Baby Universes from Domain Wall Networks

Yann Gouttenoire

1st January 2025

ICTS, Bengaluru

“Hearing beyond the standard model with cosmic sources of Gravitational Waves”

Gouttenoire, Vitagliano, 2306.17841

Gouttenoire, Vitagliano, 2311.07670

Gouttenoire, King, Roshan, Wang, White, Yamazaki, 2501.XXXXX

PhD in DESY (2017-2020)

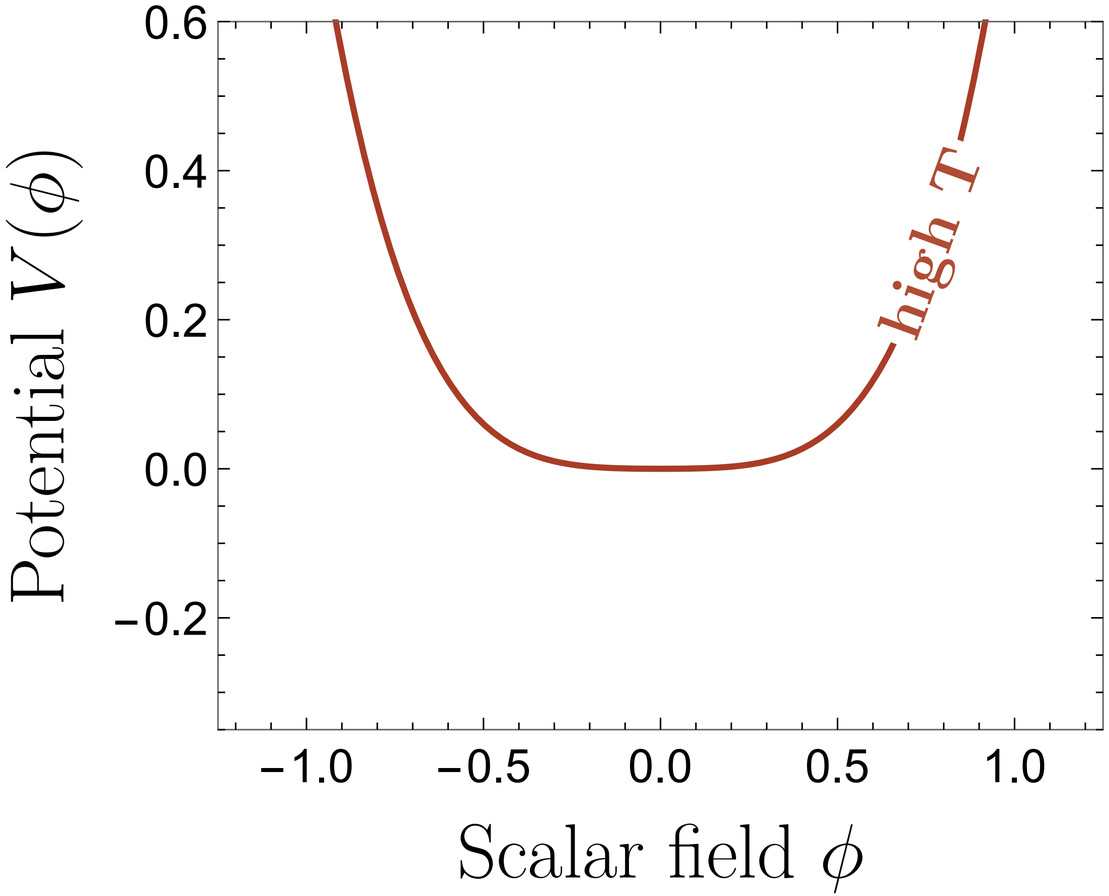
Postdoc in Tel Aviv U. (2021-2024)

Postdoc in MITP Mainz (since 2024)

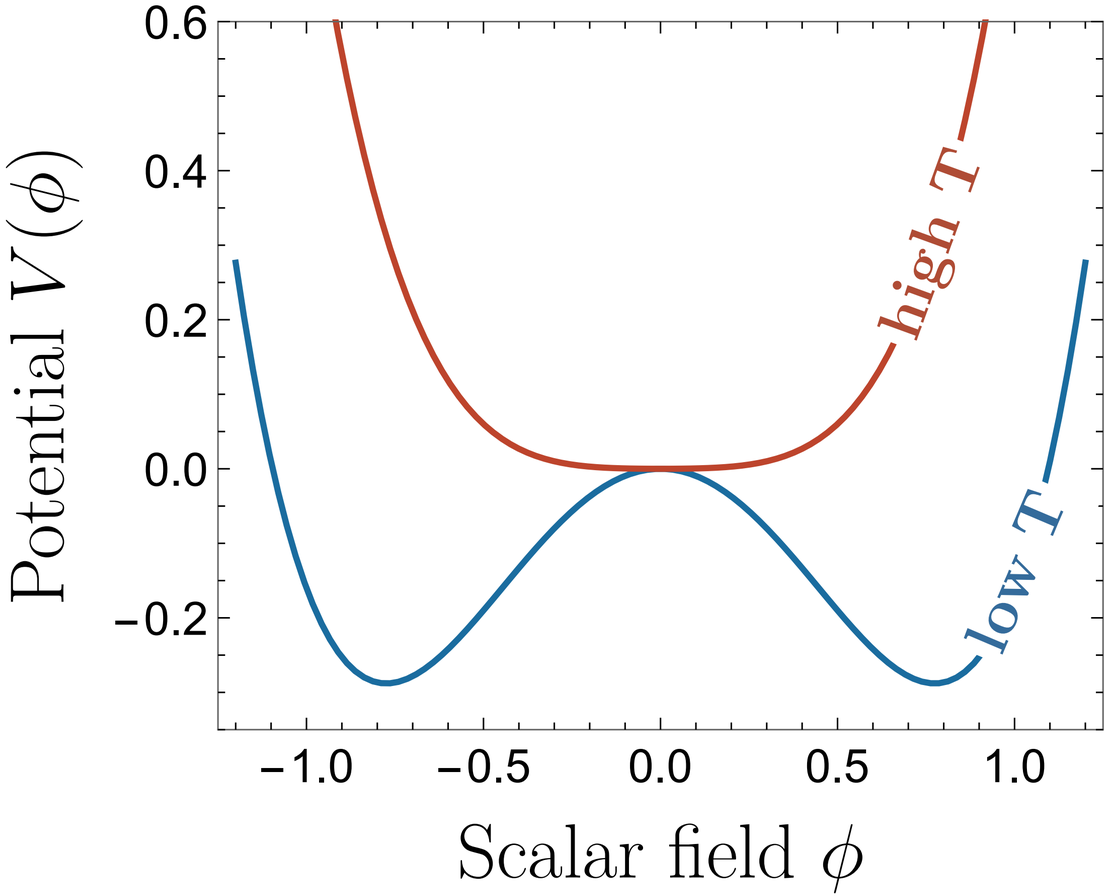
ICTS INTERNATIONAL CENTRE for THEORETICAL SCIENCES
TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Mainz Institute for Theoretical Physics

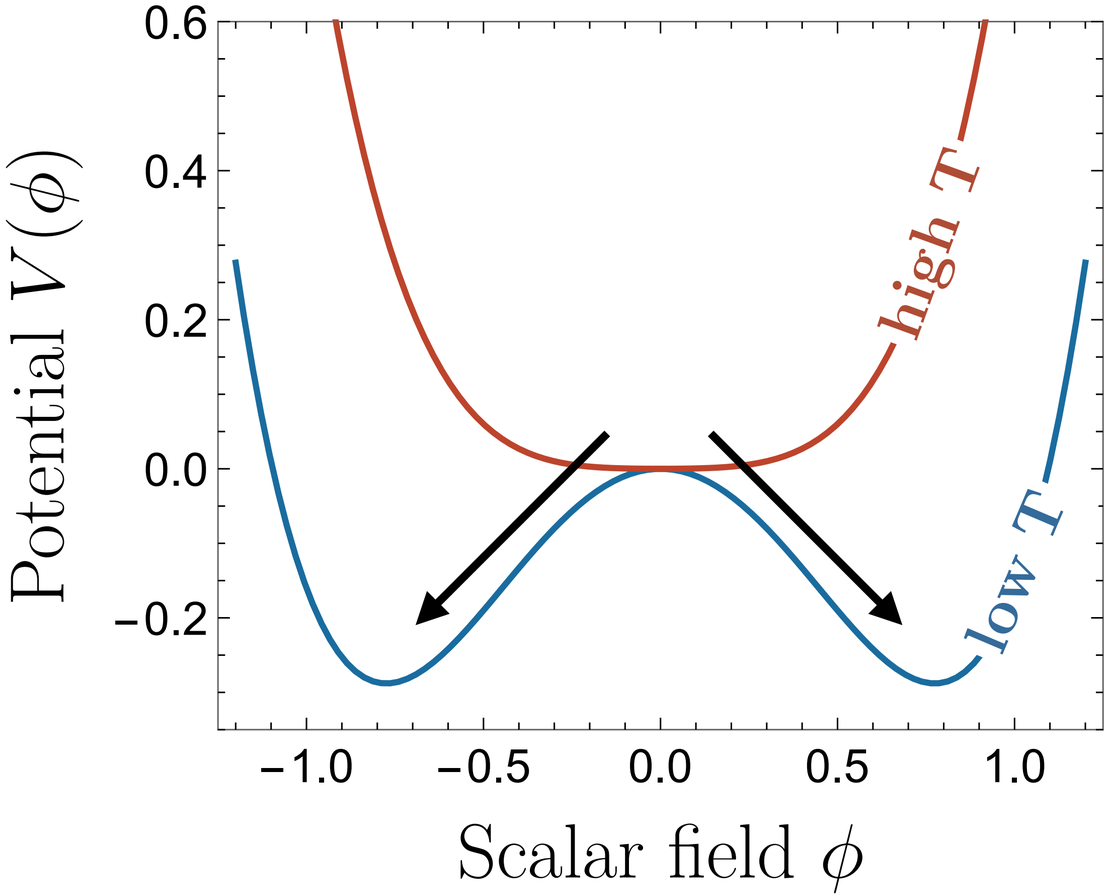
Formation of Domain Wall



Formation of Domain Wall

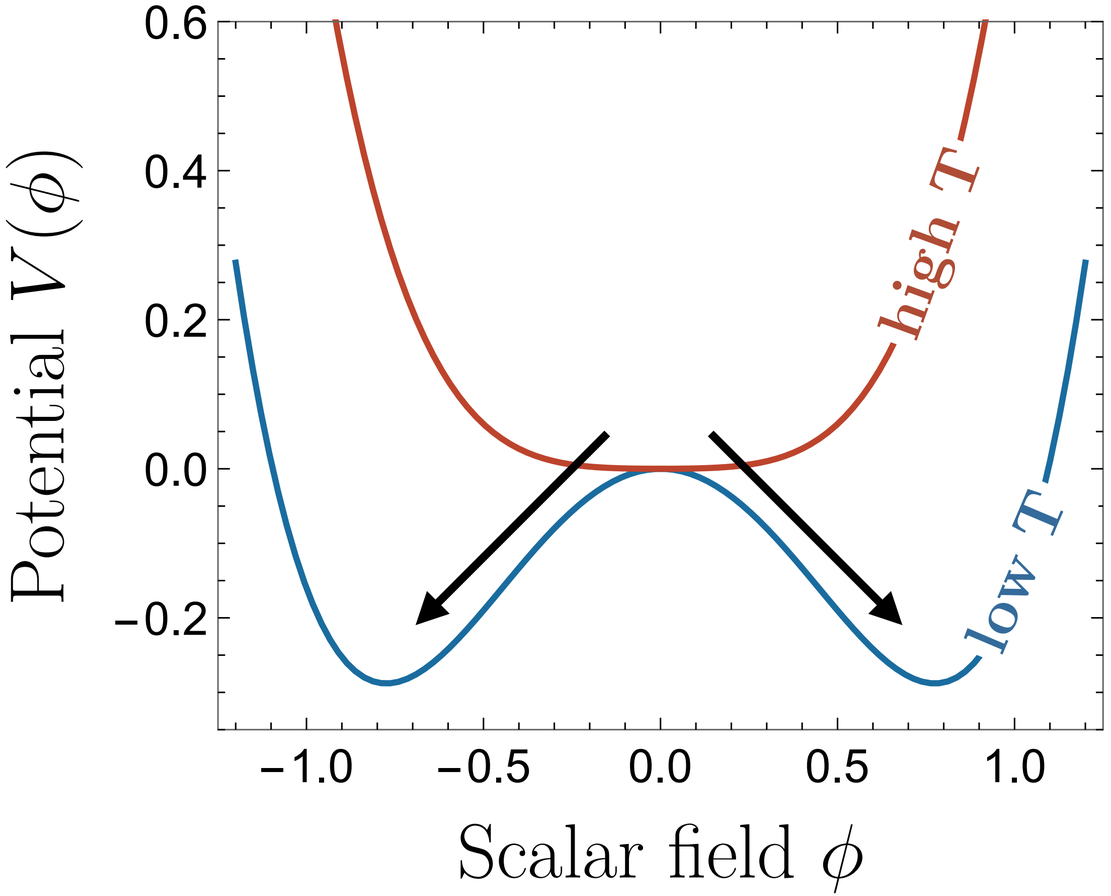


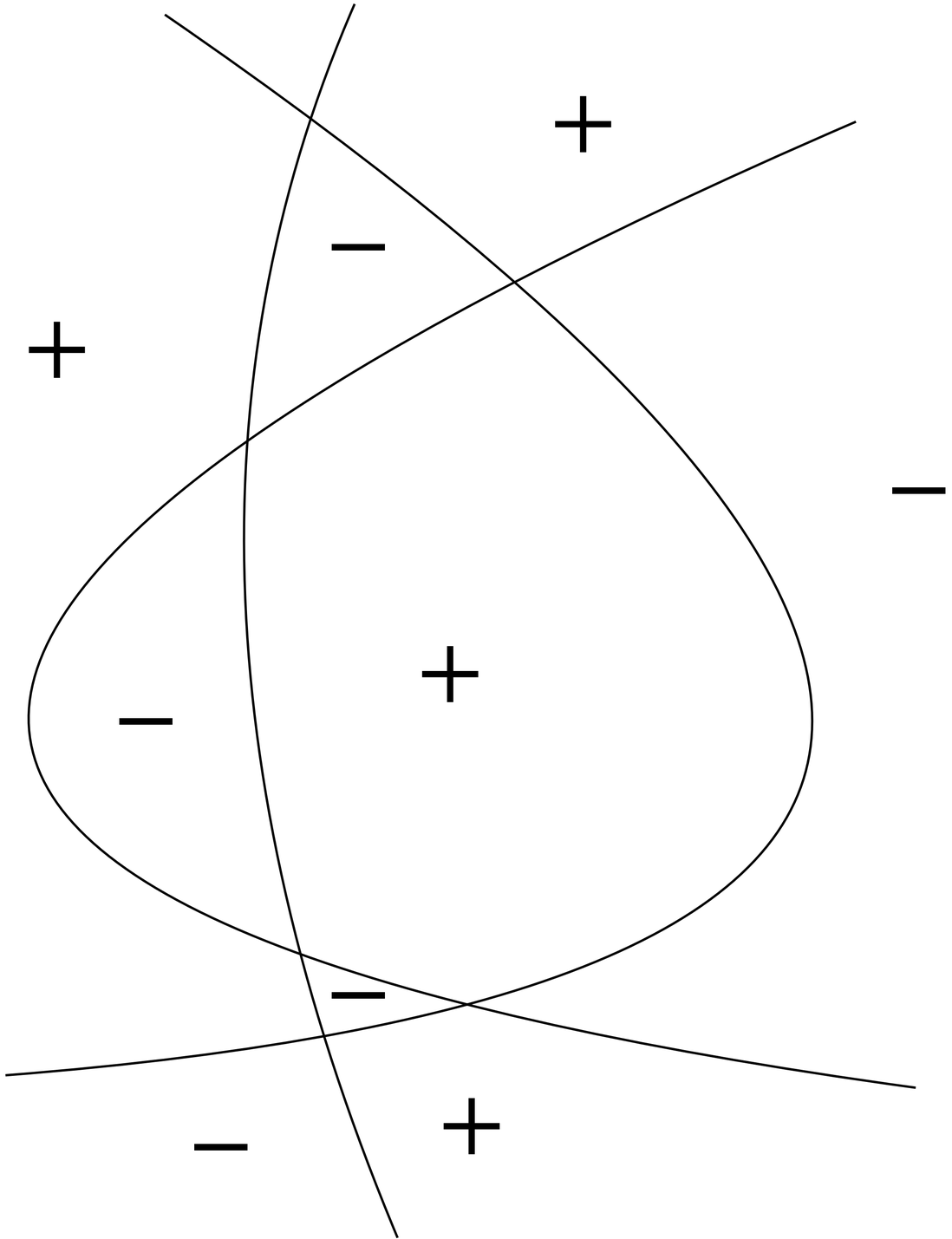
Formation of Domain Wall



Spontaneous breaking of $\mathbb{Z}_2$

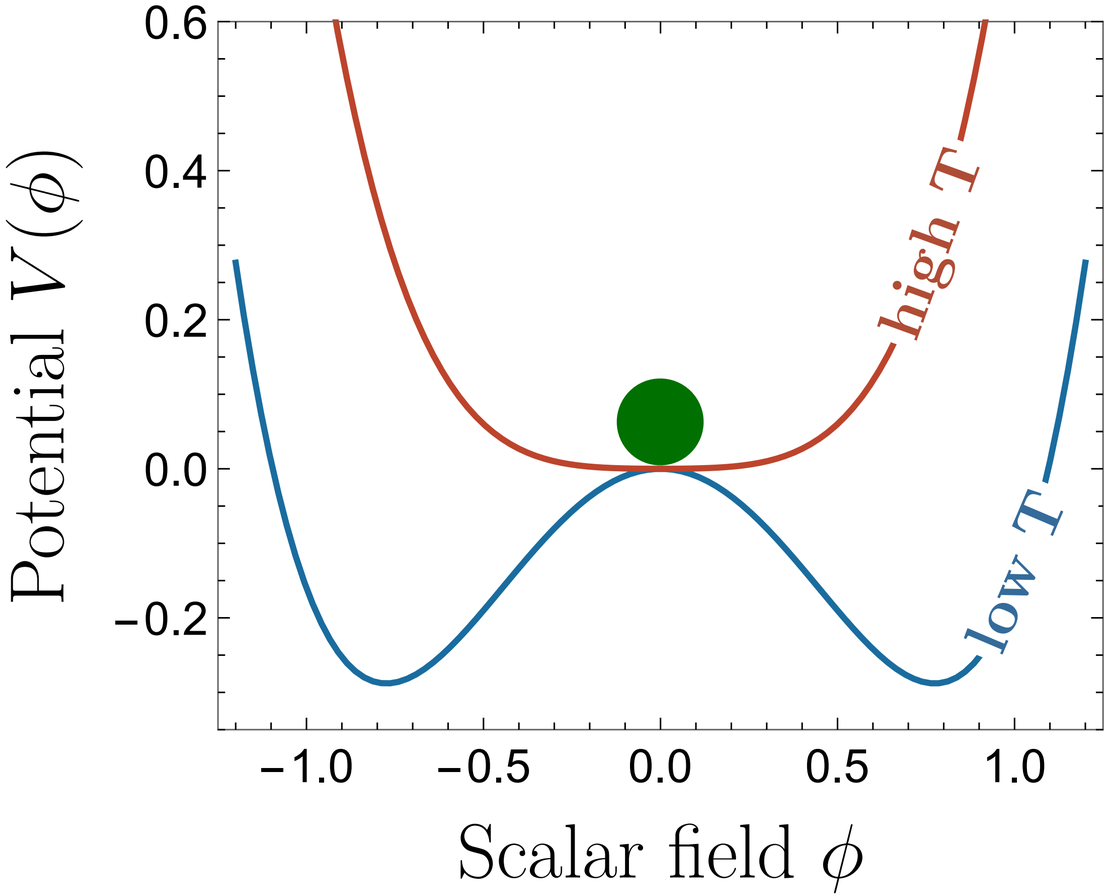
Formation of Domain Wall

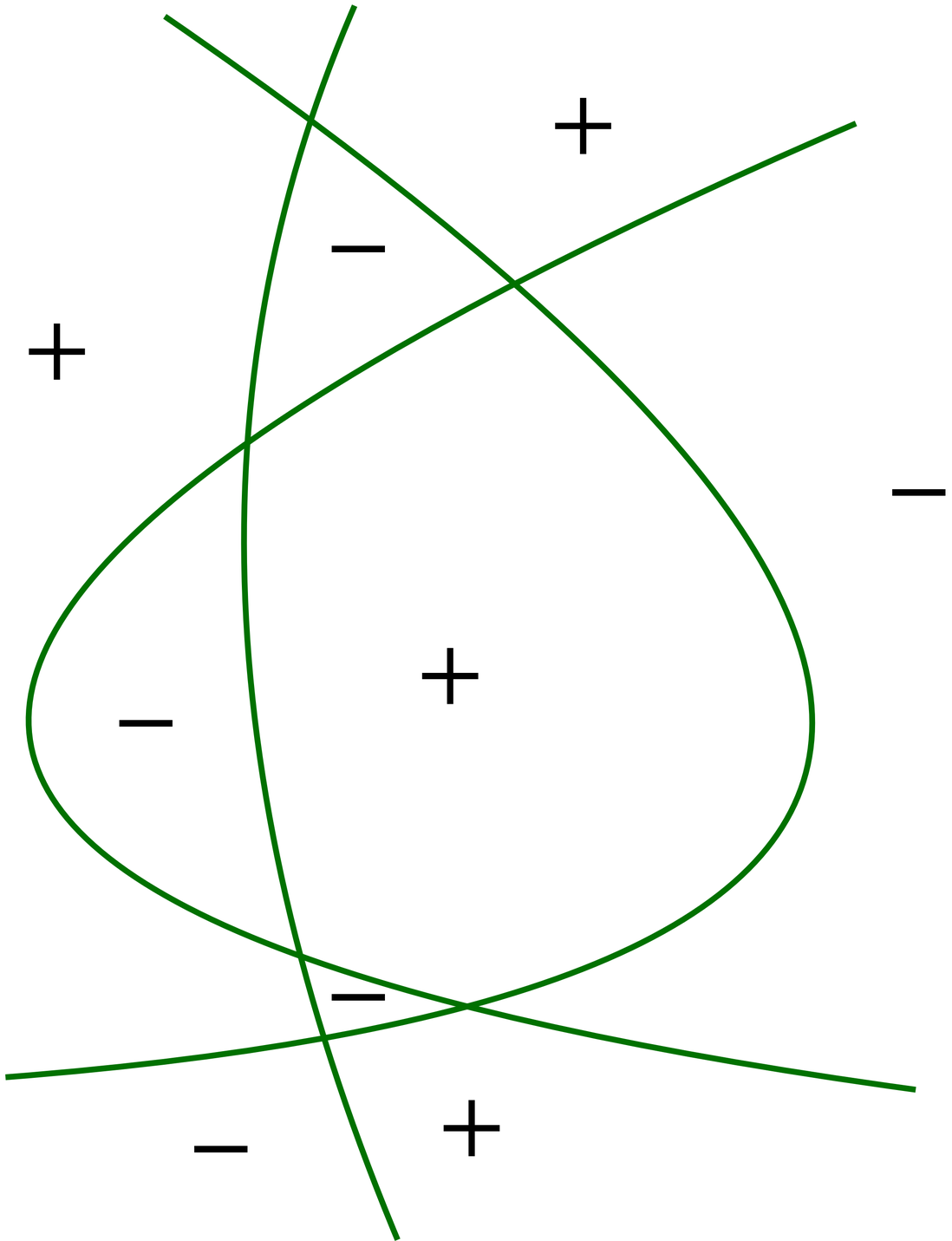




Spontaneous breaking of $\mathbb{Z}_2$

Formation of Domain Wall





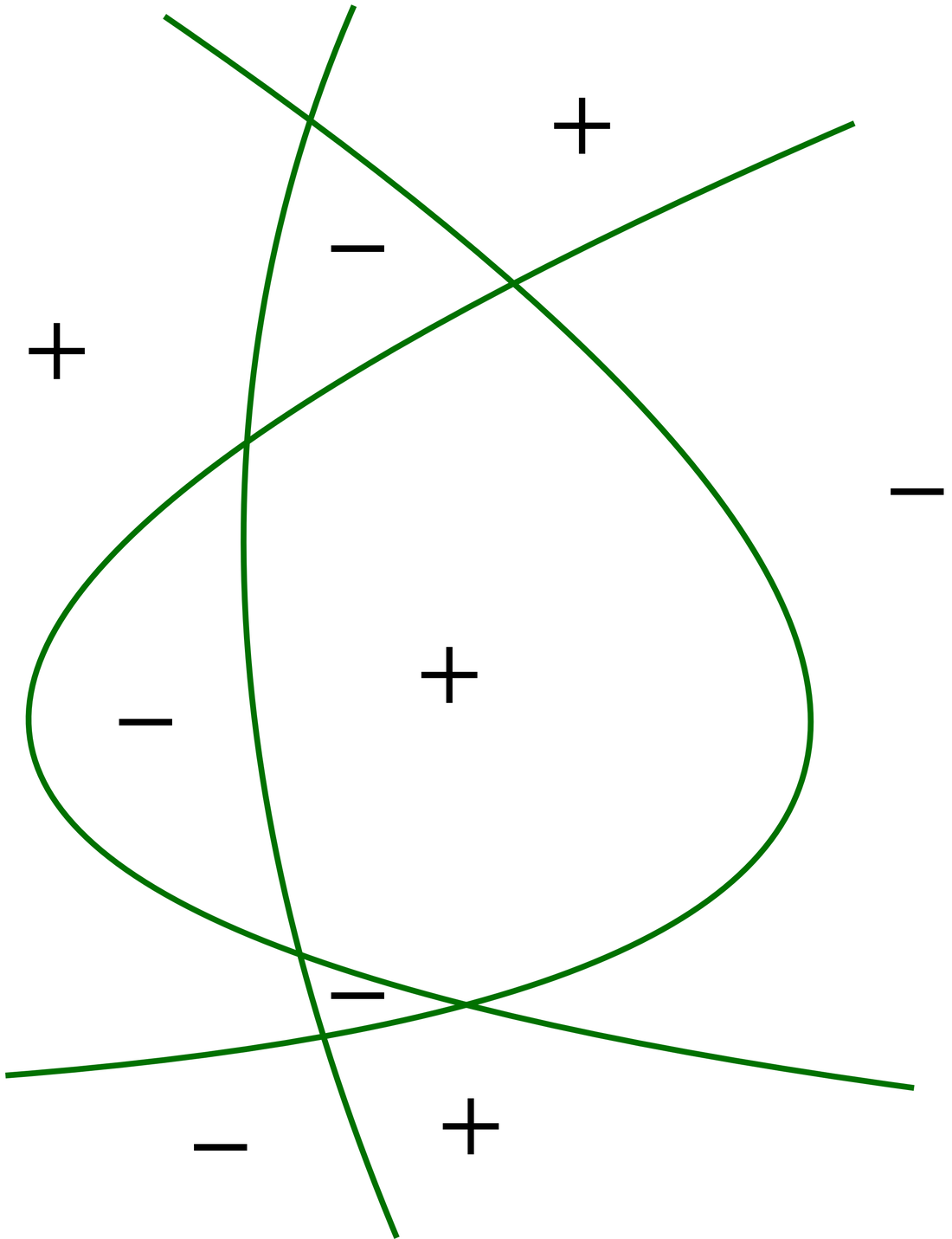
Spontaneous breaking of $\mathbb{Z}_2$

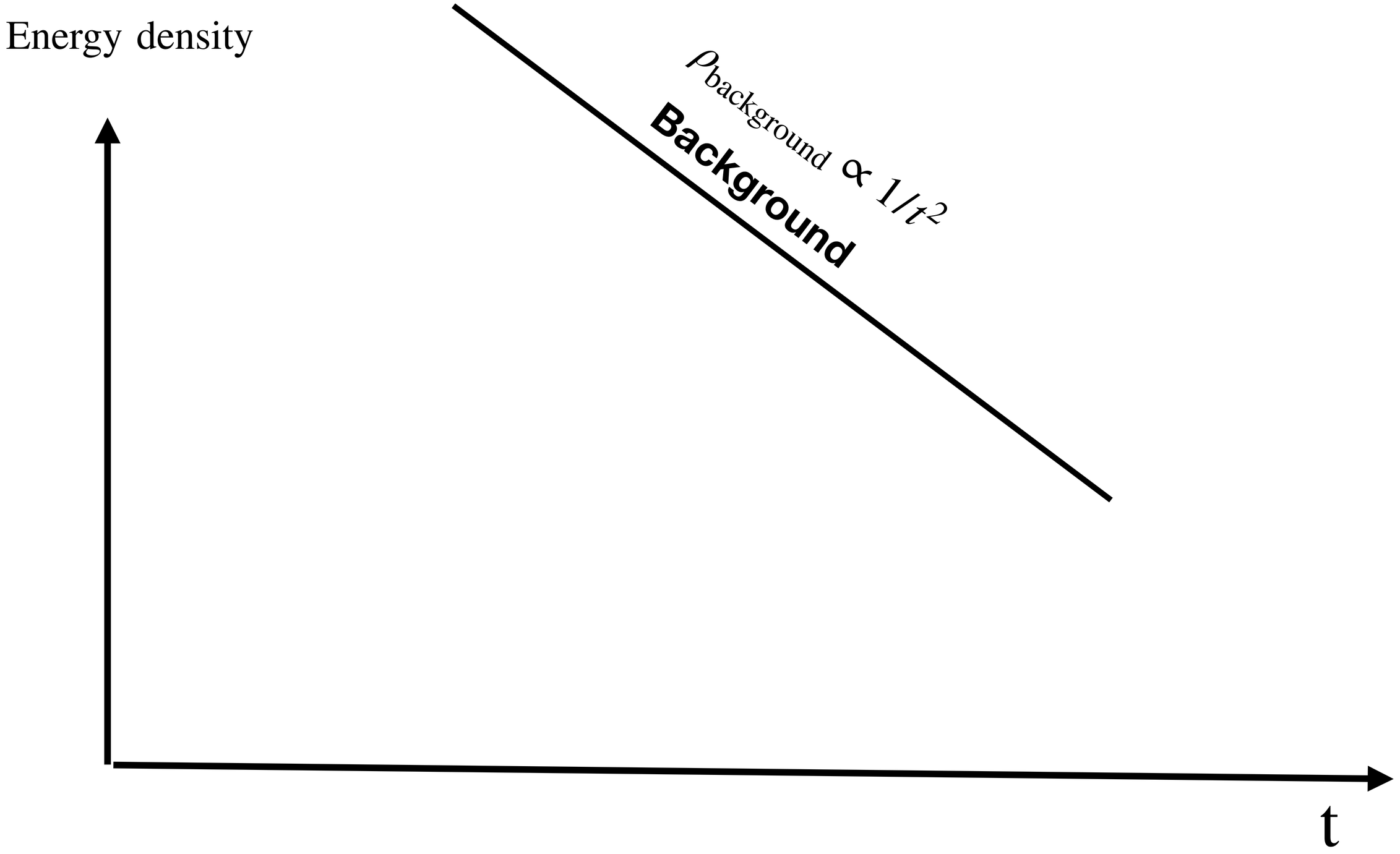
Formation of Domain Wall

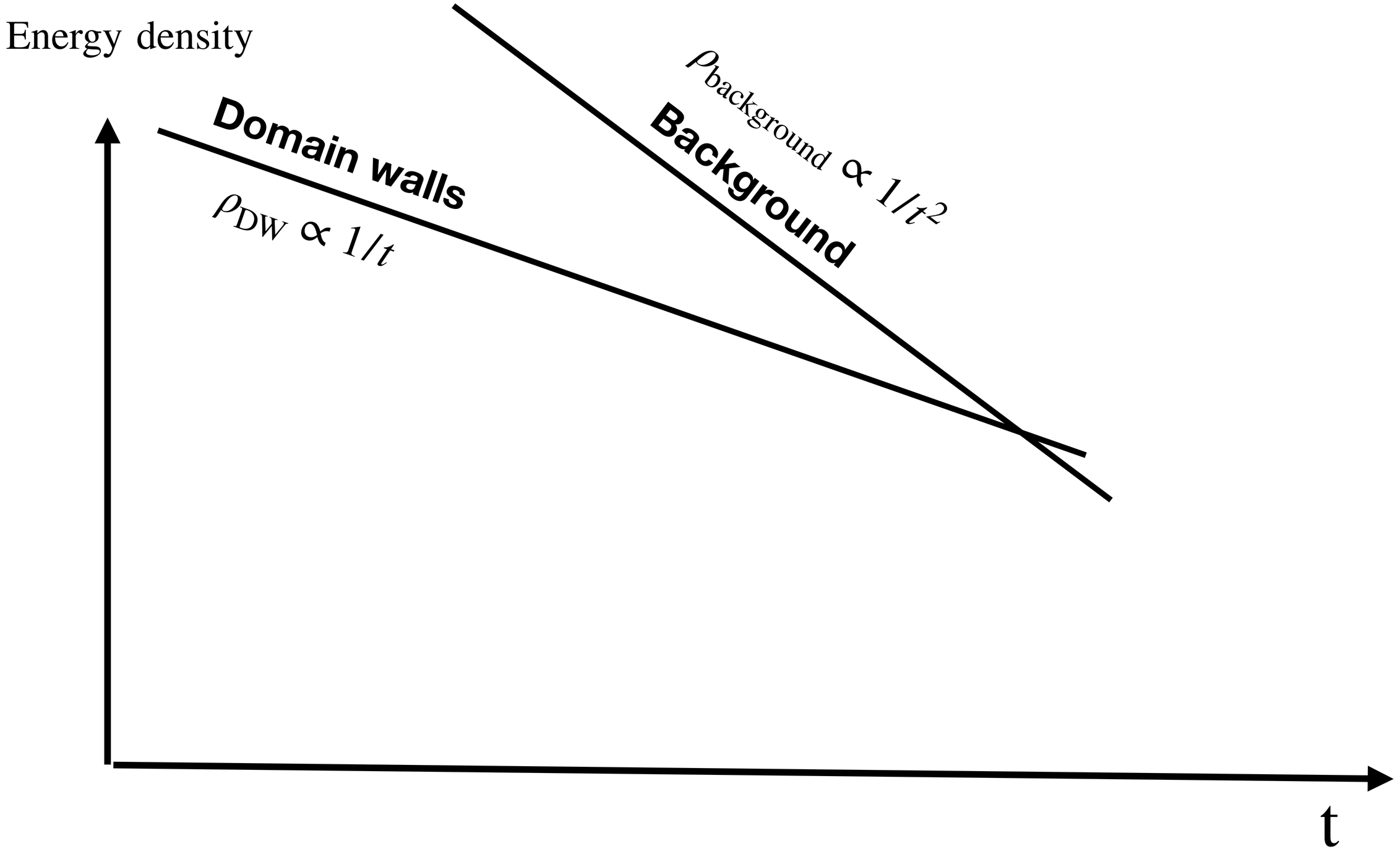
Press, Ryden, Spergel 1989 (3D simulation)

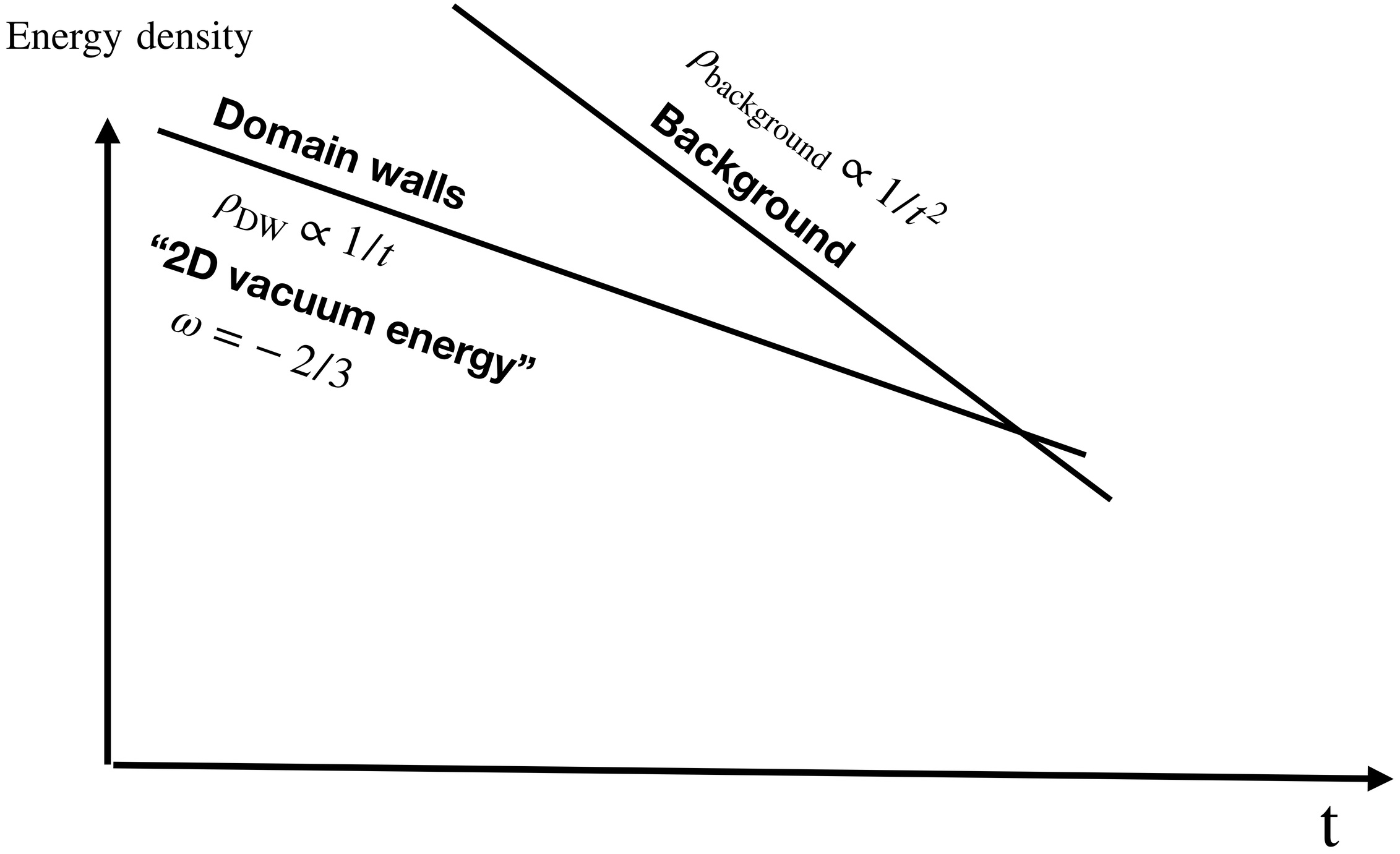
Scaling regime : $\langle R \rangle \simeq t$

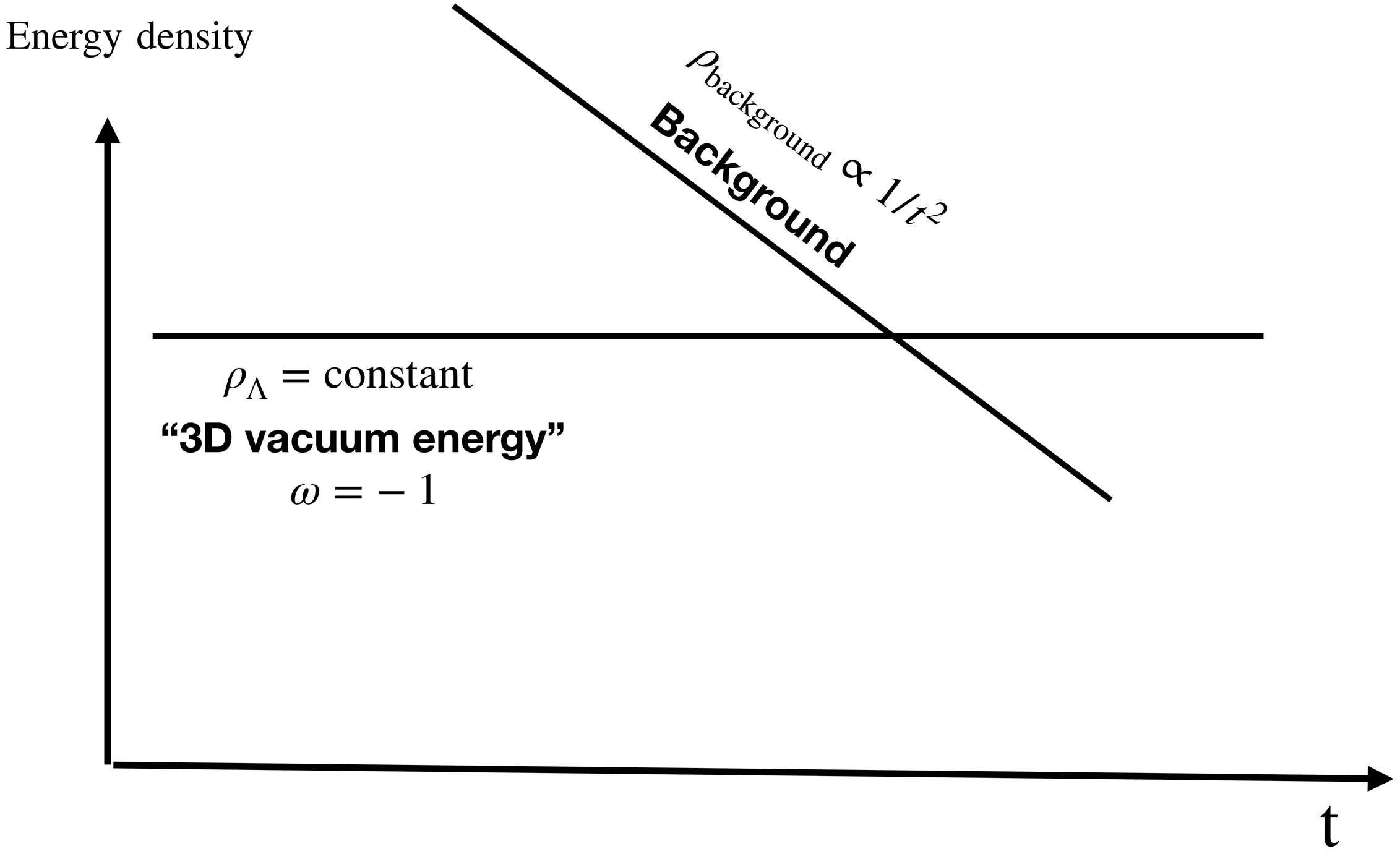
$$\rho_{\mathrm{DW}} \simeq \frac{\sigma}{\mathrm{R}} \simeq \frac{\sigma}{\mathrm{t}}$$

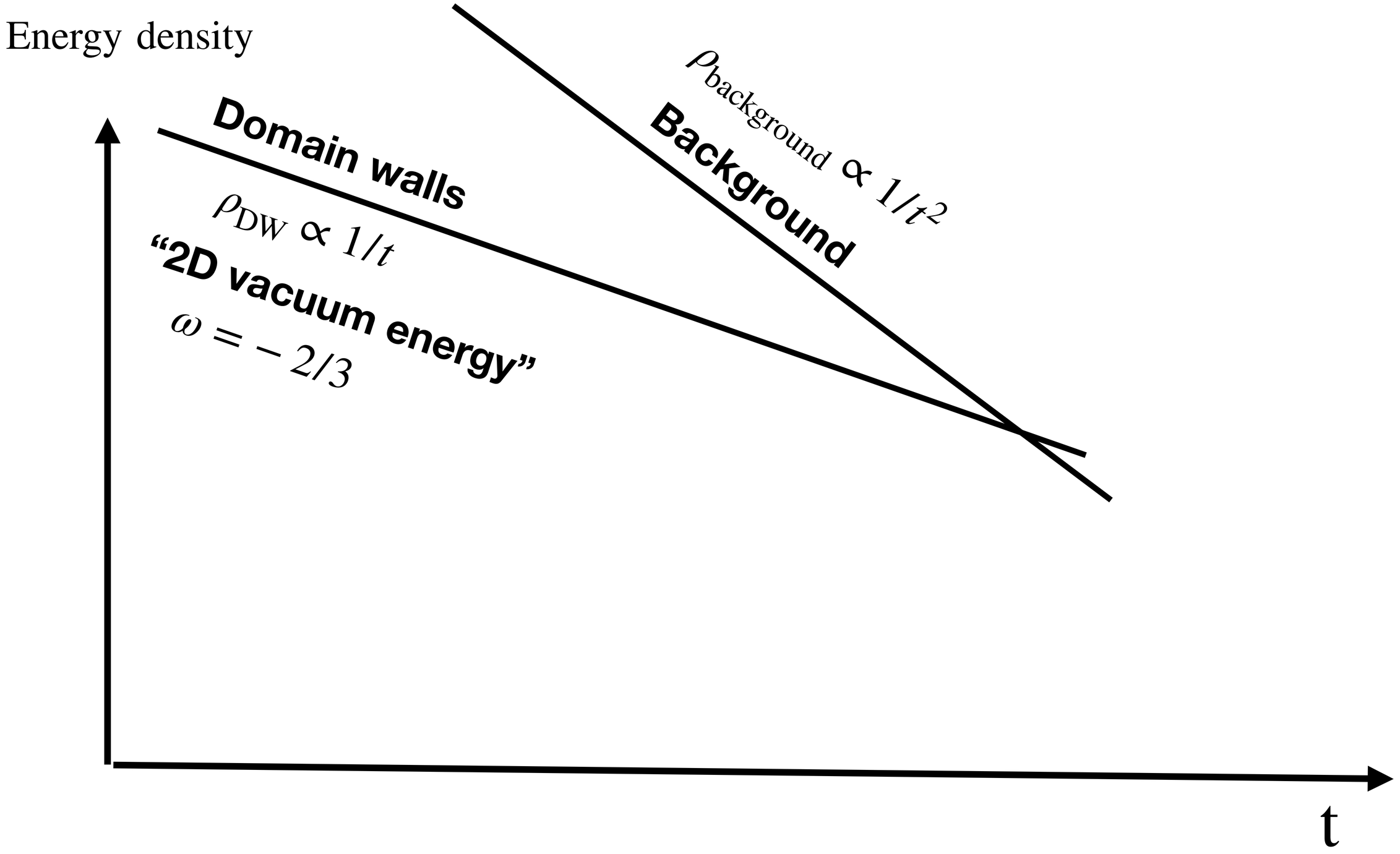



Energy density
$\rho_{\text{background}} \propto 1/t^2$
Background
t


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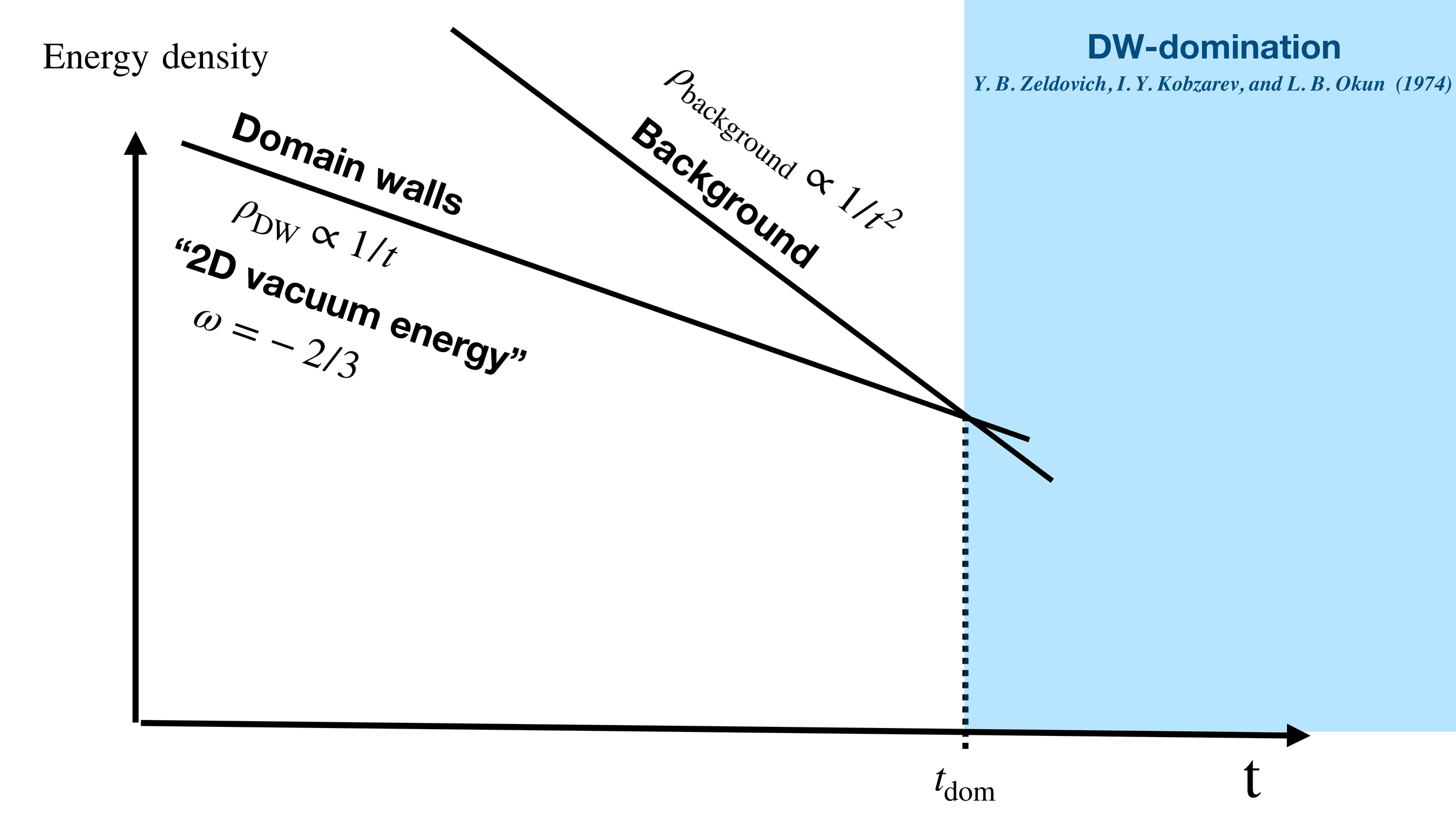
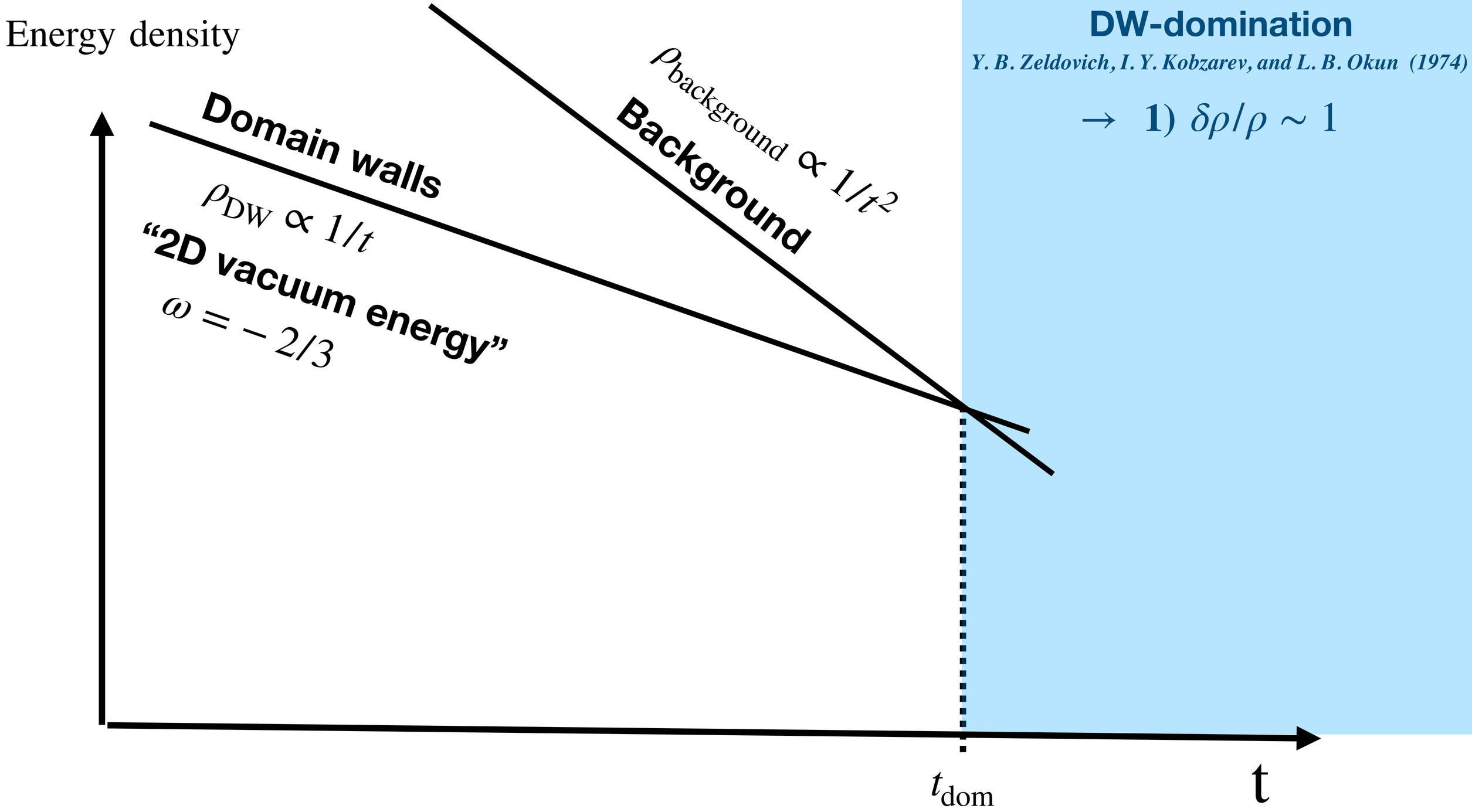

Energy density
DW-domination
Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)
$\rho_{\rm background} \propto 1/t^2$
Background
Domain walls
$\rho_{\rm DW} \propto 1/t$
"2D vacuum energy"
$\omega = -2/3$
$t_{\rm dom}$
t



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

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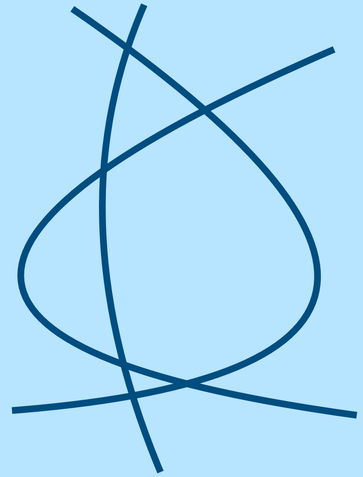
$\rightarrow$ 1) $\delta\rho/\rho \sim 1$

$\langle R \rangle \simeq t$

(scaling regime)



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Background

$t_{\rm dom}$

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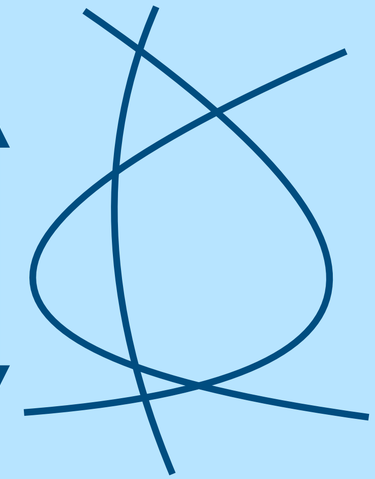

$\rightarrow$ **2)** horizon size

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

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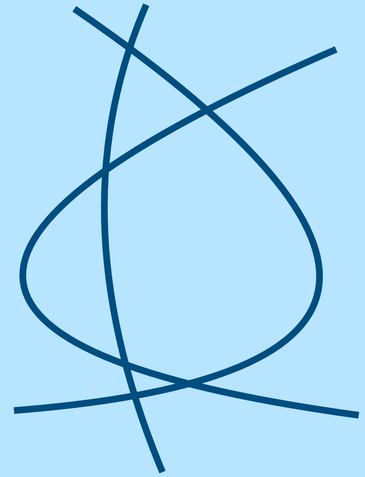


$\rightarrow$ **2)** horizon size

$\Rightarrow$ **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

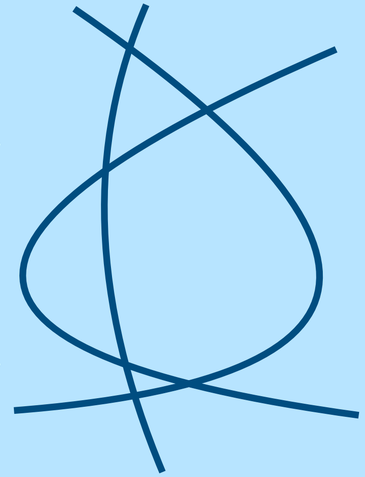
DW-domination

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)

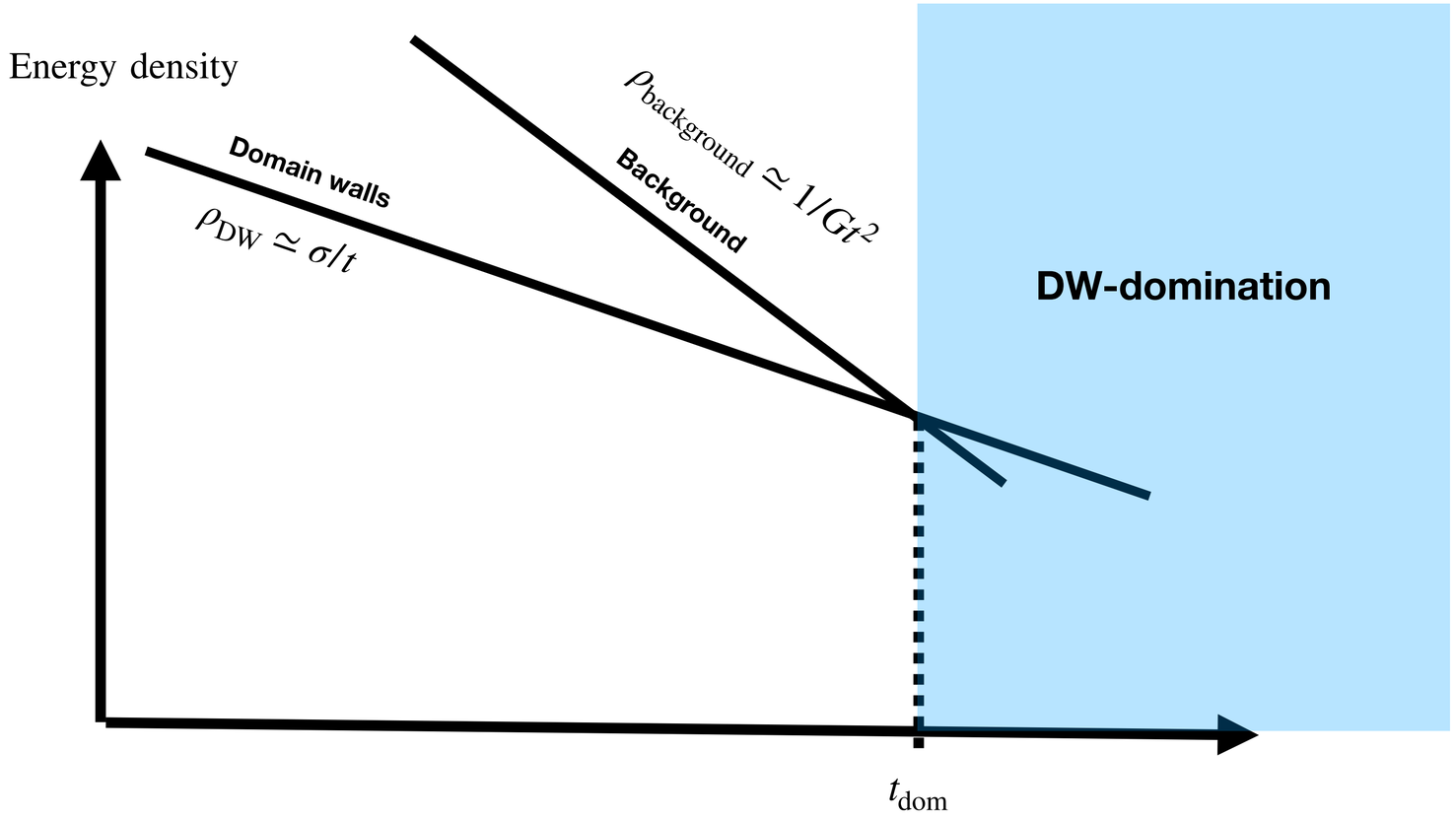


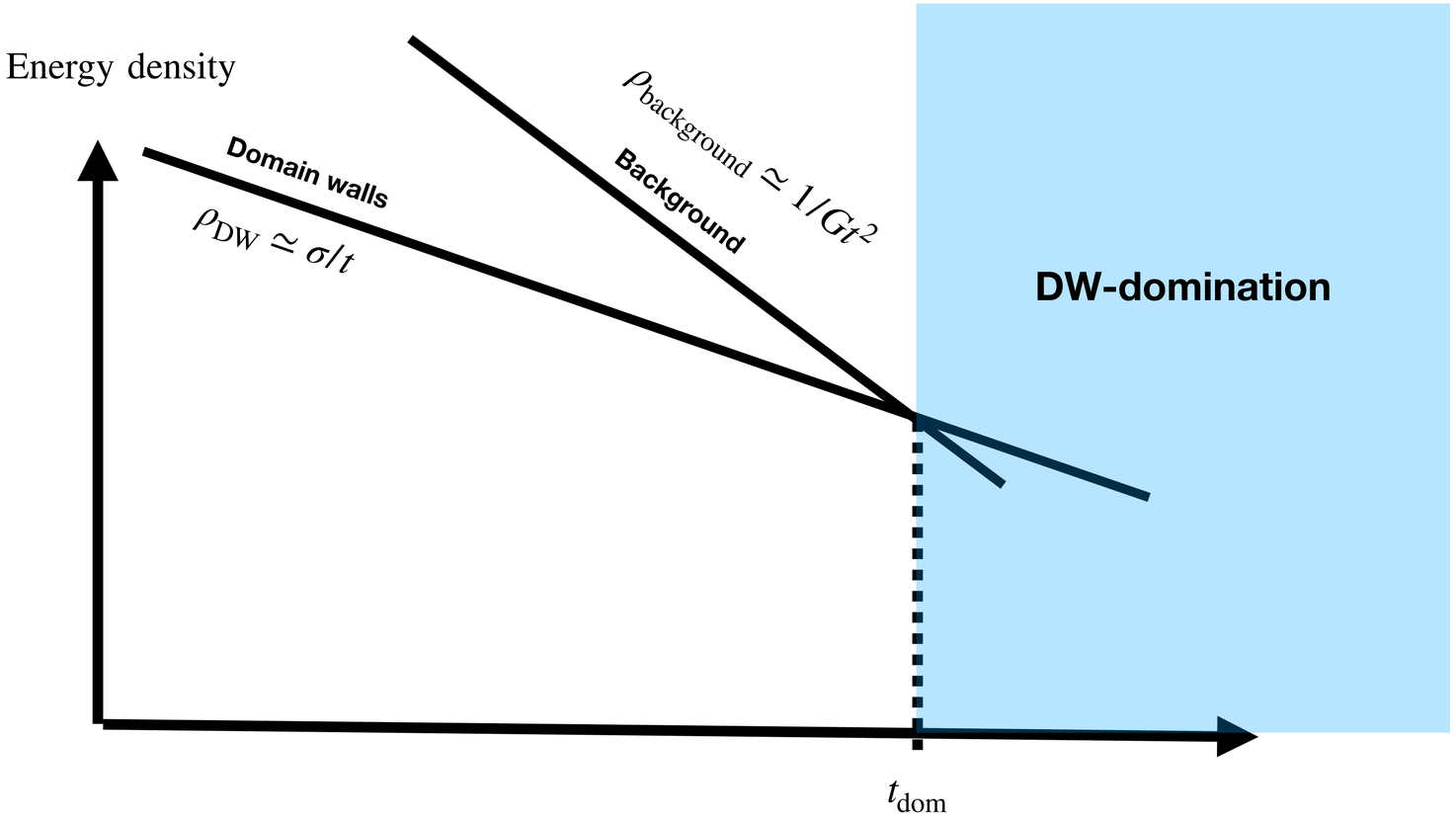
$\rightarrow$ **2)** horizon size

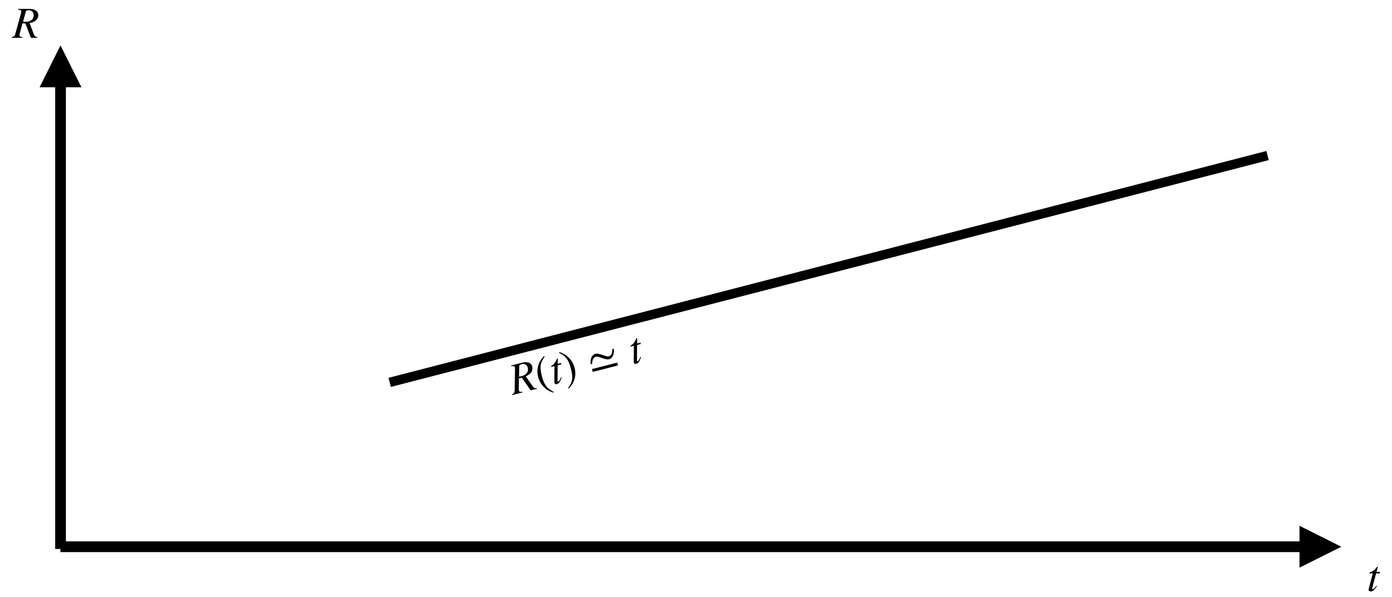
$\Rightarrow$ Efficient PBH formation

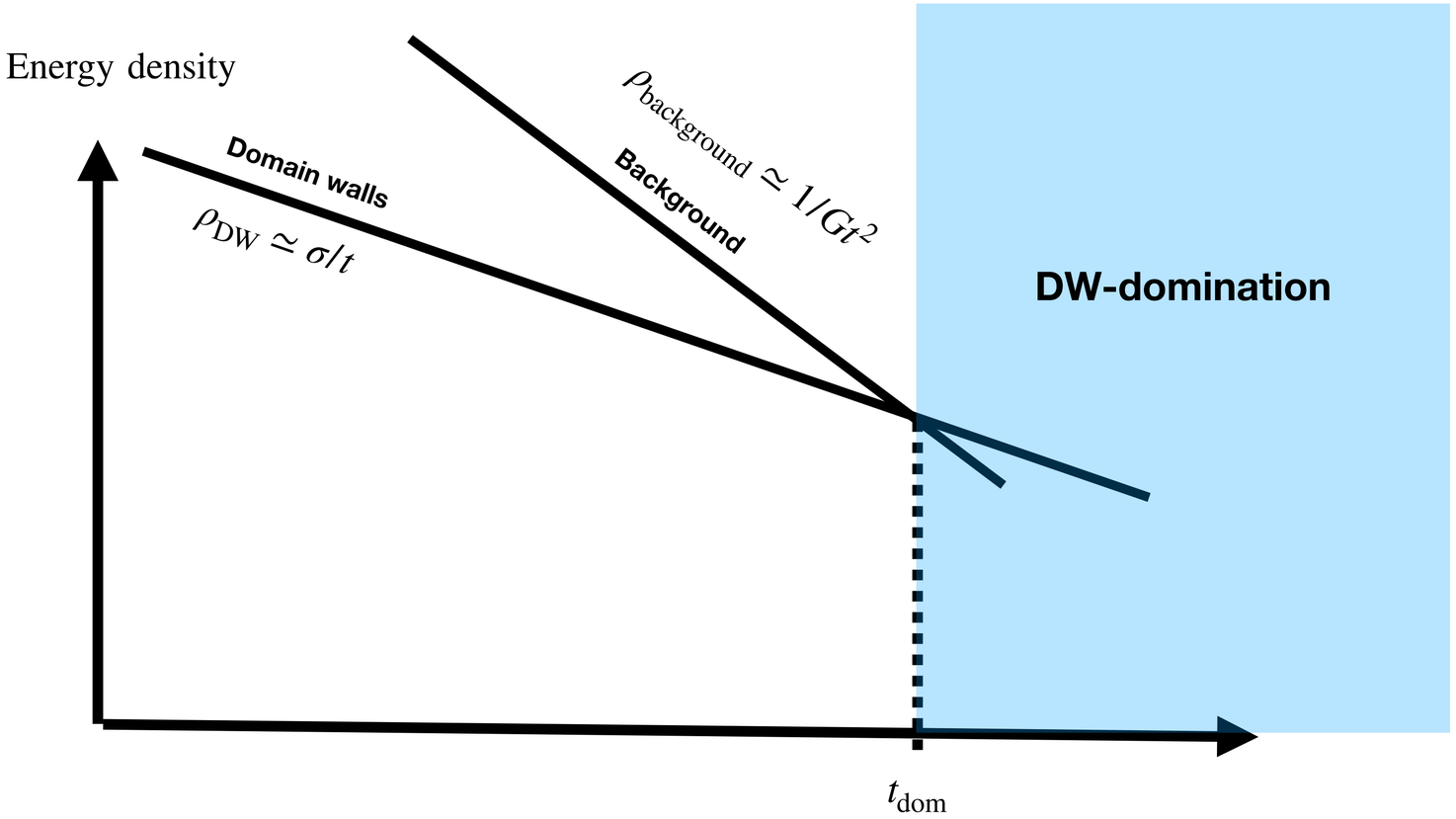
Vilenkin and Shellard's textbook, 2000

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


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


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


R
$\mathrm{R(t)} \simeq \mathrm{t}$
t


Energy density
Domain walls
$\rho_{\rm DW} \simeq \sigma/t$
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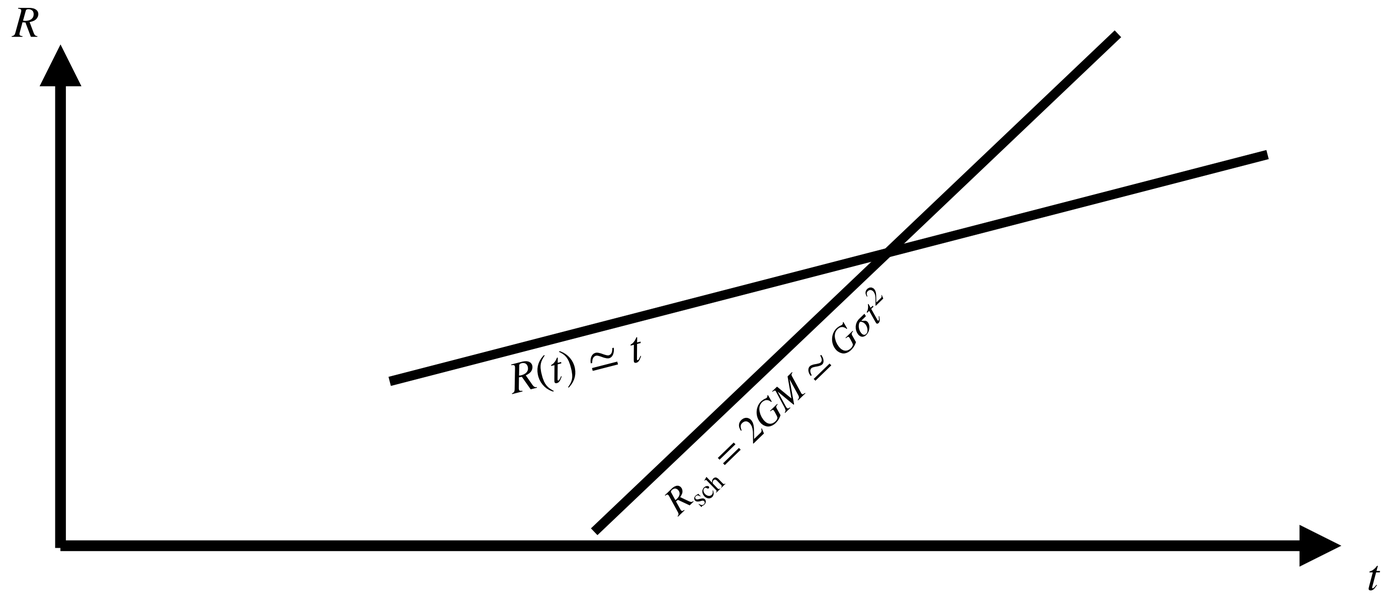
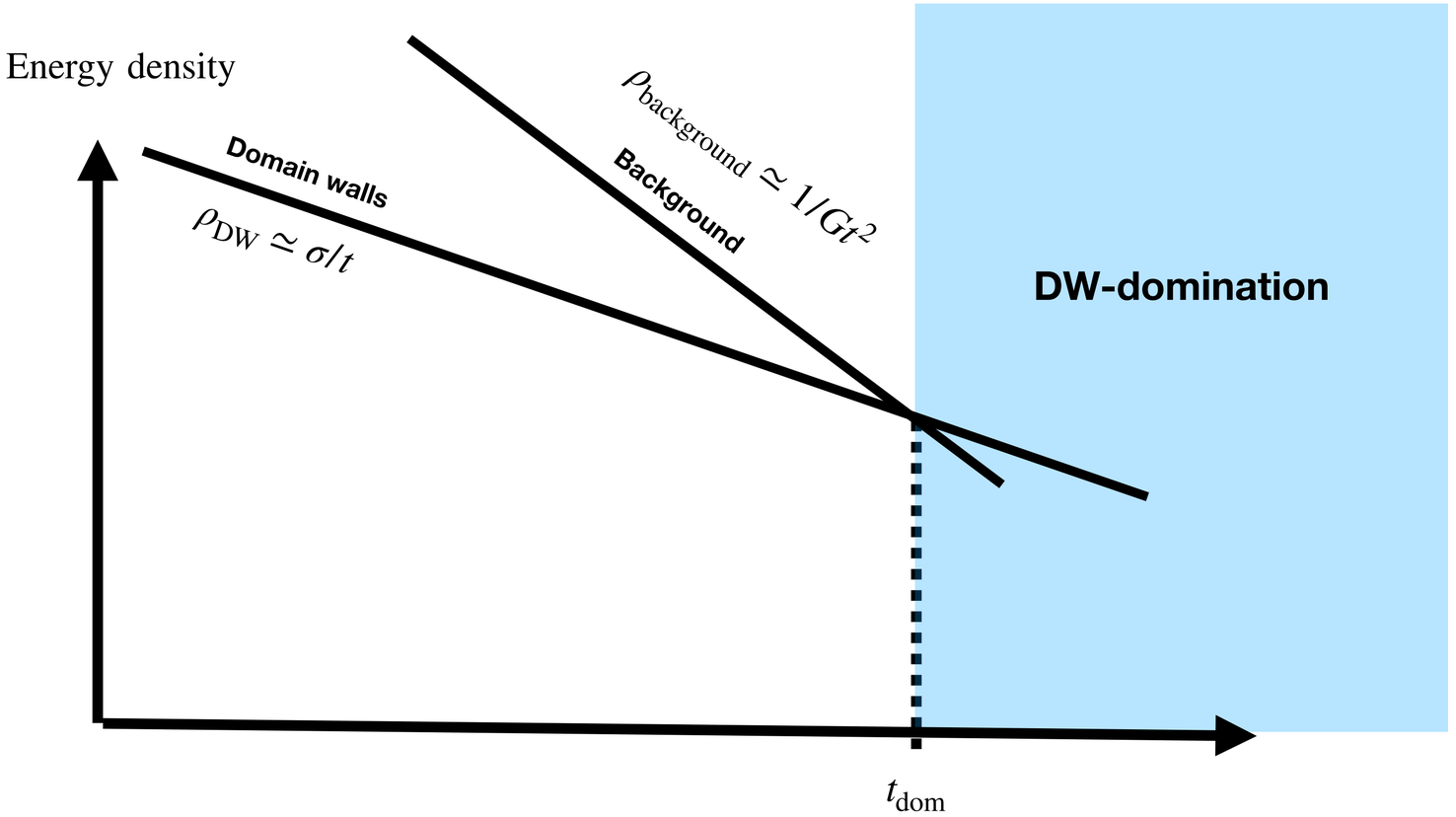
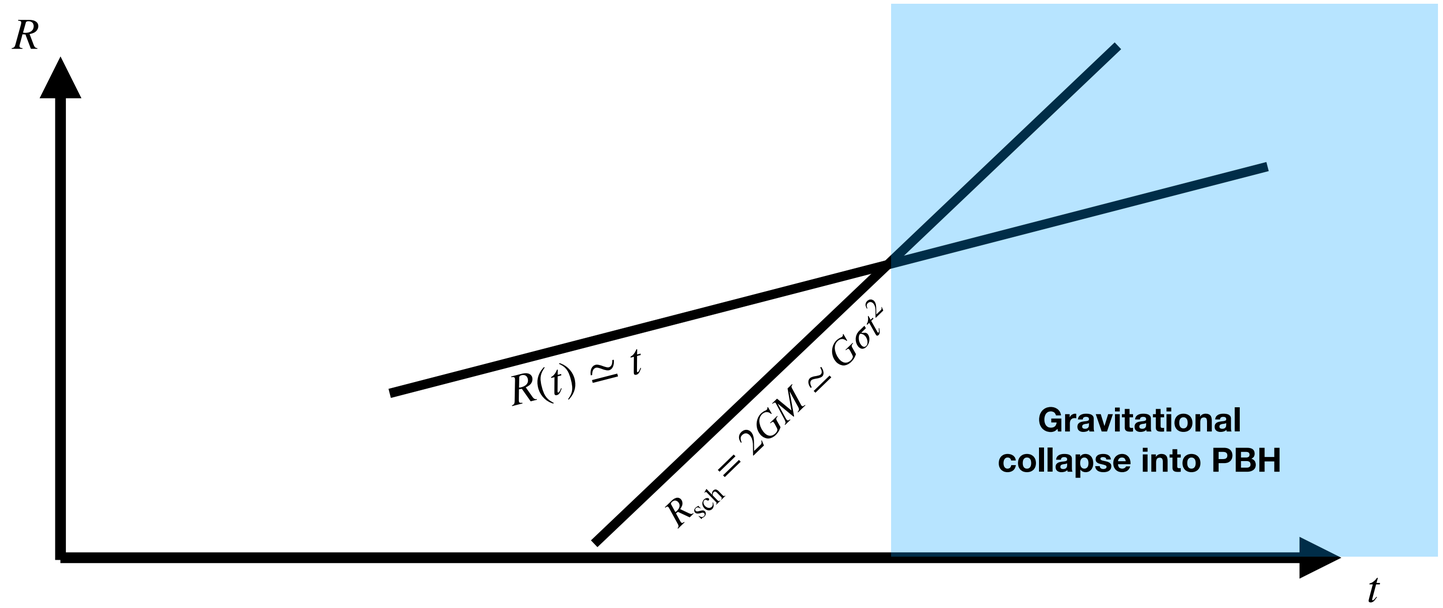
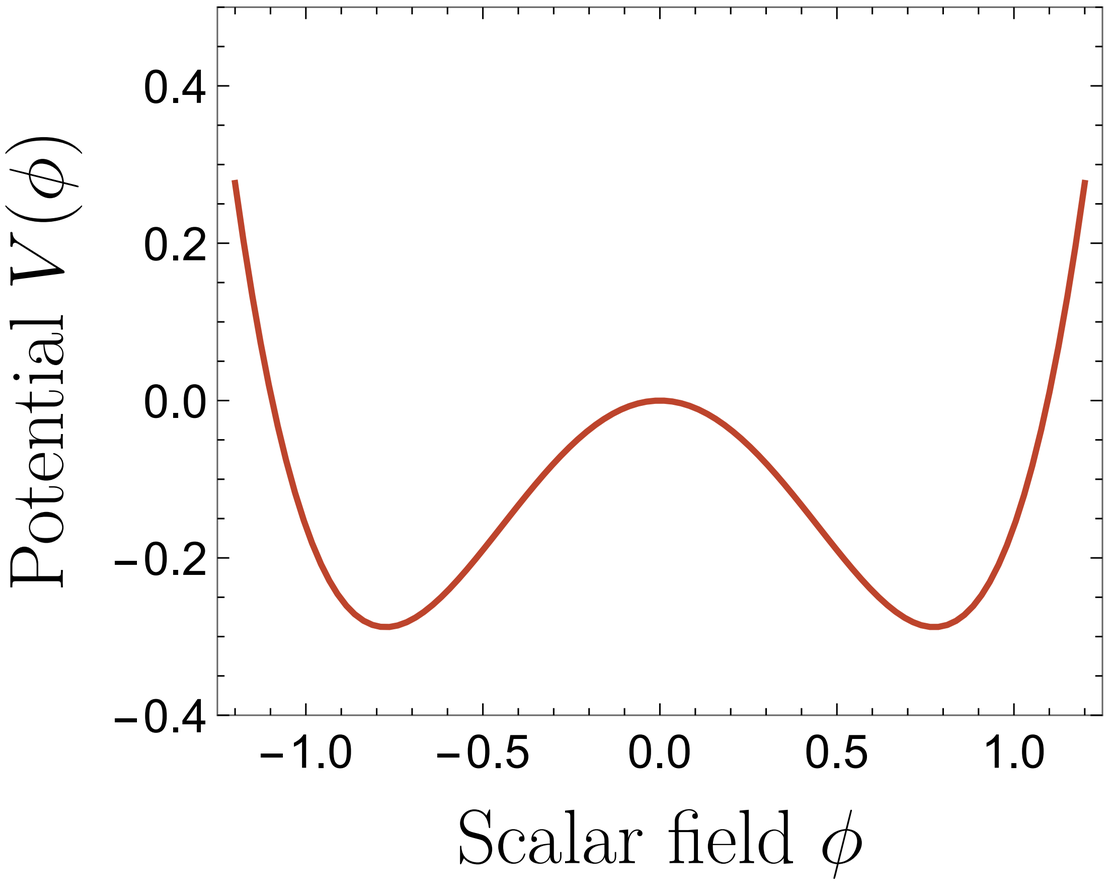
DW-domination
$t_{\rm dom}$

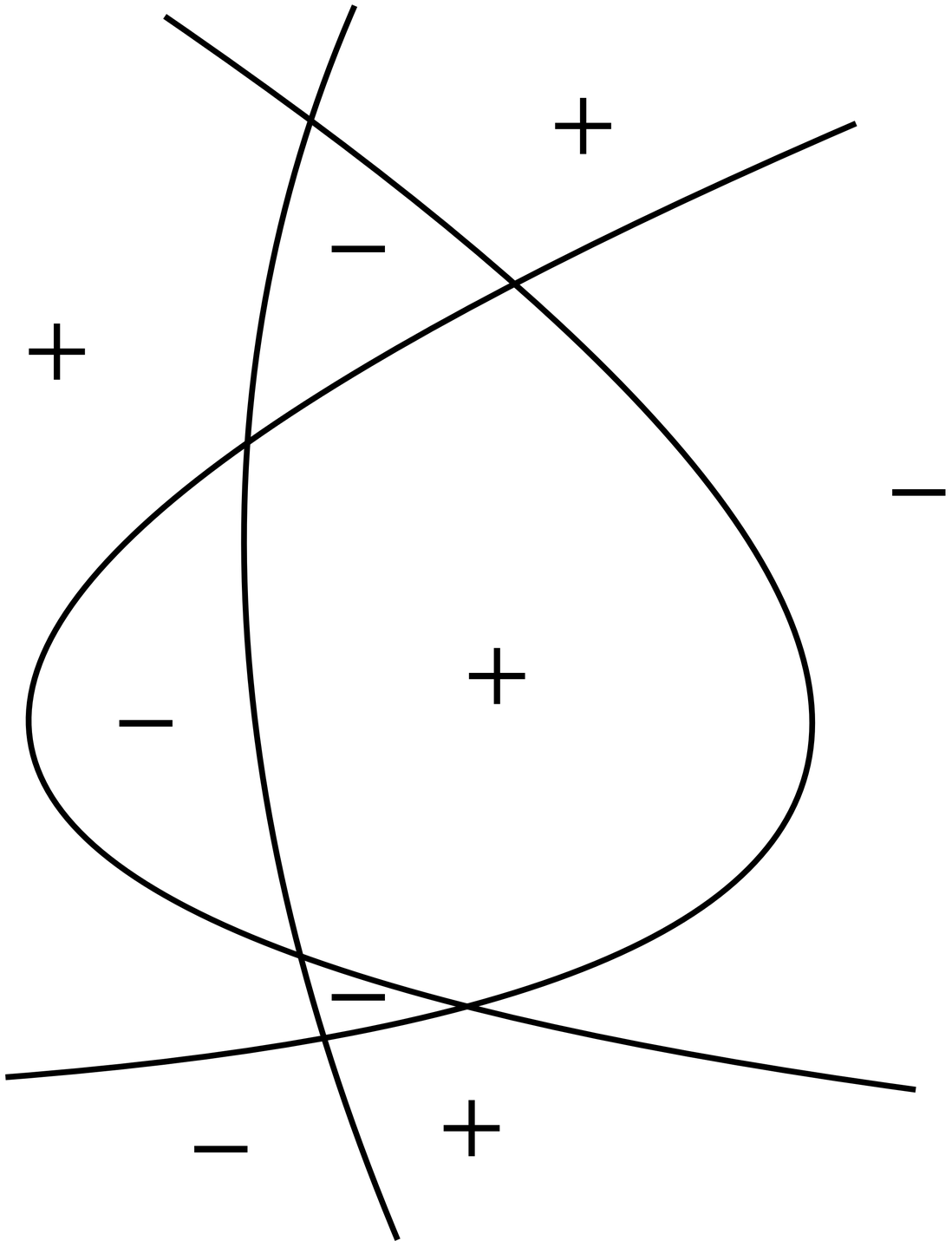

R
$R(t) \simeq t$
$R_{\rm sch} = 2GM \simeq G\sigma t^2$
t


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

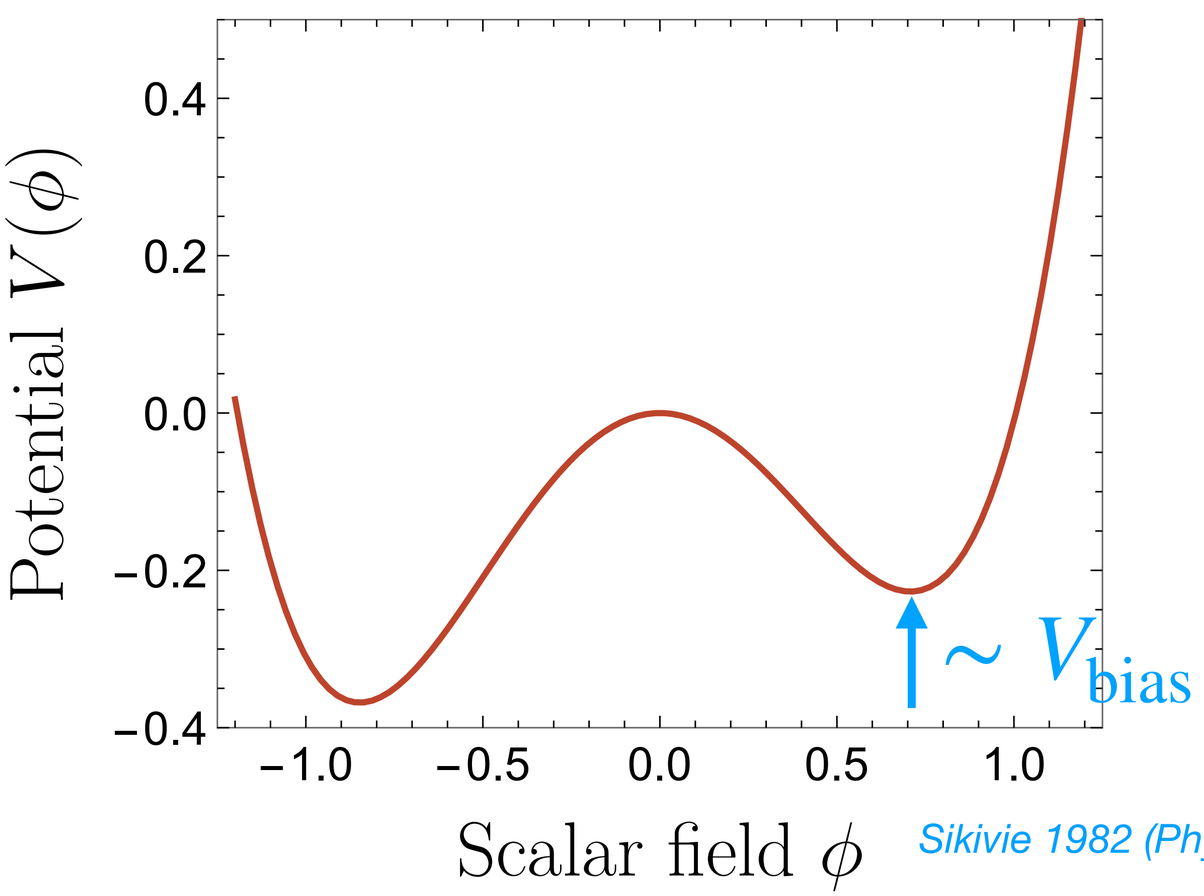

R
$R(t) \simeq t$
$R_{\rm sch} = 2GM \simeq G\sigma t^2$
Gravitational
collapse into PBH
t

Vacuum energy bias

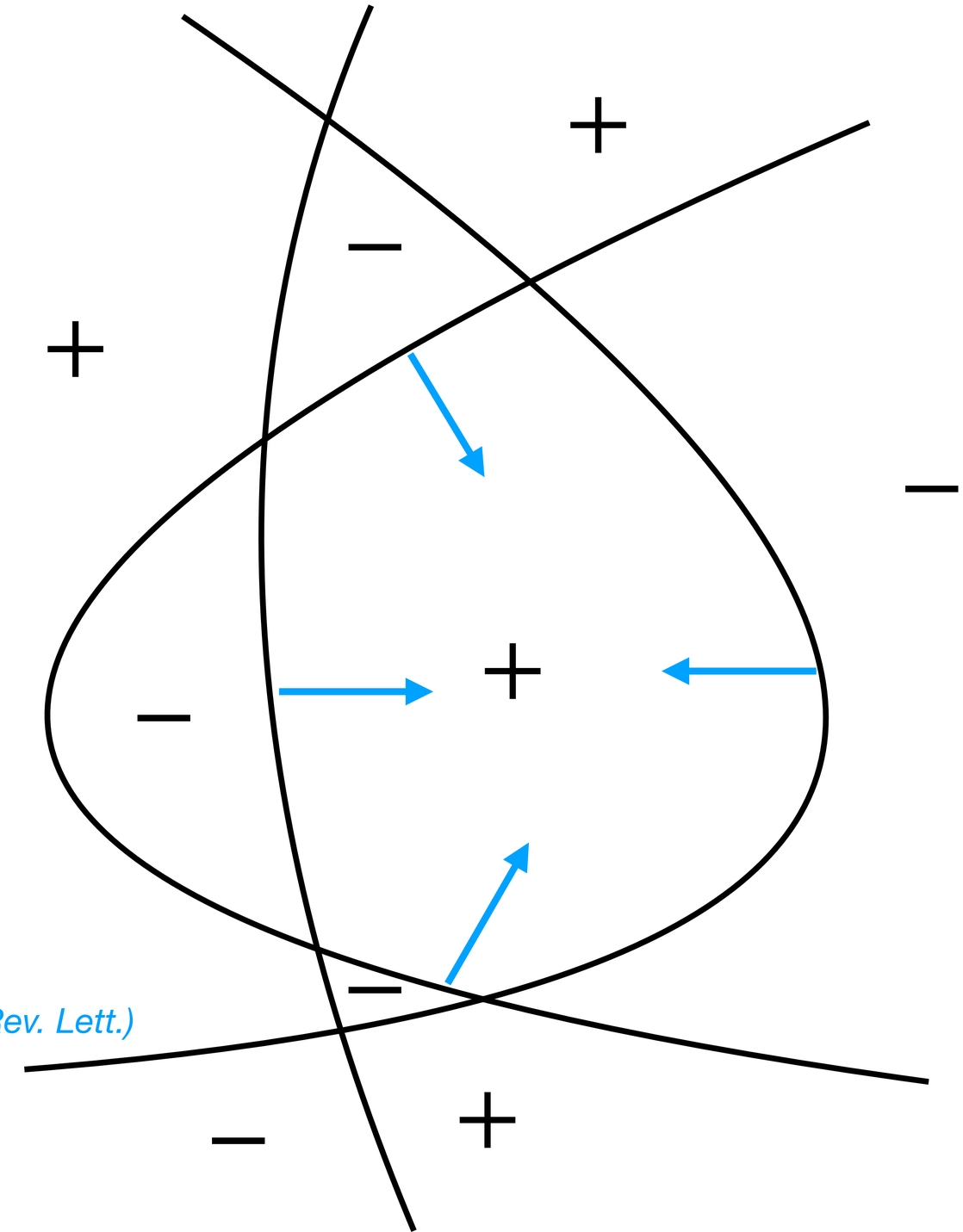


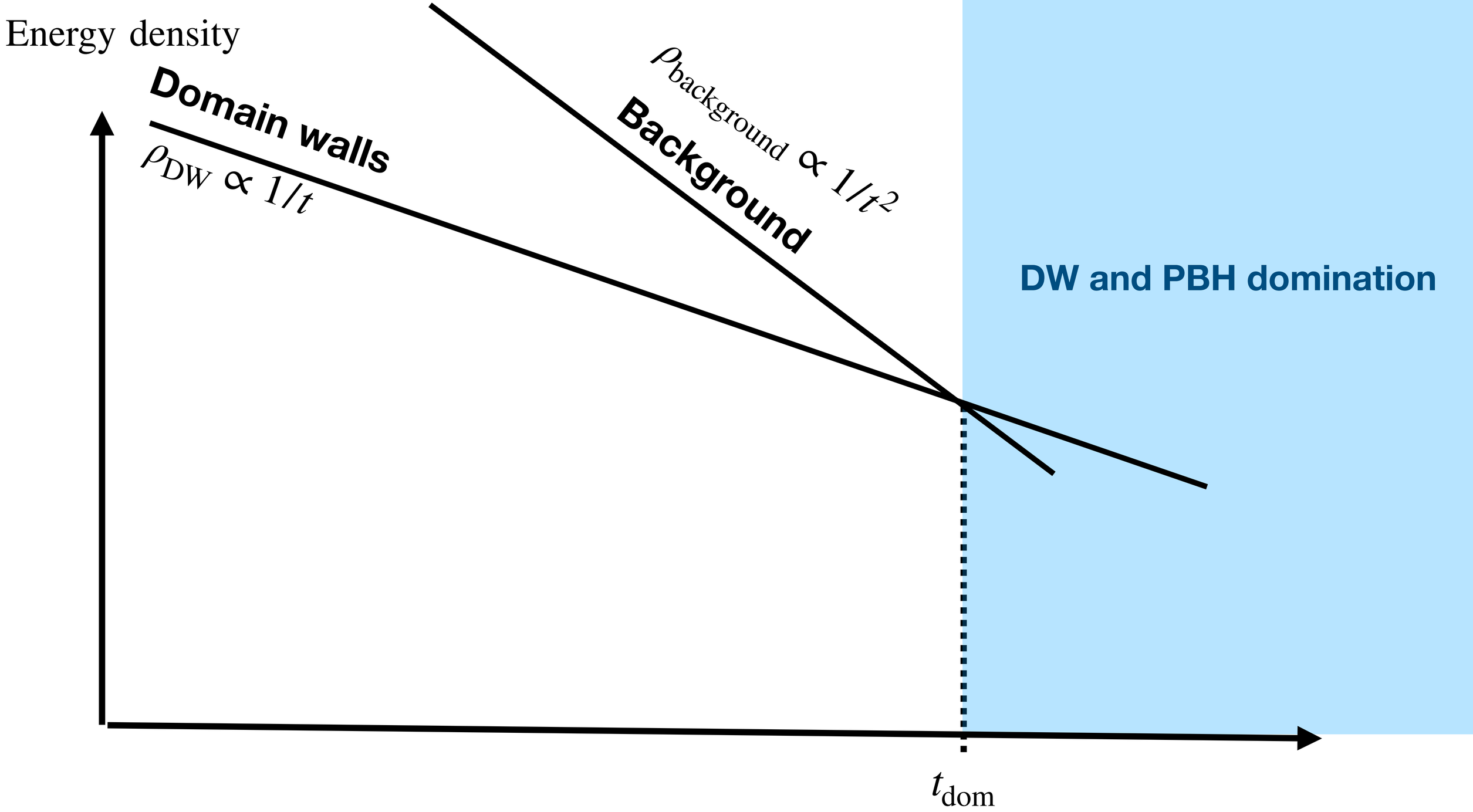


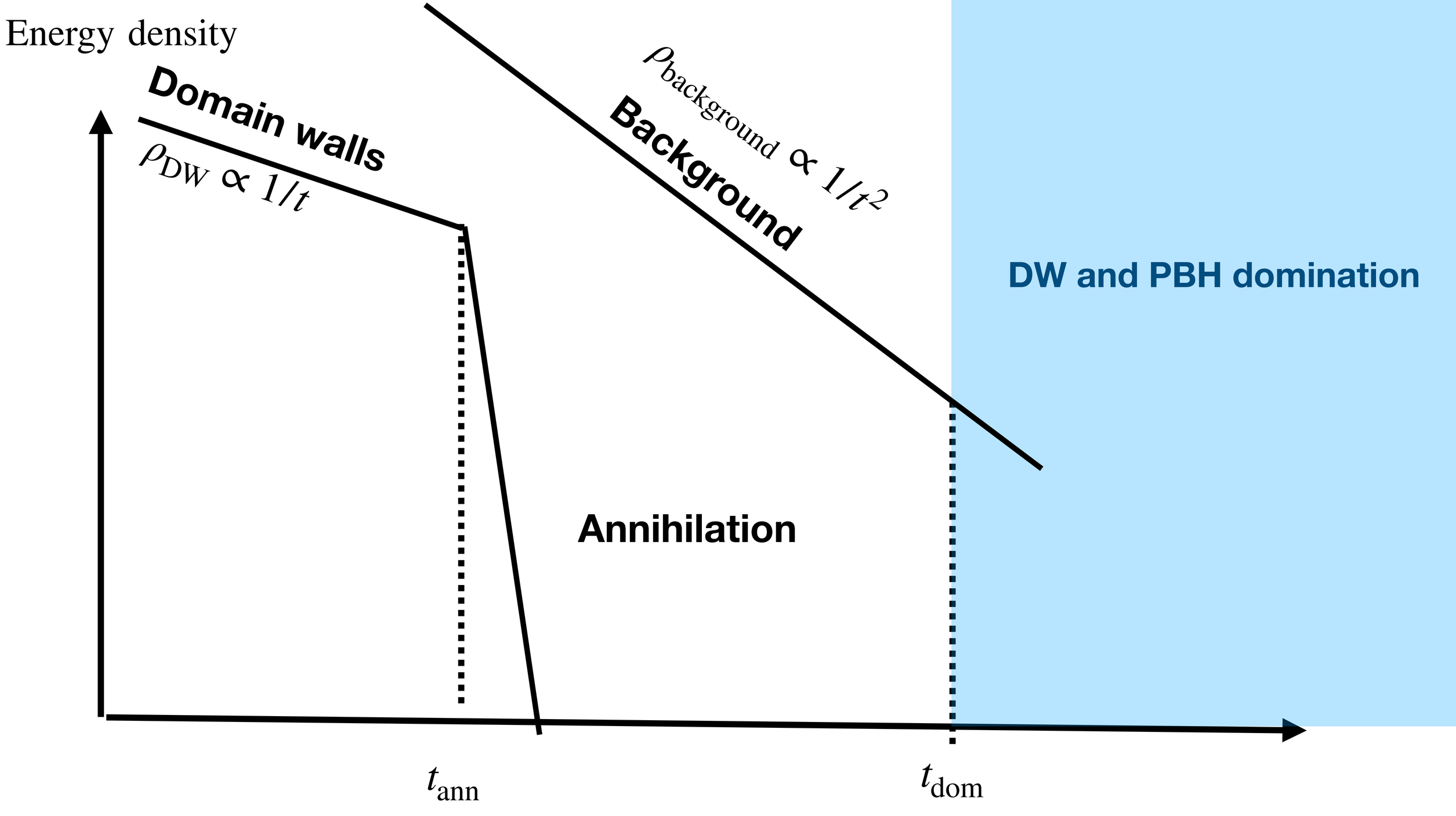
Vacuum energy bias

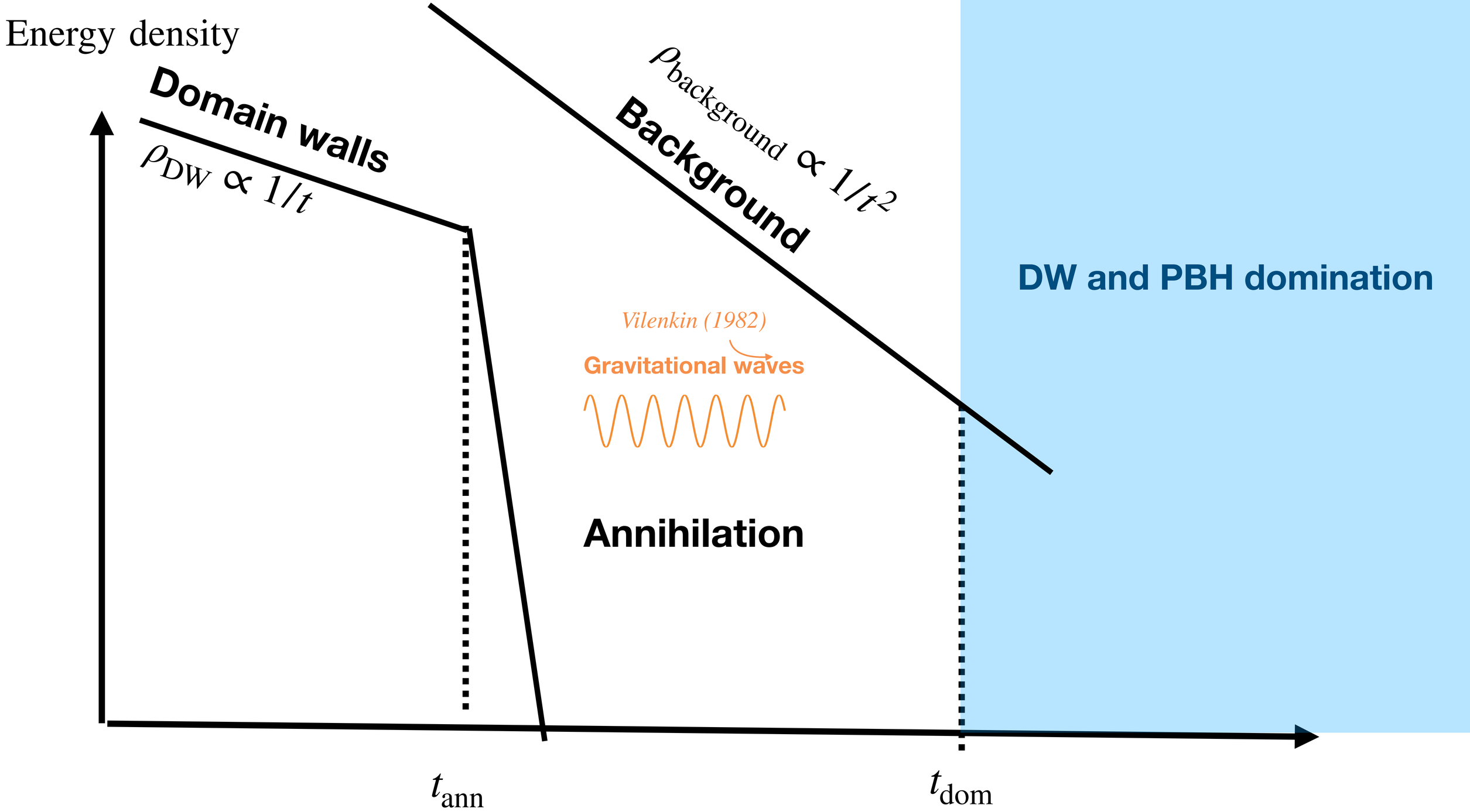


Sikivie 1982 (Phys. Rev. Lett.)




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


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


Energy density
Domain walls
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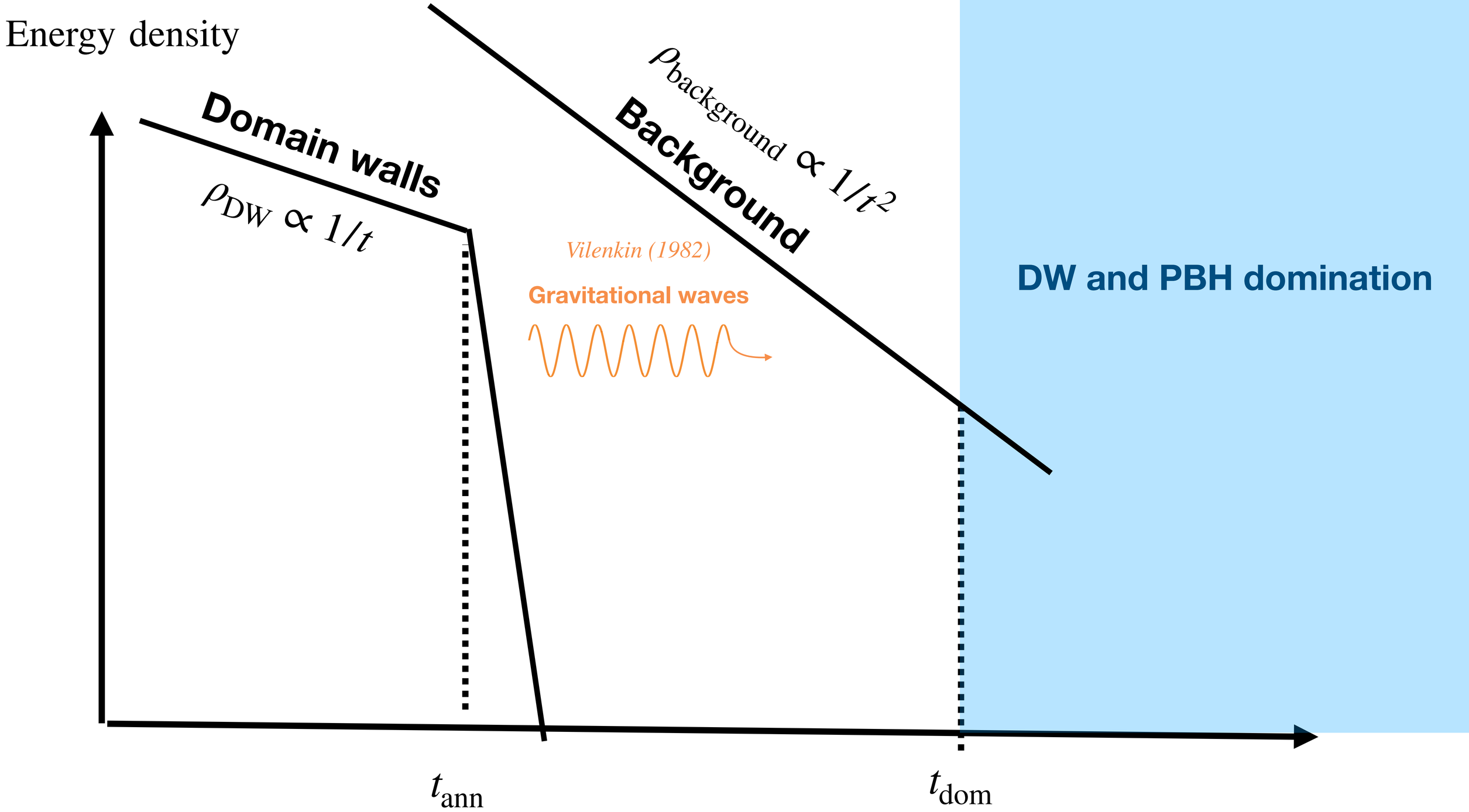
Background
DW and PBH domination
Vilenkin (1982)
Gravitational waves
Annihilation
$t_{\rm ann}$
$t_{\rm dom}$


Energy density
Domain walls
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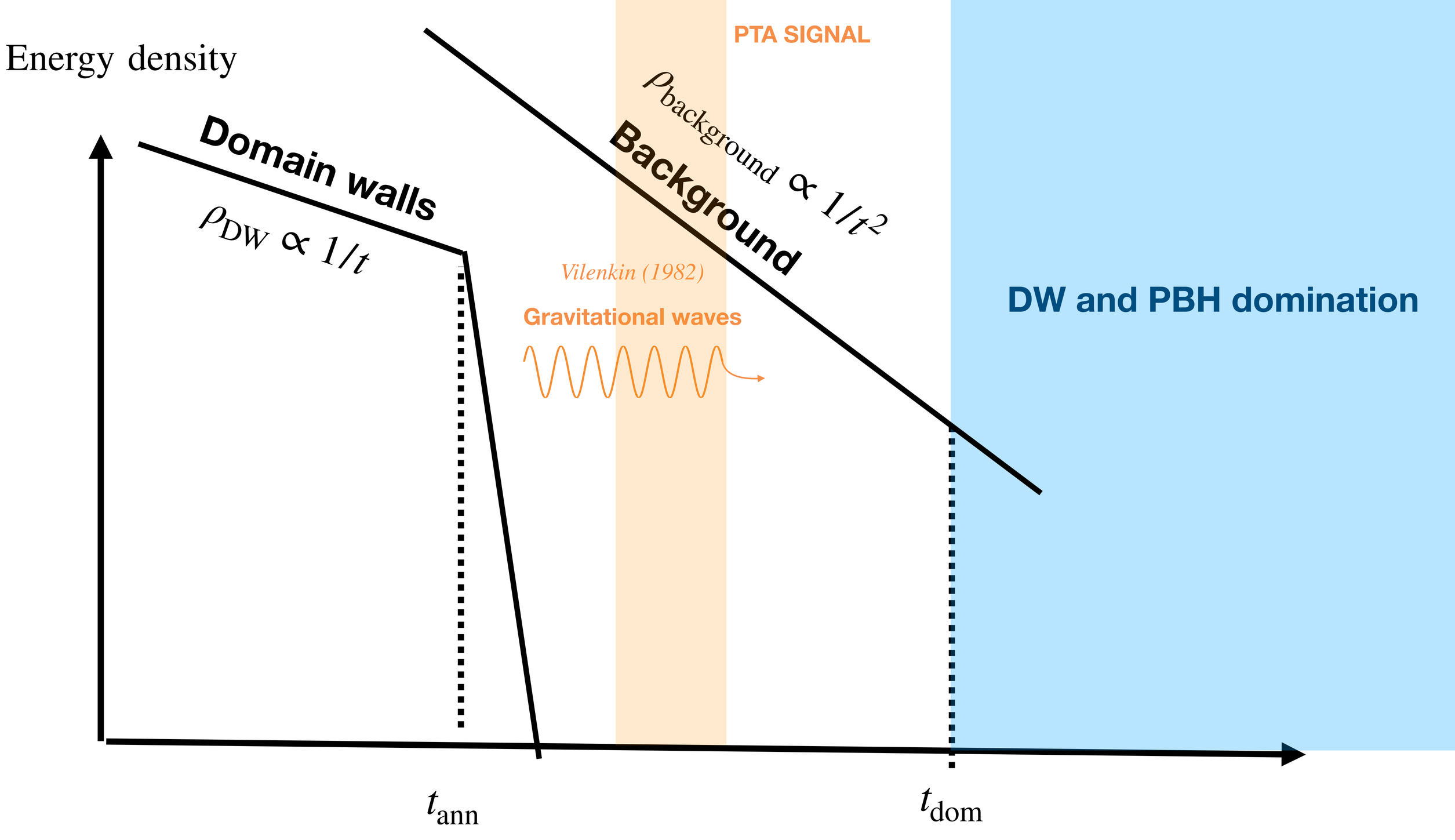
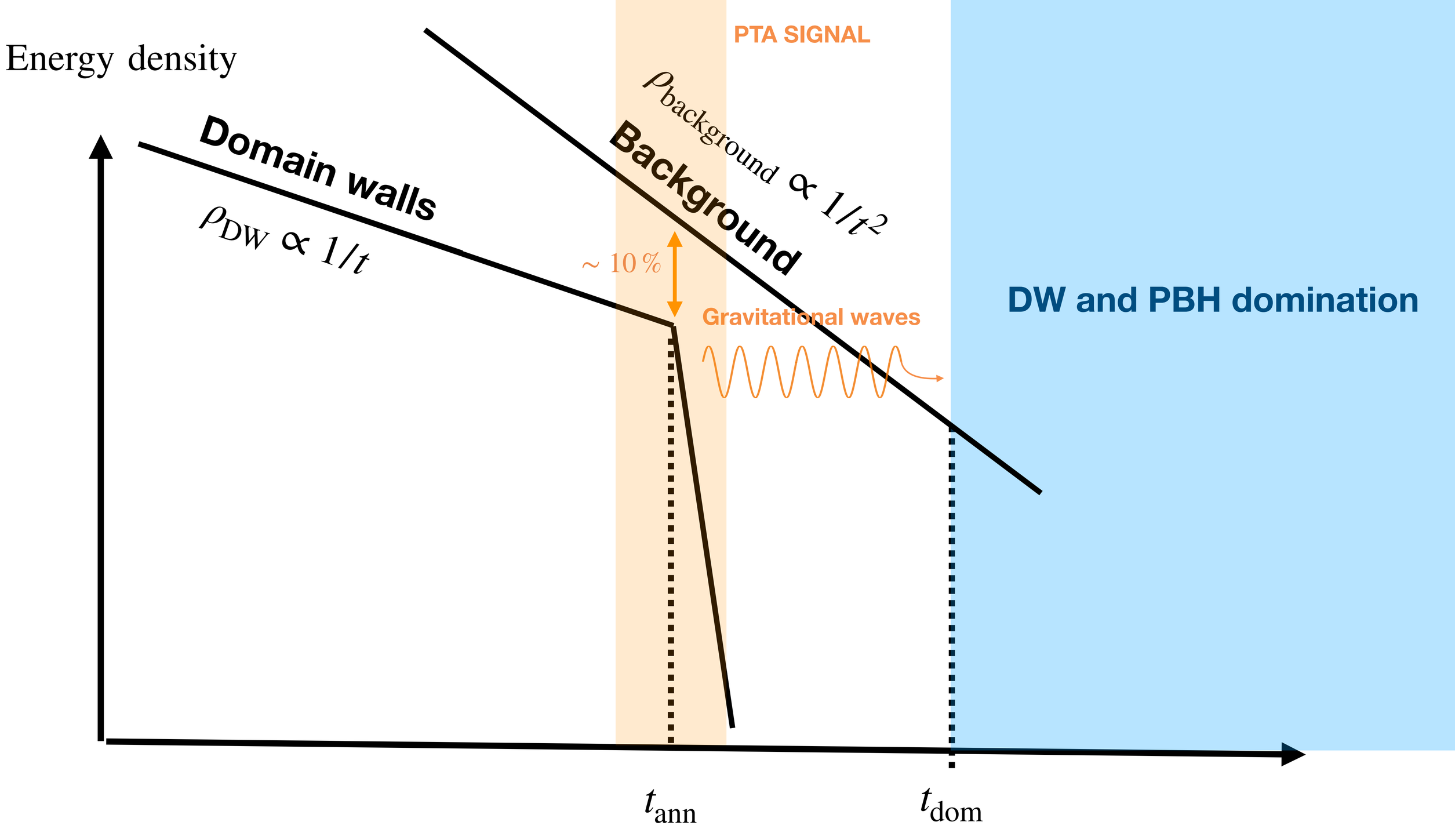
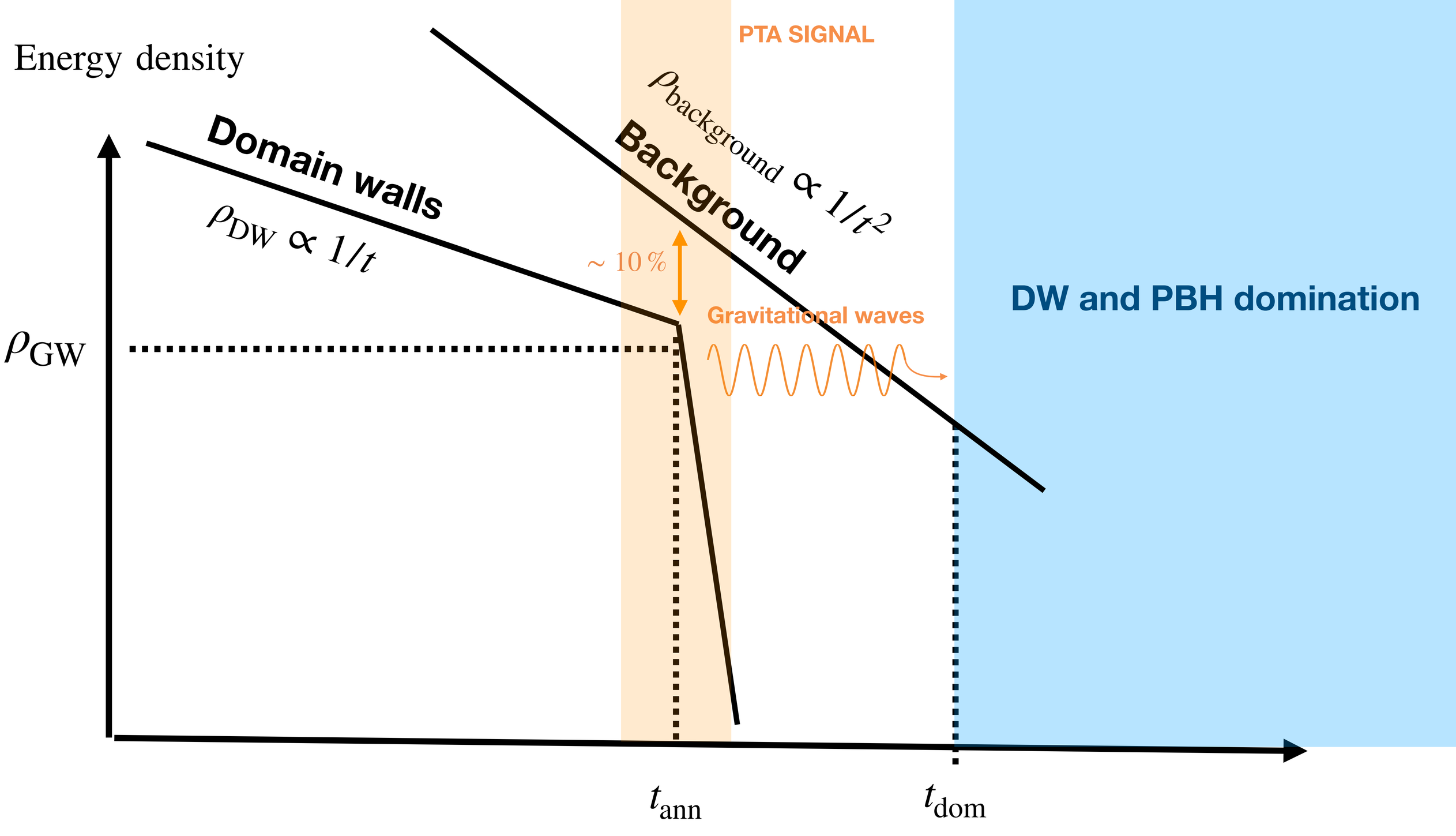
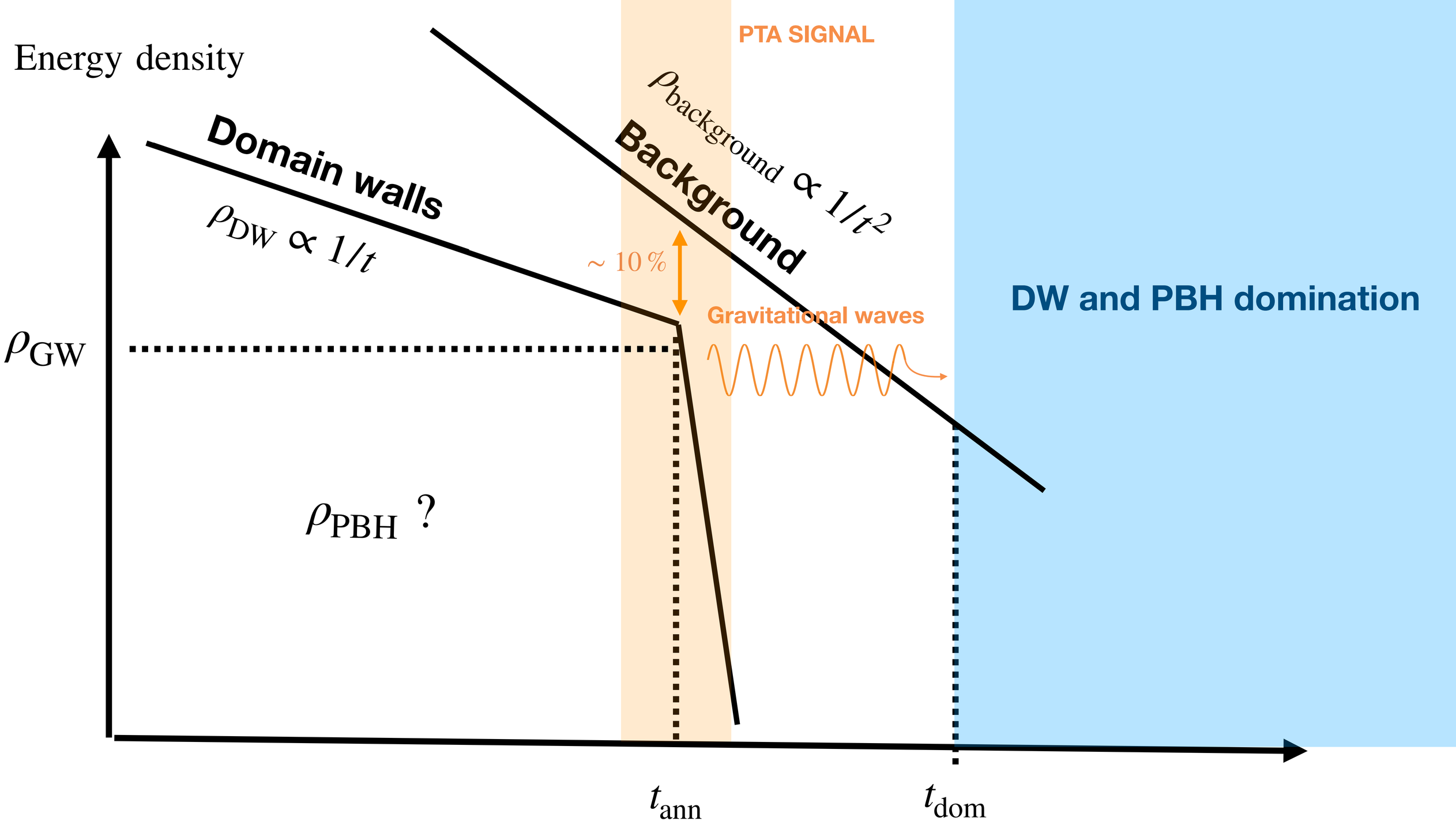
$\rho_{\rm background} \propto 1/t^2$
Background
Vilenkin (1982)
Gravitational waves
DW and PBH domination
$t_{\rm ann}$
$t_{\rm dom}$


Energy density
Domain walls
$\rho_{\rm DW} \propto 1/t$
PTA SIGNAL
$\rho_{\rm background} \propto 1/t^2$
Background
Vilenkin (1982)
Gravitational waves
DW and PBH domination
$t_{\rm ann}$
$t_{\rm dom}$


Energy density
PTA SIGNAL
$\rho_{\text{background}} \propto 1/t^2$
Domain walls
$\rho_{\text{DW}} \propto 1/t$
Background
$\sim 10\,\%$
Gravitational waves
DW and PBH domination
t_{ann}
t_{dom}


Energy density
PTA SIGNAL
$\rho_{\text{background}} \propto 1/t^2$
Domain walls
$\rho_{\text{DW}} \propto 1/t$
Background
$\sim 10\,\%$
Gravitational waves
DW and PBH domination
ρ_{GW}
t_{ann}
t_{dom}


Energy density
PTA SIGNAL
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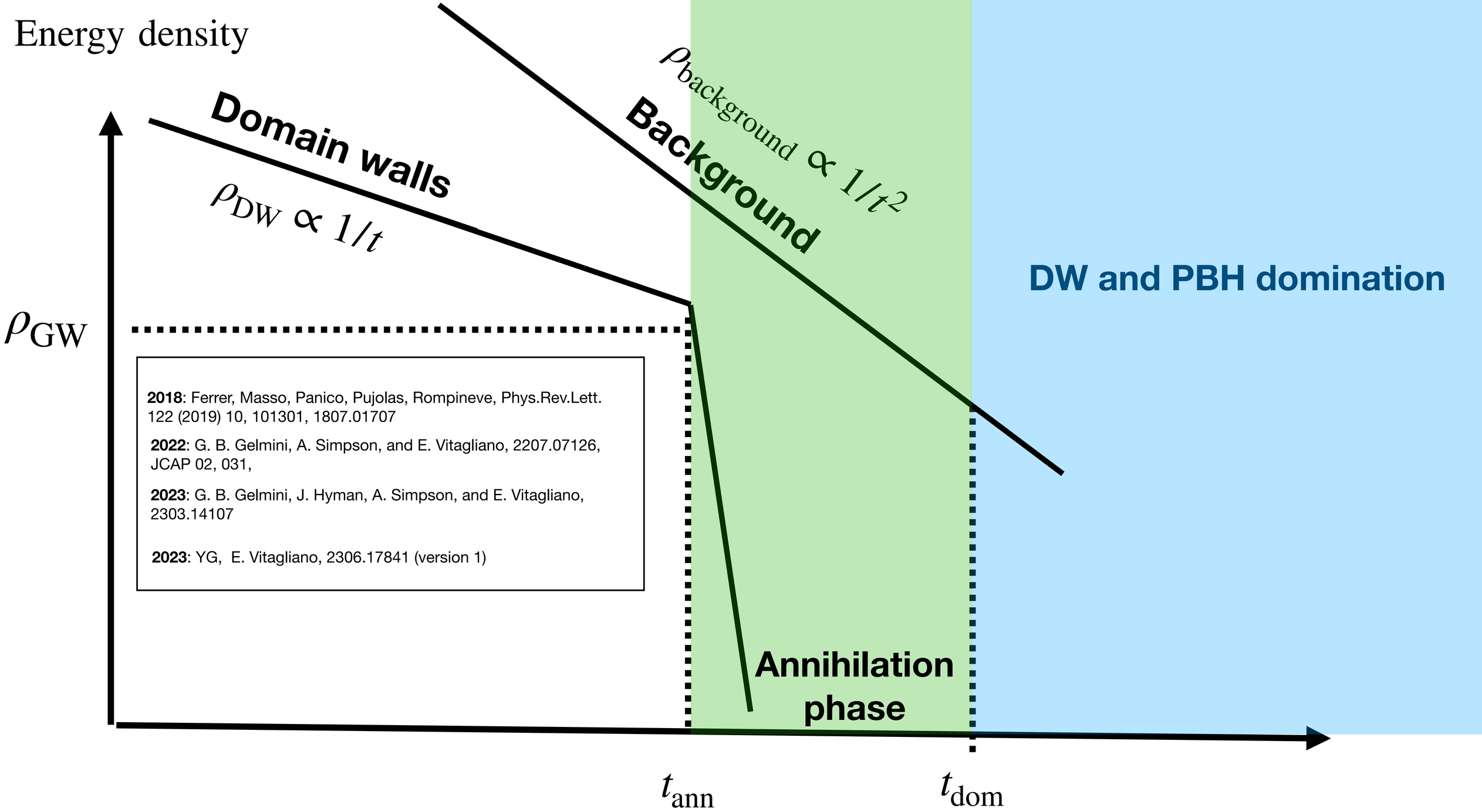
Domain walls
$\rho_{\text{DW}} \propto 1/t$
Background
$\sim 10\,\%$
Gravitational waves
DW and PBH domination
ρ_{GW}
ρ_{PBH} ?
t_{ann}
t_{dom}

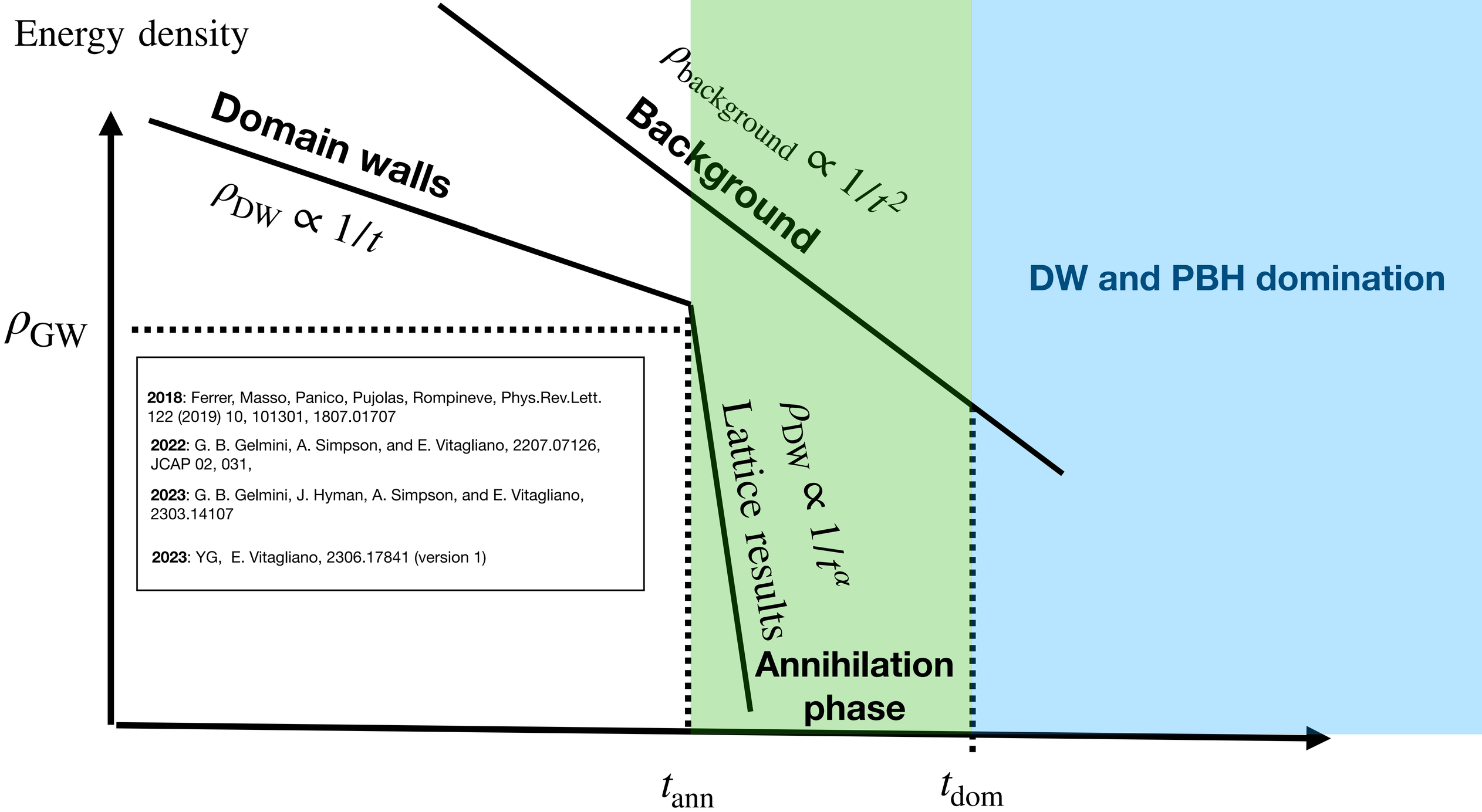


2018: Ferrer, Masso, Panico, Pujolas, Rompineve, Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707

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)



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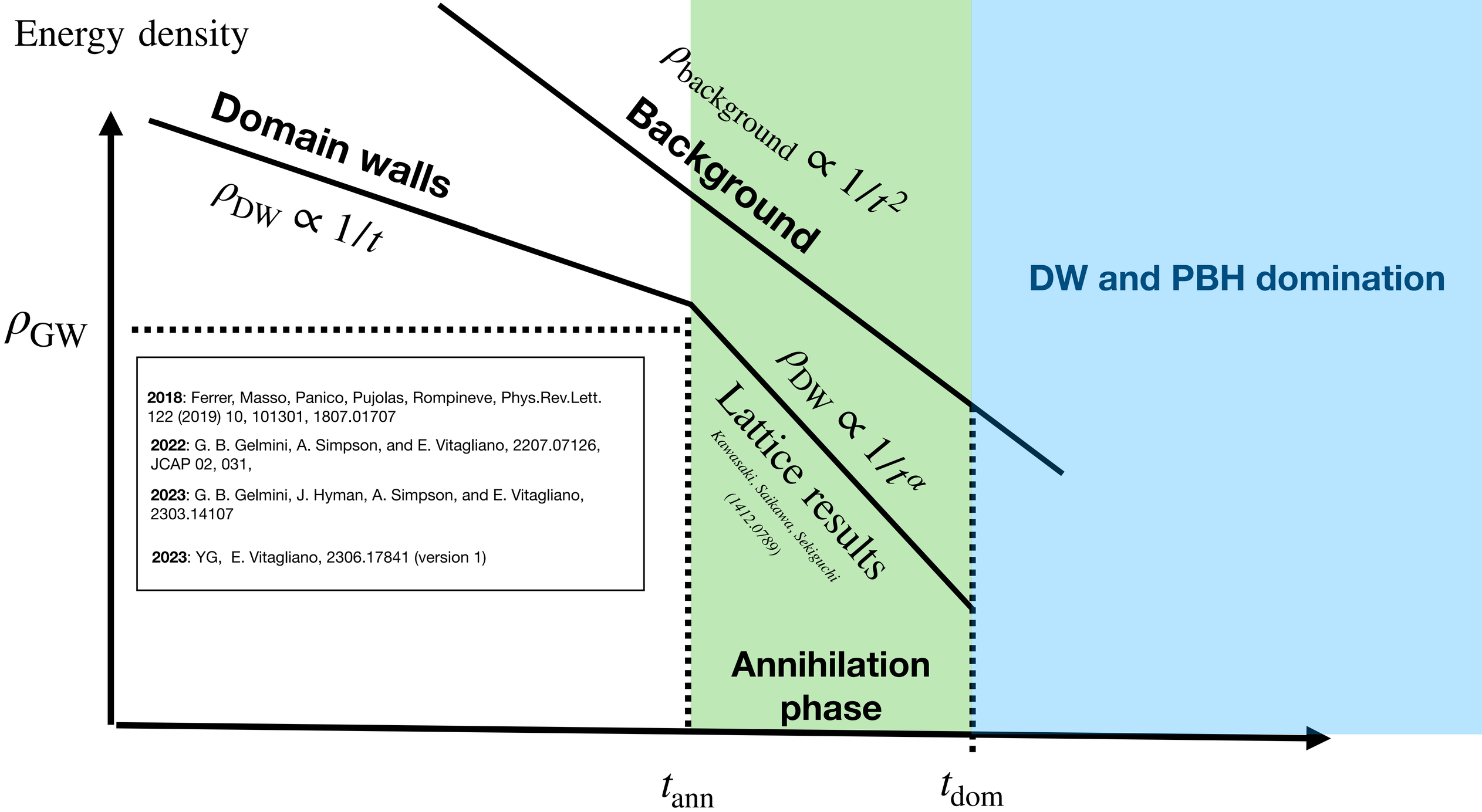

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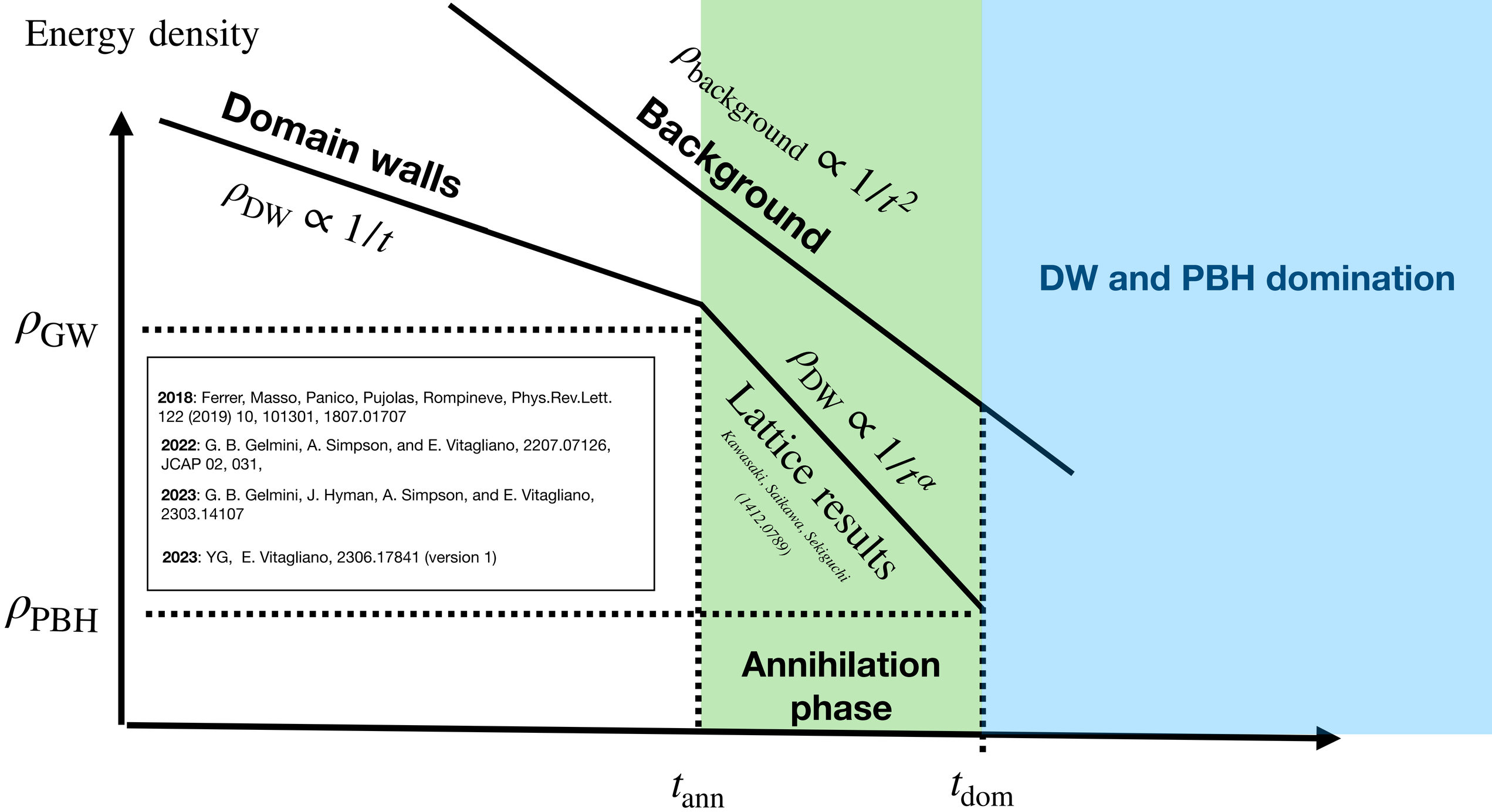

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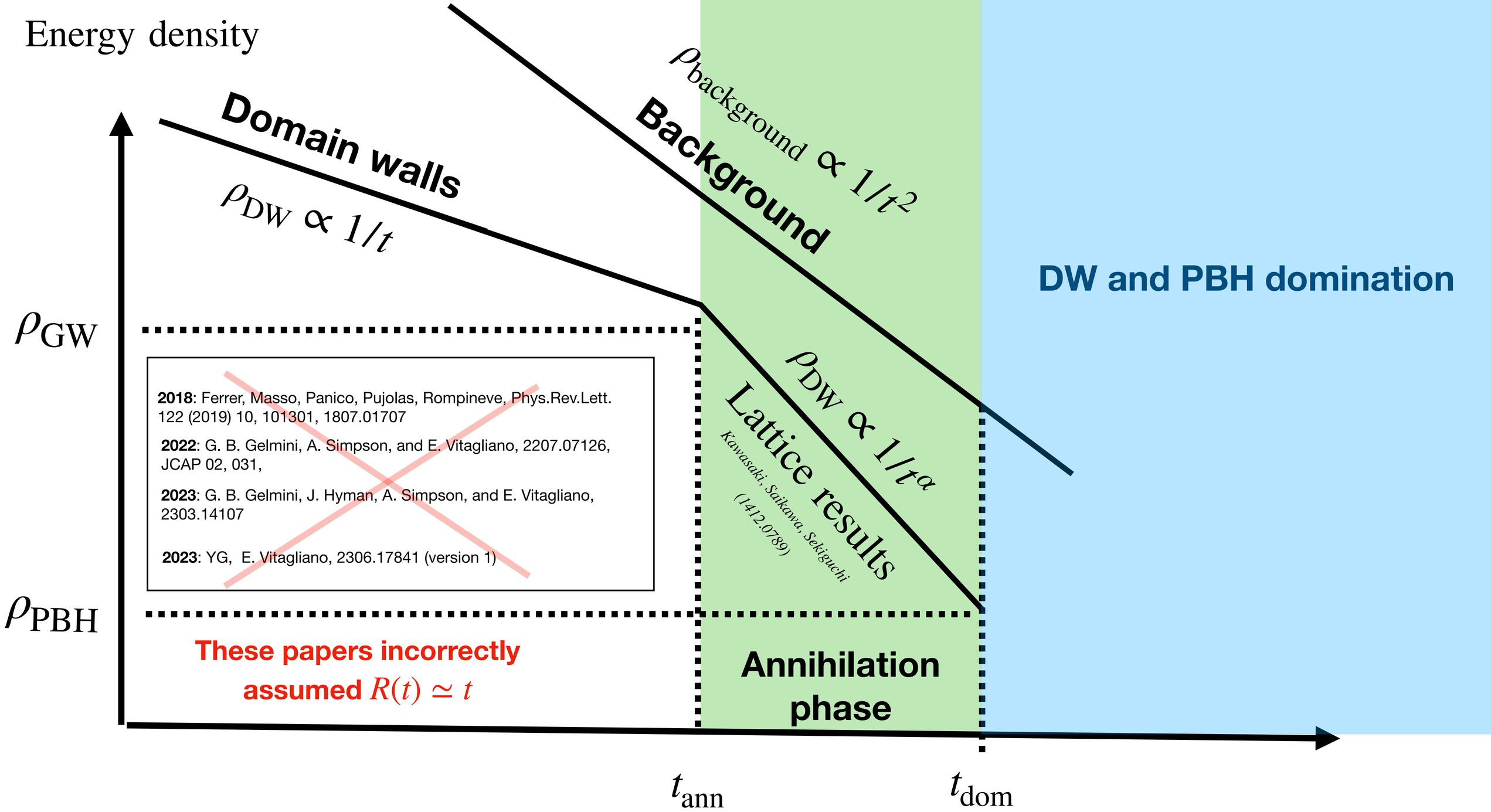
Energy density
Domain walls
$\rho_{\rm DW} \propto 1/t$
$\rho_{\rm background} \propto 1/t^2$
Background
DW and PBH domination
$\rho_{\rm GW}$
$\rho_{\rm DW} \propto 1/t^{\alpha}$
Lattice results
Kawasaki, Saikawa, Sekiguchi (1412.0789)
2018: Ferrer, Masso, Panico, Pujolas, Rompineve, Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707
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$\rho_{\rm PBH}$
These papers incorrectly assumed $R(t) \simeq t$
Annihilation phase
$t_{\rm ann}$
$t_{\rm dom}$

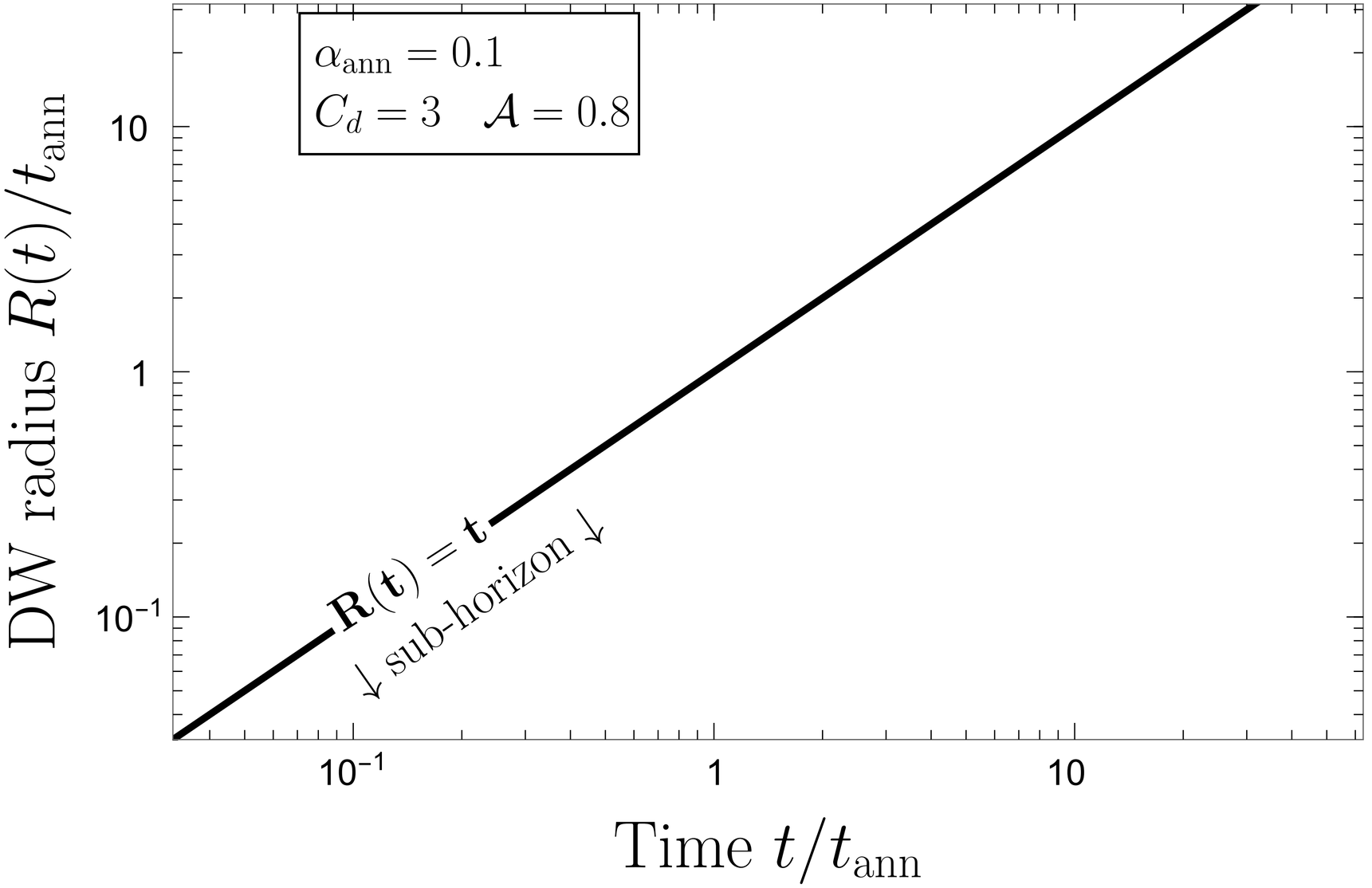
Go back to basics: $\ddot{\chi} + (4 - 3a^2\dot{\chi}^2)H\dot{\chi} + \frac{2}{a^2\chi}(1 - a^2\dot{\chi}^2) = -\left(\frac{V_{\rm bias}}{\sigma} + 6\pi\sigma\right)\frac{(1 - a^2\dot{\chi}^2)^{3/2}}{a}$ $\qquad R(t) = a(t)\chi(t)$

Berezin, Kuzmin, and Tkachev, (1983) *Deng, Vilenkin, (2016)*

Motion of a thin-shell in General Relativity

Go back to basics: $\ddot{\chi} + (4 - 3a^2\dot{\chi}^2)H\dot{\chi} + \frac{2}{a^2\chi}(1 - a^2\dot{\chi}^2) = -\left(\frac{V_{\rm bias}}{\sigma} + 6\pi\sigma\right)\frac{(1 - a^2\dot{\chi}^2)^{3/2}}{a}$ $\qquad R(t) = a(t)\chi(t)$

Berezin, Kuzmin, and Tkachev, (1983) *Deng, Vilenkin, (2016)* ***Gouttenoire**, Vitagliano, 2311.07670*



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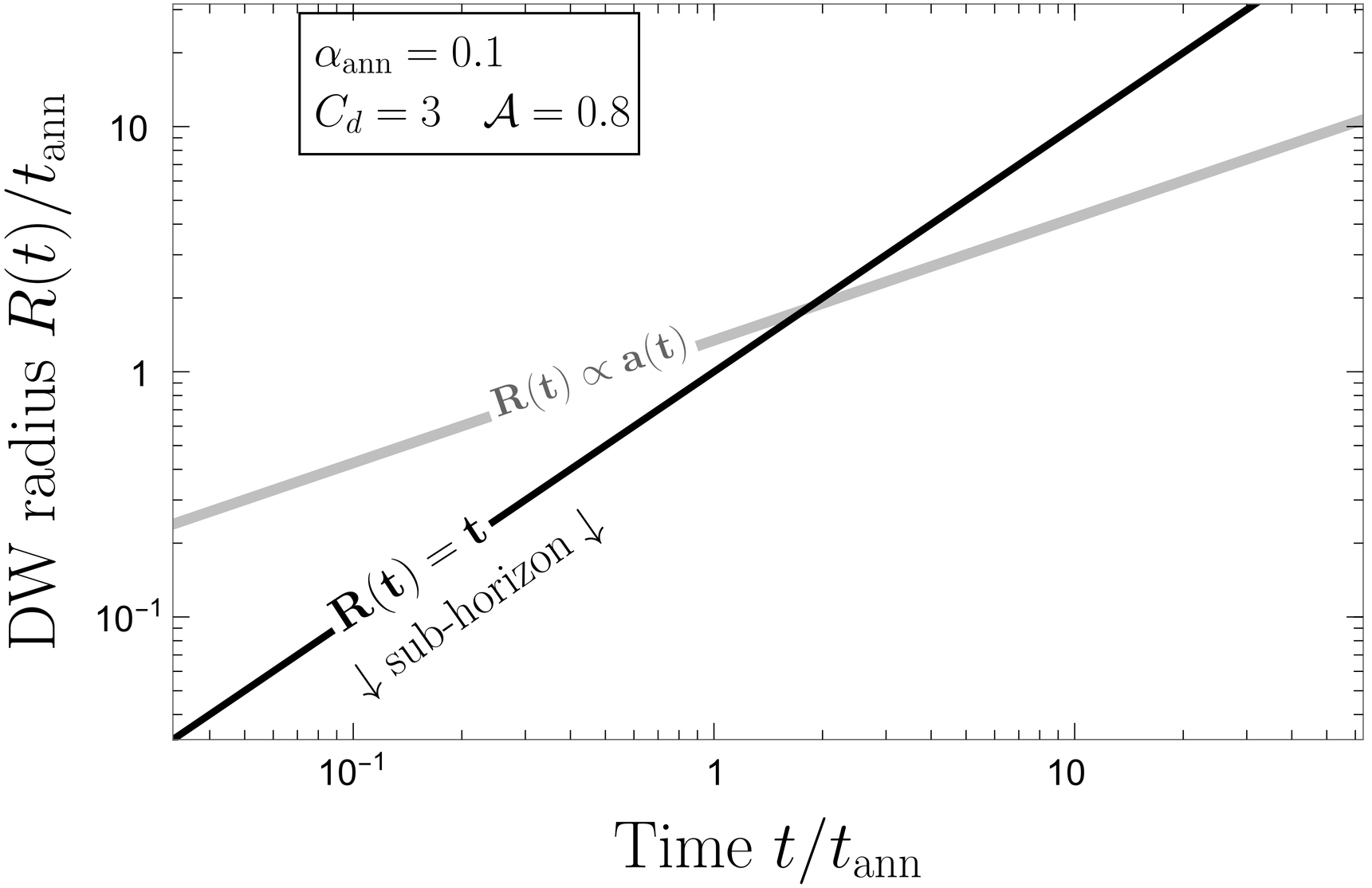

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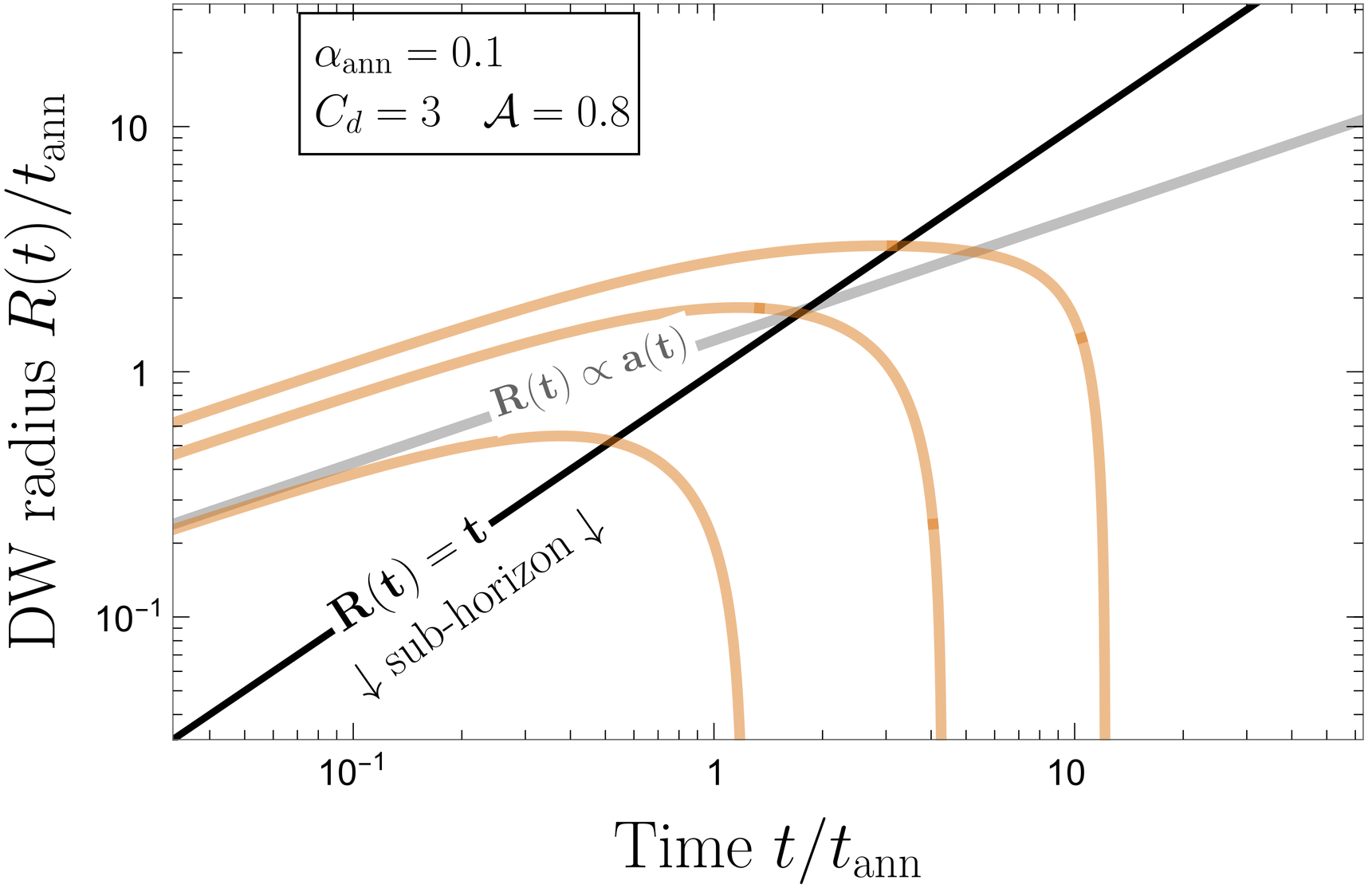

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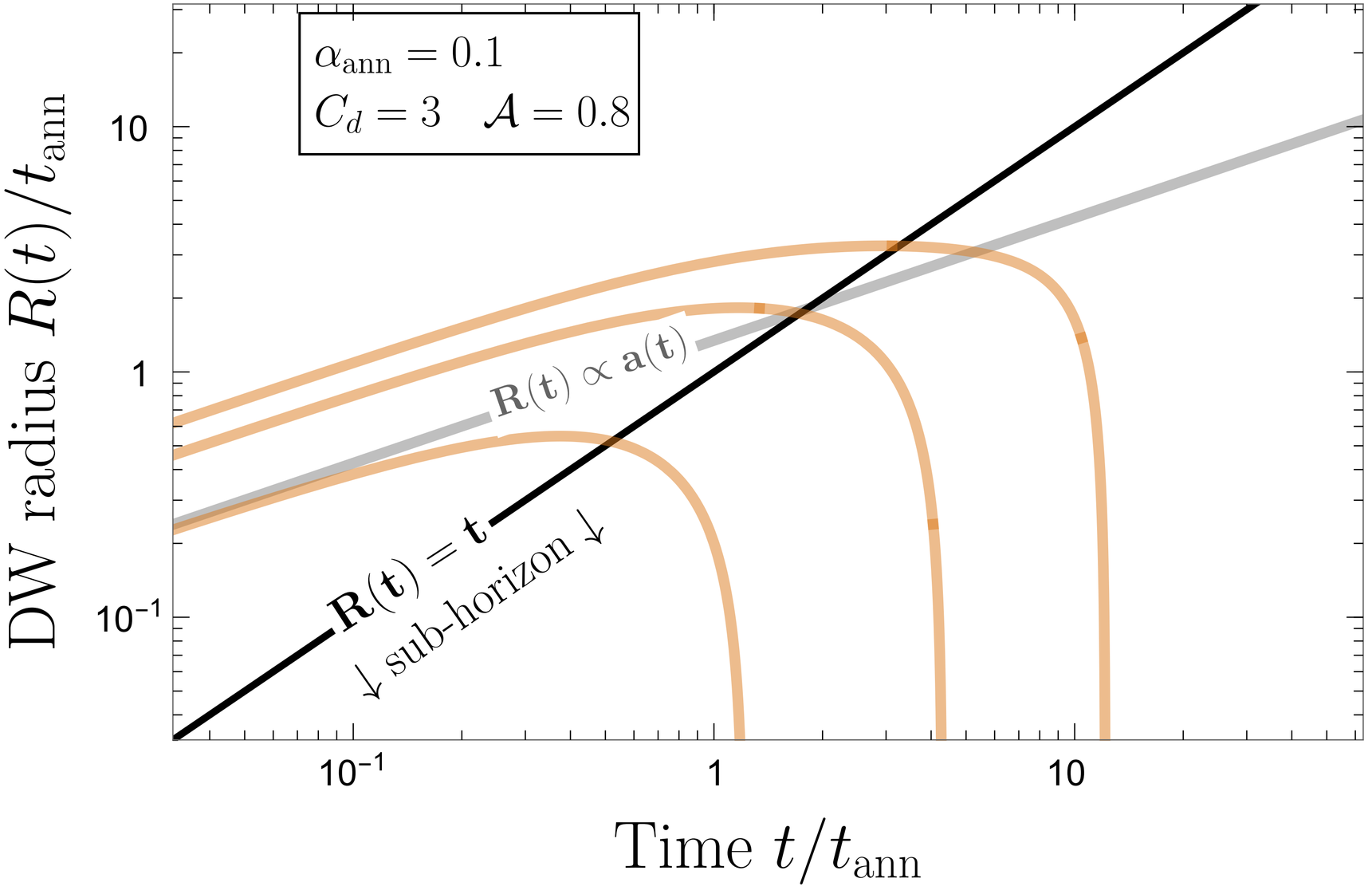

Result:

$$R(t) \propto \begin{cases} a(t), & \text{if R > t,} \\ e^{-\Gamma t}, & \text{if R < t .} \end{cases}$$

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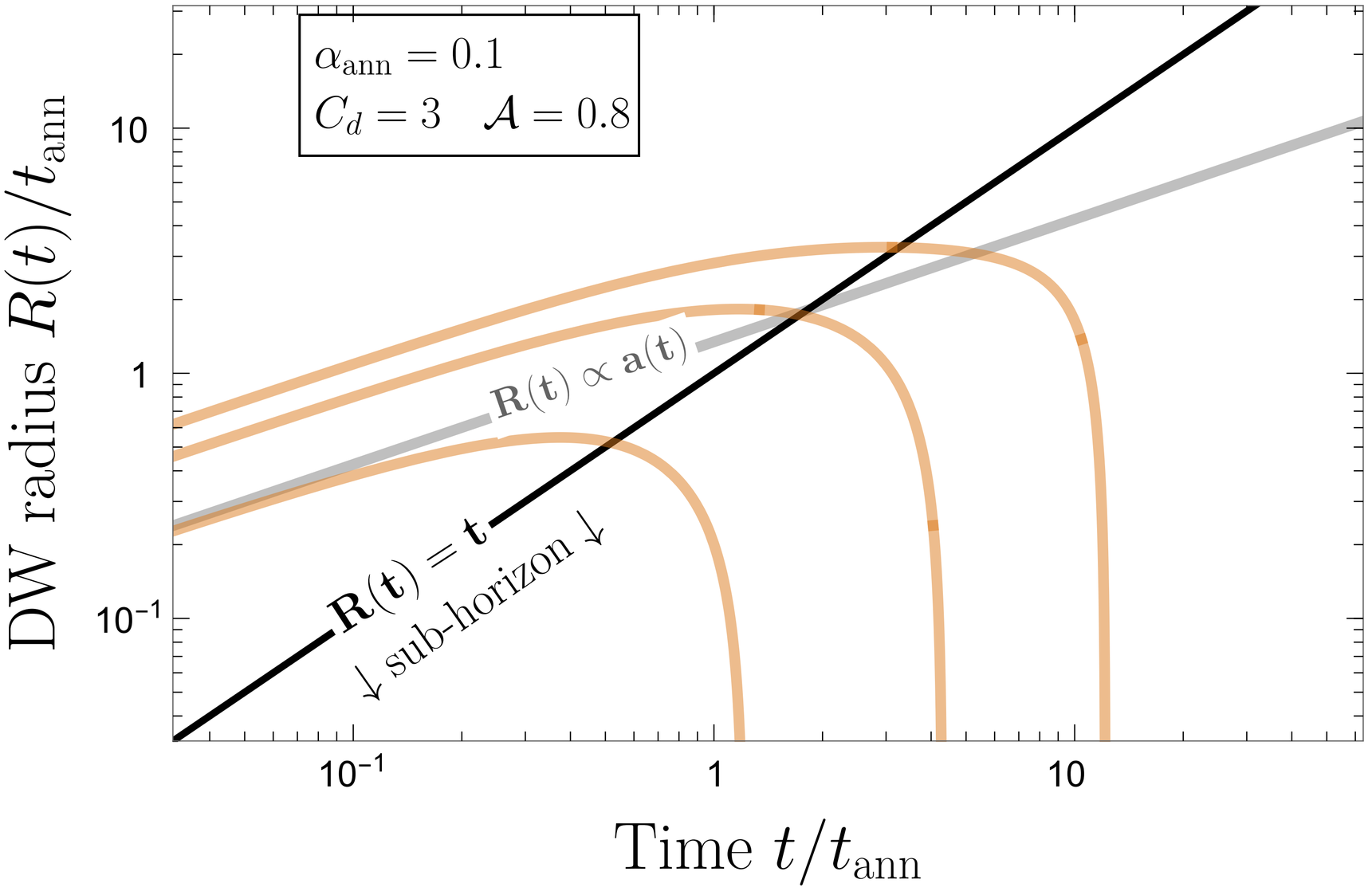

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Assumption: $R(t) \simeq t$

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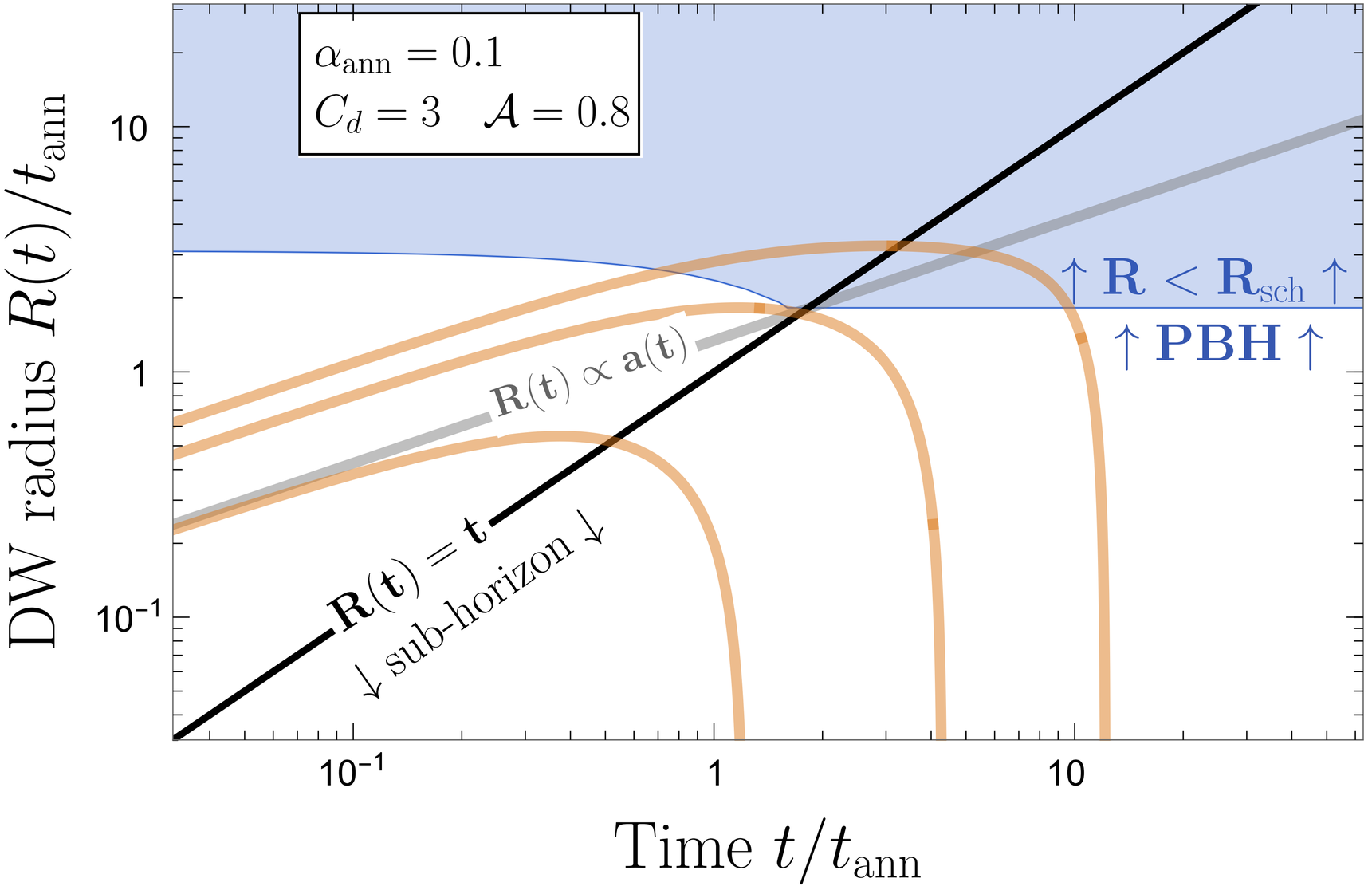

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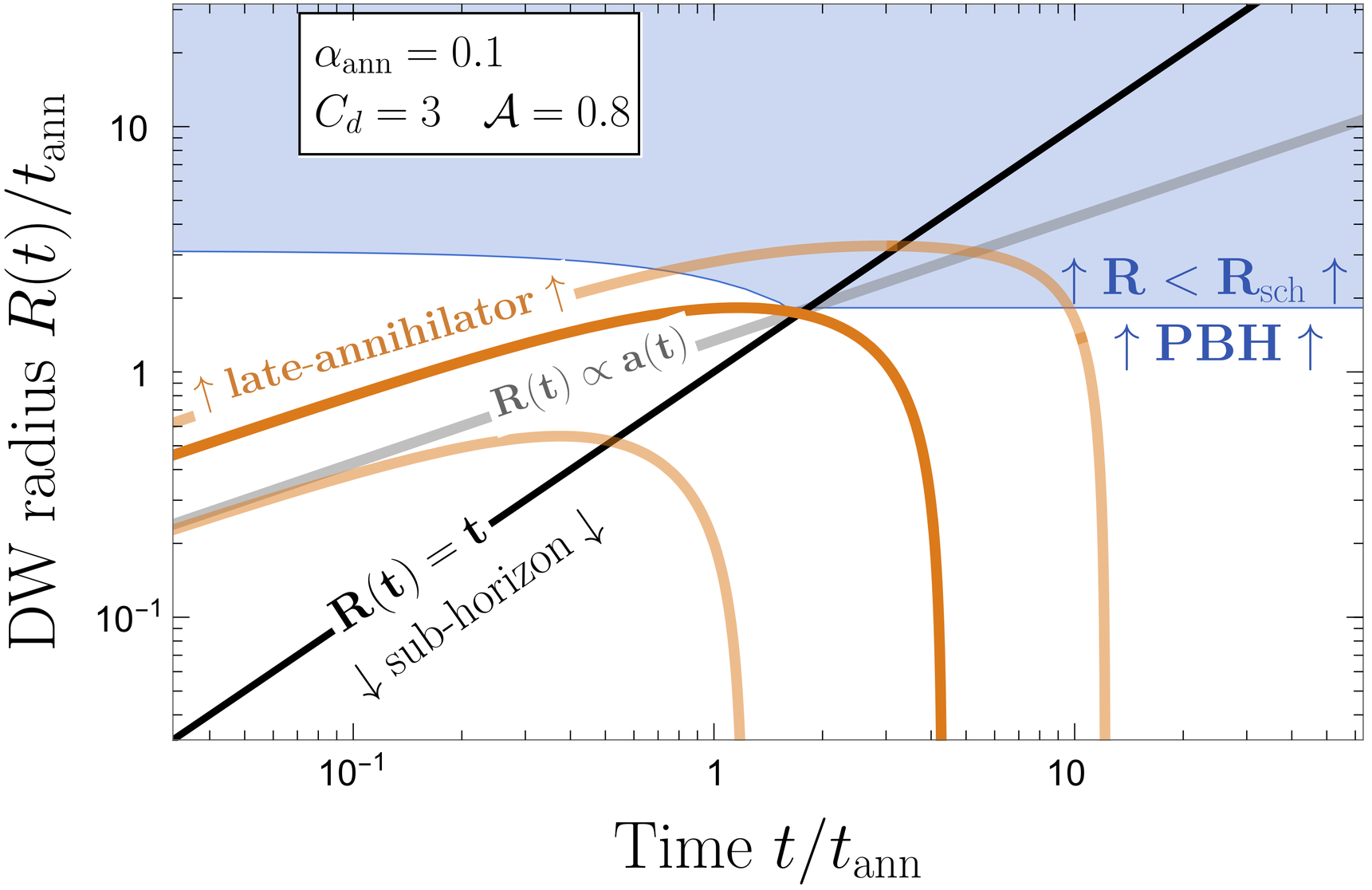

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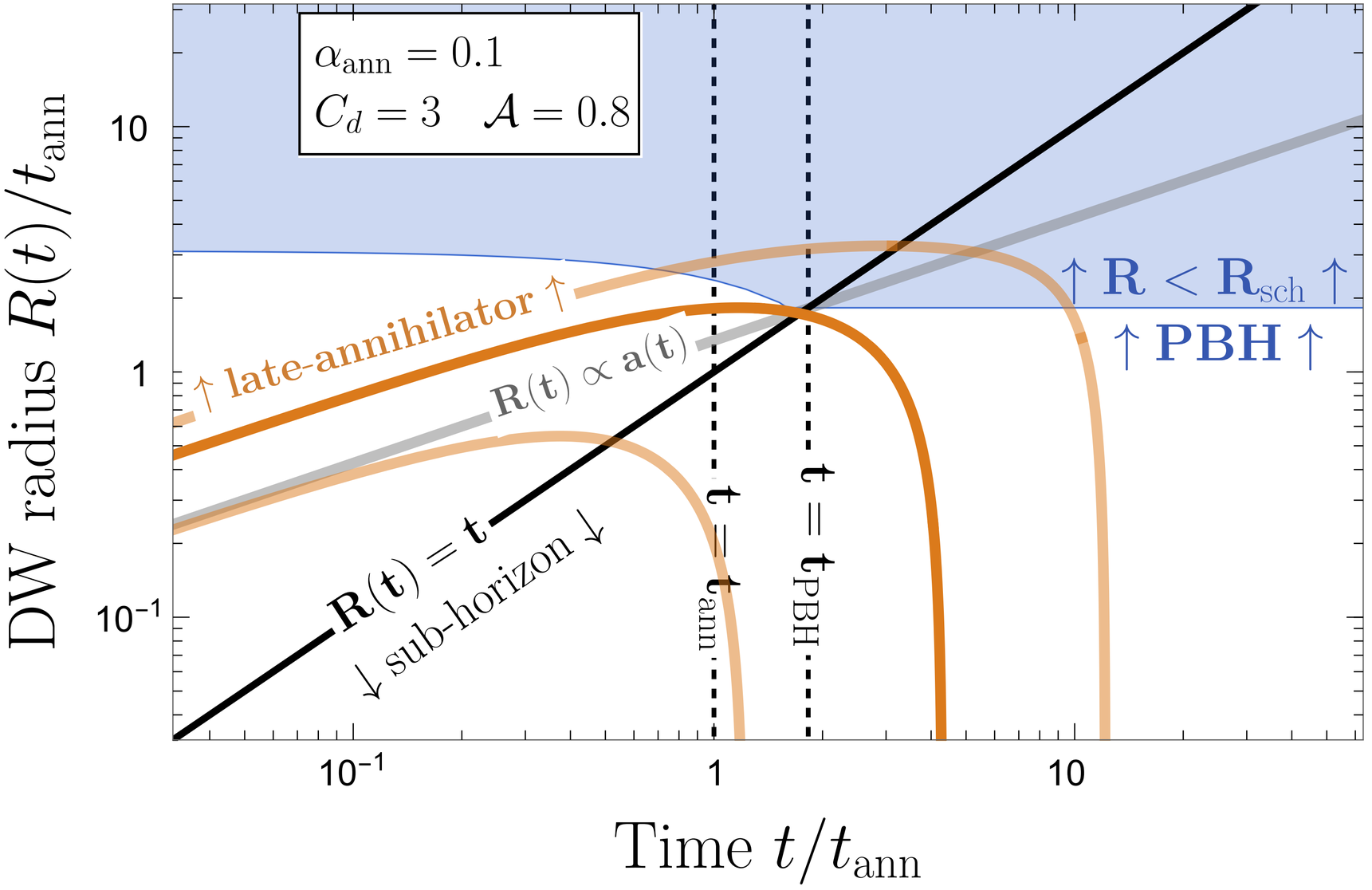

Result:

$$R(t) \propto \begin{cases} a(t), & \text{if } \mathrm{R} > \mathrm{t}, \\ e^{-\Gamma t}, & \text{if } \mathrm{R} < \mathrm{t}\,. \end{cases}$$

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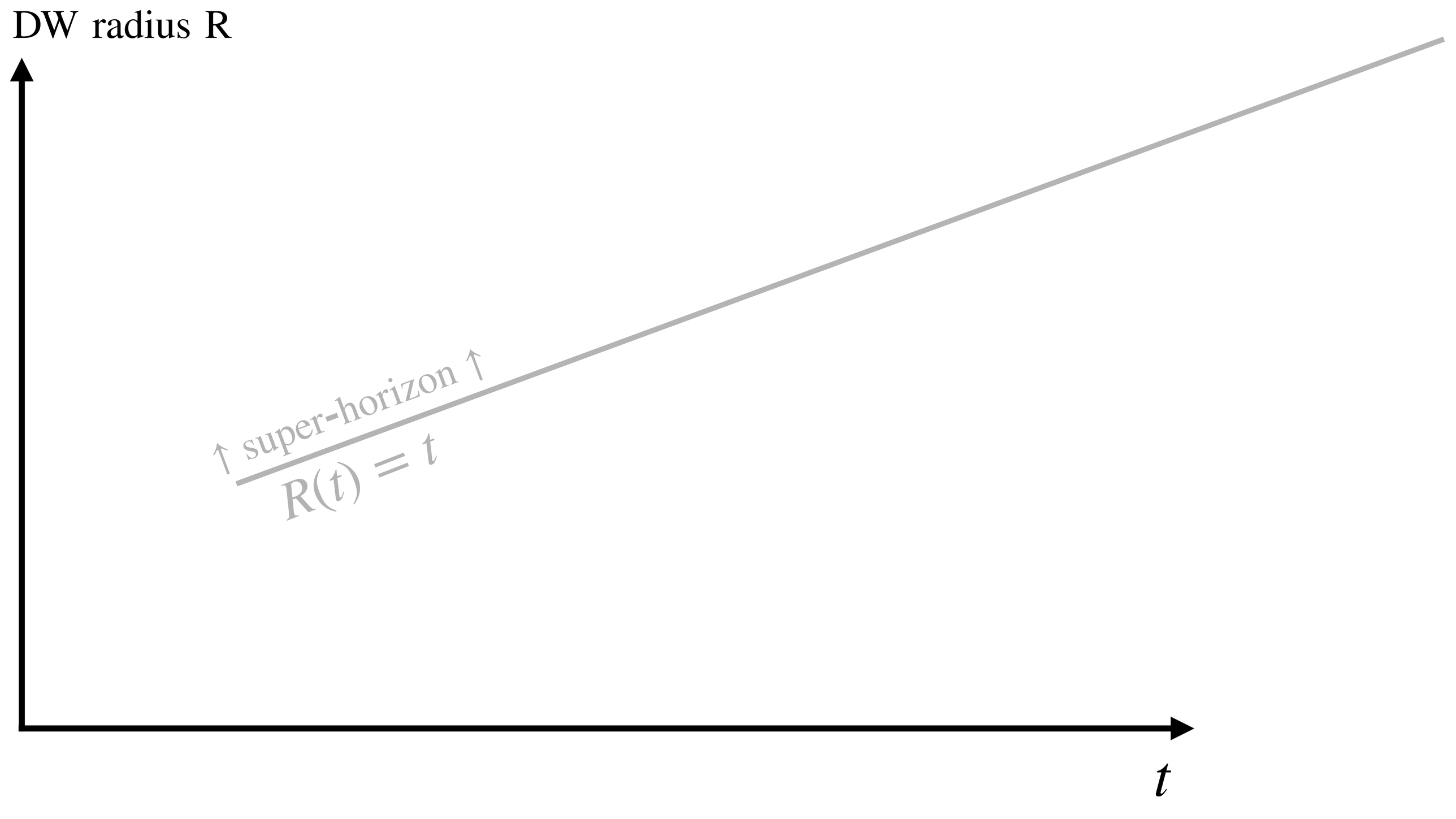
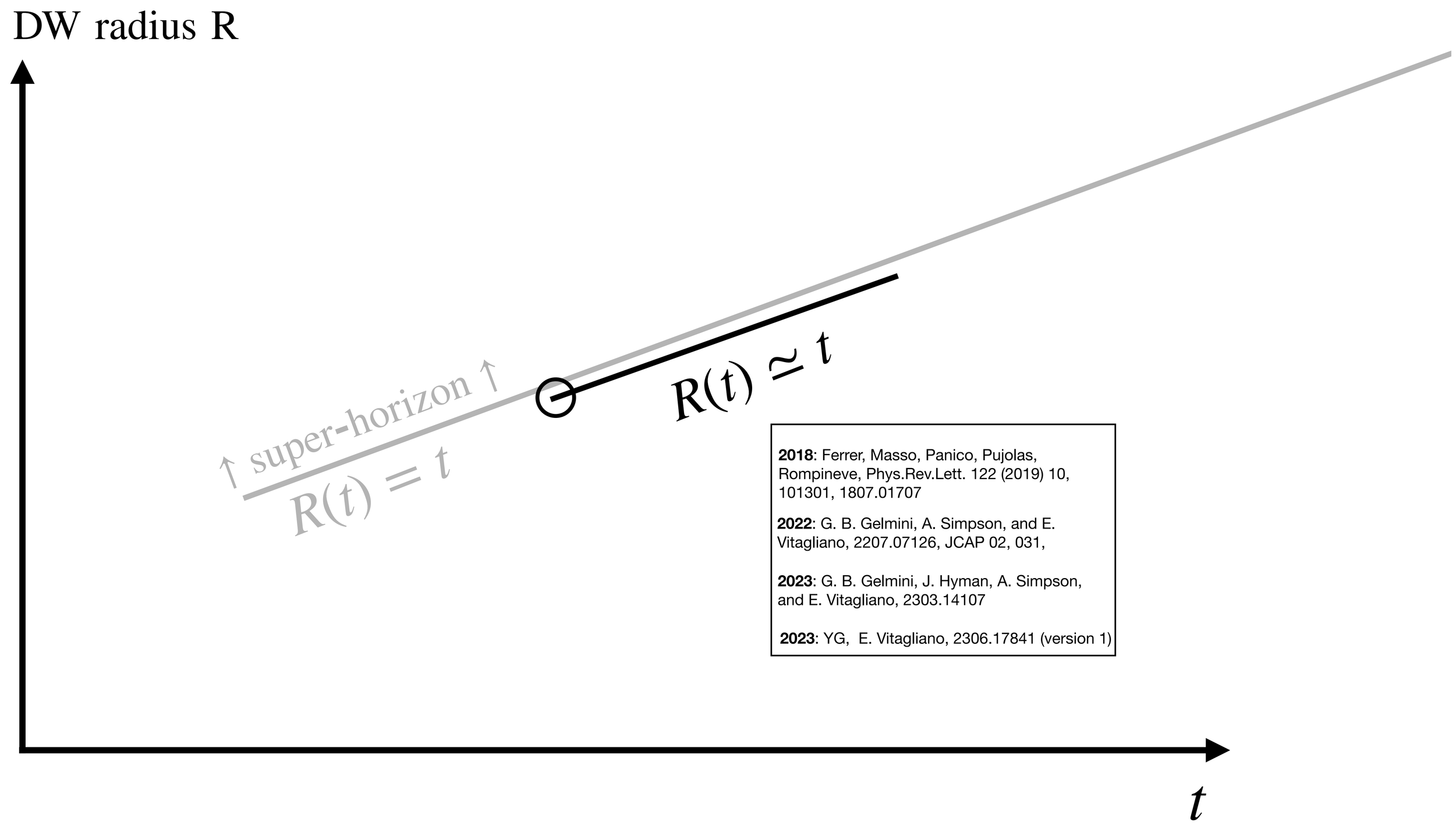

DW radius R
↑ super-horizon ↑
$R(t) = t$
t



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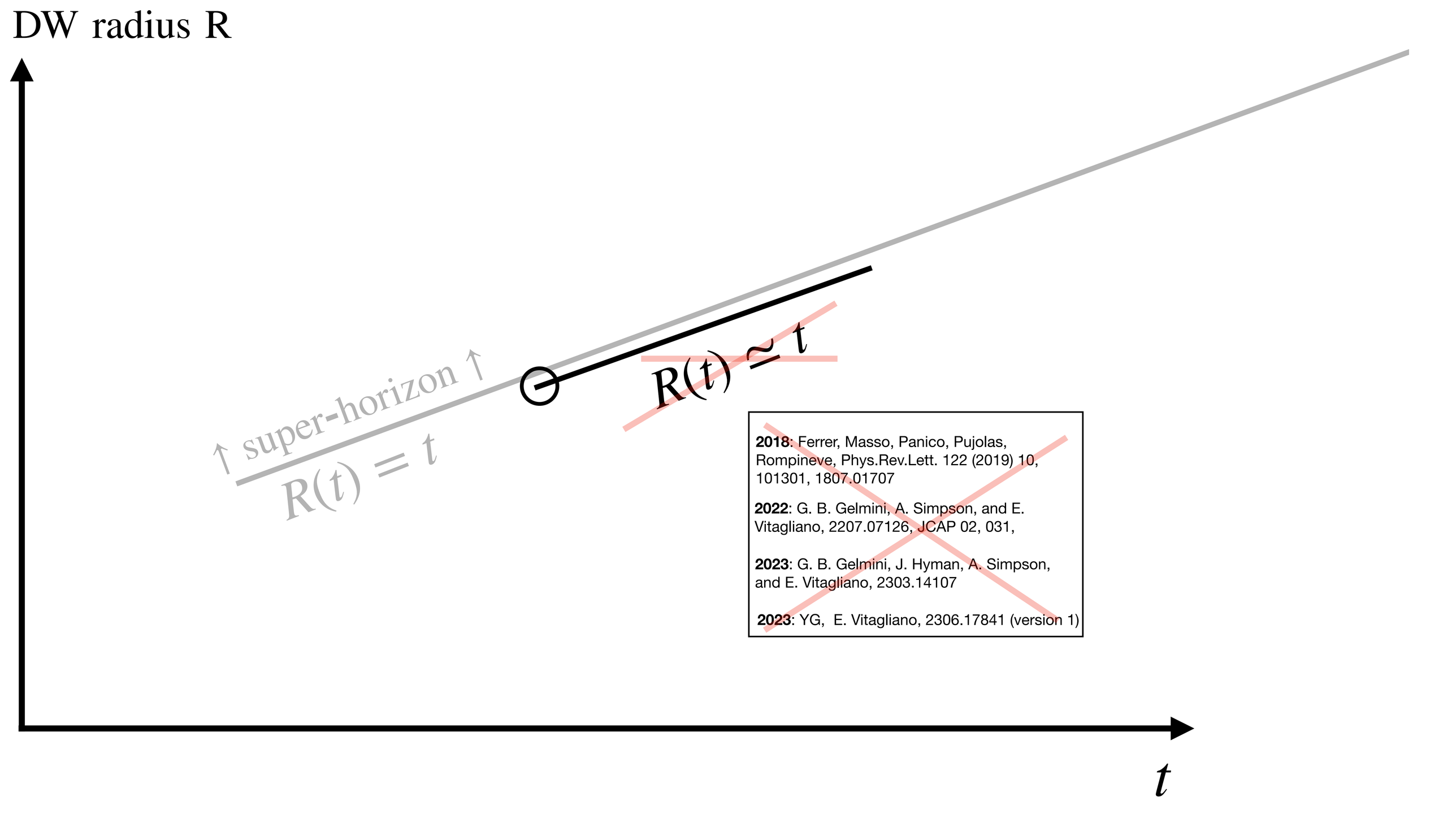
DW radius R
↑ super-horizon ↑
$R(t) = t$
$R(t) \simeq t$
2018: Ferrer, Masso, Panico, Pujolas, Rompineve, Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707
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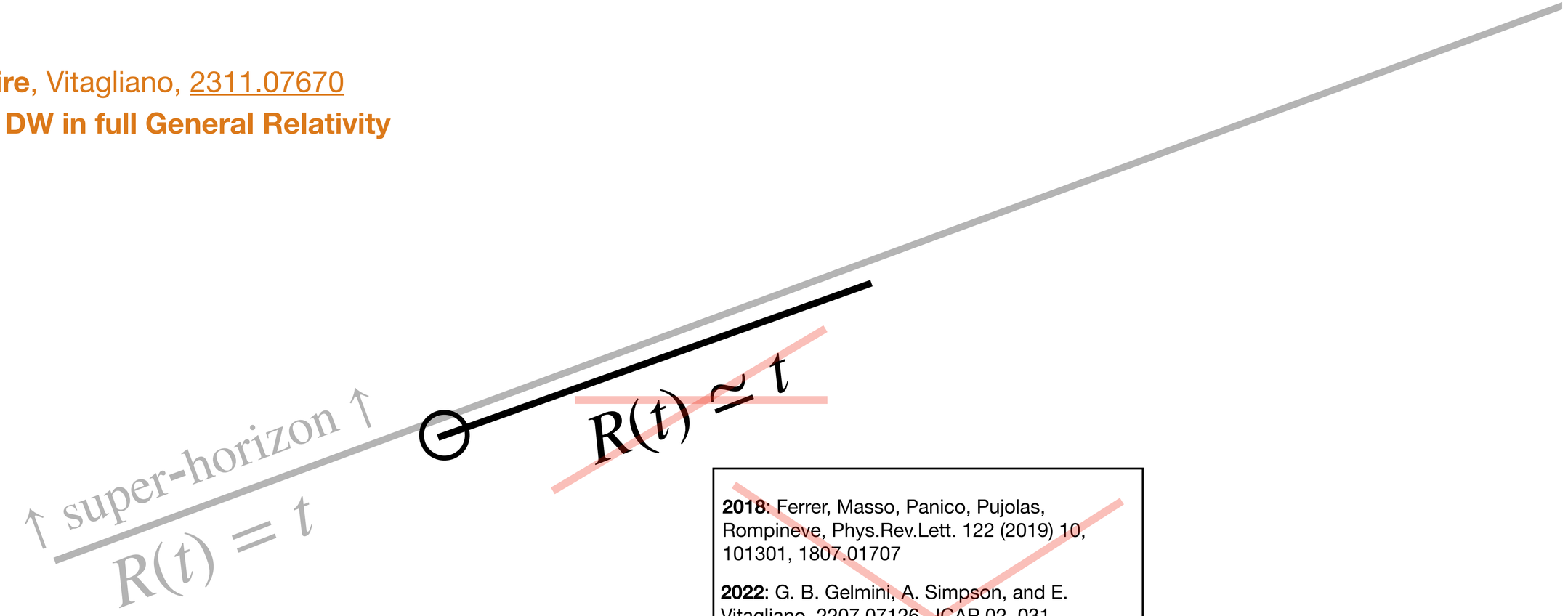
2023: YG, E. Vitagliano, 2306.17841 (version 1)
t

DW radius R

Gouttenoire, Vitagliano, 2311.07670

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



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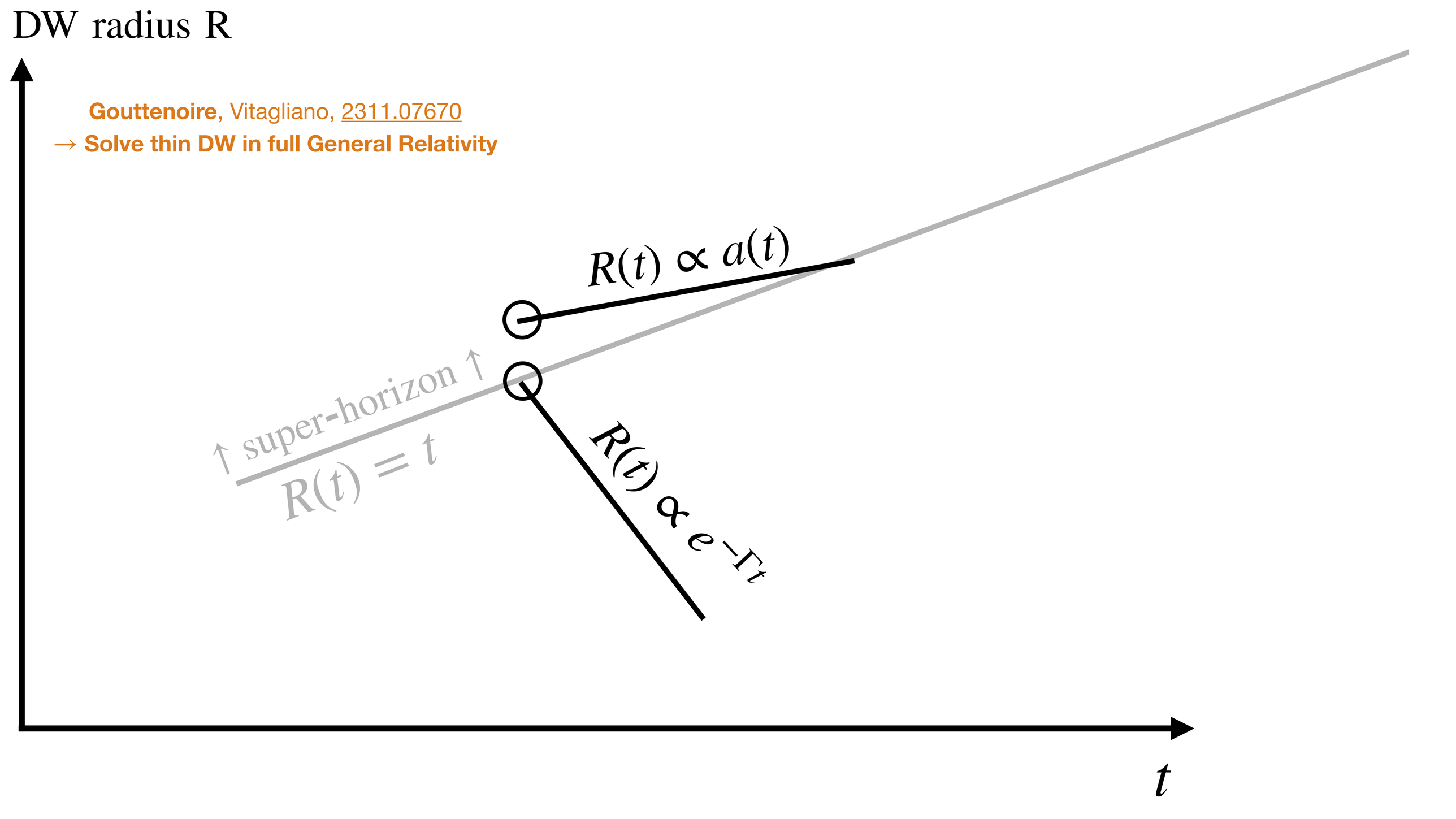
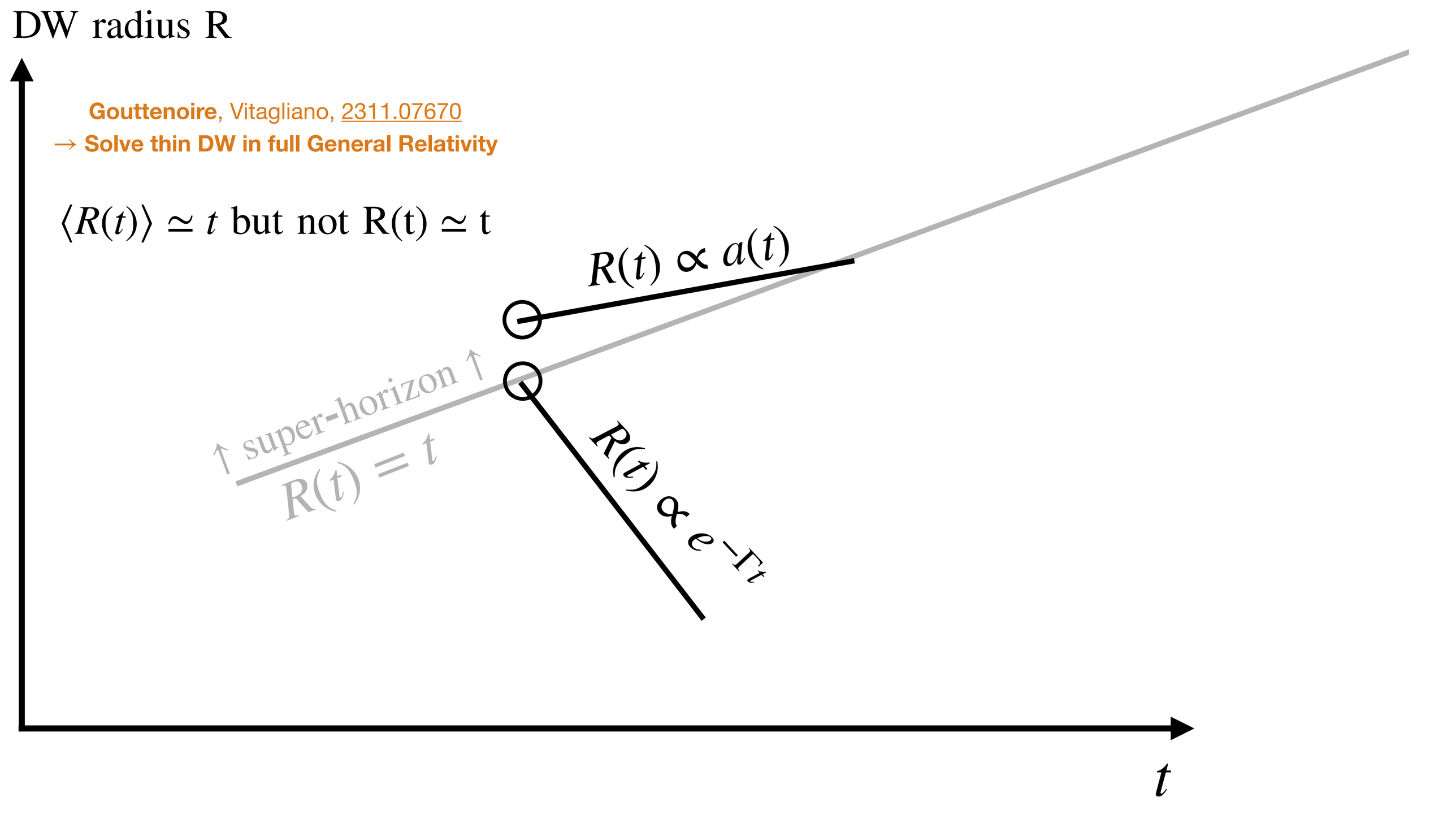
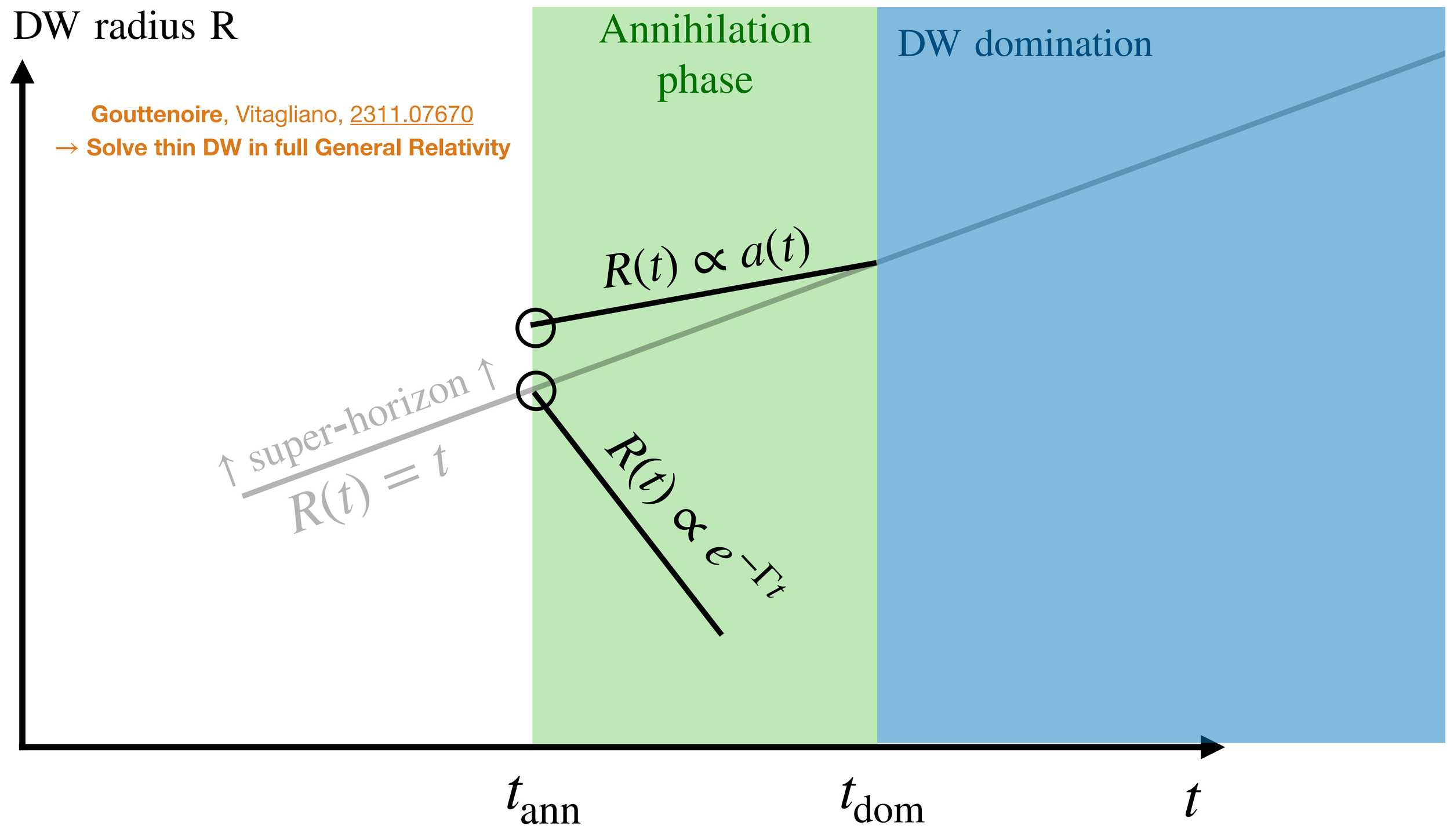
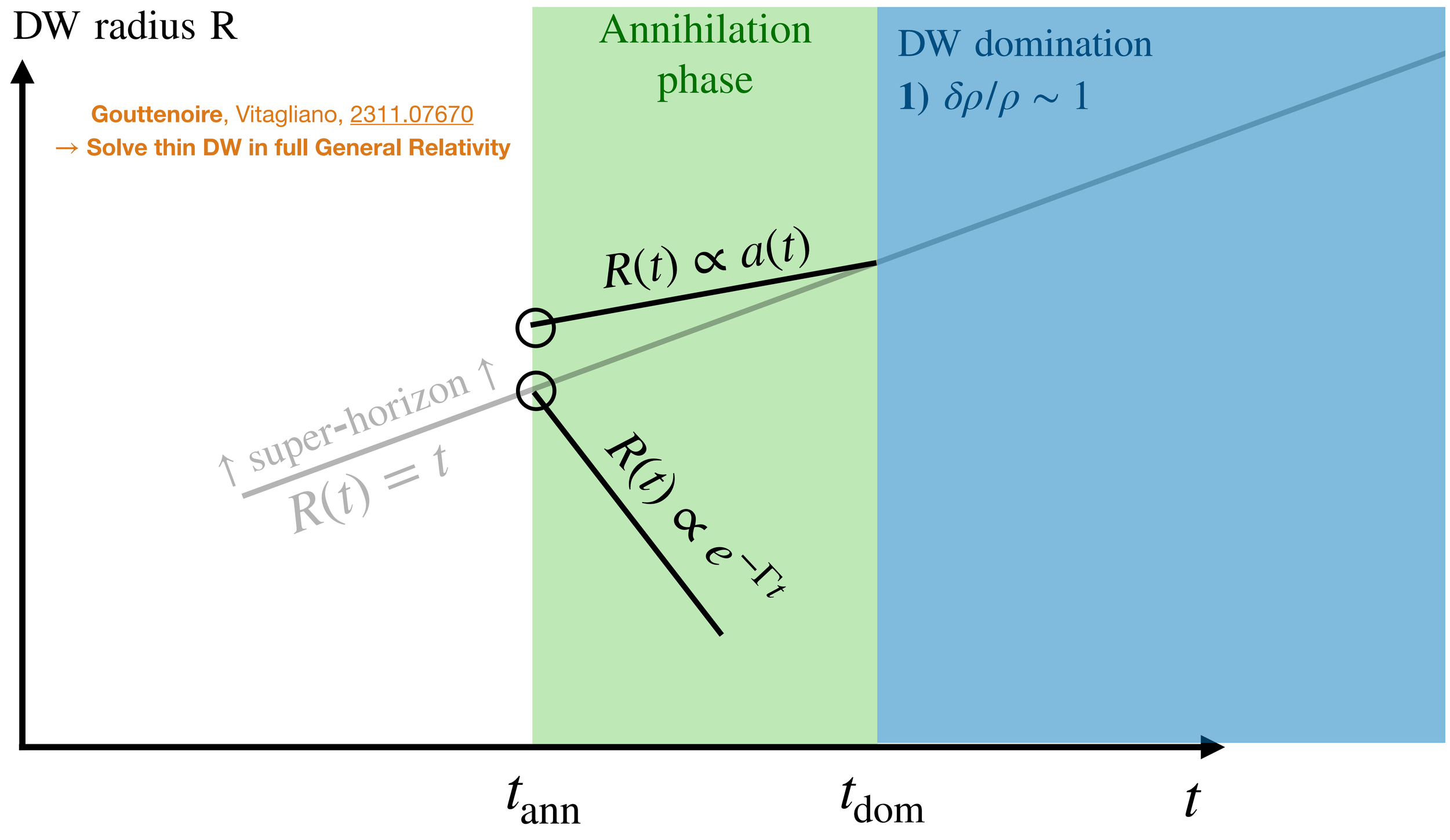
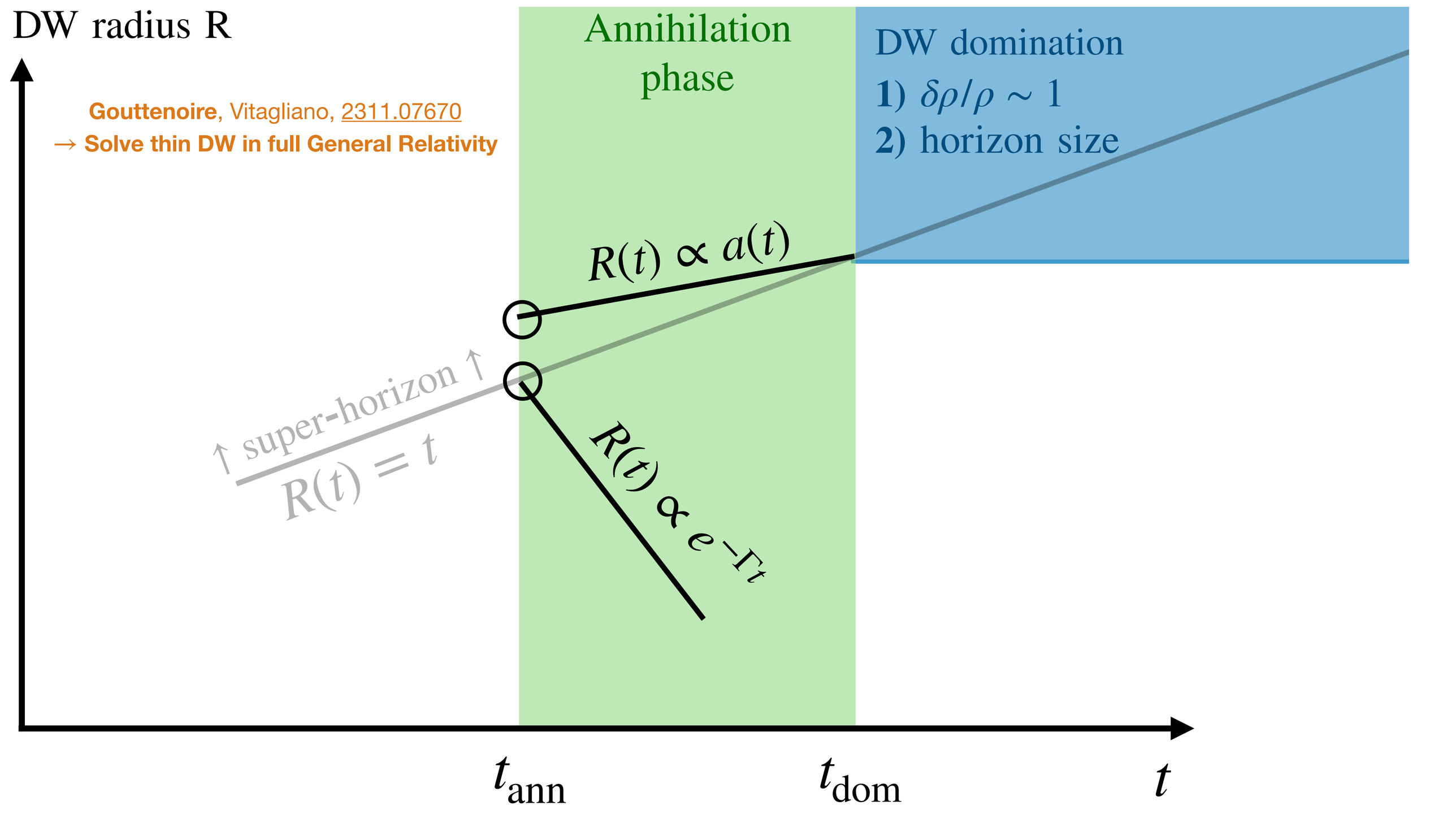
t

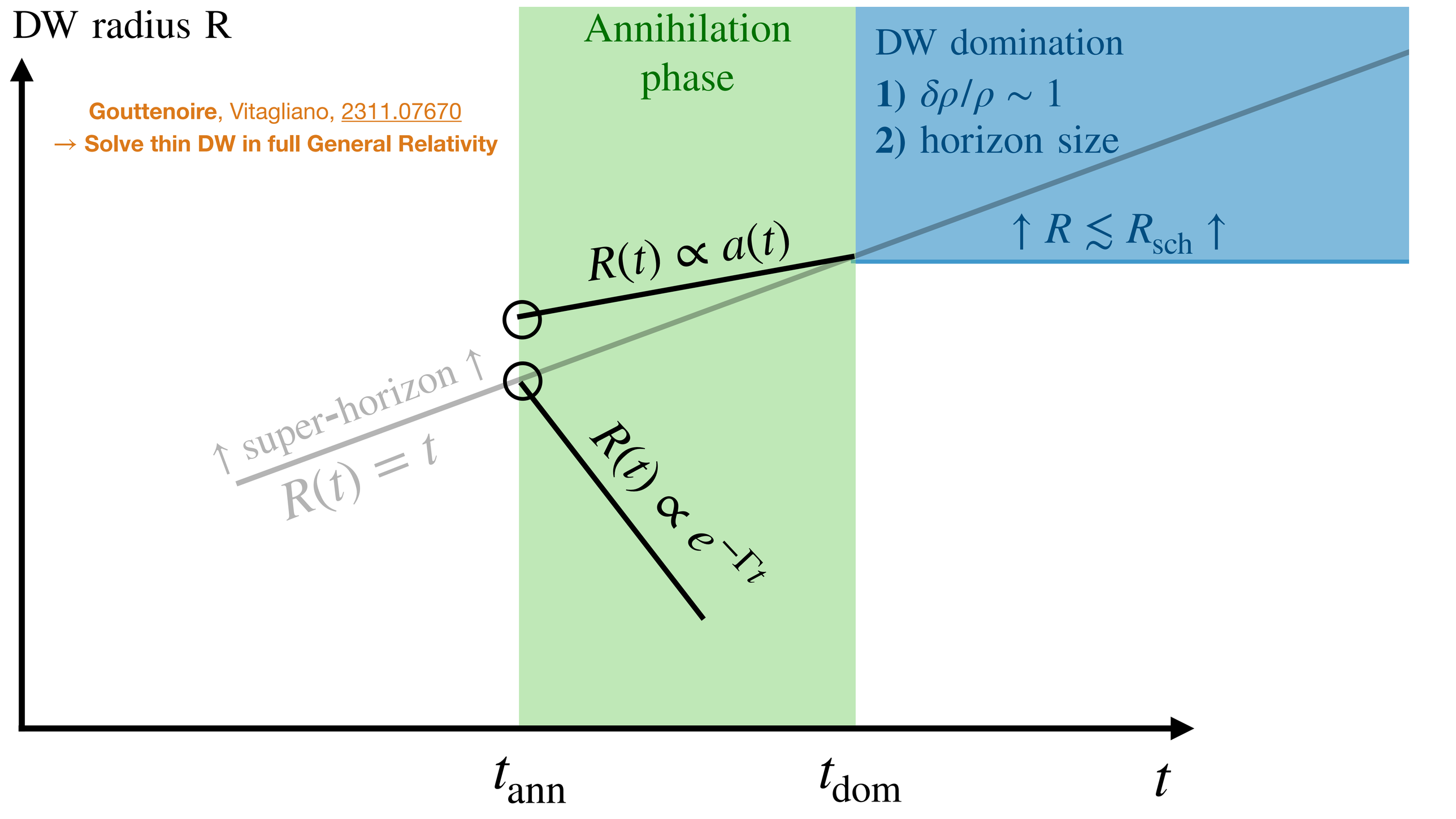

DW radius R
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
$R(t) \propto a(t)$
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
t

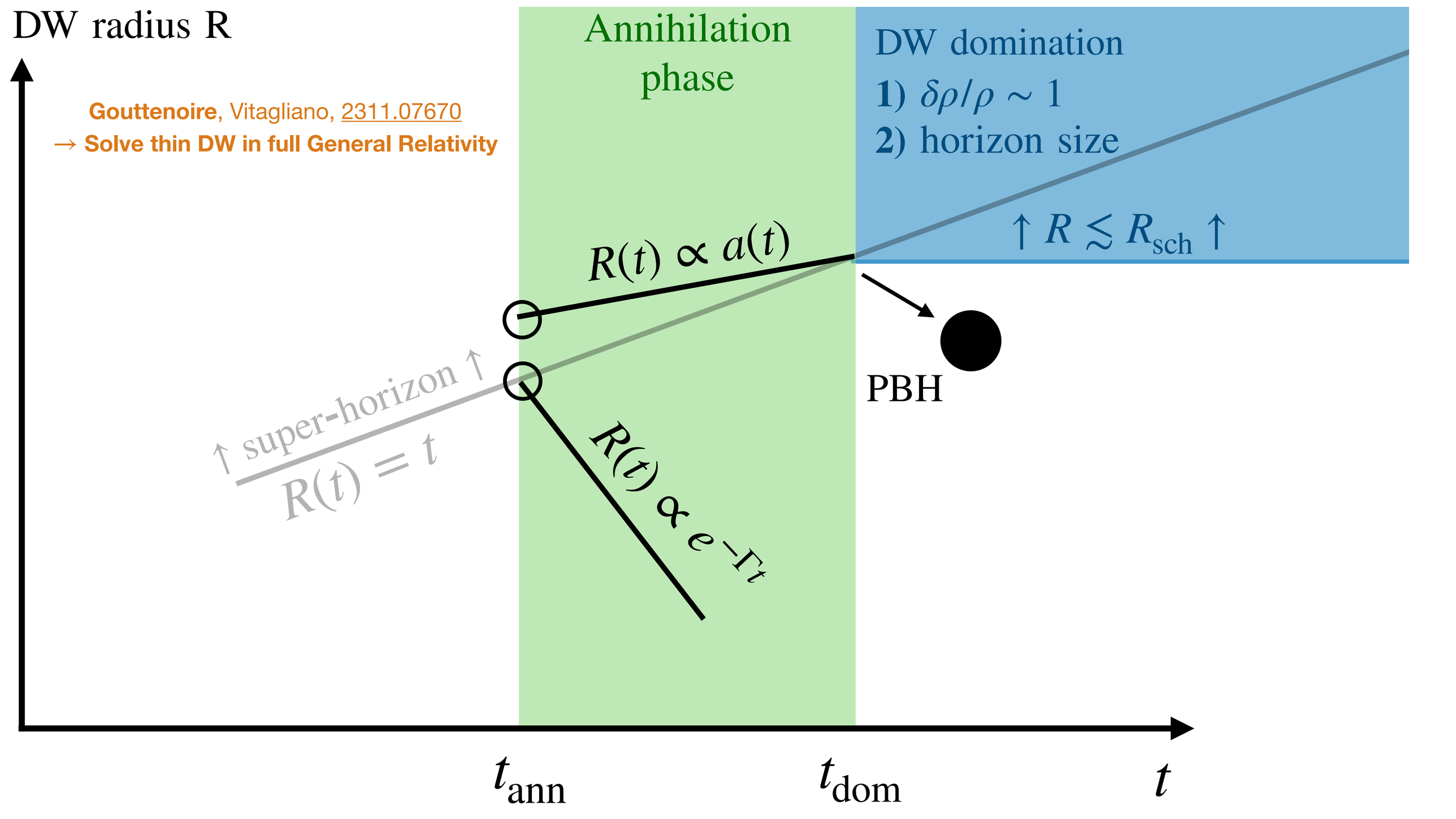

DW radius R
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
$\langle R(t) \rangle \simeq t$ but not R(t) ≃ t
$R(t) \propto a(t)$
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
t

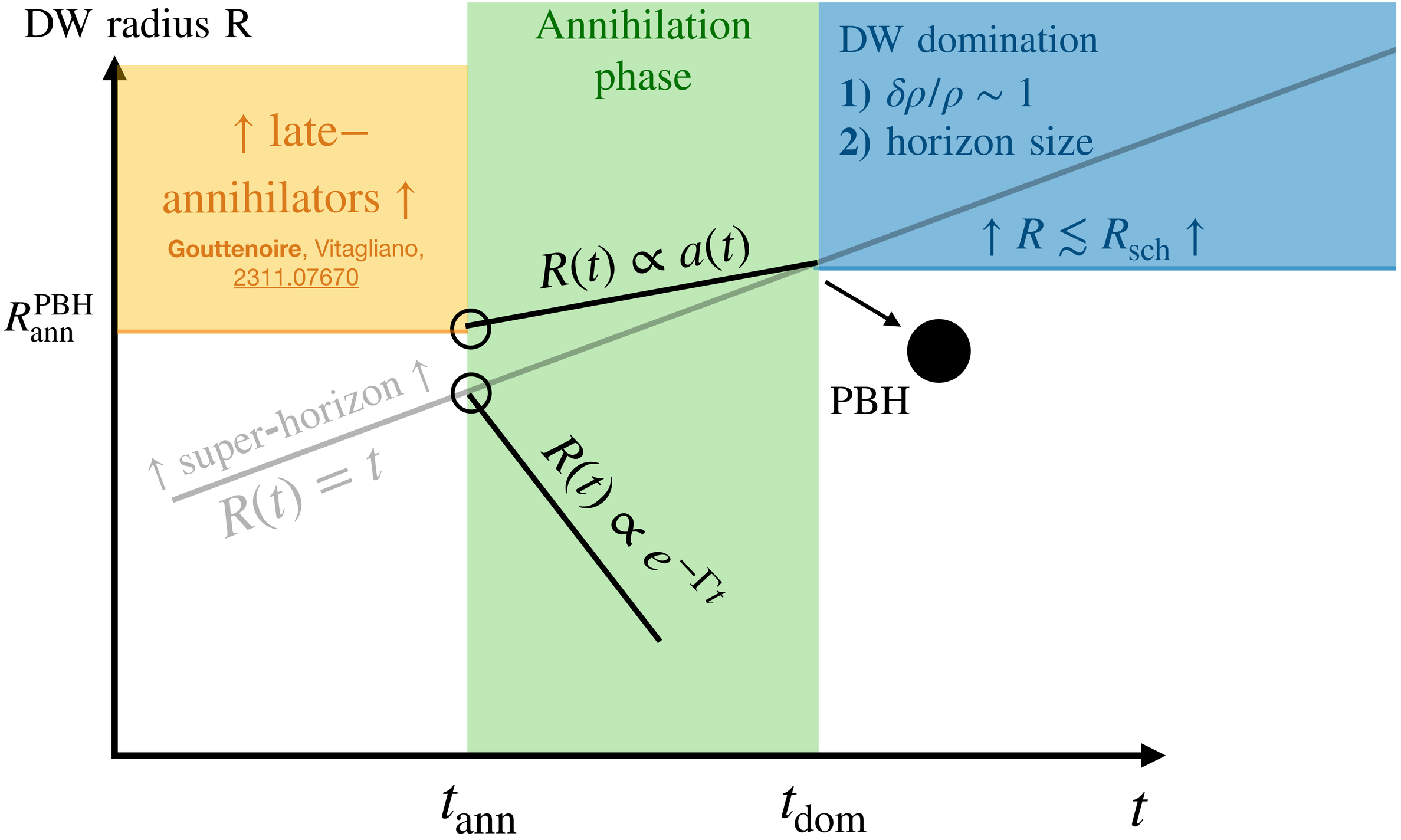

DW radius R
Annihilation phase
DW domination
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
$R(t) \propto a(t)$
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
$t_{\rm ann}$
$t_{\rm dom}$
t


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

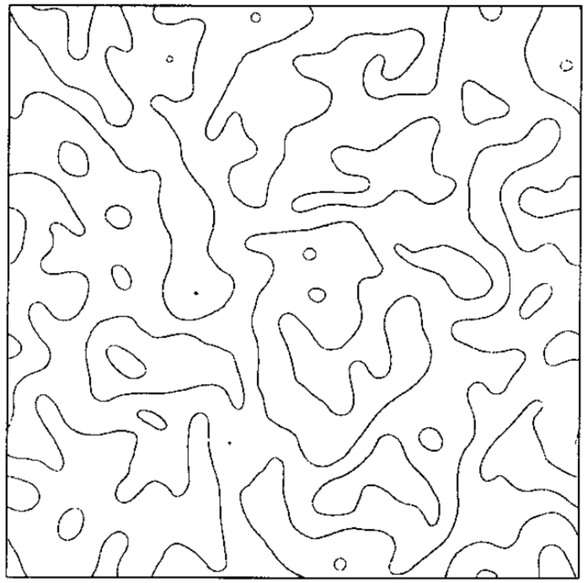

DW radius R
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
Annihilation phase
DW domination
1) $\delta\rho/\rho \sim 1$
2) horizon size
$R(t) \propto a(t)$
↑ super-horizon ↑
$R(t) = t$
$R(t) \propto e^{-\Gamma t}$
$t_{\rm ann}$
$t_{\rm dom}$
t


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

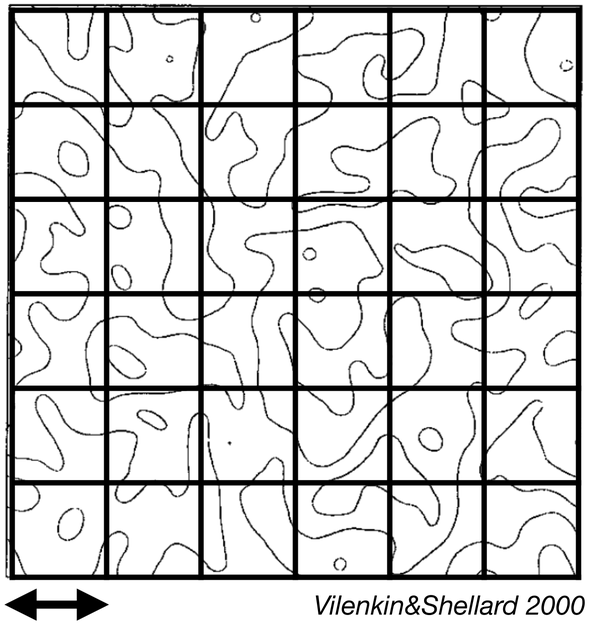

DW radius R
Gouttenoire, Vitagliano, 2311.07670
→ Solve thin DW in full General Relativity
Annihilation phase
DW domination
1) $\delta\rho/\rho \sim 1$
2) horizon size
$\uparrow R \lesssim R_{\rm sch} \uparrow$
$R(t) \propto a(t)$
PBH
$\uparrow$ super-horizon $\uparrow$
$R(t) = t$
$R(t) \propto e^{-\Gamma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

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



Vilenkin&Shellard 2000



Vilenkin&Shellard 2000

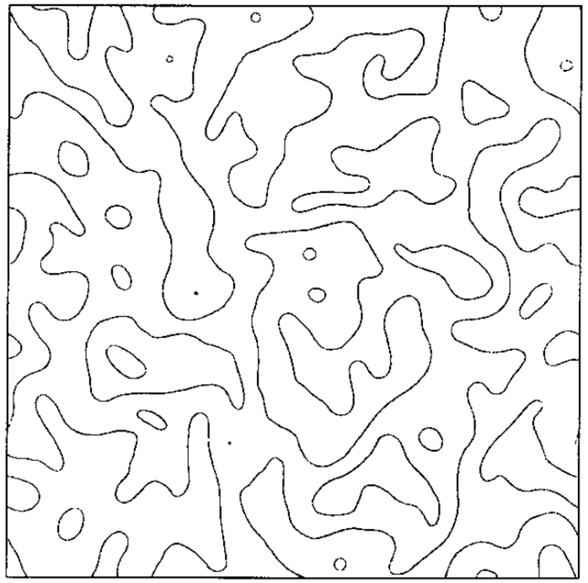
$L \sim t$

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

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

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

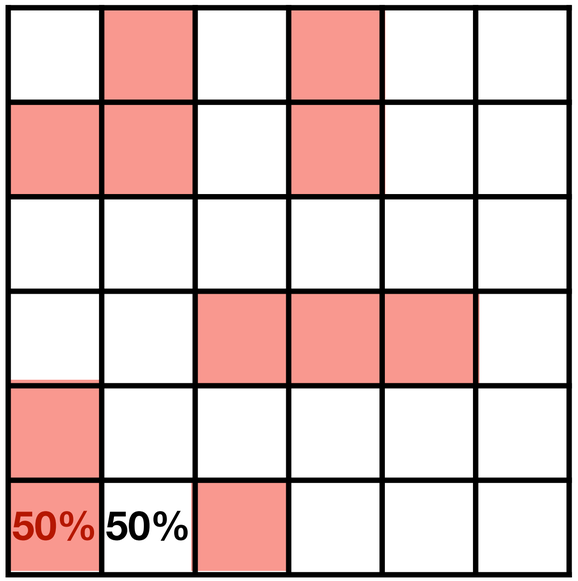
Percolation theory on a lattice *Stauffer (1979)* *Coulson, Lalak, Ovrut (1995)*

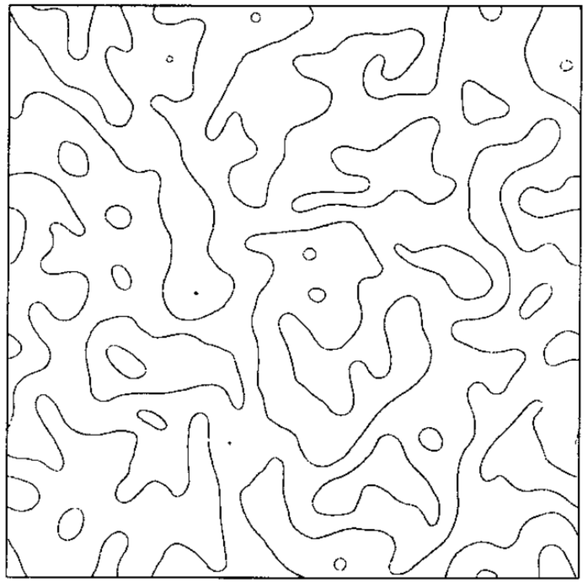


Vilenkin&Shellard 2000

$L \sim t$

Discretization

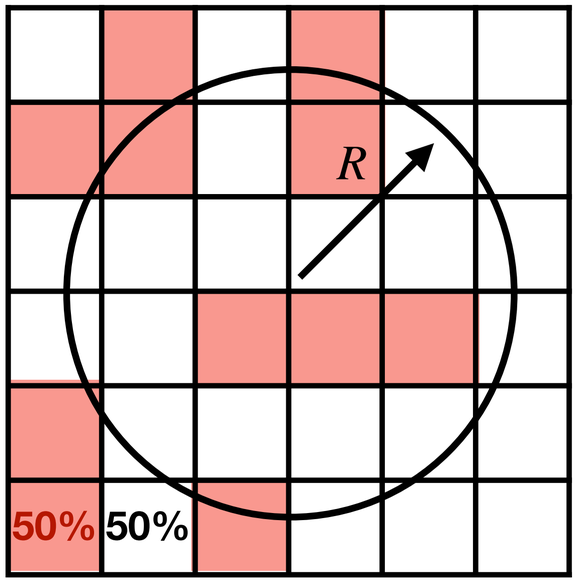




Vilenkin&Shellard 2000

$L \sim t$

Discretization

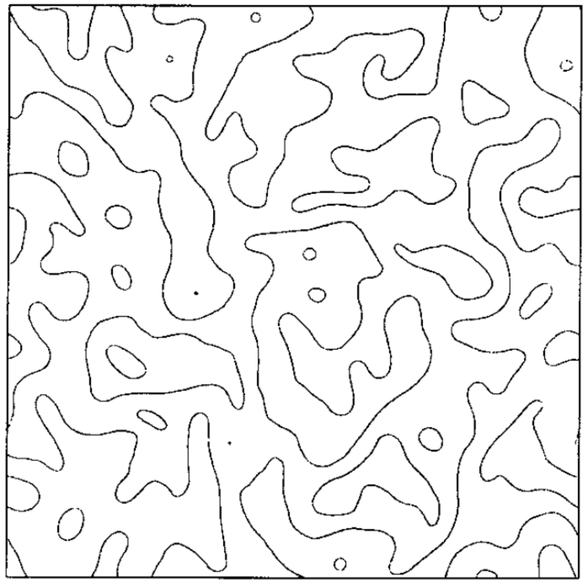


Abundance of late-annihilators $\mathcal{F}$

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

Probability of a spherical false vacuum domain of size R:

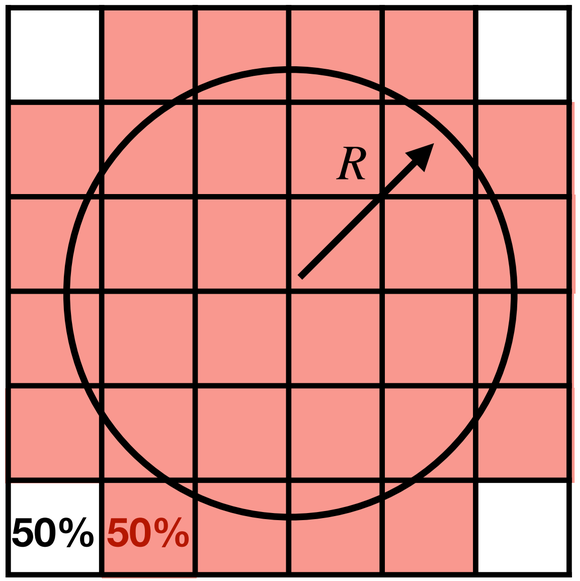
Abundance of late-annihilators $\mathcal{F}$



Vilenkin&Shellard 2000

$L \sim t$

Discretization



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

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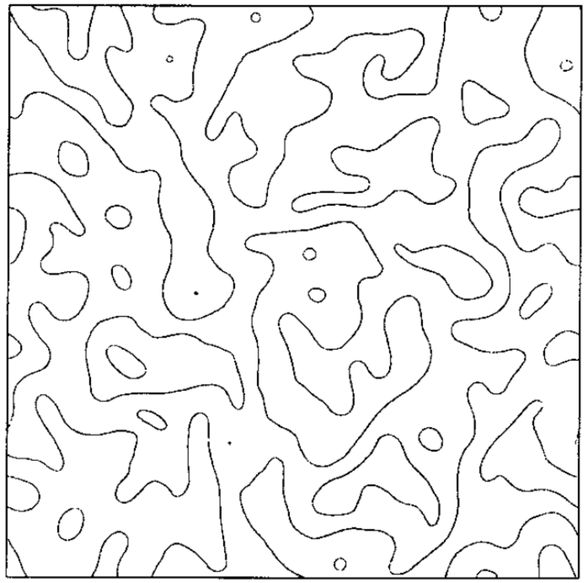
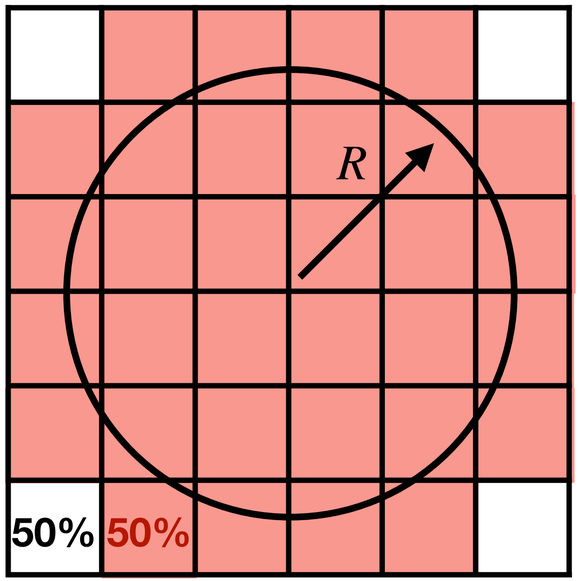


Vilenkin&Shellard 2000

$L \sim t$

Discretization

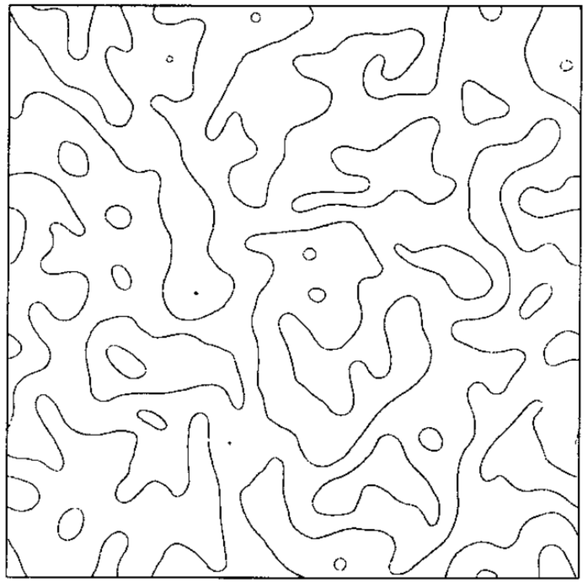


Percolation theory on a lattice *Stauffer (1979)* *Coulson, Lalak, Ovrut (1995)*

Probability of a spherical false vacuum domain of size R:

$$\mathcal{F}(R) \simeq (50\%)^{\text{number of sites}}$$

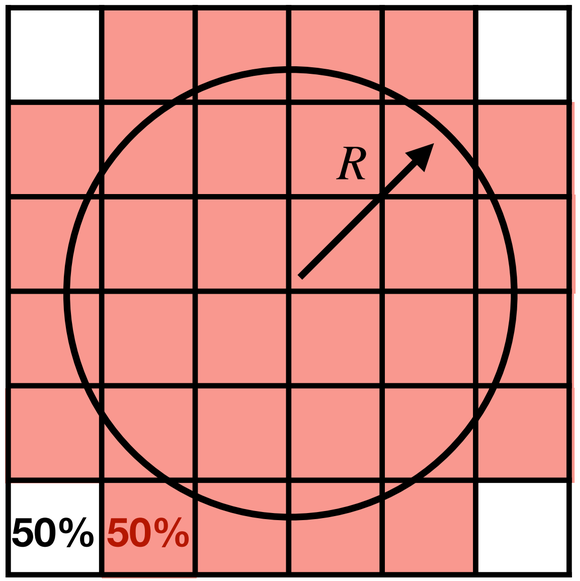
Abundance of late-annihilators $\mathcal{F}$



Vilenkin&Shellard 2000

$L \sim t$

Discretization

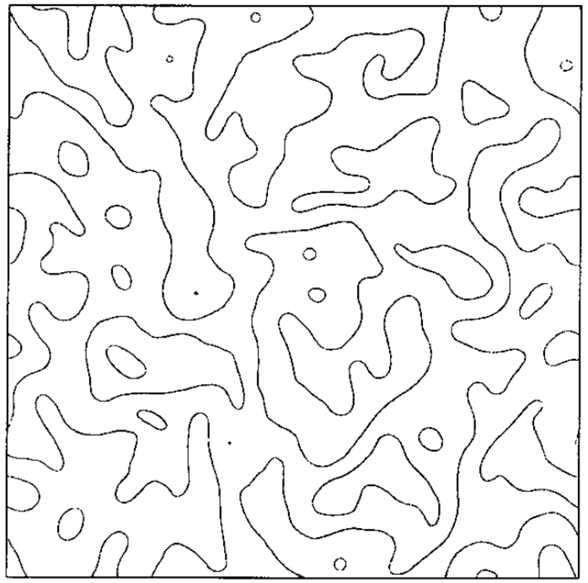


Percolation theory on a lattice *Stauffer (1979)* *Coulson, Lalak, Ovrut (1995)*

Probability of a spherical false vacuum domain of size R:

$$\mathcal{F}(R) \simeq (50\%)^{\text{number of sites}} \simeq 0.5^{\frac{4\pi}{3}\left(\frac{R}{L}\right)^3}$$

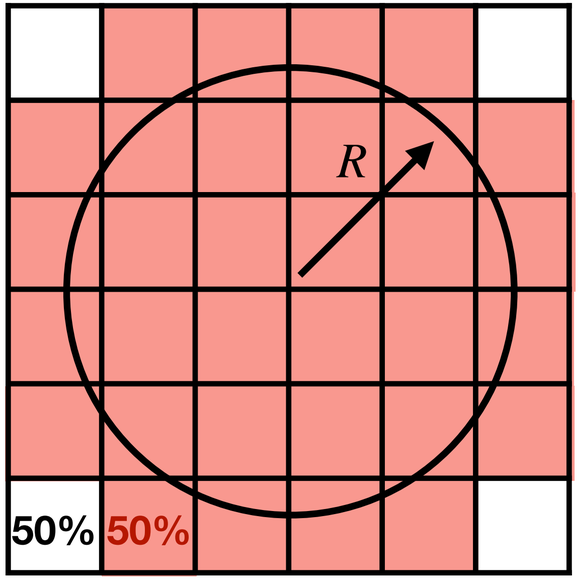
Abundance of late-annihilators $\mathscr{F}$



Vilenkin&Shellard 2000

$L \sim t$

Discretization



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

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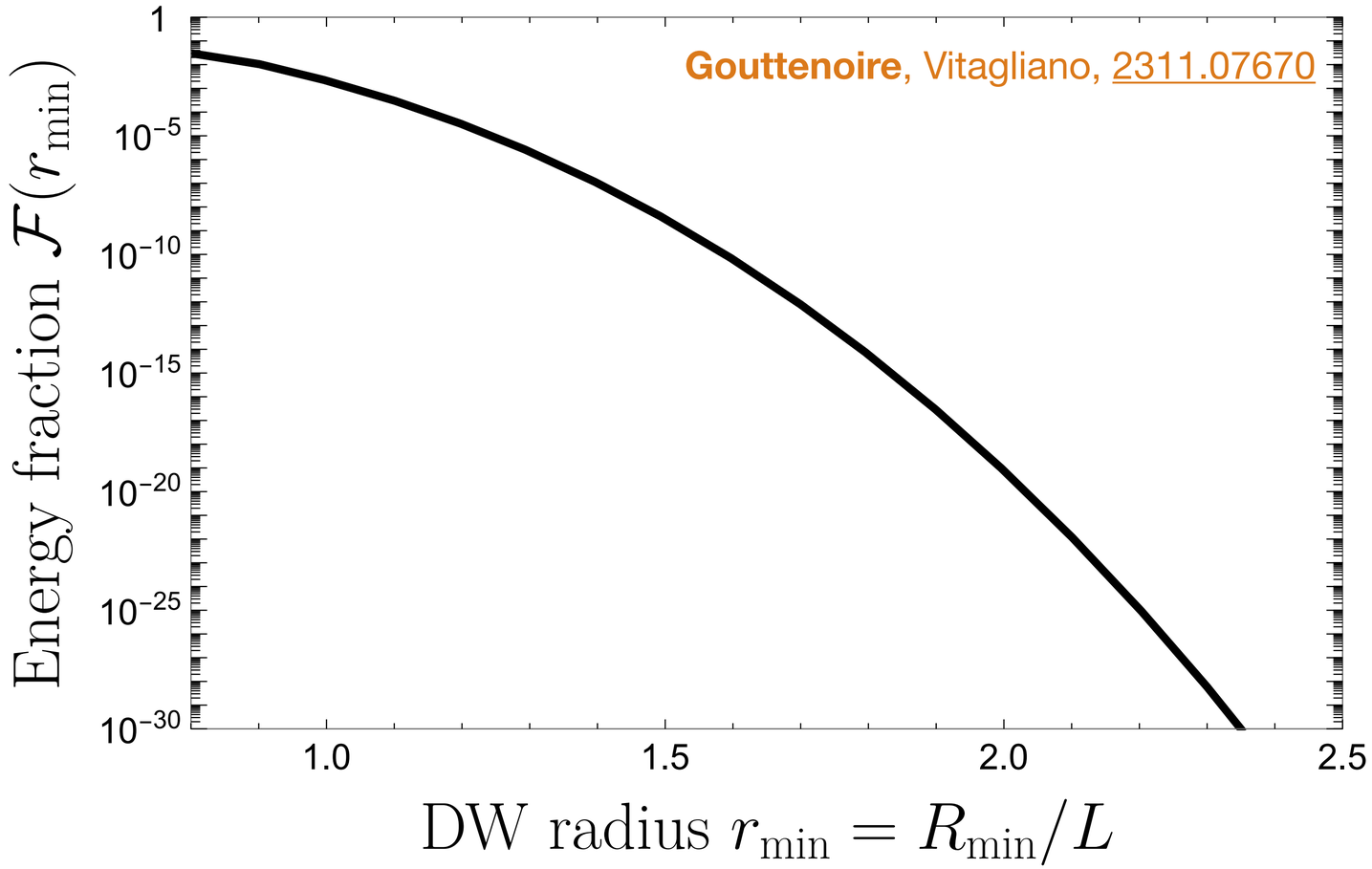
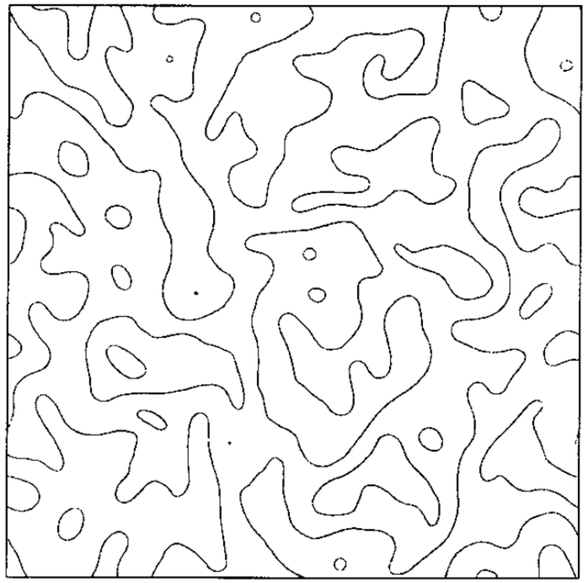


Abundance of late-annihilators $\mathscr{F}$



Vilenkin&Shellard 2000

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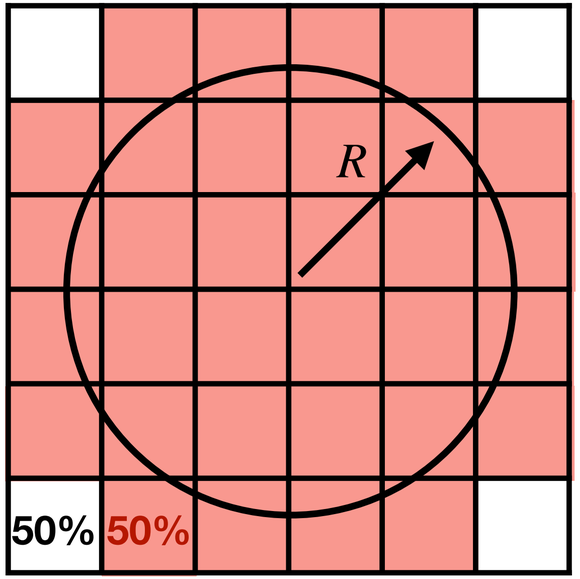
Discretization



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

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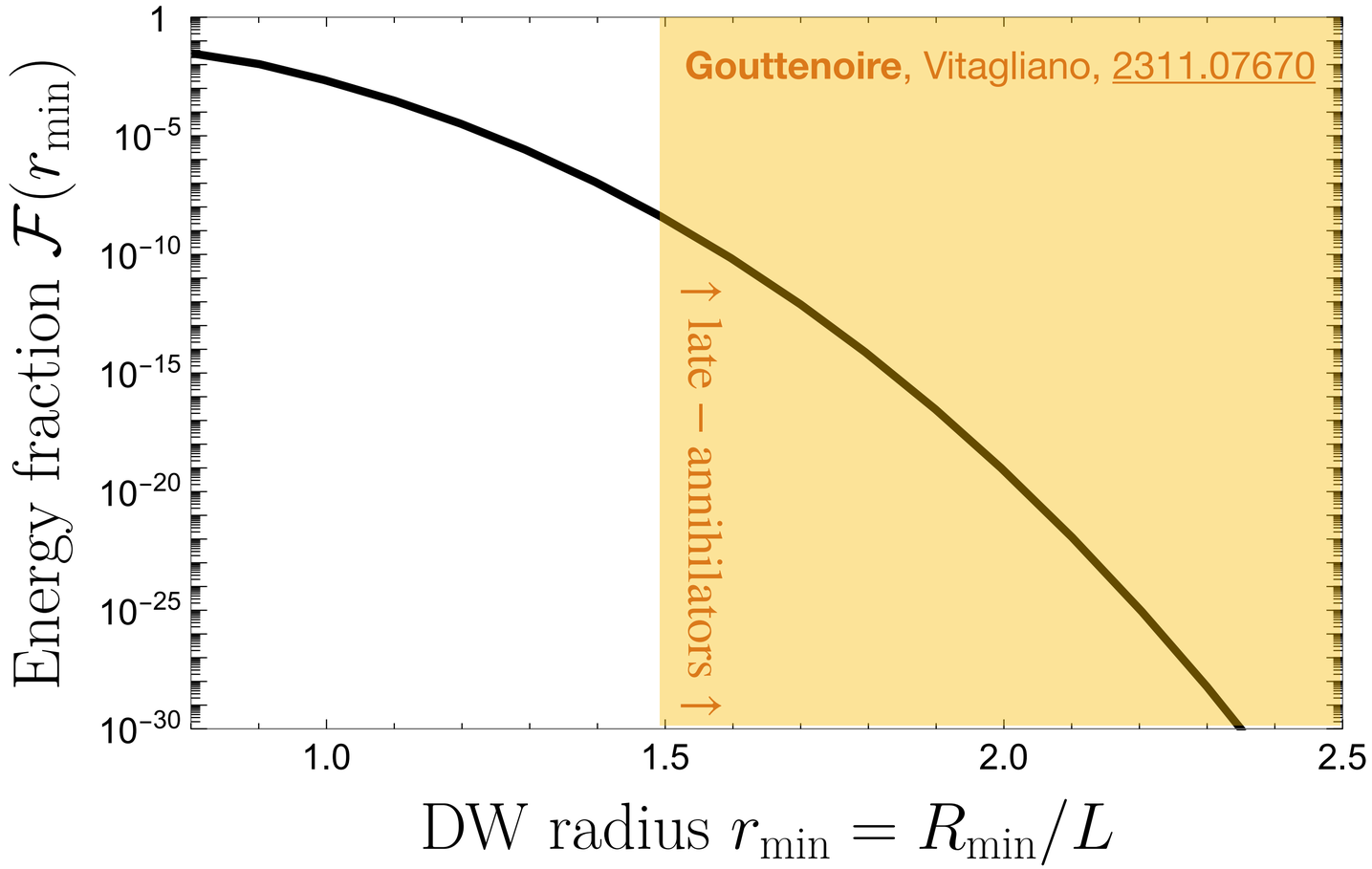
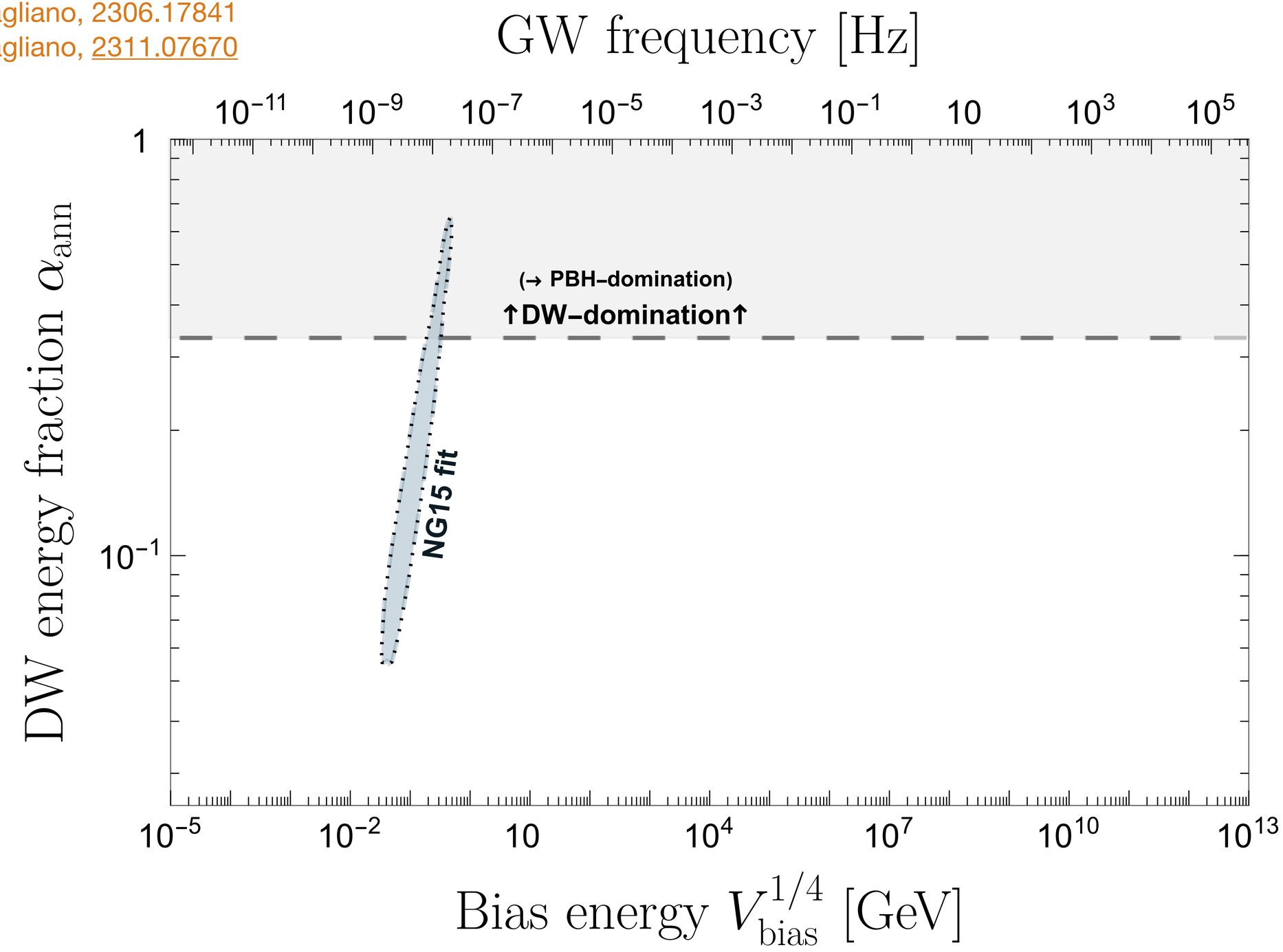


Gouttenoire, Vitagliano, 2306.17841
Gouttenoire, Vitagliano, 2311.07670



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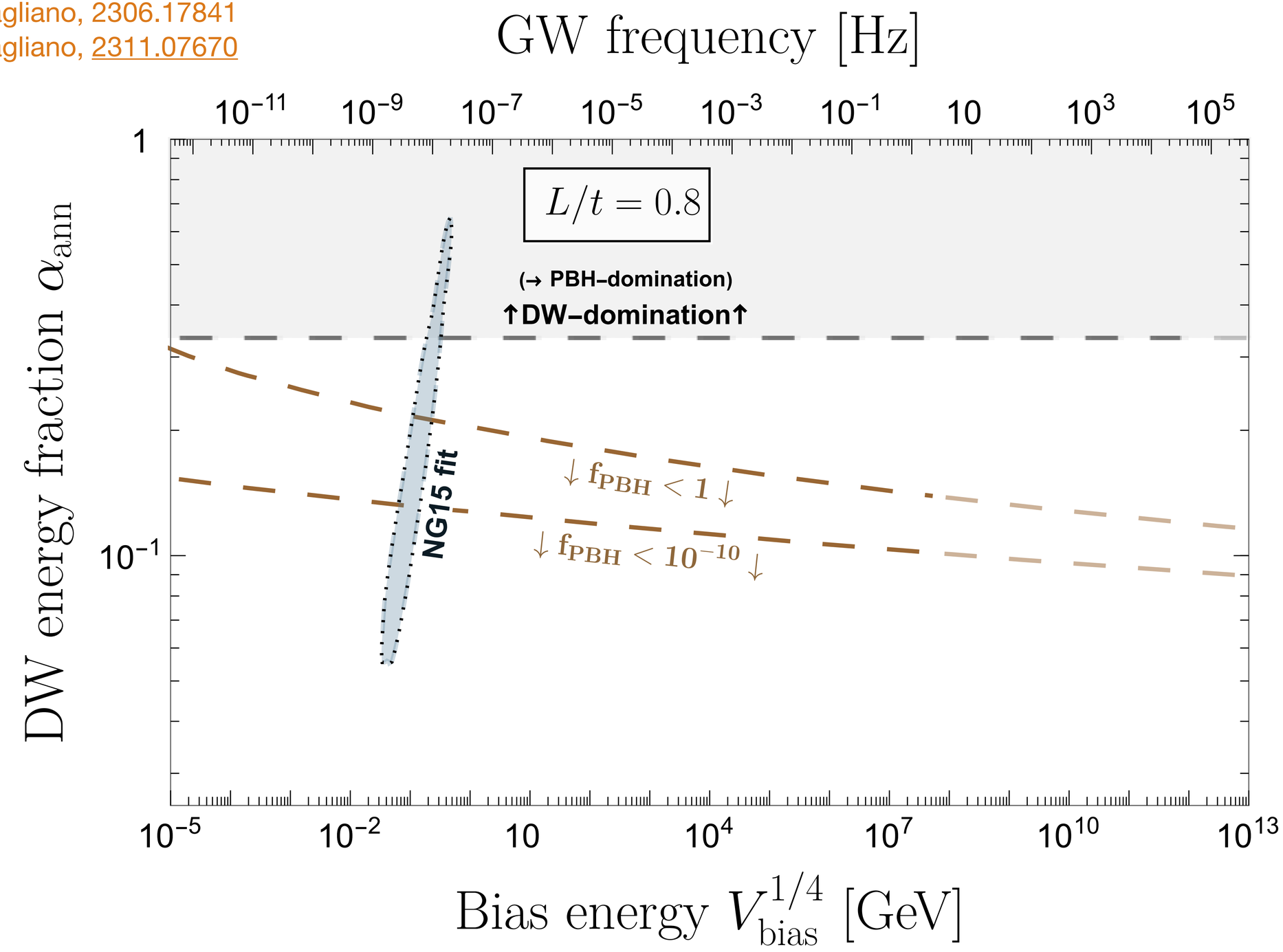

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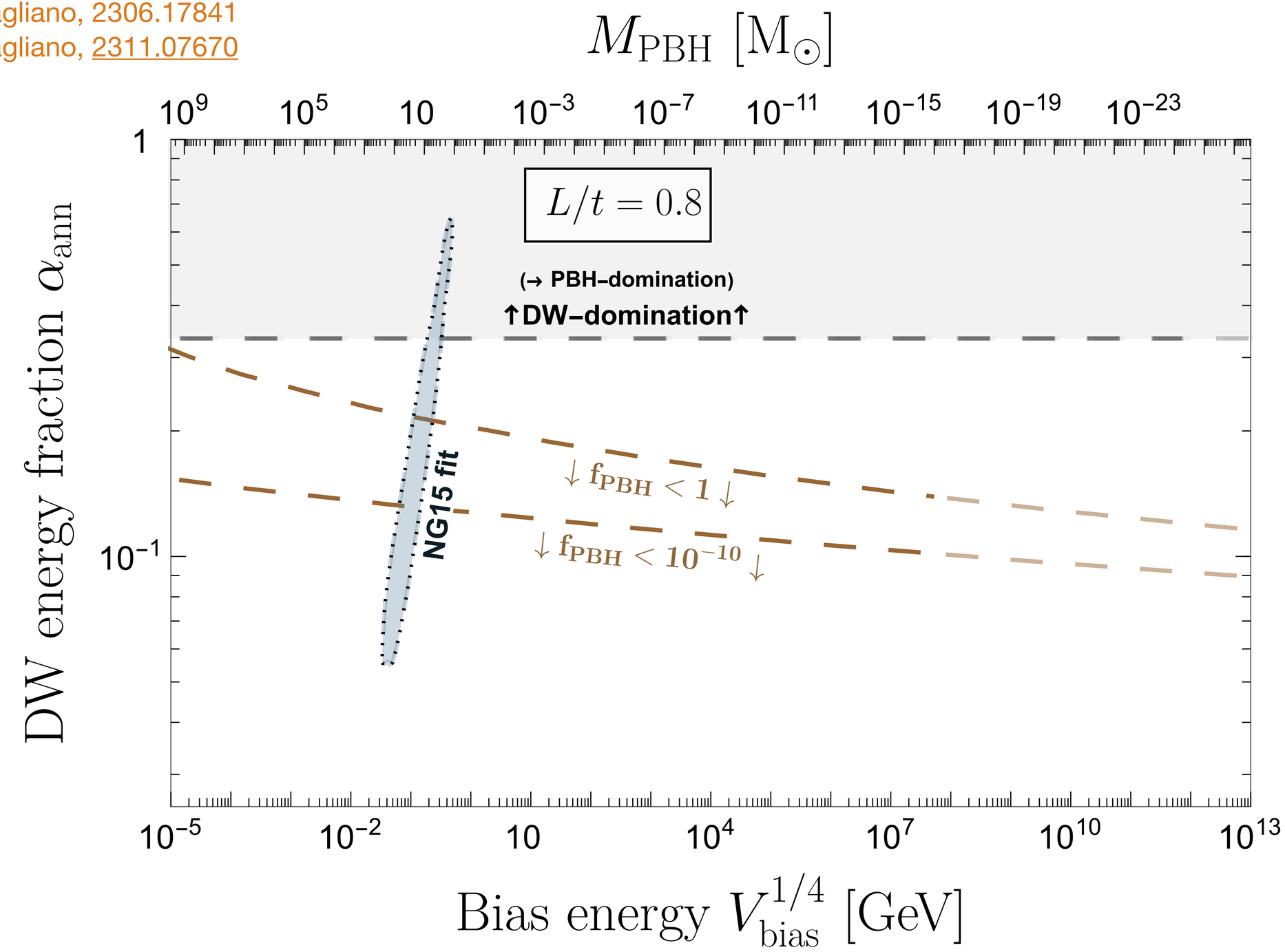

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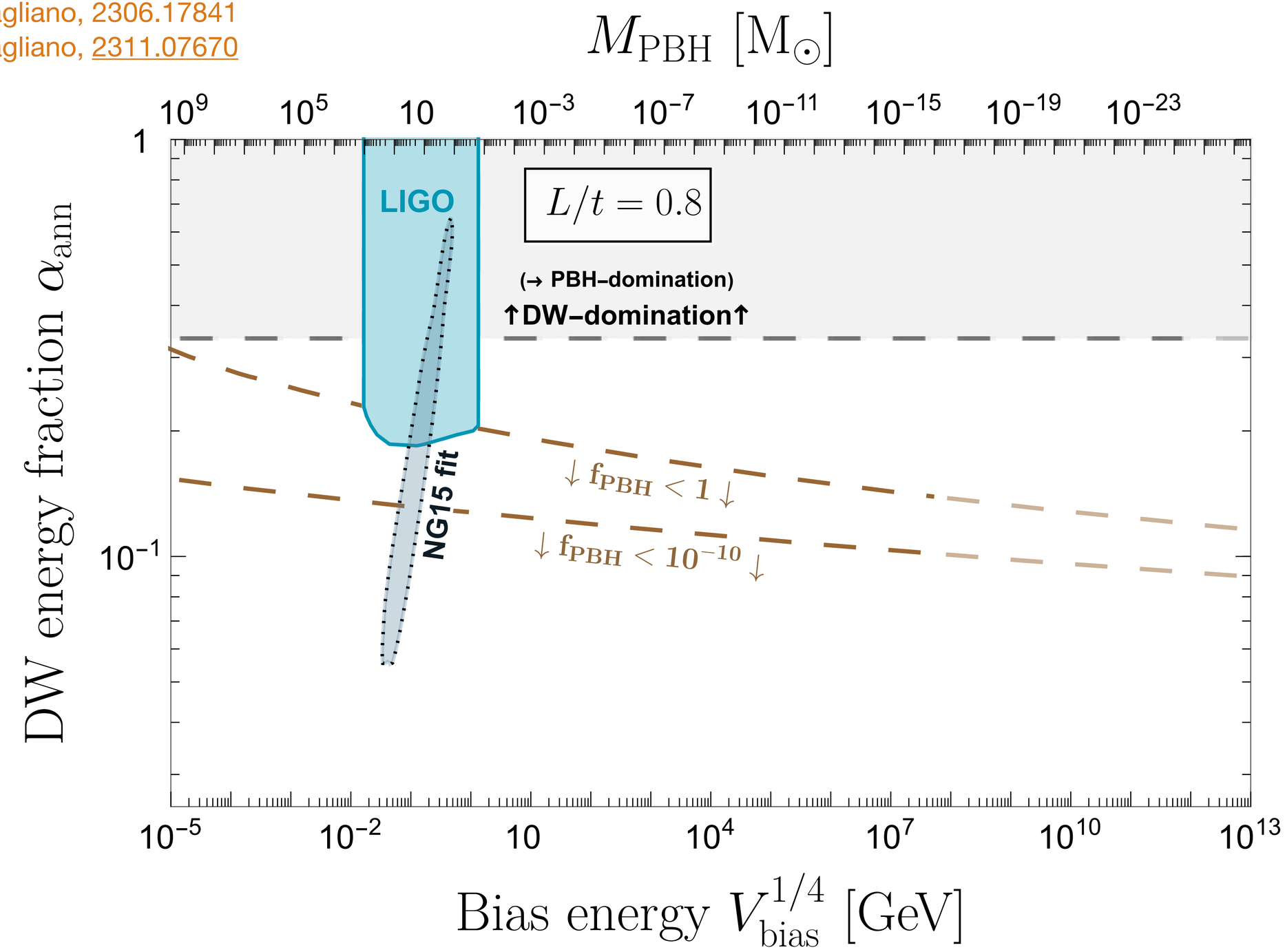

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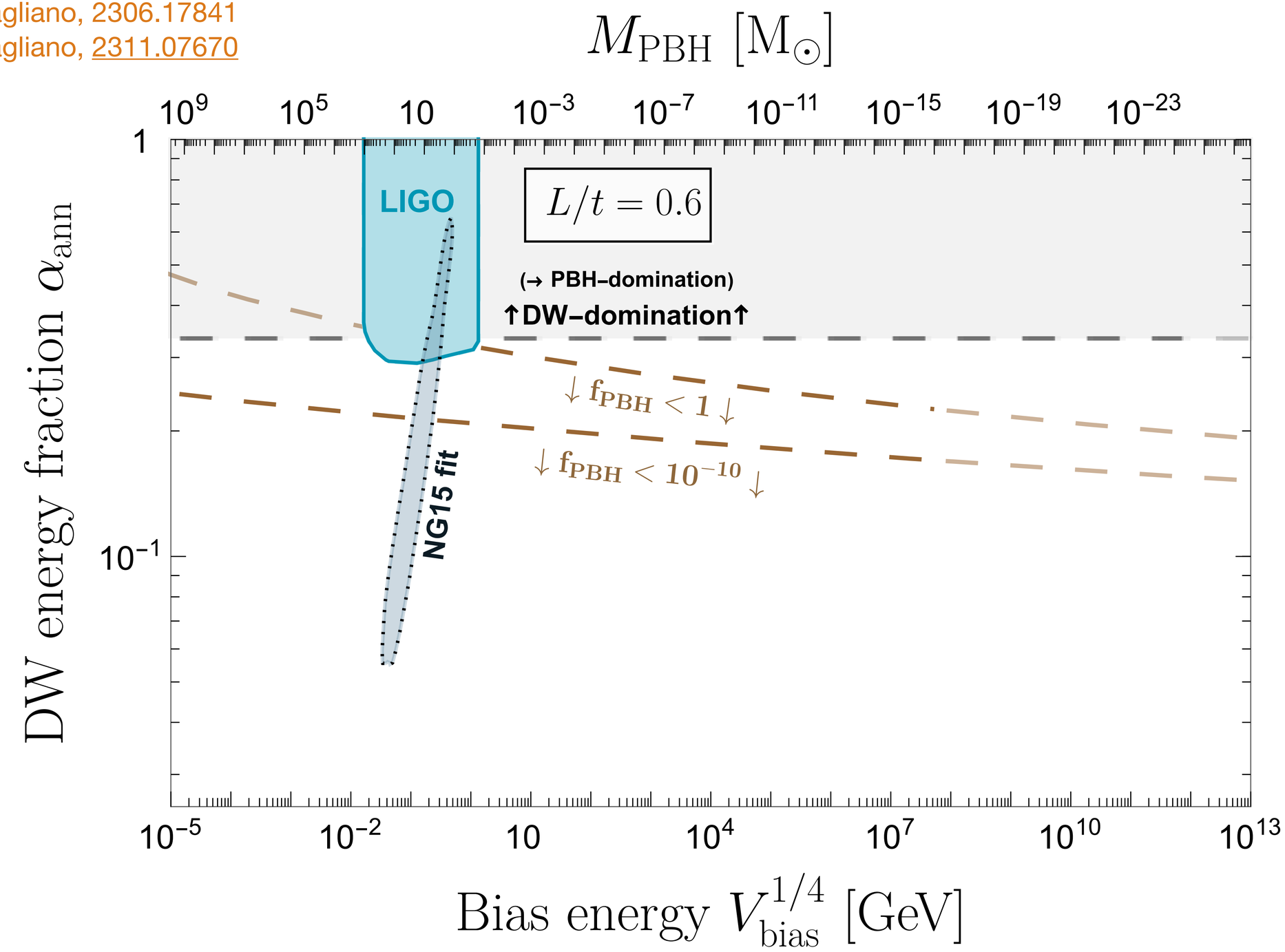

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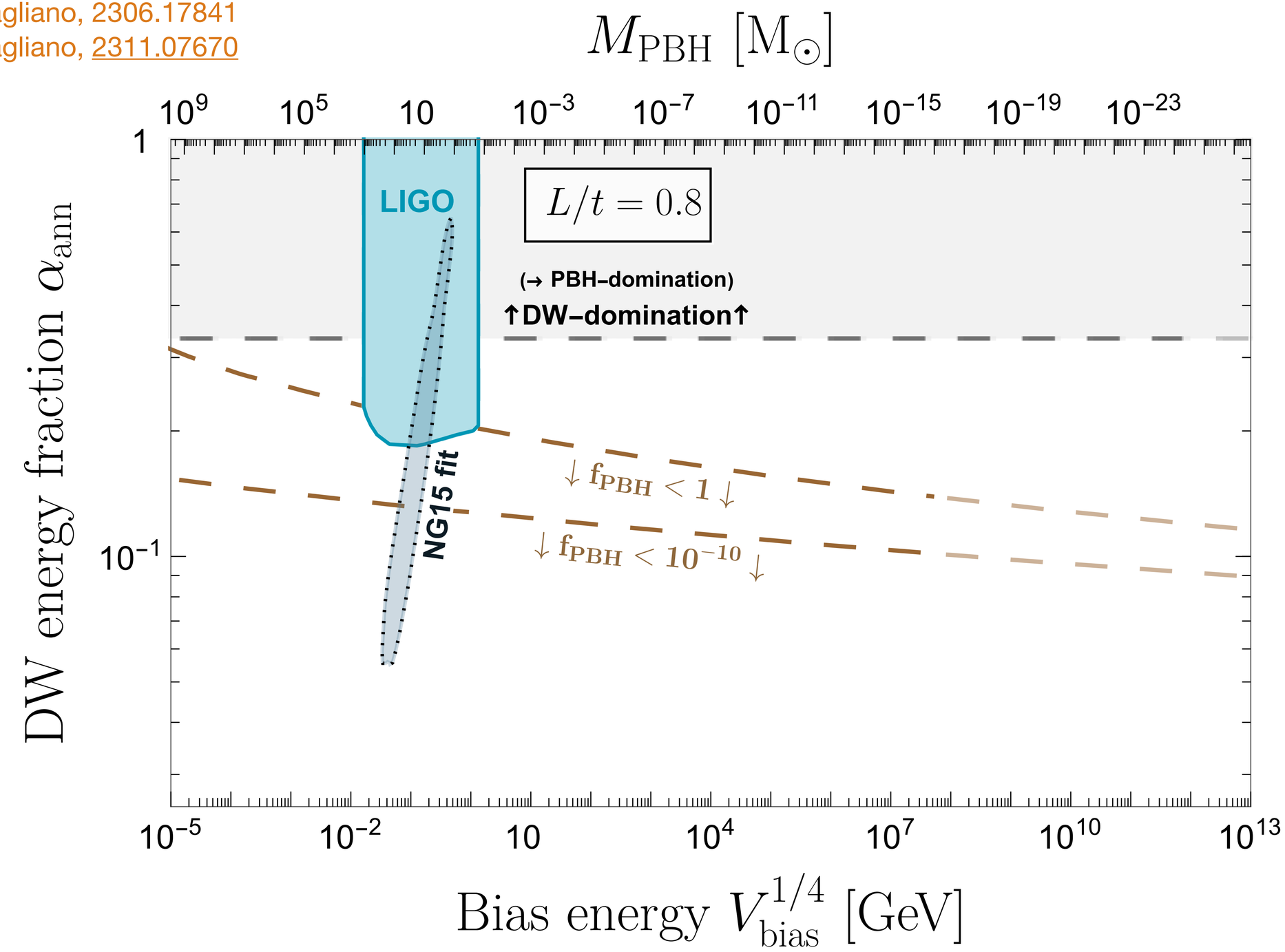

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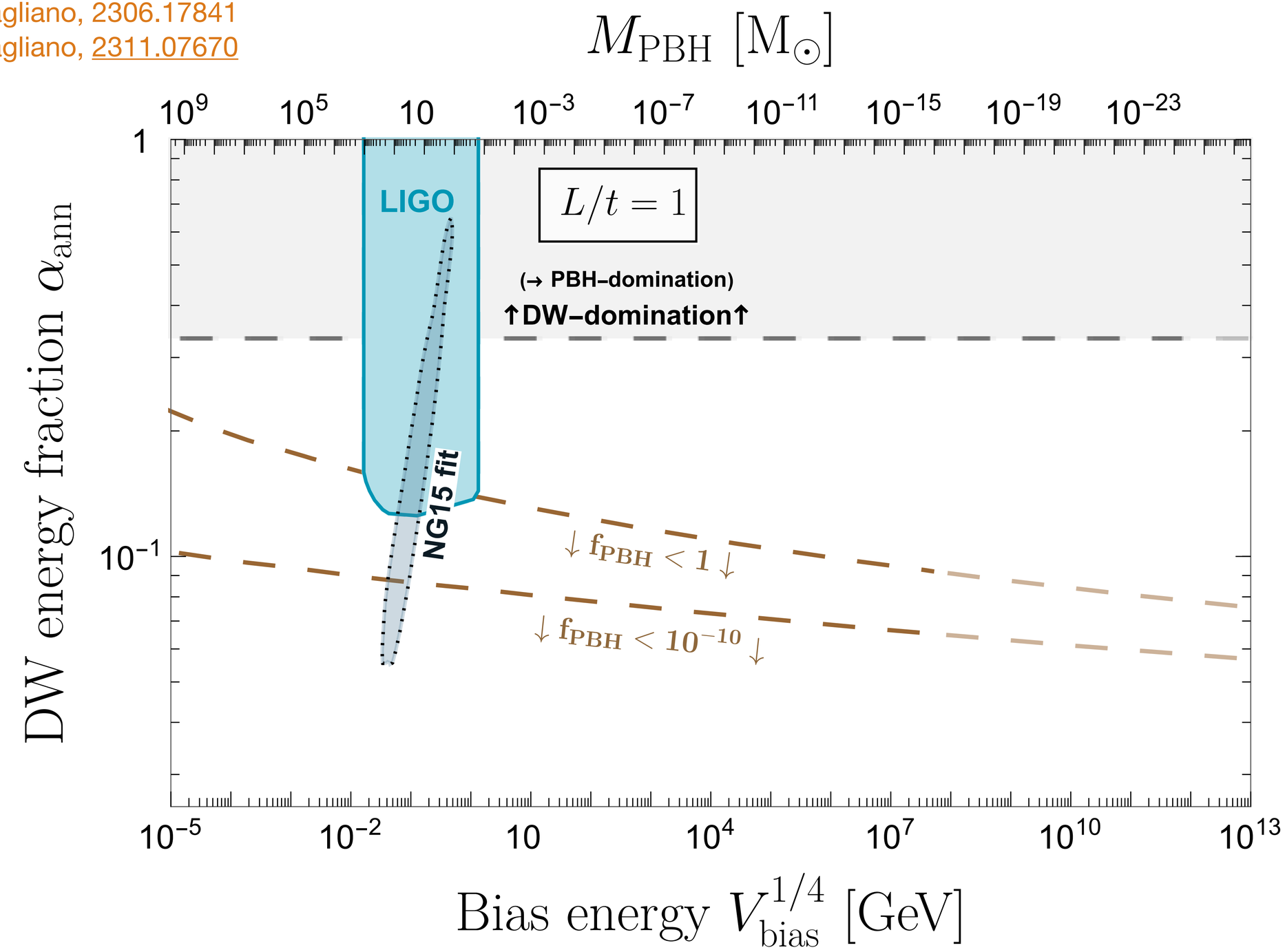

Gouttenoire, Vitagliano, 2306.17841
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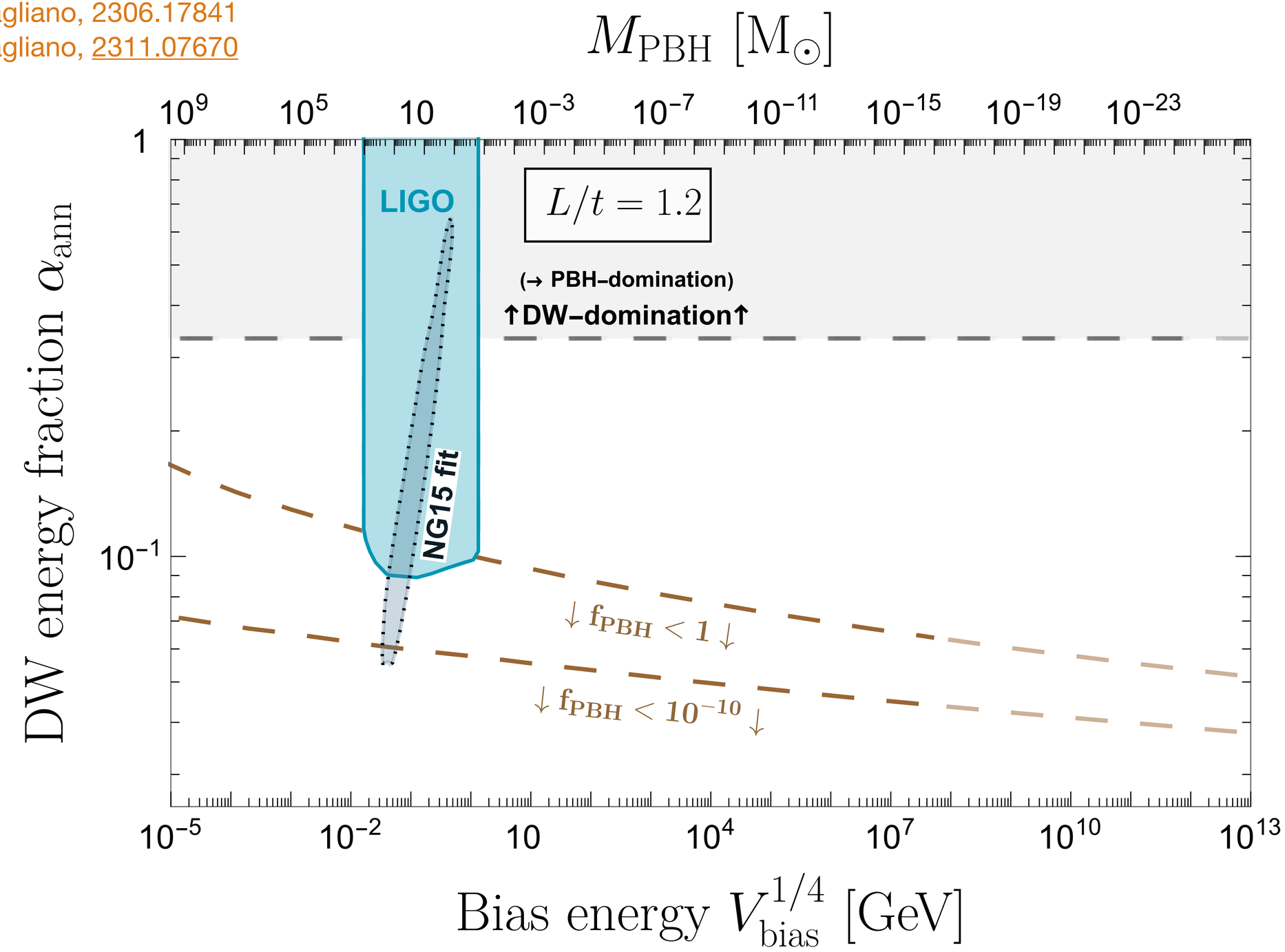

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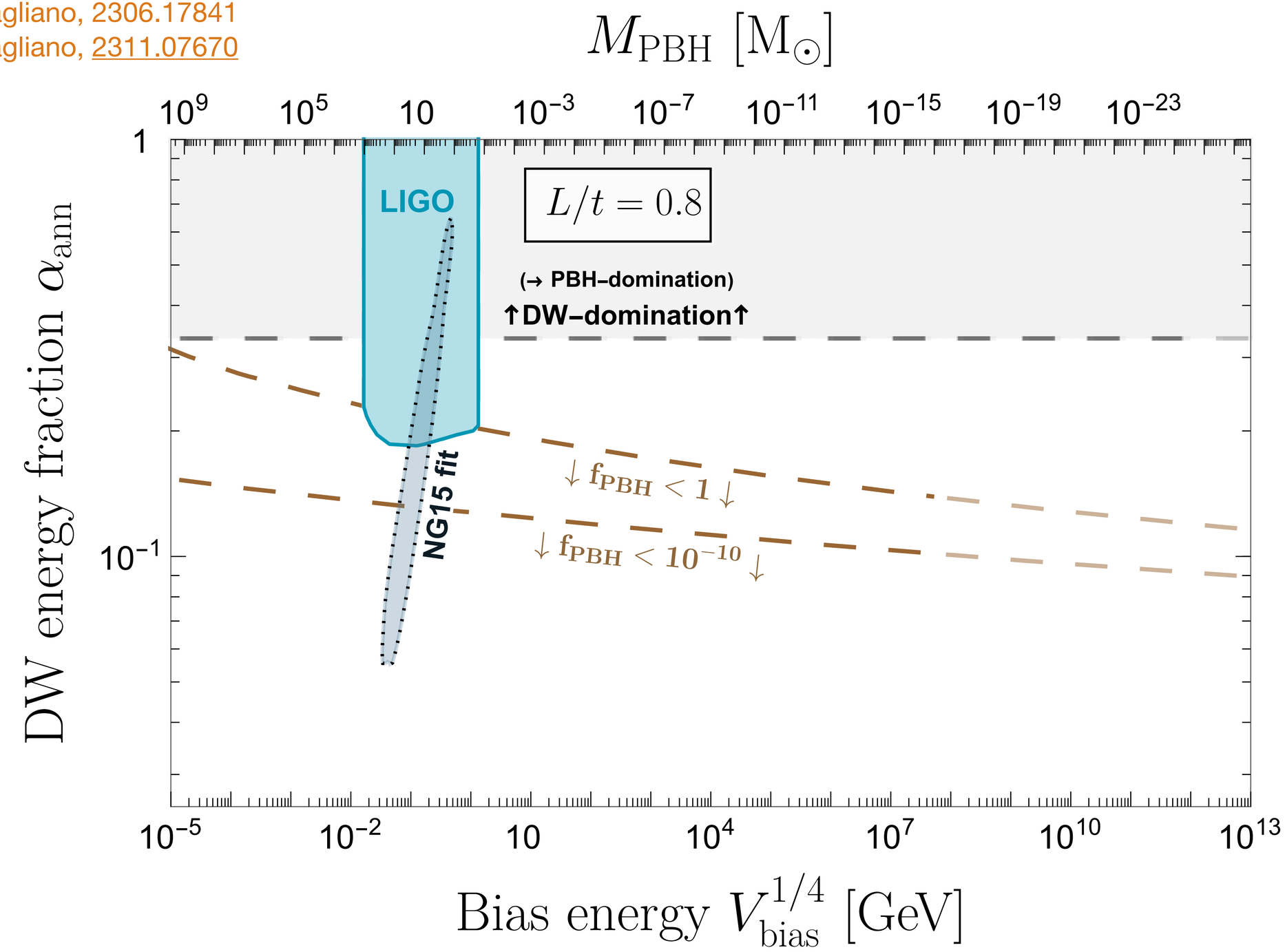

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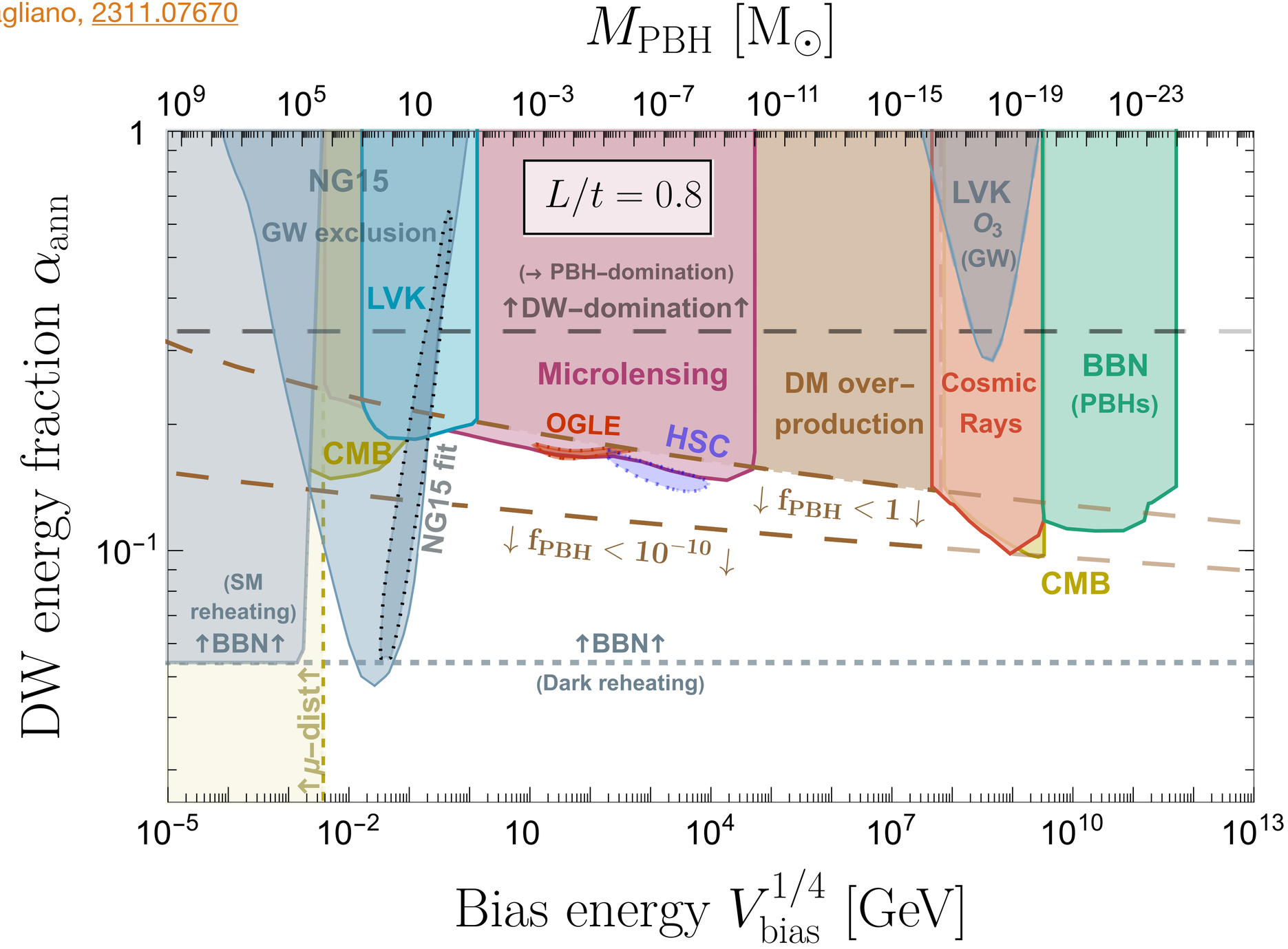

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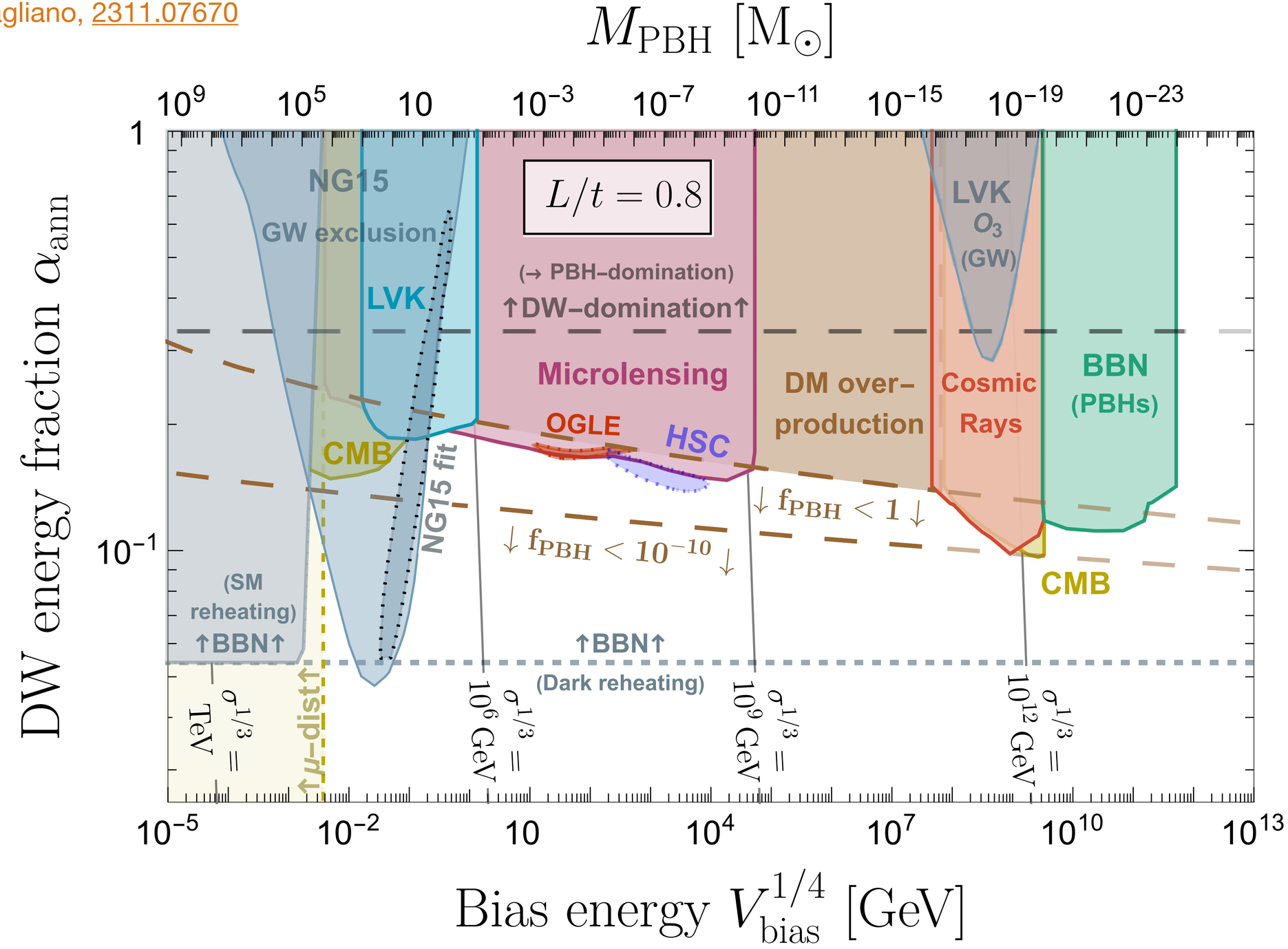
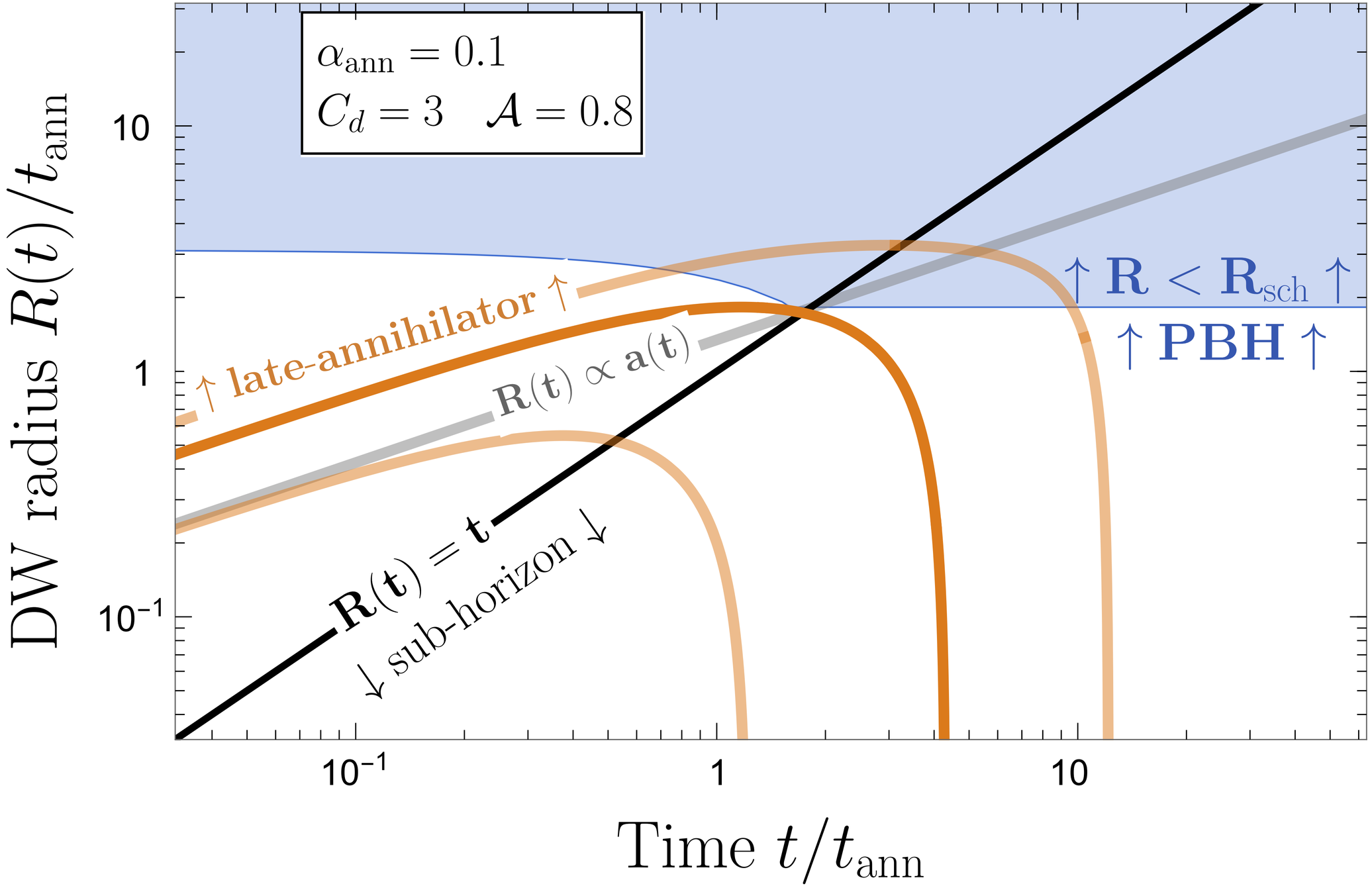


Wormholes to baby-universe

Gouttenoire, Vitagliano, 2311.07670



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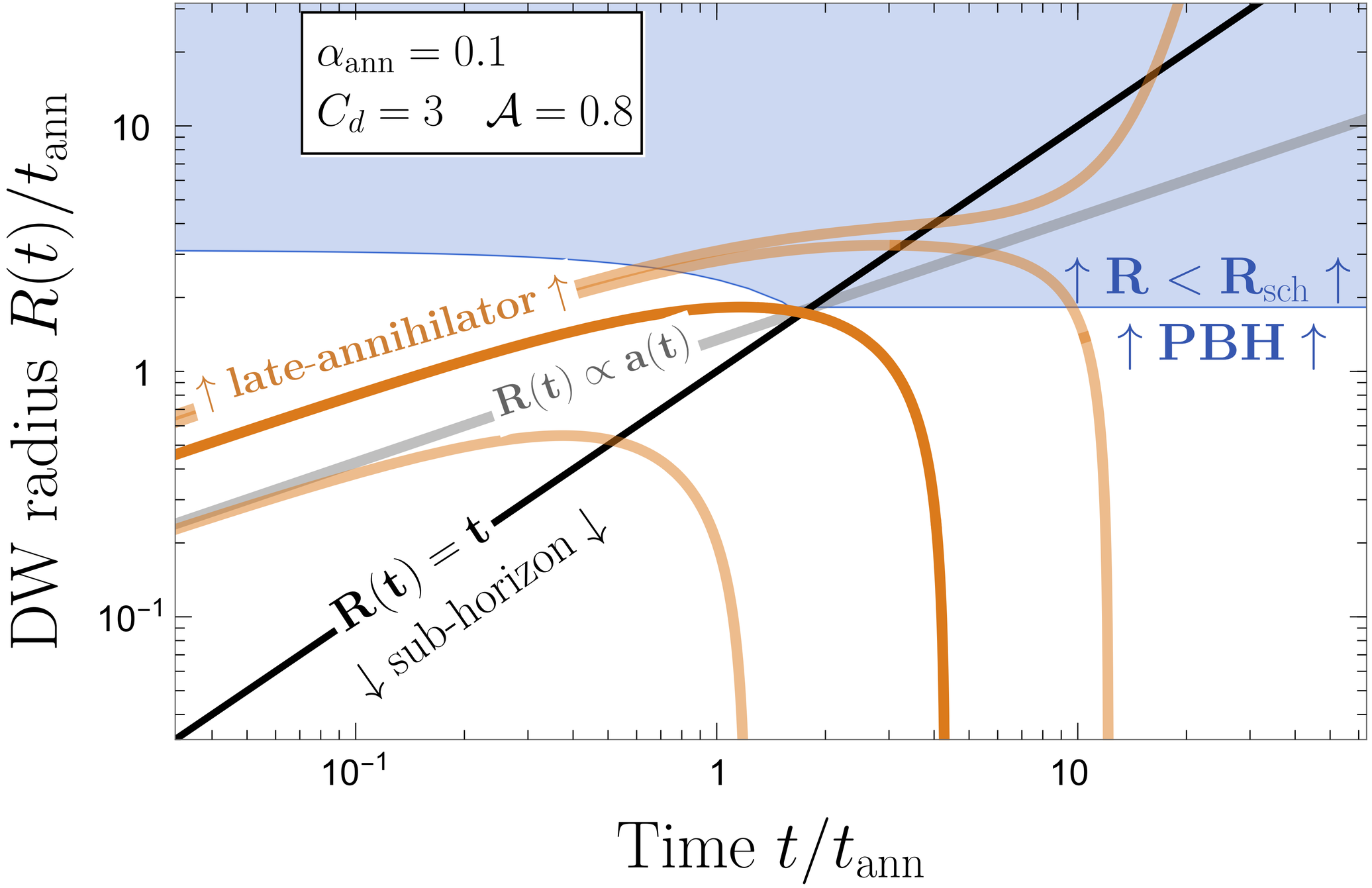

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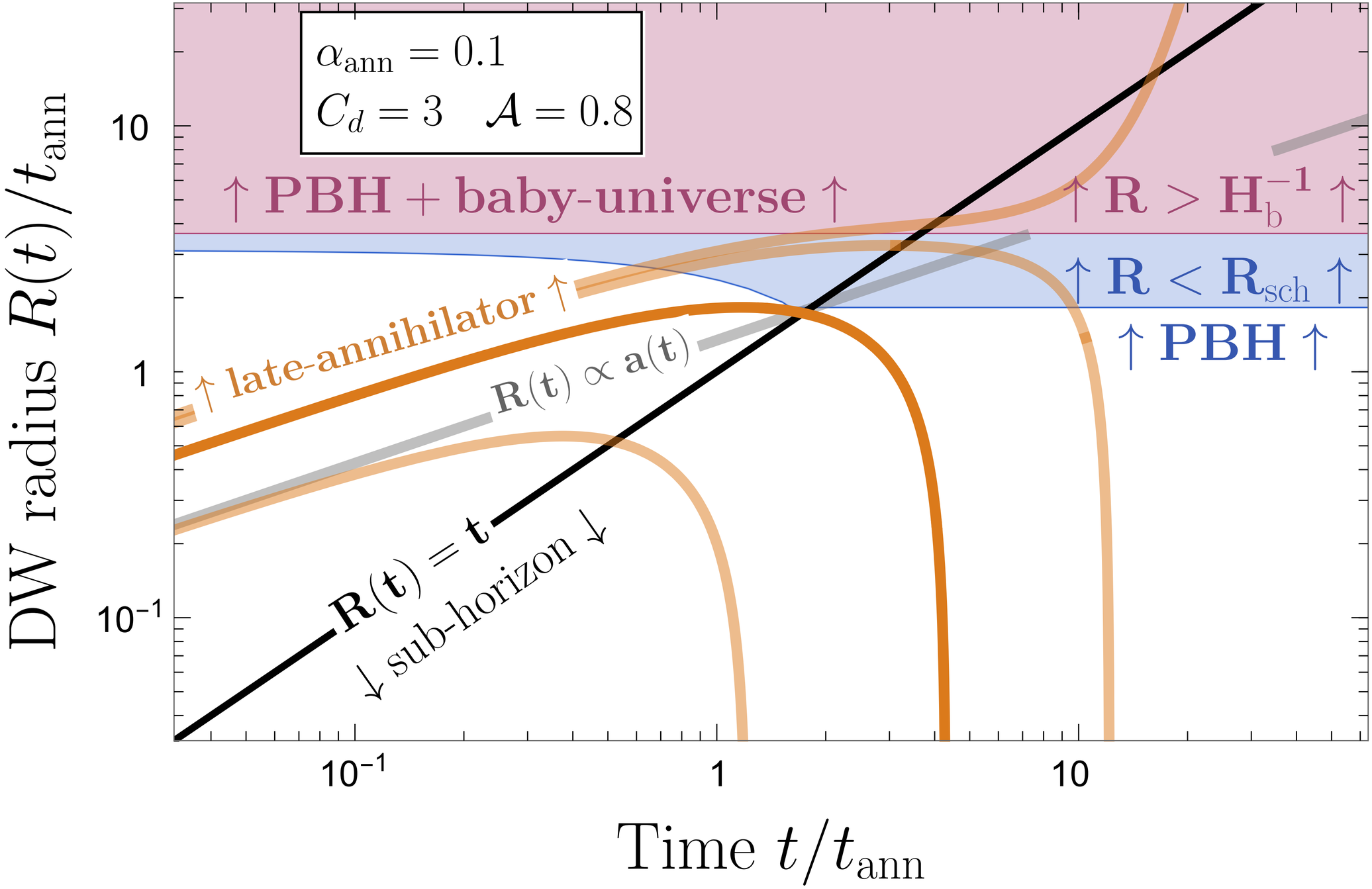

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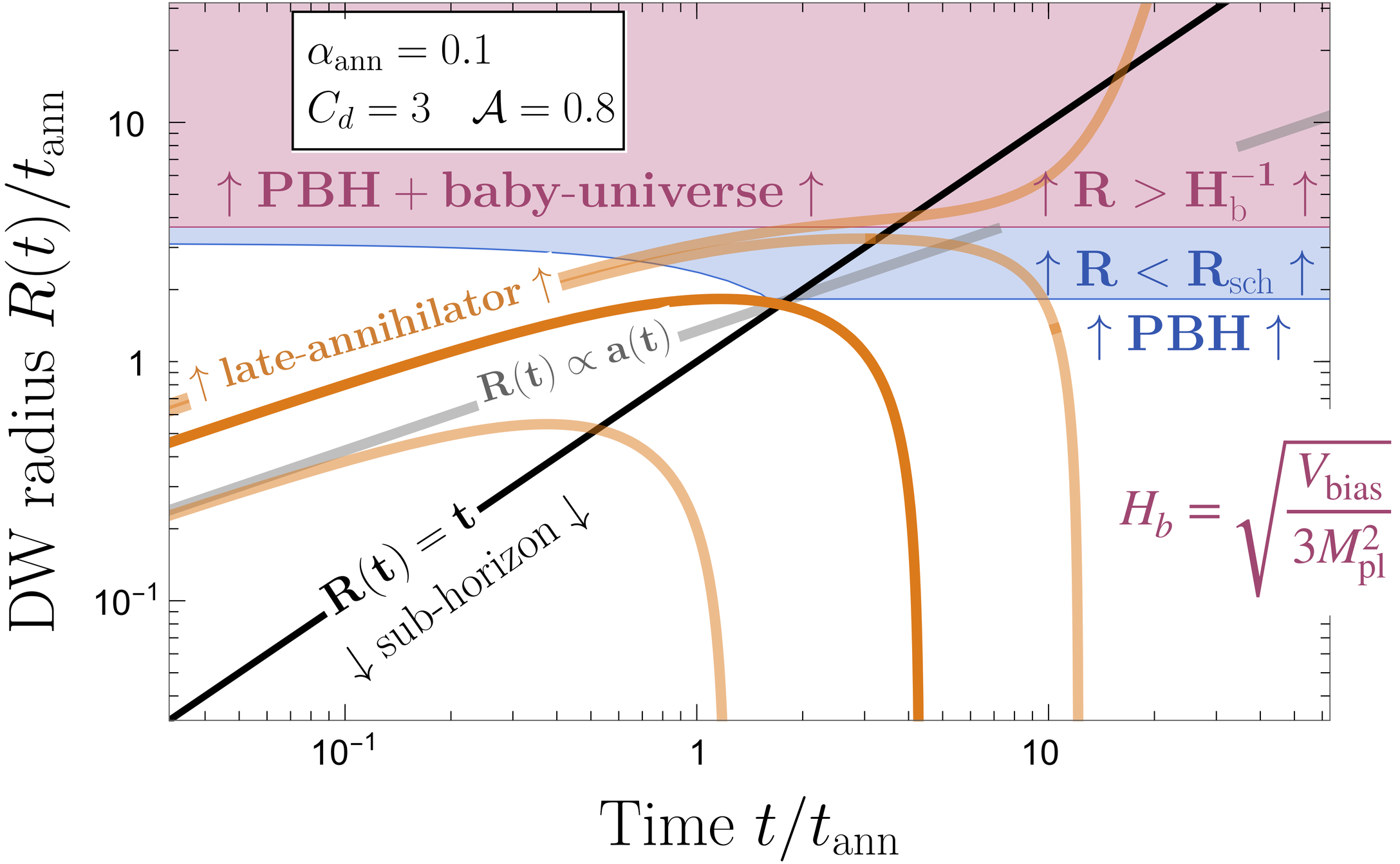

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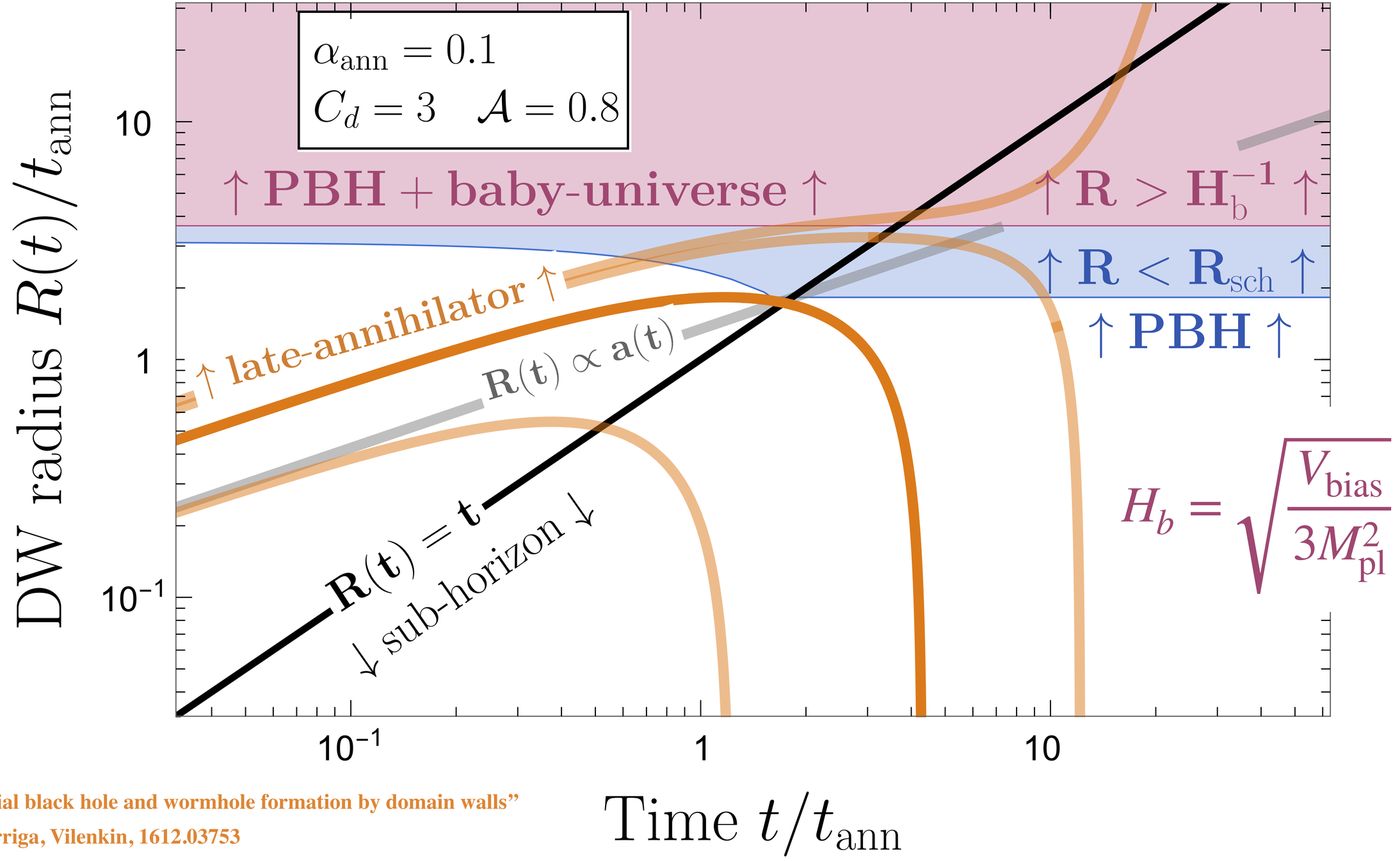
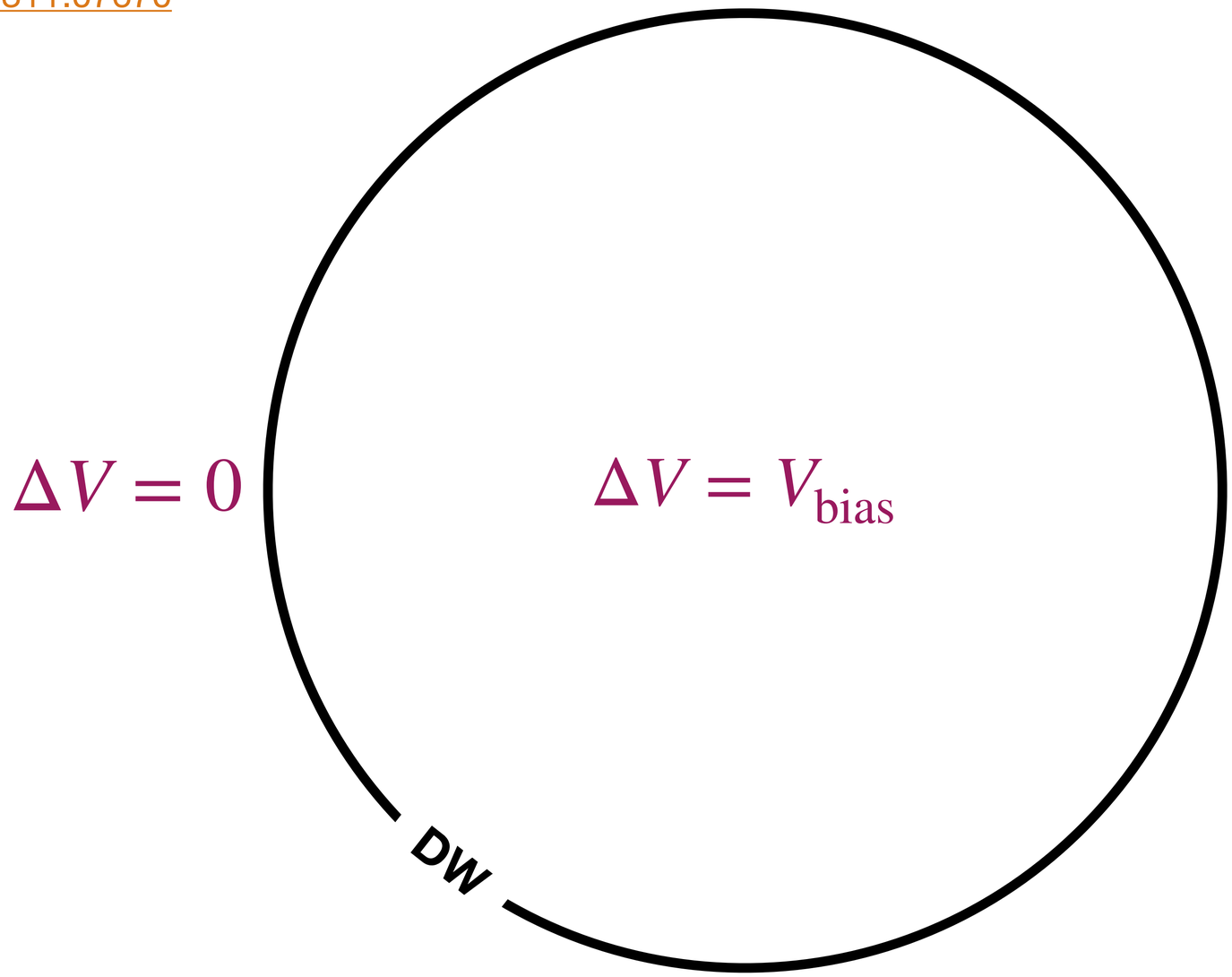
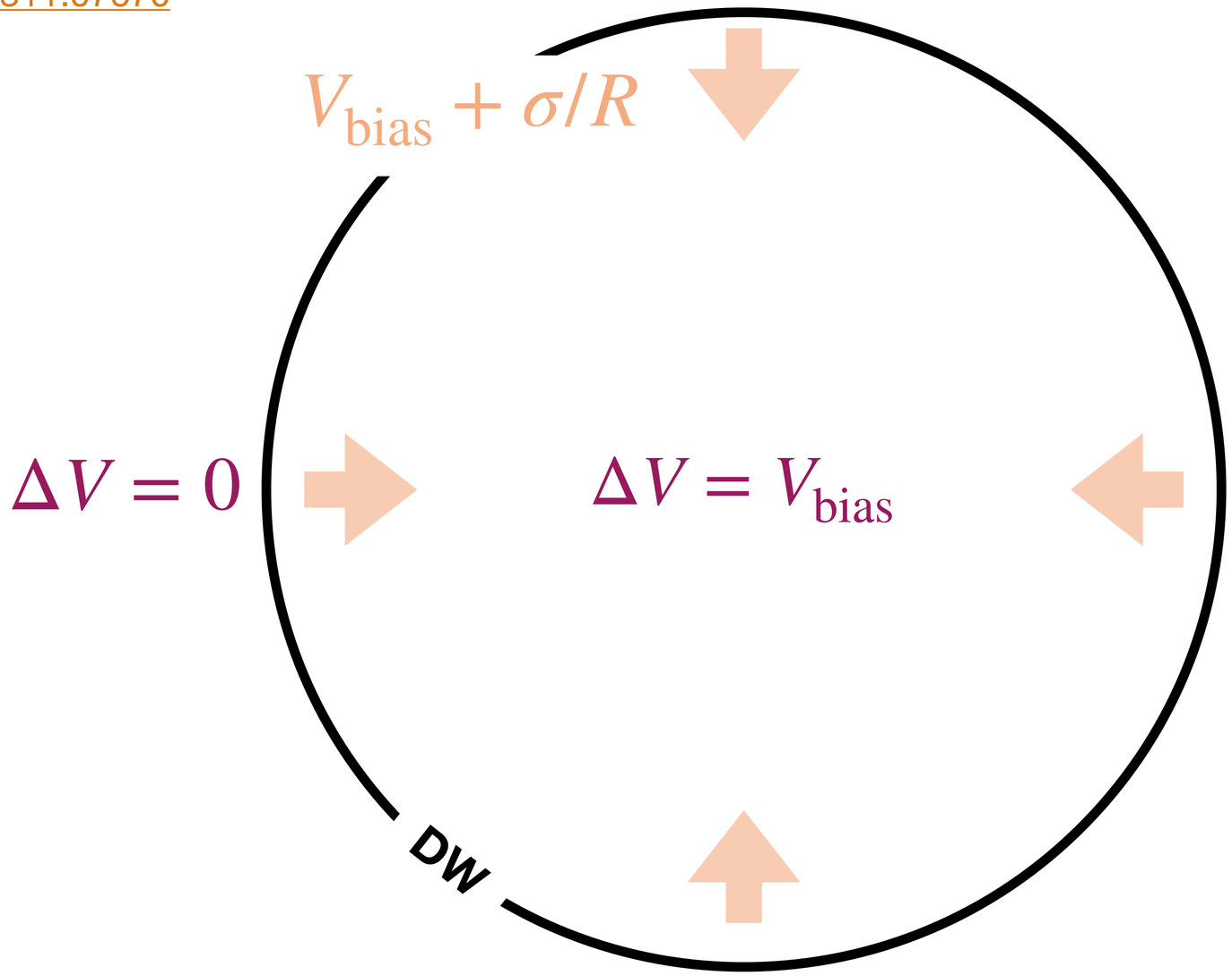


"Primordial black hole and wormhole formation by domain walls"
Deng, Garriga, Vilenkin, 1612.03753

Gouttenoire, Vitagliano, 2311.07670



Gouttenoire, Vitagliano, 2311.07670



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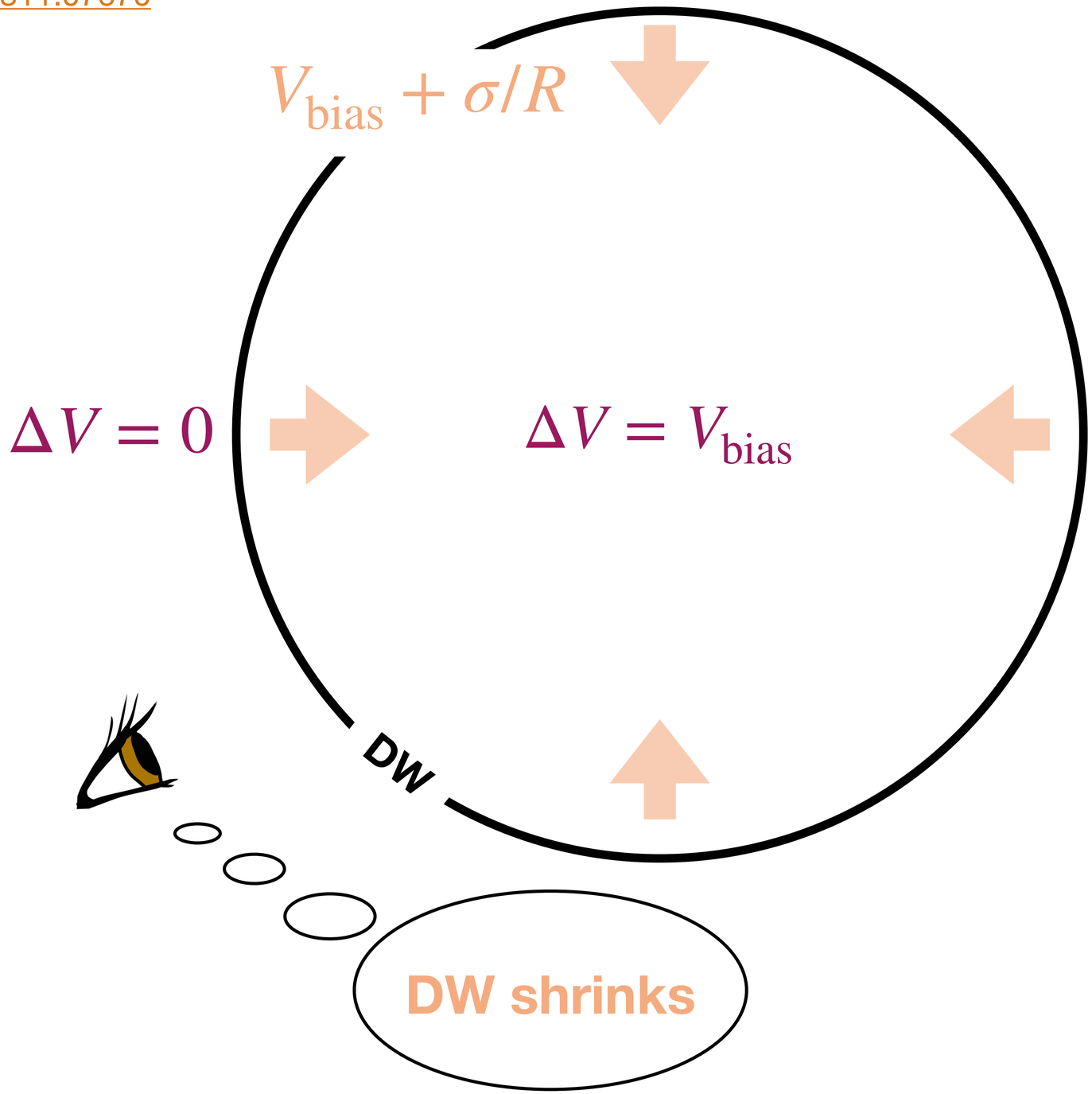

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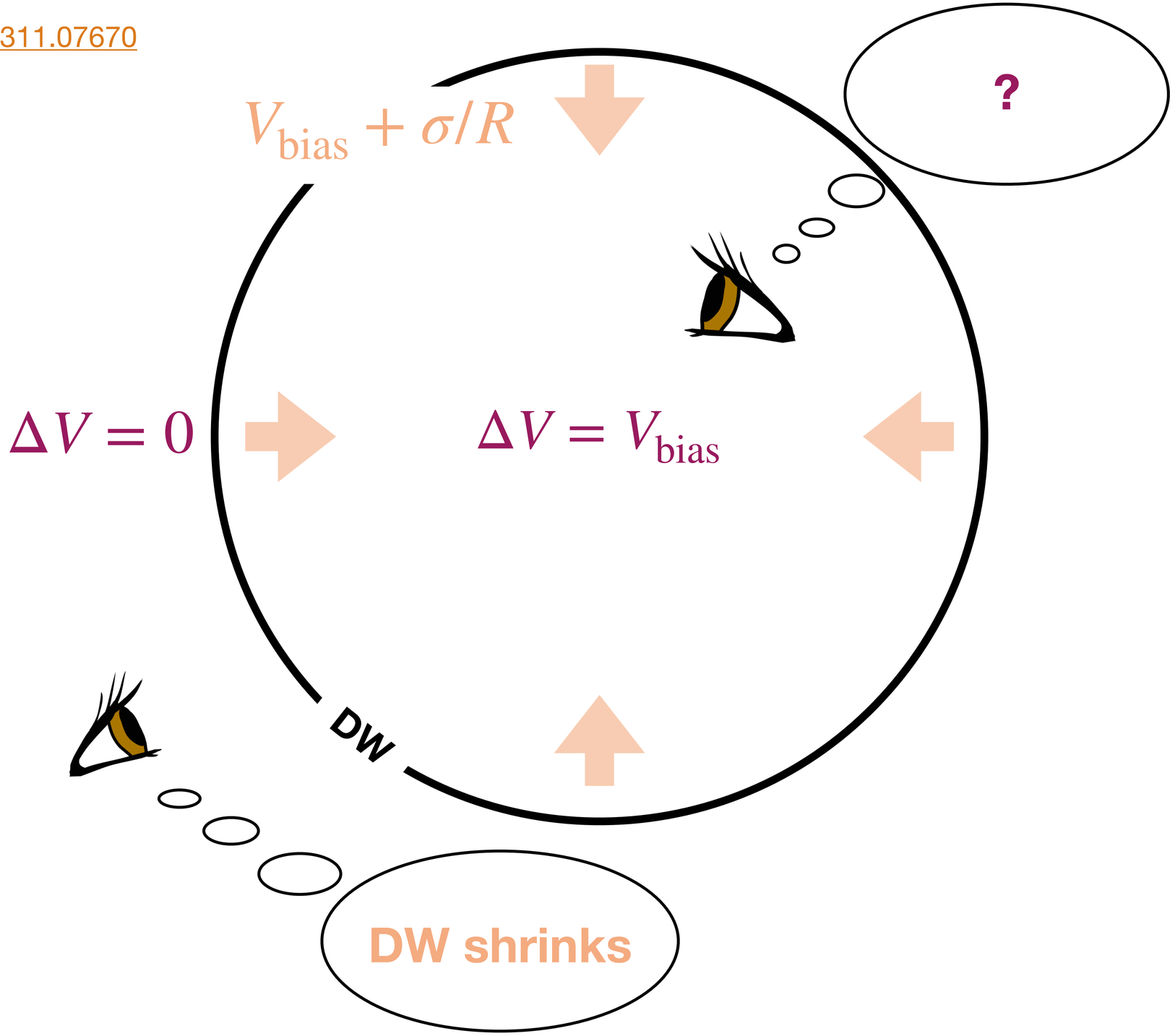

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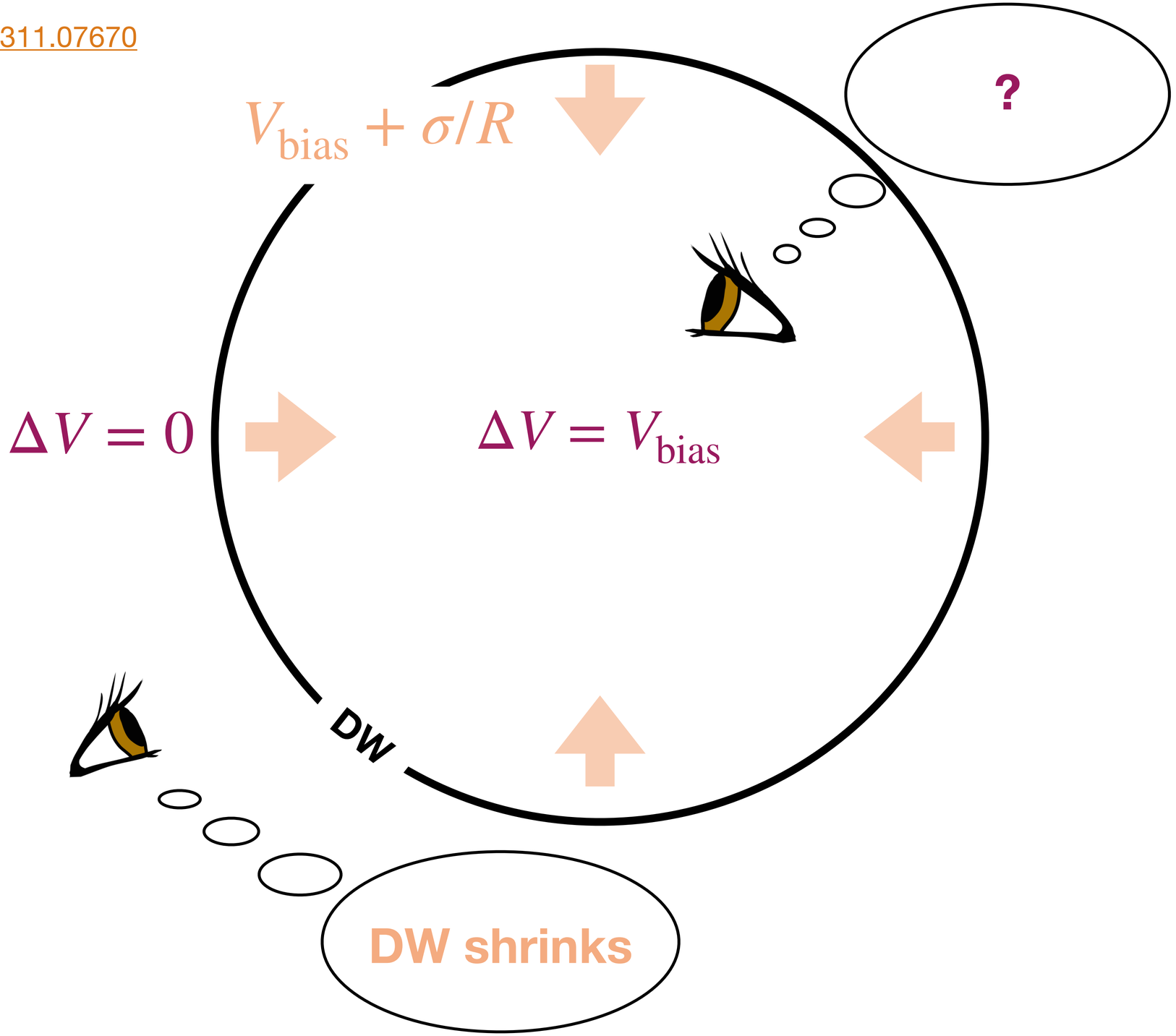
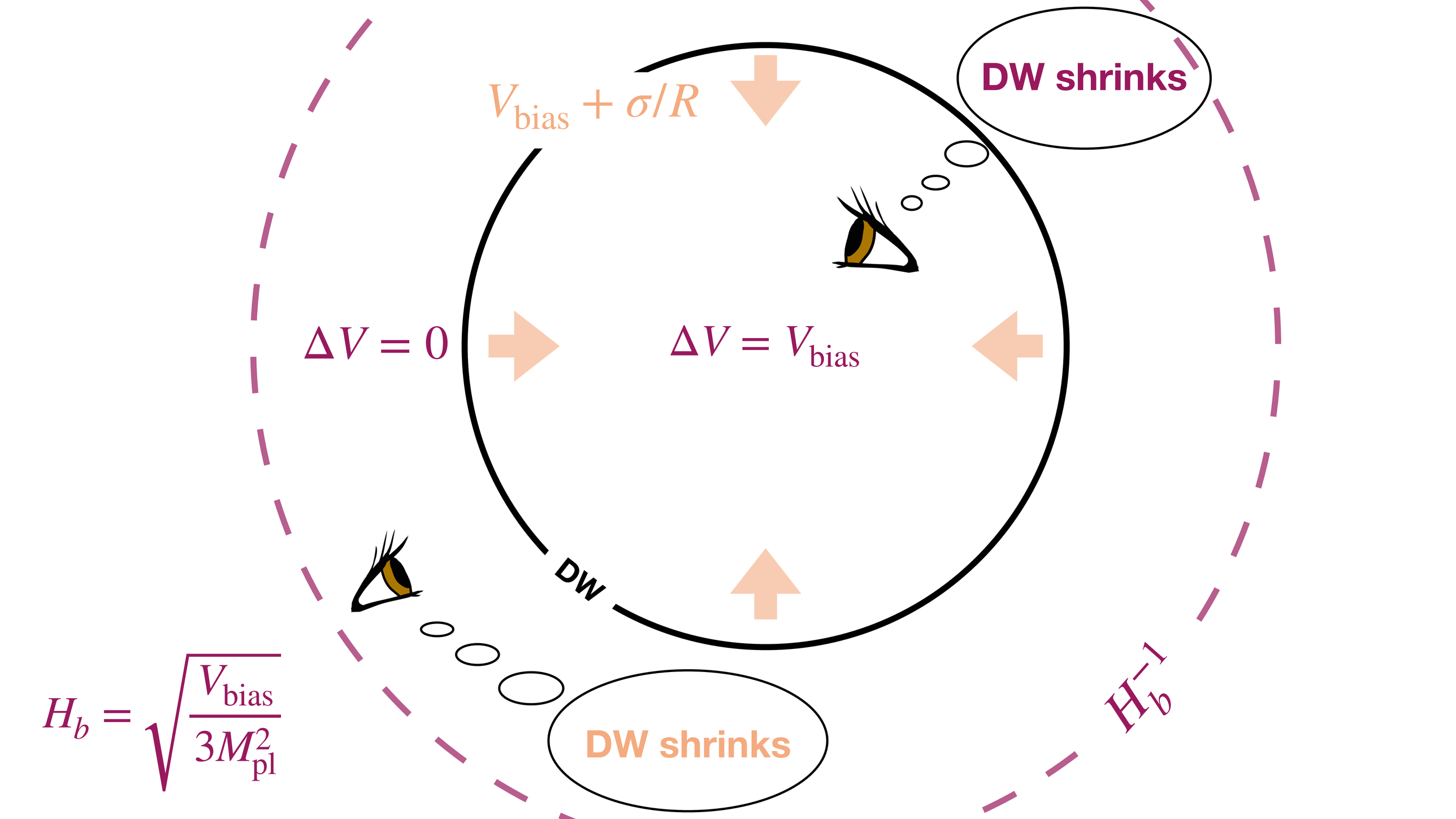
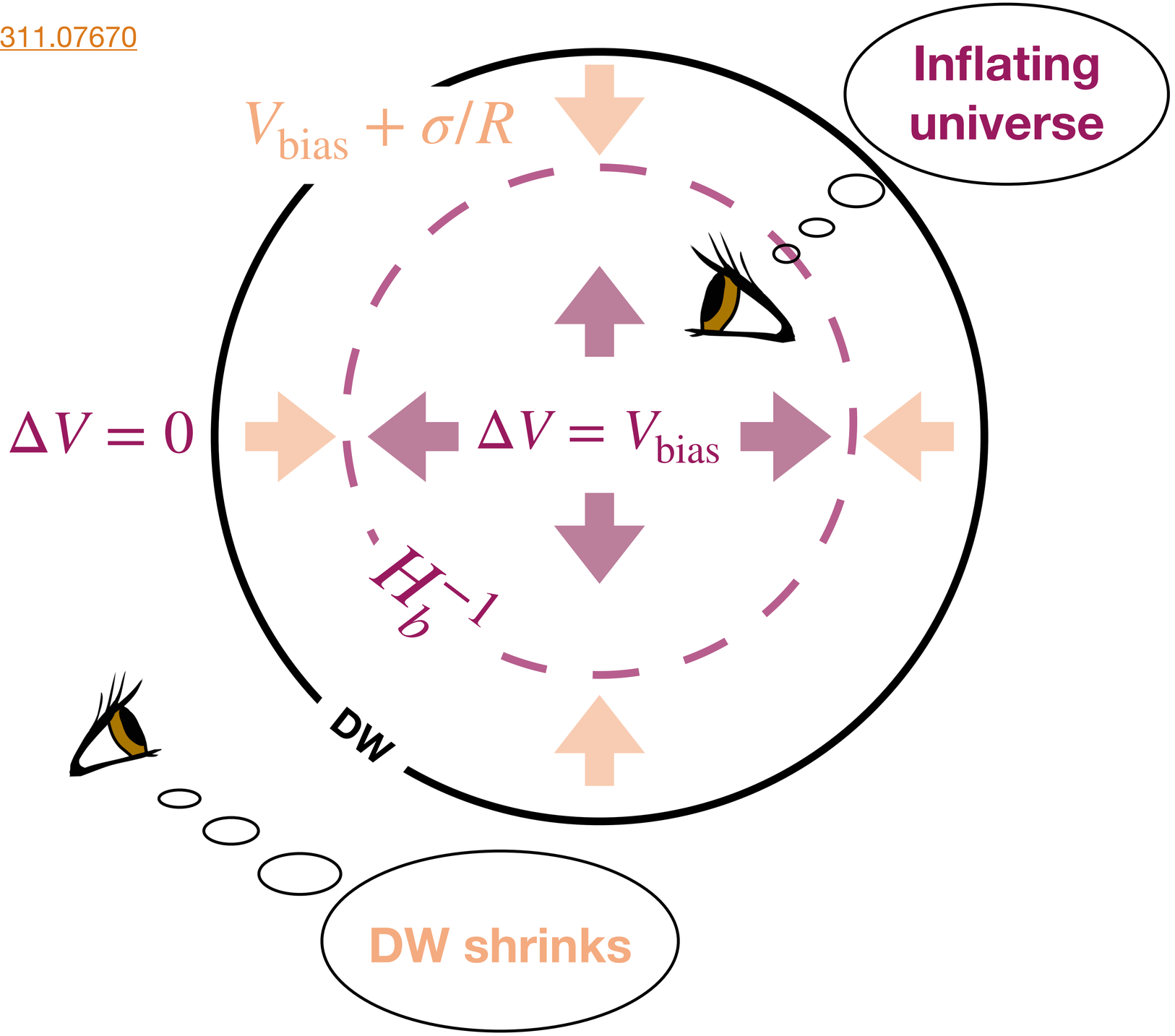
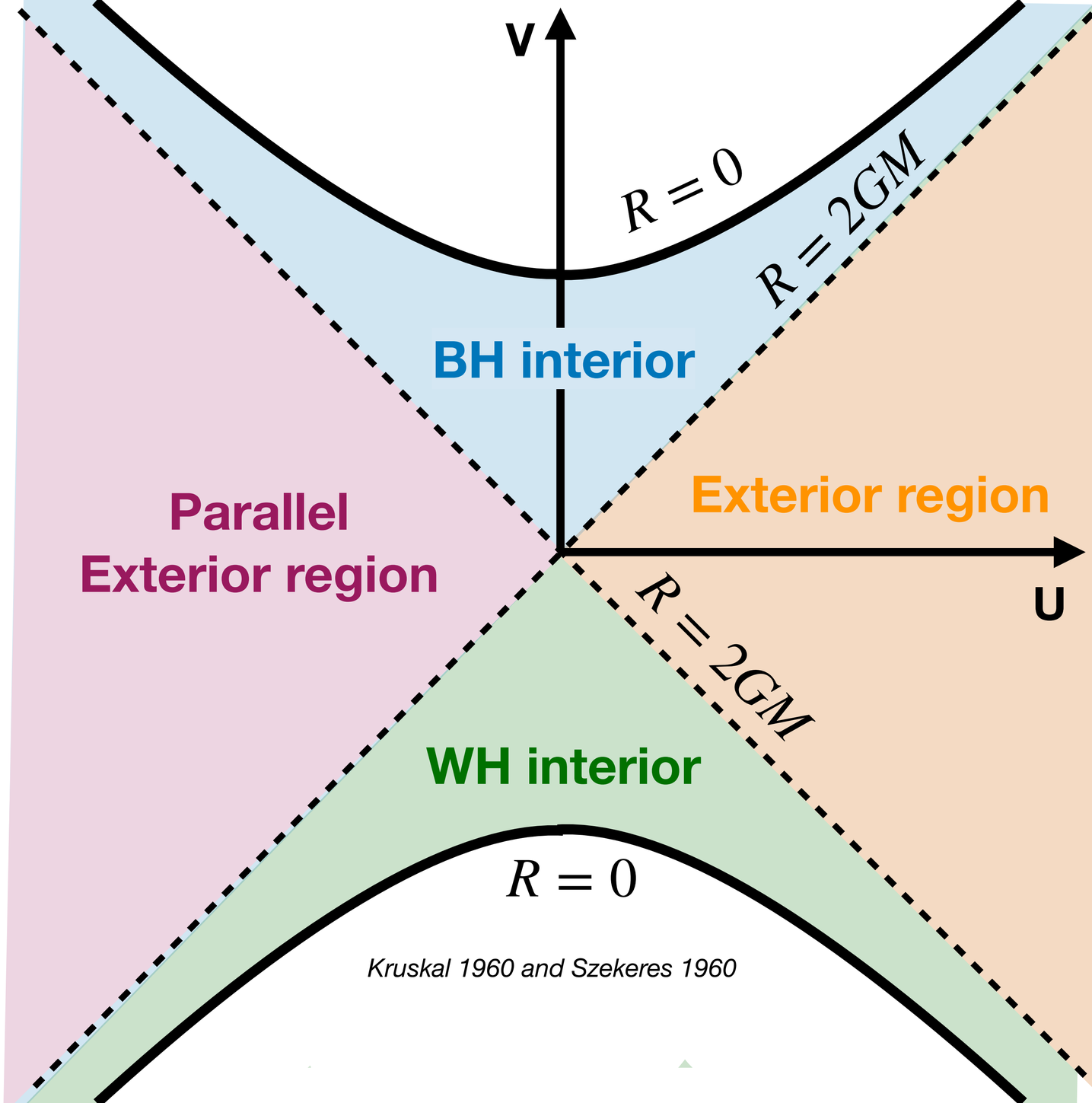


$$H_b = \sqrt{\frac{V_{\rm bias}}{3M_{\rm pl}^2}}$$

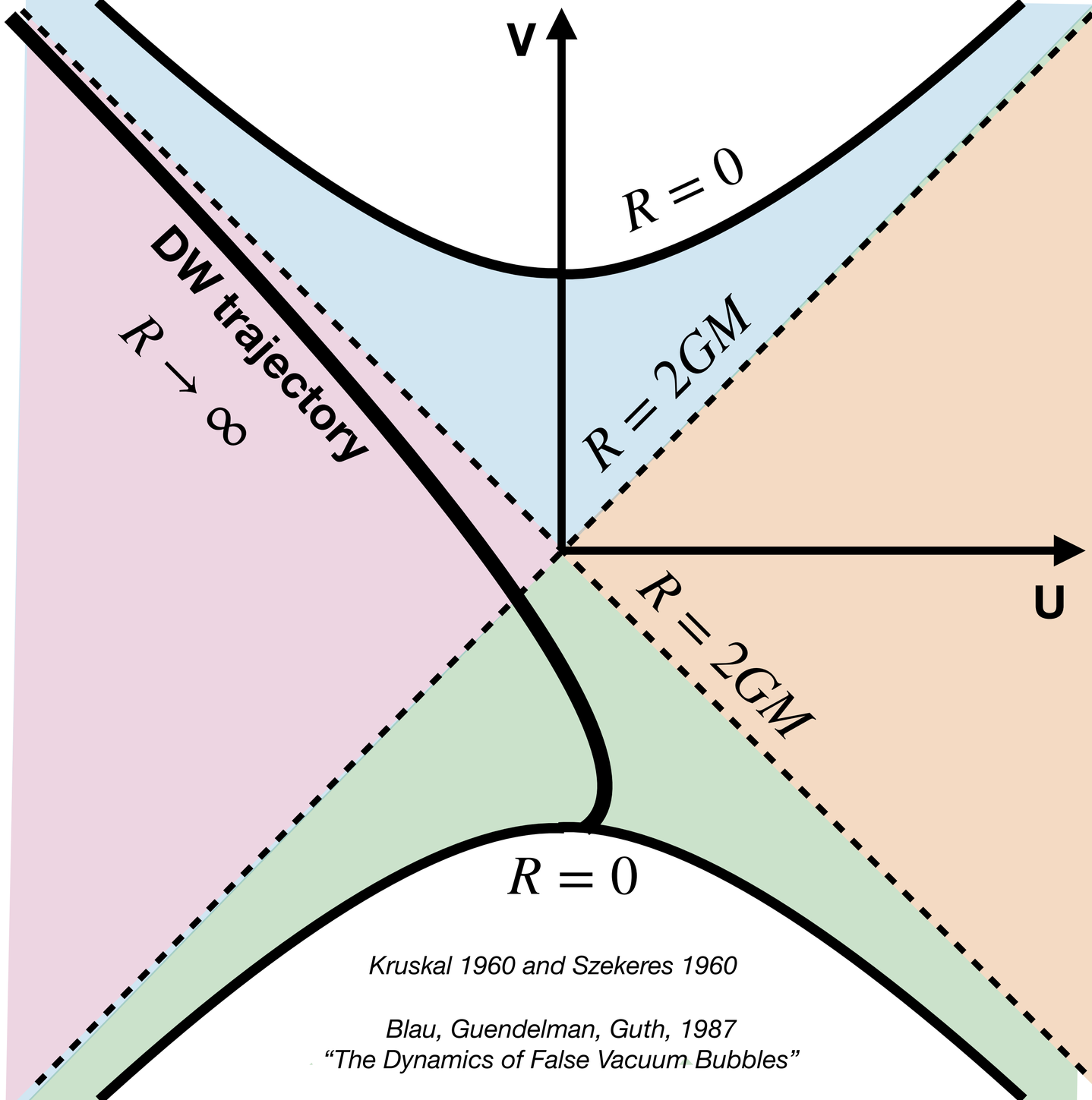

$V_{\rm bias} + \sigma/R$
DW shrinks
$\Delta V = 0$
$\Delta V = V_{\rm bias}$
DW
DW shrinks
$H_b = \sqrt{\dfrac{V_{\rm bias}}{3M_{\rm pl}^2}}$
H_b^{-1}

Gouttenoire, Vitagliano, 2311.07670



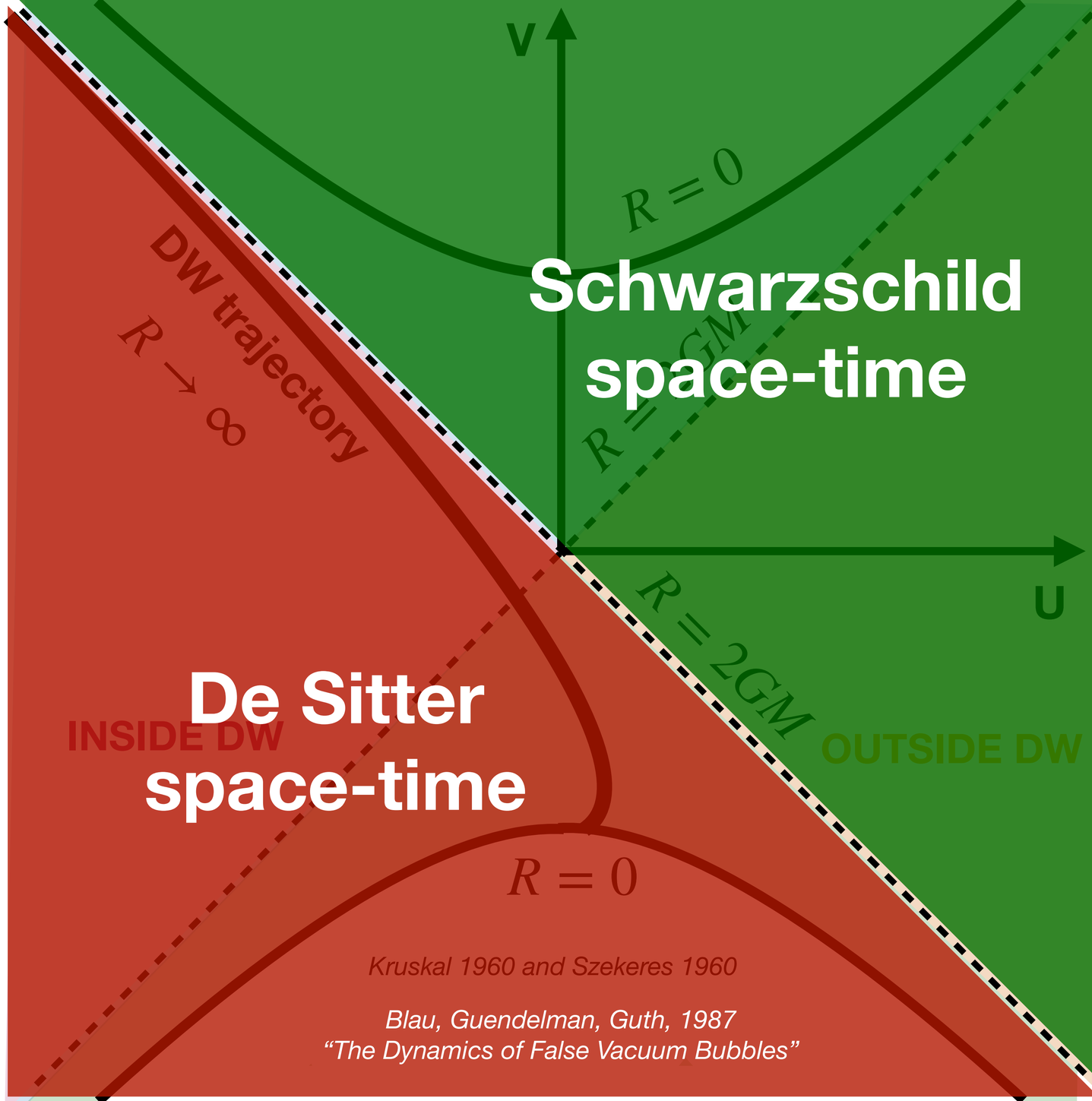


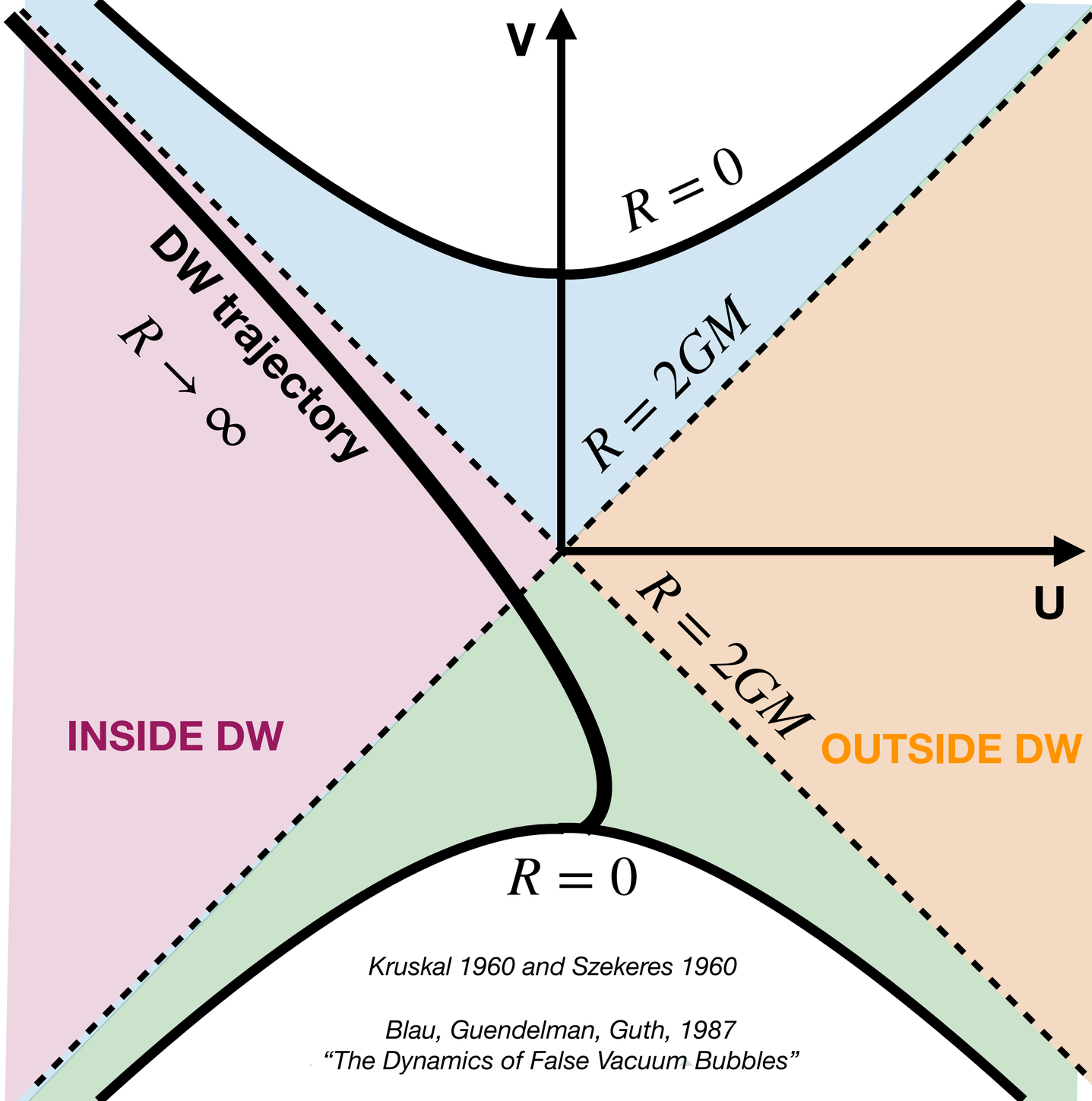
Kruskal 1960 and Szekeres 1960



Kruskal 1960 and Szekeres 1960

Blau, Guendelman, Guth, 1987
"The Dynamics of False Vacuum Bubbles"


V
U
$R = 0$
$R = GM$
$R = 2GM$
Schwarzschild
space-time
DW trajectory
$R \to \infty$
De Sitter
space-time
INSIDE DW
OUTSIDE DW
$R = 0$
Kruskal 1960 and Szekeres 1960
Blau, Guendelman, Guth, 1987
“The Dynamics of False Vacuum Bubbles”



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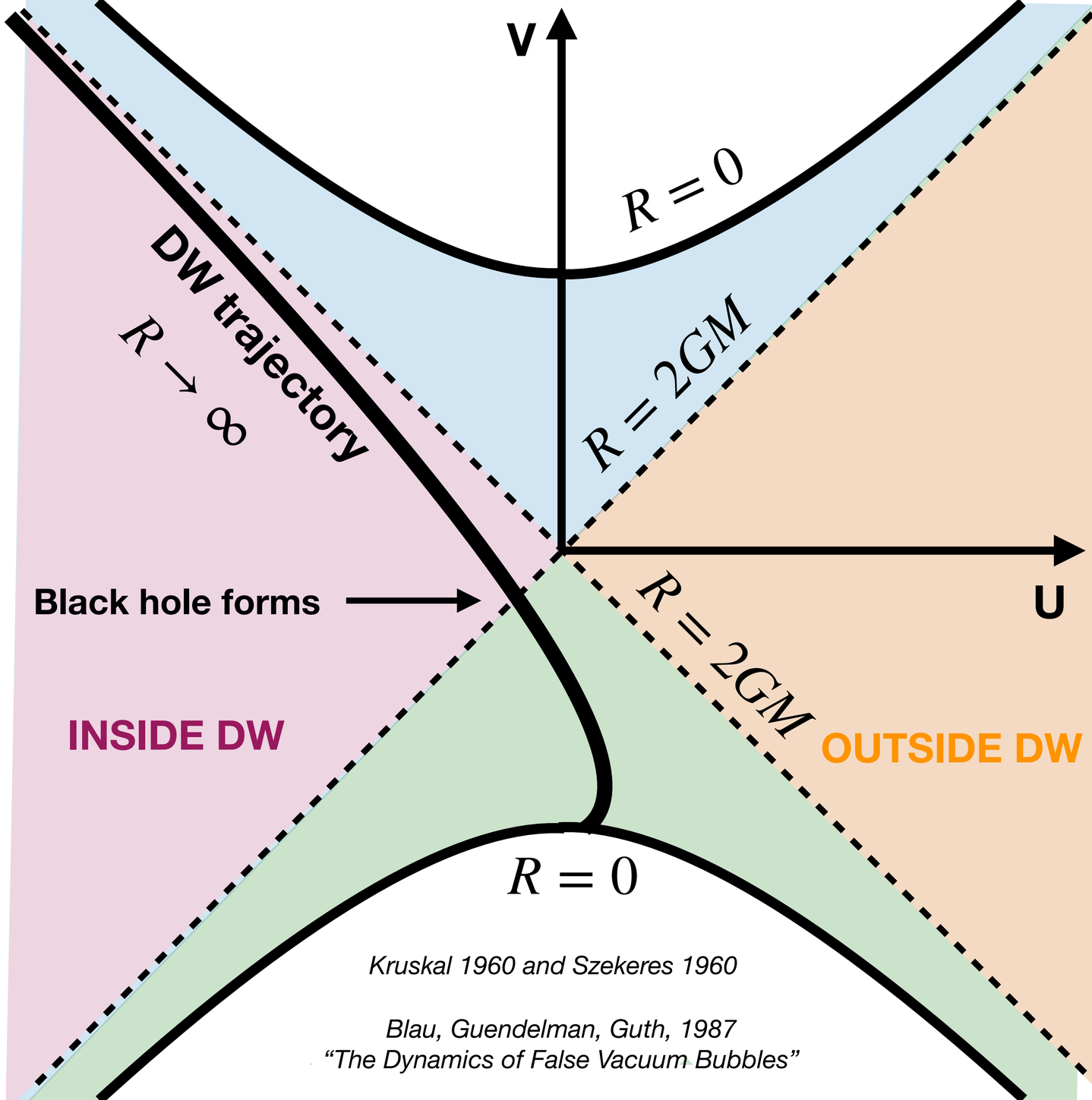

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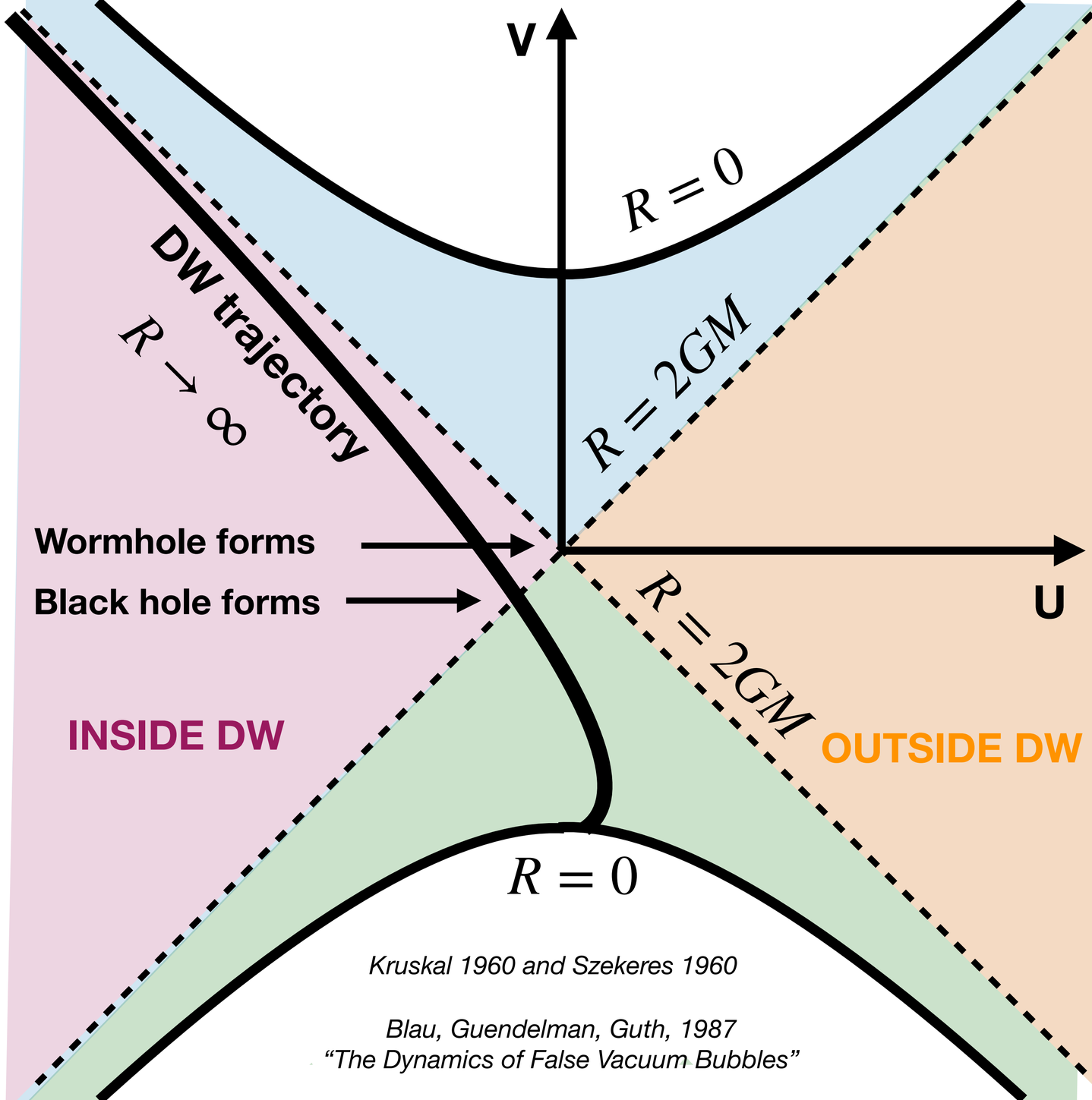

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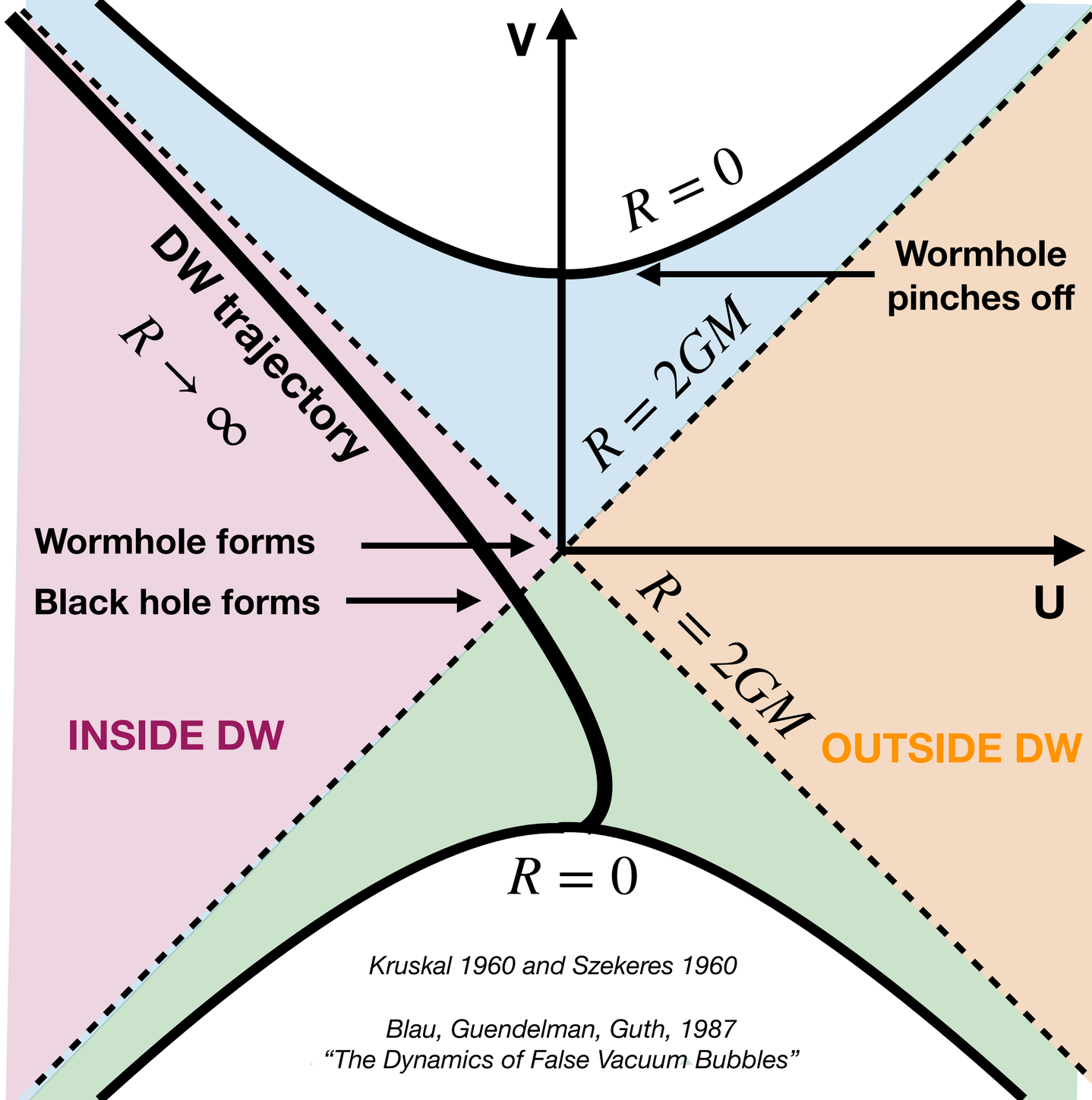

Kruskal 1960 and Szekeres 1960

Blau, Guendelman, Guth, 1987
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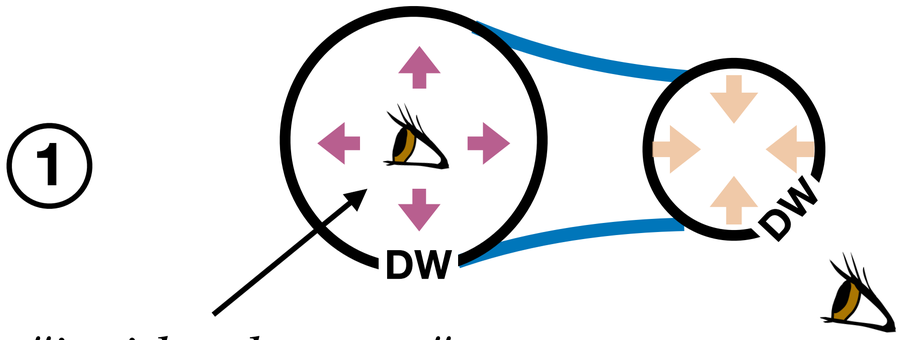


"inside observer"

"outside observer"

***Gouttenoire**, King, Roshan, Wang, White, Yamazaki, 2501.XXXXX*

V

$R = 0$

Wormhole pinches off

DW trajectory

$R \to \infty$

$R = 2GM$

Wormhole forms

Black hole forms

U

$R = 2GM$

INSIDE

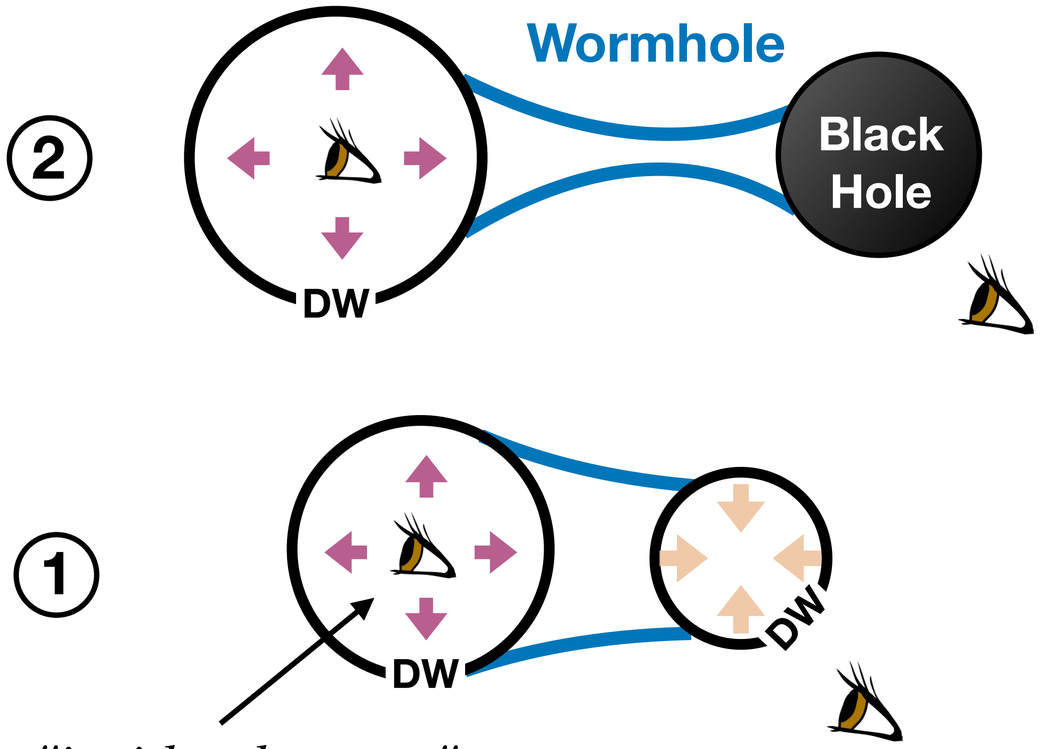
OUTSIDE

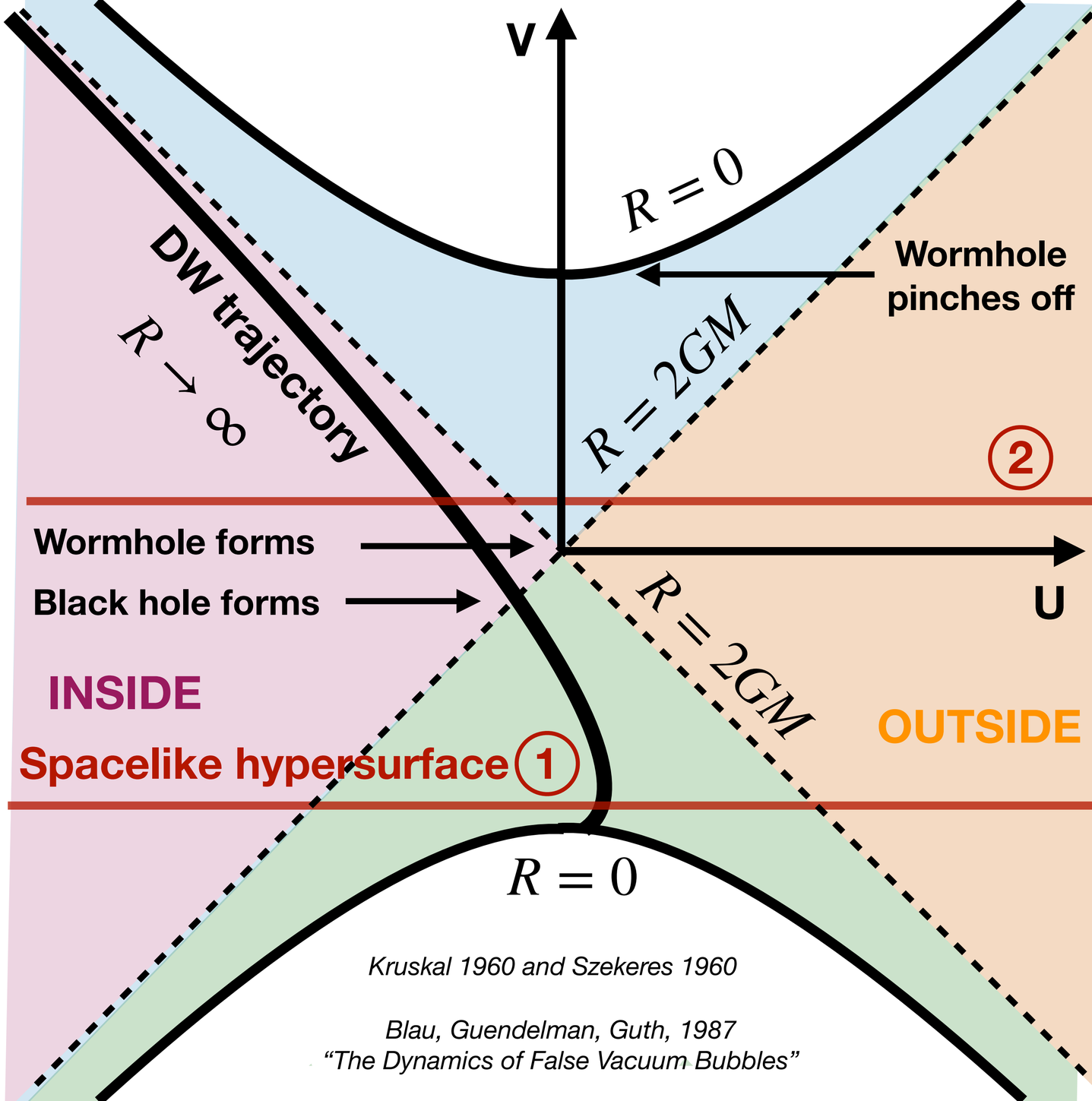
Spacelike hypersurface 1

$R = 0$

Kruskal 1960 and Szekeres 1960

Blau, Guendelman, Guth, 1987
"The Dynamics of False Vacuum Bubbles"





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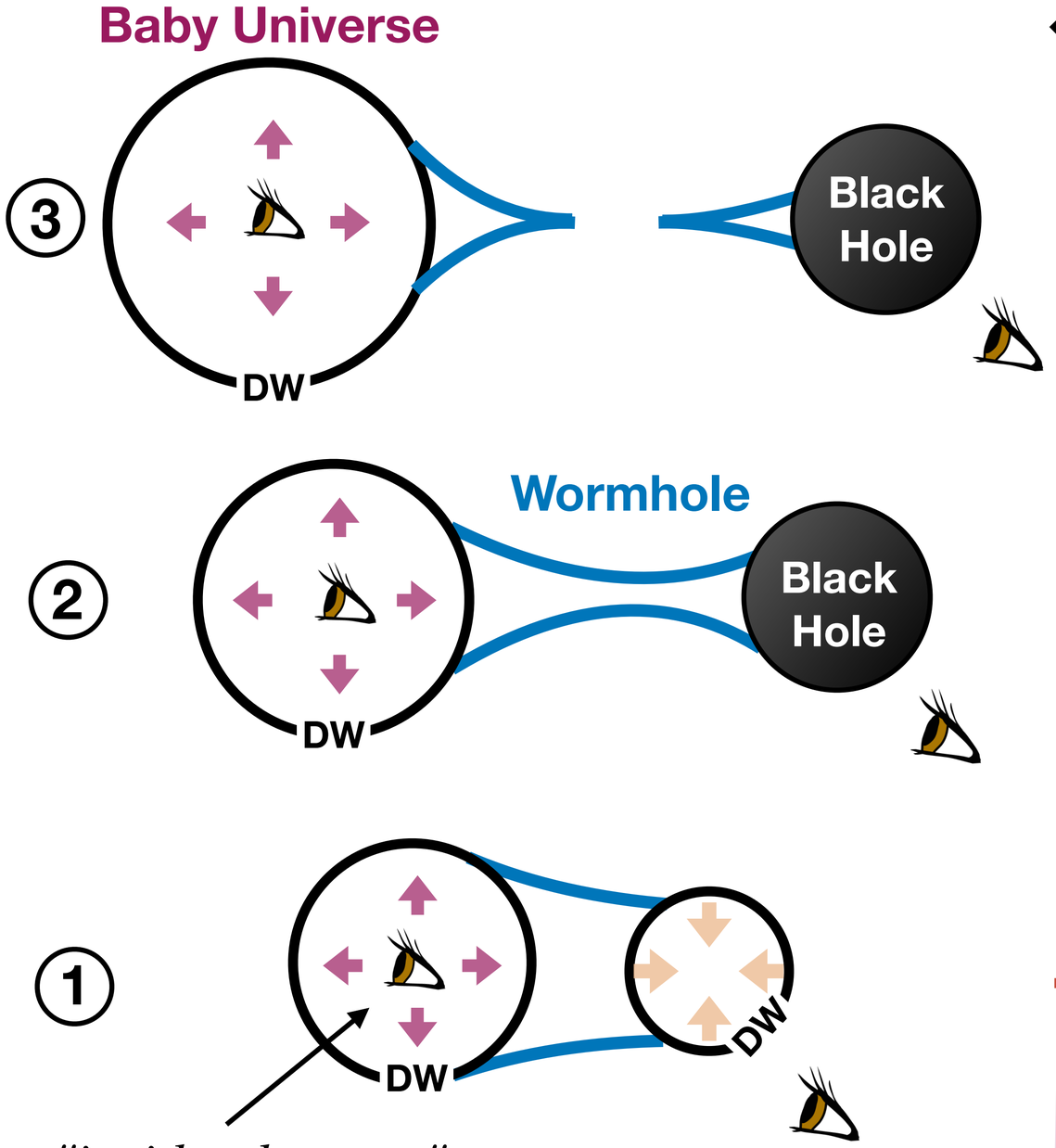
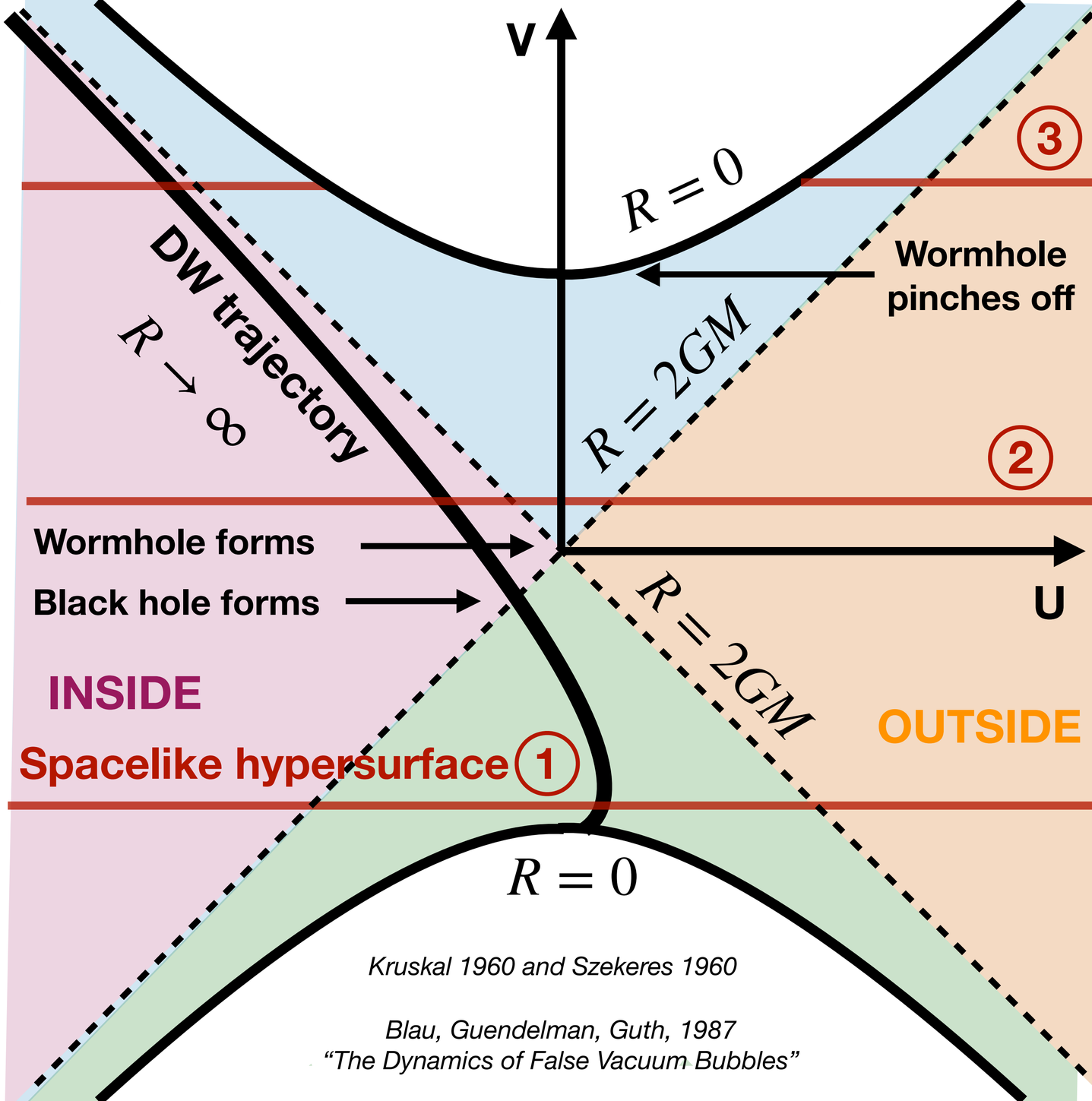
***Gouttenoire**, King, Roshan, Wang, White, Yamazaki, 2501.XXXXX*





Kruskal 1960 and Szekeres 1960

Blau, Guendelman, Guth, 1987
"The Dynamics of False Vacuum Bubbles"

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Dark Sector

$S : \mathbb{Z}_2$

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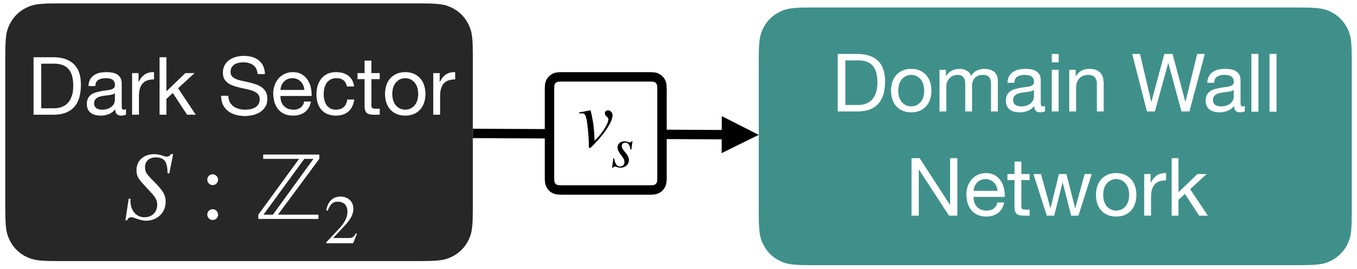

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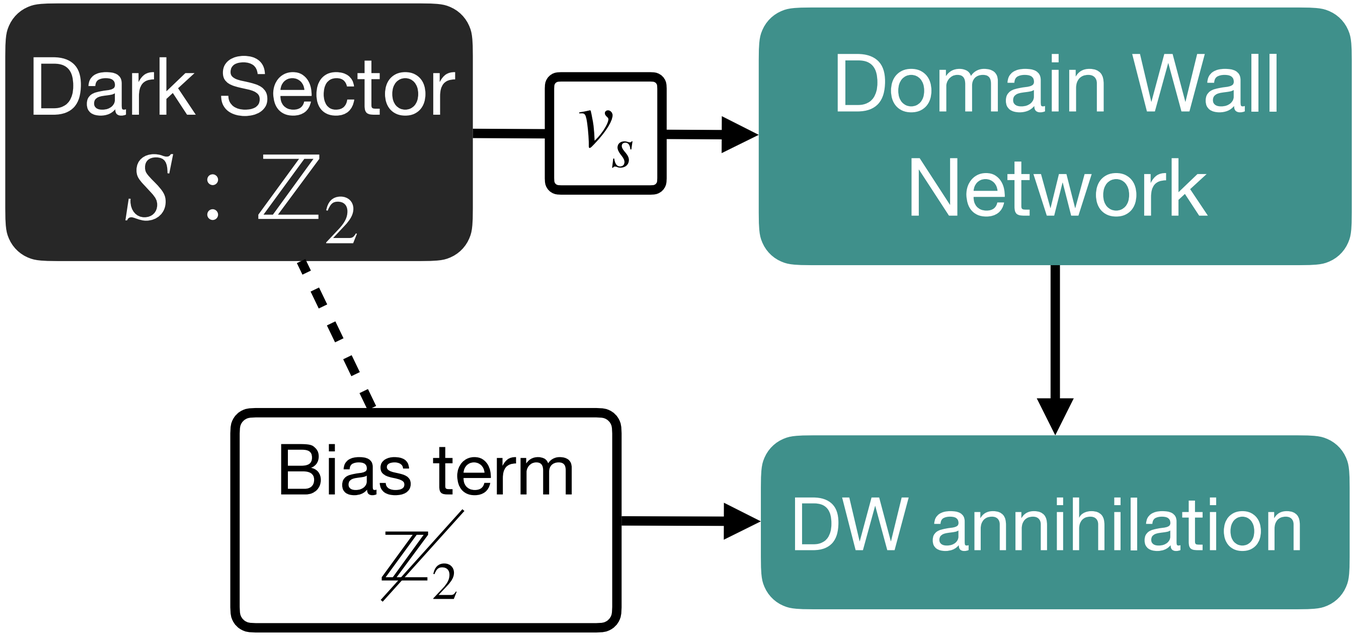
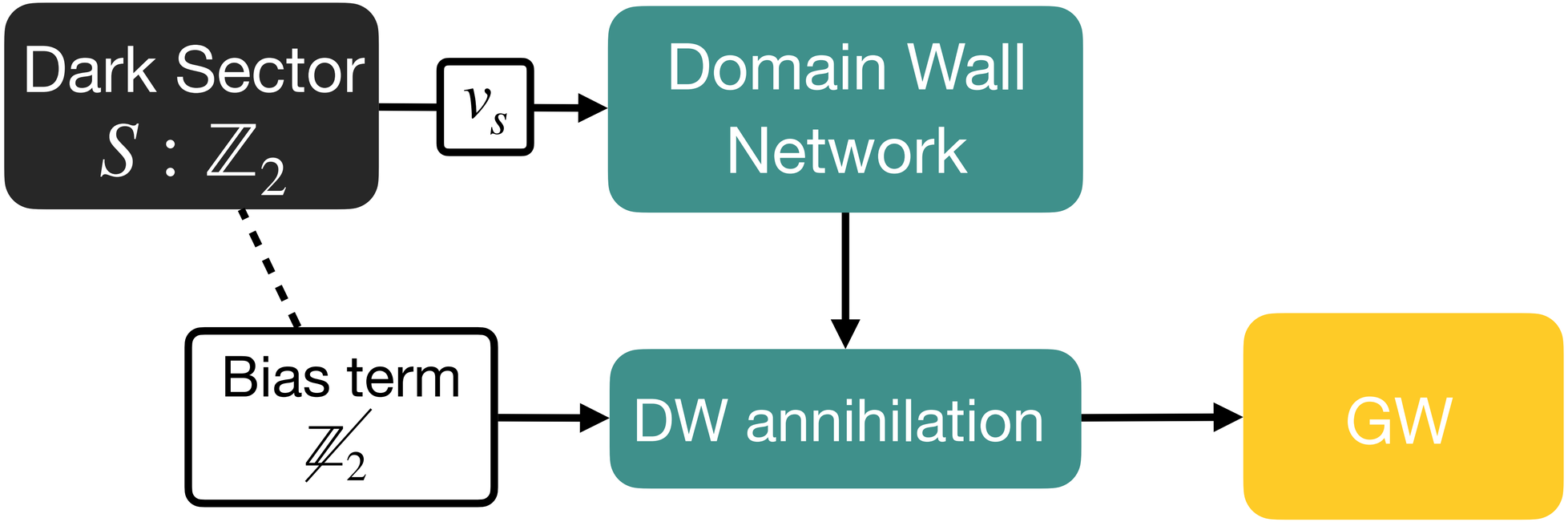


***Gouttenoire**, King, Roshan, Wang, White, Yamazaki, 2501.XXXXX*



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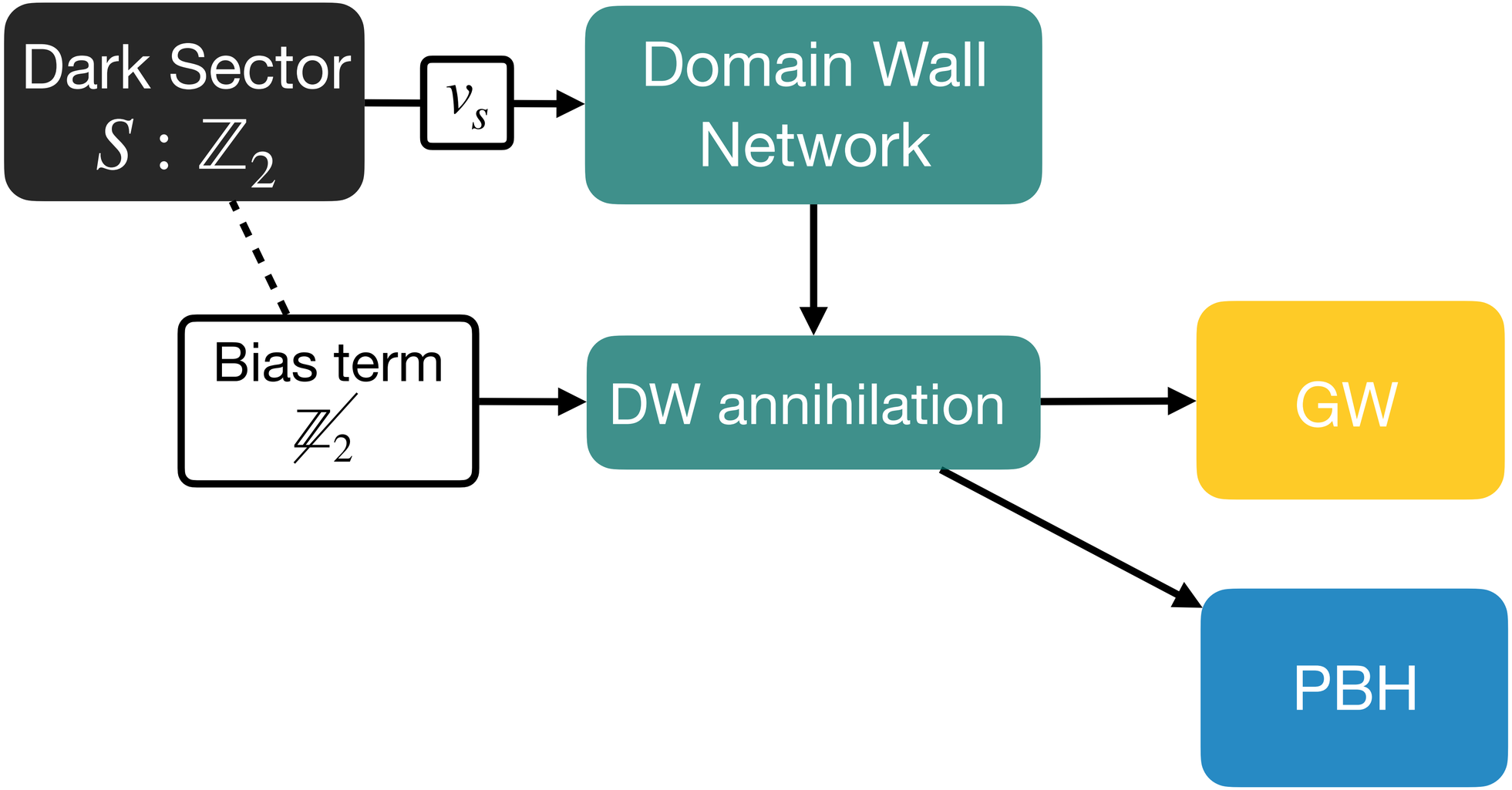

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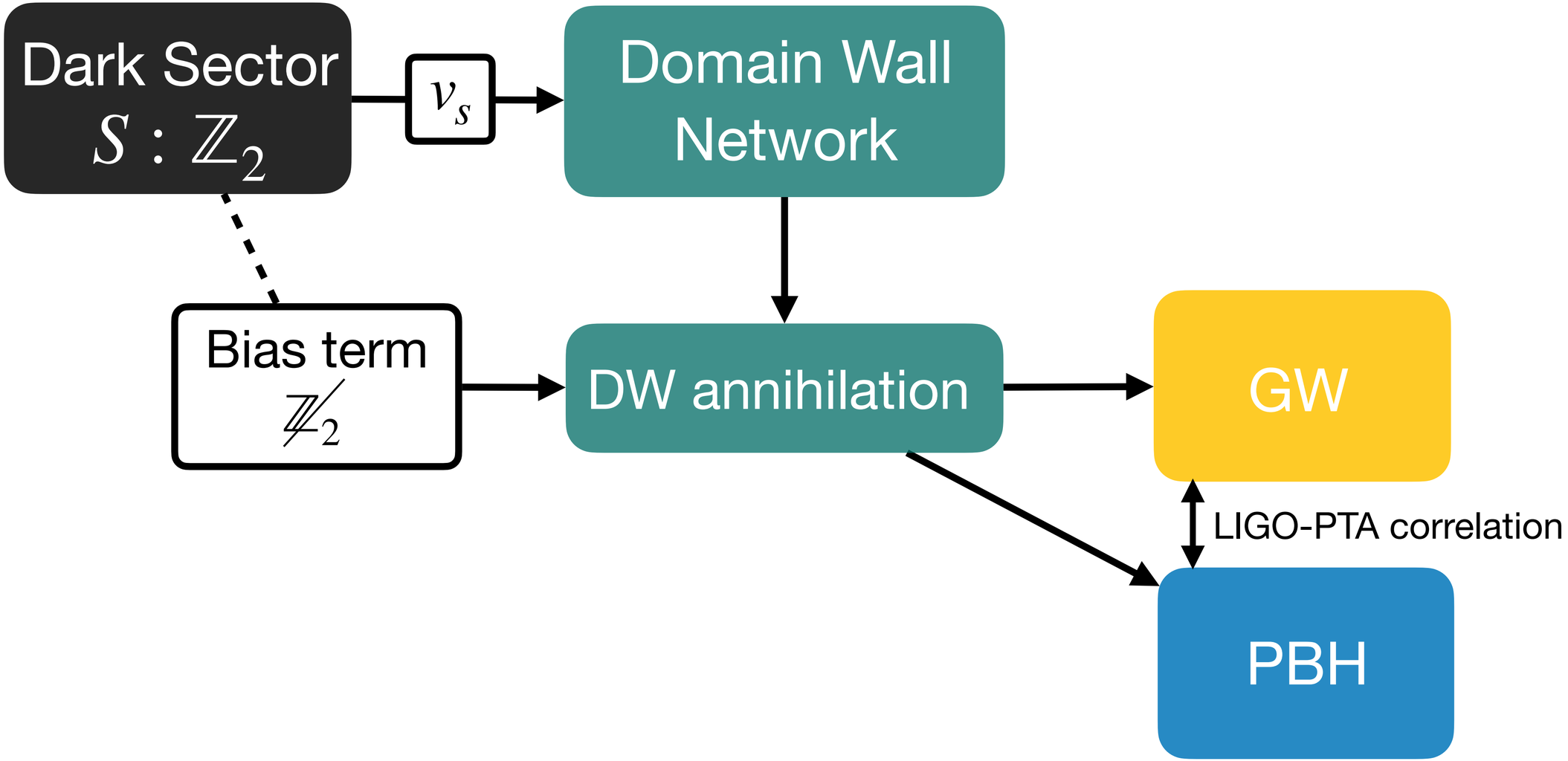
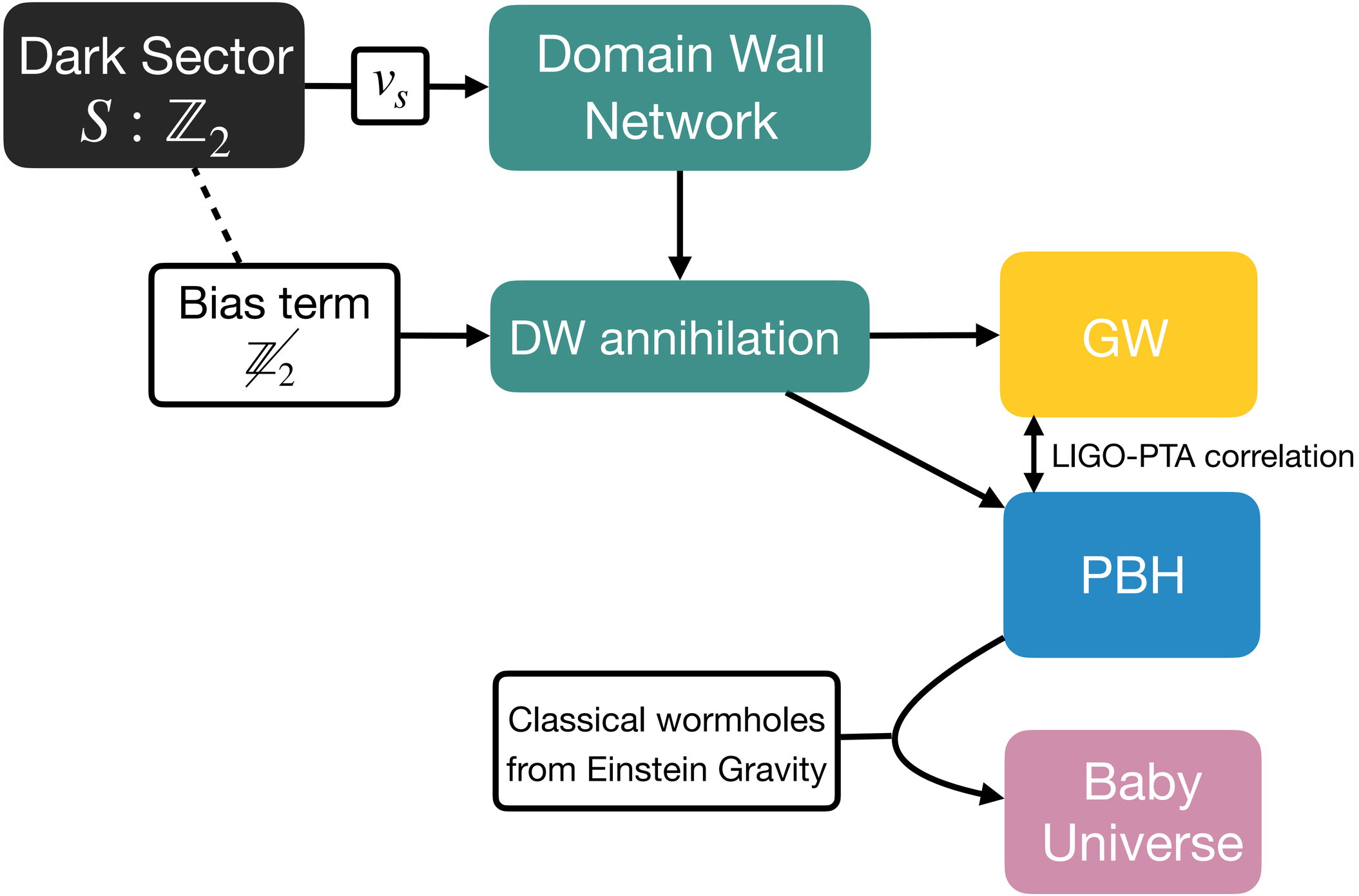
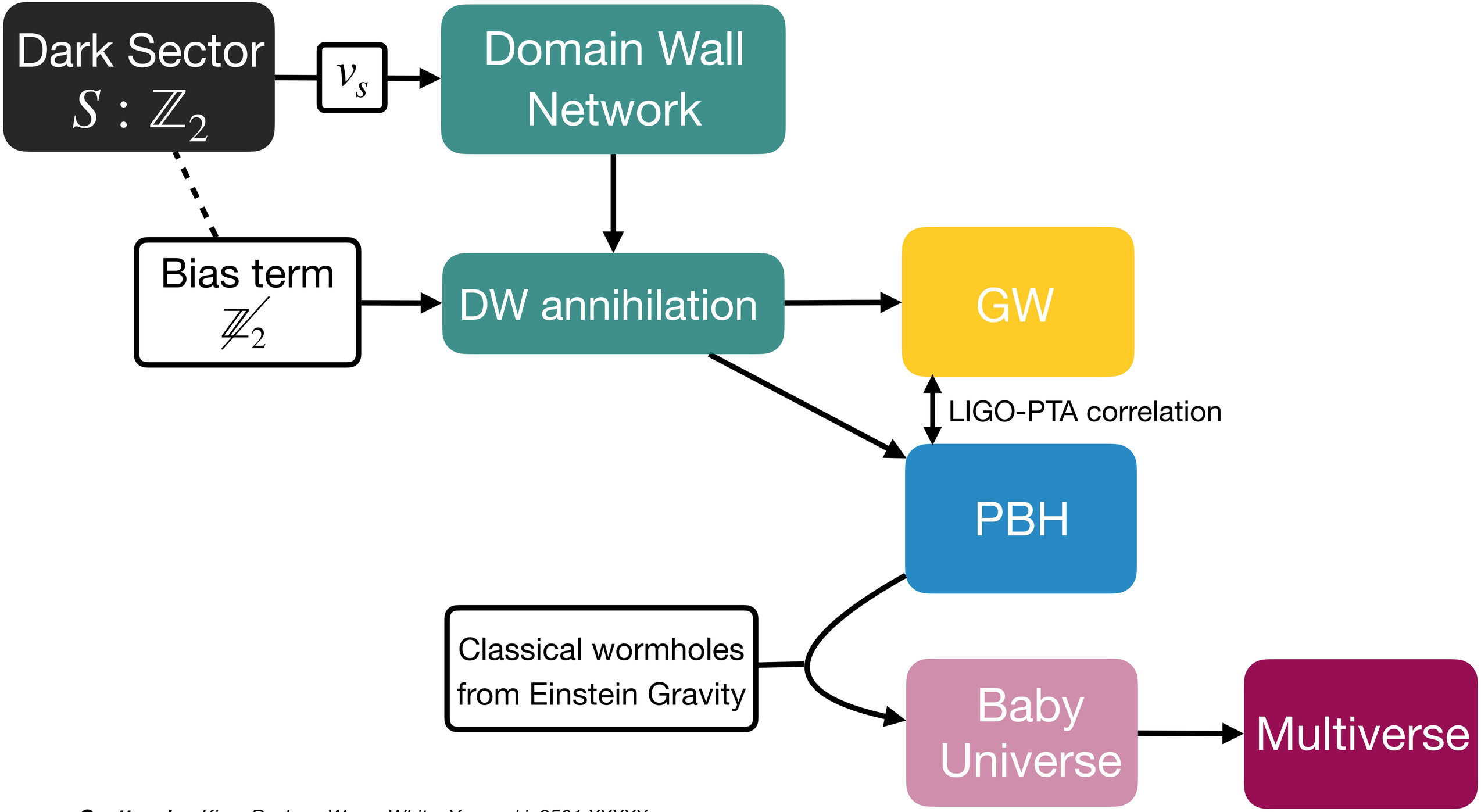


***Gouttenoire**, King, Roshan, Wang, White, Yamazaki, 2501.XXXXX*



***Gouttenoire**, King, Roshan, Wang, White, Yamazaki, 2501.XXXXX*



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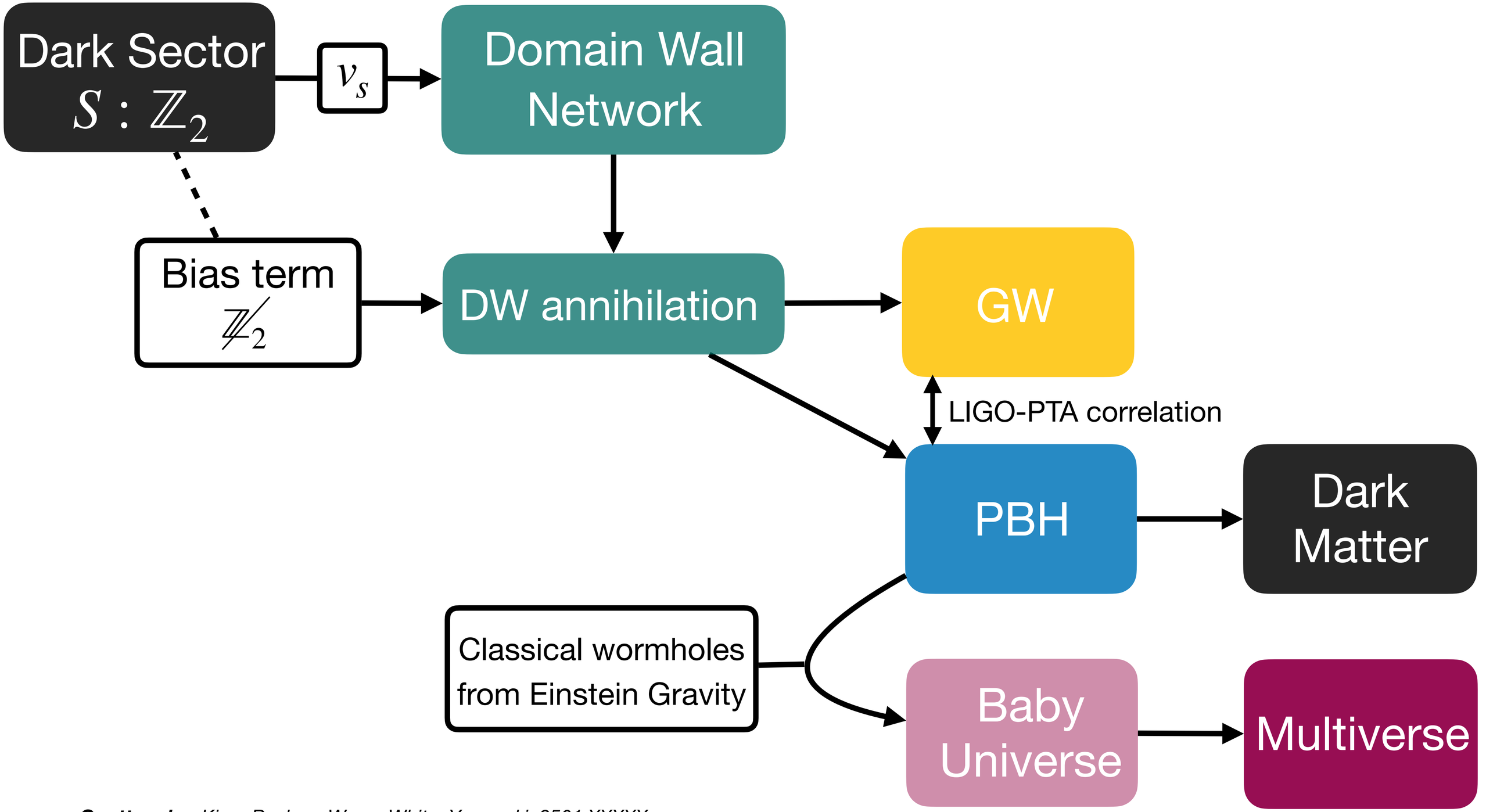

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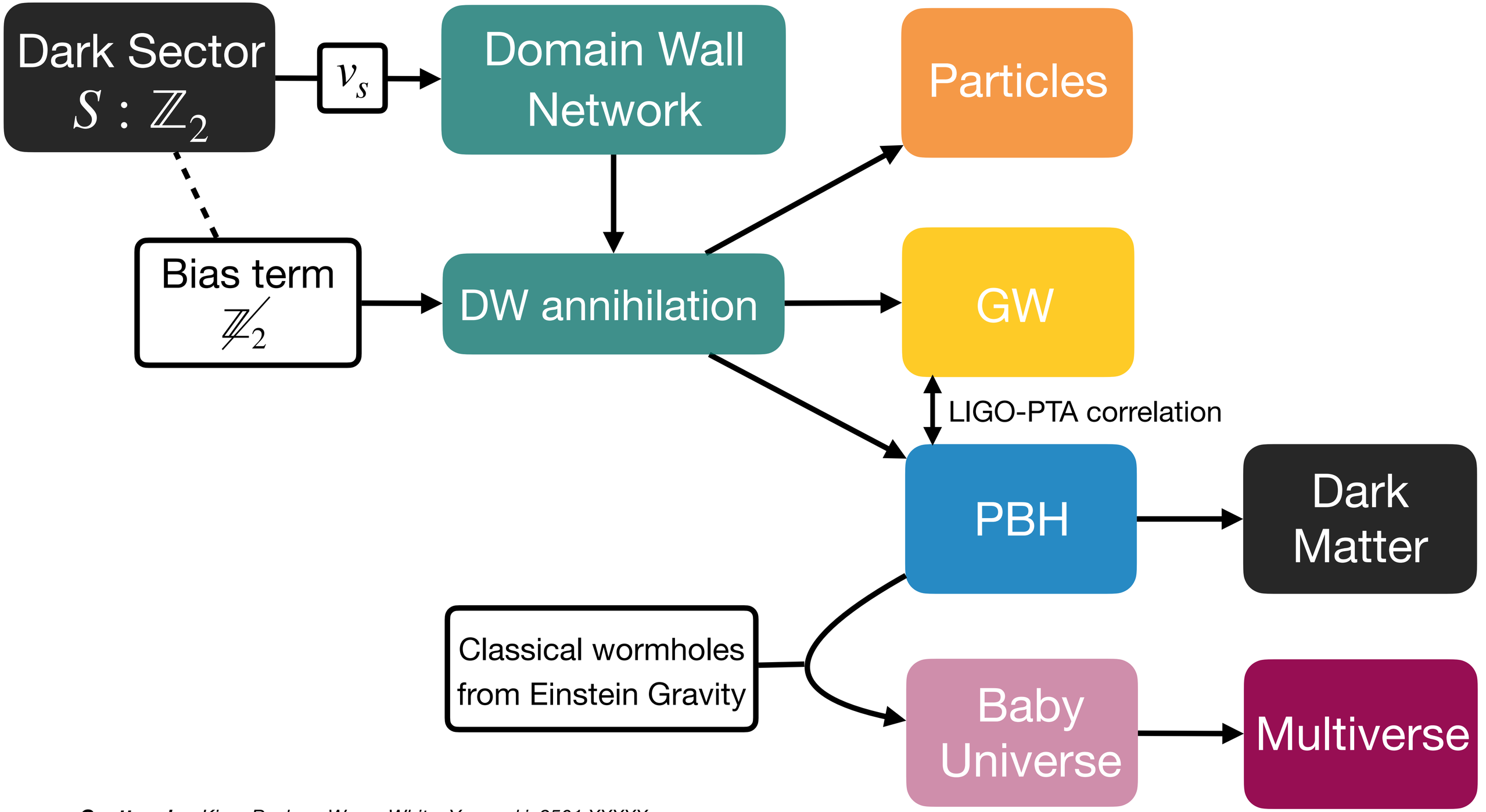

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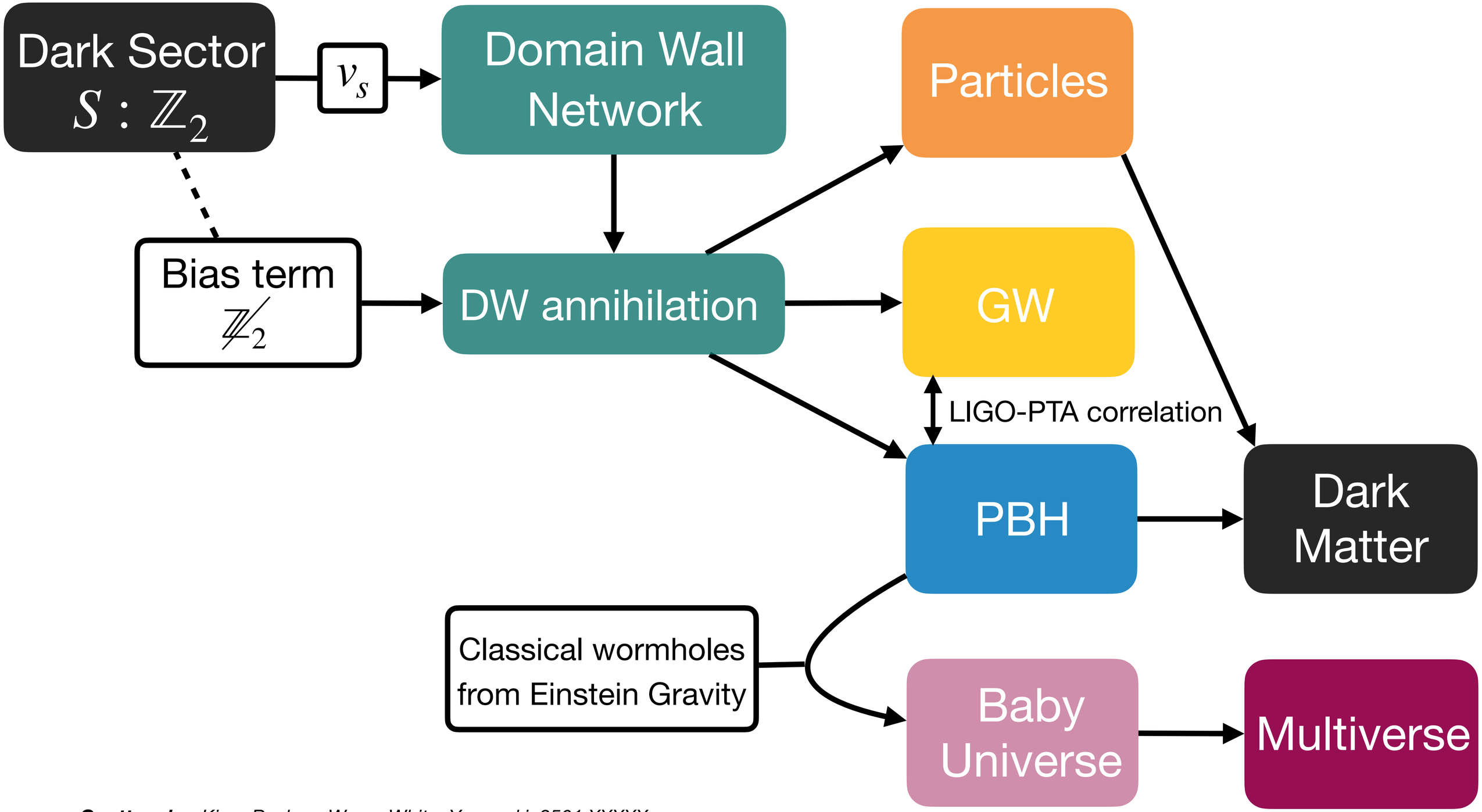

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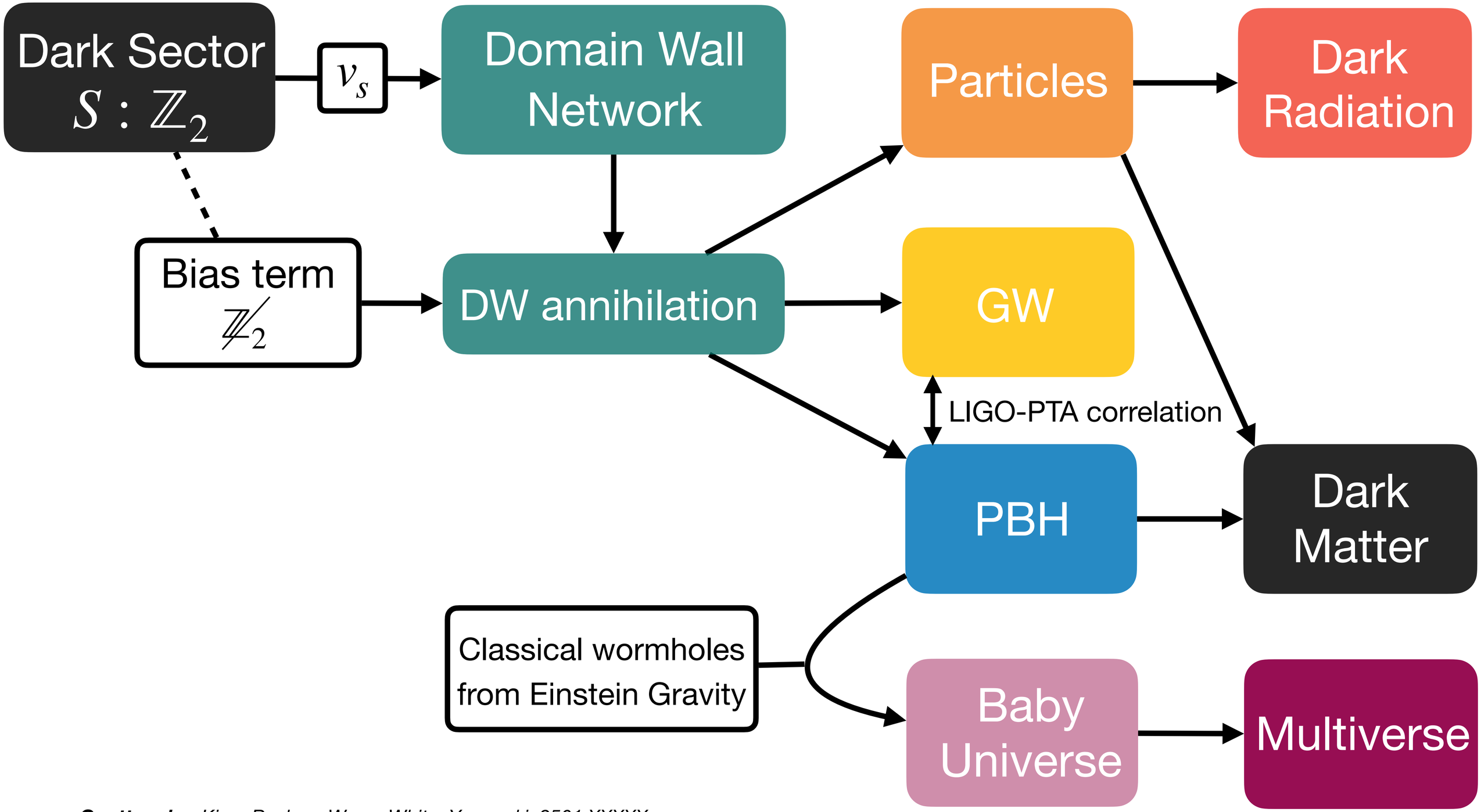

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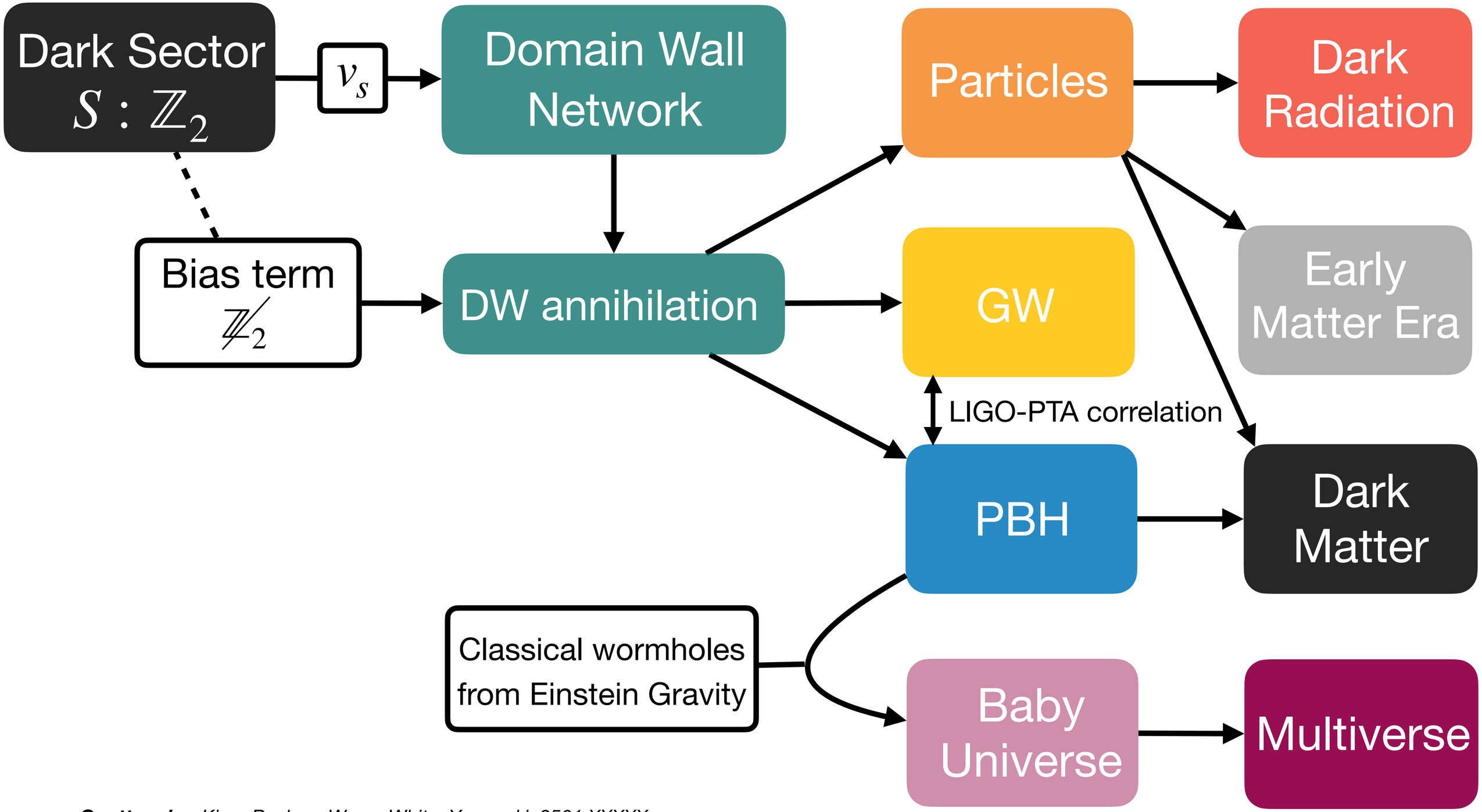

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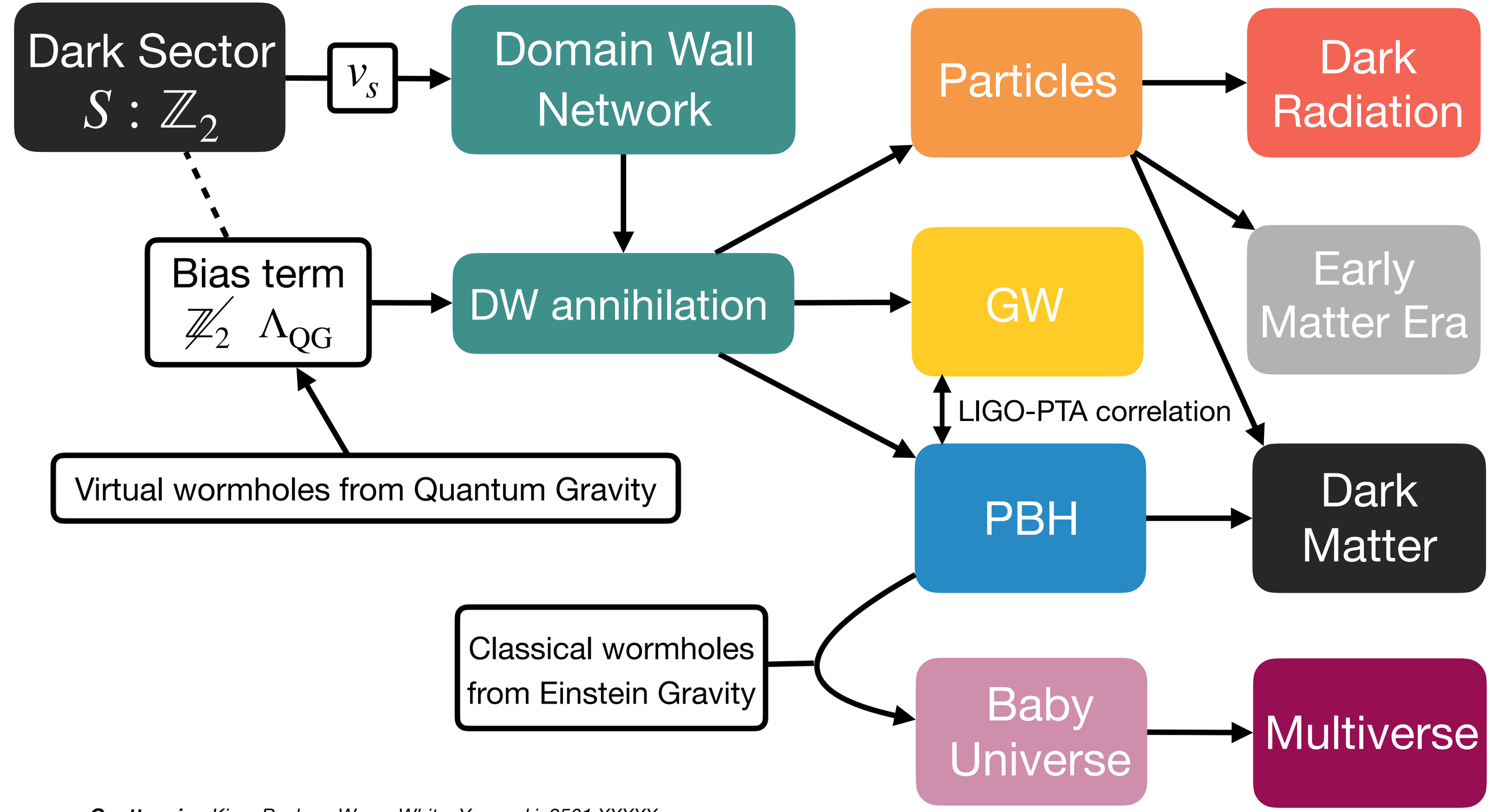

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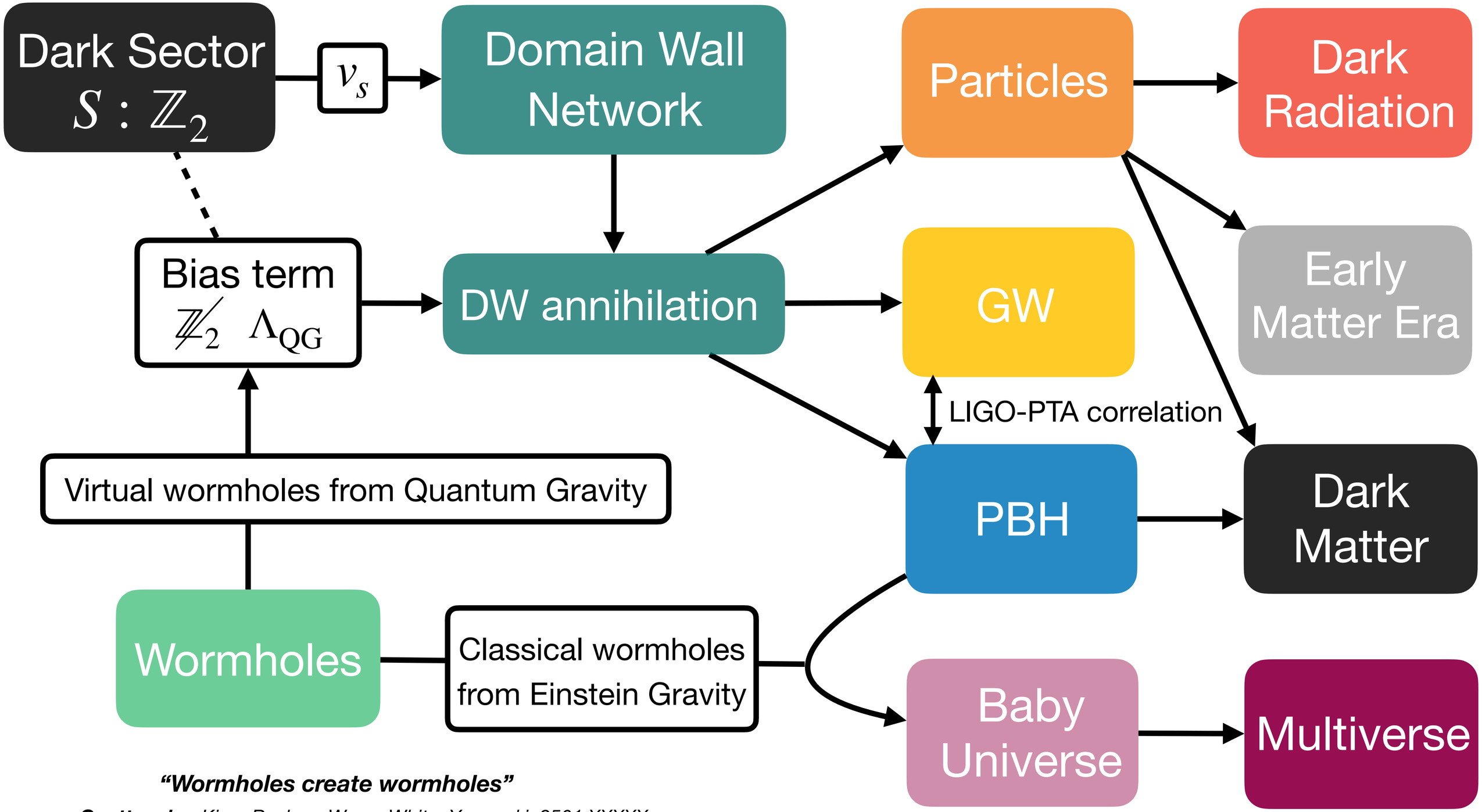

"Wormholes create wormholes"

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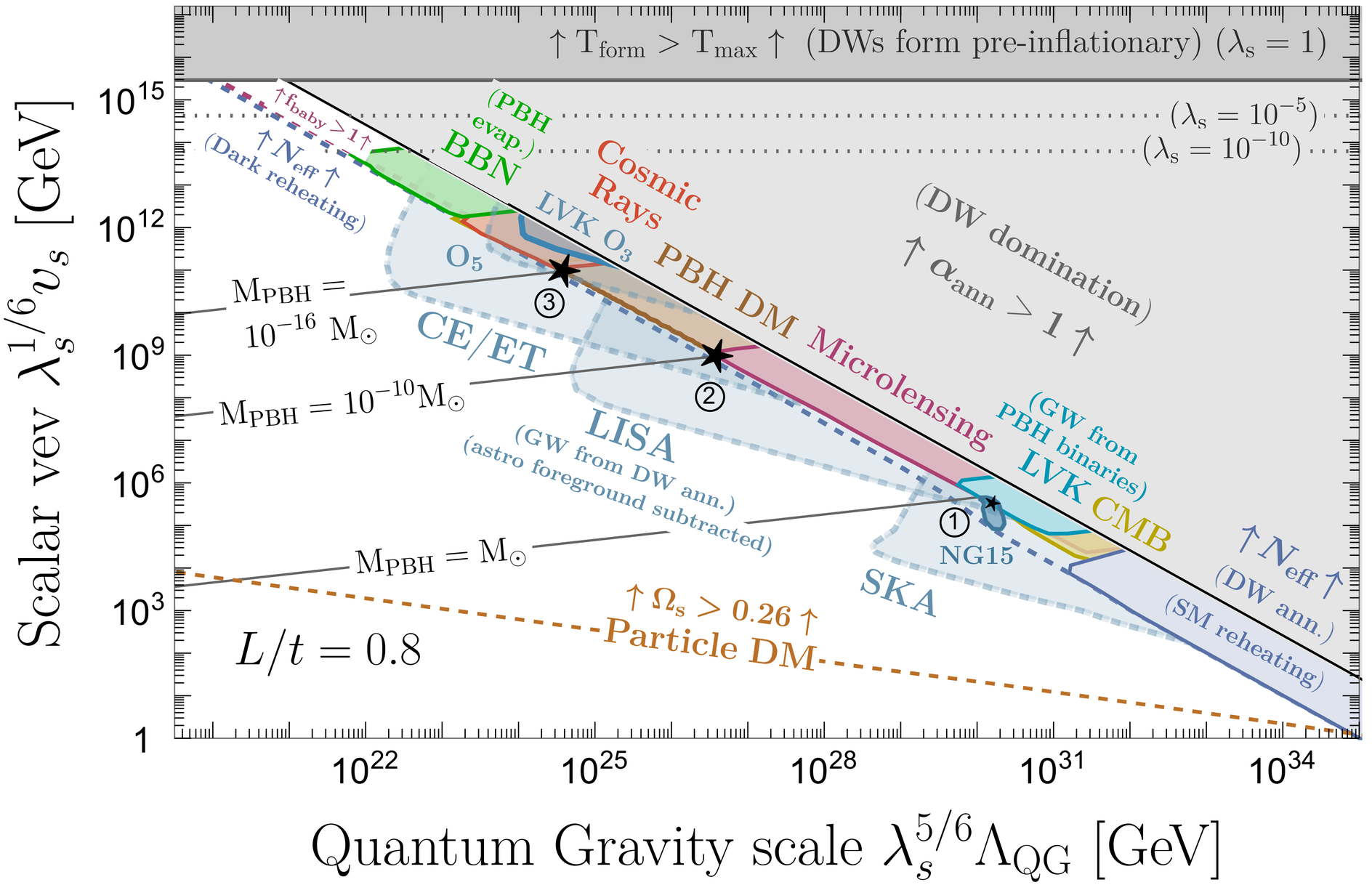
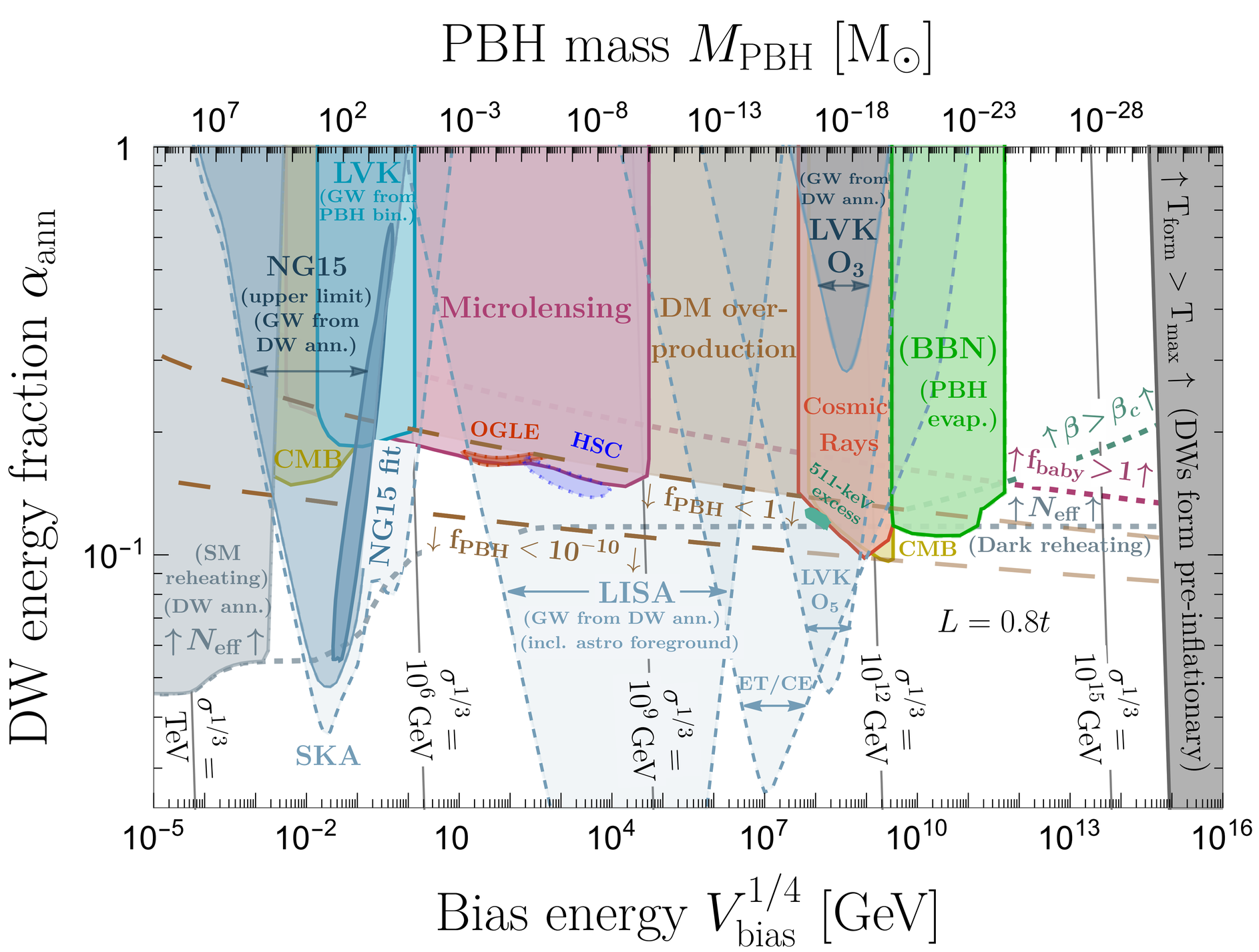
Domain wall networks biased by Quantum Gravity

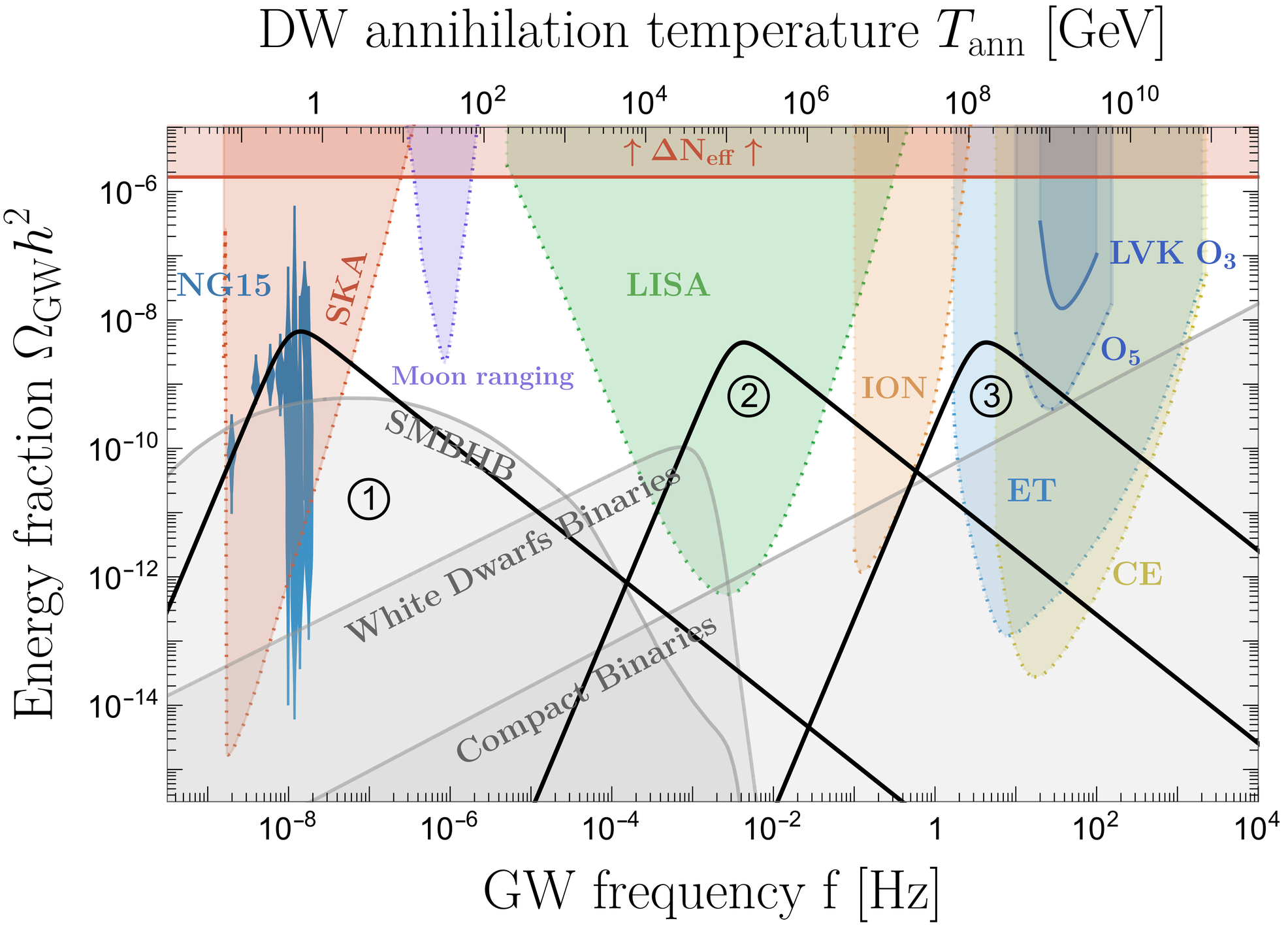


$$\sigma \simeq \frac{4}{3}\sqrt{\frac{\lambda_s}{2}}v_s^3$$

$$V_{\rm bias} \simeq \frac{v_s^5}{\Lambda_{\rm QG}}$$

$$\alpha_{\rm ann} \simeq \lambda_s \frac{v_s \Lambda_{\rm QG}}{M_{\rm pl}^2}$$


PBH mass $M_{\rm PBH}$ [$M_\odot$]
10^{7}
10^{2}
10^{-3}
10^{-8}
10^{-13}
10^{-18}
10^{-23}
10^{-28}
DW energy fraction $\alpha_{\rm ann}$
1
10^{-1}
LVK
(GW from PBH bin.)
NG15
(upper limit)
(GW from DW ann.)
Microlensing
DM over-production
(GW from DW ann.)
LVK
O_3
(BBN)
(PBH evap.)
Cosmic Rays
511-keV excess
OGLE
HSC
CMB
NG15 fit
$\uparrow \beta > \beta_c \uparrow$
$\uparrow f_{\rm baby} > 1 \uparrow$
$\uparrow N_{\rm eff} \uparrow$
$\downarrow f_{\rm PBH} < 1 \downarrow$
$\downarrow f_{\rm PBH} < 10^{-10} \downarrow$
CMB (Dark reheating)
(SM reheating)
(DW ann.)
$\uparrow N_{\rm eff} \uparrow$
LISA
(GW from DW ann.)
(incl. astro foreground)
LVK
O_5
$L = 0.8t$
SKA
ET/CE
$\sigma^{1/3} = 10^{6}$ GeV
$\sigma^{1/3} = 10^{9}$ GeV
$\sigma^{1/3} = 10^{12}$ GeV
$\sigma^{1/3} = 10^{15}$ GeV
$\sigma^{1/3} =$ TeV
$\uparrow T_{\rm form} > T_{\rm max} \uparrow$ (DWs form pre-inflationary)
10^{-5}
10^{-2}
10
10^{4}
10^{7}
10^{10}
10^{13}
10^{16}
Bias energy $V_{\rm bias}^{1/4}$ [GeV]


DW annihilation temperature $T_{\rm ann}$ [GeV]
1
10^2
10^4
10^6
10^8
10^{10}
↑ $\Delta N_{\rm eff}$ ↑
Energy fraction $\Omega_{\rm GW}h^2$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
NG15
SKA
Moon ranging
LISA
ION
LVK O_3
O_5
ET
CE
SMBHB
White Dwarfs Binaries
Compact Binaries
①
②
③
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^2
10^4
GW frequency f [Hz]