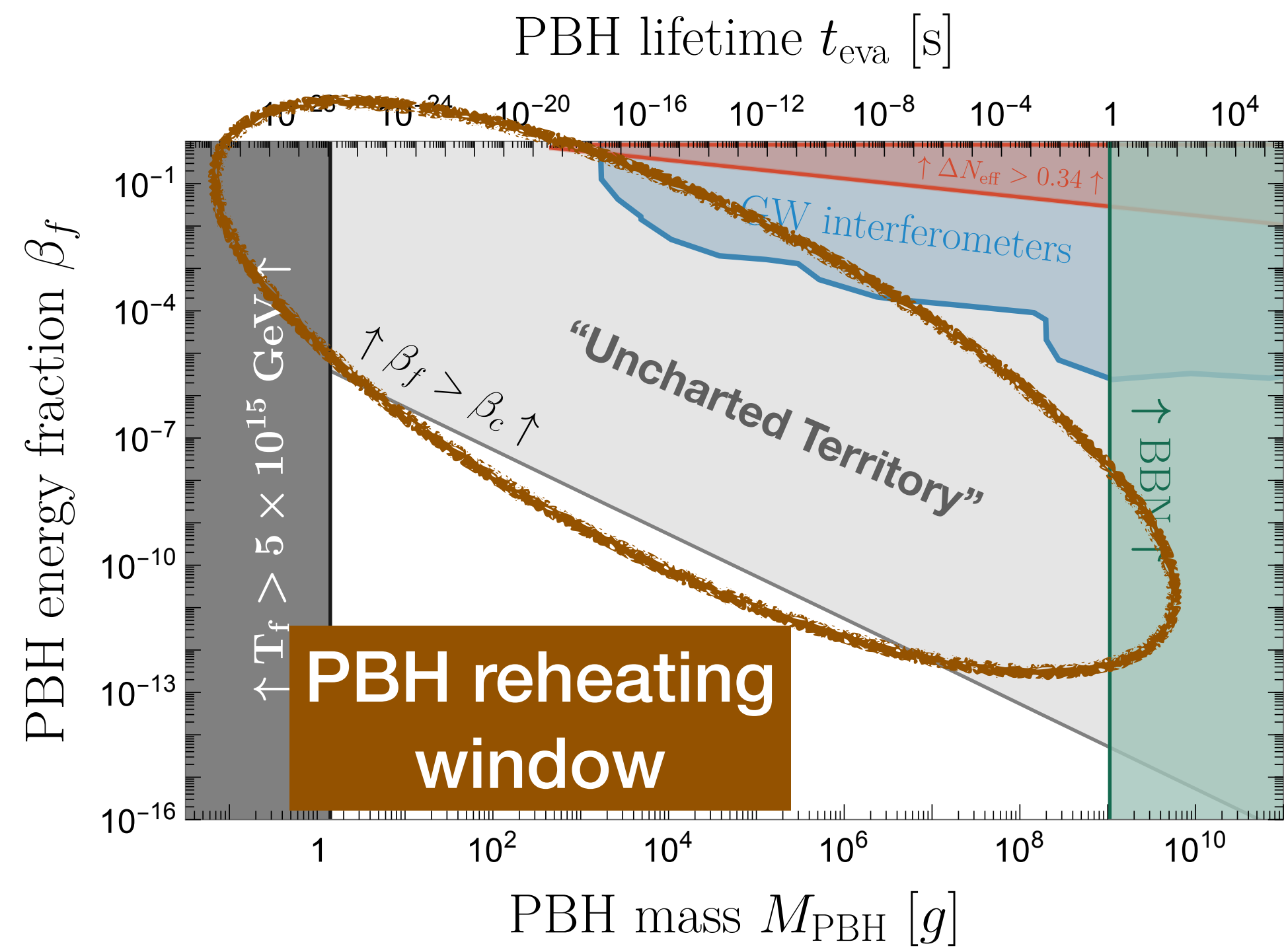
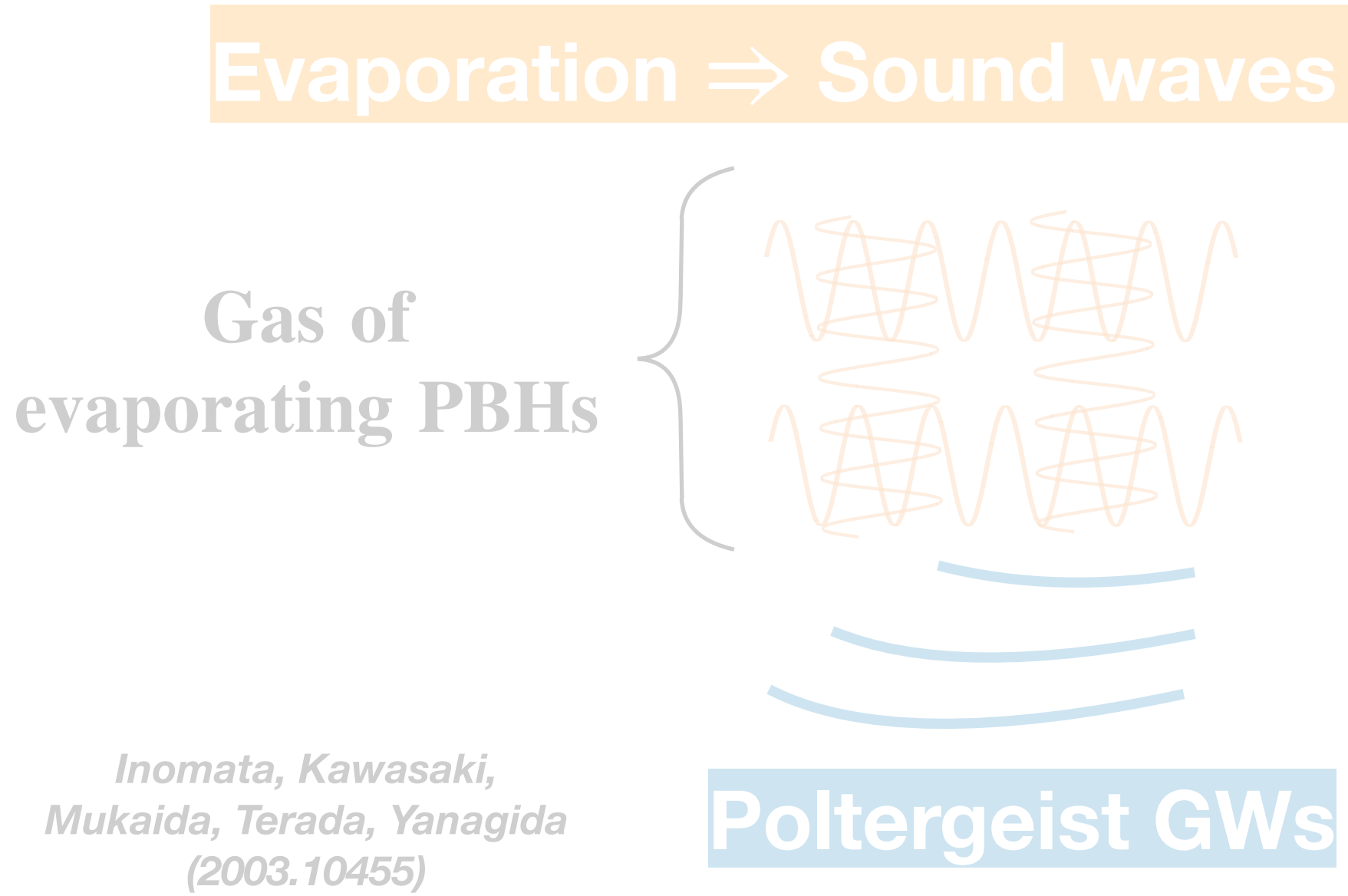


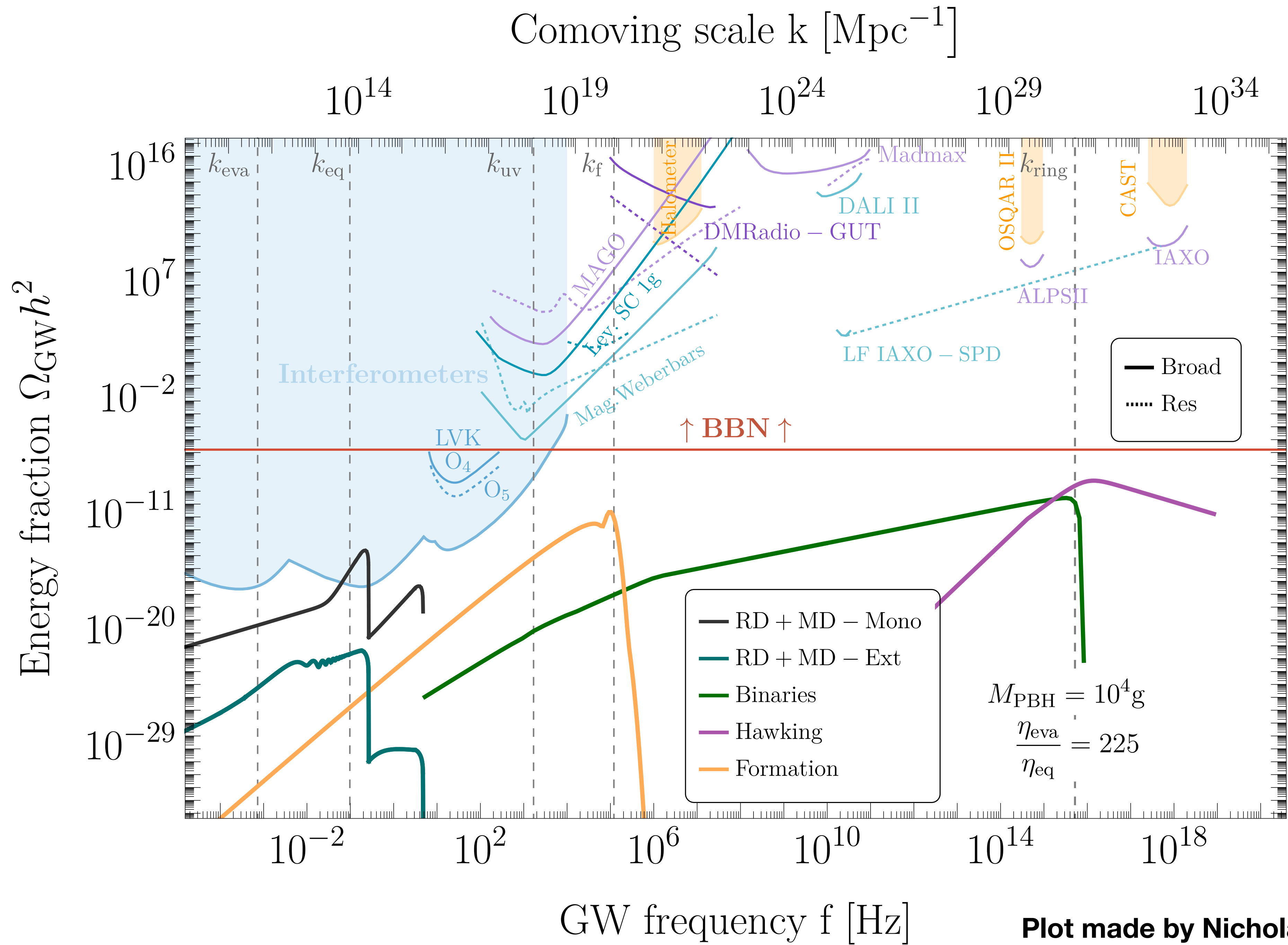
$$\frac{df_{\text{PBH}}}{d \log M} \propto M^{1+1/\gamma}$$
$$\gamma \simeq 0.36$$

Choptuik's law
(Choptuik 93')









Plan of the talk

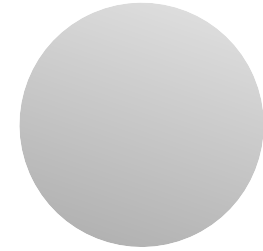
1)

Gravitational Waves (GWs)

$$h_{ij}(\vec{x}, t)$$

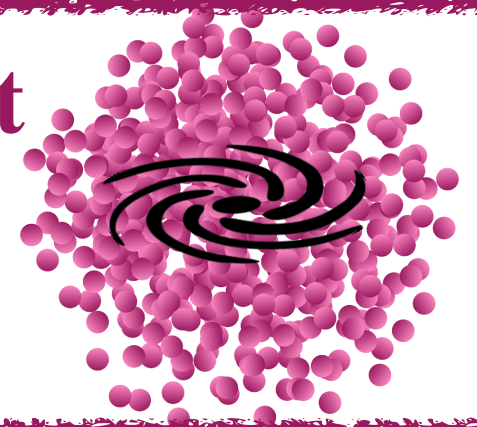
2)

Primordial
Black Holes
(PBHs)



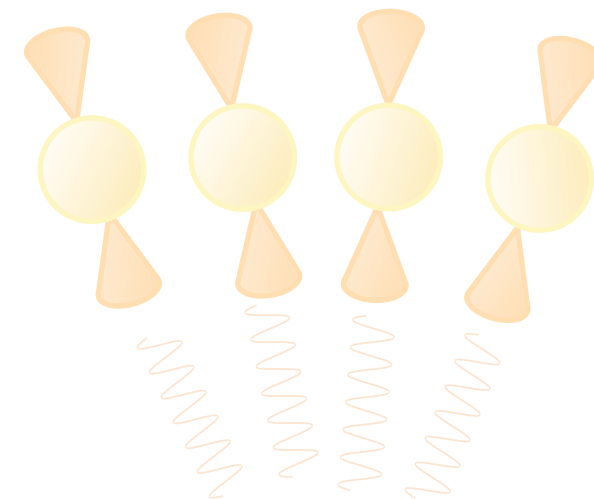
3)

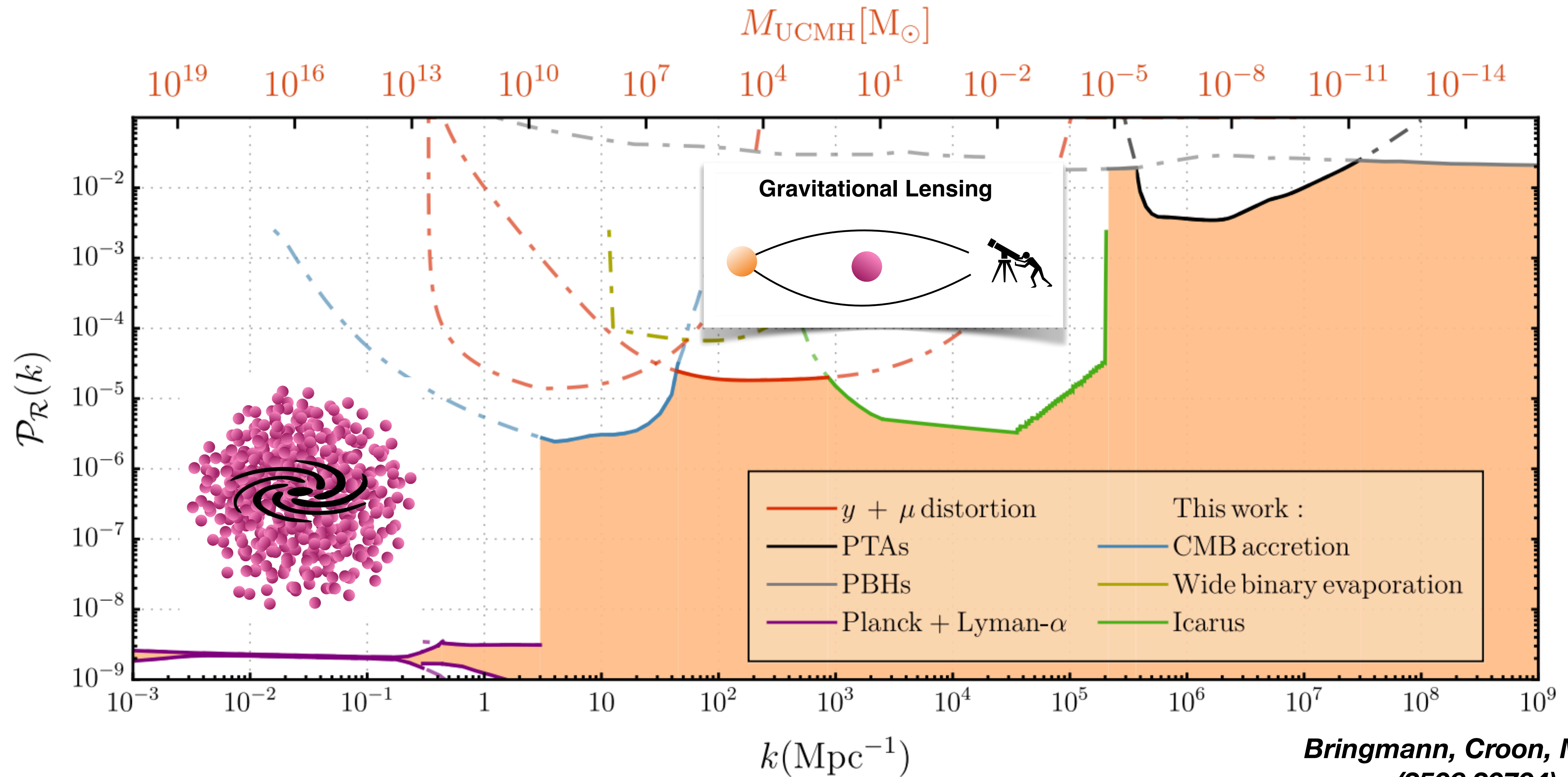
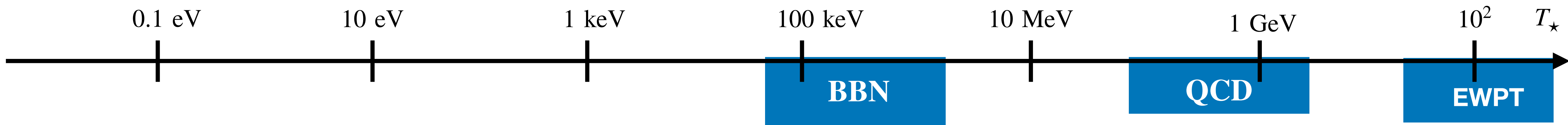
DM Ultra Compact
Mini Halos
(UCMH)



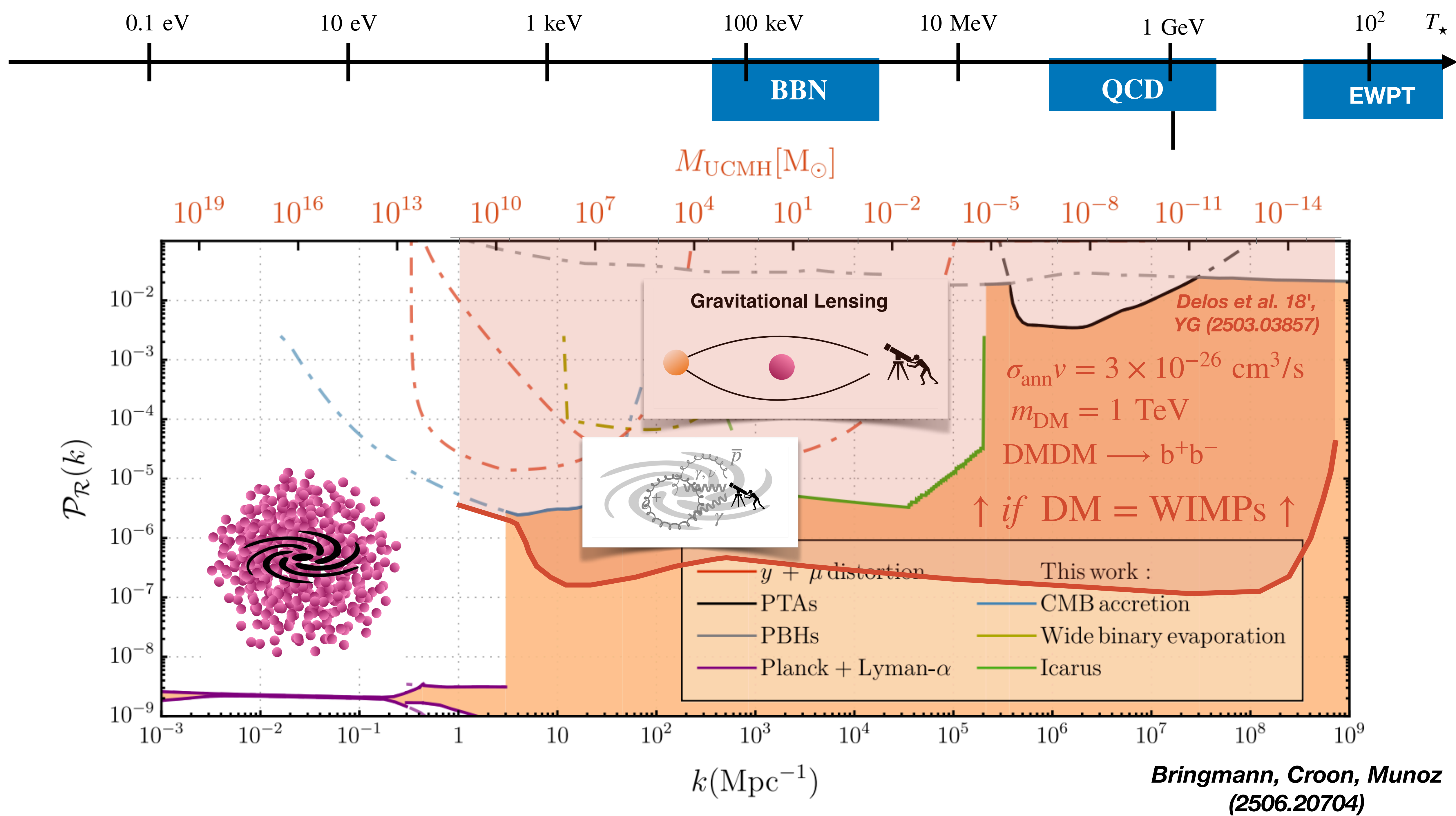
4)

What is the PTA
signal ?

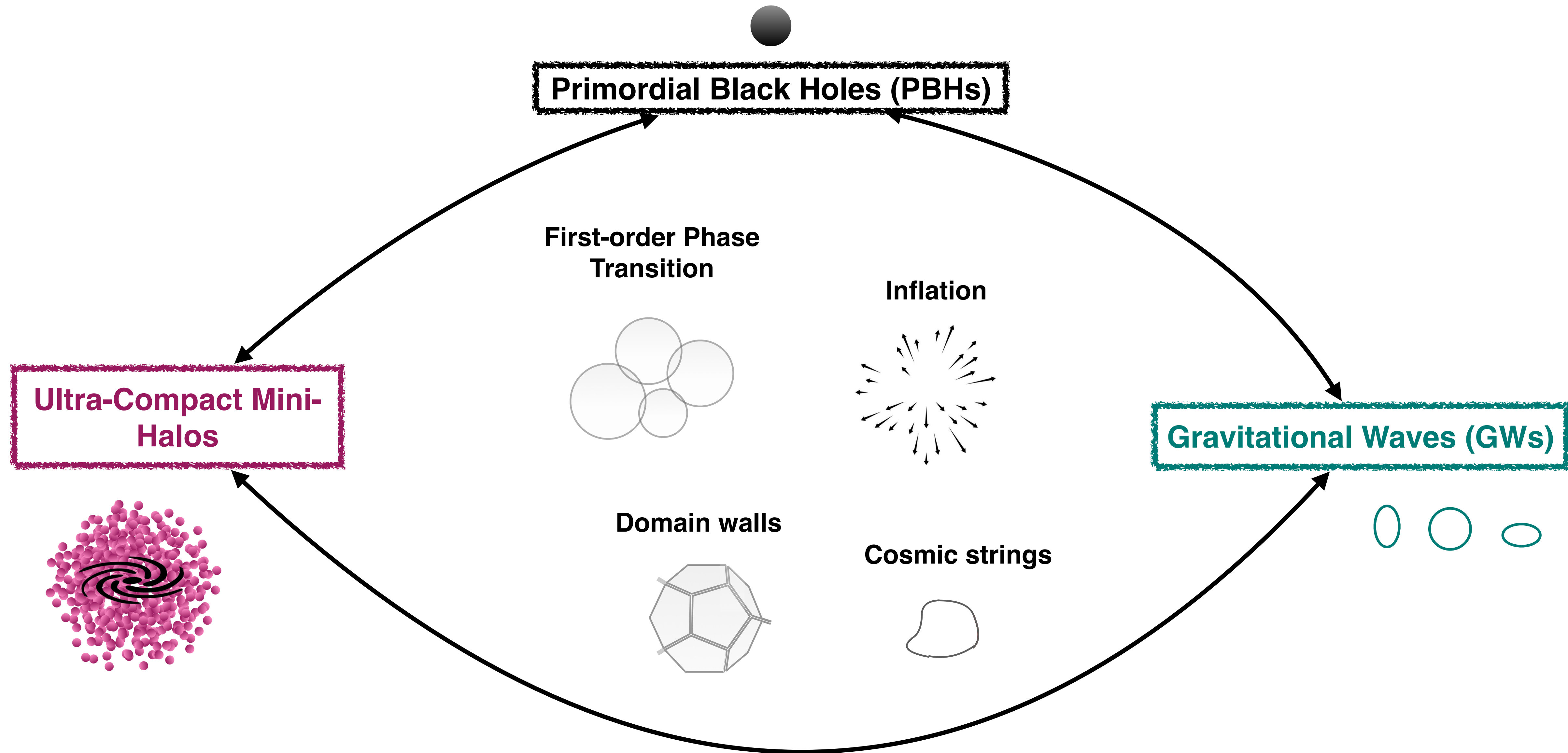


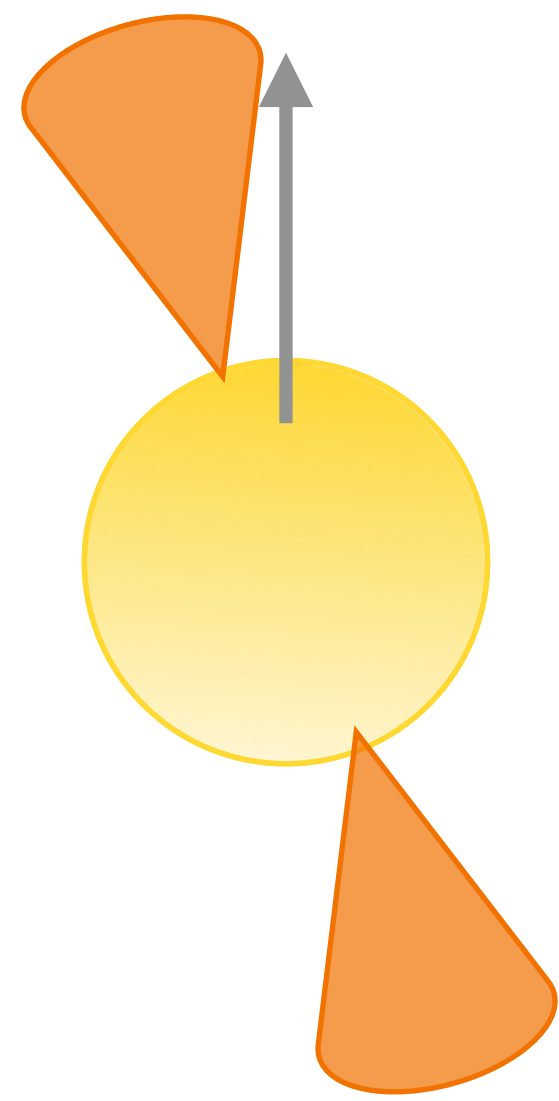


Bringmann, Croon, Munoz
(2506.20704)

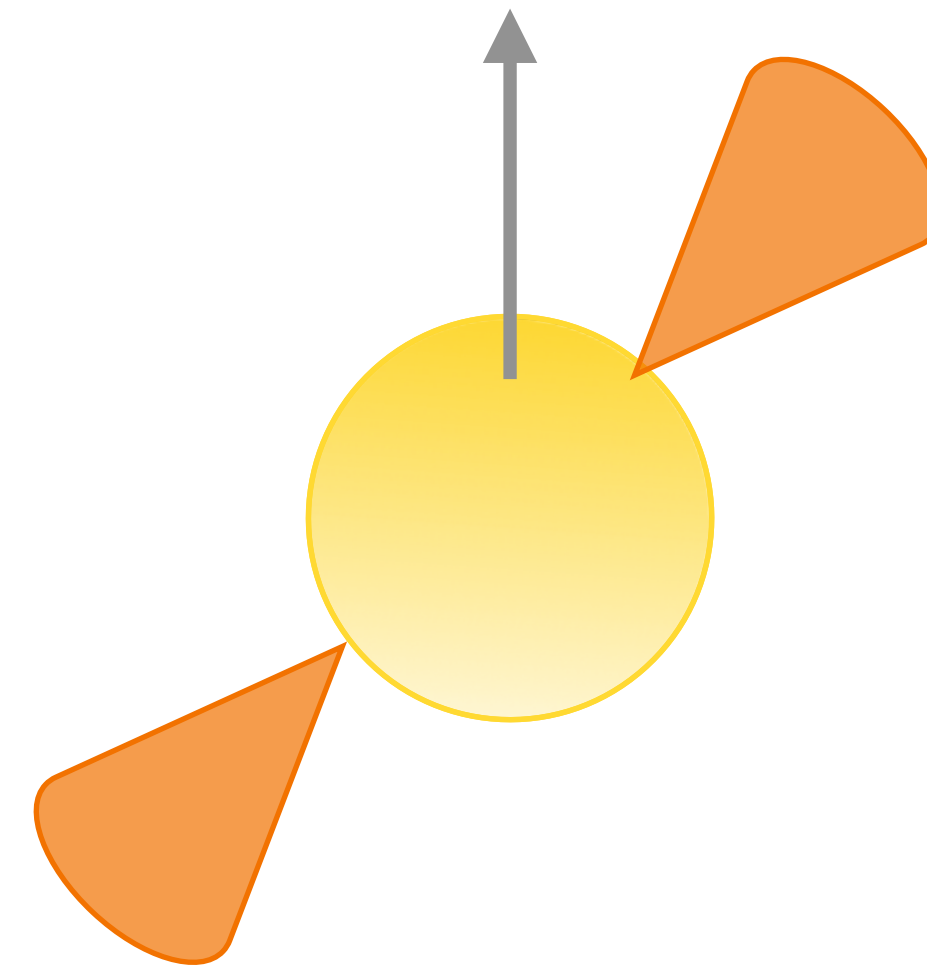


What can we learn from cross-correlation ?





Pulsar Timing Arrays (PTA)



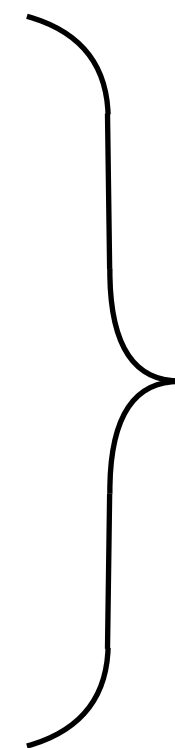
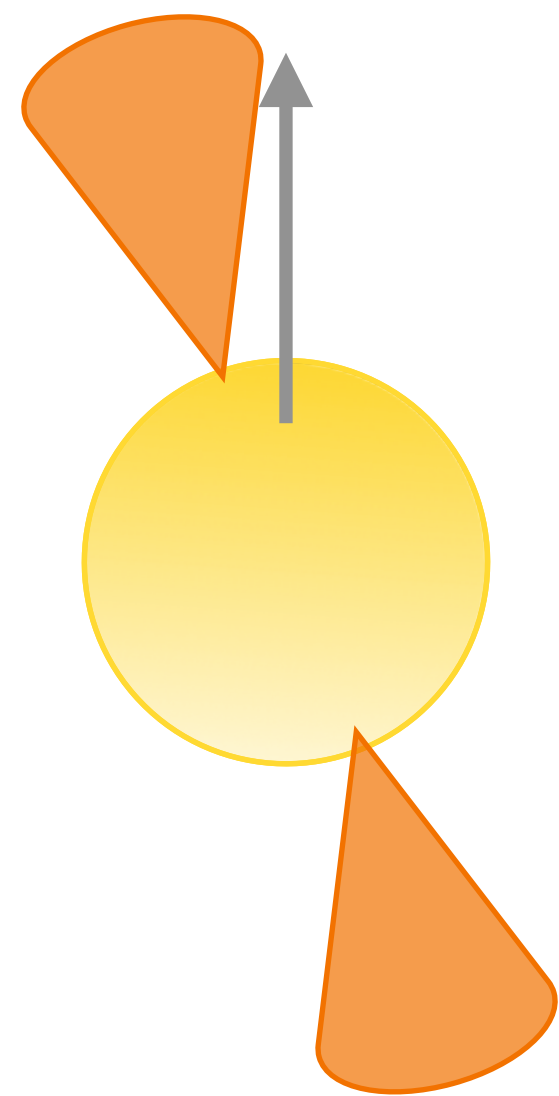
The New York Times

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NEW YORK, THURSDAY, JUNE 29, 2023

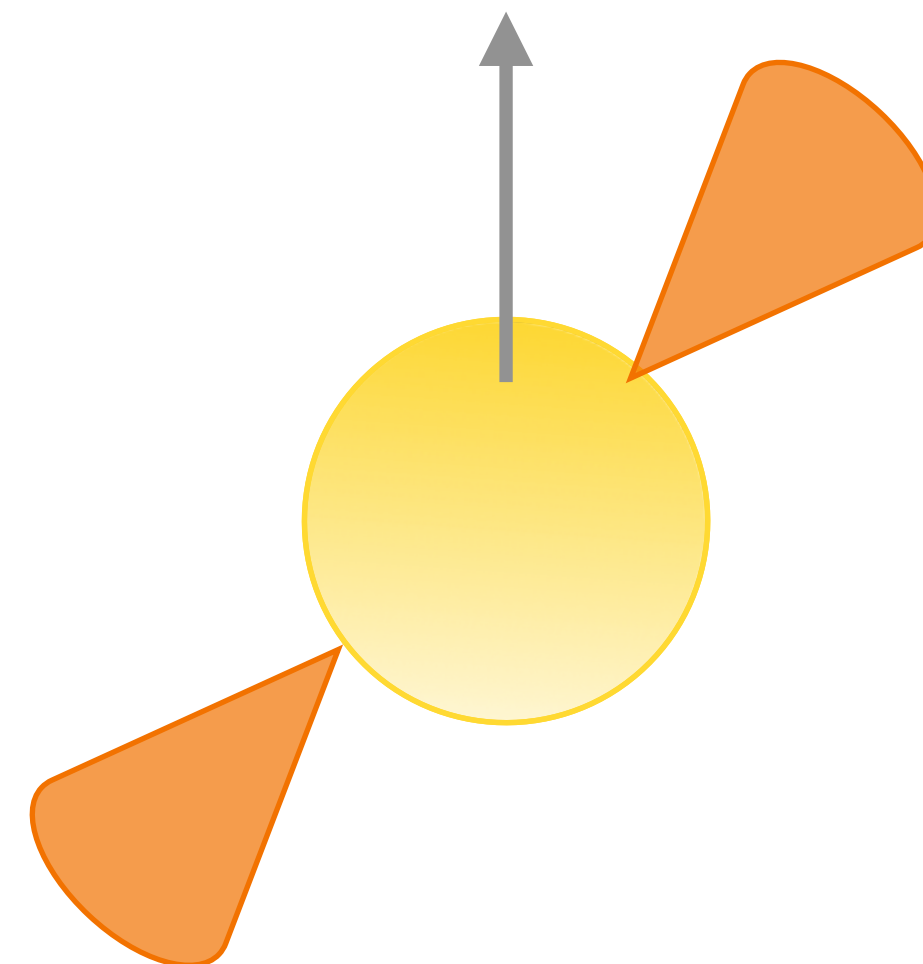
The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find





Pulsar Timing Arrays (PTA)

$1 M_{\odot}$



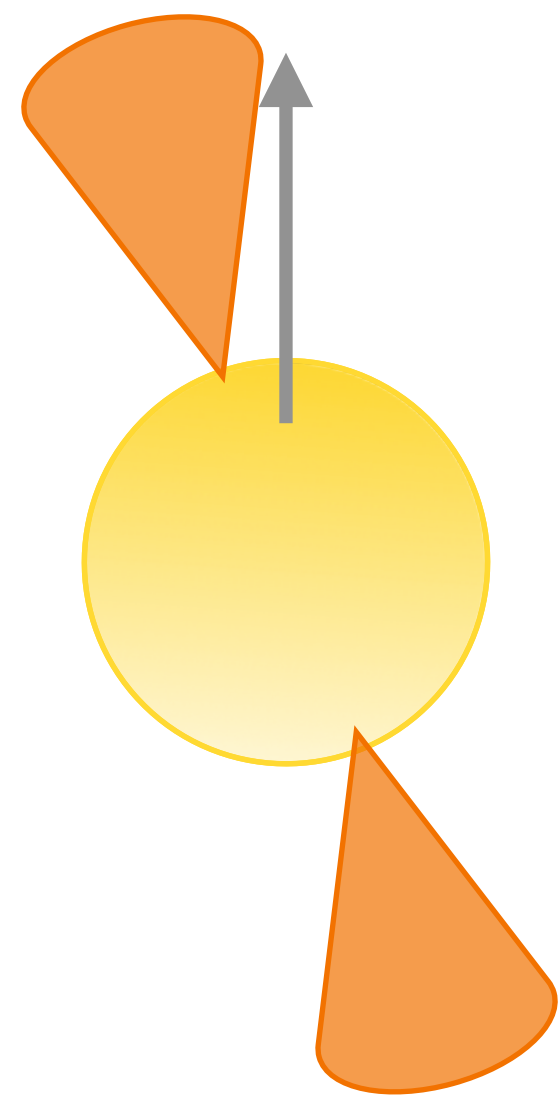
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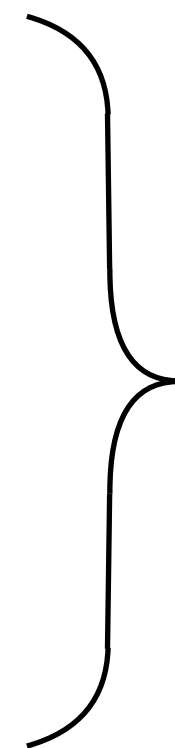
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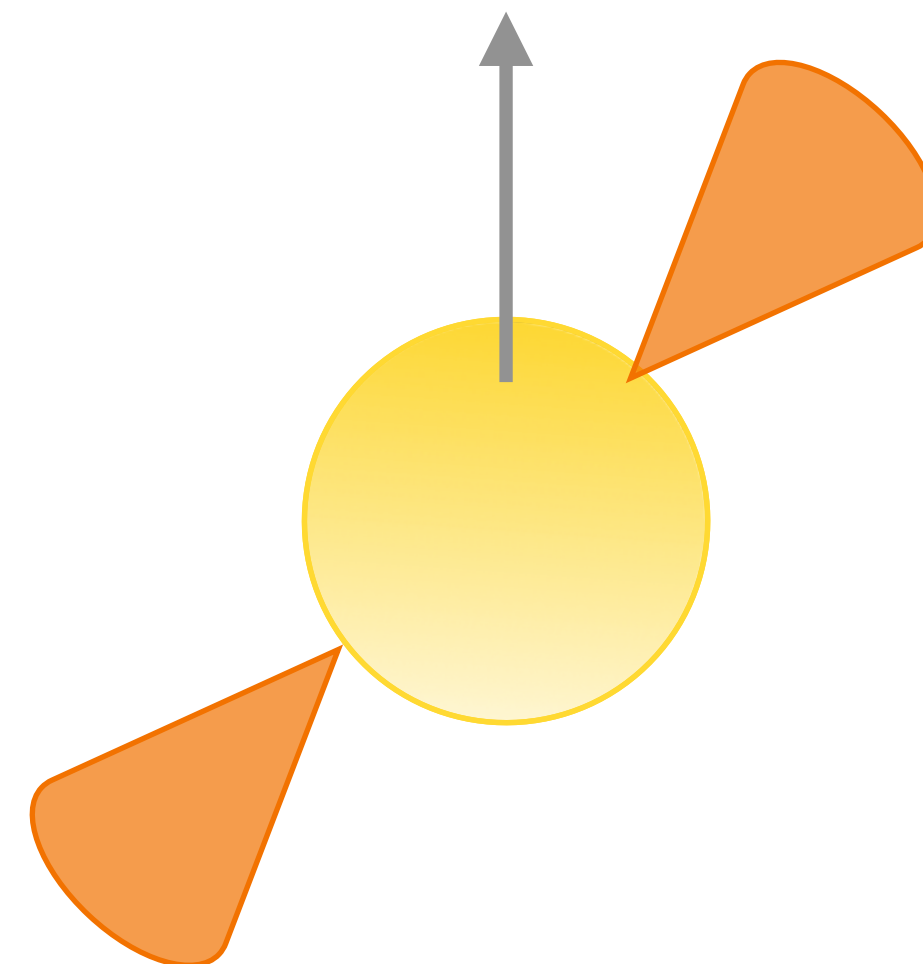


Pulsar Timing Arrays (PTA)



1 $M_{\odot}$

10 km



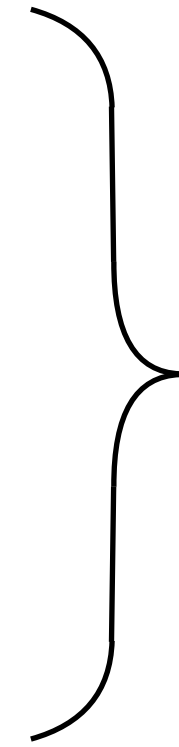
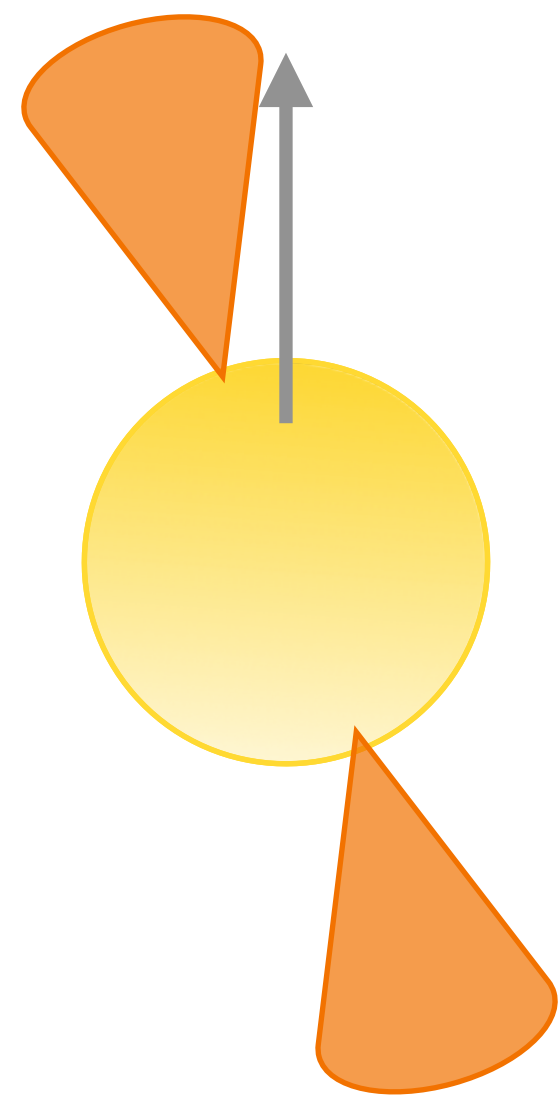
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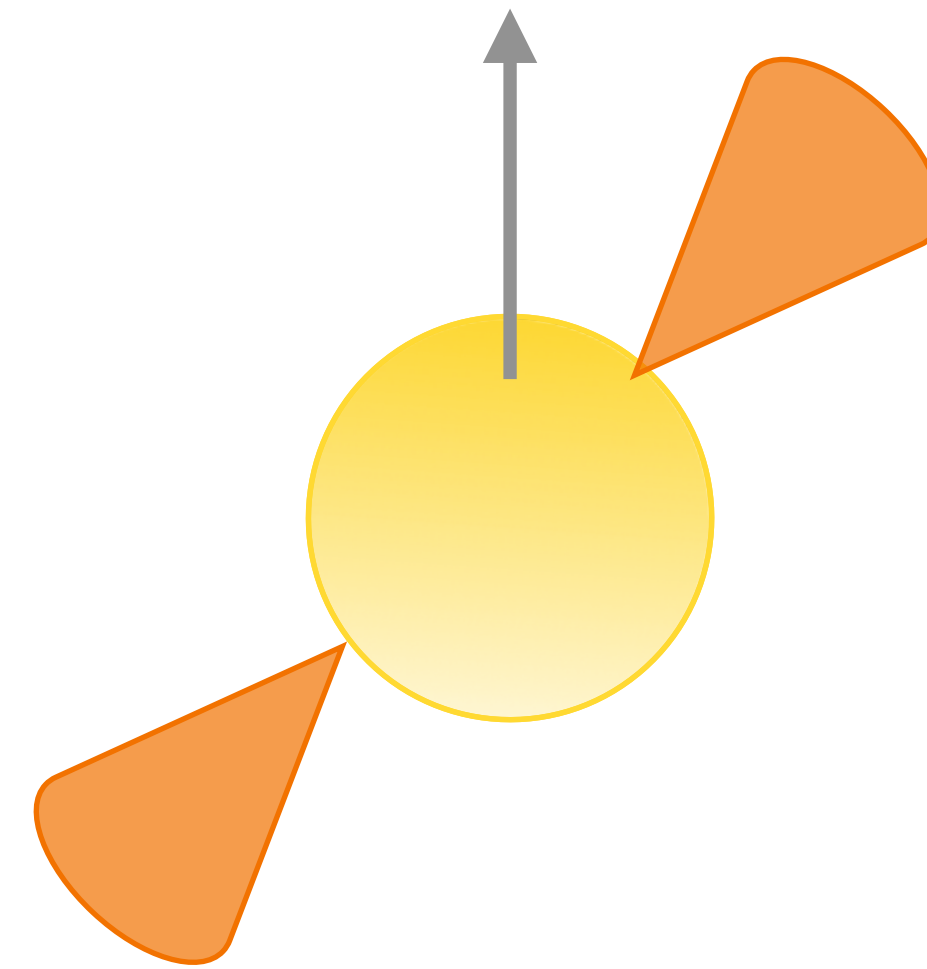


Pulsar Timing Arrays (PTA)

$1 M_{\odot}$

10 km

500 rotations/s



The New York Times

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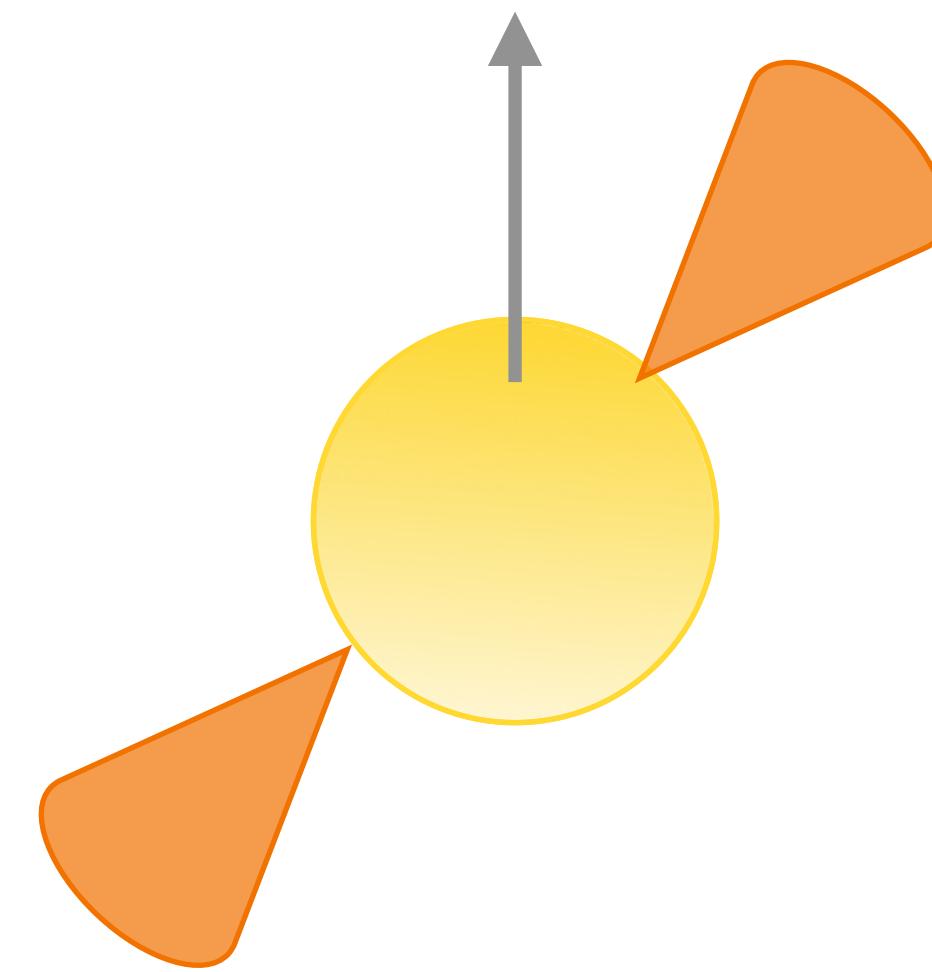
Pulsar Timing Arrays (PTA)

1 M_⊙

10 km

500 rotations/s

1 kpc



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***The Cosmos Is Thrumming With
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Find***



Pulsar Timing Arrays (PTA)

1 $M_{\odot}$

10 km

500 rotations/s

Pulses

Pulses

1 kpc



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Pulsar Timing Arrays (PTA)

1 $M_{\odot}$

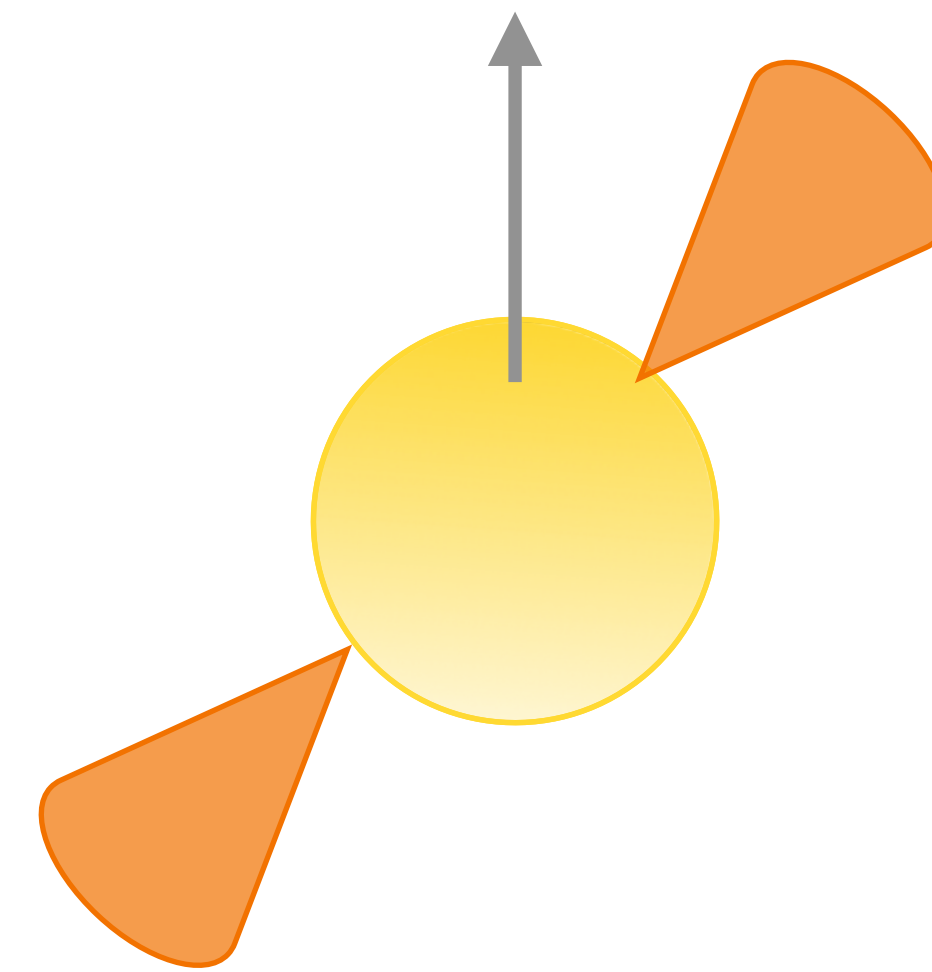
10 km

500 rotations/s

Pulses

Pulses

Gravitational
Waves



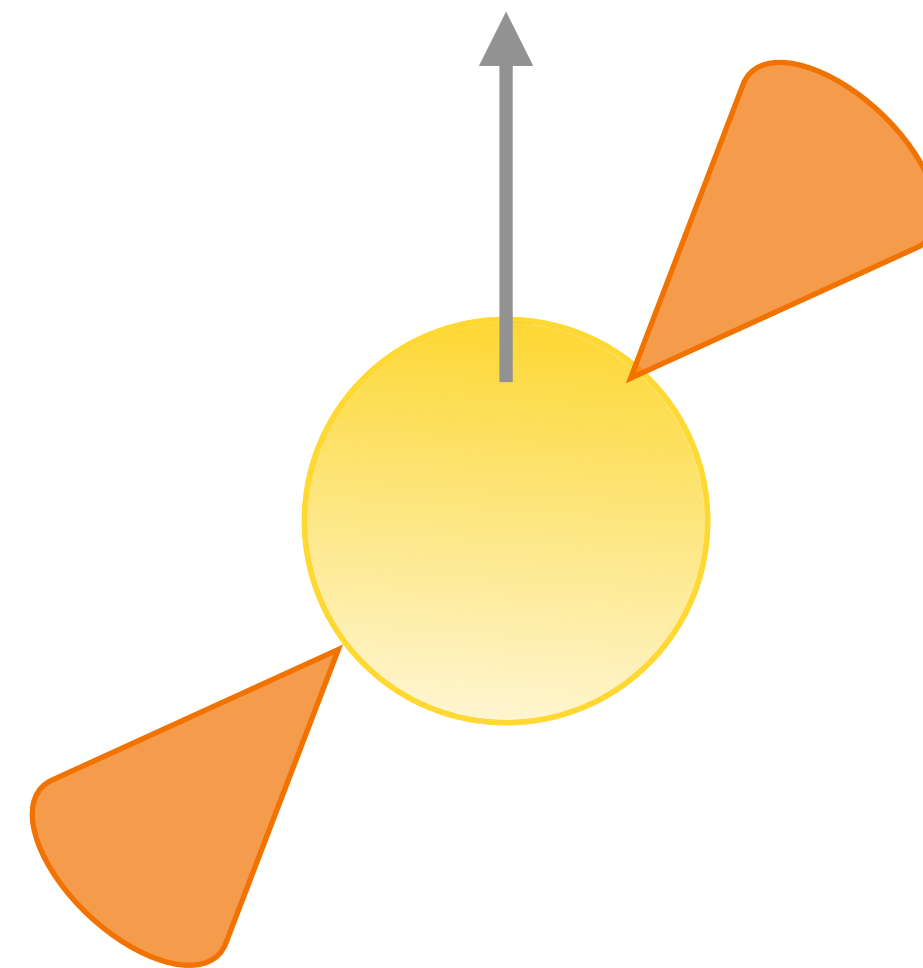
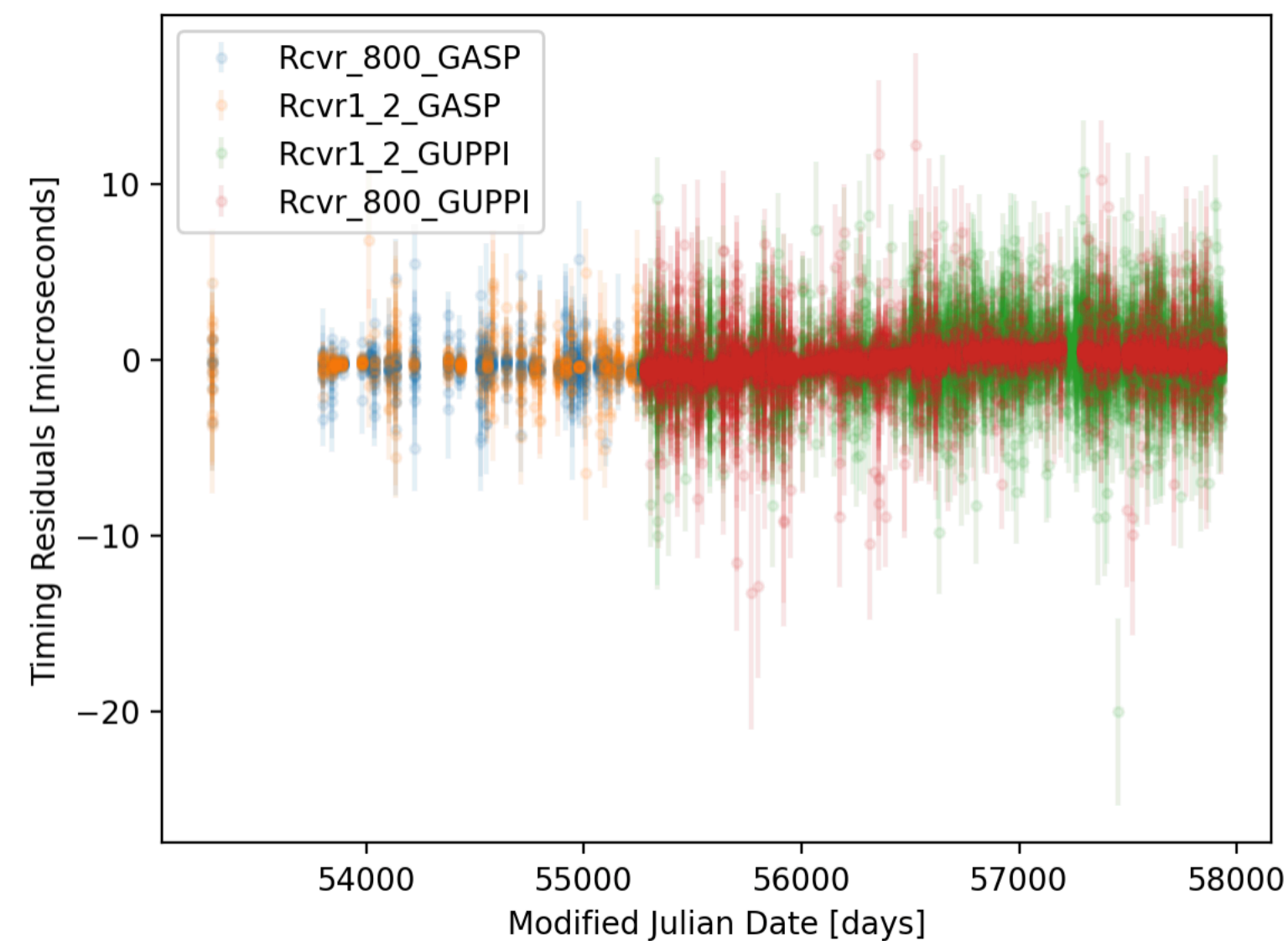
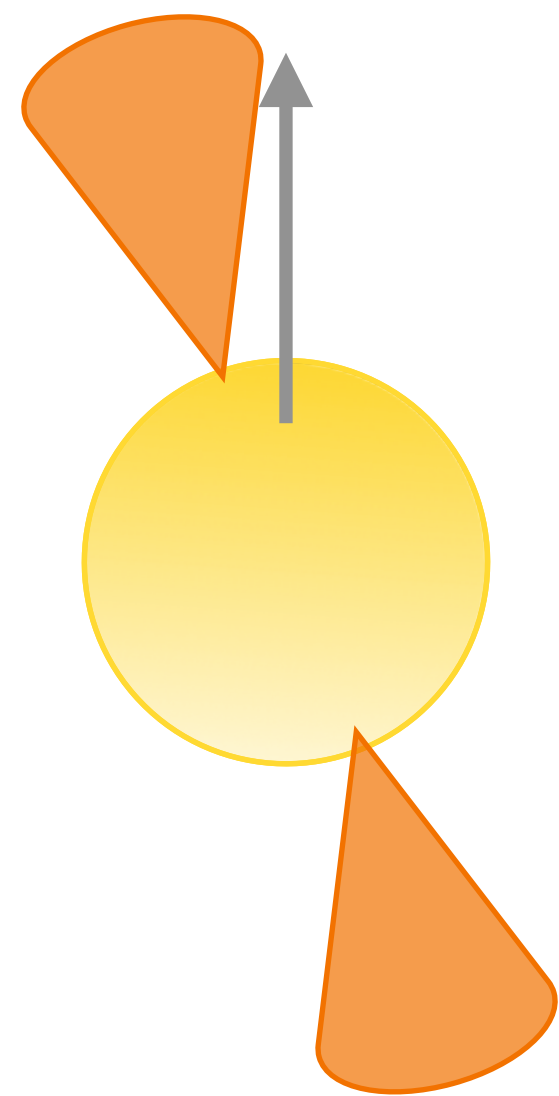
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Gravitational Waves, Astronomers
Find***





Pulses

Pulses

Gravitational
Waves



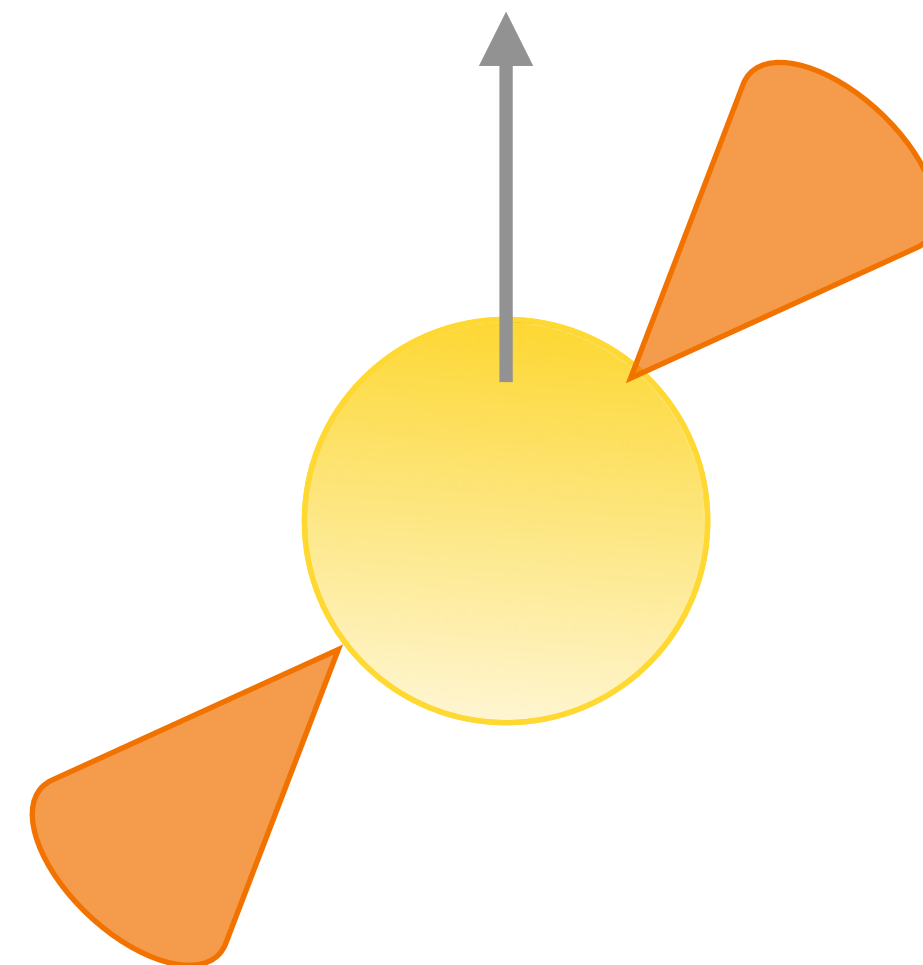
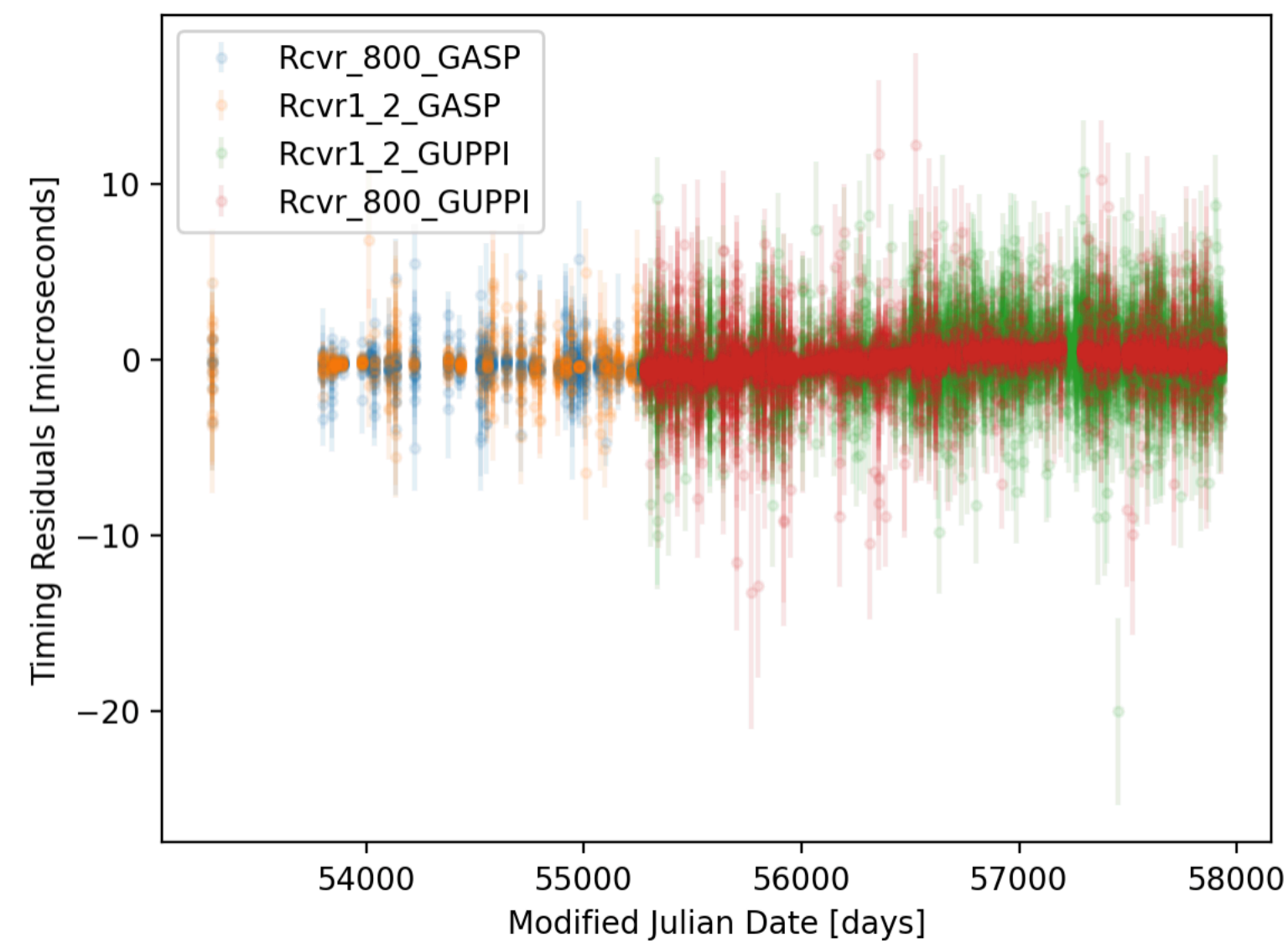
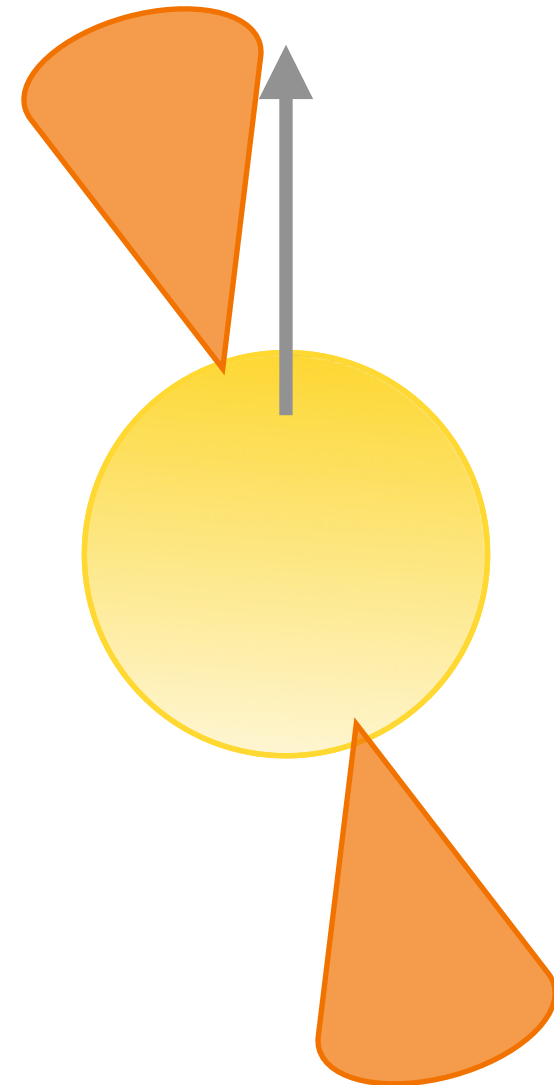
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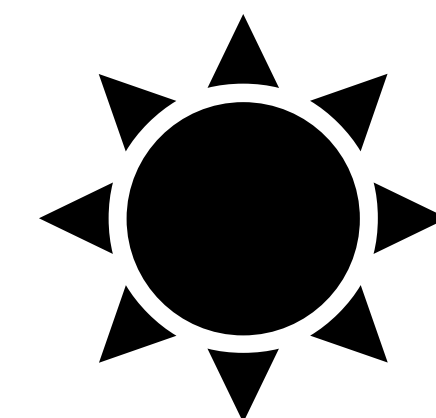
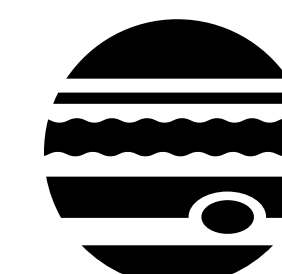
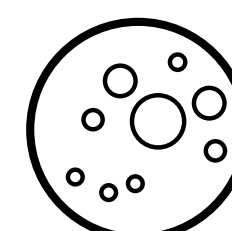




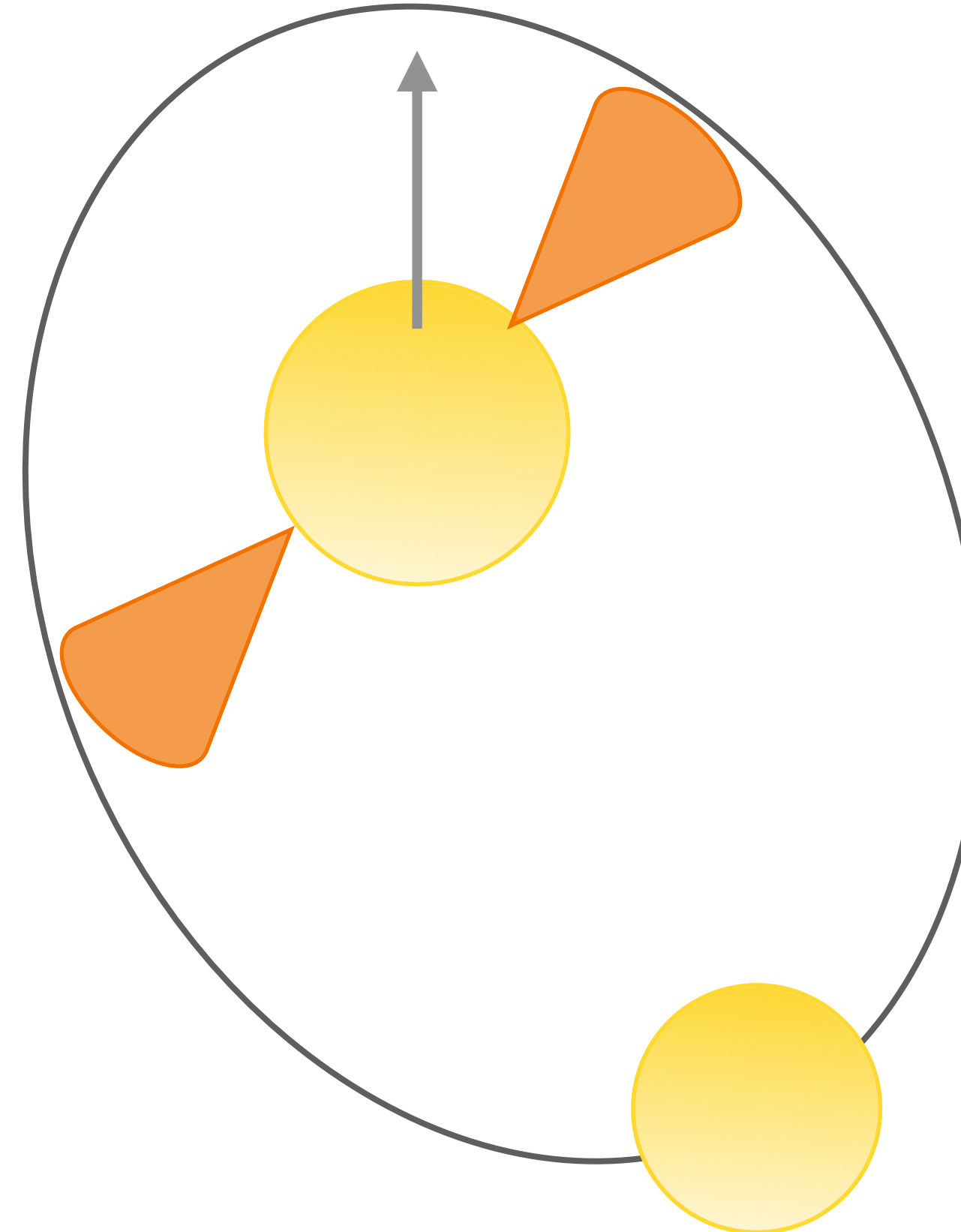
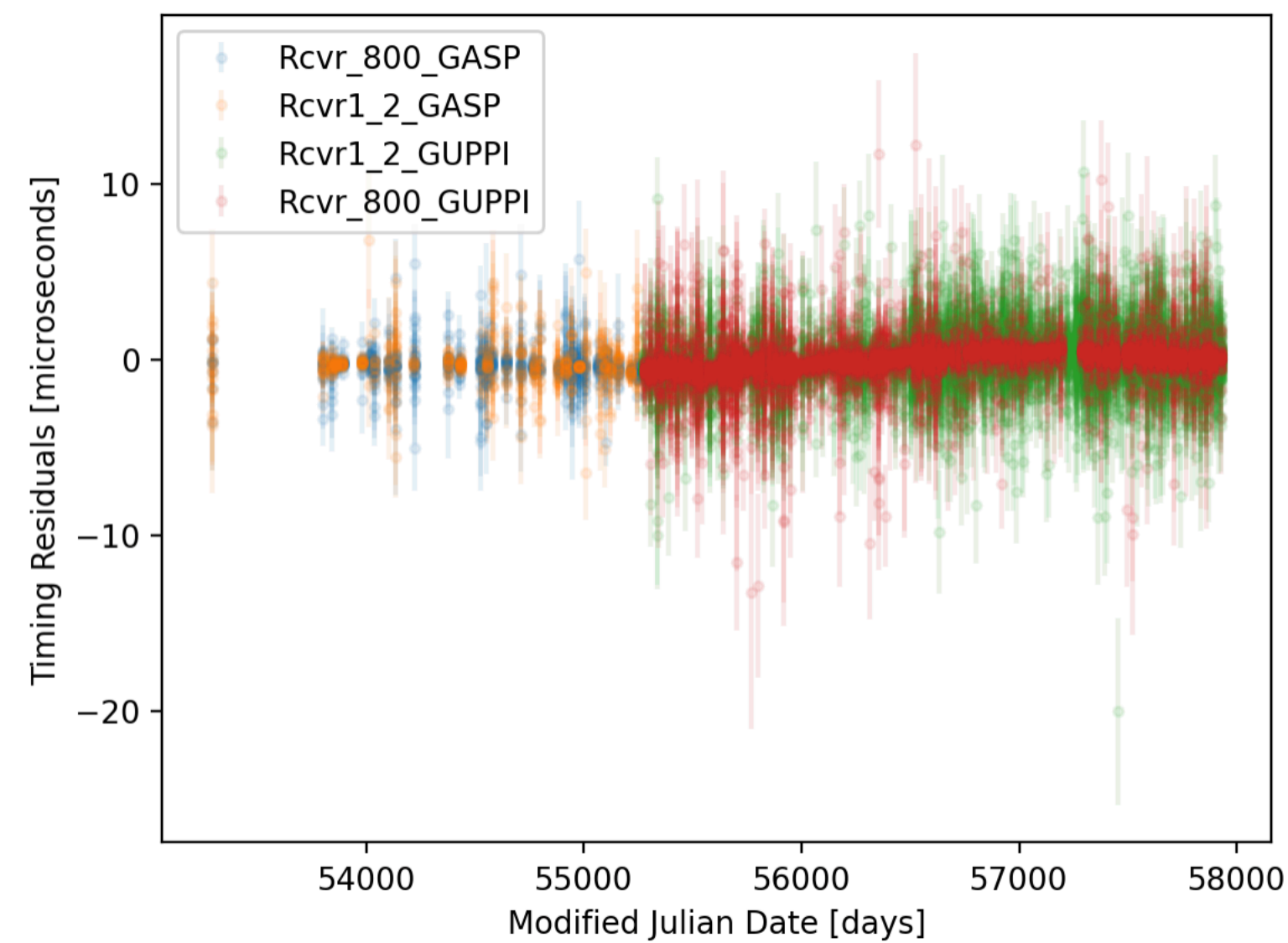
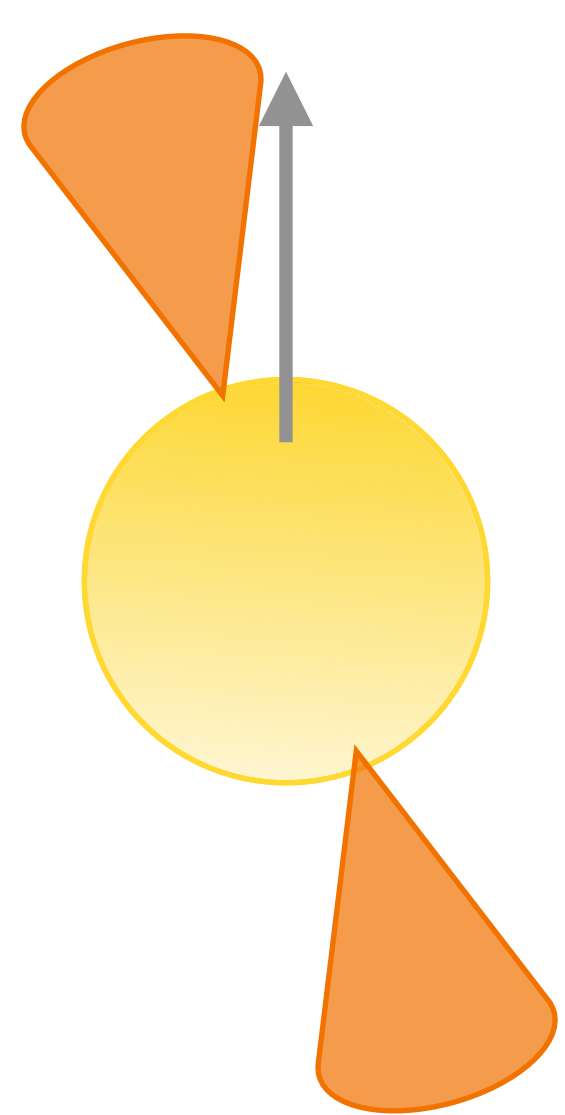
Pulses

Pulses

Gravitational
Waves



Solar system systematics

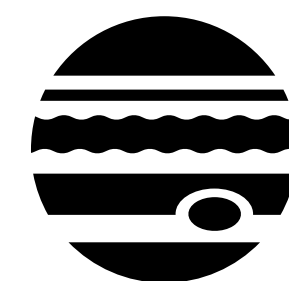
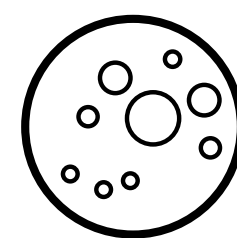


Pulses

Pulses

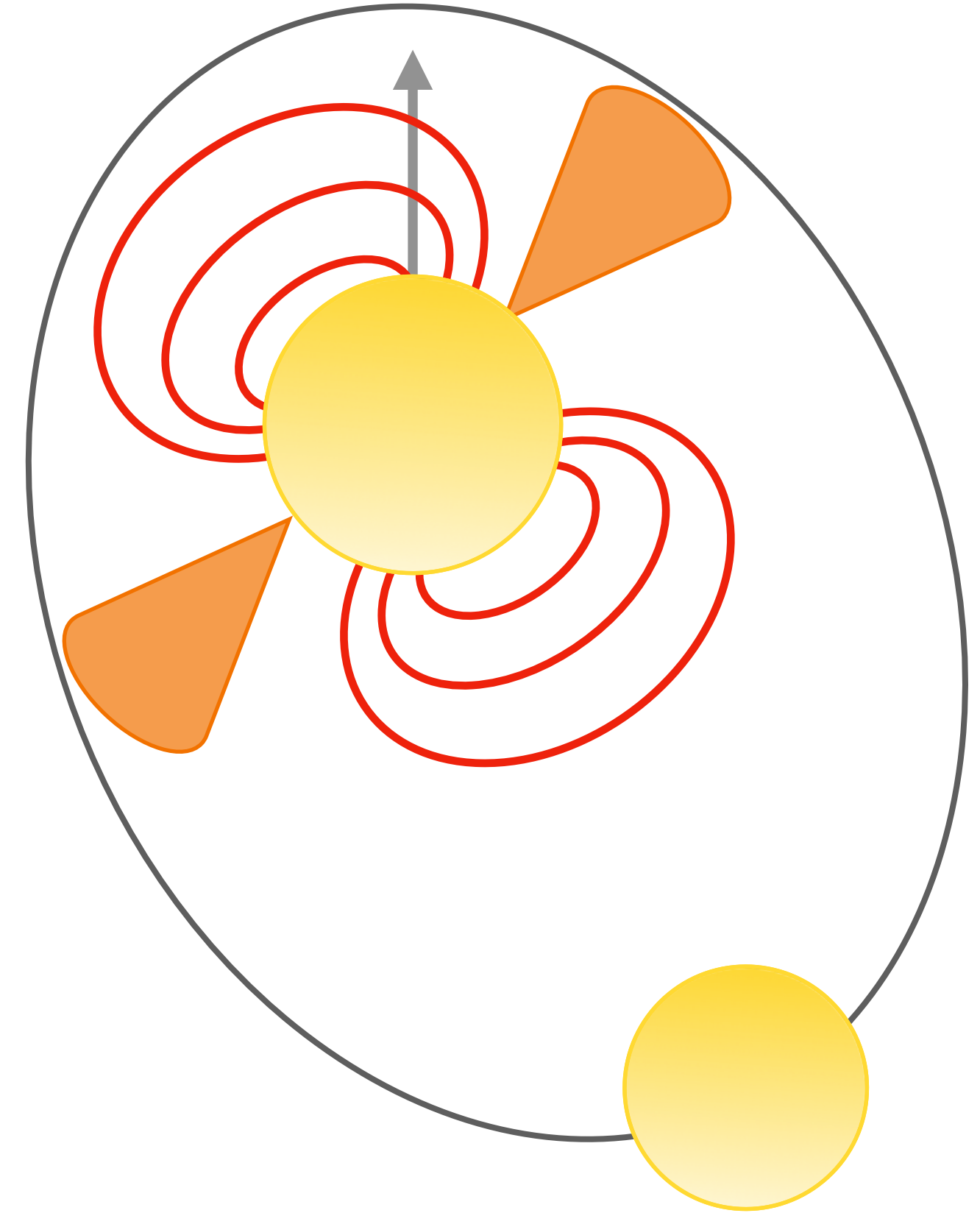
Pulsar companion systematics

Gravitational Waves



Solar system systematics

Pulsar red noise
(e . g . magnetosphere fluctuation)

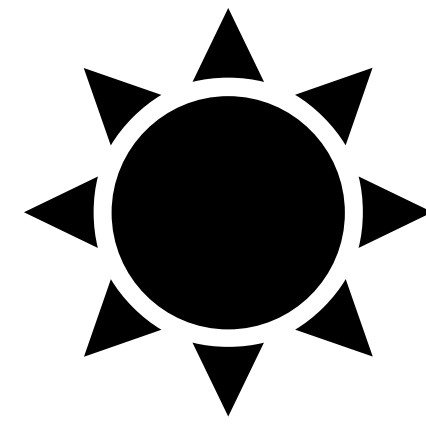
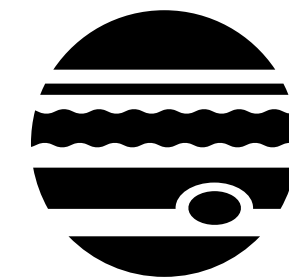
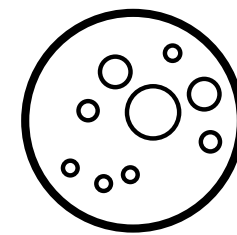


Pulsar companion
systematics

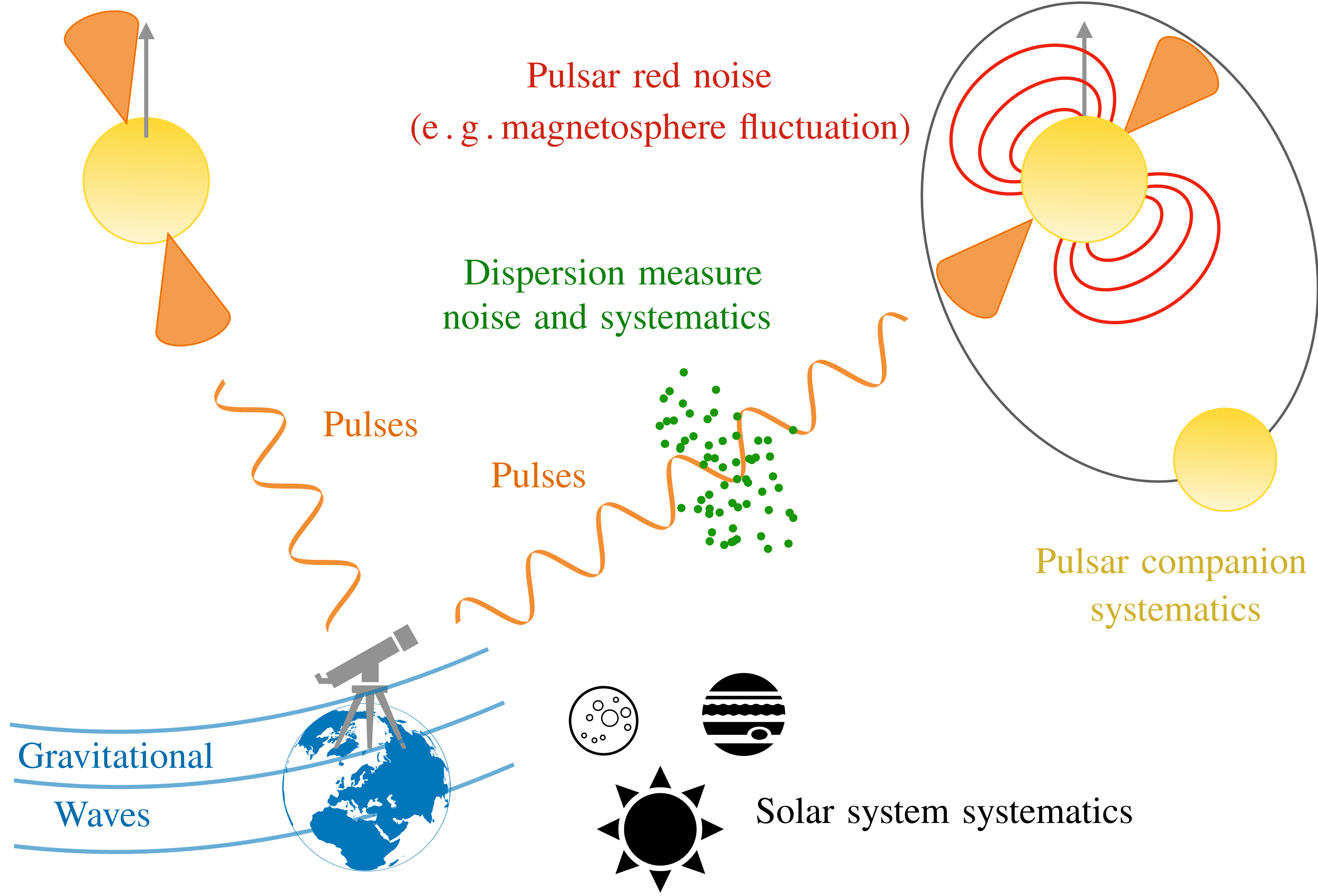
Pulses

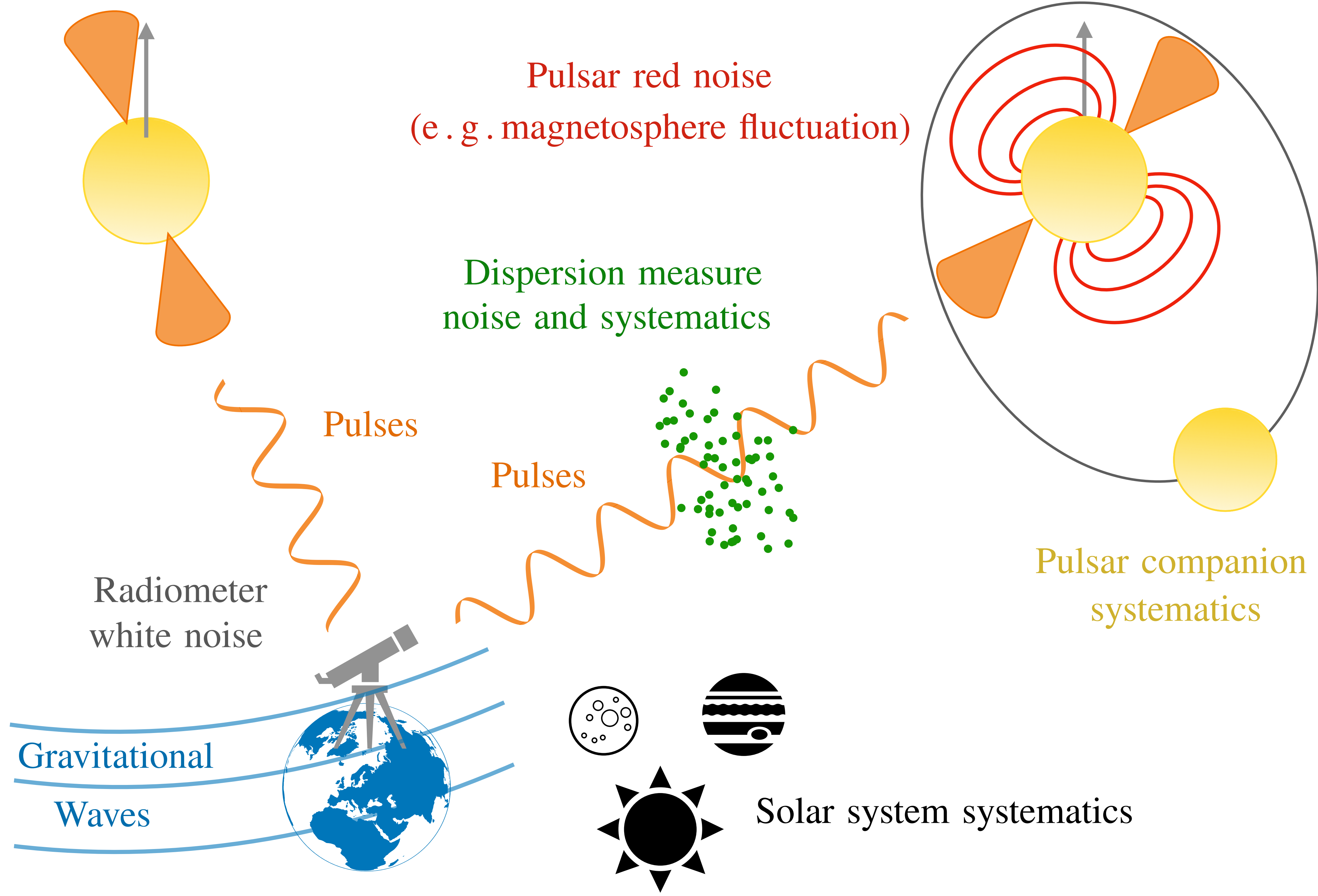
Pulses

Gravitational
Waves

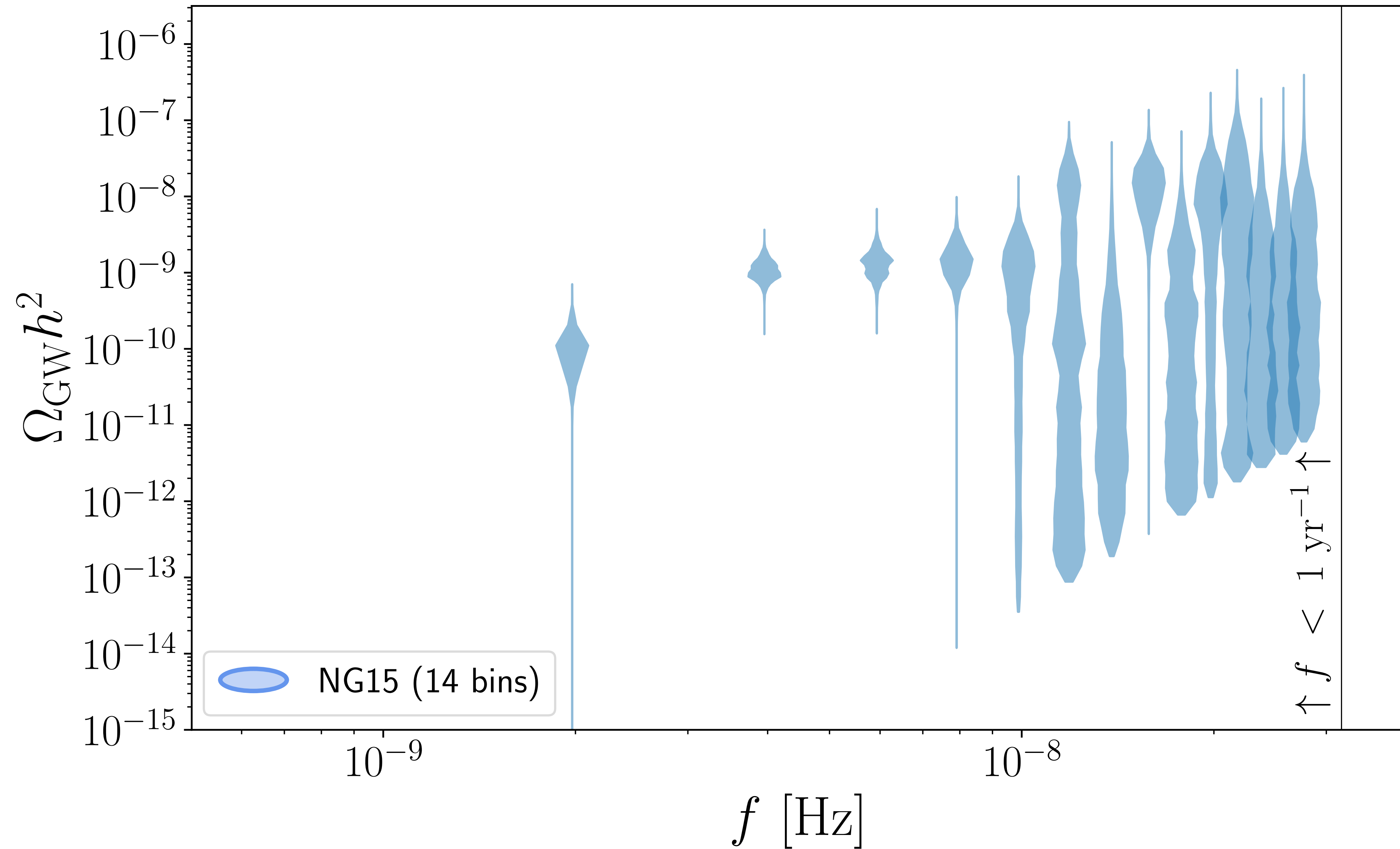


Solar system systematics

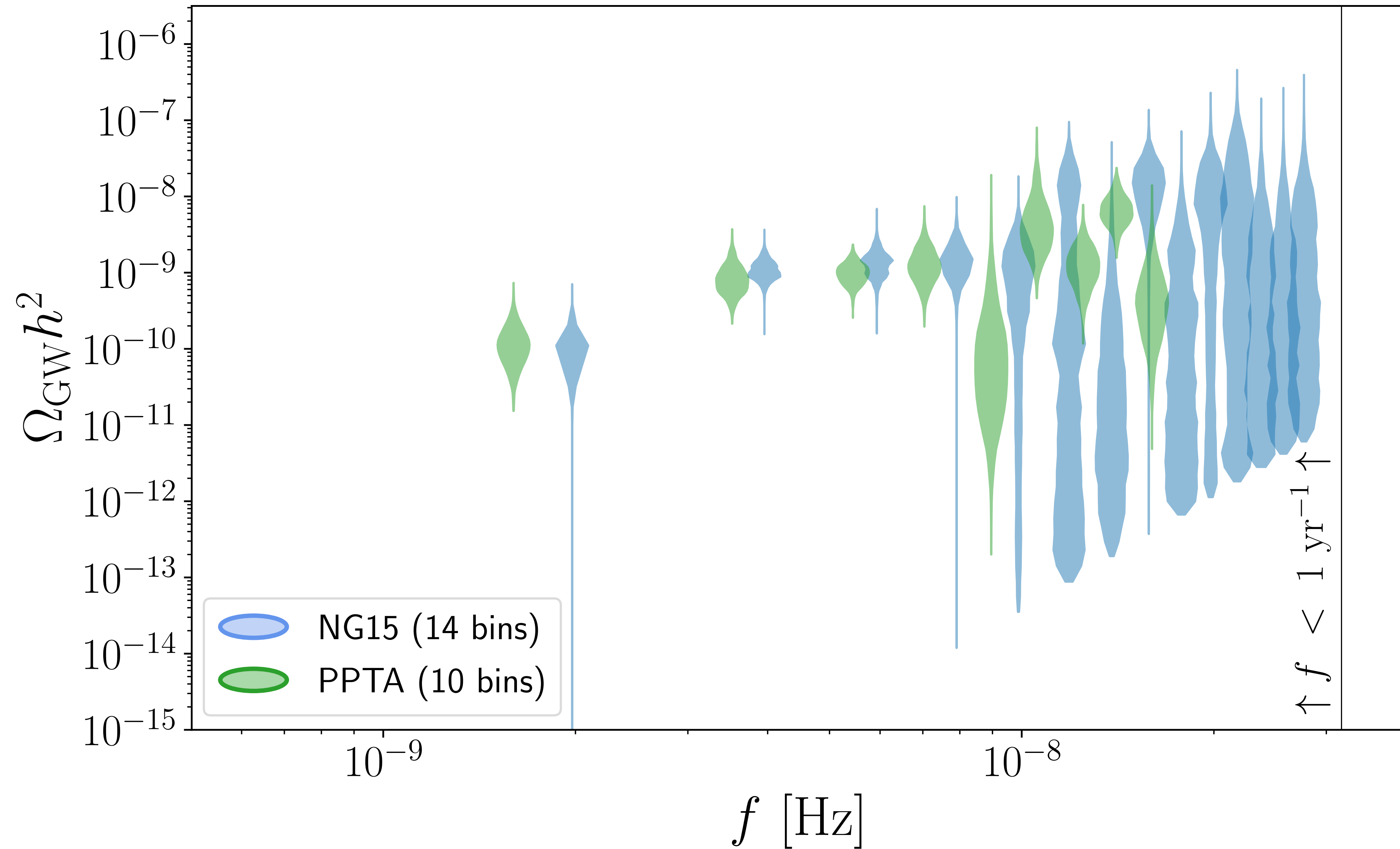




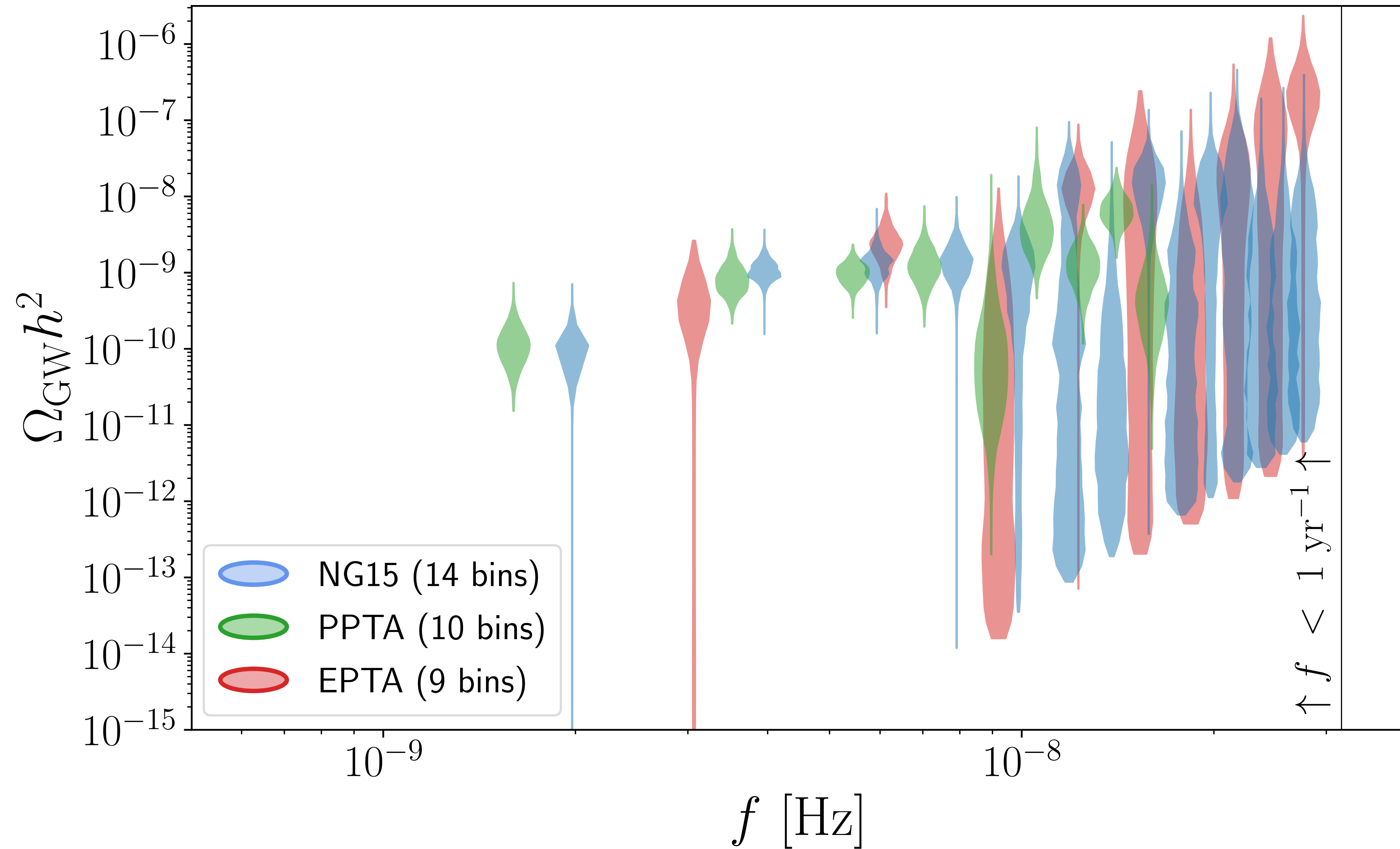
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



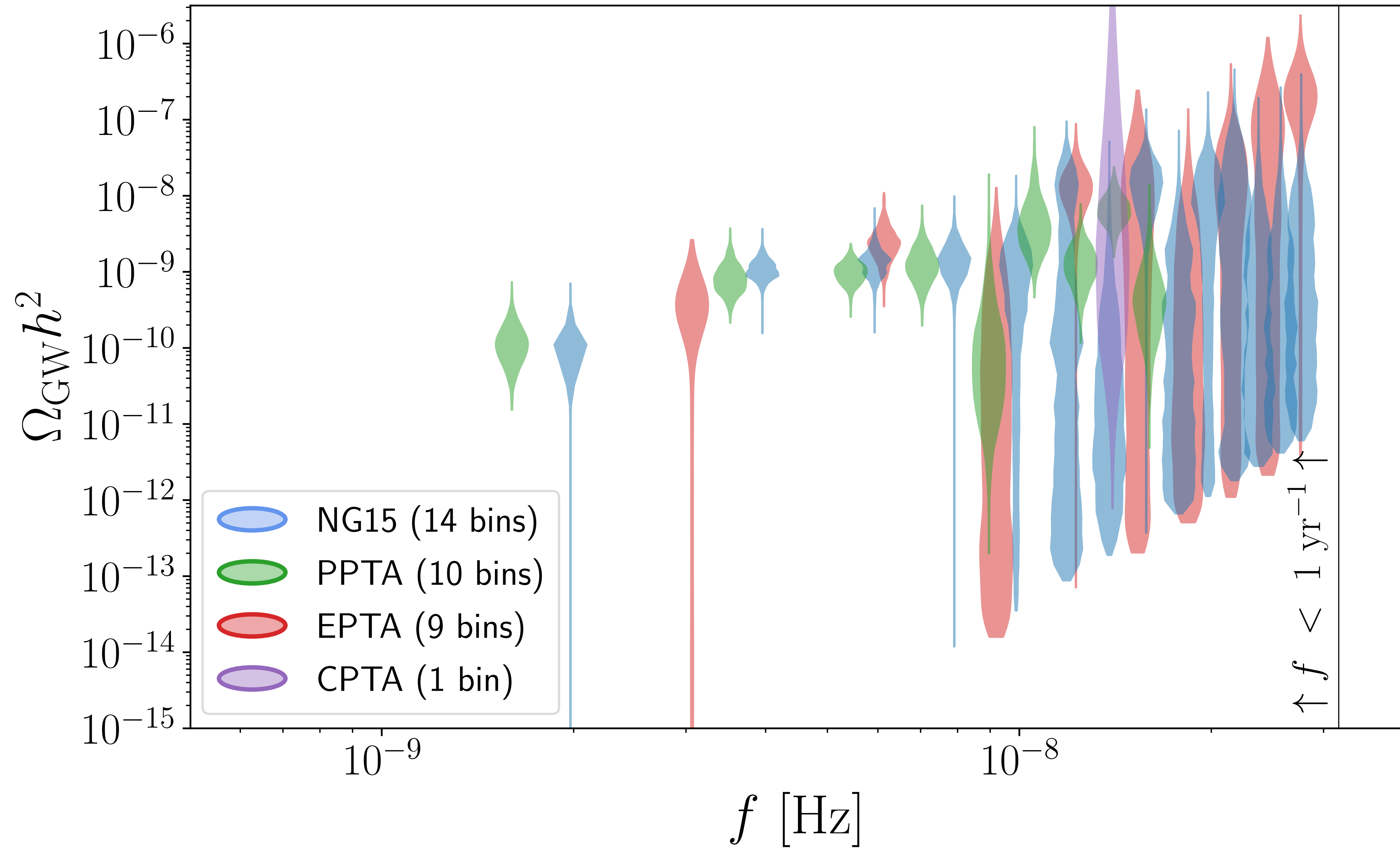
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



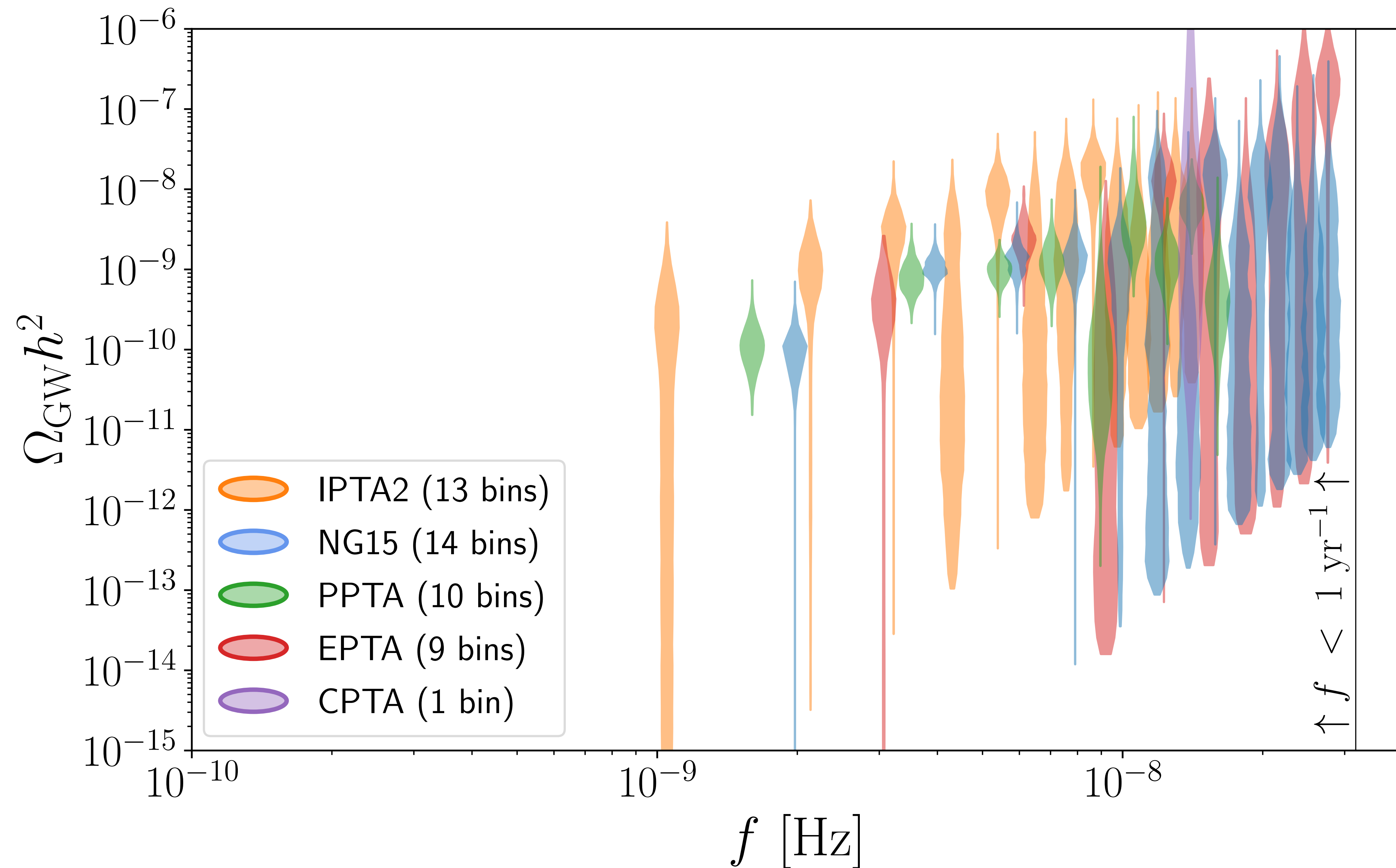
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



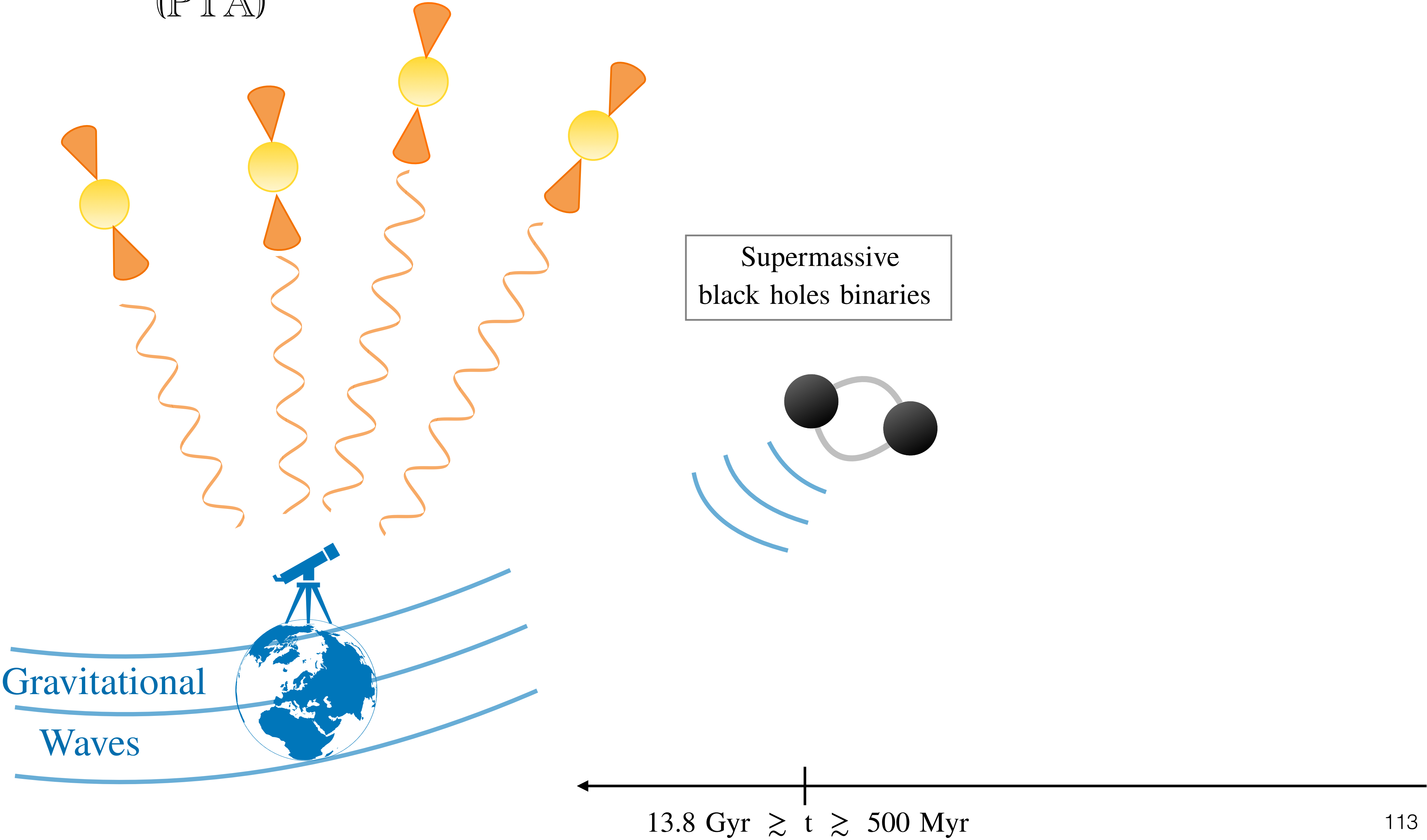
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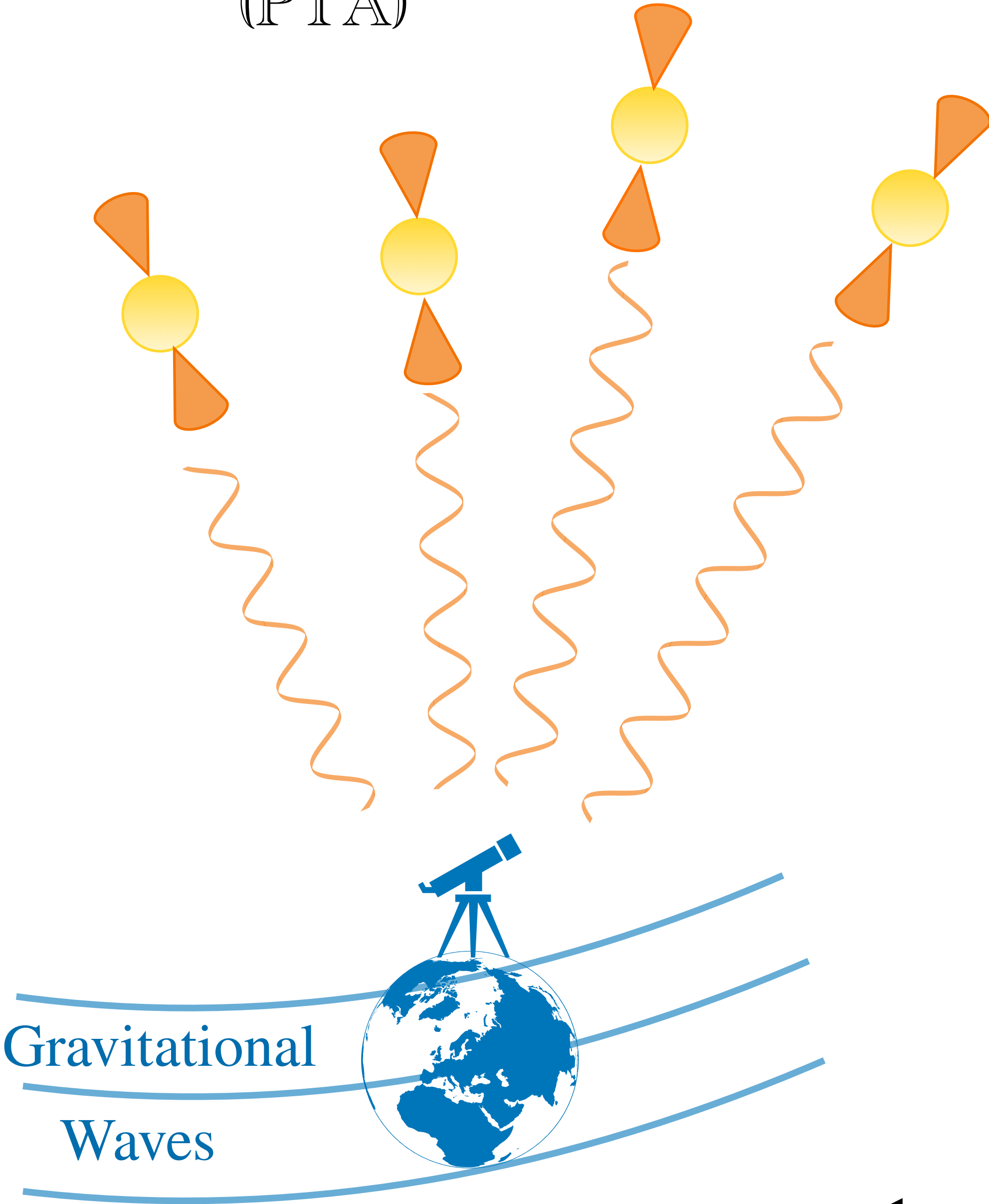
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



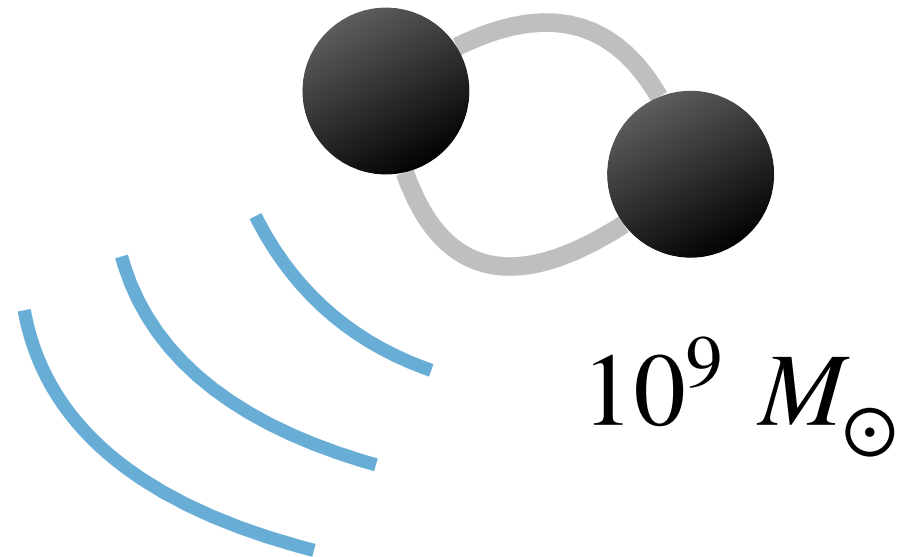
Pulsar Timing Arrays (PTA)



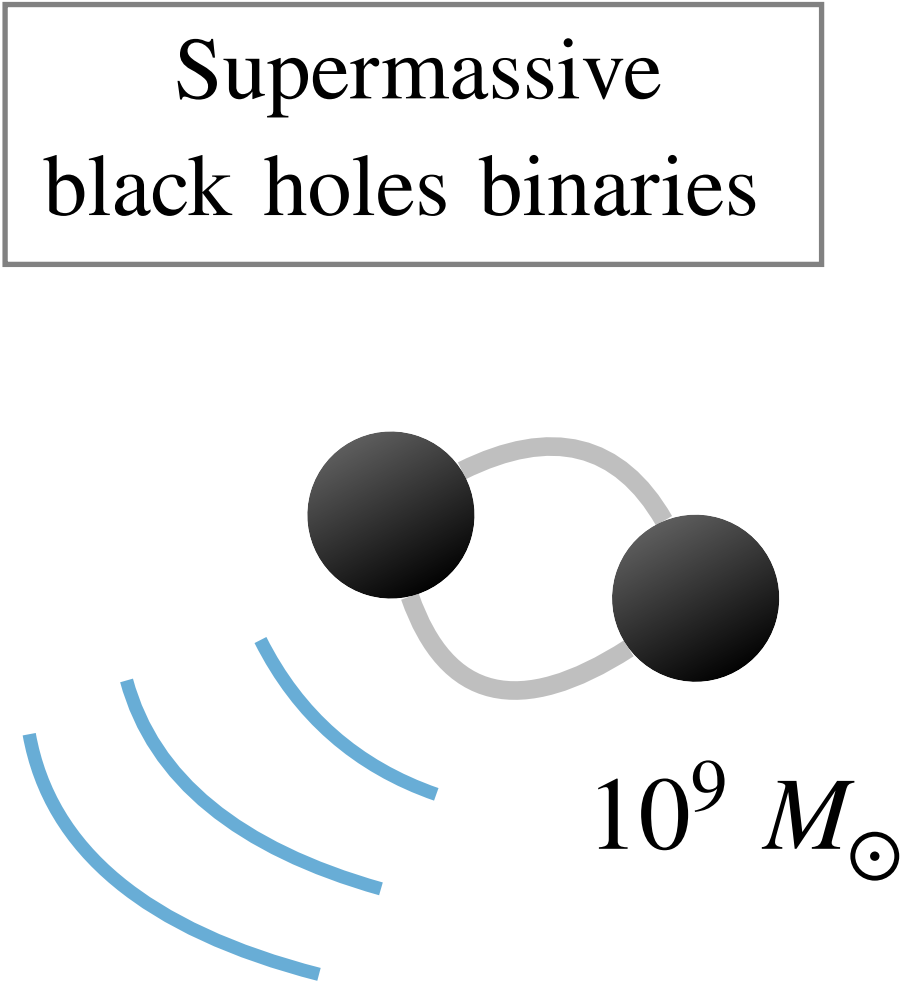
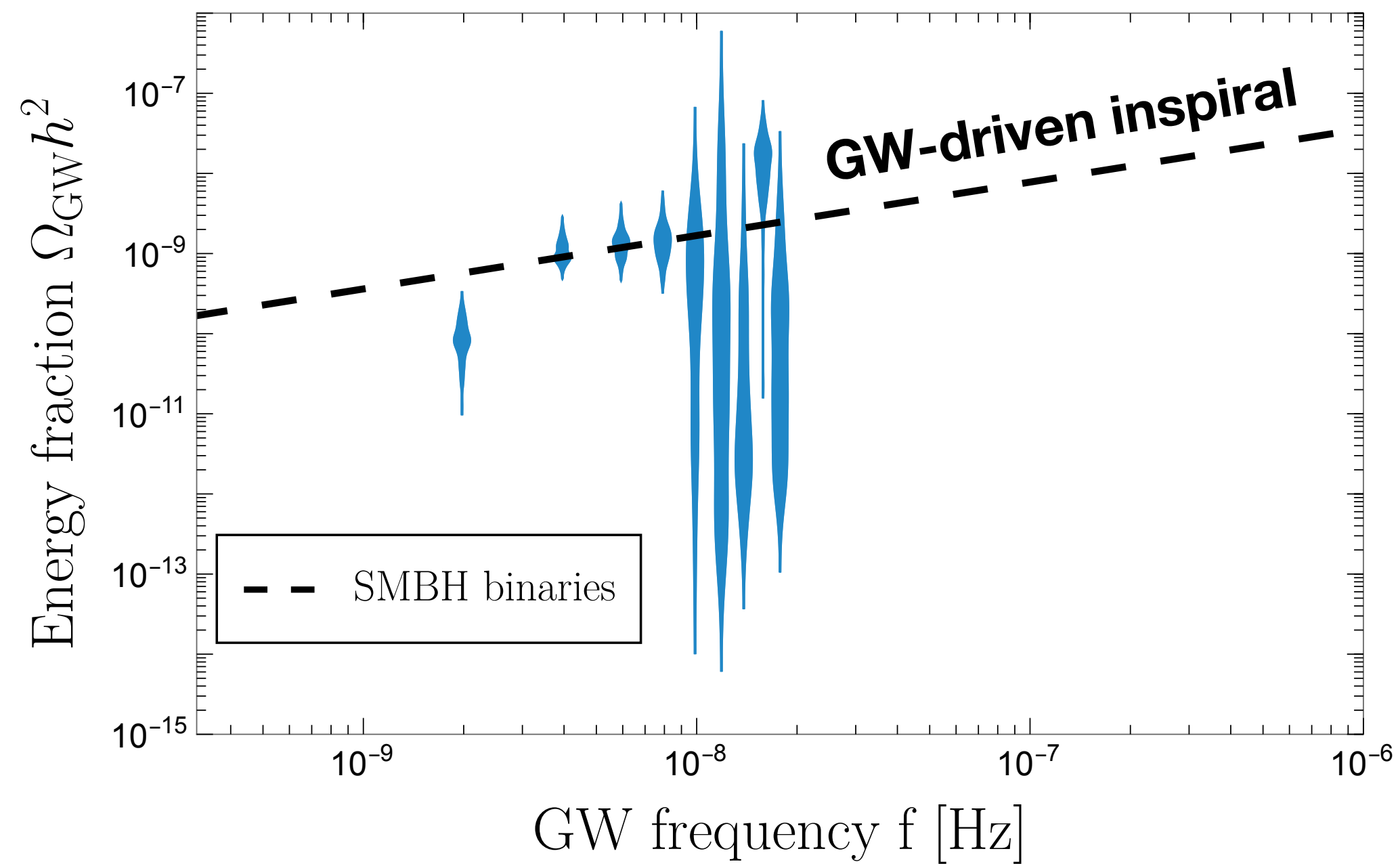
Pulsar Timing Arrays
(PTA)



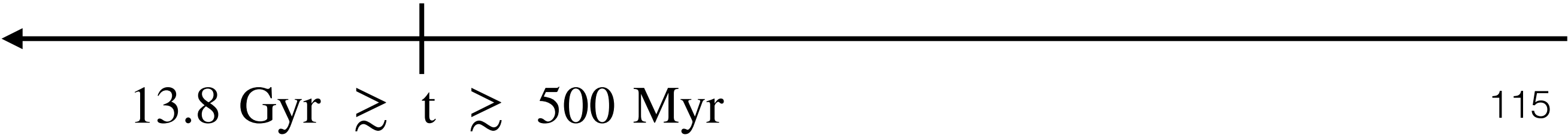
Supermassive
black holes binaries

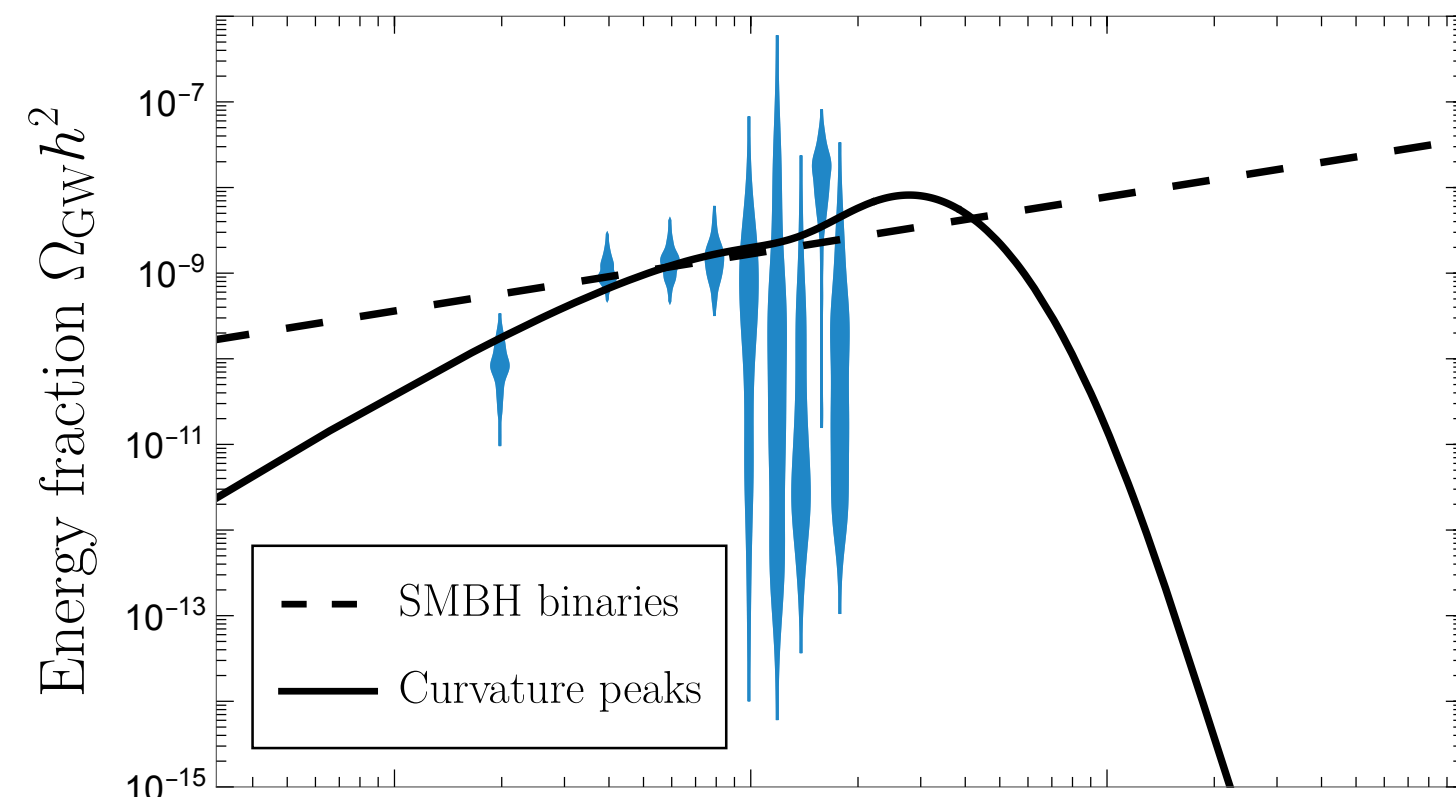


Pulsar Timing Arrays (PTA)



Gravitational Waves



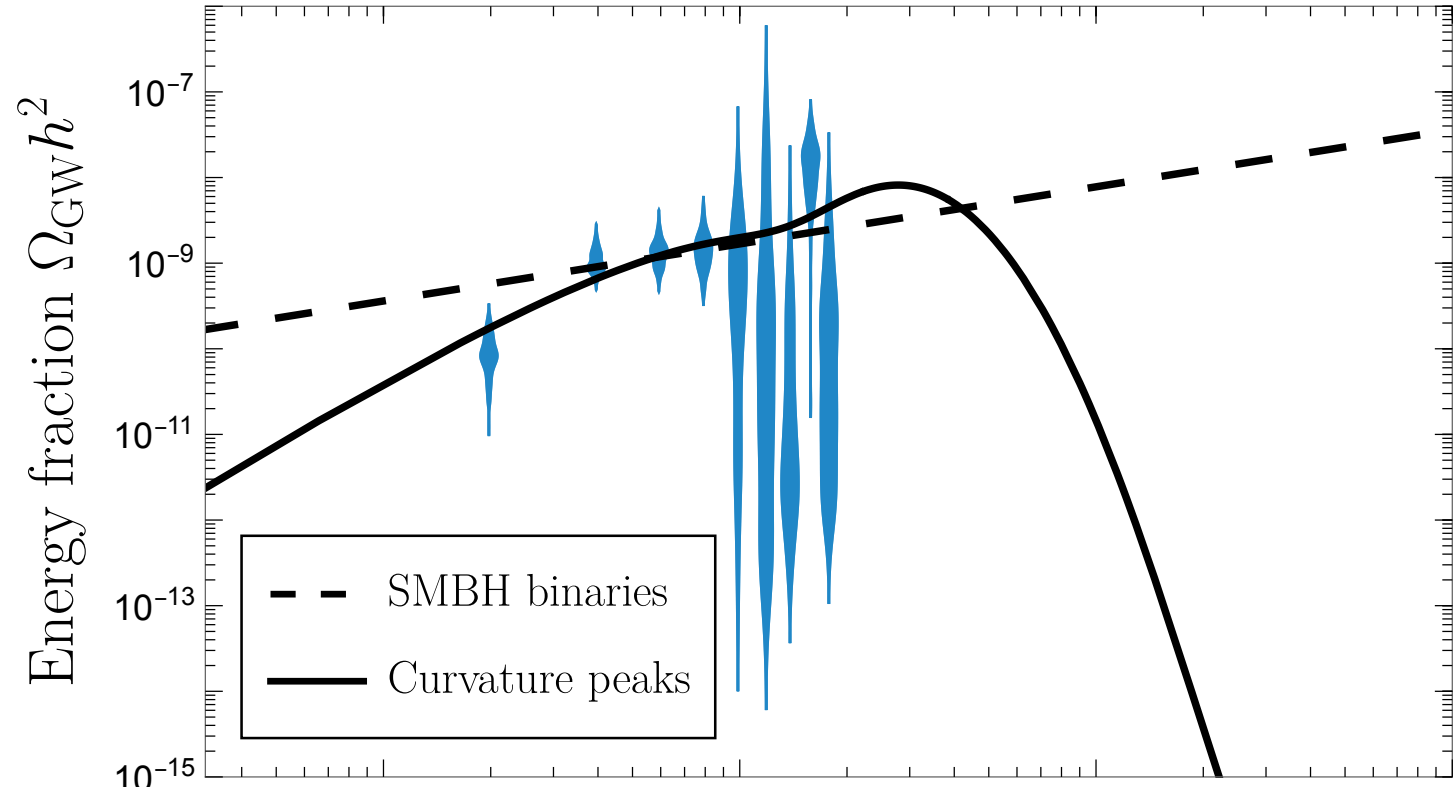


Curvature peaks

Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
Franciolini, Vaskonen, Vermae (2306.17143)
Cecchini, Franciolini, Pieroni (2503.10805)
 ...

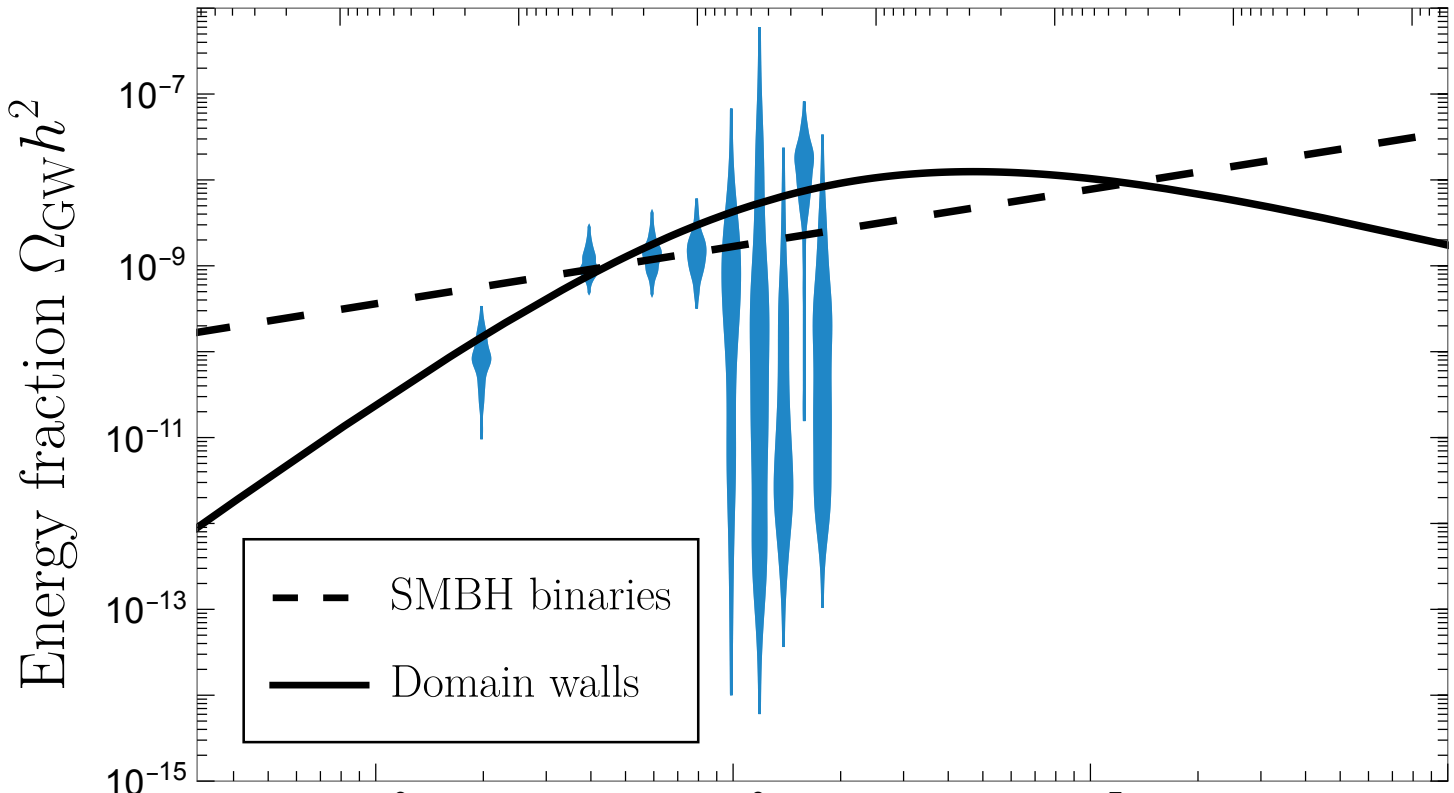


Reviews: Madge et al (2306.14856),
Figueroa et al (2307.02399),
Ellis et al (2308.08546)



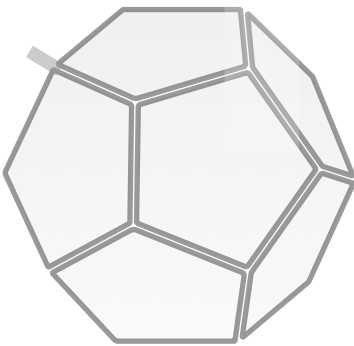
Curvature peaks

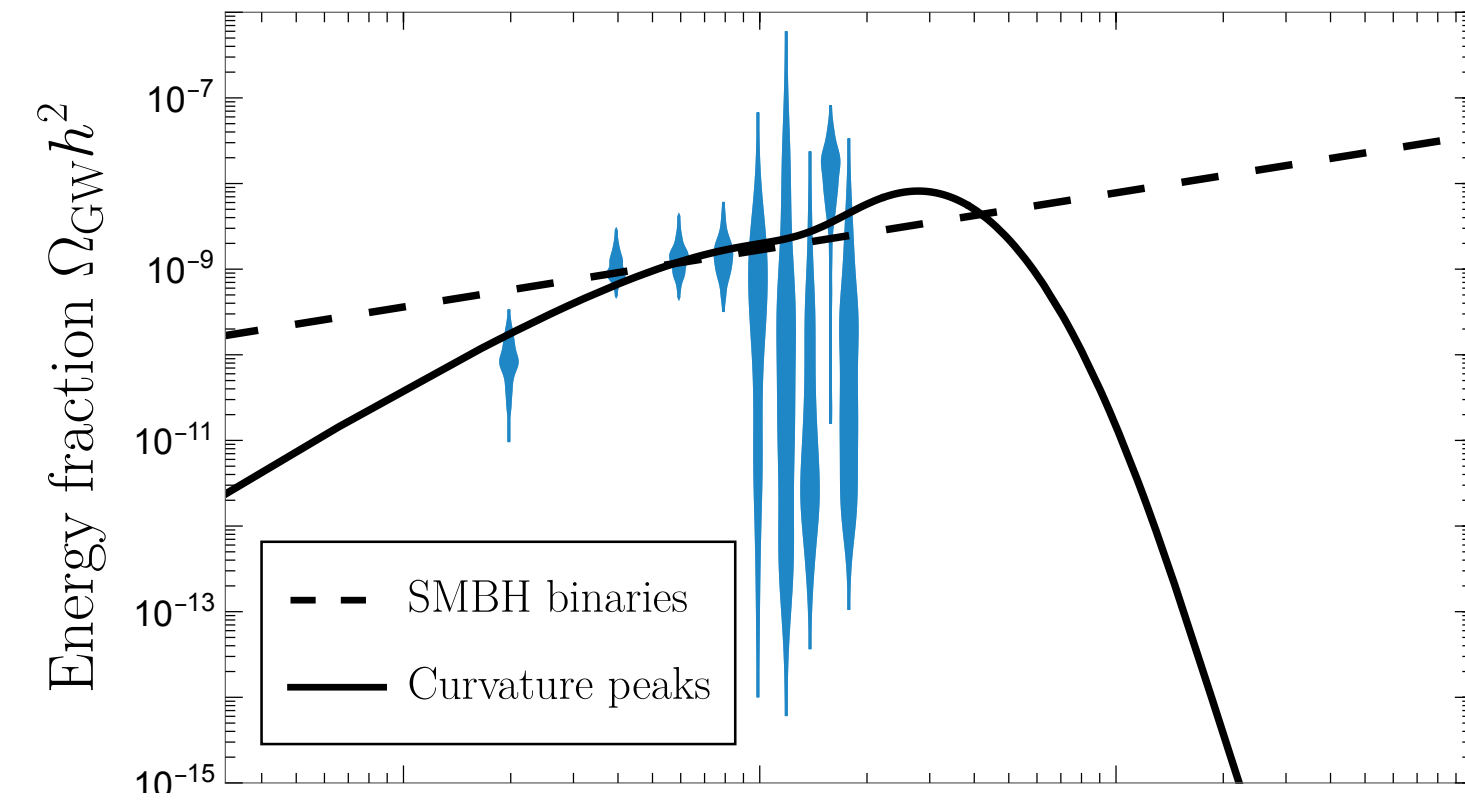
Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
Franciolini, Vaskonen, Vermae (2306.17143)
Cecchini, Franciolini, Pieroni (2503.10805)
...



Domain wall networks

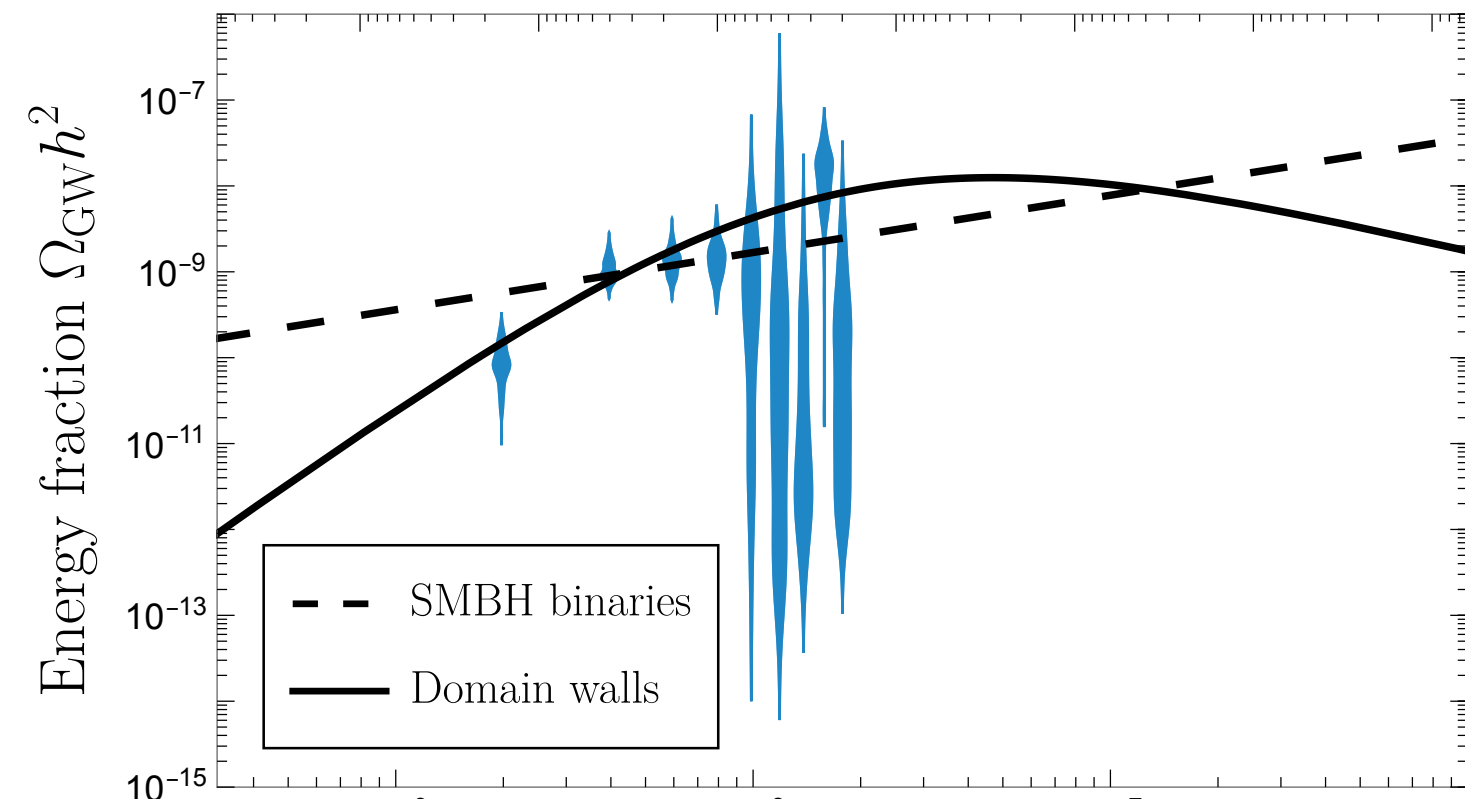
Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
...





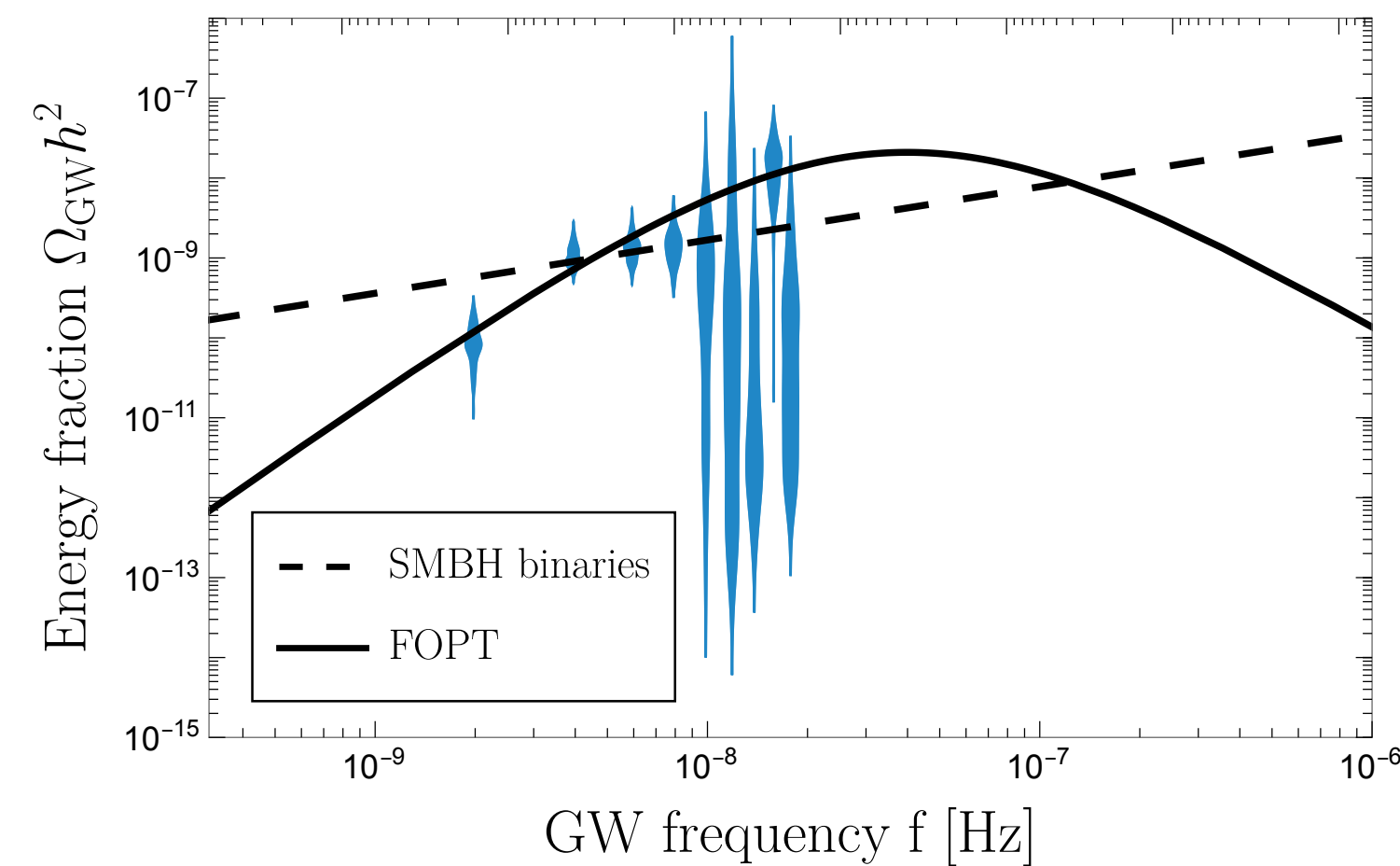
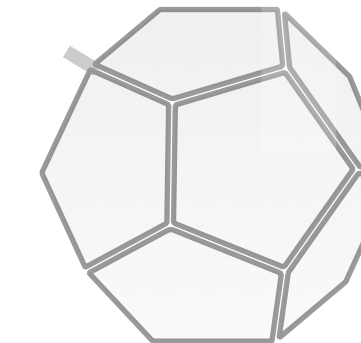
Curvature peaks

***Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
Franciolini, Vaskonen, Vermae (2306.17143)
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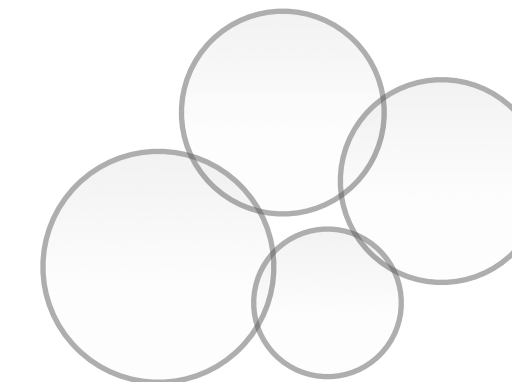
Domain wall networks

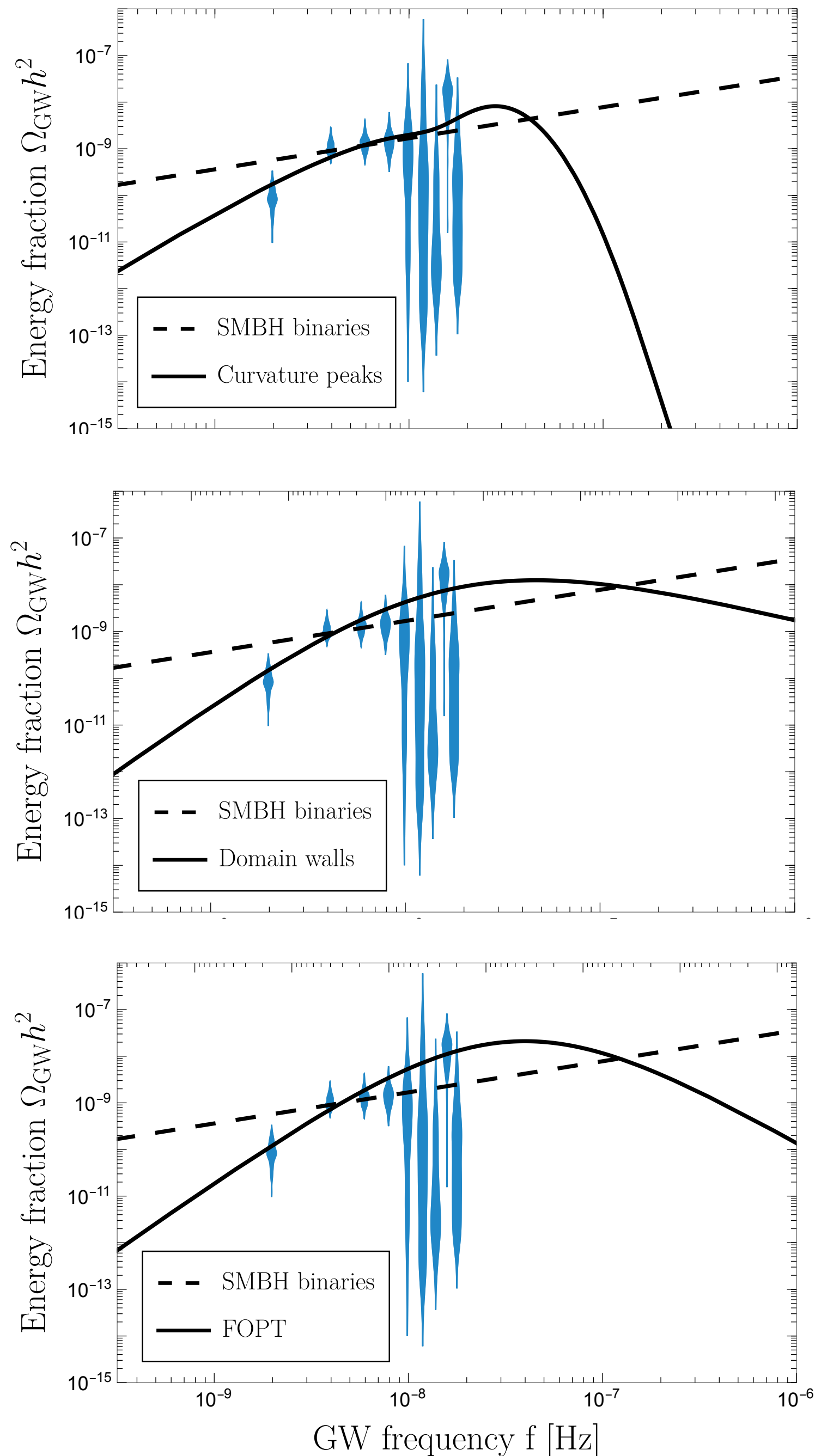
***Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
...***



First-order phase transitions

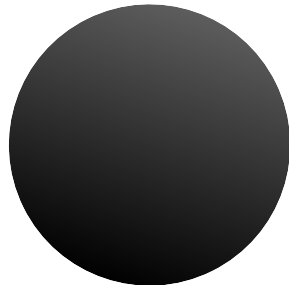
***Roper Pol et al. (2201.05630)
Ghoshal, White et al. (2307.02259)
YG (2307.04239)
Lewicki, Toczek, Vaskonen (2402.04158)
Hoefken Zink et al. (2501.15649)
...***





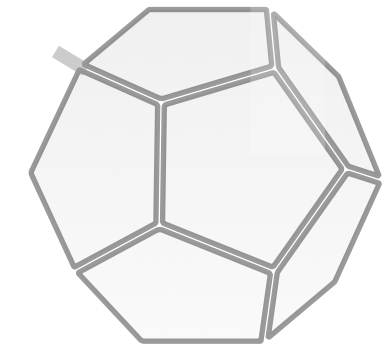
Curvature peaks

Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
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...



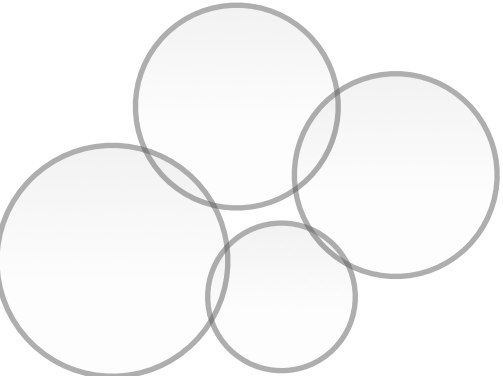
Domain wall networks

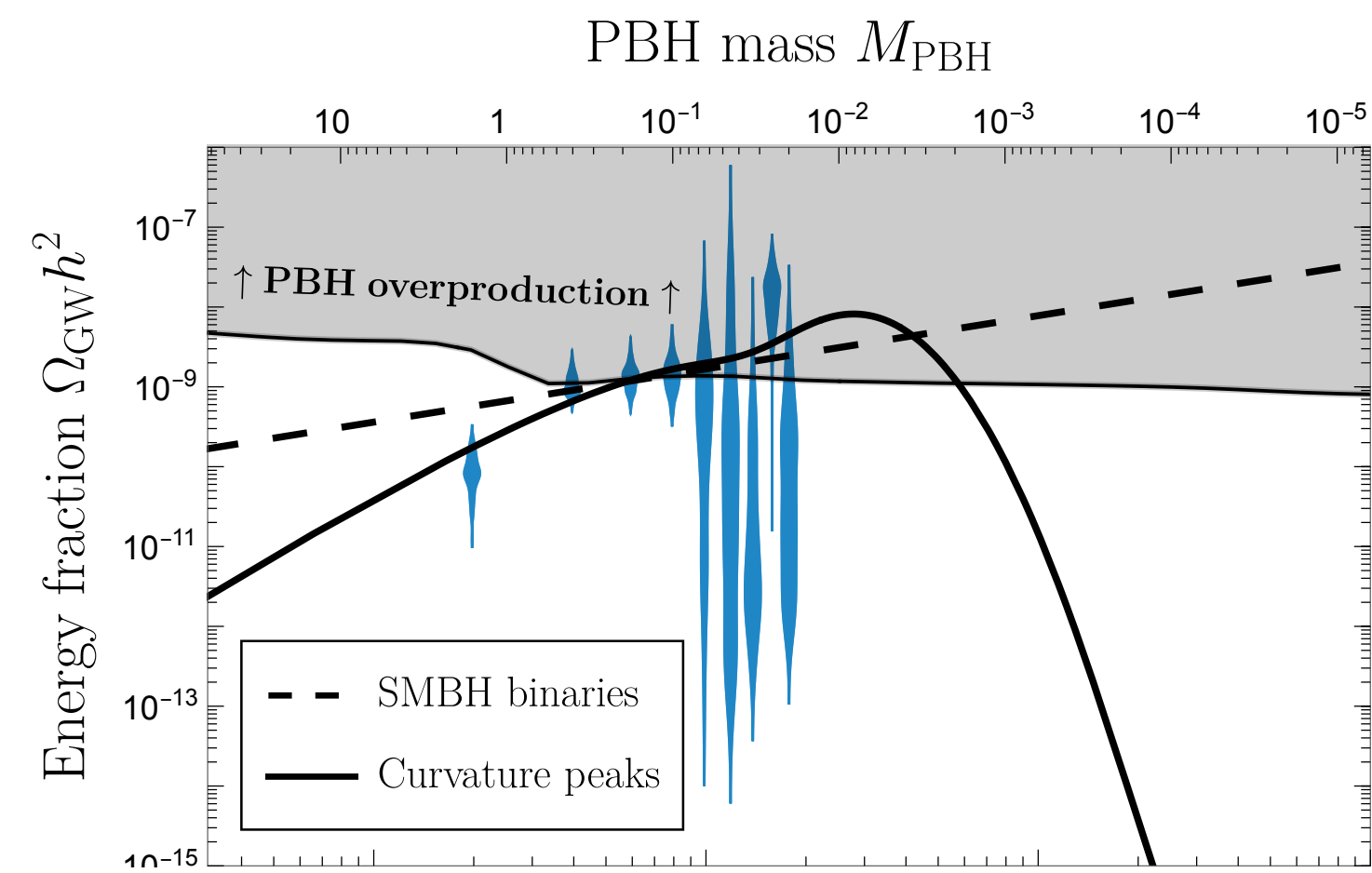
Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
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First-order phase transitions

Roper Pol et al. (2201.05630)
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Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

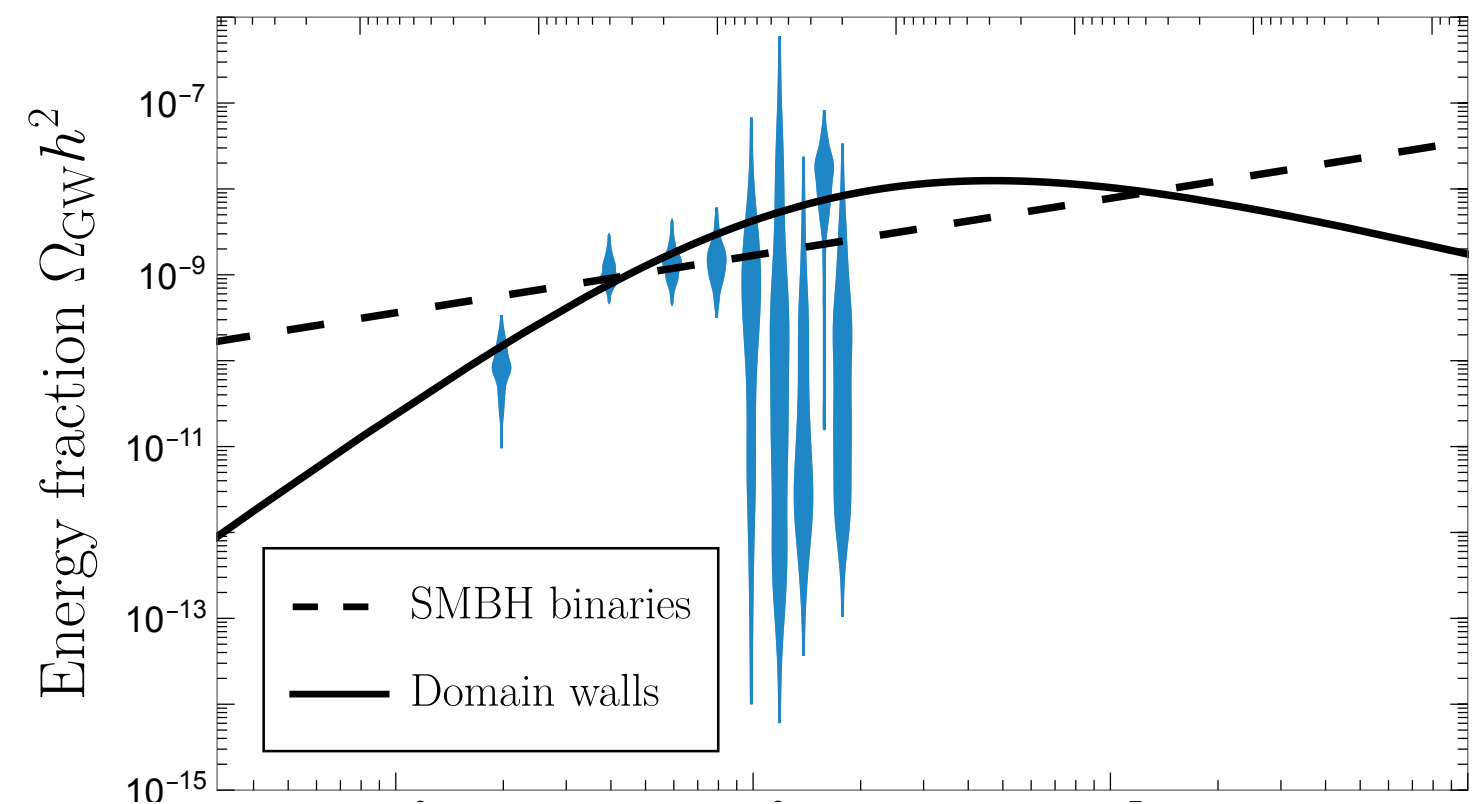
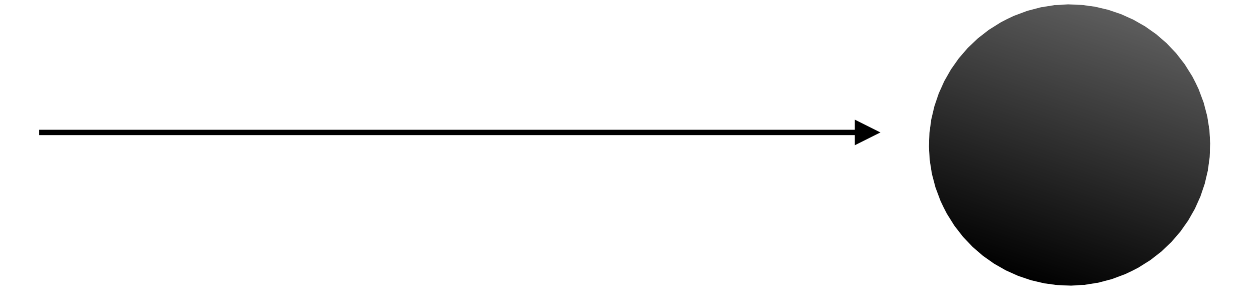
Vaskonen, Veermae (2009.07832),

De Luca, Franciolini, Riotto (2009.08268)

Except if negative non-Gaussianities

Franciolini, Vaskonen, Vermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)

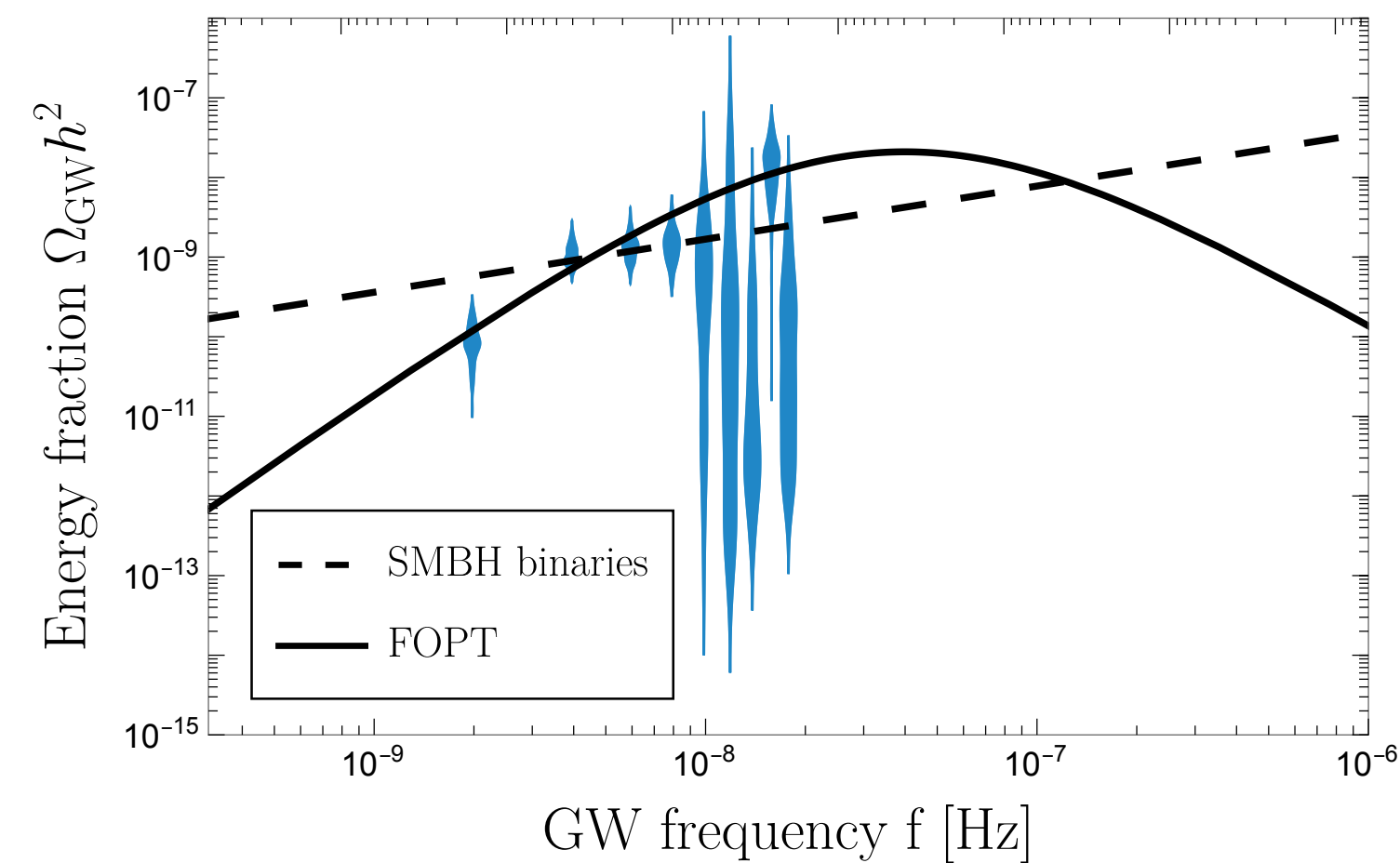
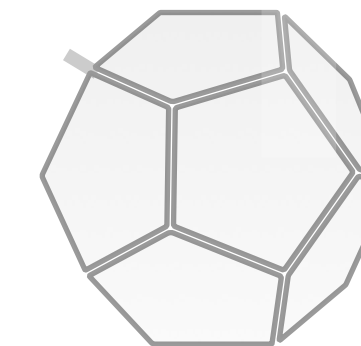


Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...



First-order phase transitions

Roper Pol et al. (2201.05630)

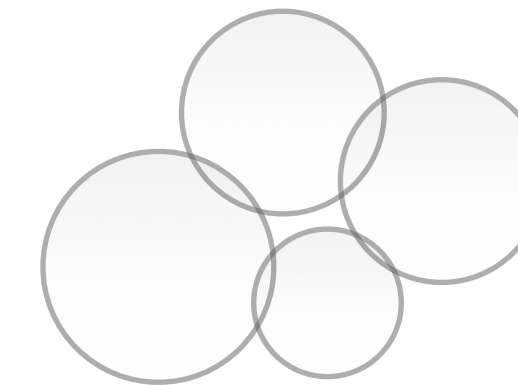
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

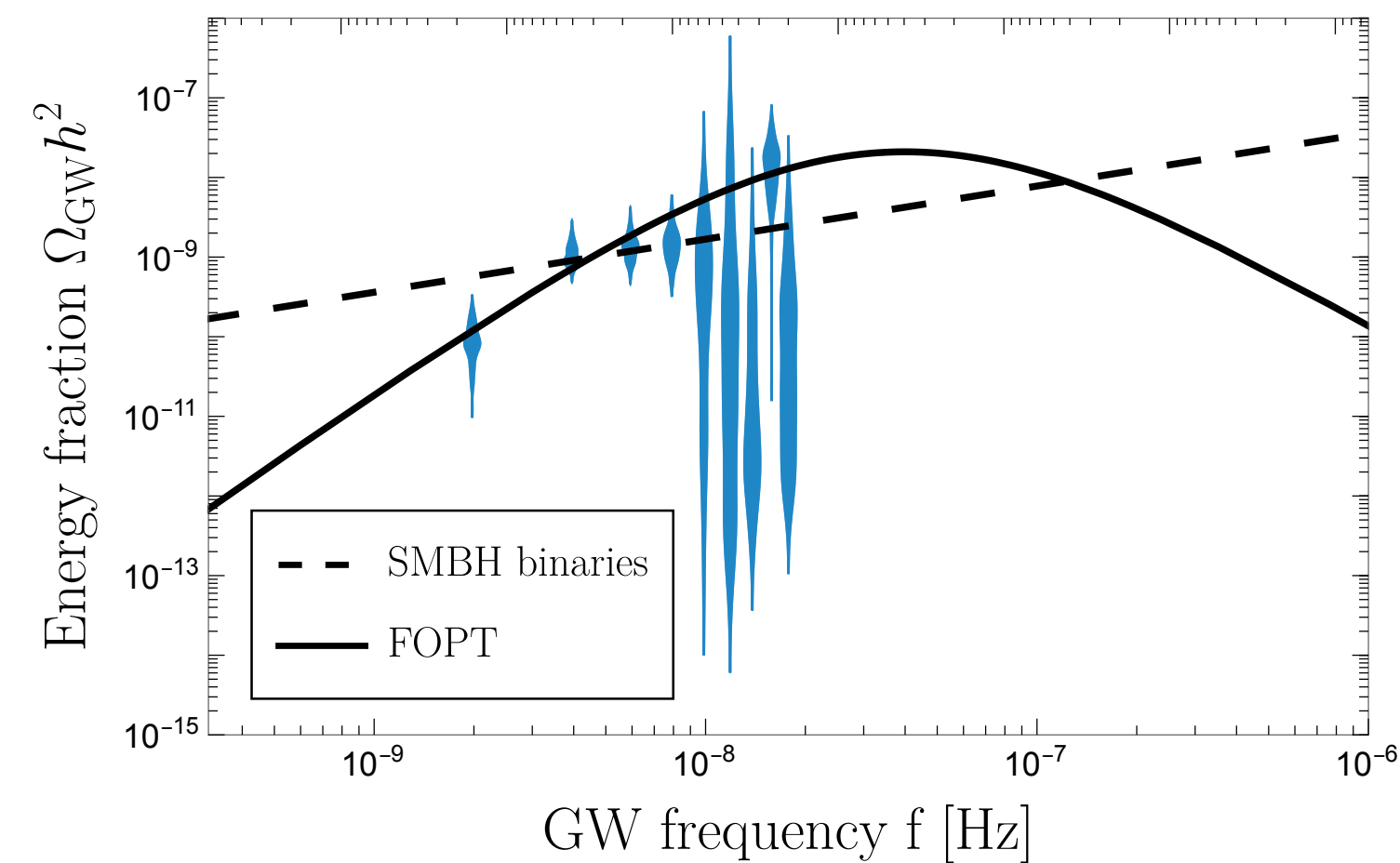
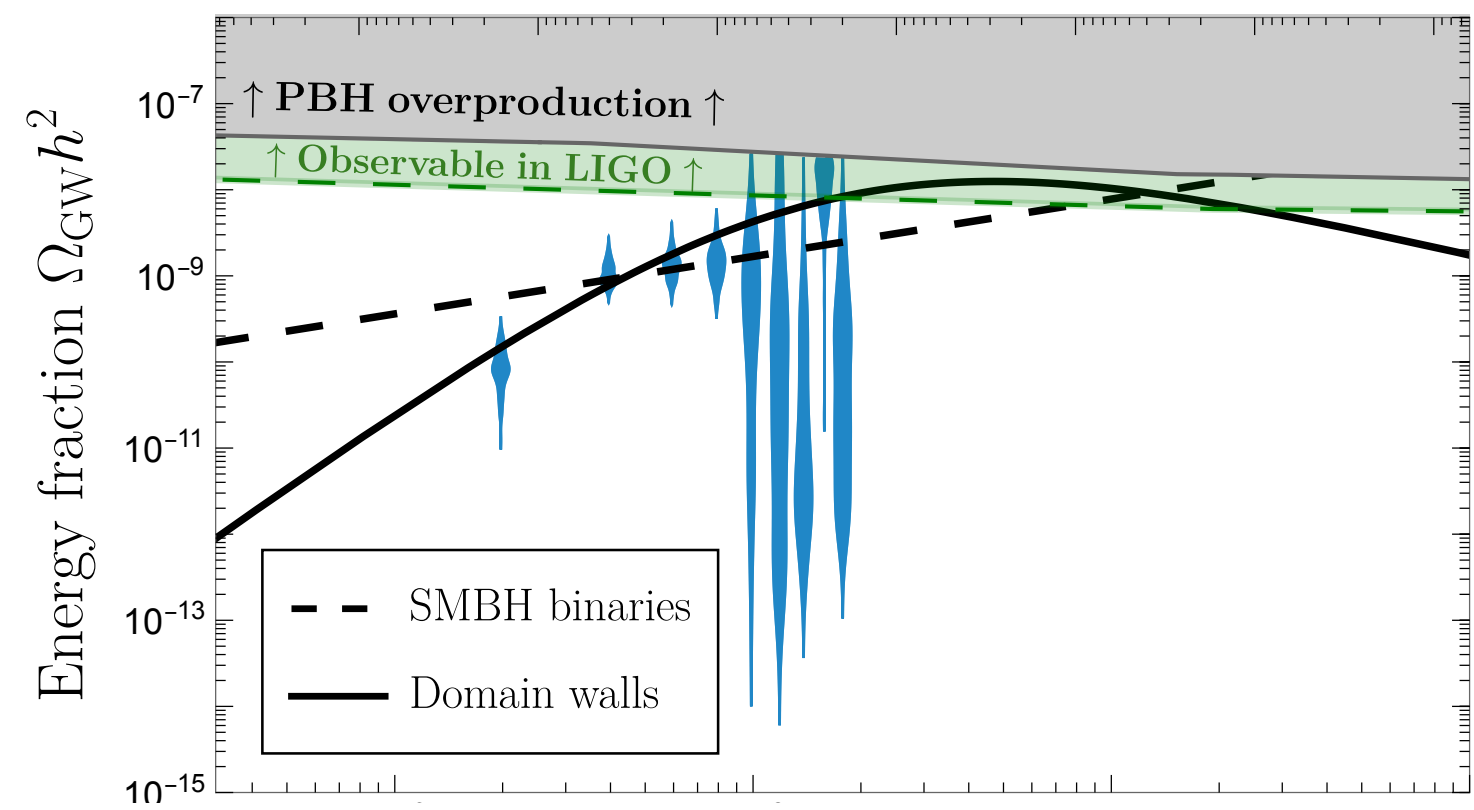
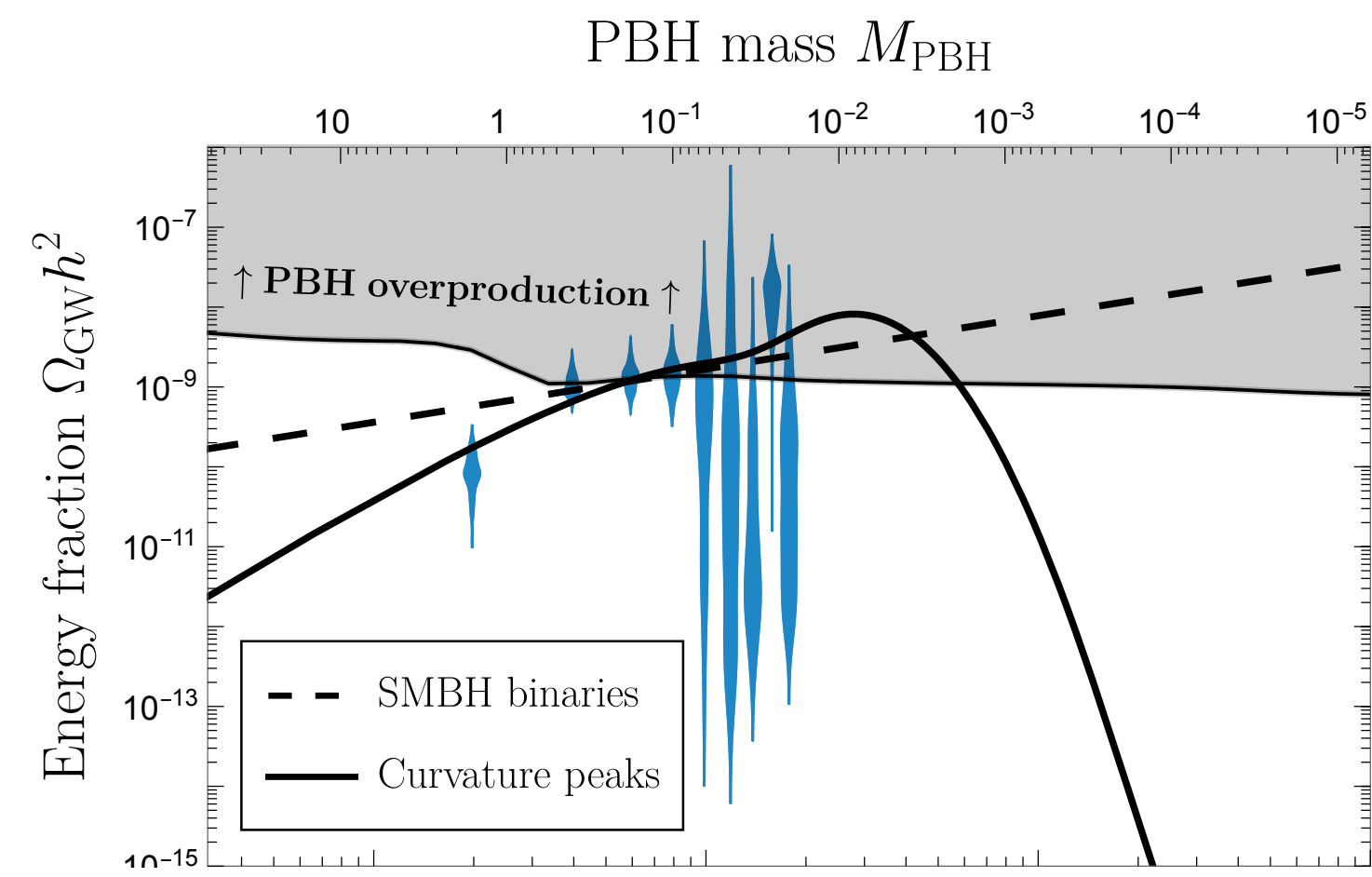
Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...



Reviews: *Madge et al (2306.14856),*
Figueroa et al (2307.02399),
Ellis et al (2308.08546)



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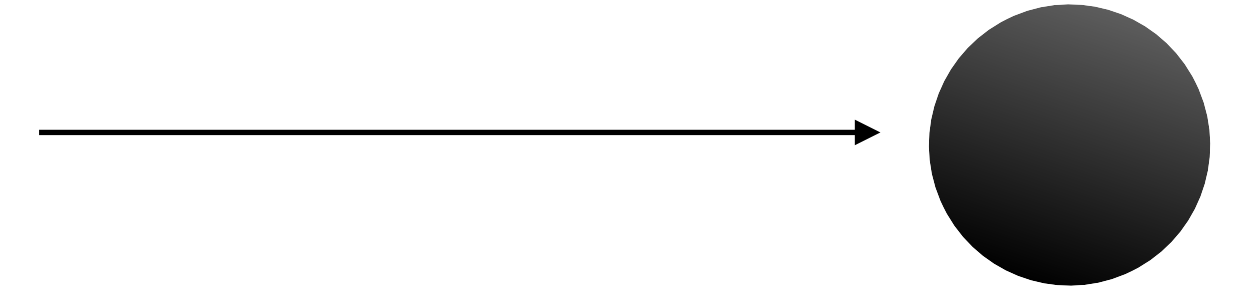
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Domain wall networks

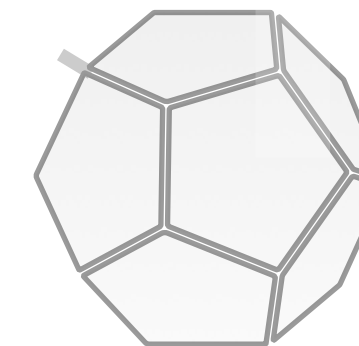
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

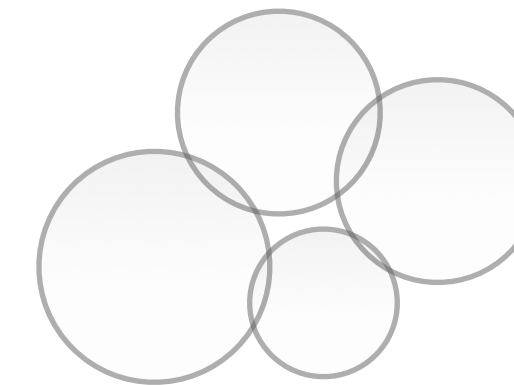
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

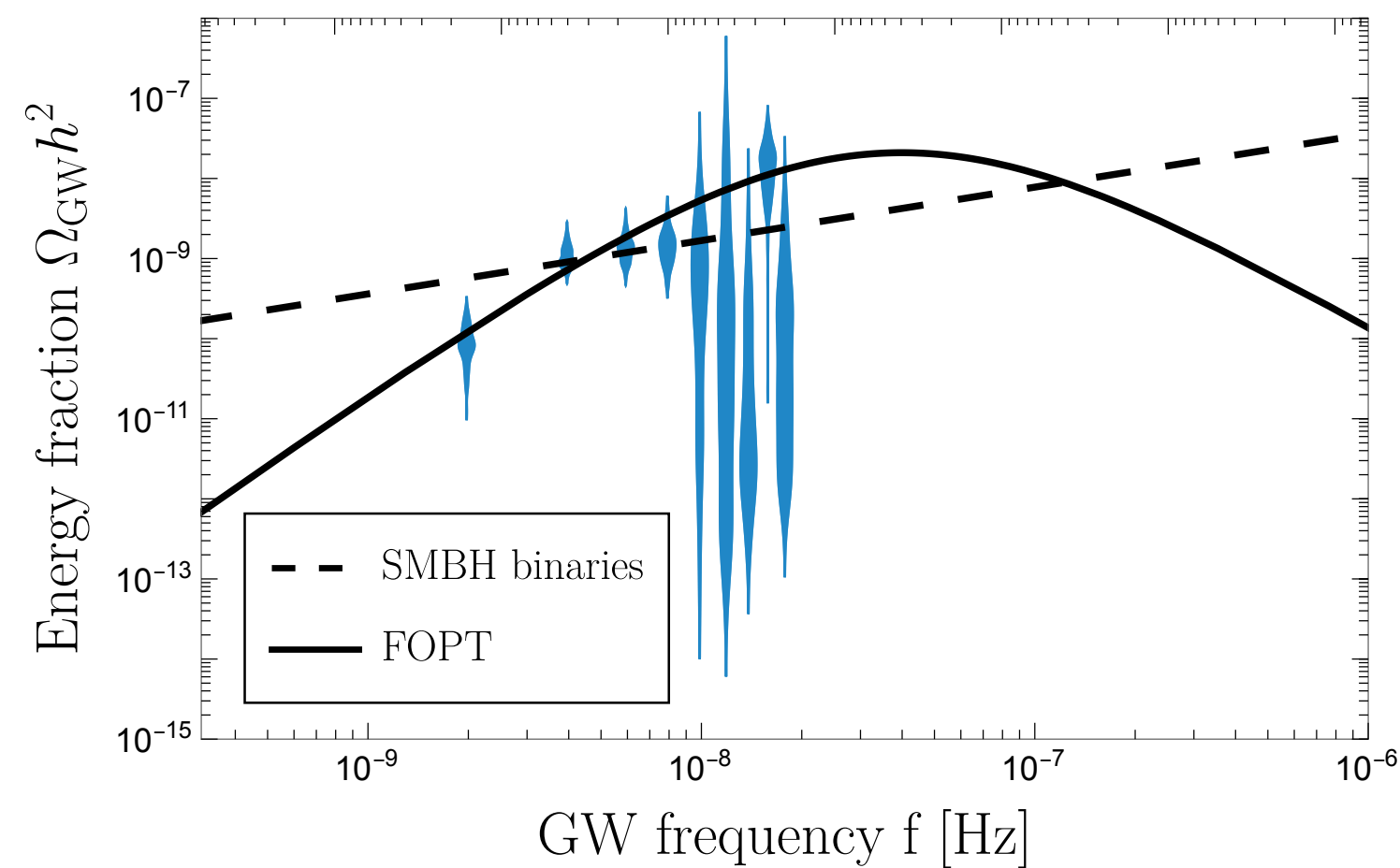
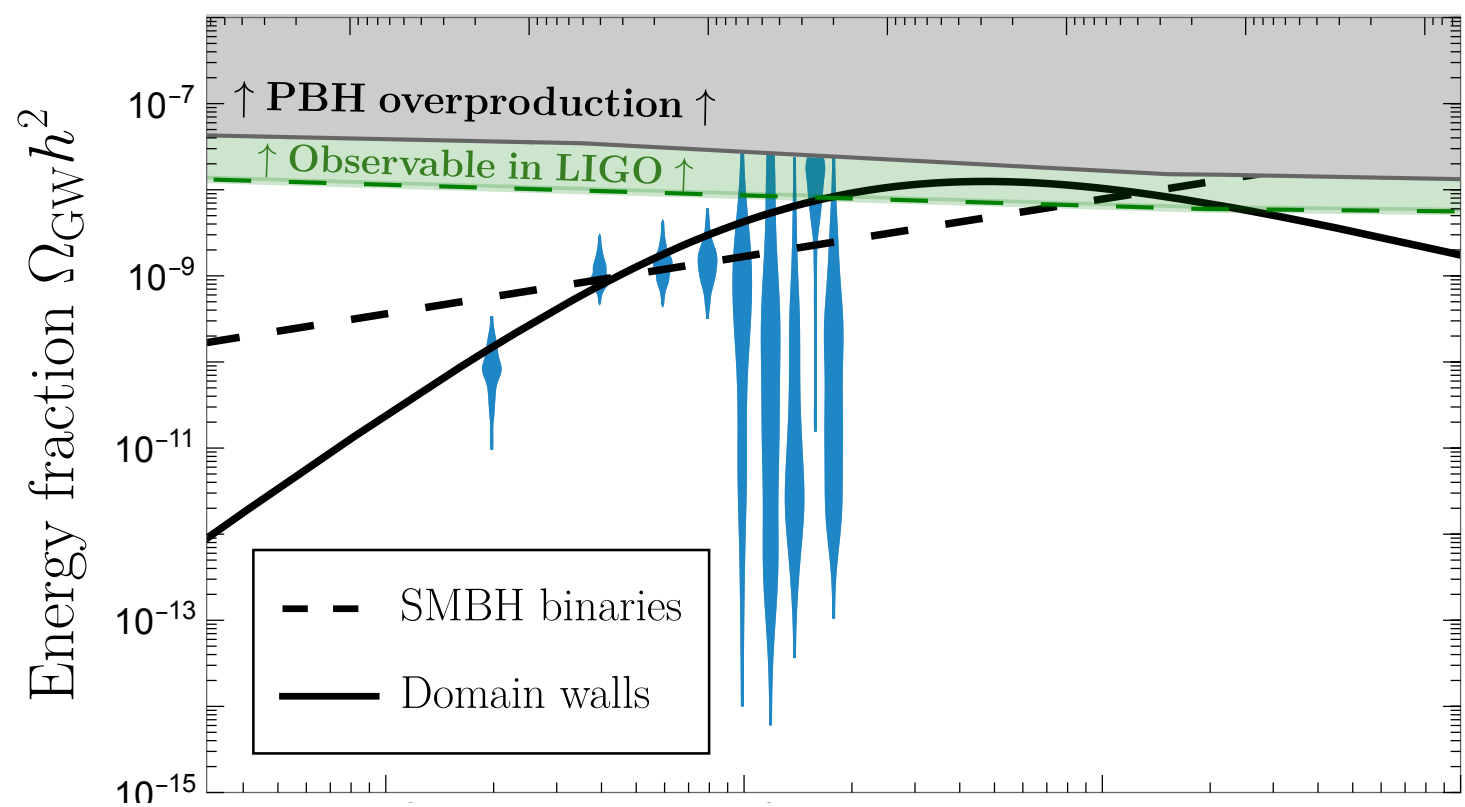
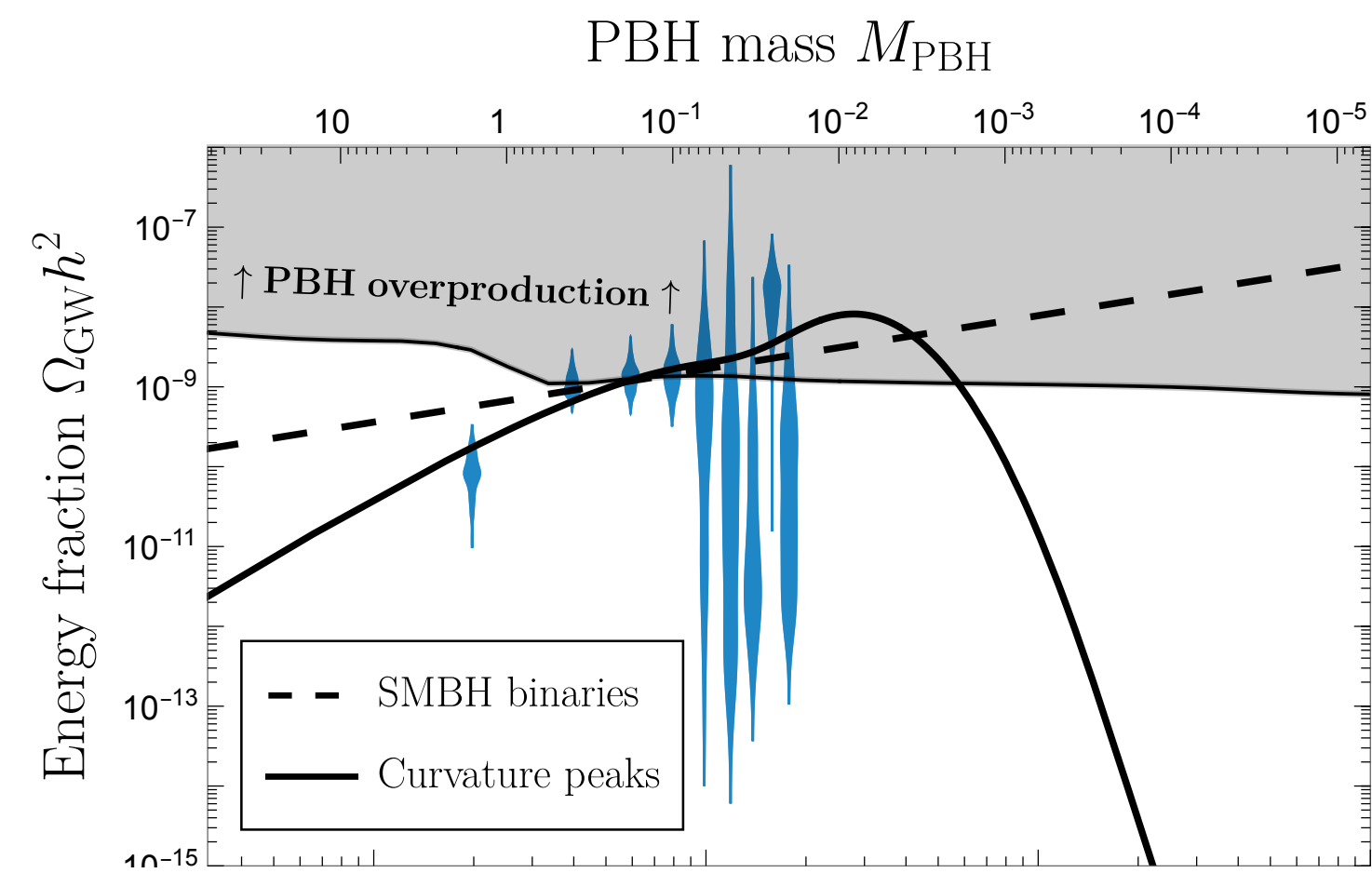
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Domain wall networks

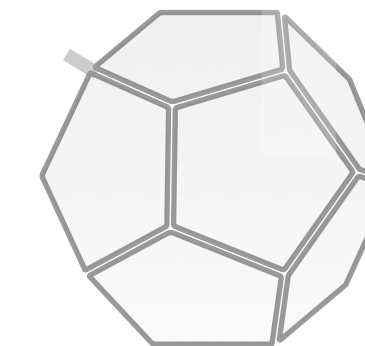
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670

PBH

First-order phase transitions

Roper Pol et al. (2201.05630)

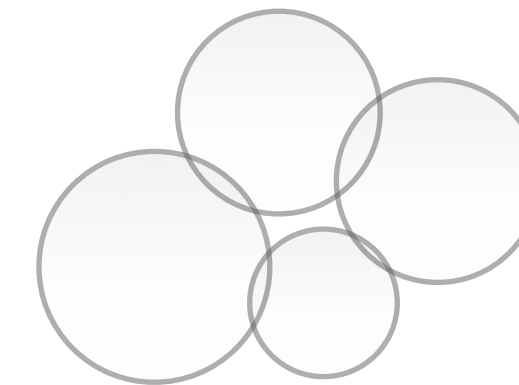
Ghoshal, White et al. (2307.02259)

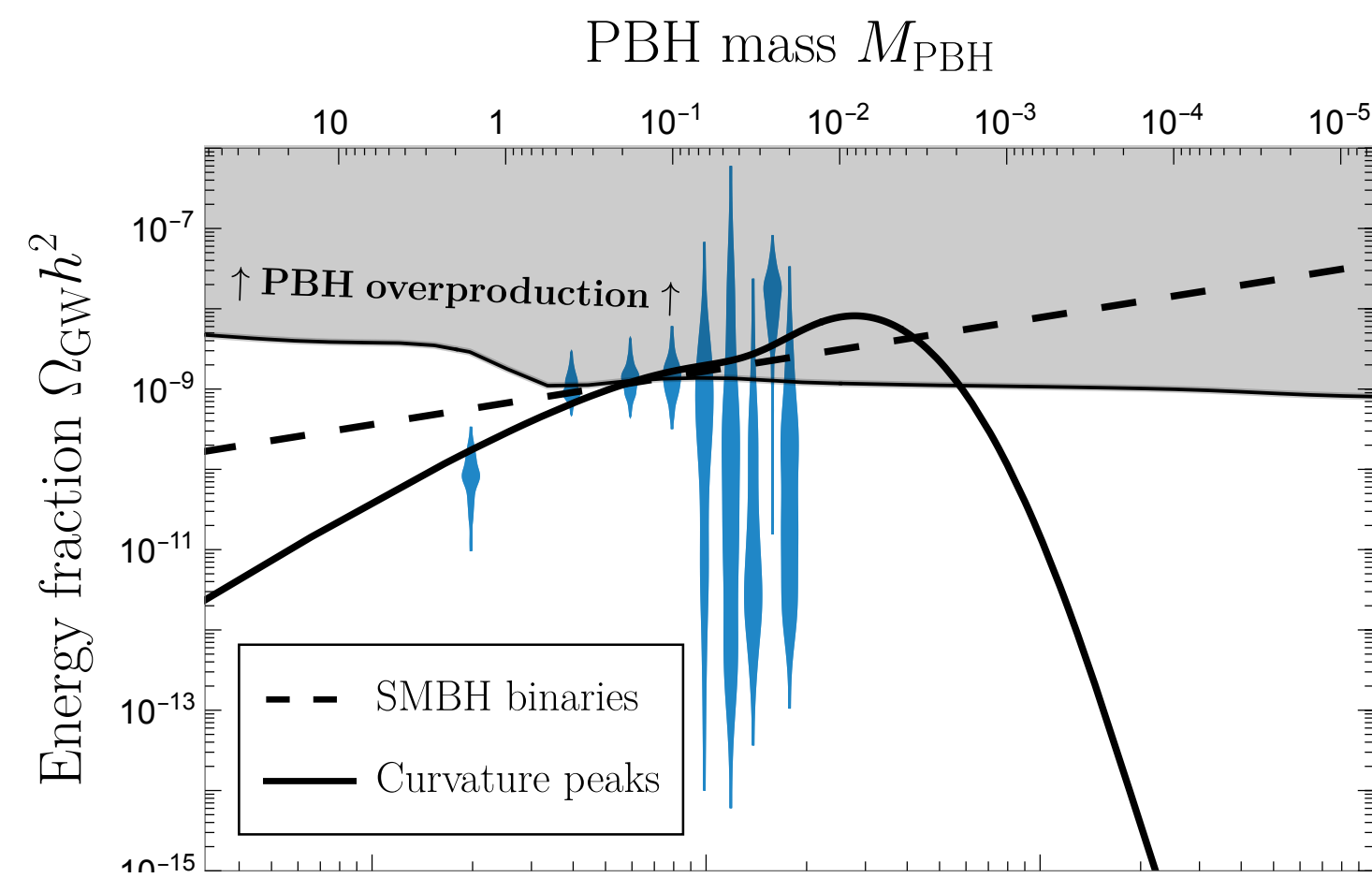
YG (2307.04239)

Lewicki, Toczec, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...





Curvature peaks

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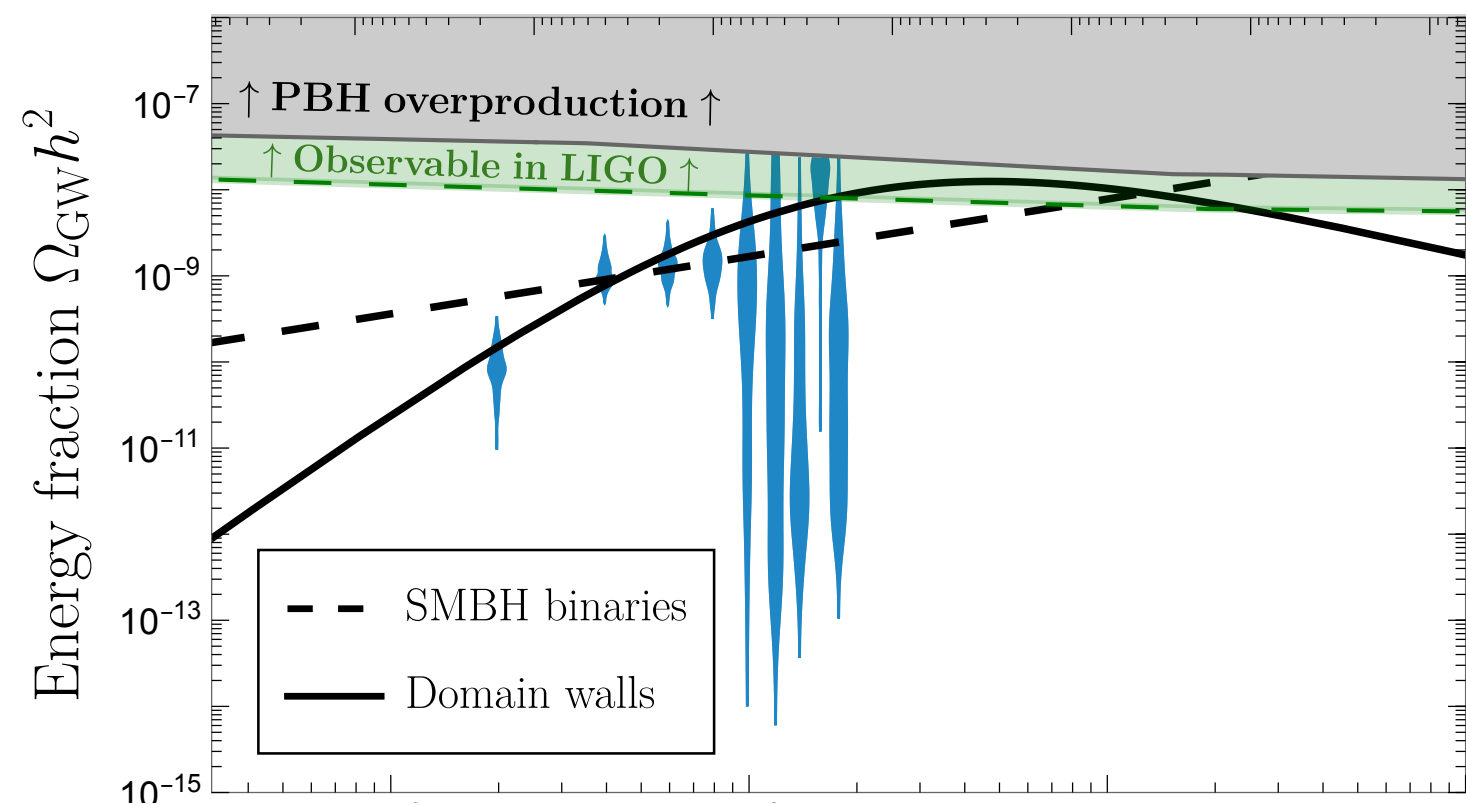
Except if negative non-Gaussianities

Franciolini, Vaskonen, Vermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)



***Reviews: Madge et al (2306.14856),
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Domain wall networks

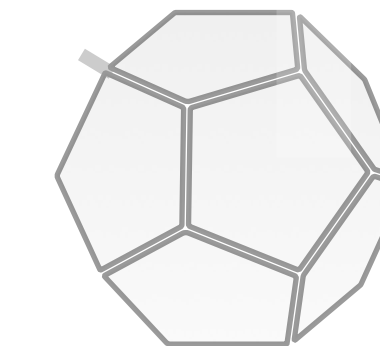
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841

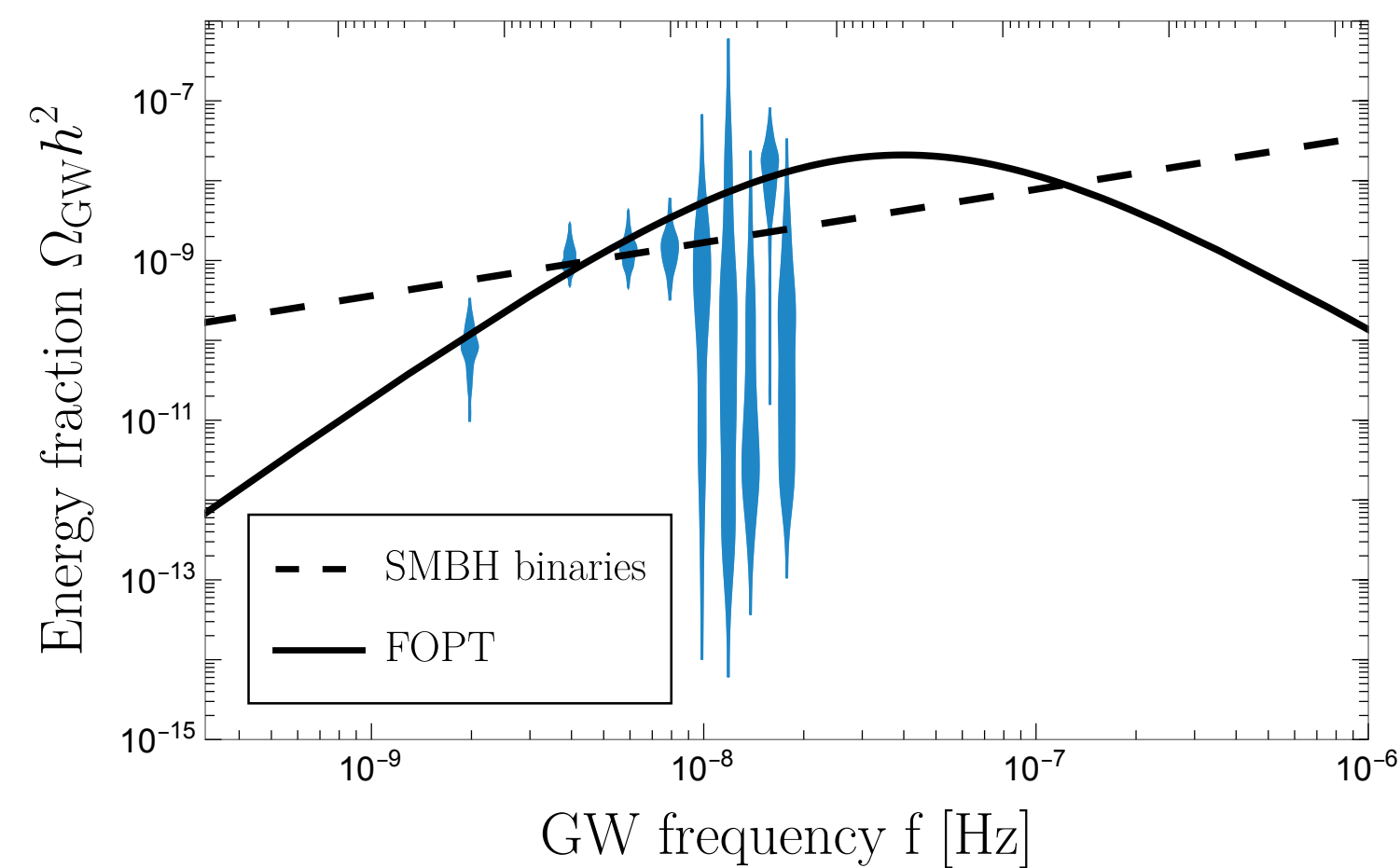


Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)
Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670

**1) Solve DW trajectory
in full GR**

PBH



First-order phase transitions

Roper Pol et al. (2201.05630)

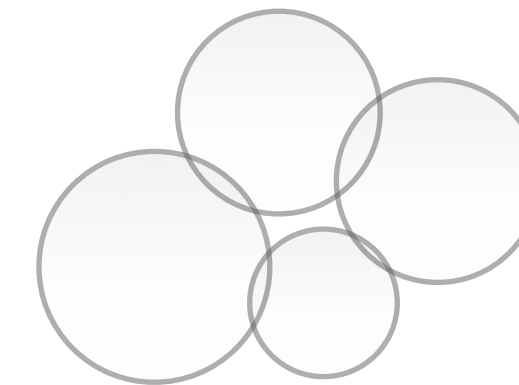
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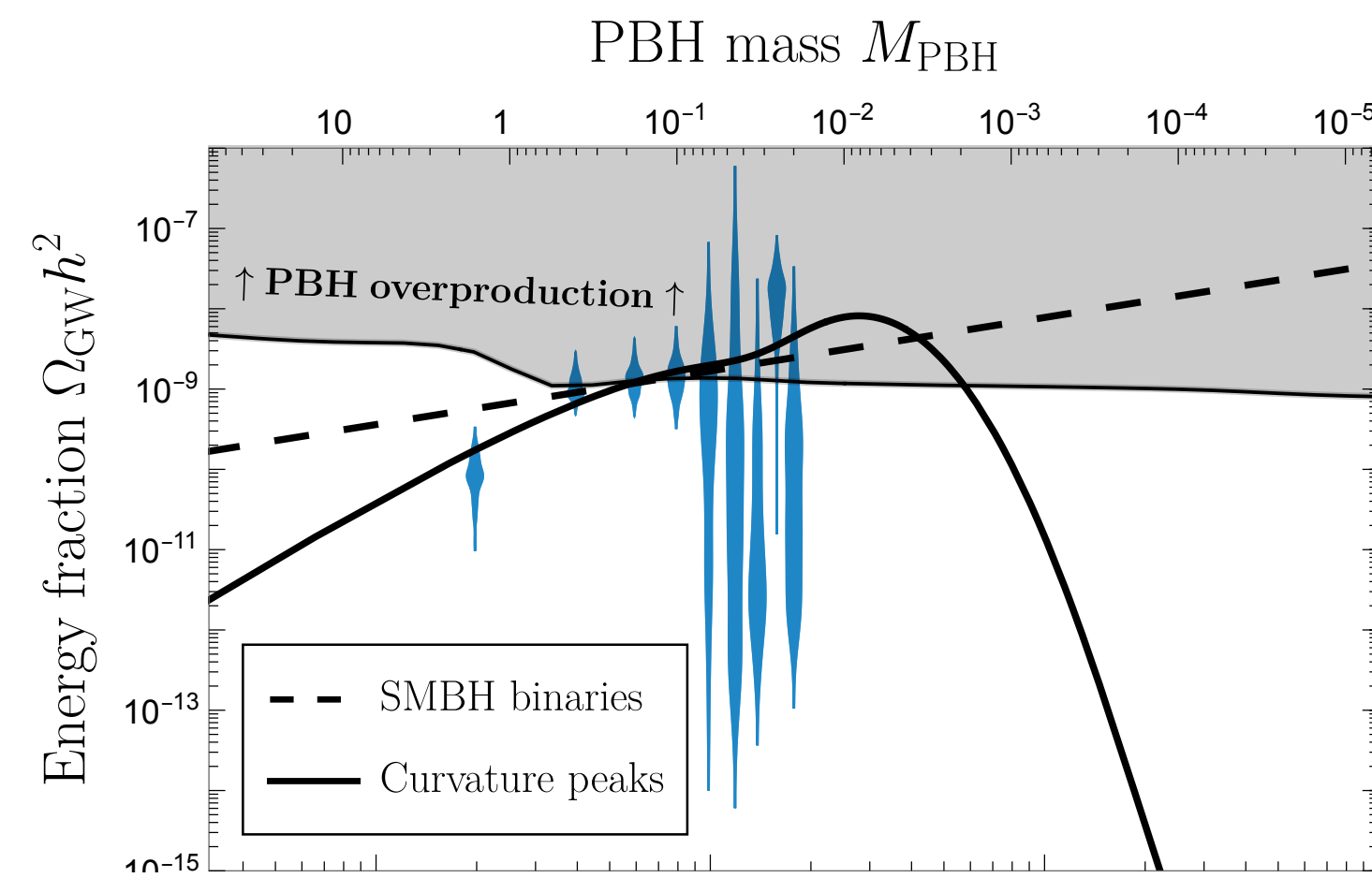
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Curvature peaks

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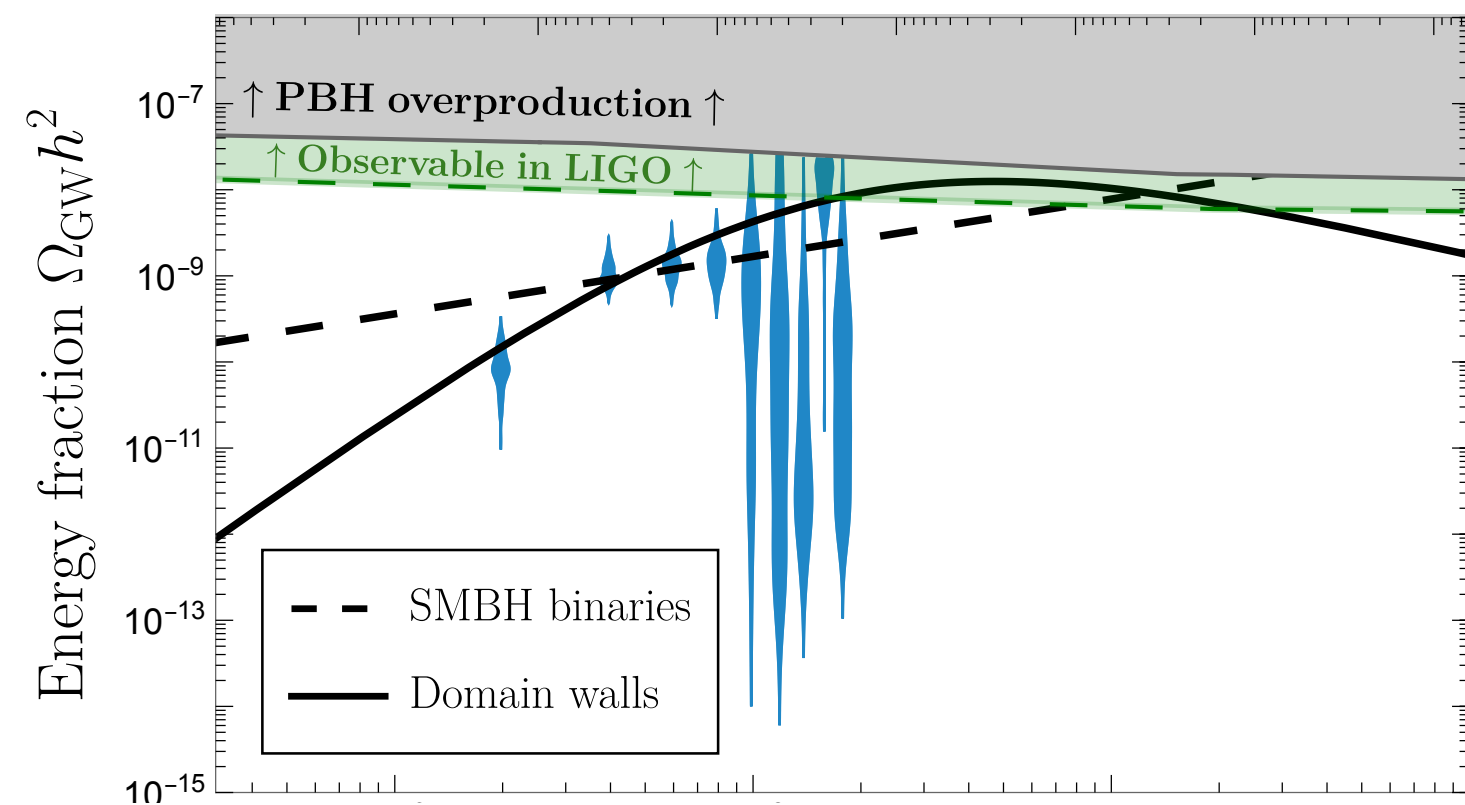
Except if negative non-Gaussianities

Franciolini, Vaskonen, Vermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Reviews: *Madge et al (2306.14856),*
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Domain wall networks

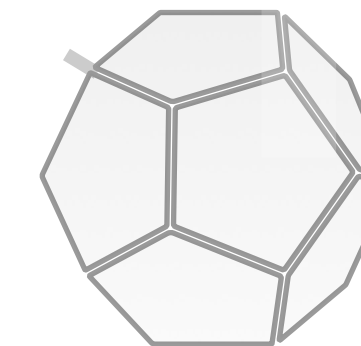
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



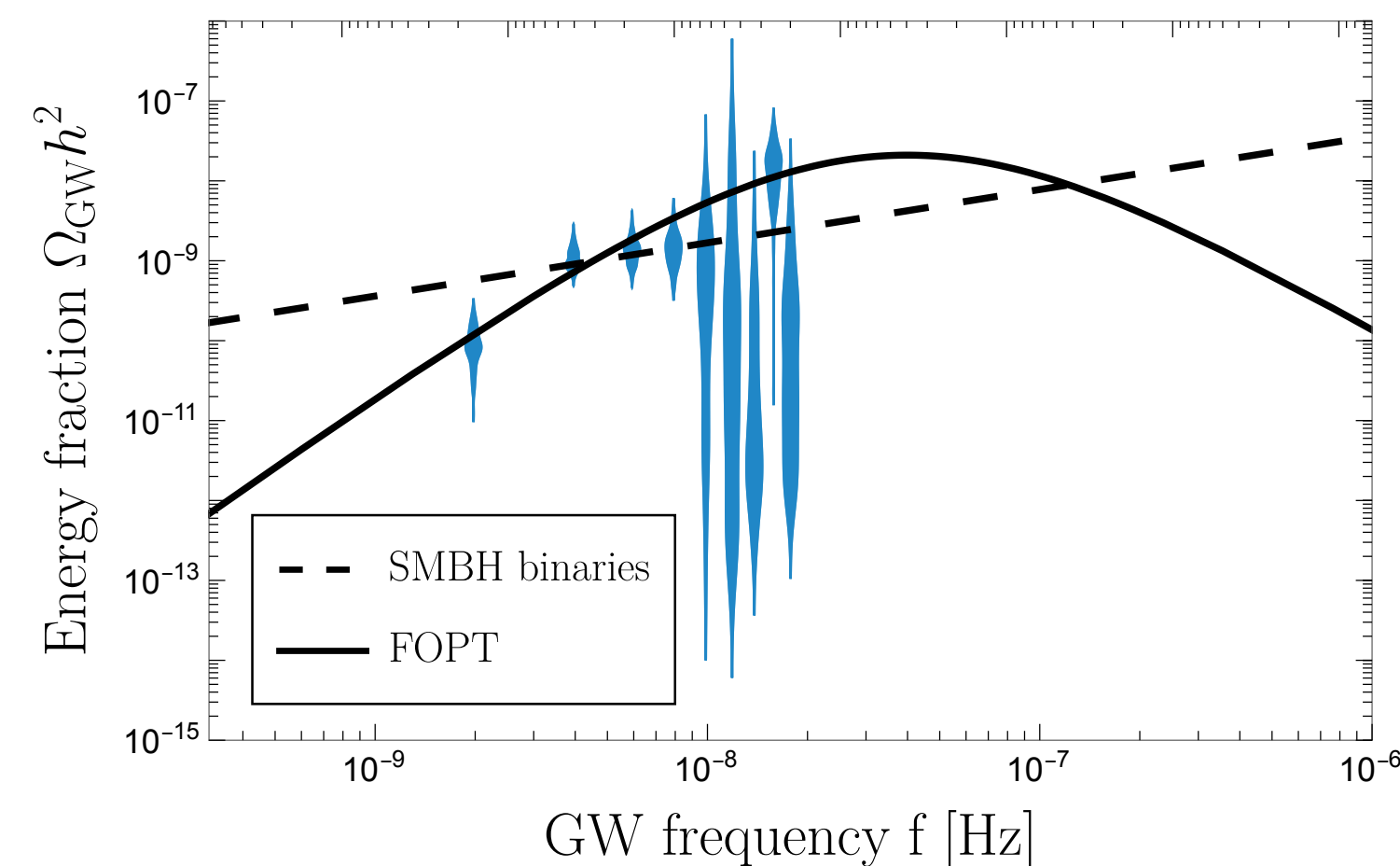
Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)
Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670

**1) Solve DW trajectory
in full GR**

2) Percolation theory

PBH



First-order phase transitions

Roper Pol et al. (2201.05630)

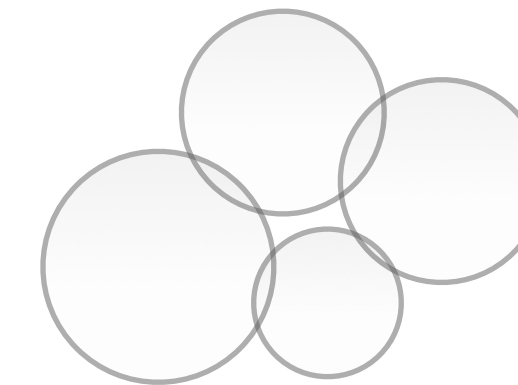
Ghoshal, White et al. (2307.02259)

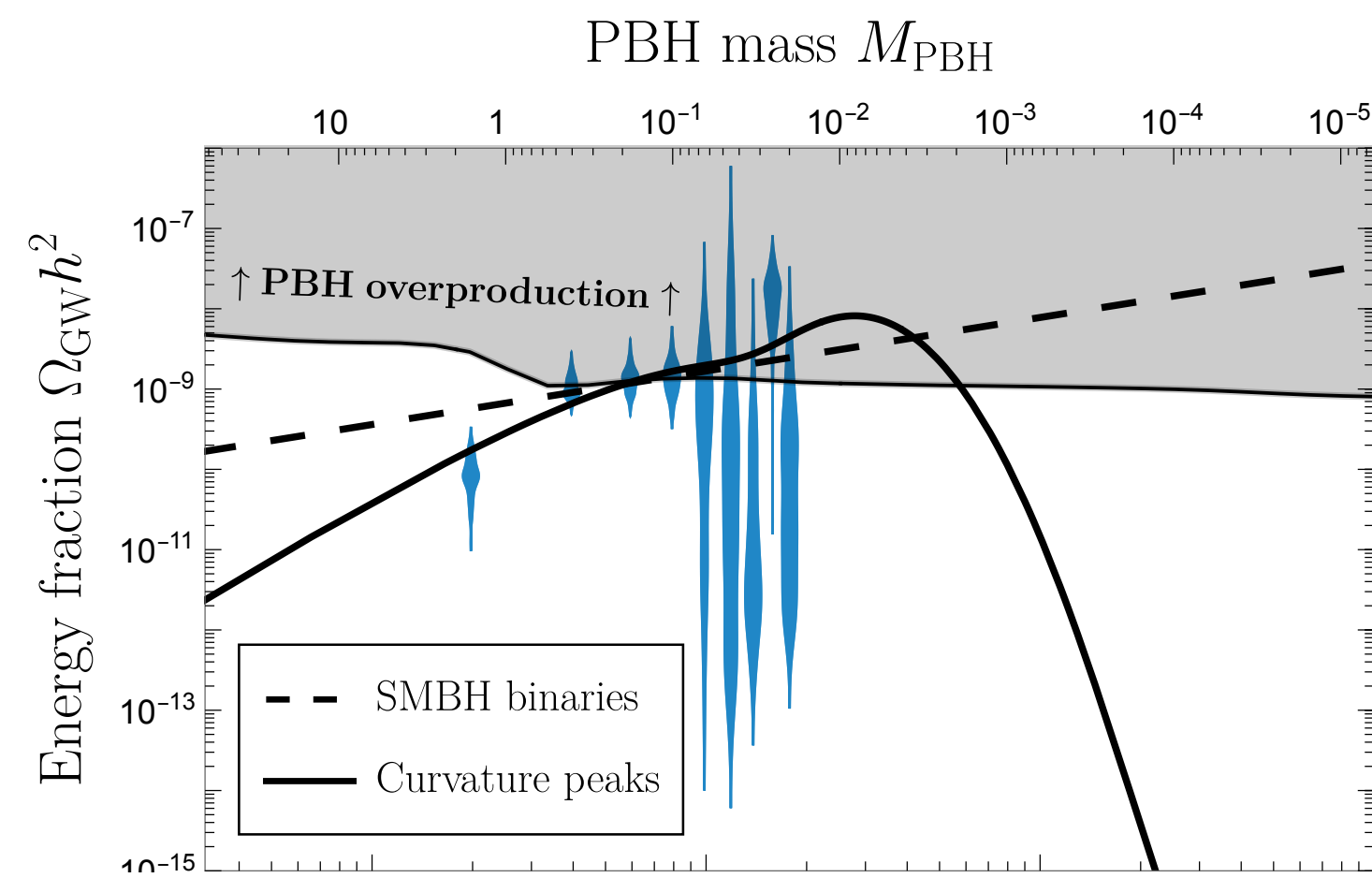
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Curvature peaks

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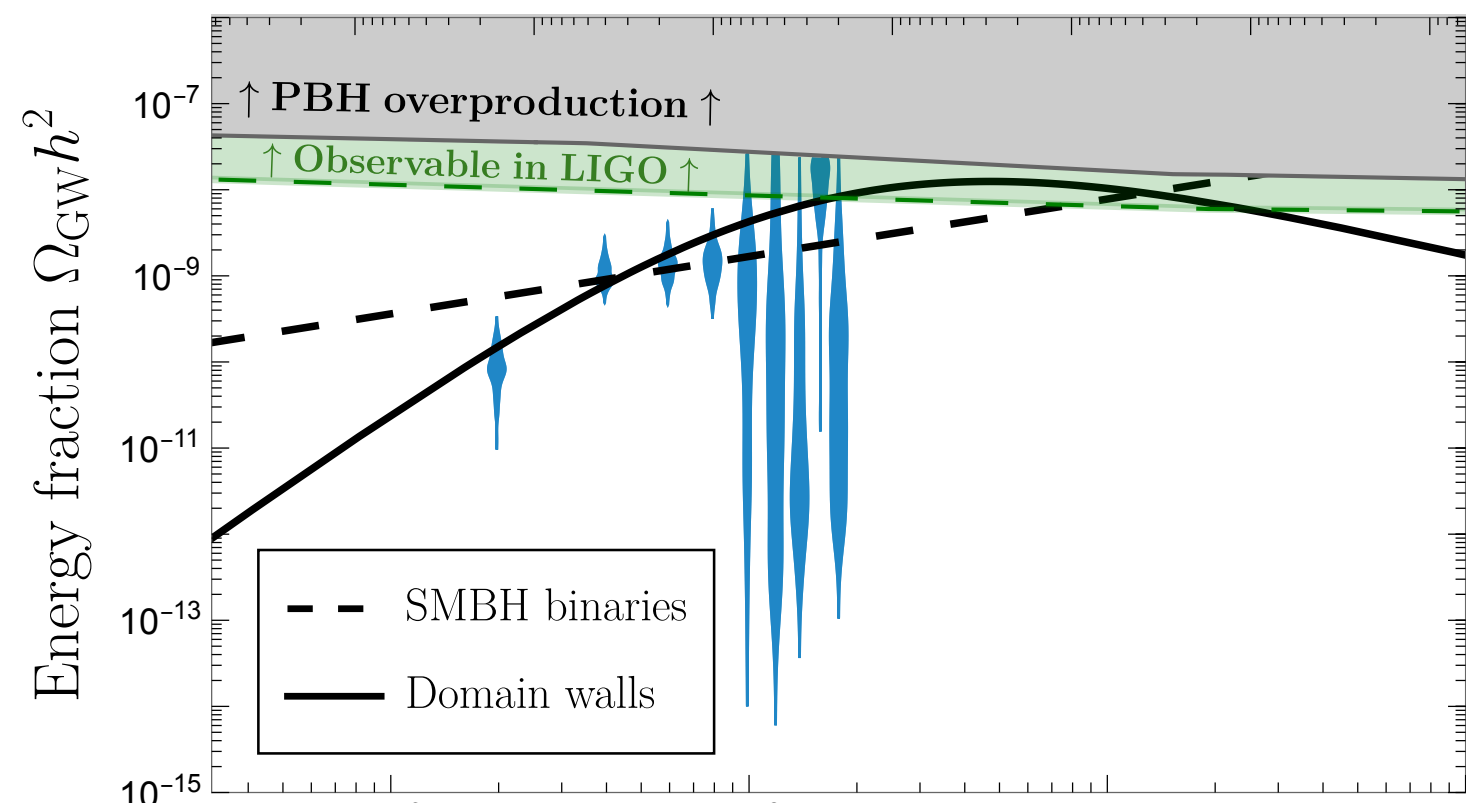
Vaskonen, Veermae (2009.07832),

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Domain wall networks

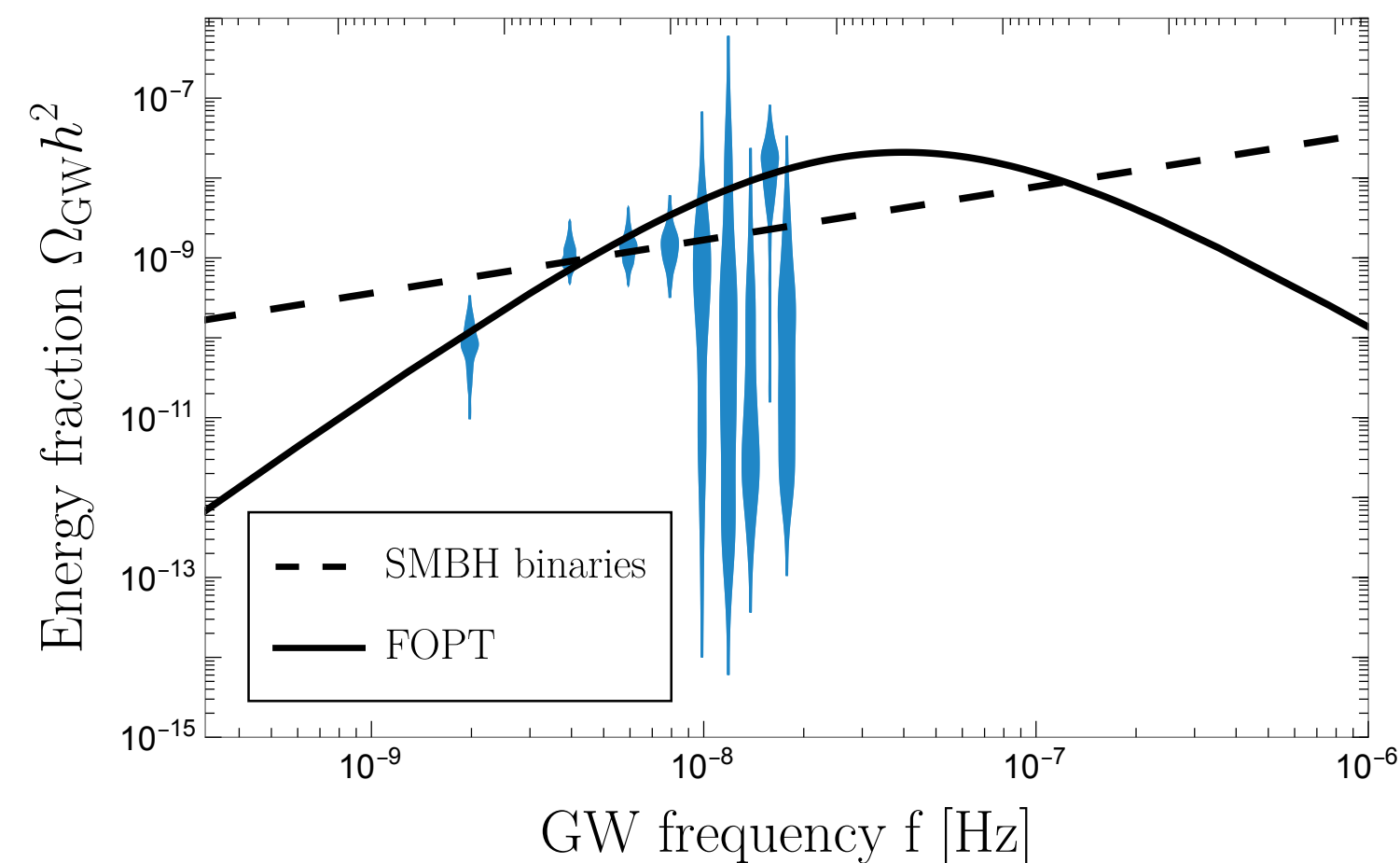
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

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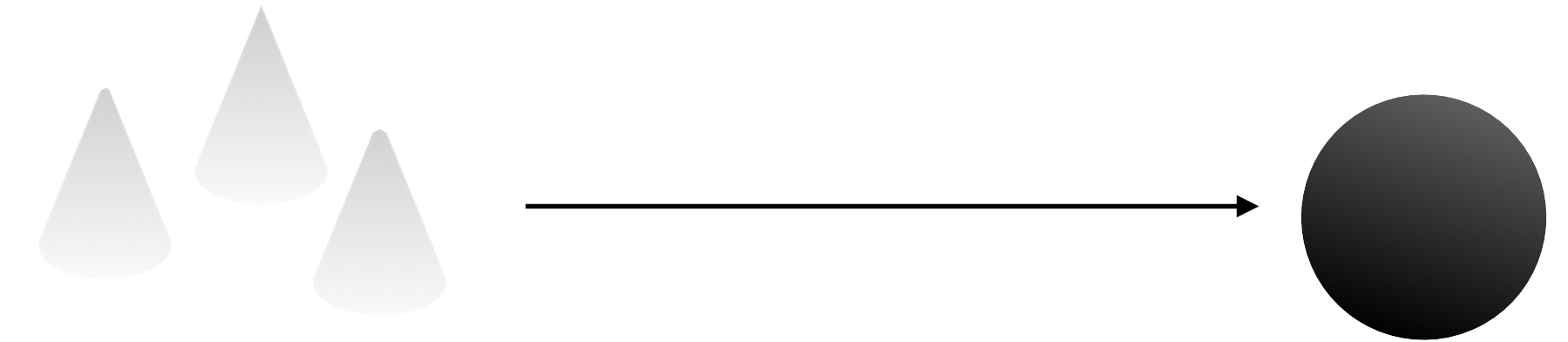
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...



Baby-universe

Deng, Garriga, Vilenkin (1612.03753)

Wormhole

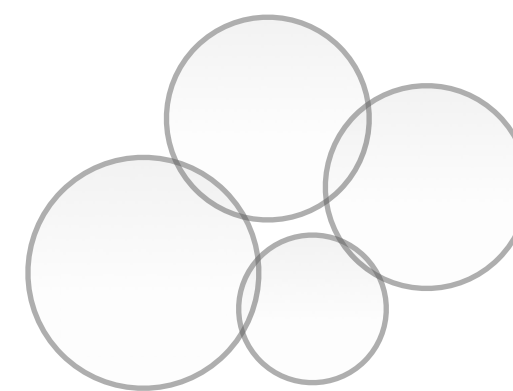
Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

Ferreira, Notari, Pujolas, Rompineve (2401.14331)

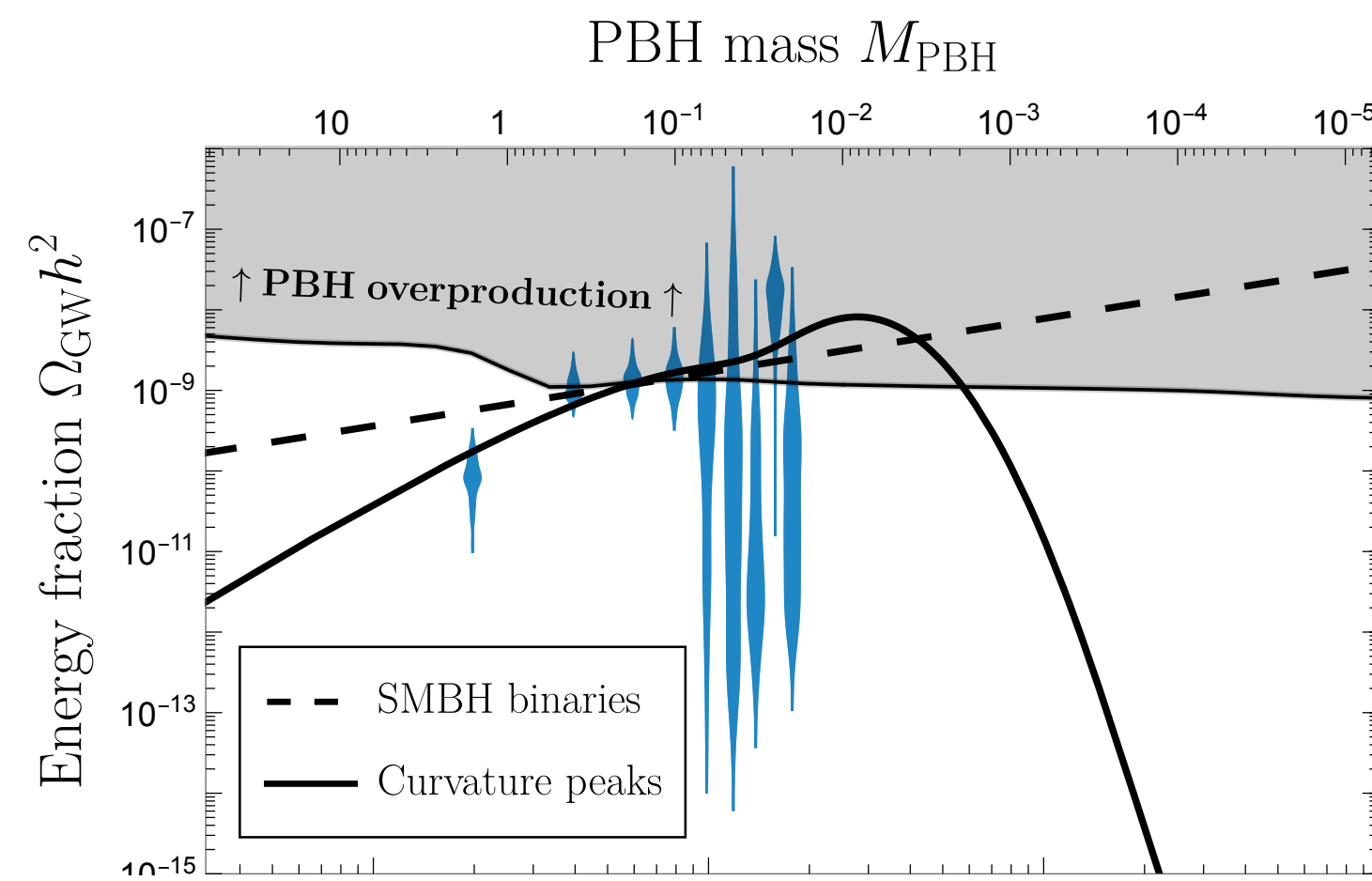
YG, Vitagliano, 2311.07670

**1) Solve DW trajectory
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PBH



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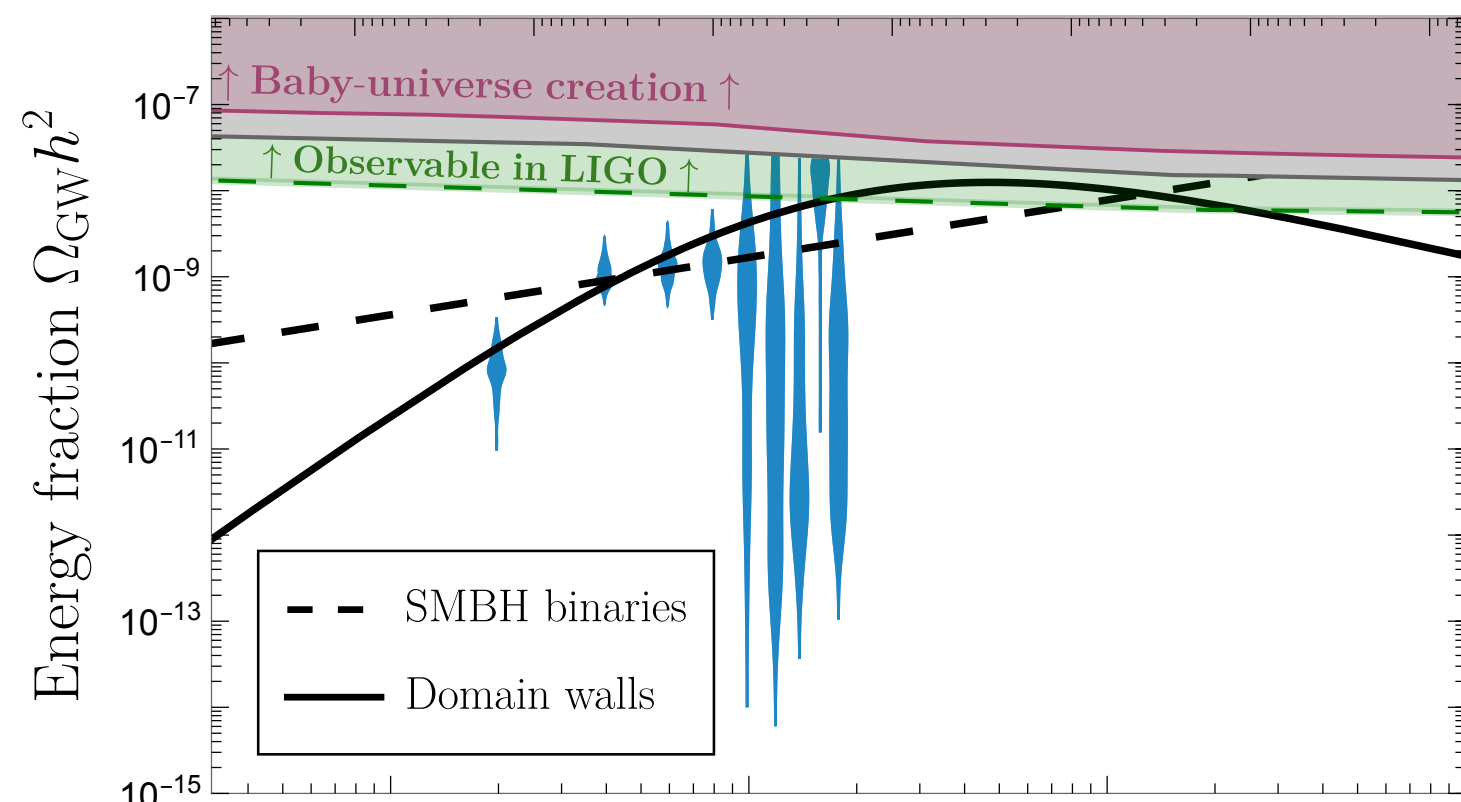
Chen, Yuan, Huang (1910.12239)
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Reviews: *Madge et al (2306.14856),*
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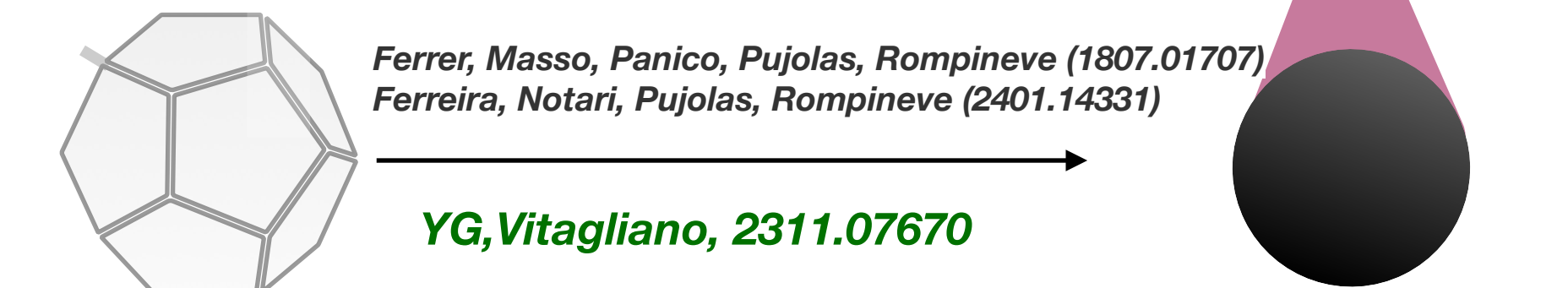


Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
 ...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



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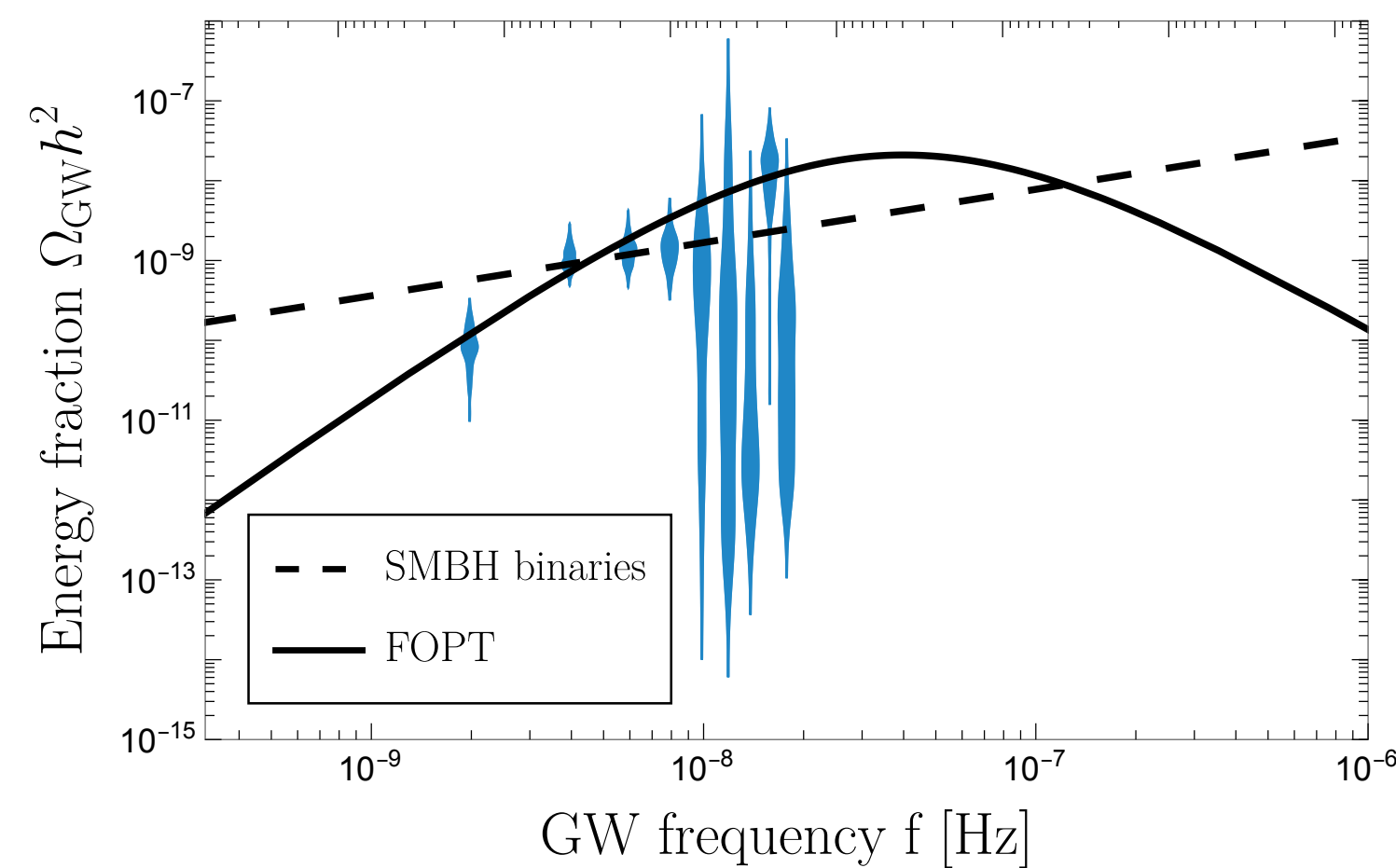
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Ferreira, Notari, Pujolas, Rompineve (2401.14331)

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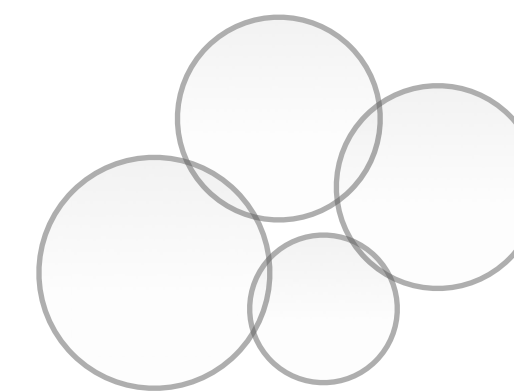
2) Percolation theory

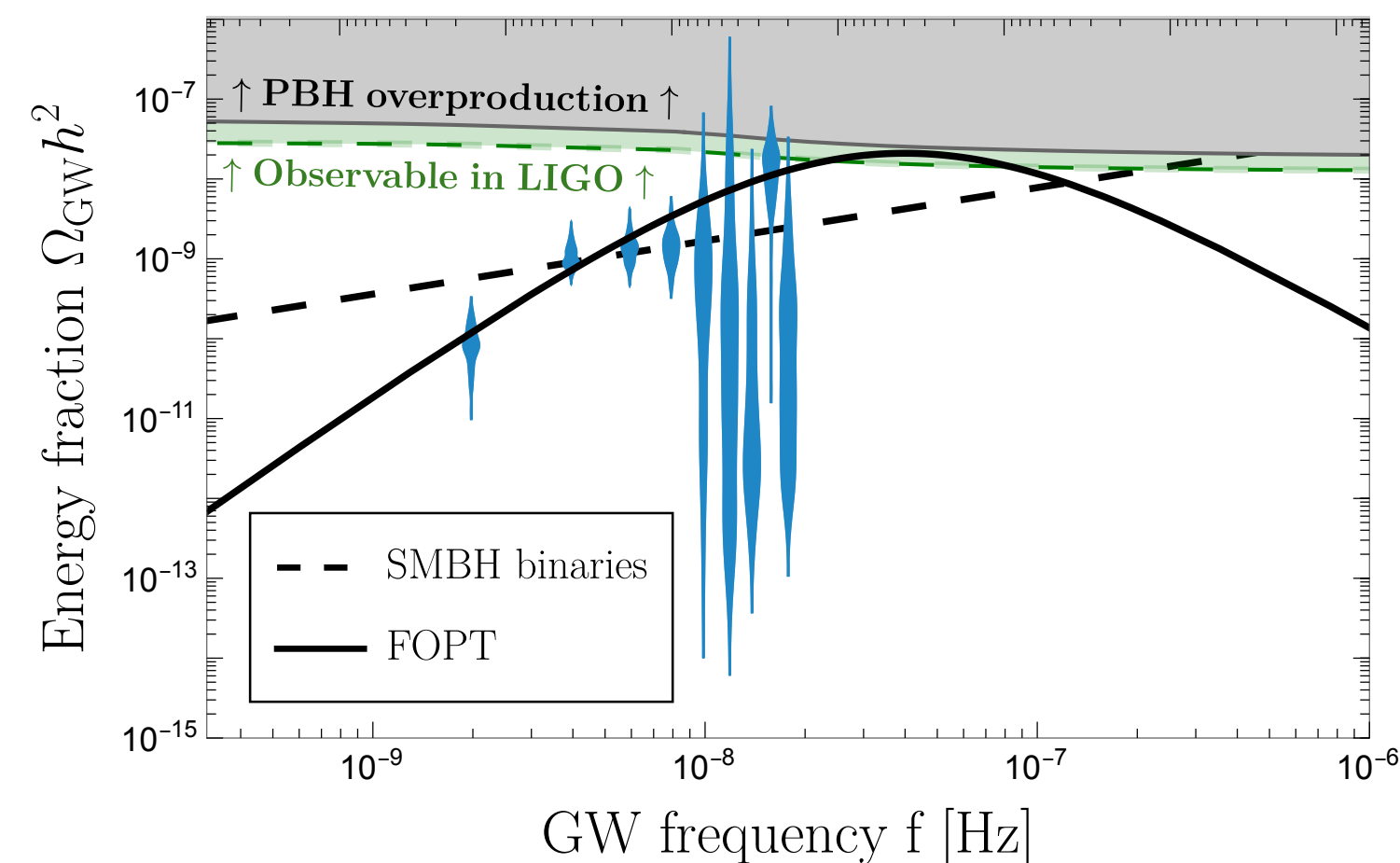
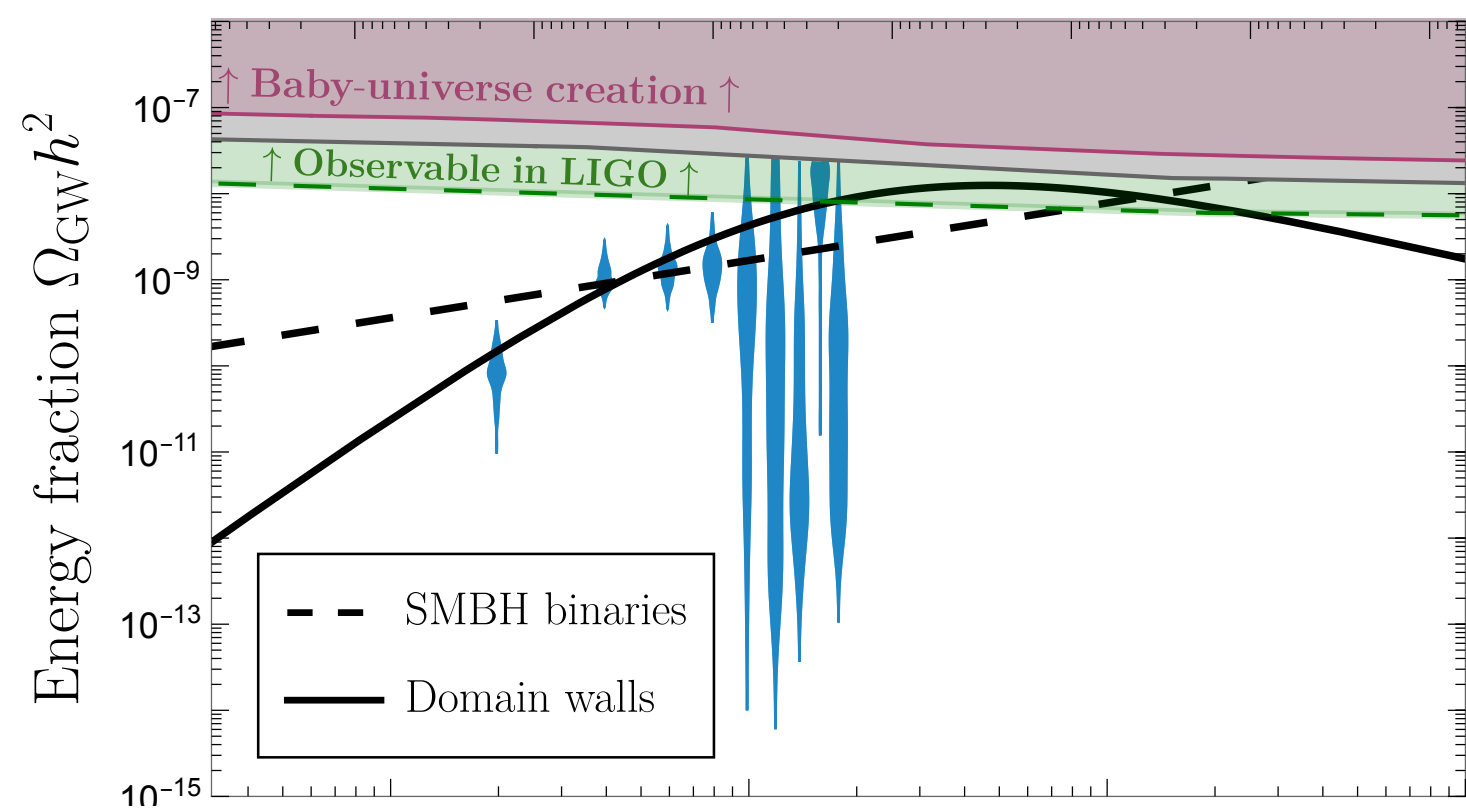
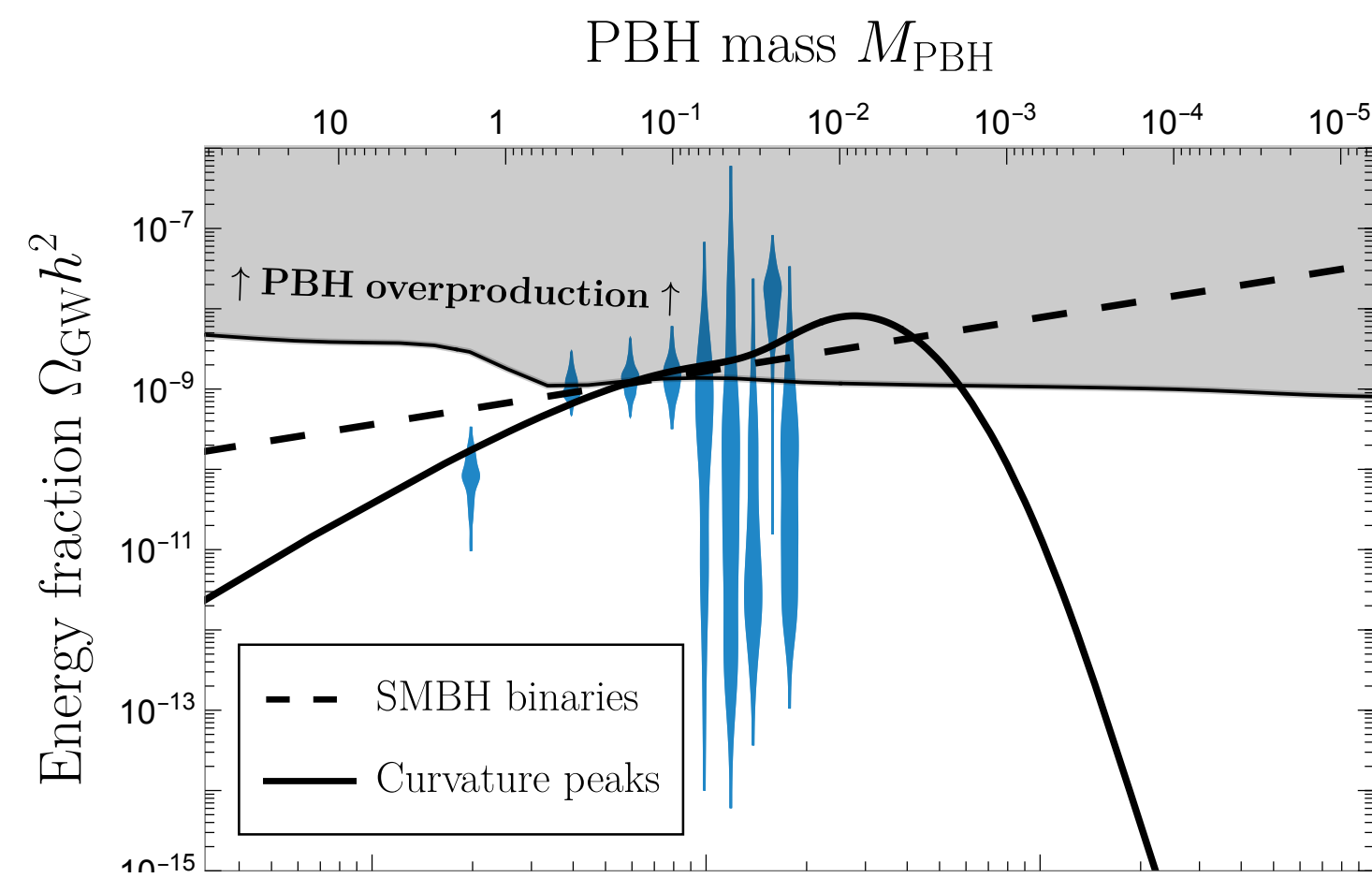
PBH



First-order phase transitions

Roper Pol et al. (2201.05630)
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YG, Vitagliano, 2311.07670

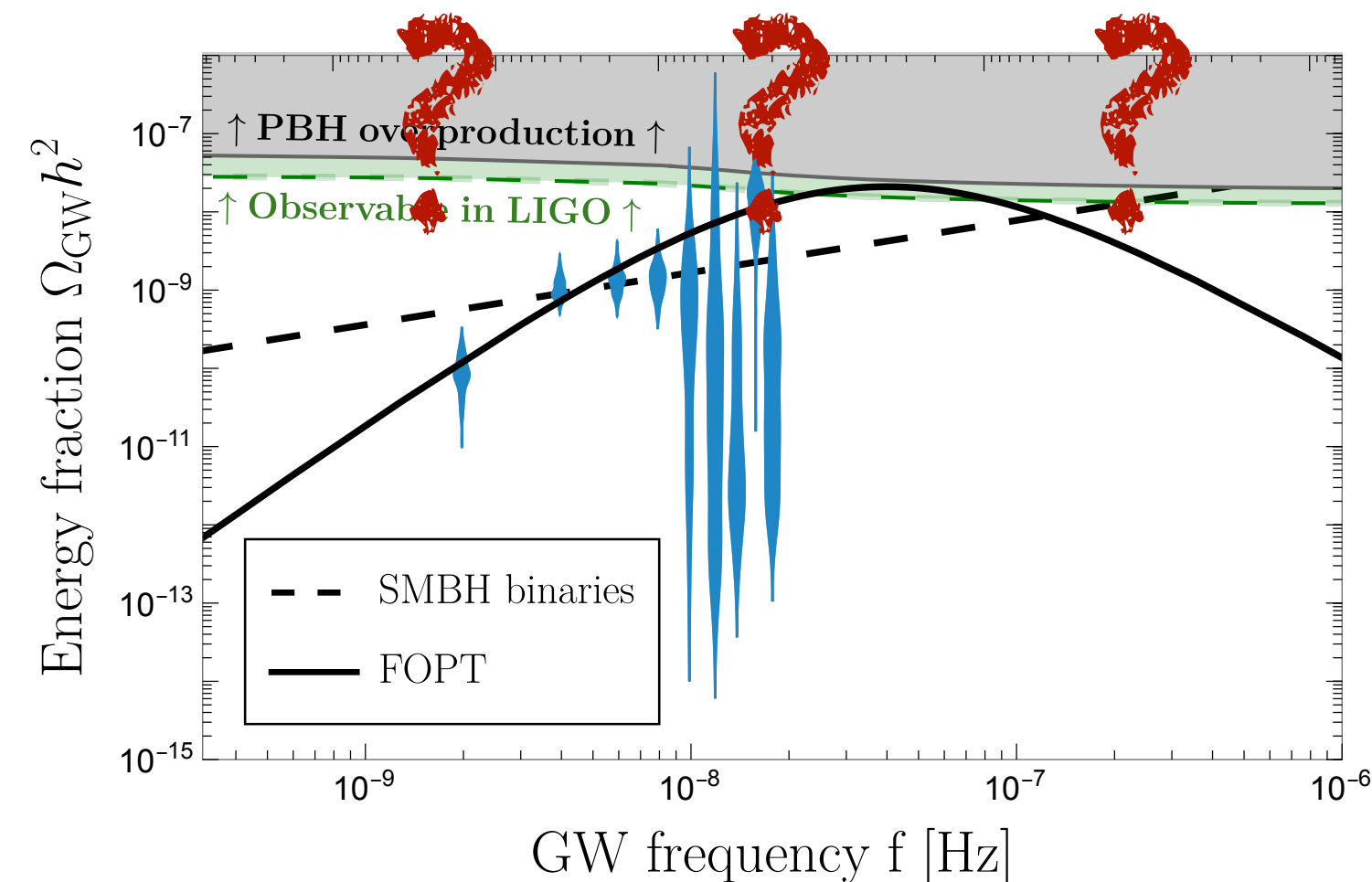
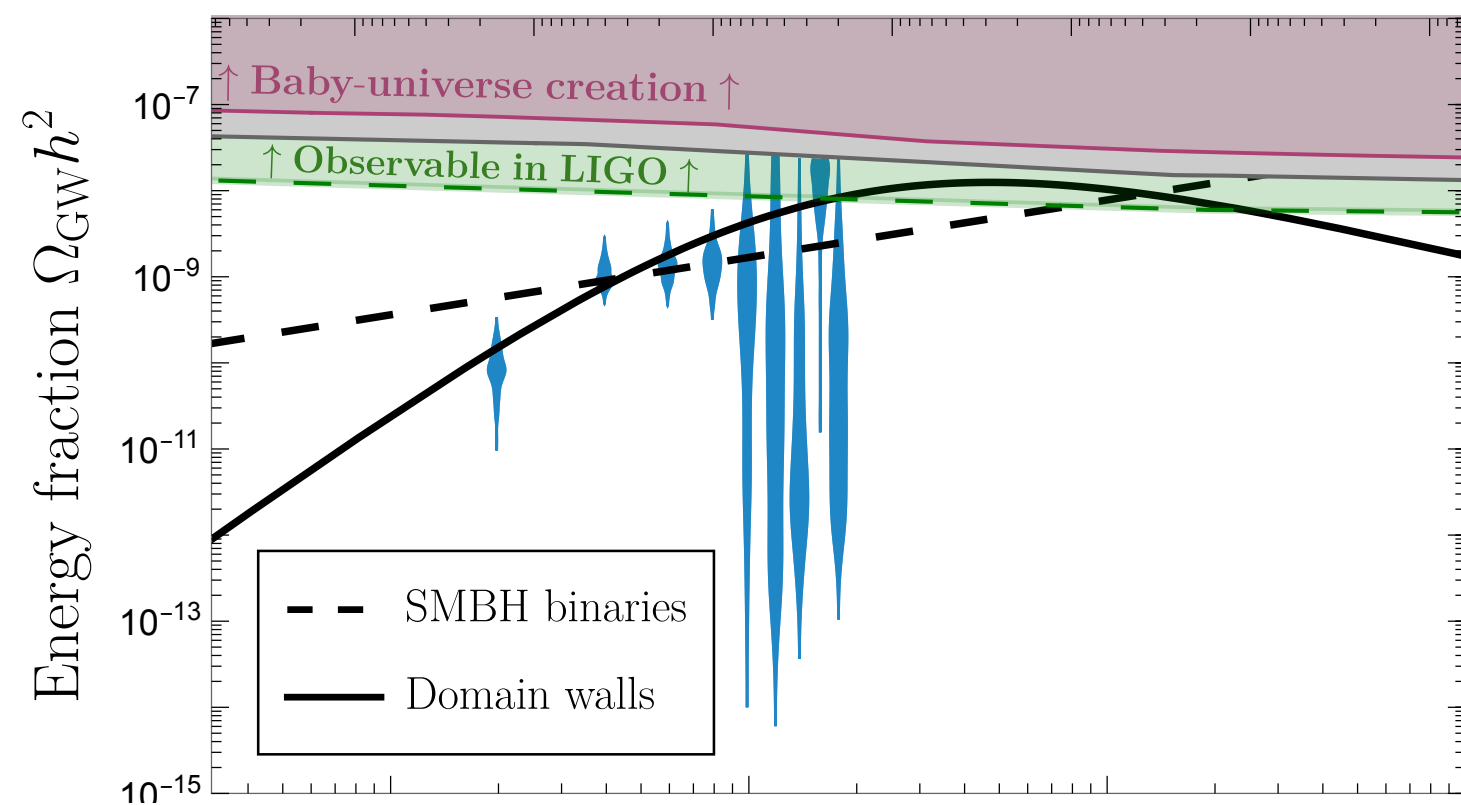
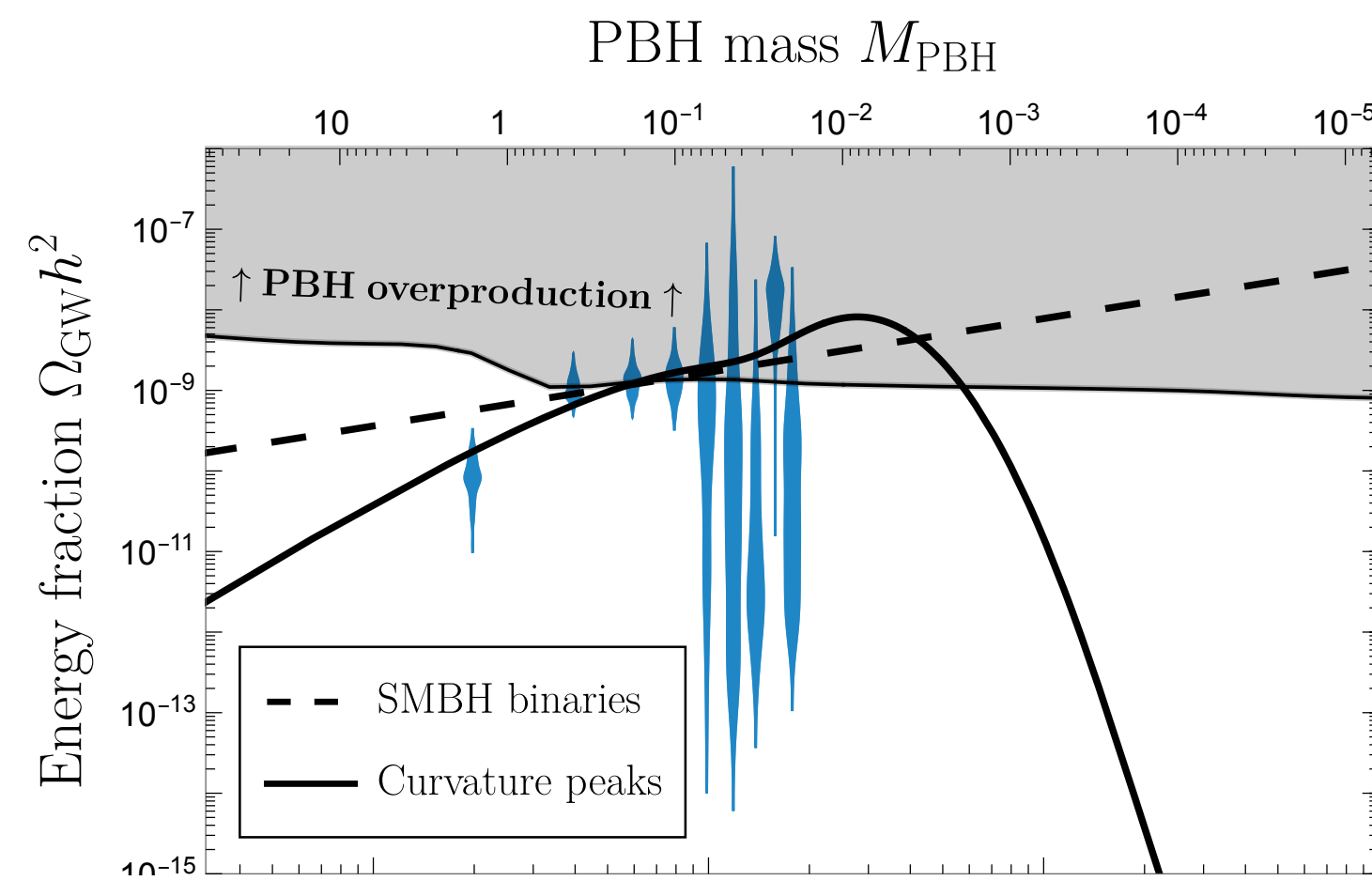
**1) Solve DW trajectory
in full GR**

2) Percolation theory

PBH



*Sasaki+ 1982, Bian+ 2021, Lu+ 2022,
Lewicki, Toczek, Vaskonen 2023,
YG&Volansky 2023, Baldes+ 2023,
Lewicki, Toczek, Vaskonen 2024,*



Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

Vaskonen, Veermae (2009.07832),

De Luca, Franciolini, Riotto (2009.08268)

Except if negative non-Gaussianities

Franciolini, Vaskonen, Vermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)

Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841

First-order phase transitions

Roper Pol et al. (2201.05630)

Ghoshal, White et al. (2307.02259)

YG (2307.04239)

Lewicki, Toczec, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

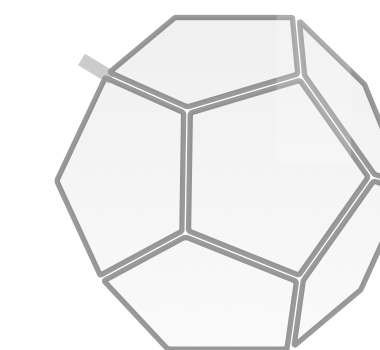
...



Baby-universe

Deng, Garriga, Vilenkin (1612.03753)

Wormhole



Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670

**1) Solve DW trajectory
in full GR**

2) Percolation theory

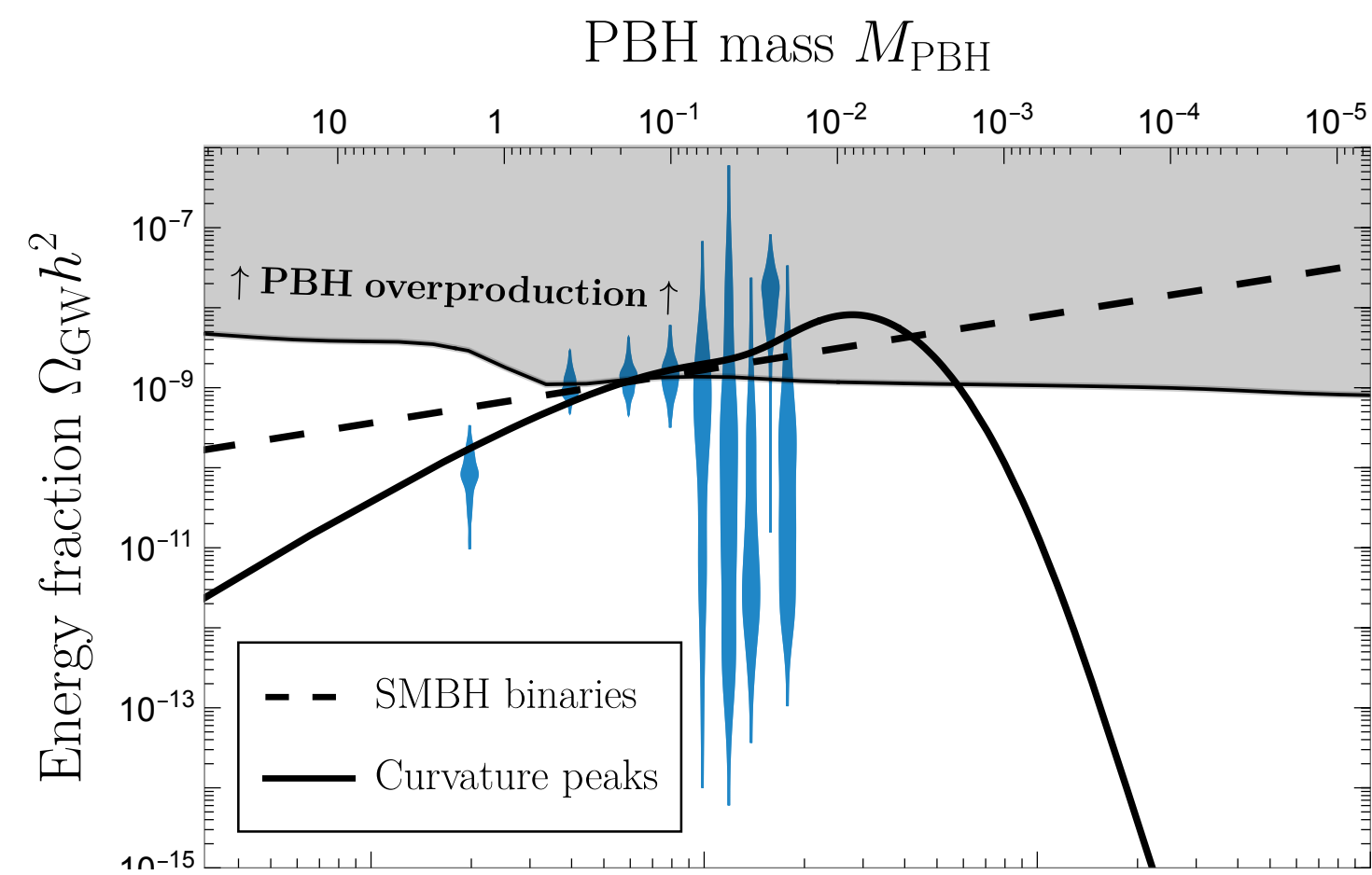
Franciolini, YG, Jinno, 2503.01962

YG, Lewicki, Toczec, Vaskonen (in preparation)



*Sasaki+ 1982, Bian+ 2021, Lu+ 2022,
Lewicki, Toczec, Vaskonen 2023,
YG&Volansky 2023, Baldes+ 2023,
Lewicki, Toczec, Vaskonen 2024,*

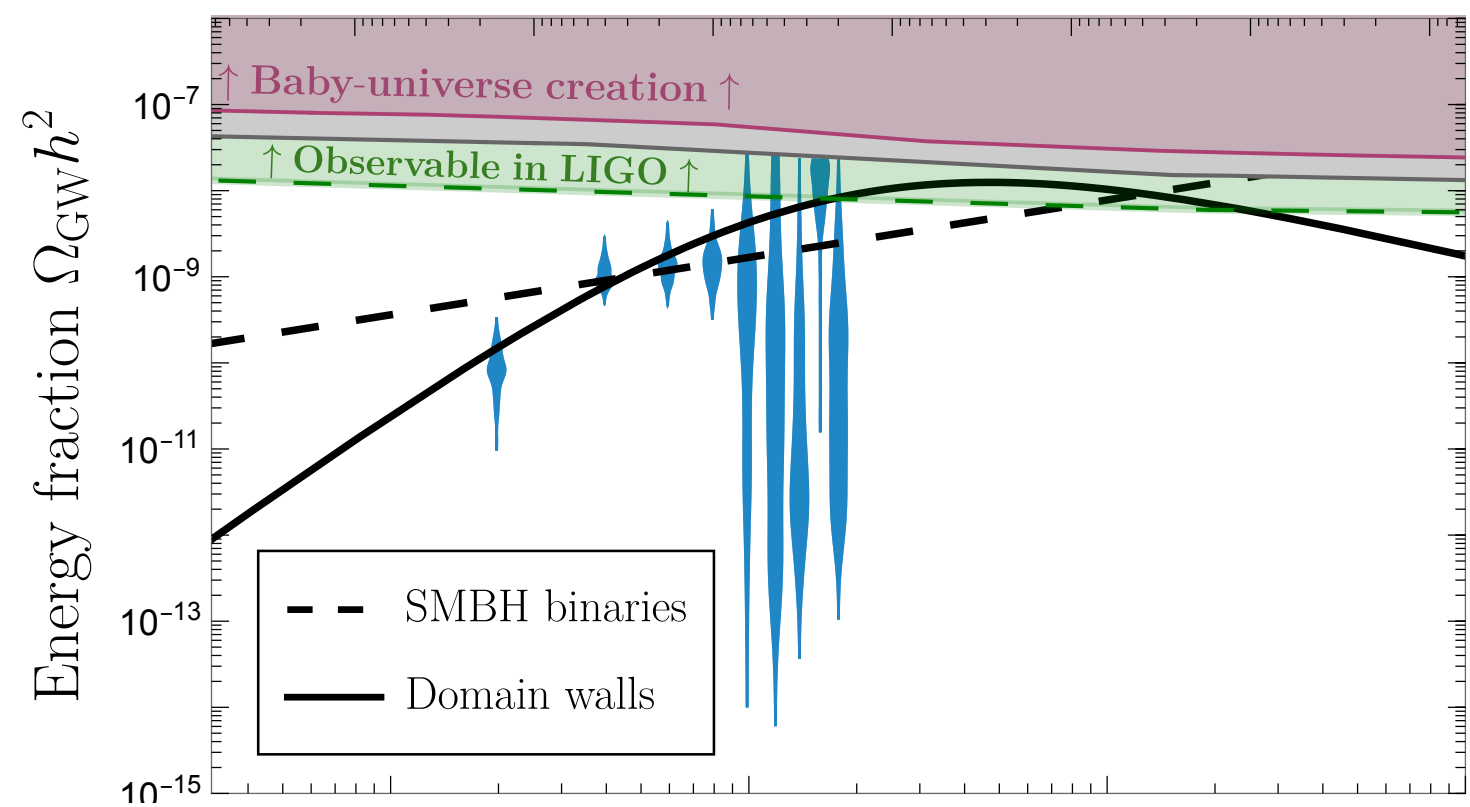
PBH



Curvature peaks

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Kohri, Terada (2009.11853)
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Vaskonen, Veermae (2009.07832),
De Luca, Franciolini, Riotto (2009.08268)

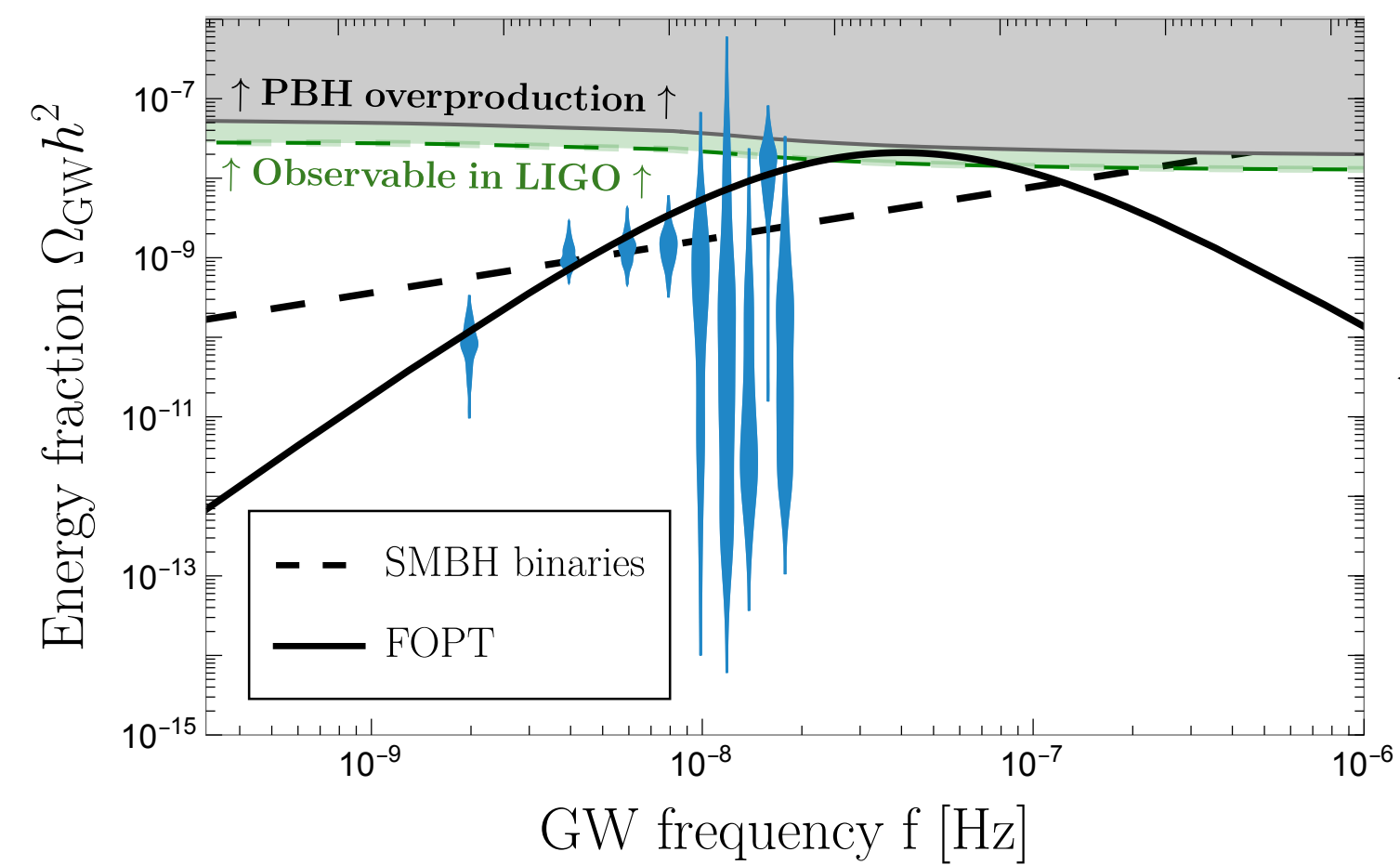
Except if negative non-Gaussianities
Franciolini, Vaskonen, Vermae (2306.17143)
YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
 ...

Produce sub-solar-mass PBH
YG, Vitagliano 2306.17841



First-order phase transitions

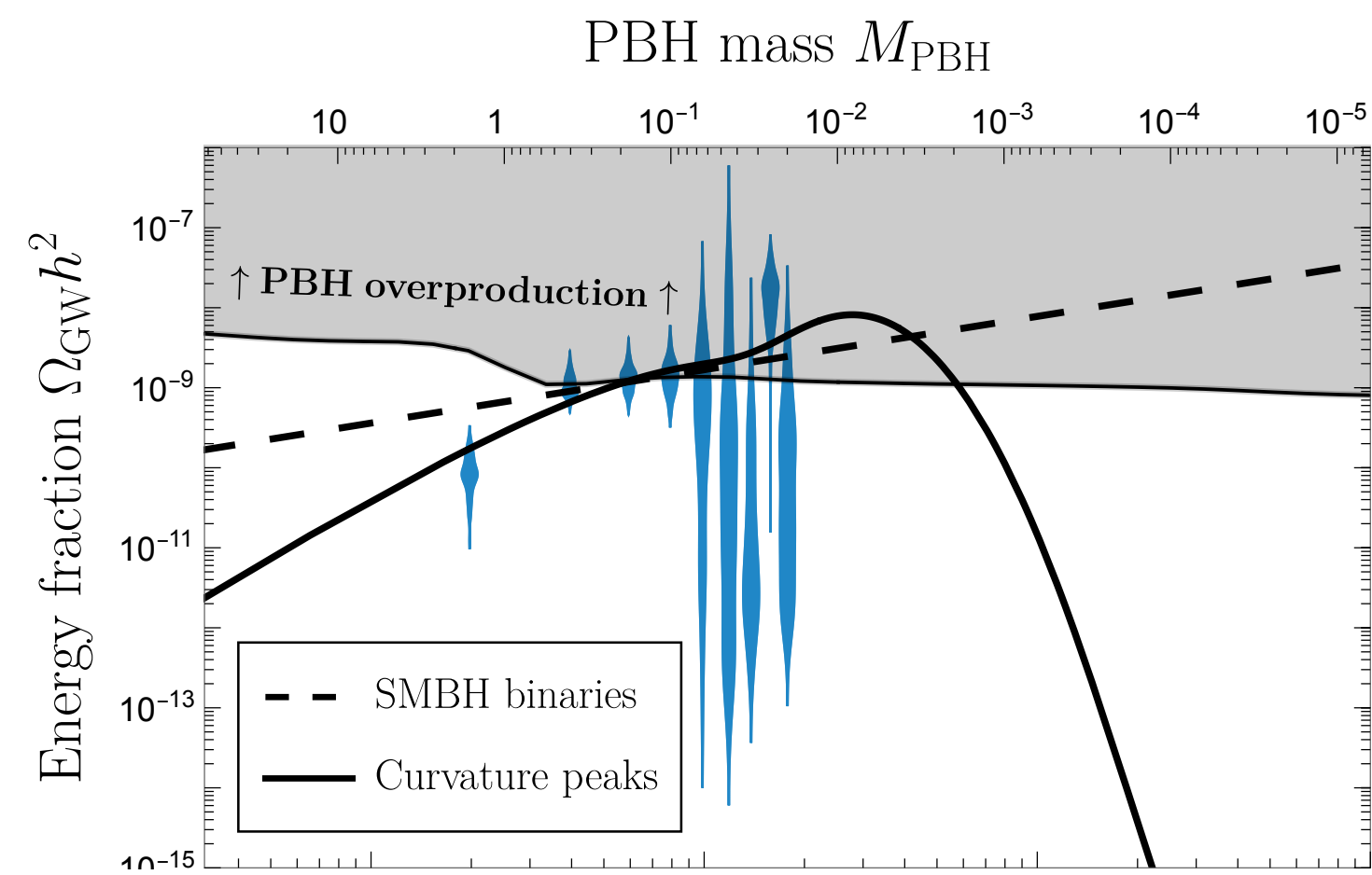
Roper Pol et al. (2201.05630)
Ghoshal, White et al. (2307.02259)
YG (2307.04239)
Lewicki, Toczek, Vaskonen (2402.04158)
Hoefken Zink et al. (2501.15649)
 ...

Scalar Curvature

$\mathcal{R}(\vec{x}, t)$

YG 2503.03857

Franciolini, YG, Jinno, 2503.01962



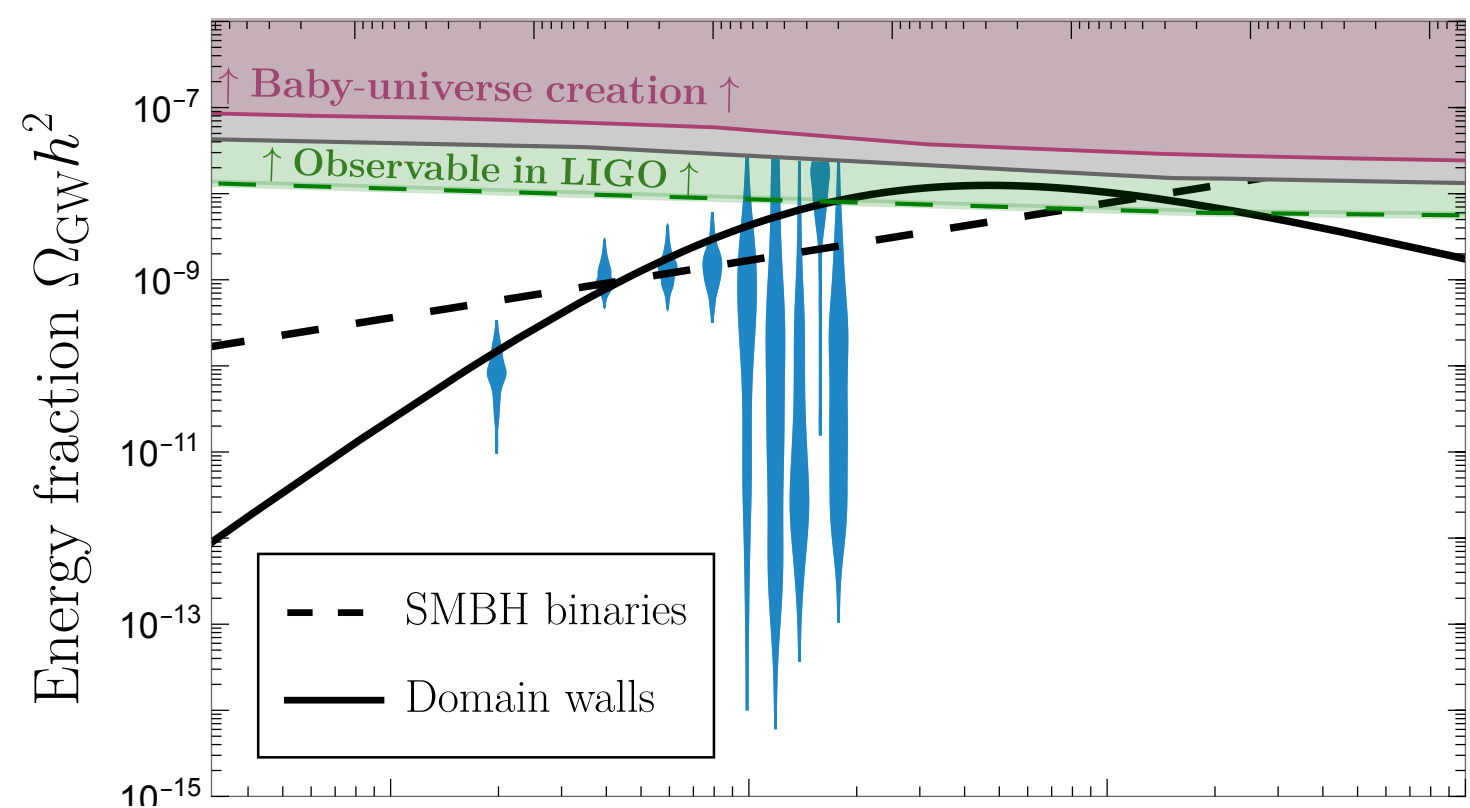
Curvature peaks

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Kohri, Terada (2009.11853)
Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)
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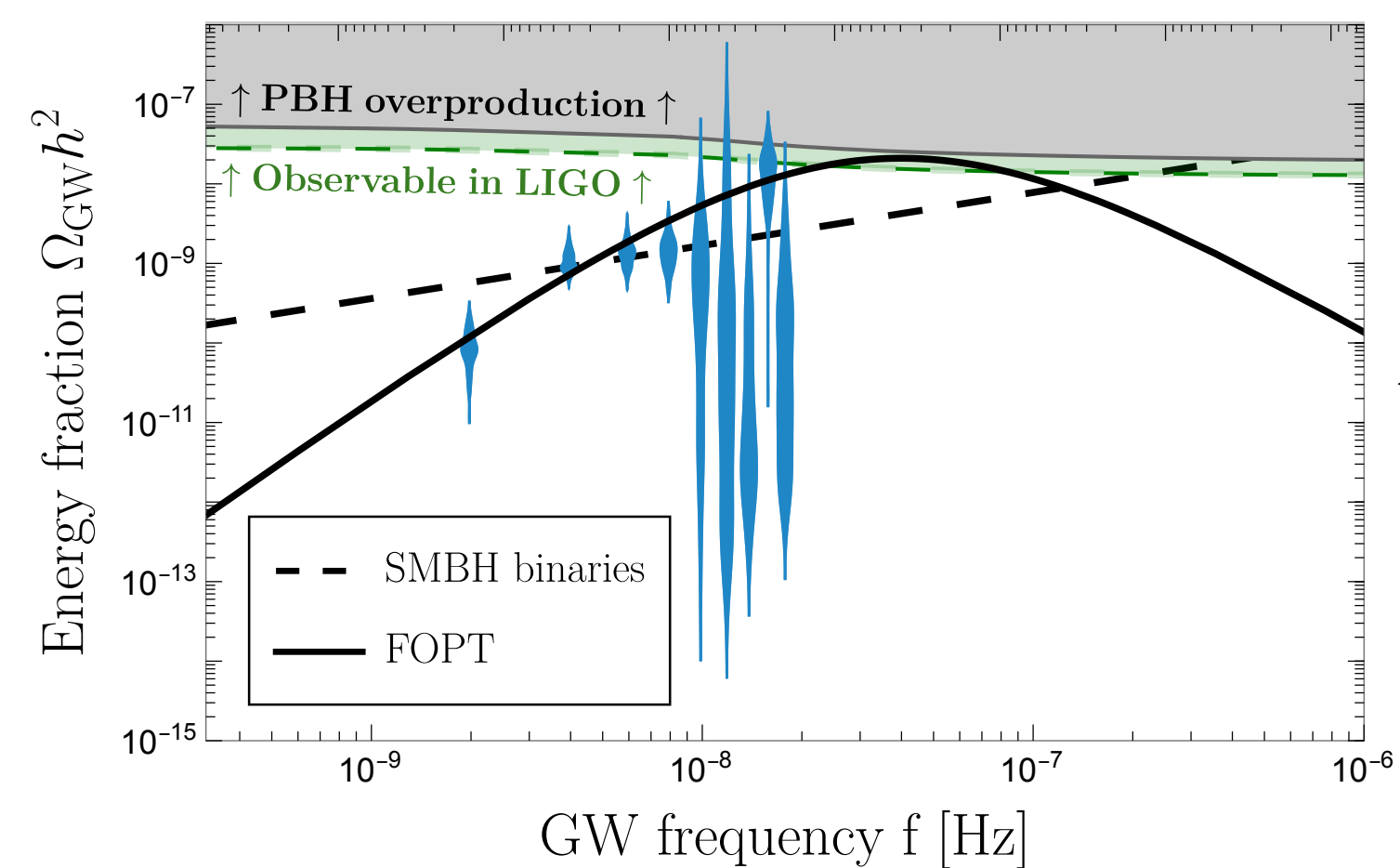


Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
 ...

Produce sub-solar-mass PBH

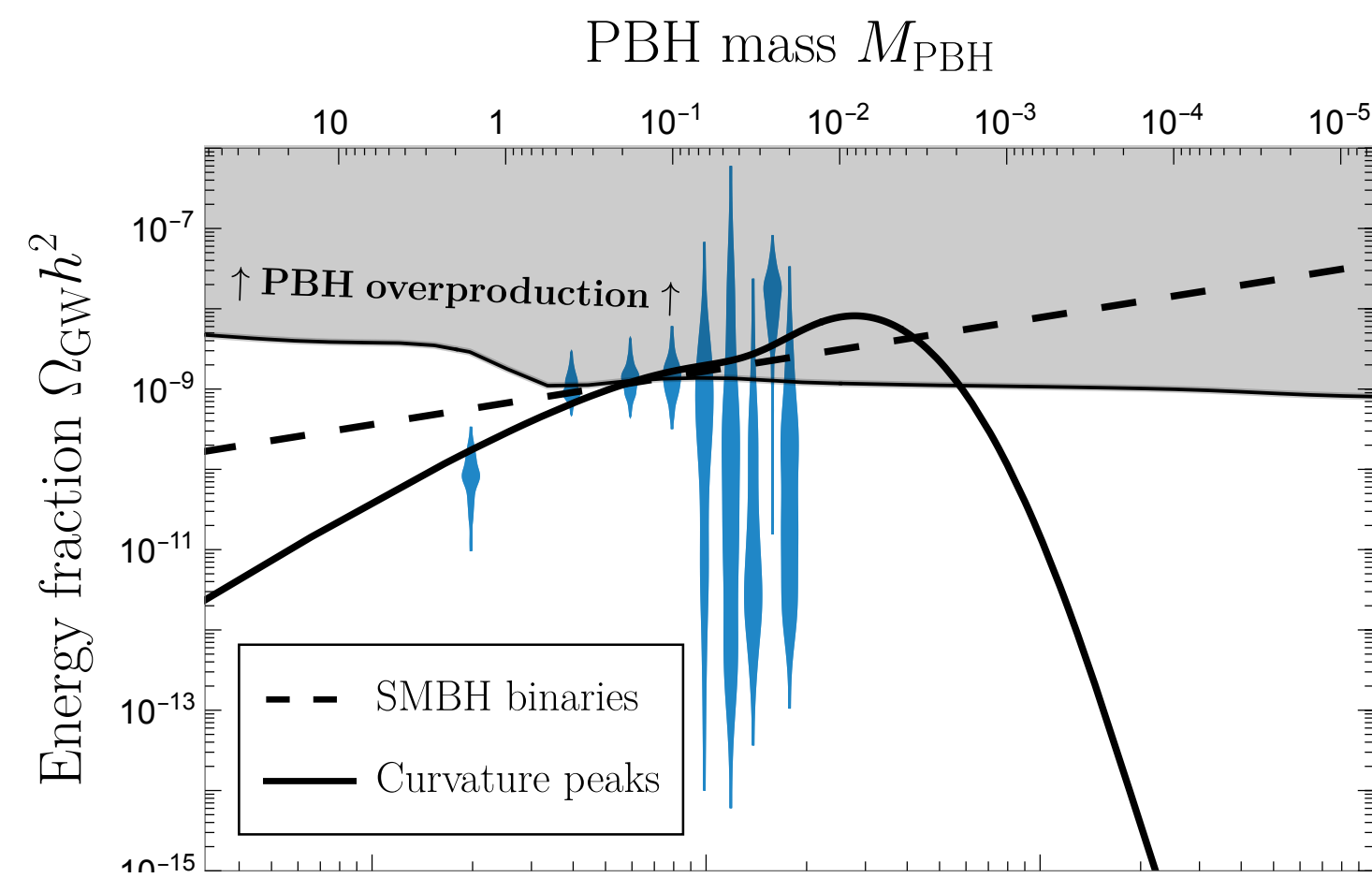
YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)
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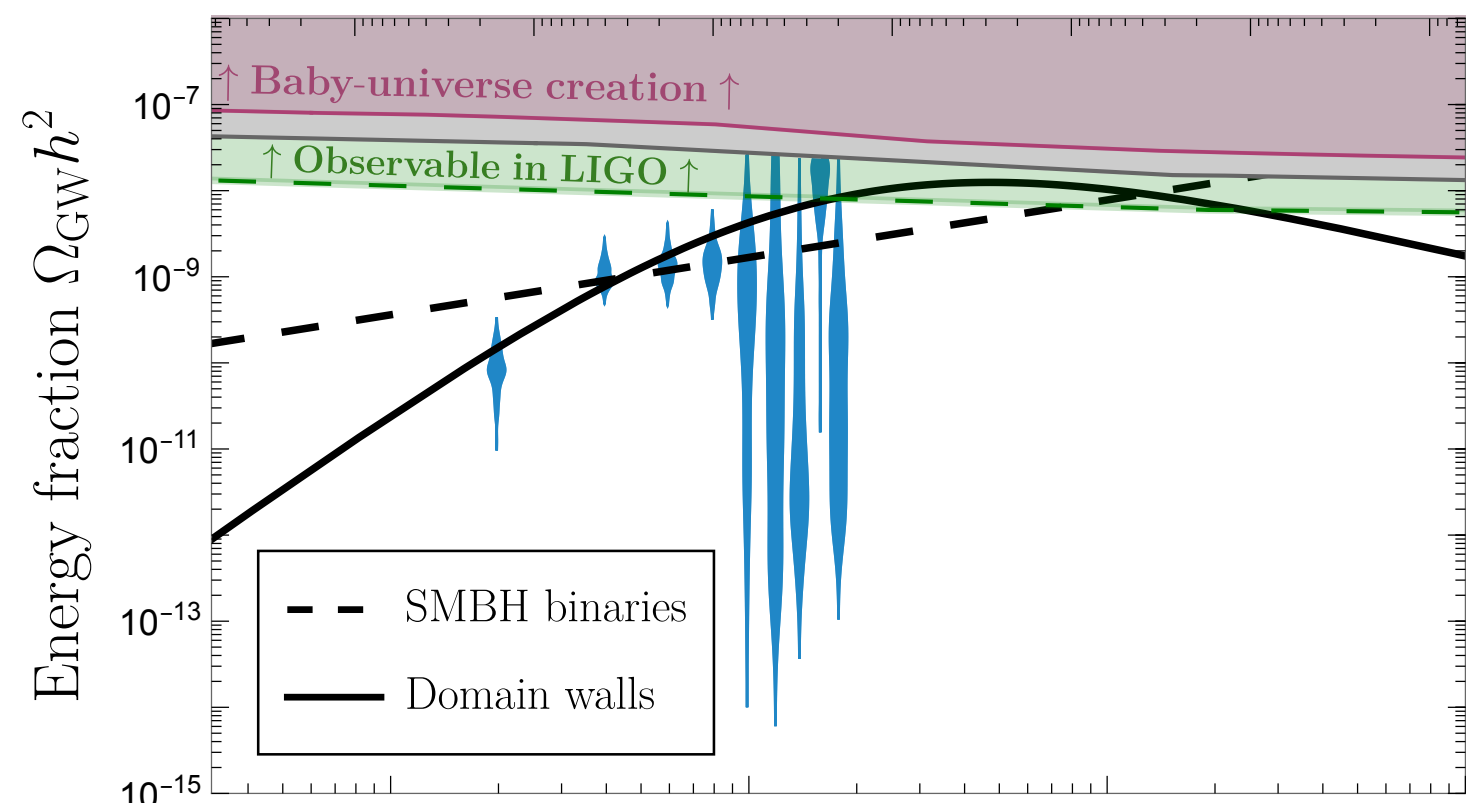
Vaskonen, Veermae (2009.07832),

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Except if negative non-Gaussianities

Franciolini, Vaskonen, Vermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Domain wall networks

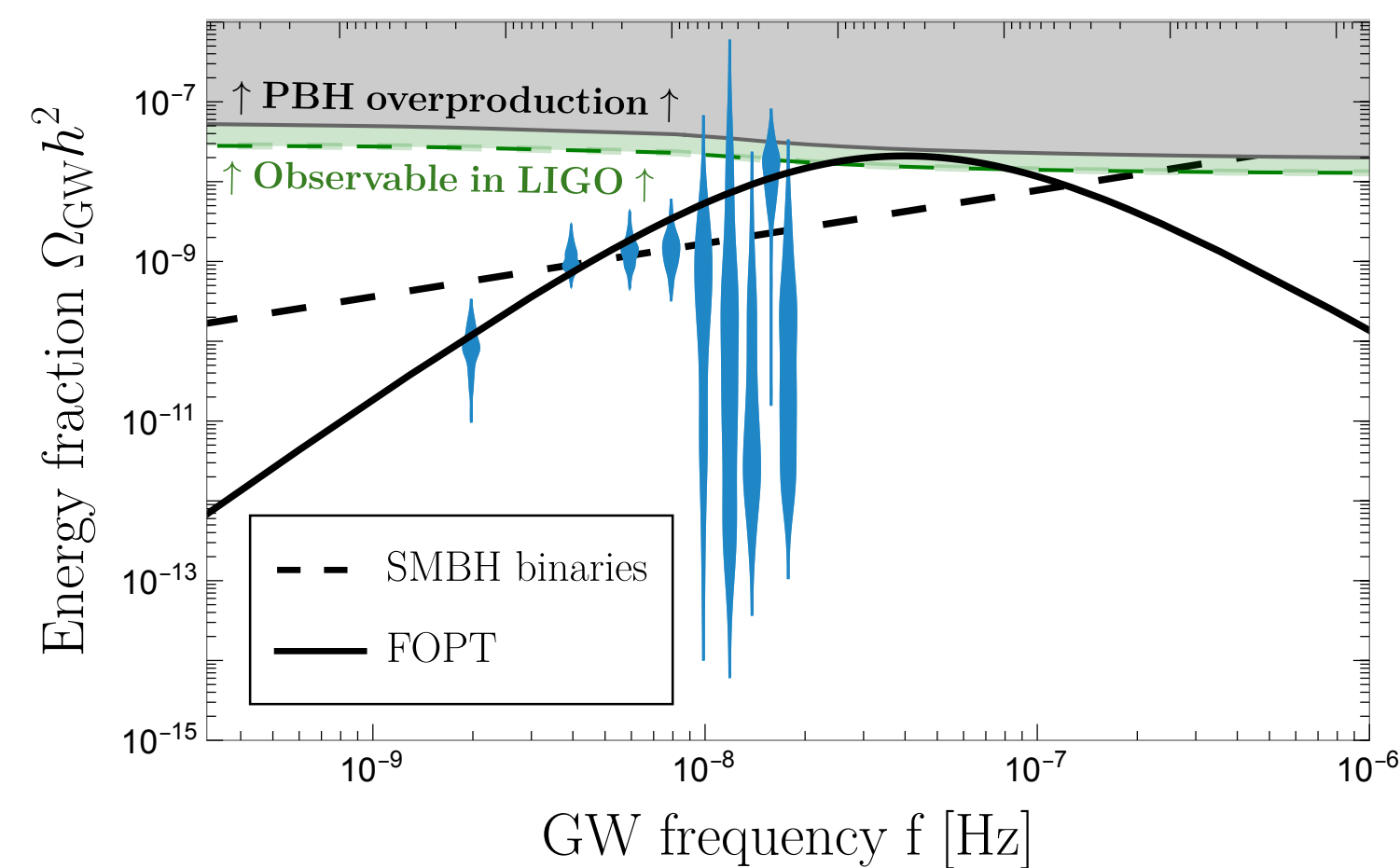
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

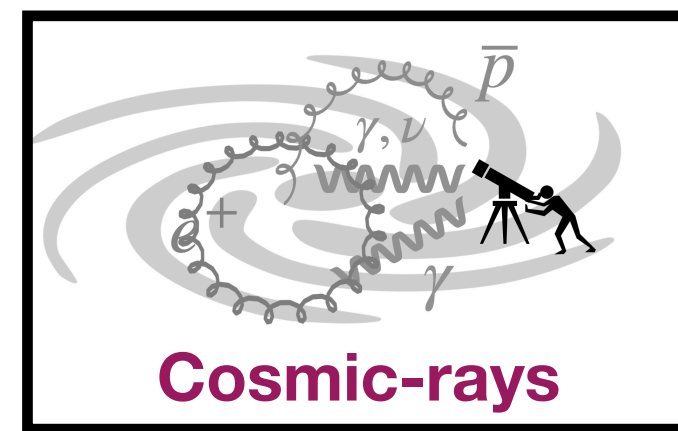
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

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Hoefken Zink et al. (2501.15649)

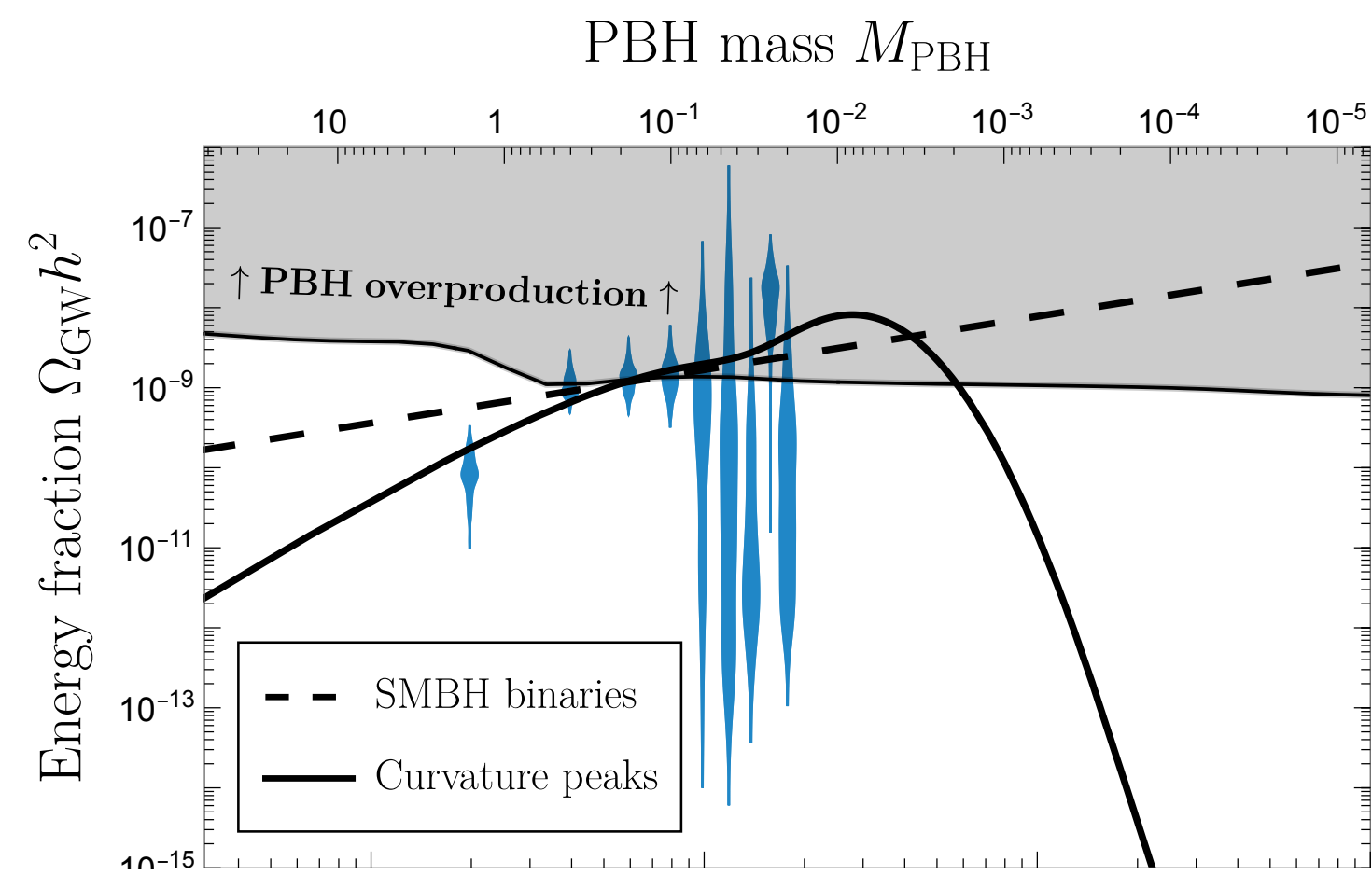
...



if DM=WIMPs

YG 2503.03857





Curvature peaks

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Kohri, Terada (2009.11853)

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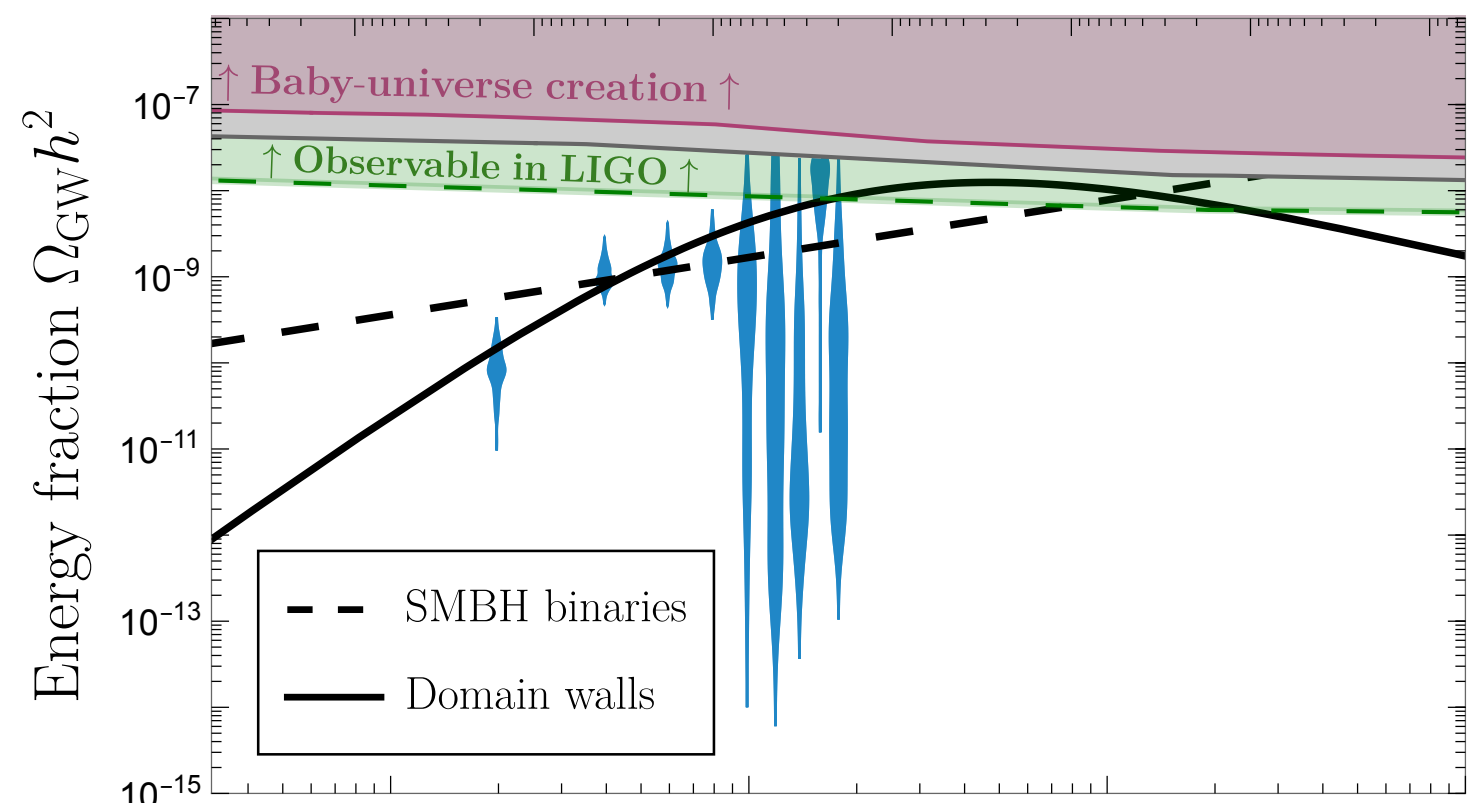
Vaskonen, Veermae (2009.07832),

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Except if negative non-Gaussianities

Franciolini, Vaskonen, Vermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Domain wall networks

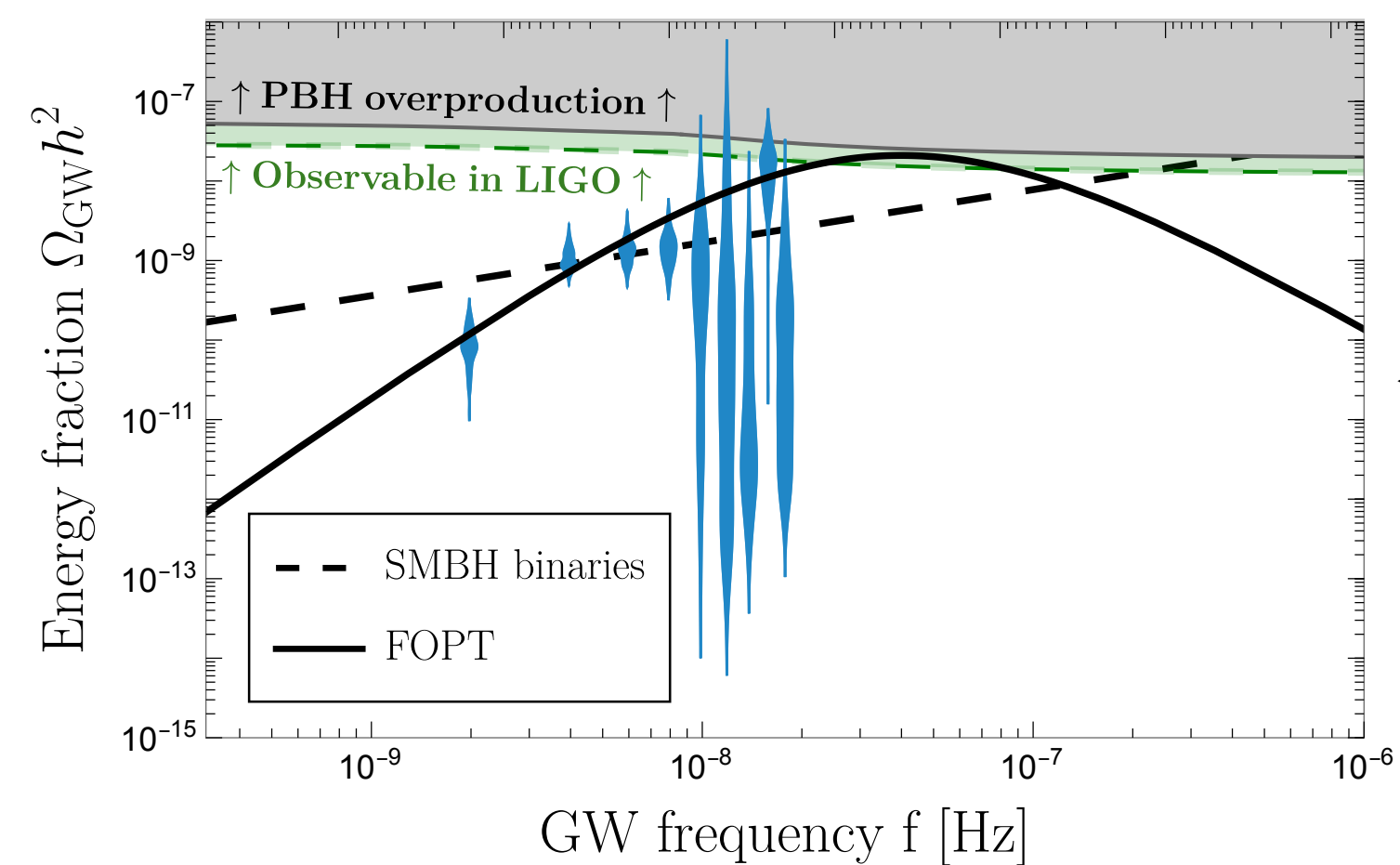
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

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...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

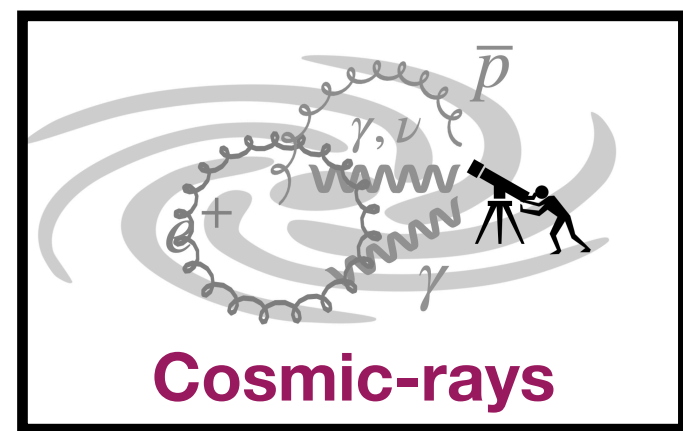
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...

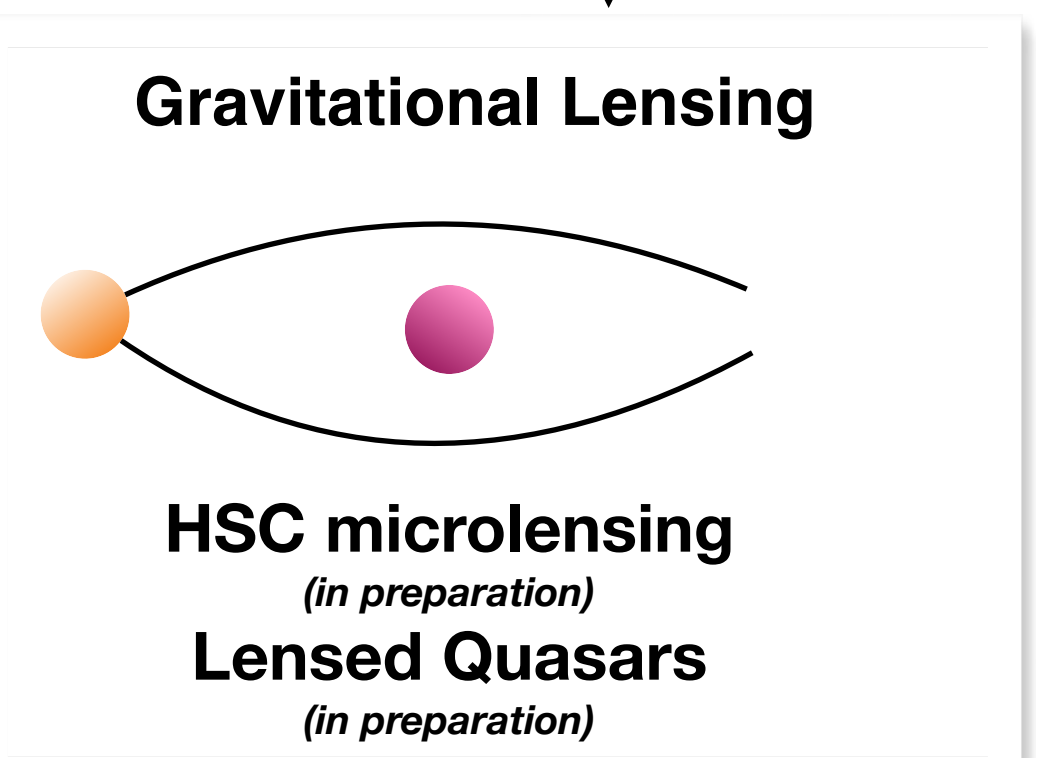


if DM=WIMPs

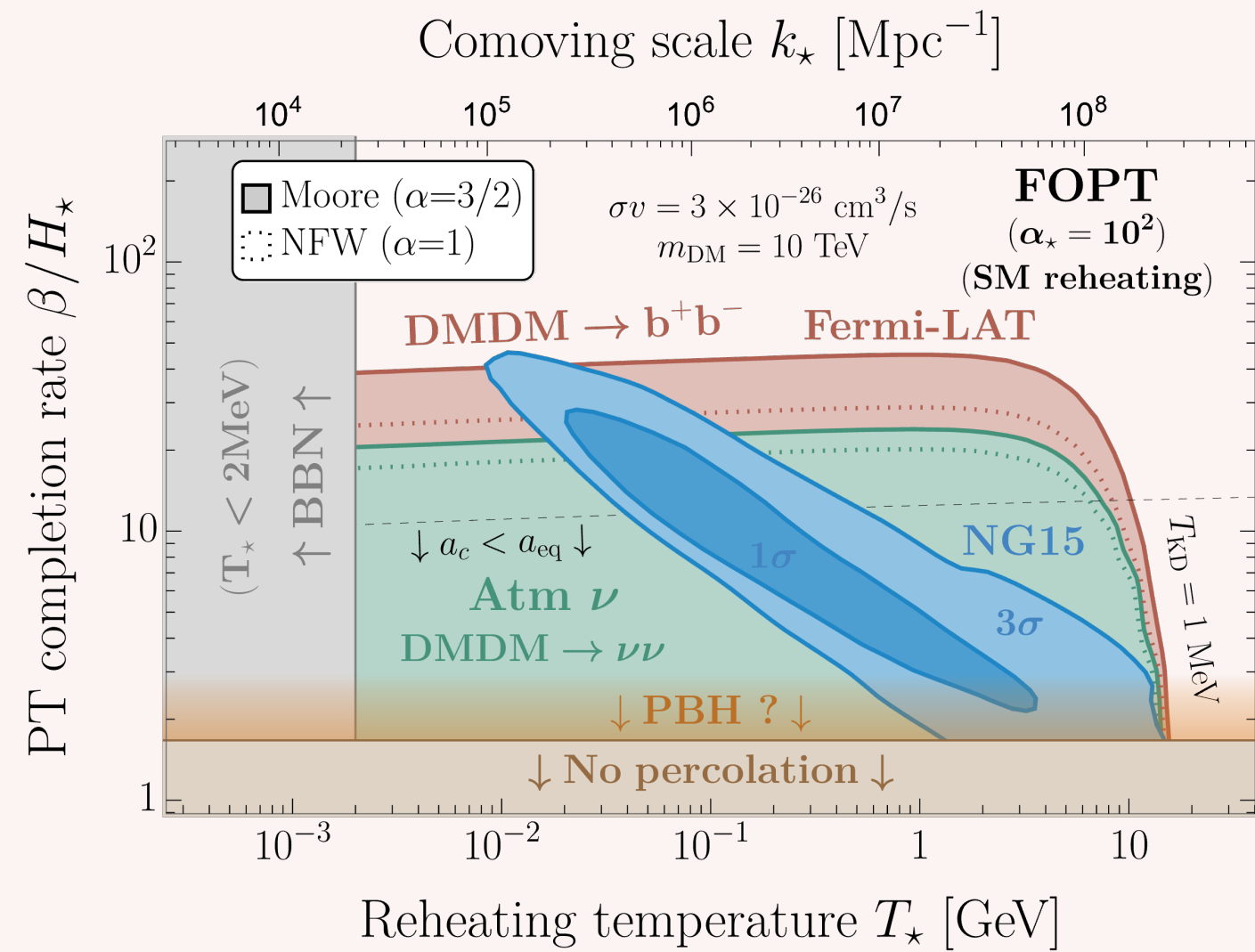
YG 2503.03857



In preparation
(with Sten Delos)



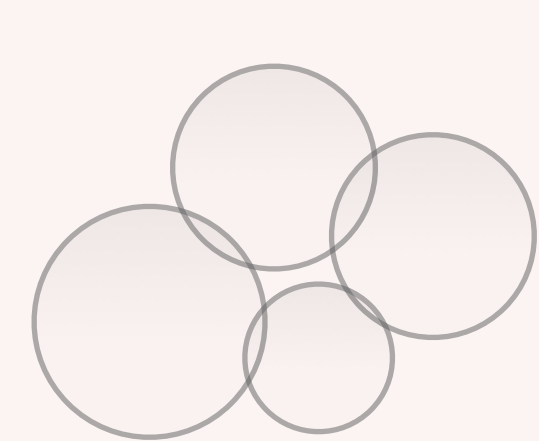
First-order Phase Transition



Franciolini, YG, Jinno
2503.01962

Elor, Jinno, Kumar,
McGehee, Tsai,
2311.16222 (PRL)

$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{\alpha_\star}{1 + \alpha_\star} \right)^2 \left(\frac{H_\star}{\beta} \right)^2 \frac{a_1(k_p/\beta)^3}{\left(a_2 + (k_p/\beta)^2 \right)^3}$$



$$k_p = k_\star/a_\star$$

YG 2503.03857

“New Physics Explanations of PTA
signal are incompatible with WIMPs
Dark Matter”

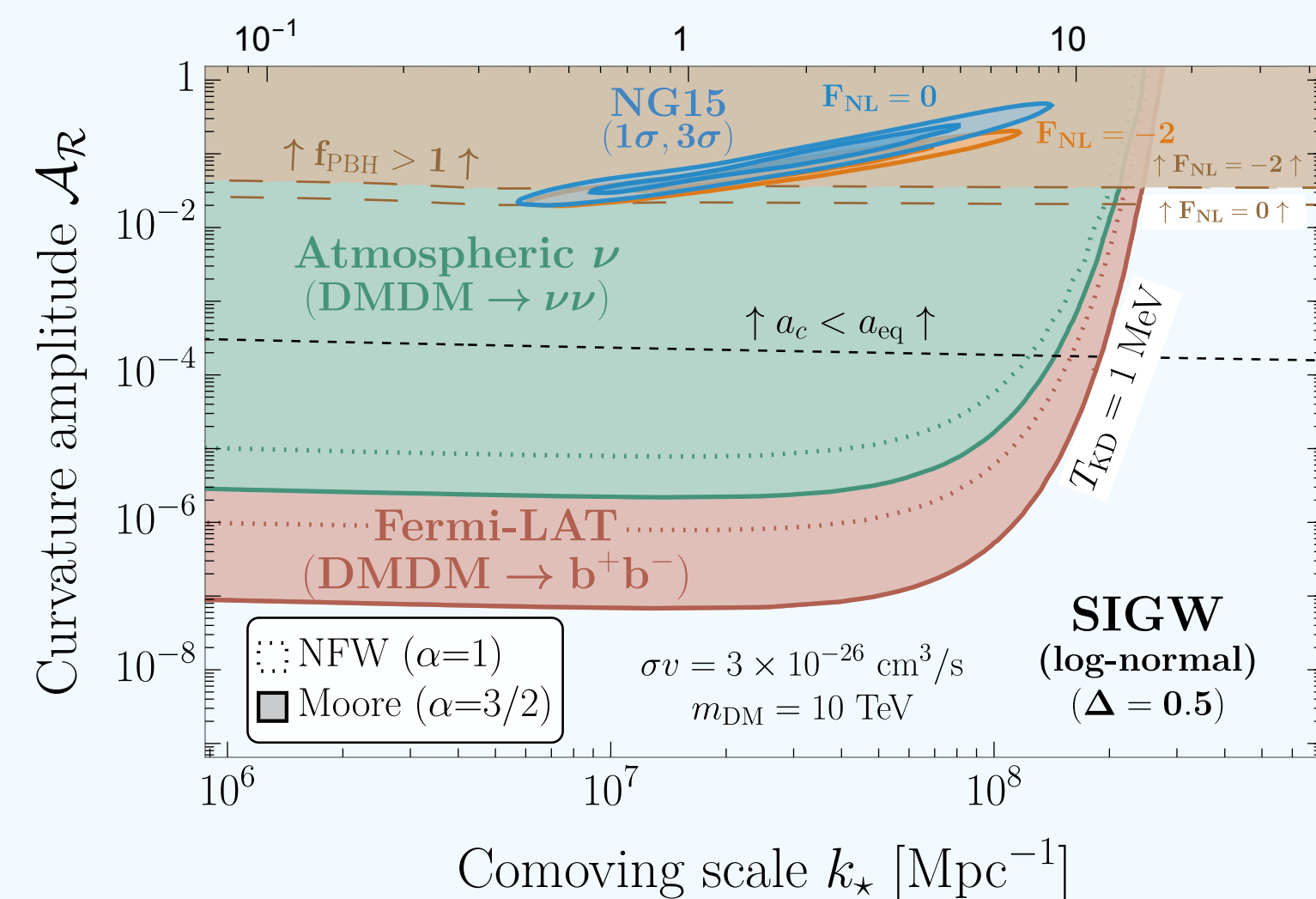
Domain Wall Networks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\alpha_V^2}{2\pi} \frac{(k_p L_{\text{ann}})^3}{\left[4 + (k_p L_{\text{ann}})^2 \right]^2}$$

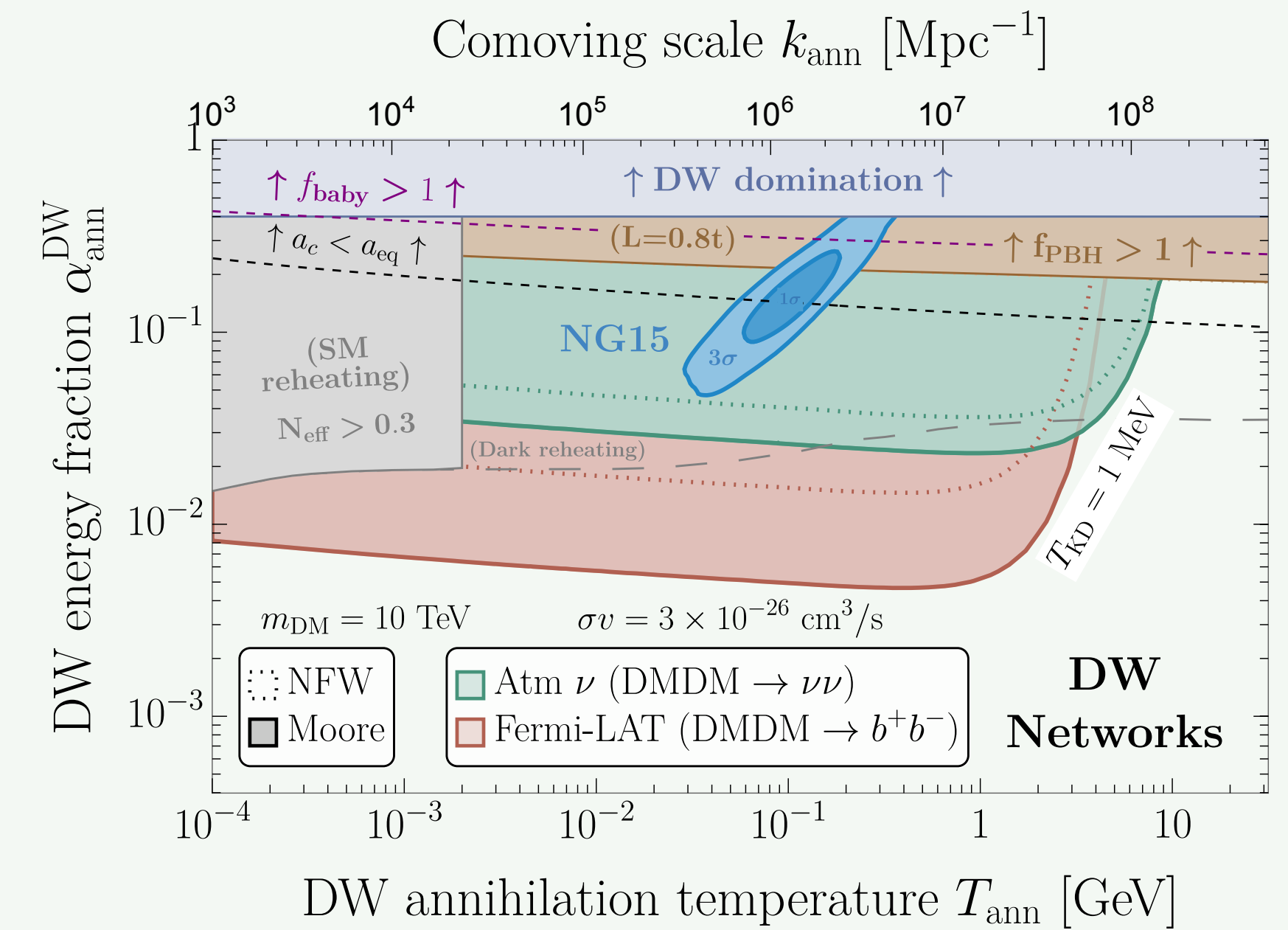
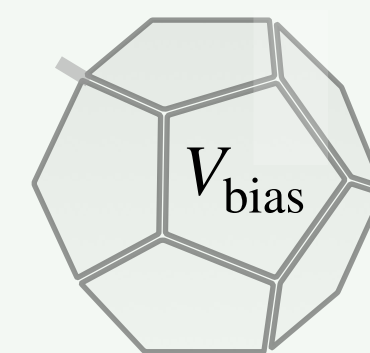
$$\alpha_V = V_{\text{bias}}/\rho_{\text{rad}} \Big|_{t=t_{\text{ann}}} \quad L_{\text{ann}} \sim t_{\text{ann}}$$

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp \left[-\frac{\log^2(k/k_\star)}{2\Delta^2} \right]$$

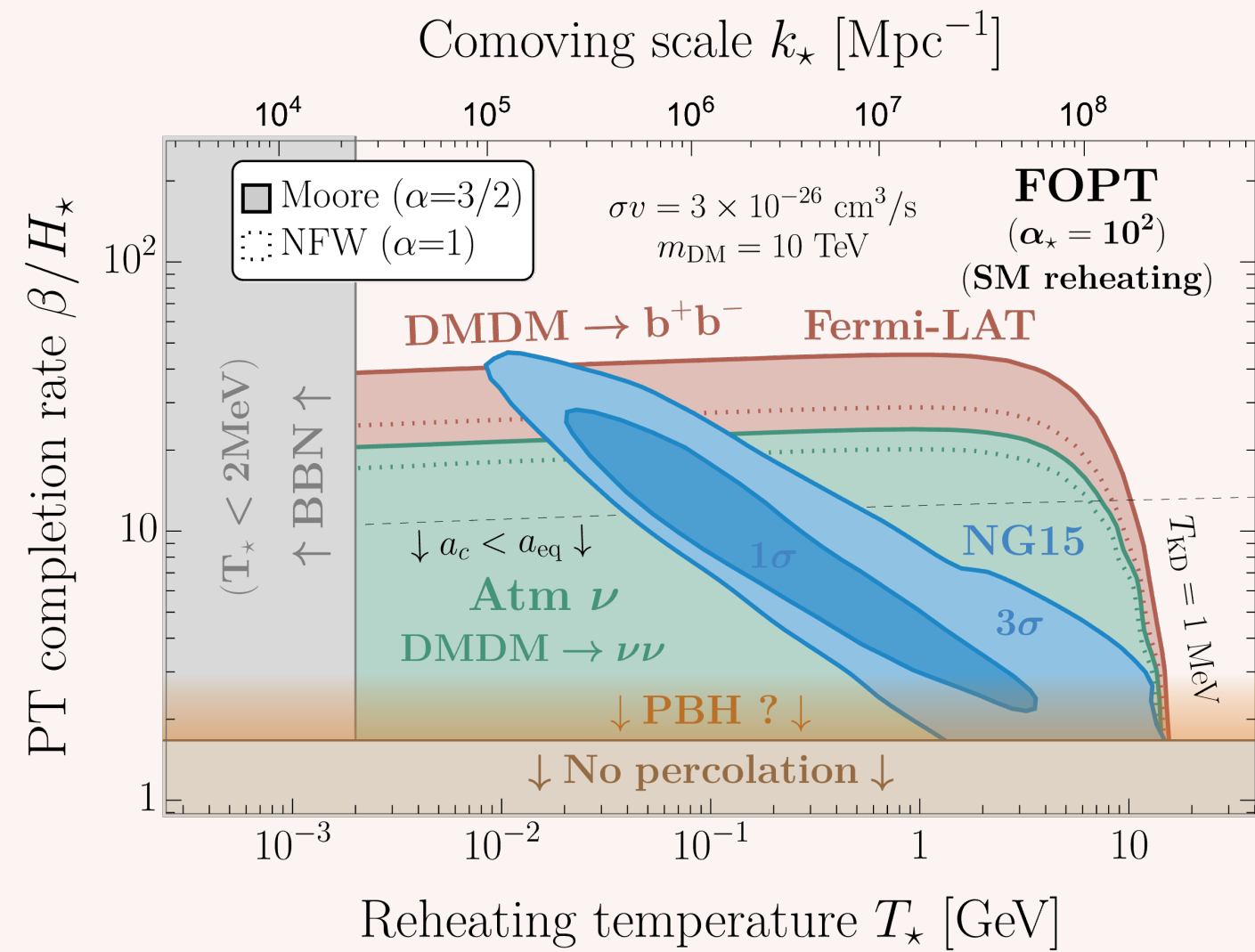
Horizon crossing temperature $T_\star$ [GeV]



See also Nakama,
Suyama, Kohri,
Hiroshima (1712.08820)

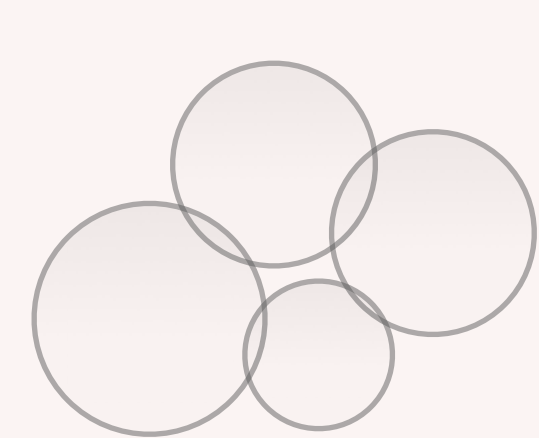


First-order Phase Transition



Franciolini, YG, Jinno
2503.01962

Elor, Jinno, Kumar,
McGehee, Tsai,
2311.16222 (PRL)



$$k_p = k_\star/a_\star$$

YG 2503.03857

“New Physics Explanations of PTA
signal are incompatible with WIMPs
Dark Matter”

Domain Wall Networks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\alpha_V^2}{2\pi} \frac{(k_p L_{\text{ann}})^3}{\left[4 + (k_p L_{\text{ann}})^2\right]^2}$$

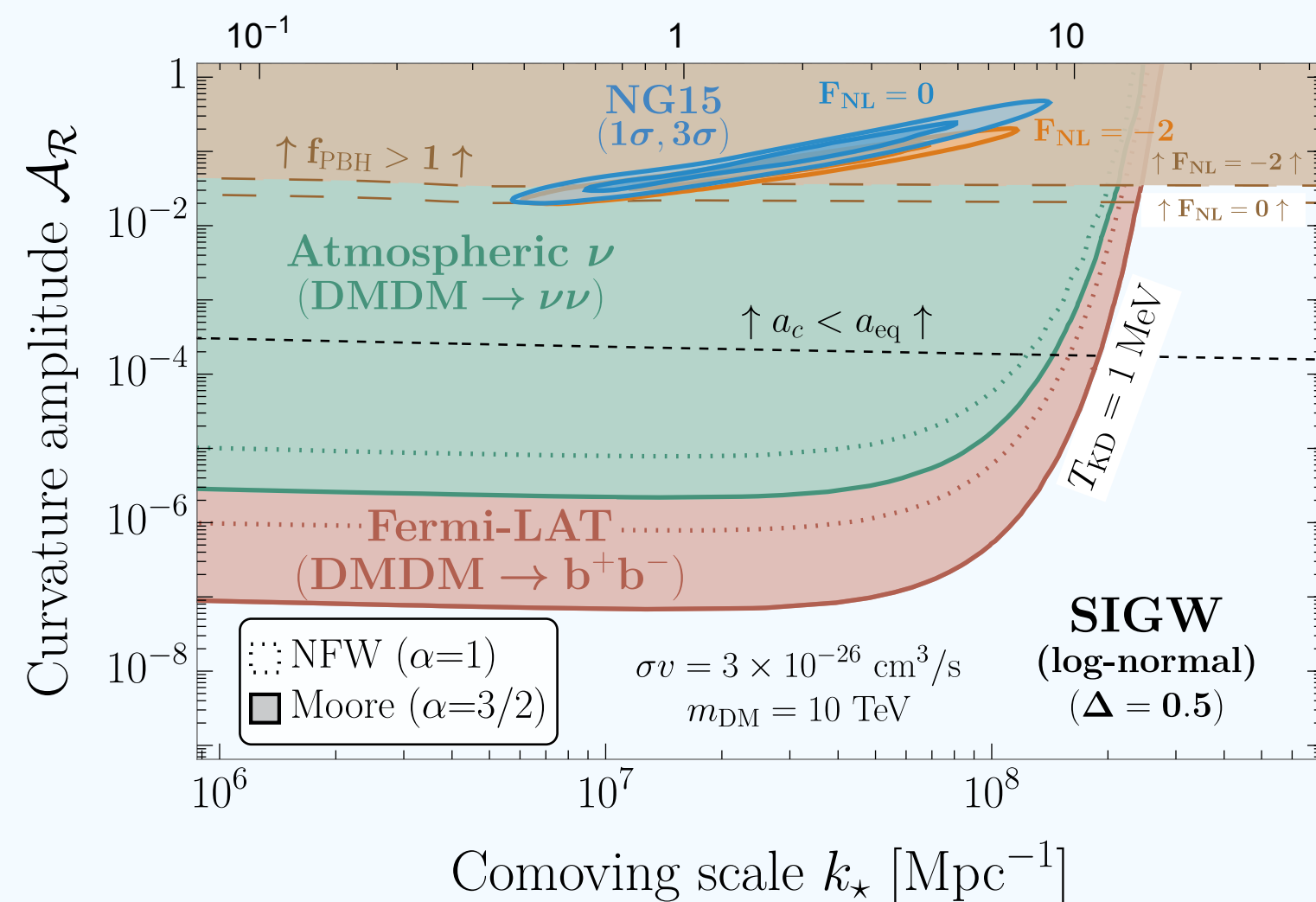
$$\alpha_V = V_{\text{bias}}/\rho_{\text{rad}} \Big|_{t=t_{\text{ann}}} \quad L_{\text{ann}} \sim t_{\text{ann}}$$



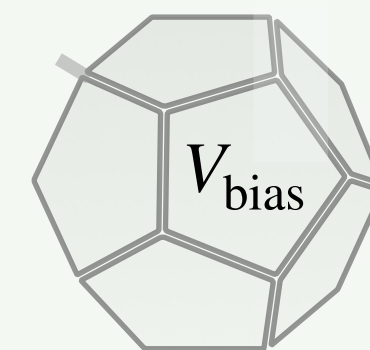
Gaussian curvature peaks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\log^2(k/k_\star)}{2\Delta^2}\right]$$

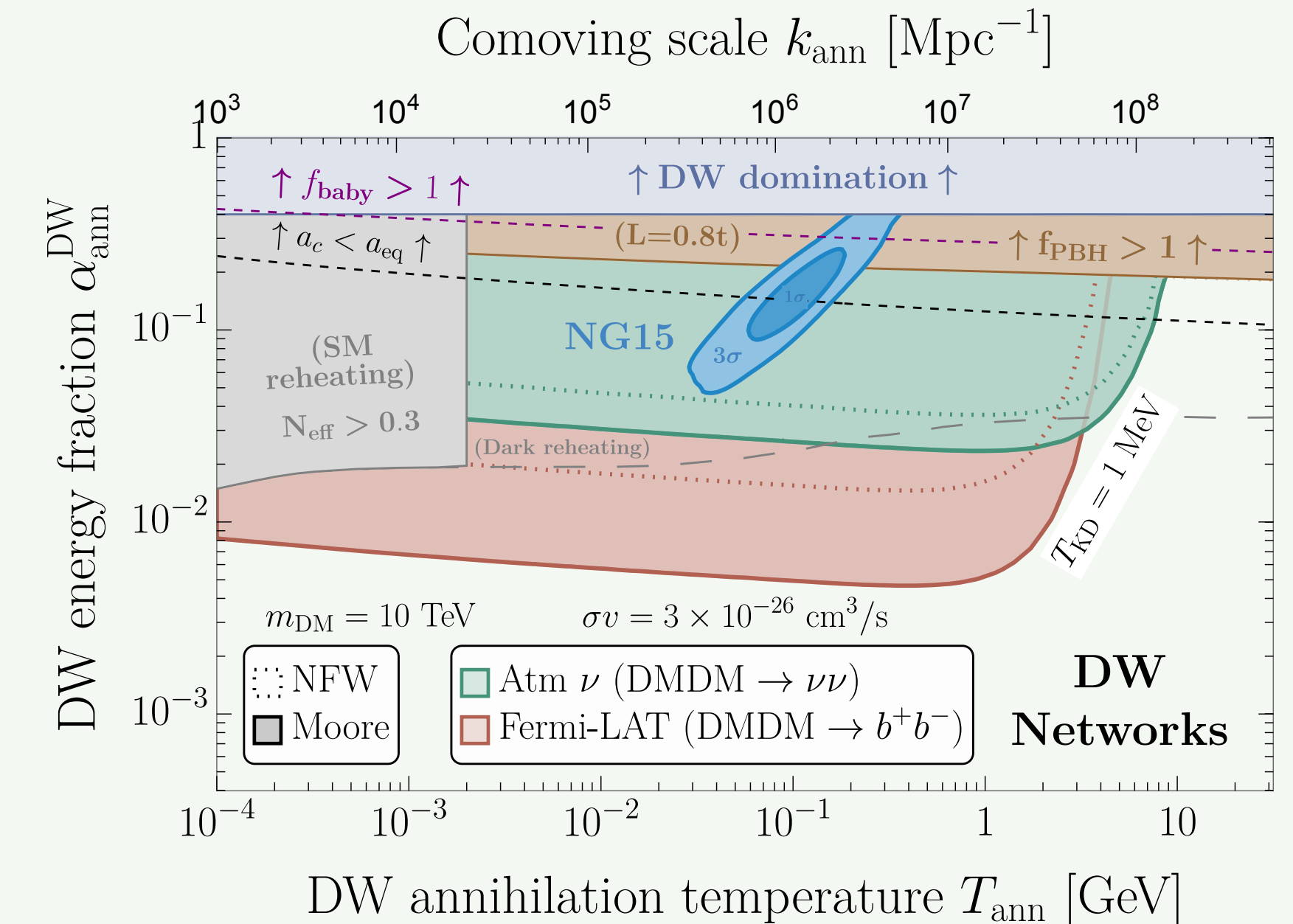
Horizon crossing temperature $T_\star$ [GeV]



See also Nakama,
Suyama, Kohri,
Hiroshima (1712.08820)



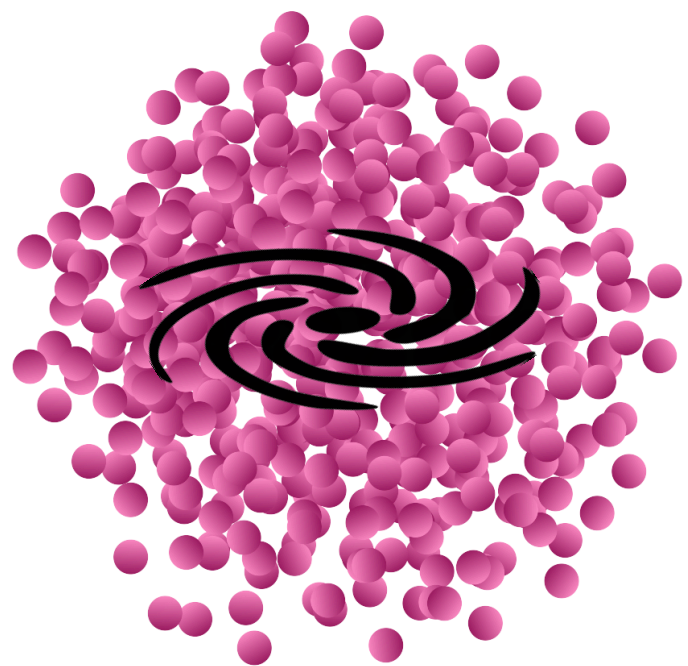
Thank you



DM Ultra Compact Mini Halos

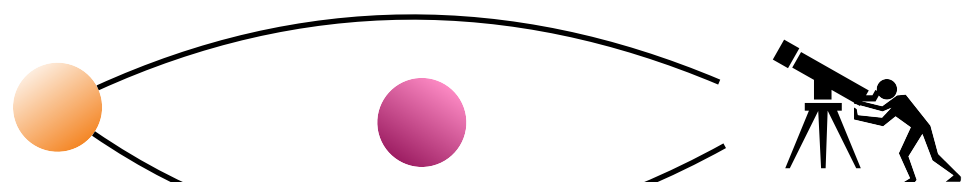
$$R_{\text{UCMH}} \sim 200 \text{ AU} \left(\frac{1000}{z_{\text{collapse}}} \right)$$

$$M_{\text{UCMH}} \sim 10^{-7} M_{\odot}$$



In preparation
(with Sten Delos)

Gravitational Lensing

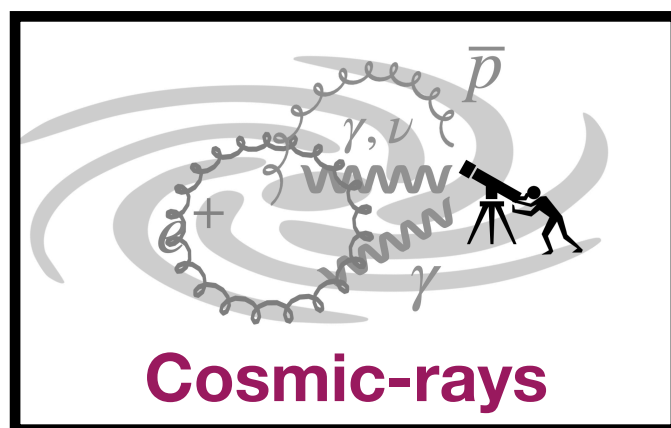


HSC microlensing
(in preparation)

Lensed Quasars
(in preparation)

if DM=WIMPs

YG 2503.03857



Cosmic-rays

$$\mathcal{R} \gtrsim 0.1$$

YG, Volansky 2305.04942

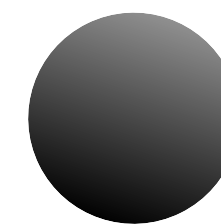
YG 2307.04239 (PRL)

Franciolini, YG, Jinno 2503.01962

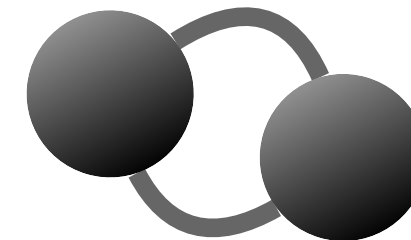
YG, Vitagliano 2306.17841, 2311.07670

Primordial Black Holes

$$M_{\text{PBH}} \sim M_{\odot}$$



Binary
formation



kilo-Hertz
GWs



New Physics around $T_{\star} \sim 0.1 \text{ GeV}$:

1) Curvature peaks

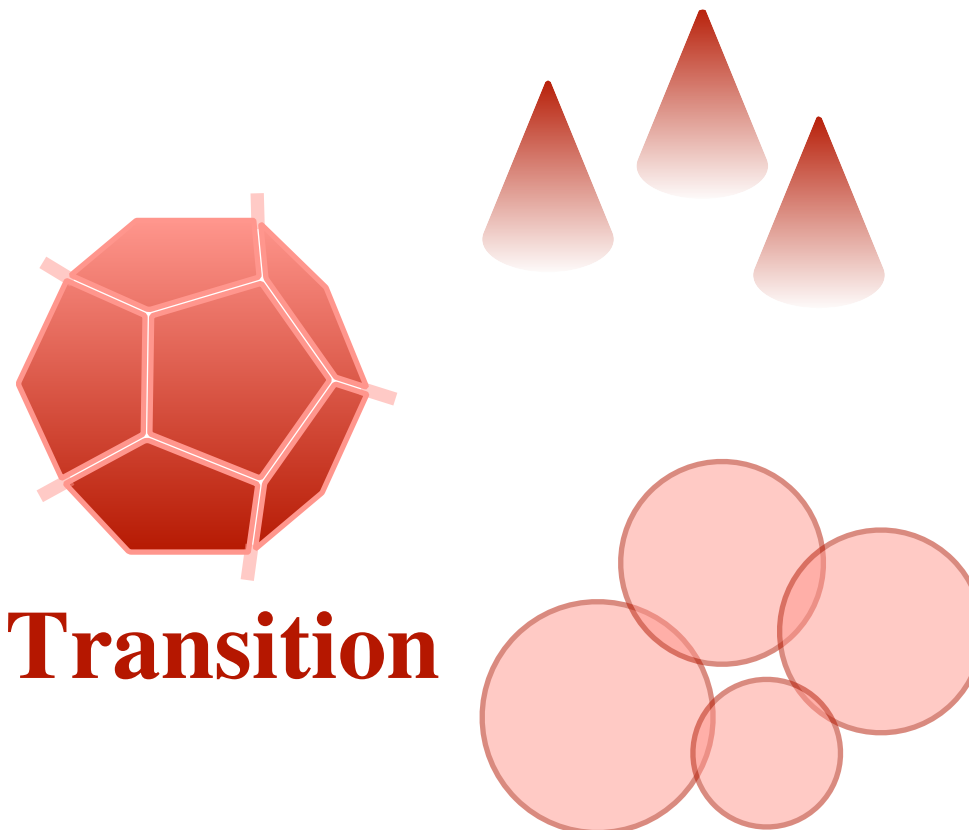
$$\mathcal{A}_{\mathcal{R}} \gtrsim 0.01$$

2) Domain Walls

$$\alpha_{\star} \gtrsim 0.1$$

3) First Order Phase Transition

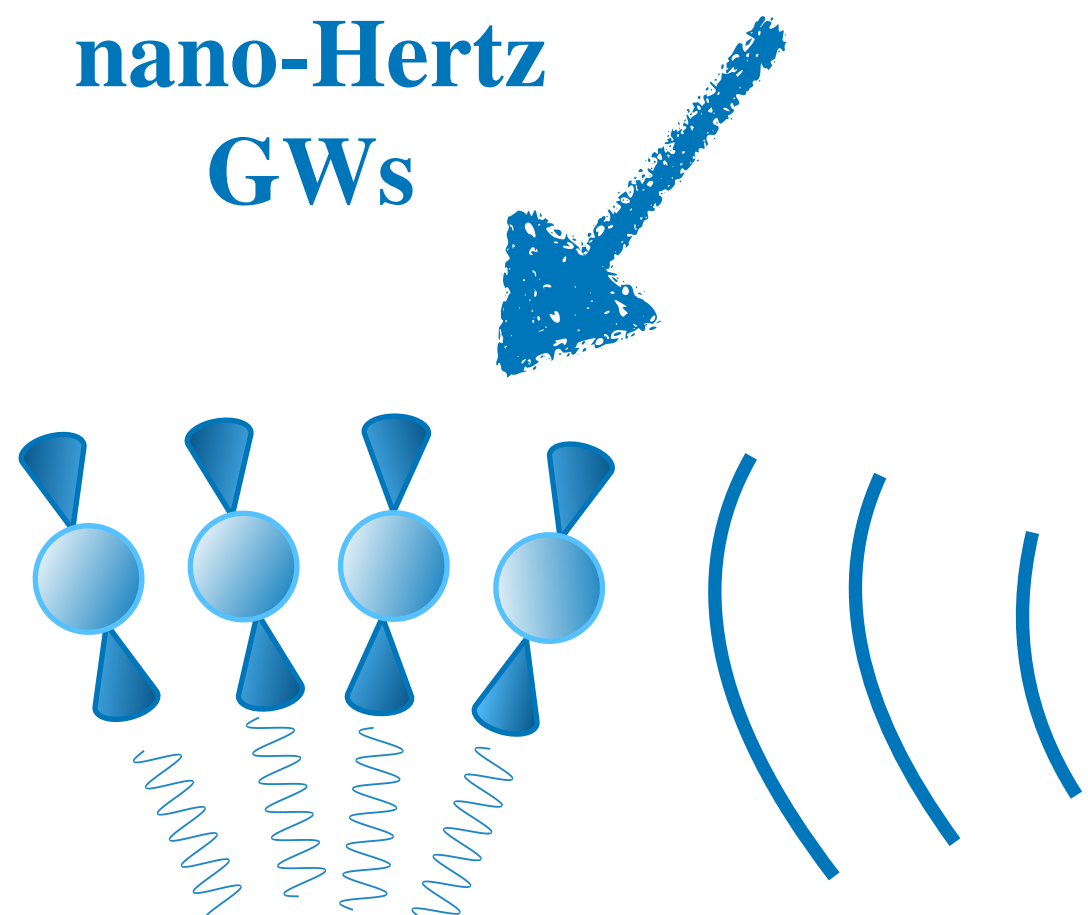
$$\beta/H_{\star} \lesssim 30$$



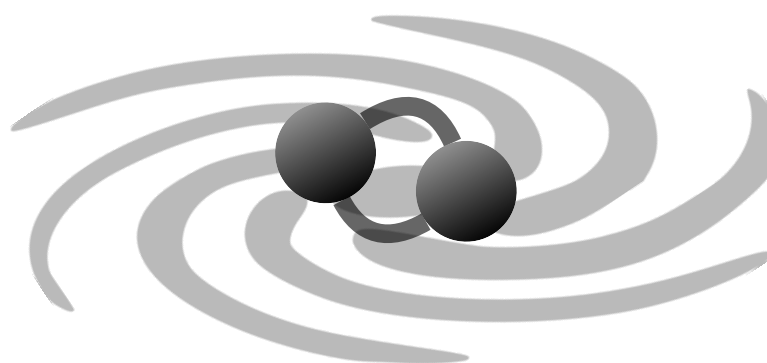
$$\mathcal{R} \gtrsim 10^{-3}$$



nano-Hertz
GWs



Astrophysical interpretation:



Super Massive Black Holes
Binary Mergers

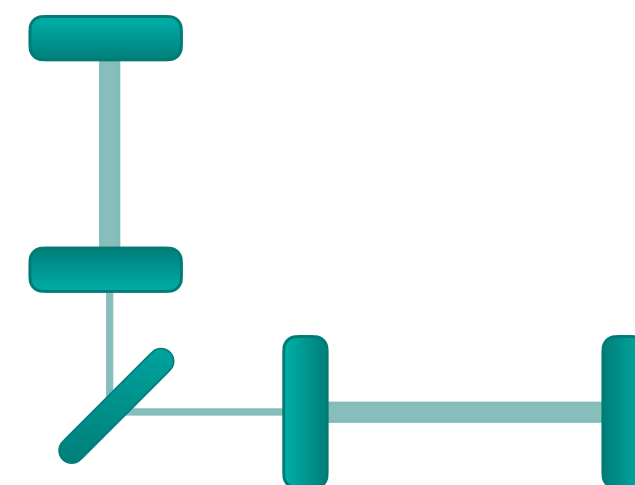
$$M_{\text{SMBH}} \sim 10^9 M_{\odot}$$

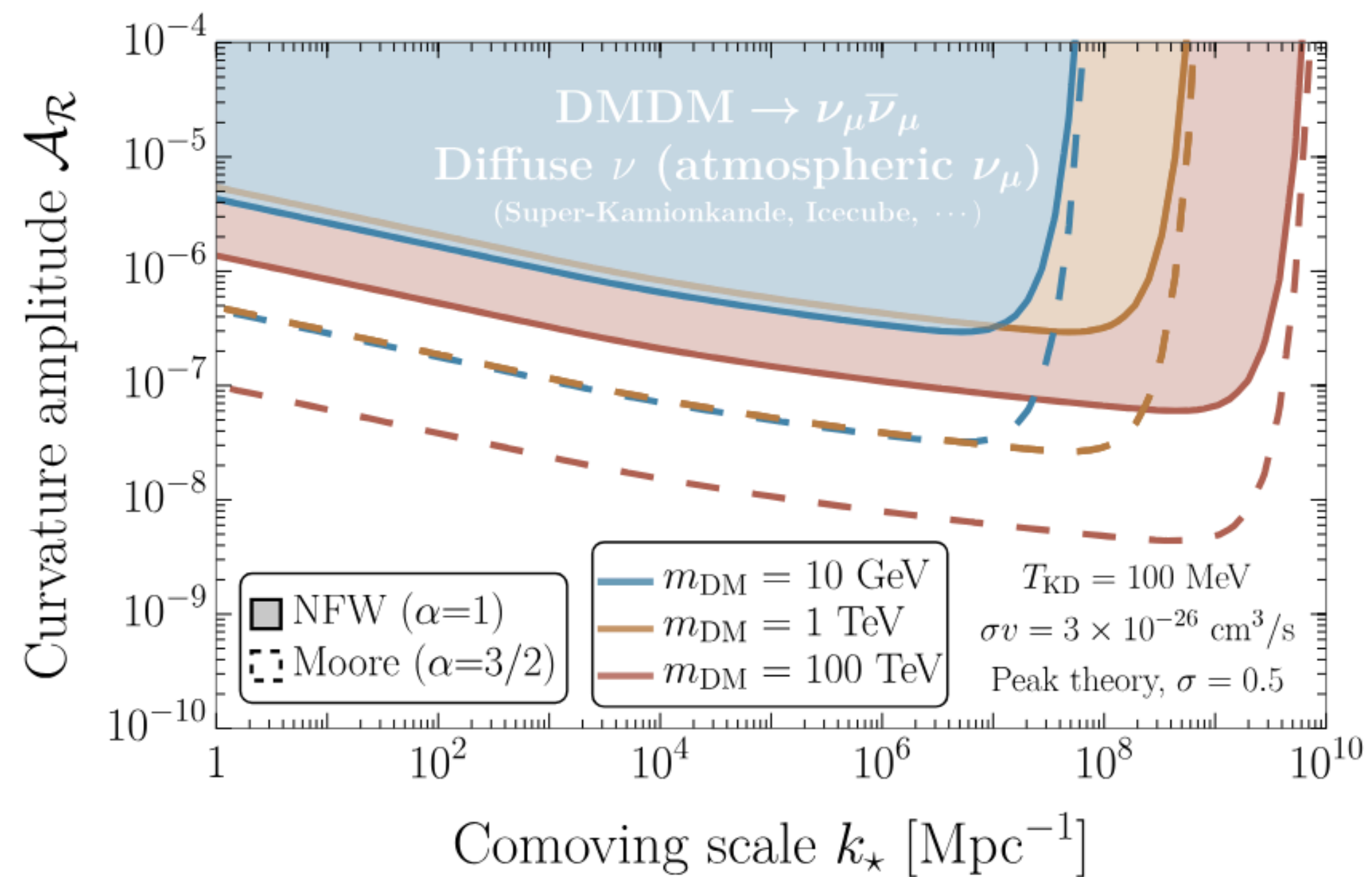
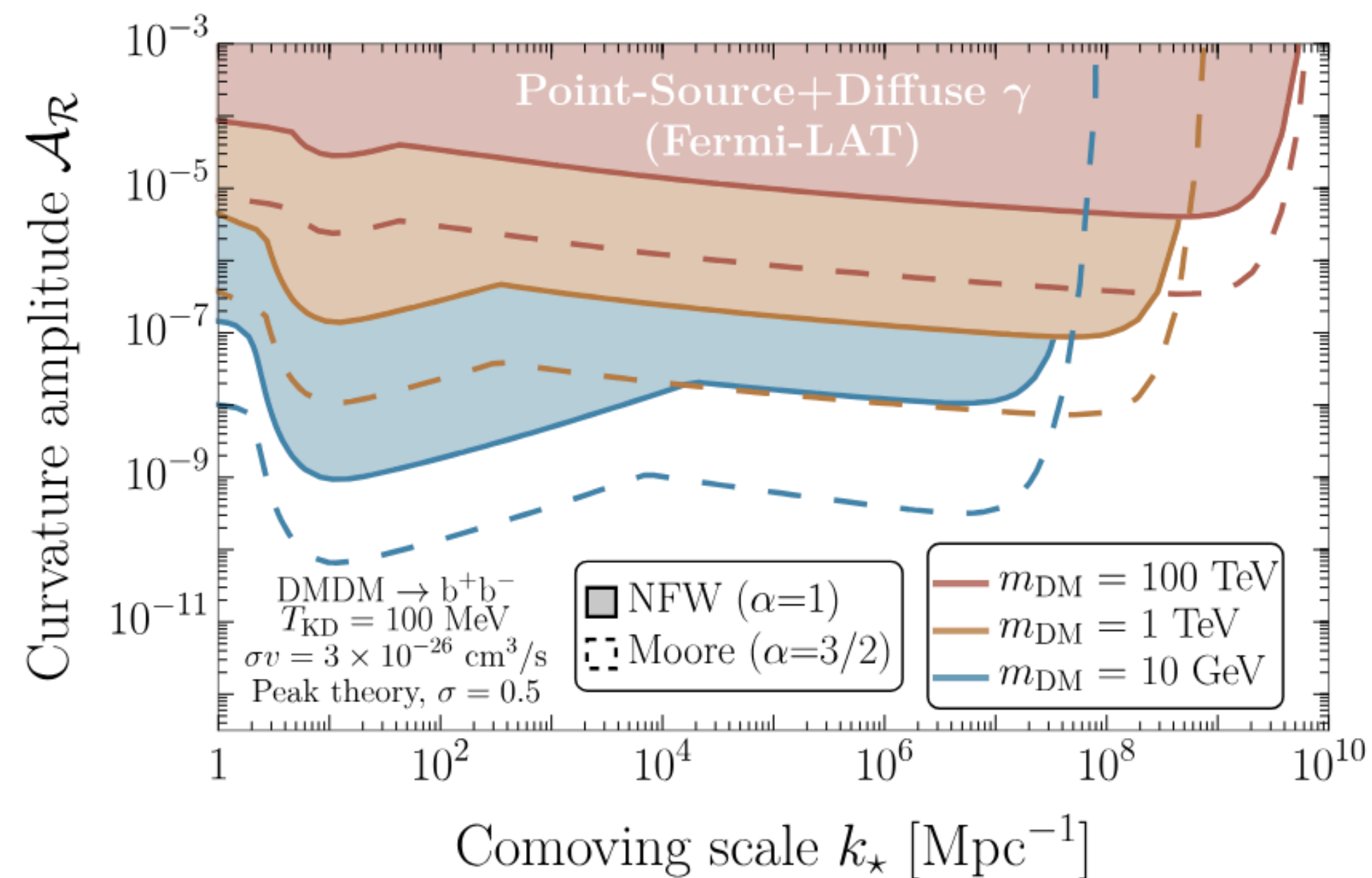
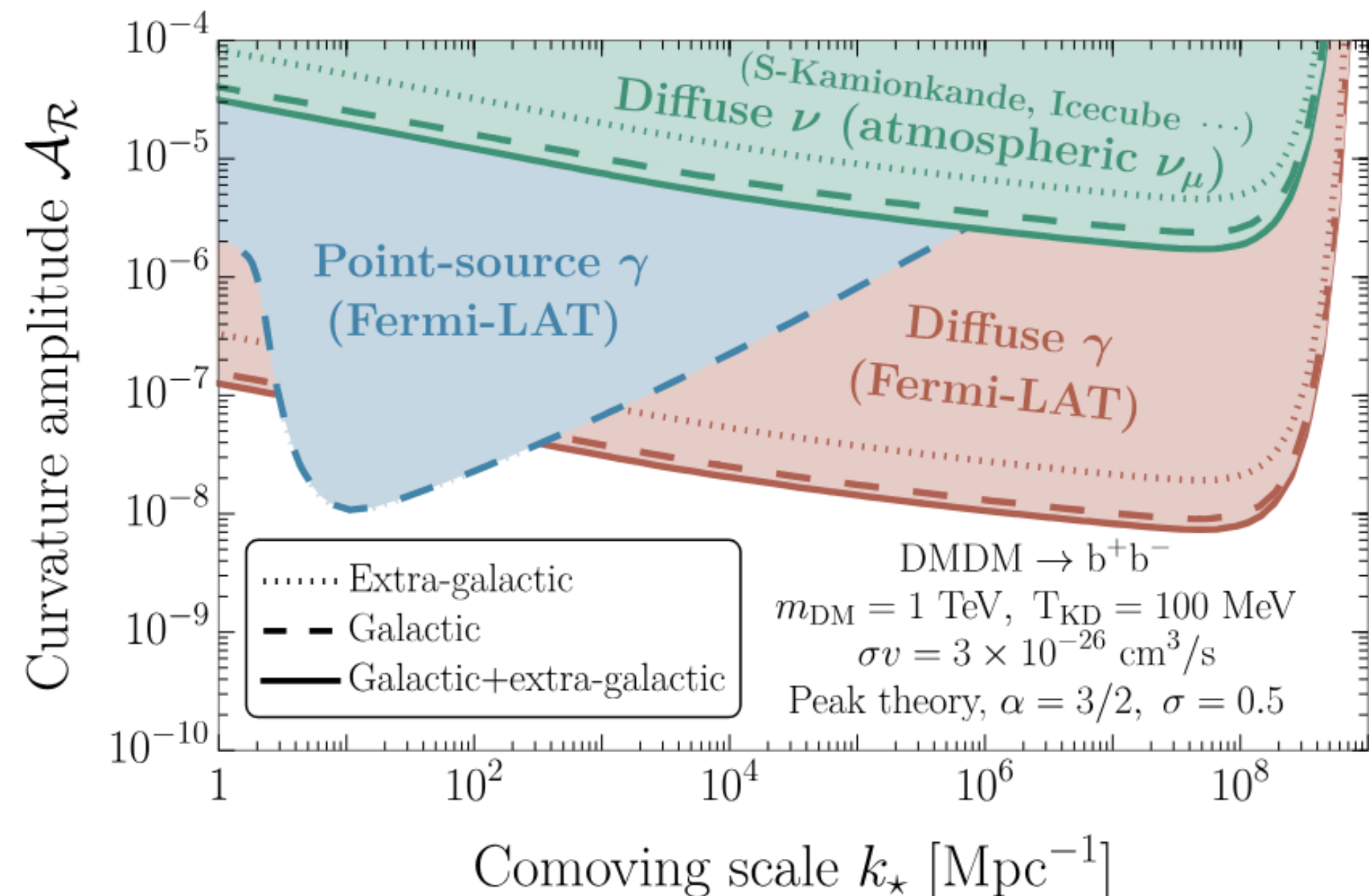
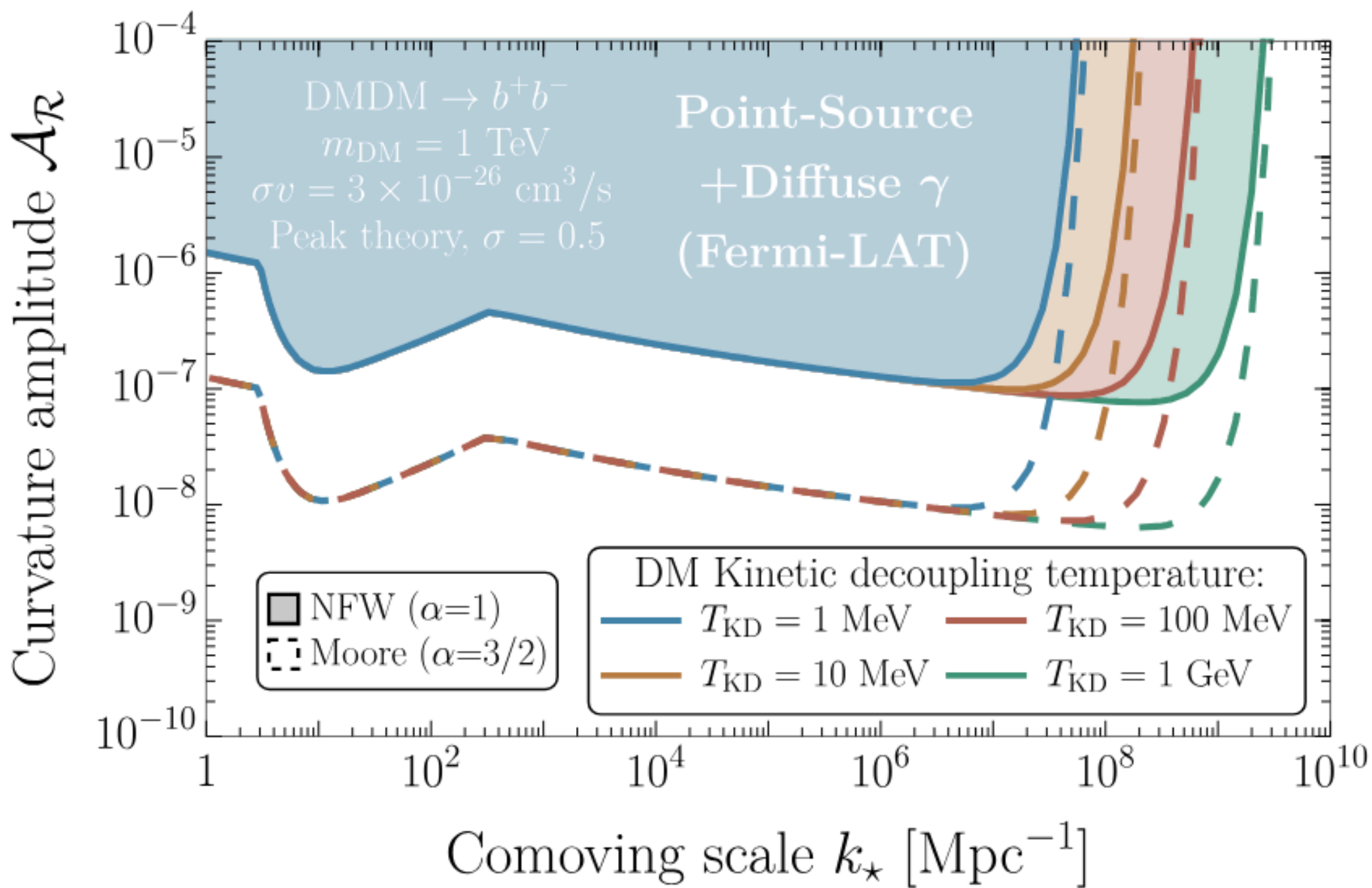
Pulsar Timing Arrays
(NG15, EPTA, PPTA, CPTA, ...)

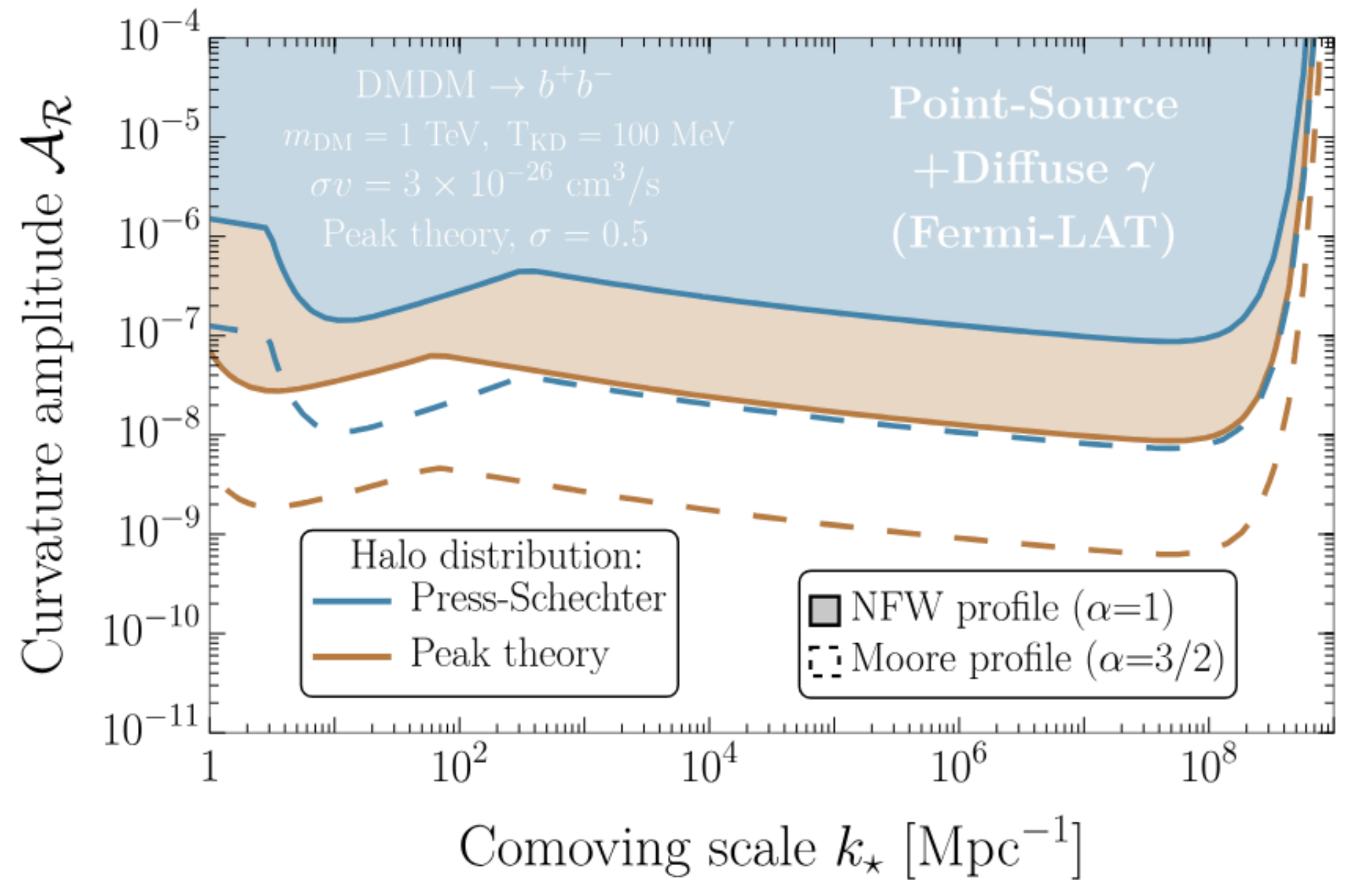
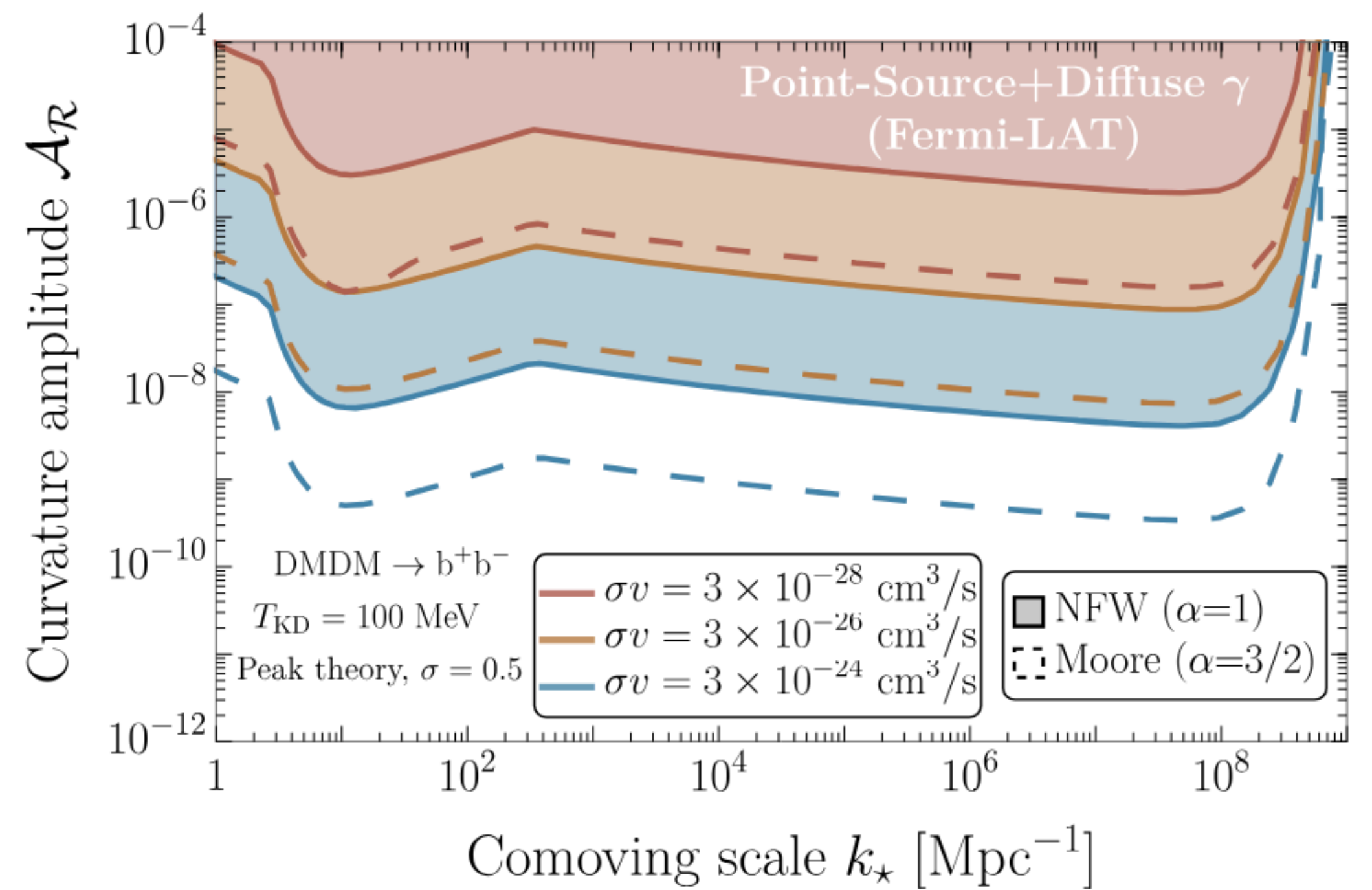
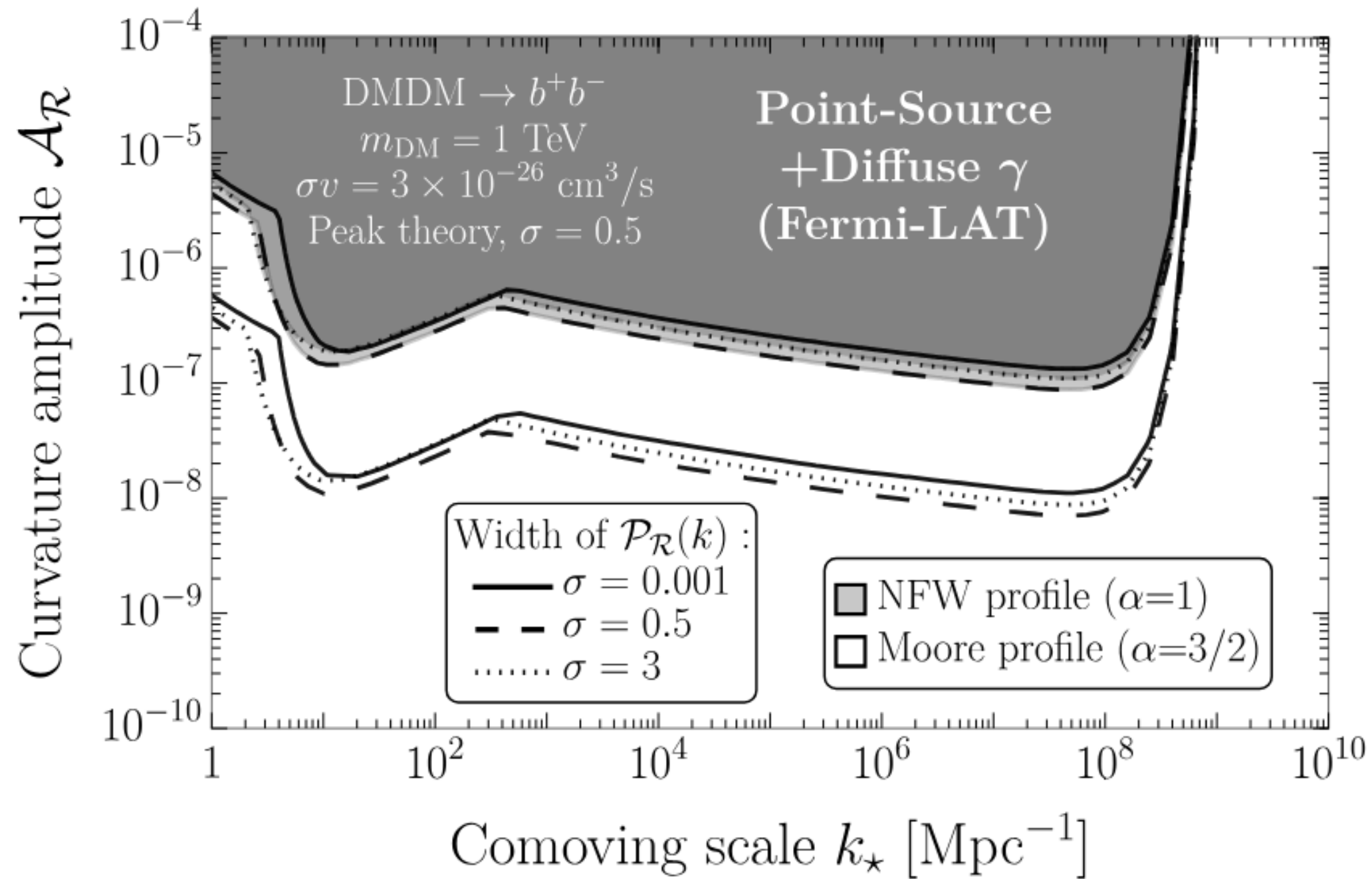
Data correlation

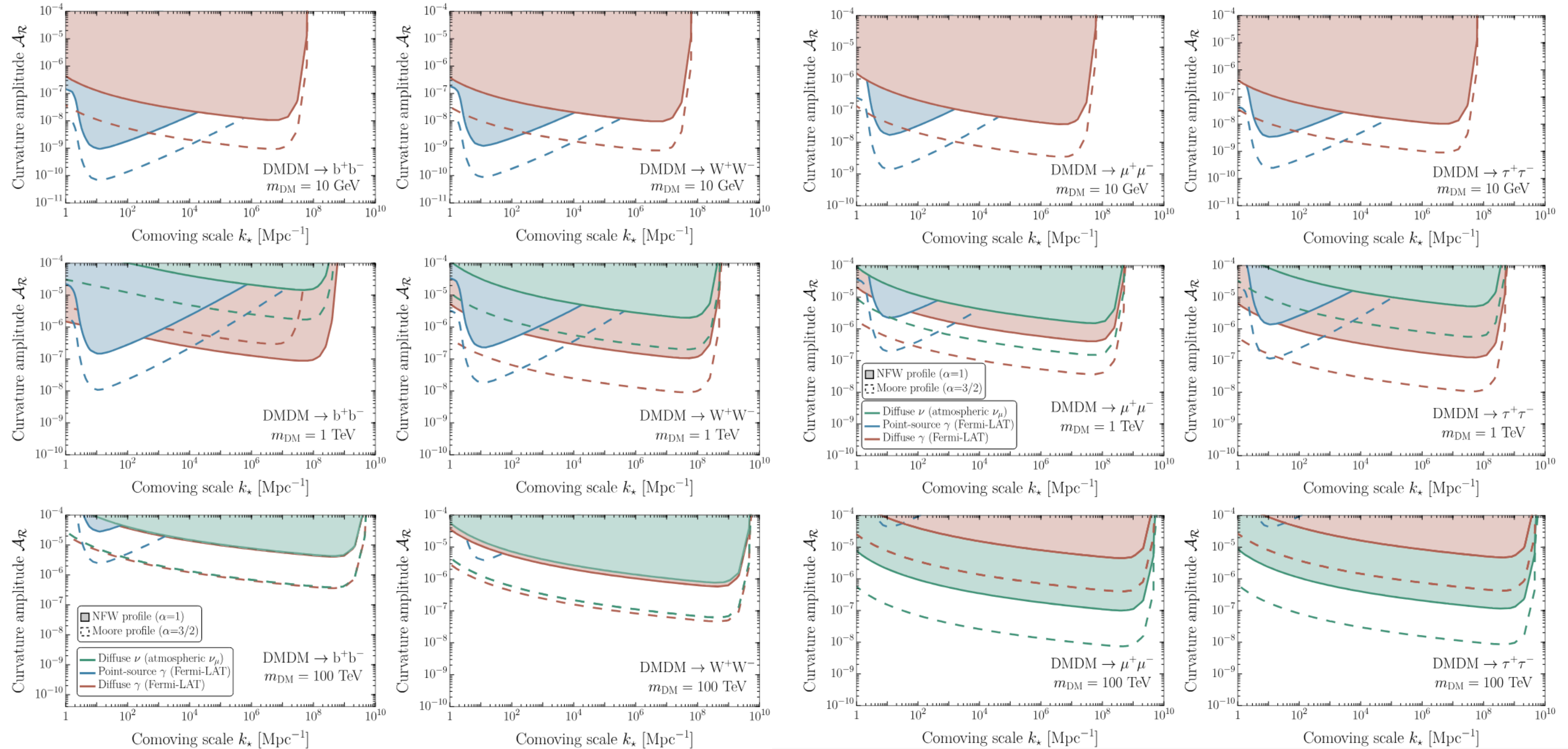
YG, Trifinopoulos, Vanvlasselaer (2508.19328)

Earth-based Laser
Interferometers
(LVK O₄, O₅, ET, CE)

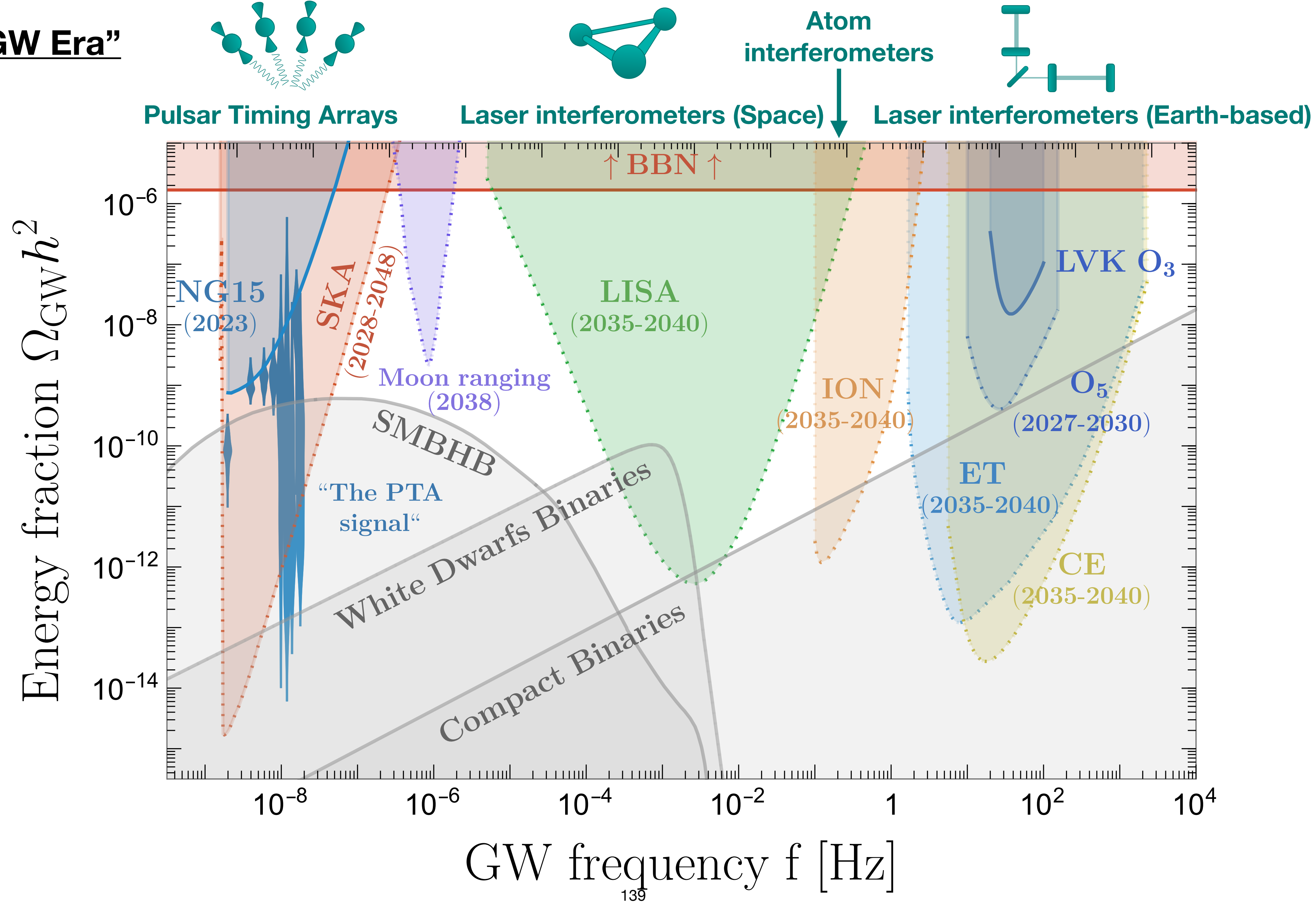


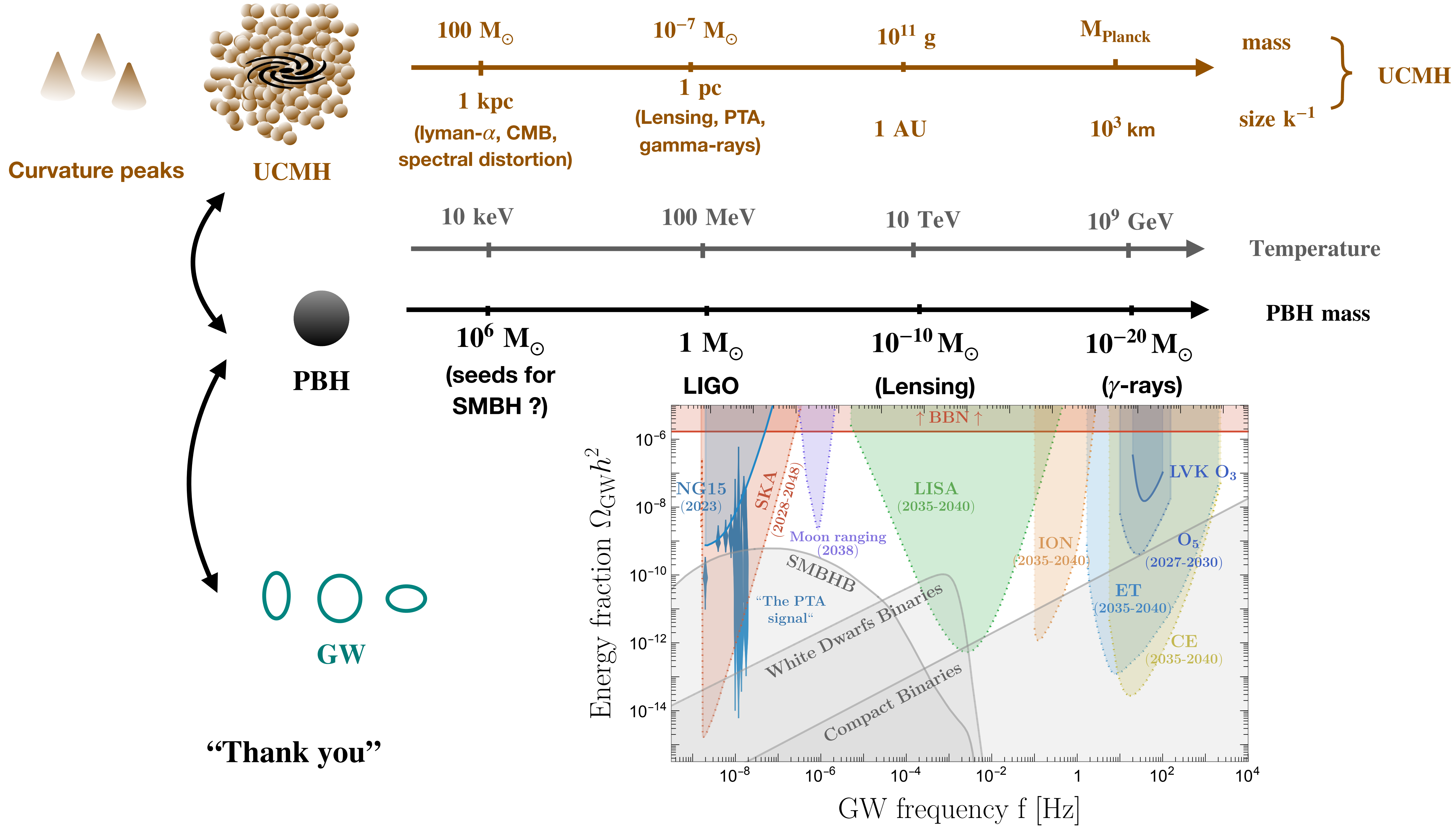


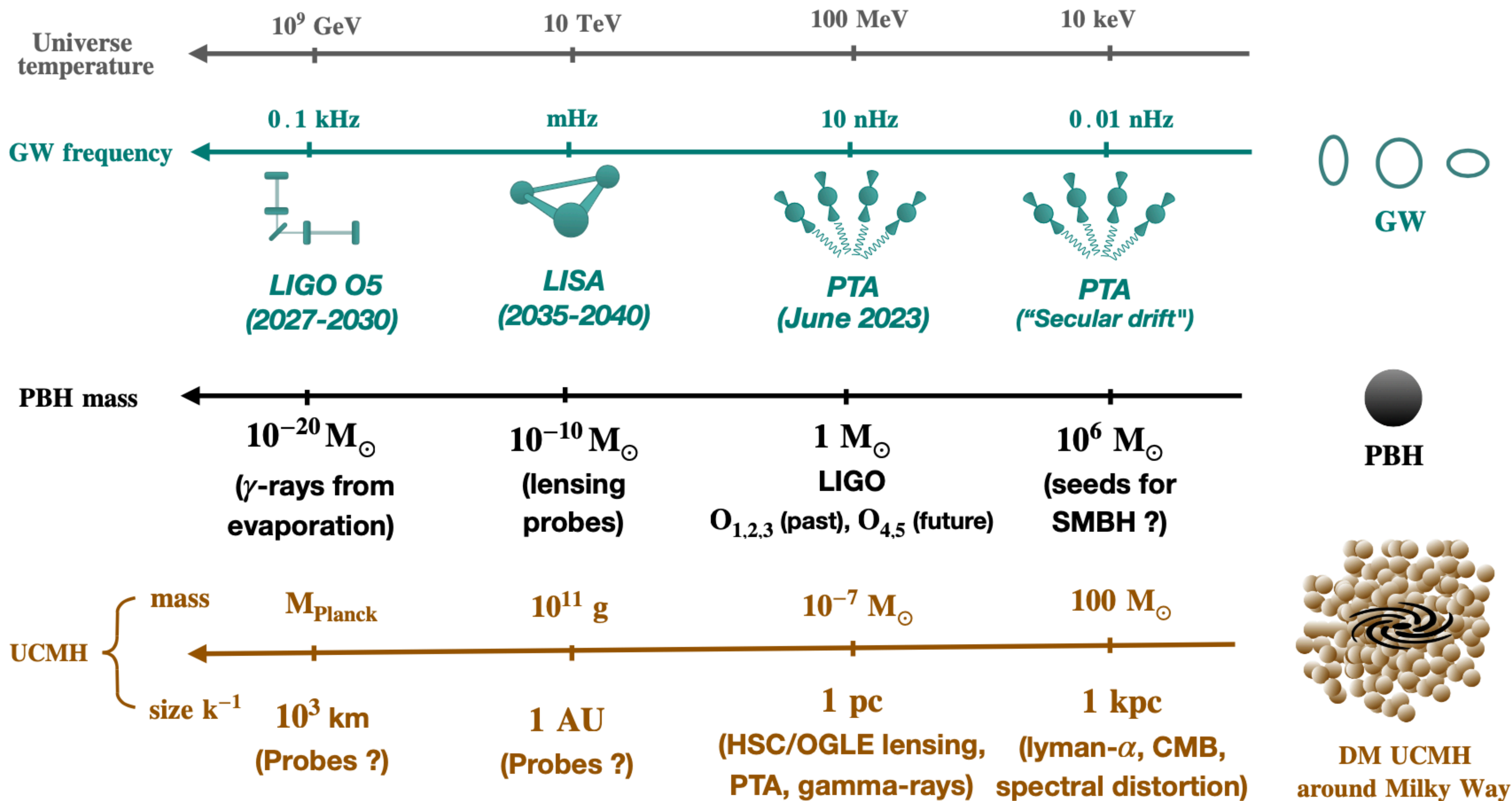


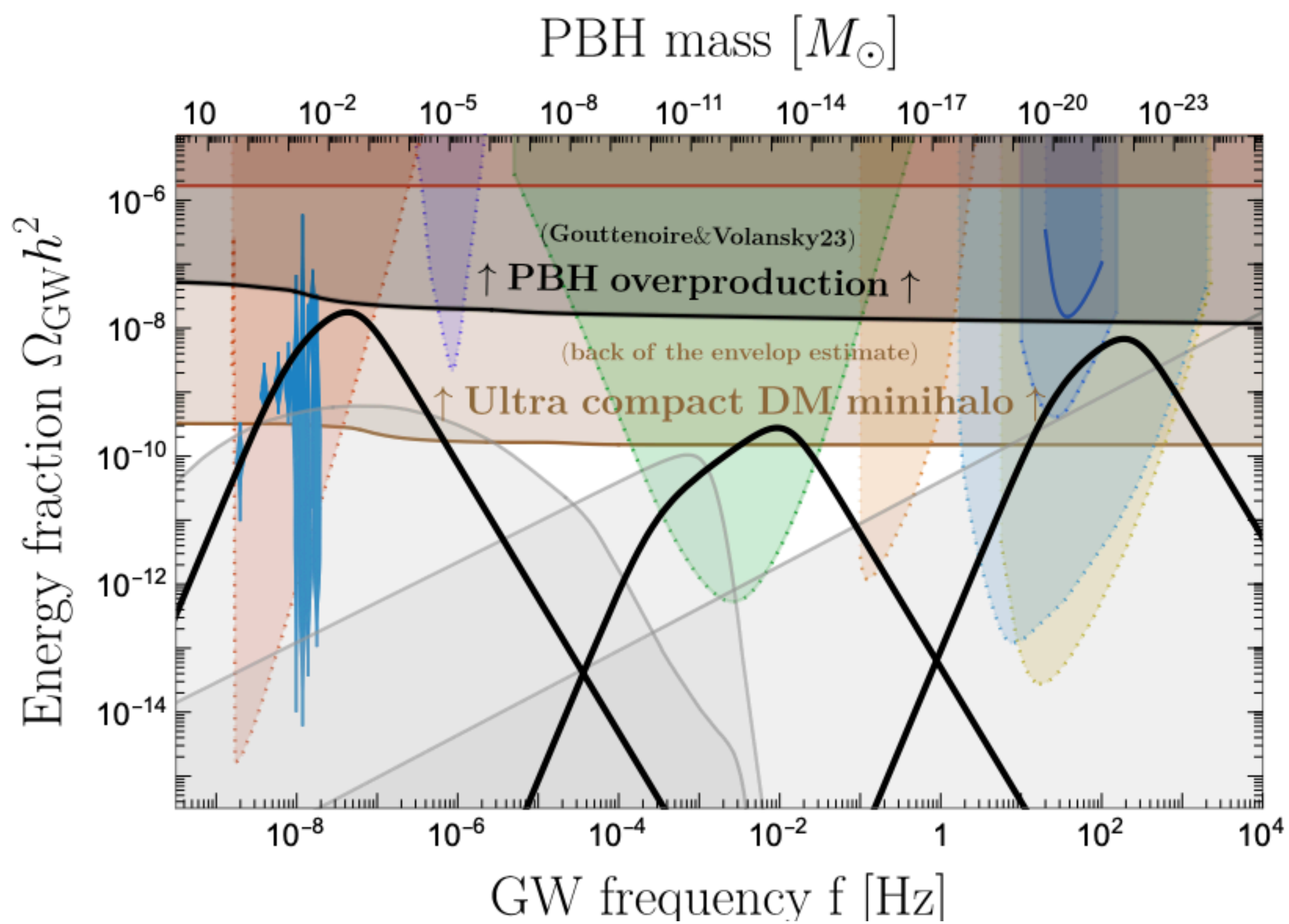


“The GW Era”



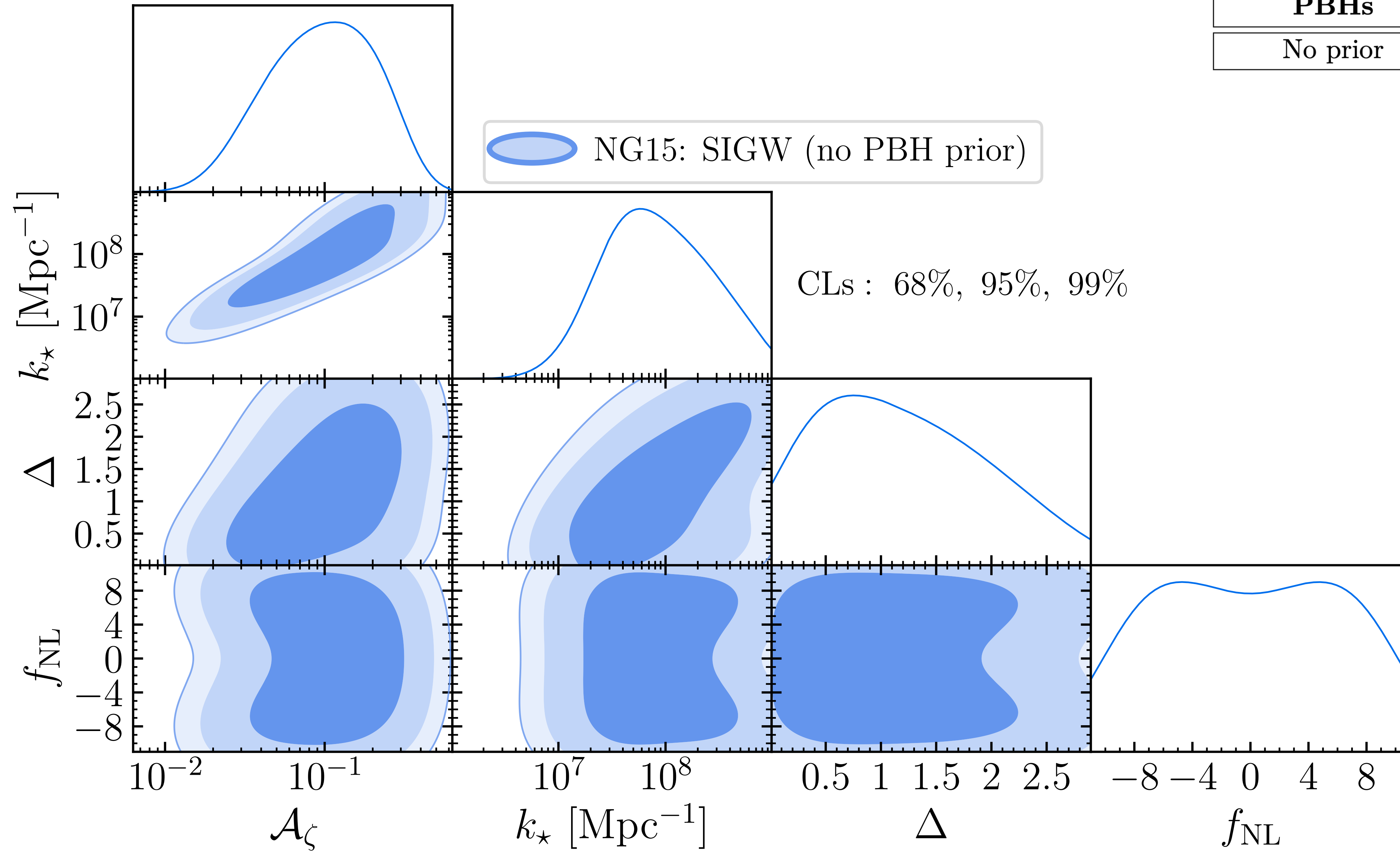




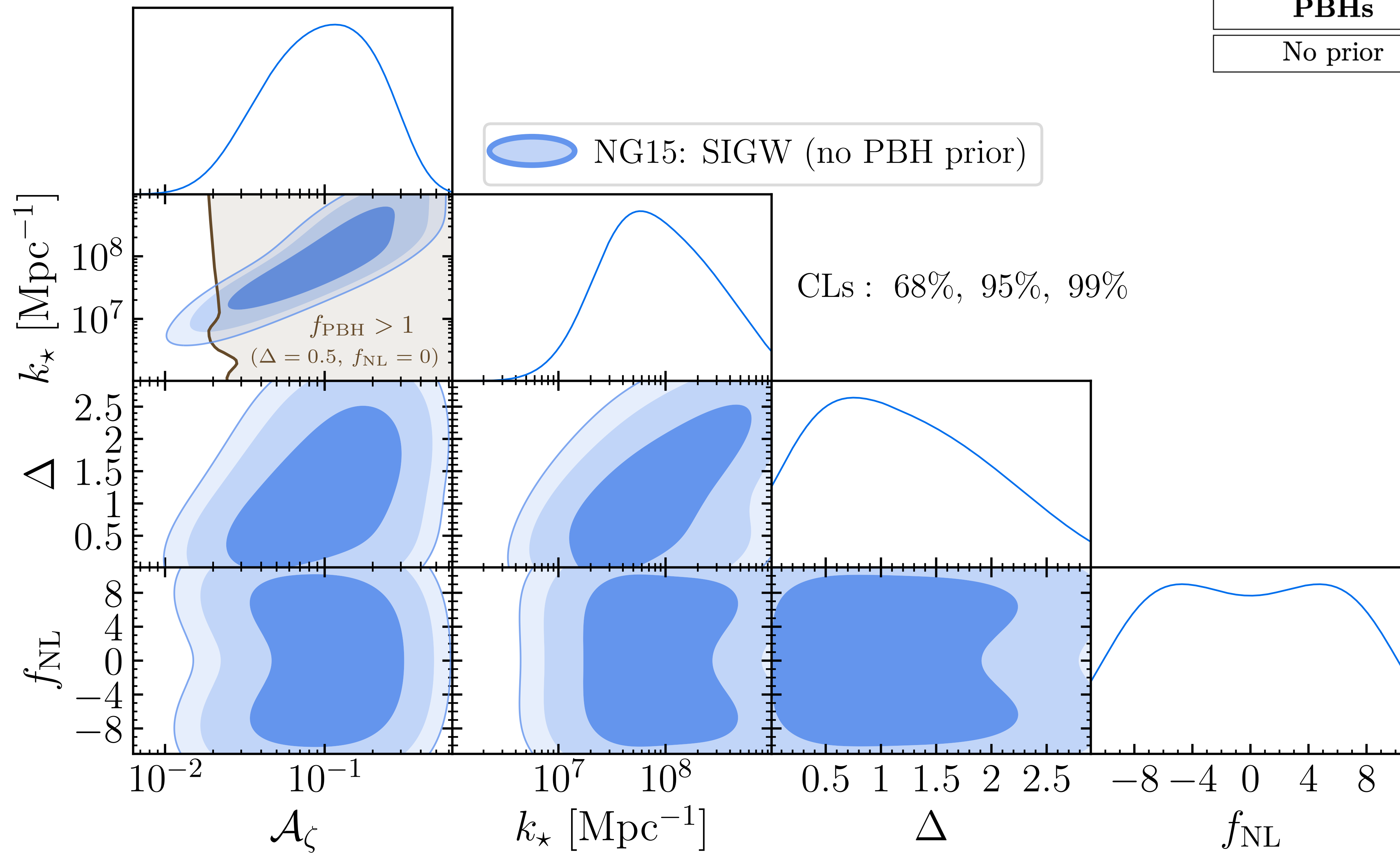


Prior on PBHs		Model X = SMBH only	Model Y	$\text{Log}_{10} \mathcal{B}_{Y,X} (\pm 0.10)$			
				Threshold statistics			Peak theory
				$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$	$ f_{\text{NL}} < 10$	
No prior		free amplitude	SIGW	1.67	1.74	1.74	1.67
			SIGW+SMBH	1.57	1.64	1.64	1.57
		GWOnly-Ext	SIGW	2.17	2.28	2.33	2.17
			SIGW+SMBH	2.05	2.16	2.22	2.05
Astrophysical		free amplitude	SIGW	−1.46	−0.70	−1.33	−3.34
			SIGW+SMBH	−0.08	−0.01	−0.11	−0.10
		GWOnly-Ext	SIGW	−0.90	−0.14	−0.75	−2.78
			SIGW+SMBH	0.05	0.20	0.06	−0.01
Sub-solar	CE	free amplitude	SIGW	−0.01	0.77	0.07	−2.20
			SIGW+SMBH	0.34	0.81	0.32	0.05
		GWOnly-Ext	SIGW	0.55	1.33	0.66	−1.64
			SIGW+SMBH	0.72	1.31	0.74	0.17
	ET	free amplitude	SIGW	0.16	0.95	0.23	−2.05
			SIGW+SMBH	0.45	0.96	0.42	0.09
		GWOnly-Ext	SIGW	0.72	1.51	0.82	−1.49
			SIGW+SMBH	0.86	1.48	0.87	0.23
	LVK O5	free amplitude	SIGW	0.62	1.40	0.69	−1.50
			SIGW+SMBH	0.74	1.36	0.72	0.20
		GWOnly-Ext	SIGW	1.18	1.96	1.28	−0.94
			SIGW+SMBH	1.21	1.90	1.25	0.37
	LVK O4	free amplitude	SIGW	0.66	1.59	0.79	−1.24
			SIGW+SMBH	0.77	1.52	0.79	0.24
		GWOnly-Ext	SIGW	1.22	2.15	1.37	−0.68
			SIGW+SMBH	1.27	2.06	1.33	0.40

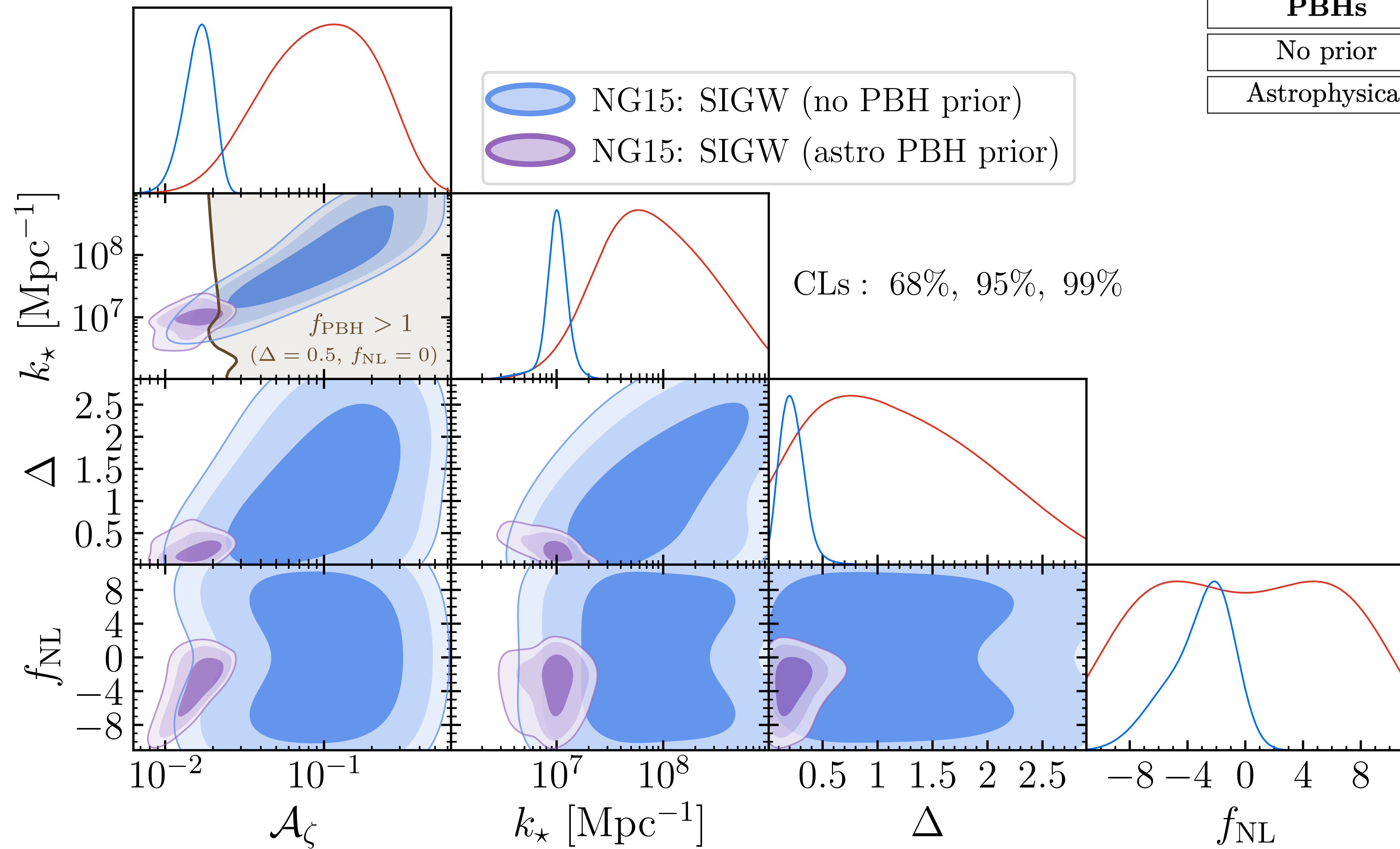
Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28

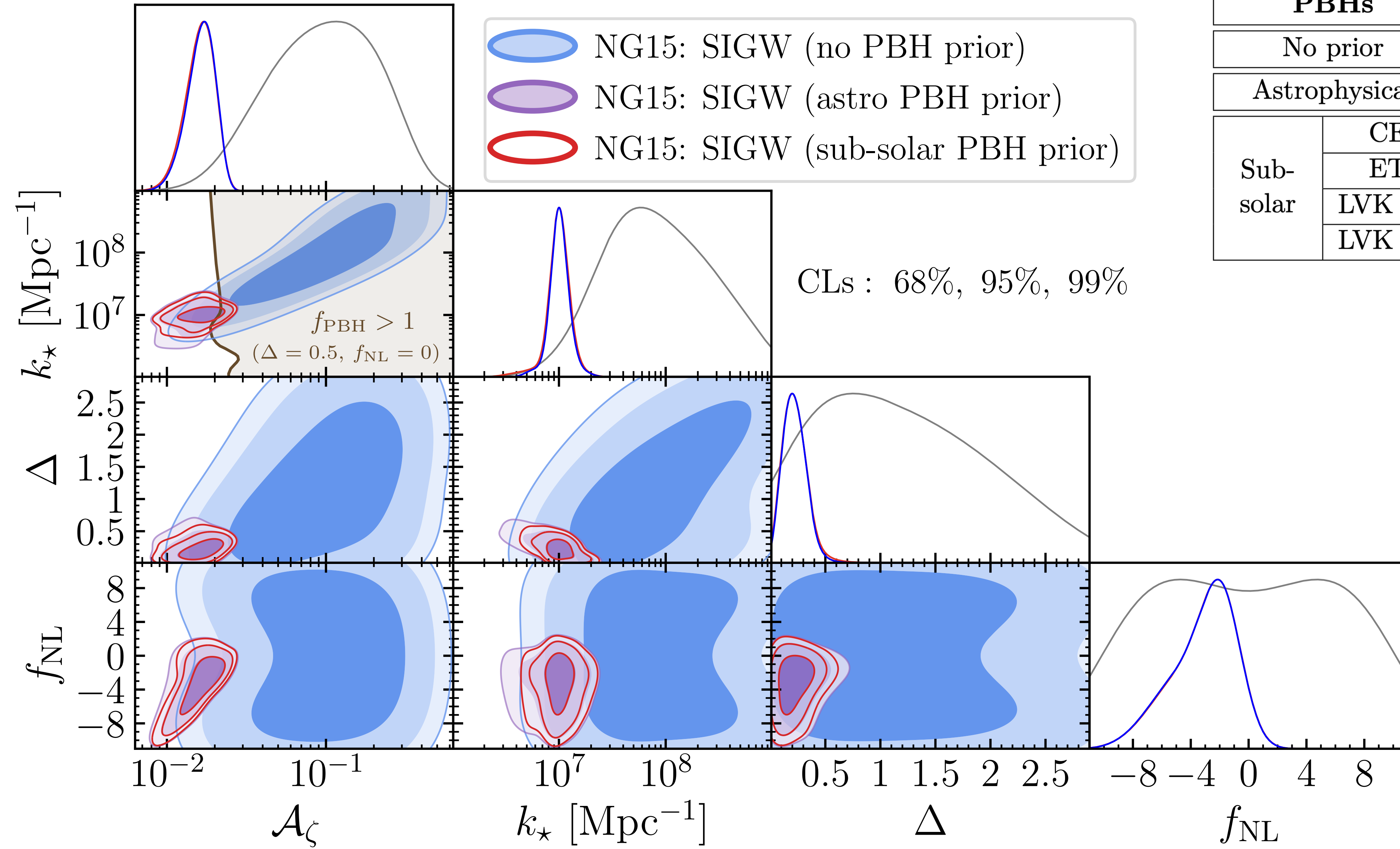


Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28

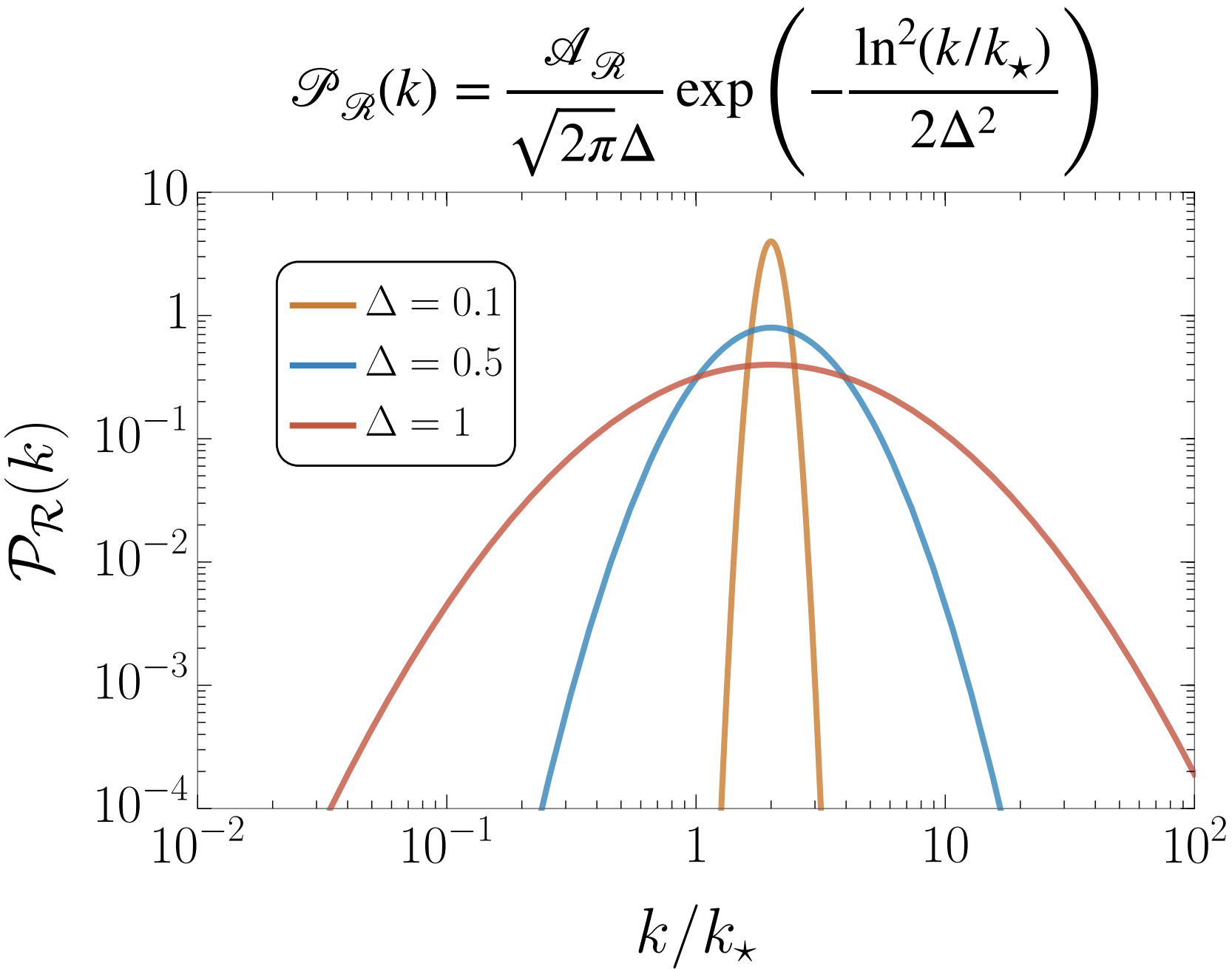


Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28
Astrophysical	-0.90	-0.14





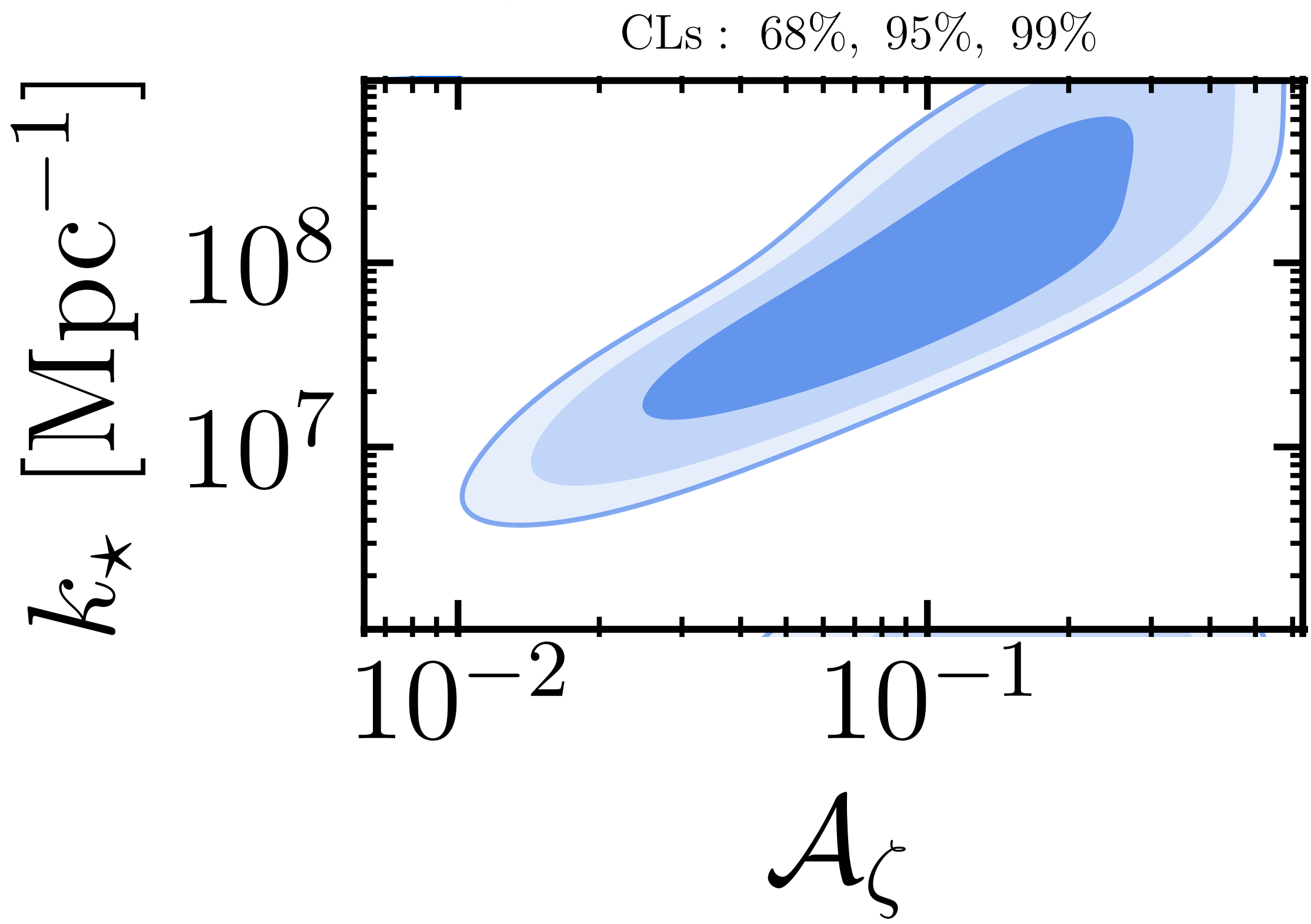
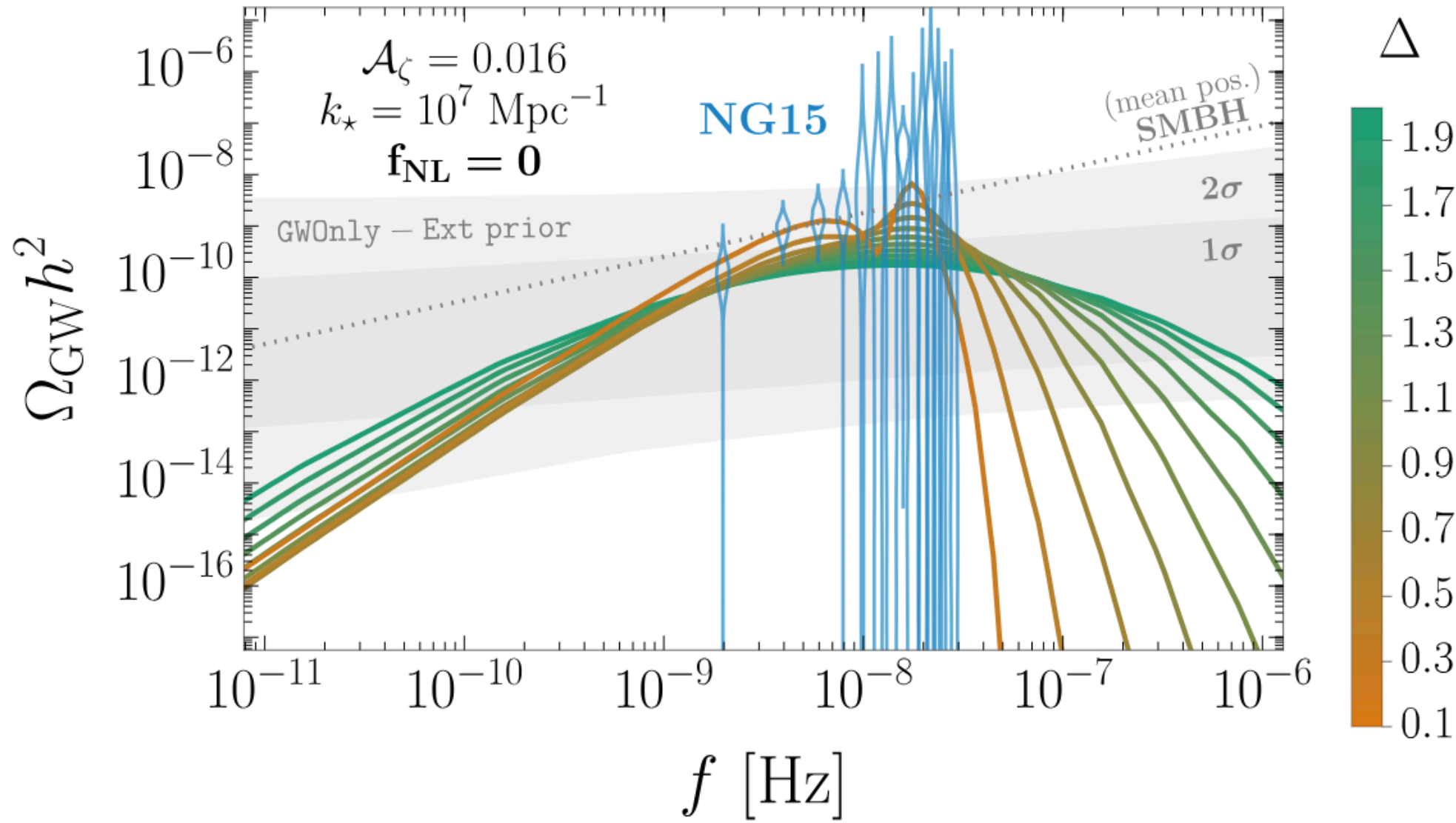
Prior on PBHs		SIGW / SMBH	
		$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior		2.17	2.28
Astrophysical		−0.90	−0.14
Sub-solar	CE	0.55	1.33
	ET	0.72	1.51
	LVK O5	1.18	1.96
	LVK O4	1.22	2.15



$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

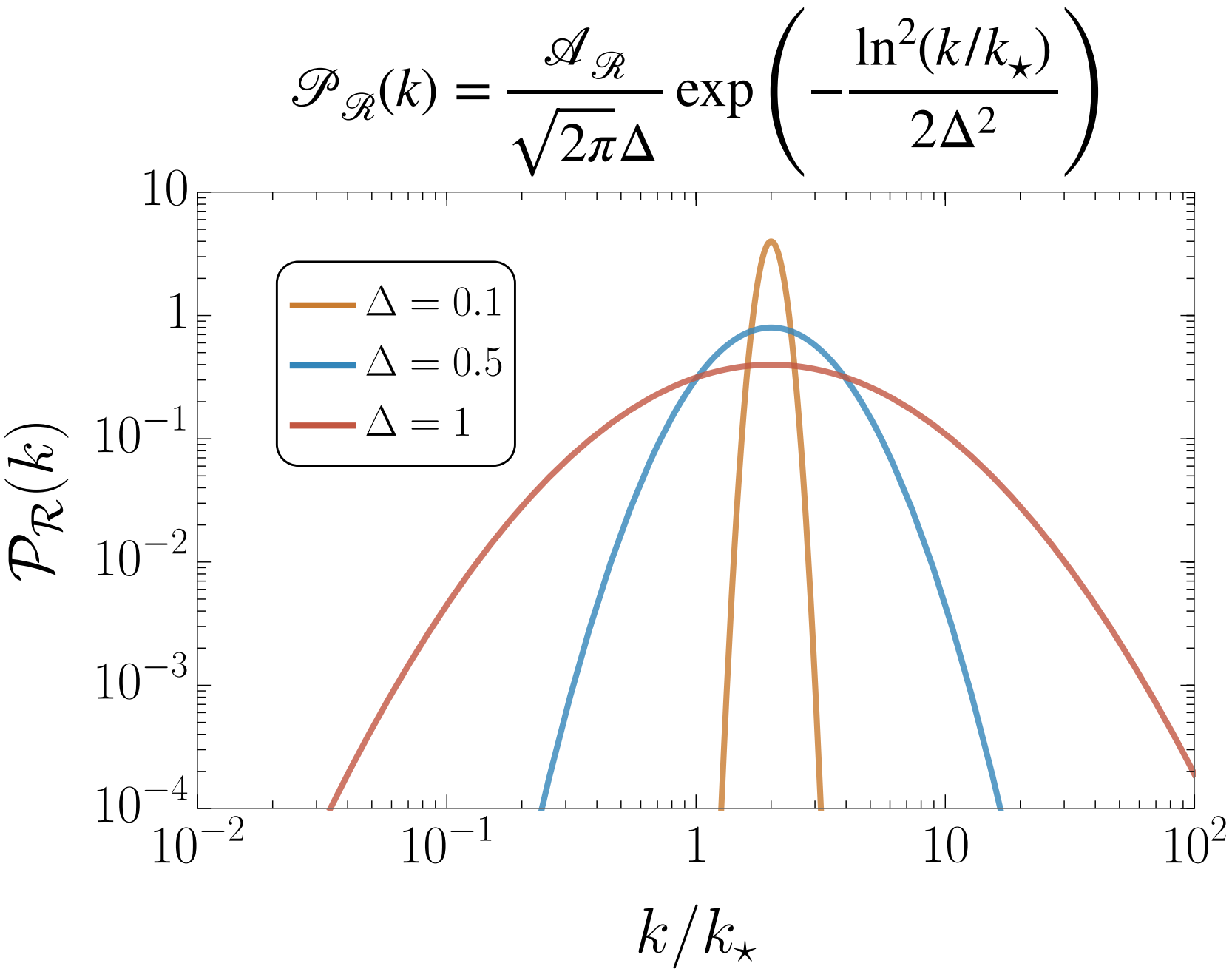
→

Scalar induced GW



NG15: SIGW (no PBH prior)

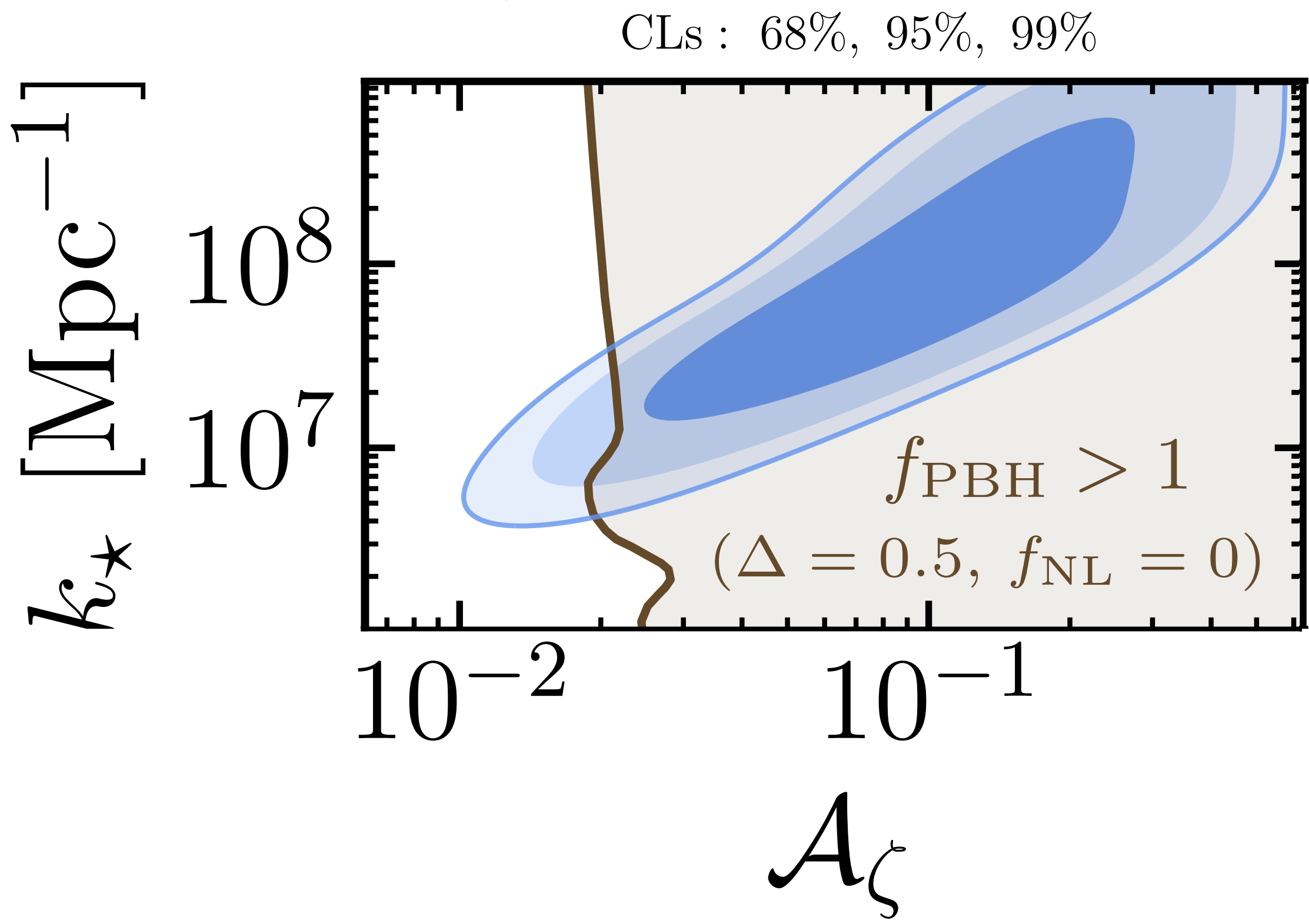
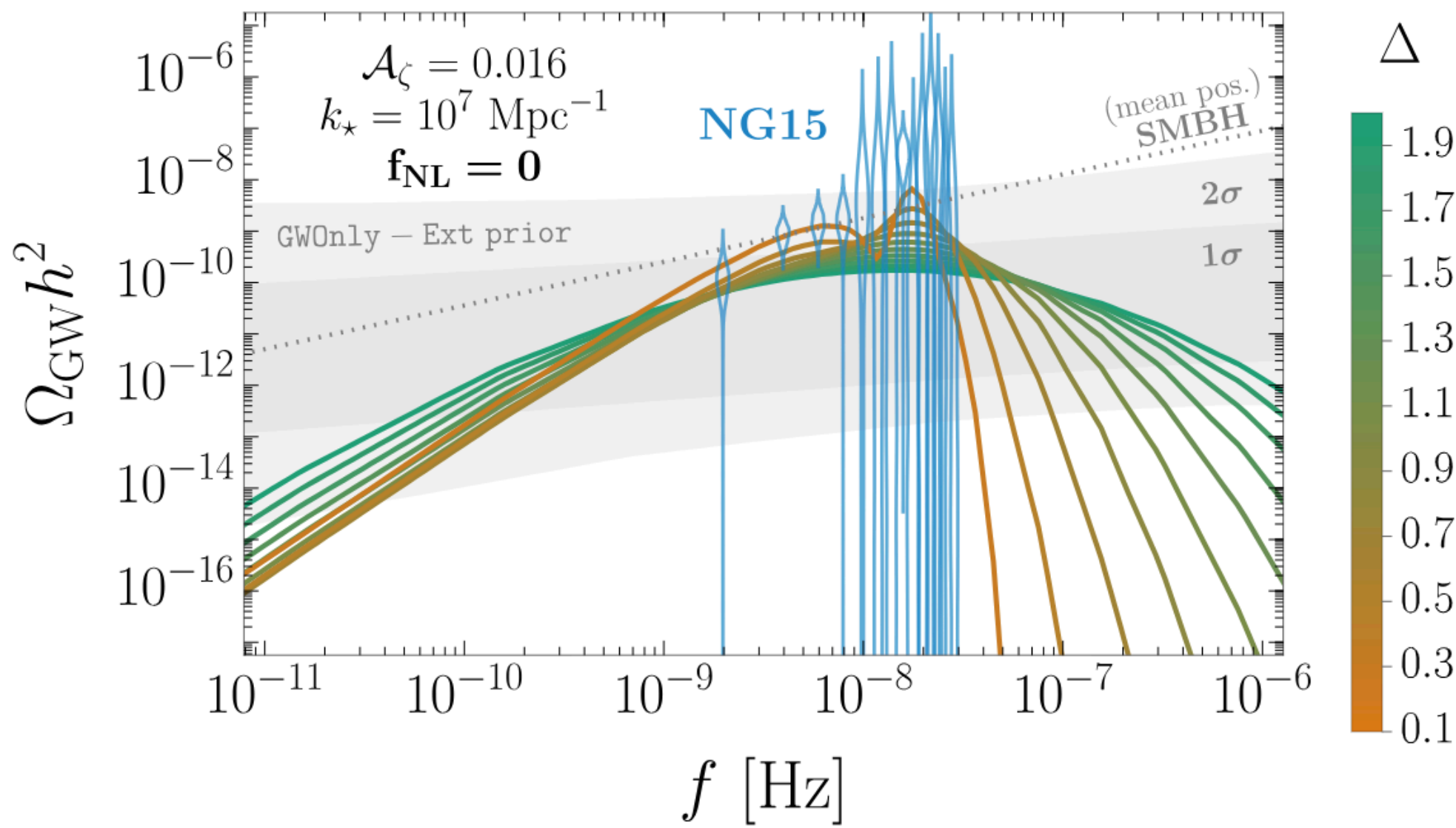
Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28



$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

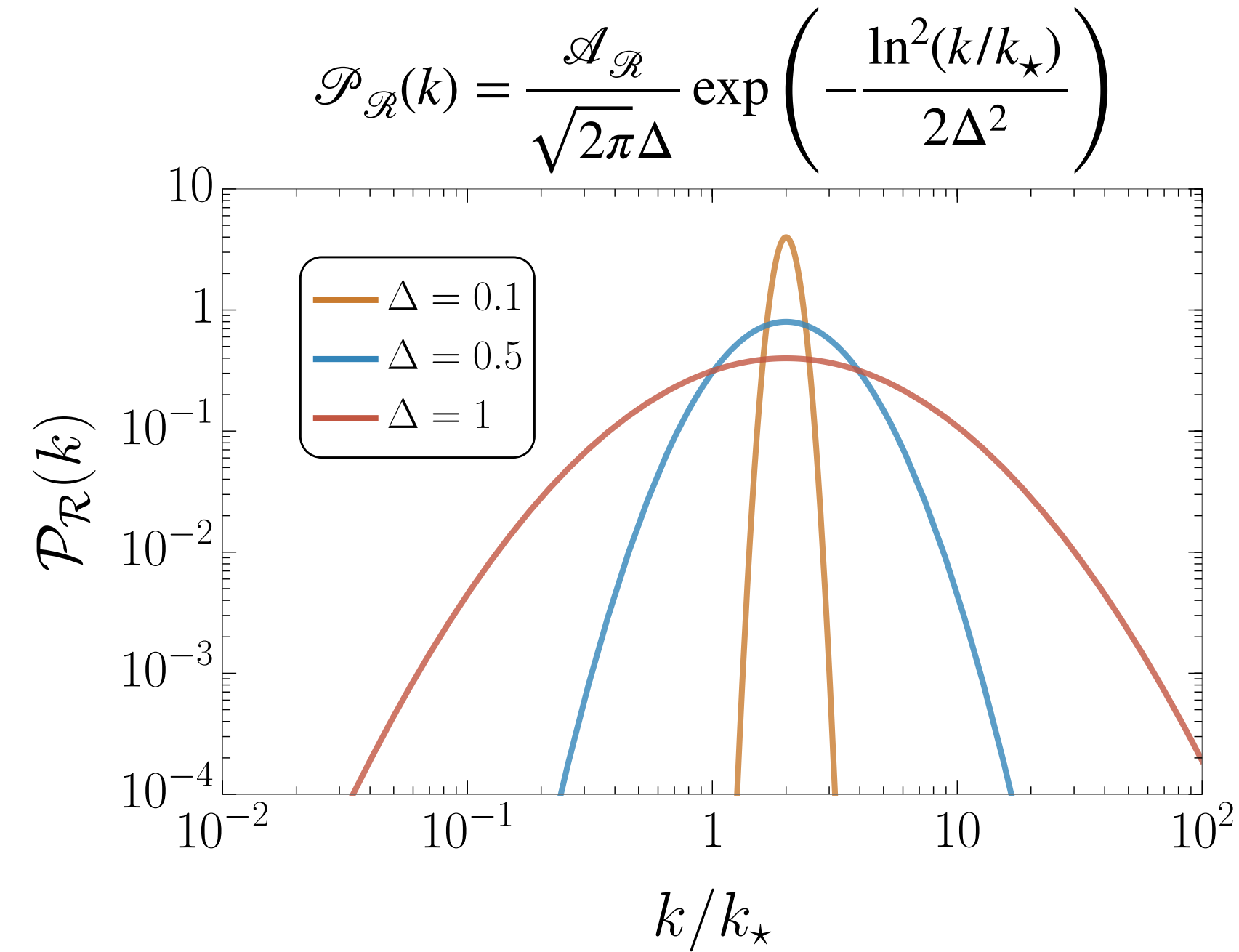
→

Scalar induced GW



NG15: SIGW (no PBH prior)

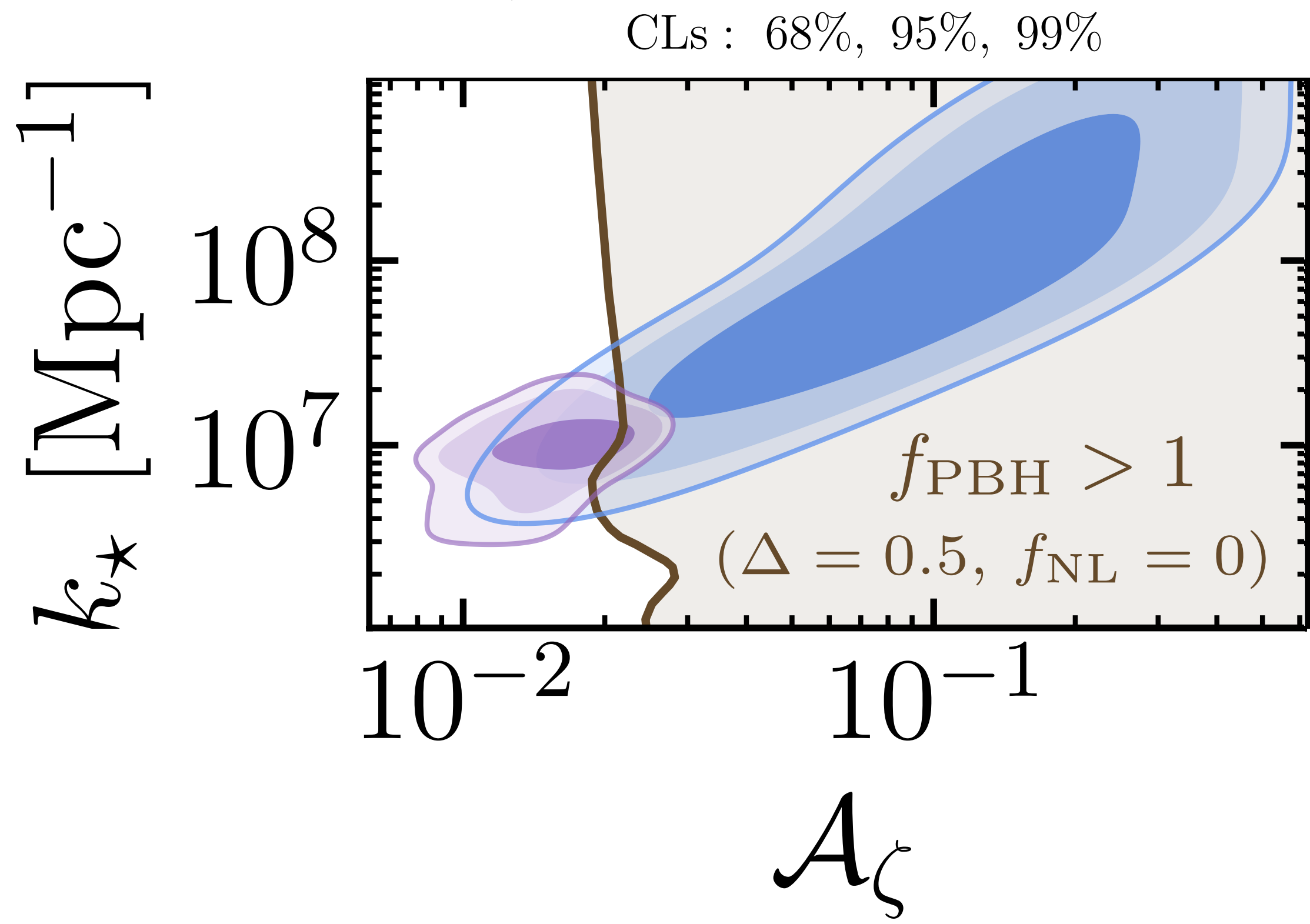
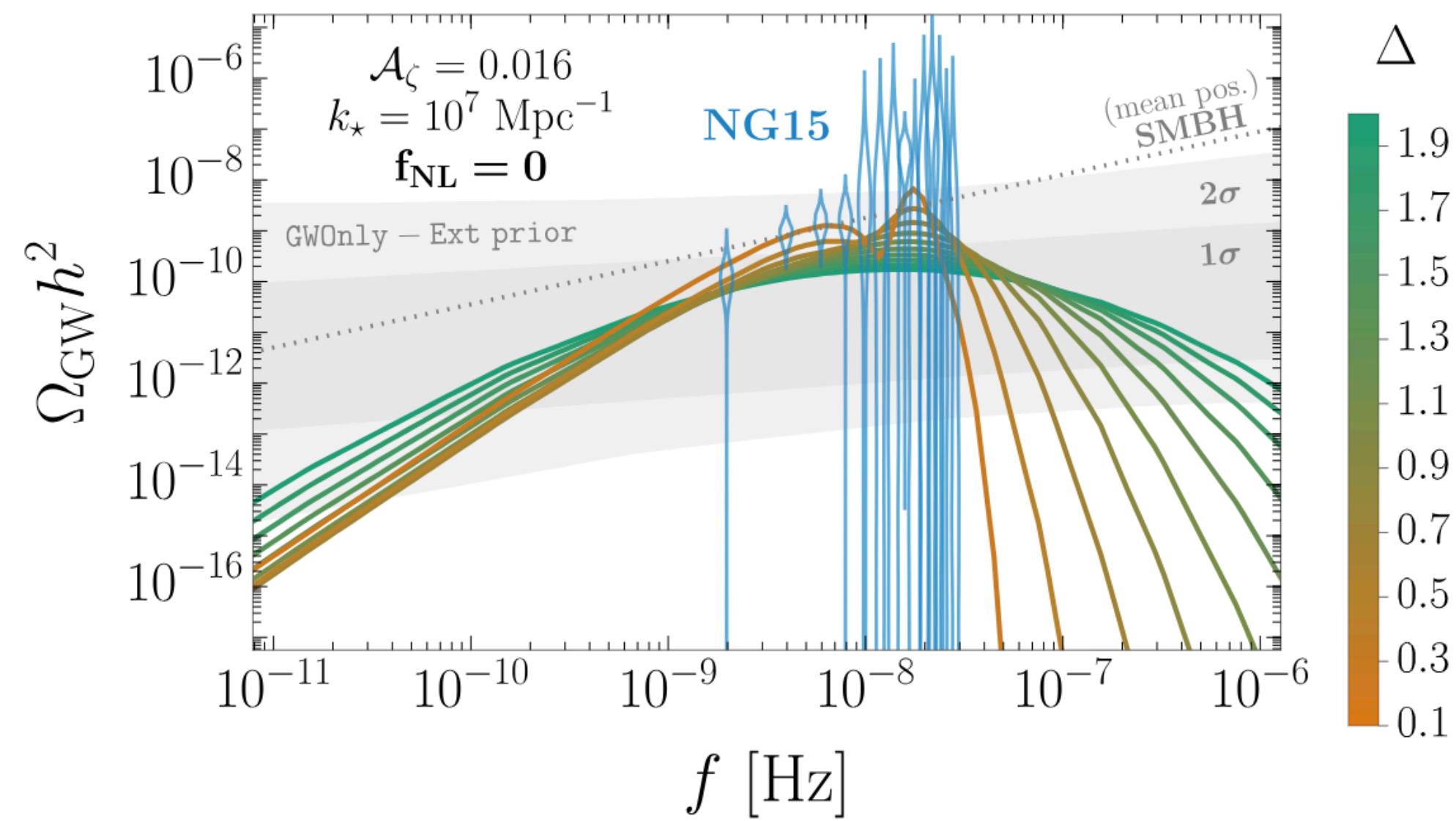
Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28



$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

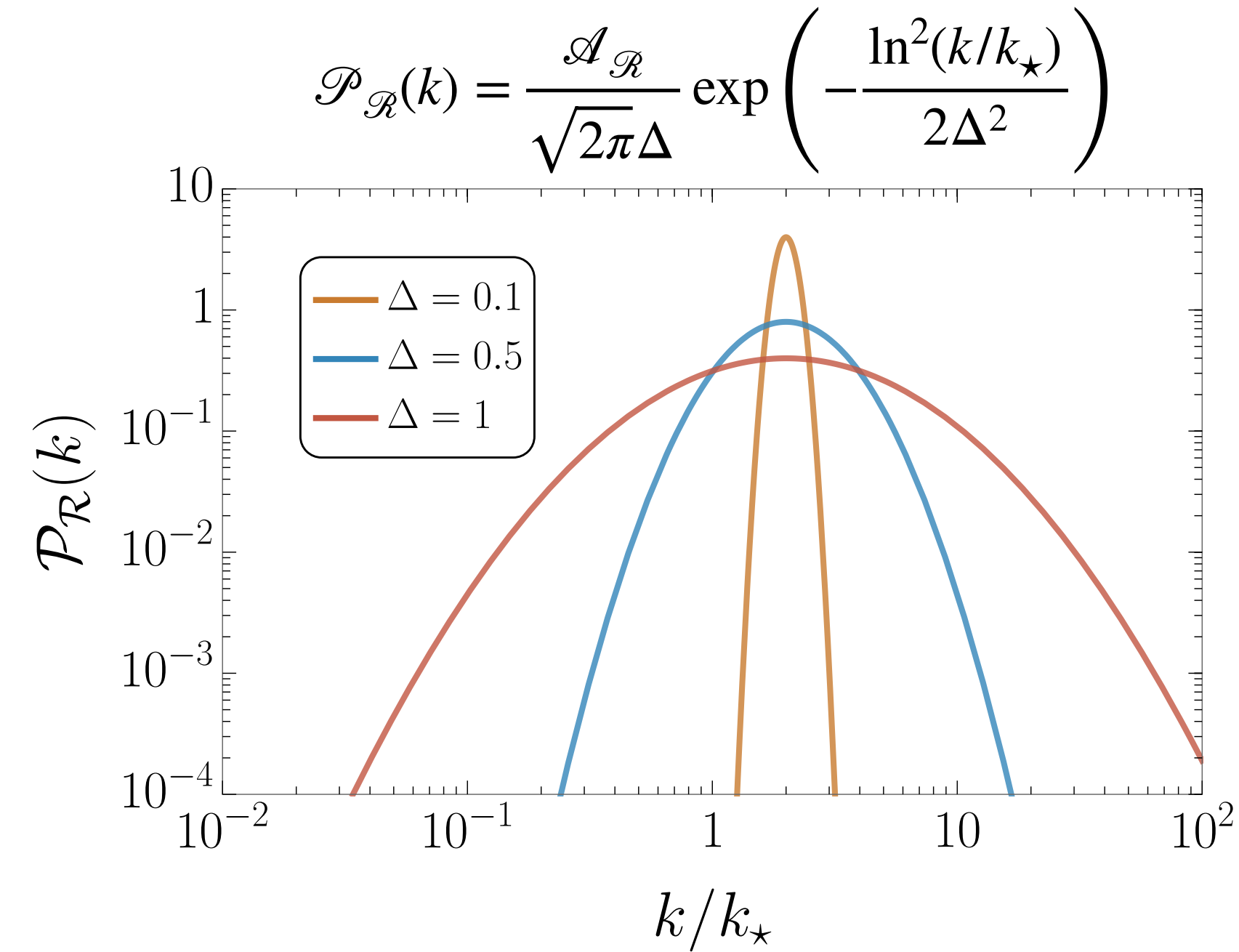
→

Scalar induced GW



- NG15: SIGW (no PBH prior)
- NG15: SIGW (astro PBH prior)

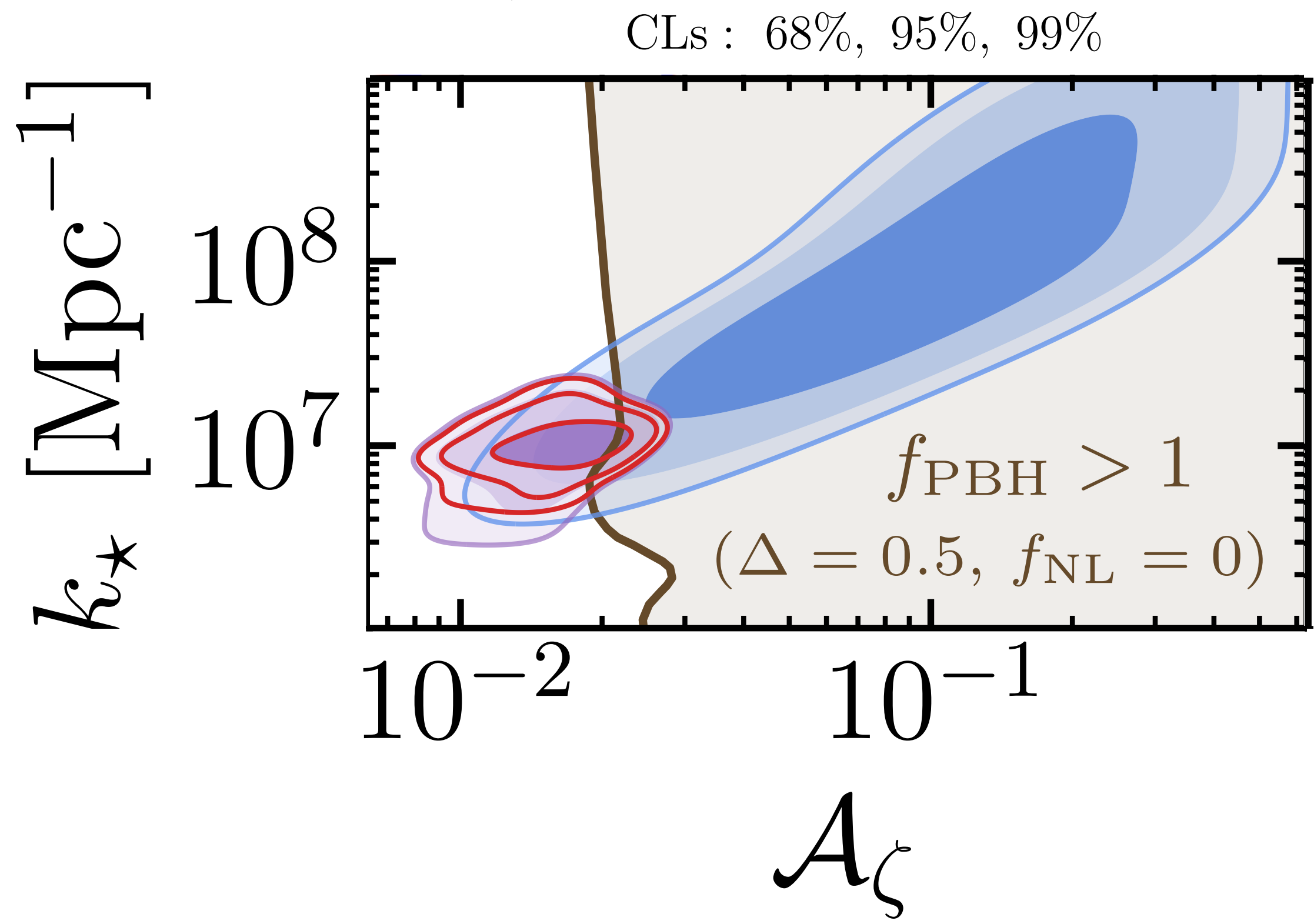
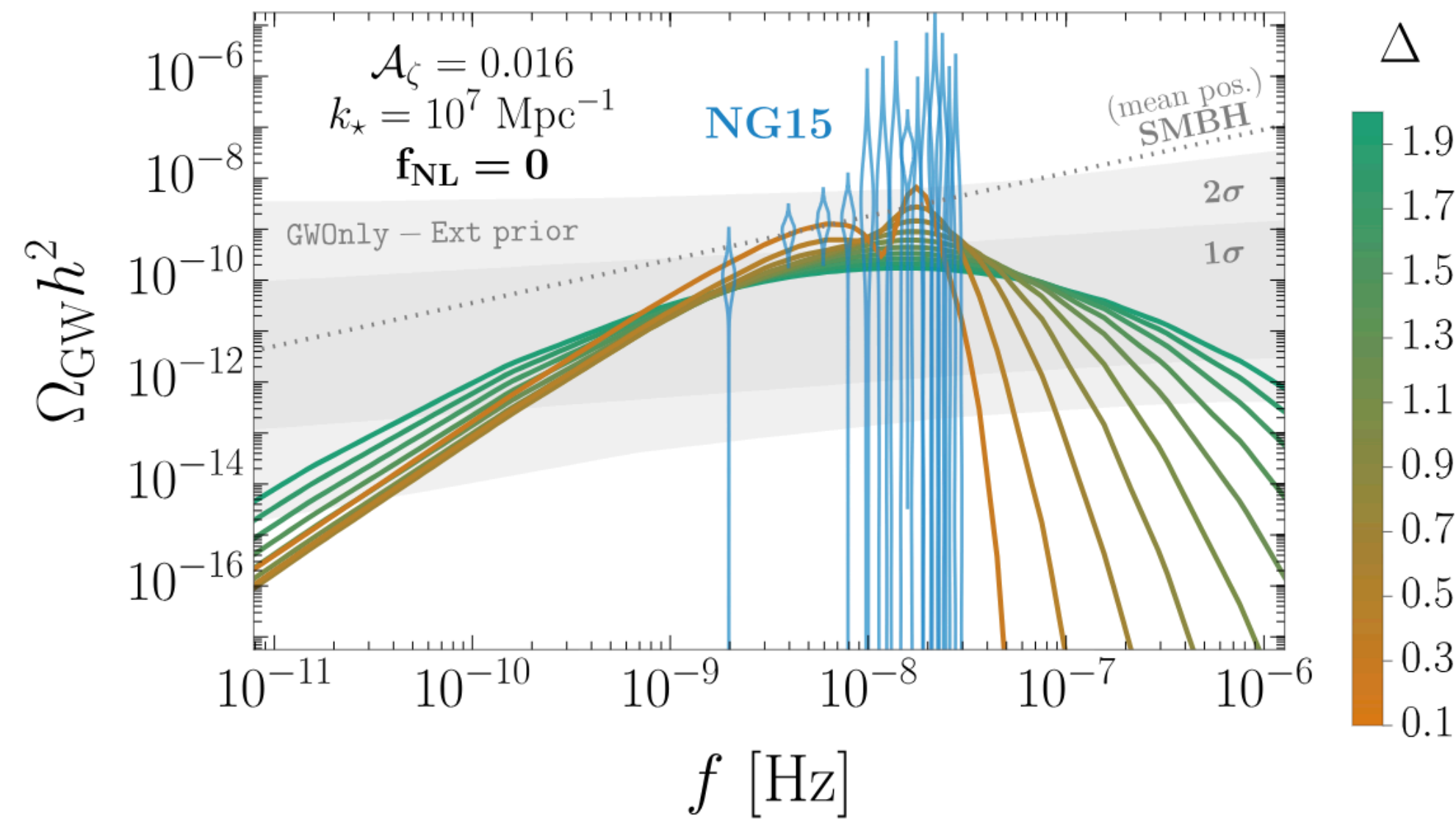
Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28
Astrophysical	-0.90	-0.14



$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

→

Scalar induced GW



- NG15: SIGW (no PBH prior)
- NG15: SIGW (astro PBH prior)
- NG15: SIGW (sub-solar PBH prior)

Prior on PBHs		SIGW / SMBH	
		$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior		2.17	2.28
Astrophysical		-0.90	-0.14
Sub-solar	CE	0.55	1.33
	ET	0.72	1.51
	LVK O5	1.18	1.96
	LVK O4	1.22	2.15