Pulsar timing arrays and Primordial Black Holes

Yann Gouttenoire

1st February 2024

COST Action COSMIC WISPers

Working group meeting

PhD in DESY (2017-2020)

Postdoc in Tel Aviv U. (2021-2024)

Sponsored by

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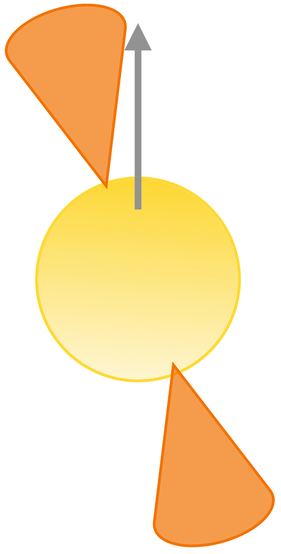

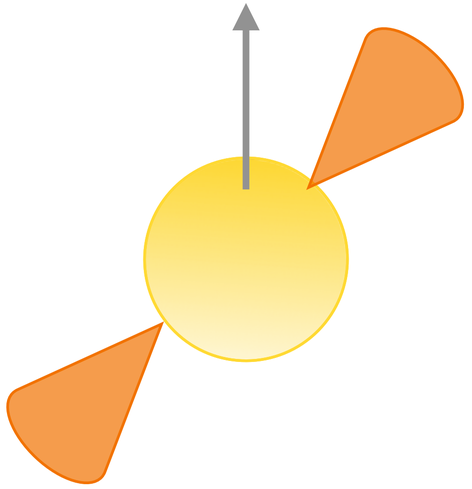

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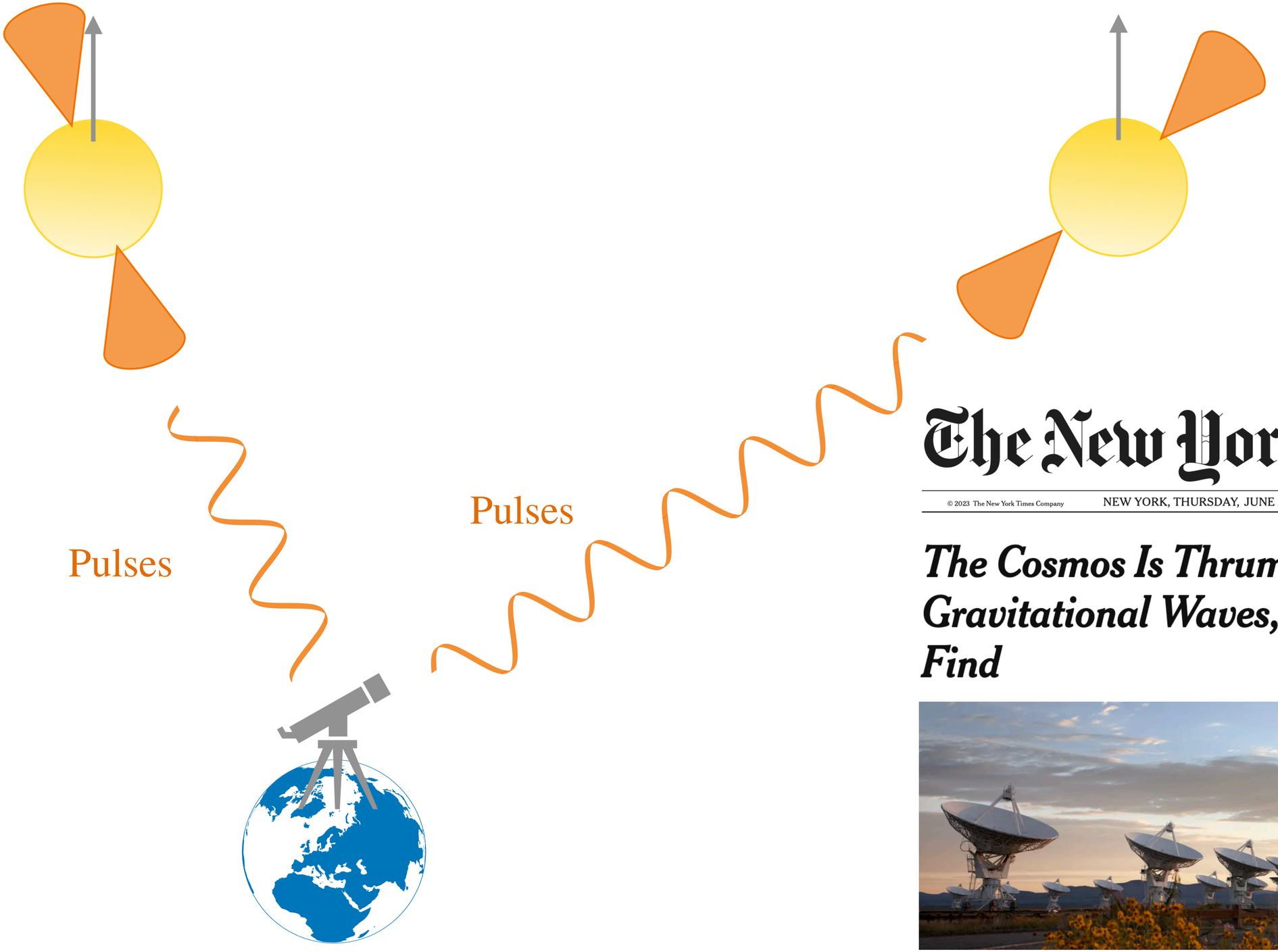
The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find



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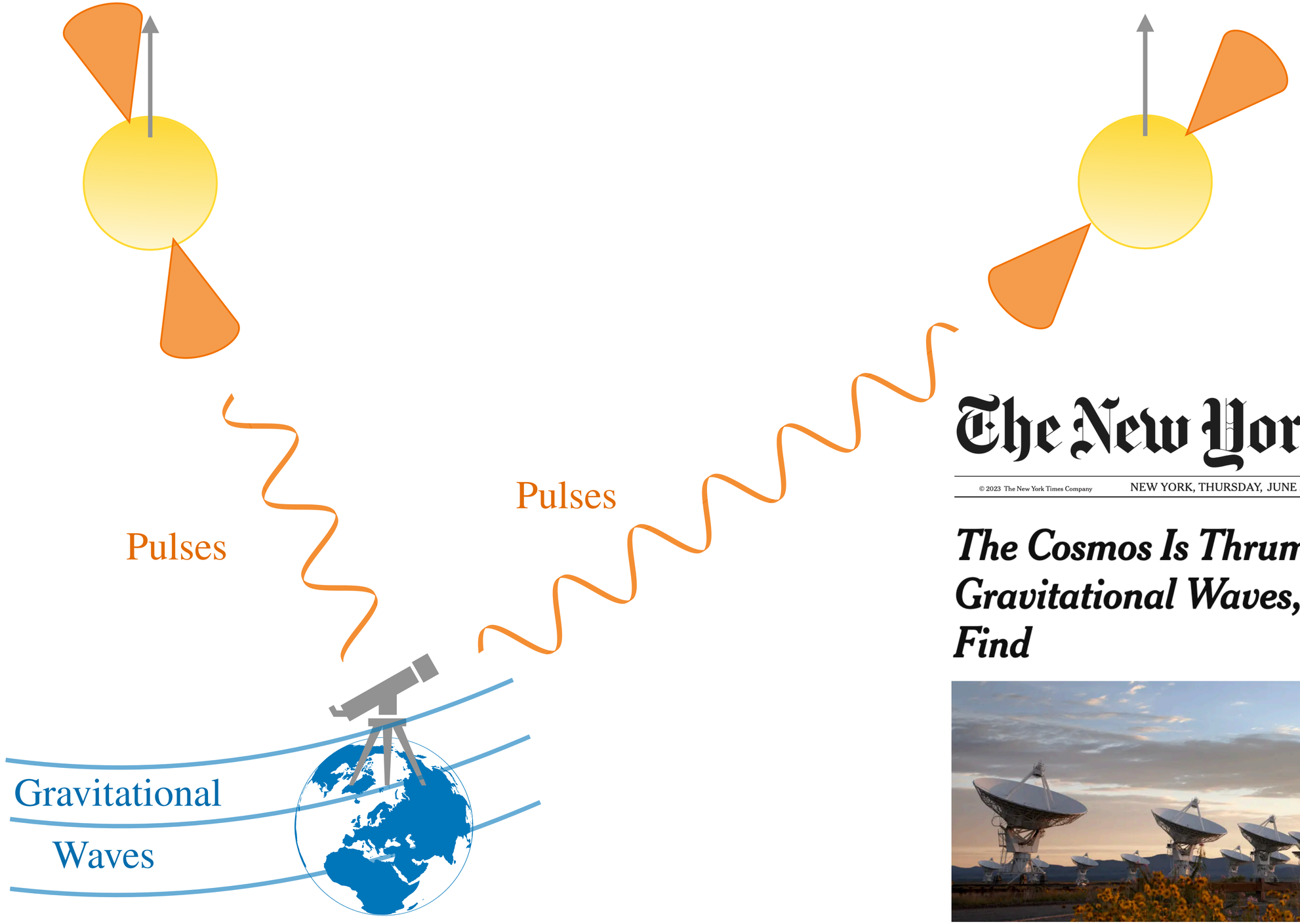

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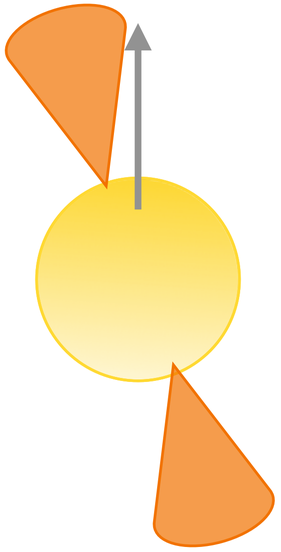

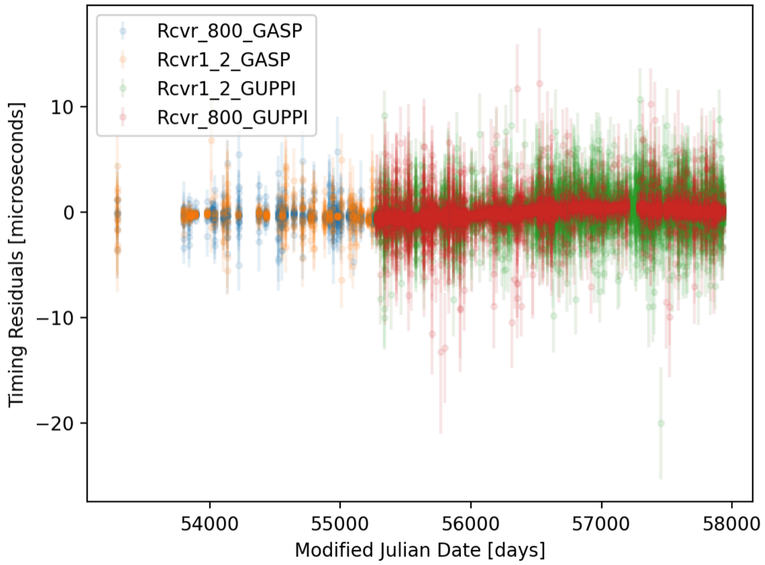

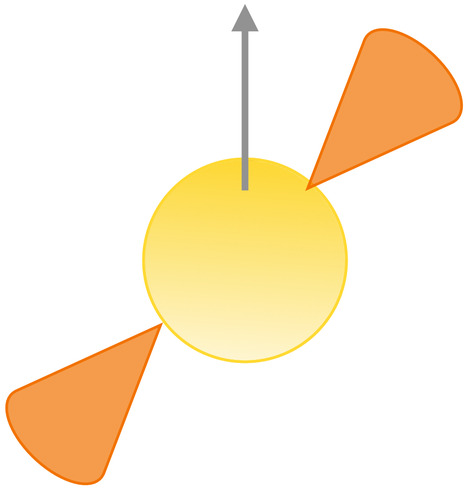

Pulses

Pulses

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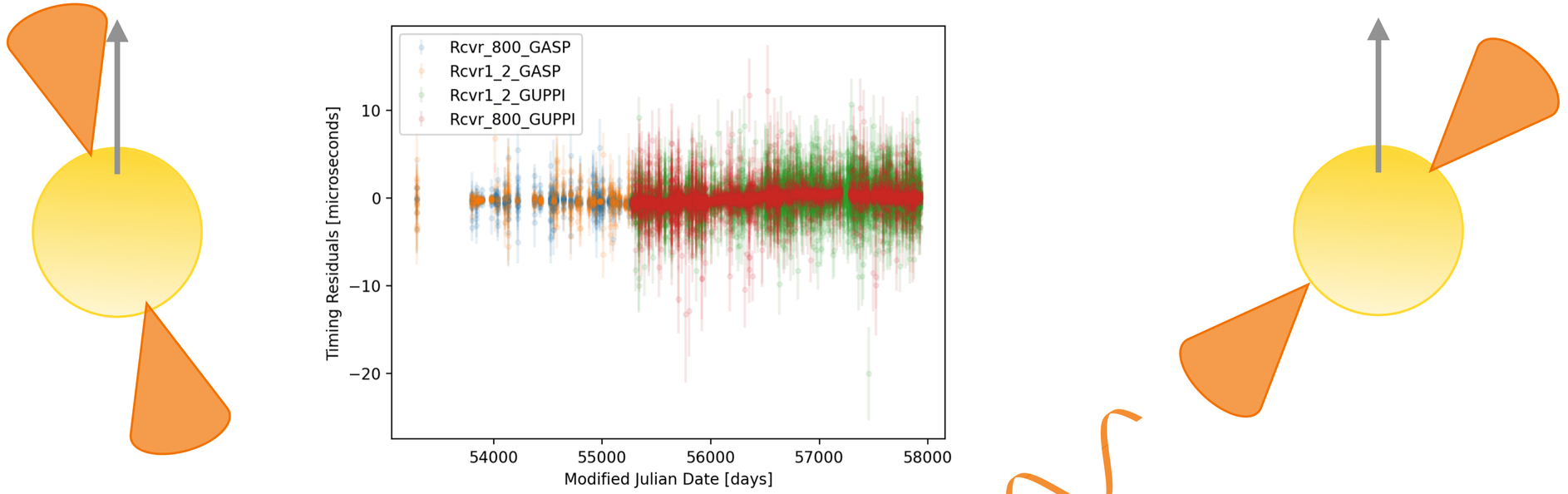


Pulses

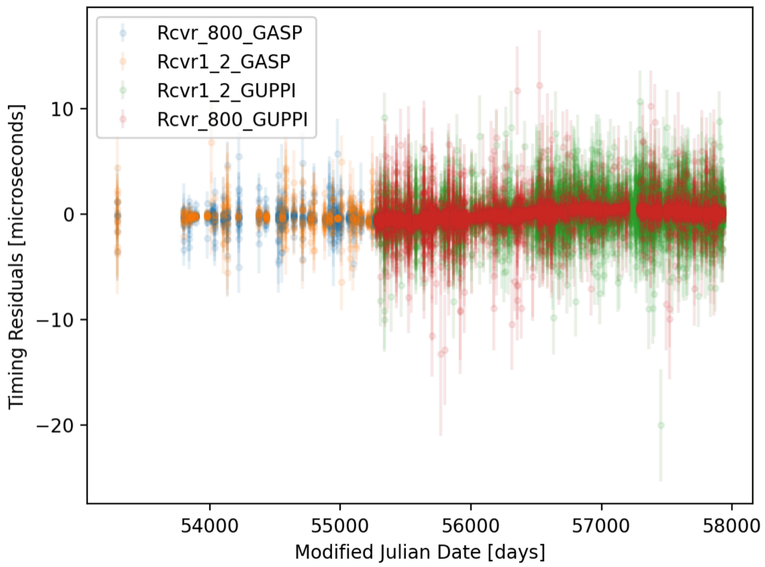
Pulses

Gravitational

Waves

Solar system systematics

Stephen R. Taylor, 2105.13270
The Nanohertz Gravitational Wave Astronomer



Pulses

Pulses

Pulsar companion systematics

Gravitational Waves

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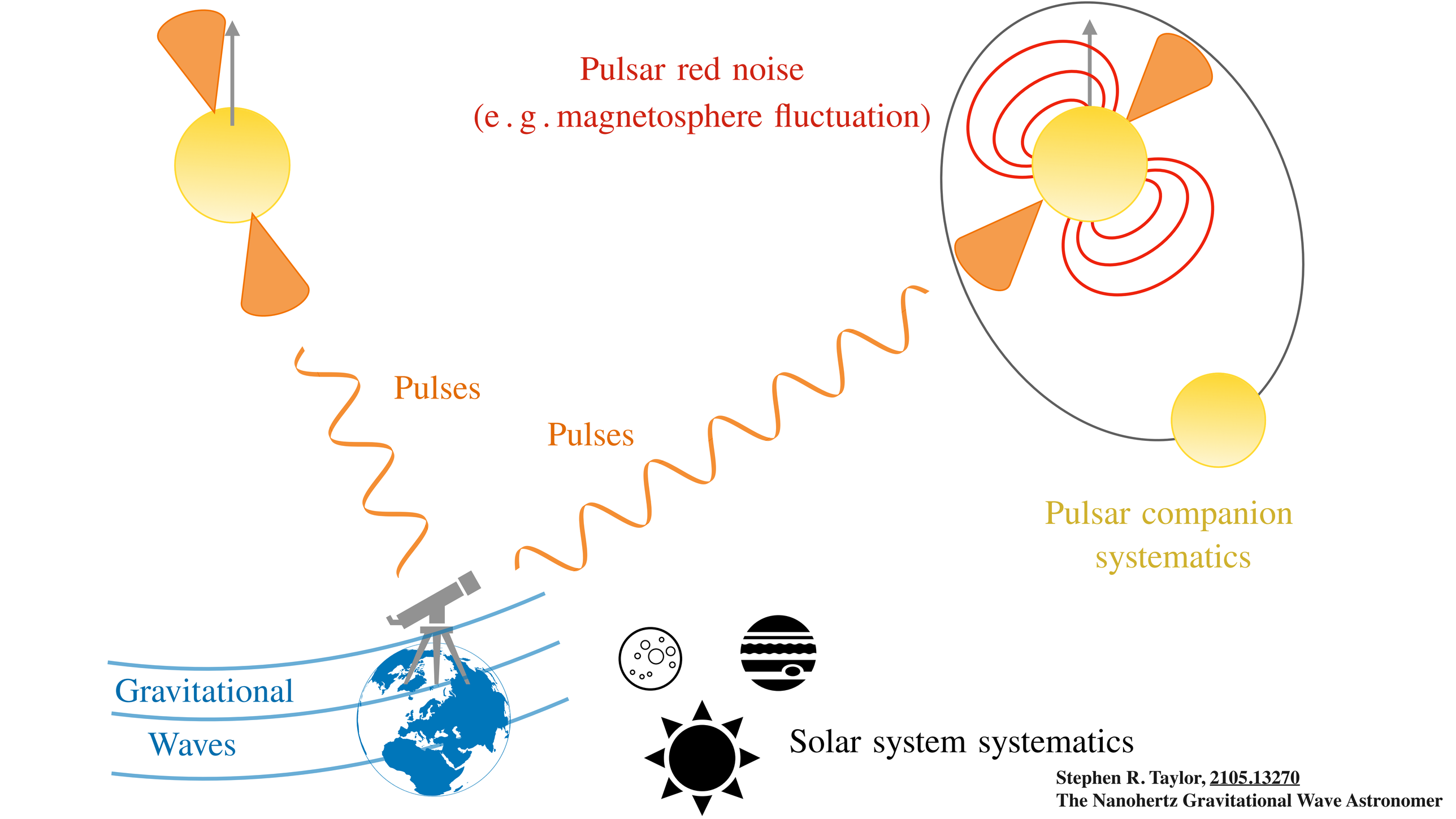

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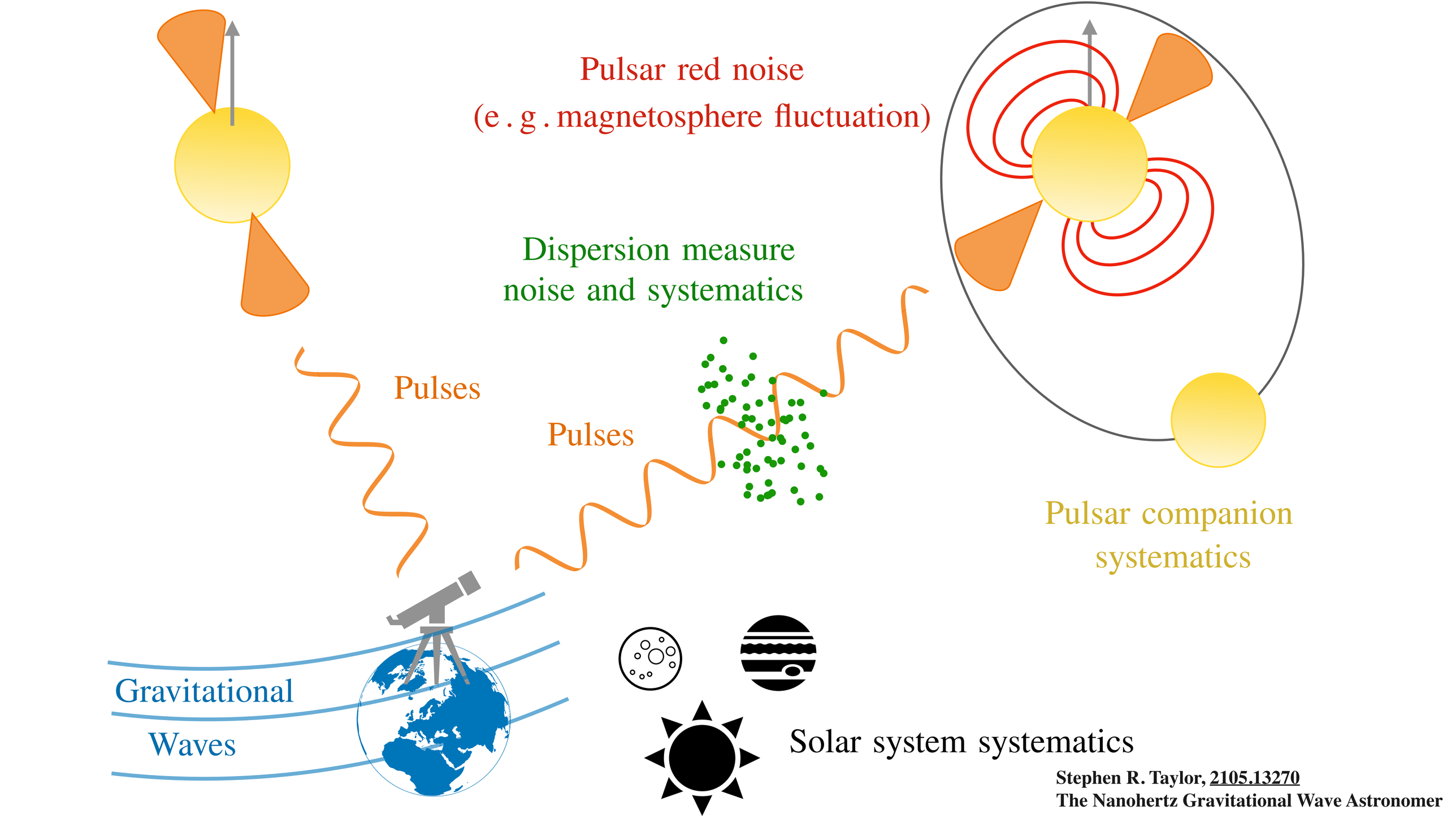

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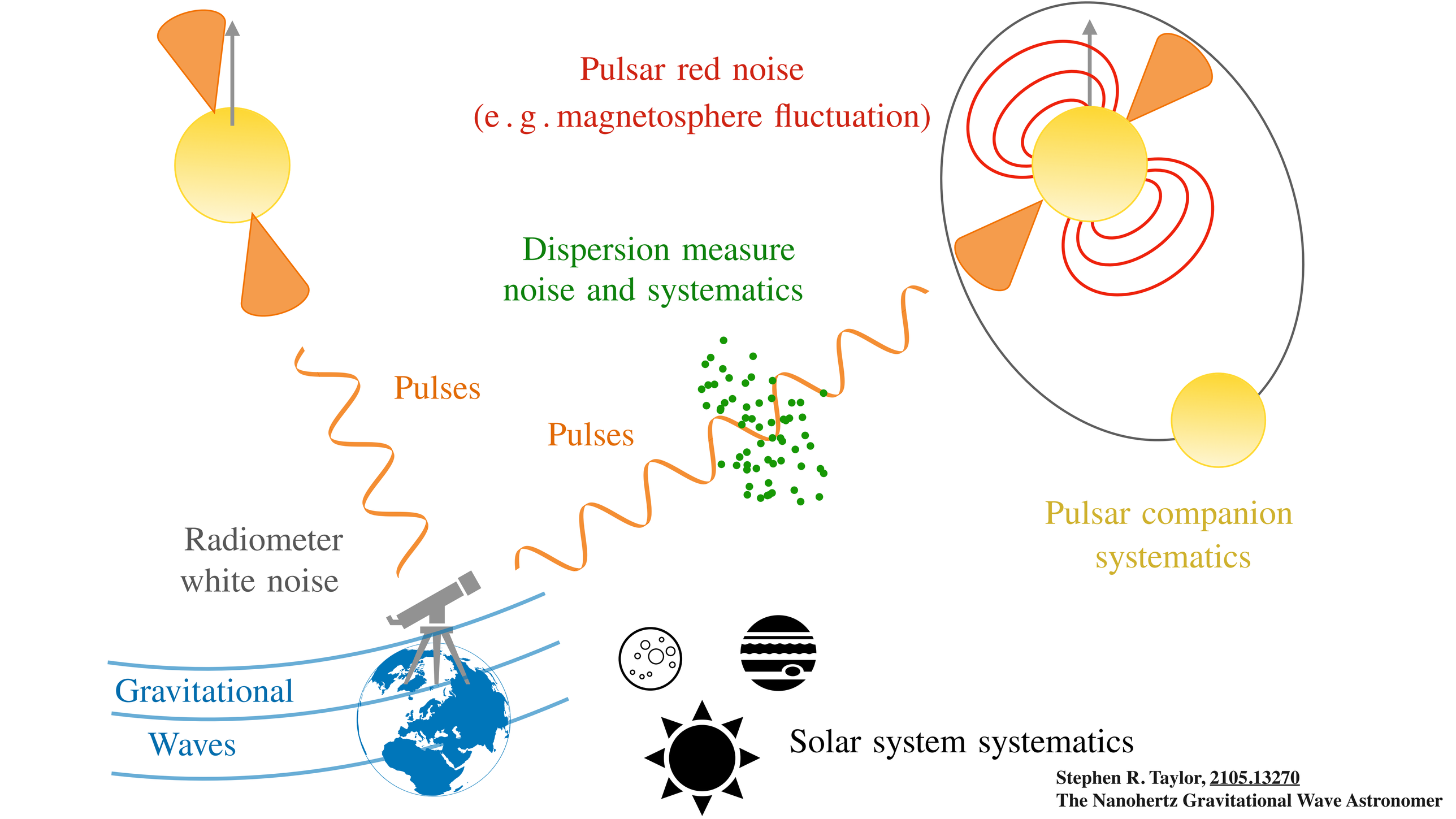

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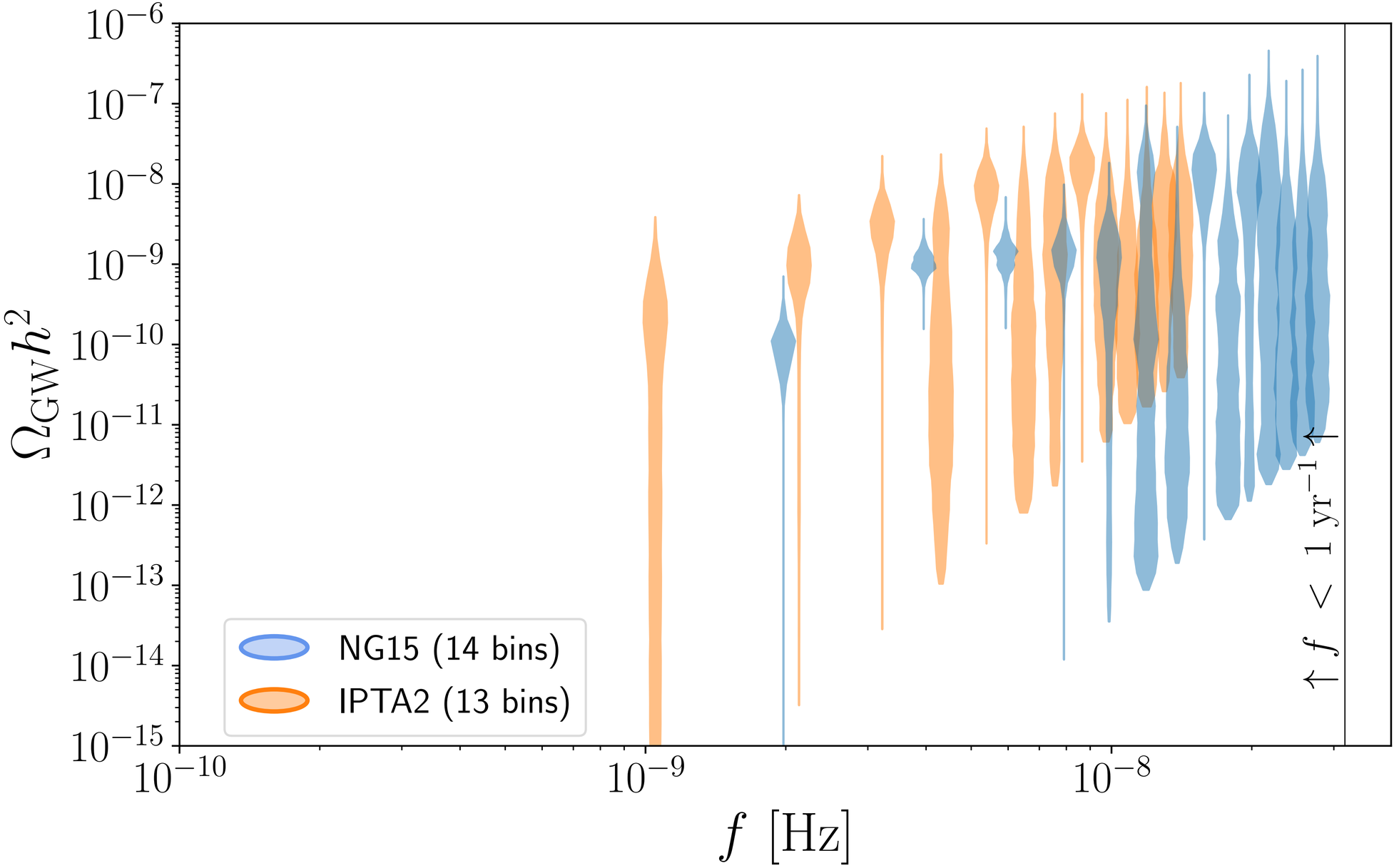
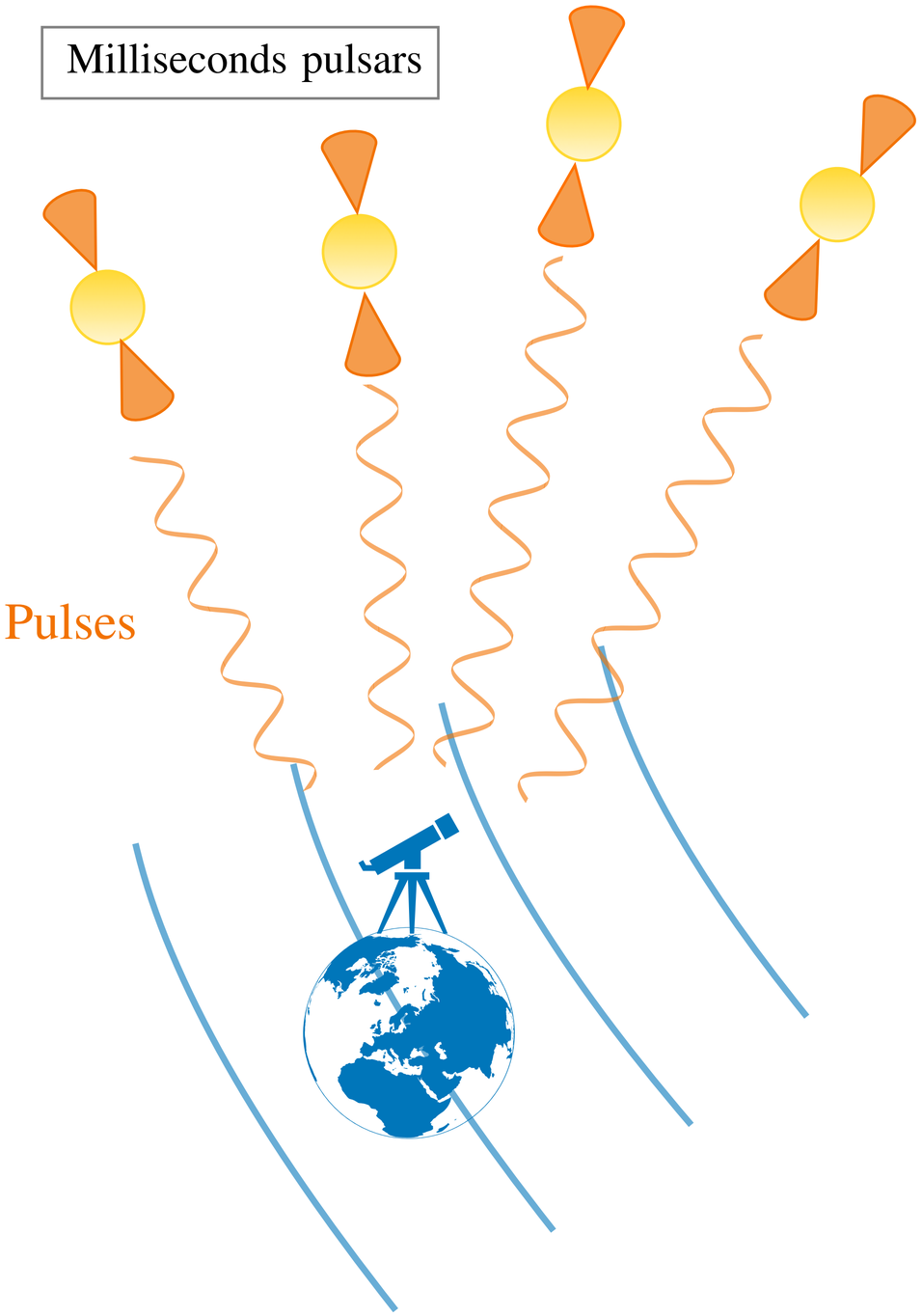
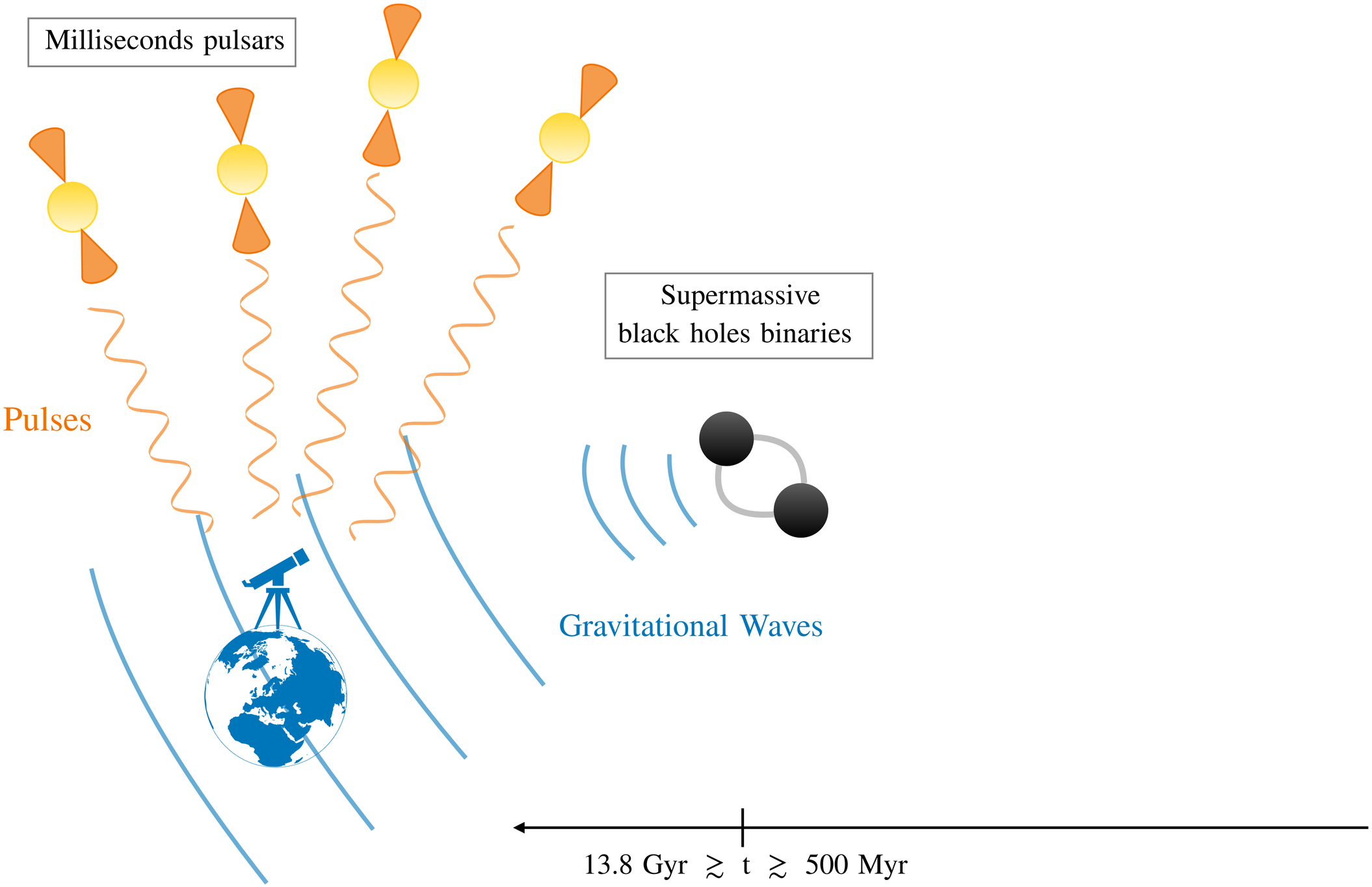
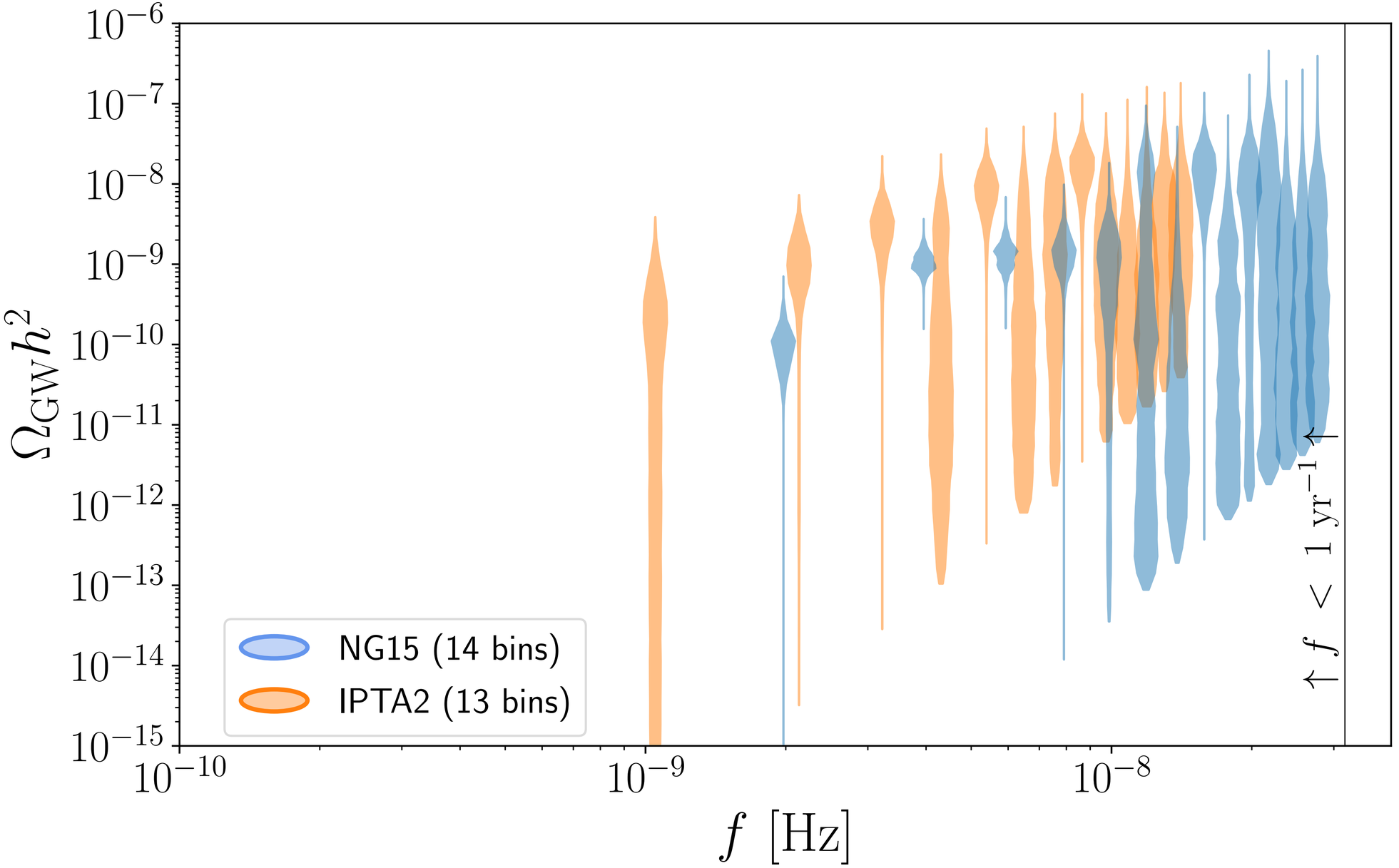

10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$\Omega_{\rm GW}h^2$
10^{-10}
10^{-9}
10^{-8}
f [Hz]
NG15 (14 bins)
IPTA2 (13 bins)
$\uparrow f < 1\ \mathrm{yr}^{-1} \uparrow$


Milliseconds pulsars
Pulses


Milliseconds pulsars
Supermassive
black holes binaries
Pulses
Gravitational Waves
13.8 Gyr ≳ t ≳ 500 Myr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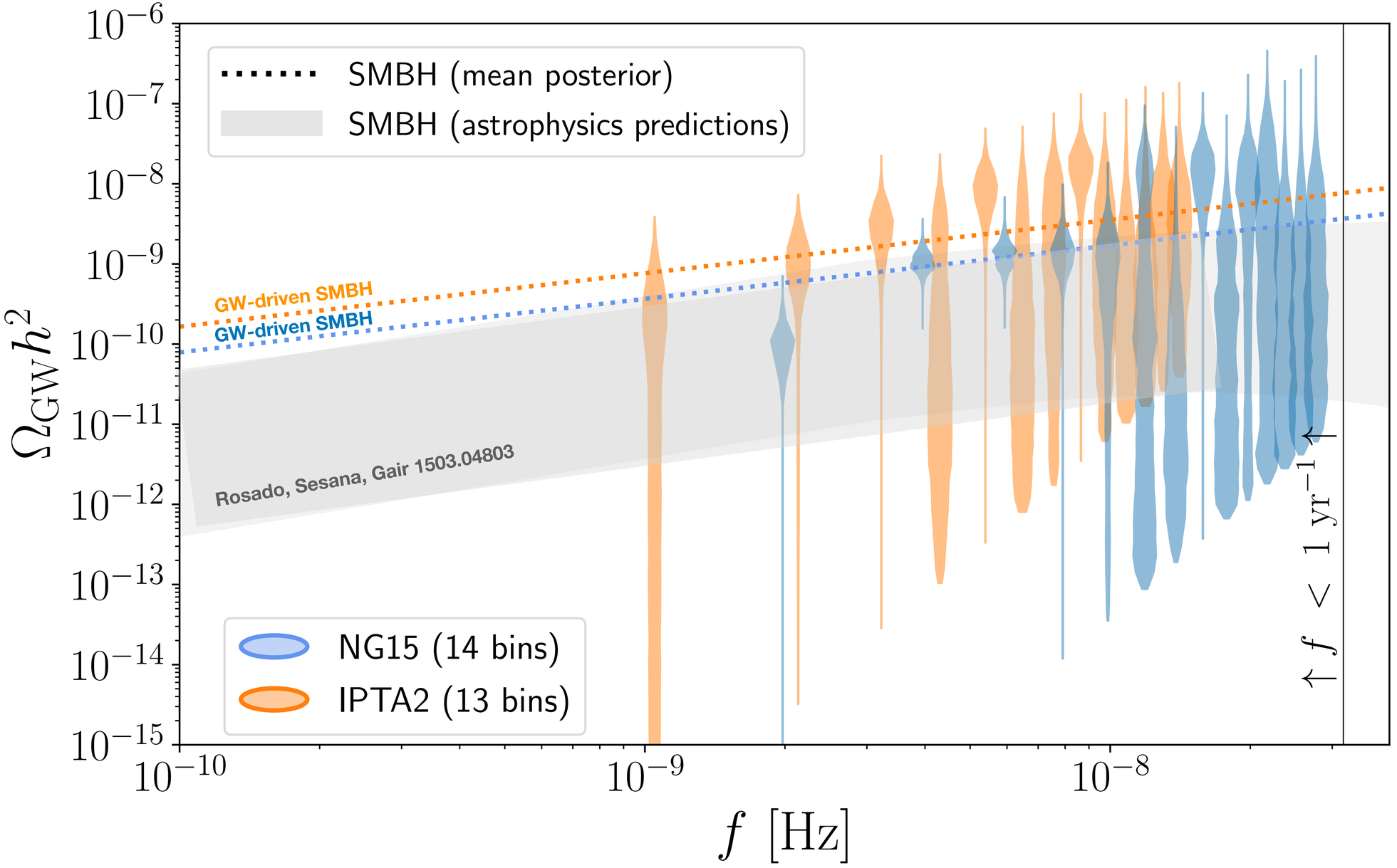
SMBH (mean posterior)
SMBH (astrophysics predictions)
GW-driven SMBH
GW-driven SMBH
Rosado, Sesana, Gair 1503.04803
NG15 (14 bins)
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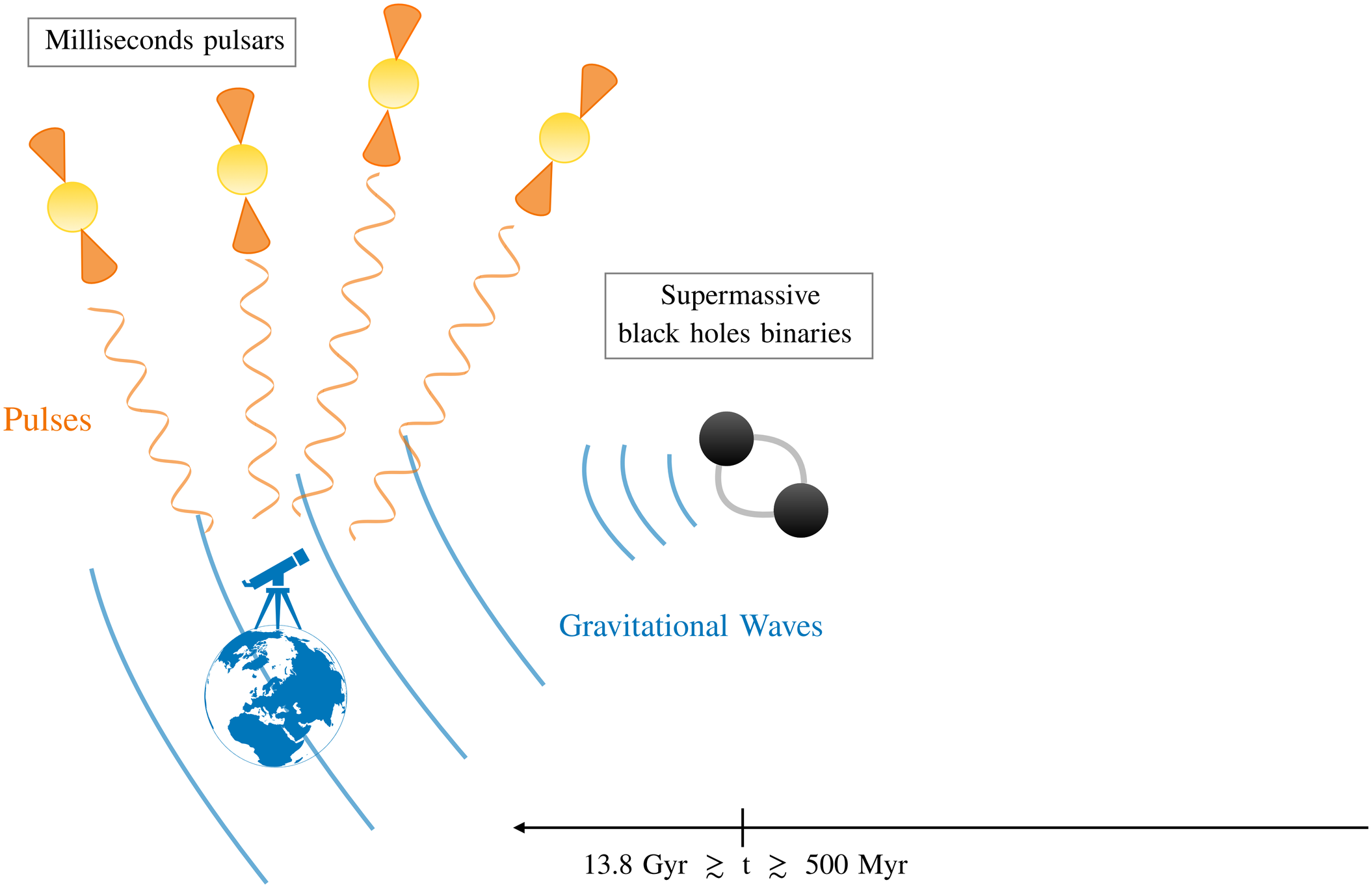
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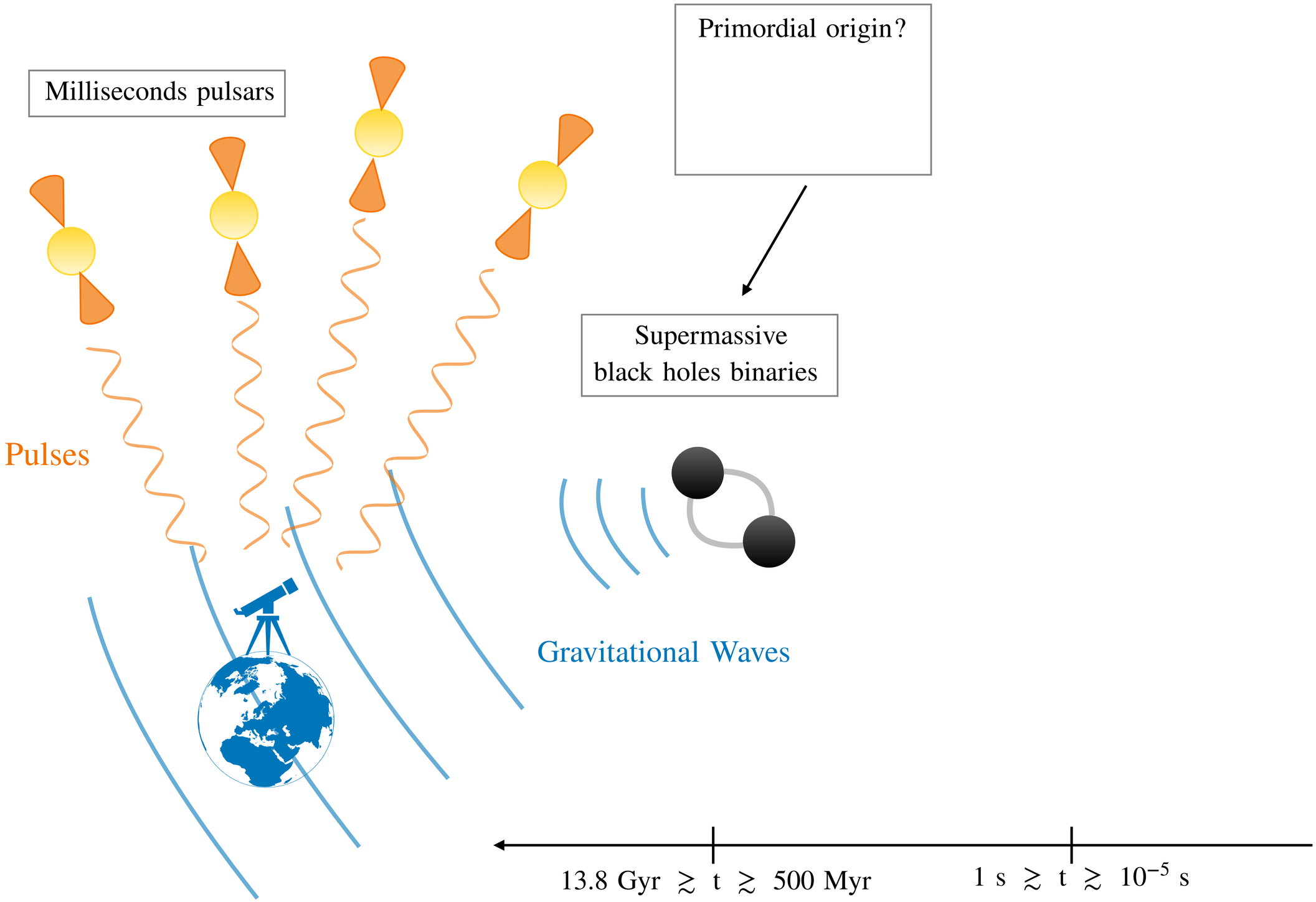
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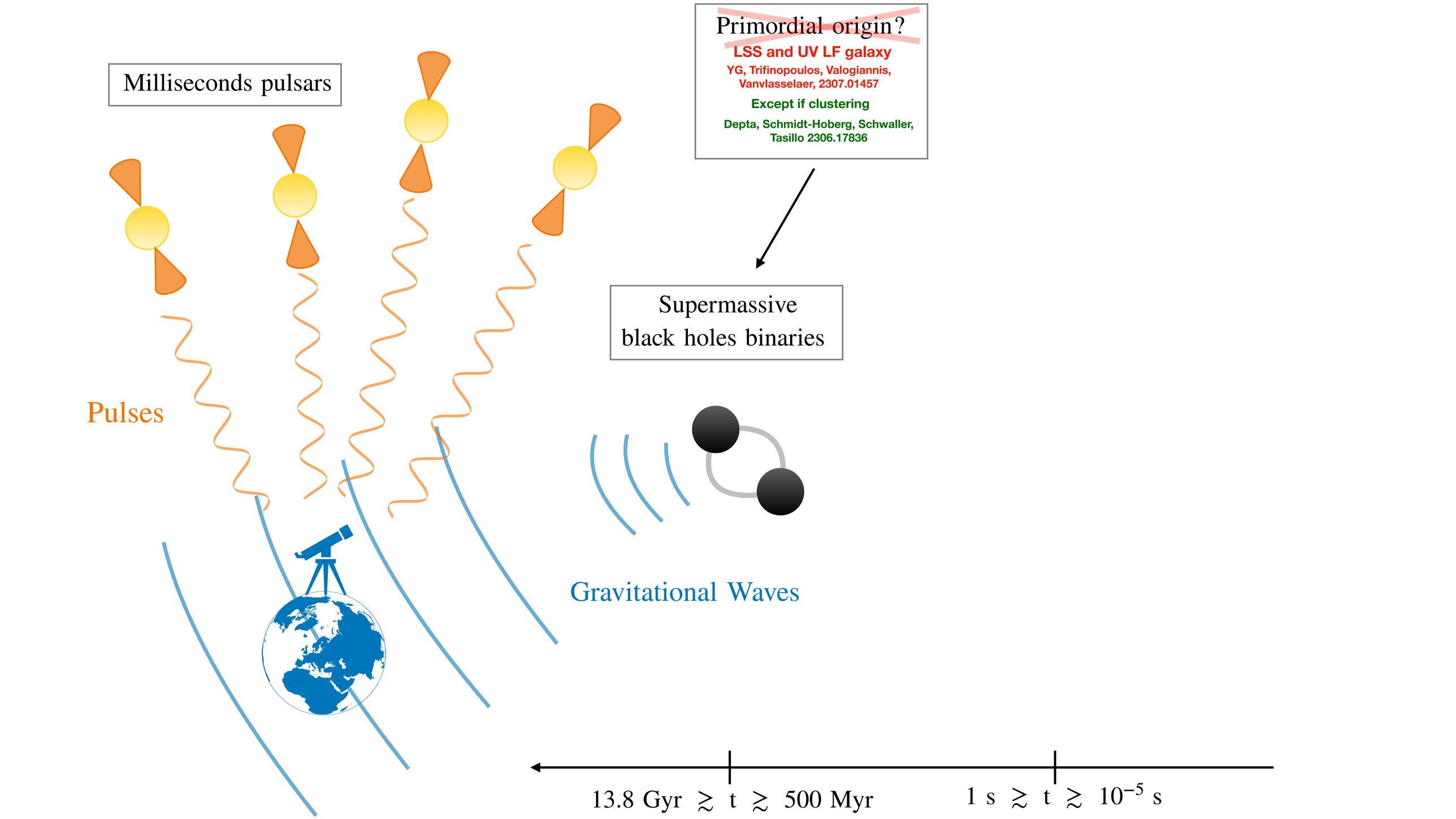
13.8 Gyr ≳ t ≳ 500 Myr
1 s ≳ t ≳ 10^{-5} s


Primordial origin?
LSS and UV LF galaxy
YG, Trifinopoulos, Valogiannis, Vanvlasselaer, 2307.01457
Except if clustering
Depta, Schmidt-Hoberg, Schwaller, Tasillo 2306.17836
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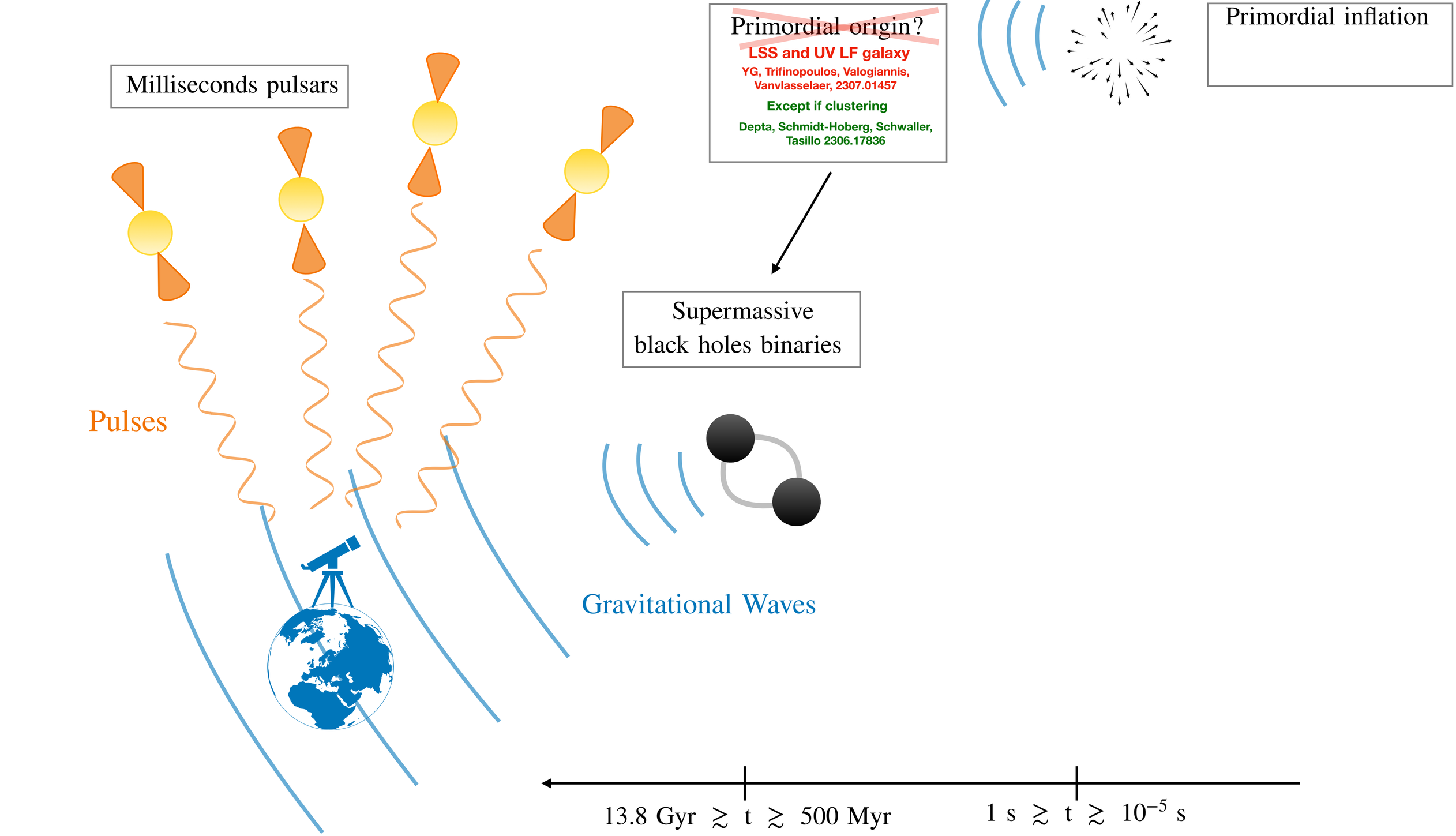
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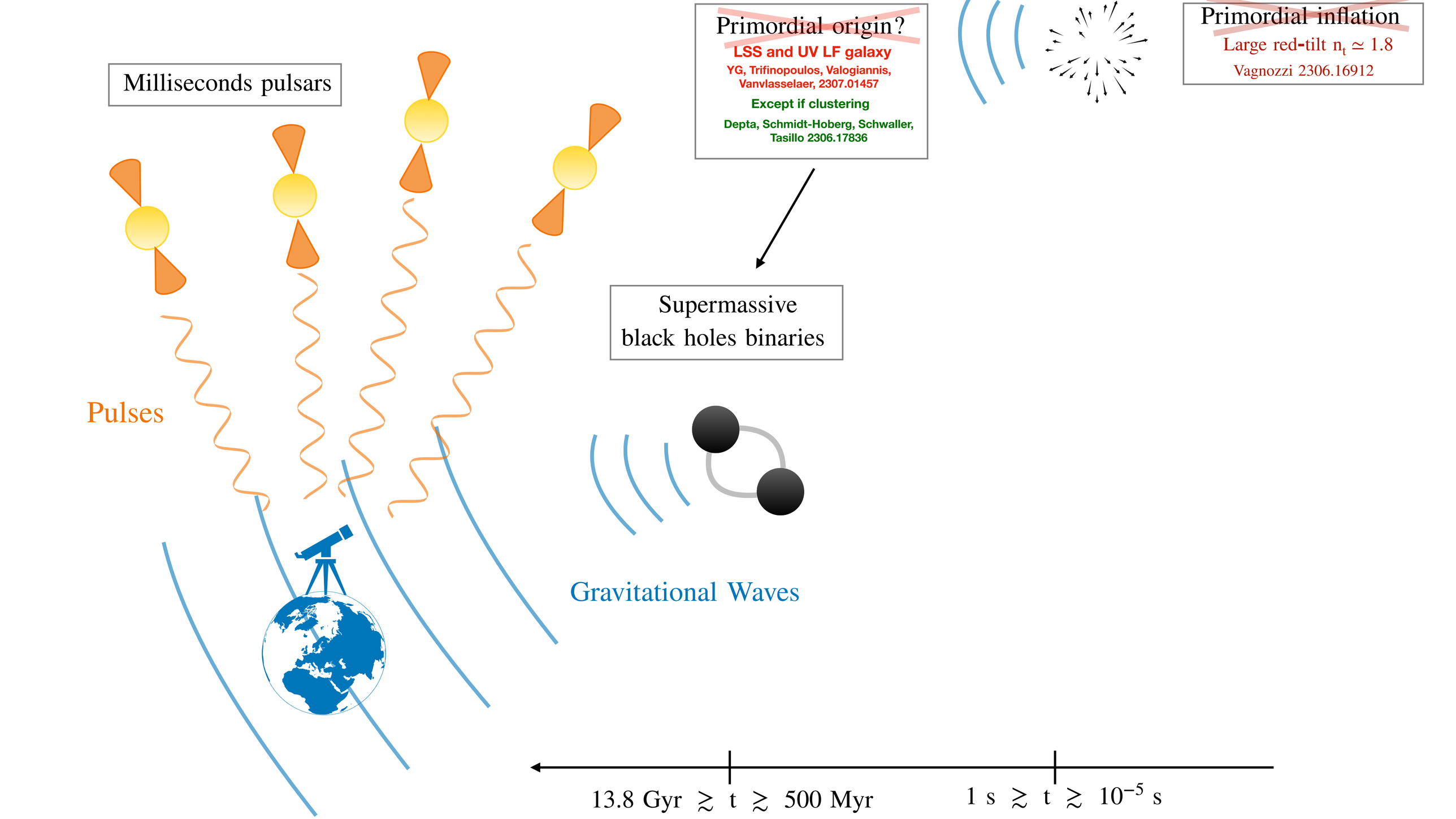
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Vagnozzi 2306.16912
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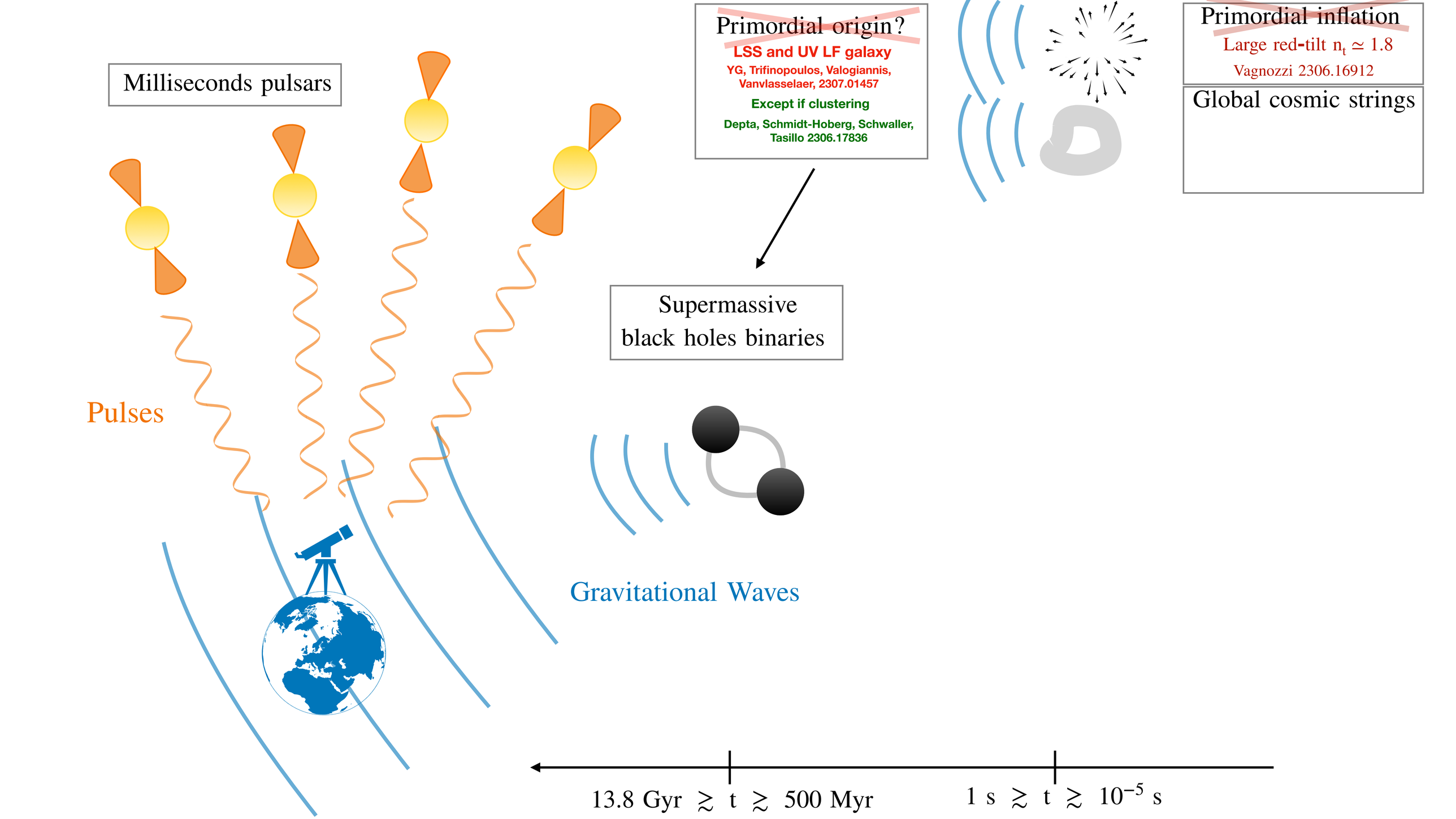
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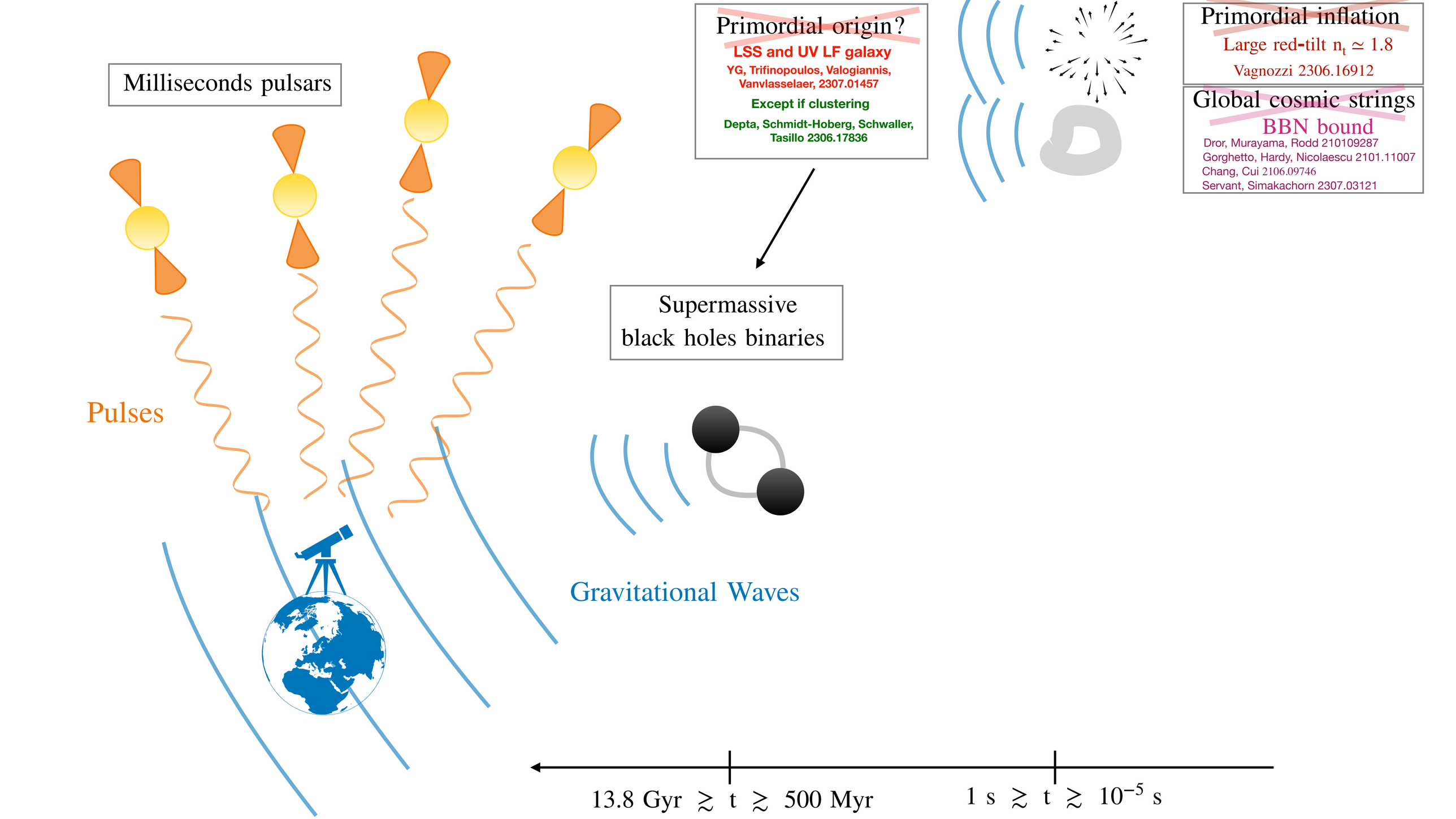
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Gorghetto, Hardy, Nicolaescu 2101.11007
Chang, Cui 2106.09746
Servant, Simakachorn 2307.03121
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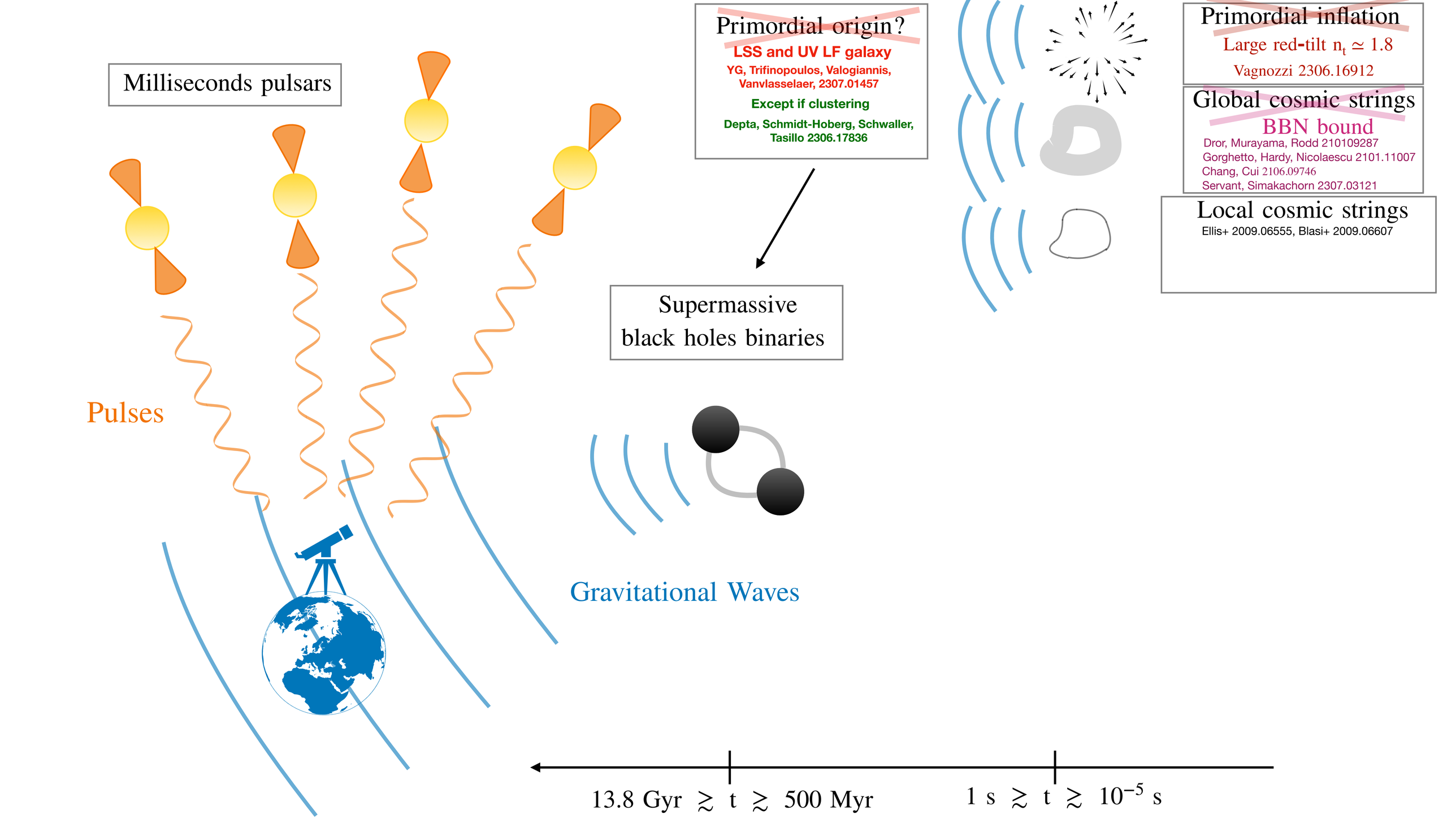
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Not very good fit (NG15+ "New physics")

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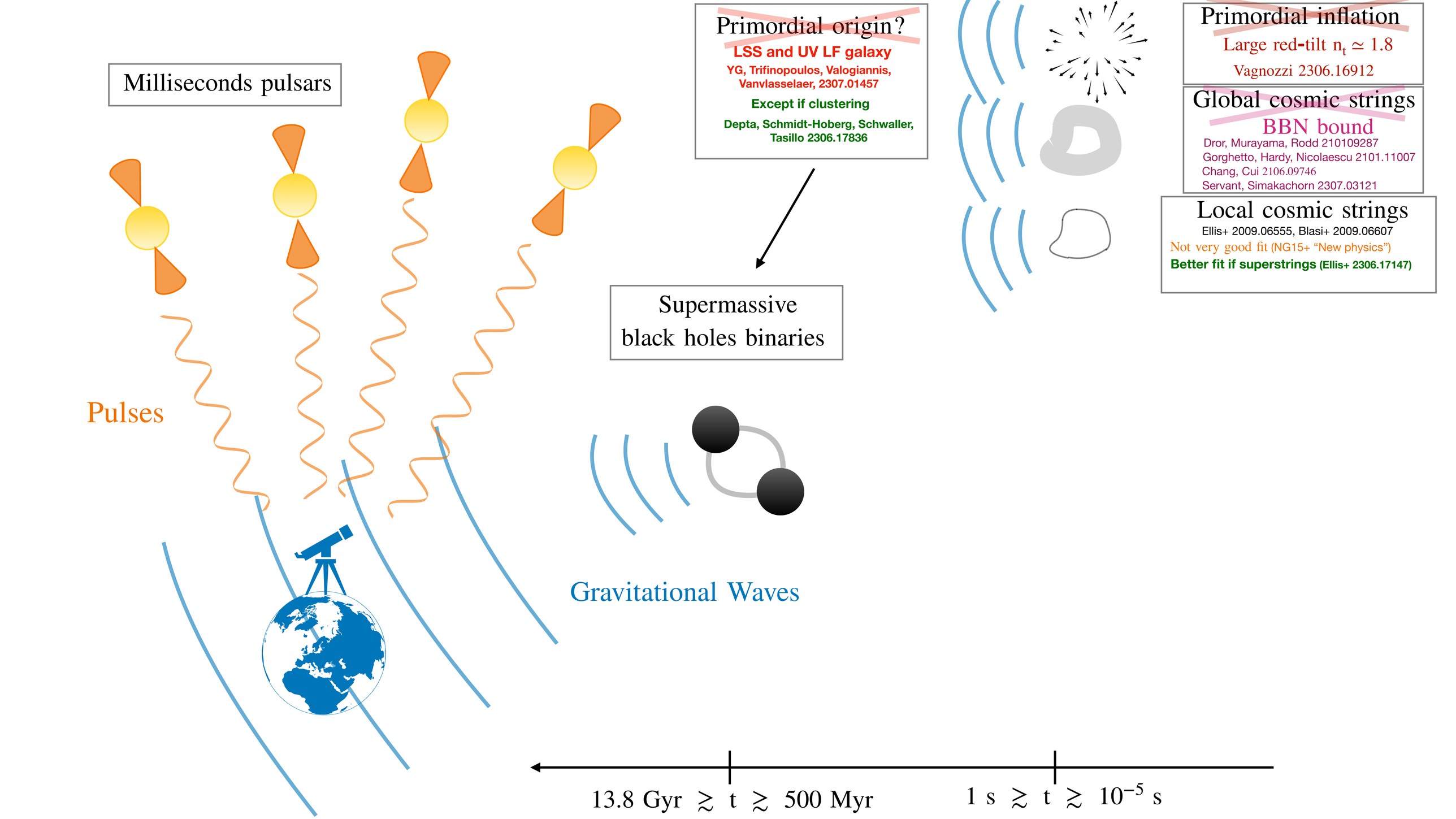
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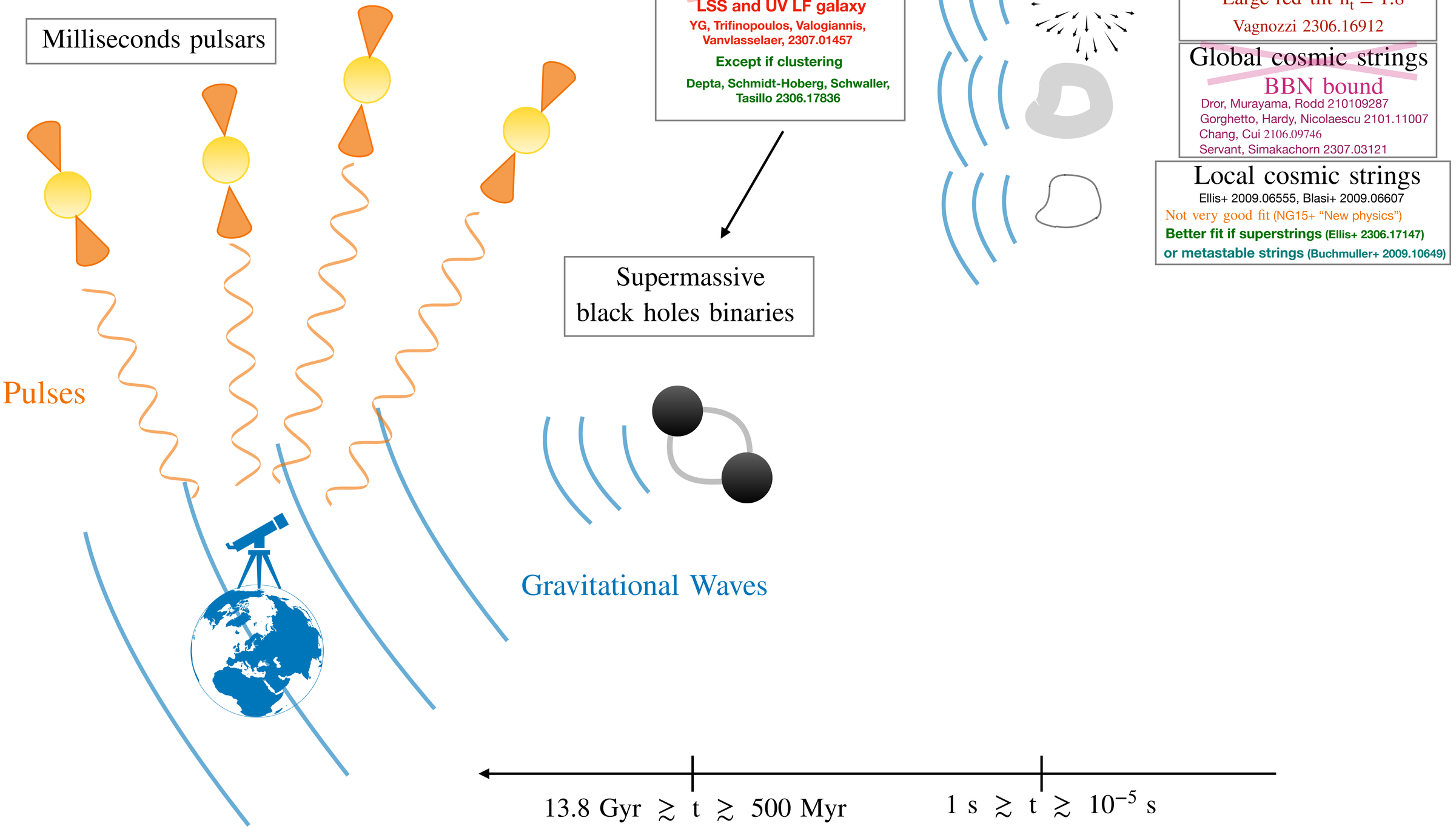
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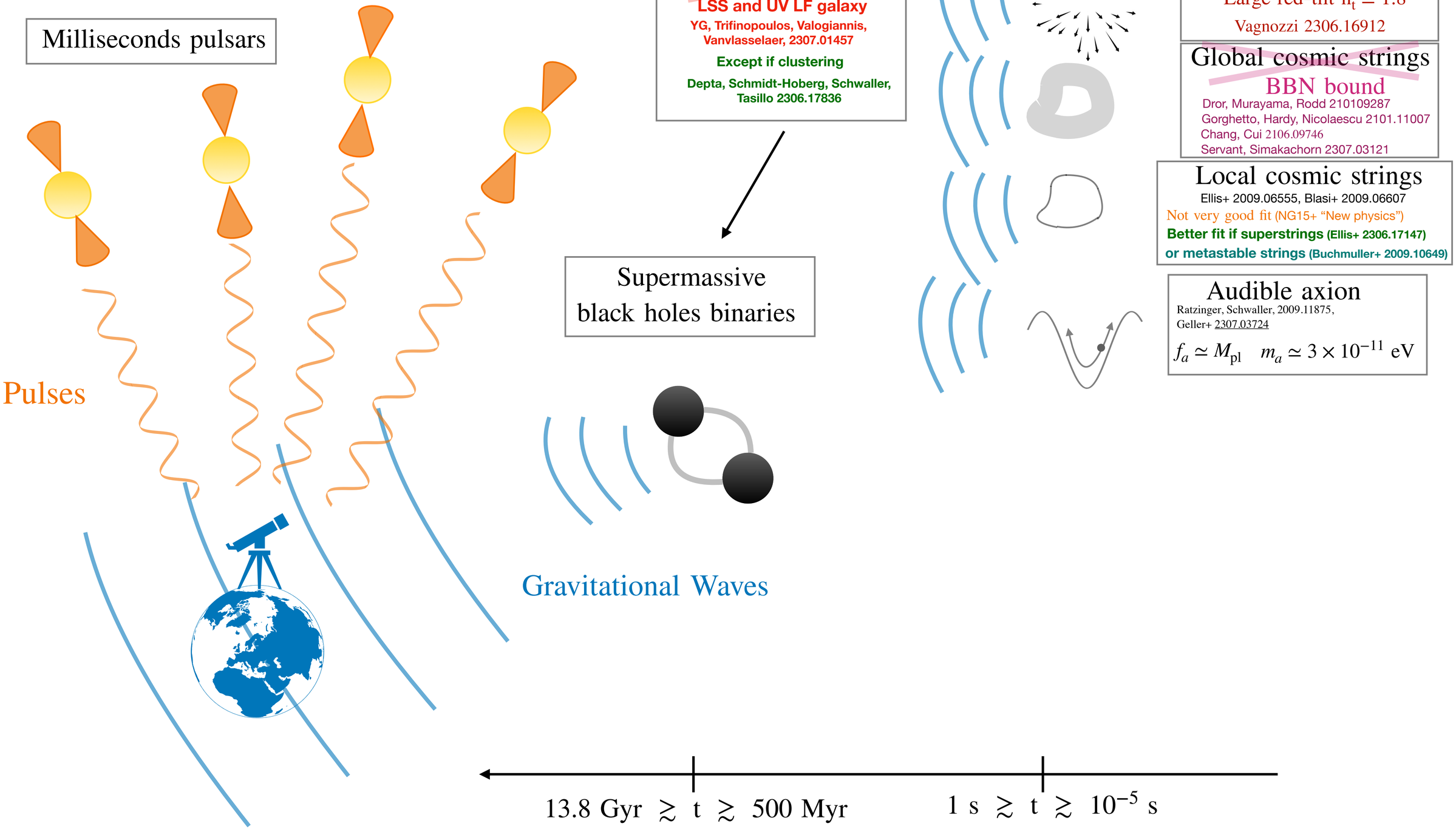
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Audible axion
Ratzinger, Schwaller, 2009.11875,
Geller+ 2307.03724
$f_a \simeq M_{\rm pl} \quad m_a \simeq 3 \times 10^{-11}$ eV
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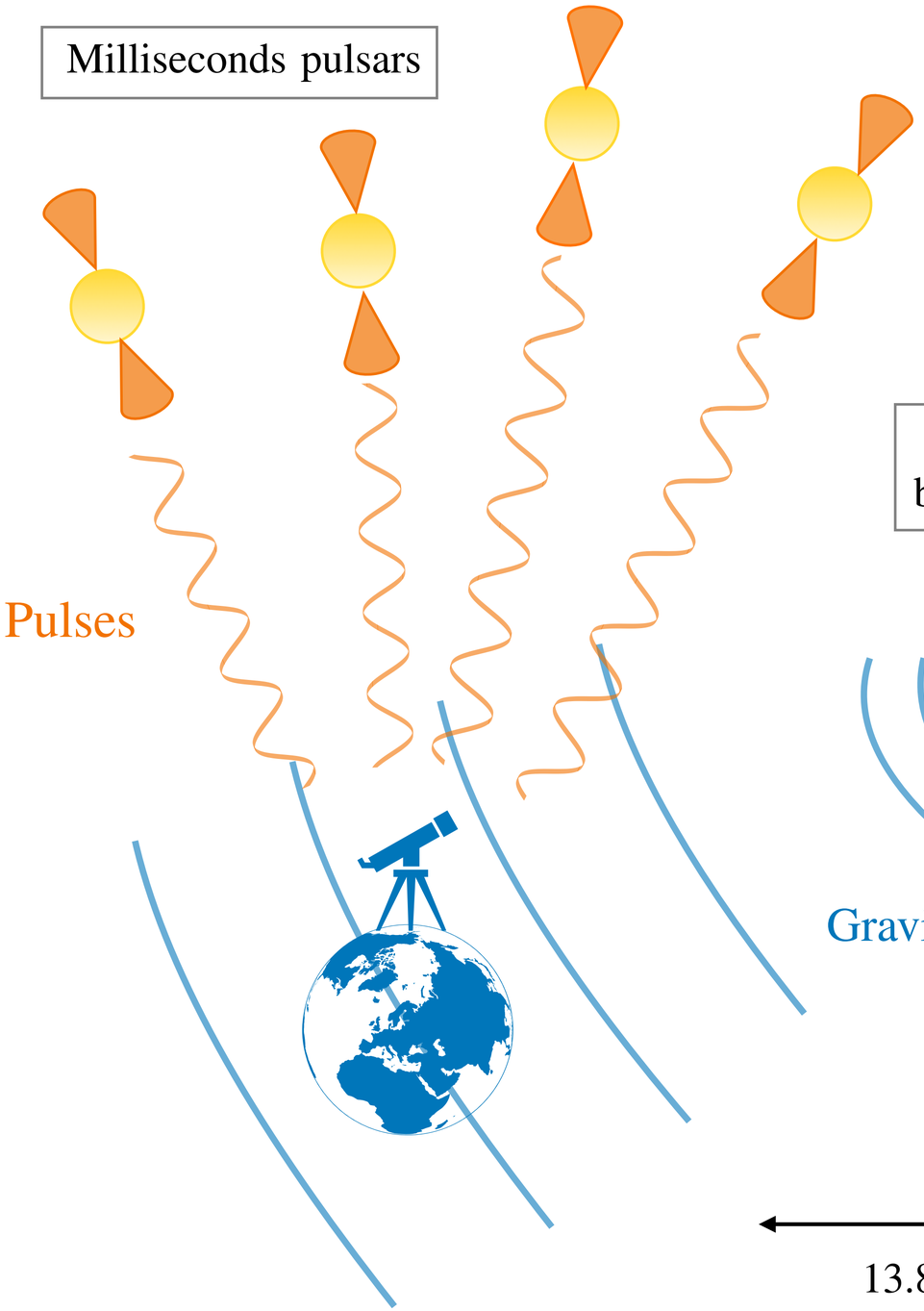

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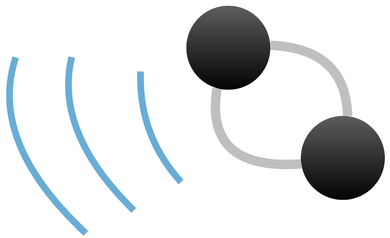
Supermassive black holes binaries



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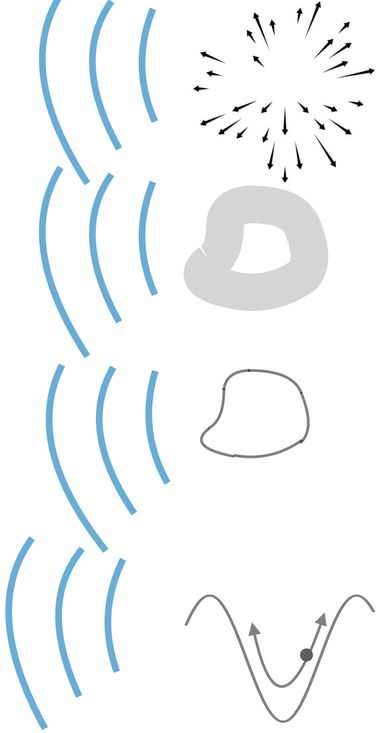

Primordial inflation

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Vagnozzi 2306.16912

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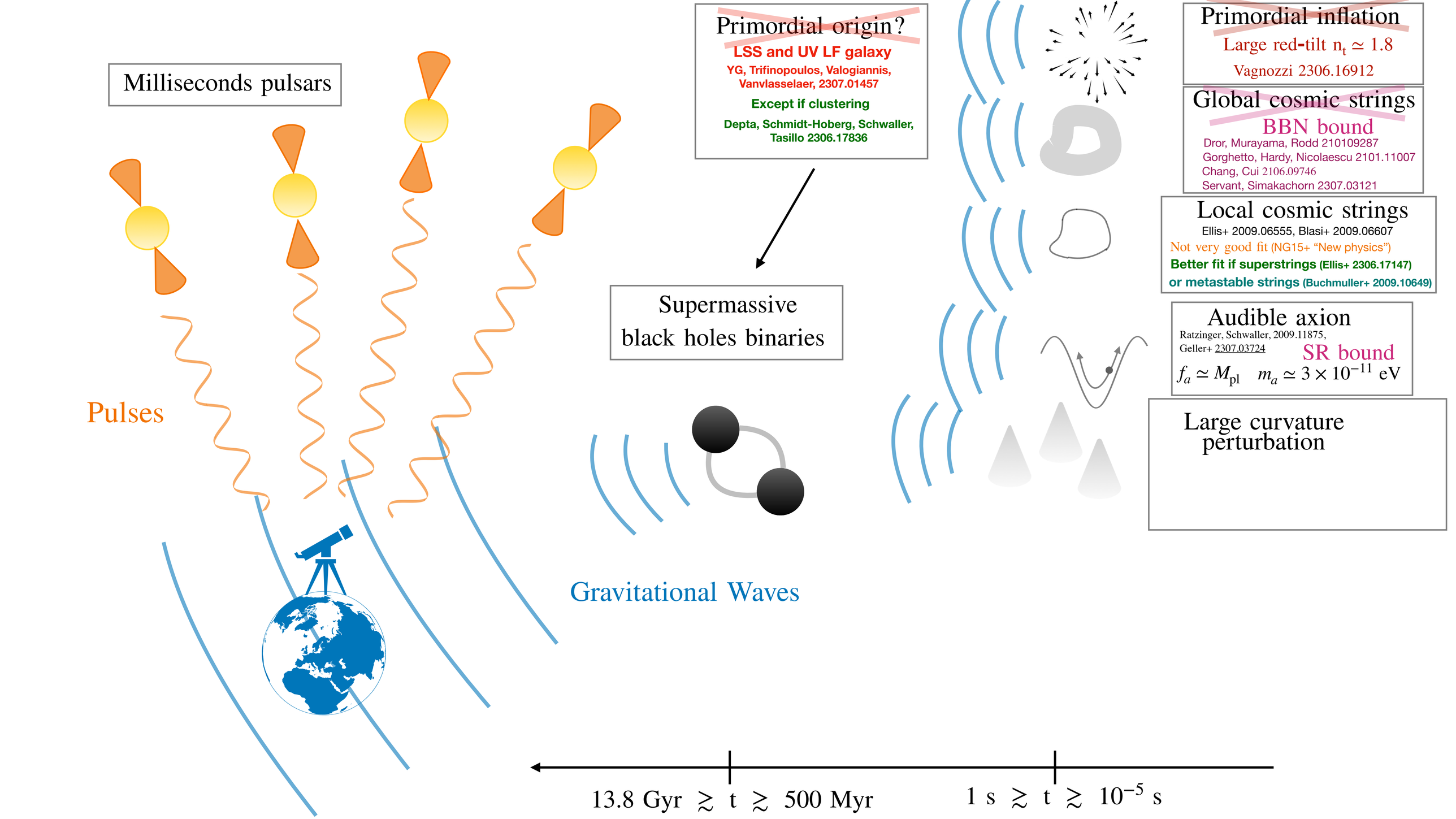
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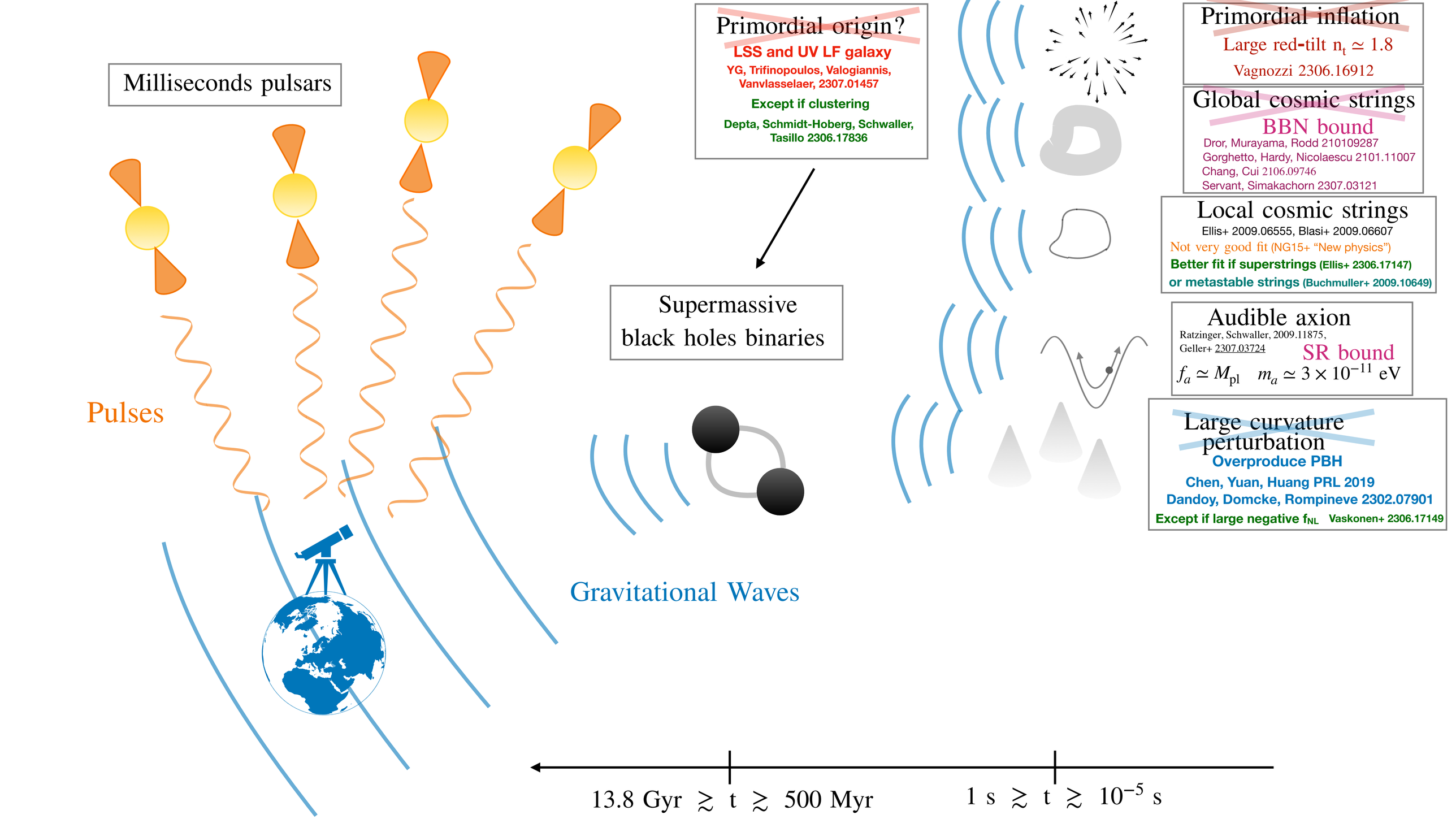
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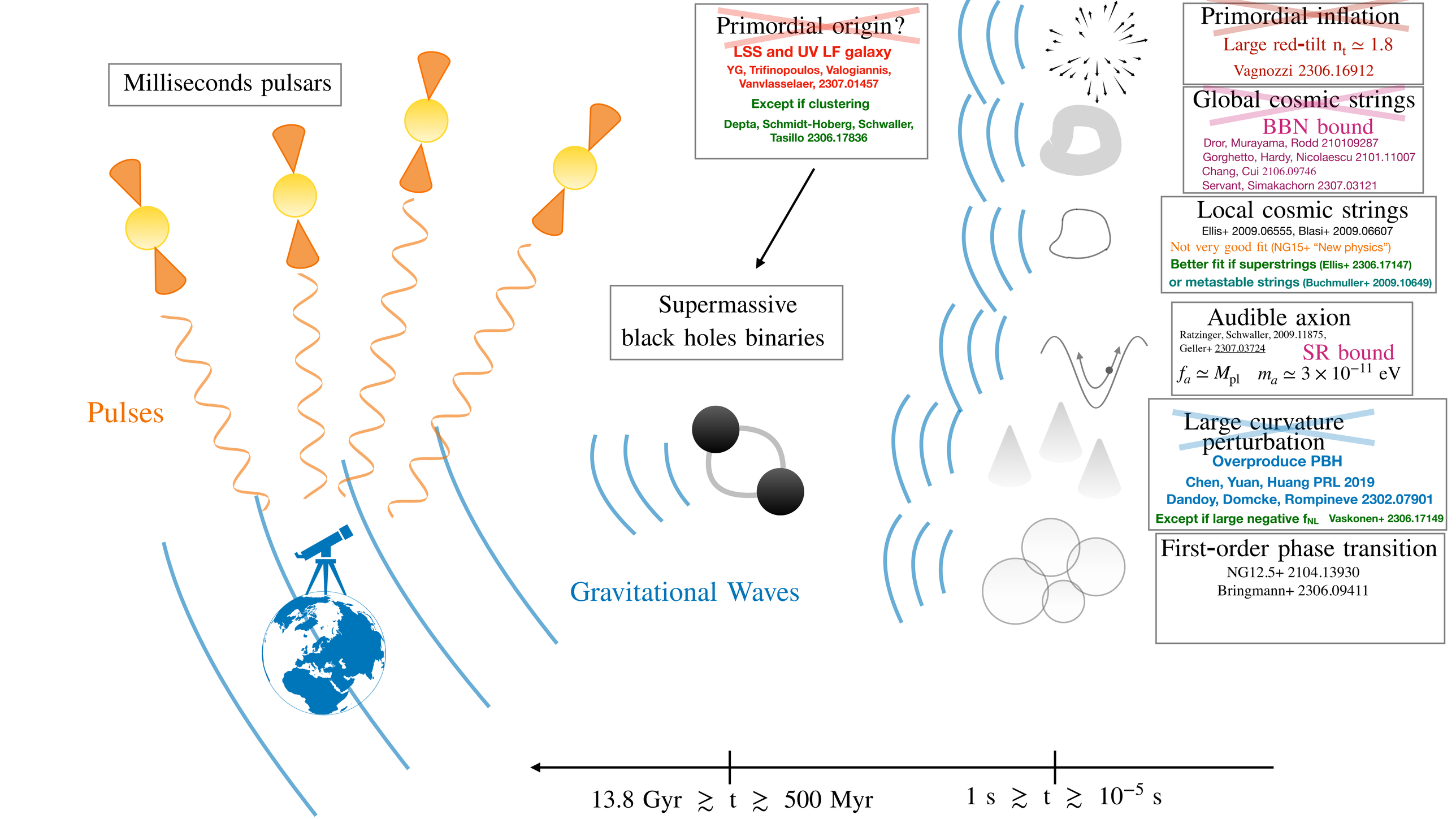
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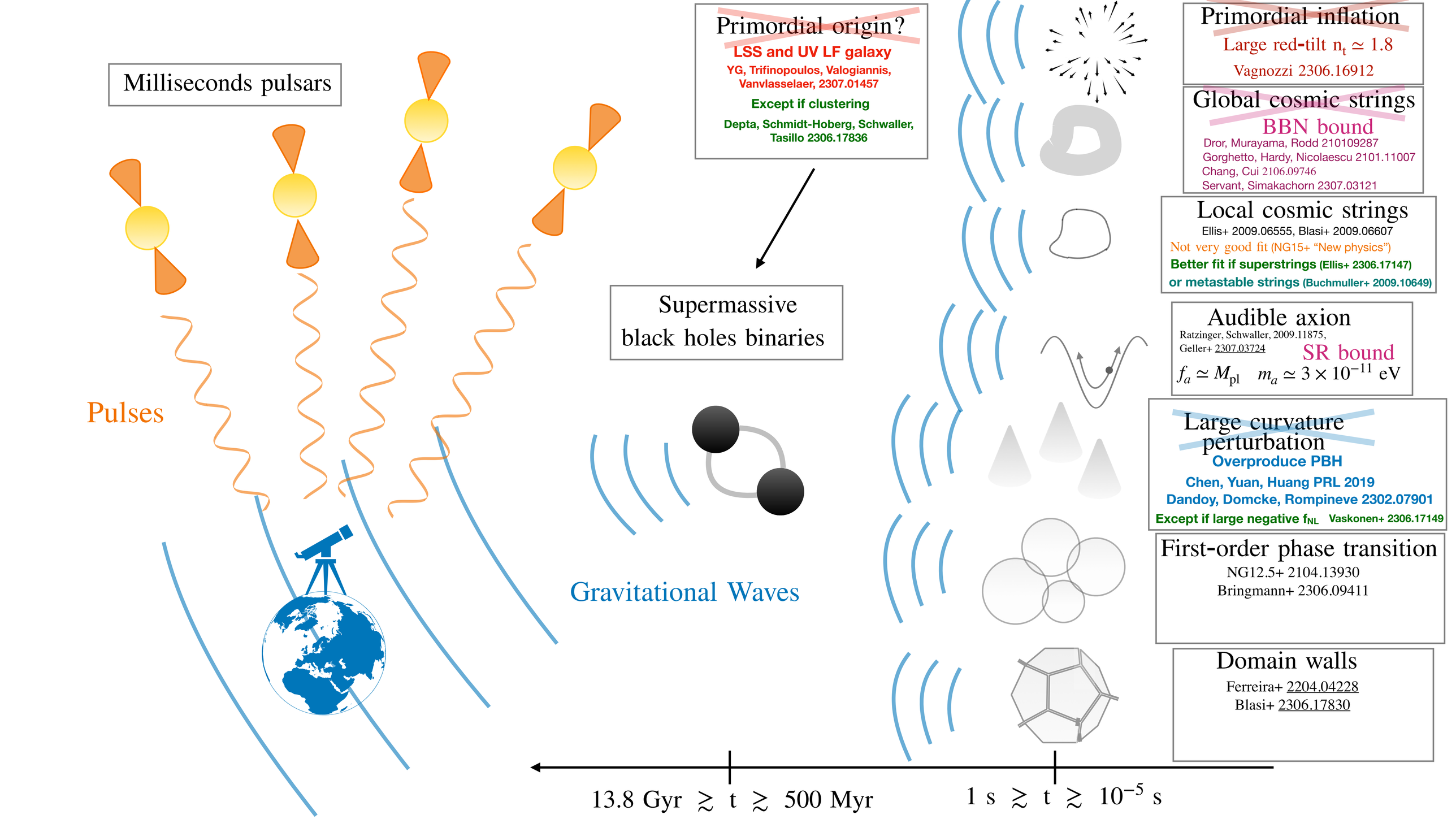
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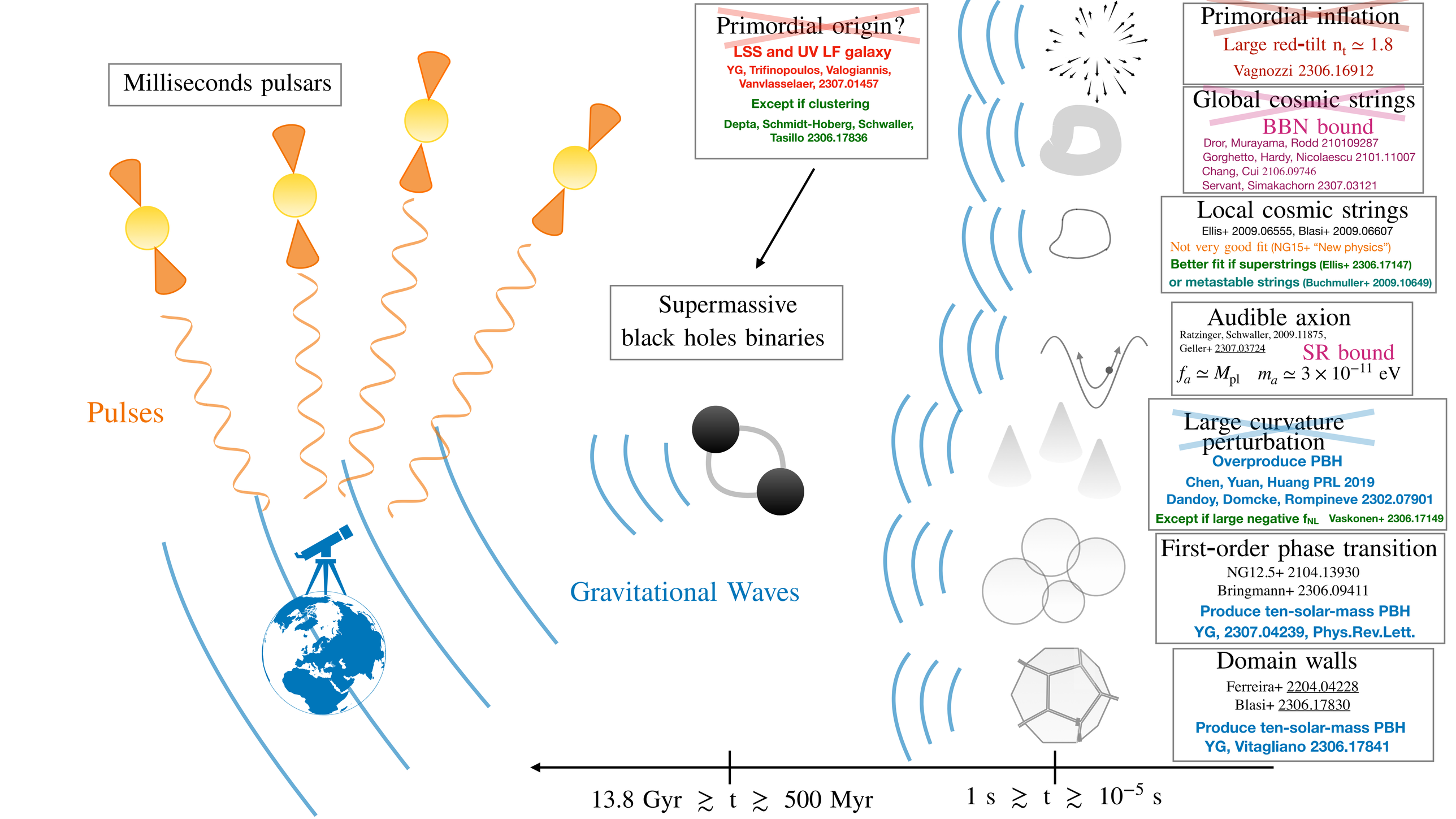
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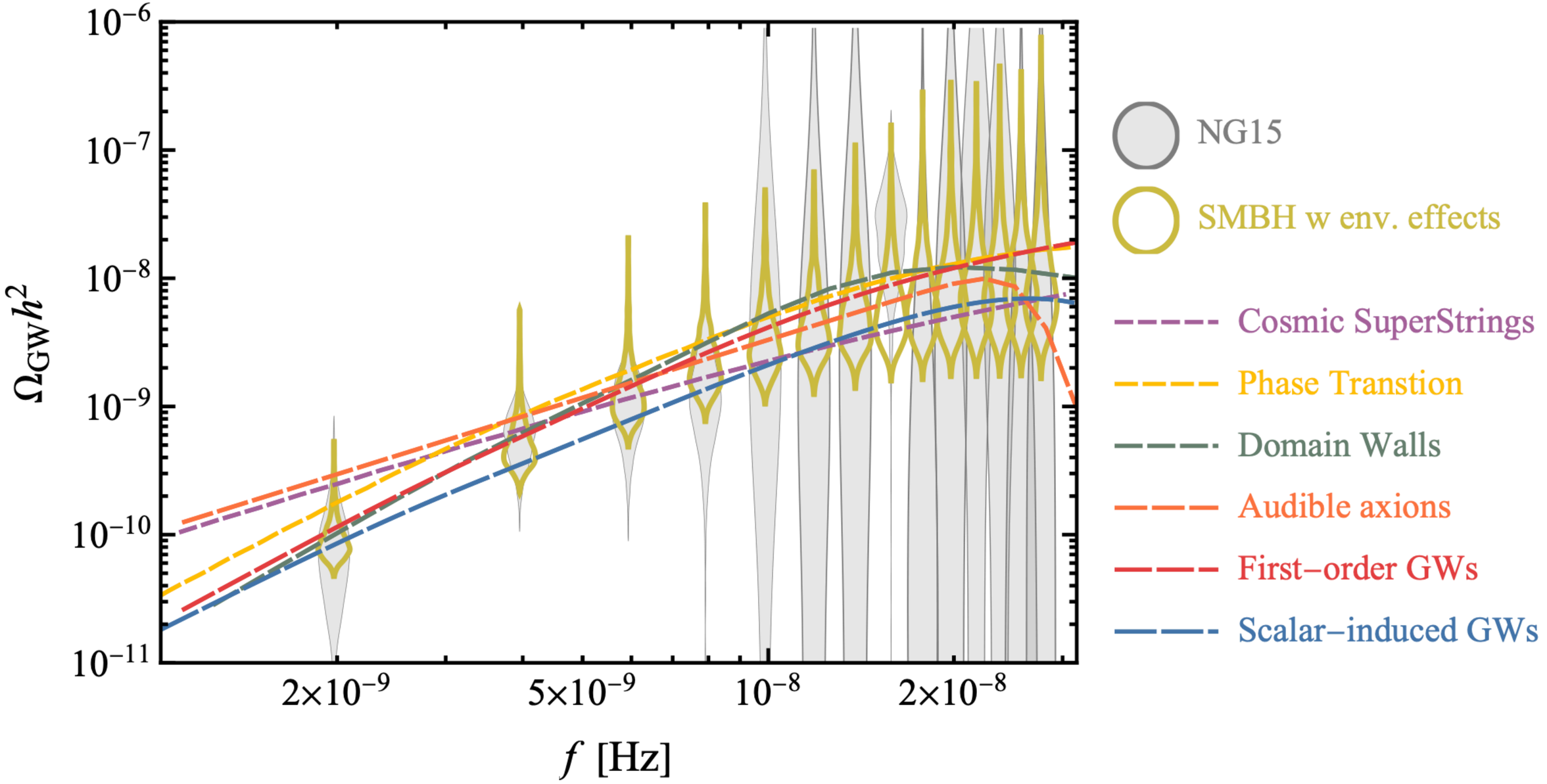

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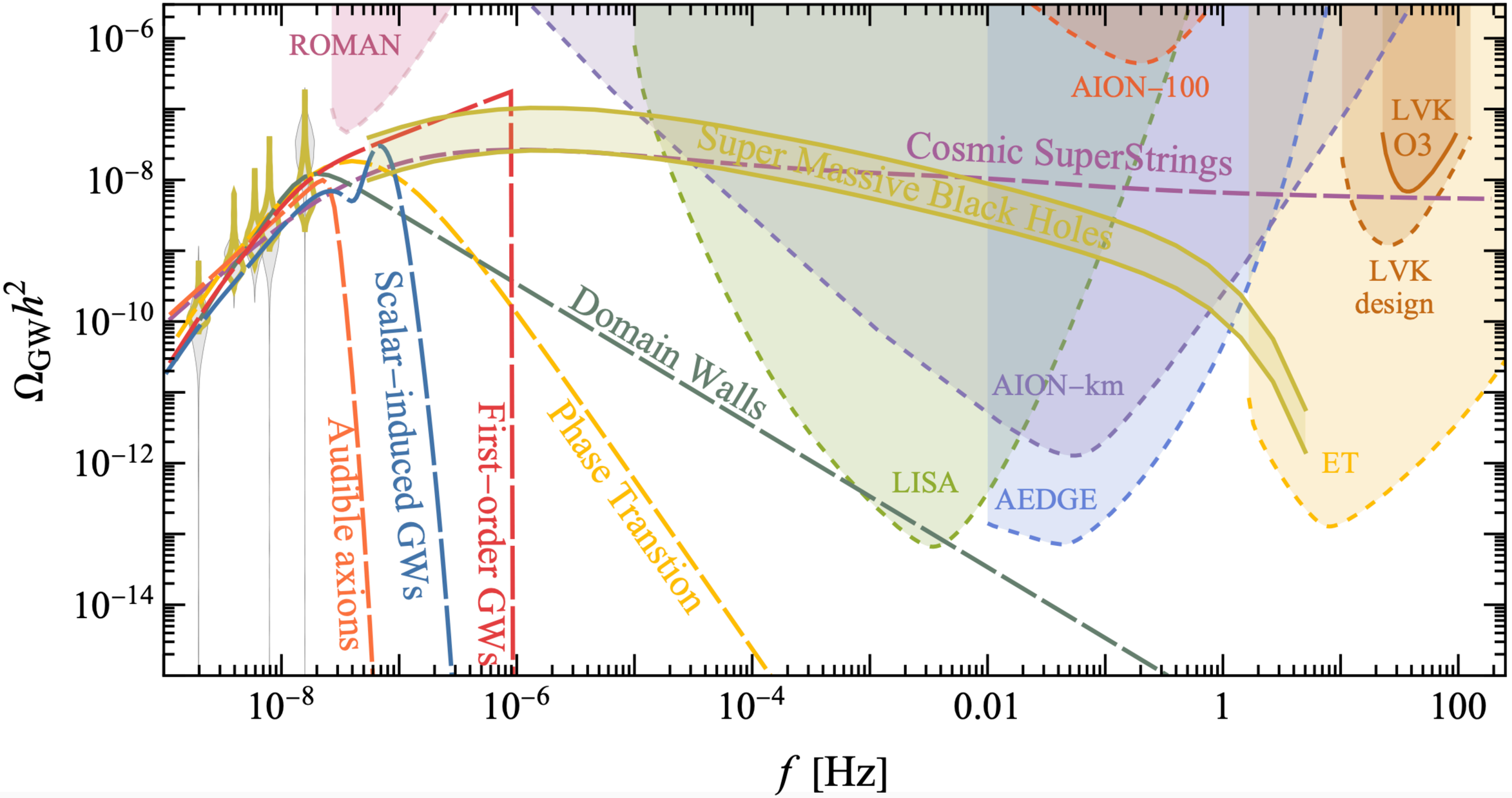

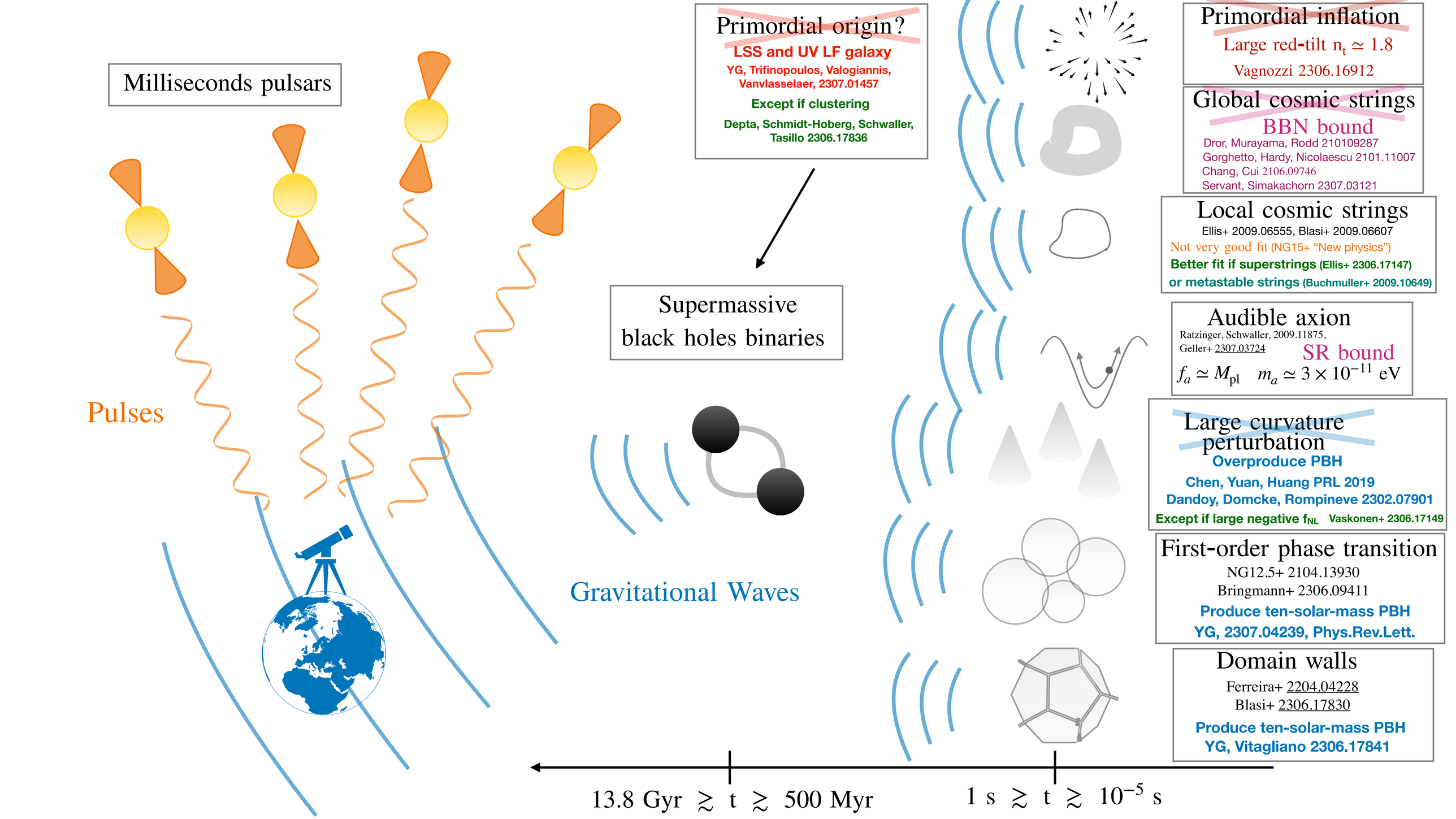
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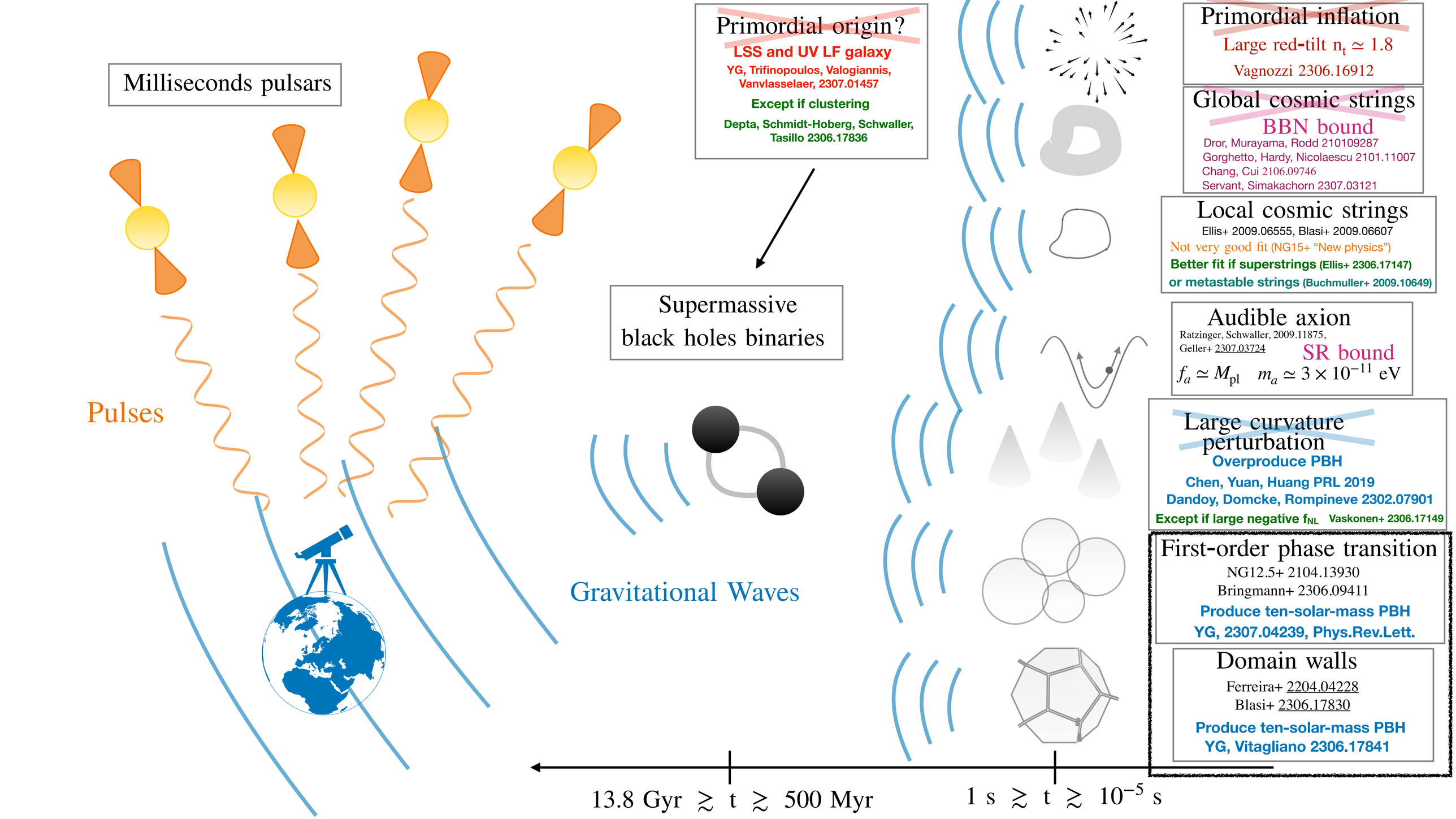
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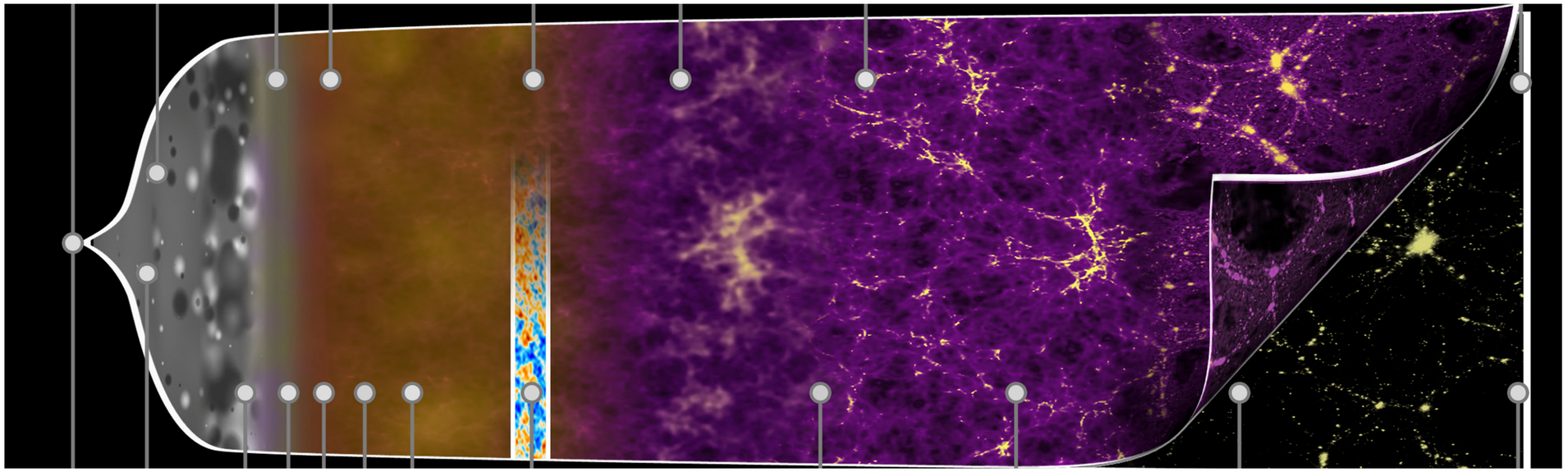

PBH formation

Star formation

in presence of large inhomogeneities:

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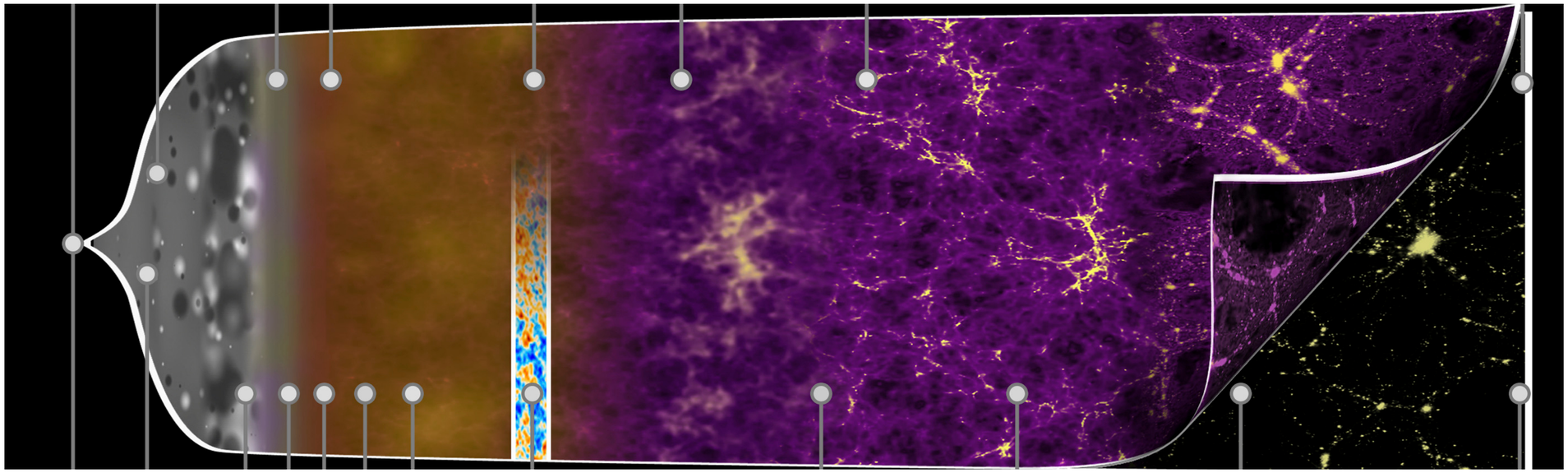


PBH formation

Star formation

in presence of large inhomogeneities:

1) $\delta\rho/\rho \sim 1$

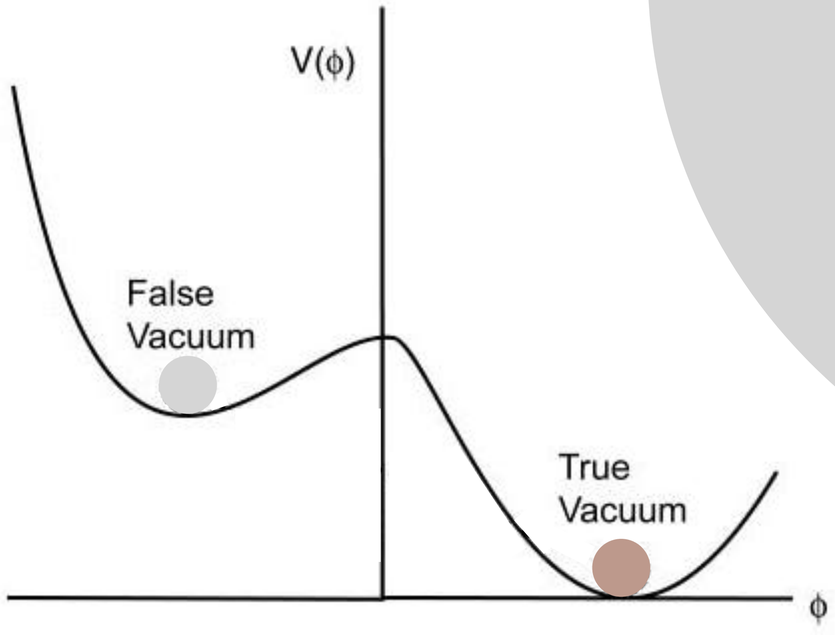
2) horizon size

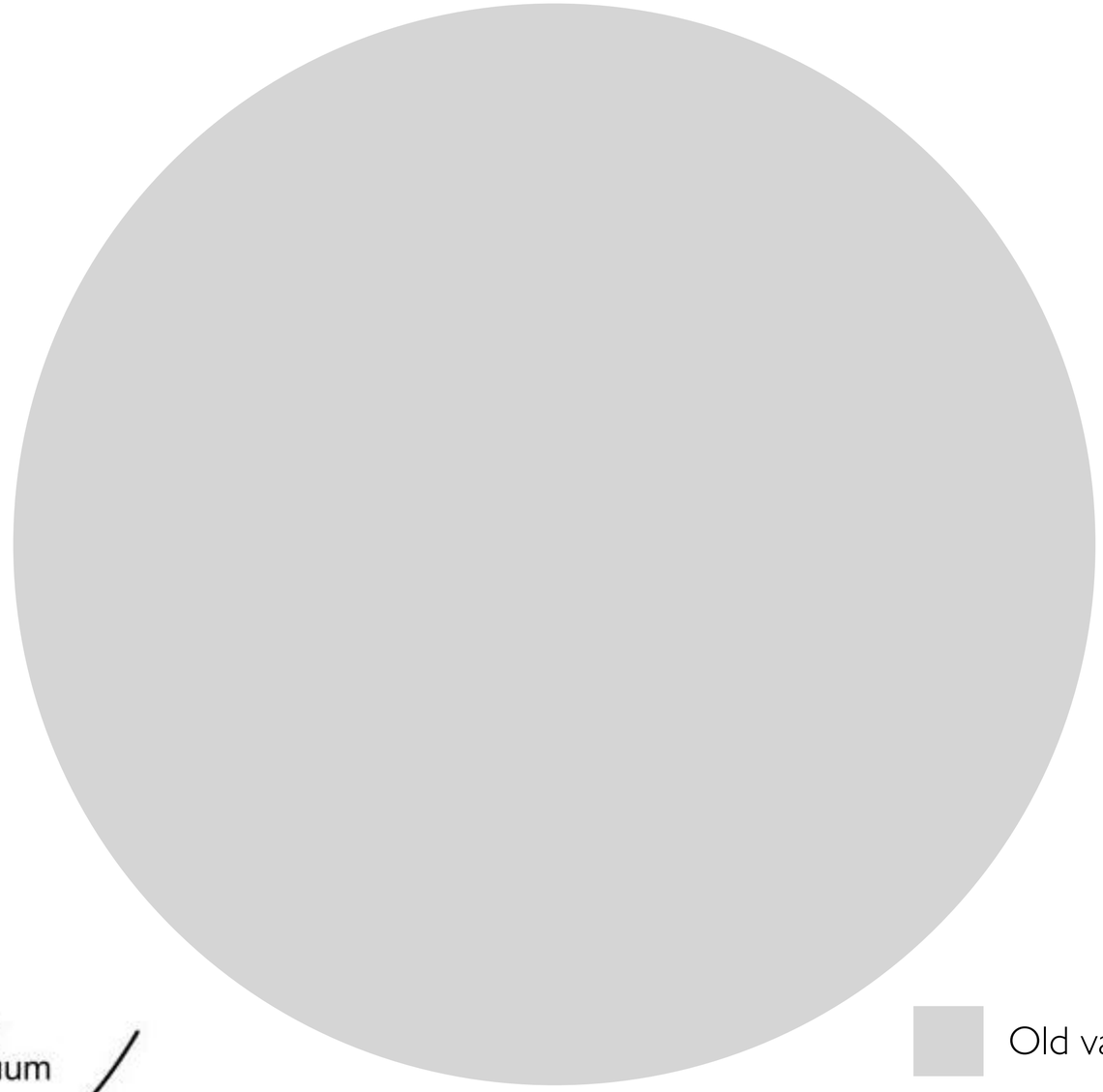
Hawking (1971)

PBHs from 1stOPT

Kodama, Sasaki, Sato (1982)

YG, Volansky 2305:04942





Old vacuum-dominated region (outside bubbles)

New radiation-dominated region (inside bubbles)

PBHs from 1stOPT

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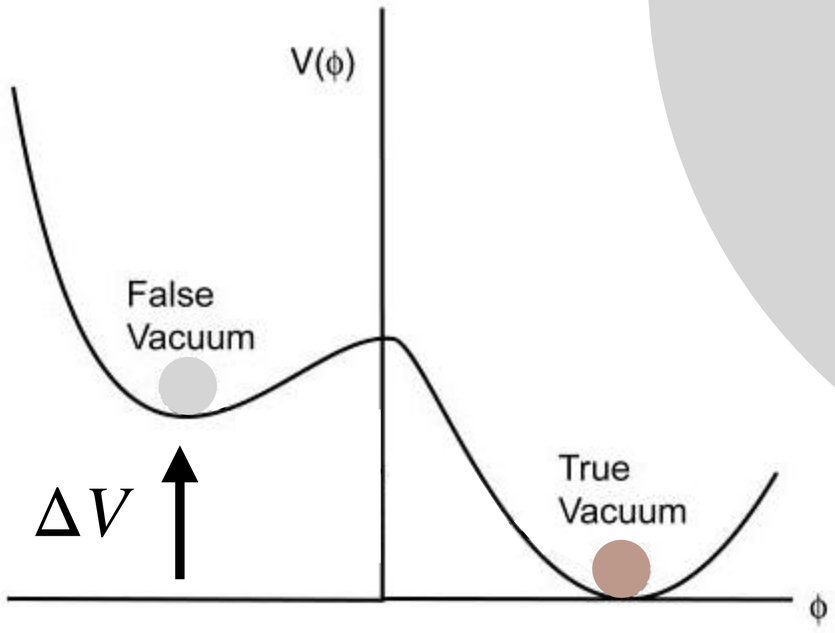

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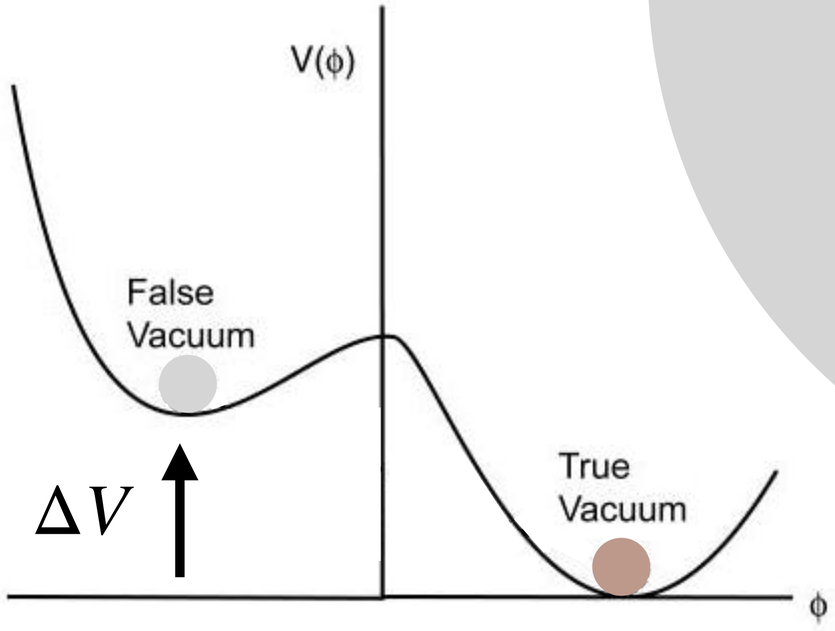

Vacuum-dominated

$$\rho_{\rm tot} \simeq \Delta V$$

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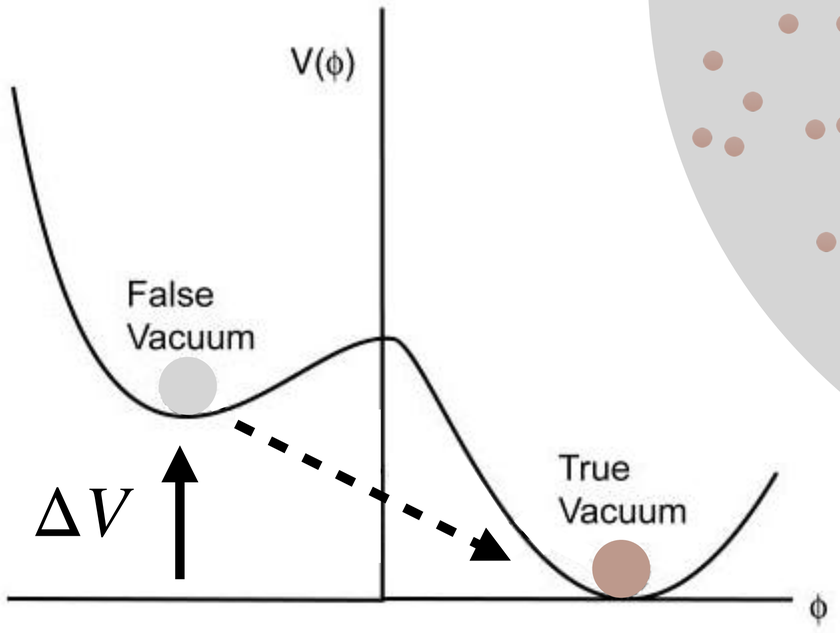
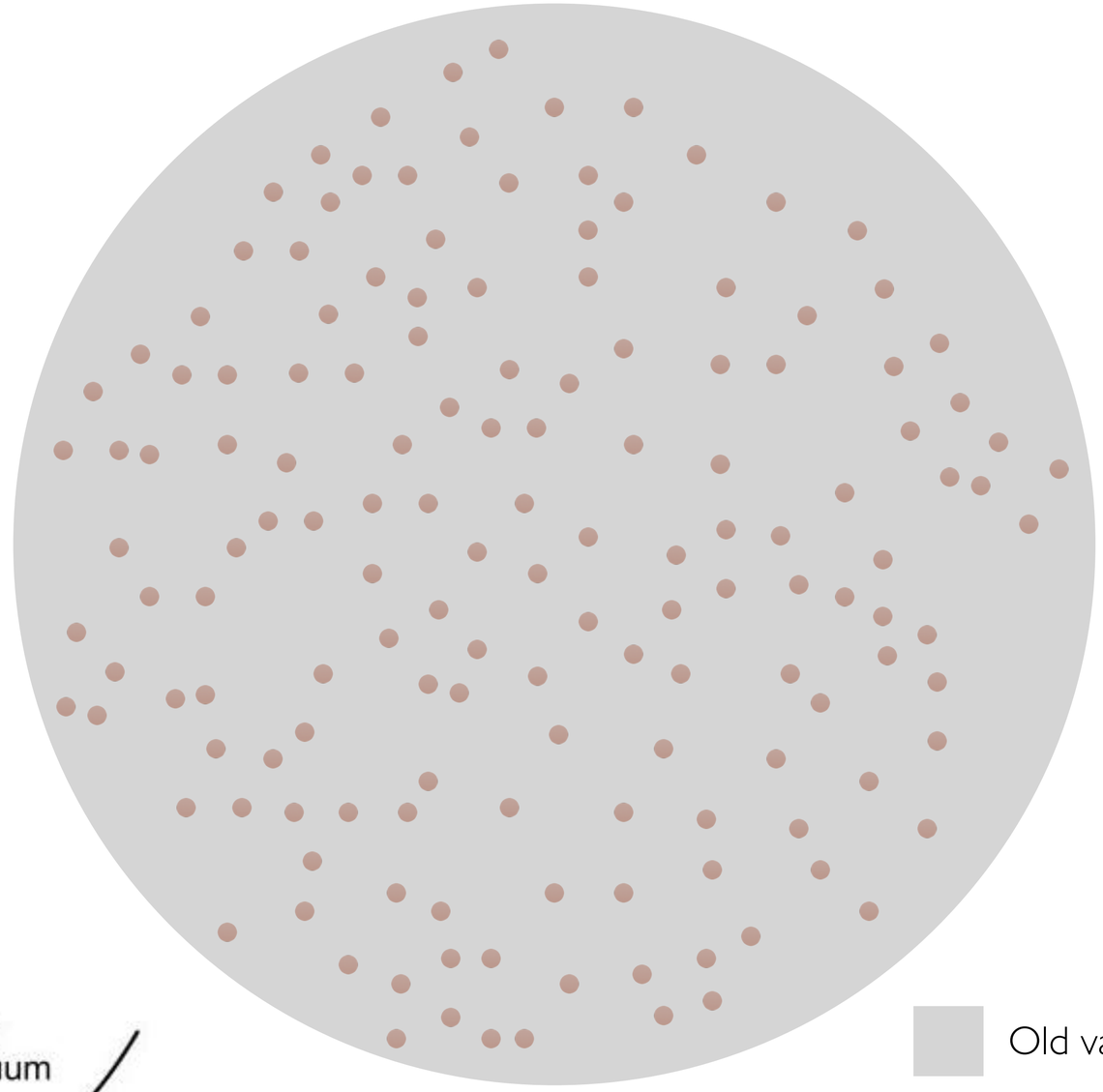
PBHs from 1stOPT

YG, Volansky 2305:04942





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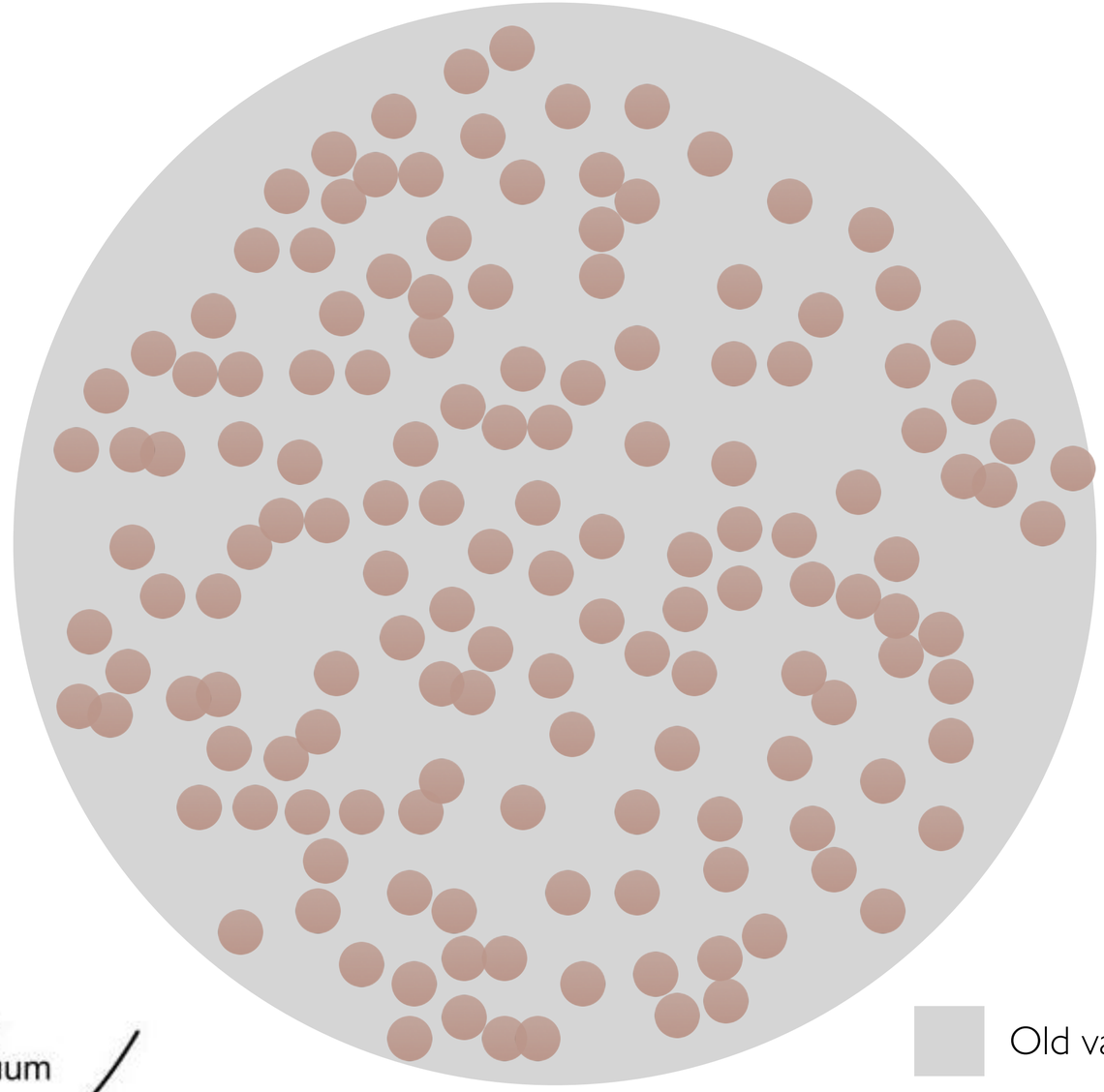

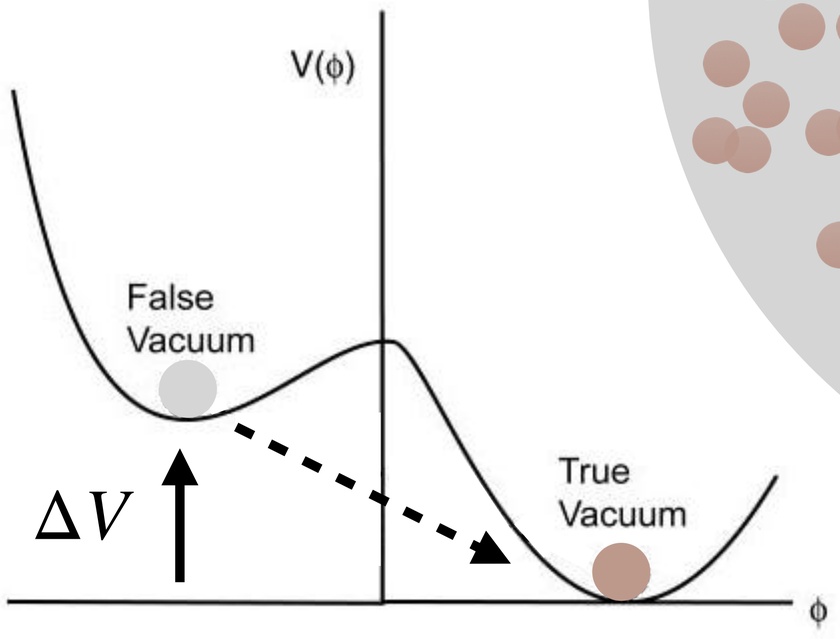

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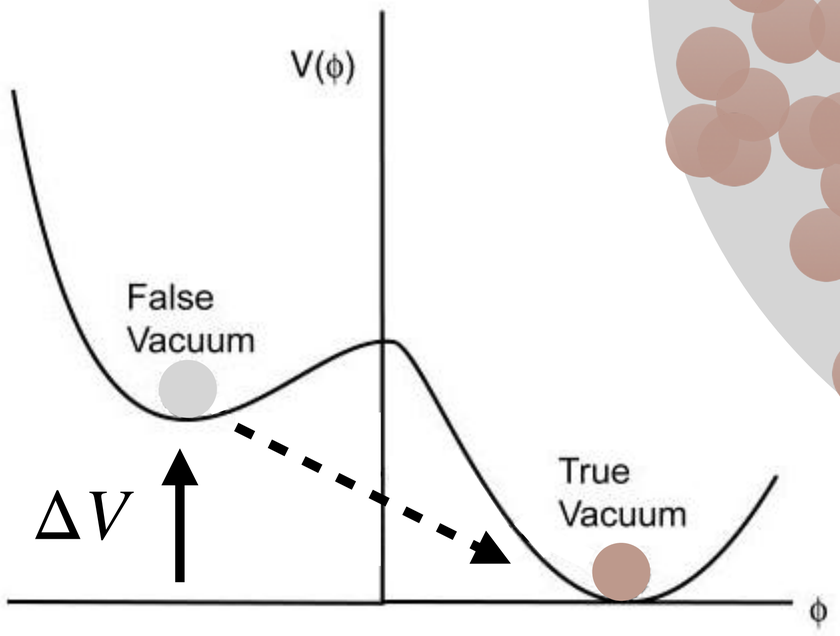

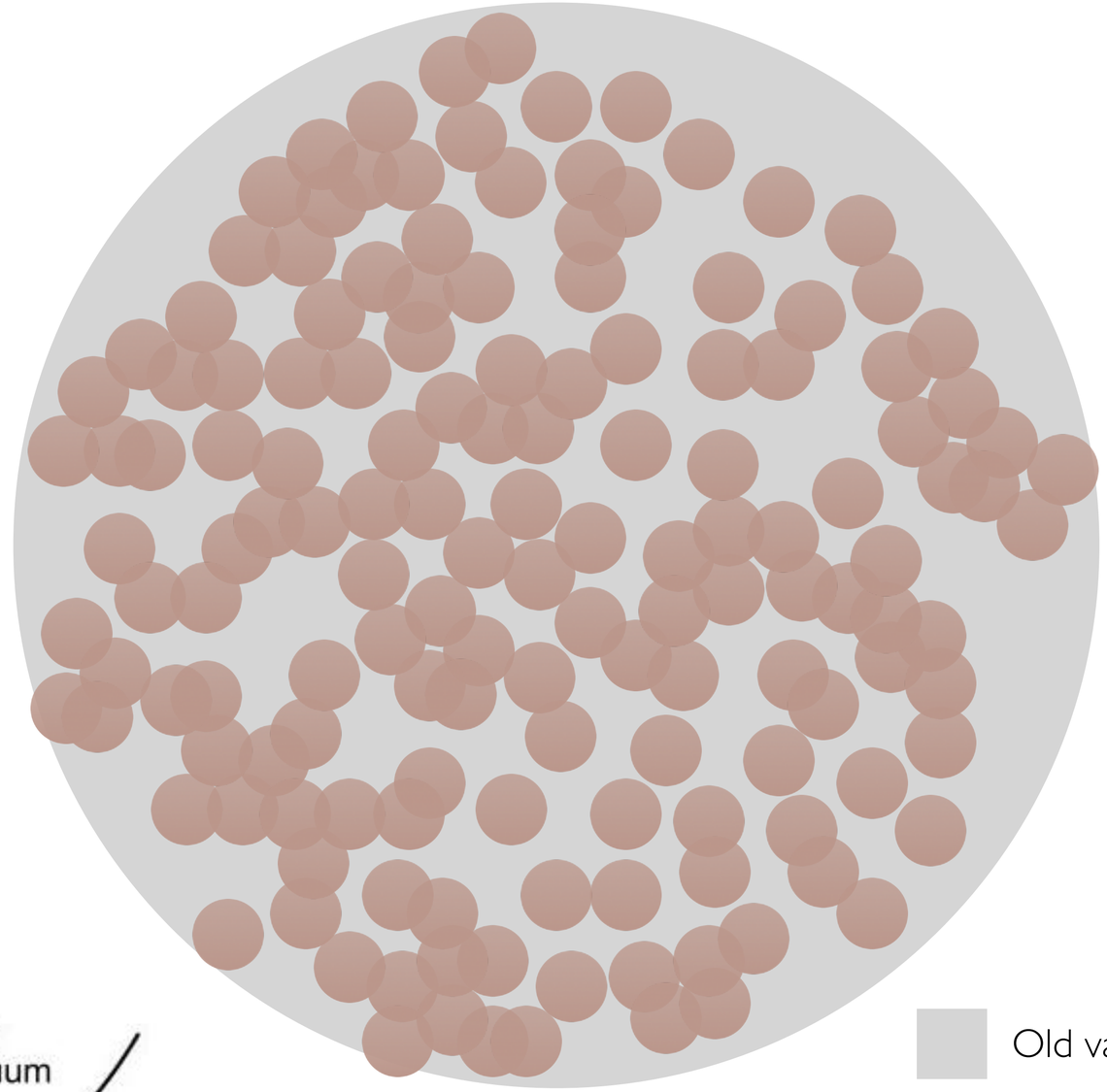

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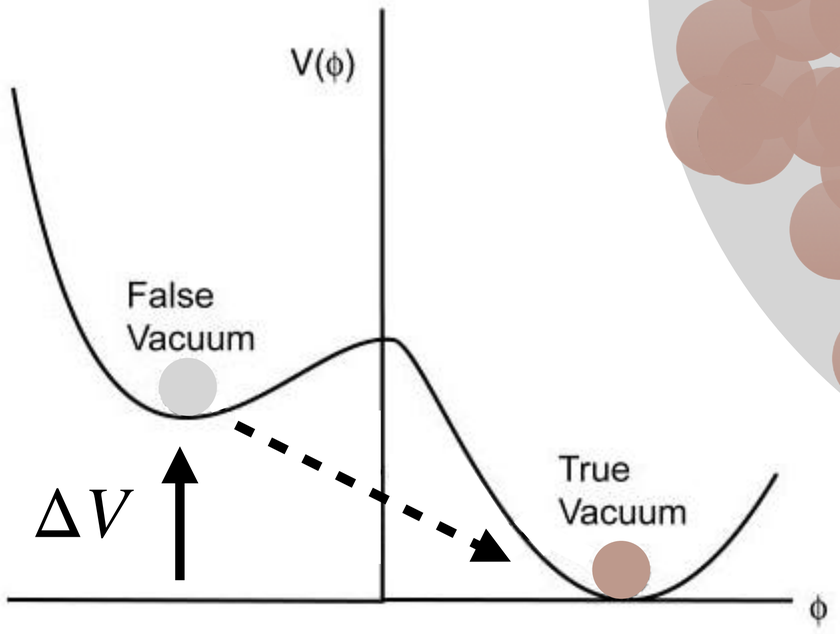

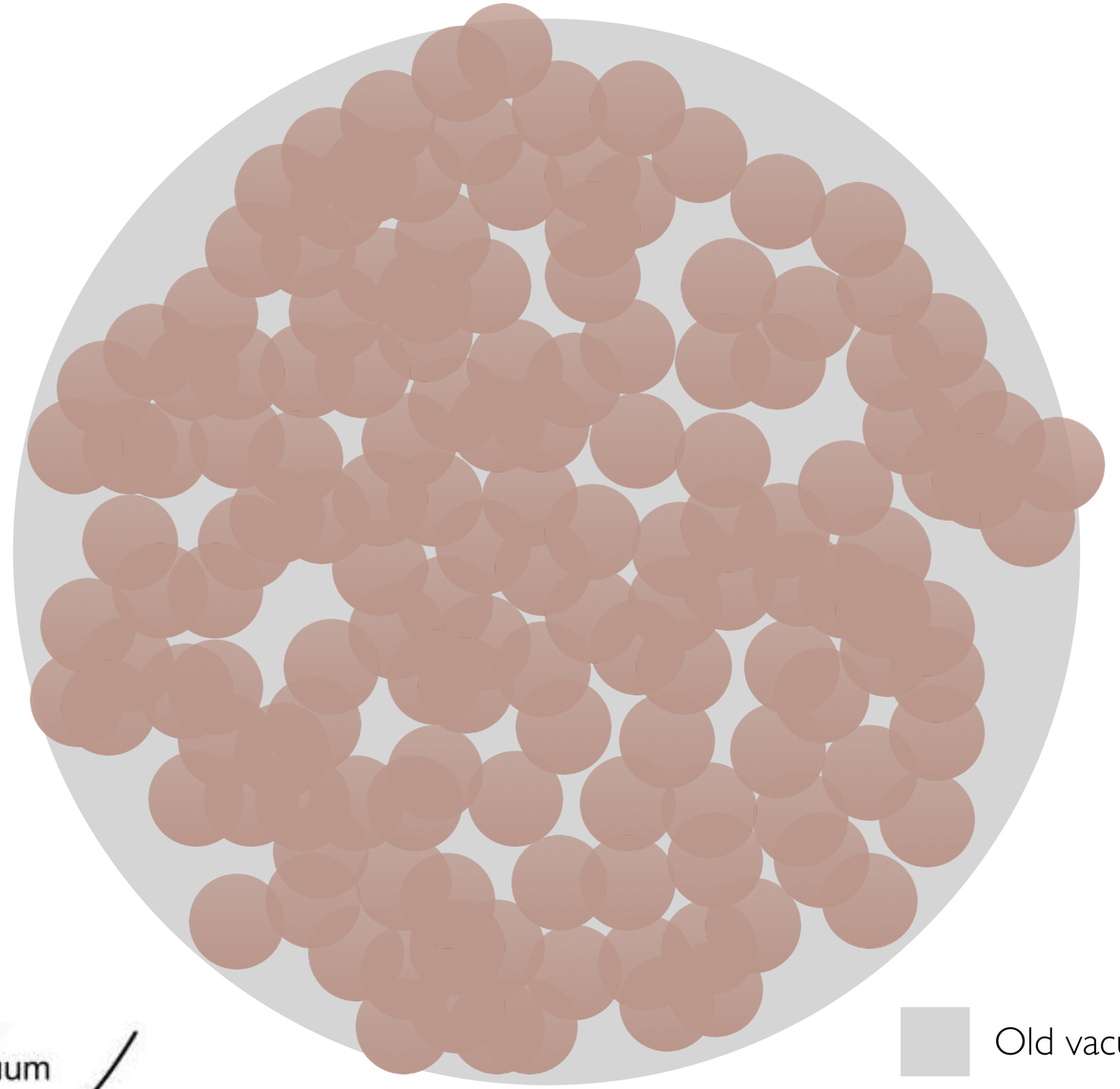

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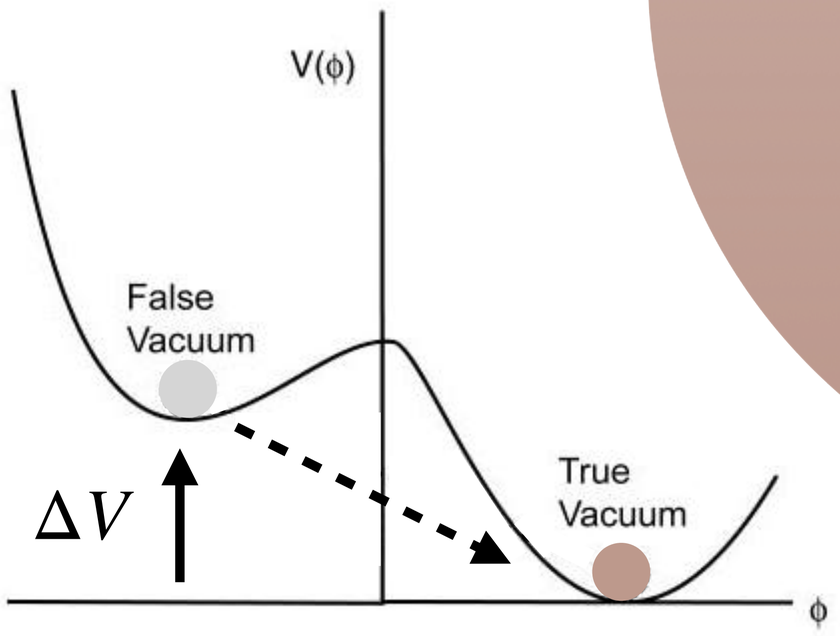

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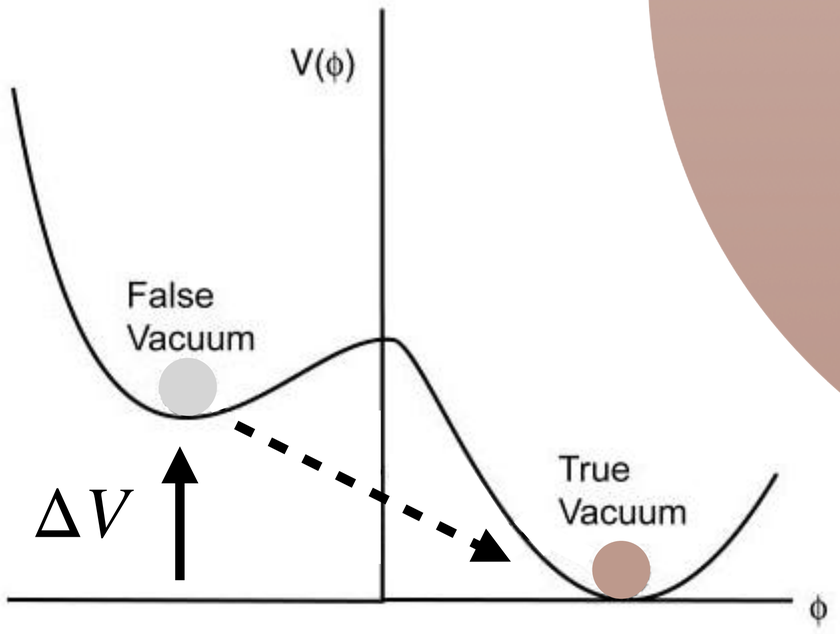

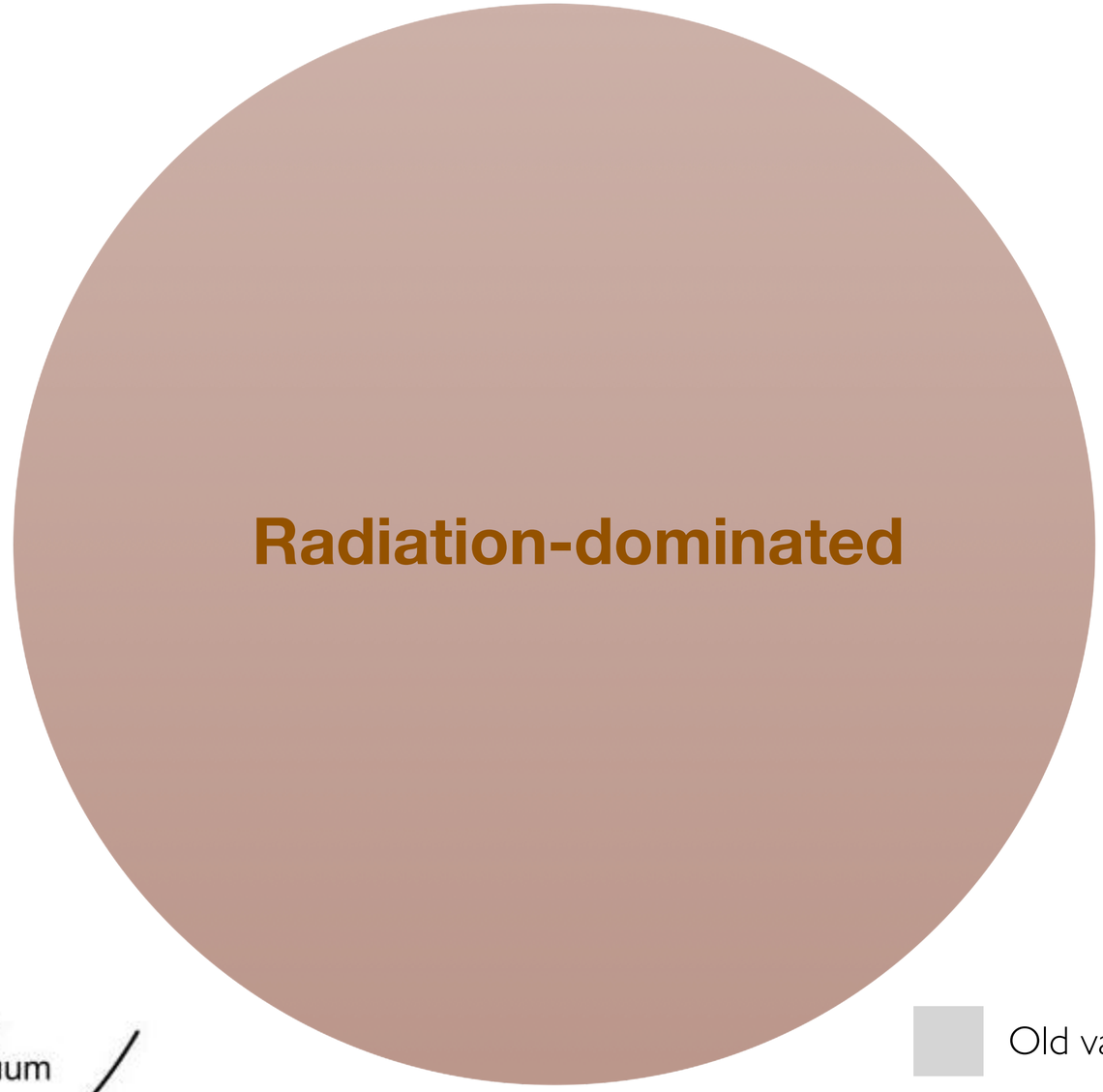

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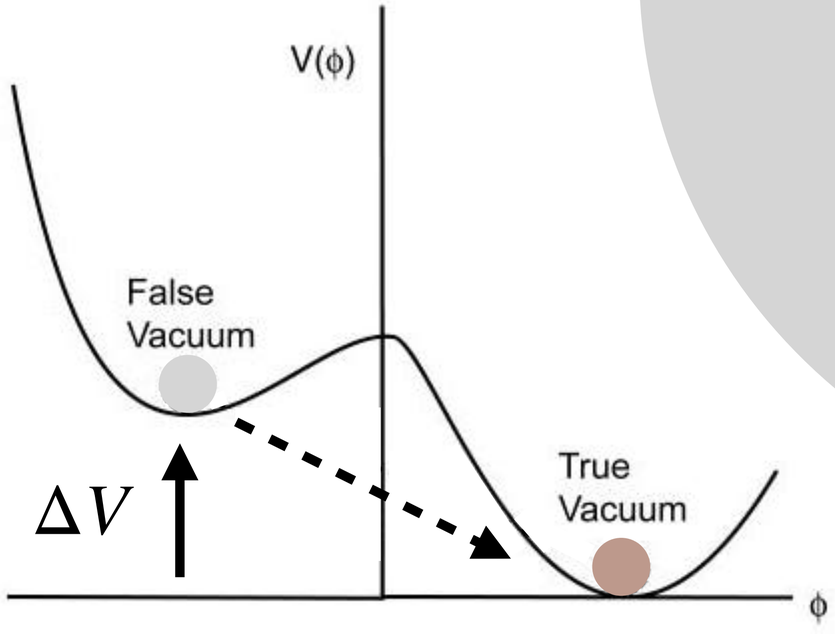

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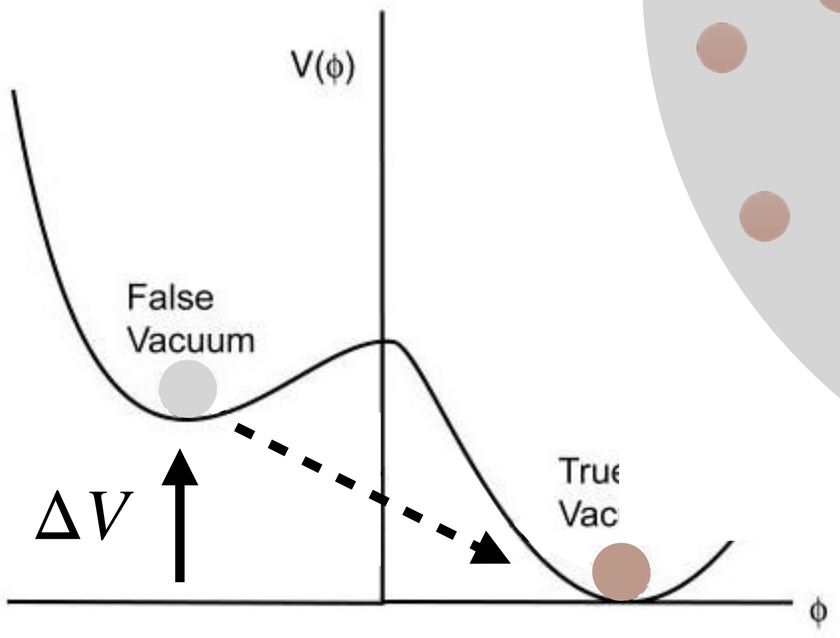

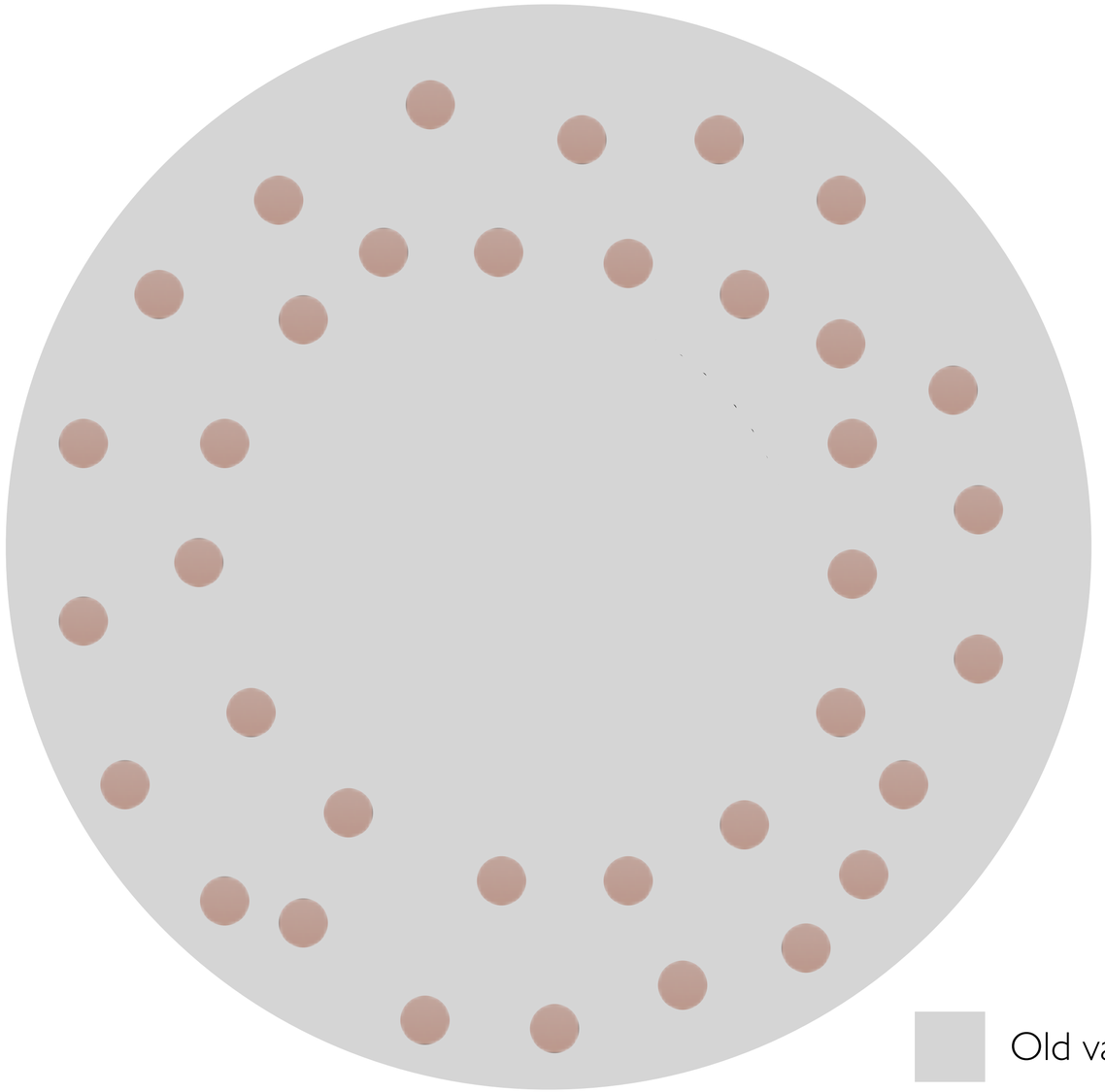

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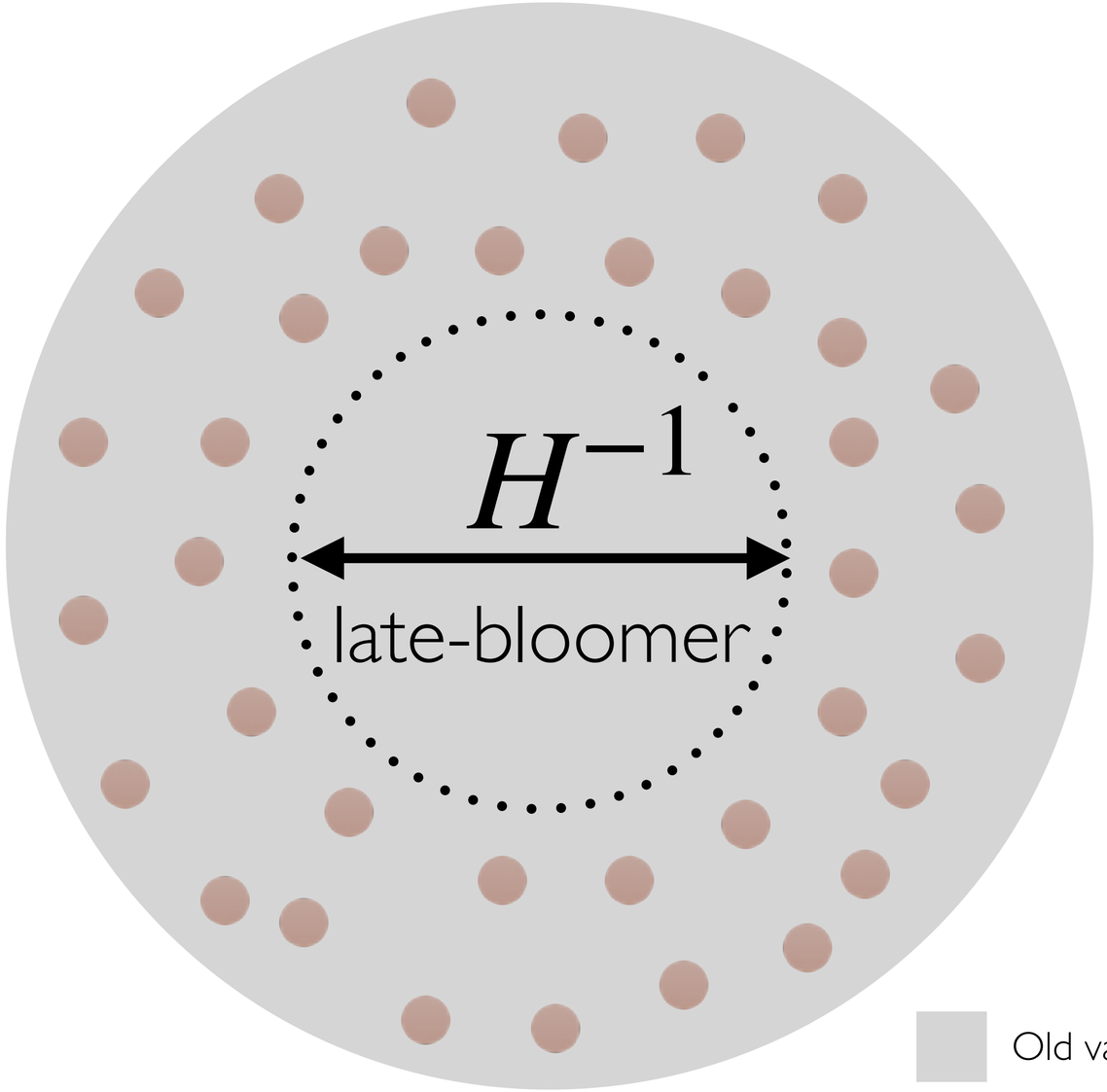

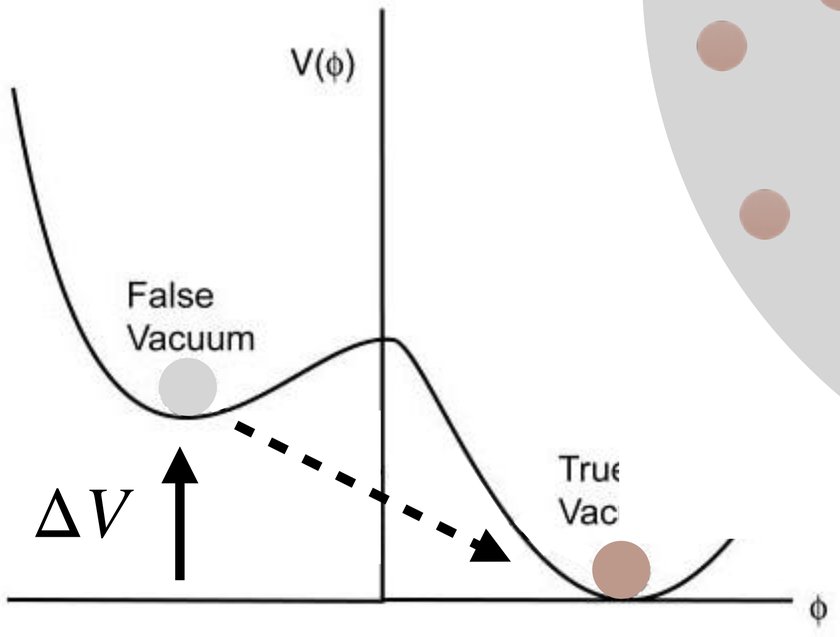

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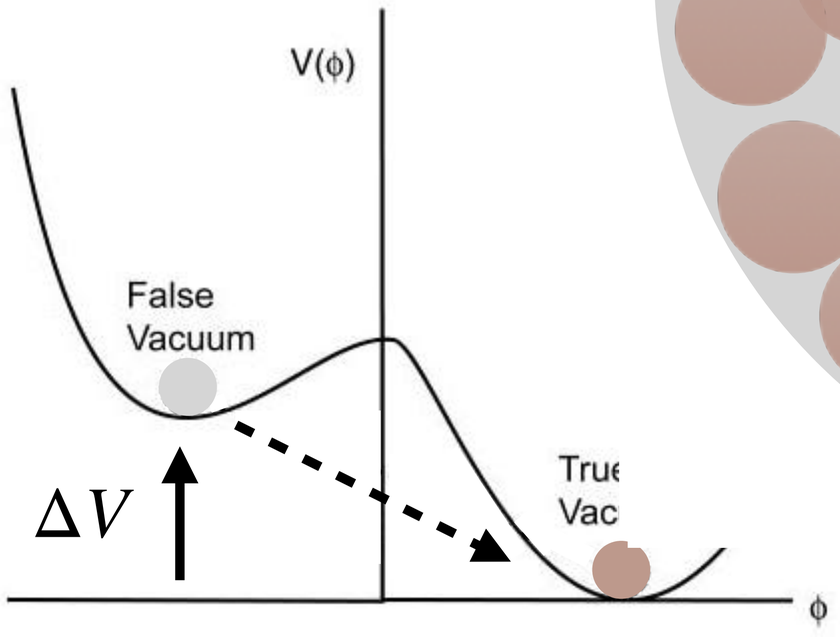

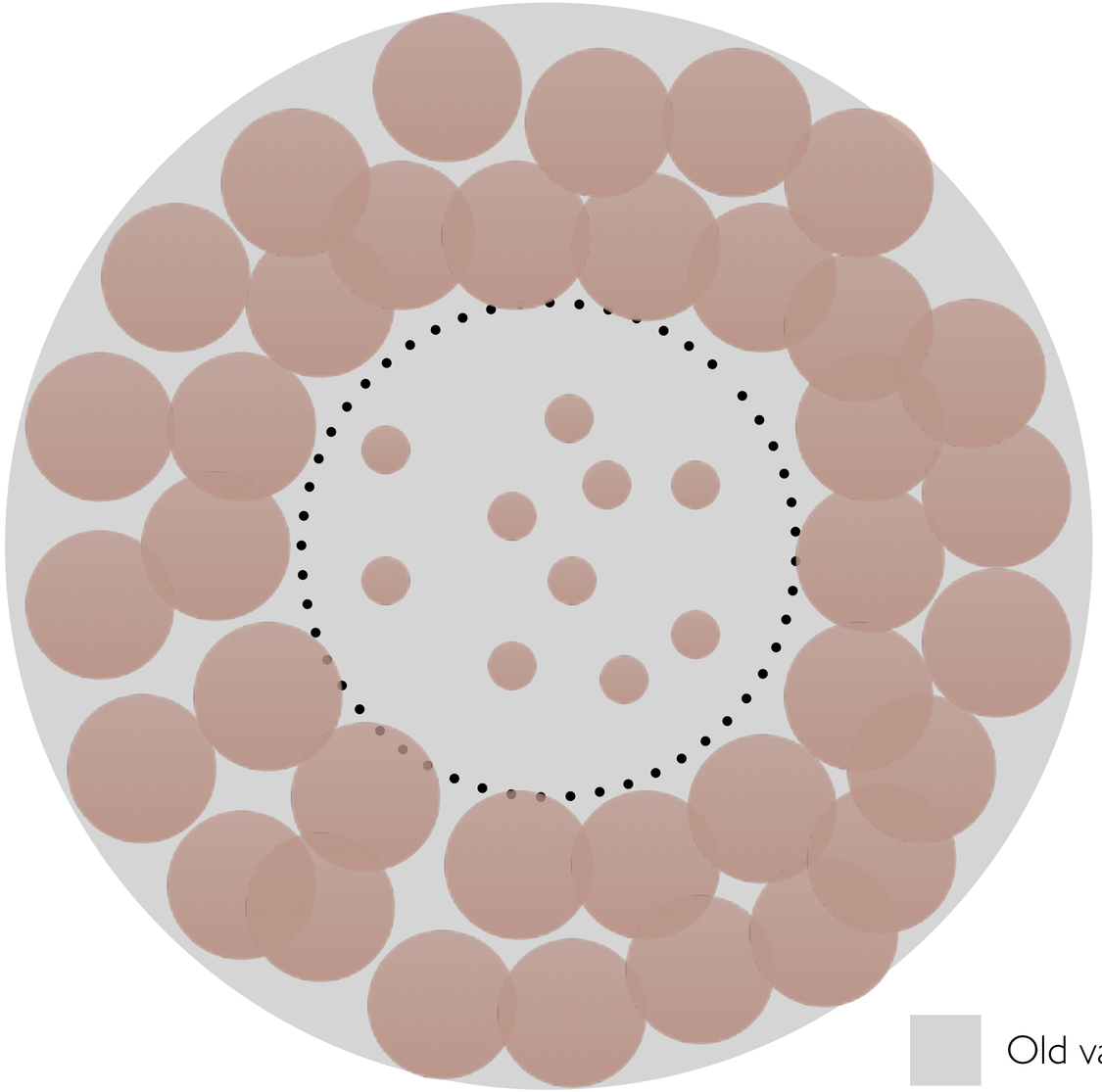

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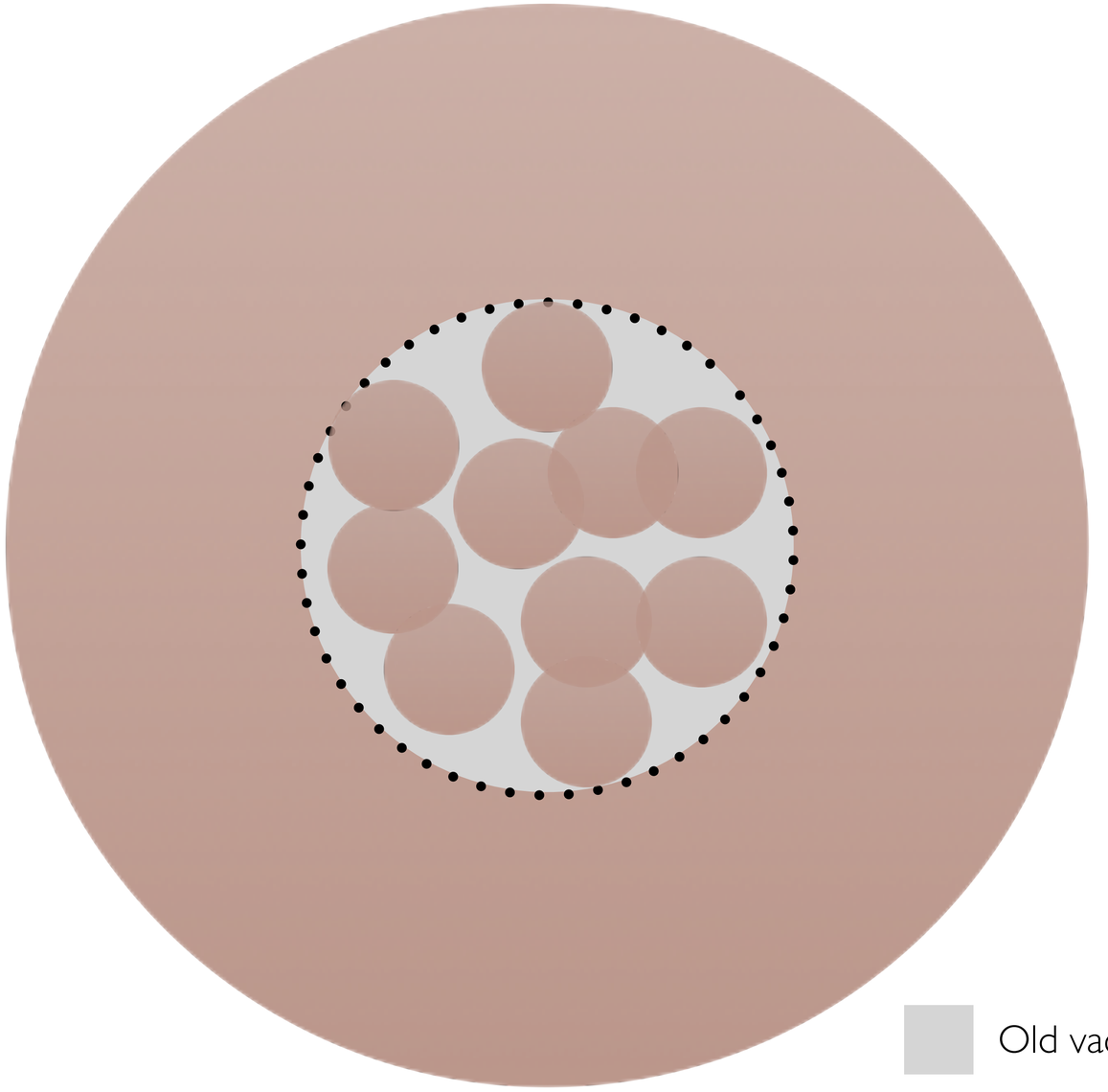
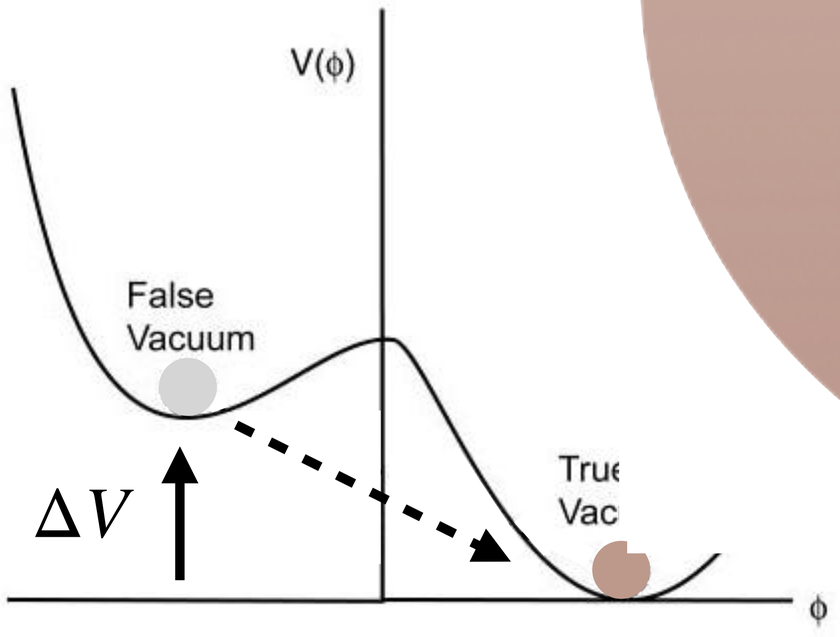


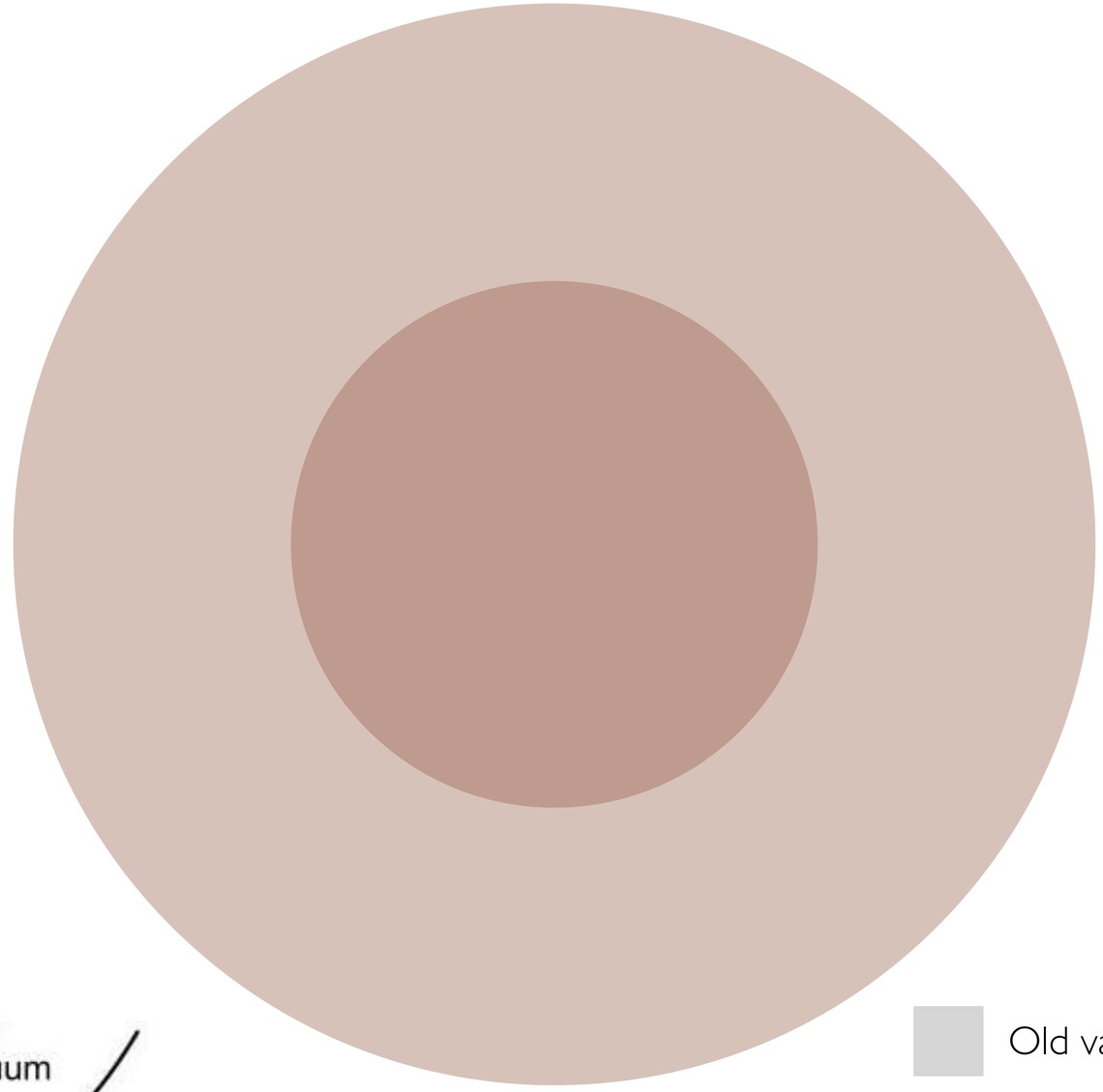


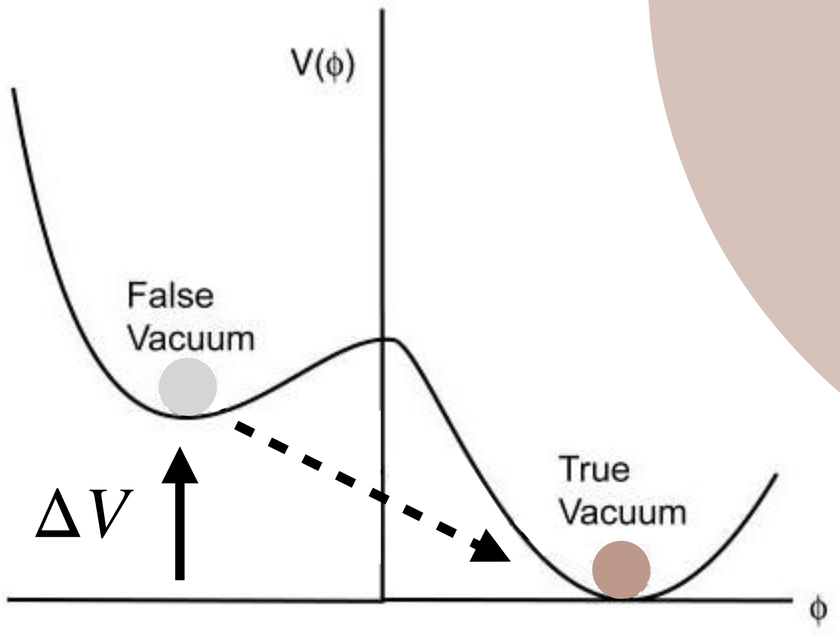
Old vacuum-dominated region (outside bubbles)

New radiation-dominated region (inside bubbles)

PBHs from 1stOPT

YG, Volansky 2305:04942



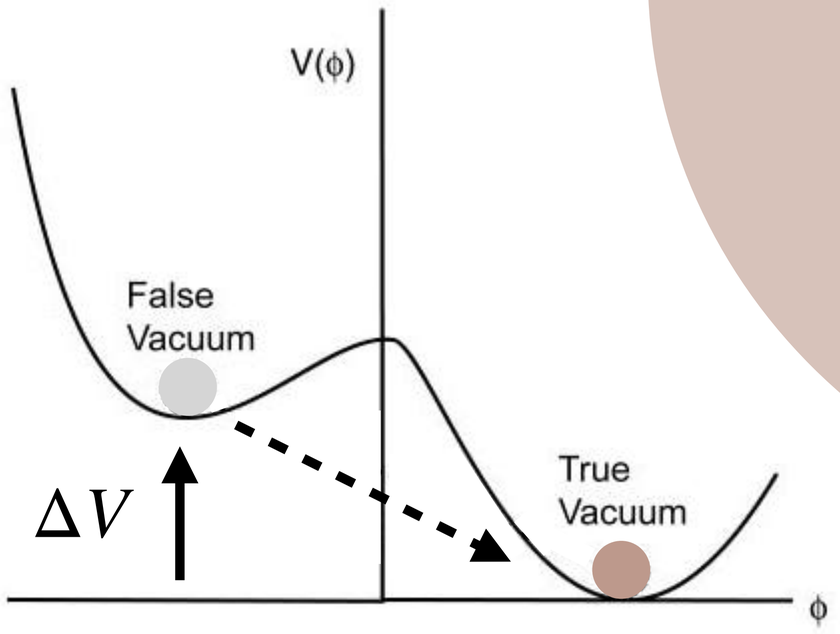


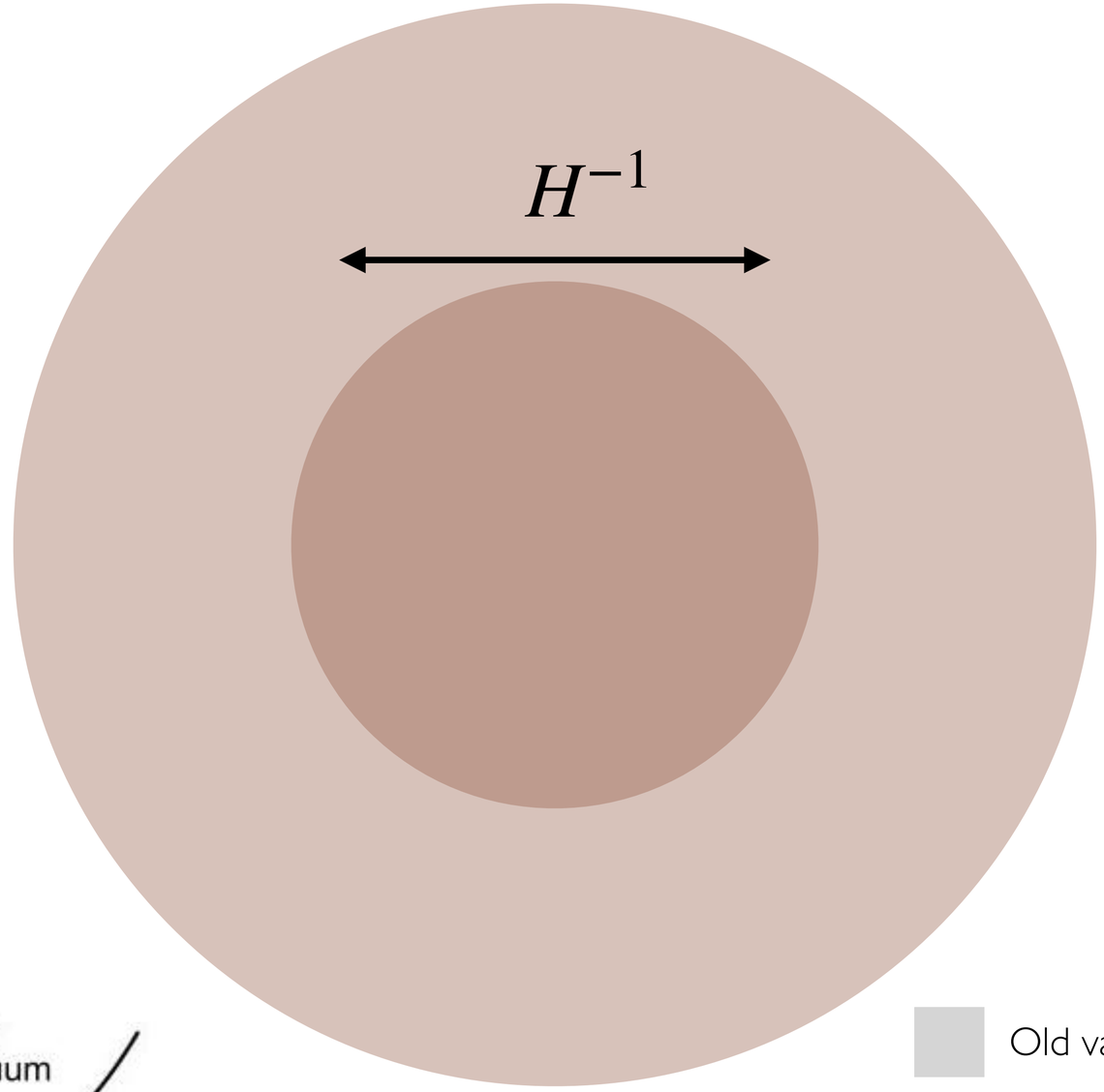
Old vacuum-dominated region (outside bubbles)

New radiation-dominated region (inside bubbles)

PBHs from 1stOPT

YG, Volansky 2305:04942





if

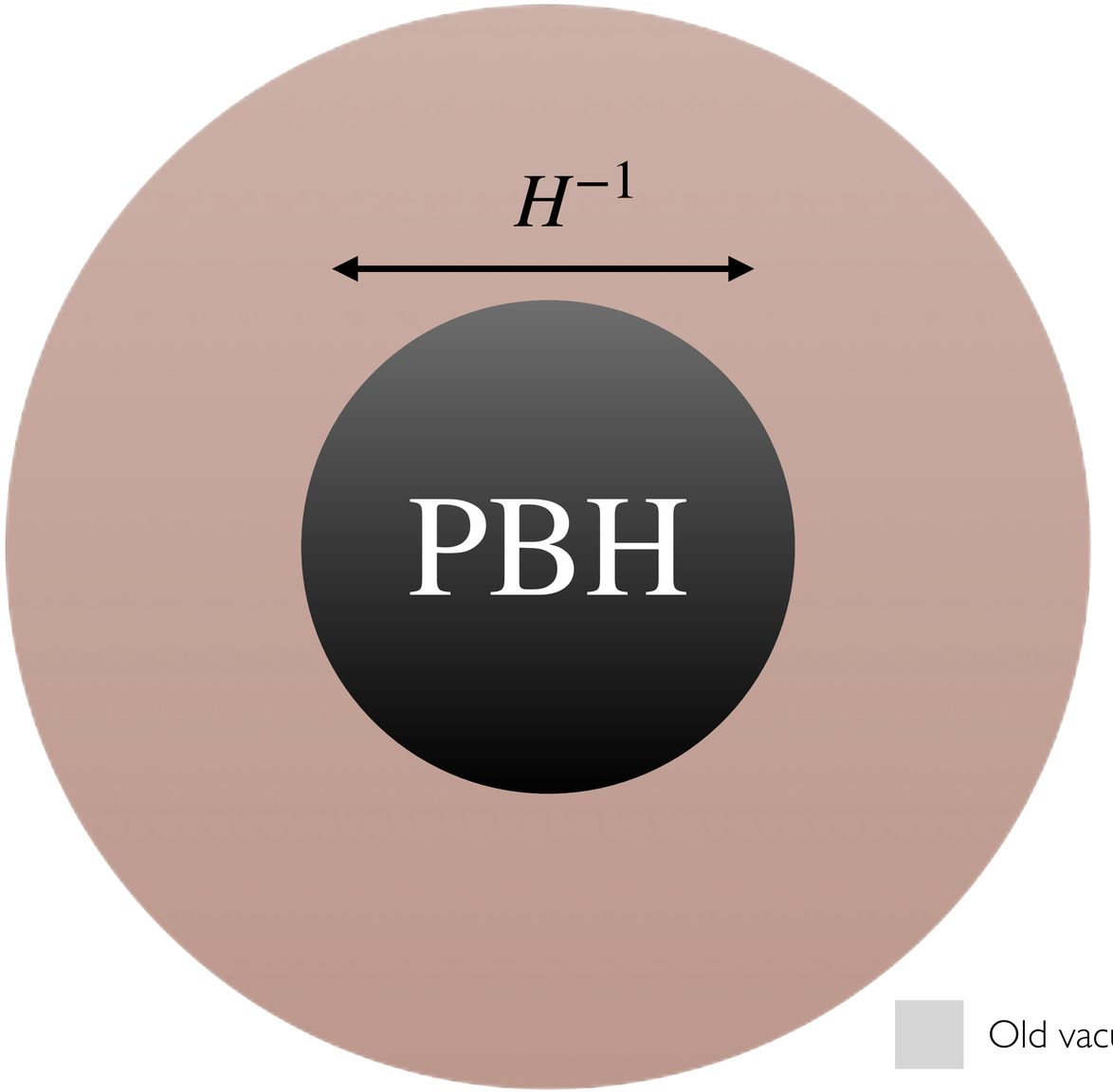
$$\delta\rho/\rho \gtrsim 0.45.$$

Old vacuum-dominated region (outside bubbles)

New radiation-dominated region (inside bubbles)

PBHs from 1stOPT

YG, Volansky 2305:04942

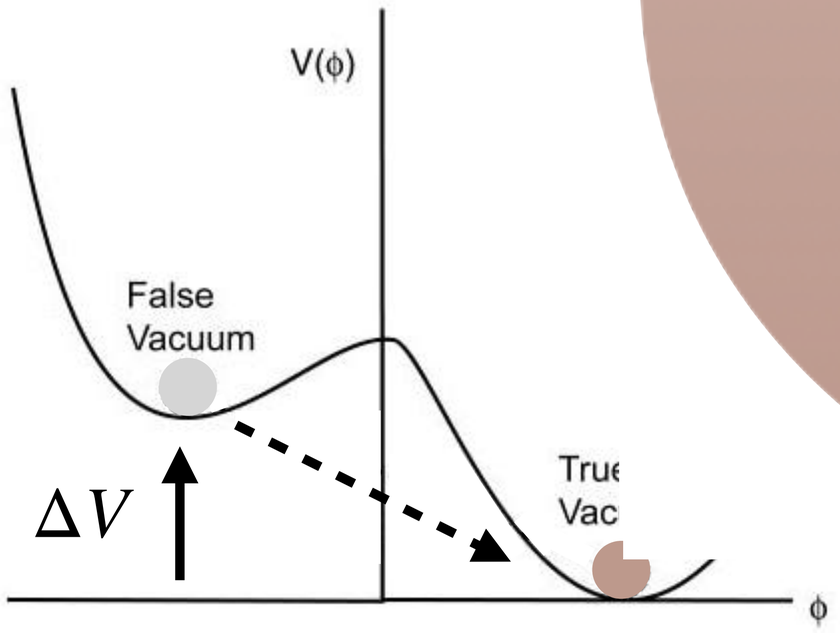


if

$$\delta\rho/\rho \gtrsim 0.45.$$

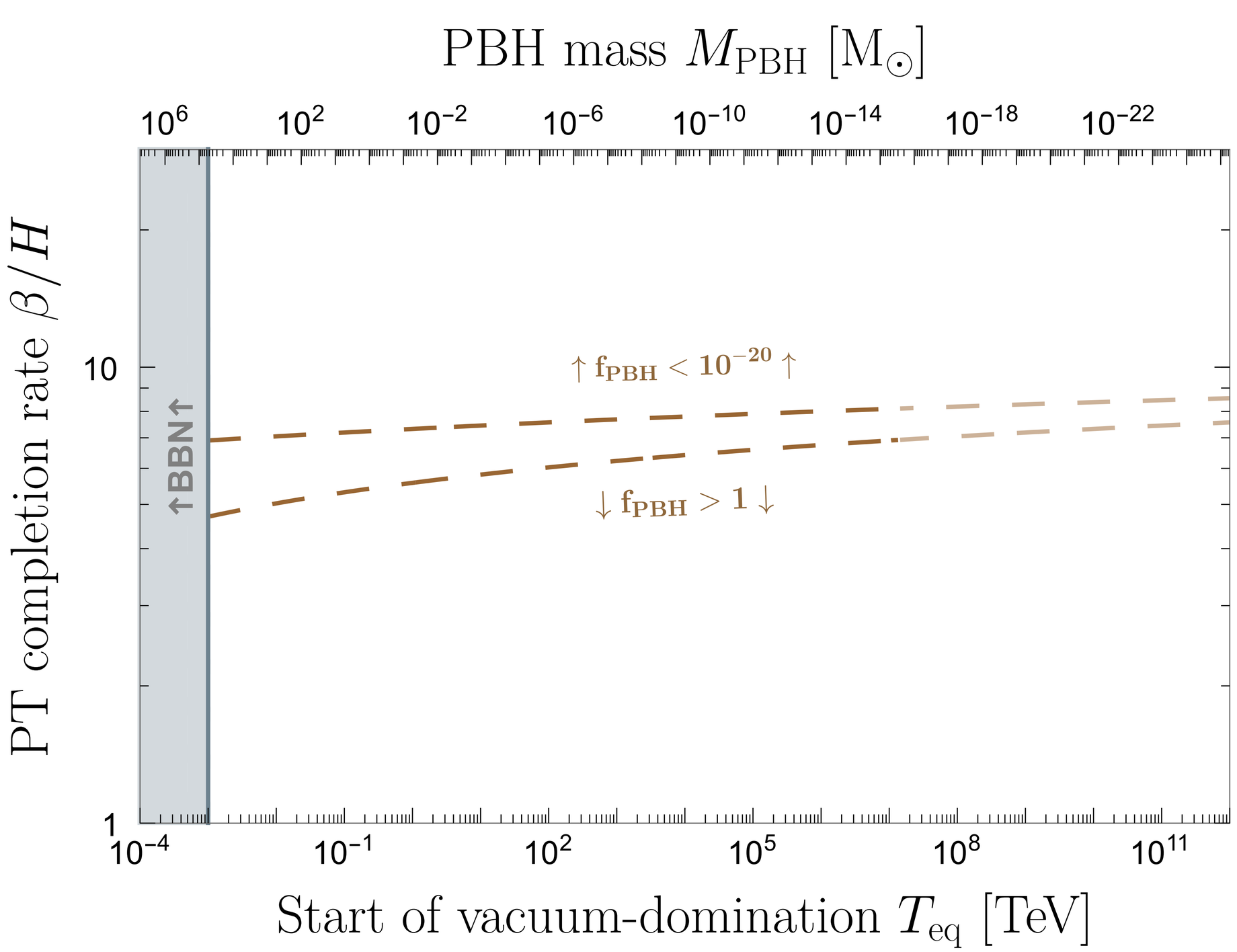
then

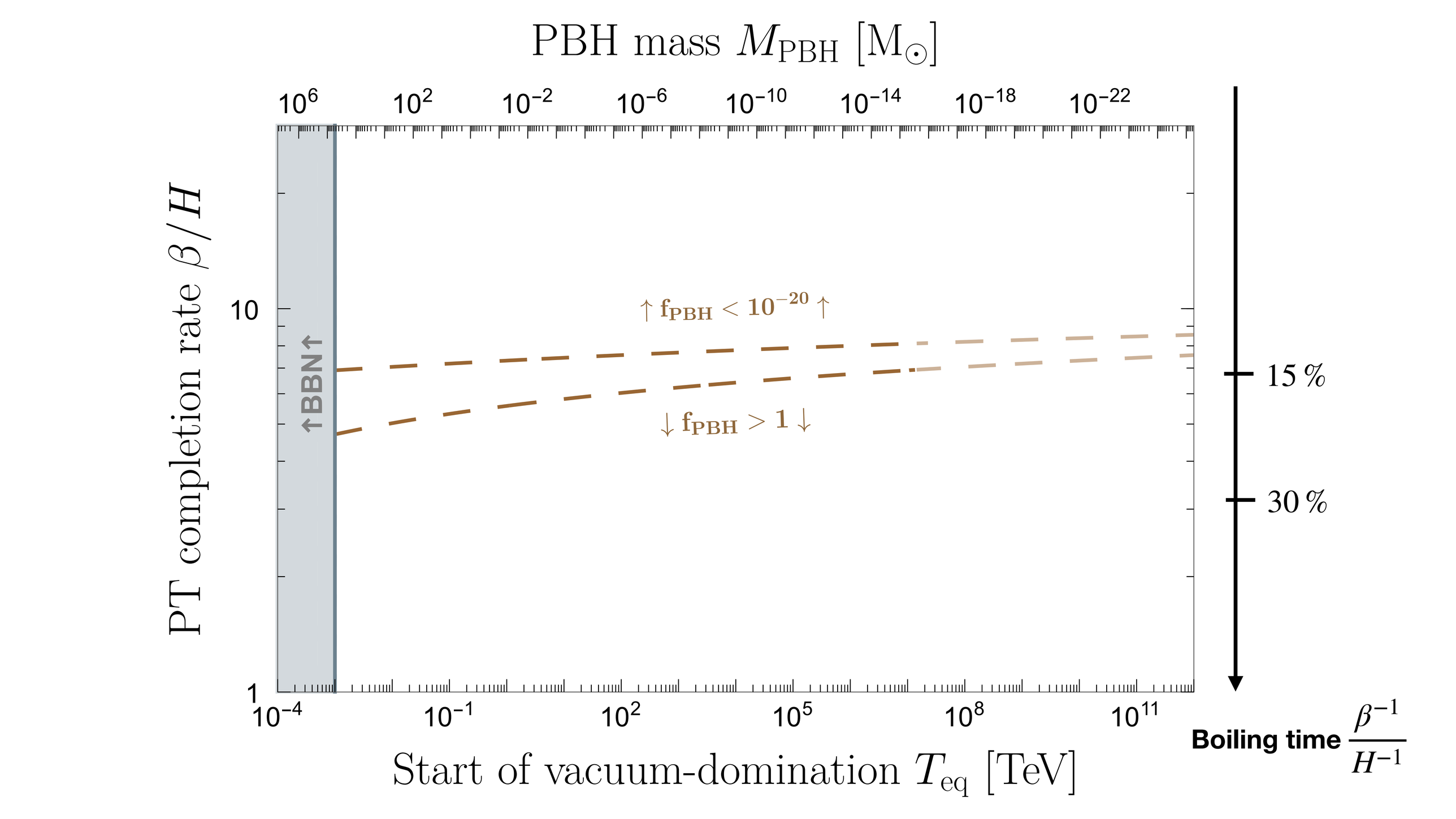
PBH

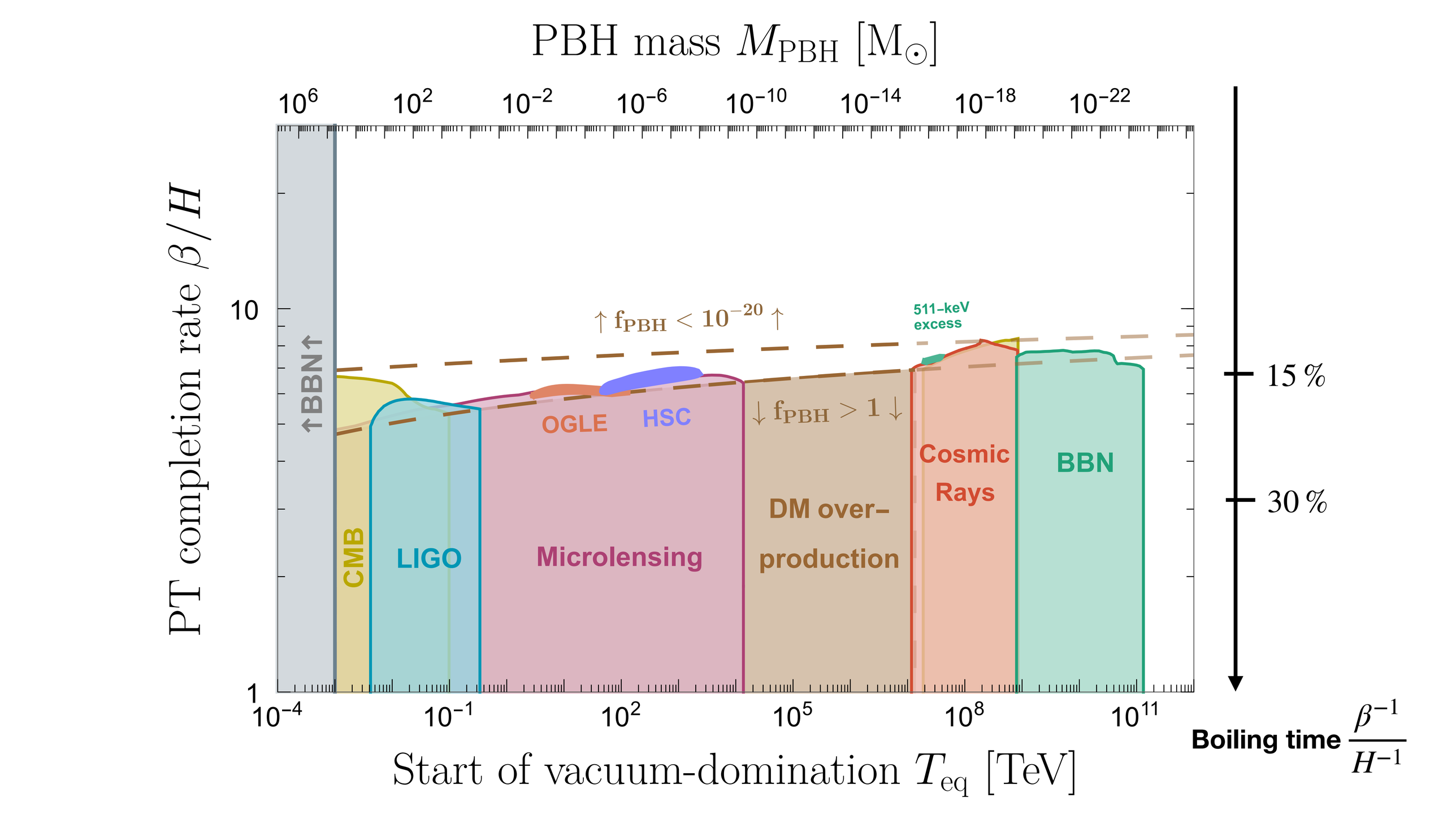


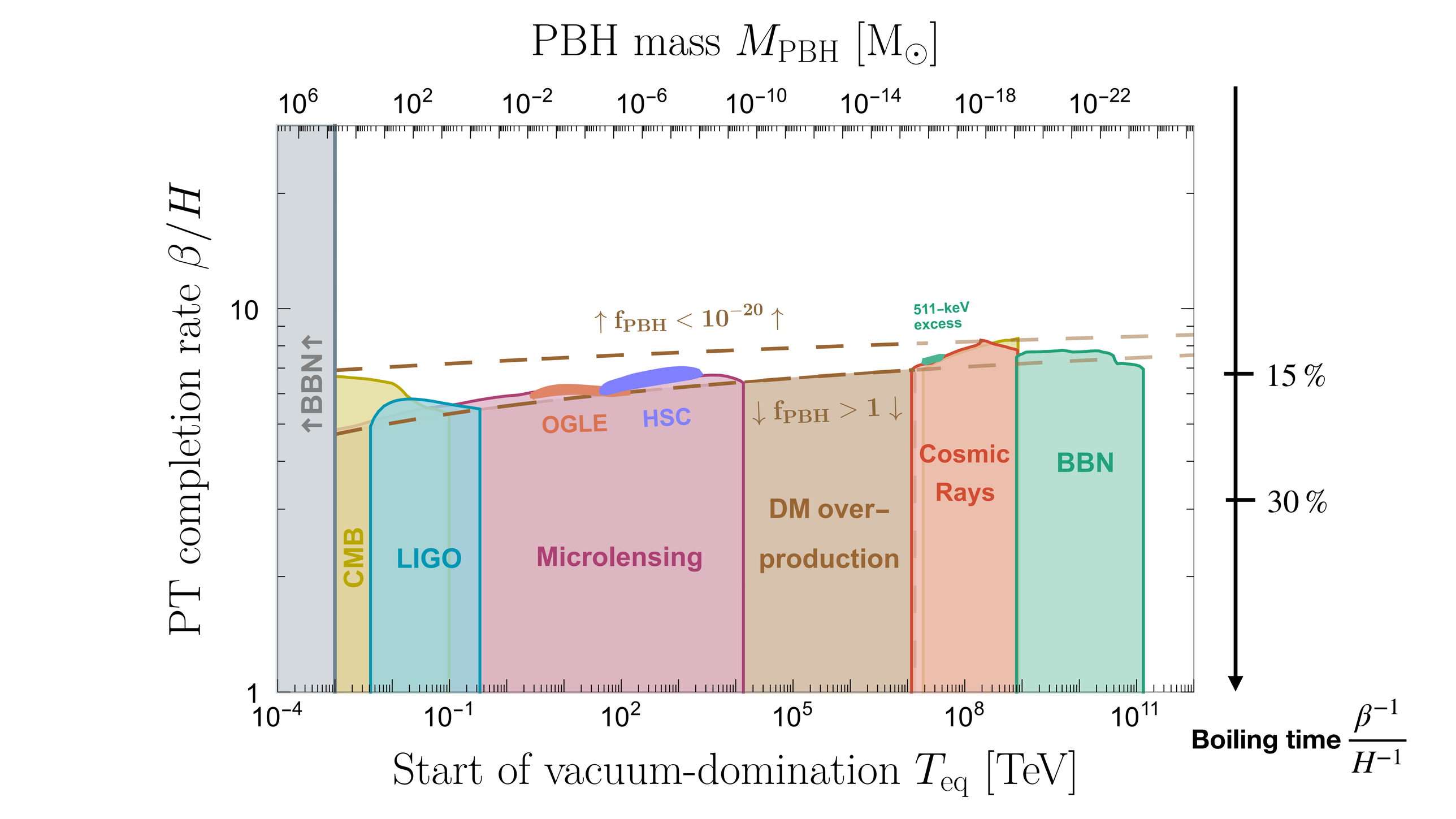
Old vacuum-dominated region (outside bubbles)

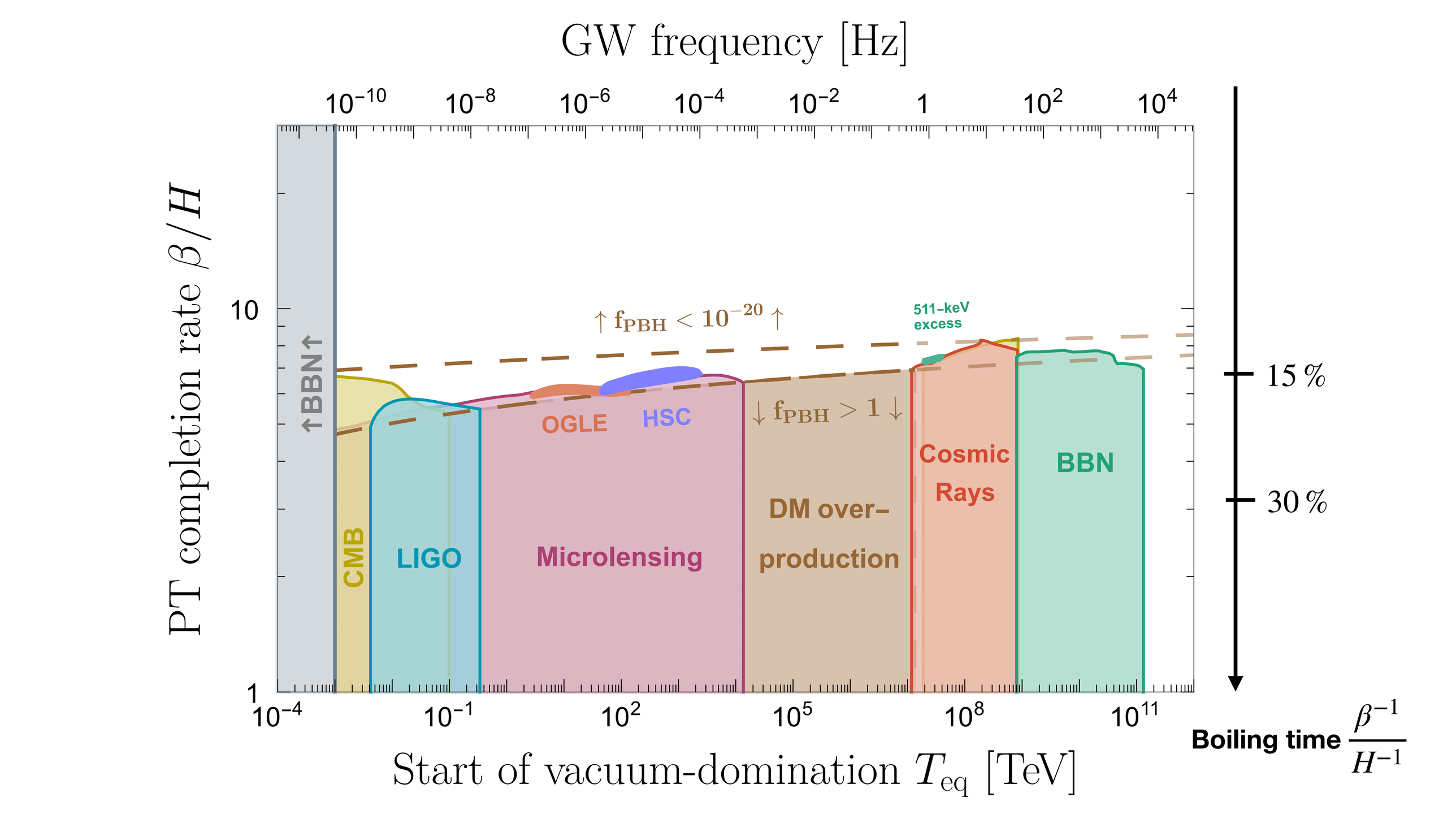
New radiation-dominated region (inside bubbles)

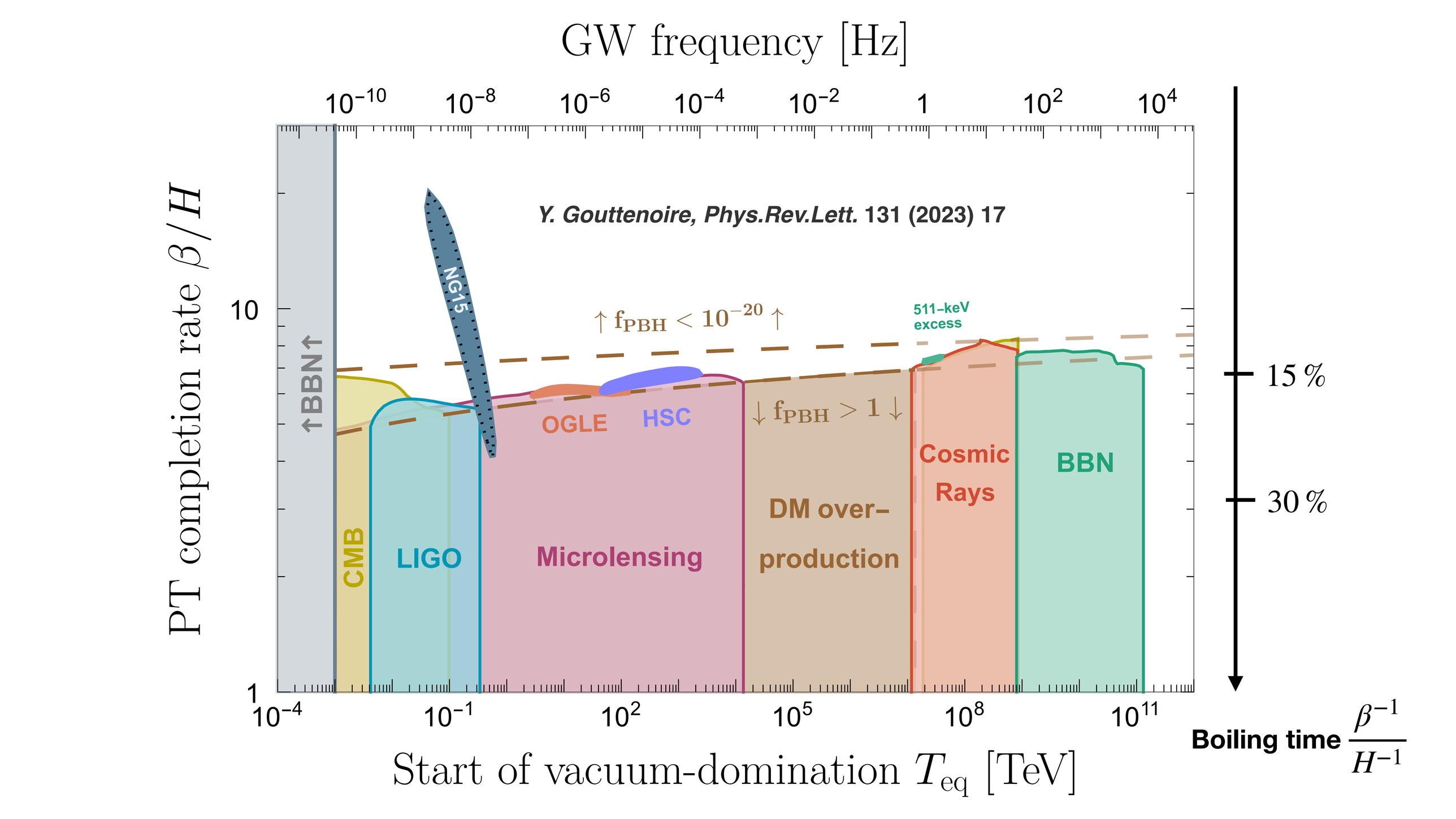

PBH mass $M_{\rm PBH}$ [$M_\odot$]
10^{6}
10^{2}
10^{-2}
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
PT completion rate β/H
10
1
↑BBN↑
$\uparrow f_{\rm PBH} < 10^{-20} \uparrow$
$\downarrow f_{\rm PBH} > 1 \downarrow$
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
Start of vacuum-domination $T_{\rm eq}$ [TeV]

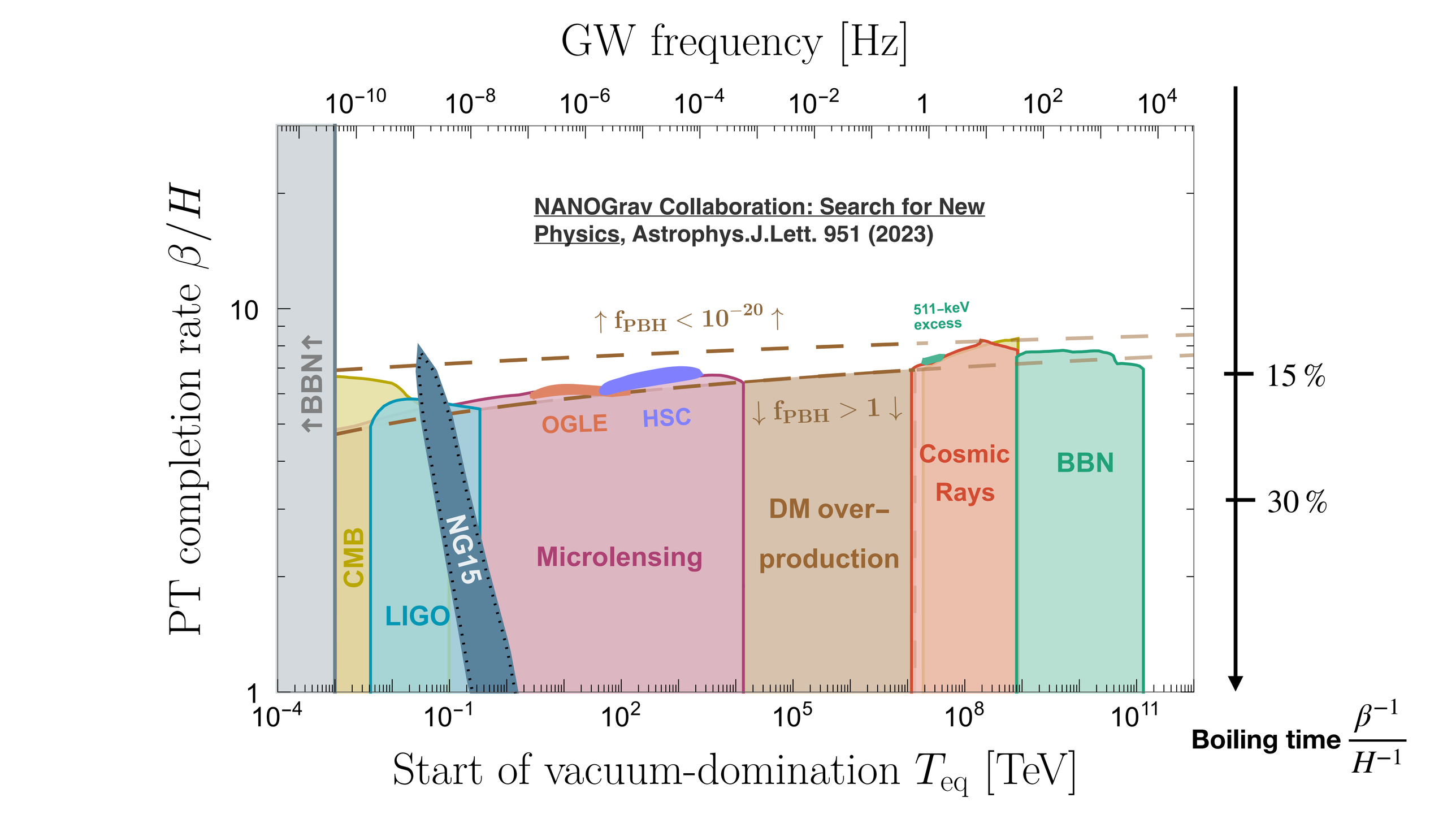

PBH mass $M_{\rm PBH}$ [$M_\odot$]
10^{6}
10^{2}
10^{-2}
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
PT completion rate β/H
10
1
↑BBN↑
↑ $f_{\rm PBH} < 10^{-20}$ ↑
↓ $f_{\rm PBH} > 1$ ↓
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
Start of vacuum-domination $T_{\rm eq}$ [TeV]
15 %
30 %
Boiling time $\frac{\beta^{-1}}{H^{-1}}$

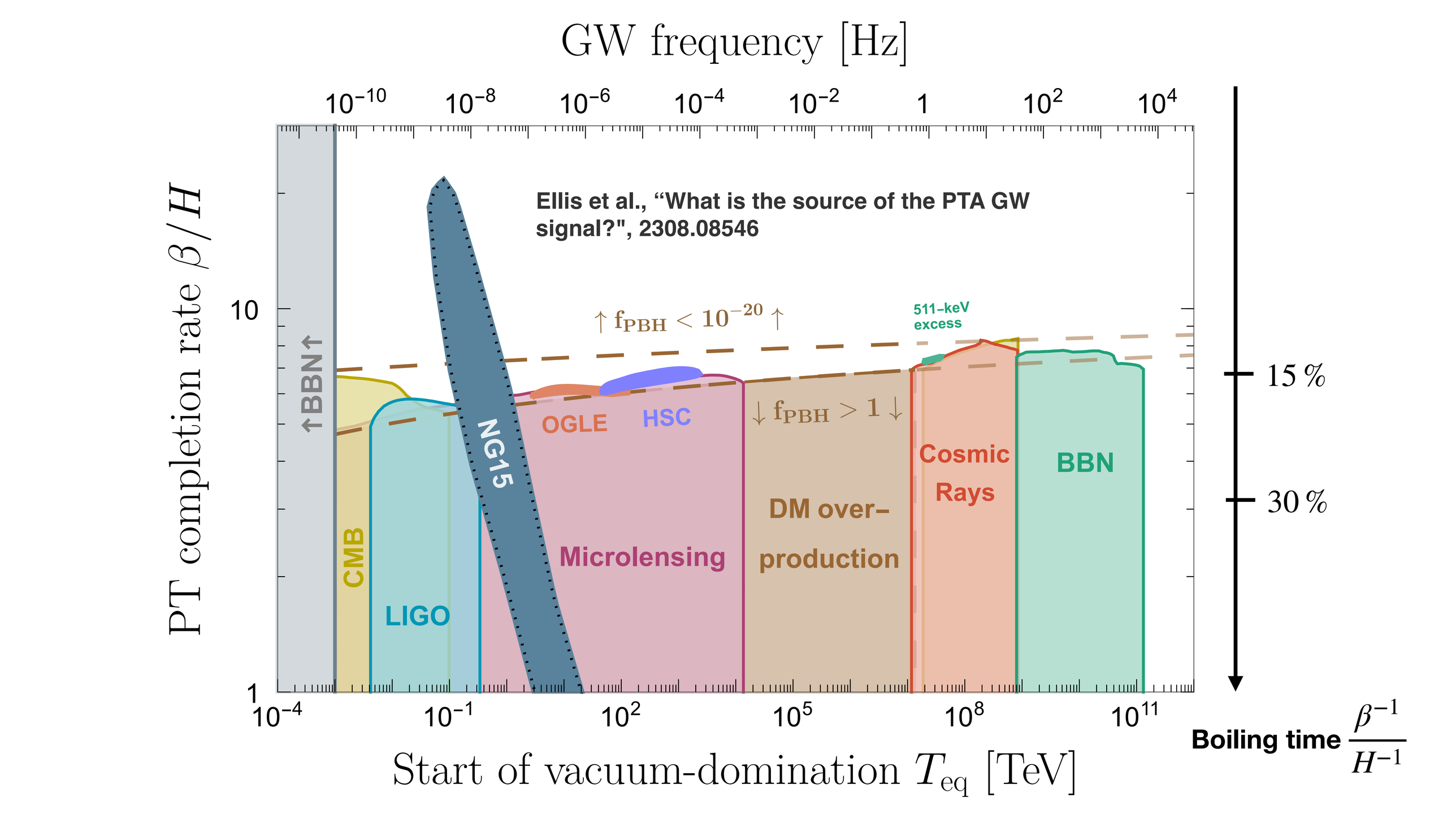

PBH mass $M_{\rm PBH}$ [$M_\odot$]
10^{6}
10^{2}
10^{-2}
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
PT completion rate β/H
10
1
↑BBN↑
CMB
LIGO
OGLE
HSC
Microlensing
$\uparrow f_{\rm PBH} < 10^{-20} \uparrow$
$\downarrow f_{\rm PBH} > 1 \downarrow$
DM over–production
511–keV excess
Cosmic Rays
BBN
15 %
30 %
Boiling time $\frac{\beta^{-1}}{H^{-1}}$
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
Start of vacuum-domination $T_{\rm eq}$ [TeV]


PBH mass $M_{\rm PBH}$ [$M_\odot$]
10^{6}
10^{2}
10^{-2}
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
PT completion rate β/H
10
1
↑BBN↑
CMB
LIGO
OGLE
HSC
Microlensing
$\uparrow f_{\rm PBH} < 10^{-20} \uparrow$
$\downarrow f_{\rm PBH} > 1 \downarrow$
DM over–production
511–keV excess
Cosmic Rays
BBN
15 %
30 %
Boiling time $\frac{\beta^{-1}}{H^{-1}}$
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
Start of vacuum-domination $T_{\rm eq}$ [TeV]

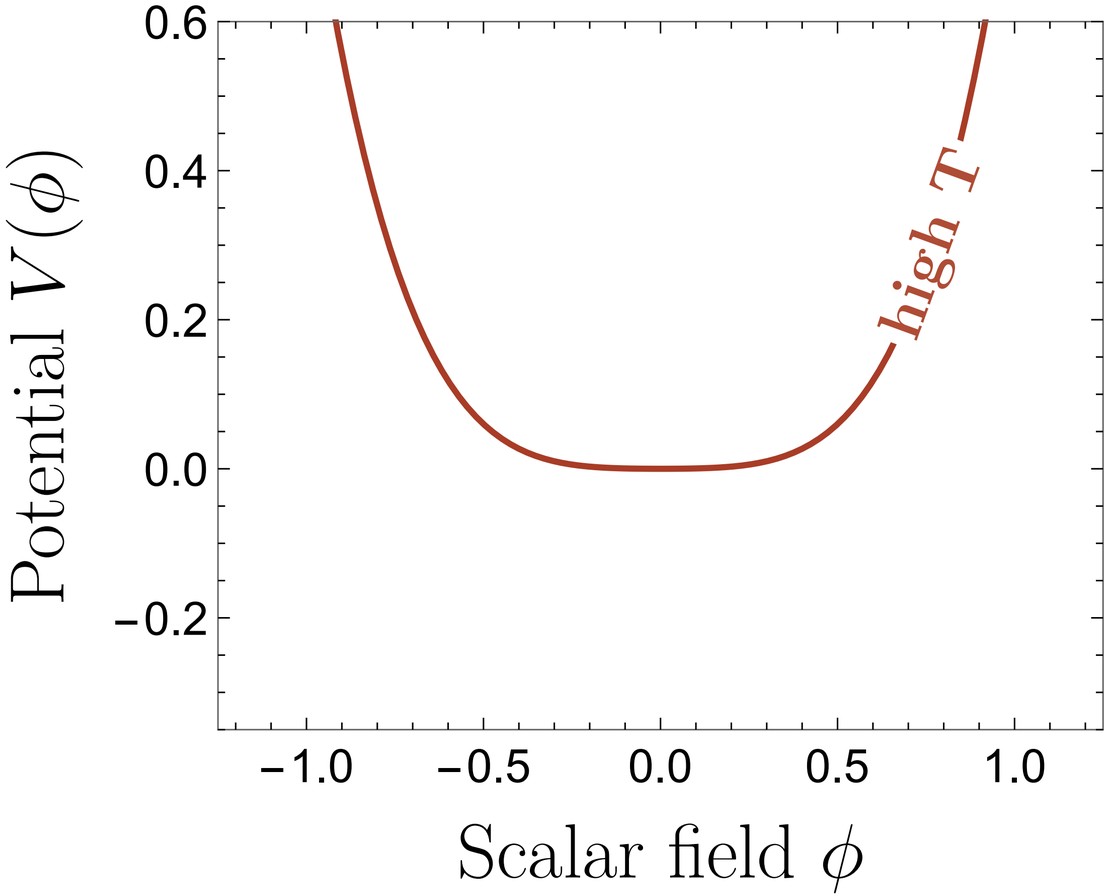

GW frequency [Hz]
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
PT completion rate β/H
10
1
↑BBN↑
CMB
LIGO
OGLE
HSC
Microlensing
$\uparrow f_{PBH} < 10^{-20} \uparrow$
$\downarrow f_{PBH} > 1 \downarrow$
DM over–production
511–keV excess
Cosmic Rays
BBN
15 %
30 %
Boiling time $\frac{\beta^{-1}}{H^{-1}}$
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
Start of vacuum-domination T_{eq} [TeV]


GW frequency [Hz]
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
Y. Gouttenoire, Phys.Rev.Lett. 131 (2023) 17
NG15
↑BBN↑
$\uparrow f_{PBH} < 10^{-20} \uparrow$
511-keV excess
OGLE
HSC
$\downarrow f_{PBH} > 1 \downarrow$
CMB
LIGO
Microlensing
DM over-production
Cosmic Rays
BBN
PT completion rate β/H
10
1
15 %
30 %
Boiling time $\frac{\beta^{-1}}{H^{-1}}$
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
Start of vacuum-domination T_{eq} [TeV]

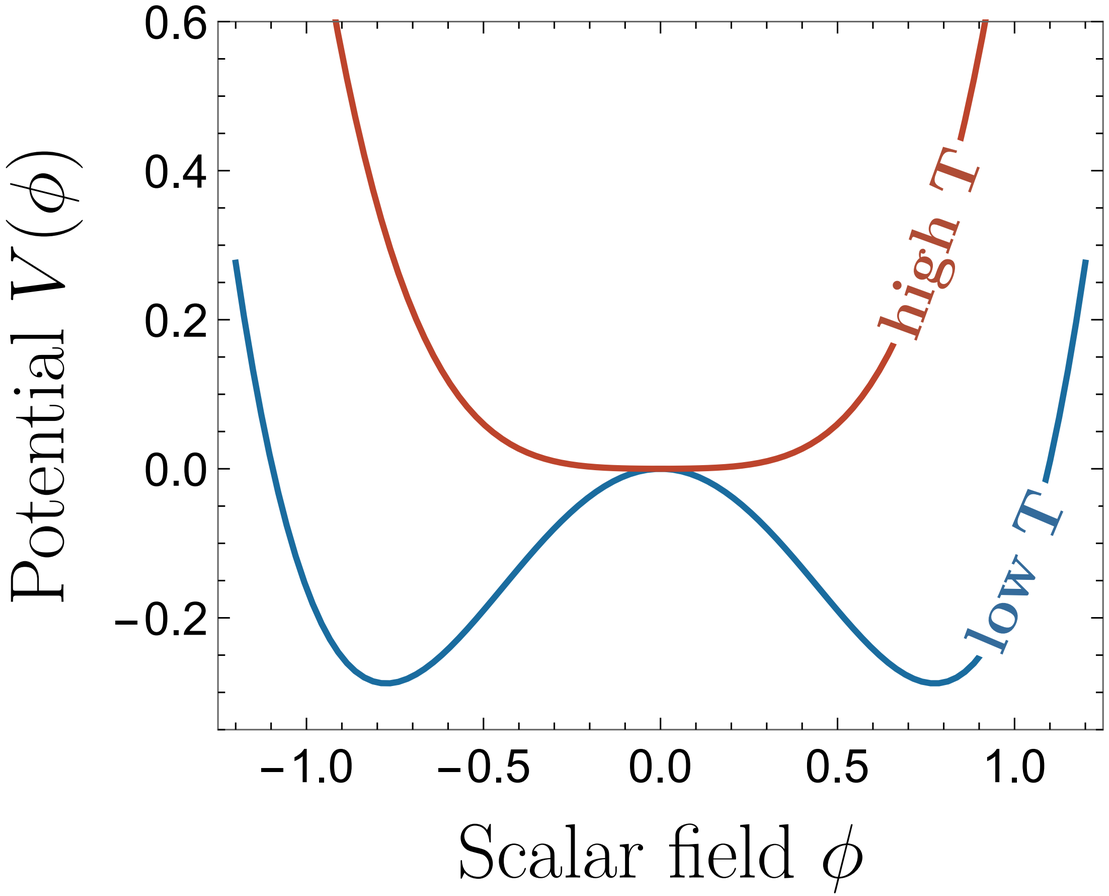

GW frequency [Hz]
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
NANOGrav Collaboration: Search for New Physics, Astrophys.J.Lett. 951 (2023)
PT completion rate β/H
10
1
↑BBN↑
$\uparrow f_{PBH} < 10^{-20} \uparrow$
511-keV excess
OGLE
HSC
$\downarrow f_{PBH} > 1 \downarrow$
CMB
LIGO
NG15
Microlensing
DM over-production
Cosmic Rays
BBN
15 %
30 %
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
Start of vacuum-domination T_{eq} [TeV]
Boiling time $\frac{\beta^{-1}}{H^{-1}}$


GW frequency [Hz]
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
PT completion rate β/H
10
1
Ellis et al., “What is the source of the PTA GW signal?", 2308.08546
↑BBN↑
CMB
LIGO
NG15
OGLE
HSC
Microlensing
$\uparrow f_{PBH} < 10^{-20} \uparrow$
$\downarrow f_{PBH} > 1 \downarrow$
DM over–production
511–keV excess
Cosmic Rays
BBN
15 %
30 %
Boiling time $\frac{\beta^{-1}}{H^{-1}}$
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
Start of vacuum-domination T_{eq} [TeV]

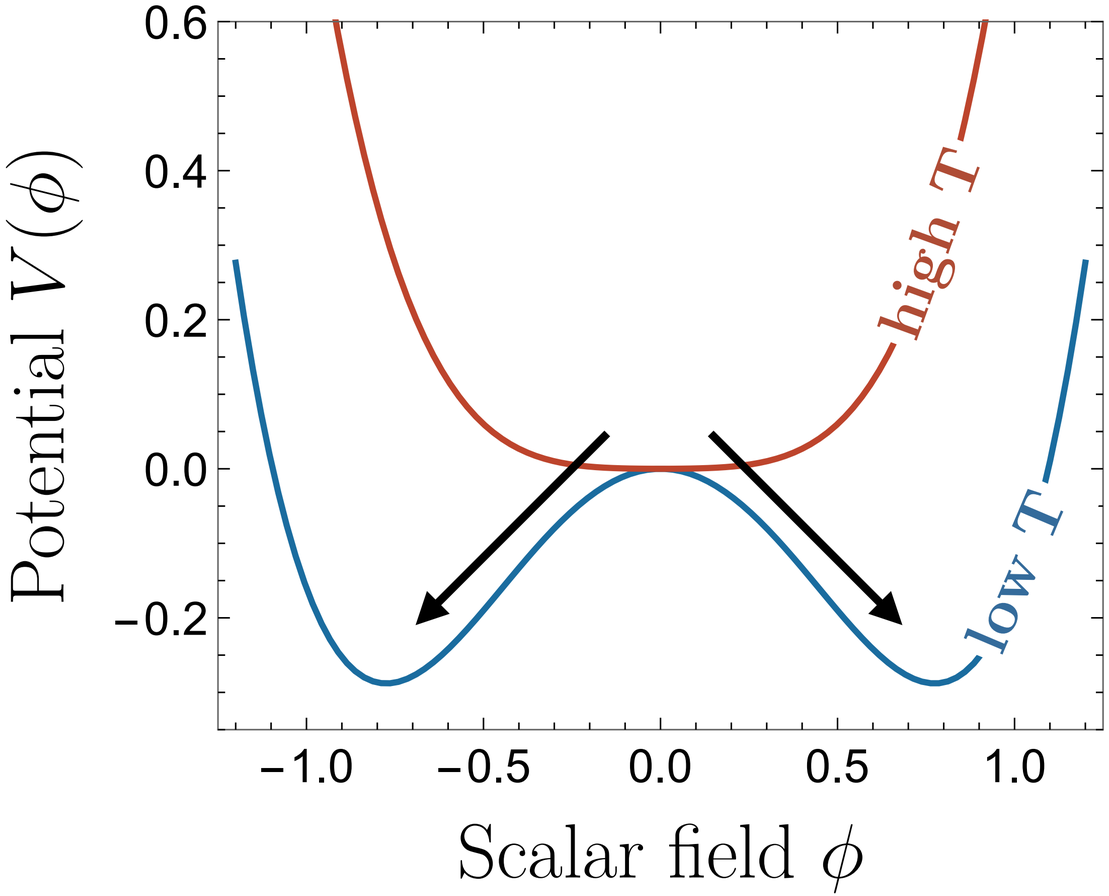
Formation of Domain Wall



Formation of Domain Wall

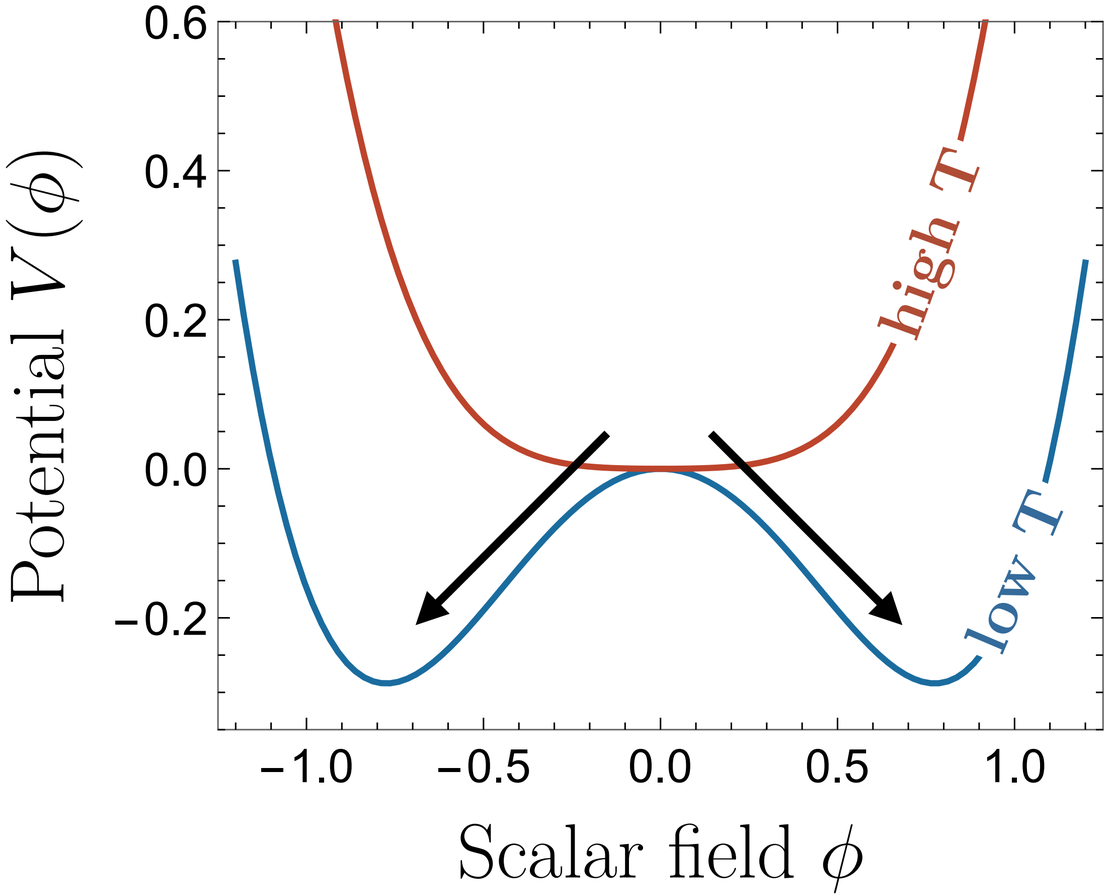


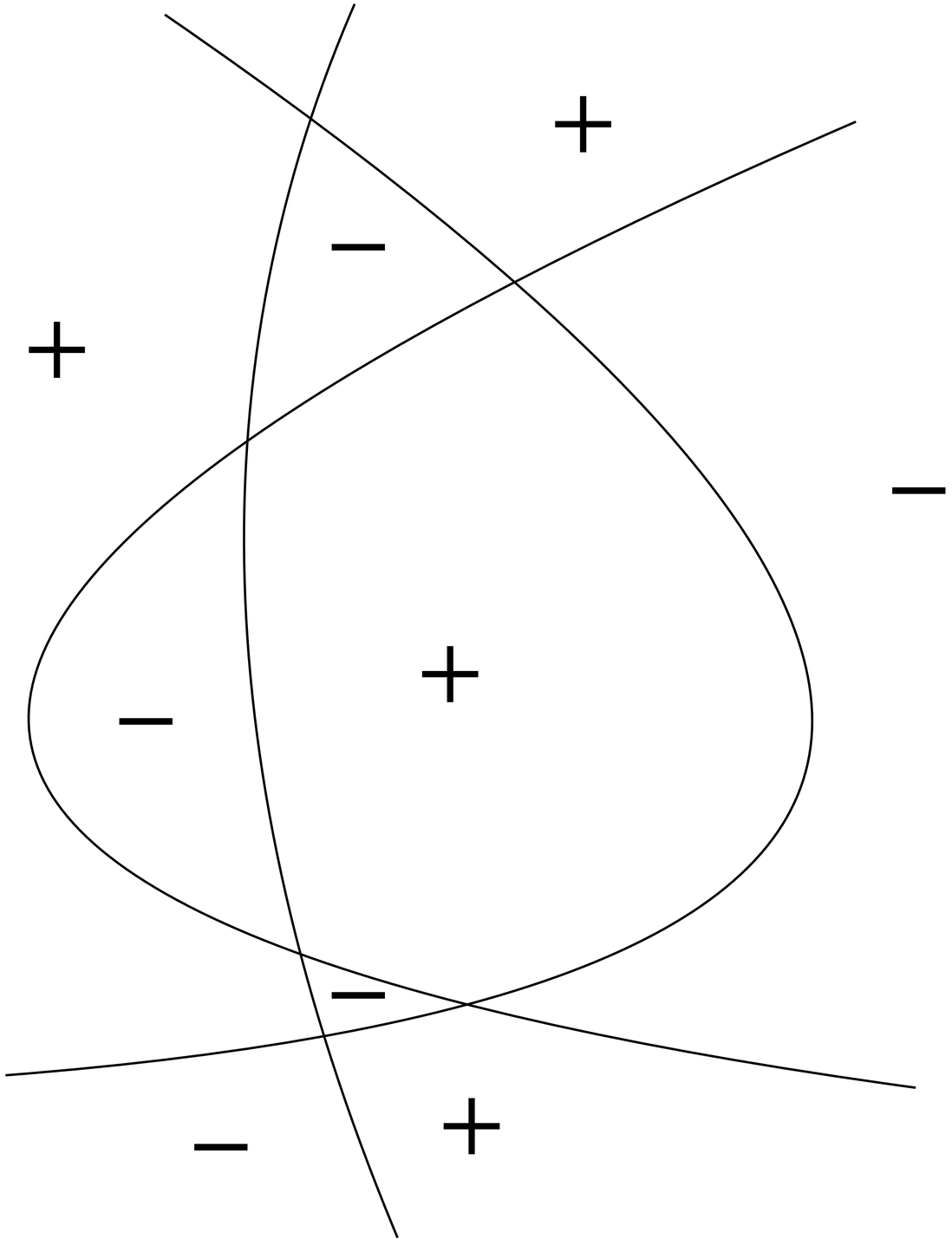
Formation of Domain Wall



Spontaneous breaking of $\mathbb{Z}_2$

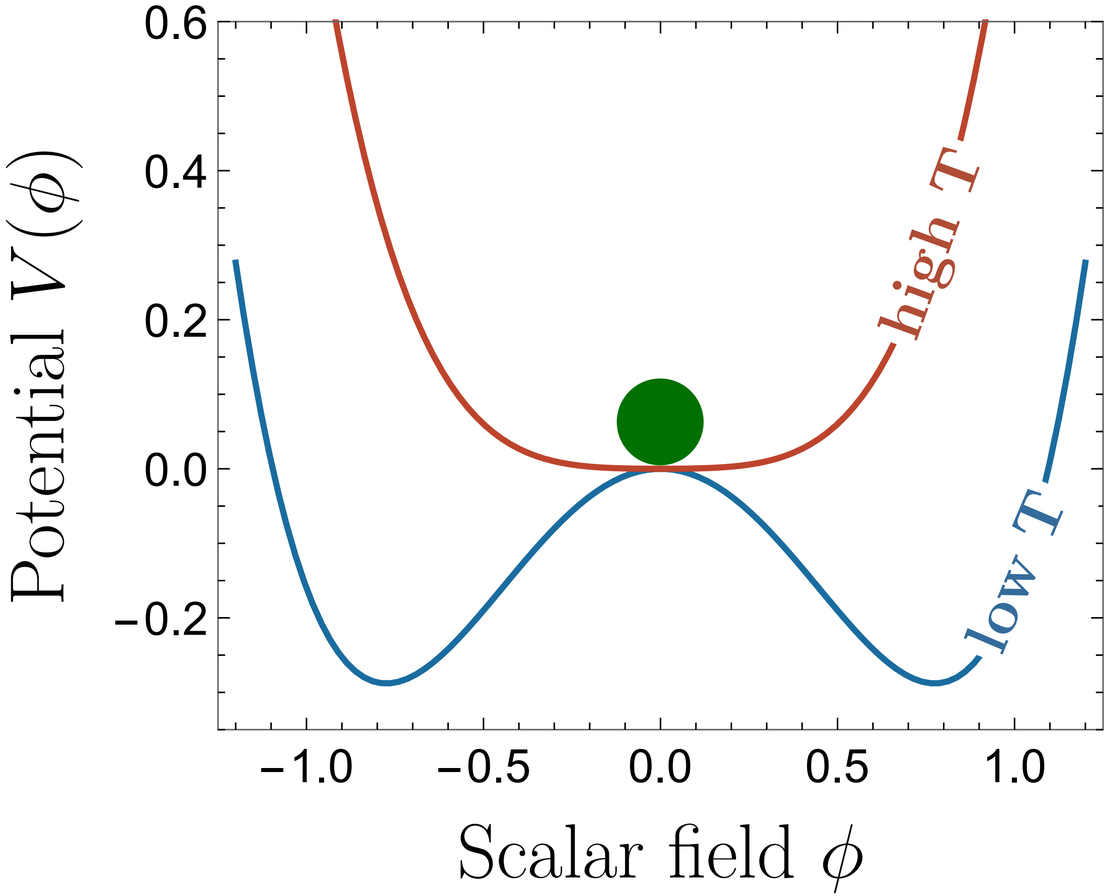
Formation of Domain Wall

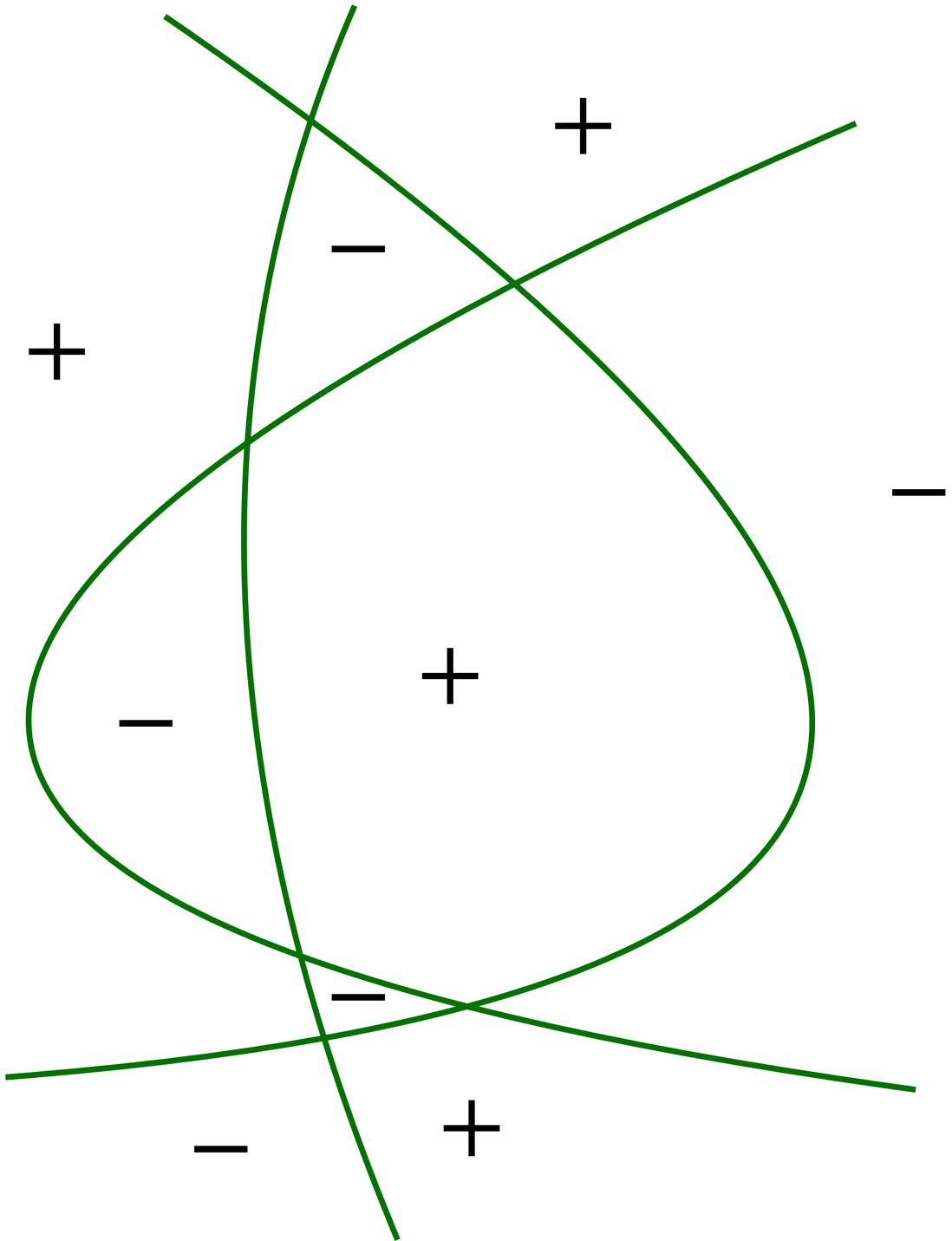




Spontaneous breaking of $\mathbb{Z}_2$

Formation of Domain Wall



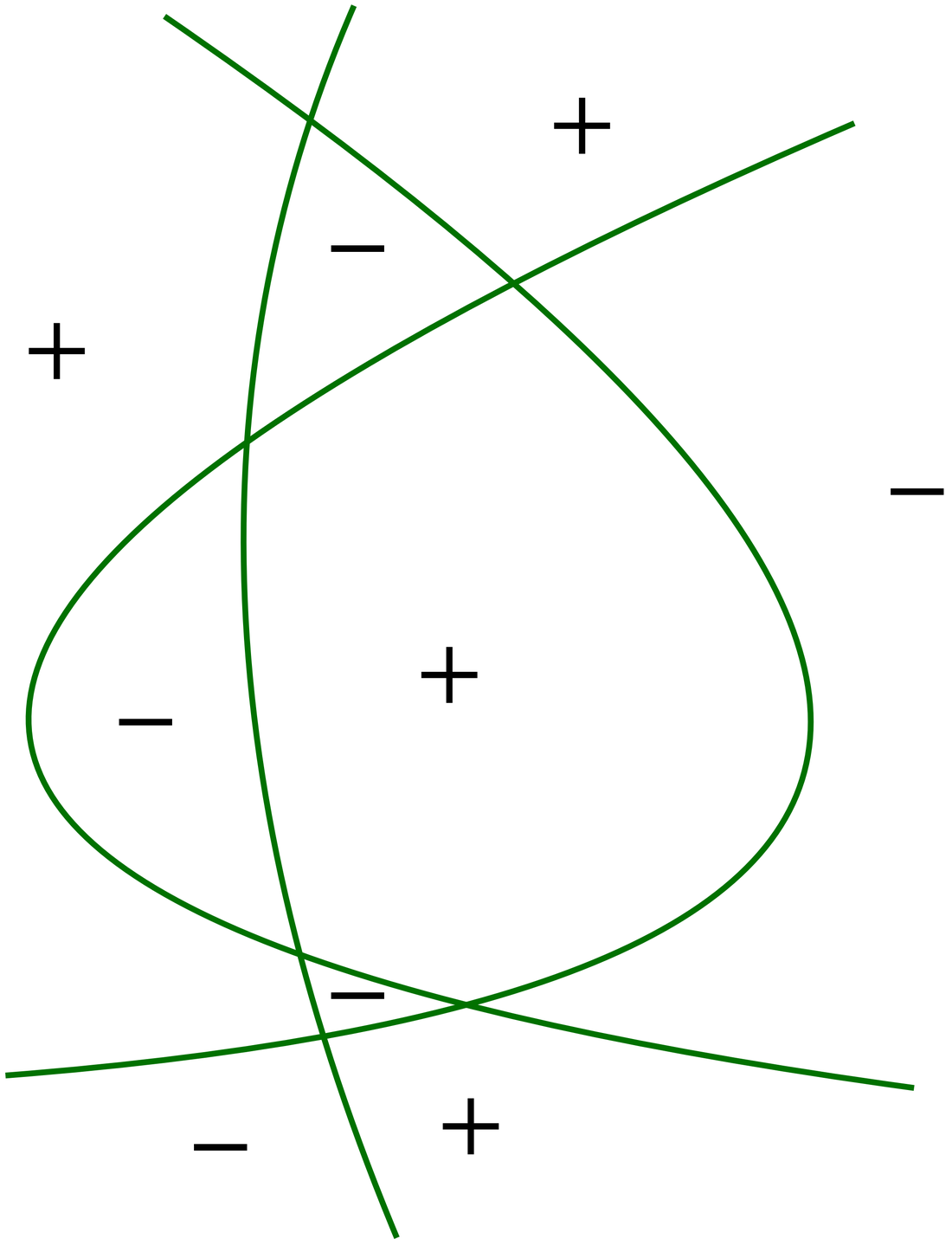


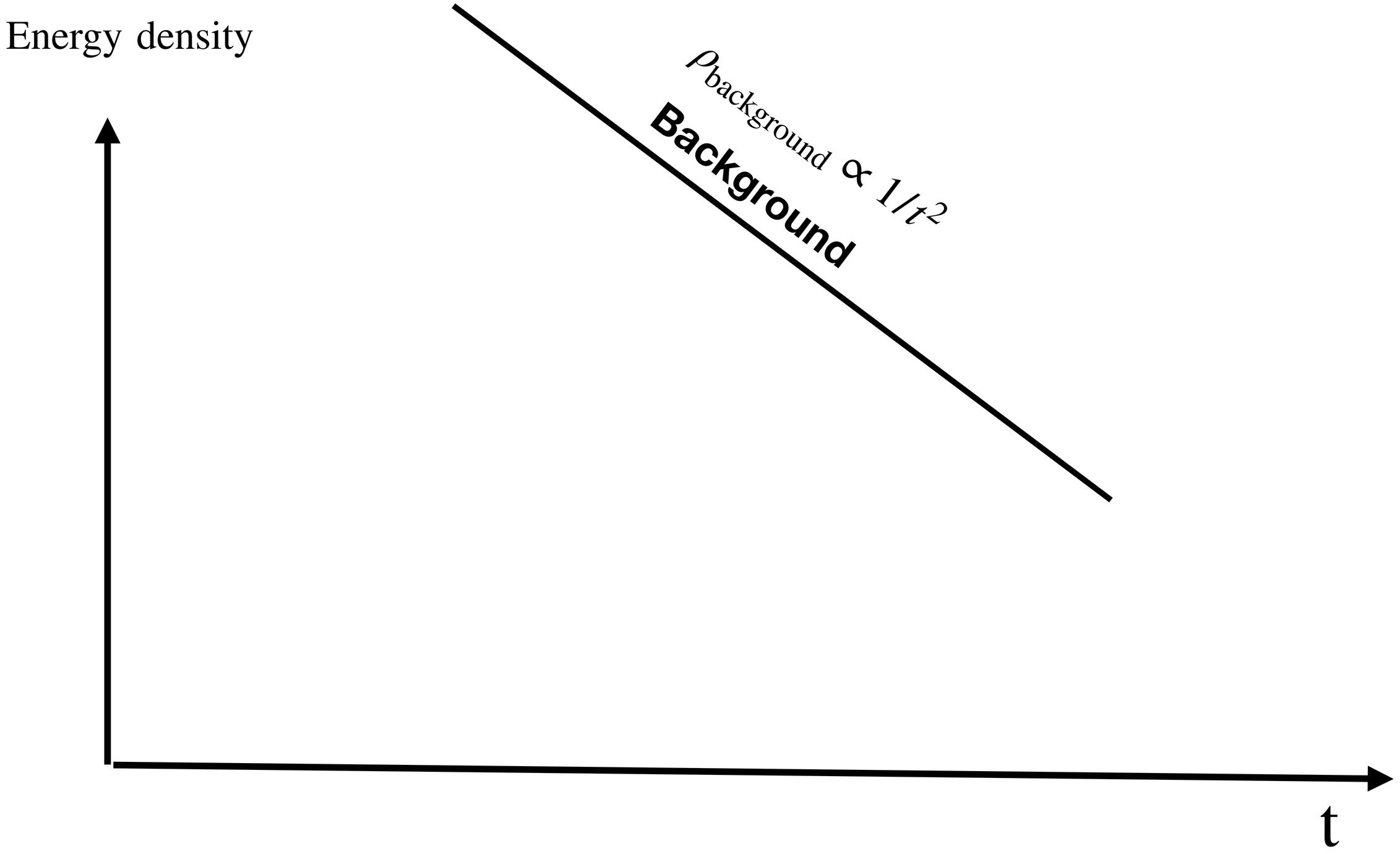
Spontaneous breaking of $\mathbb{Z}_2$

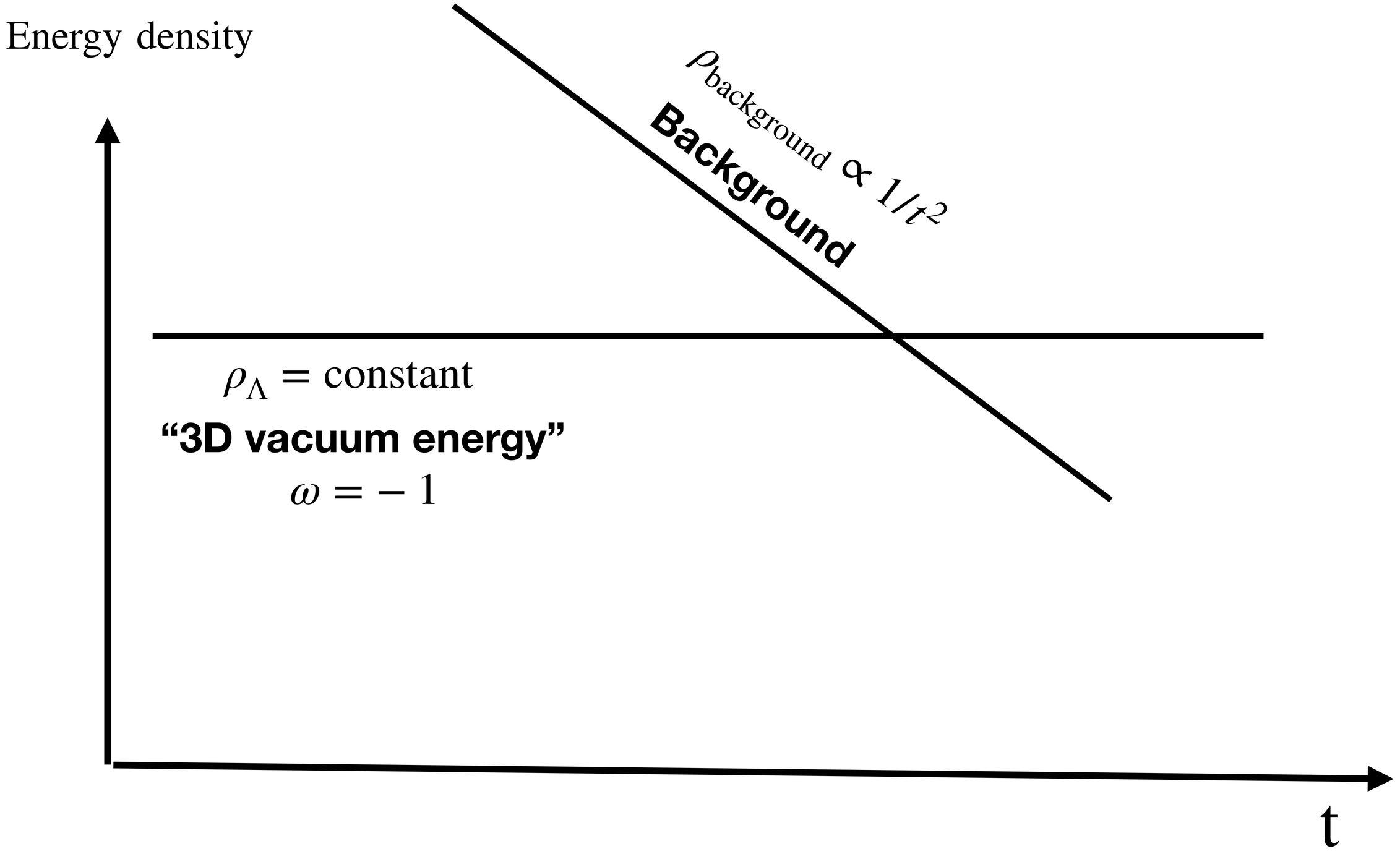
Formation of Domain Wall

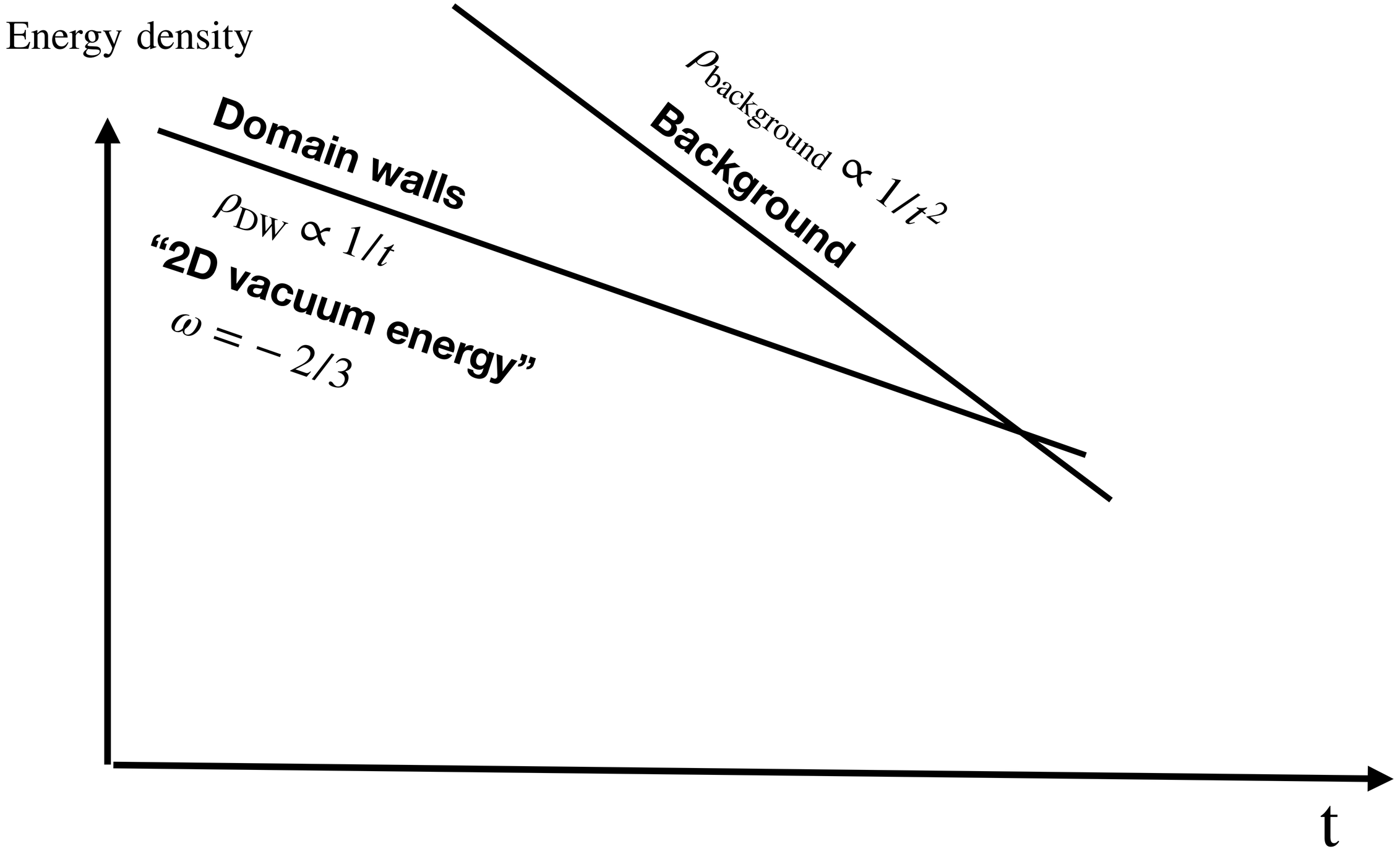
Press, Ryden, Spergel 1989 (3D simulation)

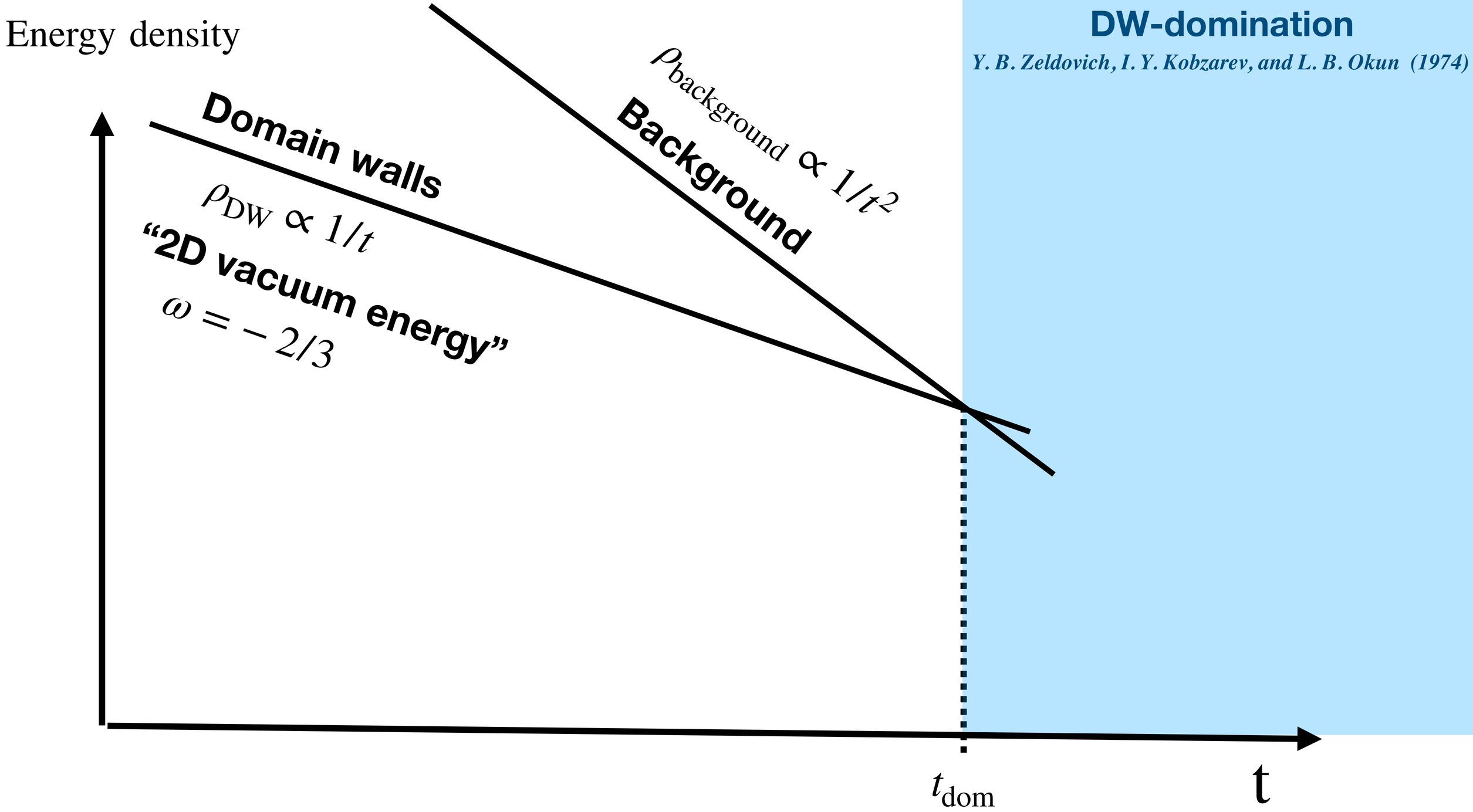
Scaling regime : $\langle R \rangle \simeq t$

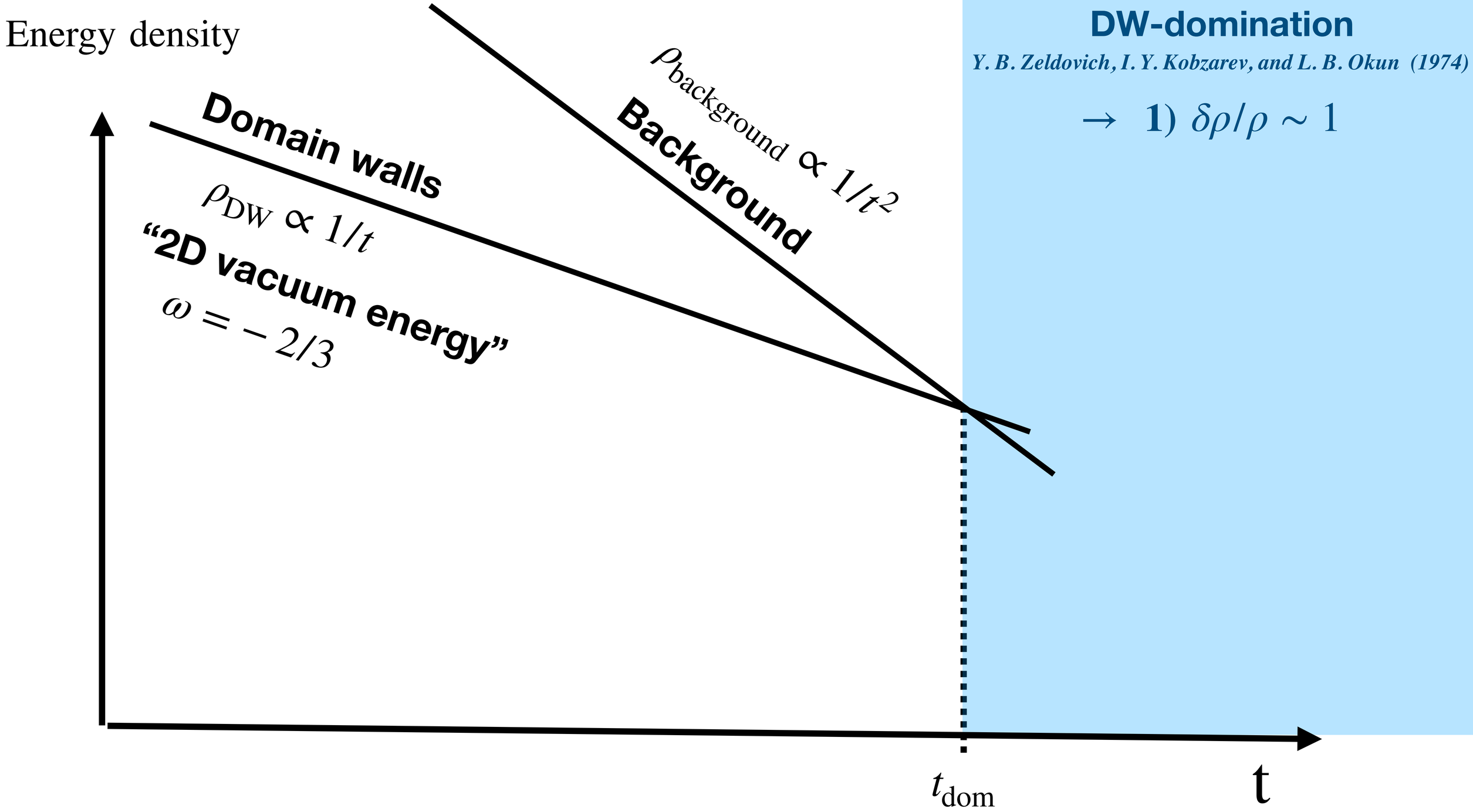



Energy density
$\rho_{\text{background}} \propto 1/t^2$
Background
t


Energy density
$\rho_{\text{background}} \propto 1/t^2$
Background
$\rho_\Lambda = \text{constant}$
“3D vacuum energy”
$\omega = -1$
t


Energy density
$\rho_{\text{background}} \propto 1/t^2$
Background
Domain walls
$\rho_{\text{DW}} \propto 1/t$
"2D vacuum energy"
$\omega = -2/3$
t


Energy density
DW-domination
Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)
$\rho_{\rm background} \propto 1/t^2$
Background
Domain walls
$\rho_{\rm DW} \propto 1/t$
"2D vacuum energy"
$\omega = -2/3$
$t_{\rm dom}$
t



DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

$\rightarrow$ 1) $\delta\rho/\rho \sim 1$

Energy density

Domain walls

$\rho_{\rm DW} \propto 1/t$

"2D vacuum energy"

$\omega = -2/3$

$\rho_{\rm background} \propto 1/t^2$

Background

$t_{\rm dom}$

t

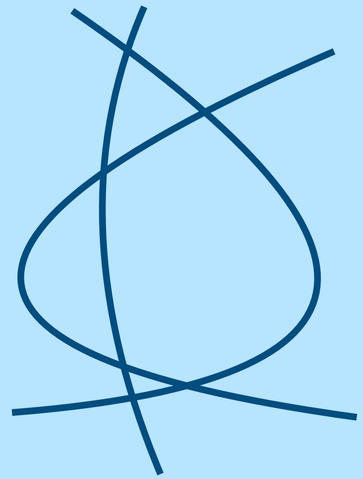
DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

$\rightarrow$ 1) $\delta\rho/\rho \sim 1$

$\langle R \rangle \simeq t$

(scaling regime)



Energy density

Domain walls

$\rho_{\rm DW} \propto 1/t$

"2D vacuum energy"

$\omega = -2/3$

$\rho_{\rm background} \propto 1/t^2$

Background

$t_{\rm dom}$

t

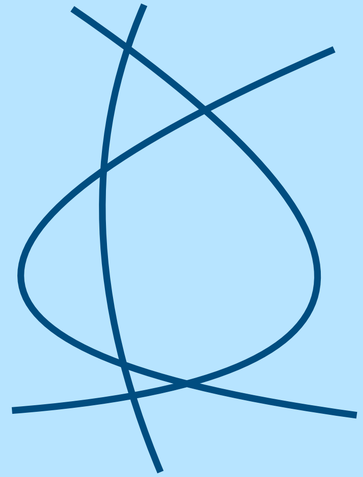
DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

$\rightarrow$ **1)** $\delta\rho/\rho \sim 1$

$\langle R \rangle \simeq t$

(scaling regime)



$\rightarrow$ **2)** horizon size

Energy density

Domain walls

$\rho_{\rm DW} \propto 1/t$

"2D vacuum energy"

$\omega = -2/3$

$\rho_{\rm background} \propto 1/t^2$

Background

$t_{\rm dom}$

t

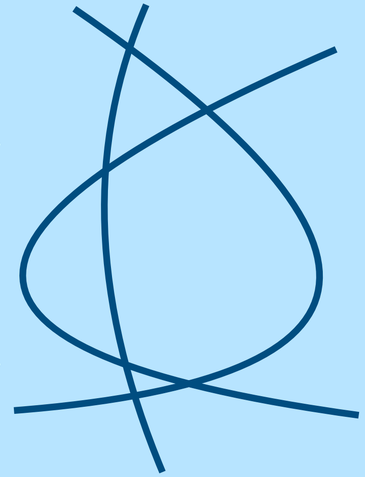
DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

$\rightarrow$ **1)** $\delta\rho/\rho \sim 1$

$\langle R \rangle \simeq t$

(scaling regime)



$\rightarrow$ **2)** horizon size

$\Rightarrow$ **Efficient PBH formation**

Energy density

Domain walls

$\rho_{\rm DW} \propto 1/t$

"2D vacuum energy"

$\omega = -2/3$

$\rho_{\rm background} \propto 1/t^2$

Background

$t_{\rm dom}$

t

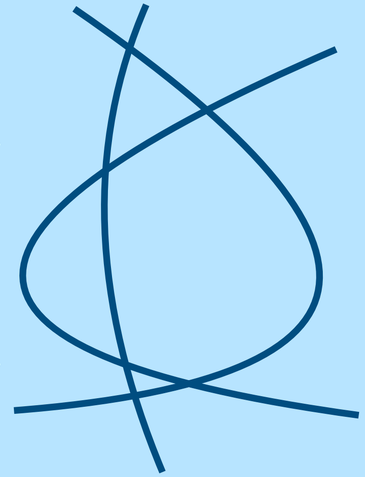
DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

$\rightarrow$ **1)** $\delta\rho/\rho \sim 1$

$\langle R \rangle \simeq t$

(scaling regime)



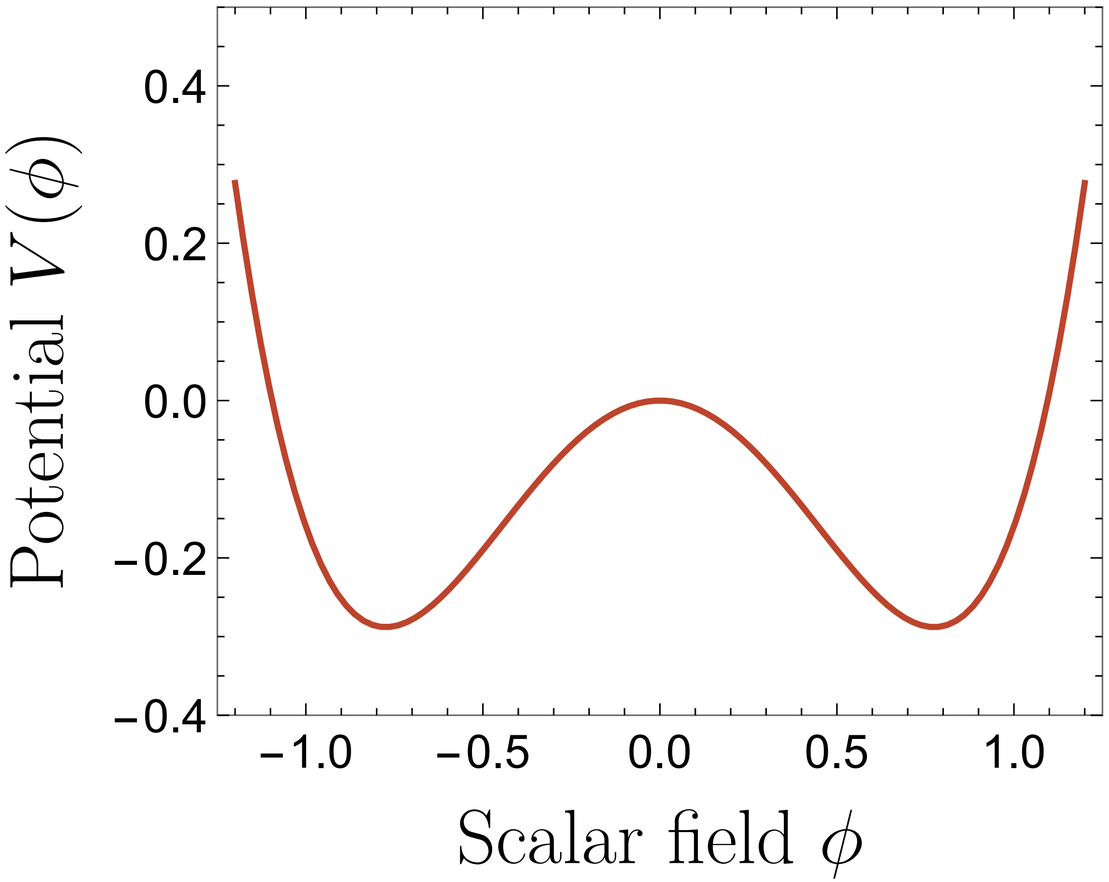
$\rightarrow$ **2)** horizon size

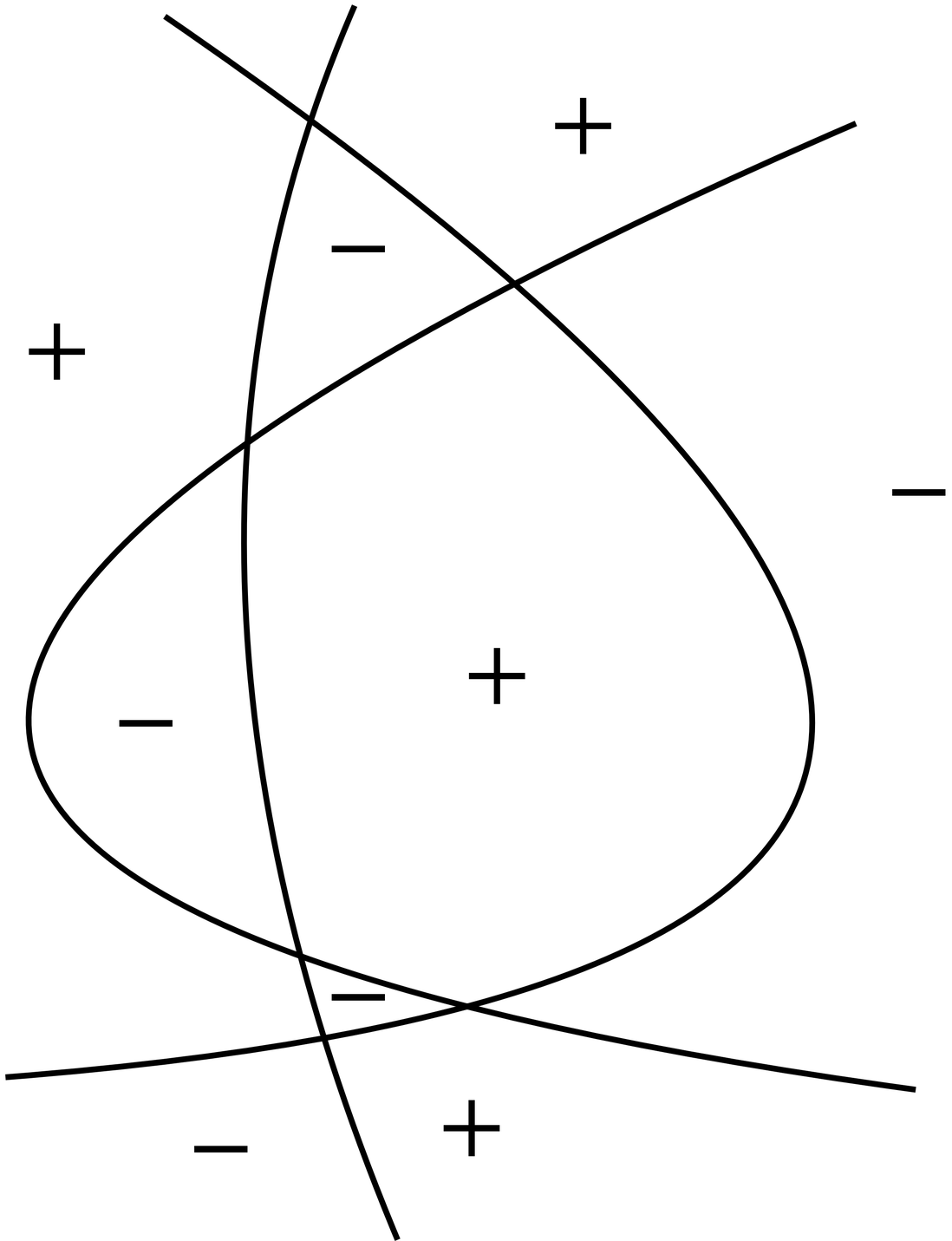
$\Rightarrow$ **Efficient PBH formation**

Vilenkin and Shellard's textbook, 2000

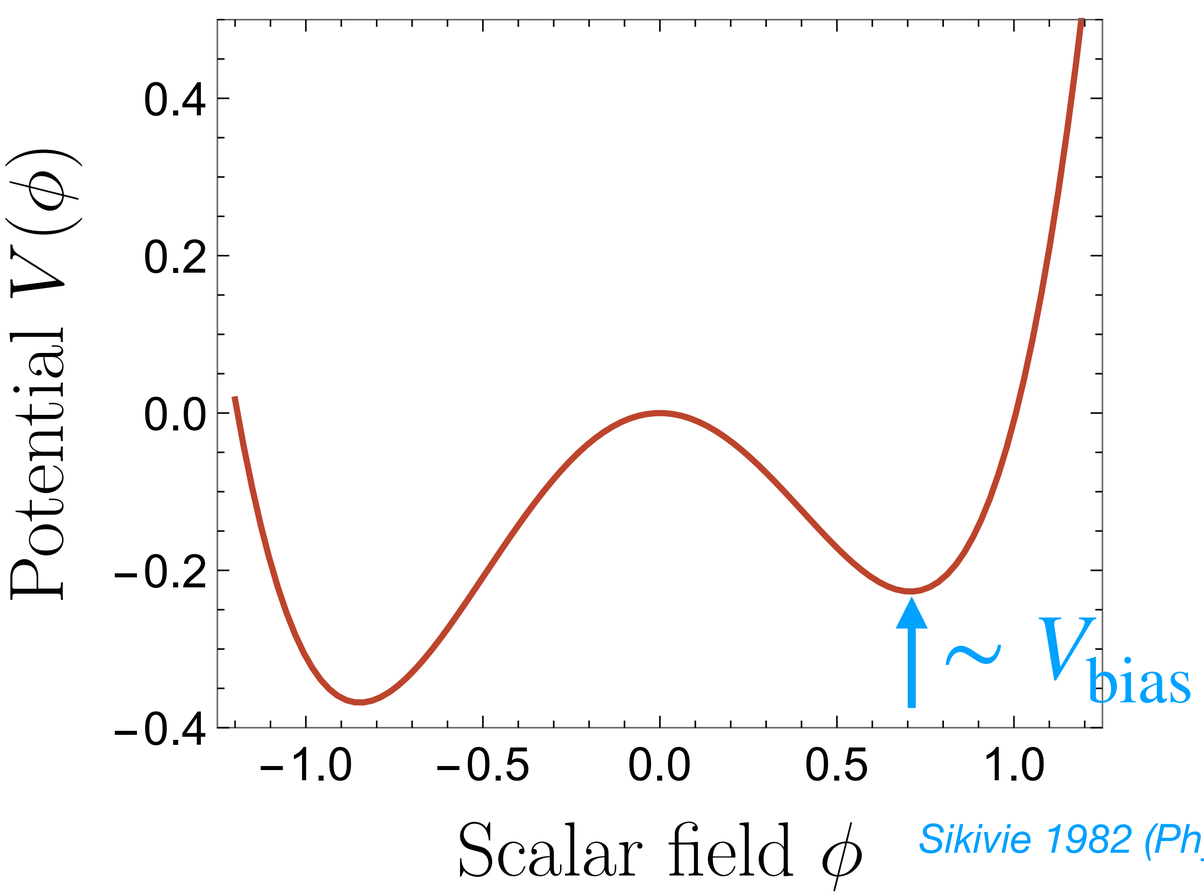
Ferrer, Masso, Panico, Pujolas, Rompineve, Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707

Vacuum energy bias

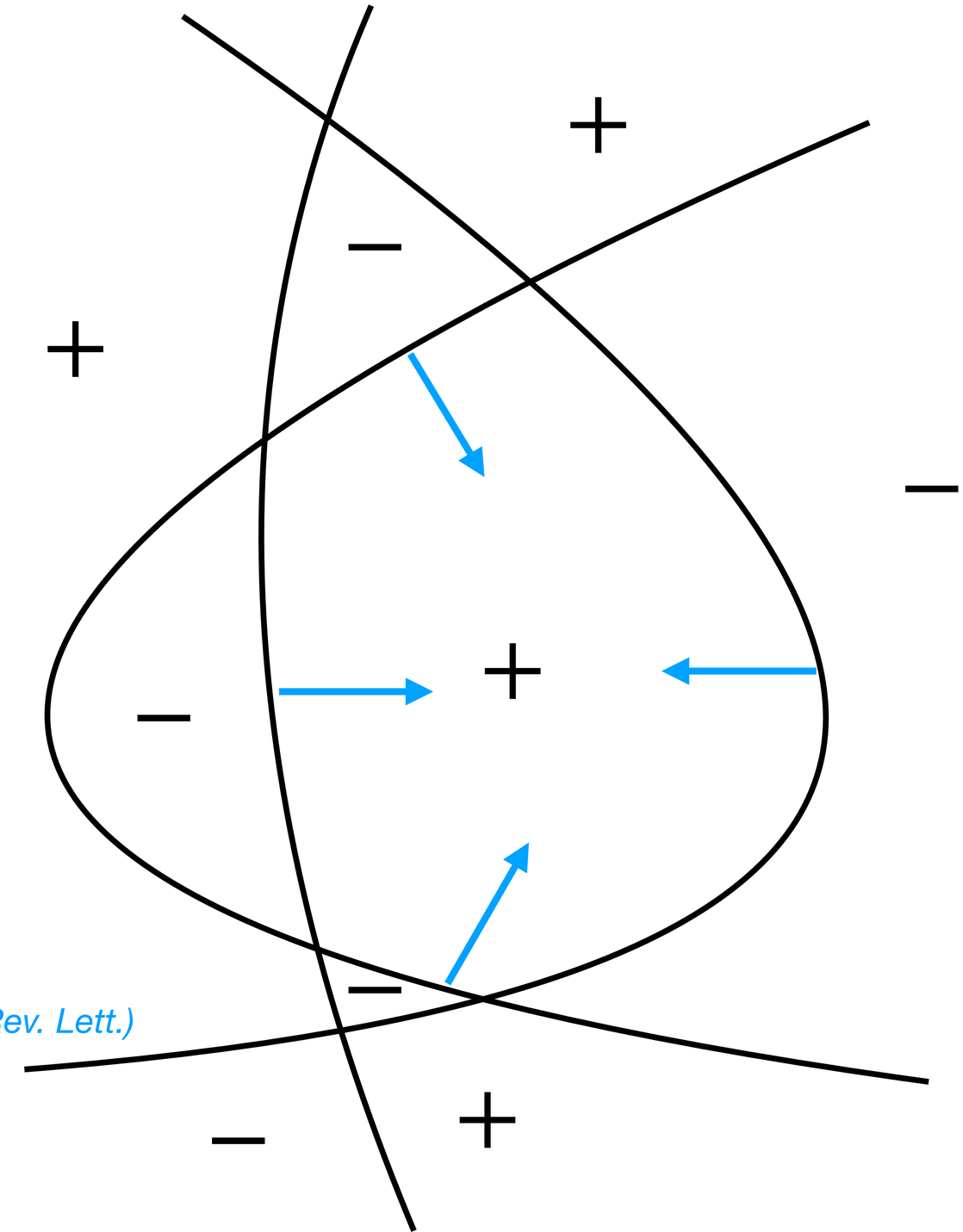


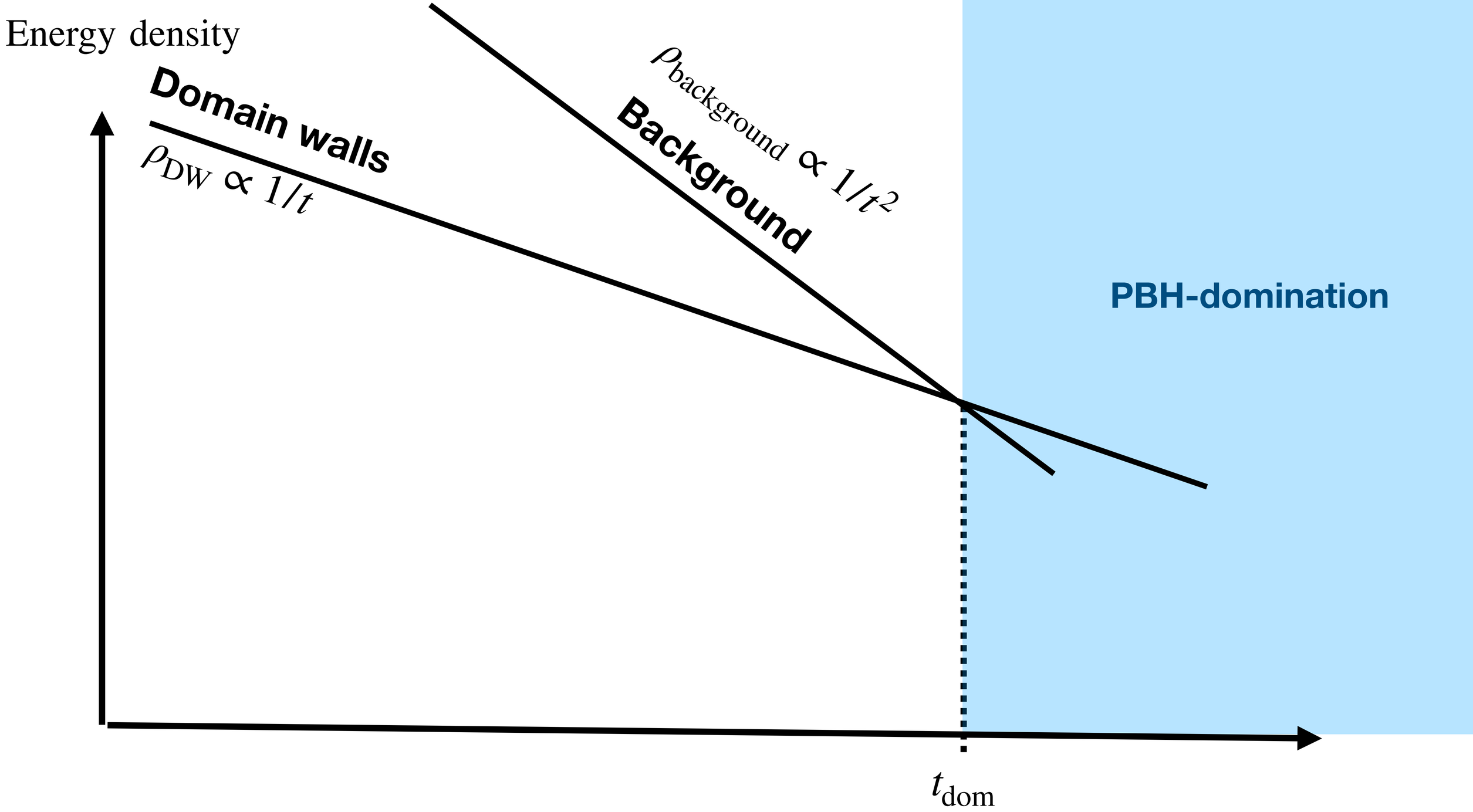


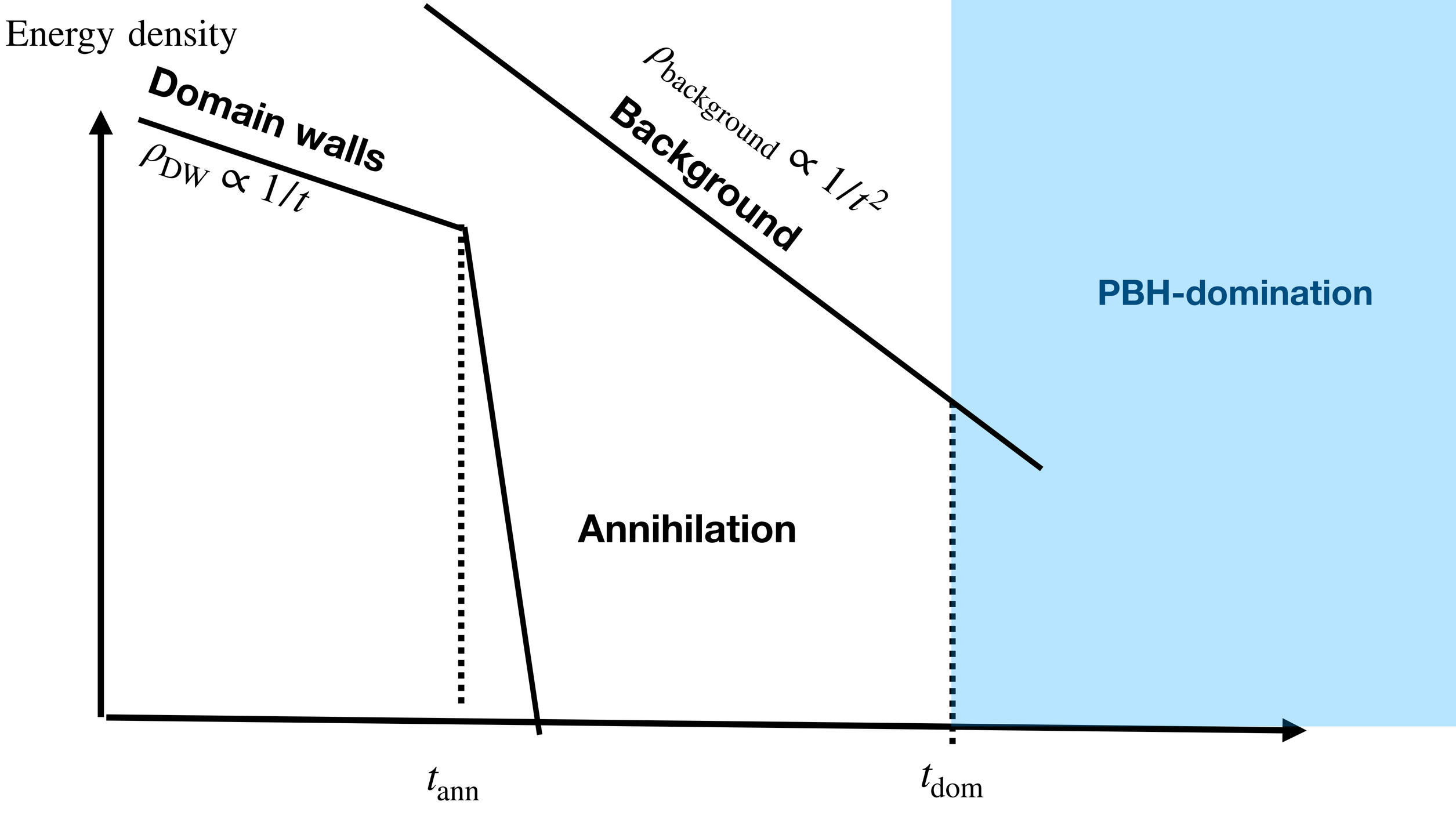
Vacuum energy bias

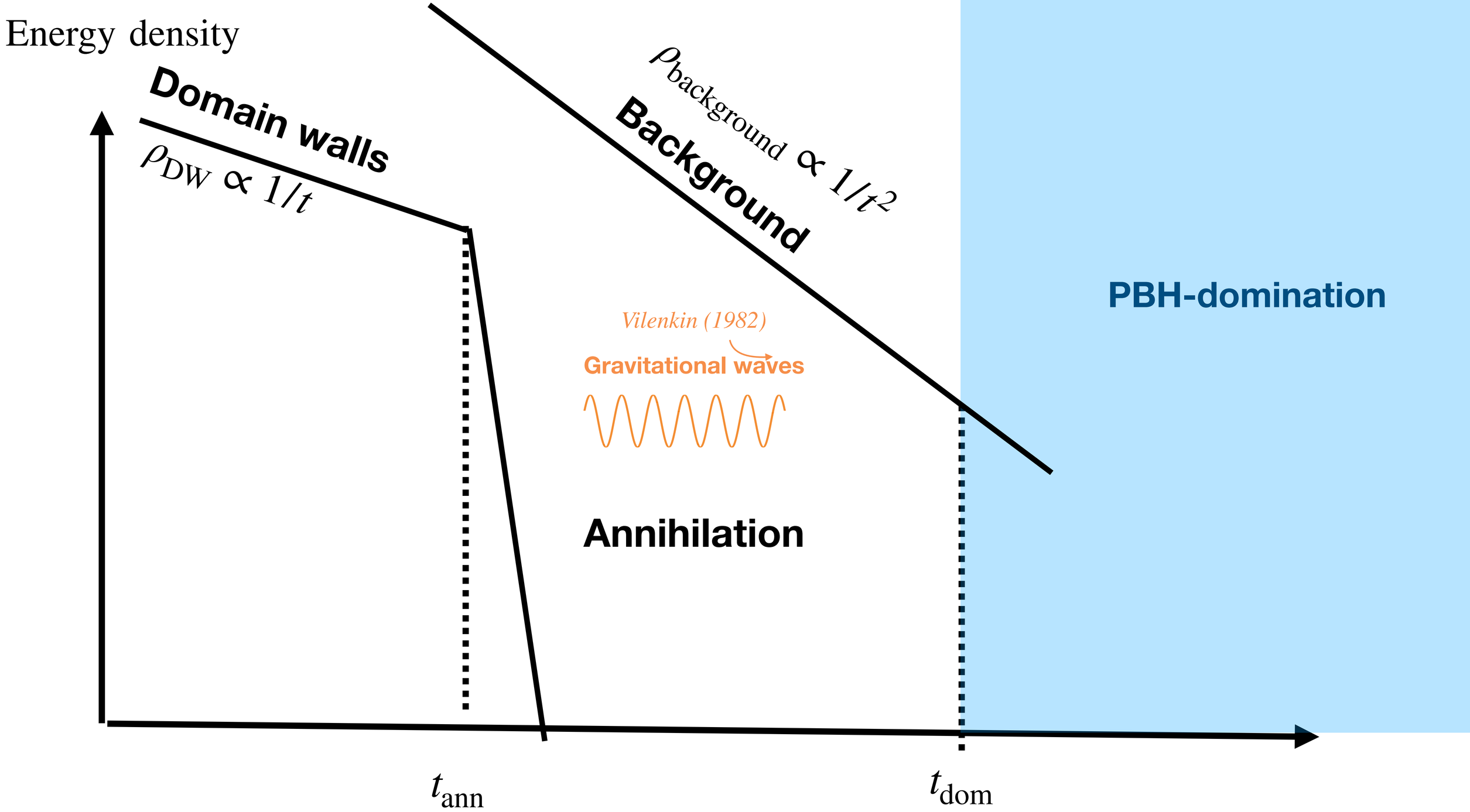


Sikivie 1982 (Phys. Rev. Lett.)




Energy density
Domain walls
$\rho_{\rm DW} \propto 1/t$
$\rho_{\rm background} \propto 1/t^2$
Background
PBH-domination
$t_{\rm dom}$


Energy density
Domain walls
$\rho_{\rm DW} \propto 1/t$
$\rho_{\rm background} \propto 1/t^2$
Background
PBH-domination
Annihilation
$t_{\rm ann}$
$t_{\rm dom}$


Energy density
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$\rho_{\rm DW} \propto 1/t$
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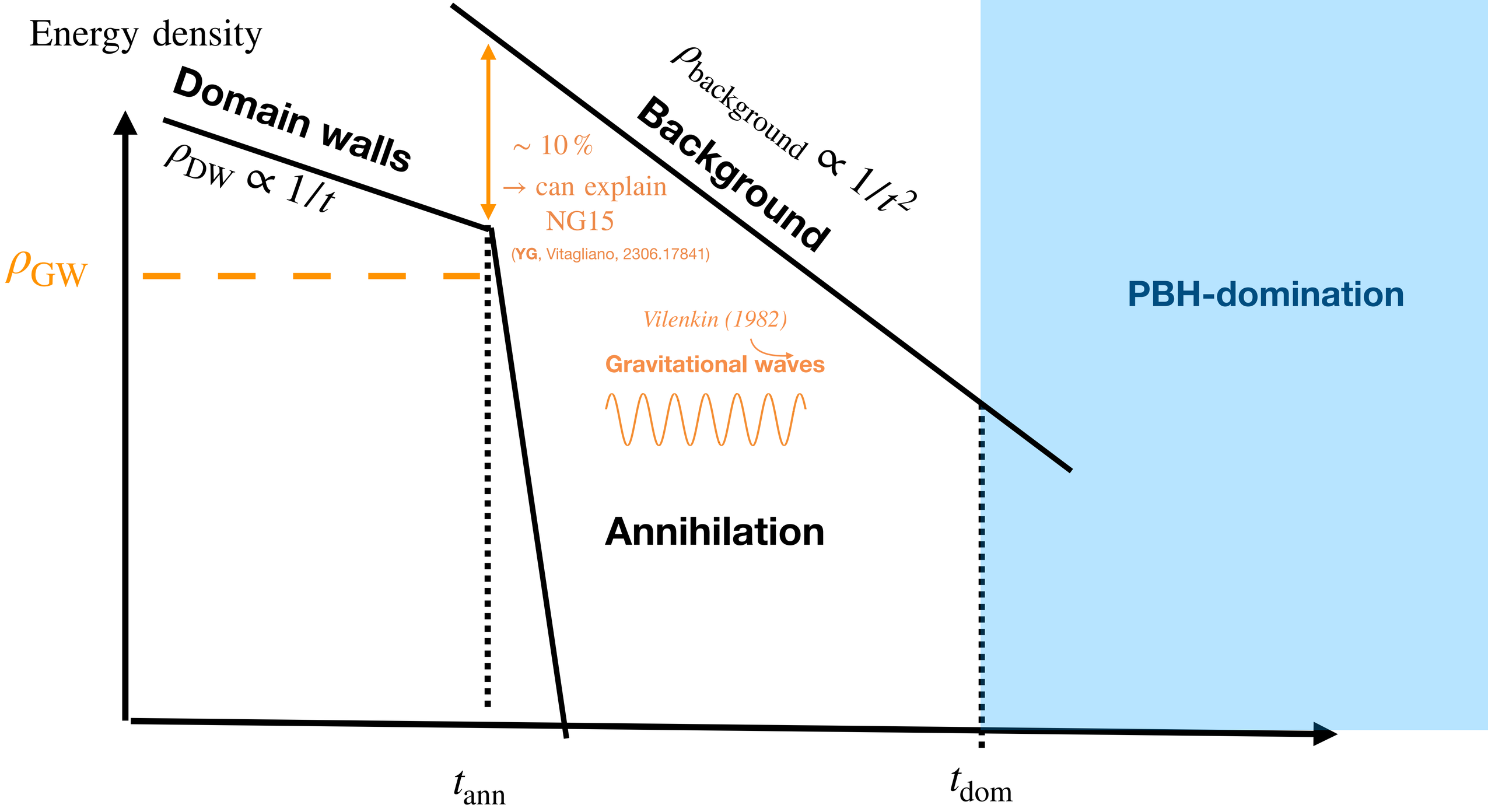
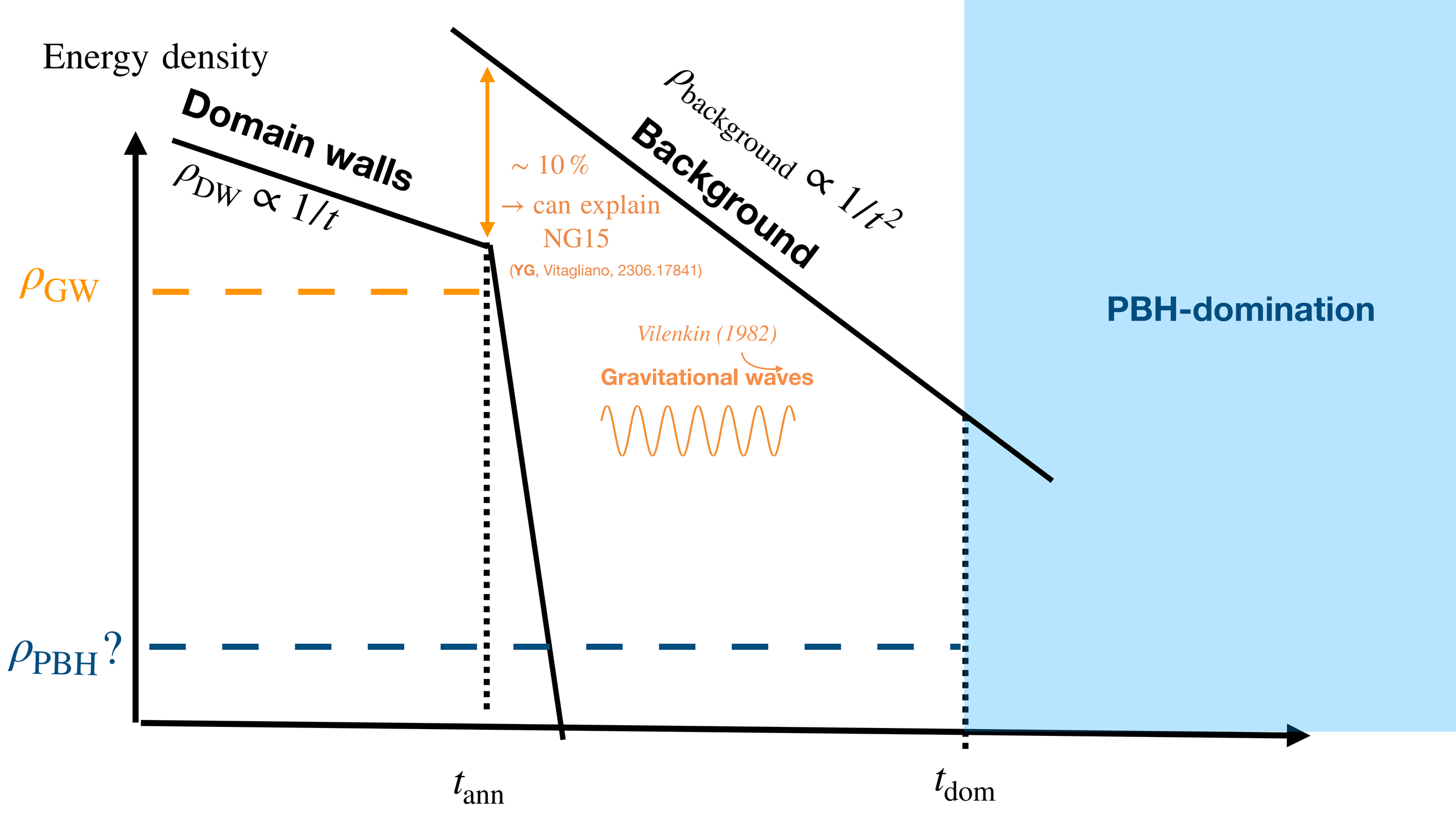
Background
PBH-domination
Vilenkin (1982)
Gravitational waves
Annihilation
$t_{\rm ann}$
$t_{\rm dom}$


Energy density
Domain walls
$\rho_{\rm DW} \propto 1/t$
$\rho_{\rm GW}$
$\sim 10\,\%$
→ can explain NG15
(YG, Vitagliano, 2306.17841)
$\rho_{\rm background} \propto 1/t^2$
Background
PBH-domination
Vilenkin (1982)
Gravitational waves
Annihilation
$t_{\rm ann}$
$t_{\rm dom}$


Energy density
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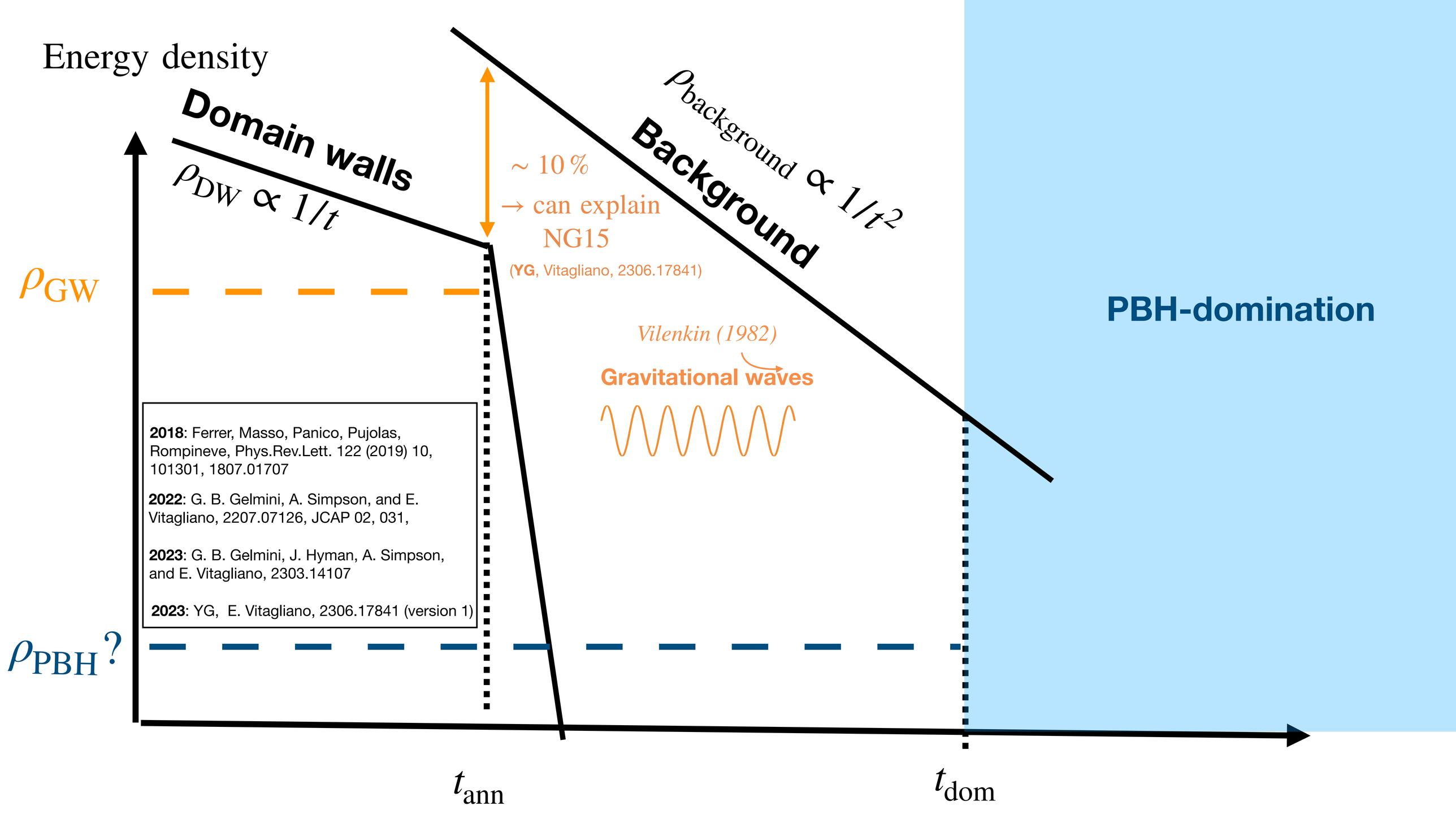
Gravitational waves
PBH-domination
$\rho_{\rm PBH}$?
$t_{\rm ann}$
$t_{\rm dom}$


Energy density
Domain walls
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Gravitational waves
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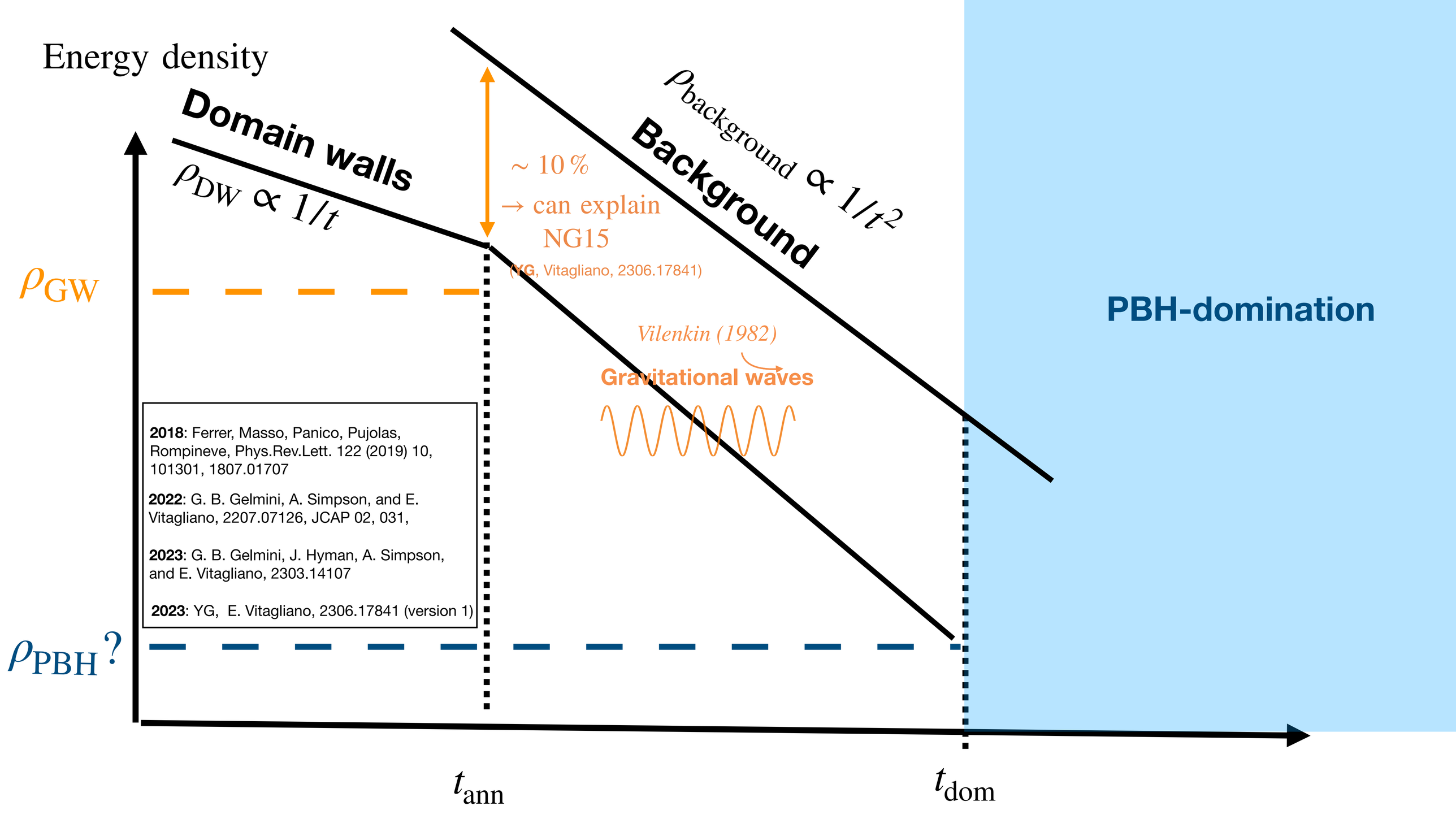
2018: Ferrer, Masso, Panico, Pujolas, Rompineve, Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707
2022: G. B. Gelmini, A. Simpson, and E. Vitagliano, 2207.07126, JCAP 02, 031,
2023: G. B. Gelmini, J. Hyman, A. Simpson, and E. Vitagliano, 2303.14107
2023: YG, E. Vitagliano, 2306.17841 (version 1)
$\rho_{\rm PBH}$?
$t_{\rm ann}$
$t_{\rm dom}$


Energy density
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$\rho_{\rm PBH}$?
$t_{\rm ann}$
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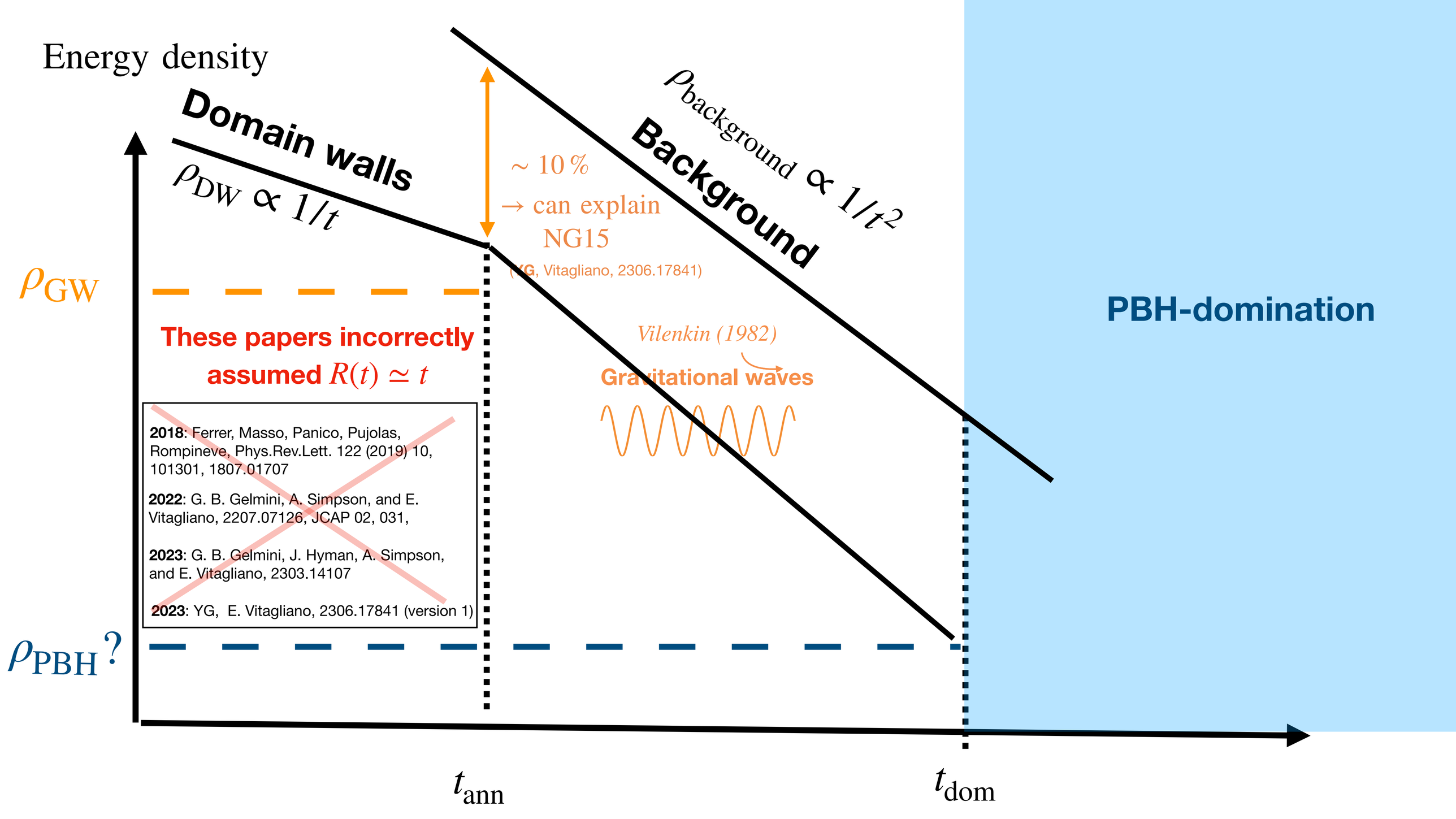
Energy density
Domain walls
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Background
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$\rho_{\rm GW}$
These papers incorrectly assumed $R(t) \simeq t$
Vilenkin (1982)
Gravitational waves
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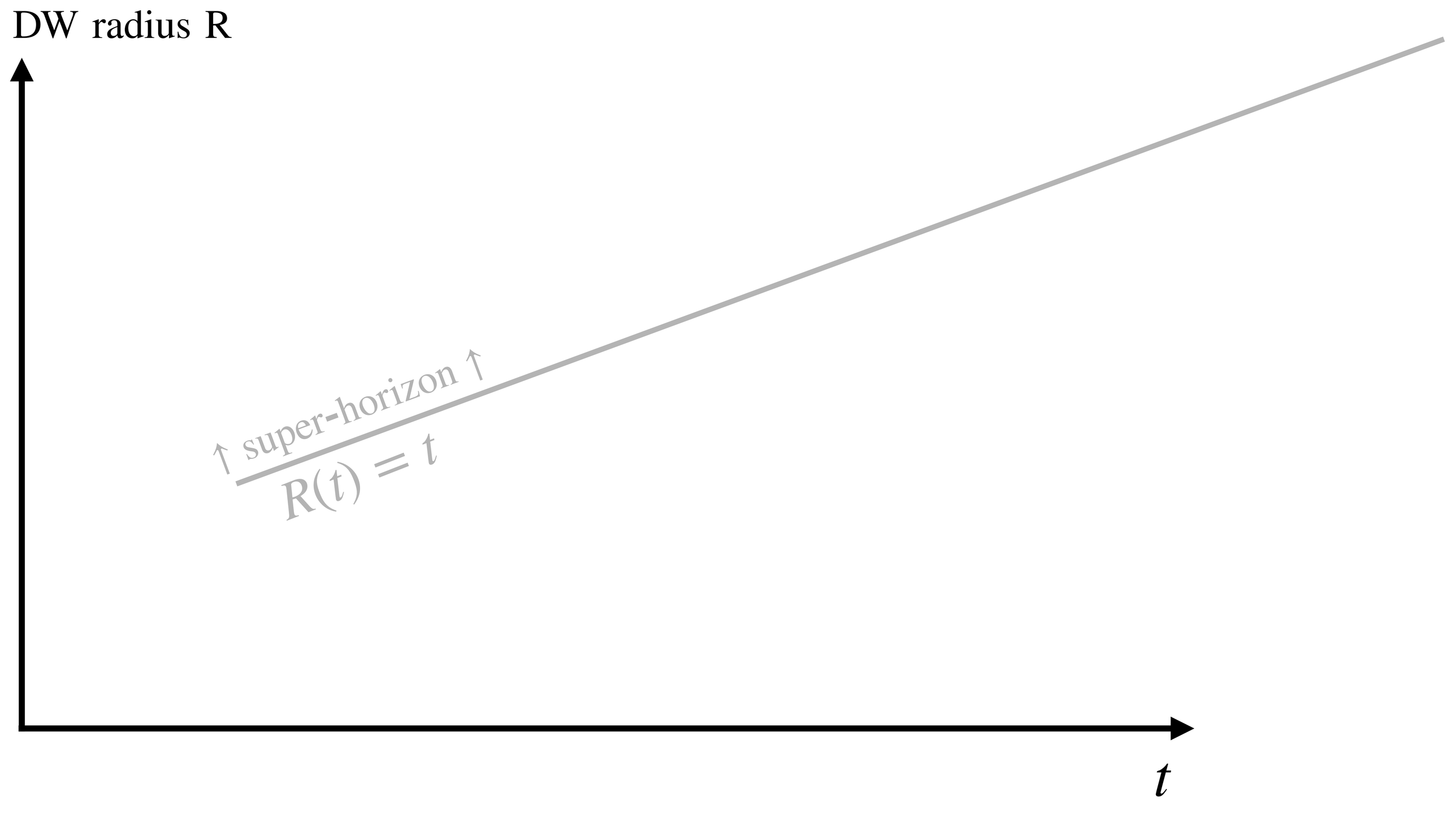
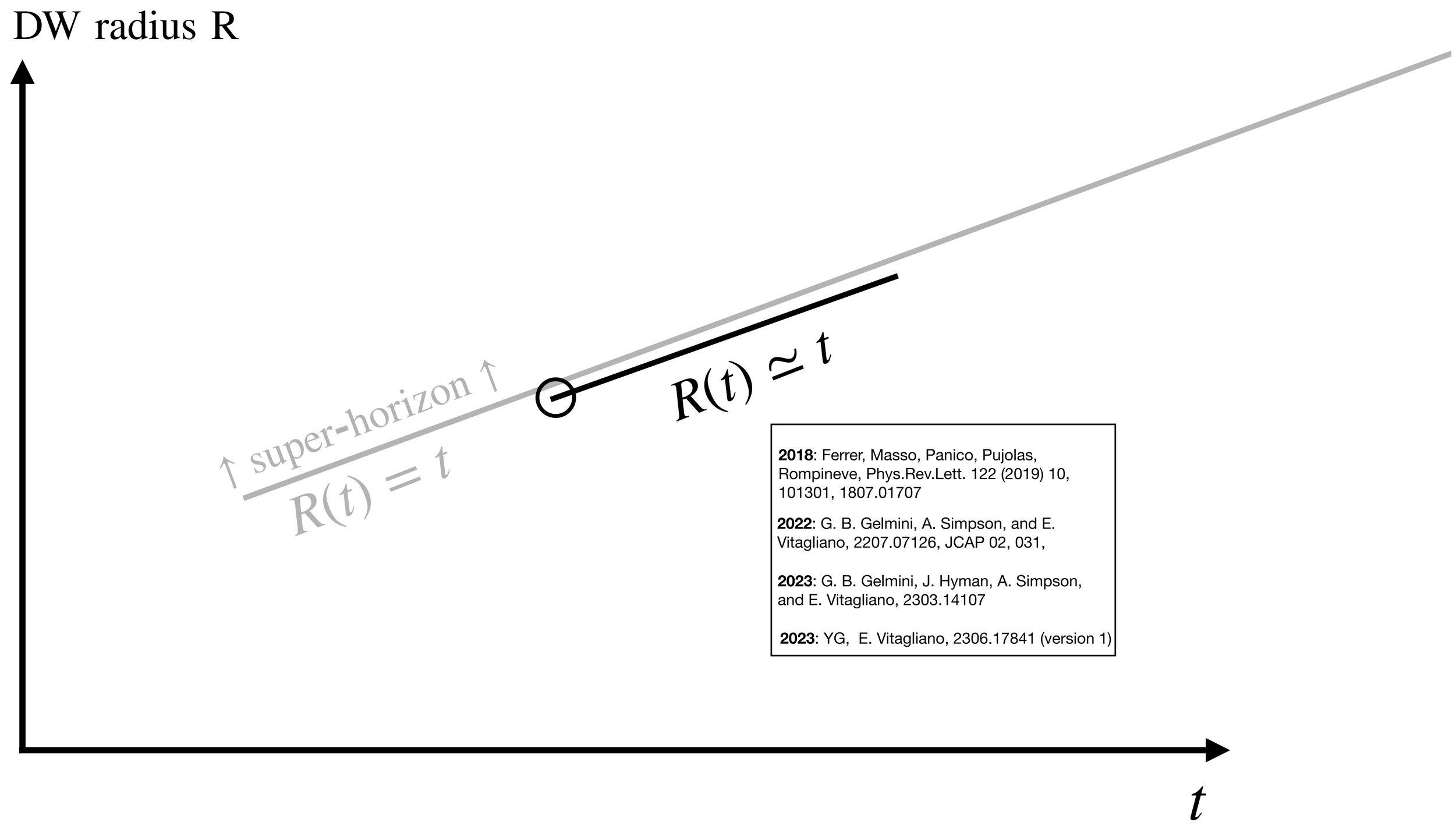
$\rho_{\rm PBH}$?
PBH-domination
$t_{\rm ann}$
$t_{\rm dom}$


DW radius R
↑ super-horizon ↑
$R(t) = t$
t



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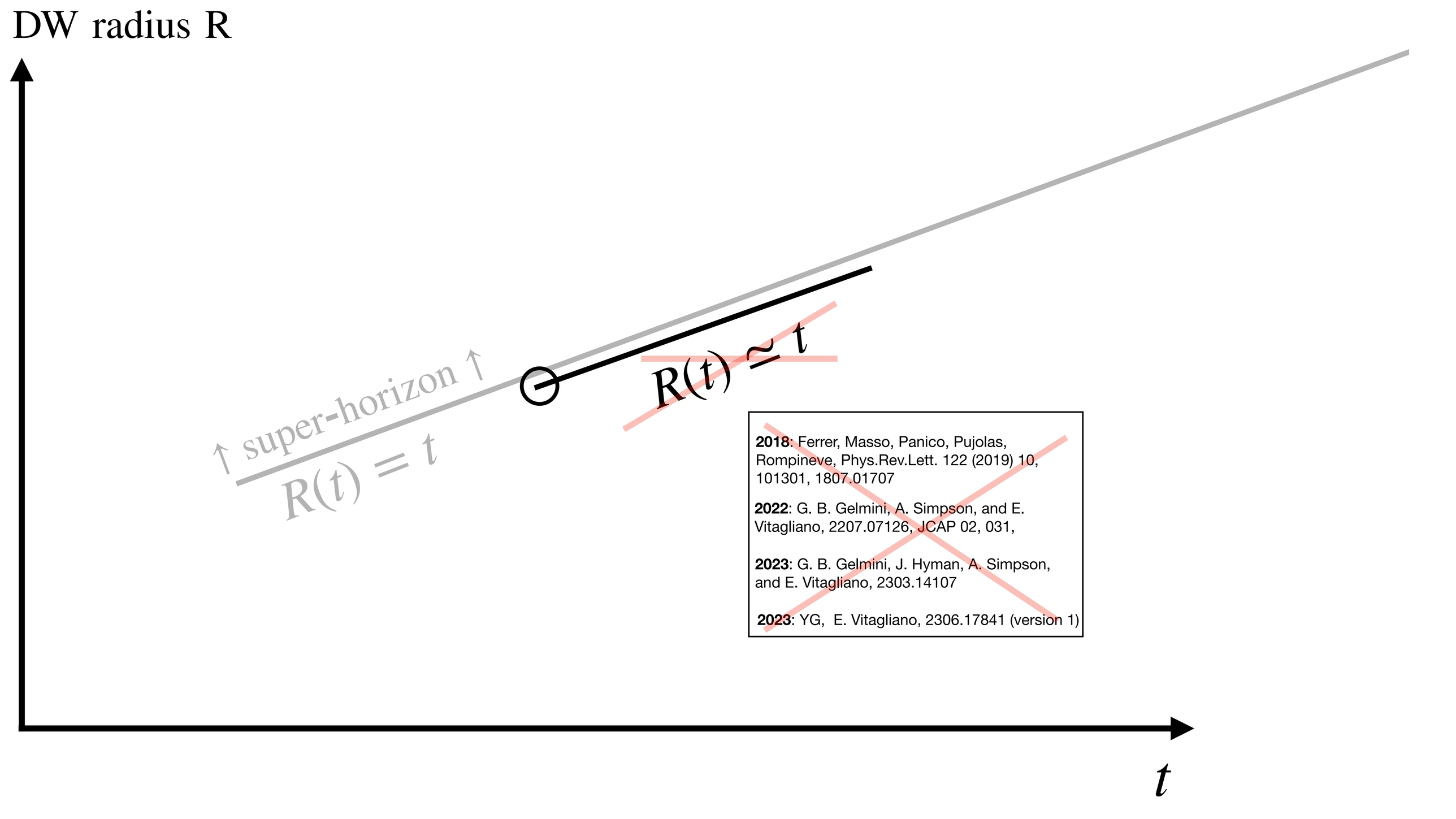
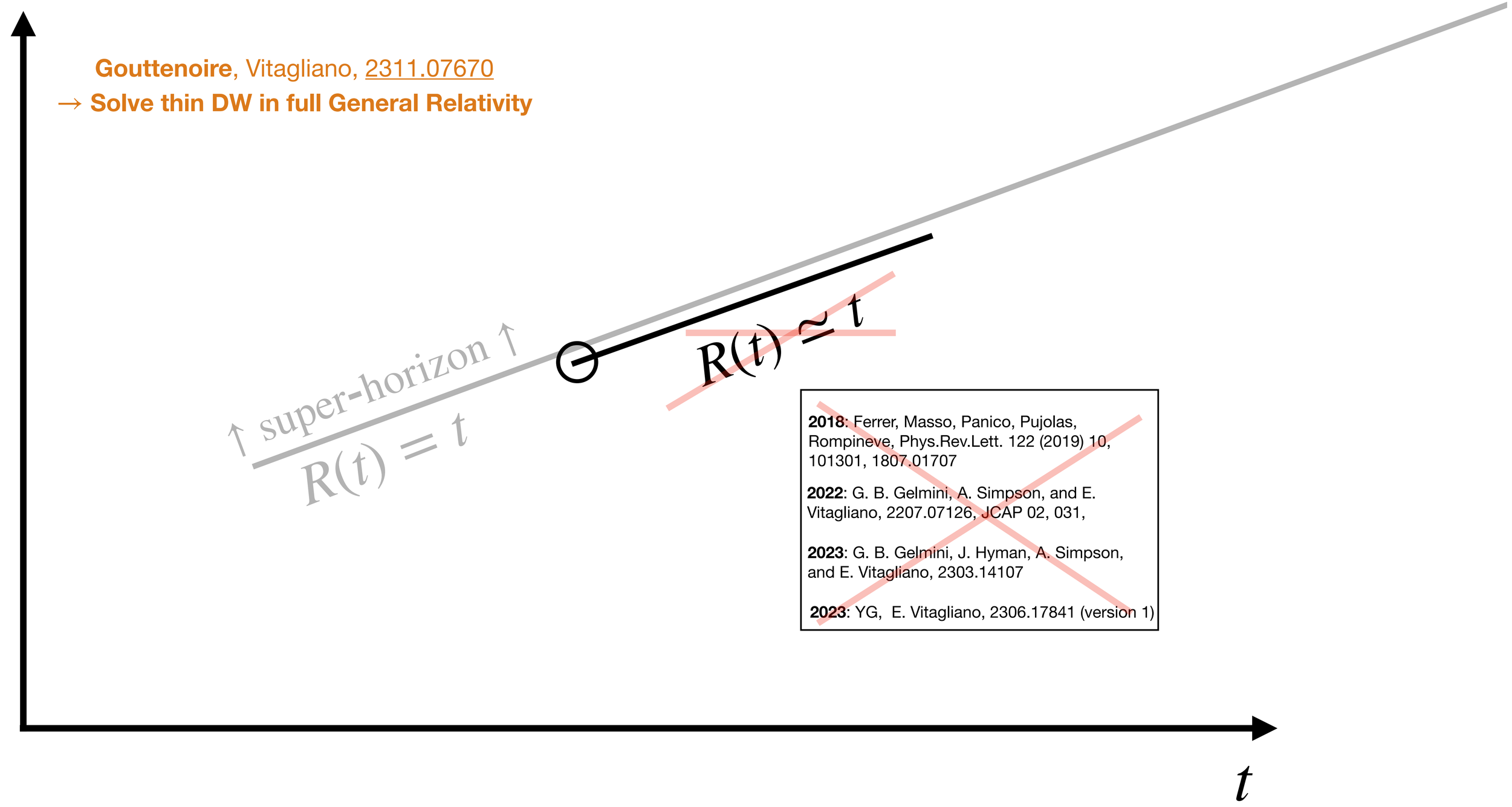

DW radius R
↑ super-horizon ↑
$R(t) = t$
$R(t) \simeq t$
2018: Ferrer, Masso, Panico, Pujolas, Rompineve, Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707
2022: G. B. Gelmini, A. Simpson, and E. Vitagliano, 2207.07126, JCAP 02, 031,
2023: G. B. Gelmini, J. Hyman, A. Simpson, and E. Vitagliano, 2303.14107
2023: YG, E. Vitagliano, 2306.17841 (version 1)
t

DW radius R

Gouttenoire, Vitagliano, 2311.07670

→ **Solve thin DW in full General Relativity**



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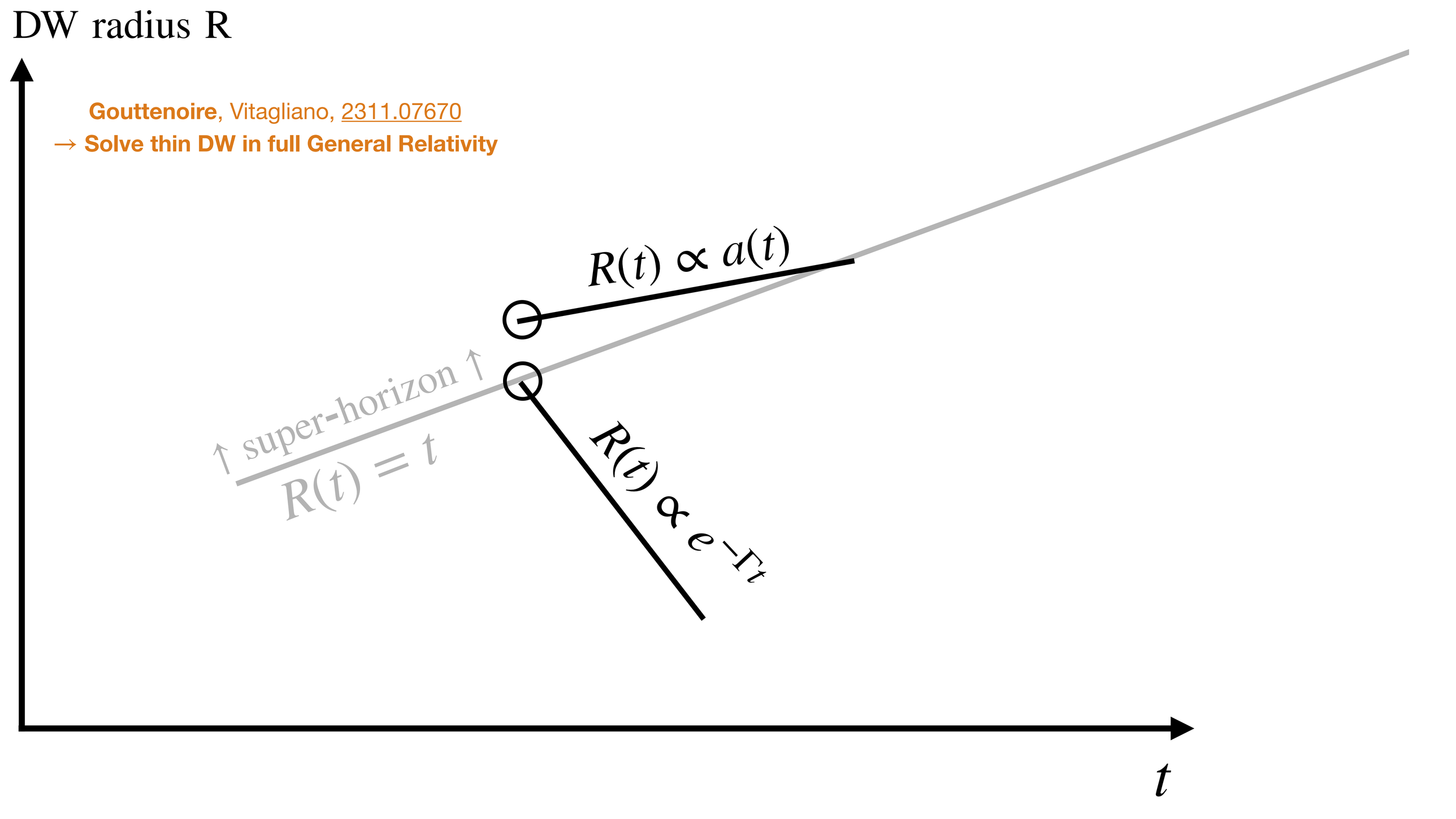
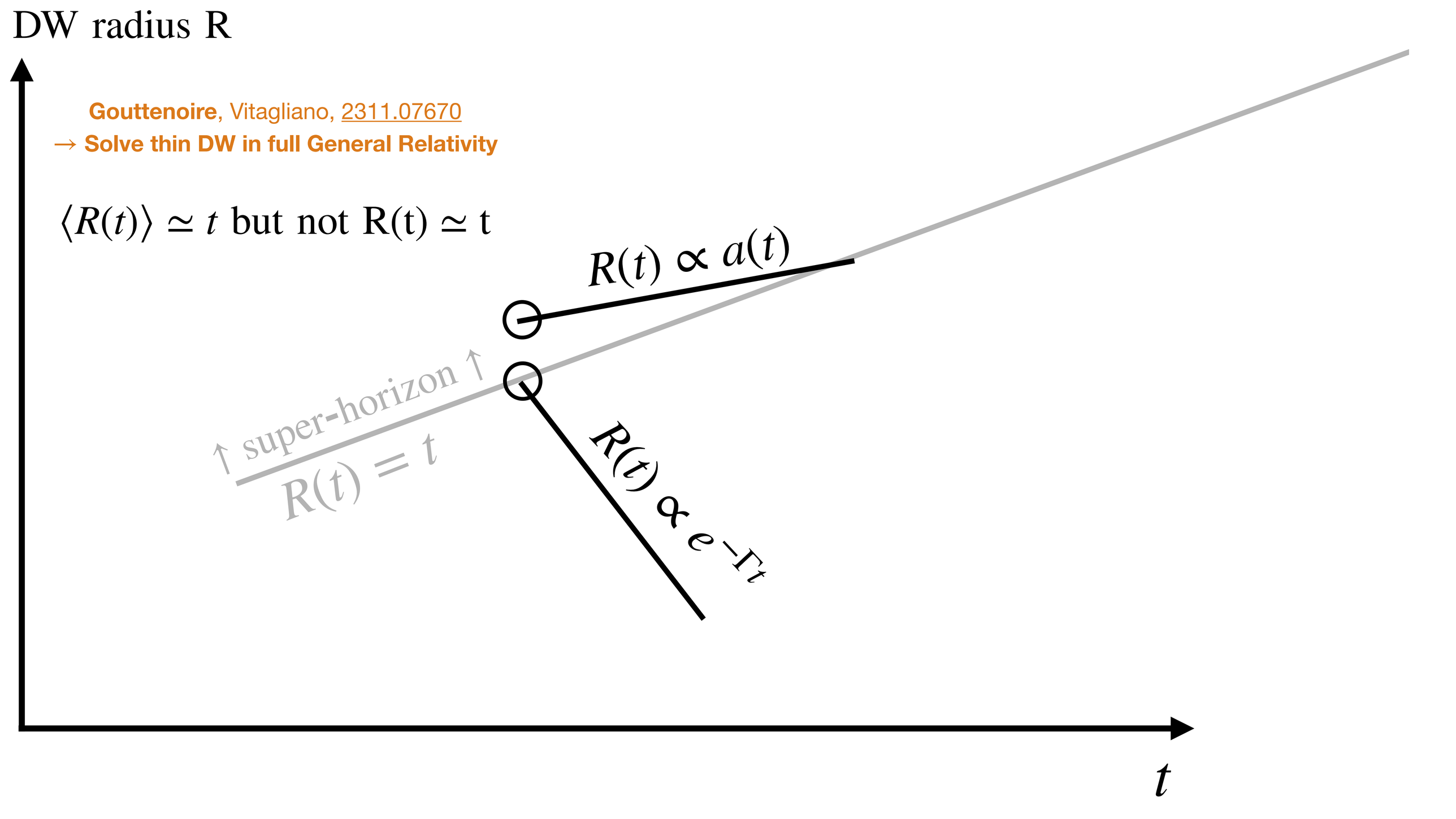
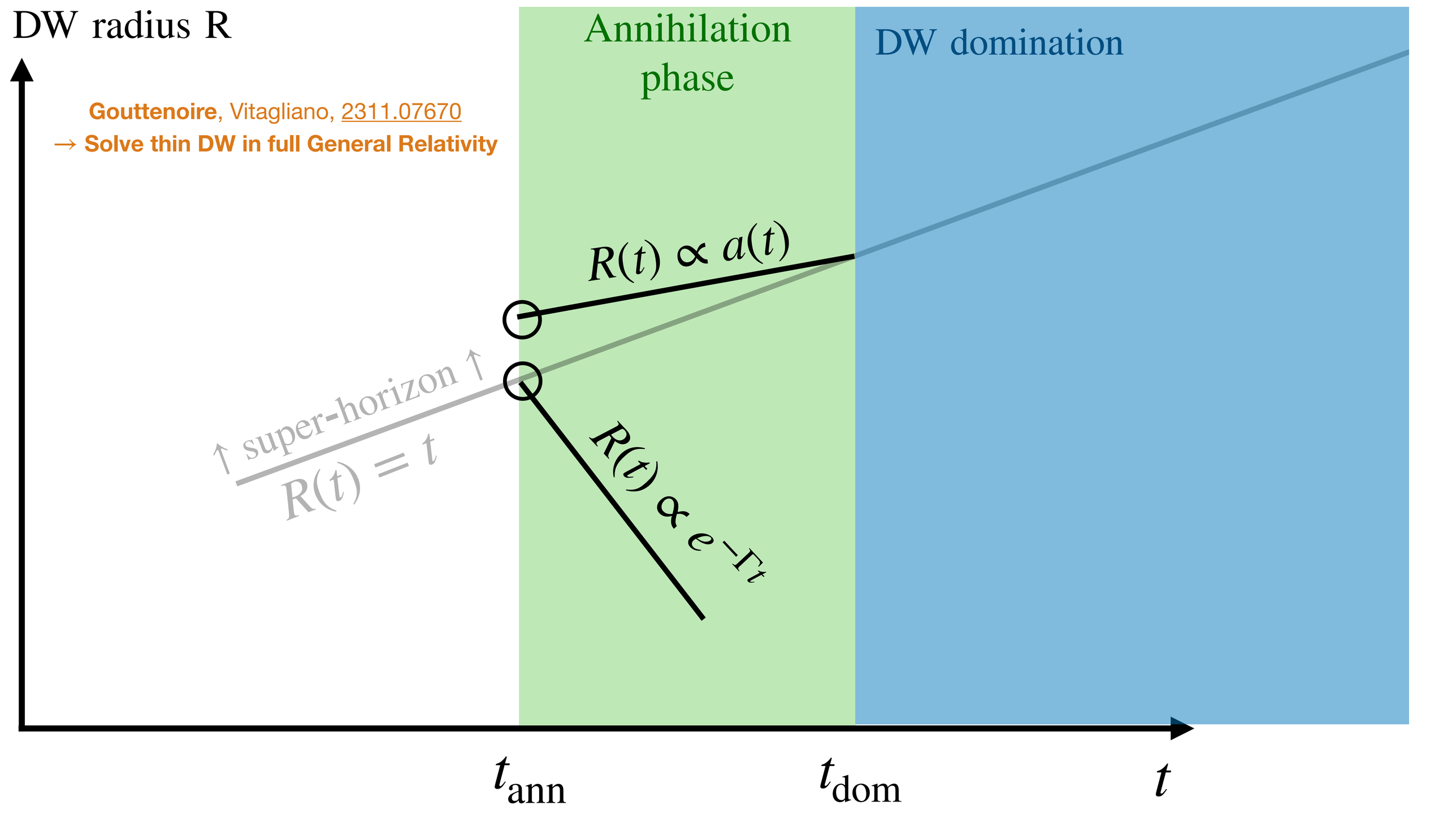
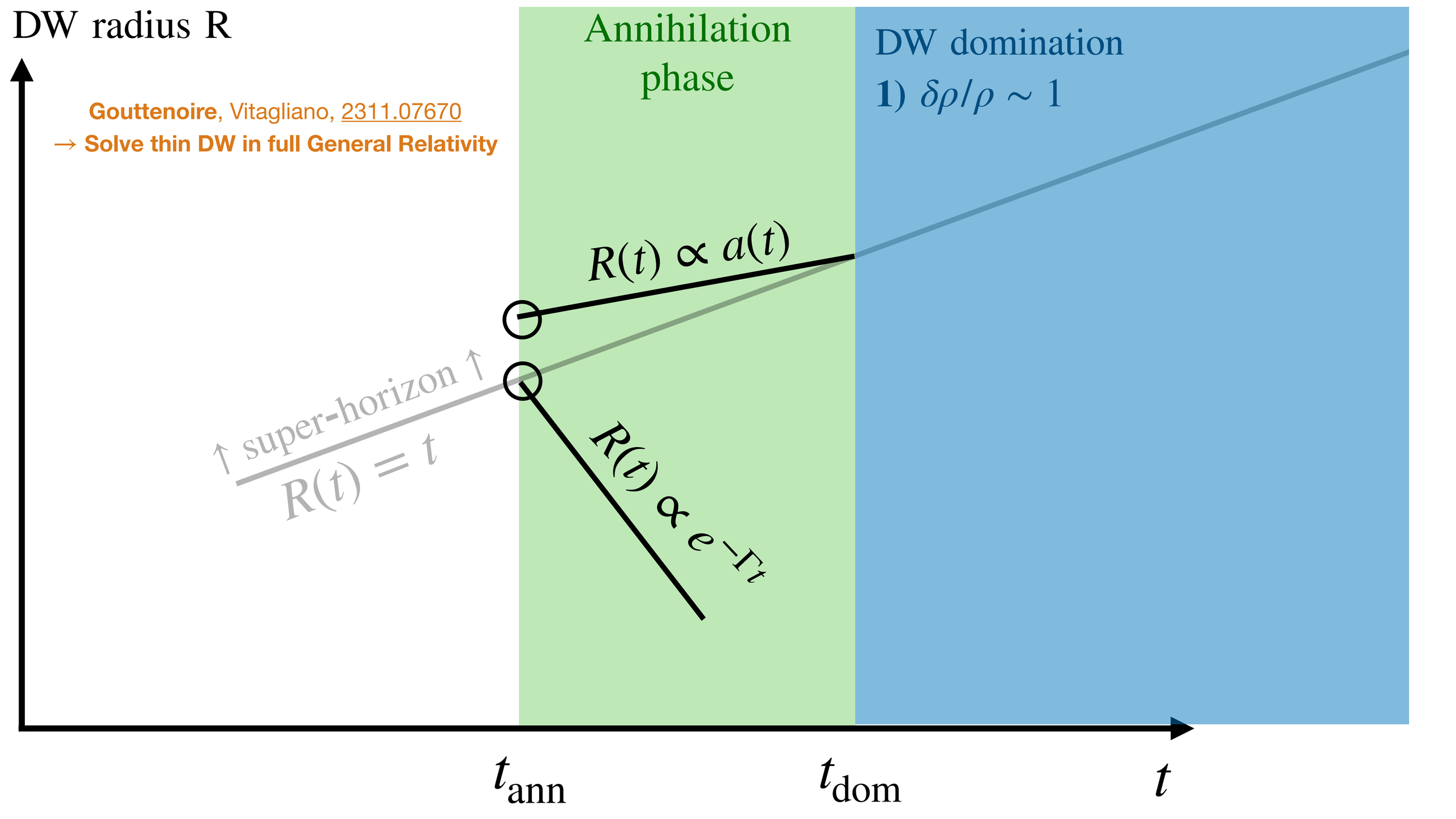
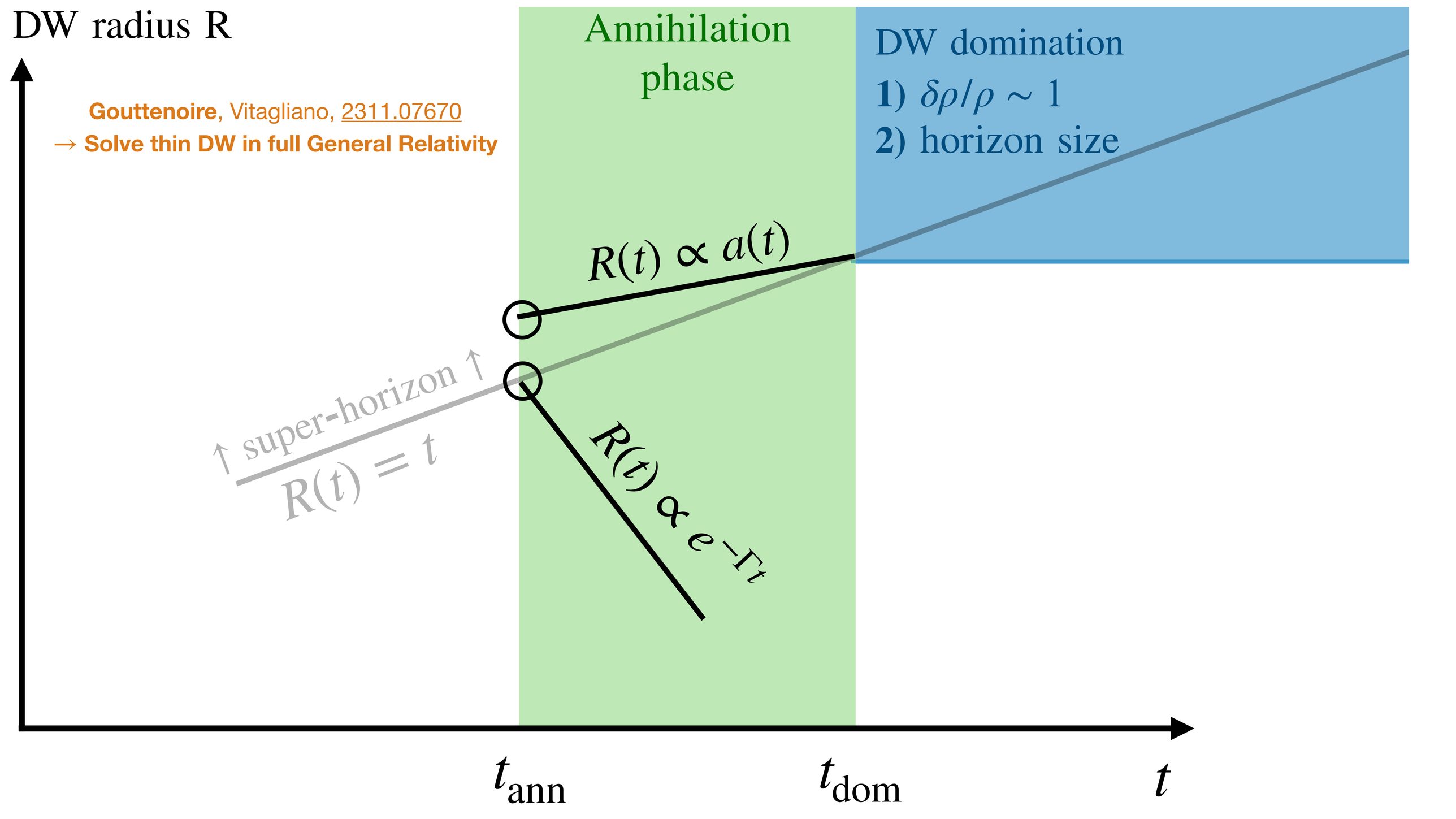
2023: YG, E. Vitagliano, 2306.17841 (version 1)

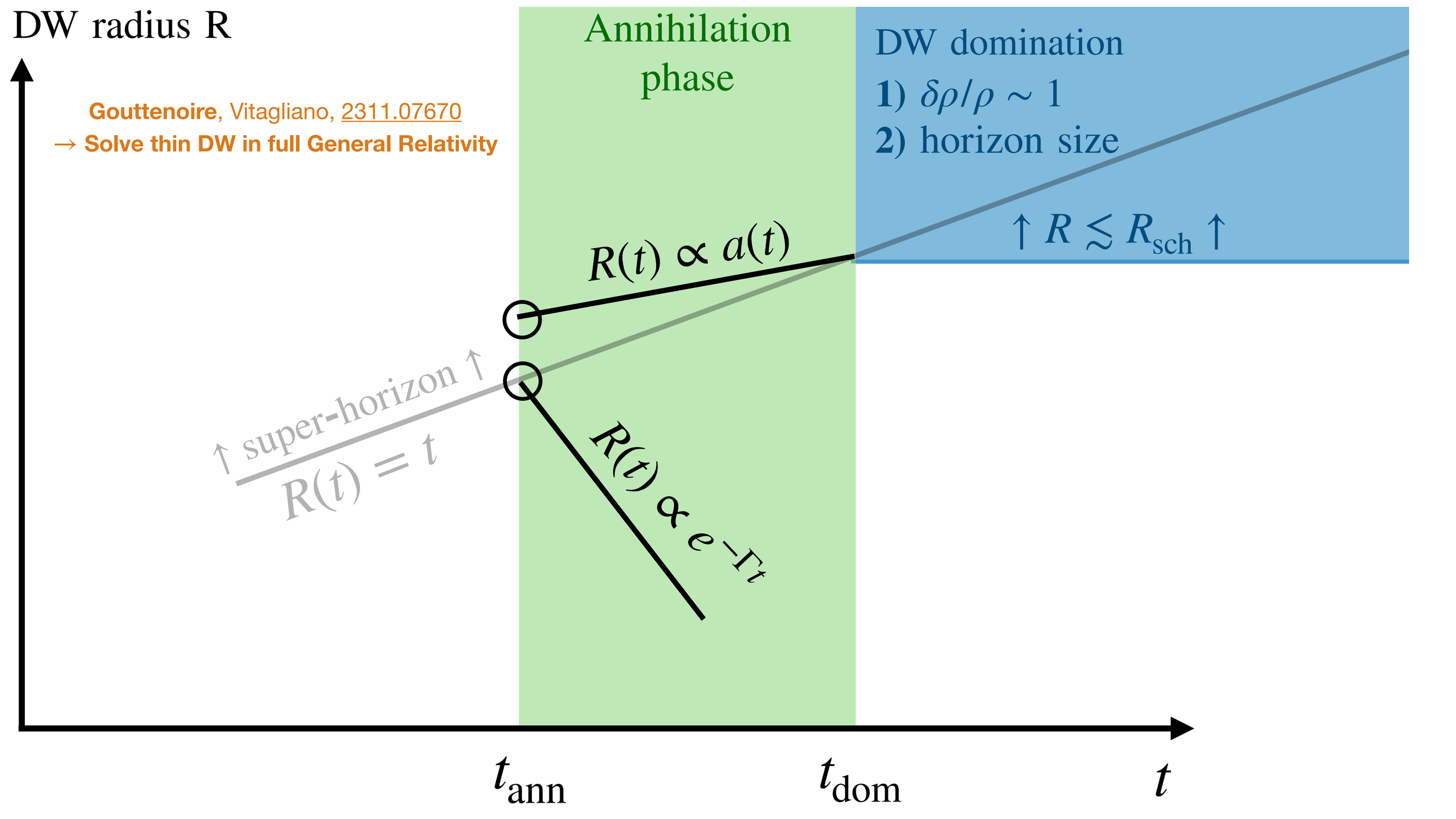

DW radius R
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
$R(t) \propto a(t)$
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
t

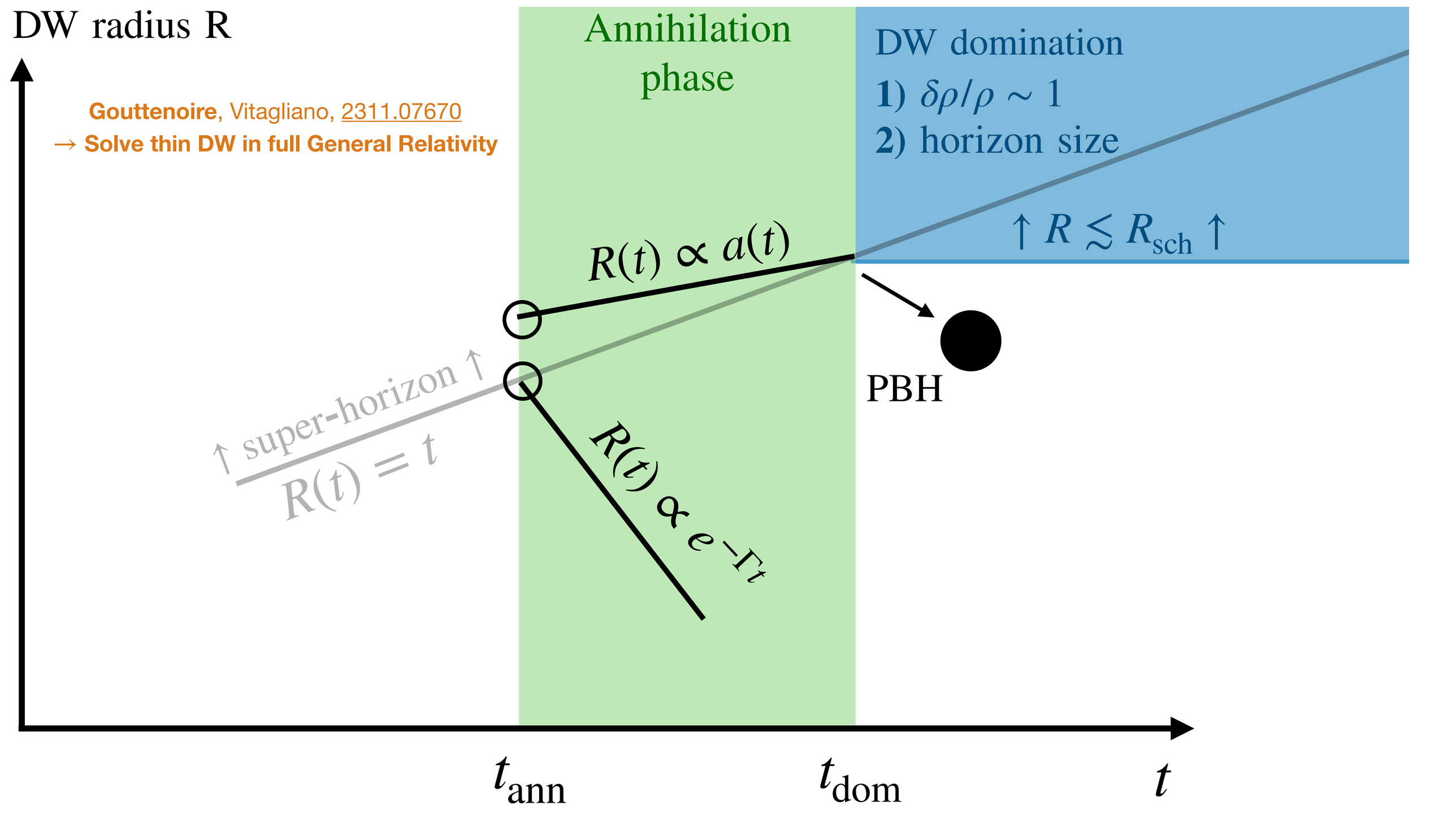

DW radius R
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
$\langle R(t) \rangle \simeq t$ but not R(t) ≃ t
$R(t) \propto a(t)$
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
t

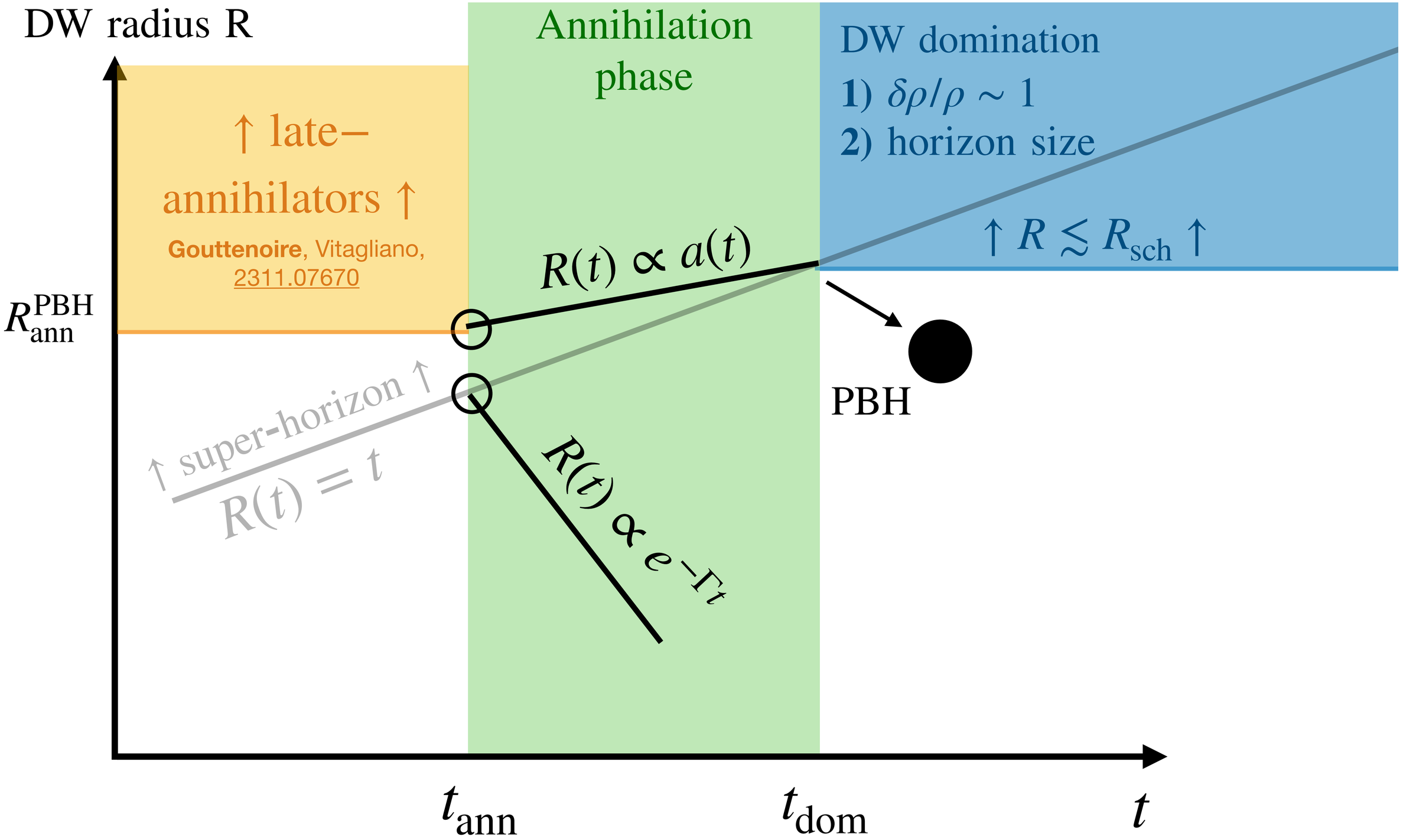

DW radius R
Annihilation phase
DW domination
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
$R(t) \propto a(t)$
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
$t_{\rm ann}$
$t_{\rm dom}$
t

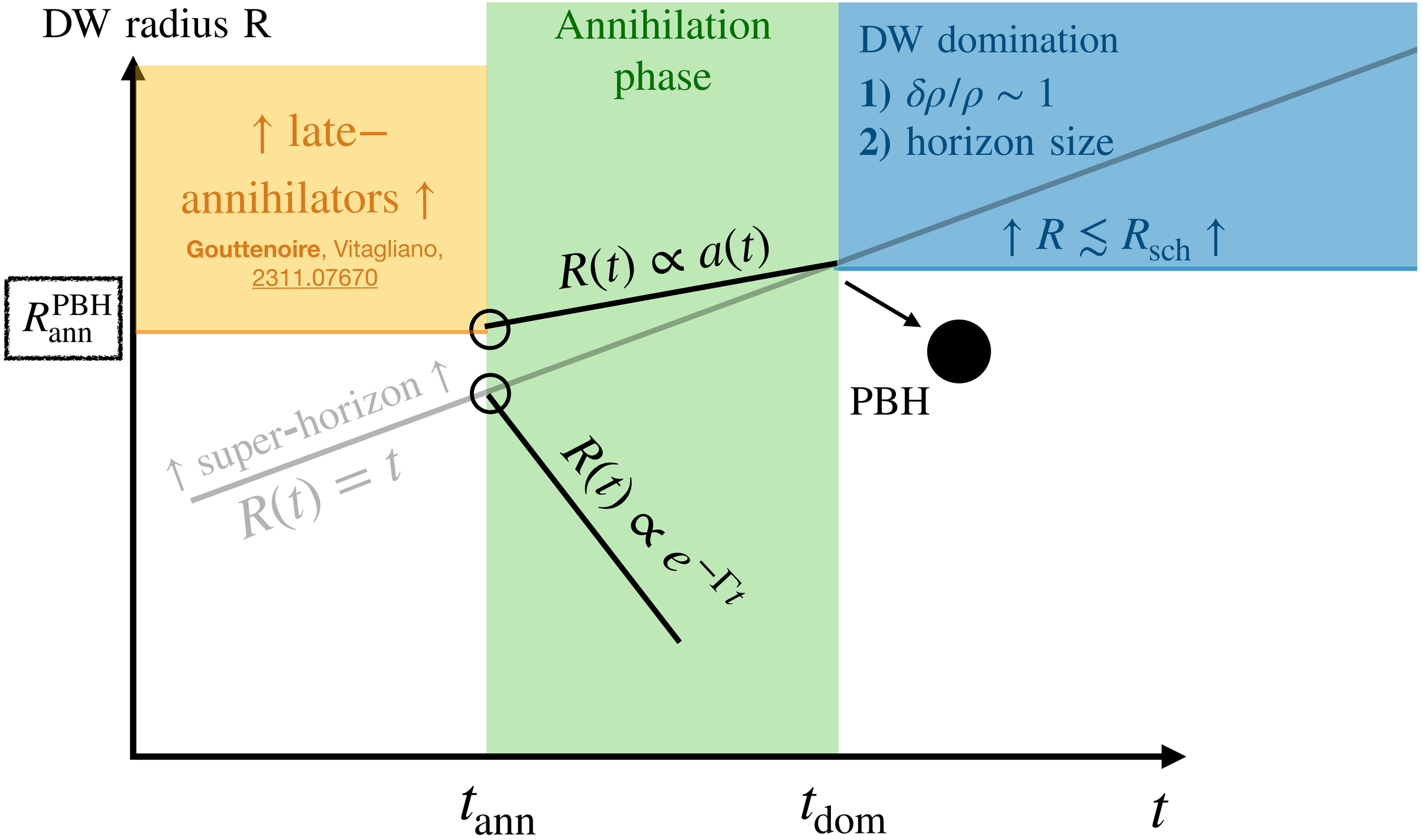

DW radius R
Annihilation phase
DW domination
1) $\delta\rho/\rho \sim 1$
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
$R(t) \propto a(t)$
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
$t_{\rm ann}$
$t_{\rm dom}$
t


DW radius R
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
Annihilation phase
DW domination
1) $\delta\rho/\rho \sim 1$
2) horizon size
$R(t) \propto a(t)$
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
$t_{\rm ann}$
$t_{\rm dom}$
t


DW radius R
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
Annihilation phase
DW domination
1) $\delta\rho/\rho \sim 1$
2) horizon size
$\uparrow R \lesssim R_{\rm sch} \uparrow$
$R(t) \propto a(t)$
$\uparrow$ super-horizon $\uparrow$
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
$t_{\rm ann}$
$t_{\rm dom}$
t


DW radius R
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
Annihilation phase
DW domination
1) $\delta\rho/\rho \sim 1$
2) horizon size
$\uparrow R \lesssim R_{\rm sch} \uparrow$
$R(t) \propto a(t)$
PBH
$\uparrow$ super-horizon $\uparrow$
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
$t_{\rm ann}$
$t_{\rm dom}$
t


DW radius R
Annihilation phase
DW domination
1) $\delta\rho/\rho \sim 1$
2) horizon size
↑ late–annihilators ↑
Gouttenoire, Vitagliano, 2311.07670
↑ $R \lesssim R_{\rm sch}$ ↑
$R(t) \propto a(t)$
$R_{\rm ann}^{\rm PBH}$
PBH
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
$t_{\rm ann}$
$t_{\rm dom}$
t


DW radius R
Annihilation phase
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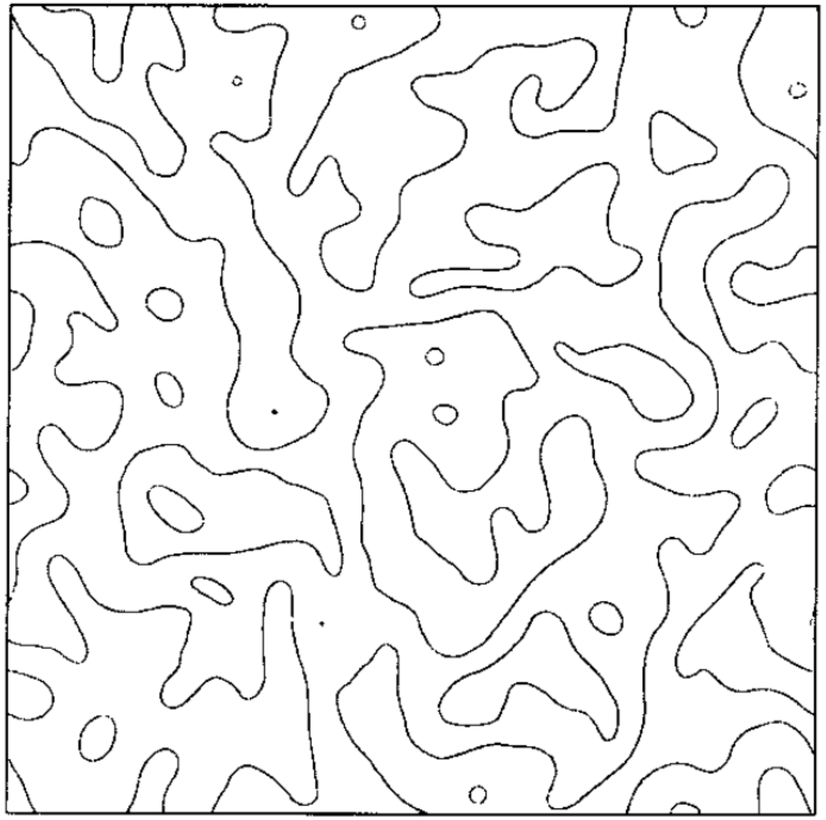
Gouttenoire, Vitagliano, 2311.07670
↑ $R \lesssim R_{\rm sch}$ ↑
$R(t) \propto a(t)$
$R_{\rm ann}^{\rm PBH}$
PBH
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
$t_{\rm ann}$
$t_{\rm dom}$
t

Gouttenoire, Vitagliano, 2311.07670

Abundance of late-annihilators $\mathcal{F}$

Percolation theory on a lattice *Stauffer (1979)* *Coulson, Lalak, Ovrut (1995)*



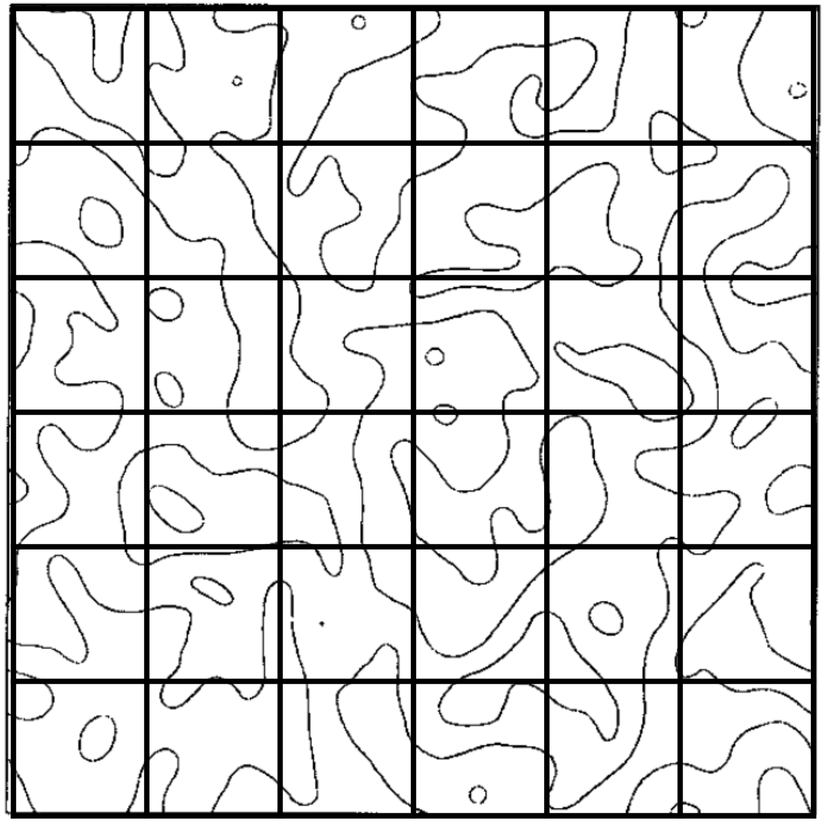
PRESS, RYDEN, AND SPERGEL 1989

Gouttenoire, Vitagliano, 2311.07670

Abundance of late-annihilators $\mathcal{F}$

Percolation theory on a lattice

Stauffer (1979) *Coulson, Lalak, Ovrut (1995)*



PRESS, RYDEN, AND SPERGEL 1989

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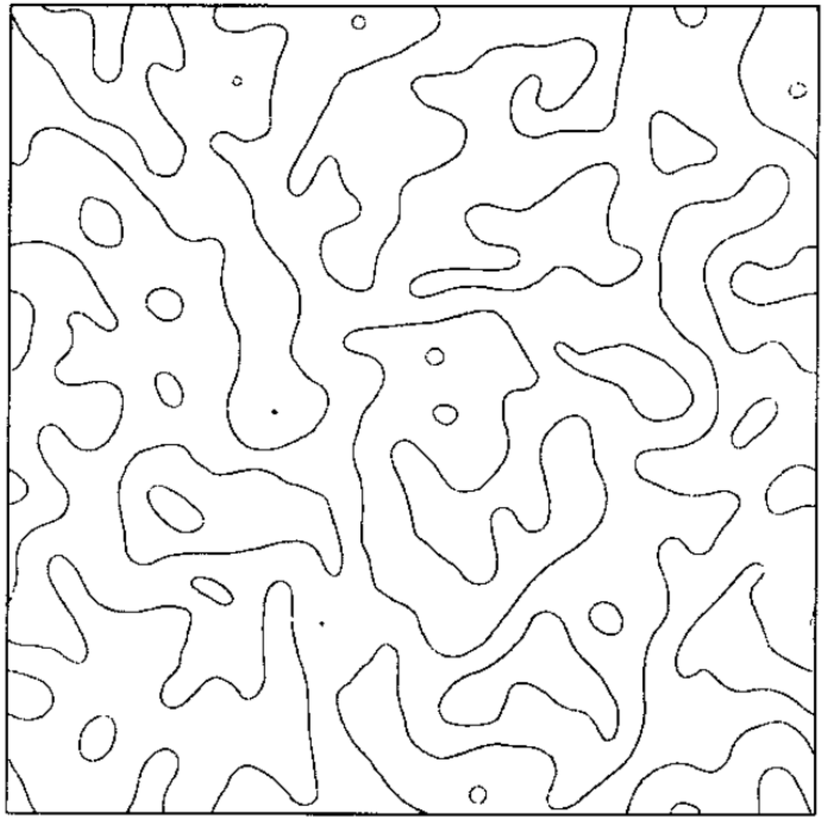
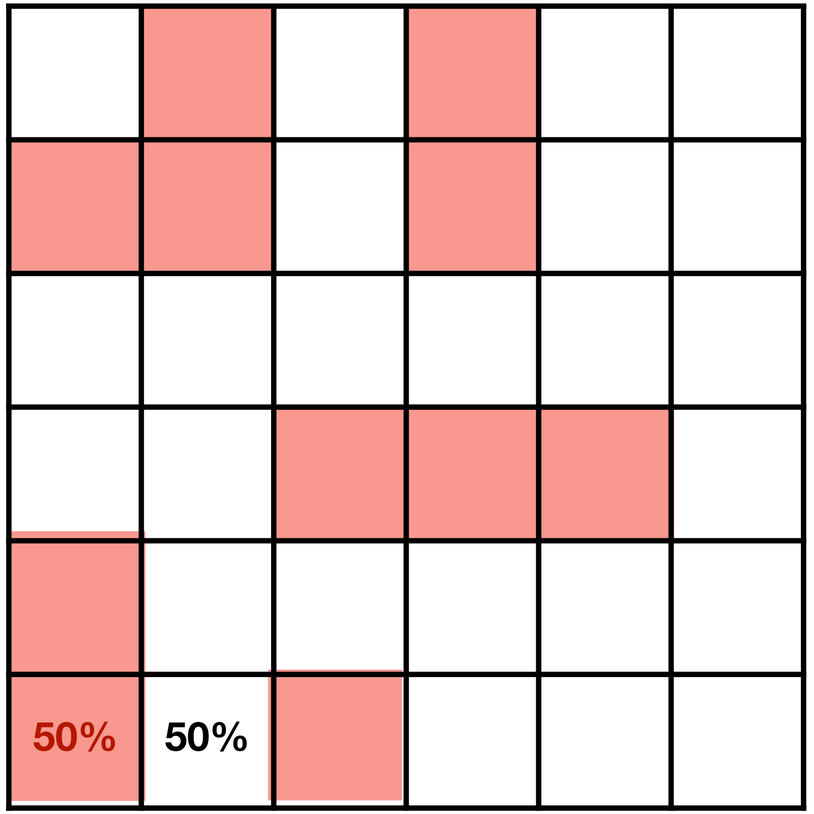


PRESS, RYDEN, AND SPERGEL 1989

Discretization

$L \sim t$

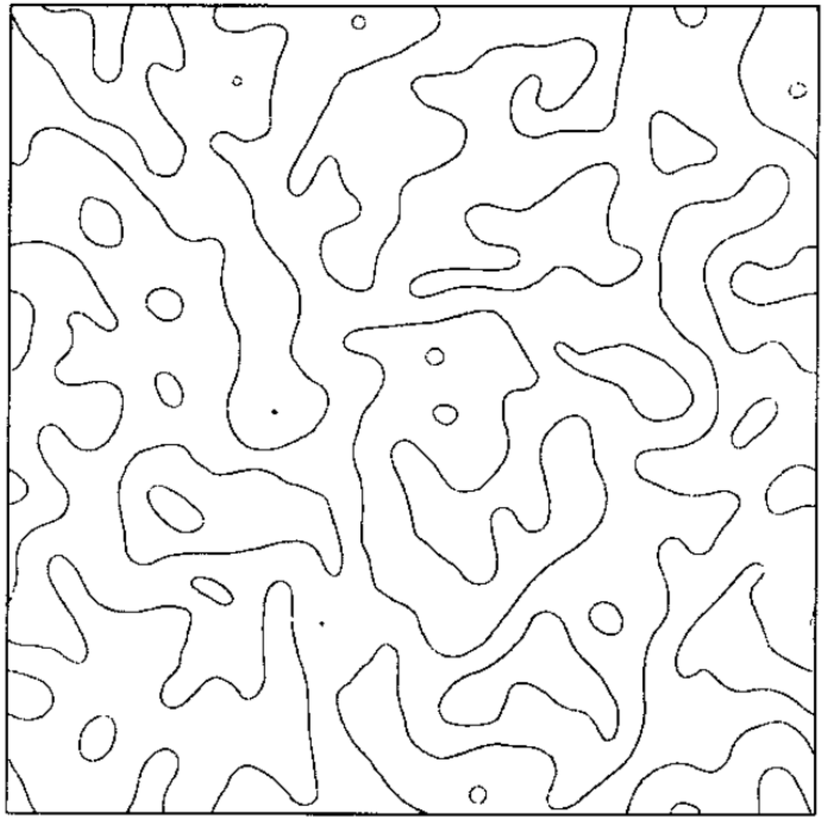


Gouttenoire, Vitagliano, 2311.07670

Abundance of late-annihilators $\mathscr{F}$

Percolation theory on a lattice *Stauffer (1979)* *Coulson, Lalak, Ovrut (1995)*

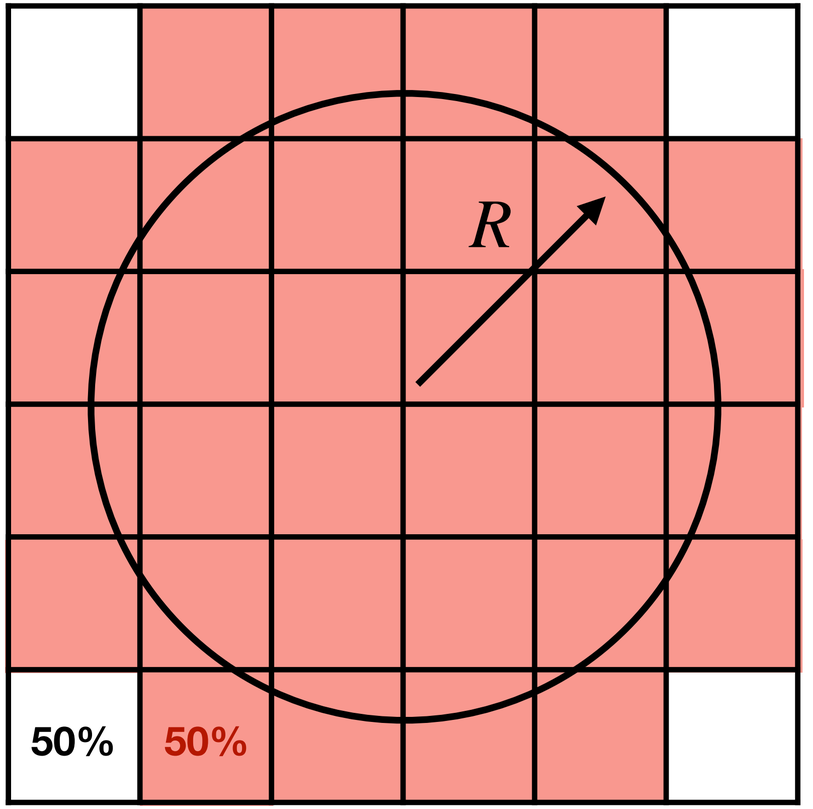
Probability of a spherical false vacuum domain of size R: $\mathscr{P} \sim \exp\left(-4\pi(R/t)^3/3\right)$



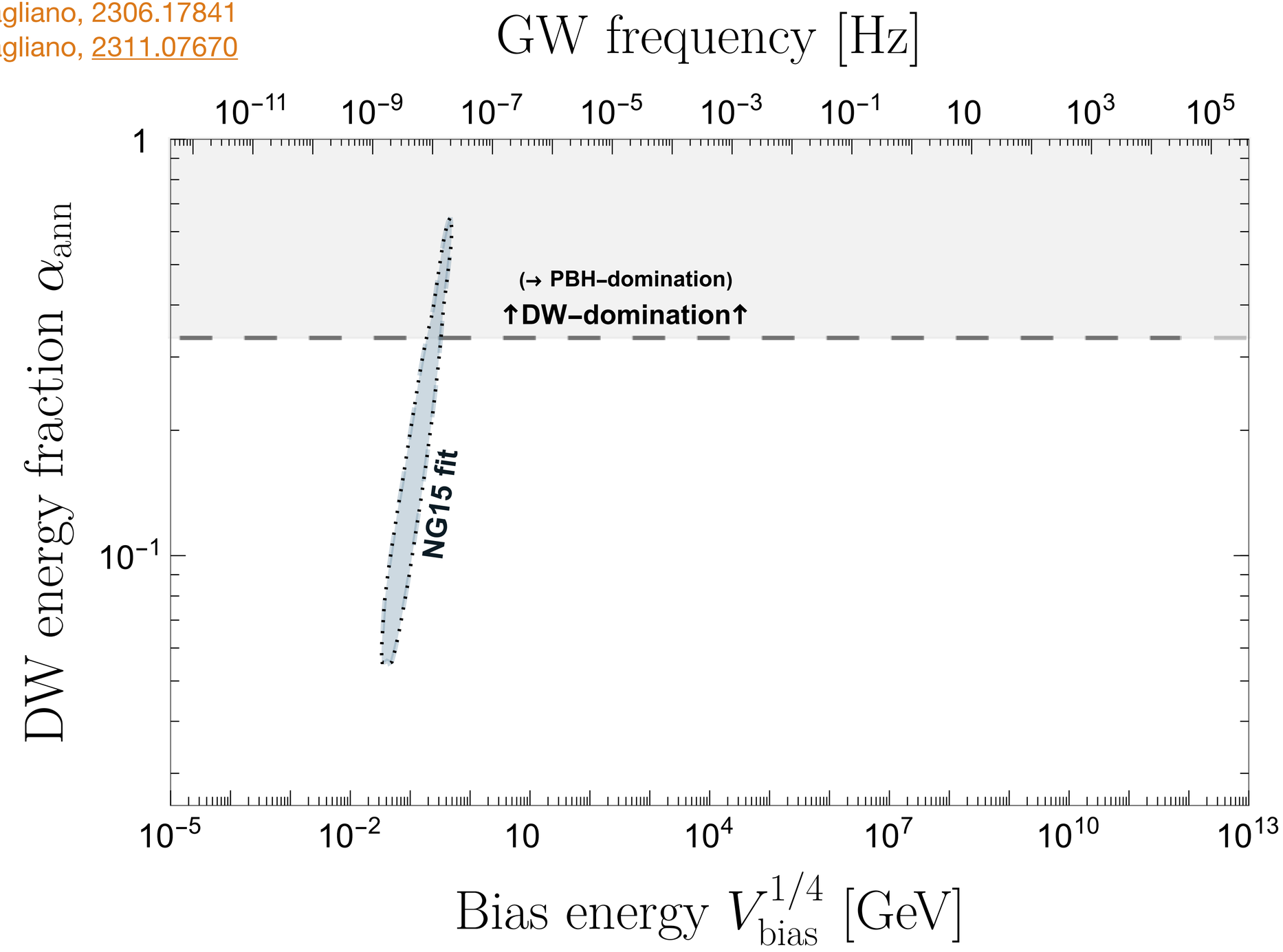
PRESS, RYDEN, AND SPERGEL 1989

Discretization

$L \sim t$



Gouttenoire, Vitagliano, 2306.17841
Gouttenoire, Vitagliano, 2311.07670



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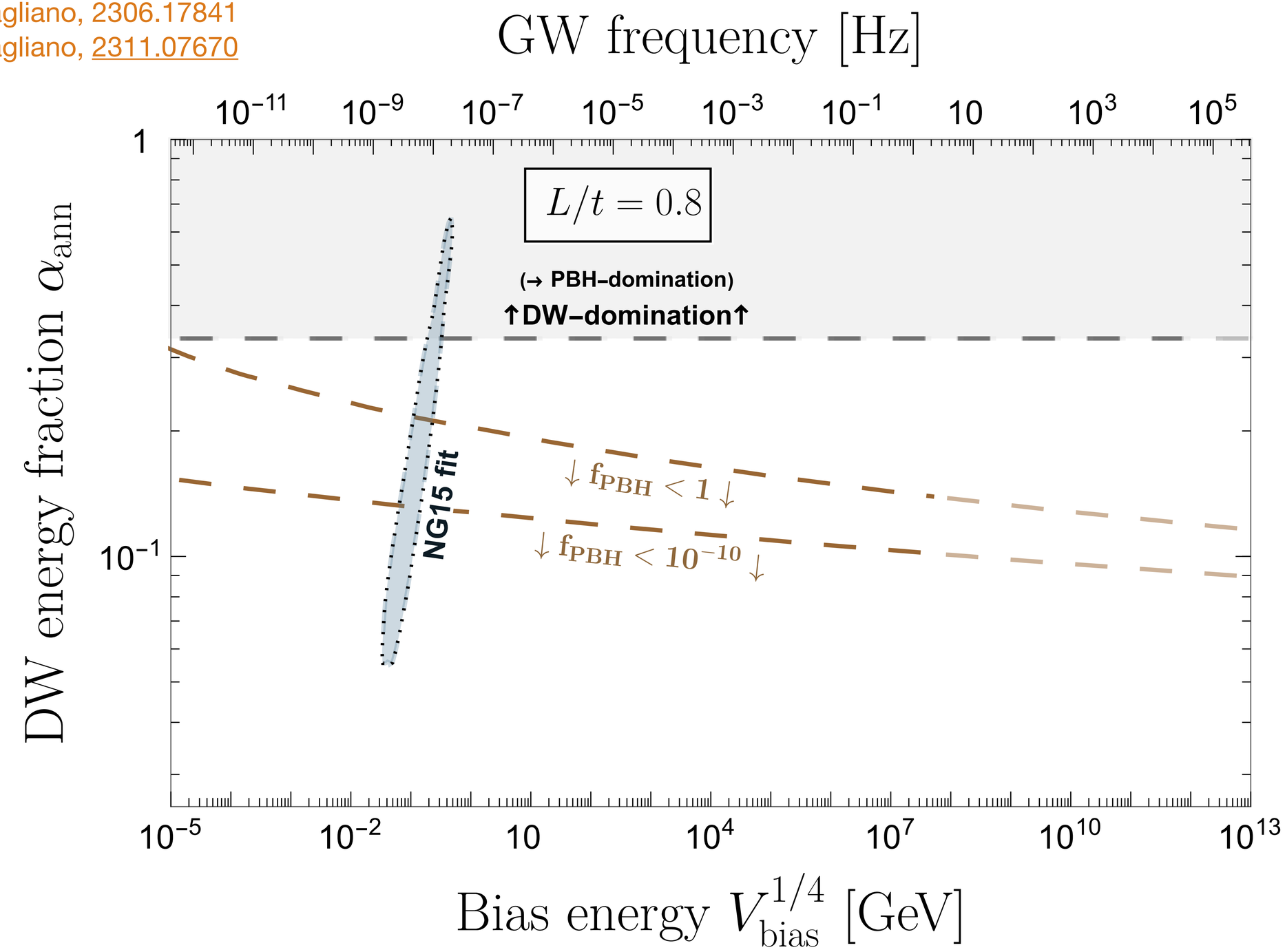

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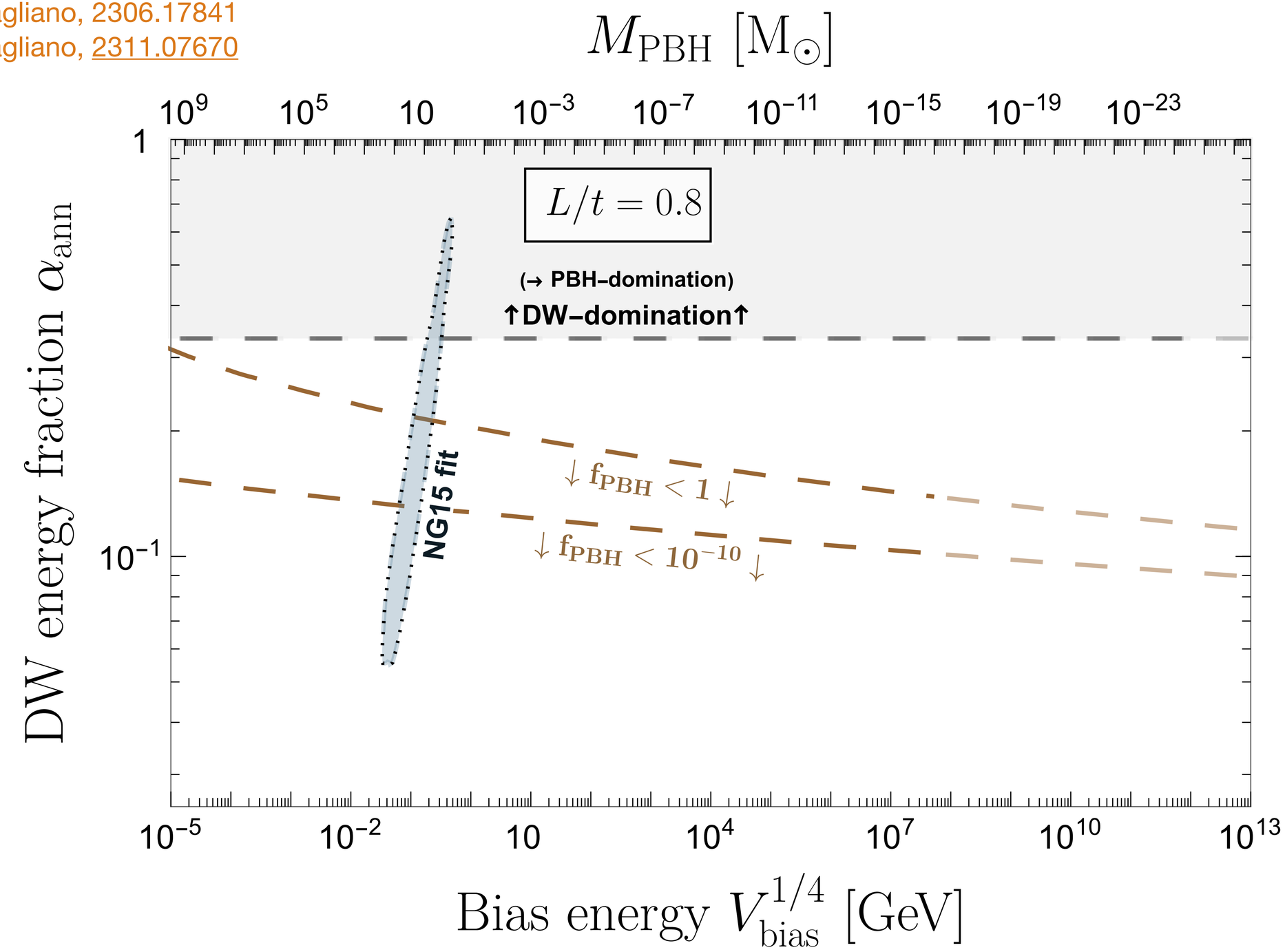

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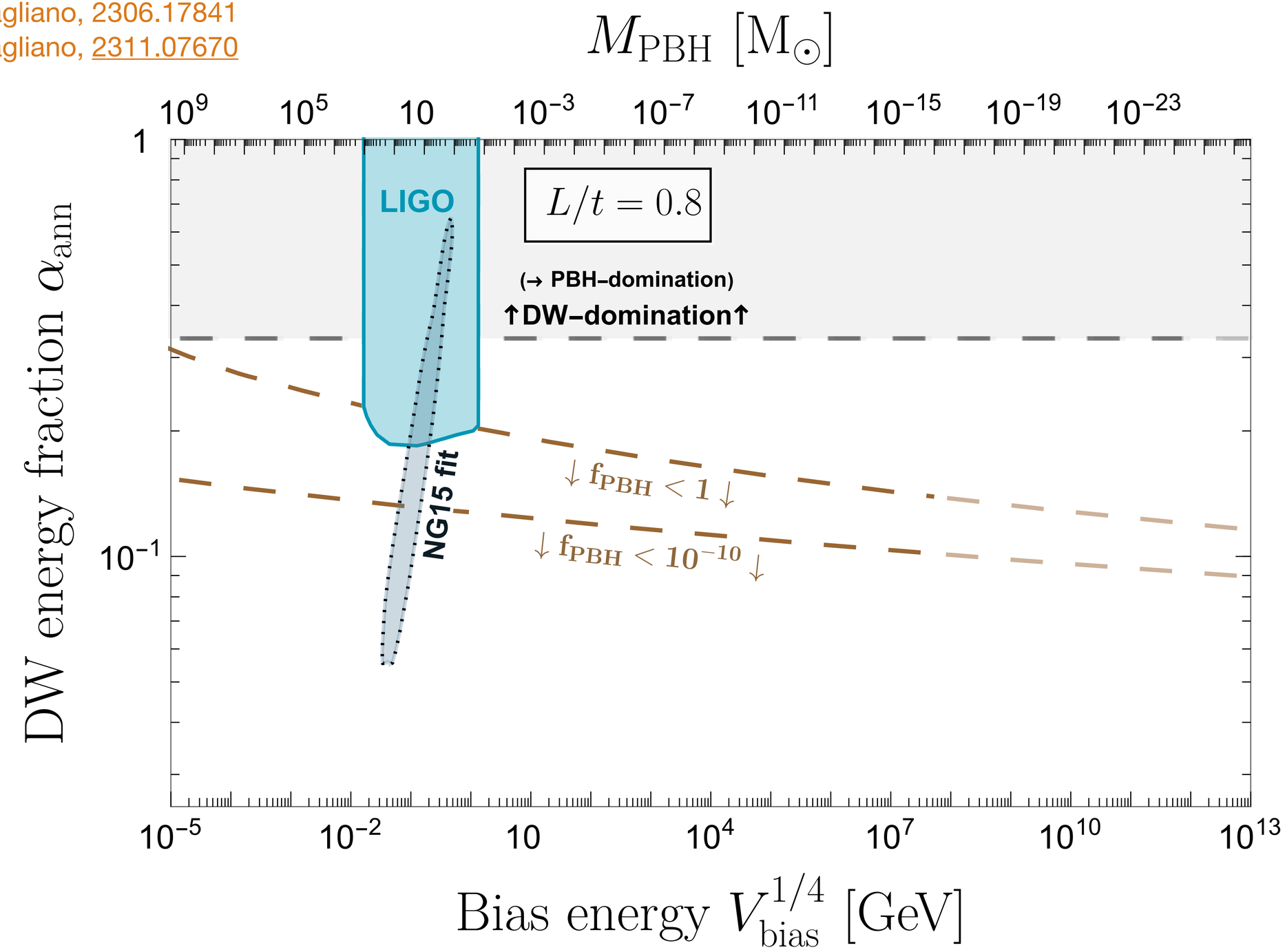

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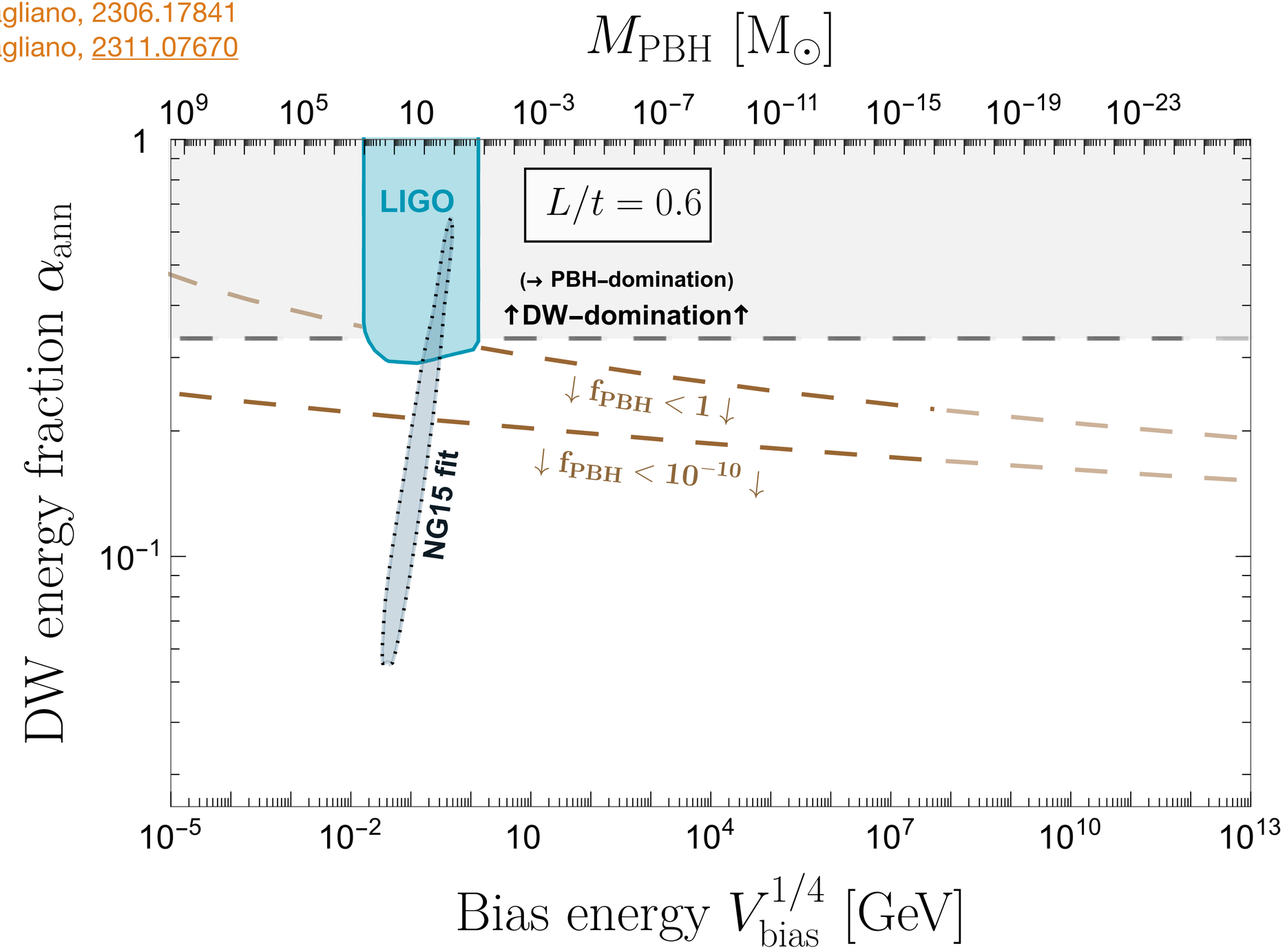

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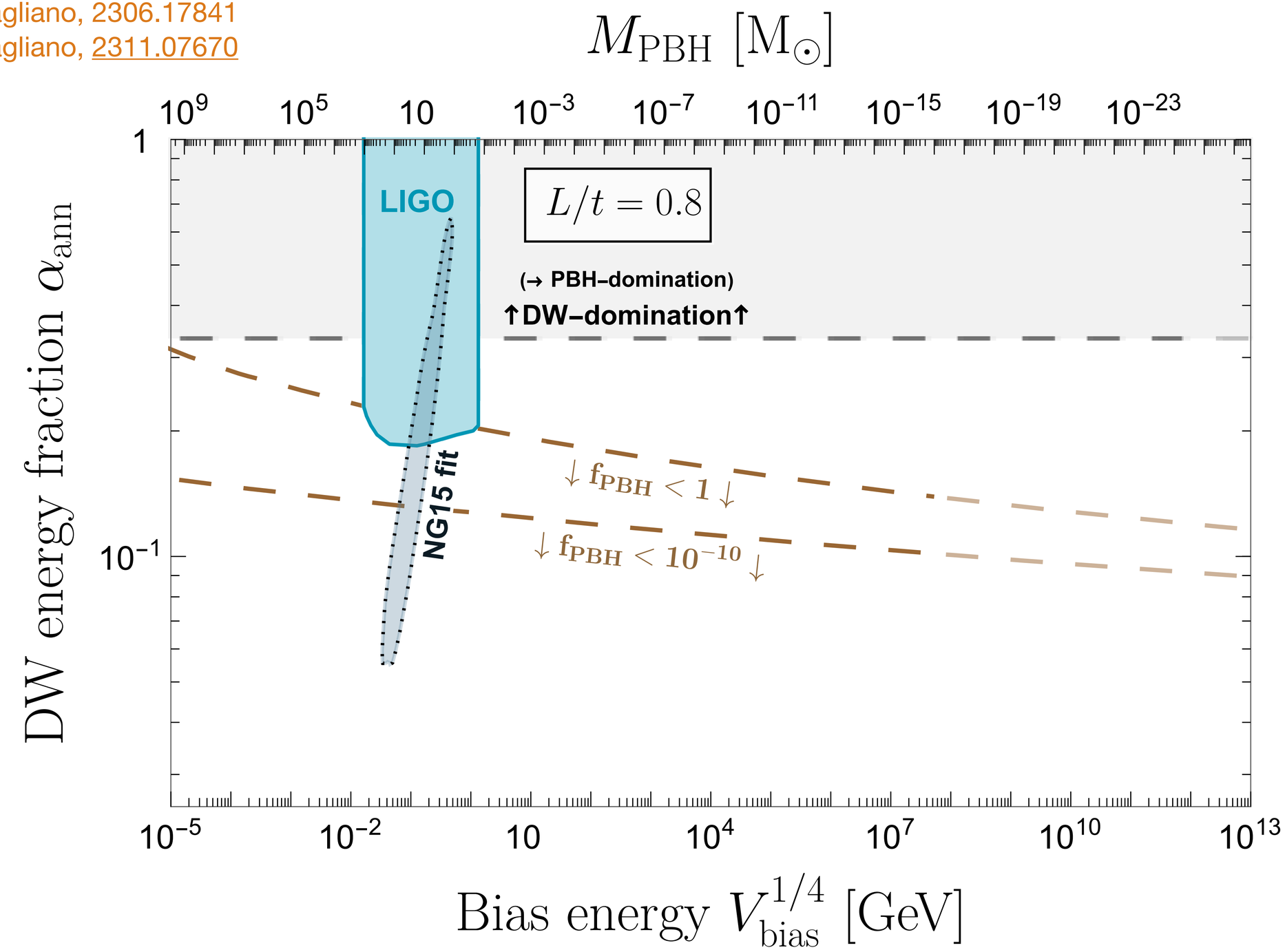

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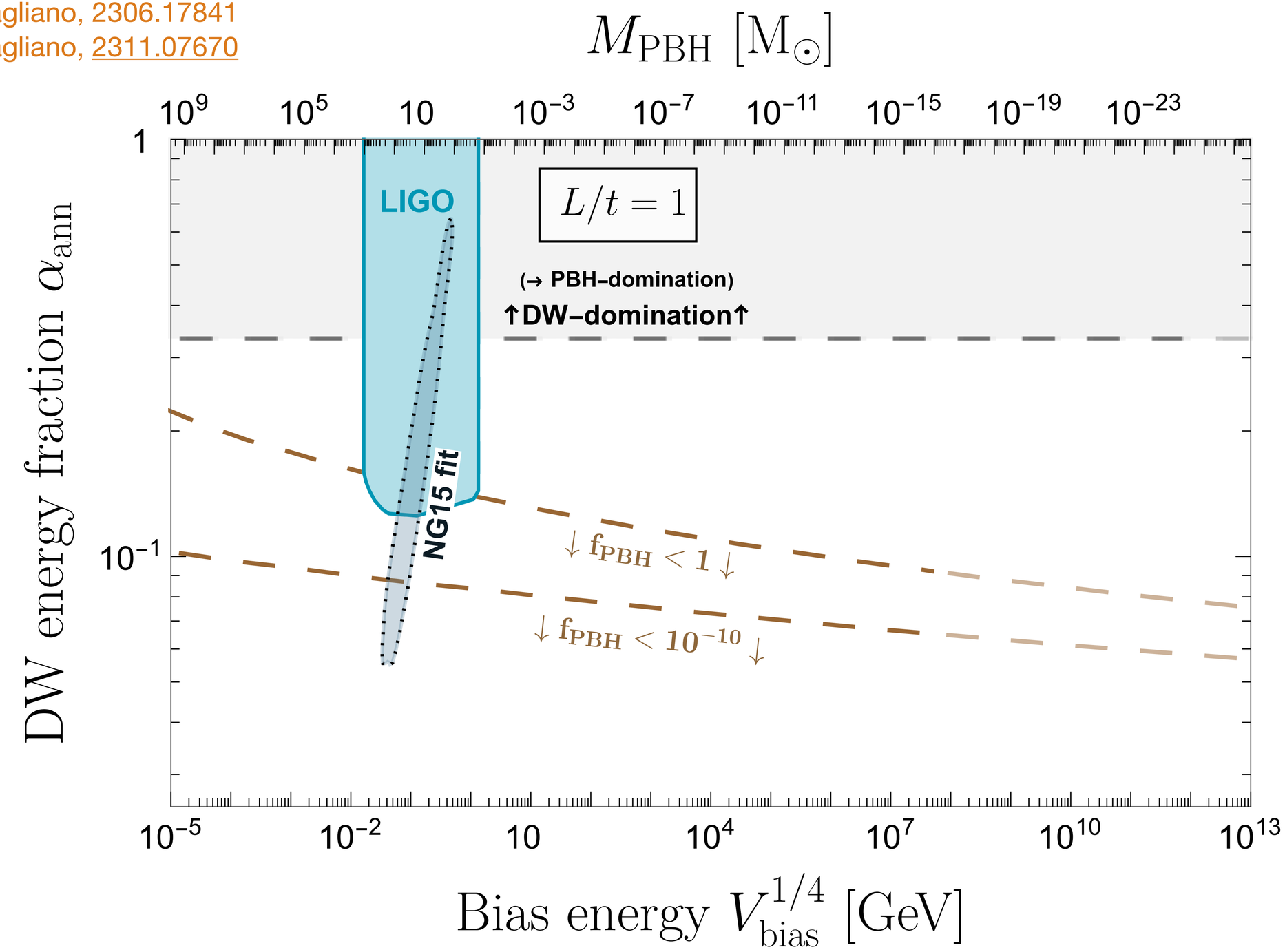

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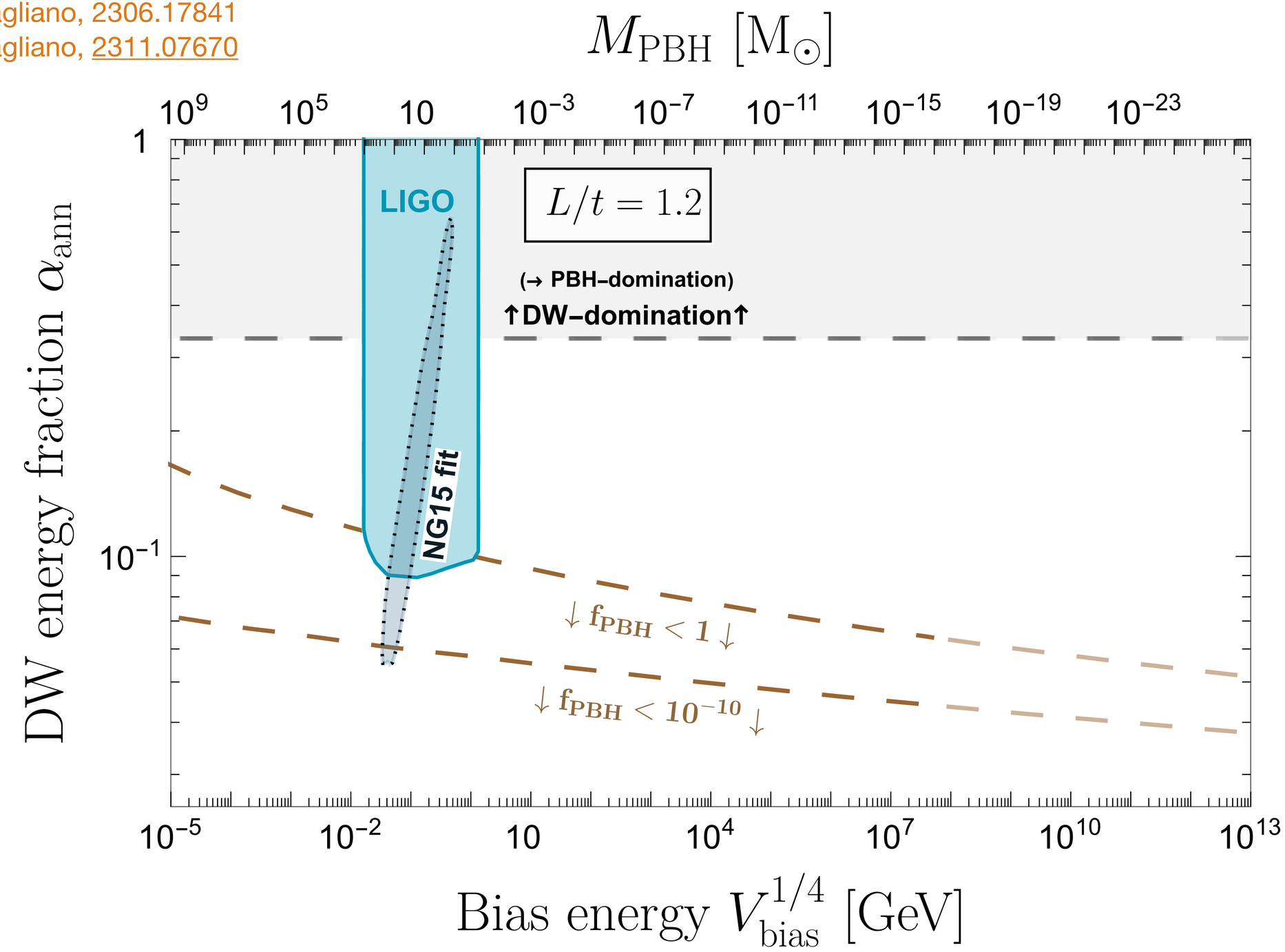
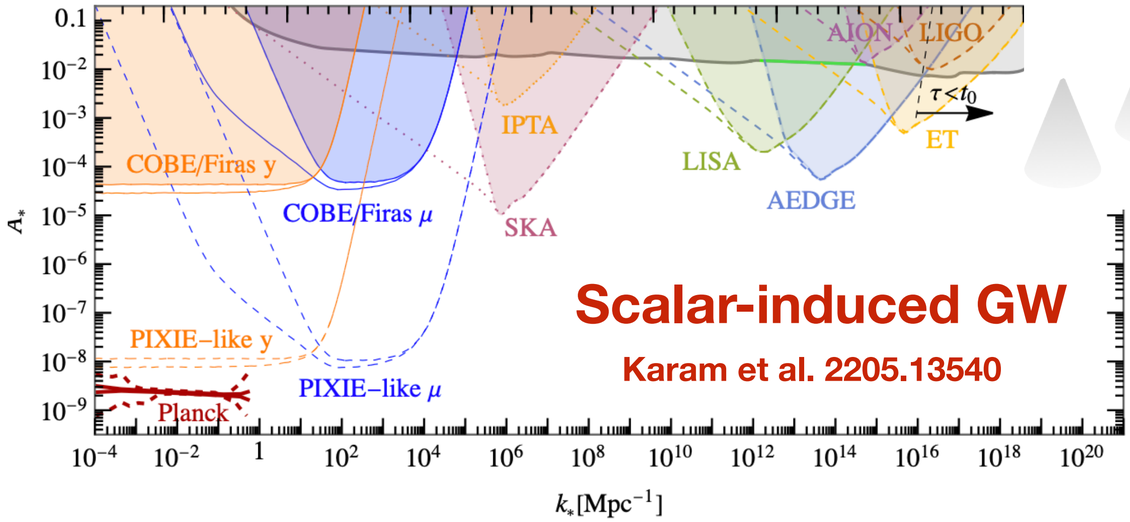


Summary

PTA signal with early universe physics :
⇒requires violent phenomena
⇒PBH as a by-product.



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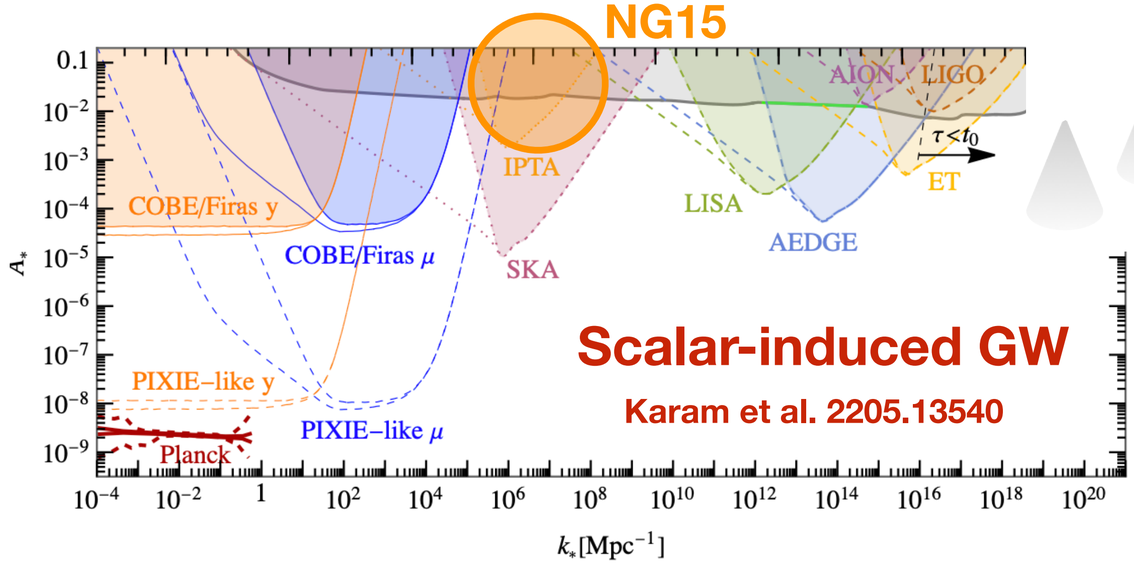

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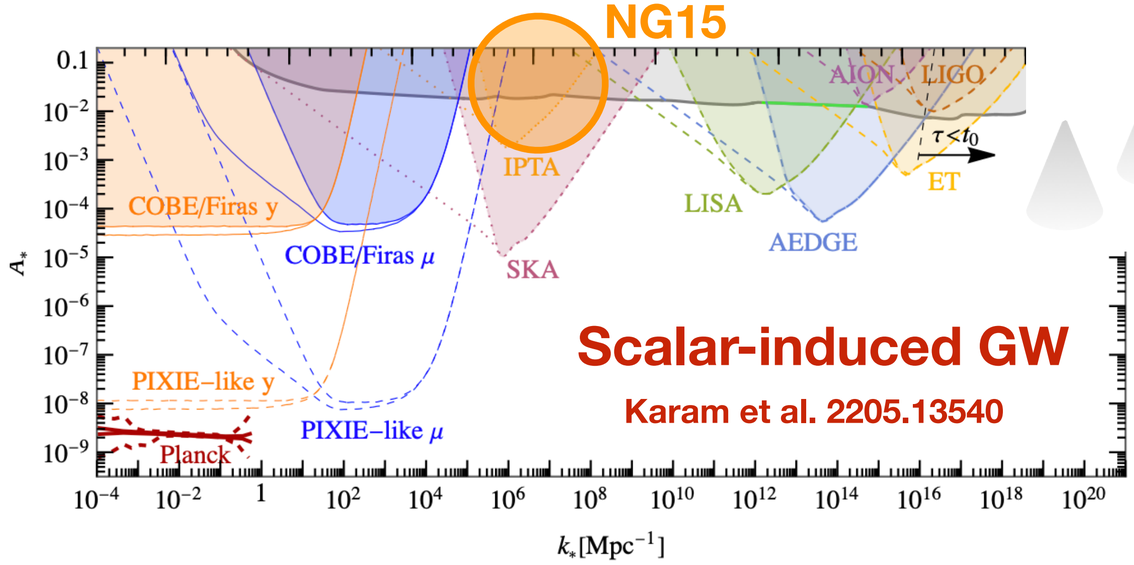
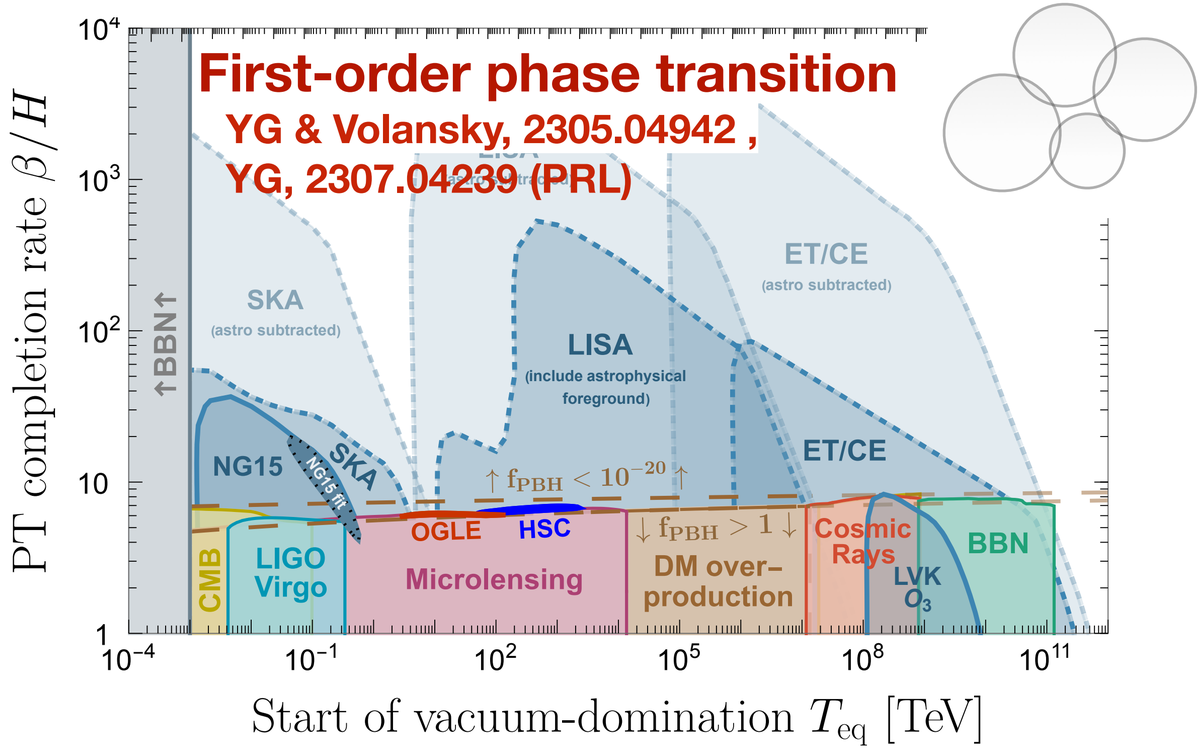


Scalar-induced GW

Karam et al. 2205.13540



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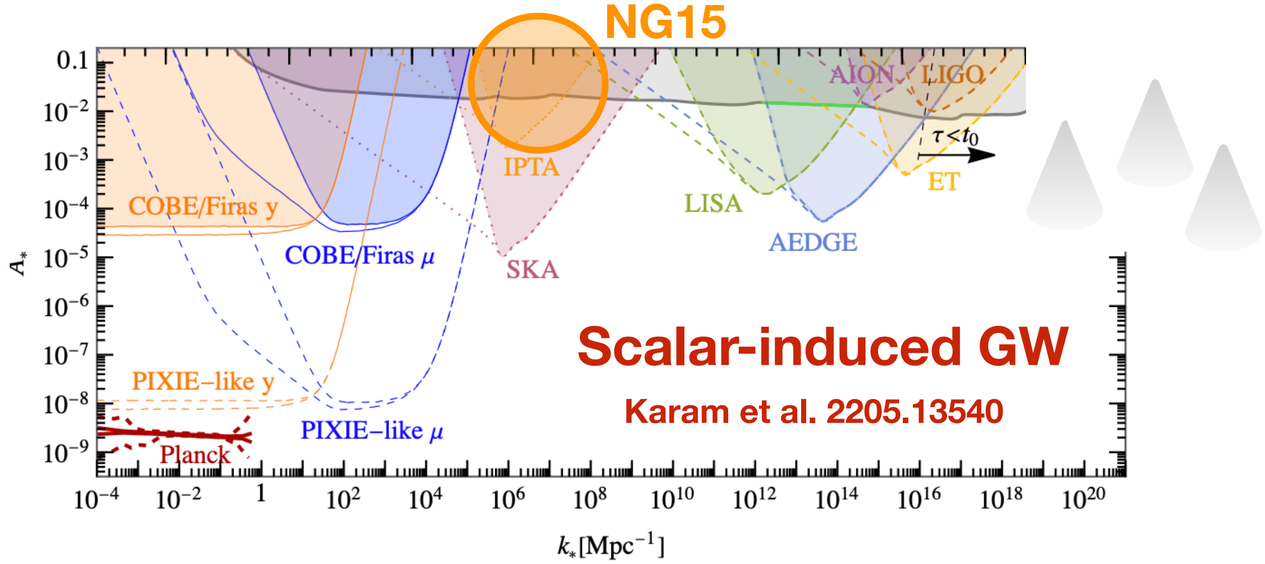

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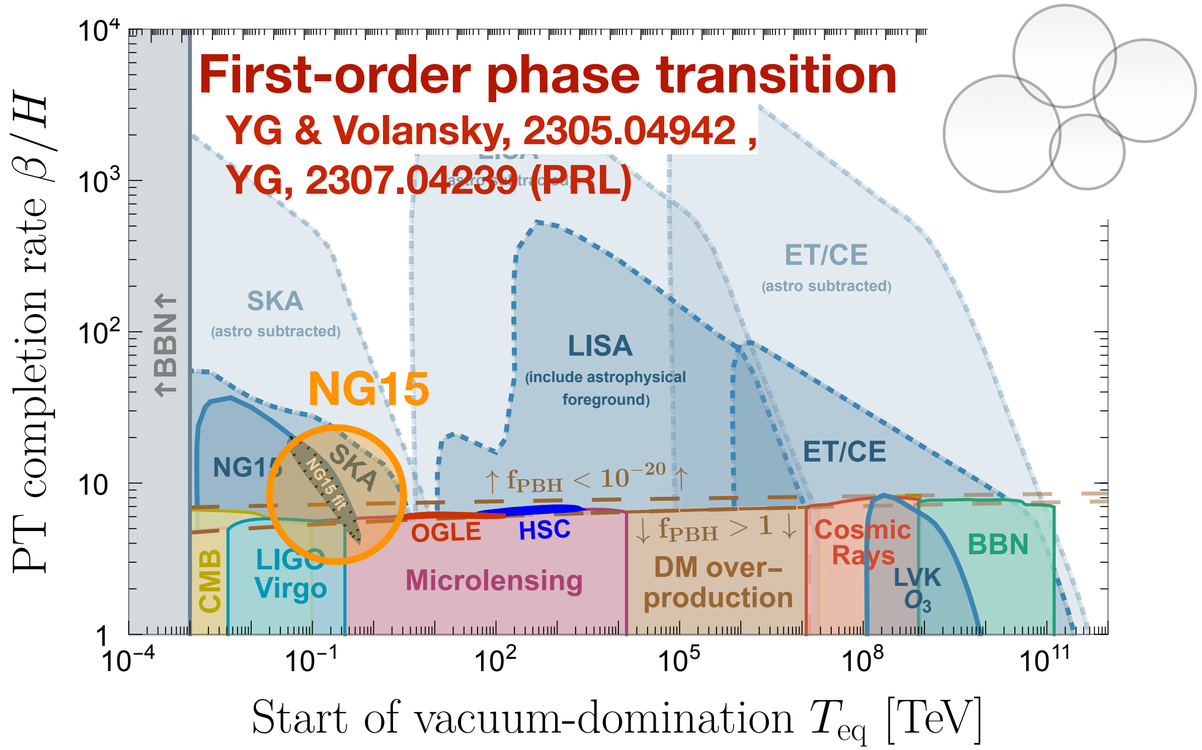

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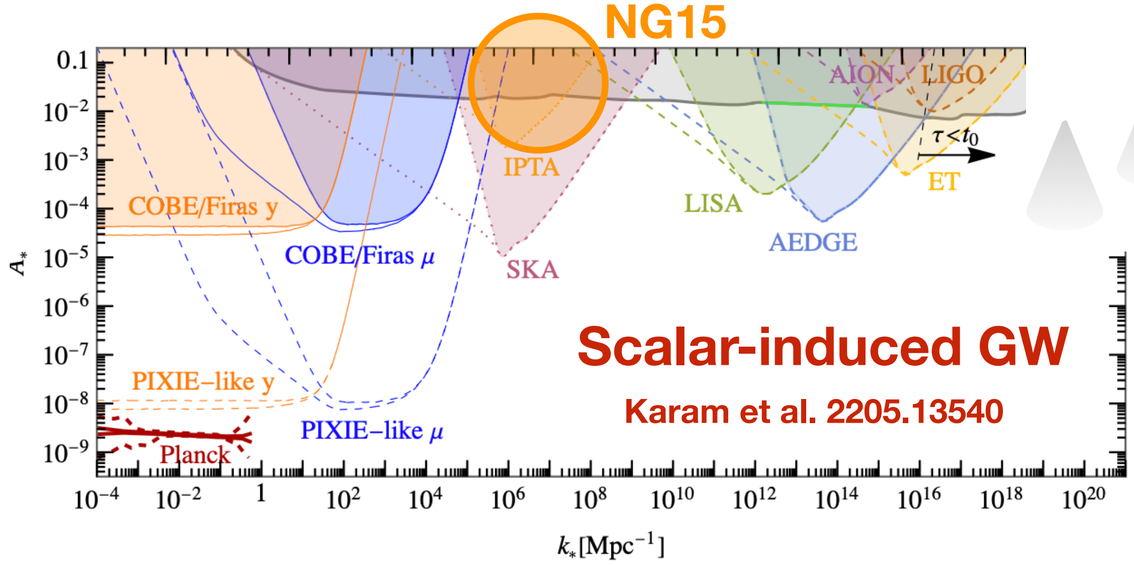

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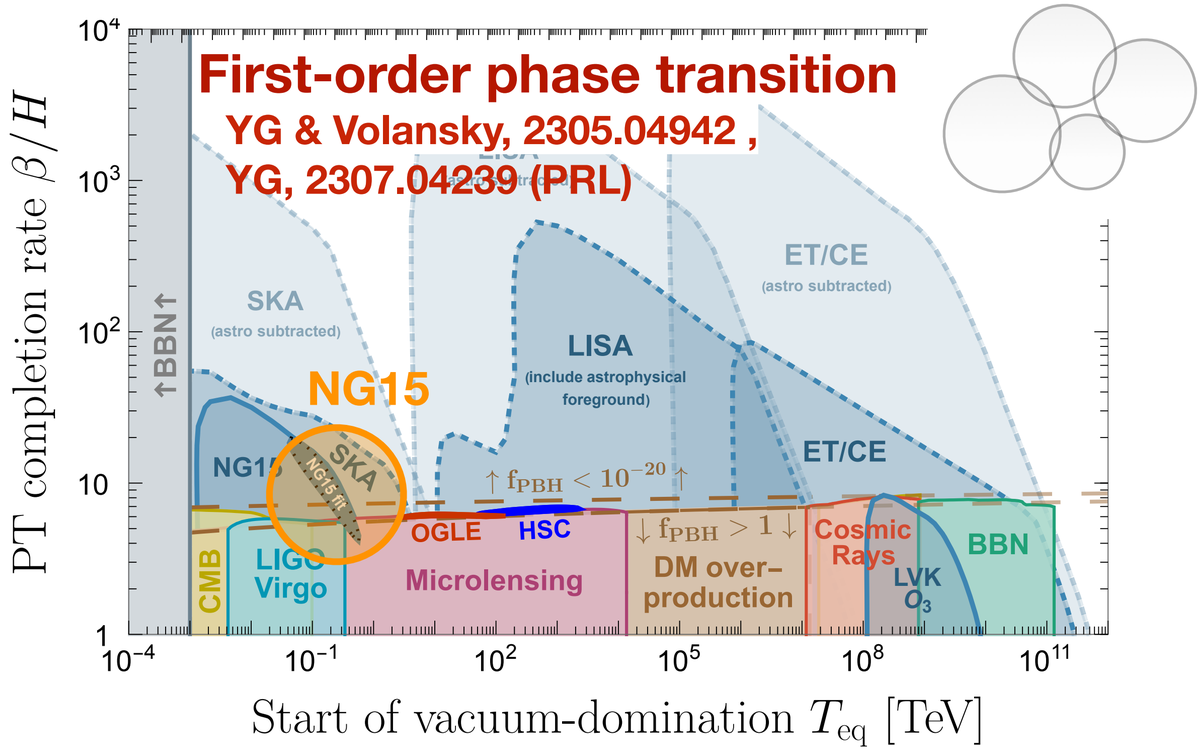
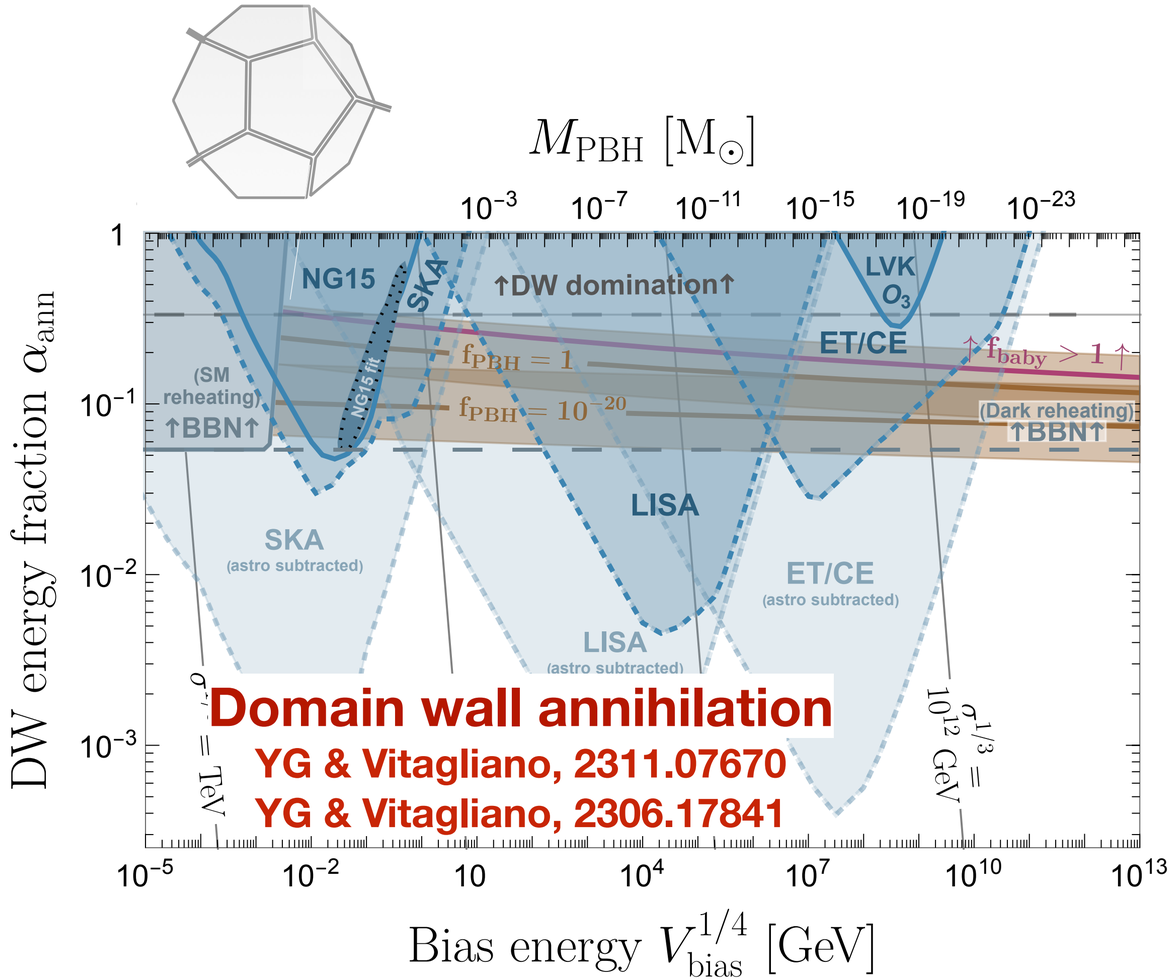


First-order phase transition

YG & Volansky, 2305.04942 ,

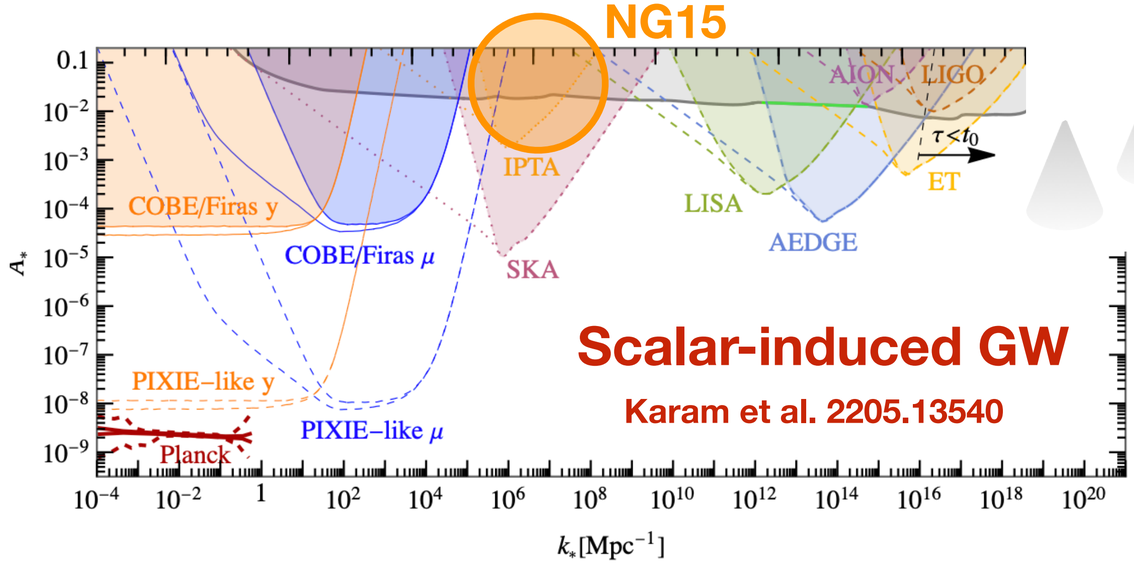
YG, 2307.04239 (PRL)



Domain wall annihilation

YG & Vitagliano, 2311.07670

YG & Vitagliano, 2306.17841



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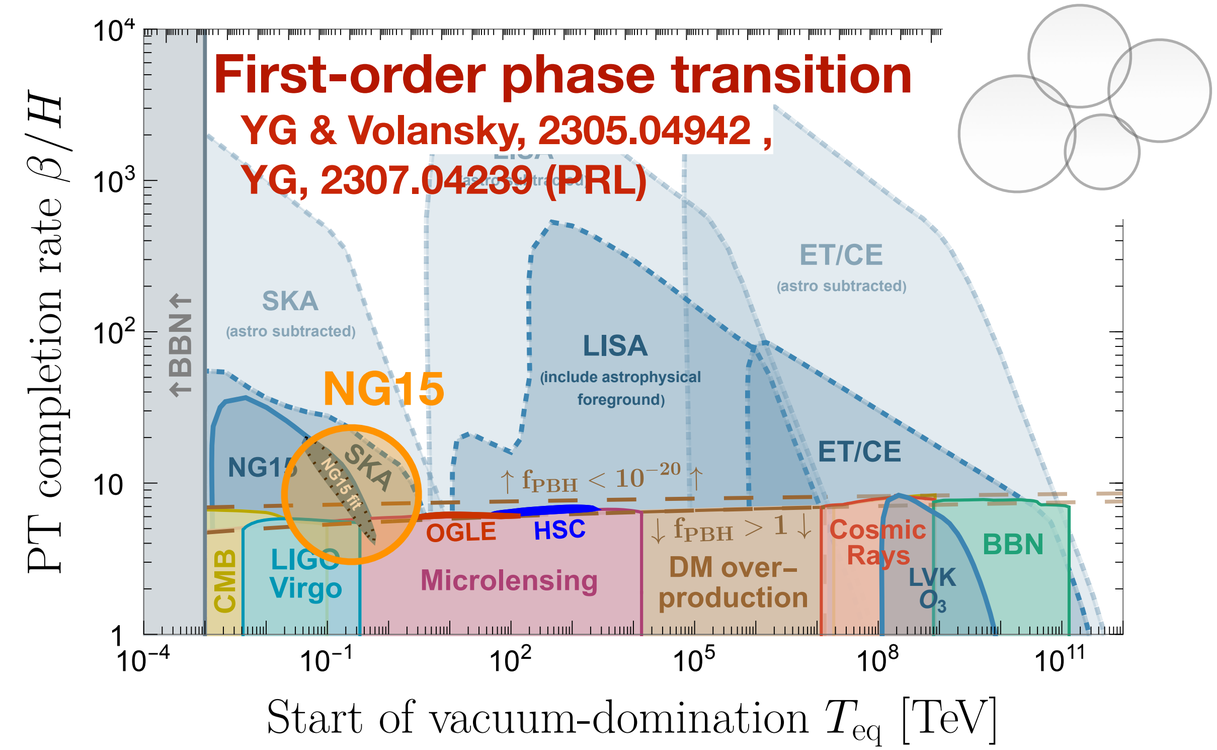

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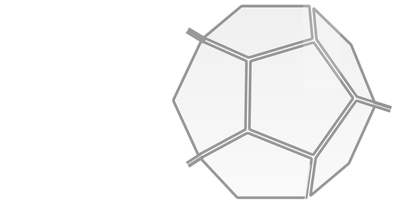

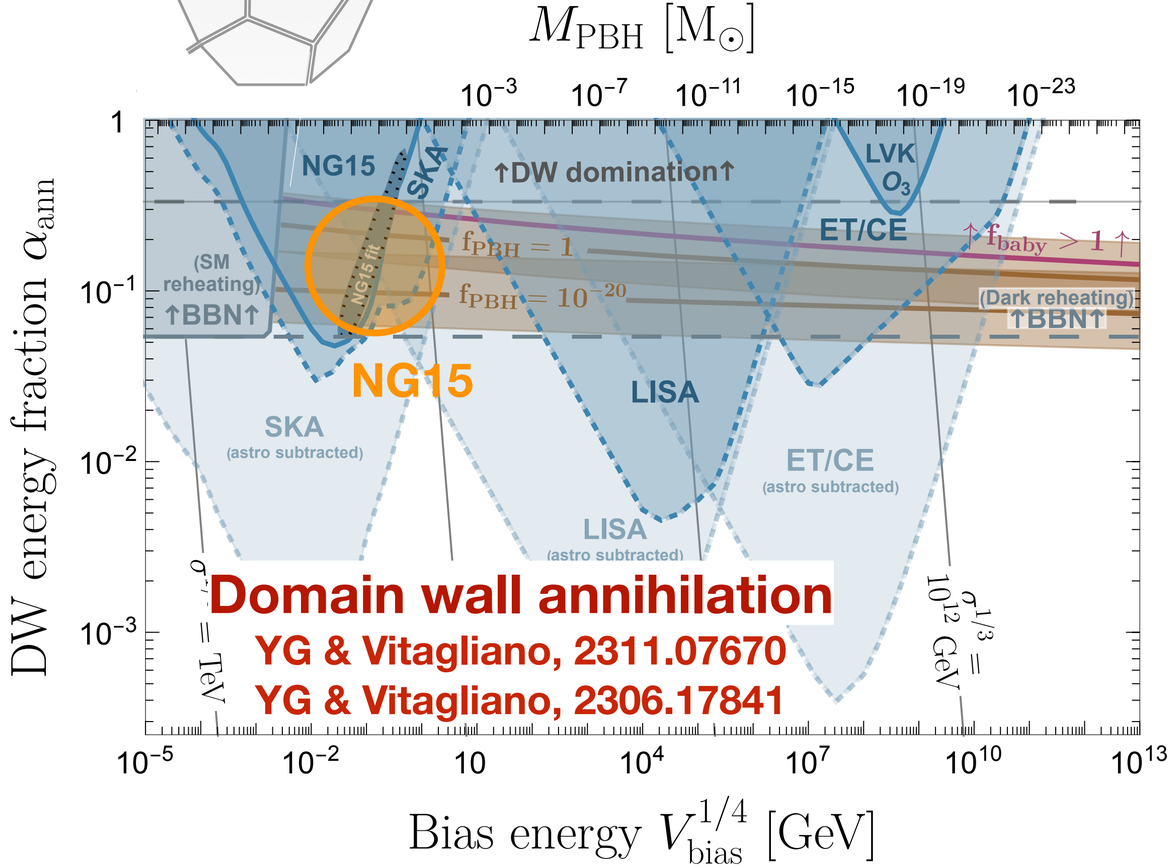

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