

# Primordial Black Holes from Domain Wall Networks

## and the discovery of nHz GWs

Gouttenoire, Vitagliano, [2306.17841](#)

Gouttenoire, Vitagliano, [2311.07670](#)

**Yann Gouttenoire**

**25th January 2024**

**Rencontres de Physique des Particules 2024**

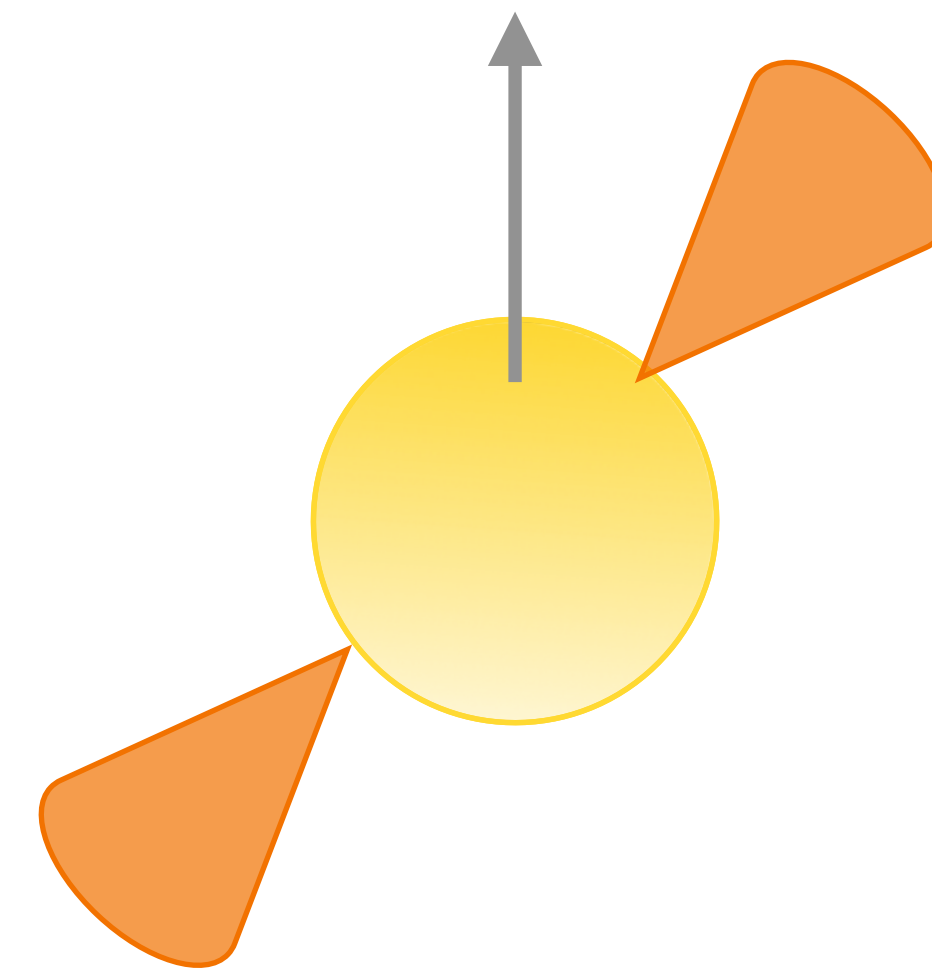
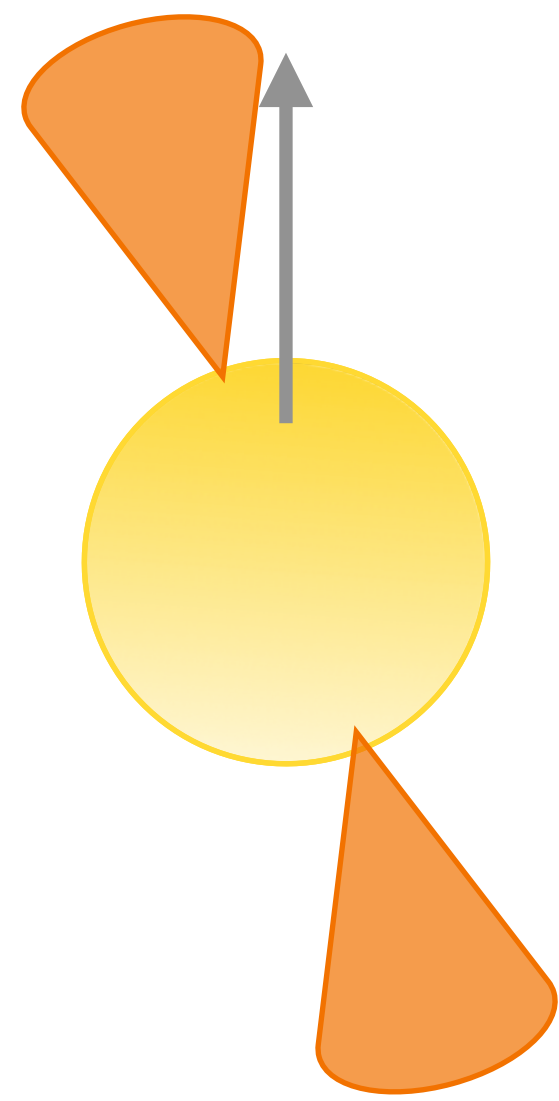
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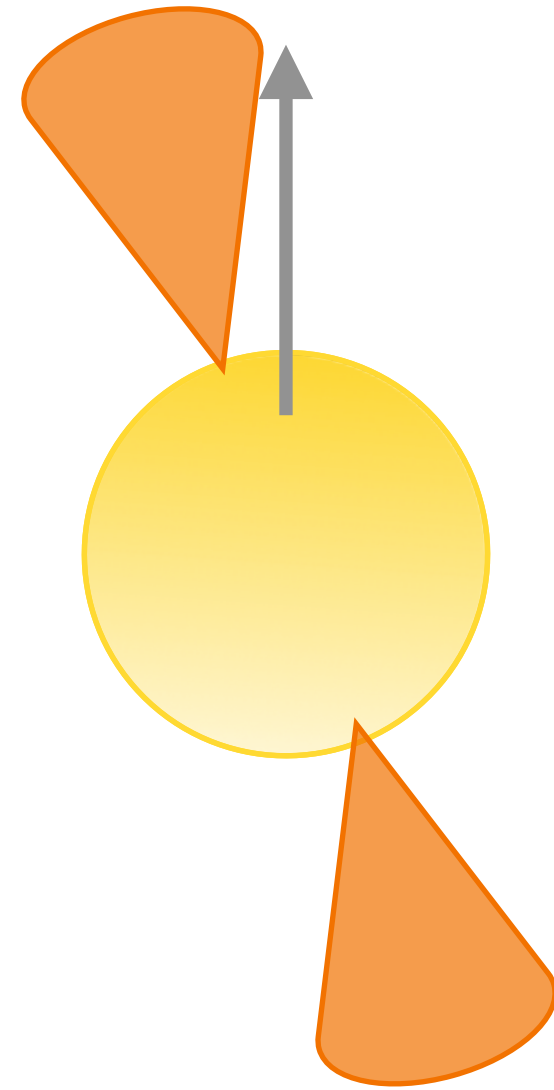
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## *The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find*



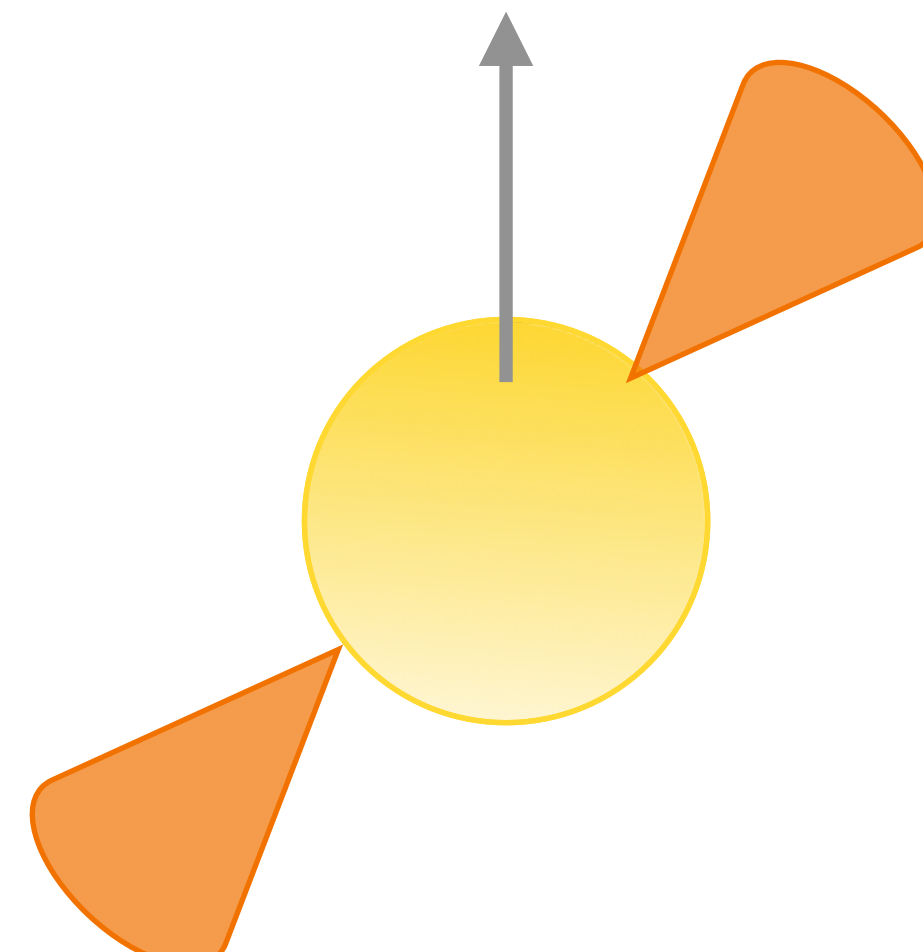
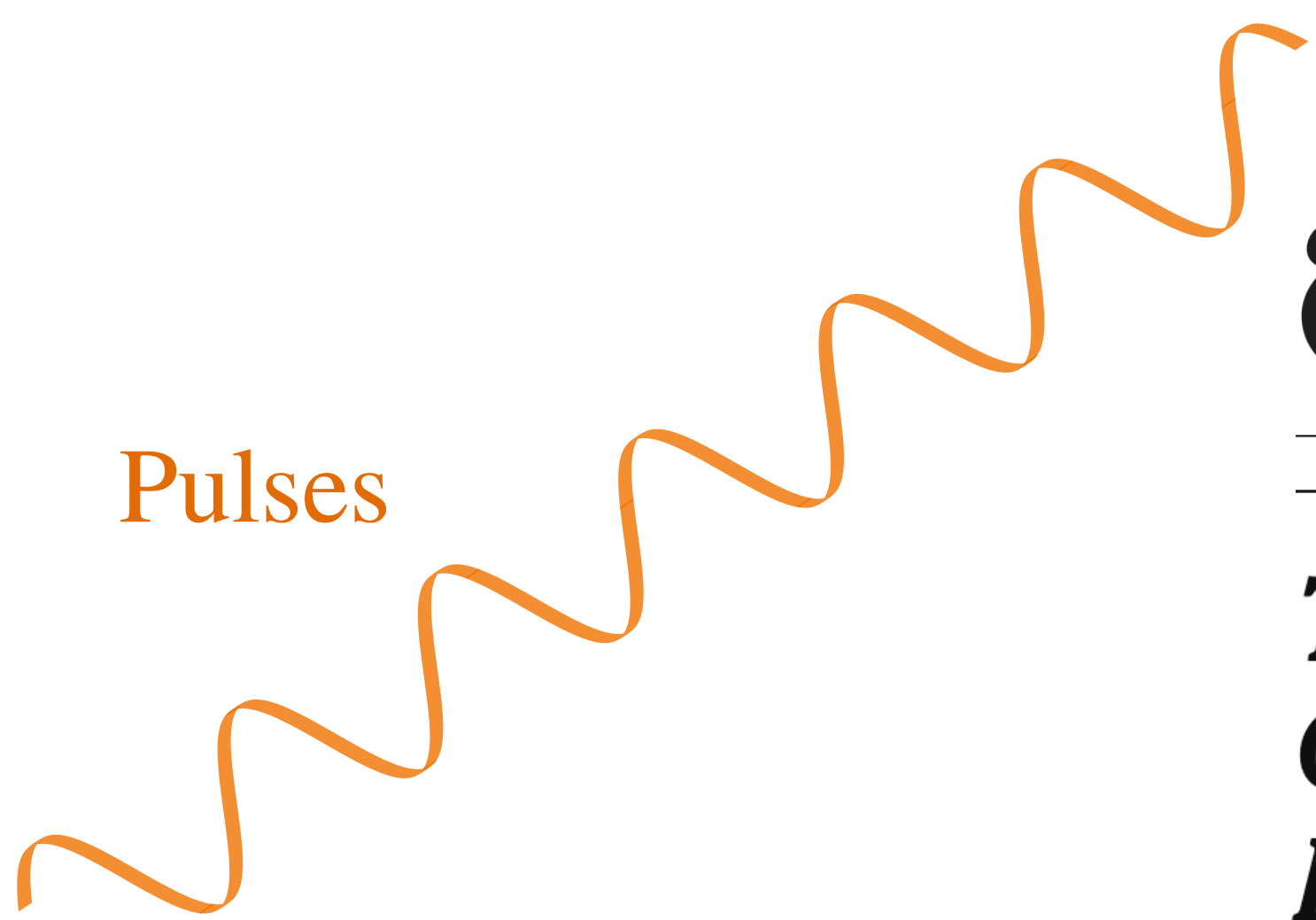




Pulses



Pulses



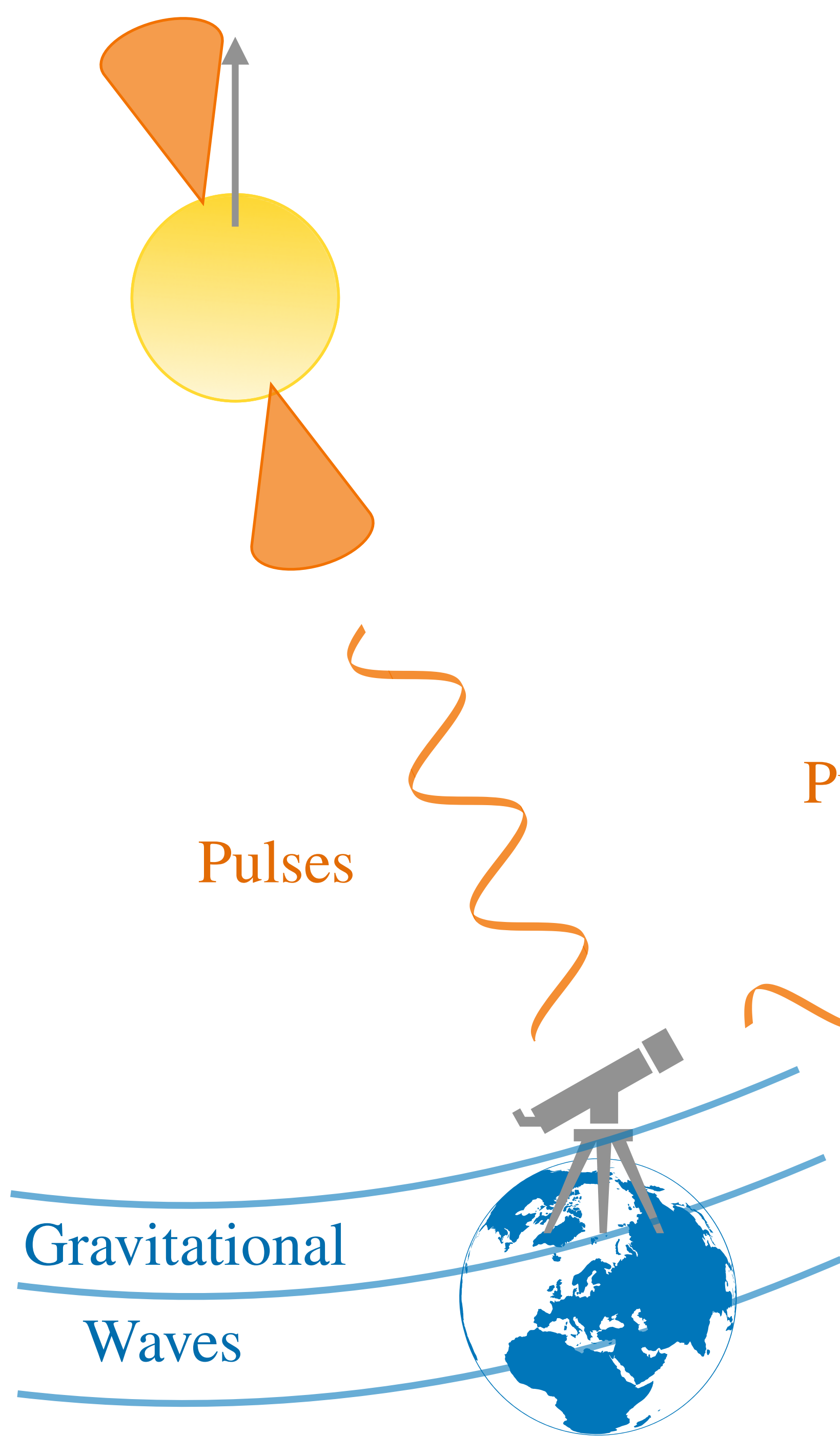
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Pulses

Pulses

Gravitational  
Waves

# The New York Times

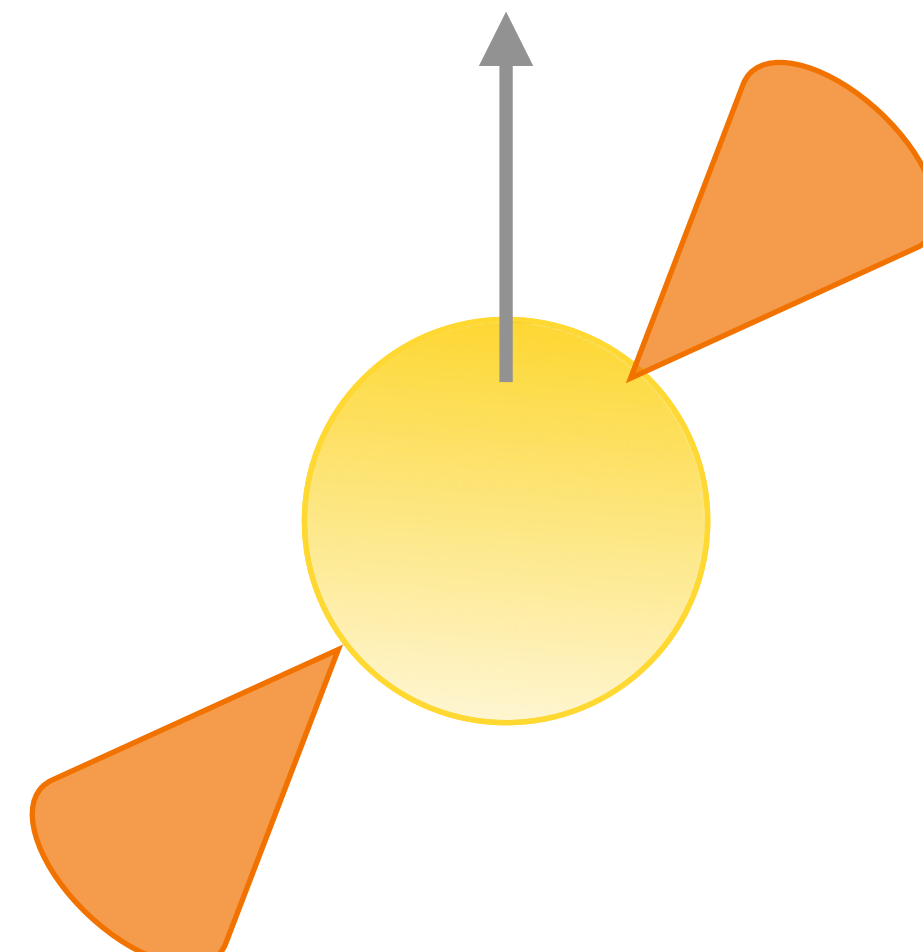
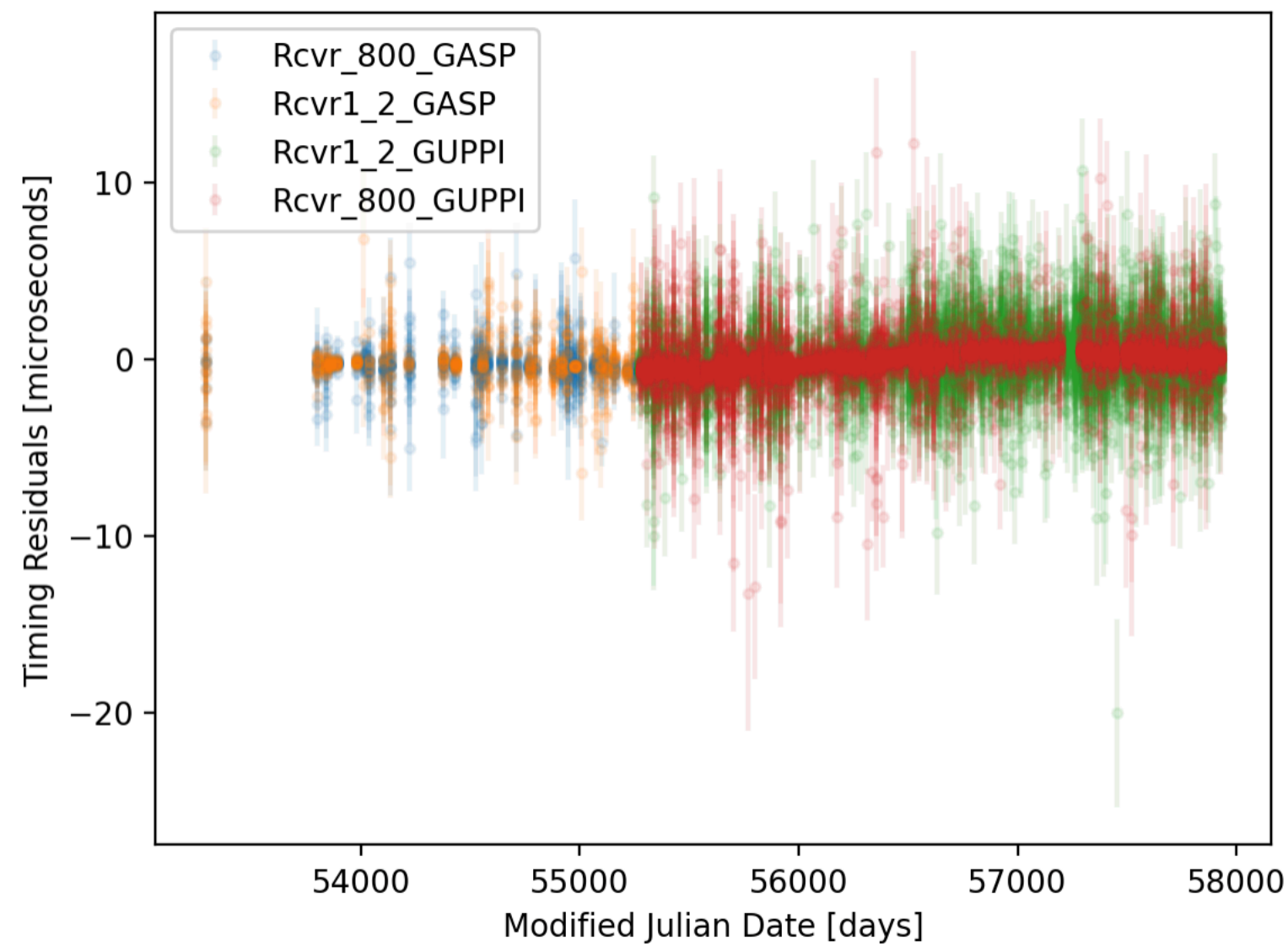
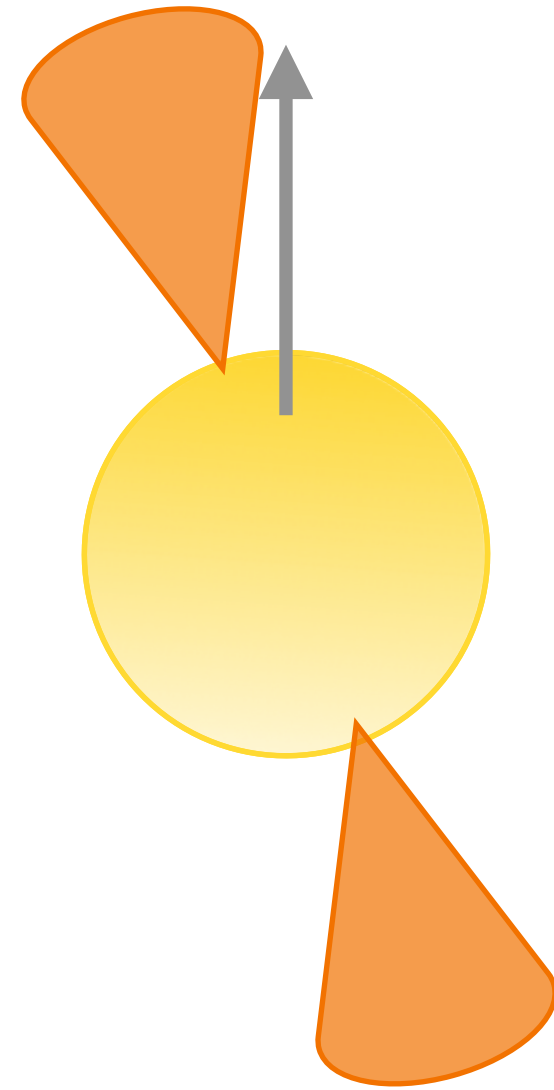
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Pulses

Pulses

Gravitational Waves

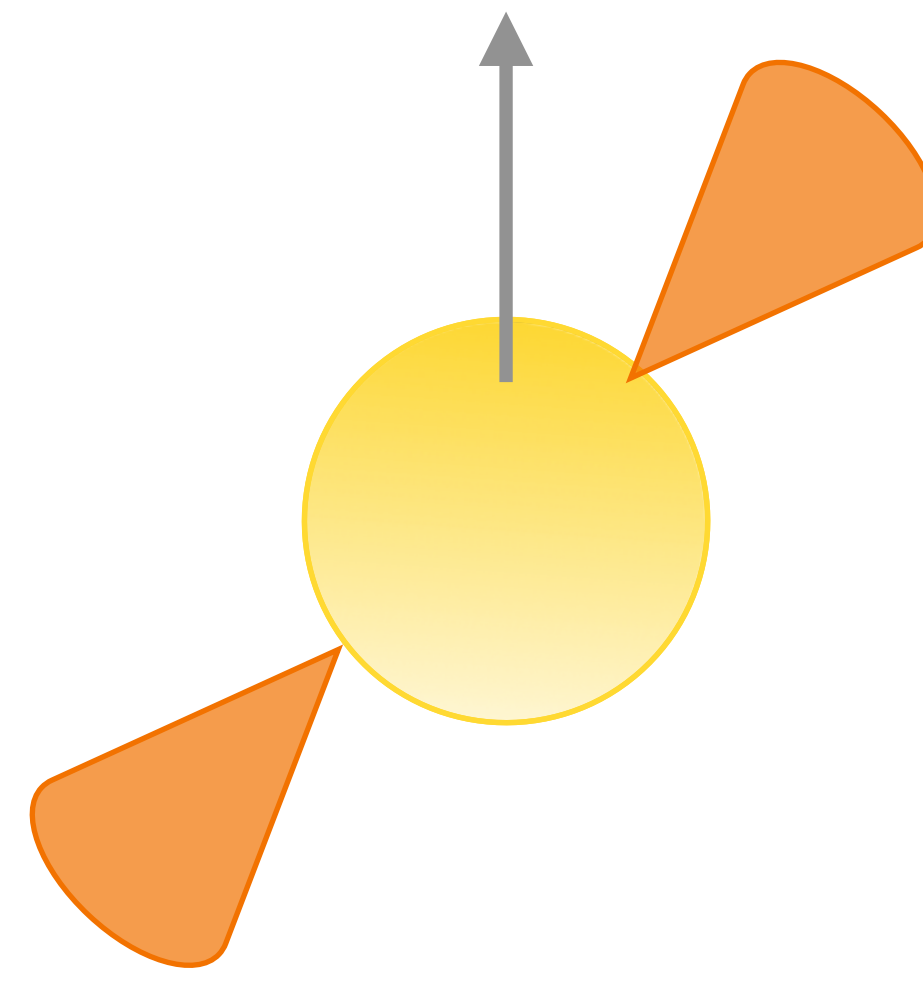
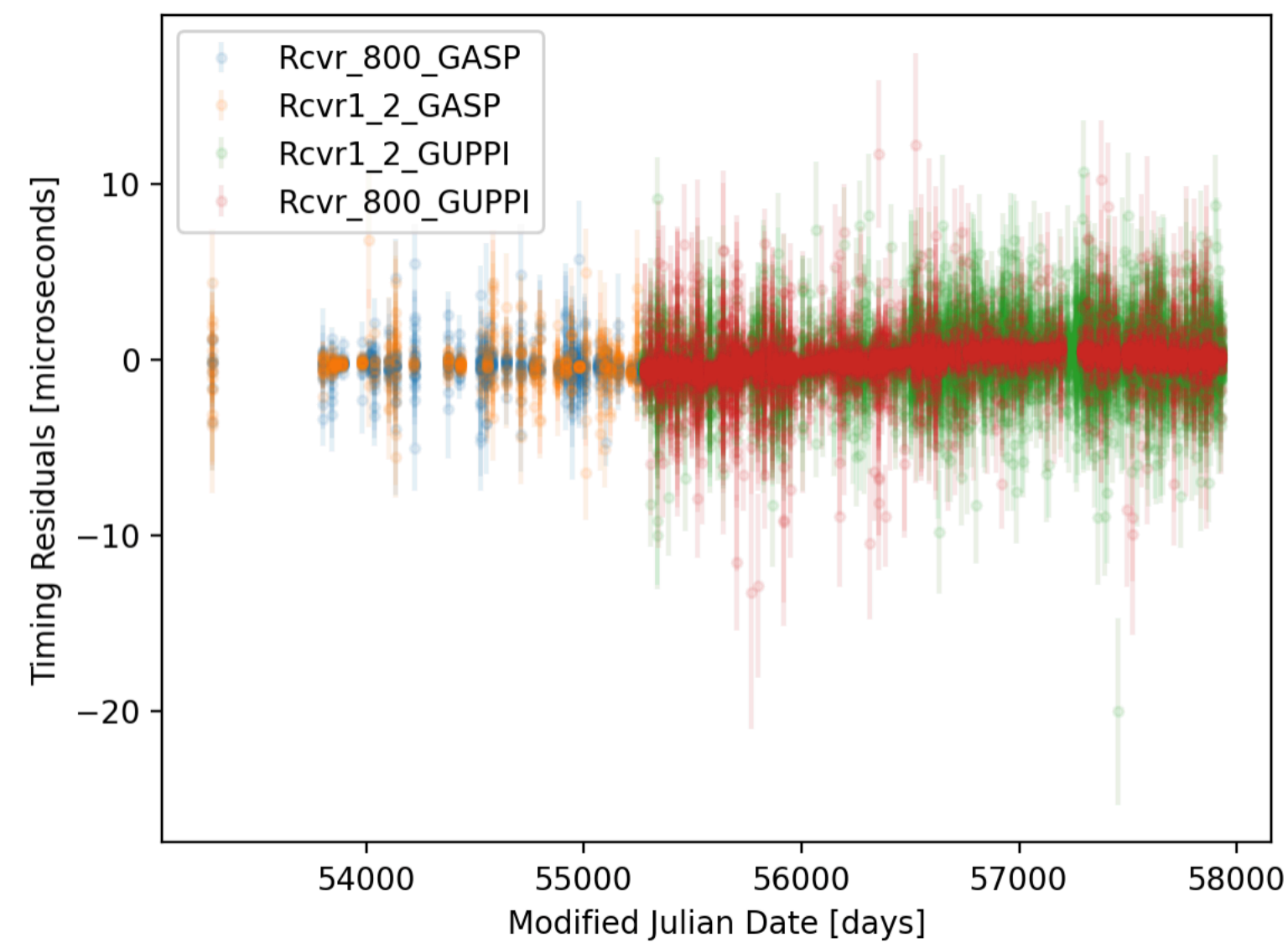
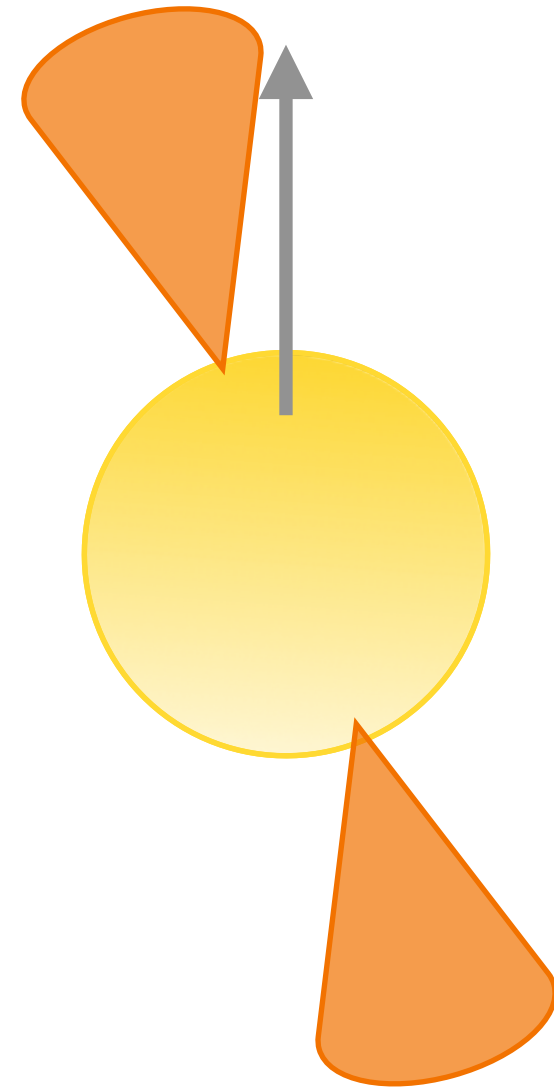


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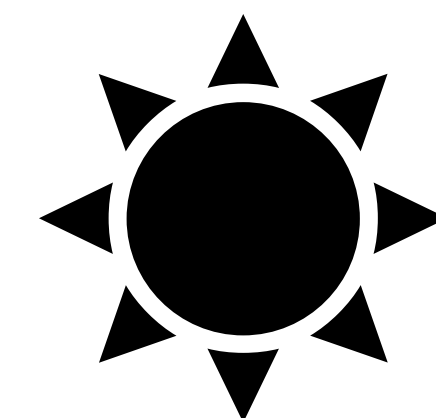
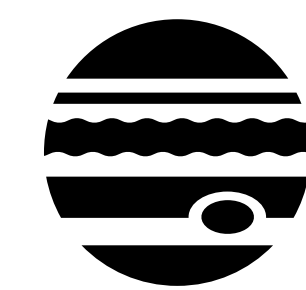
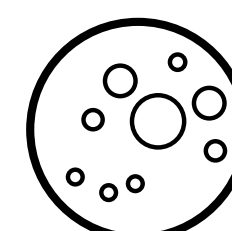




Pulses

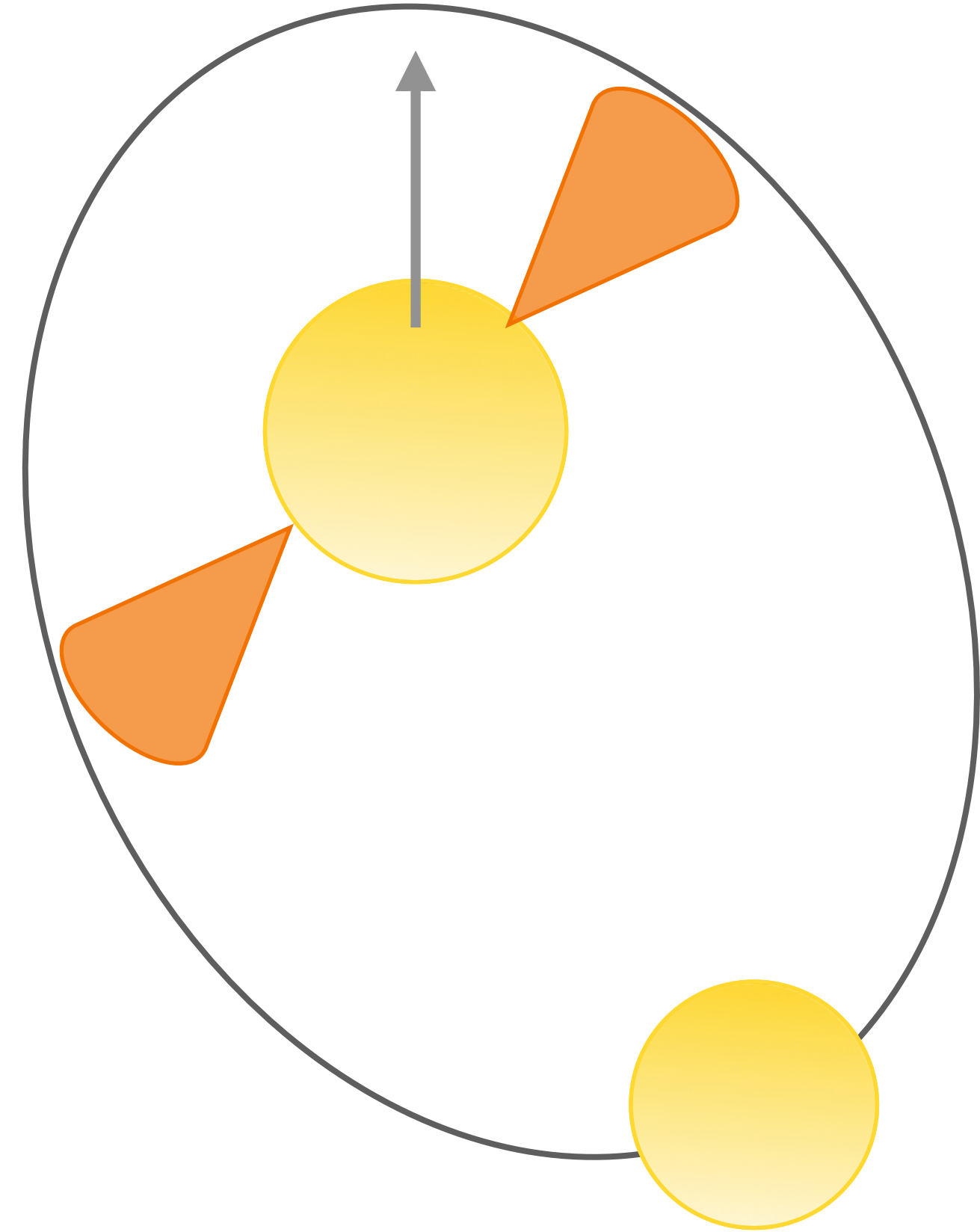
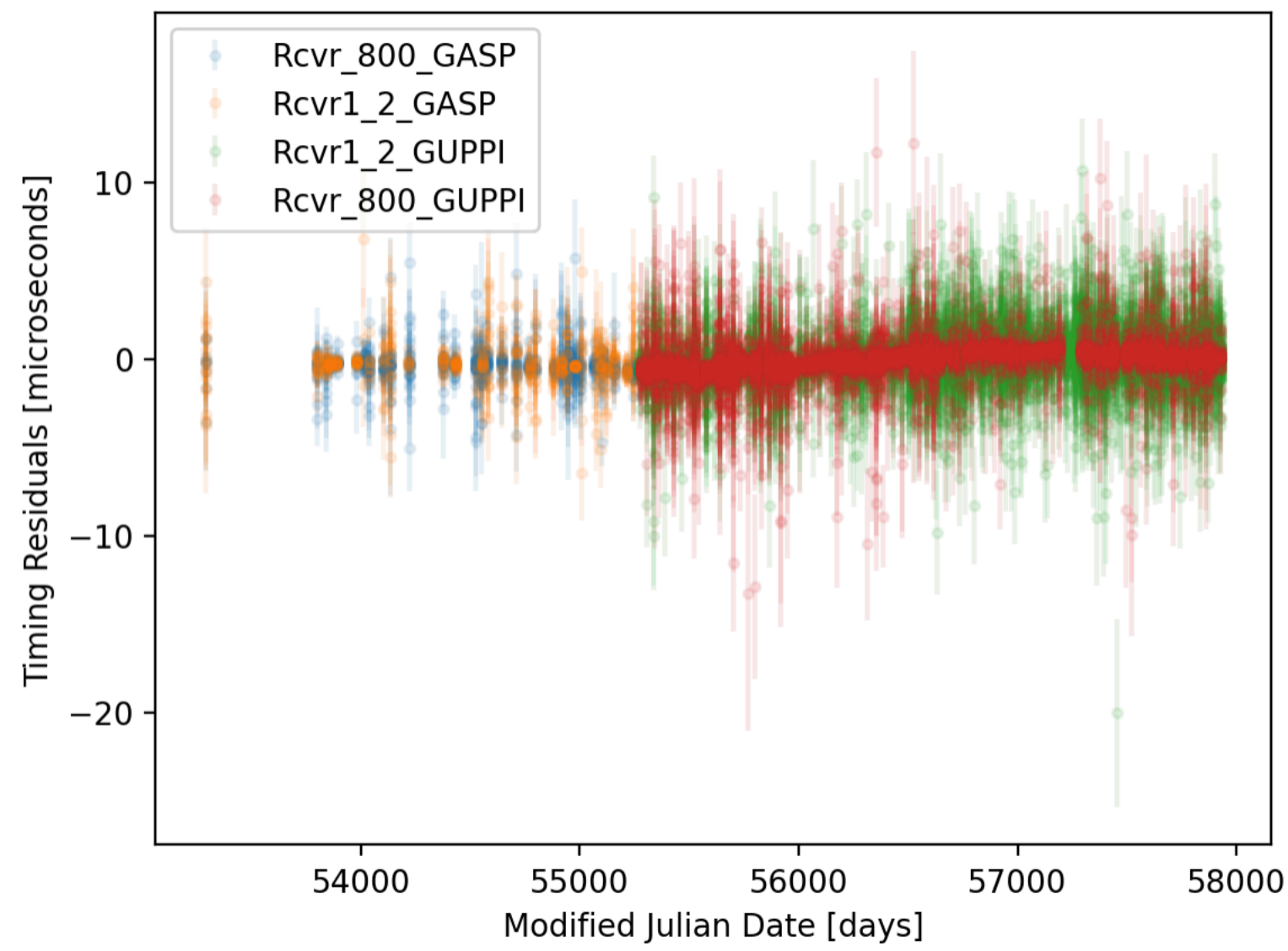
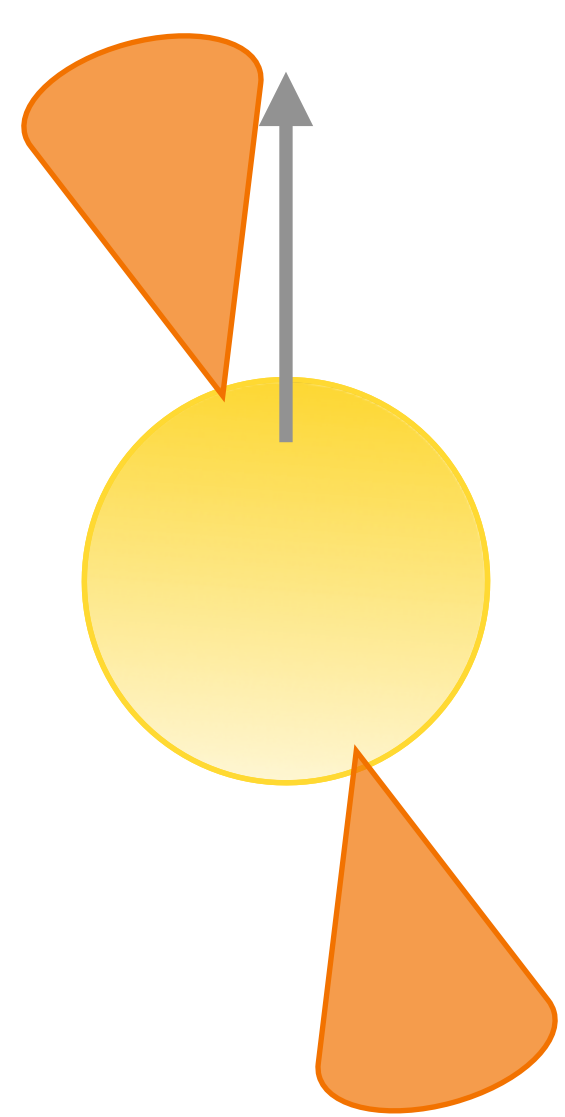
Pulses

Gravitational  
Waves



Solar system systematics



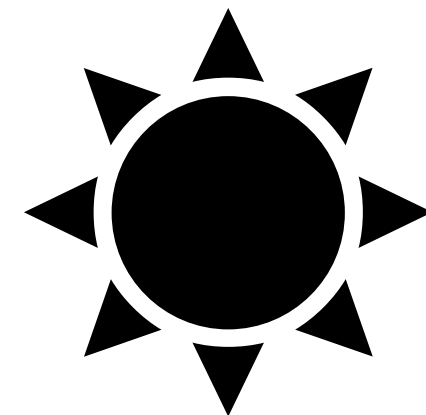
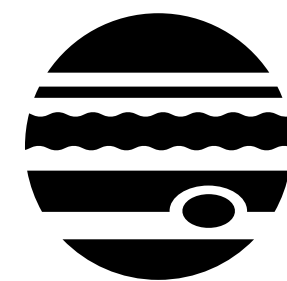
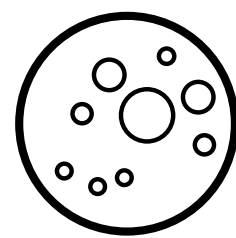


Pulses

Pulses

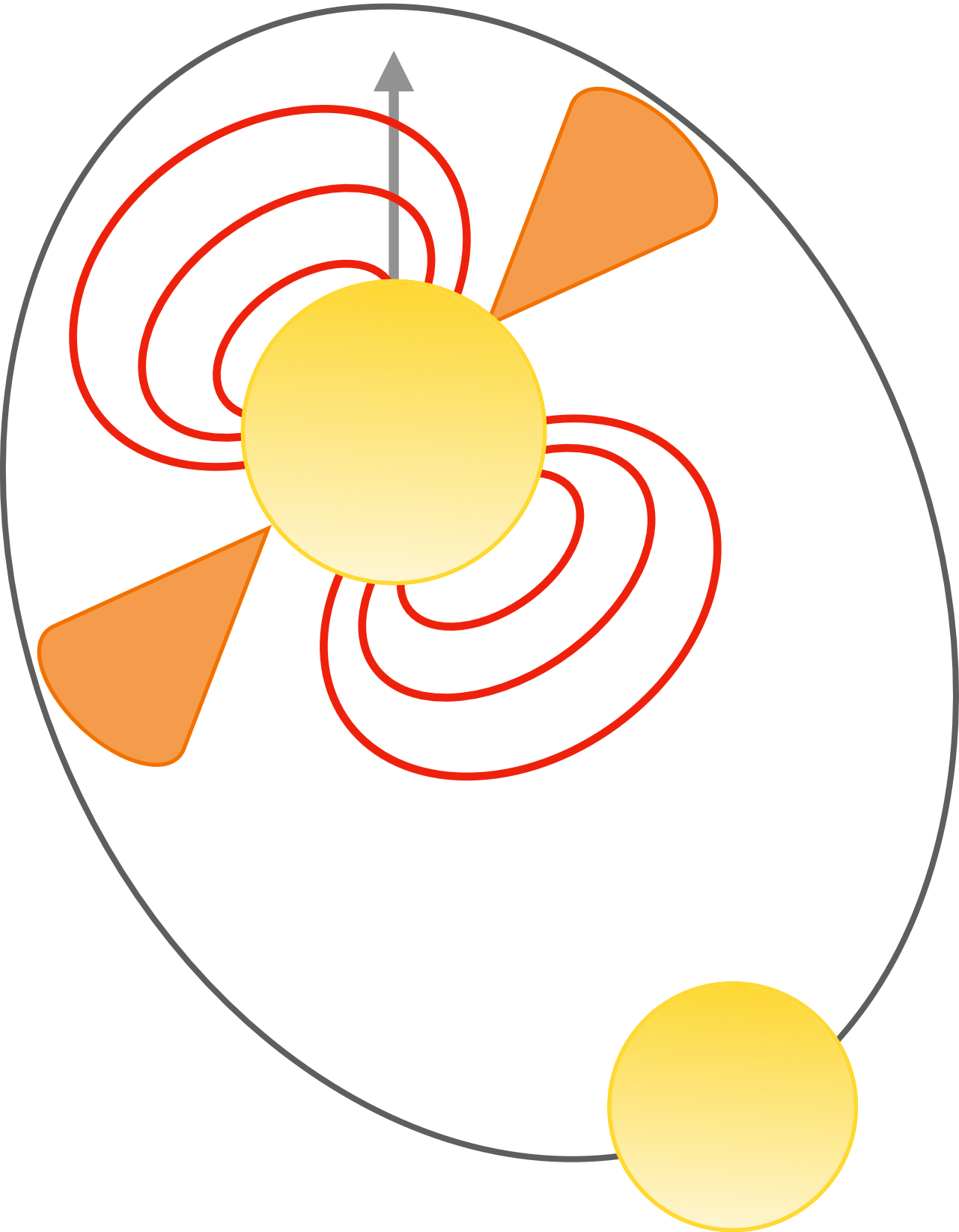
Pulsar companion systematics

Gravitational Waves



Solar system systematics

Pulsar red noise  
(e.g. magnetosphere fluctuation)



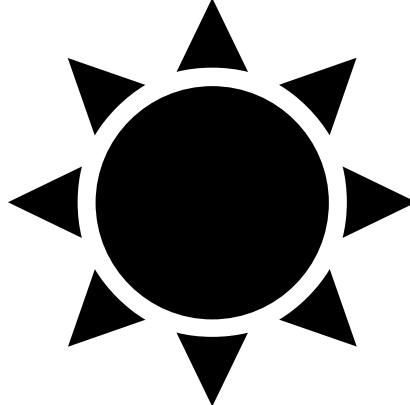
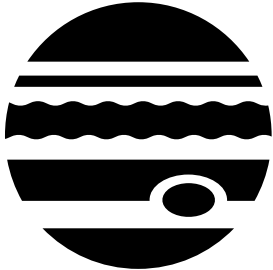
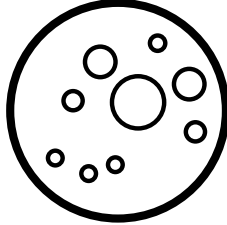
Pulsar companion systematics

Pulses

Pulses

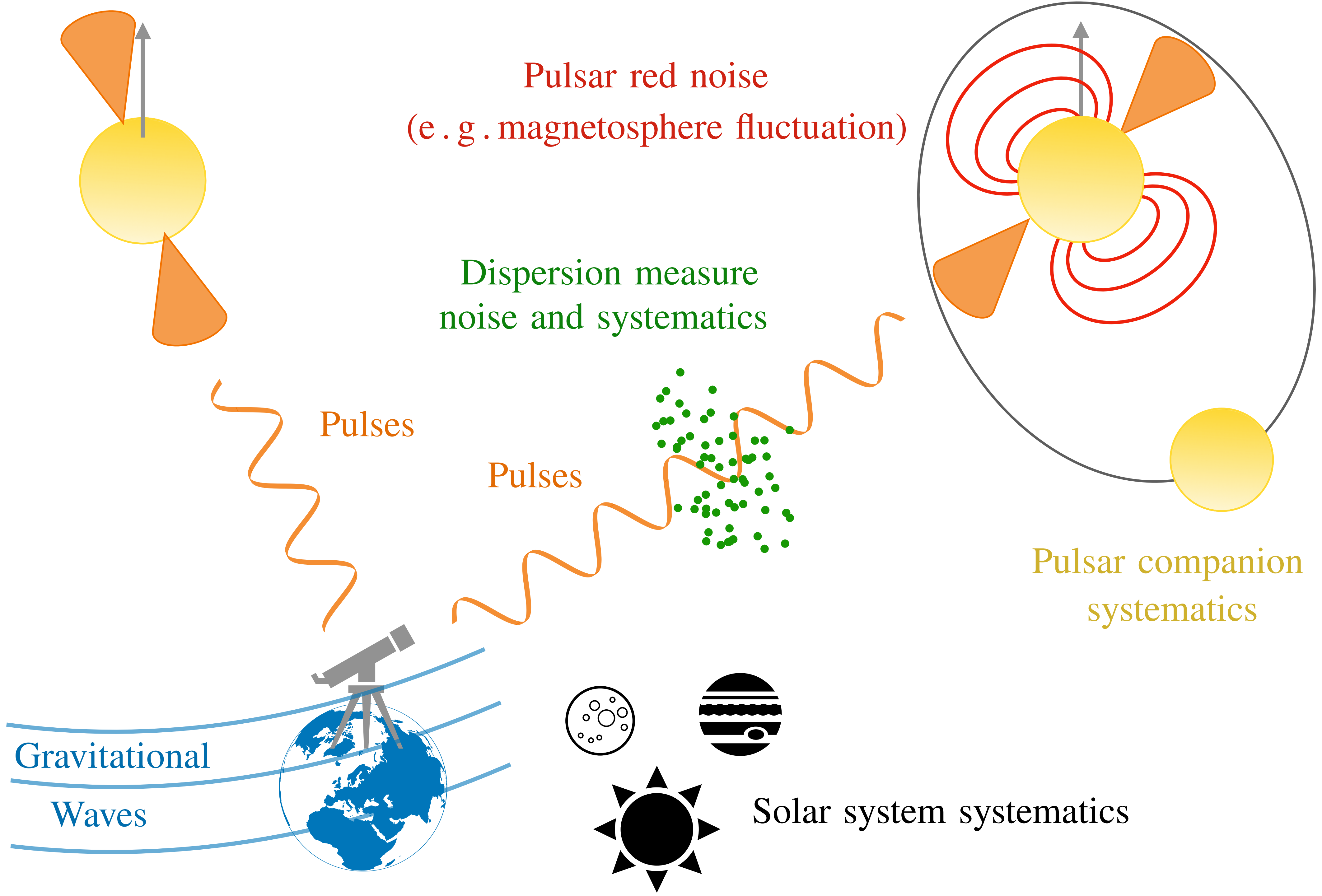


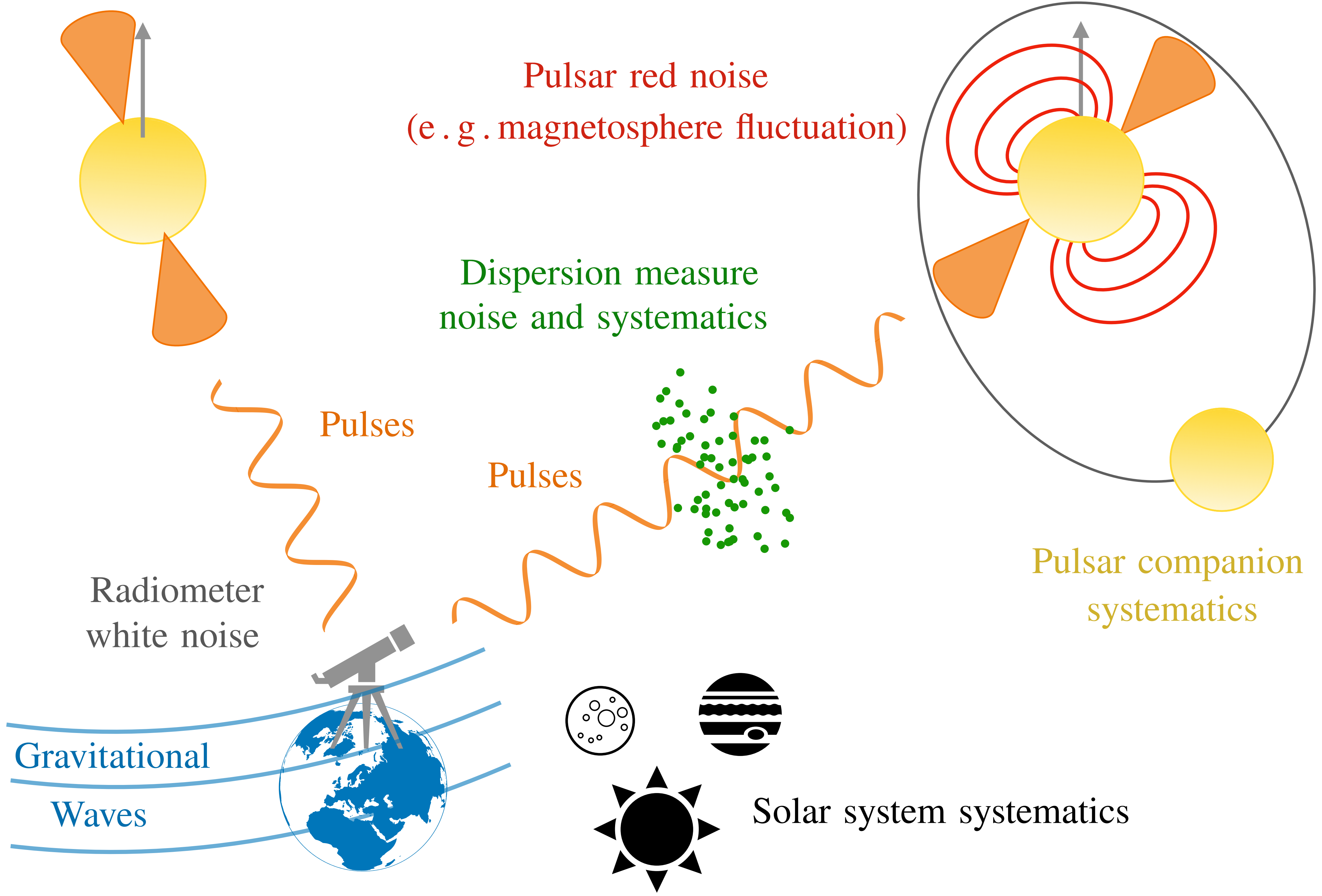
Gravitational Waves



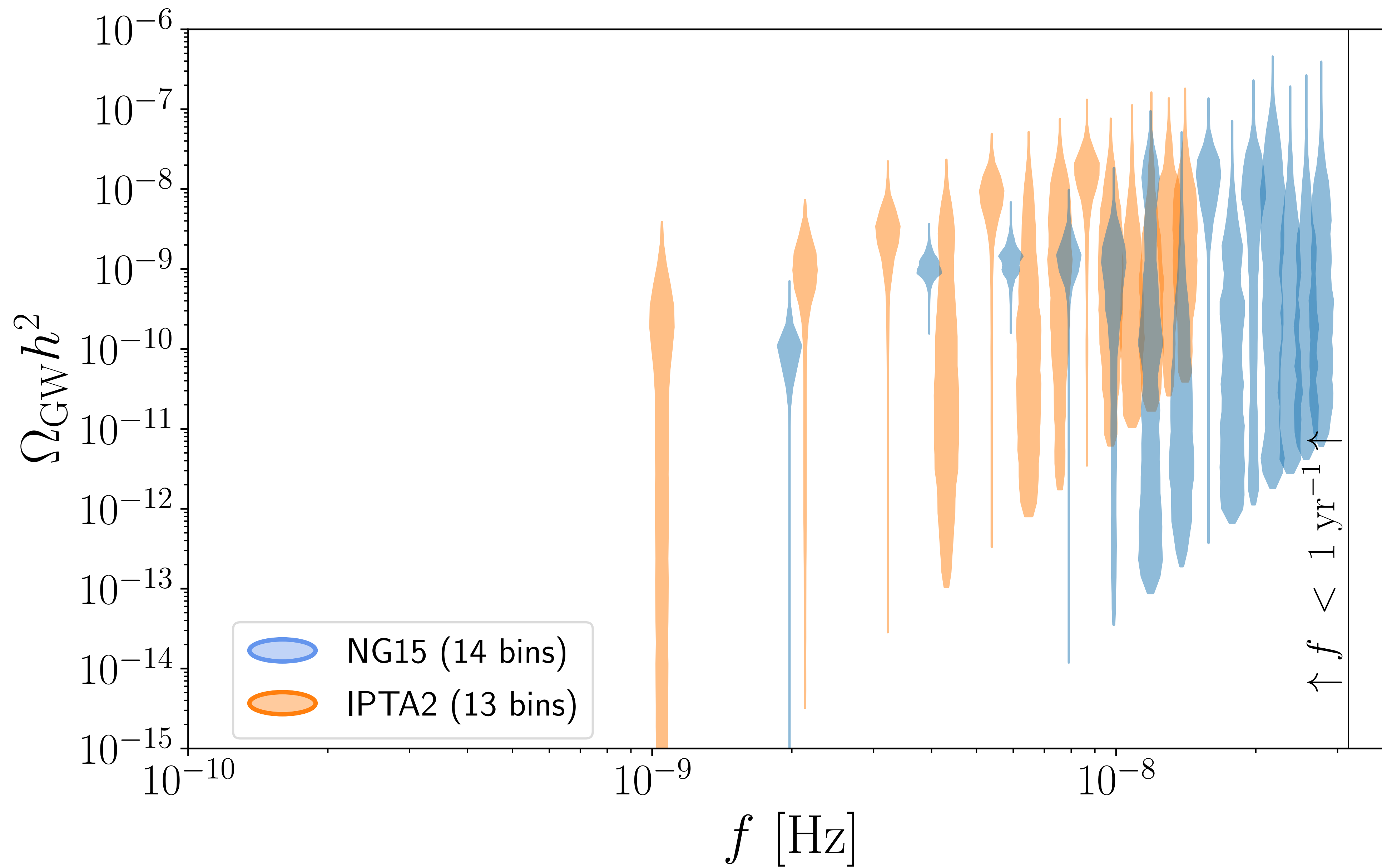
Solar system systematics



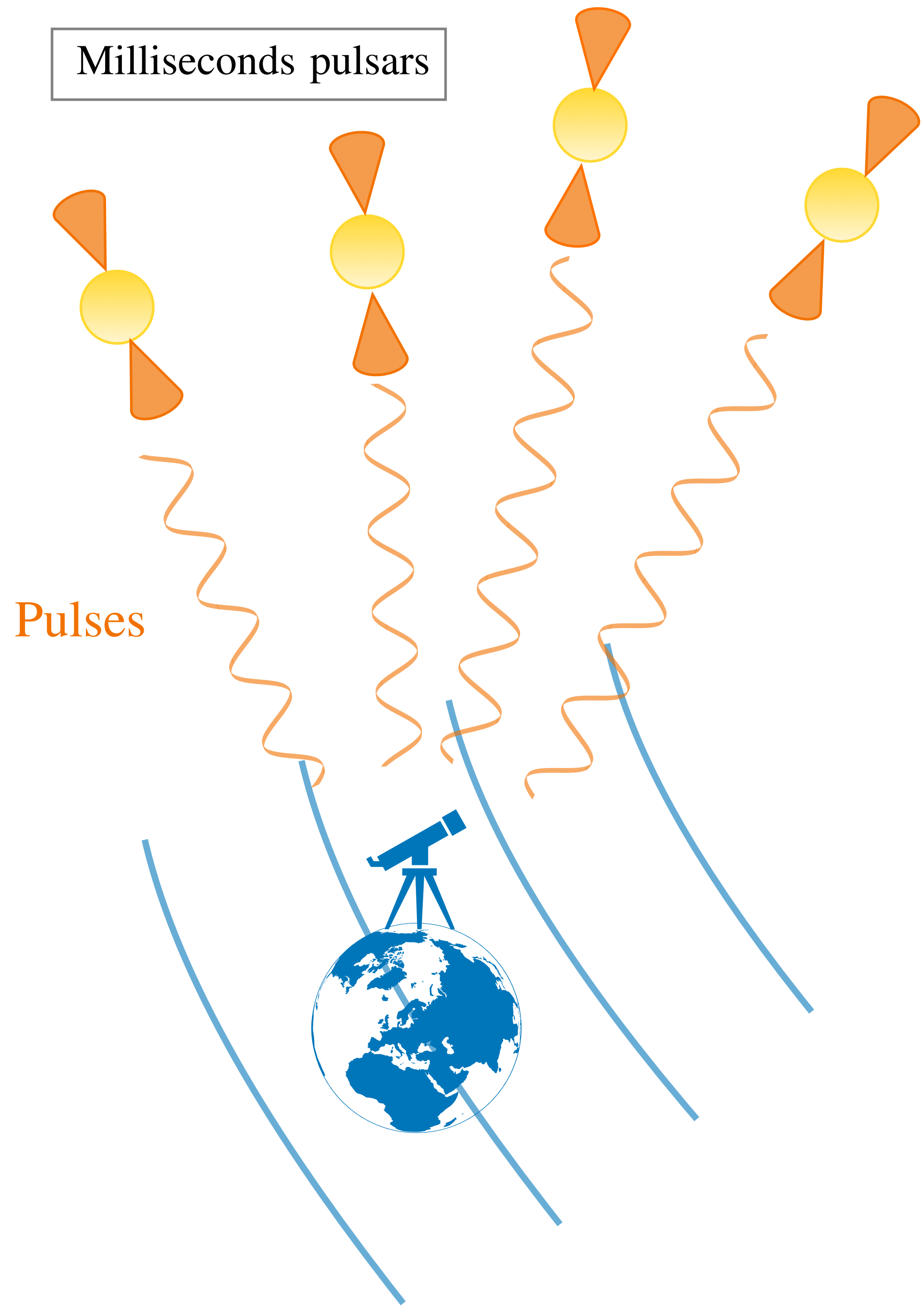








Milliseconds pulsars



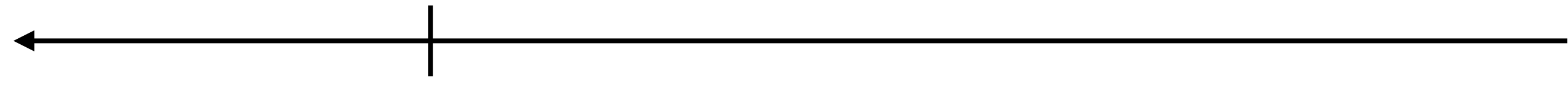


Milliseconds pulsars

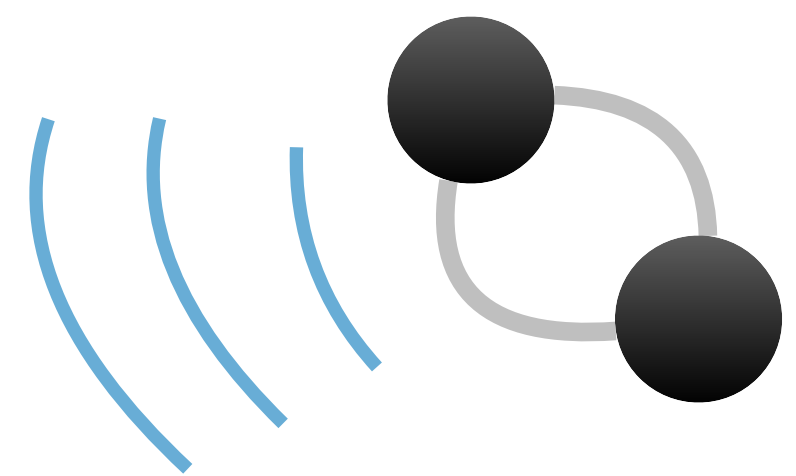
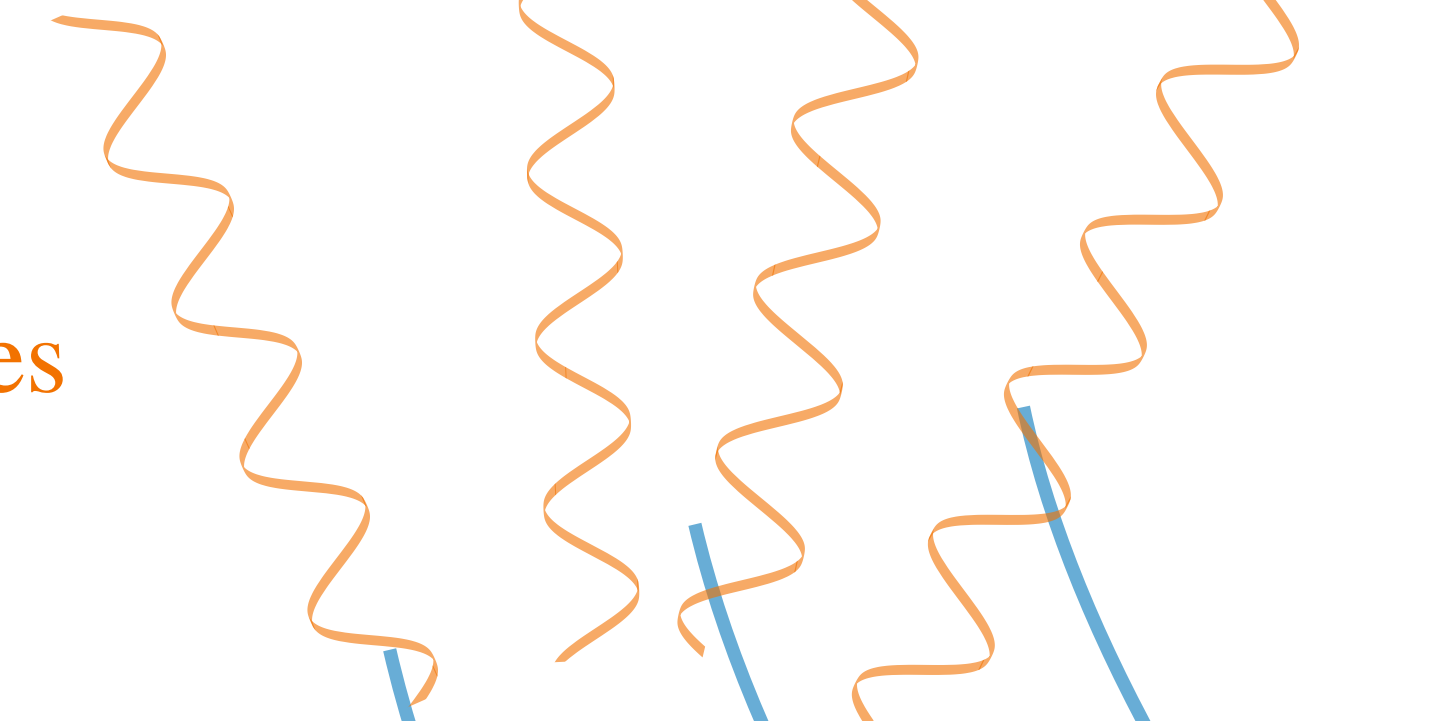
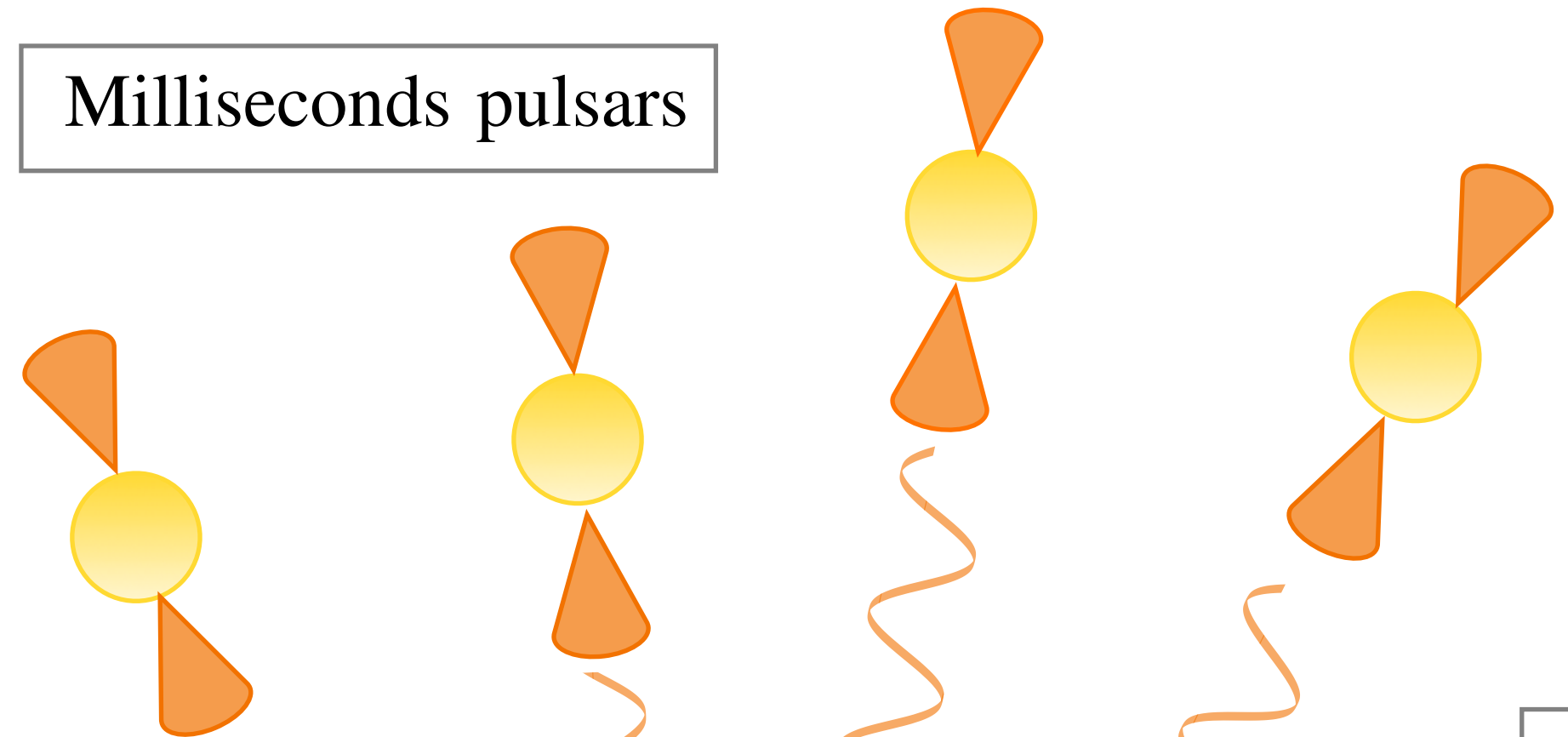
Supermassive  
black holes binaries

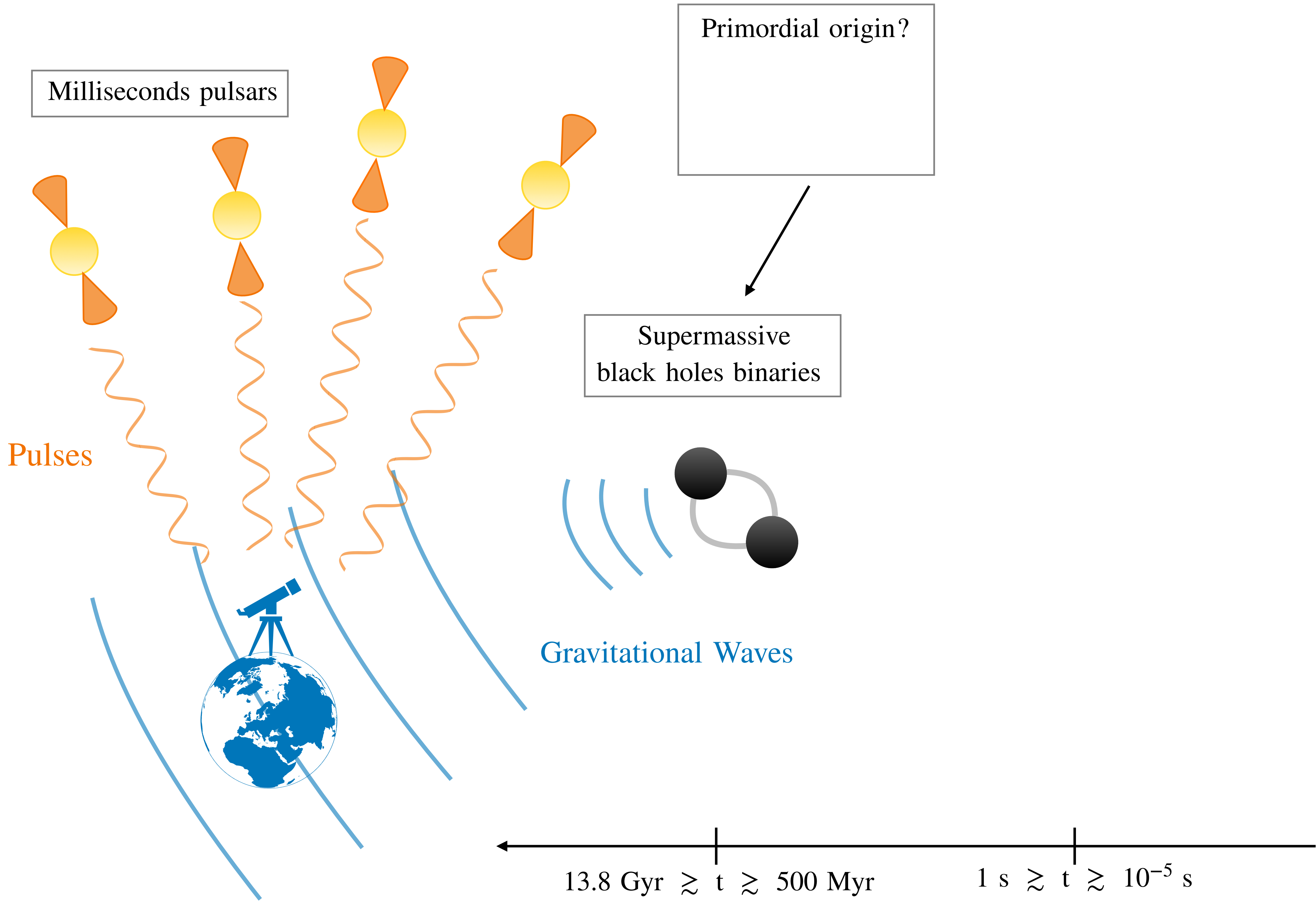
Pulses

Gravitational Waves



13.8 Gyr  $\gtrsim$  t  $\gtrsim$  500 Myr





Milliseconds pulsars

~~Primordial origin?~~  
**LSS and UV LF galaxy**  
YG, Trifinopoulos, Valogiannis, Vanvlasselaer, 2307.01457  
Except if clustering  
Depta, Schmidt-Hoberg, Schwaller, Tasillo 2306.17836

Supermassive black holes binaries

Pulses

Gravitational Waves

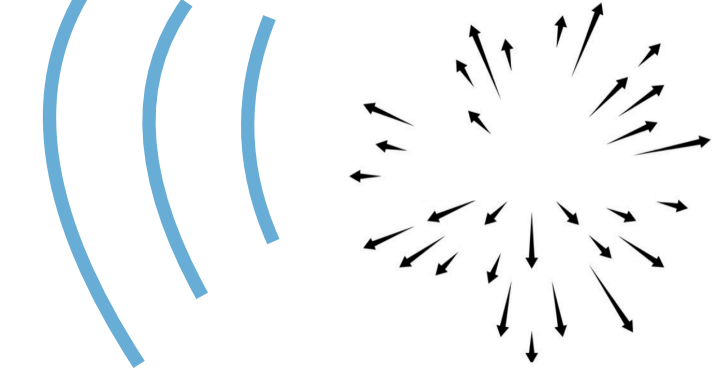




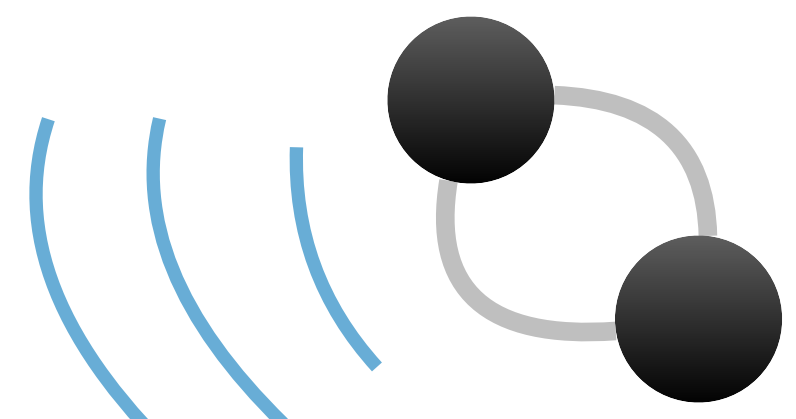
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Primordial inflation



Supermassive black holes binaries



Gravitational Waves

Pulses



Milliseconds pulsars

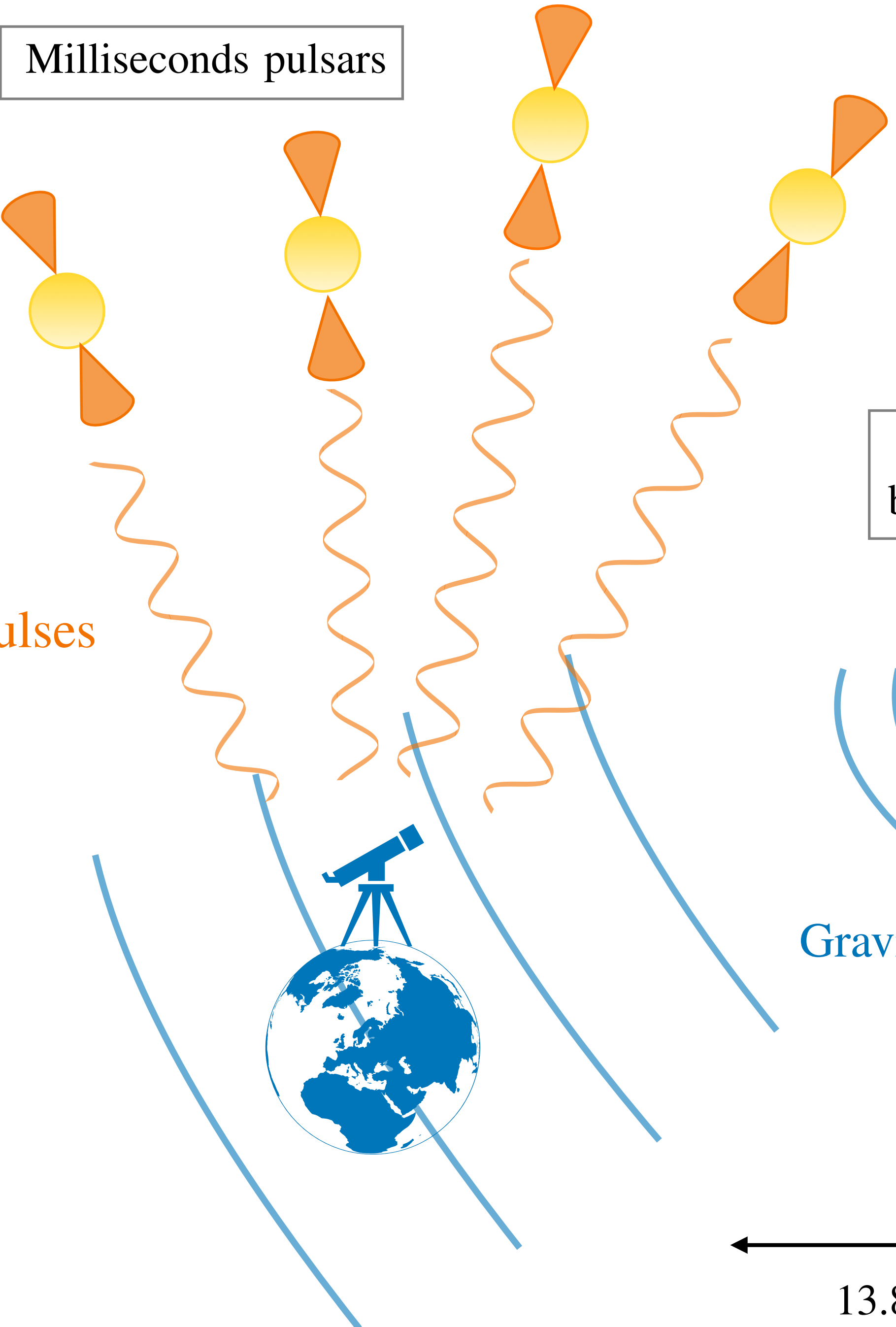
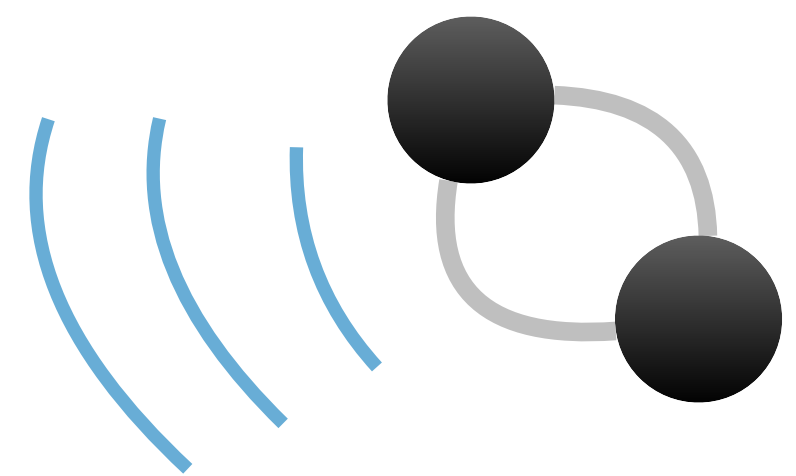
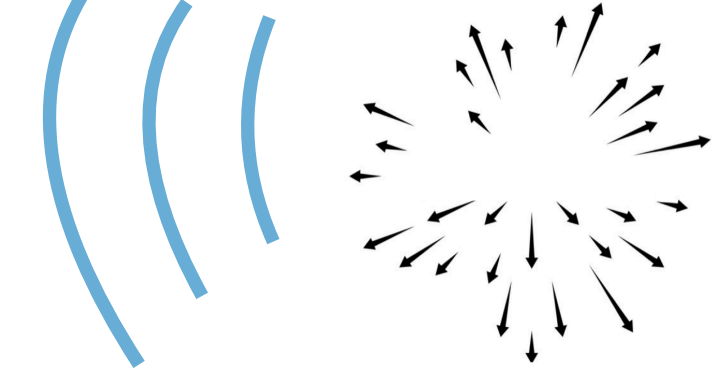
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~~Primordial inflation~~  
Large red-tilt  $n_t \simeq 1.8$   
Vagnozzi 2306.16912

Pulses

Supermassive black holes binaries

Gravitational Waves



Milliseconds pulsars

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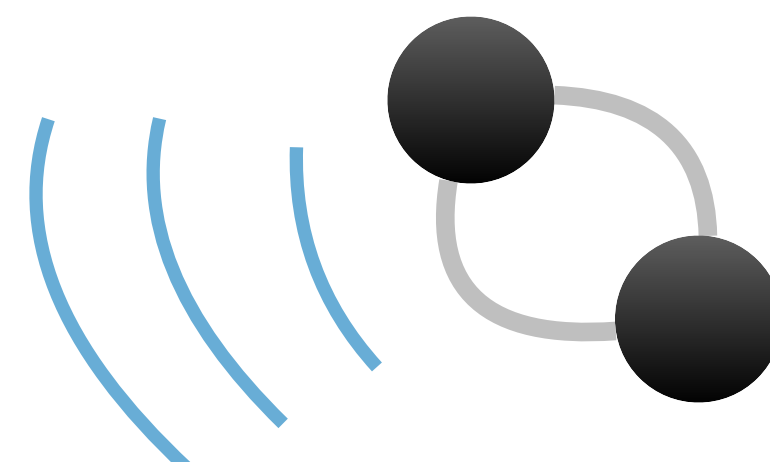
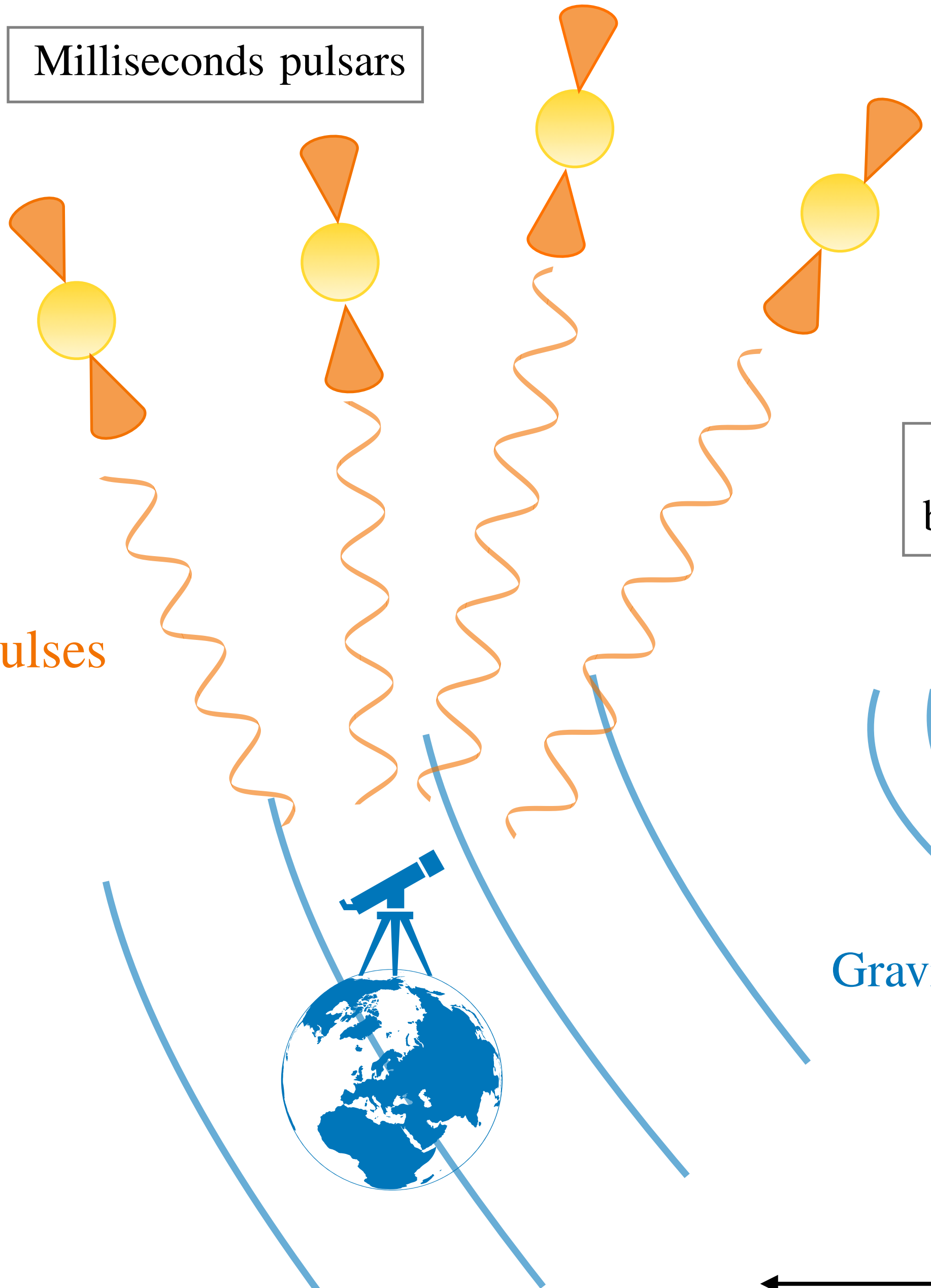
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Vagnozzi 2306.16912

Global cosmic strings

Supermassive black holes binaries

Pulses

Gravitational Waves



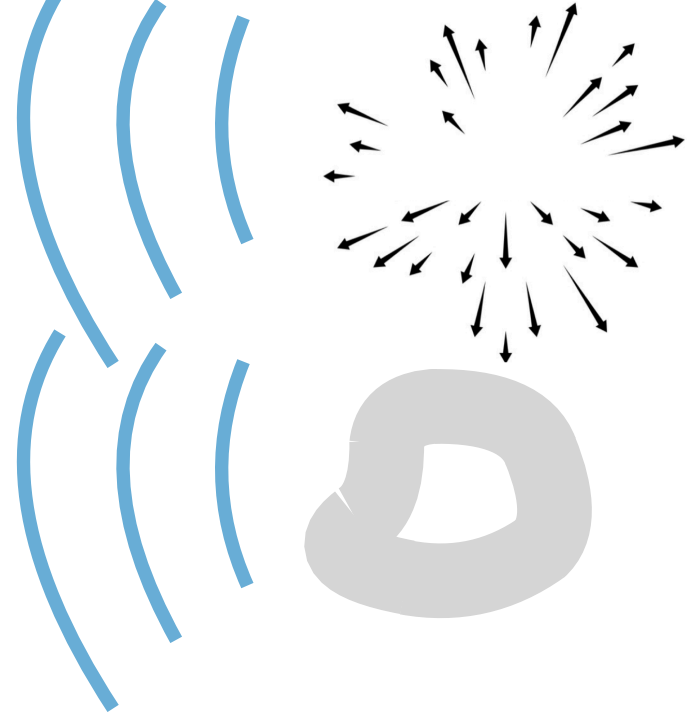


Milliseconds pulsars

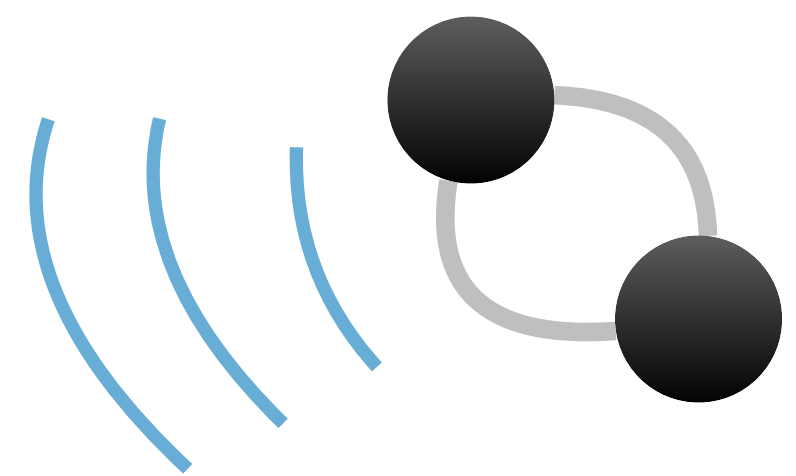
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~~Global cosmic strings~~  
BBN bound  
Servant & Simakachorn 2307.03121

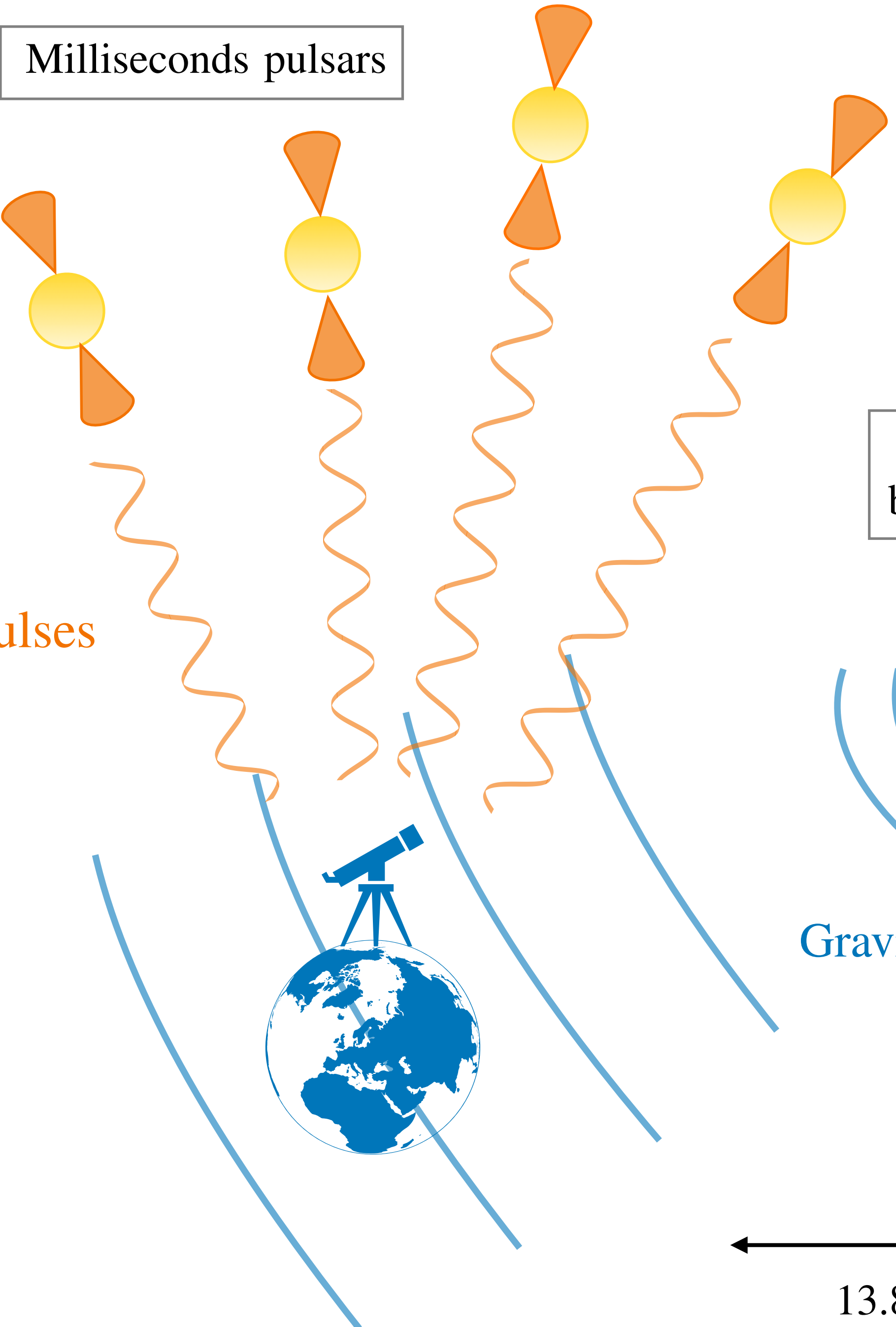


Supermassive black holes binaries



Gravitational Waves

Pulses



Milliseconds pulsars

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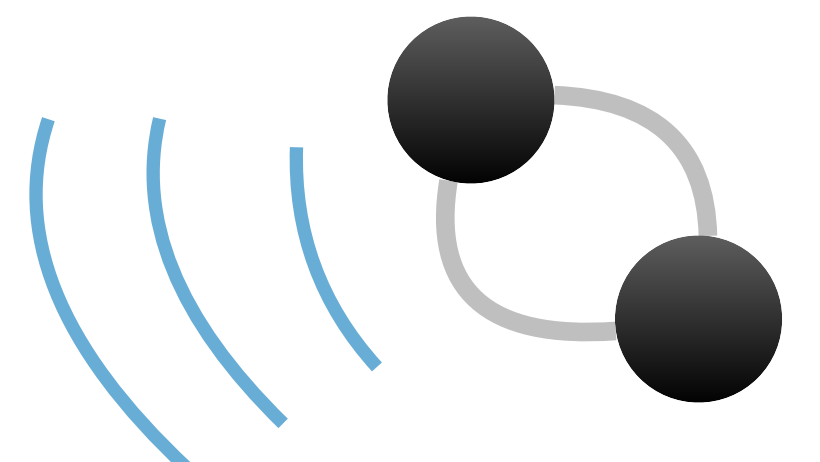
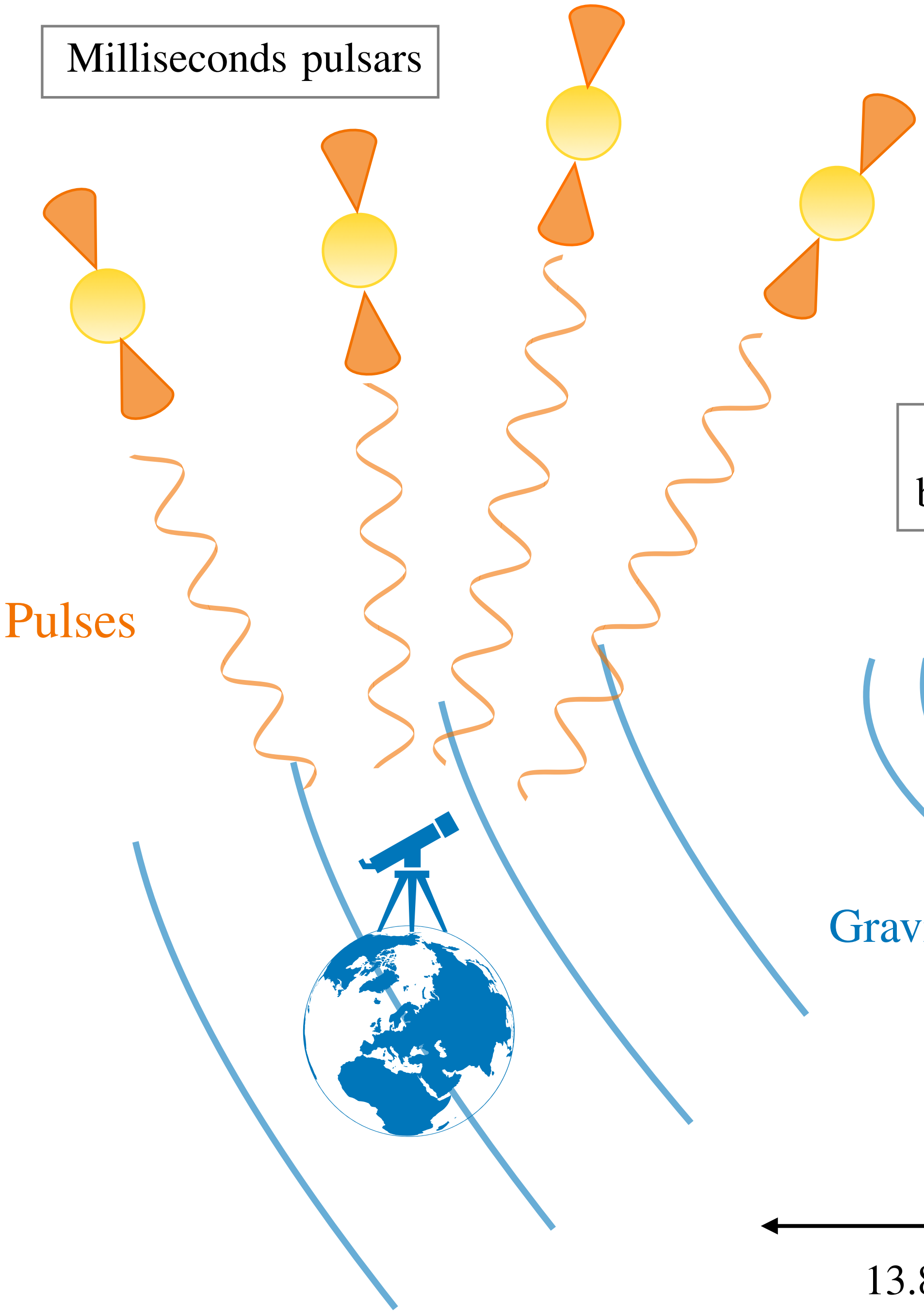
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BBN bound  
Servant & Simakachorn 2307.03121

Local cosmic strings

Supermassive black holes binaries

Pulses

Gravitational Waves



Milliseconds pulsars

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Vagnozzi 2306.16912

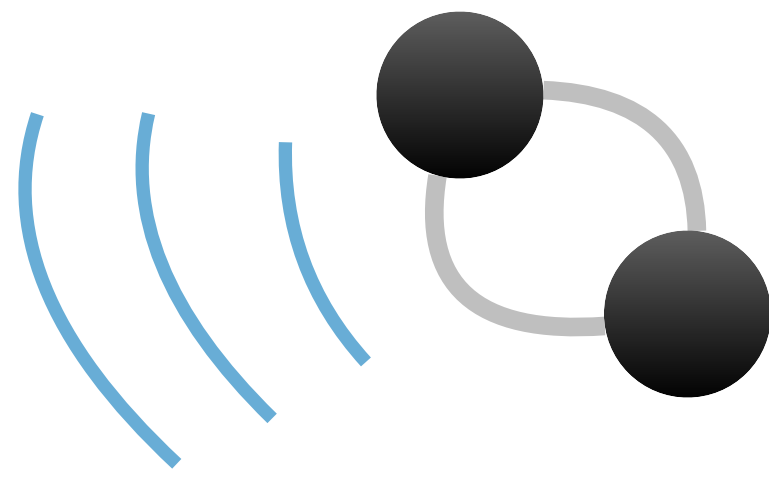
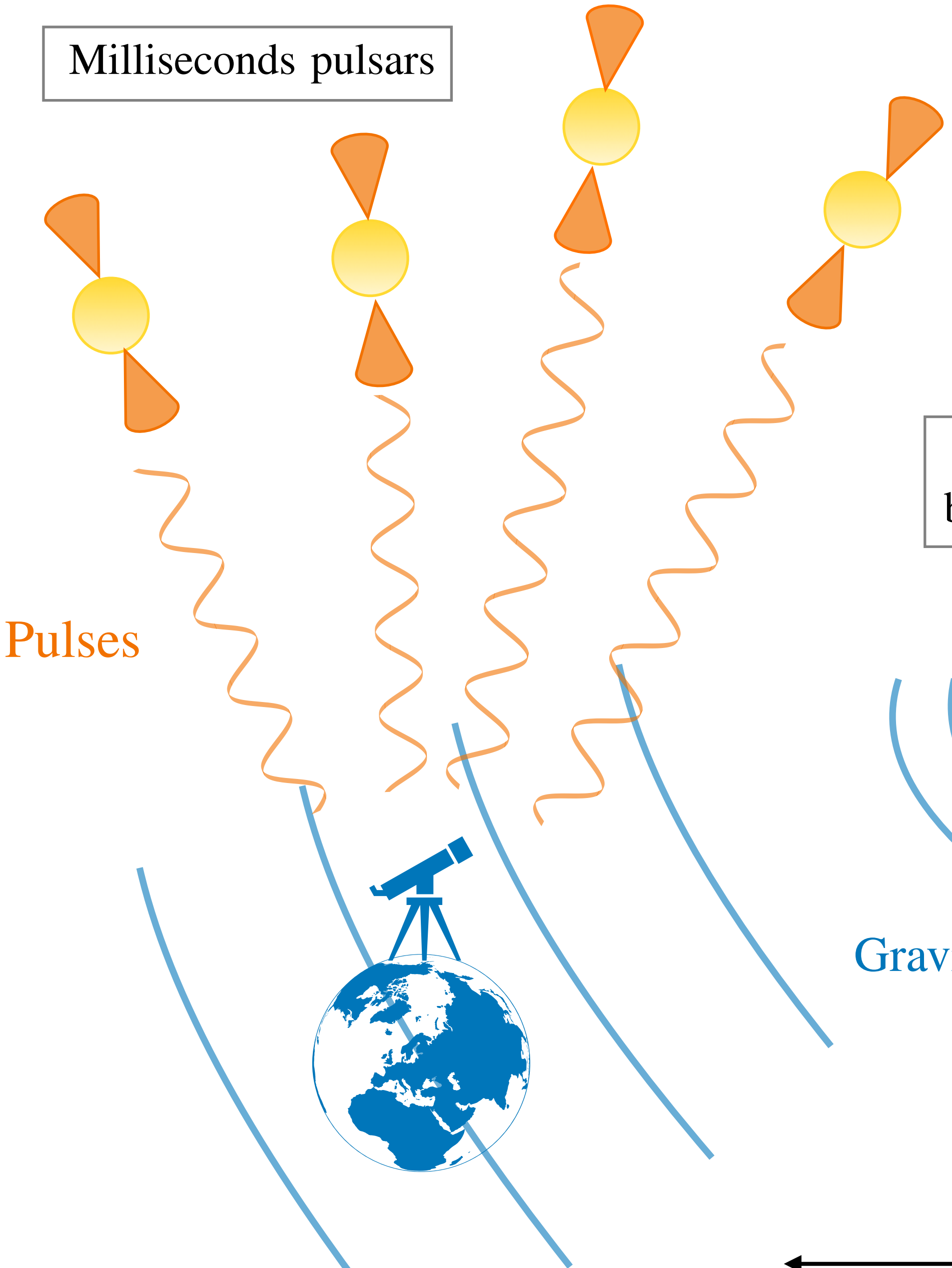
~~Global cosmic strings~~  
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Servant & Simakachorn 2307.03121

~~Local cosmic strings~~  
Not a good fit of NG15  
NG15 collab. "New physics"  
**Except if superstrings**  
Ellis, Lewicki, Lin, Vaskonen 2306.17147

Supermassive black holes binaries

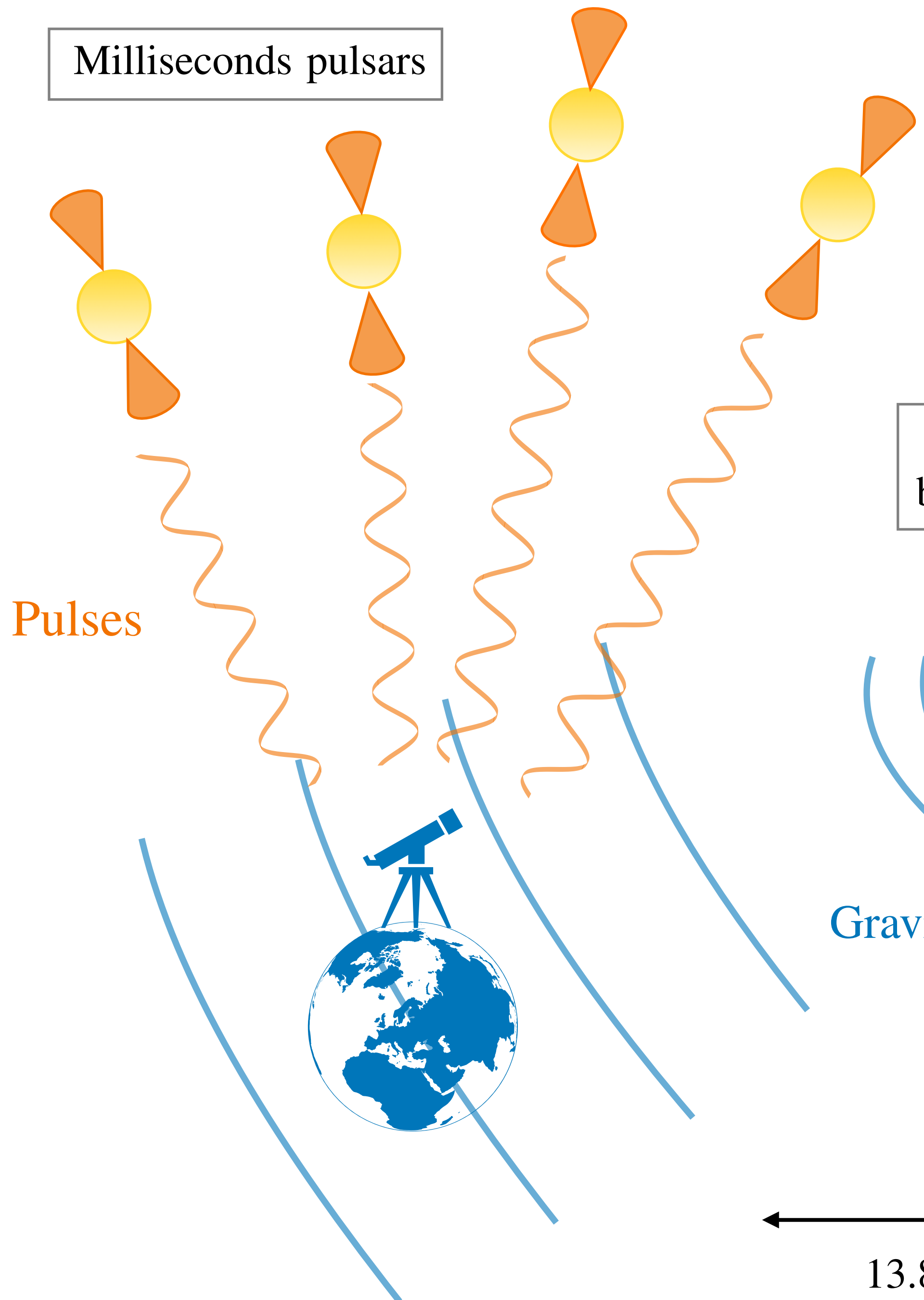
Pulses

Gravitational Waves



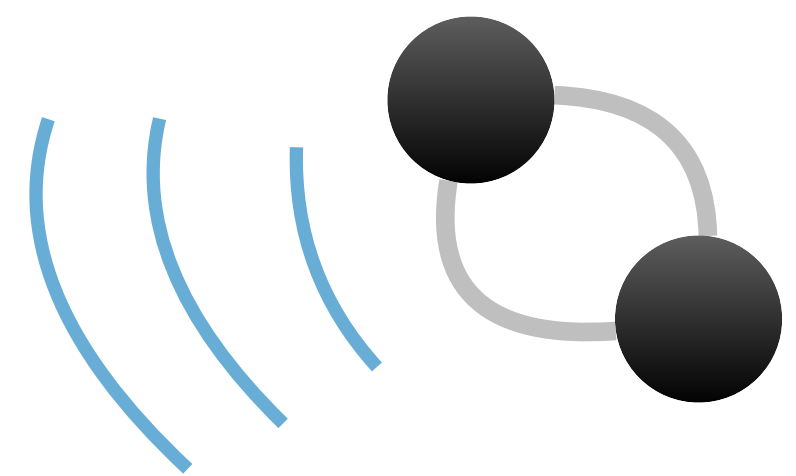


Milliseconds pulsars

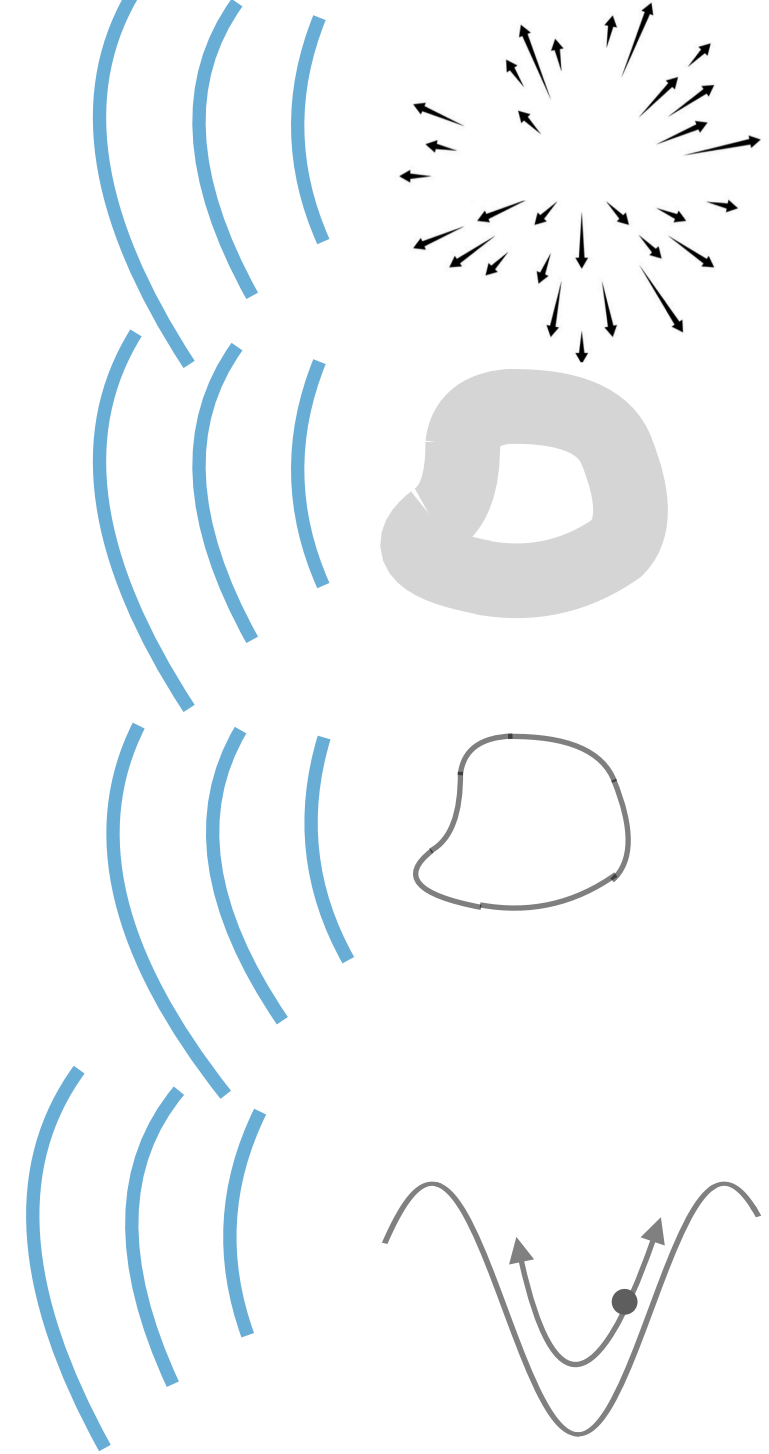


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Gravitational Waves



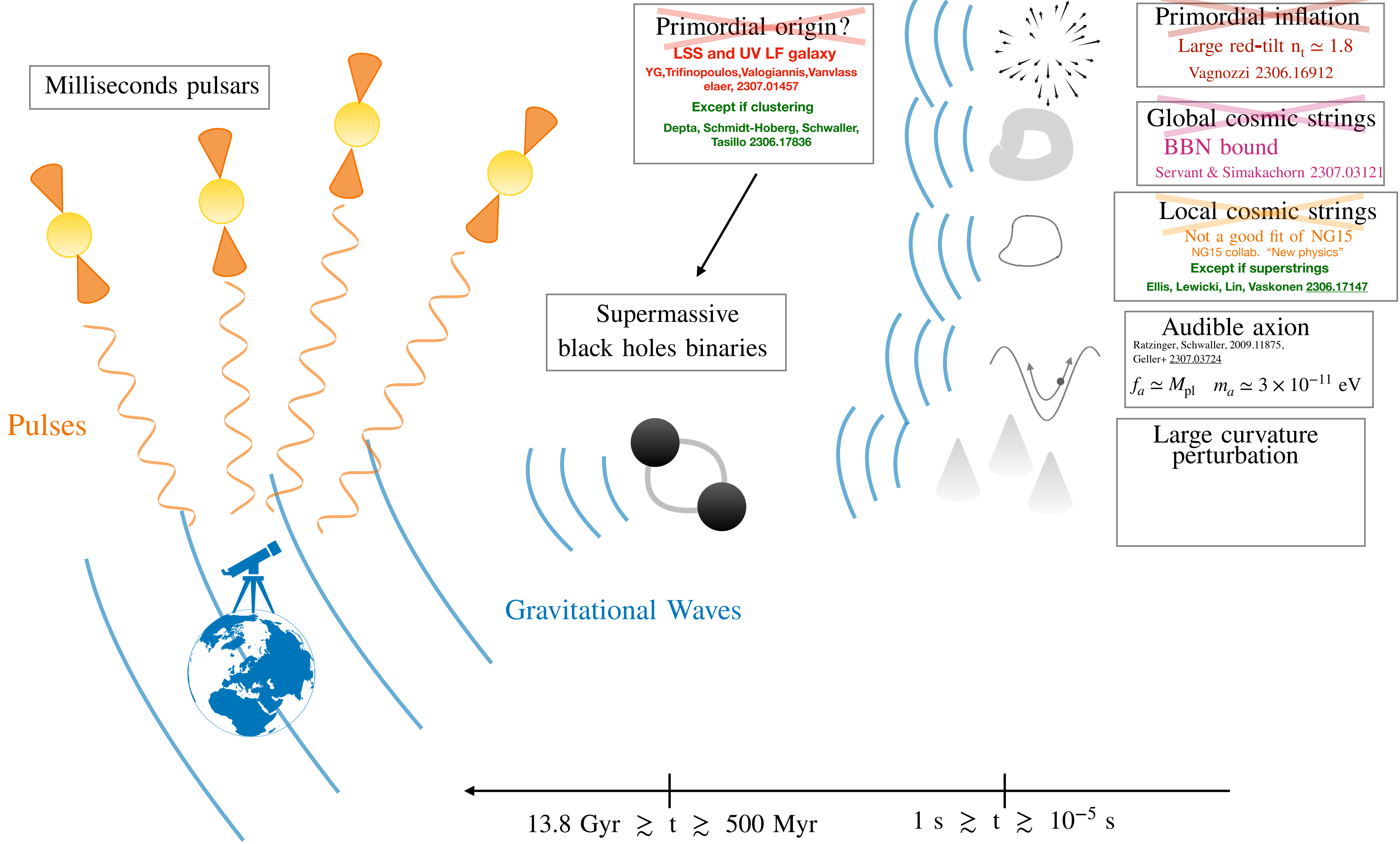
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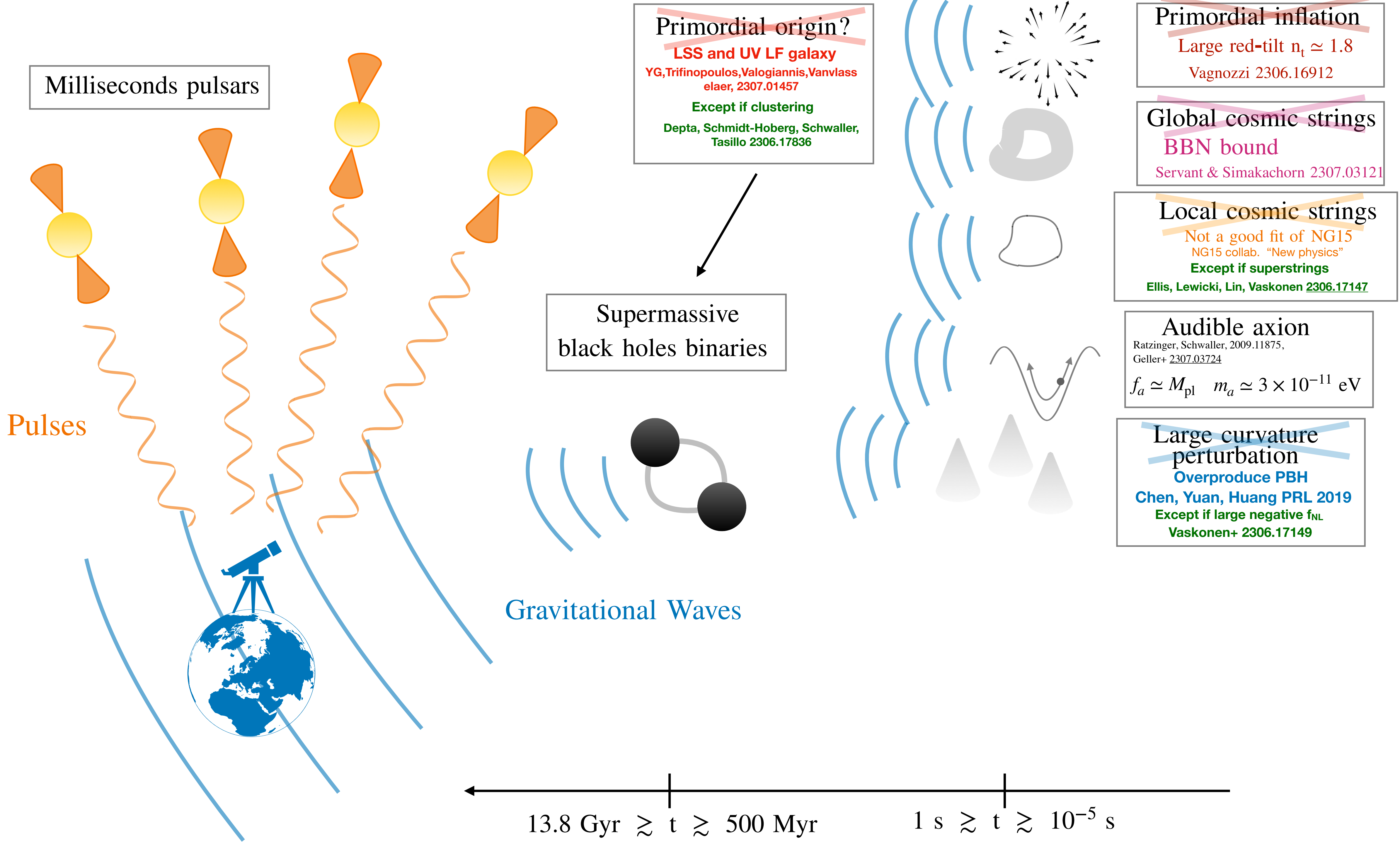
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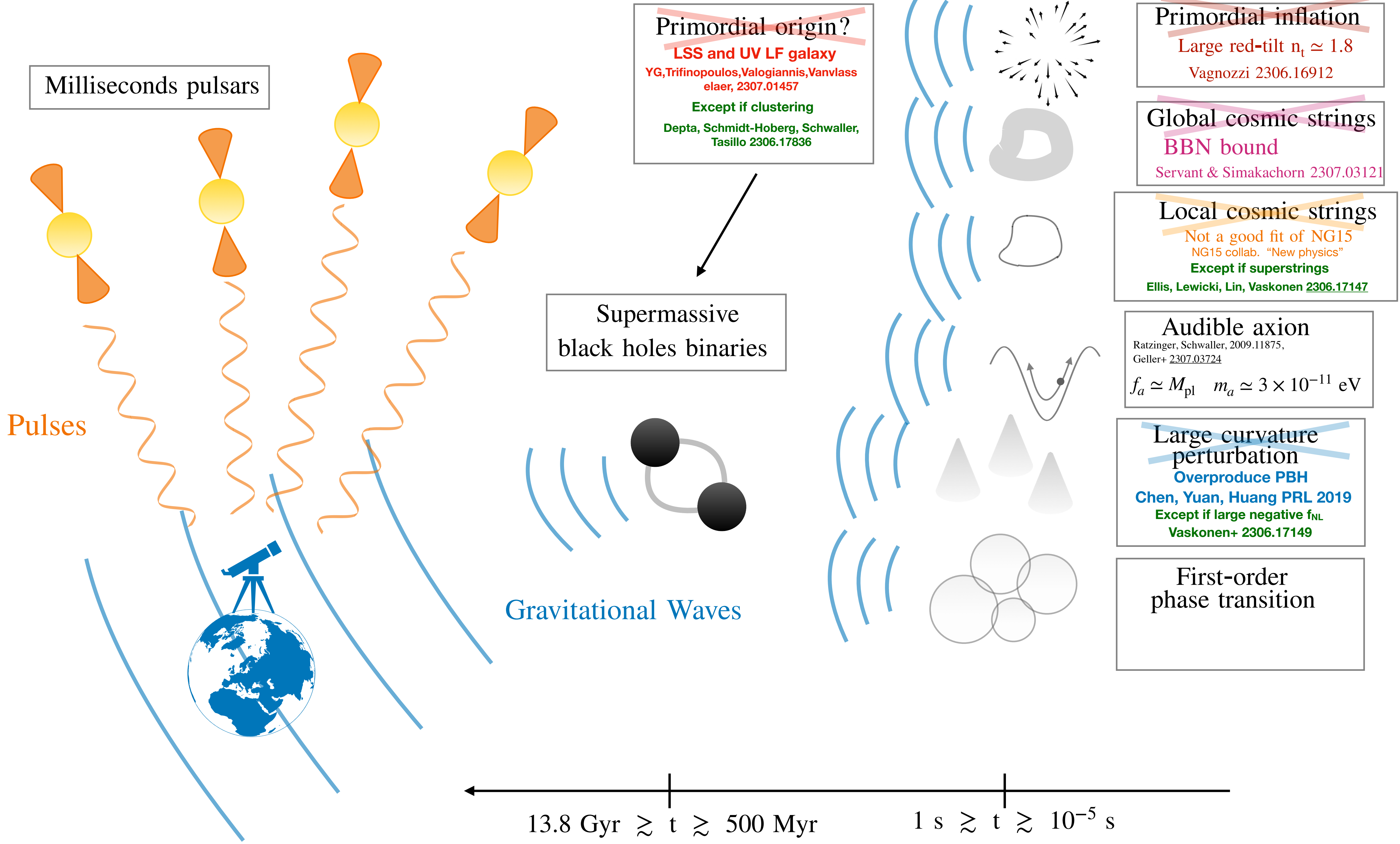
**Audible axion**  
 Ratzinger, Schwaller, 2009.11875,  
 Geller+ 2307.03724  
 $f_a \simeq M_{\text{pl}} \quad m_a \simeq 3 \times 10^{-11} \text{ eV}$

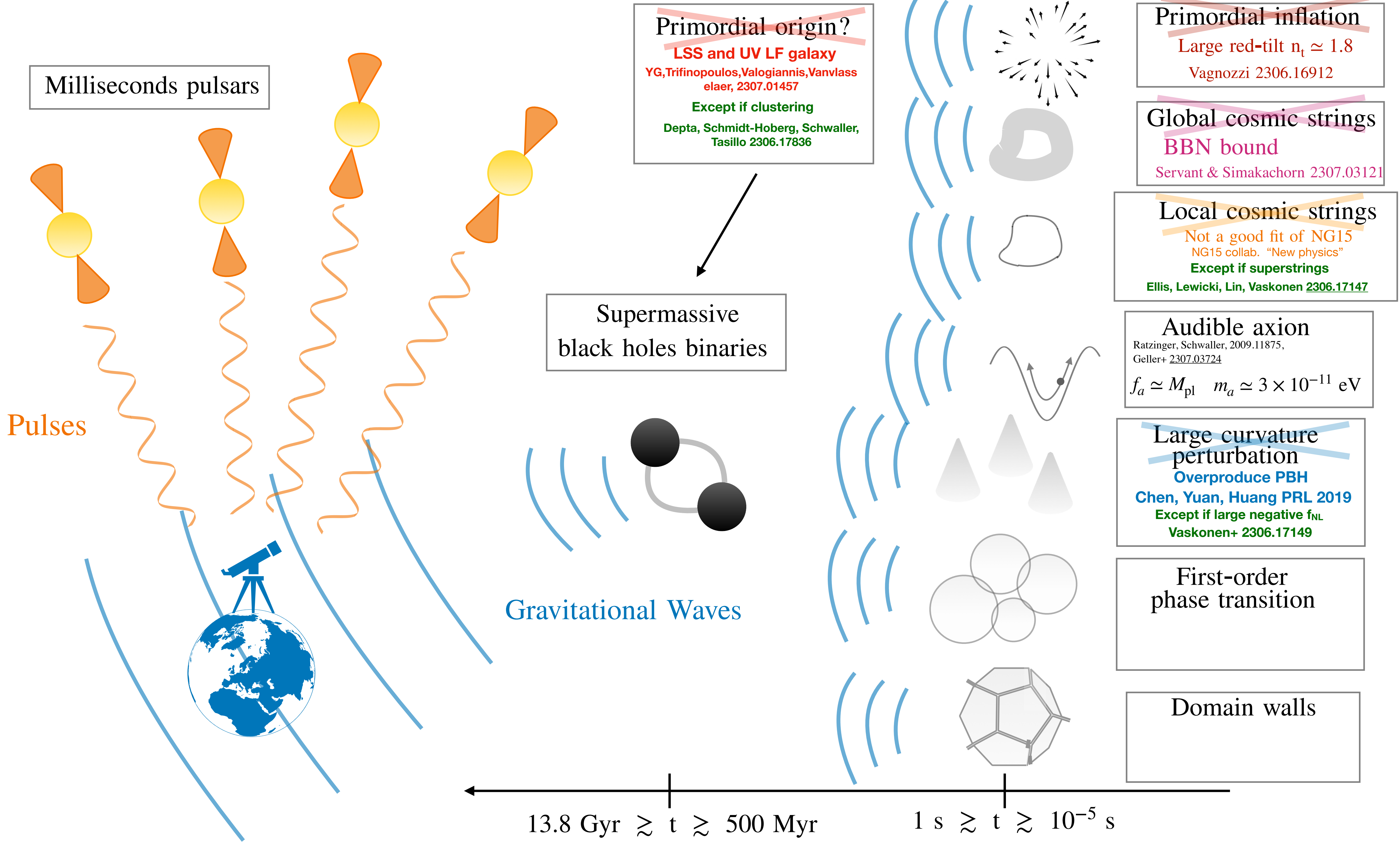


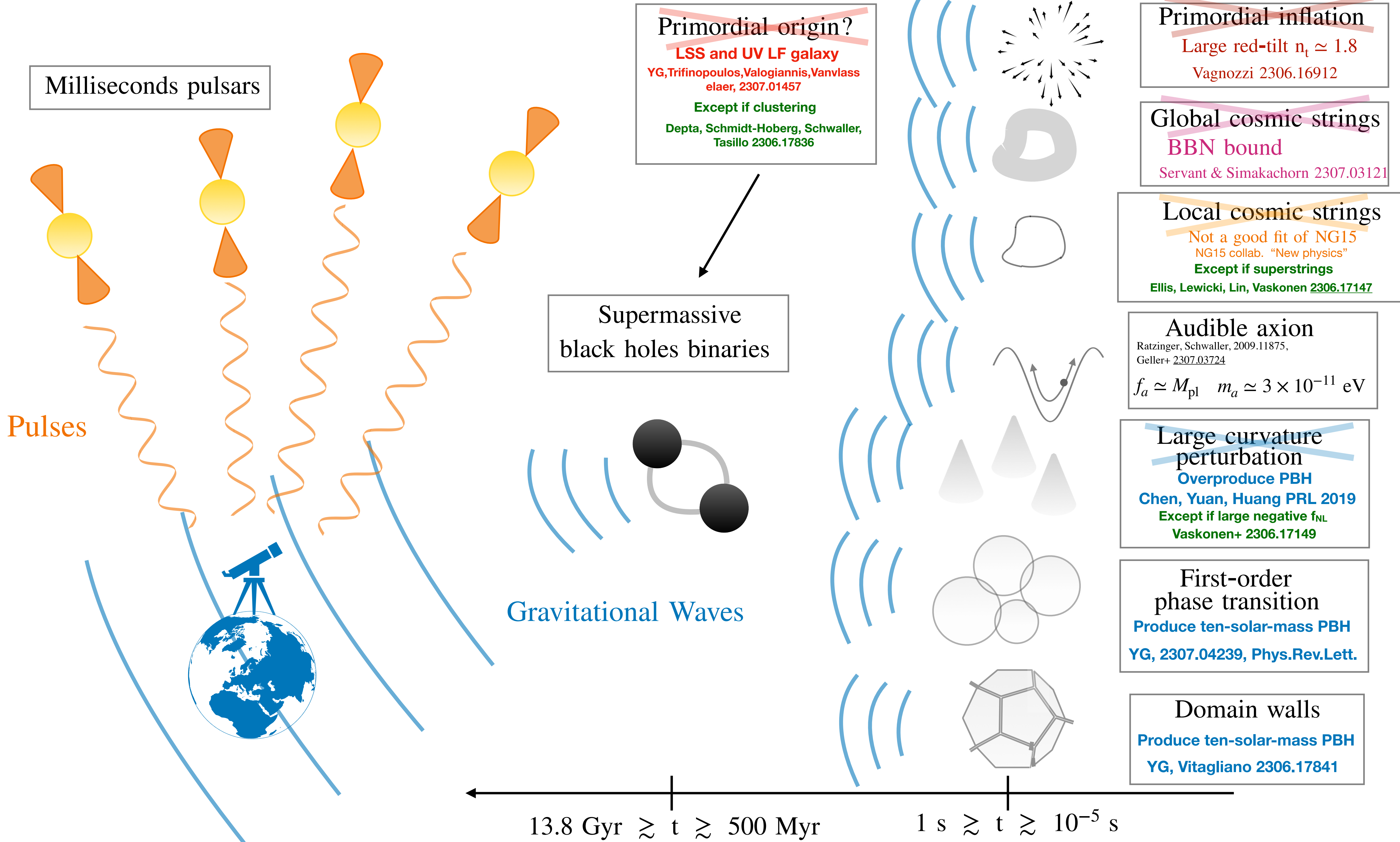




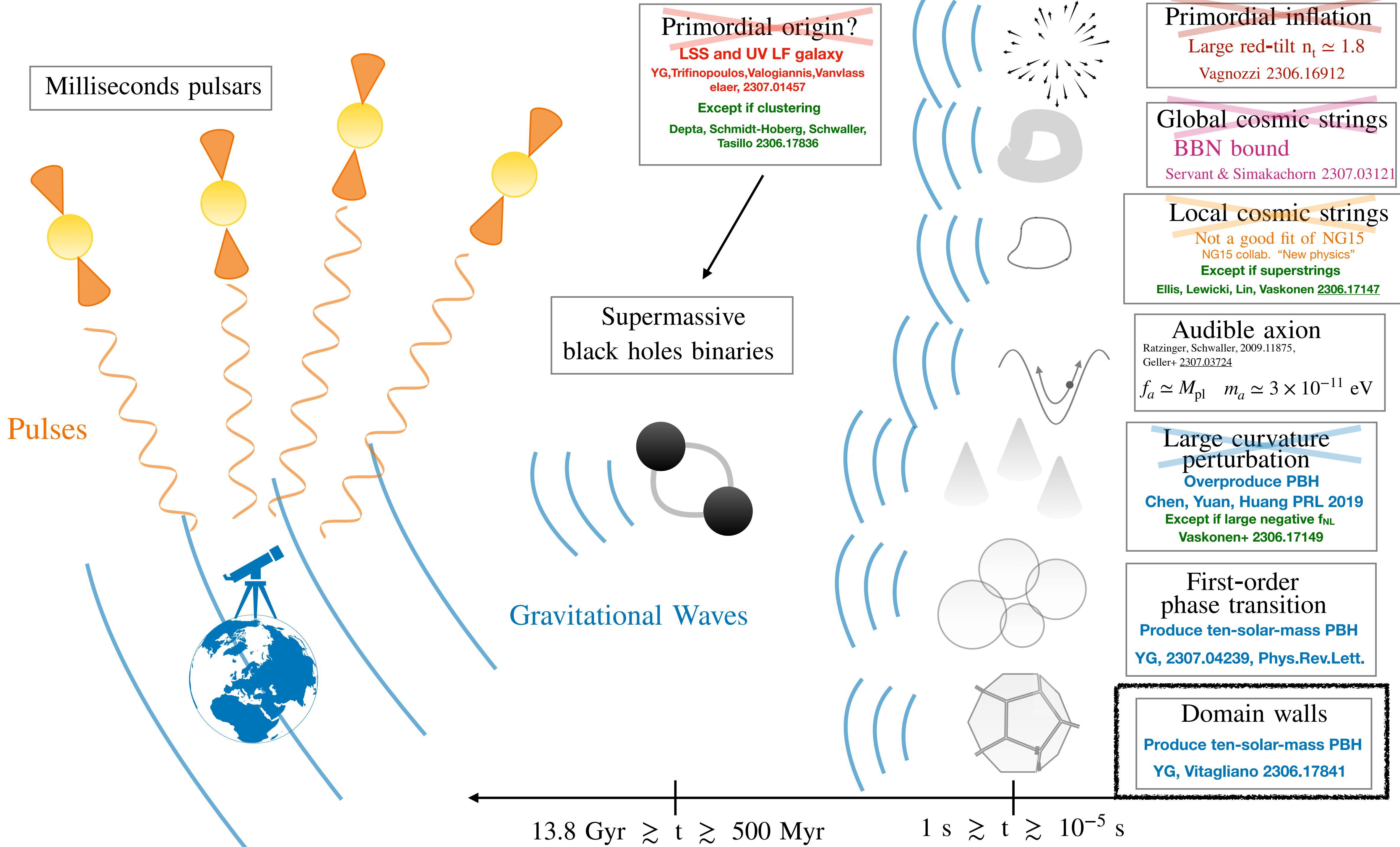








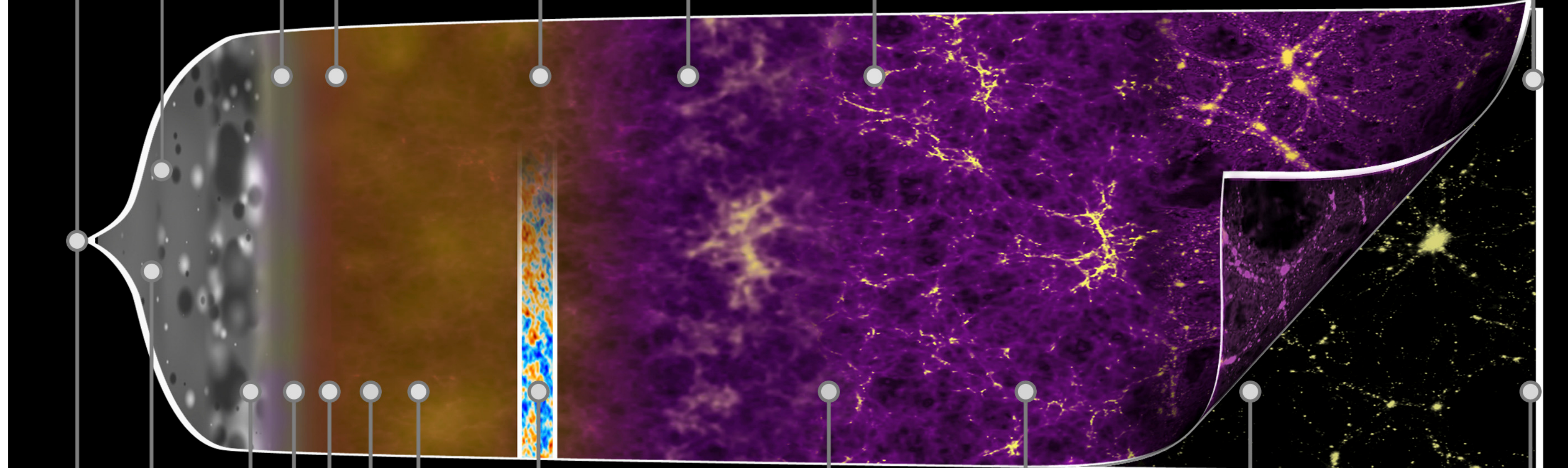






# What are Primordial Black Holes ?

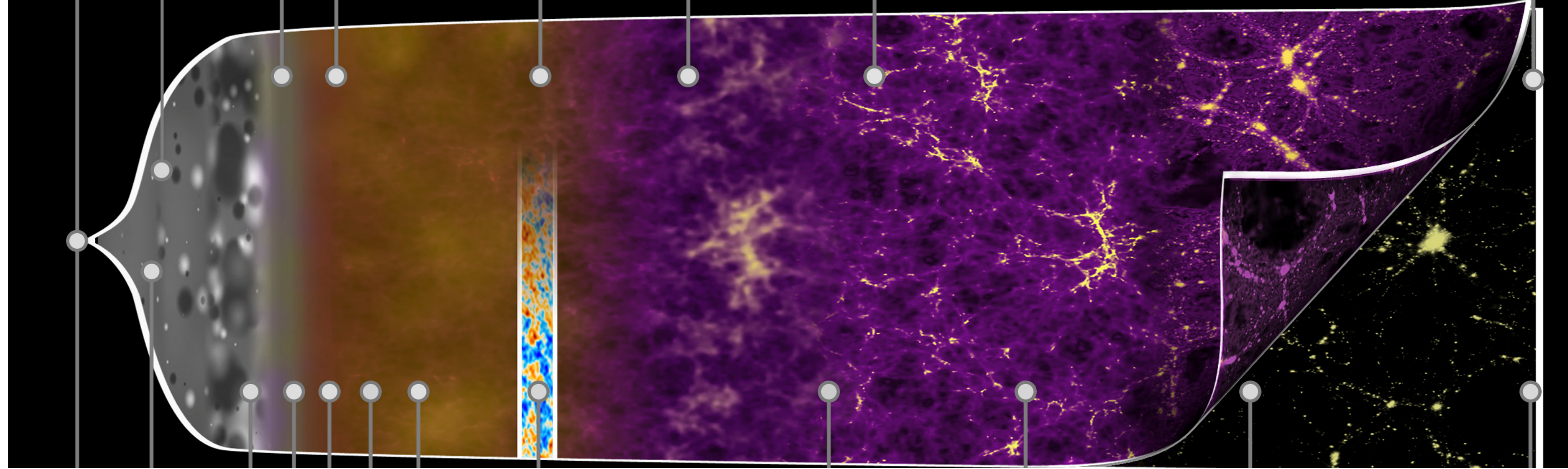
# What are Primordial Black Holes ?



Star formation



# What are Primordial Black Holes ?

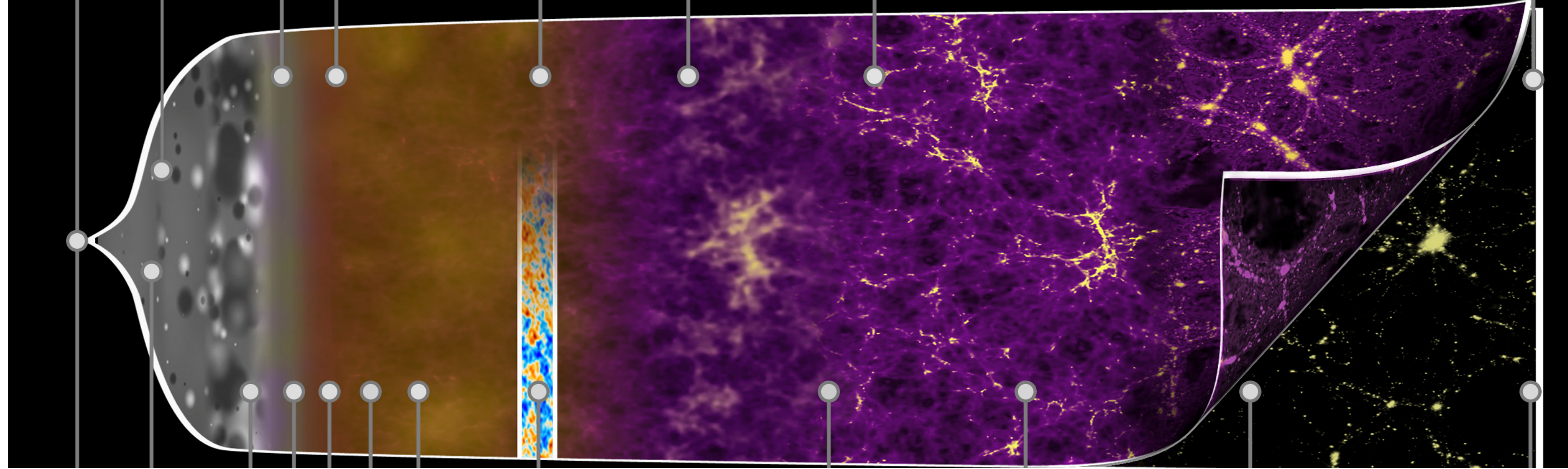


**PBH formation**

**Star formation**



# What are Primordial Black Holes ?



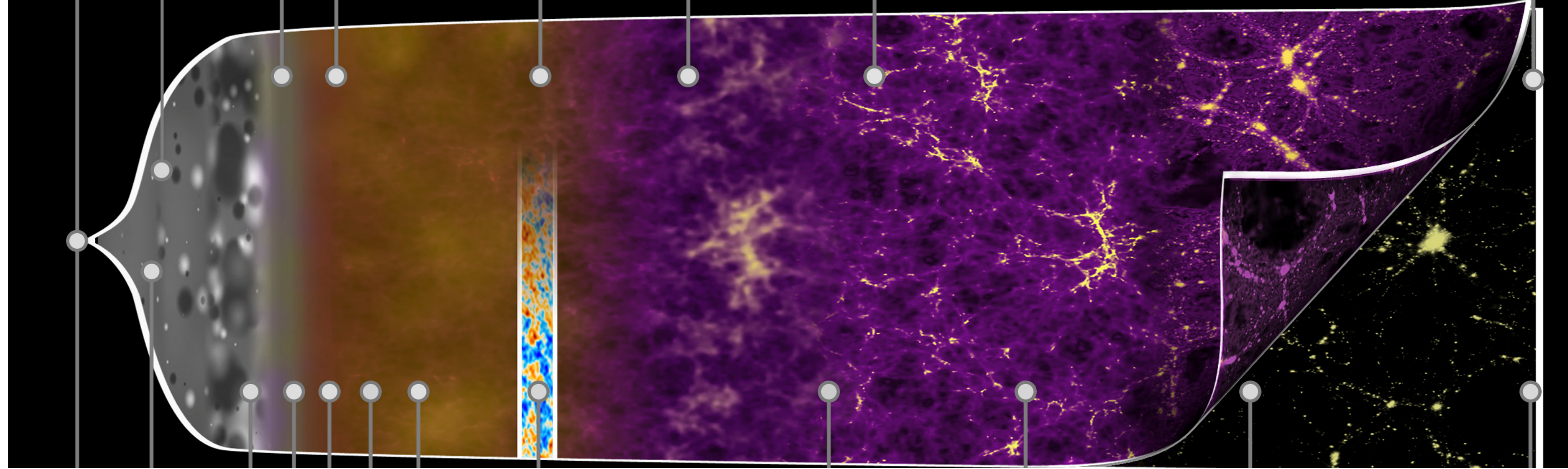
**PBH formation**

**Star formation**

**in presence of large inhomogeneities:**



# What are Primordial Black Holes ?



**PBH formation**

**Star formation**

**in presence of large inhomogeneities:**

- 1)  $\delta\rho/\rho \sim 1$
- 2) horizon size

*Hawking (1971)*

- 1)  $\delta\rho/\rho \sim 1$
- 2) horizon size

$\Rightarrow$  Where do this come from ?

**Friedmann's equation :**

$$H^2 = \frac{8\pi G}{3} \rho$$

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

2) horizon size

$\Rightarrow$  Where do this come from ?

**Friedmann's equation :**

$$H^{-3} \times H^2 = \frac{8\pi G}{3} \rho \times H^{-3}$$



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

2) horizon size

$\Rightarrow$  Where do this come from ?

**Friedmann's equation :**

$$H^{-1} = 2G \times \frac{4\pi H^{-3}}{3} \rho$$



- 1)  $\delta\rho/\rho \sim 1$
- 2) horizon size

**Friedmann's equation :**

**$\Rightarrow$  Where do this come from ?**

$$H^{-1} = 2G \times \frac{4\pi H^{-3}}{3} \rho$$

$\equiv R_H$   $\equiv M_H$

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

2) horizon size

$\Rightarrow$  Where do this come from ?

**Friedmann's equation :**

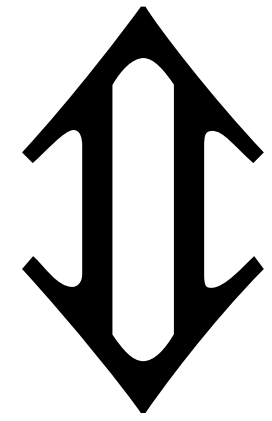
$$R_H = 2GM_H$$

- 1)  $\delta\rho/\rho \sim 1$
- 2) horizon size

$\Rightarrow$  Where do this come from ?

**Friedmann's equation :**

$$R_H = 2GM_H$$



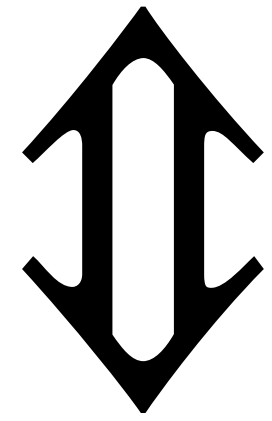
**Schwarzschild's equation**

- 1)  $\delta\rho/\rho \sim 1$
- 2) horizon size

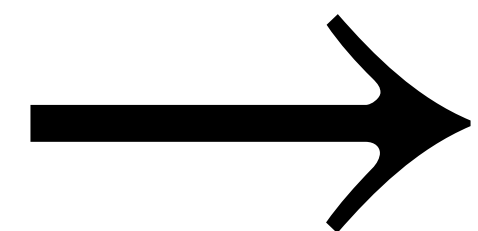
$\Rightarrow$  Where do this come from ?

**Friedmann's equation :**

$$R_H = 2GM_H$$



**Schwarzschild's equation**



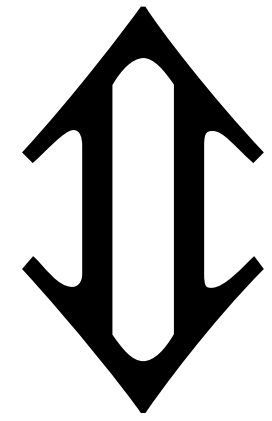
**Hubble patches are on the edge to collapse into black holes**



- 1)  $\delta\rho/\rho \sim 1$
- 2) horizon size

⇒ Where do this come from ?

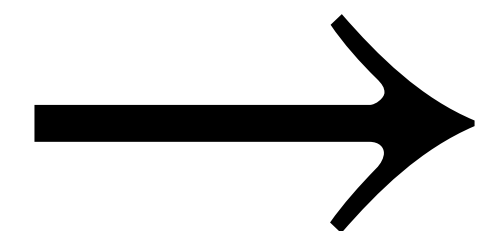
Friedmann's equation :



Schwarzschild's equation

$$\frac{R_H - 2GM_H}{R_H} \gtrsim 0.45$$

Radiation pressure

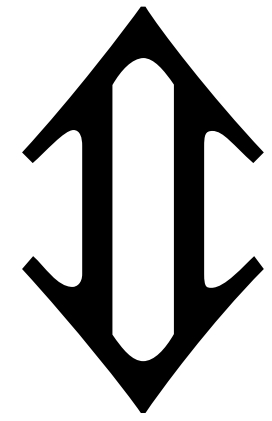


Hubble patches are on the edge to collapse into black holes

- 1)  $\delta\rho/\rho \sim 1$
- 2) horizon size

⇒ Where do this come from ?

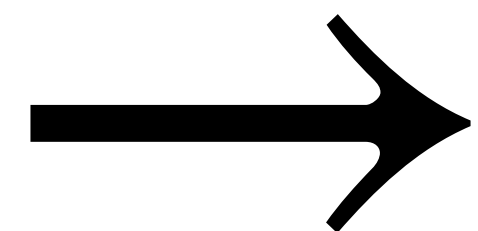
Friedmann's equation :



Schwarzschild's equation

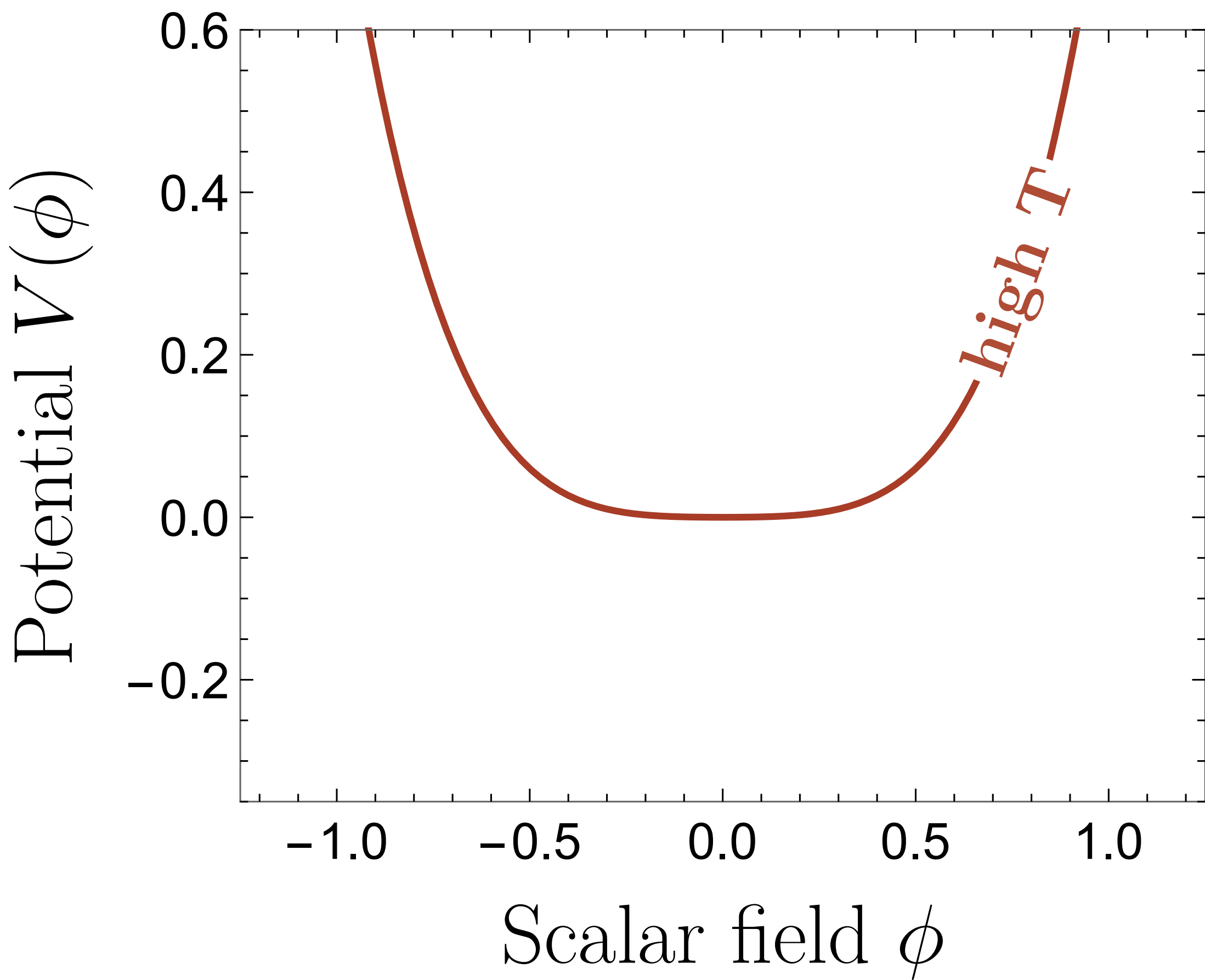
$$\frac{\langle \delta\rho \rangle_H}{\rho} \gtrsim 0.45$$

Radiation pressure

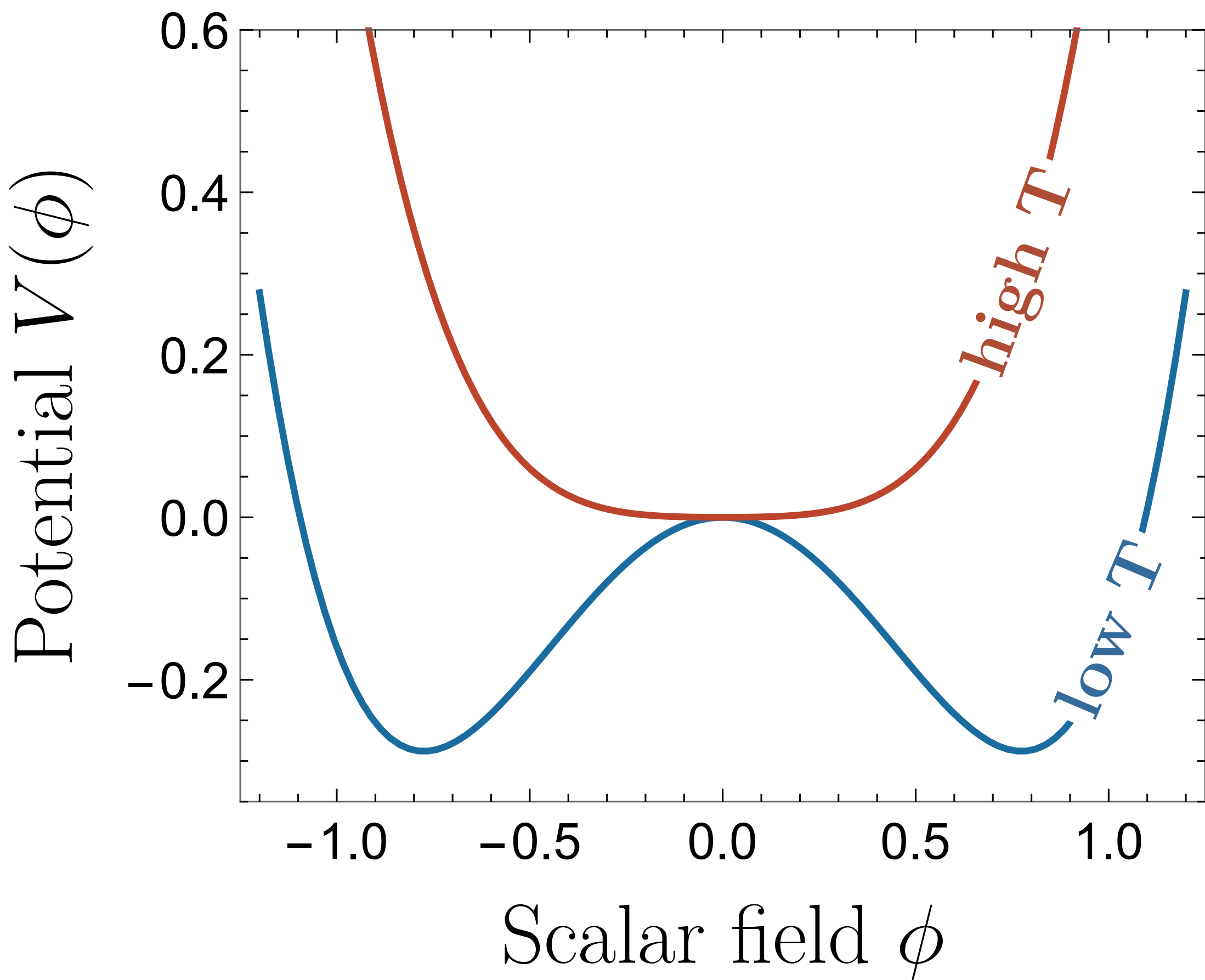


Hubble patches are on the edge to collapse into black holes

# Formation of Domain Wall

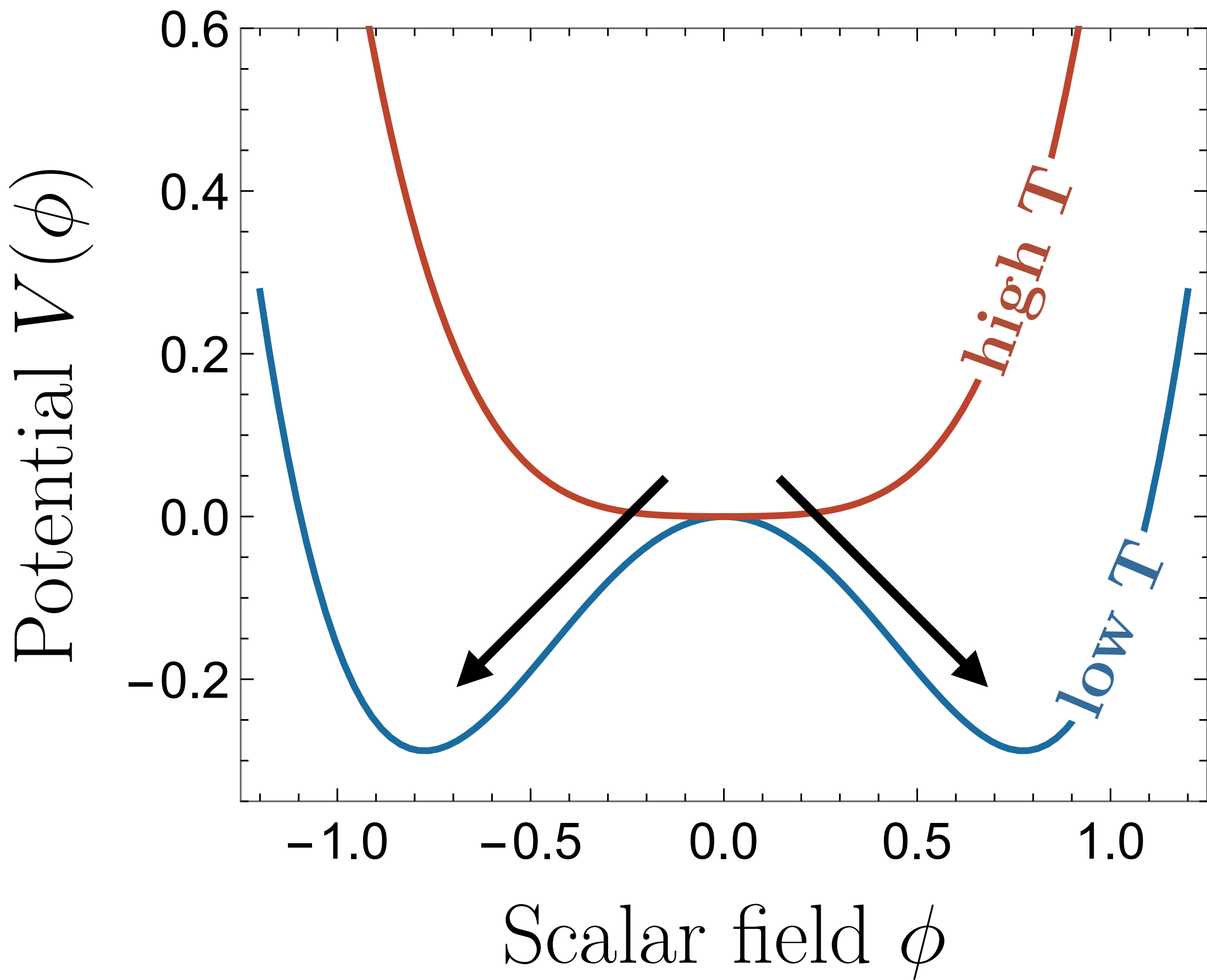


# Formation of Domain Wall



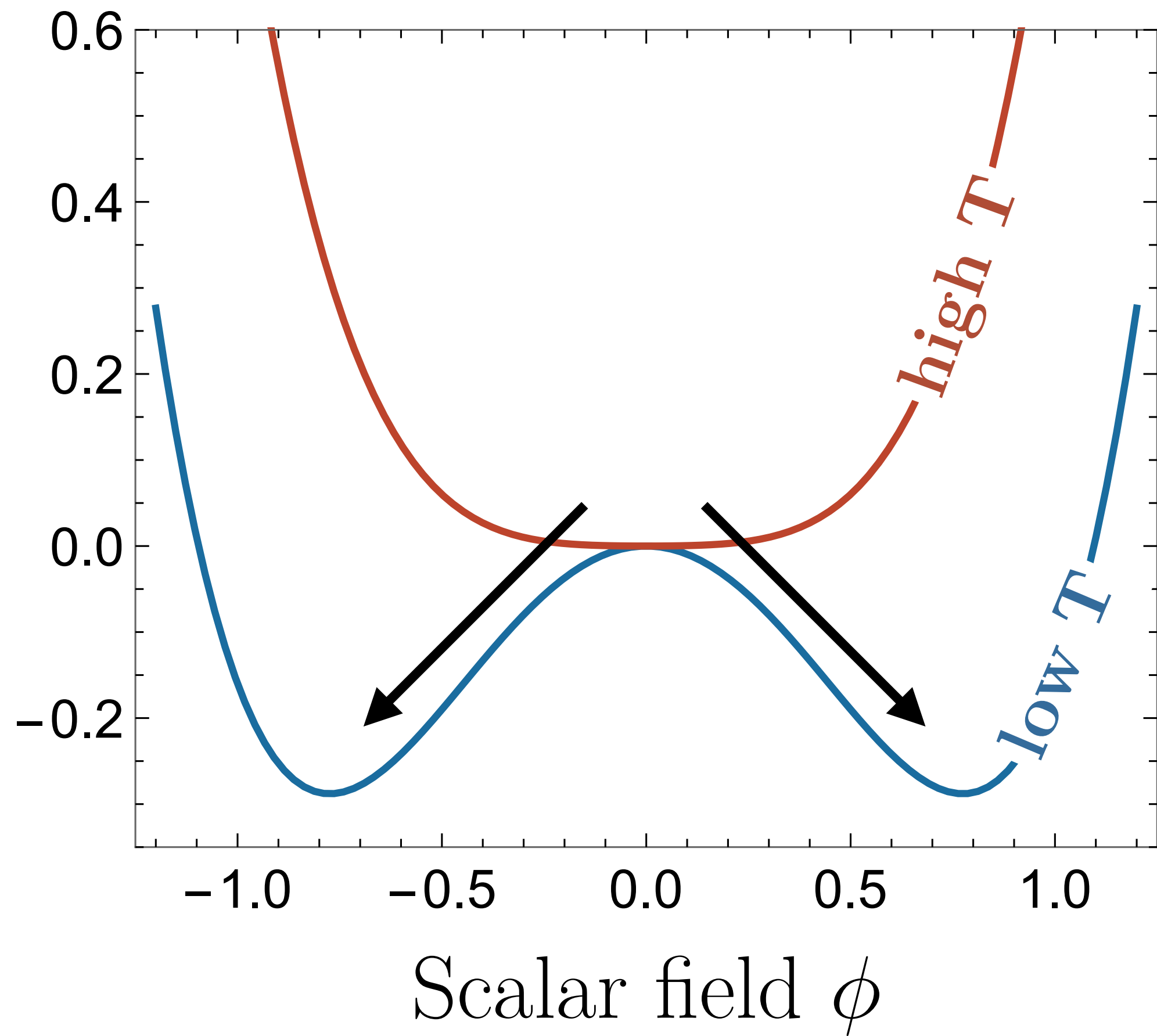


# Formation of Domain Wall

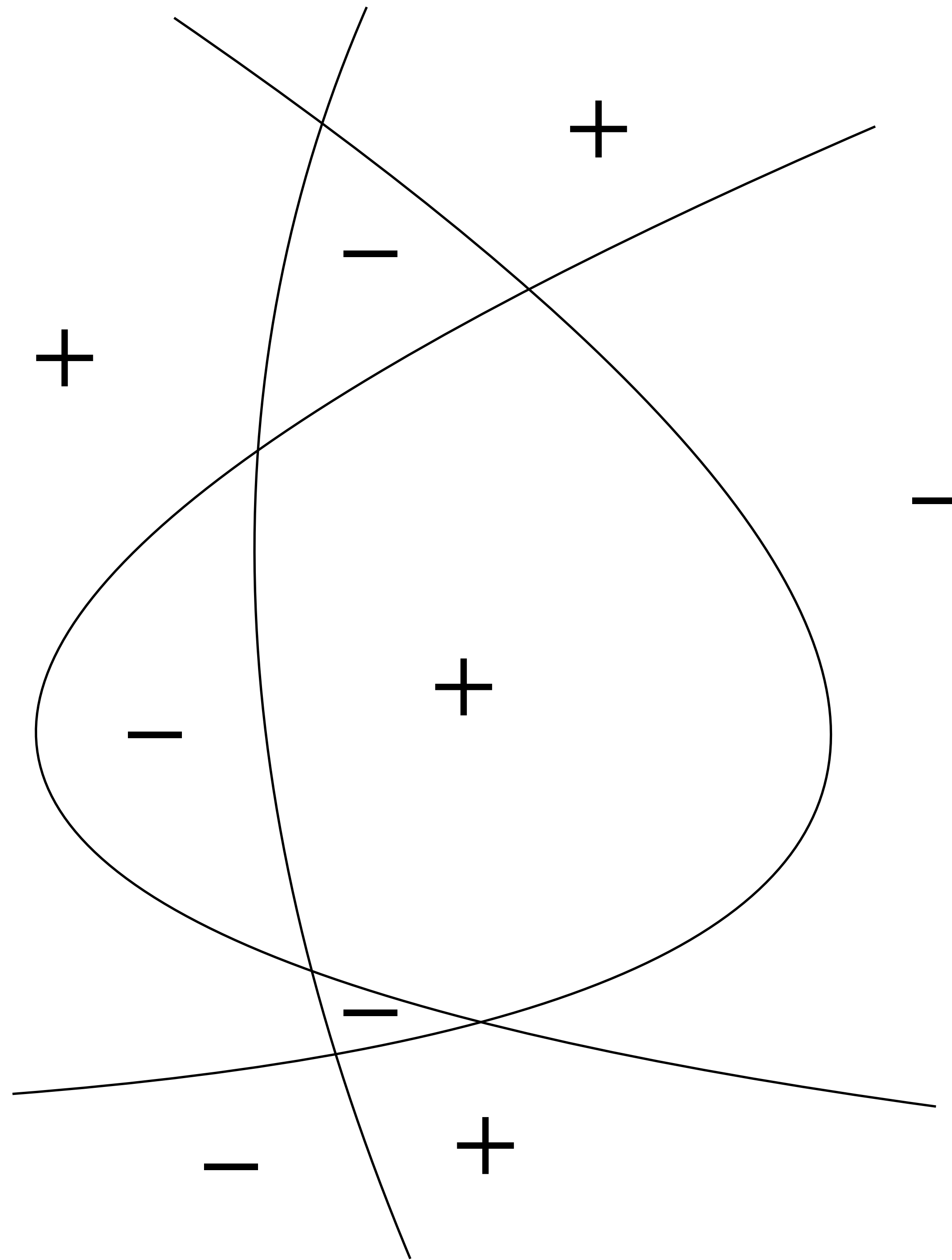


Spontaneous breaking of  $\mathbb{Z}_2$

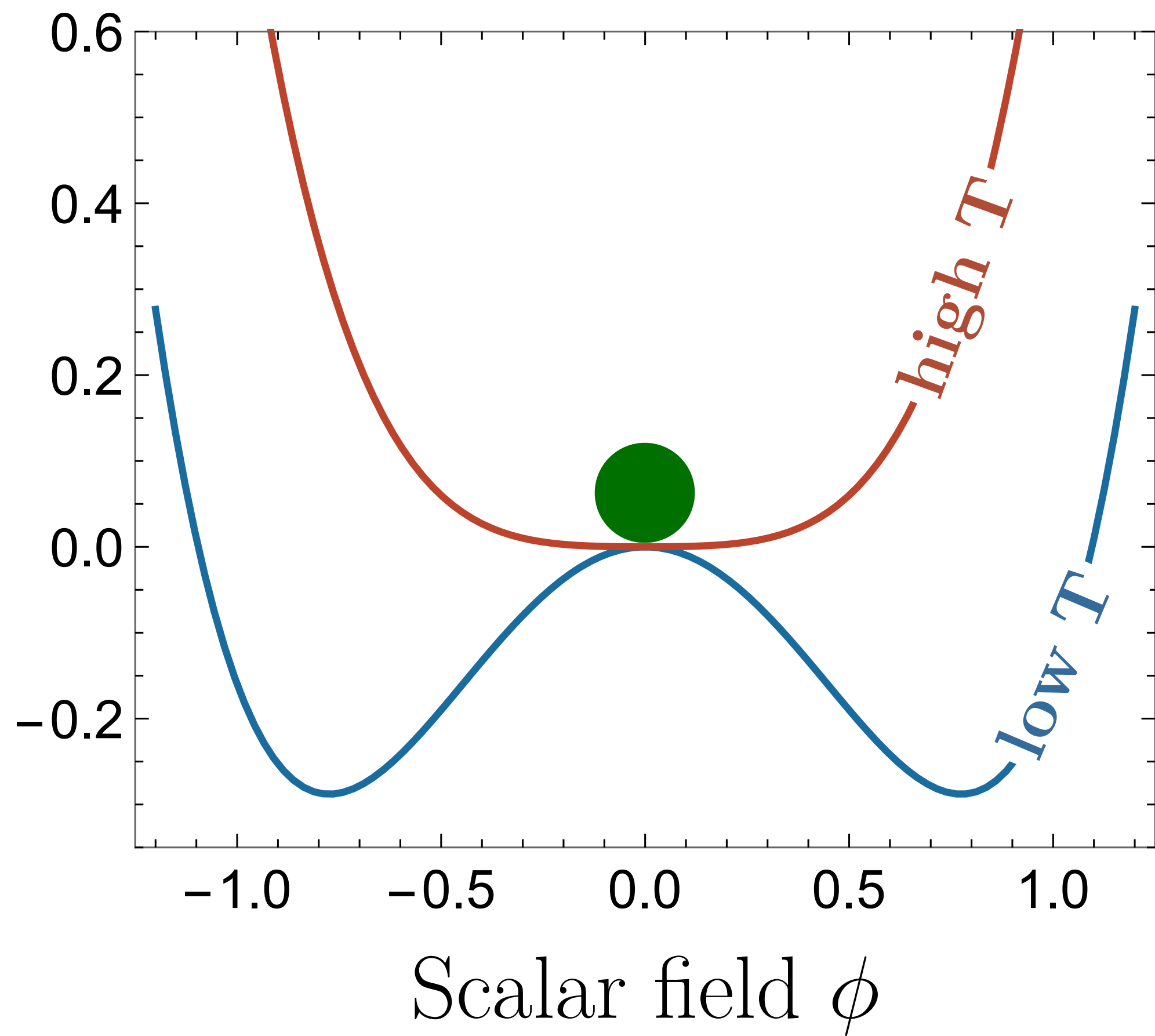
# Formation of Domain Wall



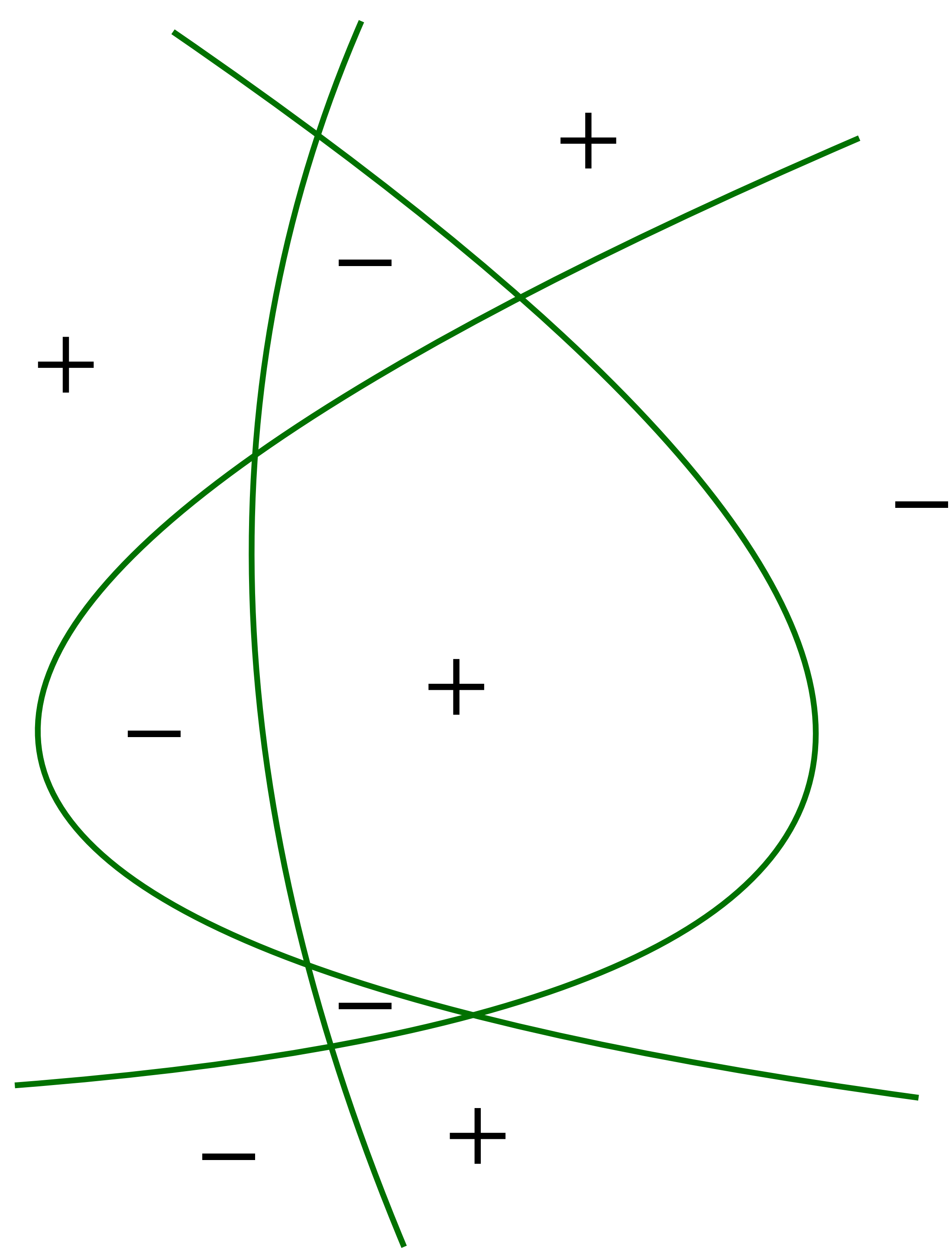
Spontaneous breaking of  $\mathbb{Z}_2$



# Formation of Domain Wall



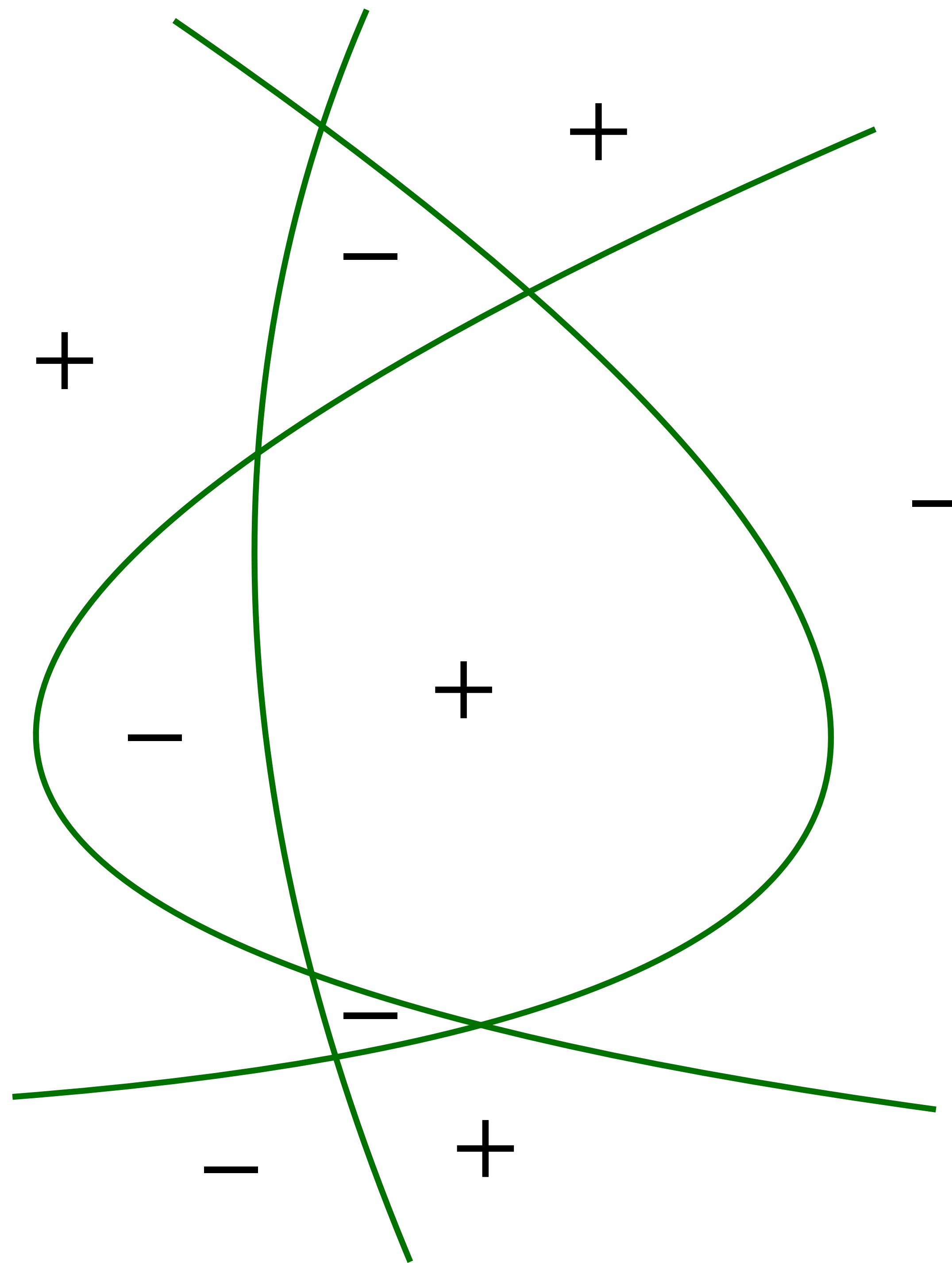
Spontaneous breaking of  $\mathbb{Z}_2$



# Formation of Domain Wall

*Press, Ryden, Spergel 1989 (3D simulation)*

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



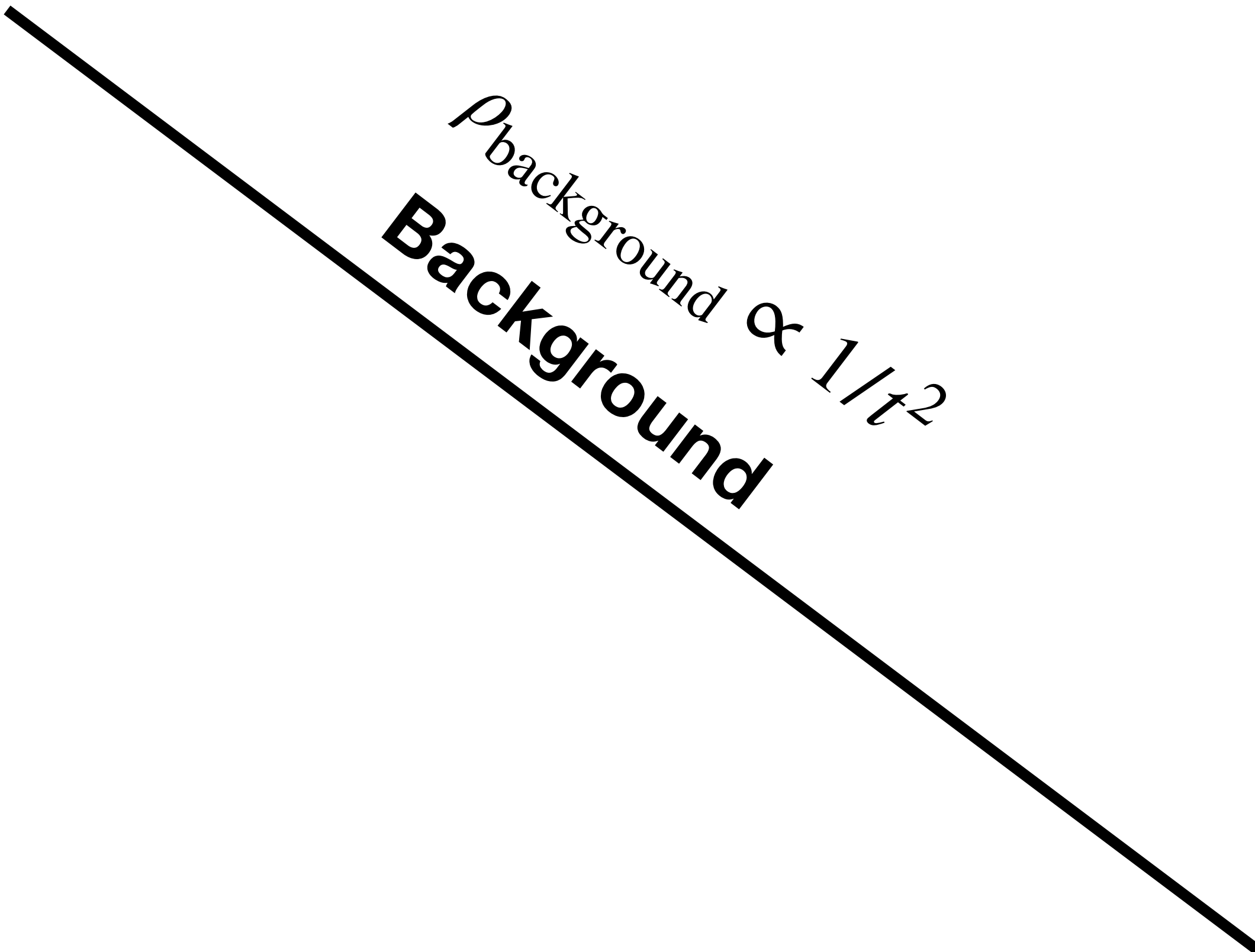


Energy density



t

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



Energy density



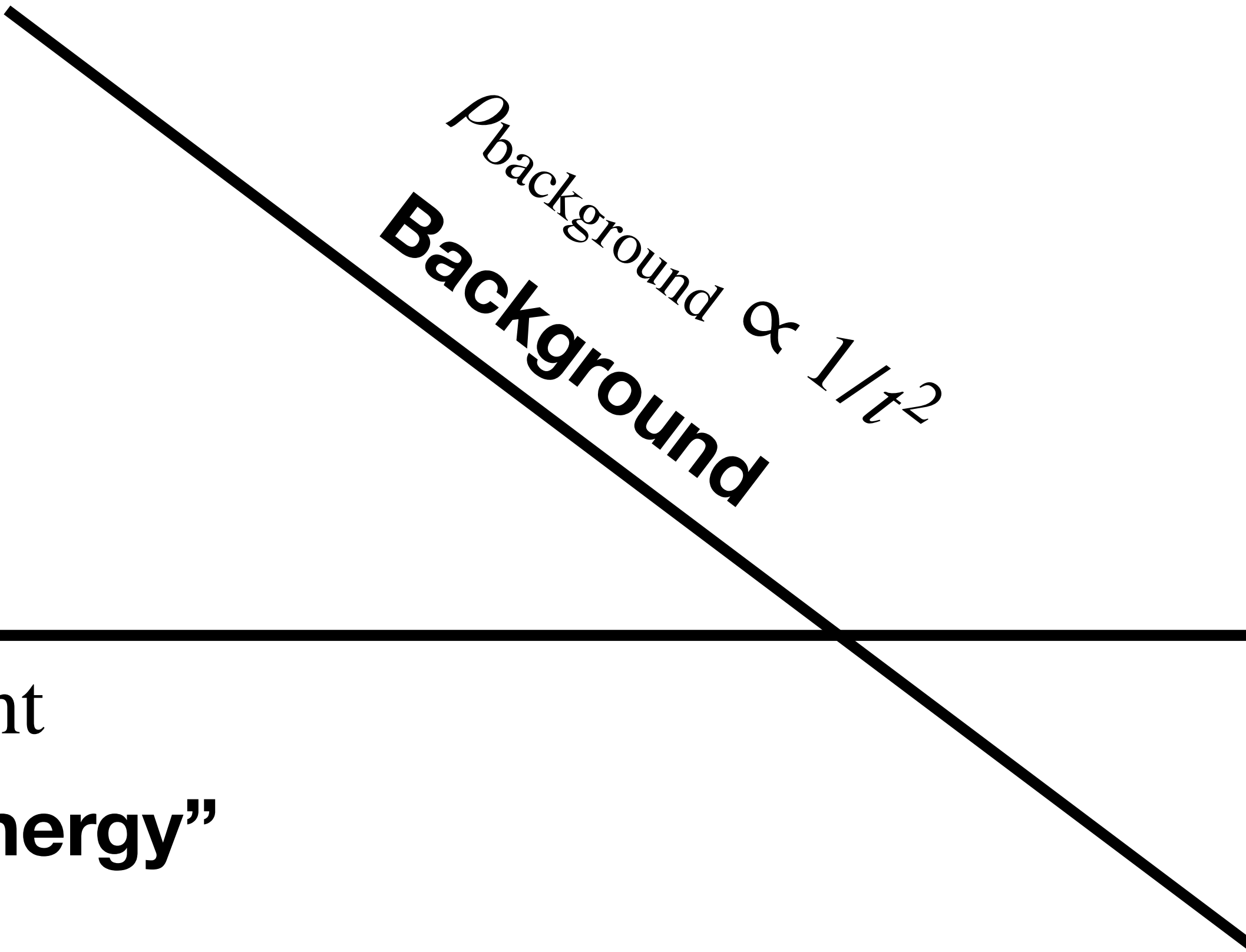
$\rho_{\Lambda} = \text{constant}$

**“3D vacuum energy”**

$\omega = -1$

**Background**

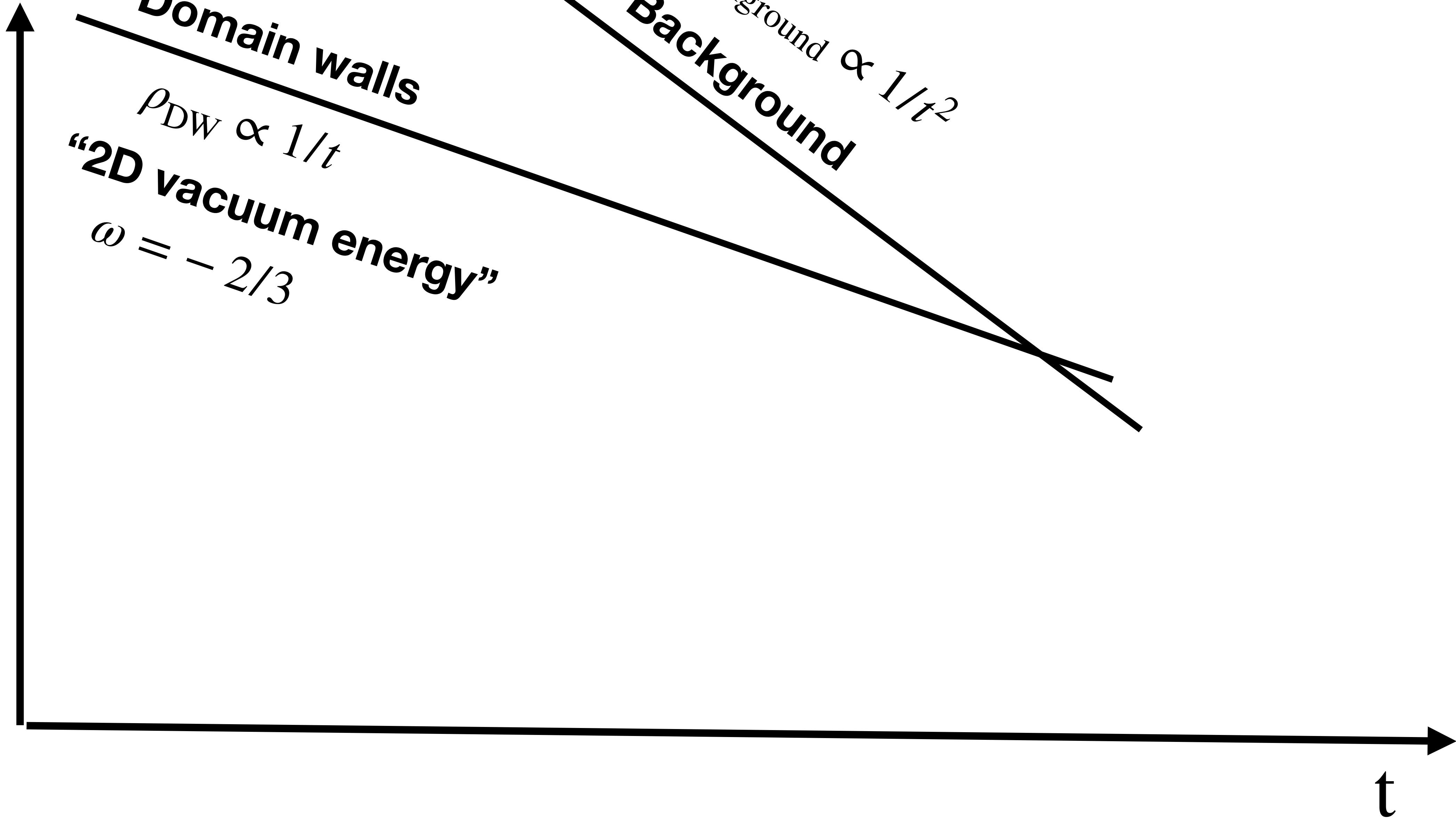
$\rho_{\text{background}} \propto 1/t^2$



t



Energy density



**Domain walls**

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

**"2D vacuum energy"**

$$\omega = -2/3$$

**Background**

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

t

Energy density

# DW-domination

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

**Domain walls**

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

**“2D vacuum energy”**

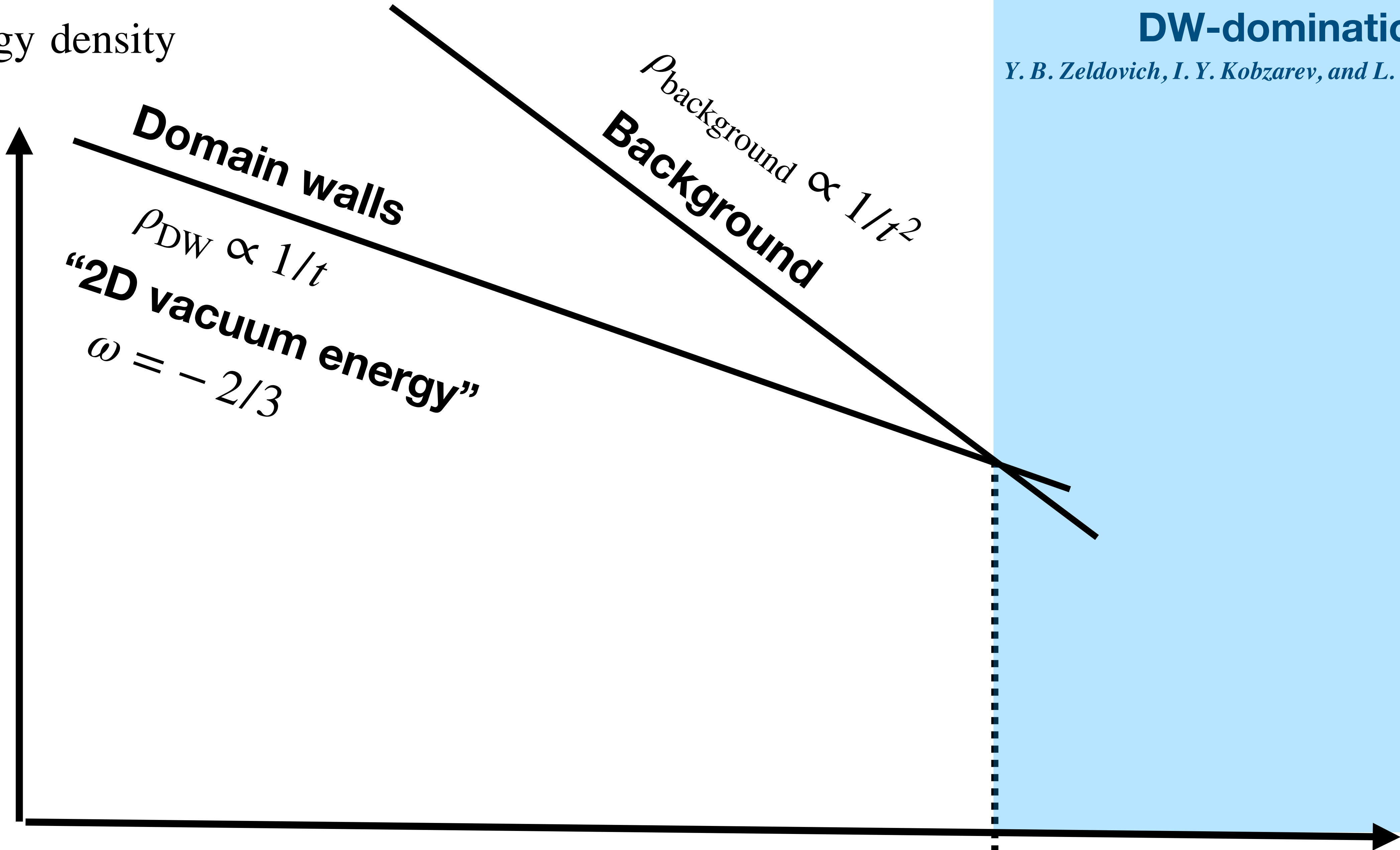
$$\omega = -2/3$$

**Background**

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

$t_{\text{dom}}$

$t$





Energy density

**Domain walls**

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

**“2D vacuum energy”**

$$\omega = -2/3$$

**Background**

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

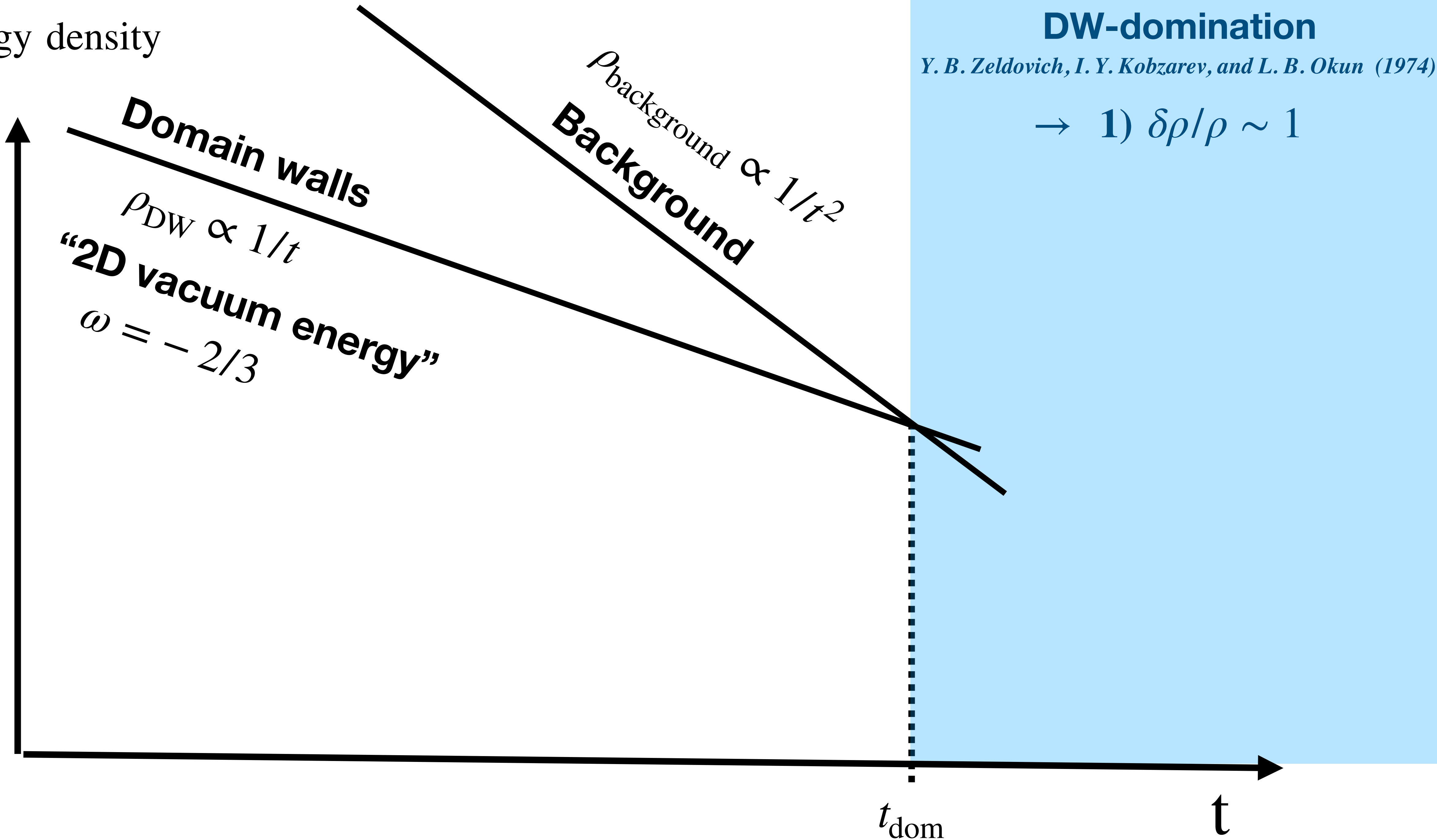
$t_{\text{dom}}$

$t$

## DW-domination

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

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



Energy density

**Domain walls**

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

**“2D vacuum energy”**

$$\omega = -2/3$$

**Background**

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

$t_{\text{dom}}$

$t$

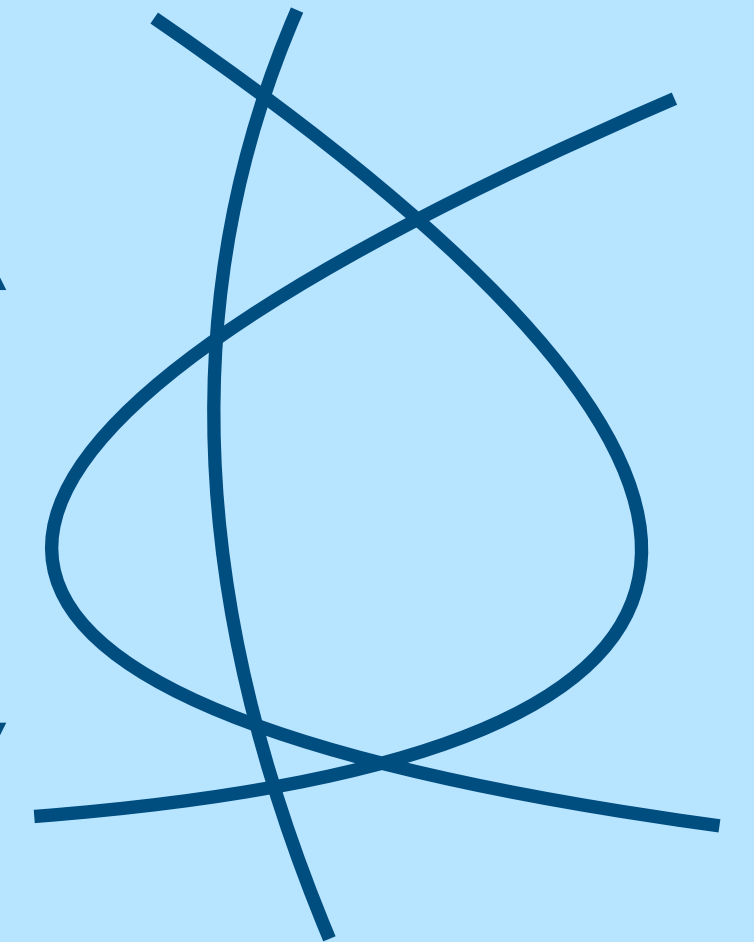
## DW-domination

*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**

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

**“2D vacuum energy”**

$$\omega = -2/3$$

**Background**

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

$t_{\text{dom}}$

$t$

## DW-domination

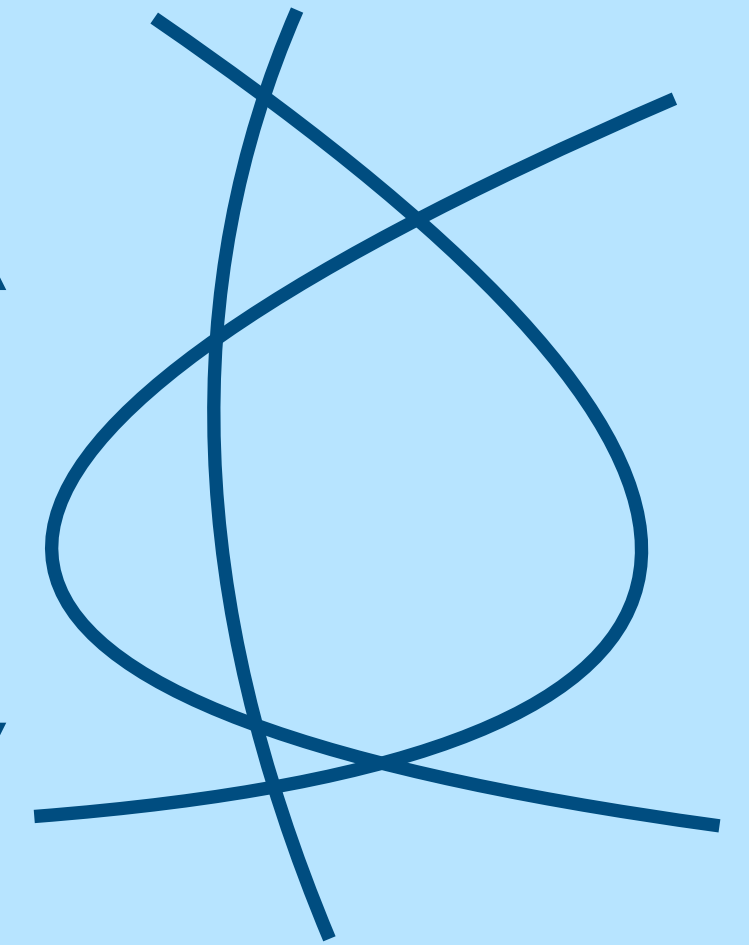
*Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)*

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

$$\langle R \rangle \simeq t$$

(scaling regime)

$$\rightarrow 2) \text{horizon size}$$





Energy density

**Domain walls**

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

**“2D vacuum energy”**

$$\omega = -2/3$$

**Background**

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

$t_{\text{dom}}$

$t$

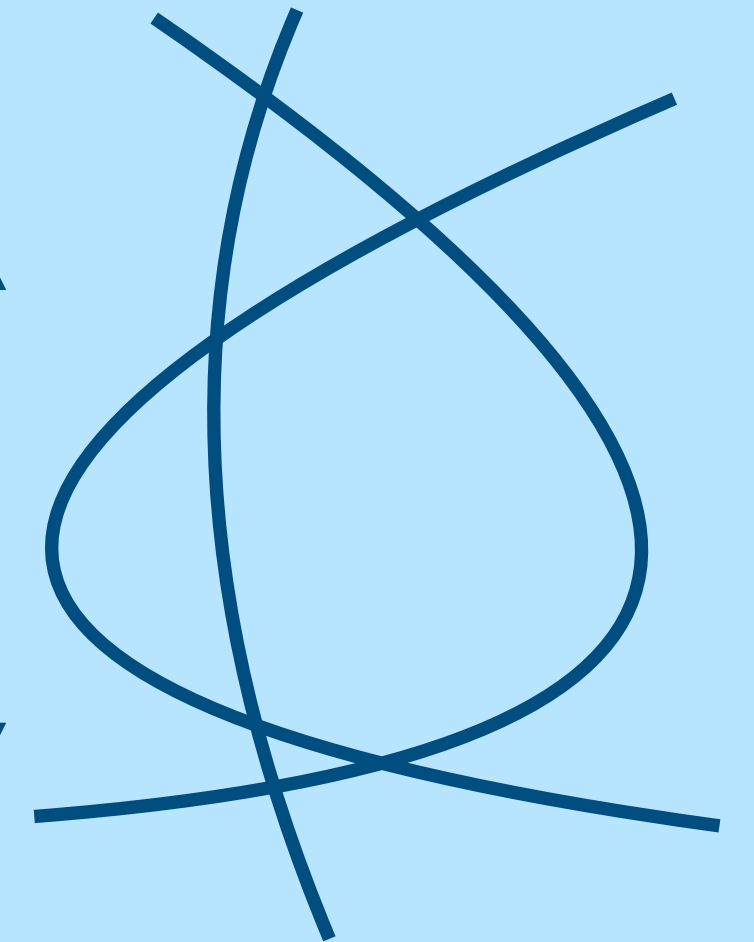
## DW-domination

*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)



$$\rightarrow 2) \text{ horizon size}$$

$\Rightarrow$  **Efficient PBH formation**

Energy density

**Domain walls**

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

**“2D vacuum energy”**

$$\omega = -2/3$$

**Background**

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

$t_{\text{dom}}$

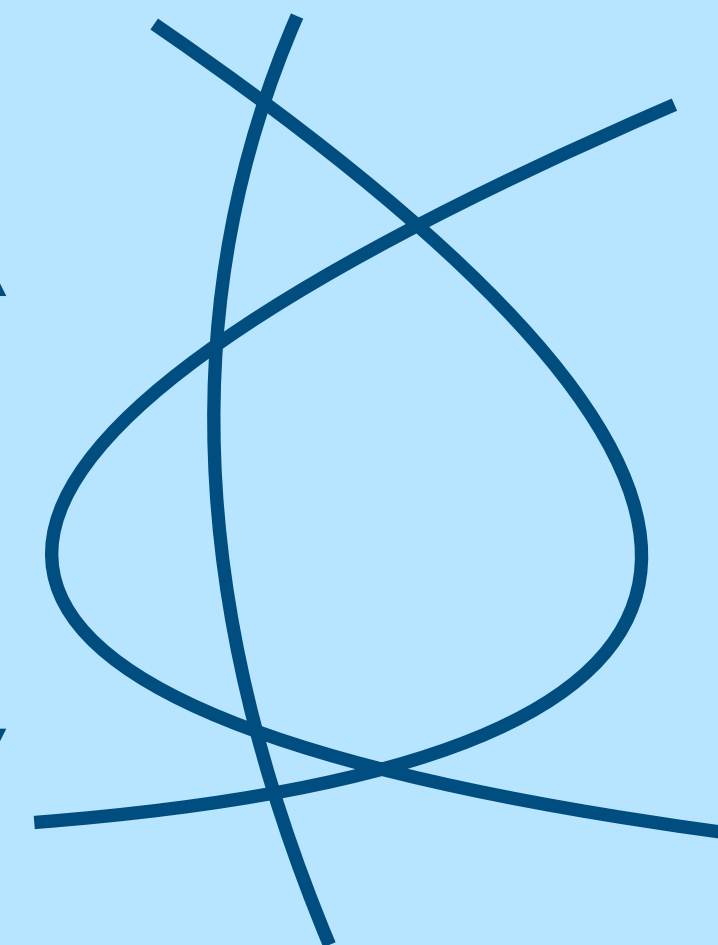
## DW-domination

*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)



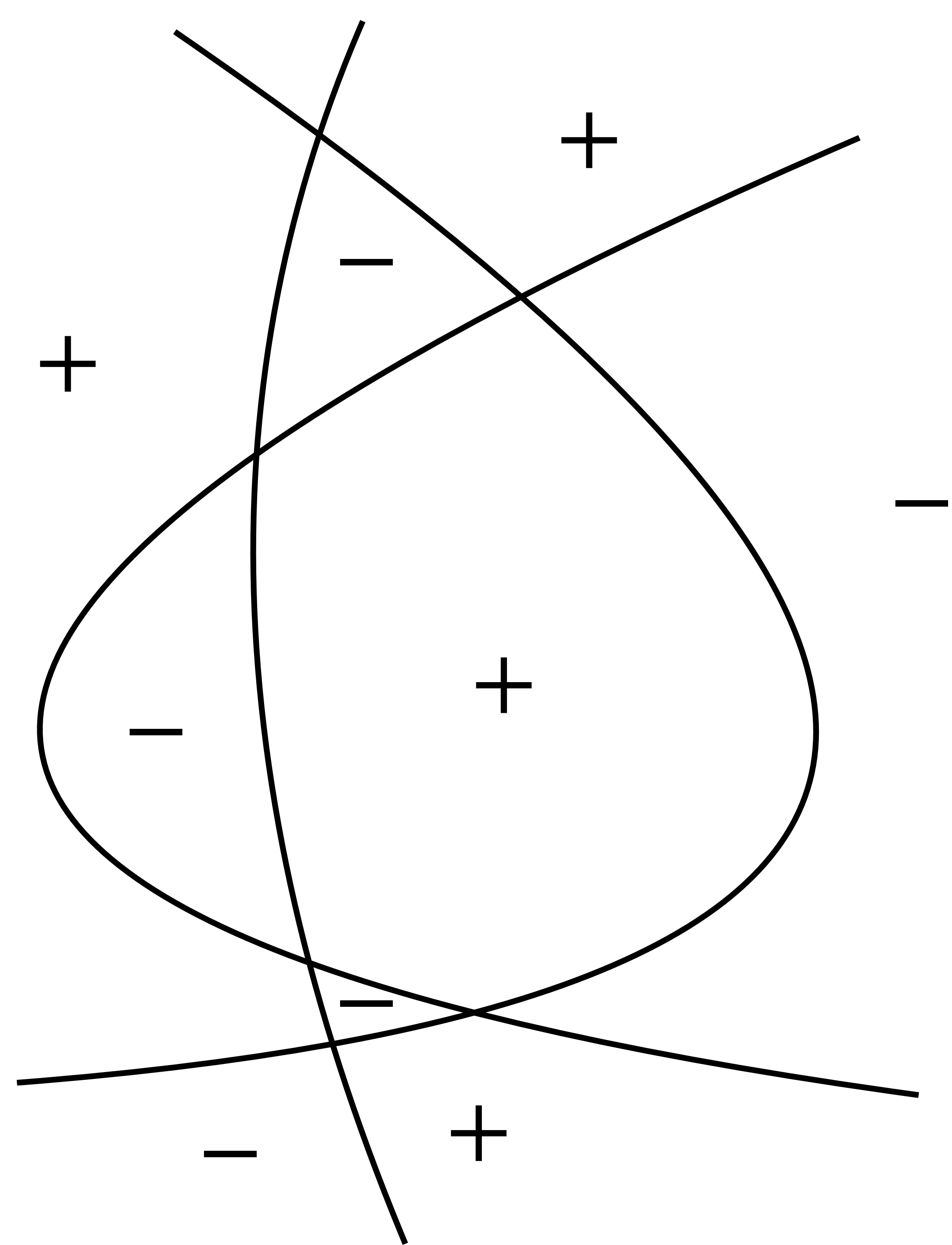
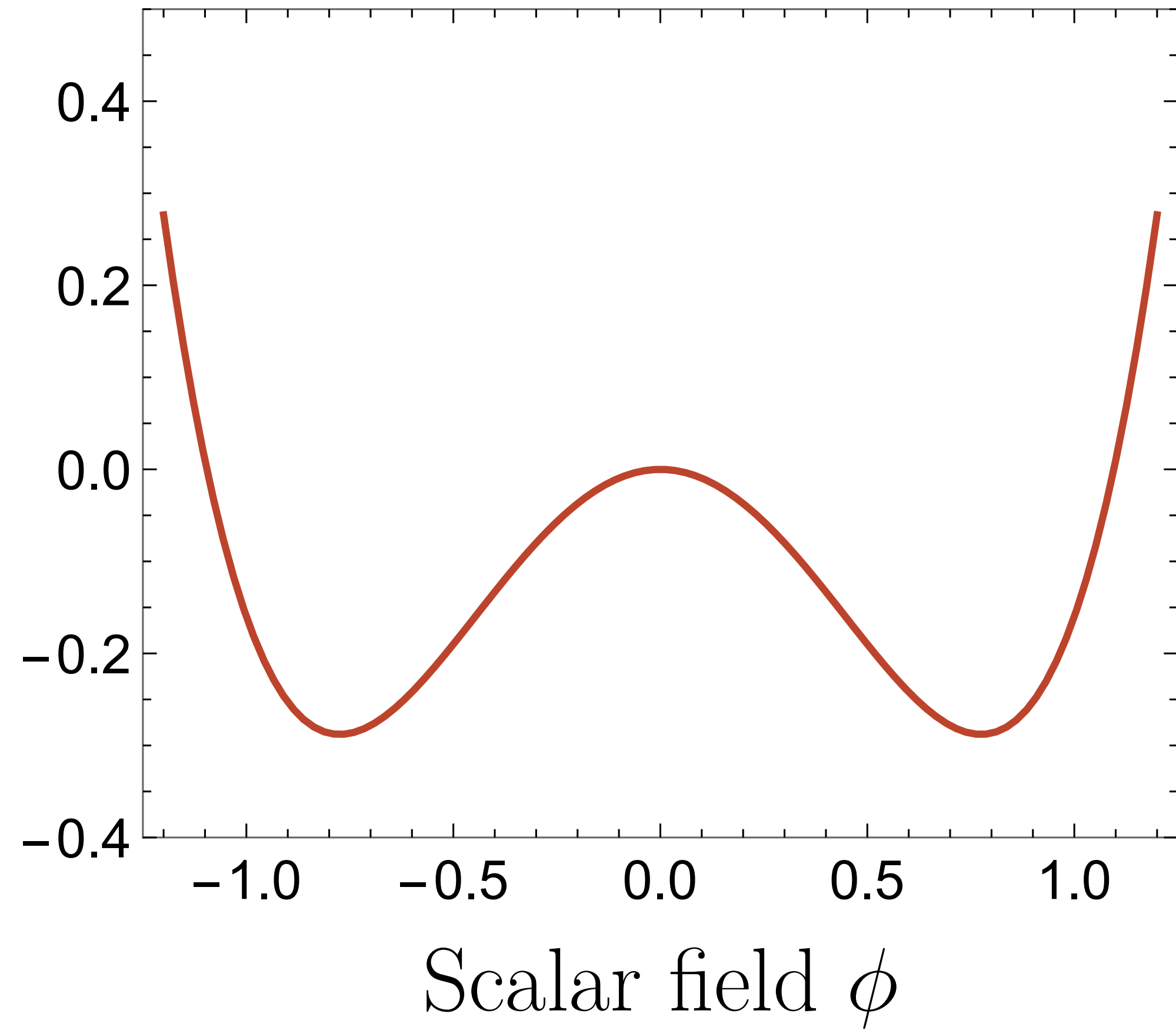
$$\rightarrow 2) \text{ horizon size}$$

$\Rightarrow$  **Efficient PBH formation**

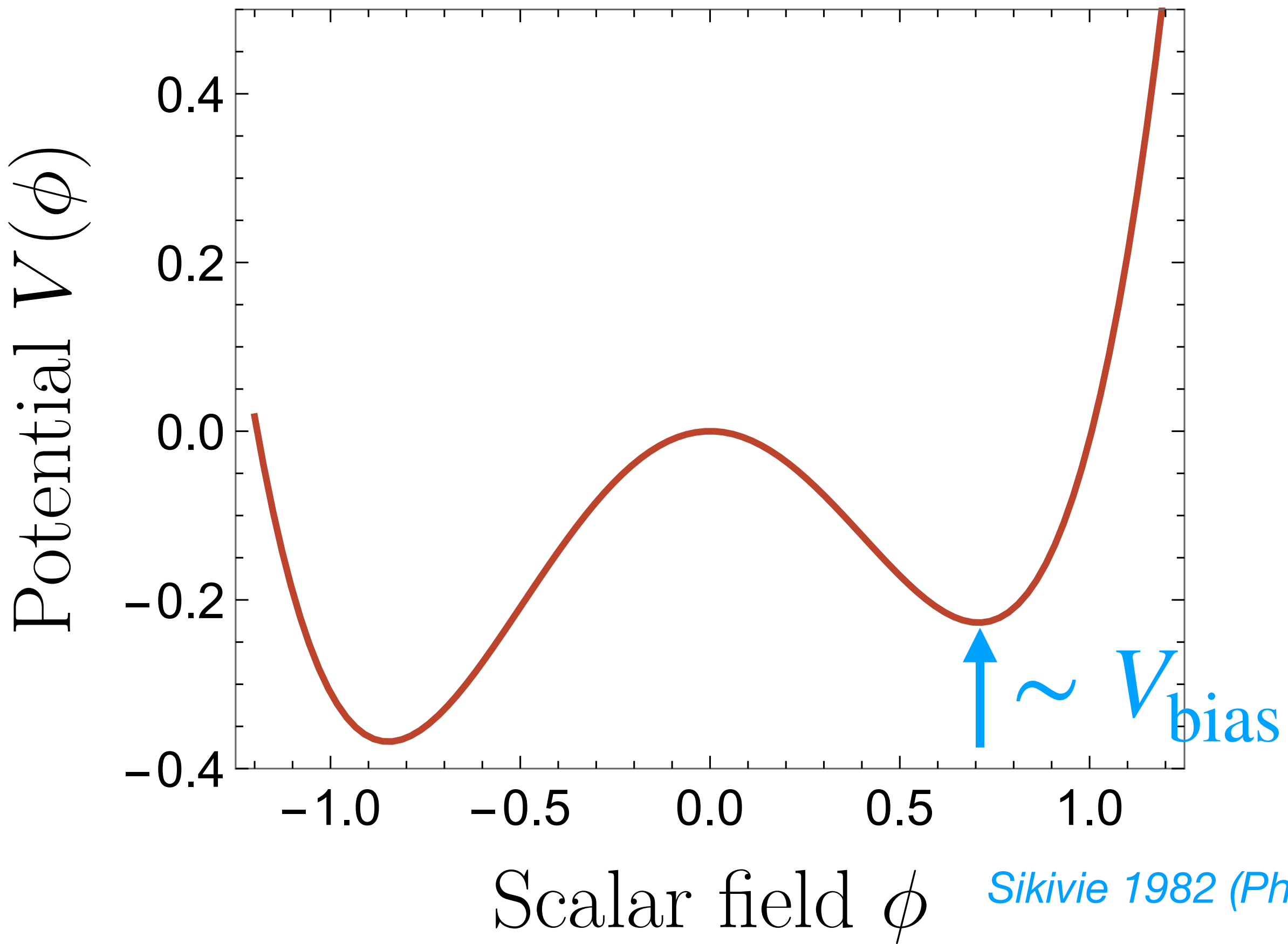
Vilenkin and Shellard's textbook, 2000

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

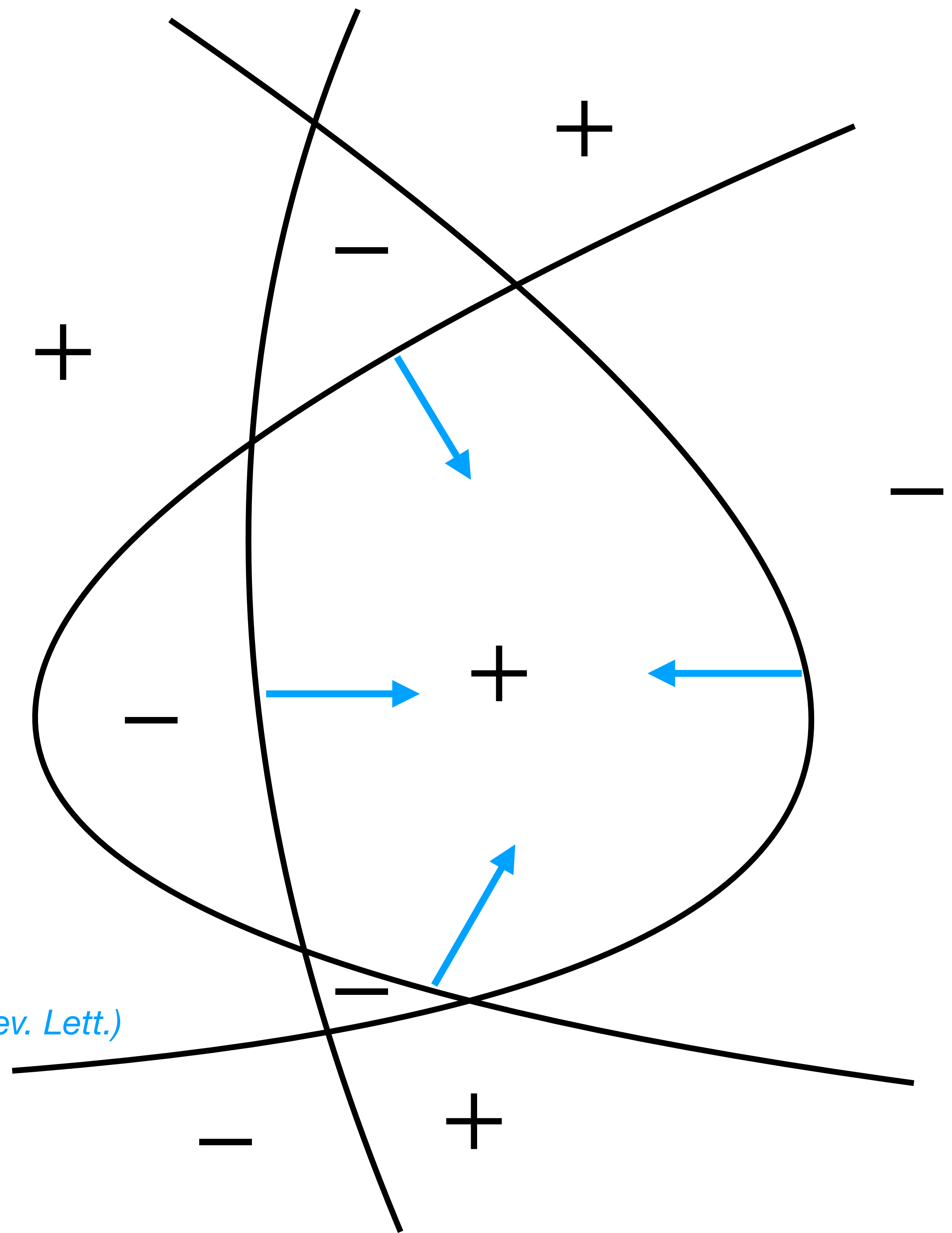
Vacuum energy bias



Vacuum energy bias



*Sikivie 1982 (Phys. Rev. Lett.)*





Energy density

**Domain walls**

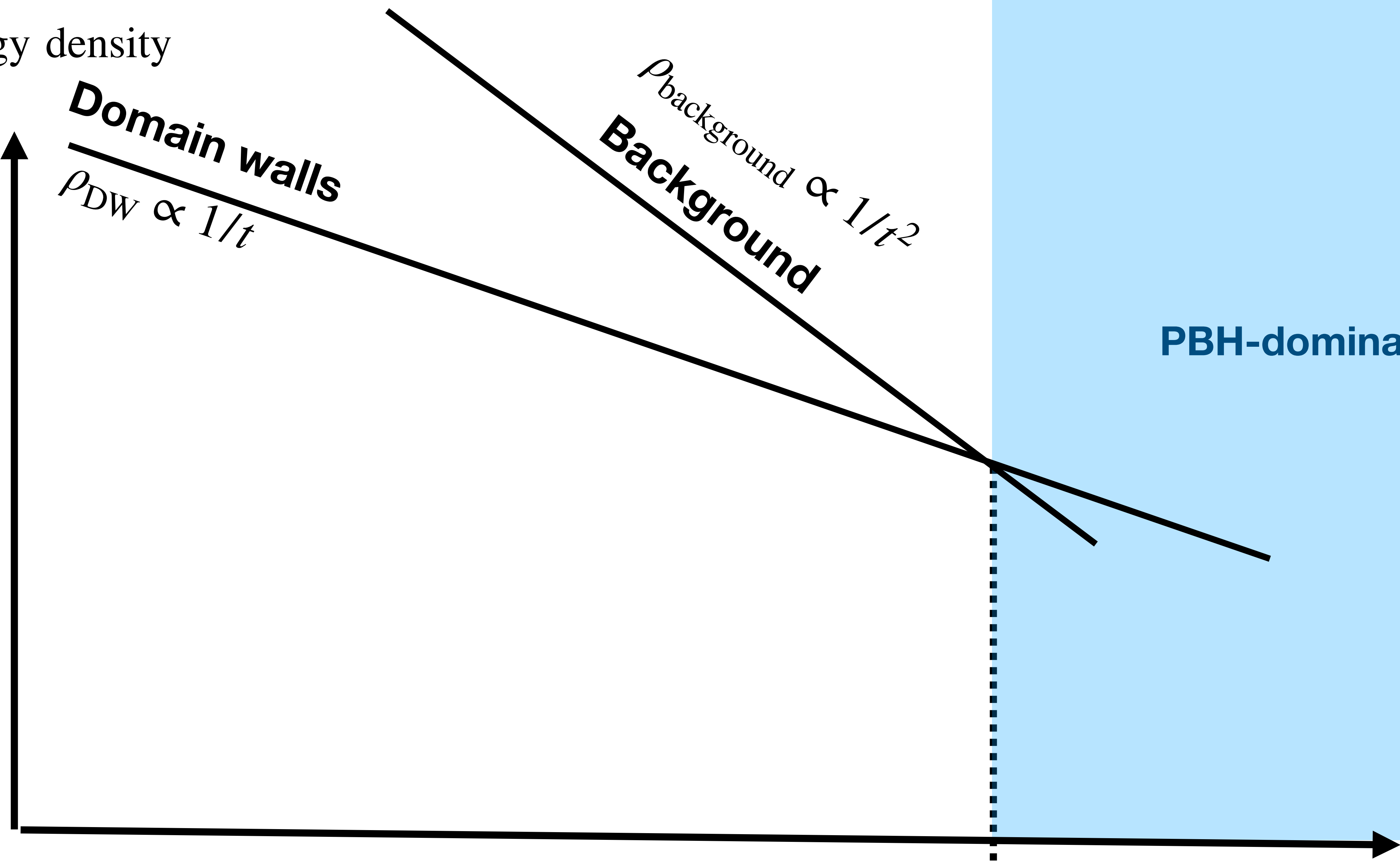
$$\rho_{DW} \propto 1/t$$

**Background**

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

**PBH-domination**

$t_{\text{dom}}$



Energy density

**Domain walls**

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

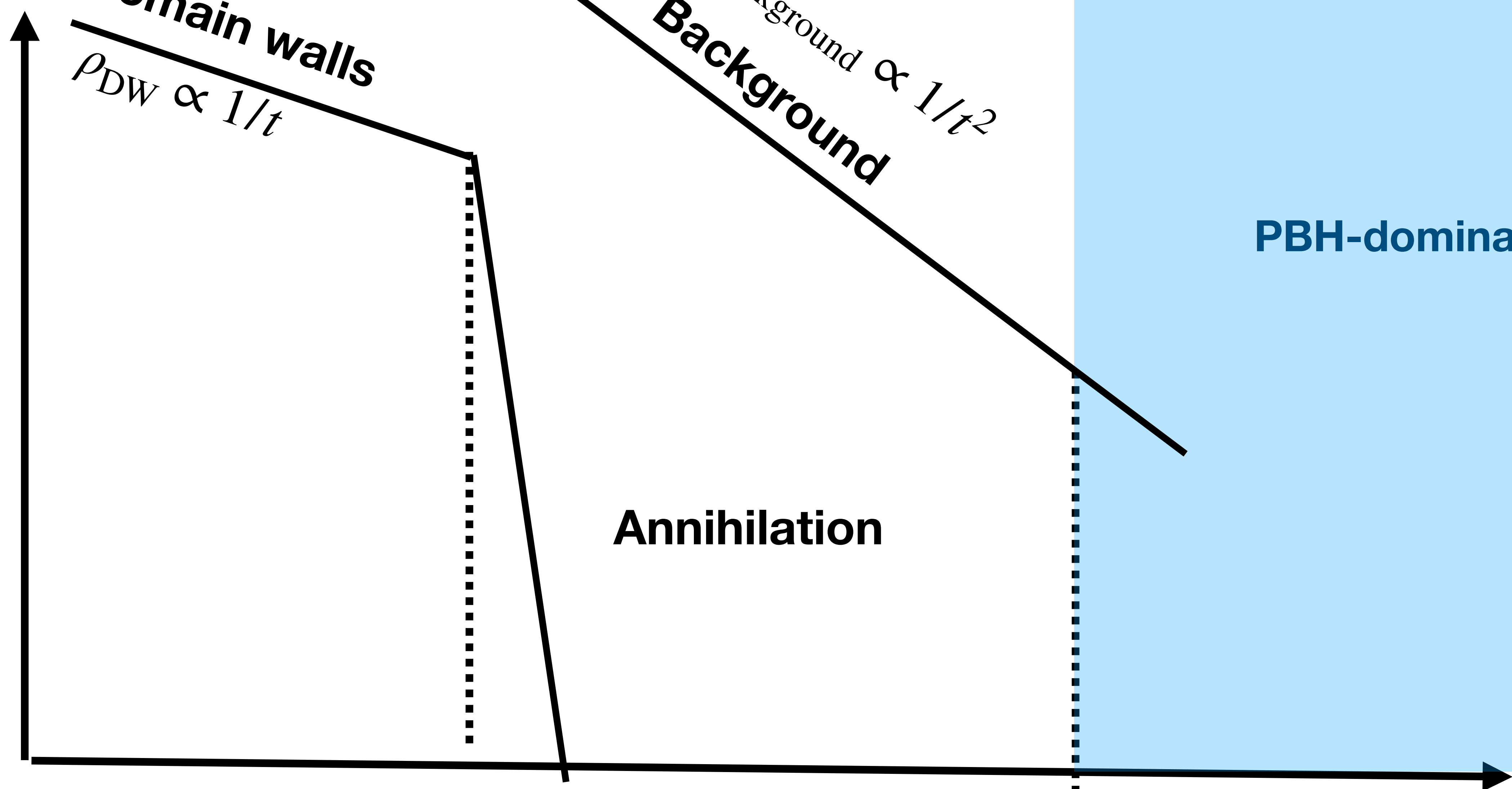
$\rho_{\text{background}} \propto 1/t^2$   
**Background**

**PBH-domination**

**Annihilation**

$t_{\text{ann}}$

$t_{\text{dom}}$



Energy density

**Domain walls**

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

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

**PBH-domination**

*Vilenkin (1982)*

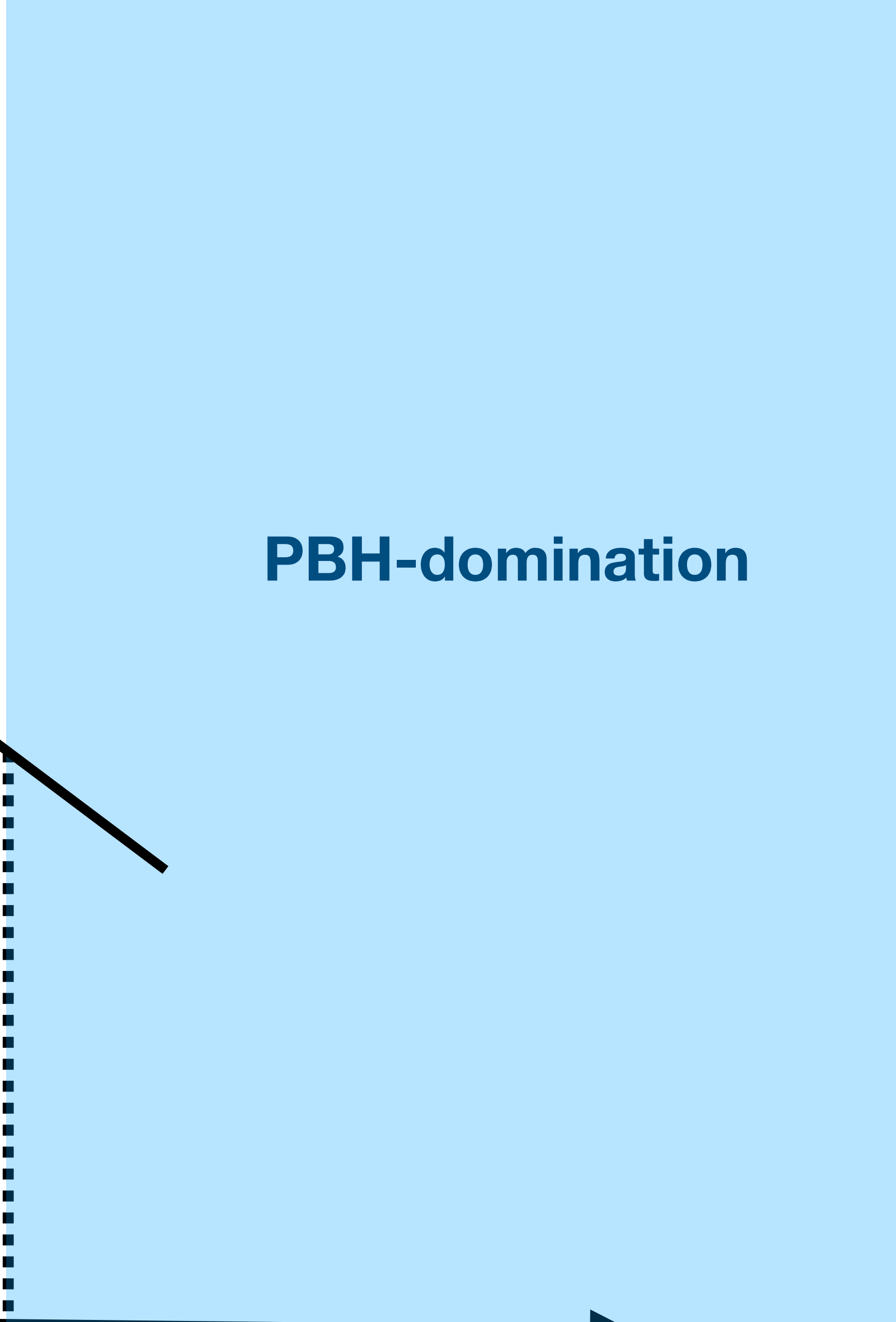
**Gravitational waves**



**Annihilation**

$t_{\text{ann}}$

$t_{\text{dom}}$



Energy density

**Domain walls**

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

**Background**

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

$\sim 10\%$

$\rightarrow$  can explain  
NG15

(YG, Vitagliano, 2306.17841)

*Vilenkin (1982)*

**Gravitational waves**



**Annihilation**

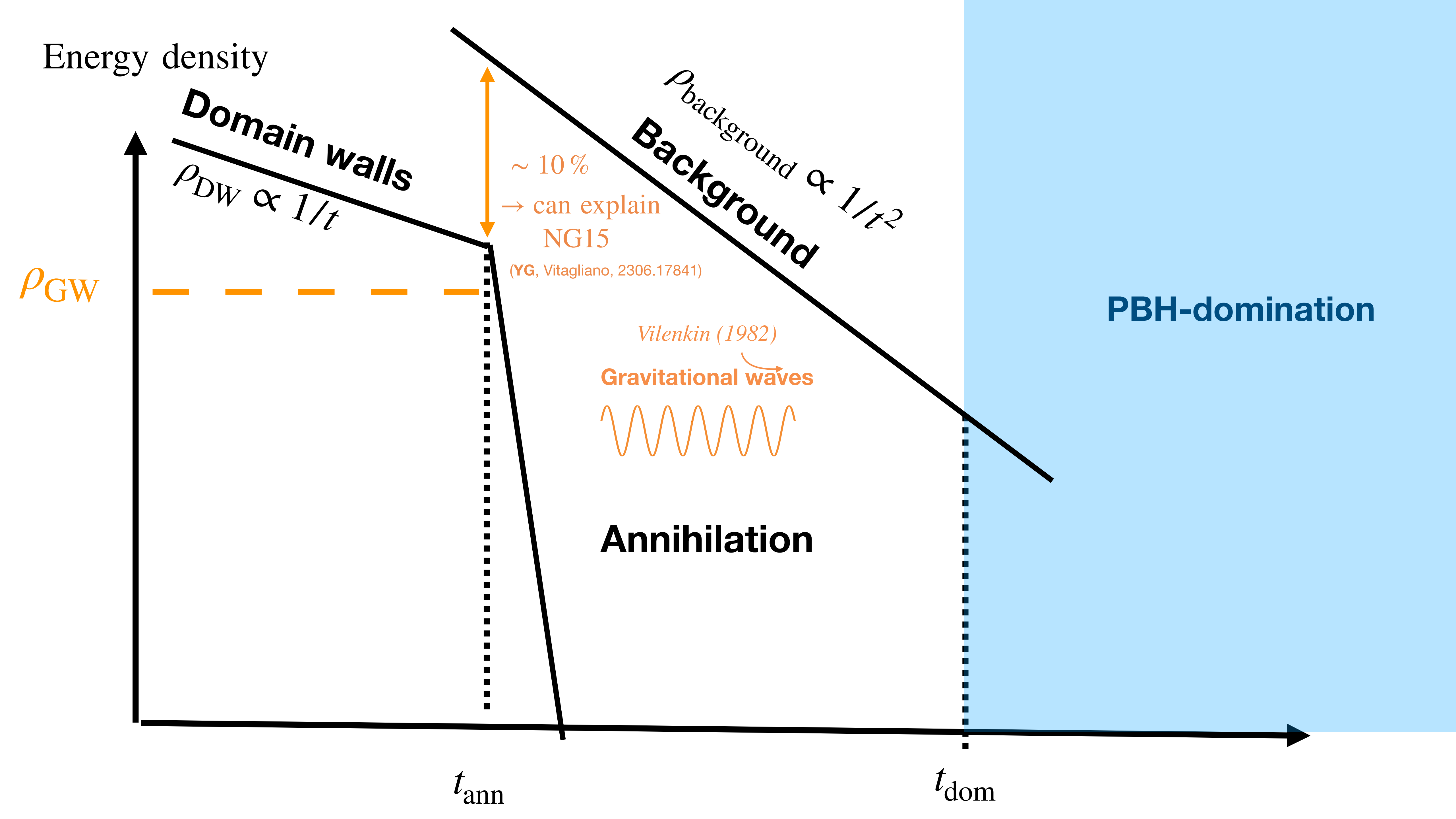
**PBH-domination**

$\rho_{GW}$



$t_{ann}$

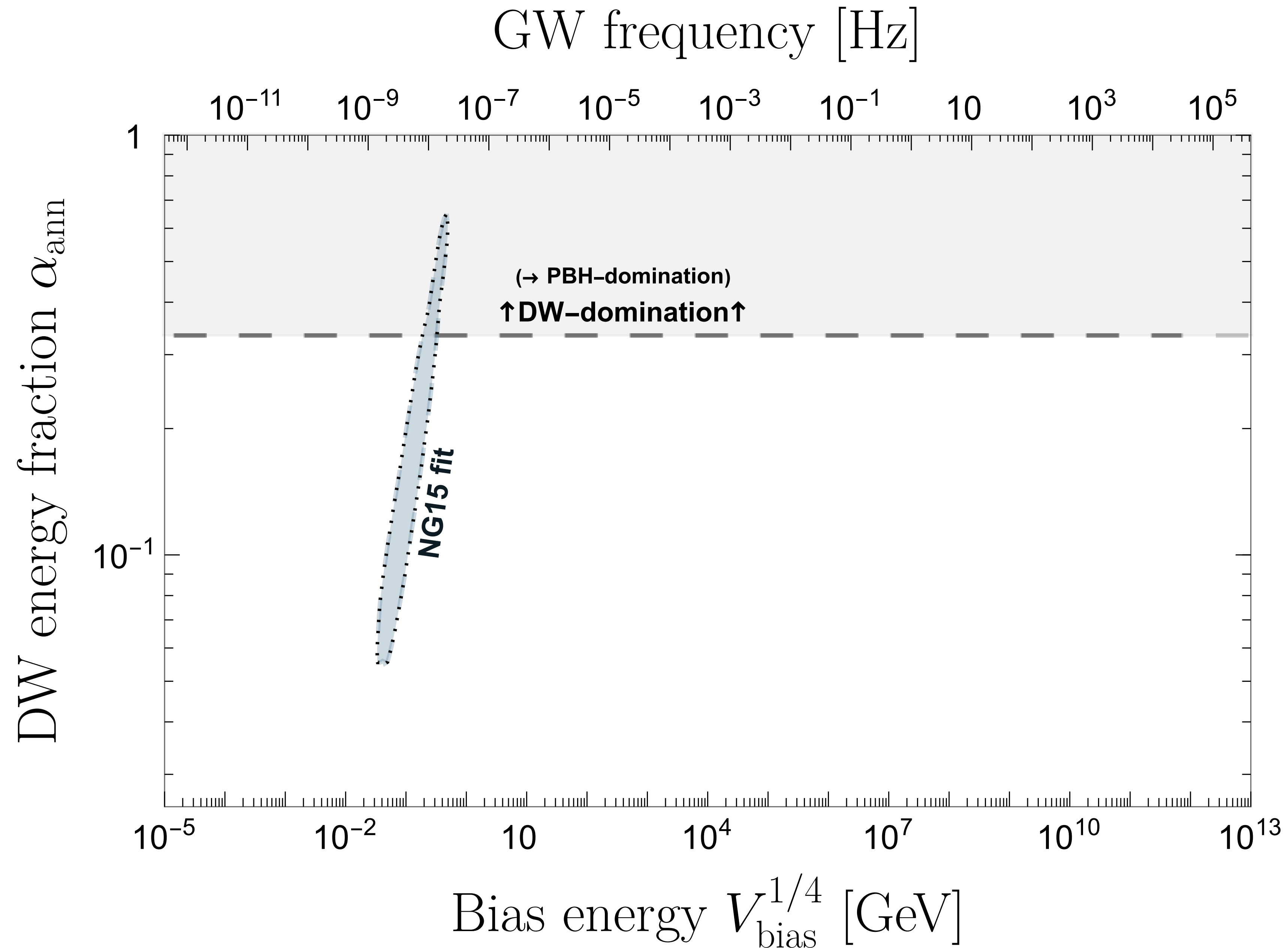
$t_{dom}$



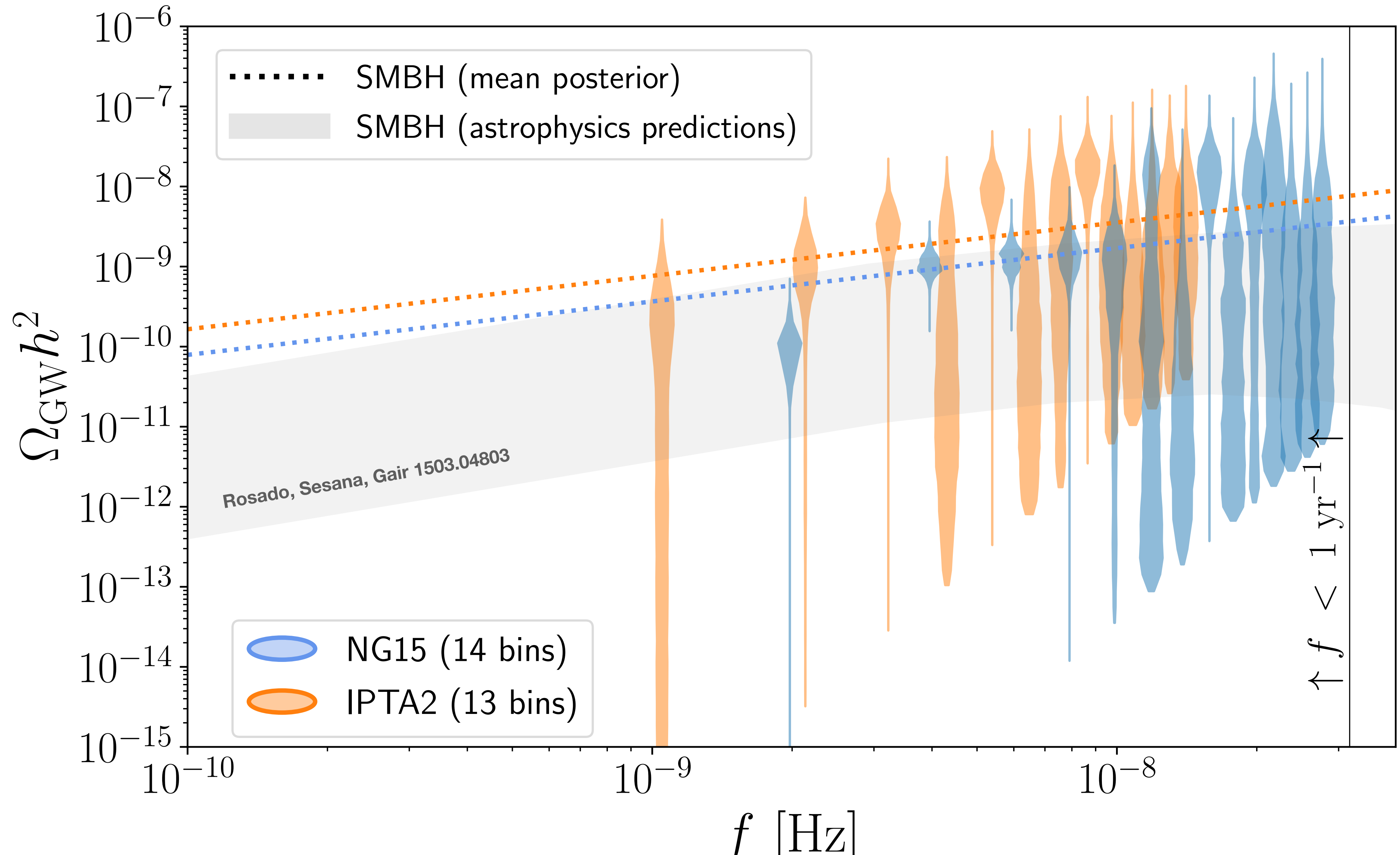


# GW from DW annihilation in Pulsar Timing arrays

Gouttenoire, Vitagliano, 2306.17841

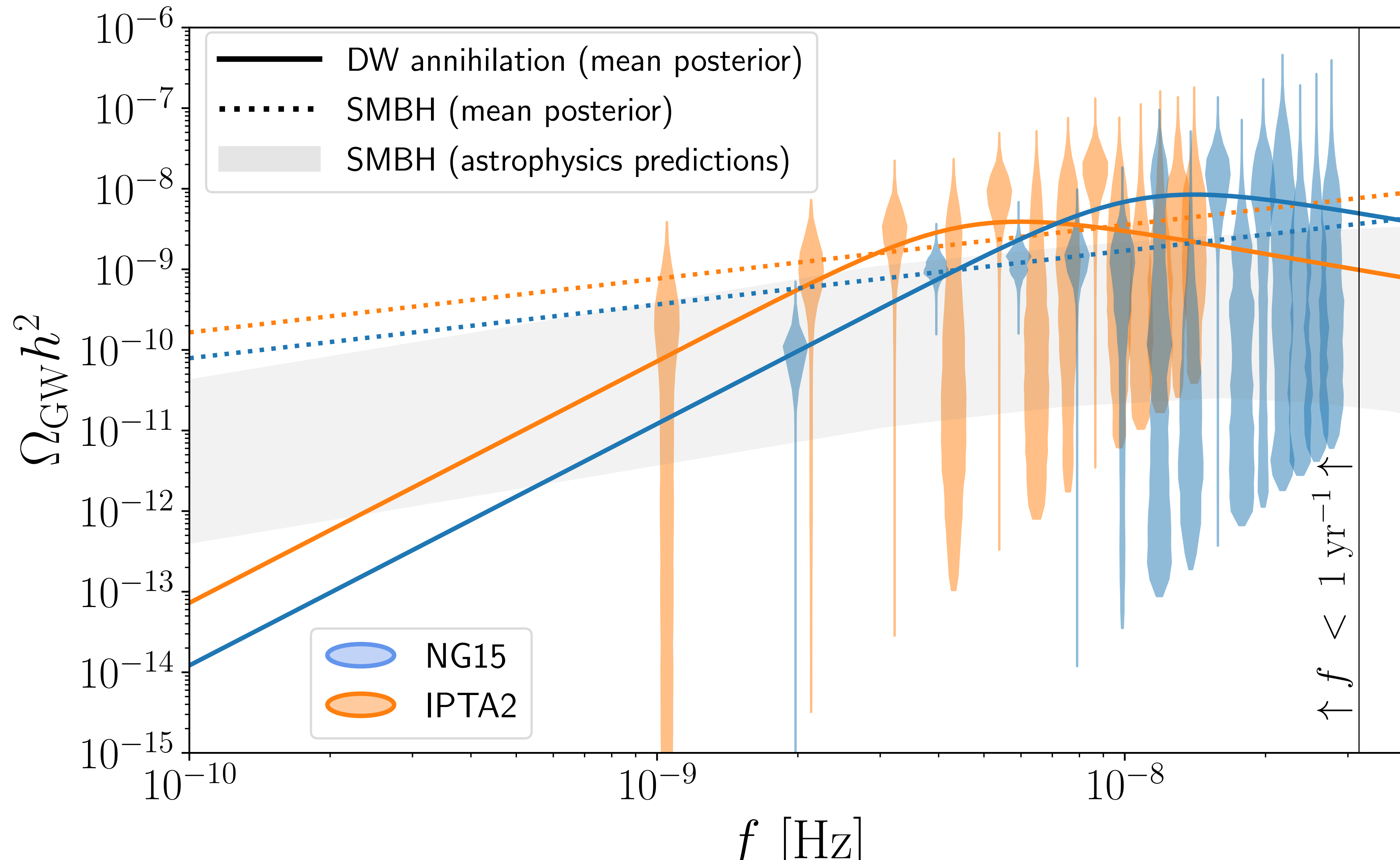


# GW from DW annihilation in Pulsar Timing arrays



# GW from DW annihilation in Pulsar Timing arrays

Gouttenoire, Vitagliano, 2306.17841



Energy density

**Domain walls**

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

**Background**

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

$\sim 10\%$

$\rightarrow$  can explain  
NG15

(YG, Vitagliano, 2306.17841)

*Vilenkin (1982)*

**Gravitational waves**



**Annihilation**

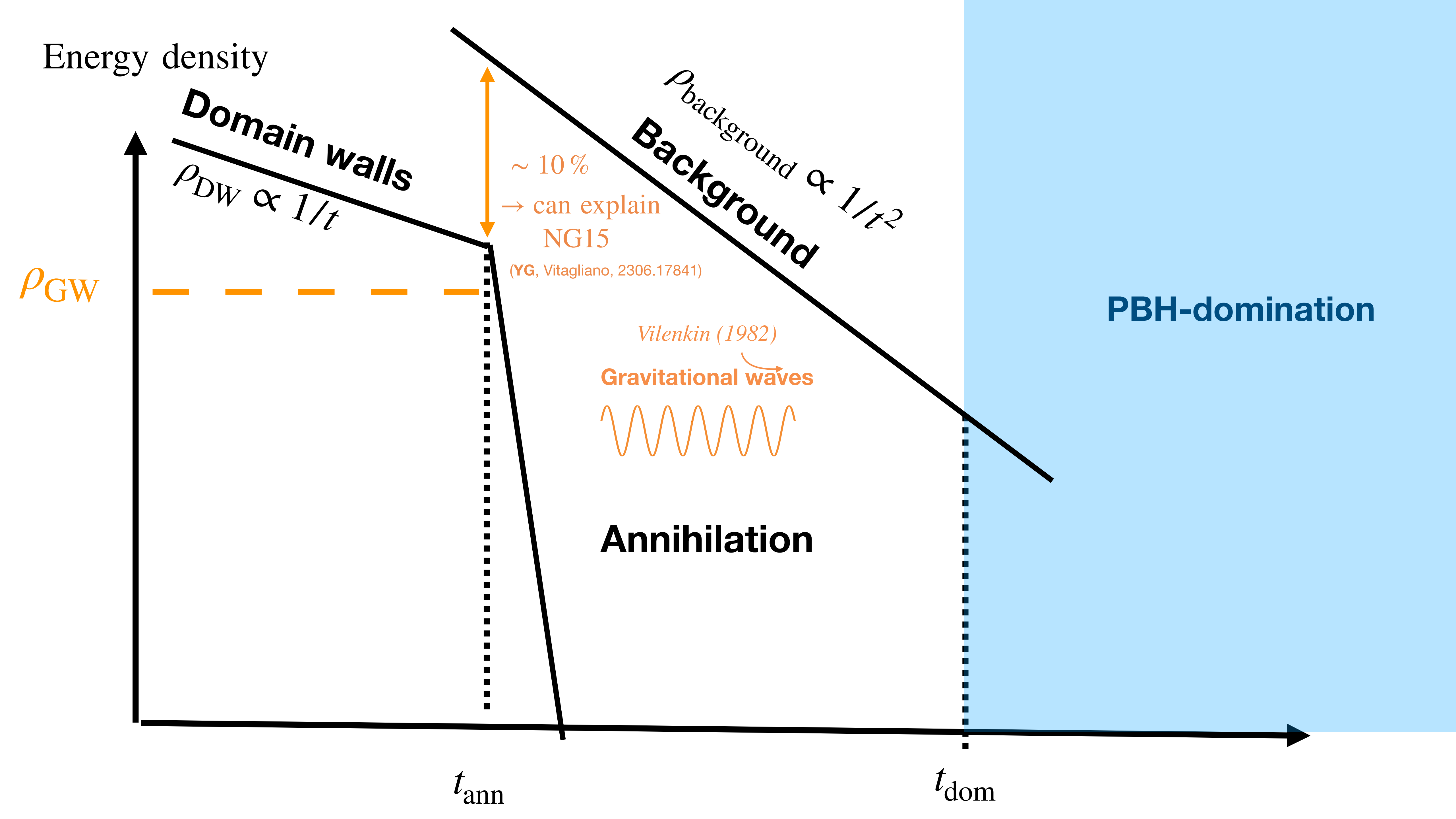
**PBH-domination**

$\rho_{GW}$

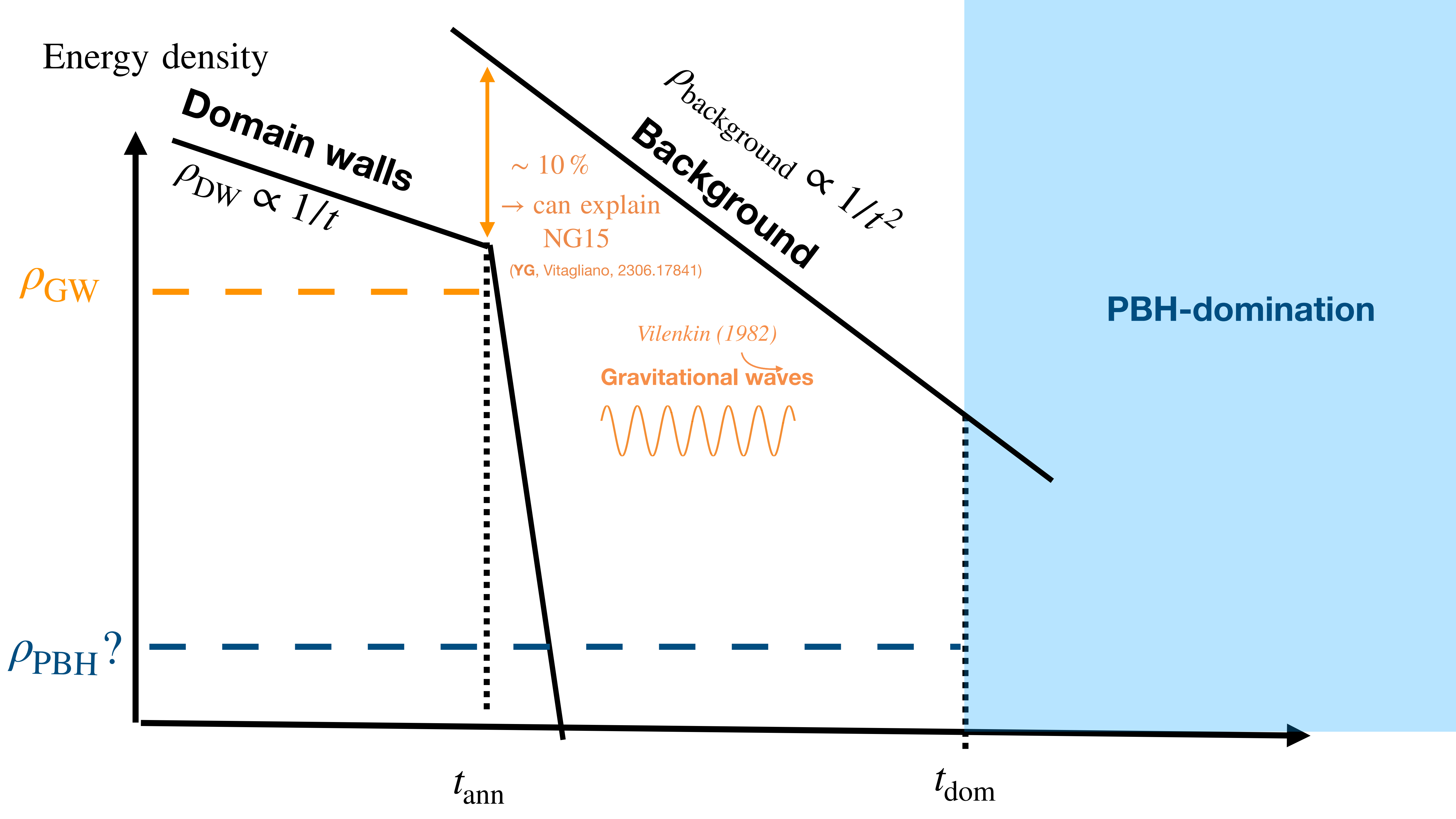


$t_{\text{ann}}$

$t_{\text{dom}}$







Energy density

**Domain walls**

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

**Background**

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

$\sim 10\%$

$\rightarrow$  can explain NG15

(YG, Vitagliano, 2306.17841)

**PBH-domination**

$\rho_{GW}$

*Vilenkin (1982)*

**Gravitational waves**



**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,

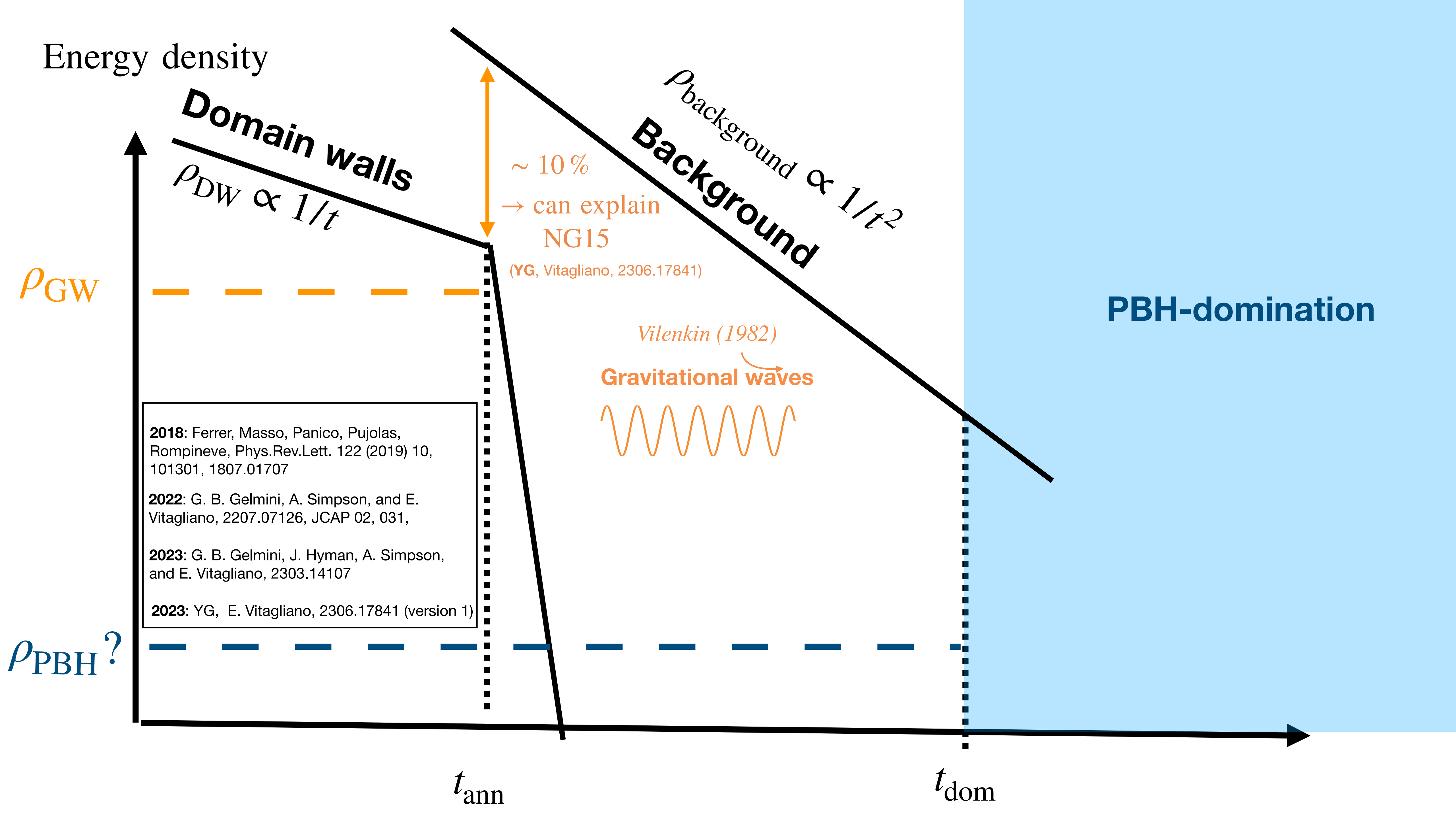
**2023:** G. B. Gelmini, J. Hyman, A. Simpson, and E. Vitagliano, 2303.14107

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

$\rho_{PBH}?$

$t_{ann}$

$t_{dom}$



Energy density

**Domain walls**

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

**Background**

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

$\sim 10\%$

$\rightarrow$  can explain NG15

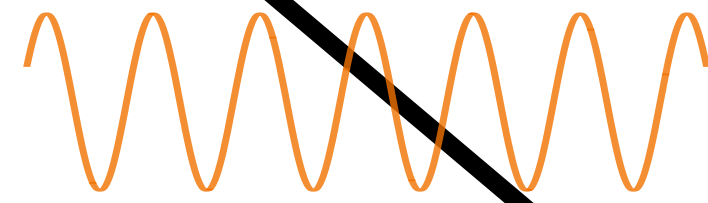
(YG, Vitagliano, 2306.17841)

**PBH-domination**

$\rho_{GW}$

*Vilenkin (1982)*

**Gravitational waves**



**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,

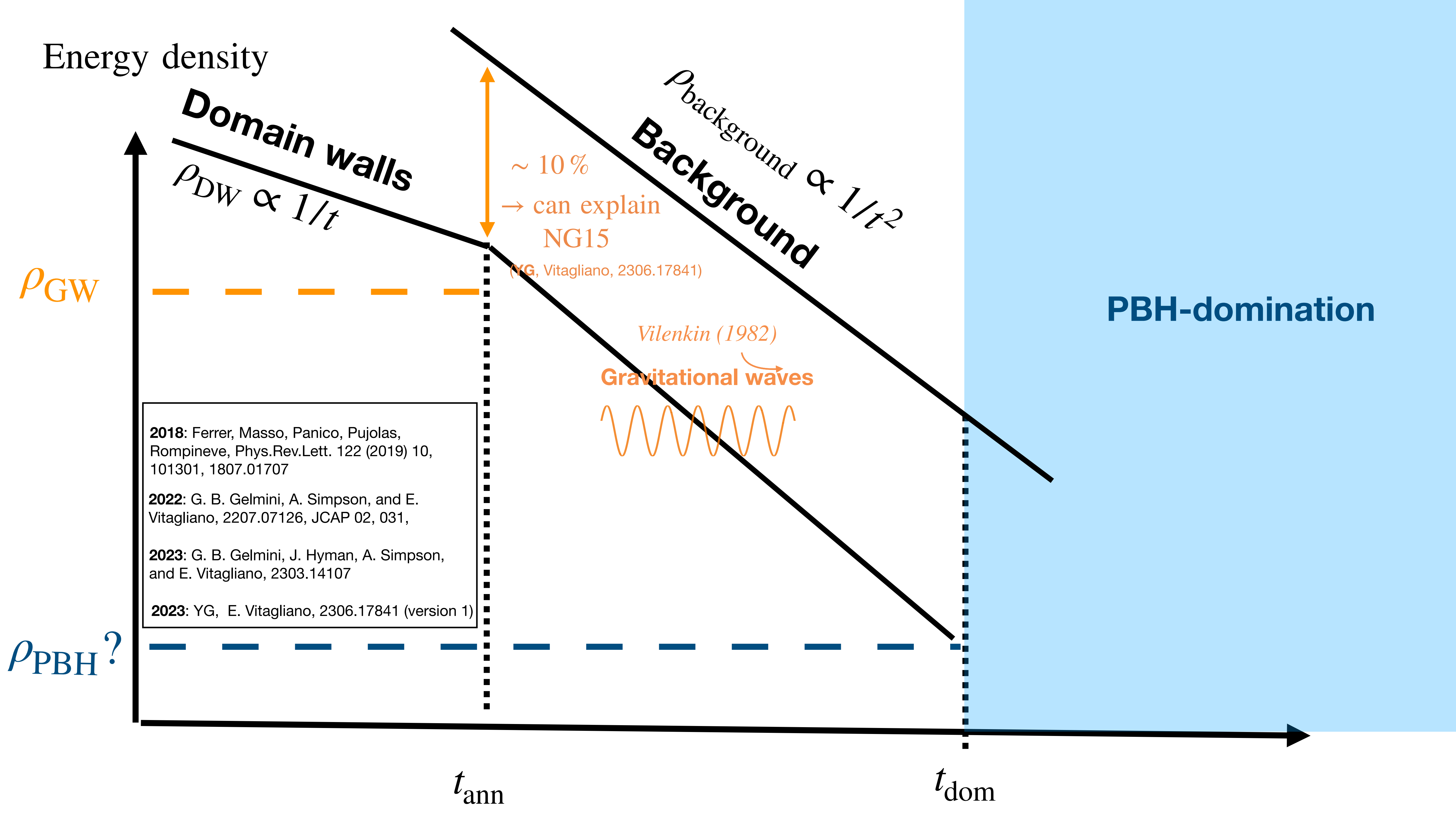
**2023:** G. B. Gelmini, J. Hyman, A. Simpson, and E. Vitagliano, 2303.14107

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

$\rho_{PBH}?$

$t_{ann}$

$t_{dom}$



Energy density

**Domain walls**

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

**Background**

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

$\sim 10\%$

$\rightarrow$  can explain NG15

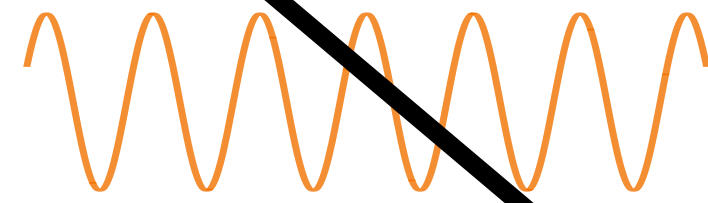
(YG, Vitagliano, 2306.17841)

$\rho_{GW}$

**These papers incorrectly assumed  $R(t) \simeq t$**

*Vilenkin (1982)*

**Gravitational waves**



~~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~~

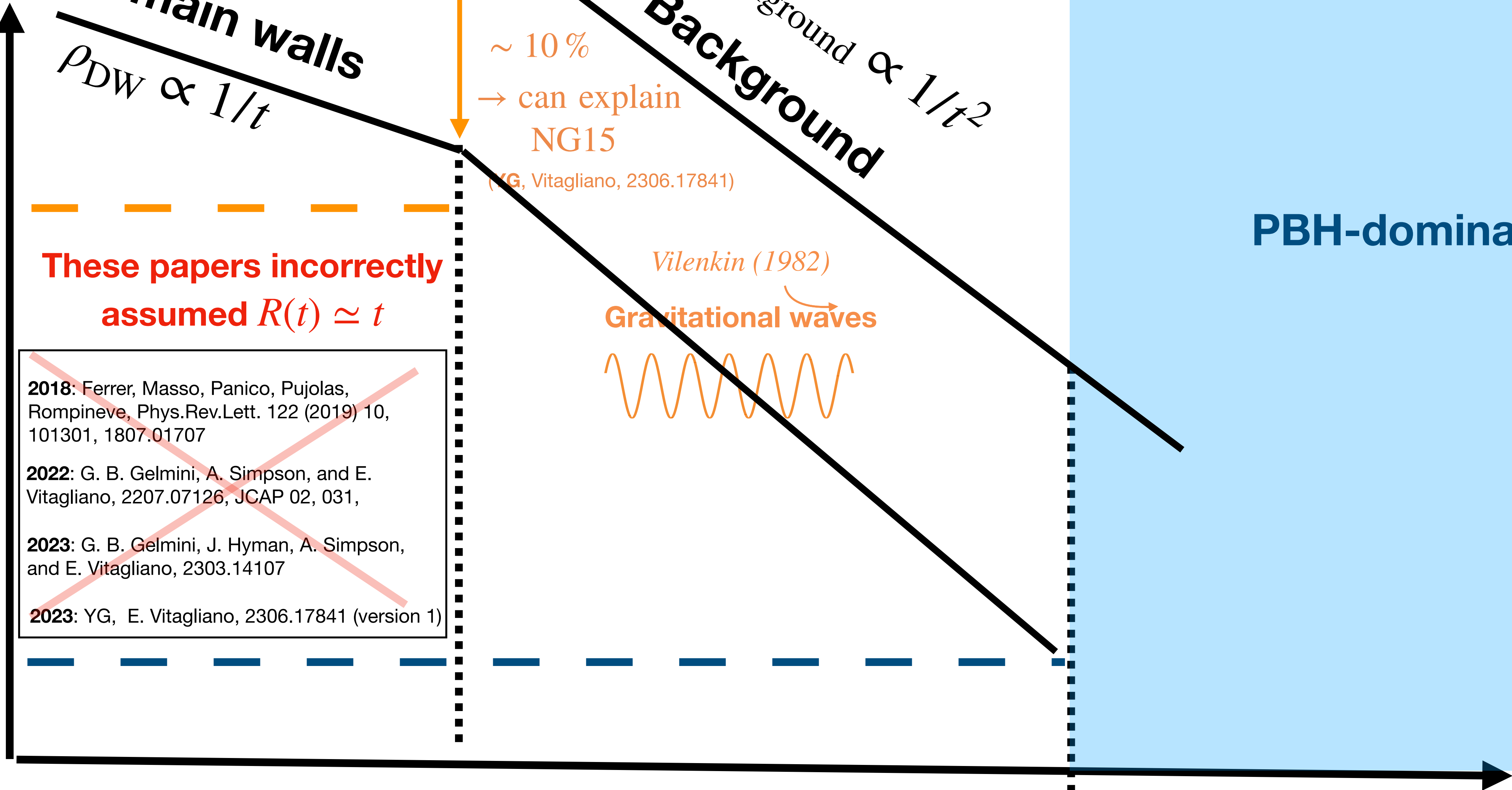
~~2023: YG, E. Vitagliano, 2306.17841 (version 1)~~

**PBH-domination**

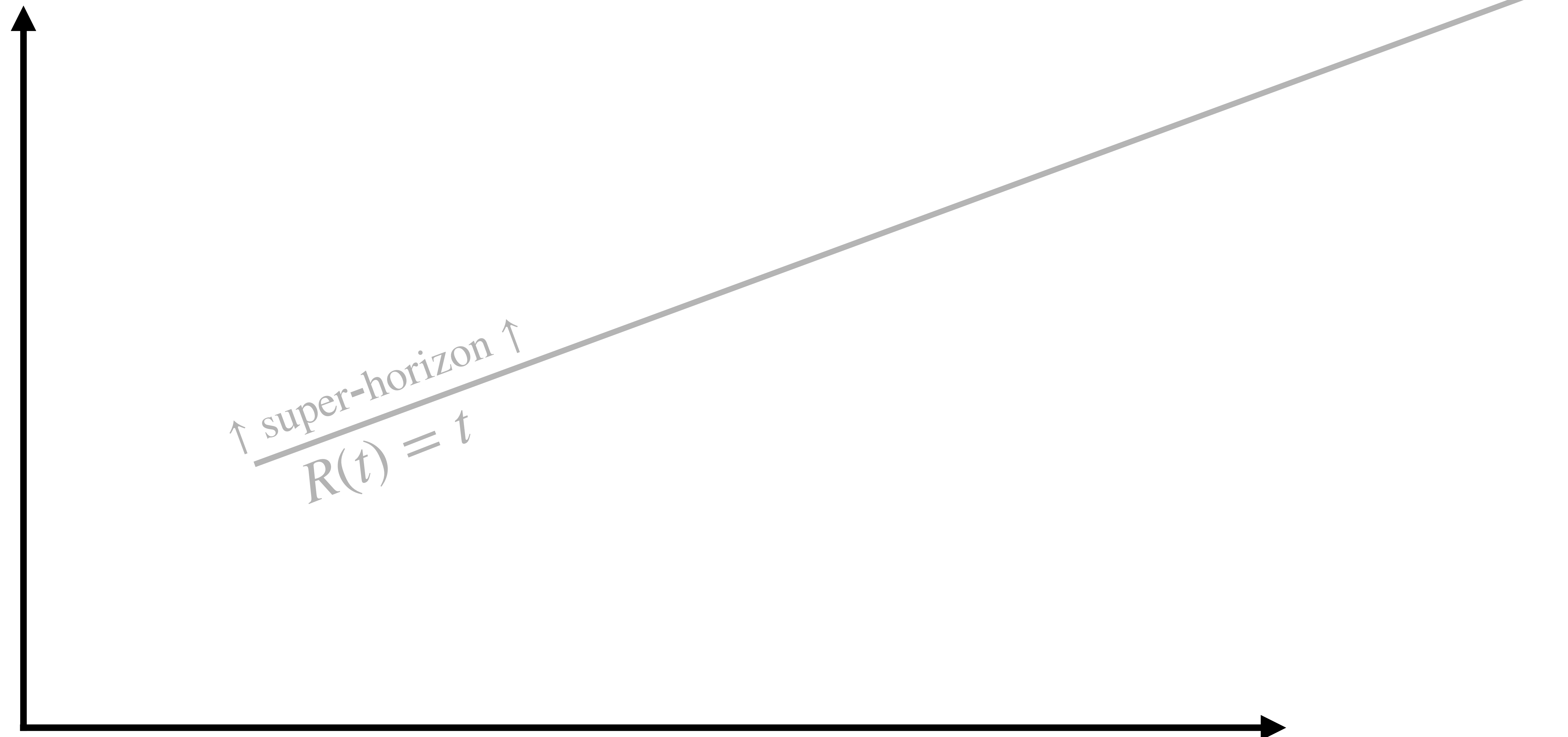
$\rho_{PBH}?$

$t_{\text{ann}}$

$t_{\text{dom}}$



DW radius  $R$

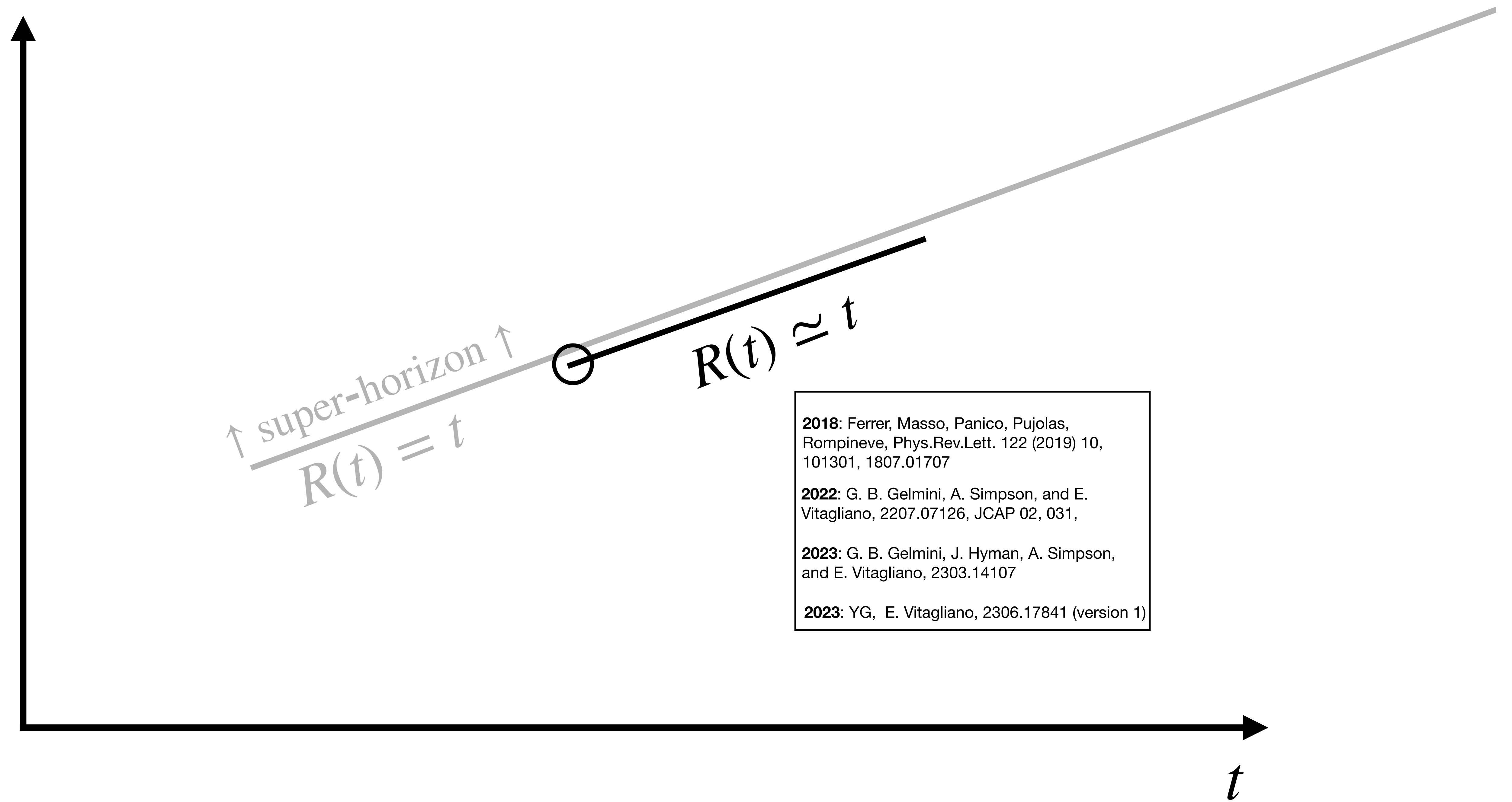


↑ super-horizon ↑  
 $R(t) = t$

$t$



DW radius  $R$



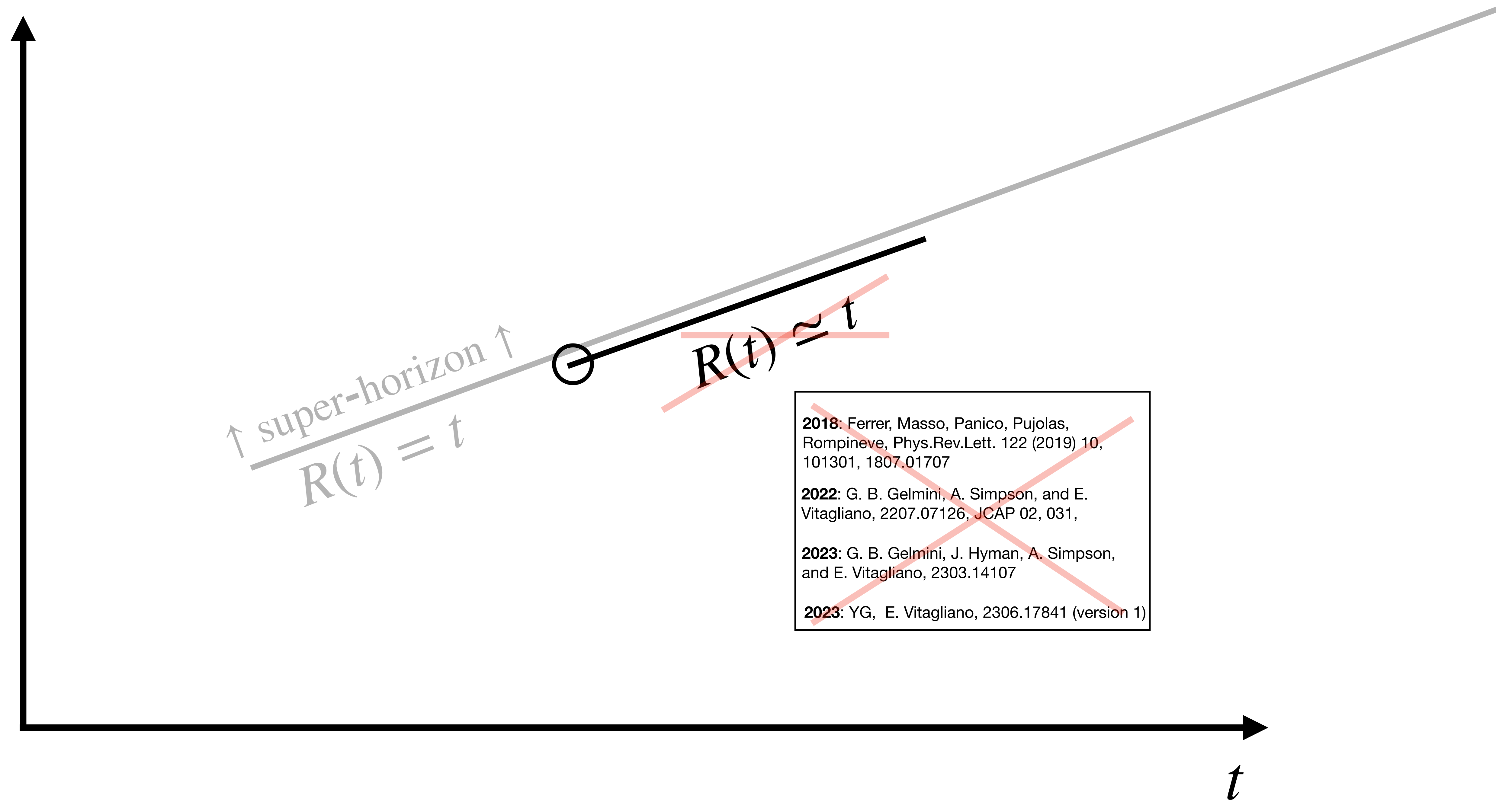
**2018:** Ferrer, Masso, Panico, Pujolas, Rompineve, Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707

**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)

DW radius  $R$



# DW radius R

Gouttenoire, Vitagliano, [2311.07670](#)

→ Solve thin DW in full General Relativity

↑ super-horizon ↑  
 $R(t) = t$

~~$R(t) \approx t$~~

~~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~~

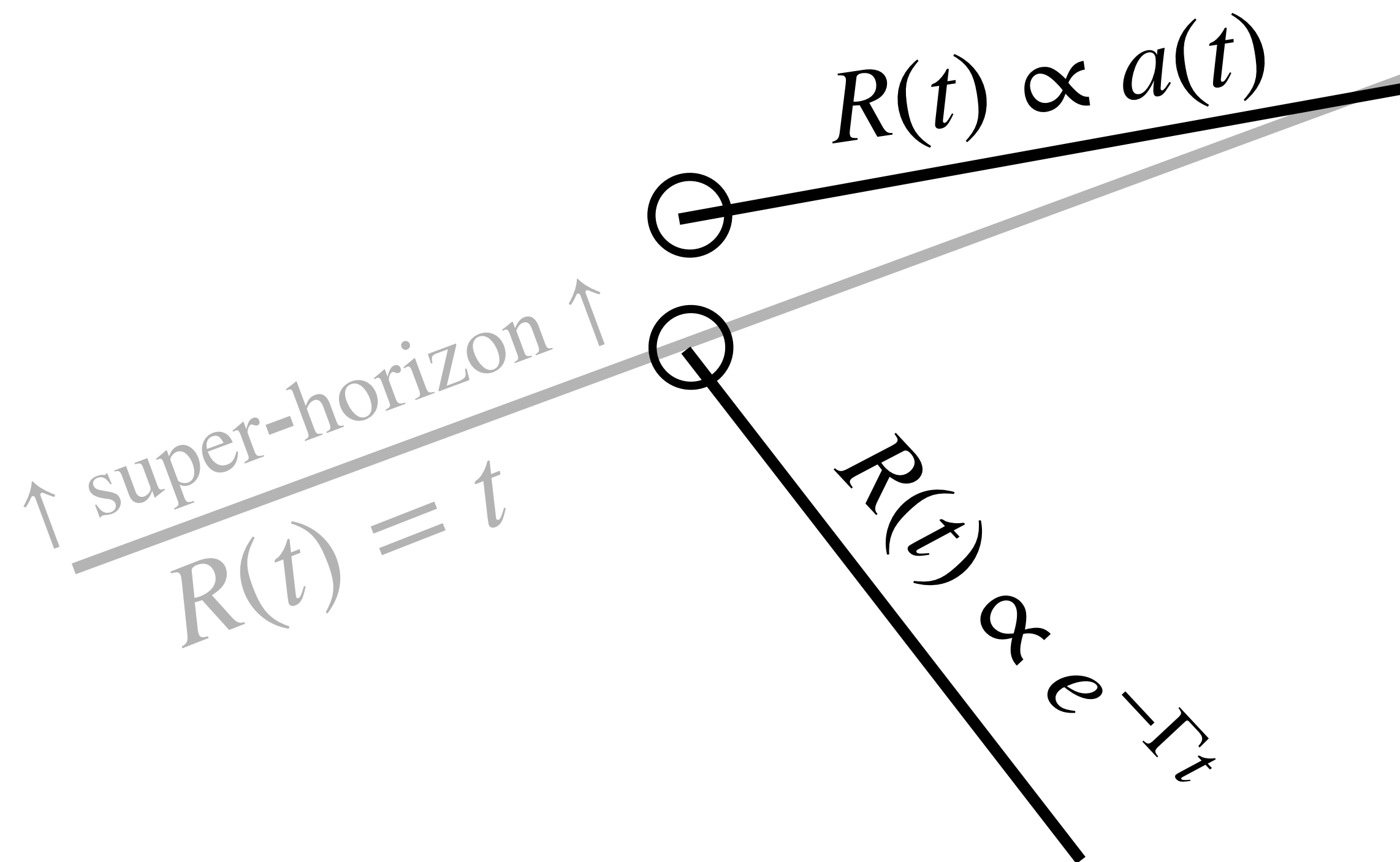
~~2023: YG, E. Vitagliano, 2306.17841 (version 1)~~

$t$

DW radius  $R$

Gouttenoire, Vitagliano, [2311.07670](#)

→ Solve thin DW in full General Relativity



DW radius  $R$

Gouttenoire, Vitagliano, [2311.07670](#)

→ Solve thin DW in full General Relativity

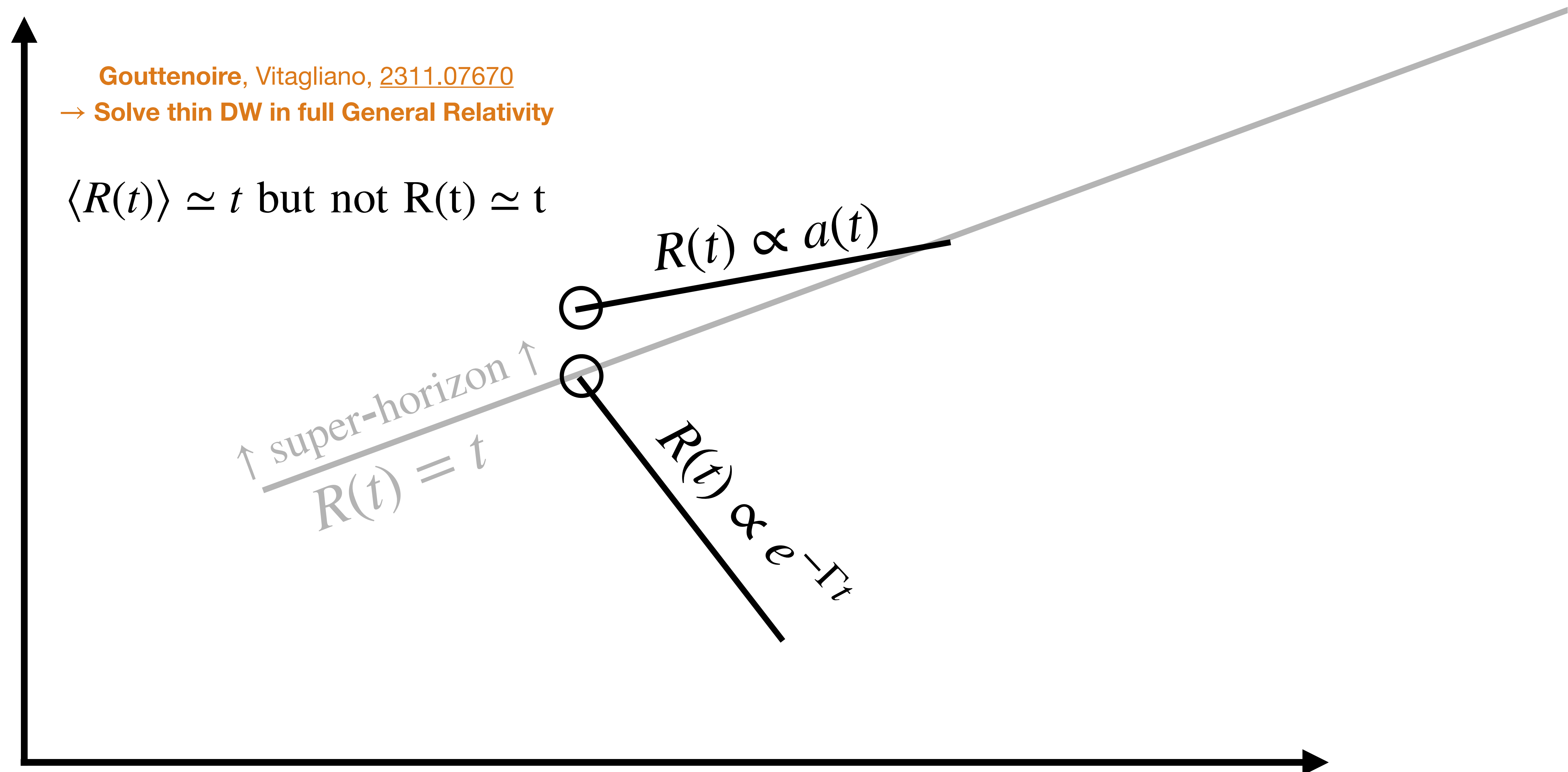
$\langle R(t) \rangle \simeq t$  but not  $R(t) \simeq t$

↑ super-horizon ↑  
 $R(t) = t$

$R(t) \propto a(t)$

$R(t) \propto e^{-\Gamma t}$

$t$





DW radius  $R$

Gouttenoire, Vitagliano, [2311.07670](#)

→ Solve thin DW in full General Relativity

Annihilation  
phase

DW domination

$$R(t) \propto a(t)$$

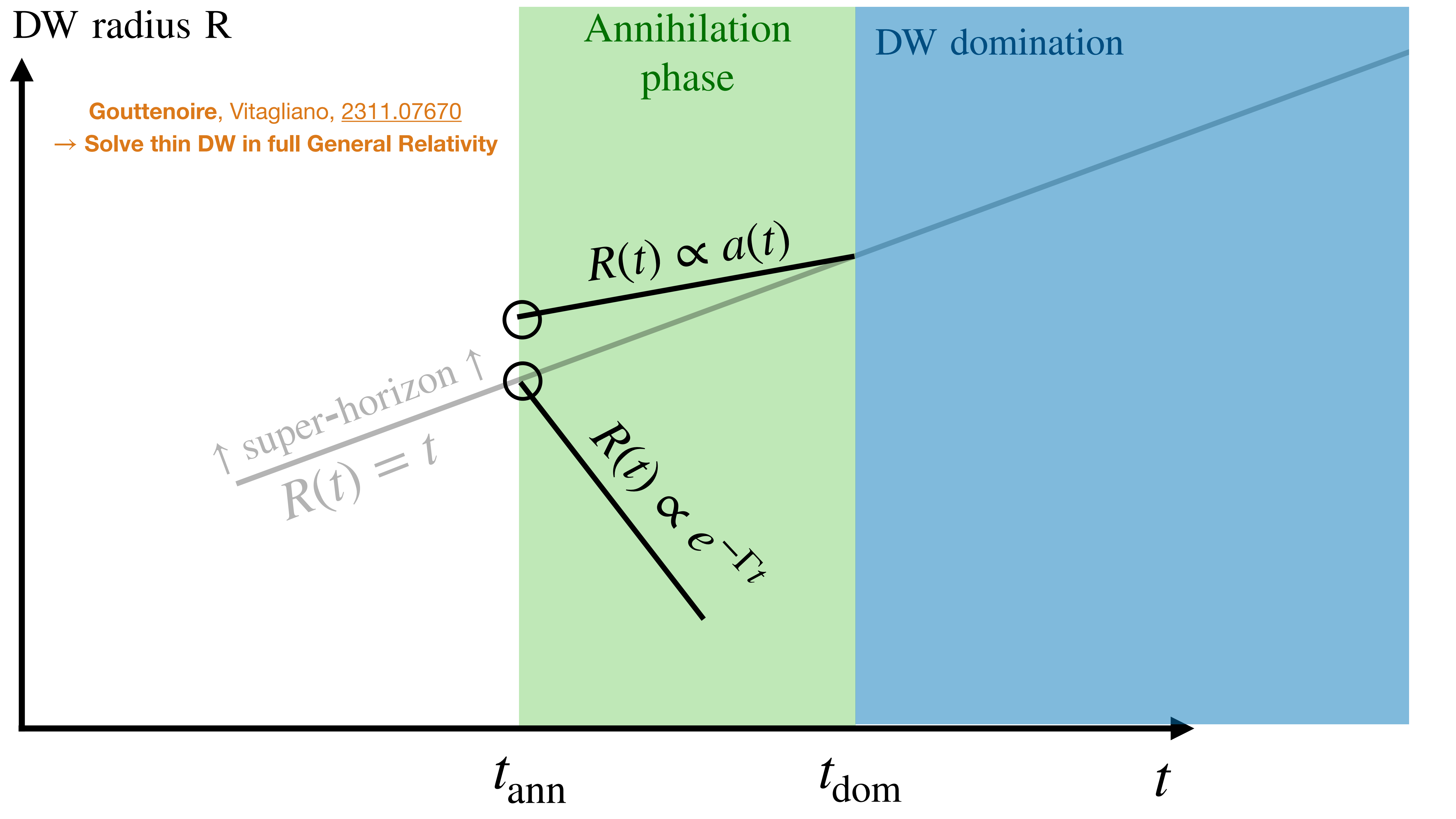
↑ super-horizon ↑  
 $R(t) = t$

$$R(t) \propto e^{-\Gamma t}$$

$t_{\text{ann}}$

$t_{\text{dom}}$

$t$



DW radius  $R$

Annihilation  
phase

DW domination

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

Gouttenoire, Vitagliano, [2311.07670](#)

→ Solve thin DW in full General Relativity

$$R(t) \propto a(t)$$

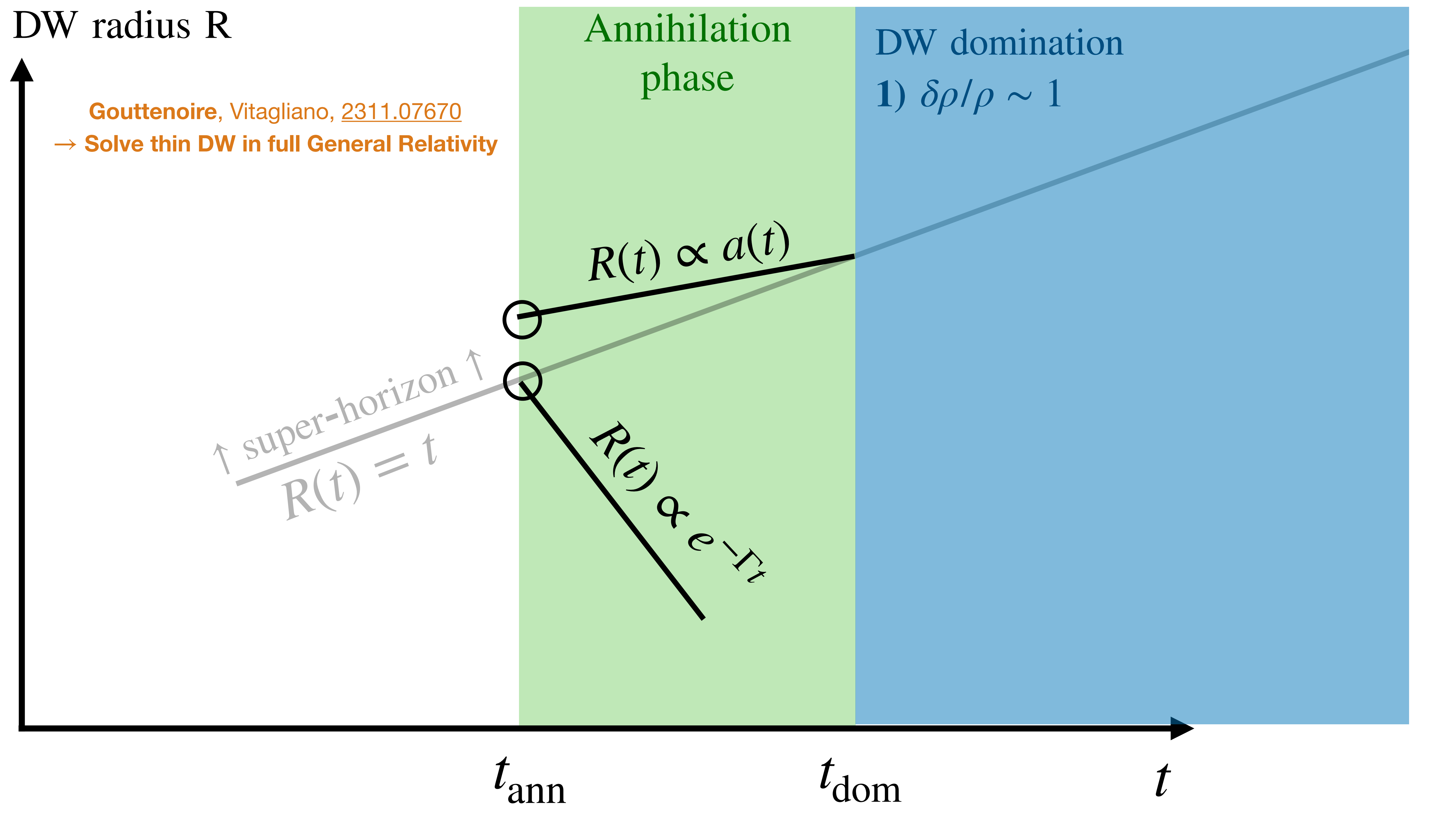
↑ super-horizon ↑  
 $R(t) = t$

$$R(t) \propto e^{-\Gamma t}$$

$t_{\text{ann}}$

$t_{\text{dom}}$

$t$



DW radius  $R$

Annihilation  
phase

DW domination

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

2) horizon size

Gouttenoire, Vitagliano, [2311.07670](#)  
→ Solve thin DW in full General Relativity

↑ super-horizon ↑  
 $R(t) = t$

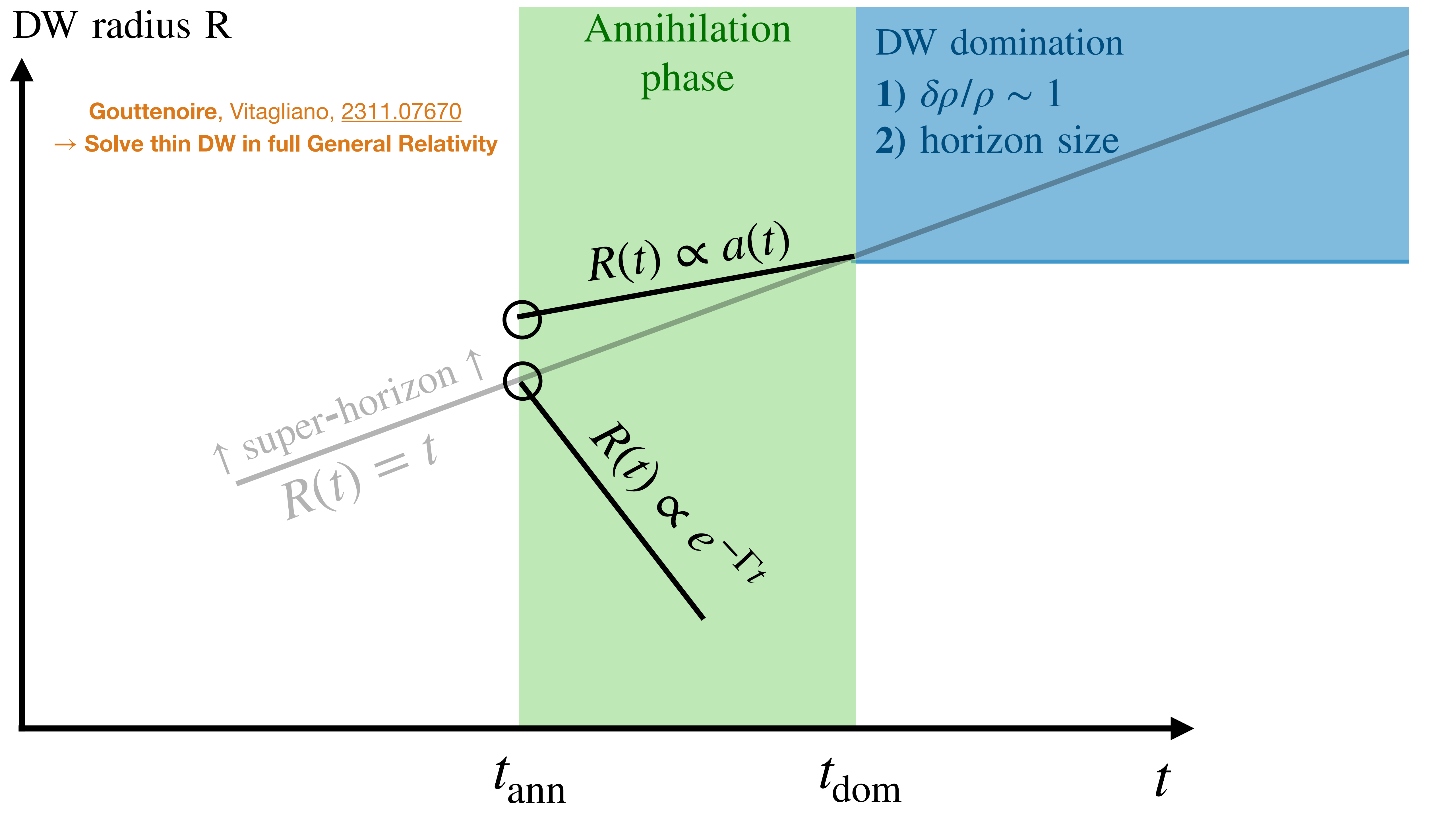
$R(t) \propto a(t)$

$R(t) \propto e^{-\Gamma t}$

$t_{\text{ann}}$

$t_{\text{dom}}$

$t$



DW radius  $R$

Annihilation  
phase

DW domination

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

2) horizon size

Gouttenoire, Vitagliano, [2311.07670](#)  
→ Solve thin DW in full General Relativity

↑  $R \lesssim R_{\text{sch}}$  ↑

$R(t) \propto a(t)$

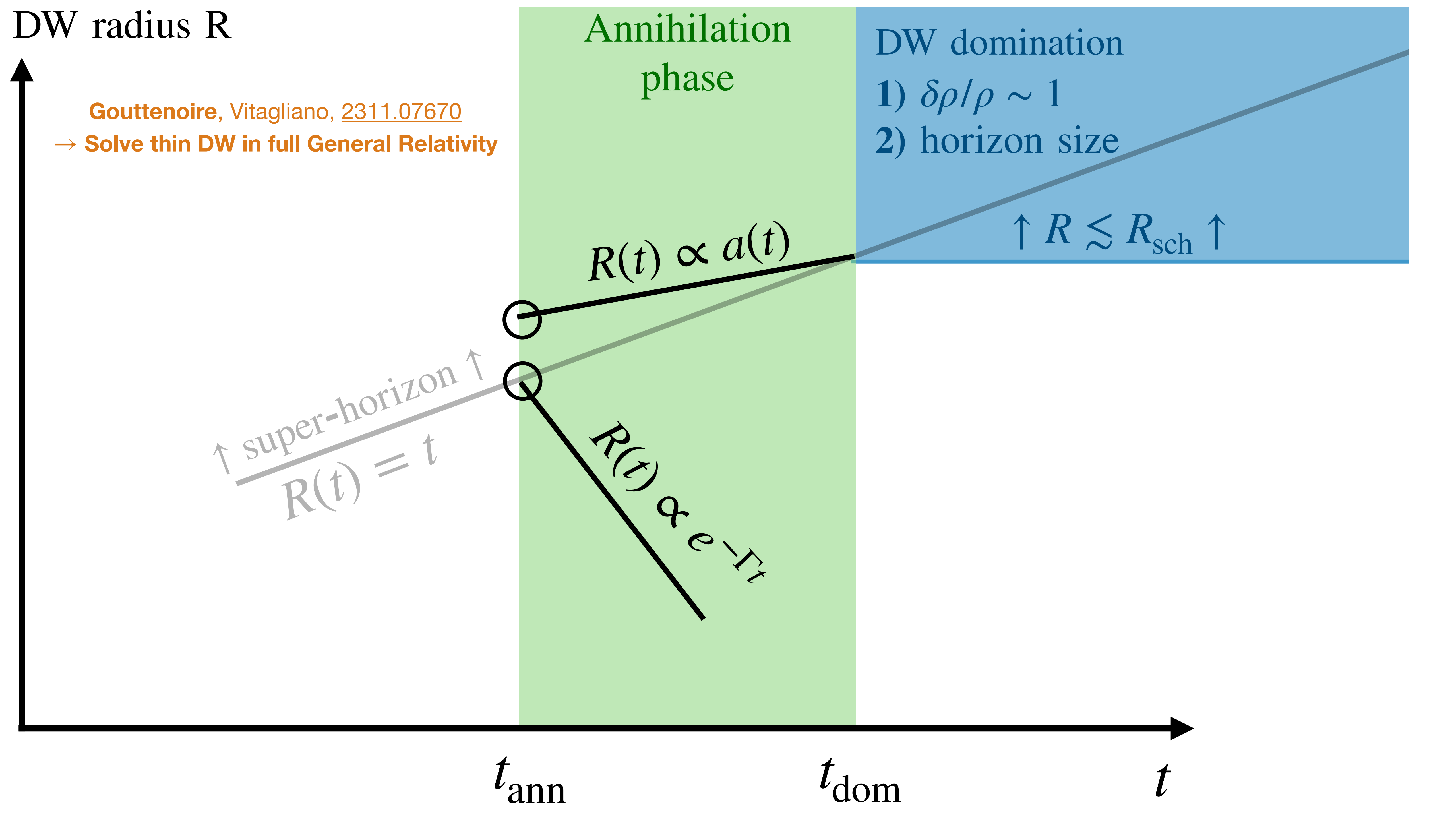
↑ super-horizon ↑  
 $R(t) = t$

$R(t) \propto e^{-\Gamma t}$

$t_{\text{ann}}$

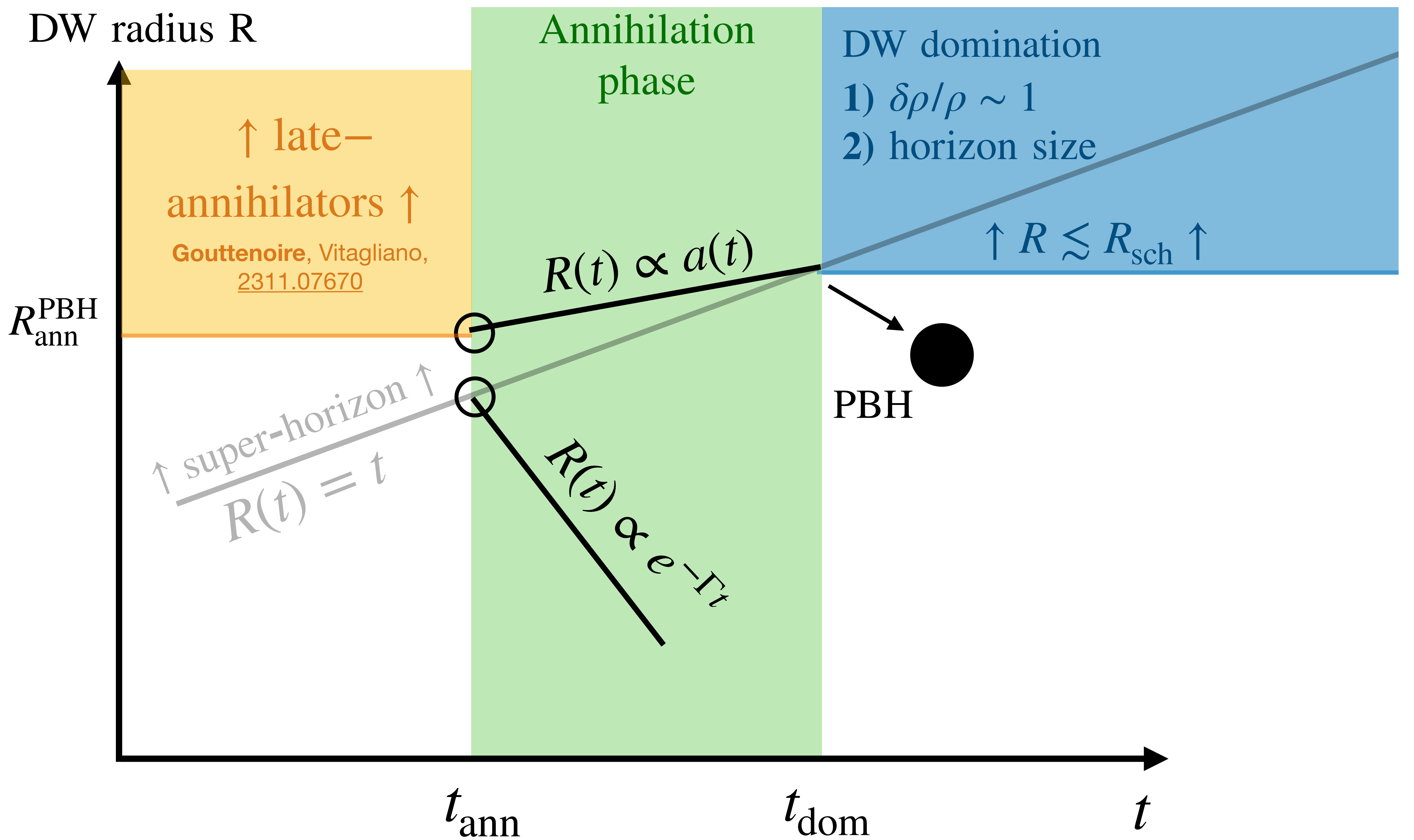
$t_{\text{dom}}$

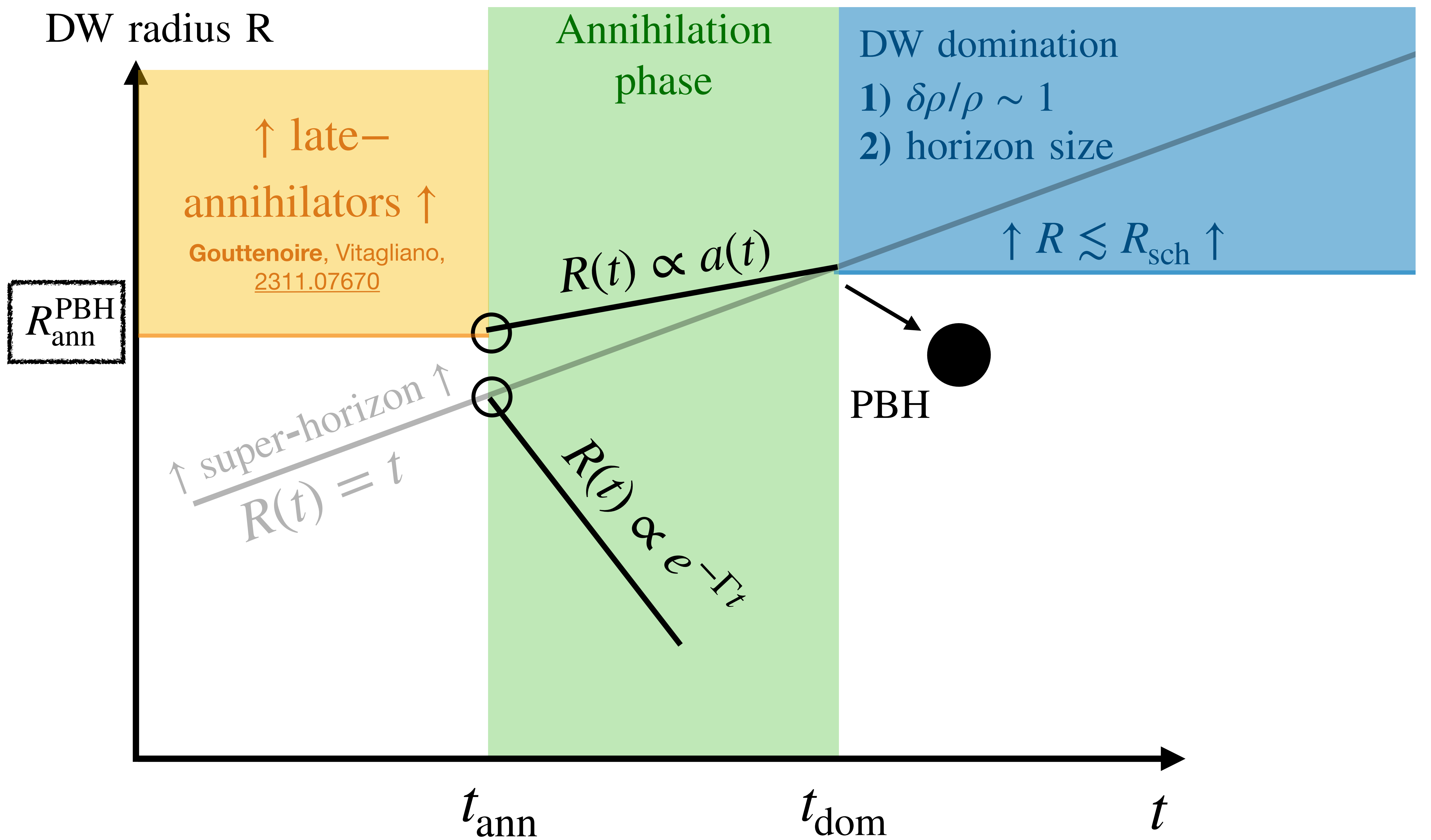
$t$







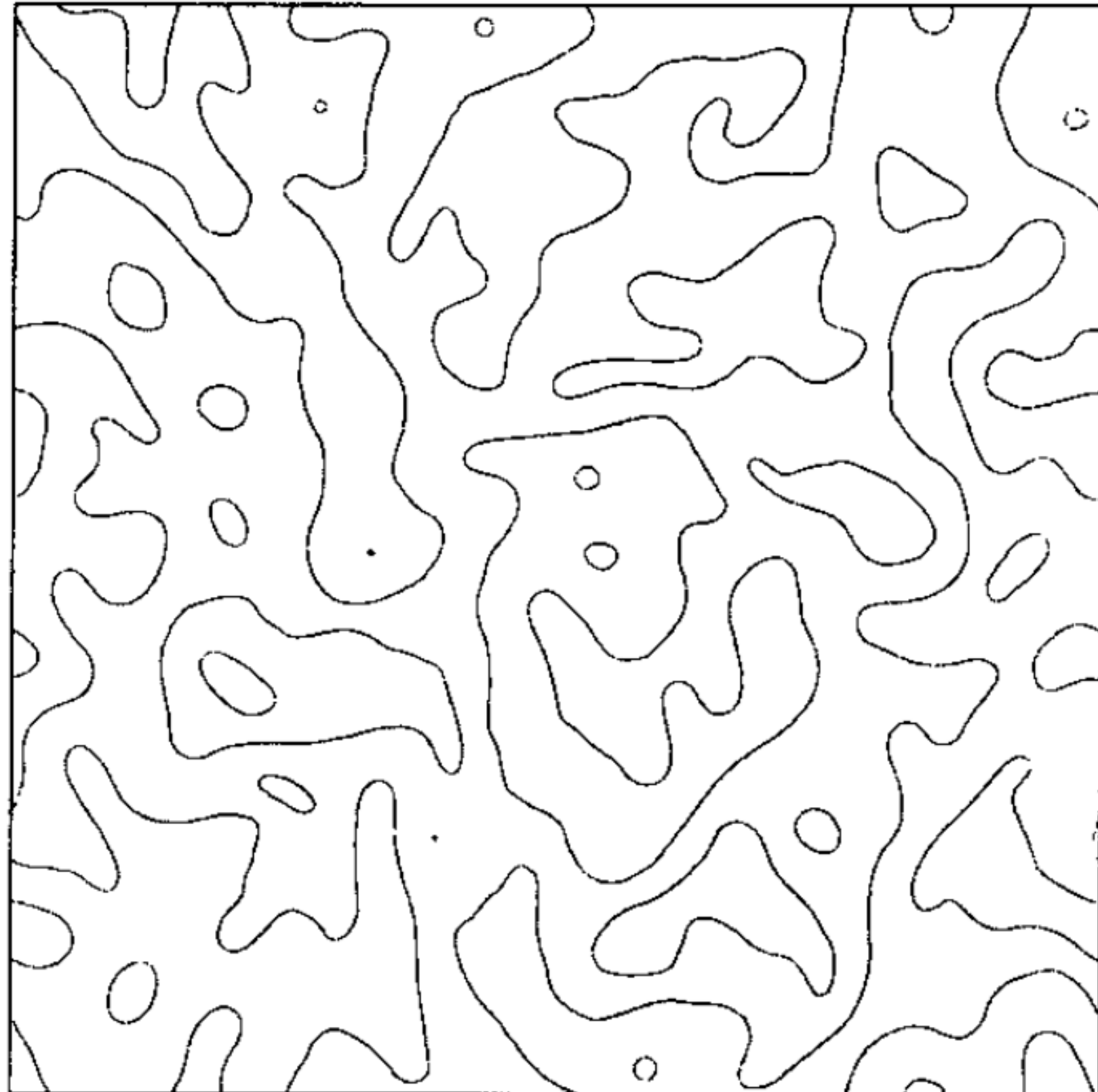




## Percolation theory on a lattice

*Stauffer (1979)*

*Coulson, Lalak, Ovrut (1995)*

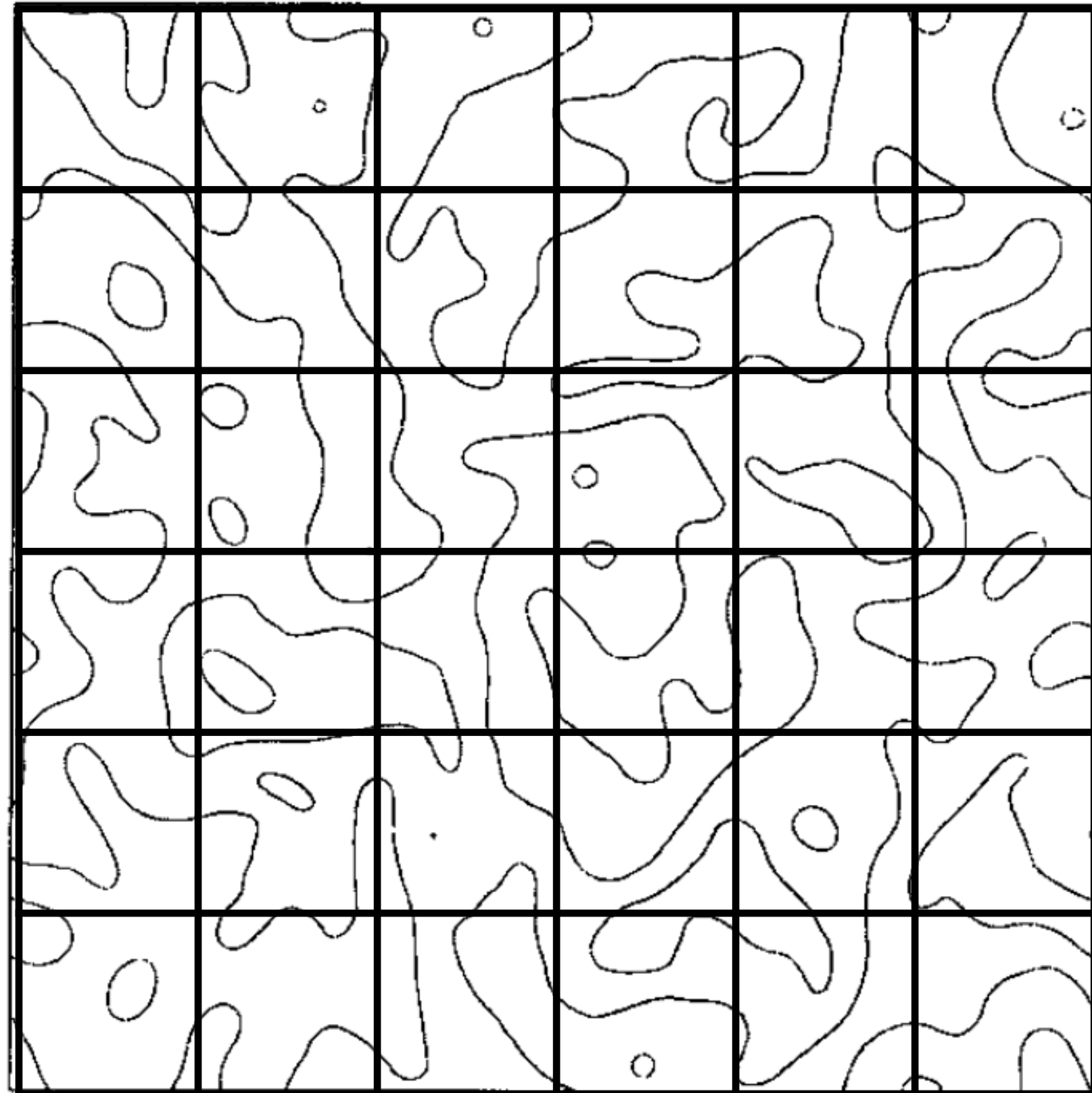


*PRESS, RYDEN, AND SPERGEL 1989*

## Percolation theory on a lattice

*Stauffer (1979)*

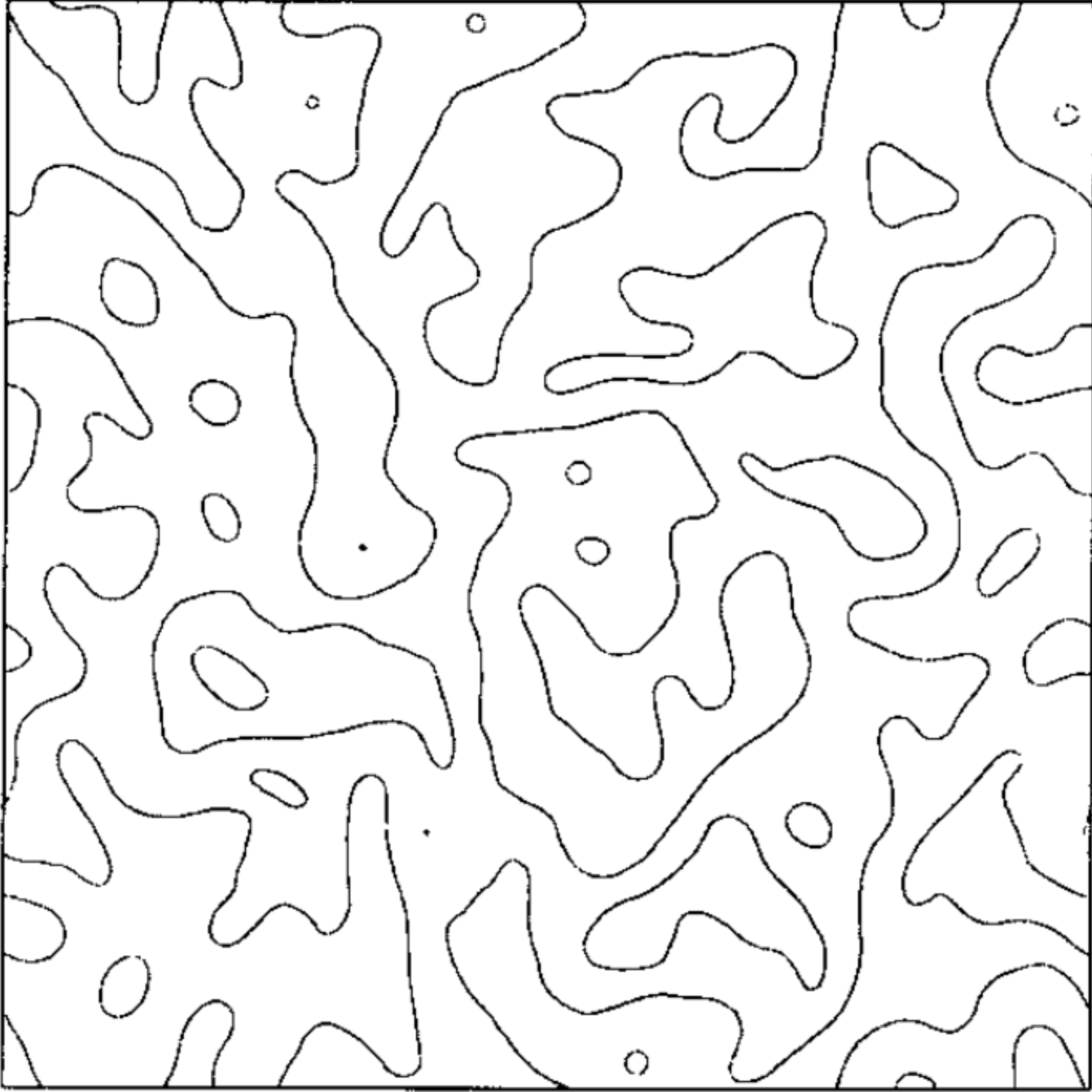
*Coulson, Lalak, Ovrut (1995)*



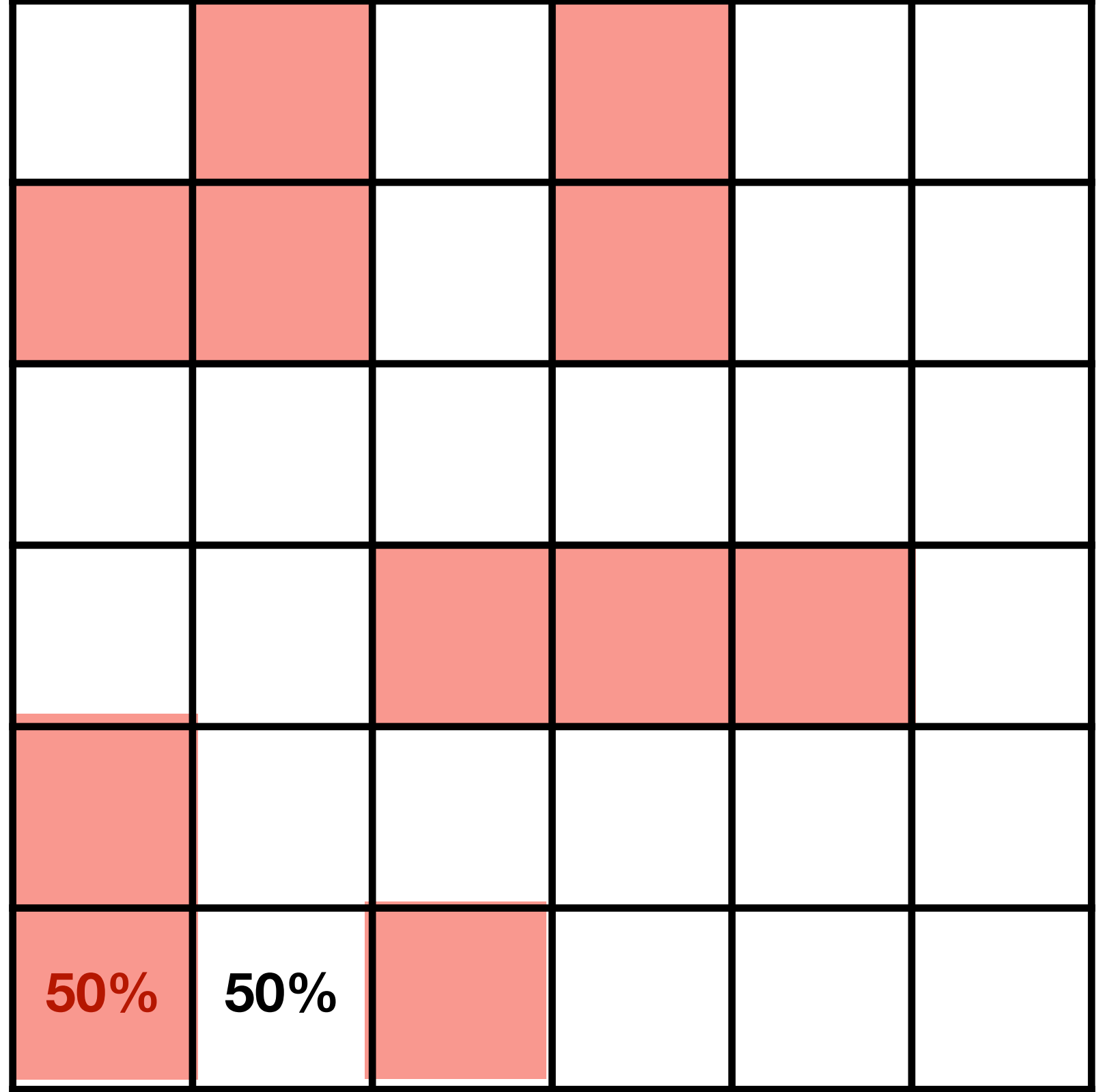
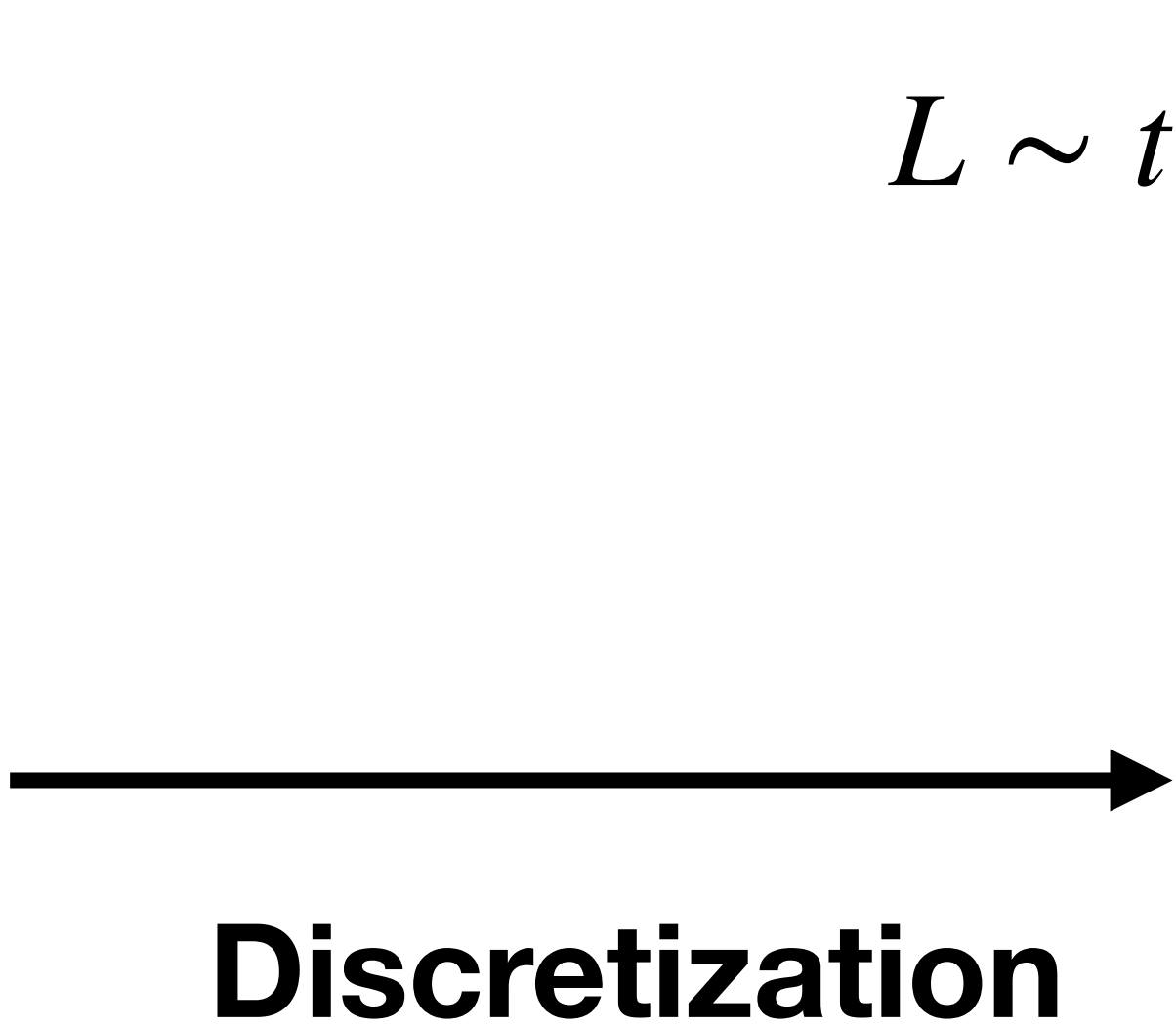
*PRESS, RYDEN, AND SPERGEL 1989*

## Percolation theory on a lattice

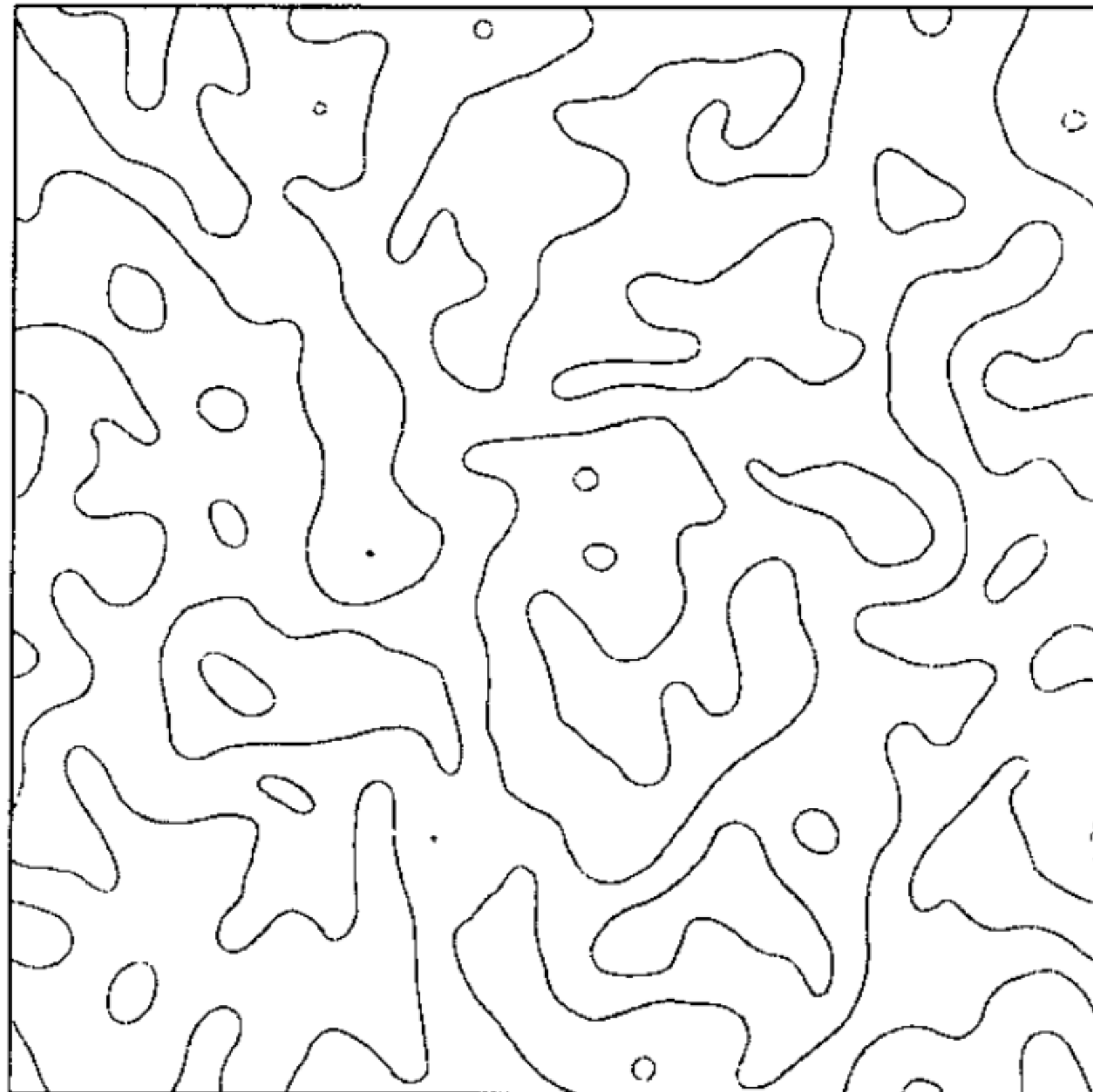
*Stauffer (1979) Coulson, Lalak, Ovrut (1995)*



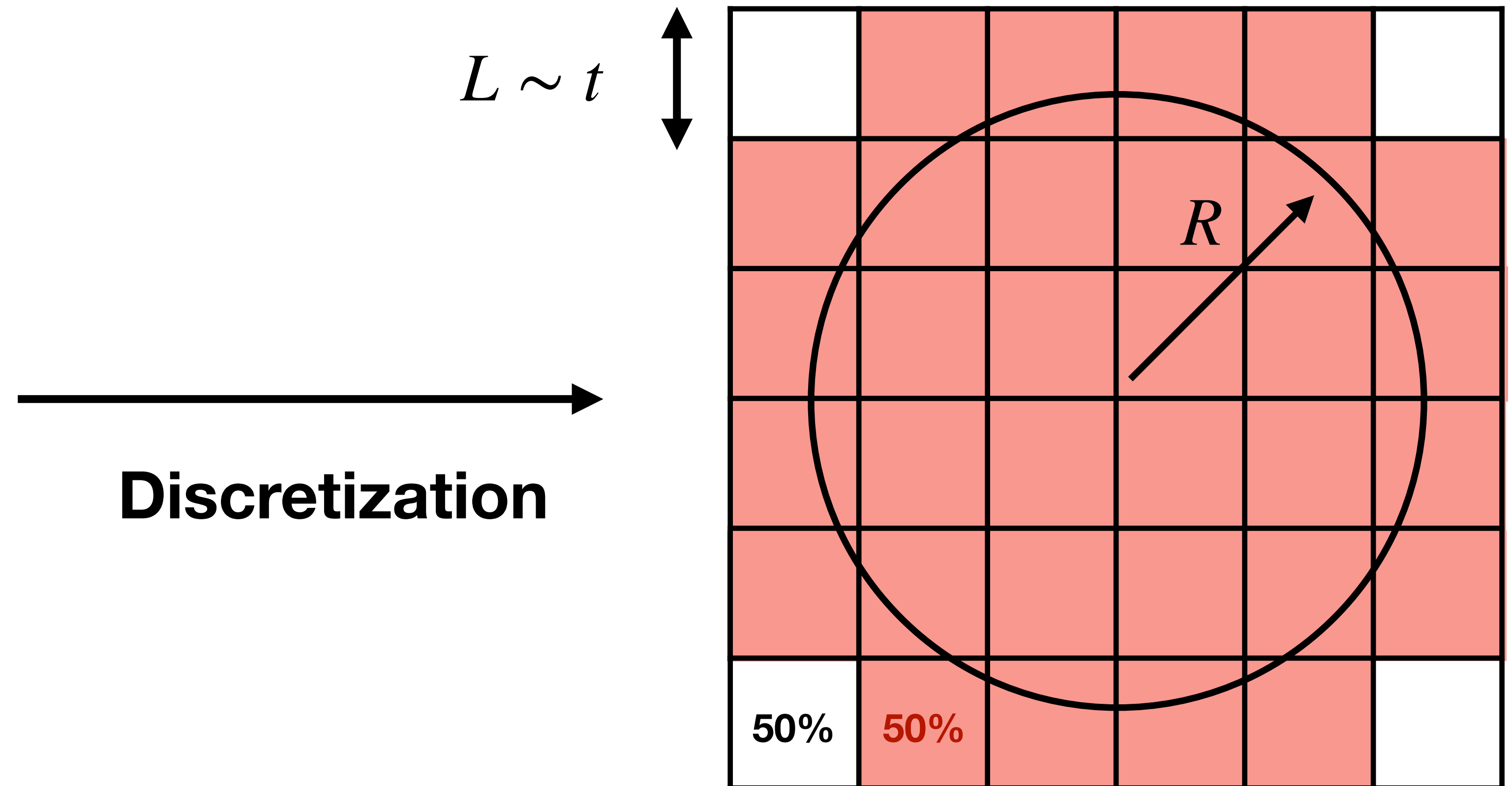
PRESS, RYDEN, AND SPERGEL 1989



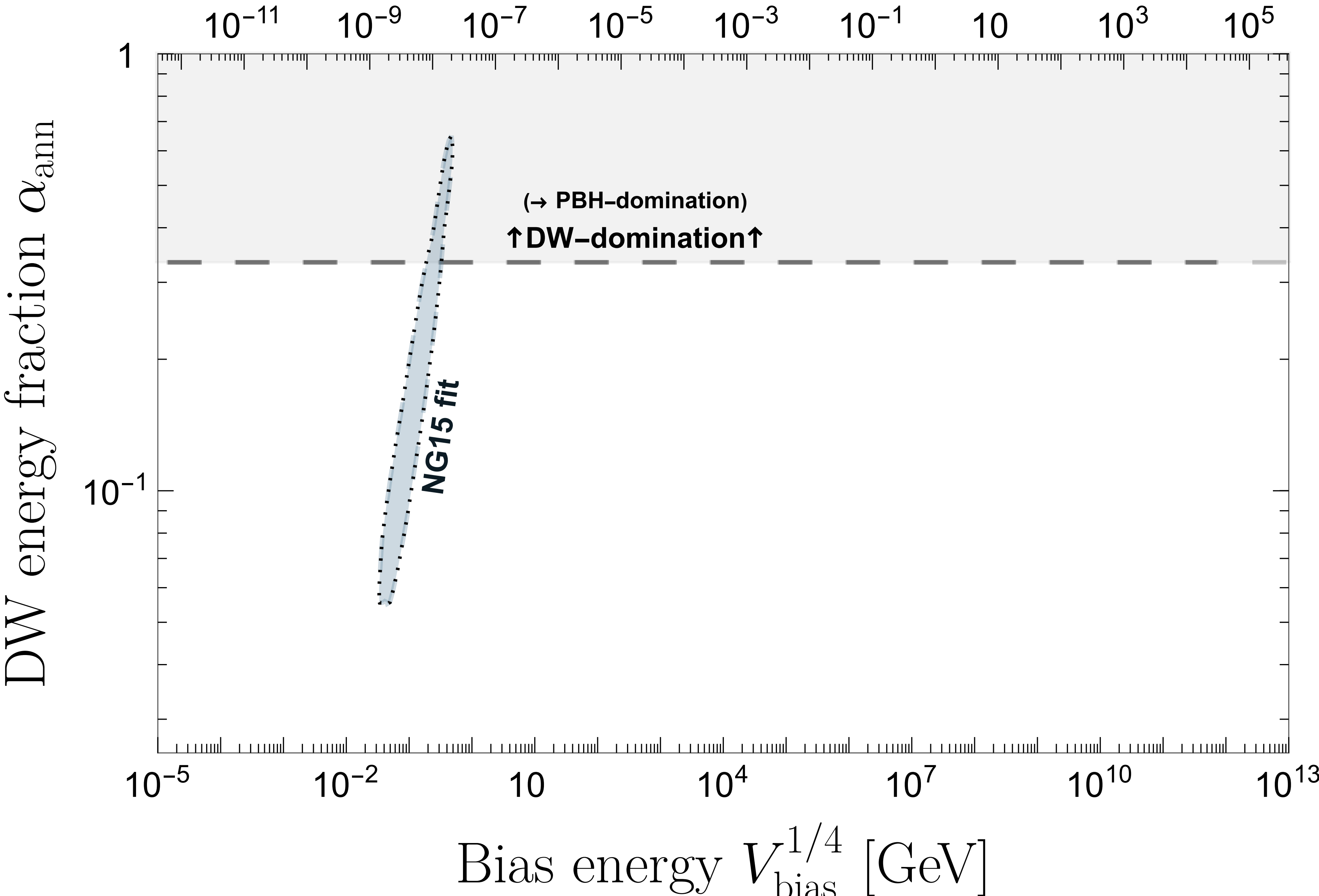


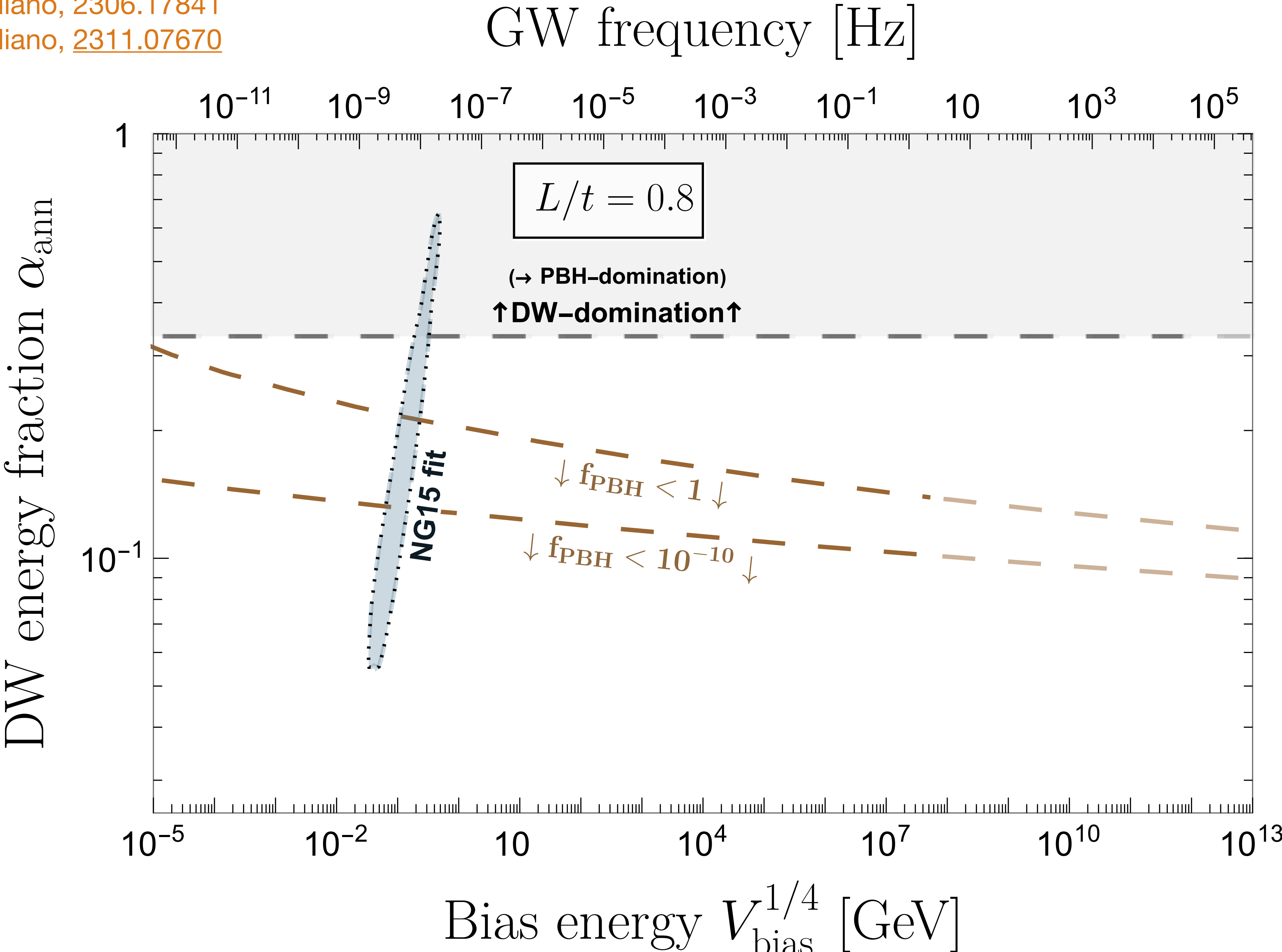
**Percolation theory on a lattice***Stauffer (1979) Coulson, Lalak, Ovrut (1995)*Probability of a spherical false vacuum domain of size  $R$ :  $\mathcal{P} \sim \exp(-4\pi(R/t)^3/3)$ 

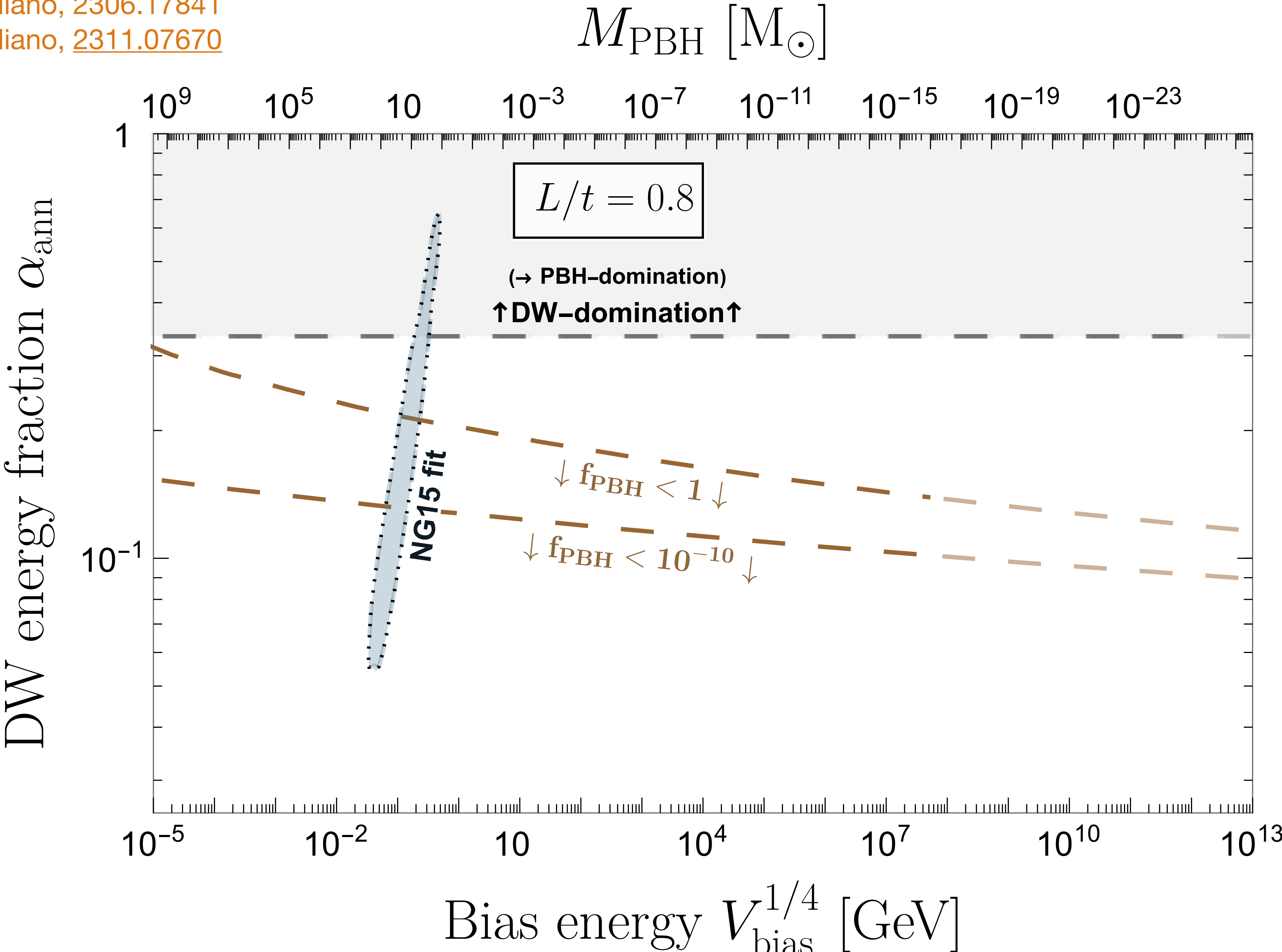
PRESS, RYDEN, AND SPERGEL 1989

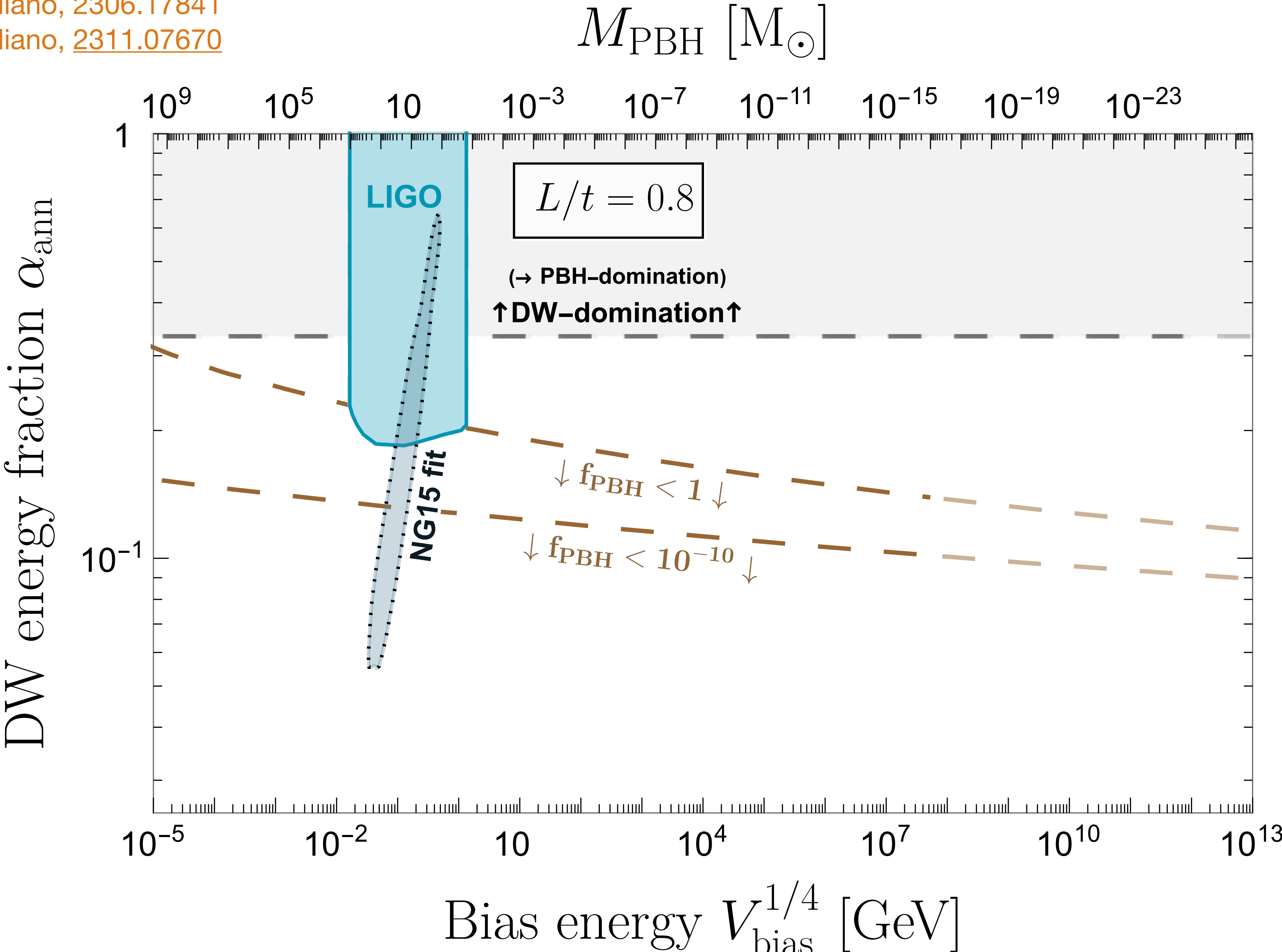


# GW frequency [Hz]

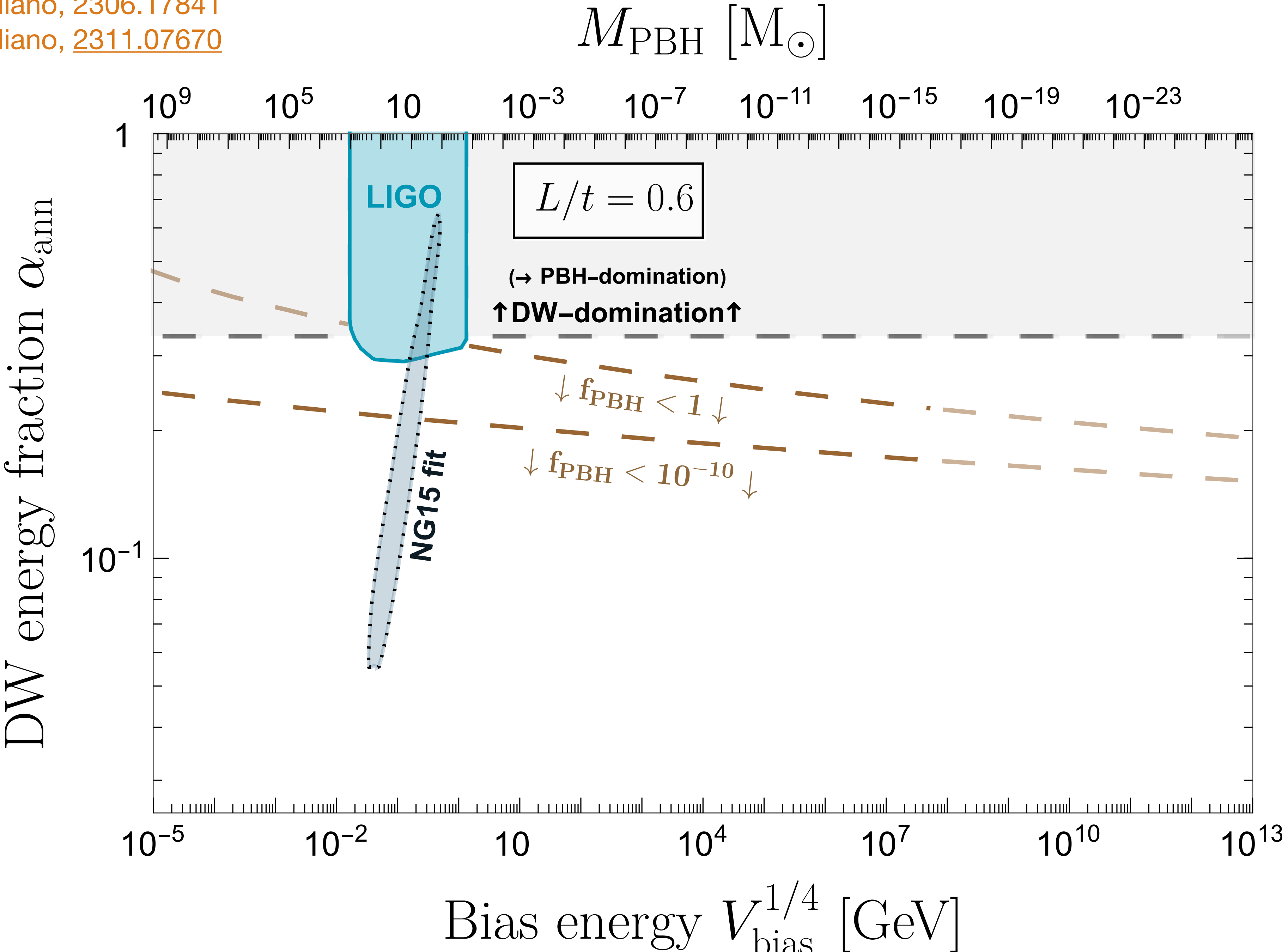


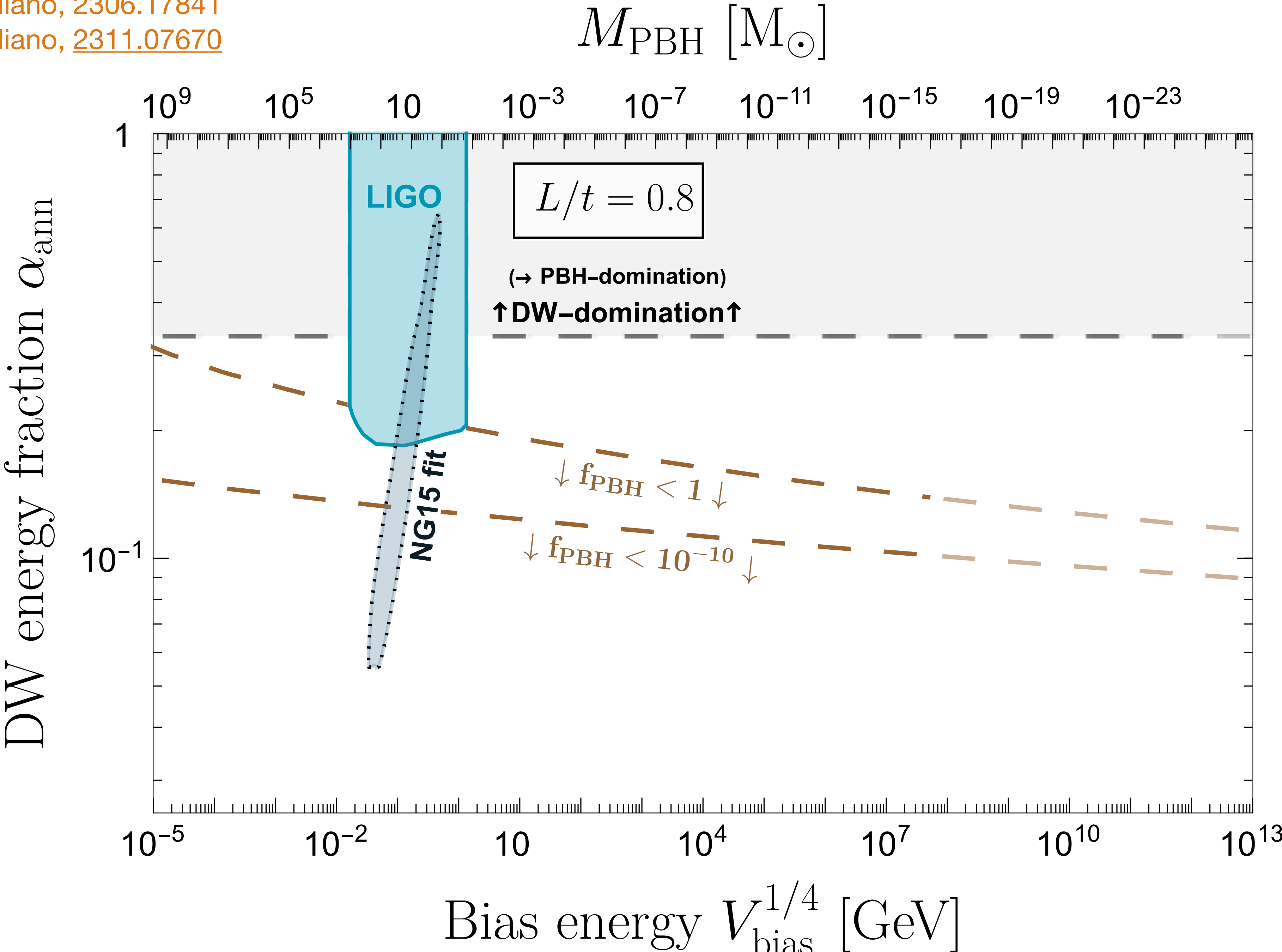


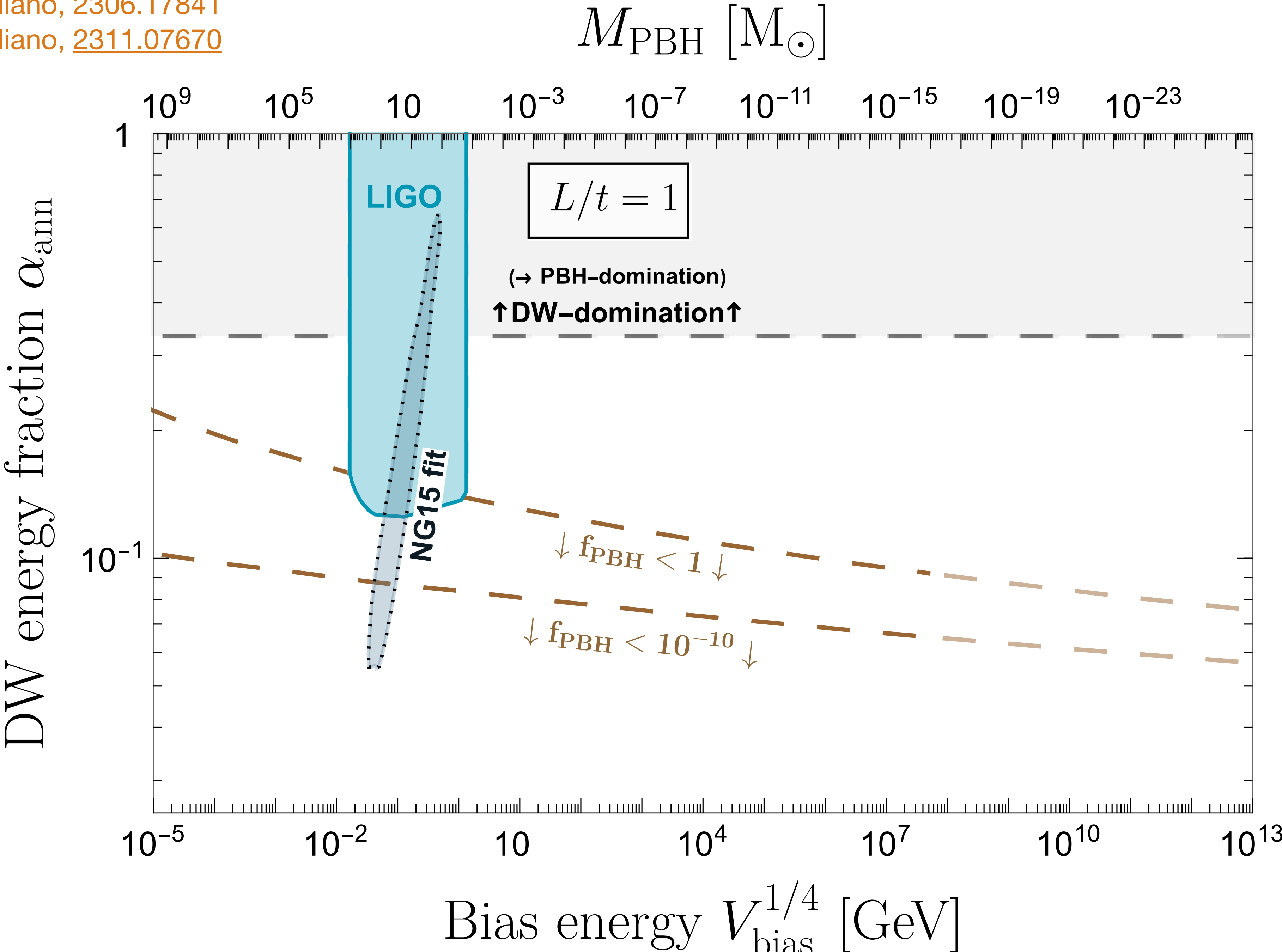


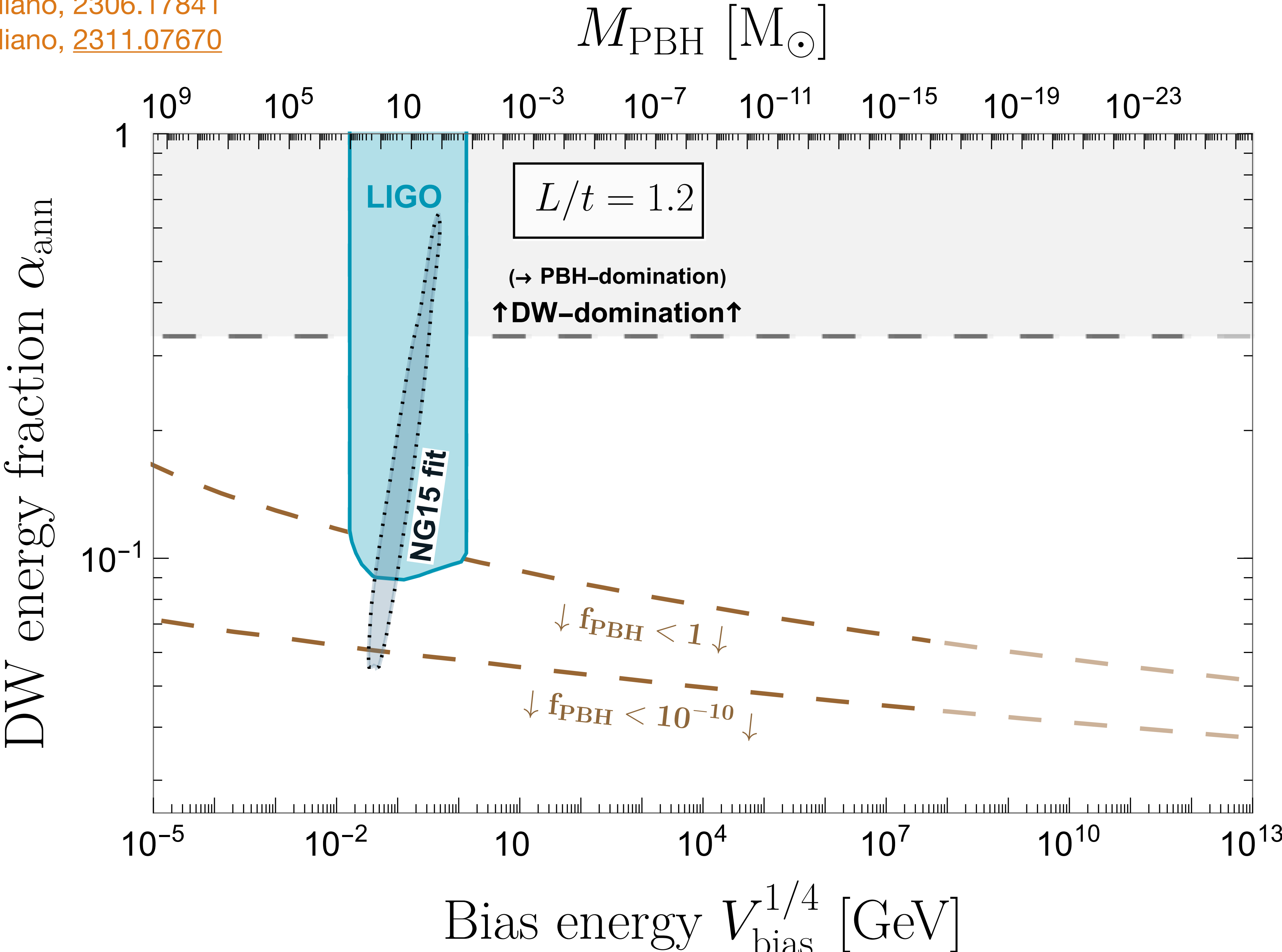










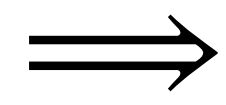


# Summary



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**Efficient PBH production due to collapse of late-annihilators (NEW)**

Gouttenoire, Vitagliano, [2311.07670](#)

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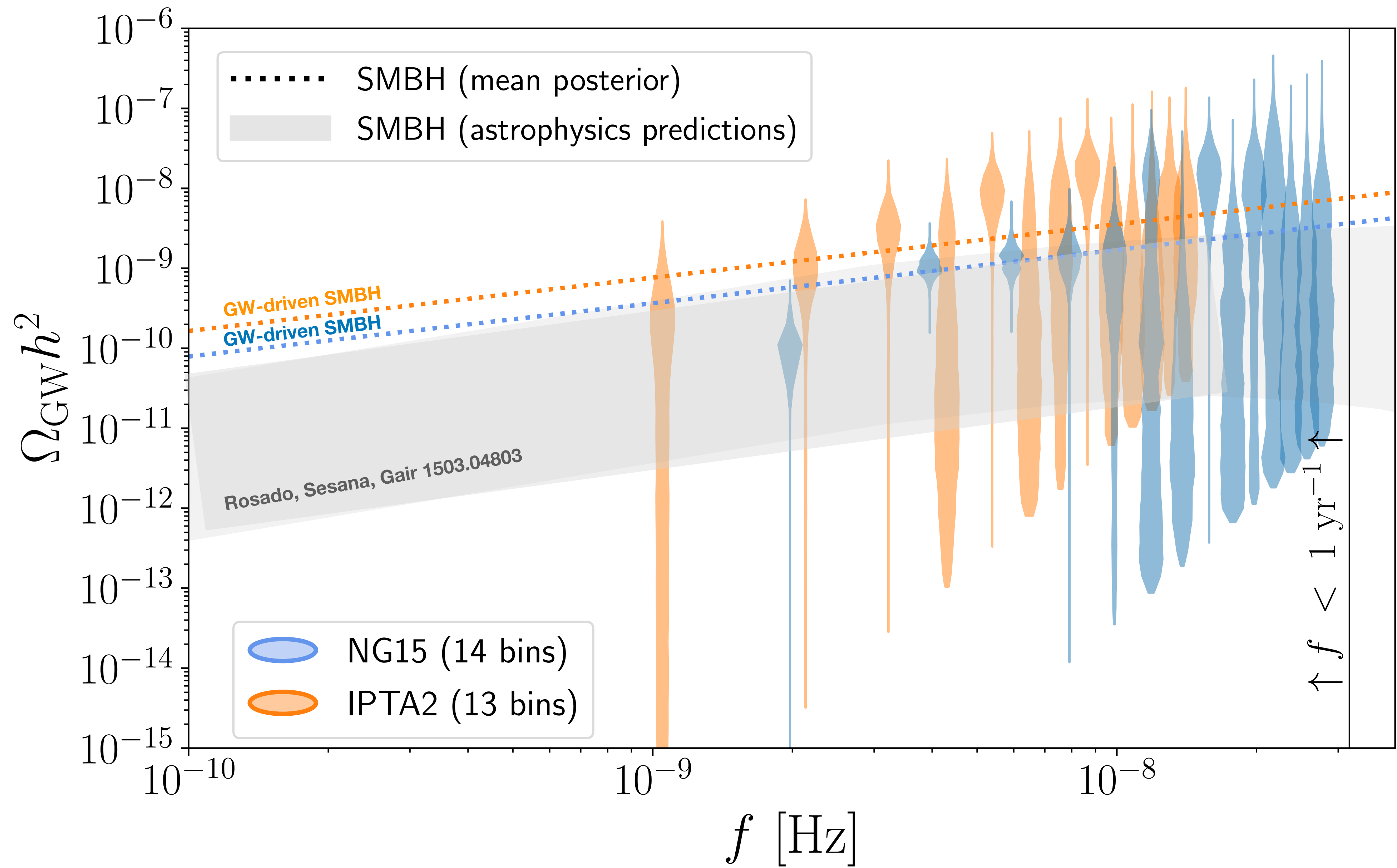
**Can produce multi-solar-mass PBH**

Gouttenoire, Vitagliano, [2306.17841](#)

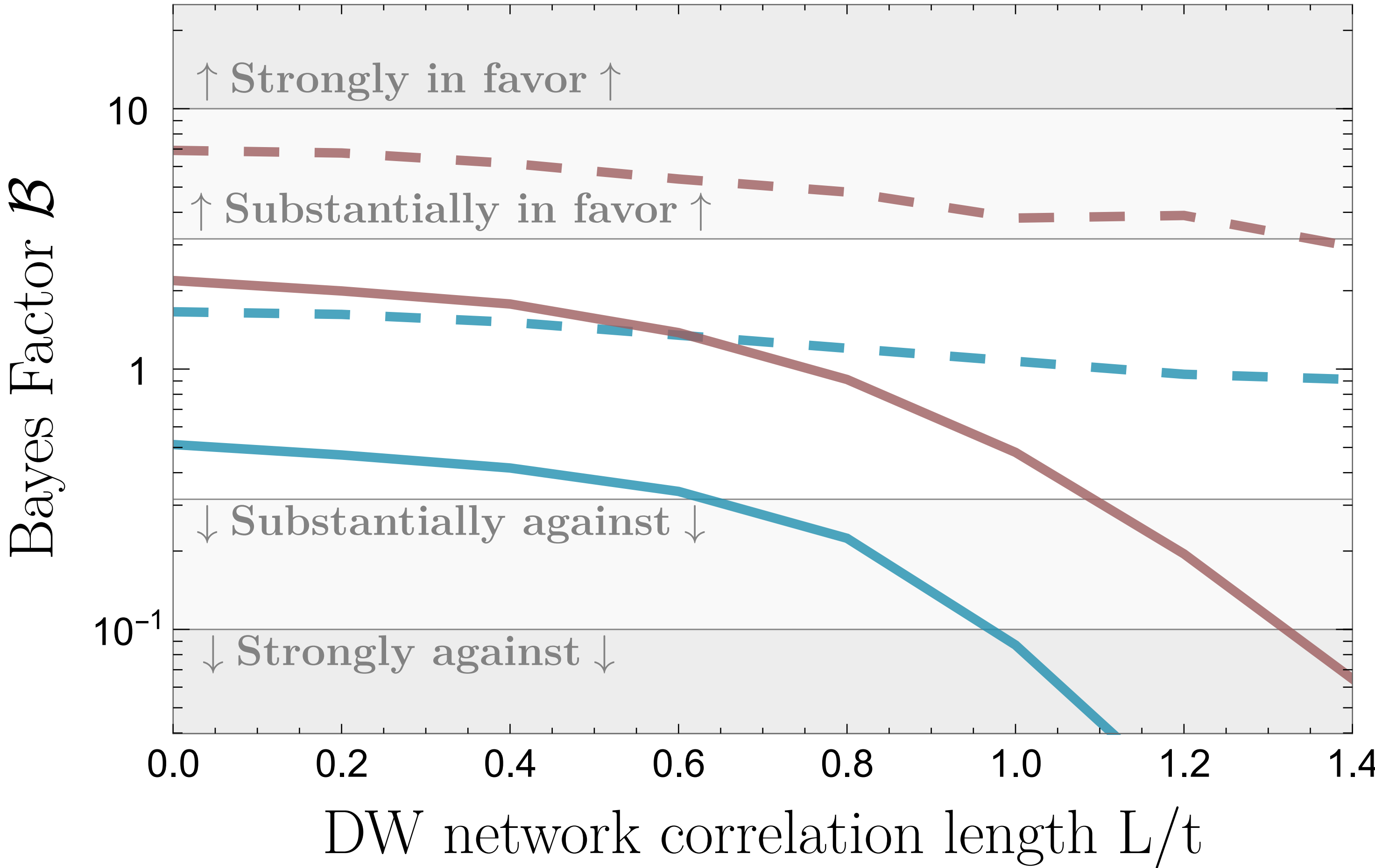
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YG, [2307.04239](#), Phys.Rev.Lett. 131 (2023) 17



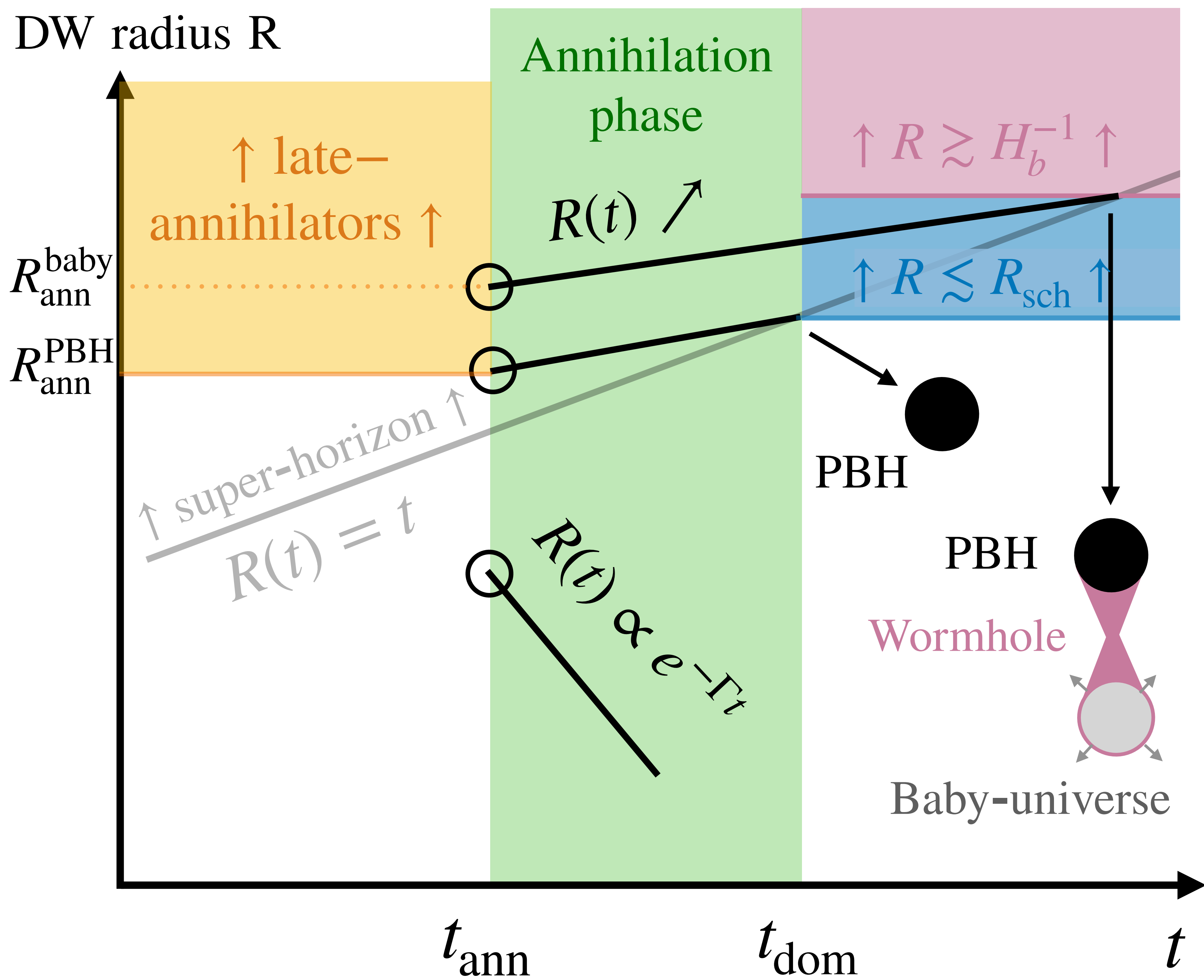


NG15 dataset



DW prior: PBH abundance  $f_{\text{PBH}} < 1$

- (DW+SMBH) vs SMBH
- DW vs SMBH
- SMBH prior: **GWOnly** – **Ext** library
- SMBH prior:  $\gamma_{\text{SMBH}} = 13/3$

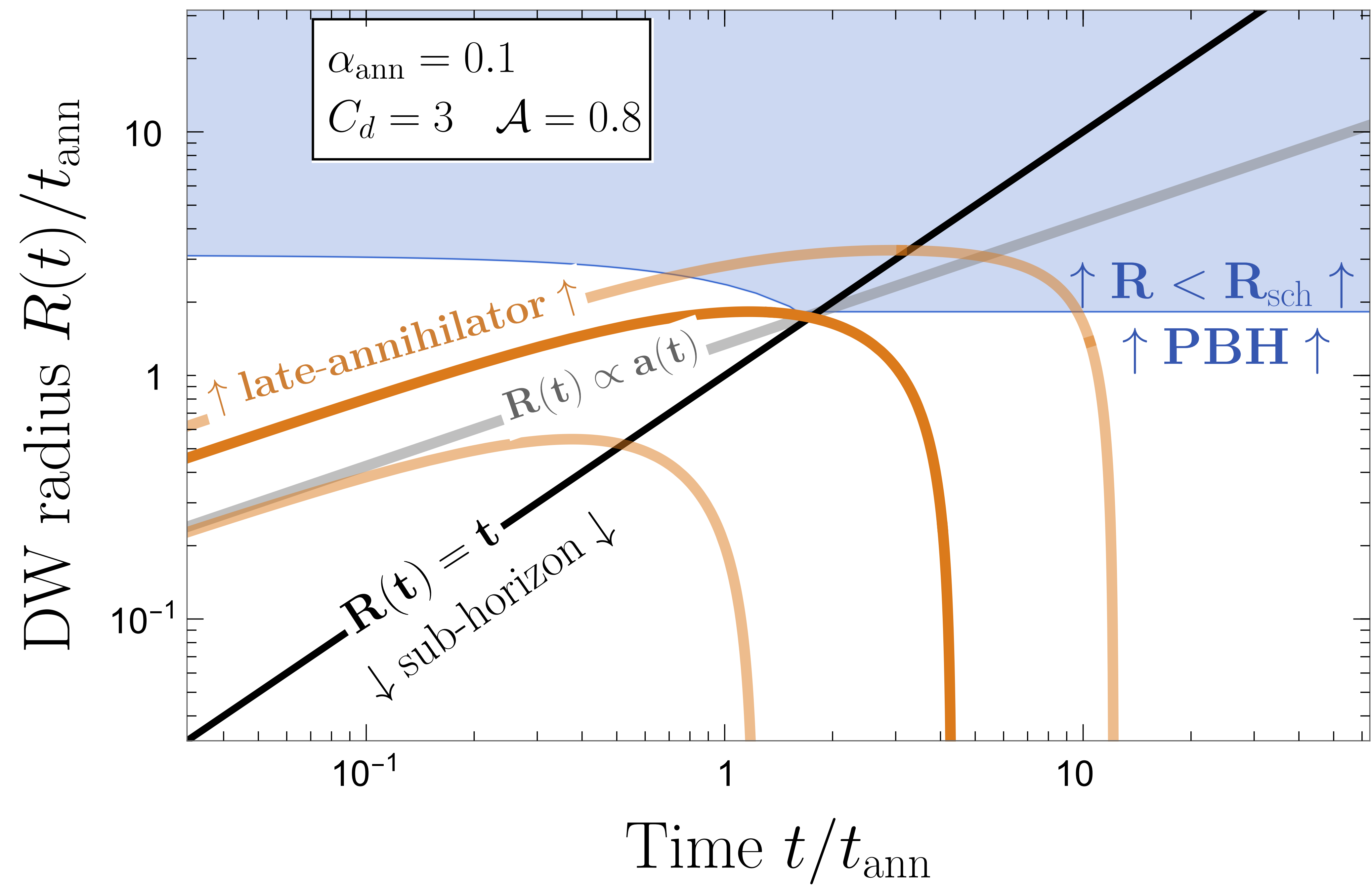




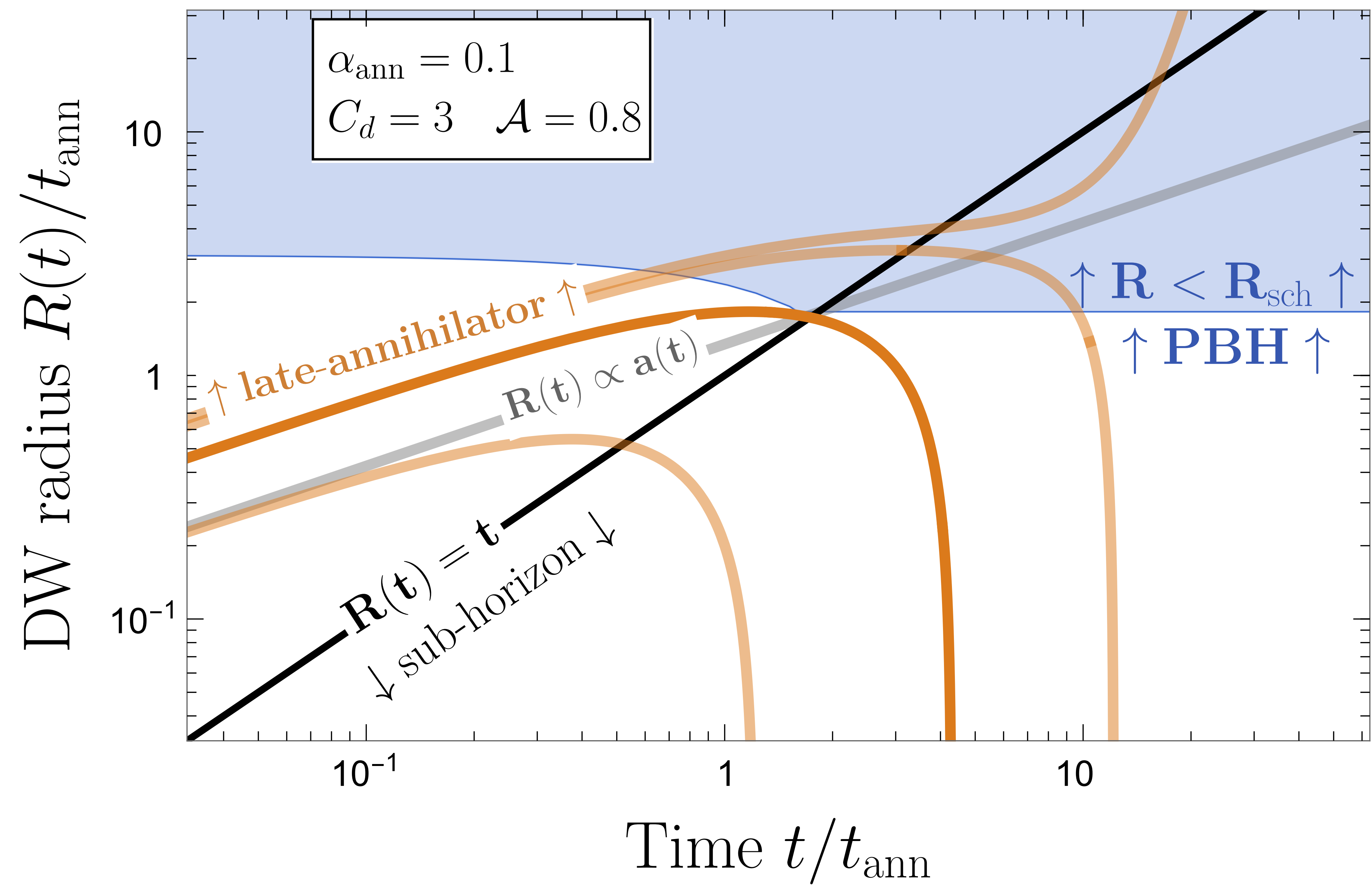
# Wormholes to baby-universe

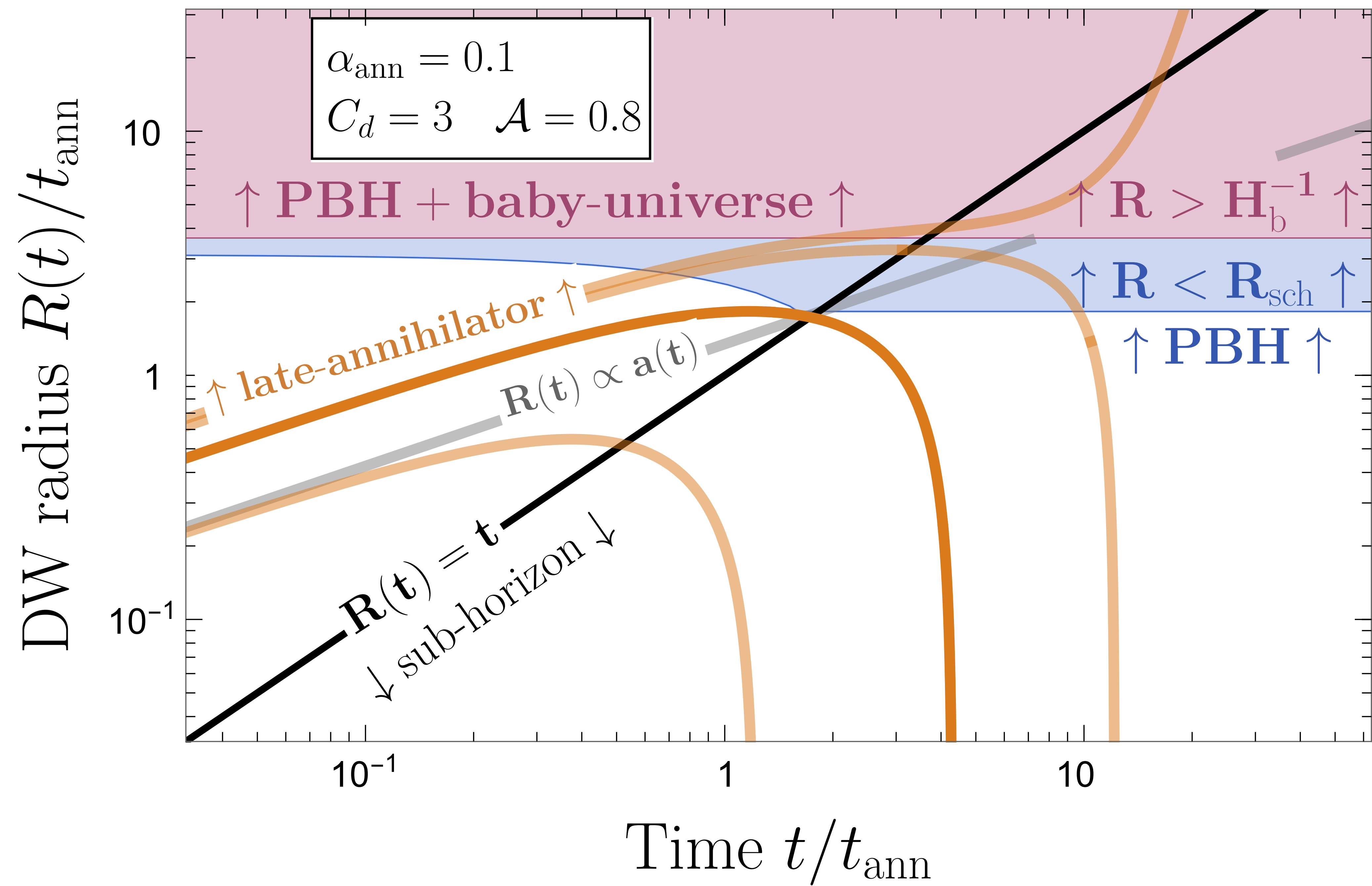


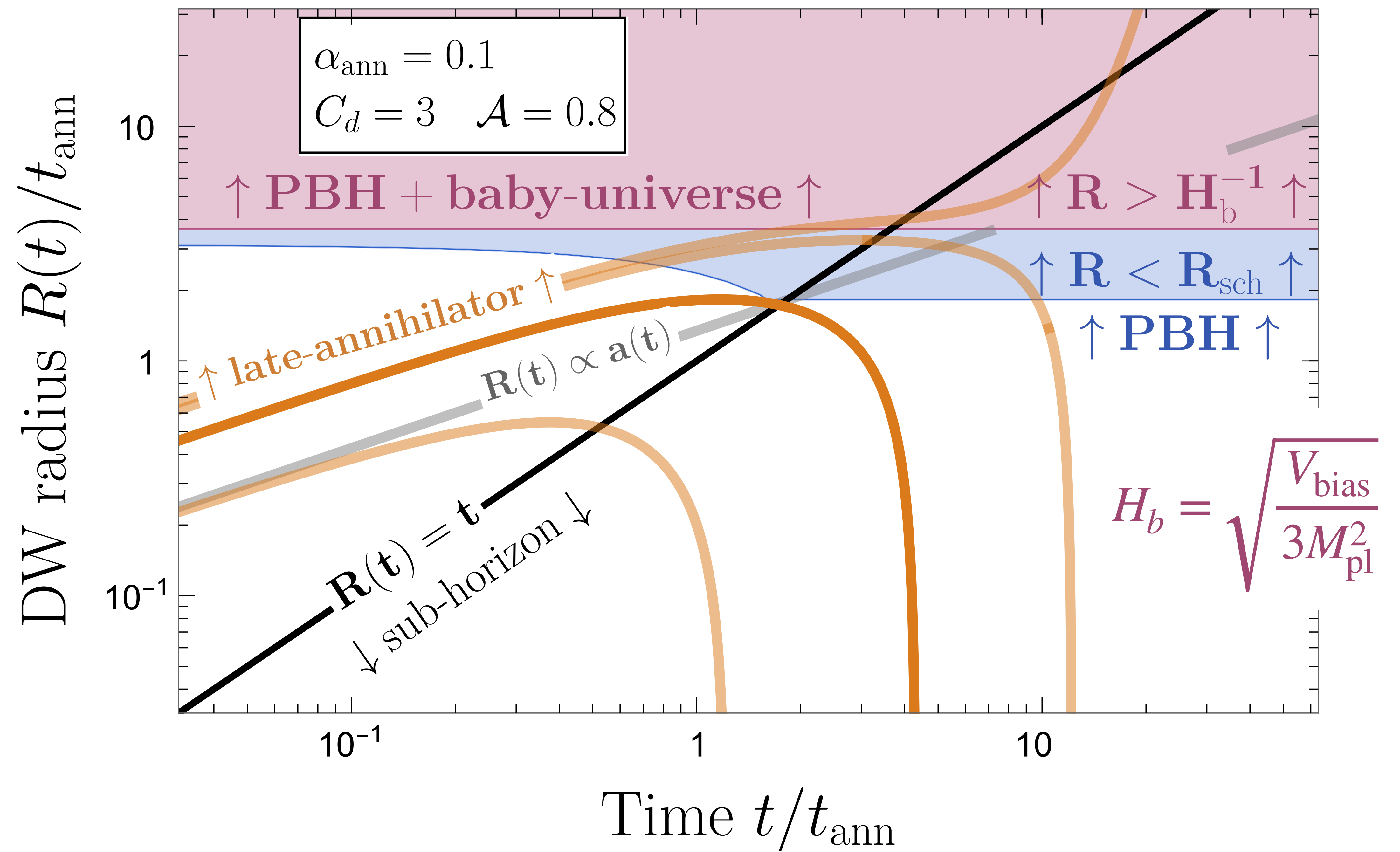


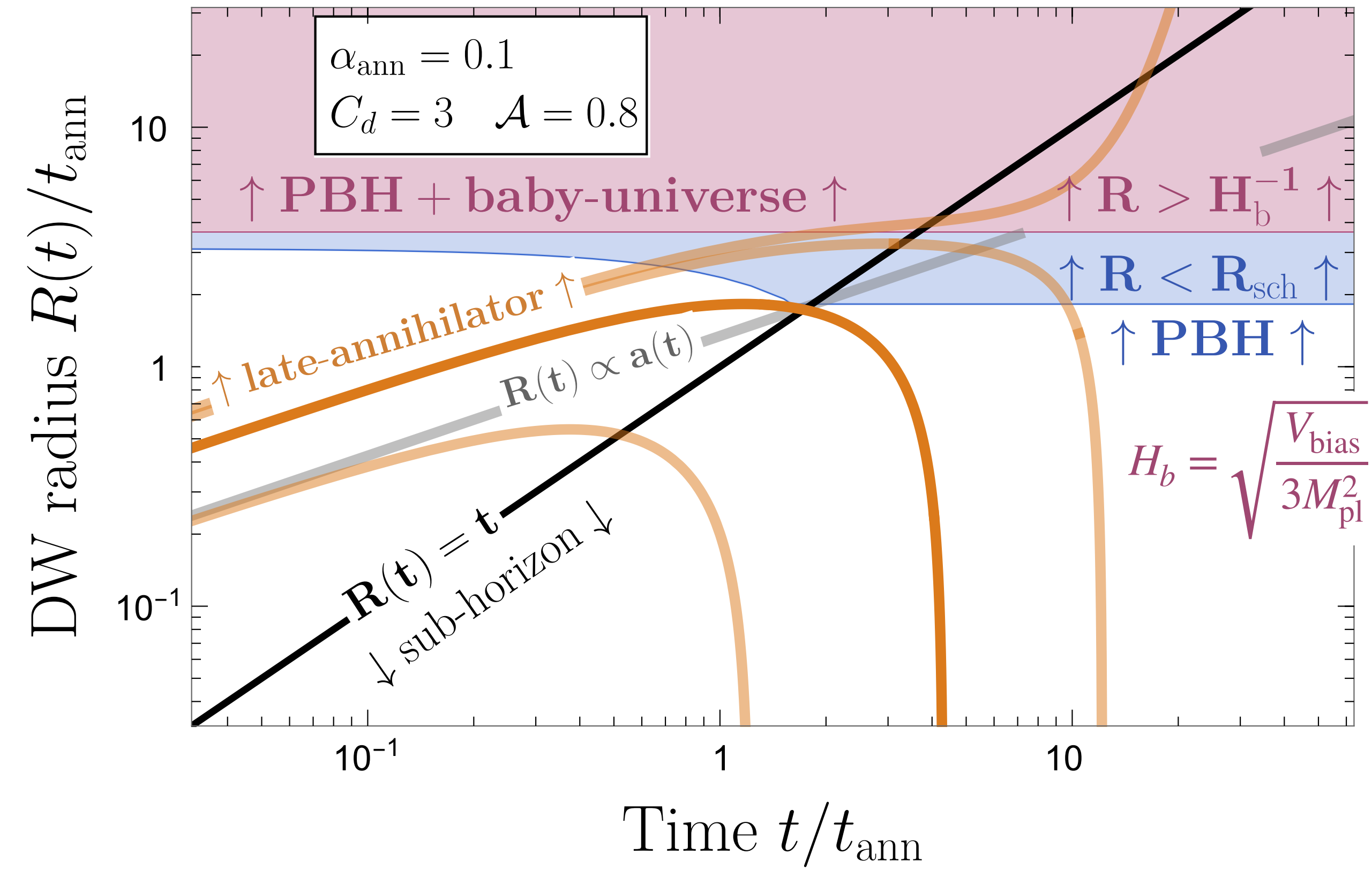
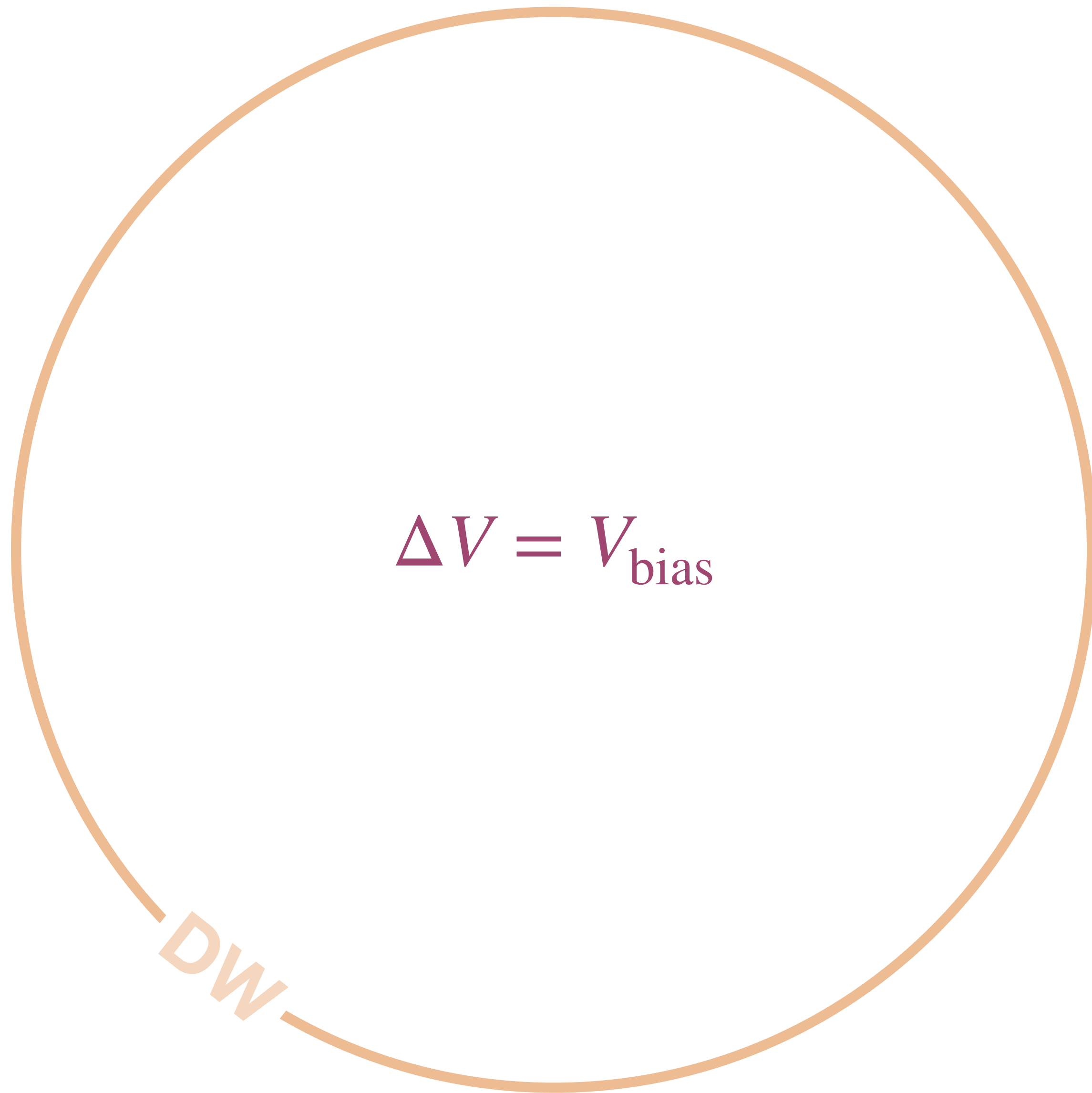


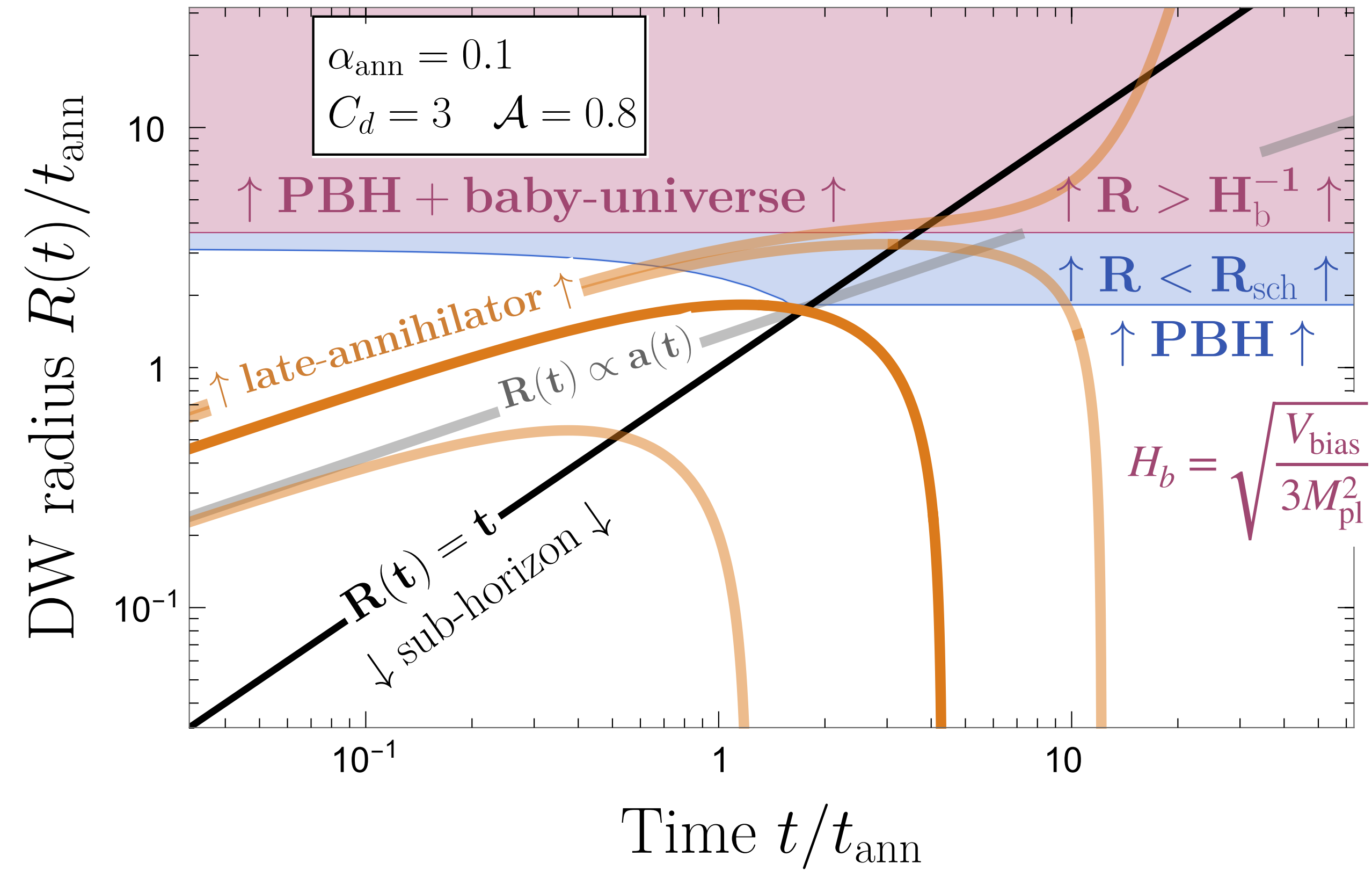
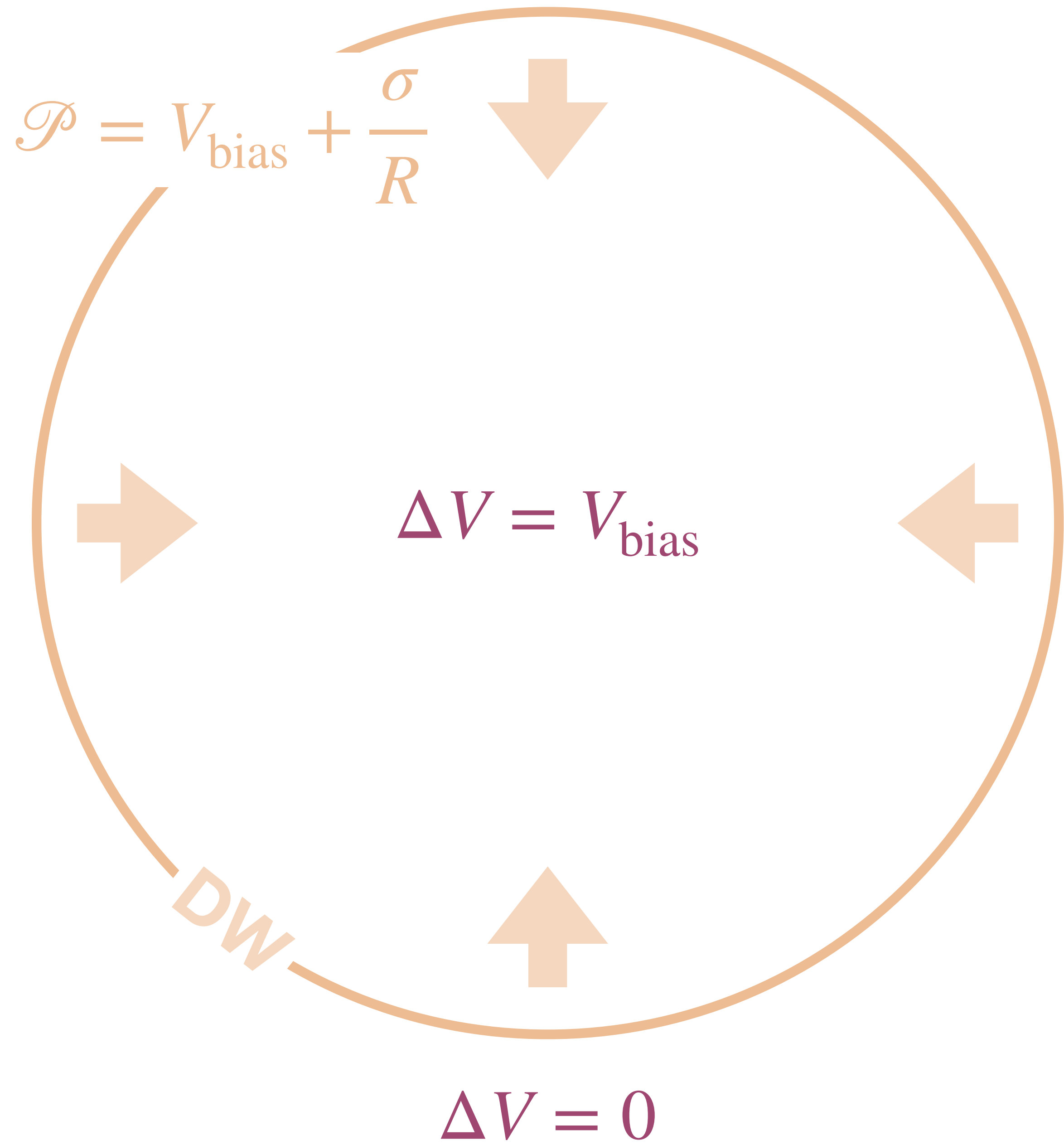




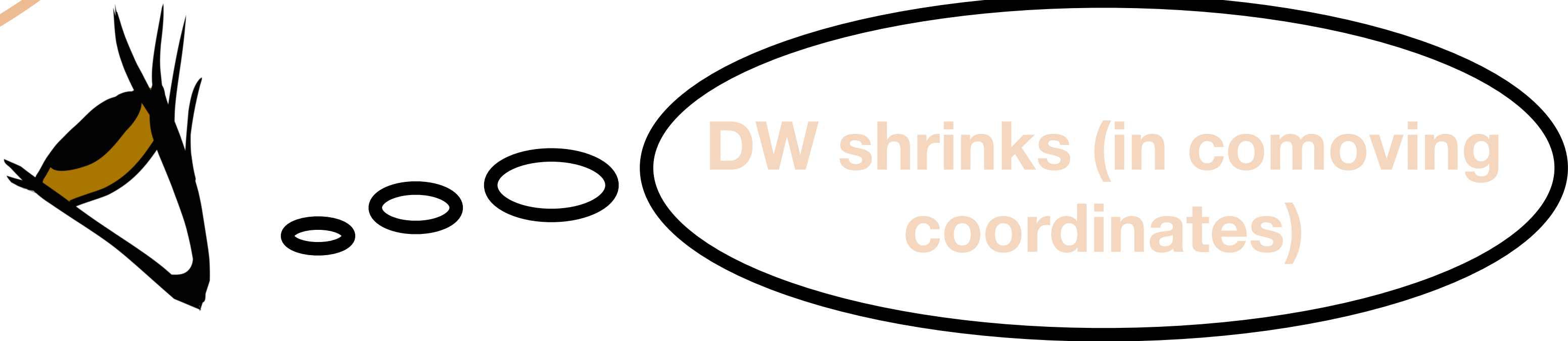
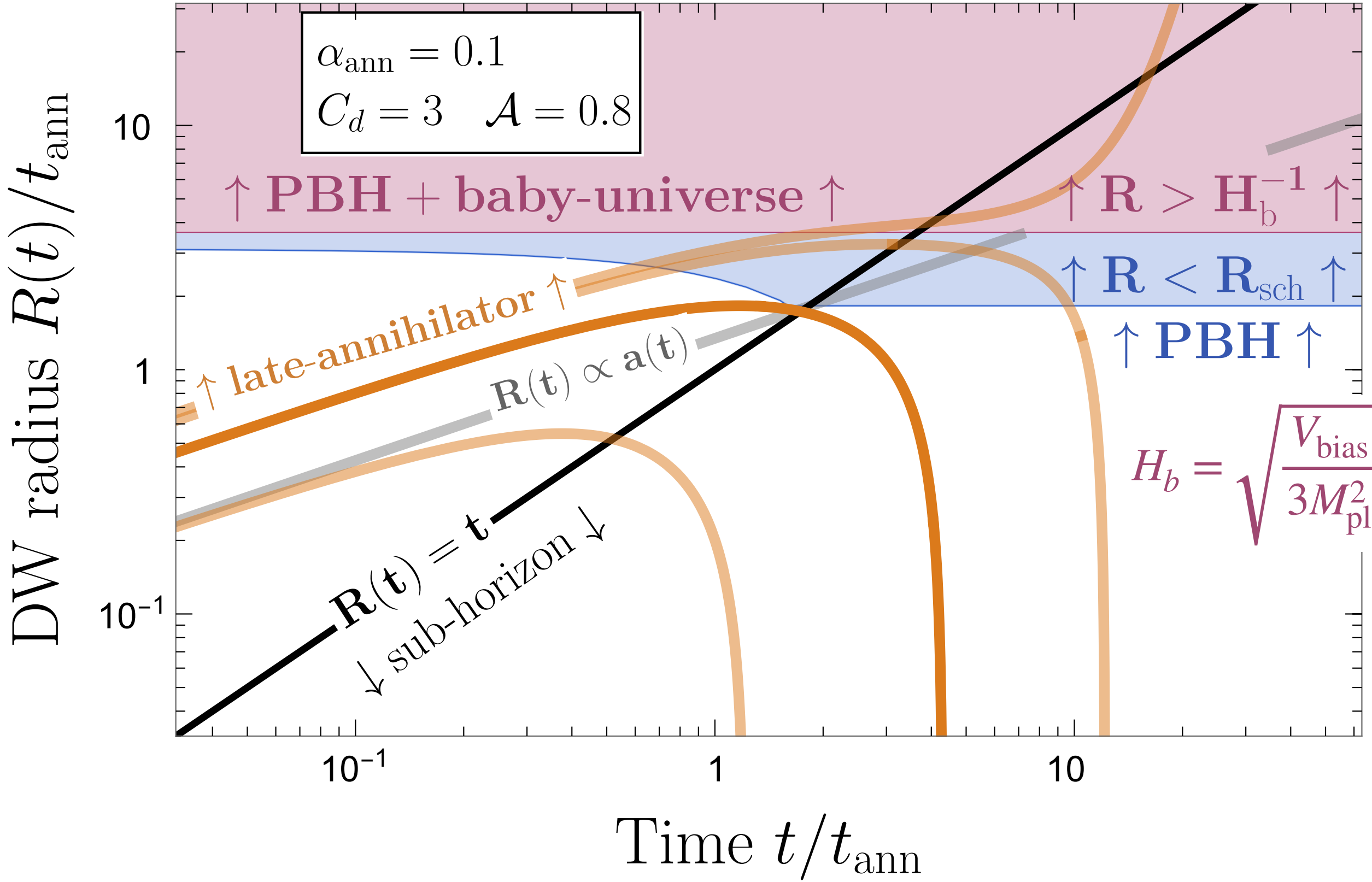
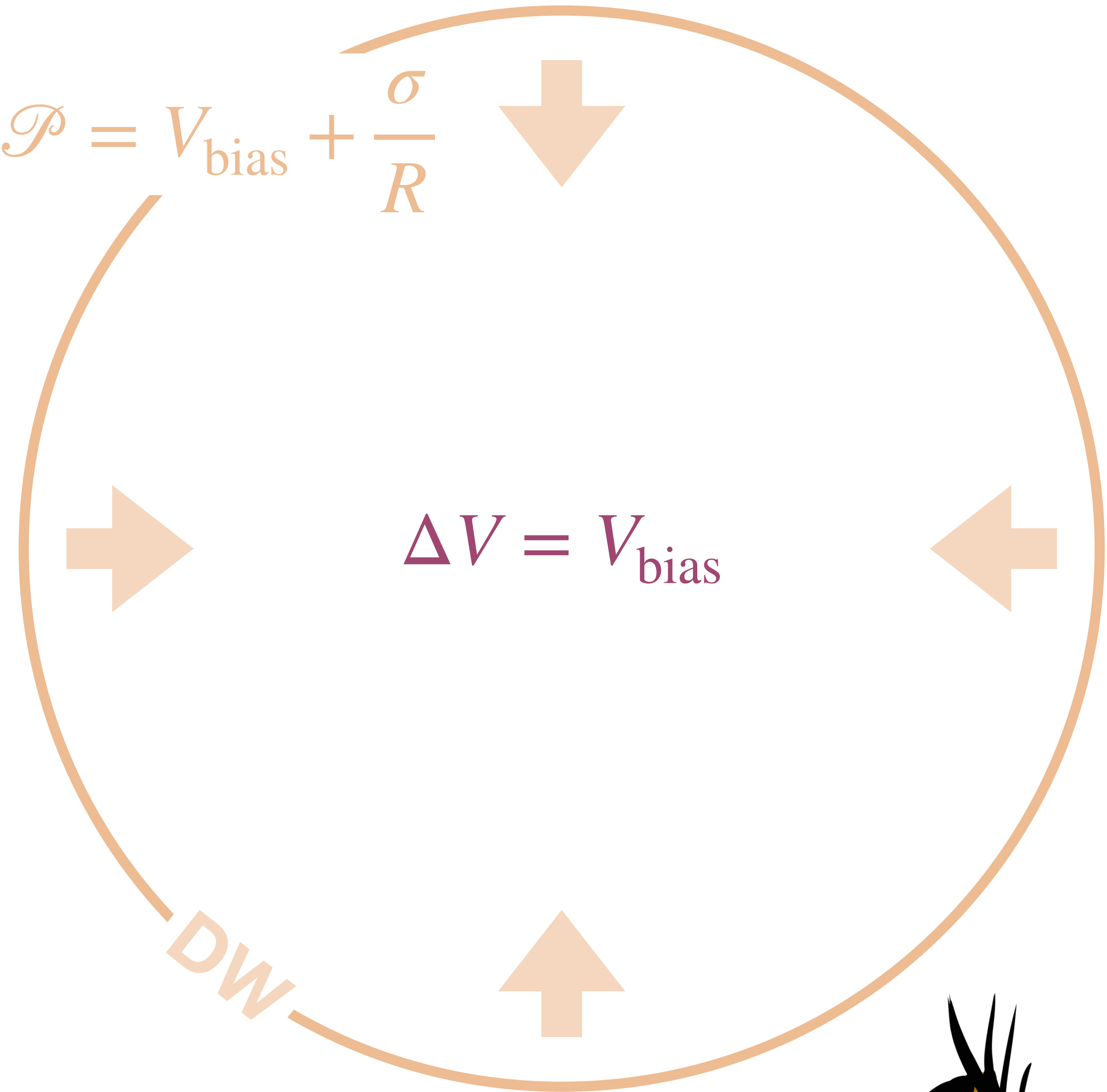


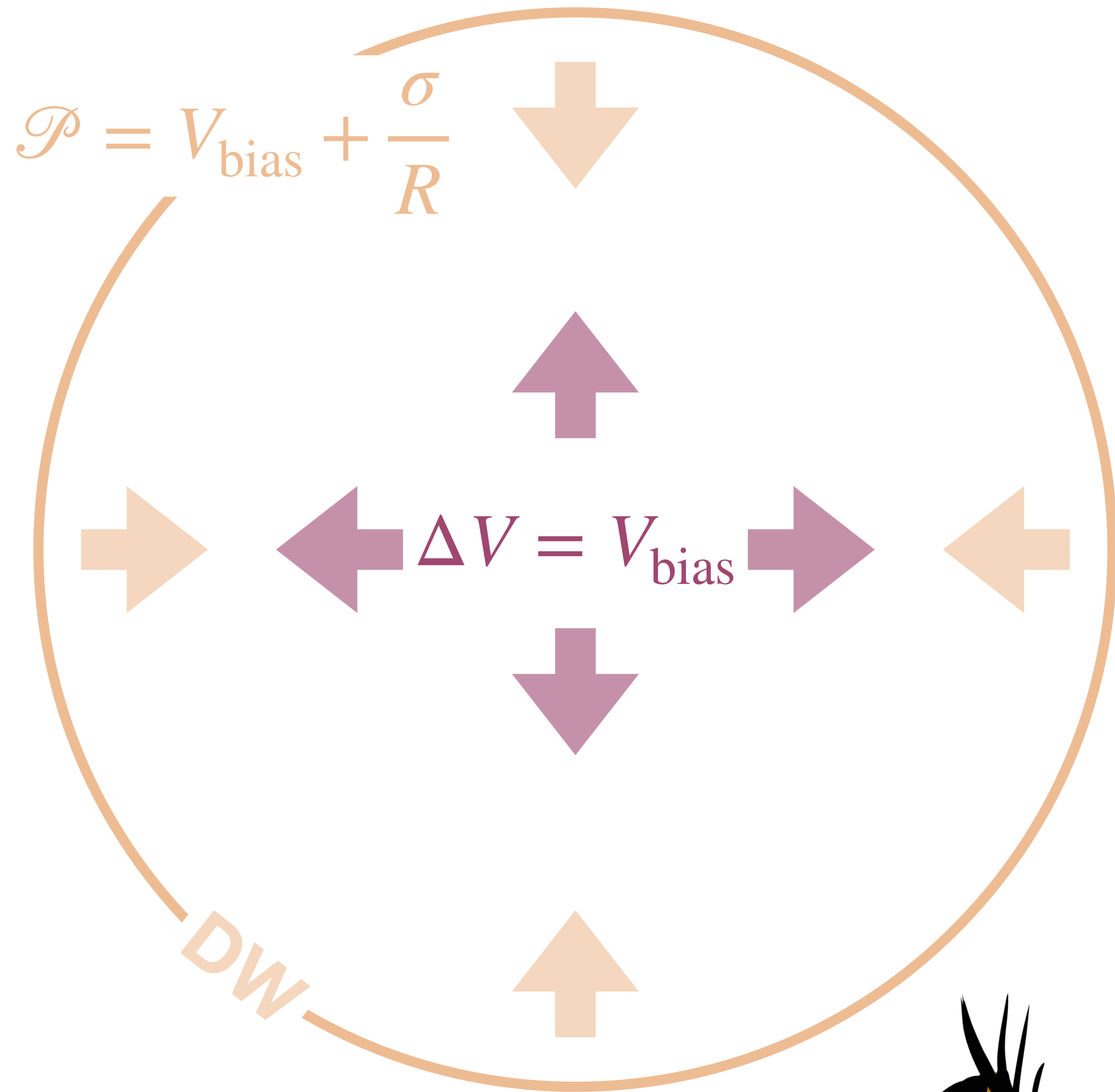




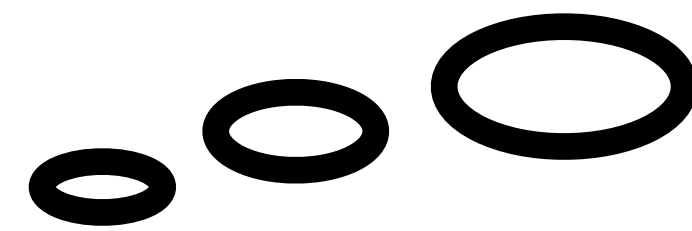




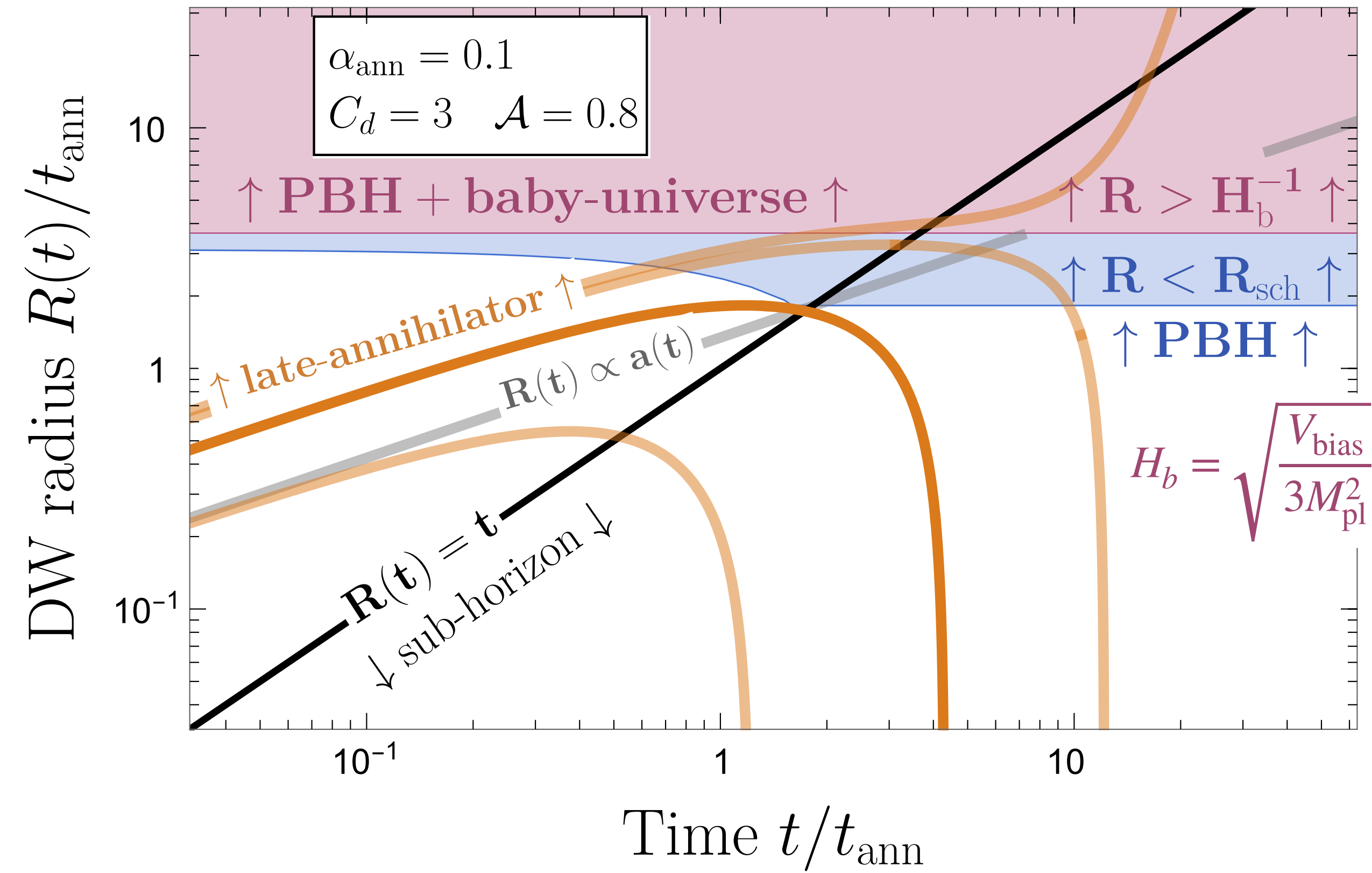


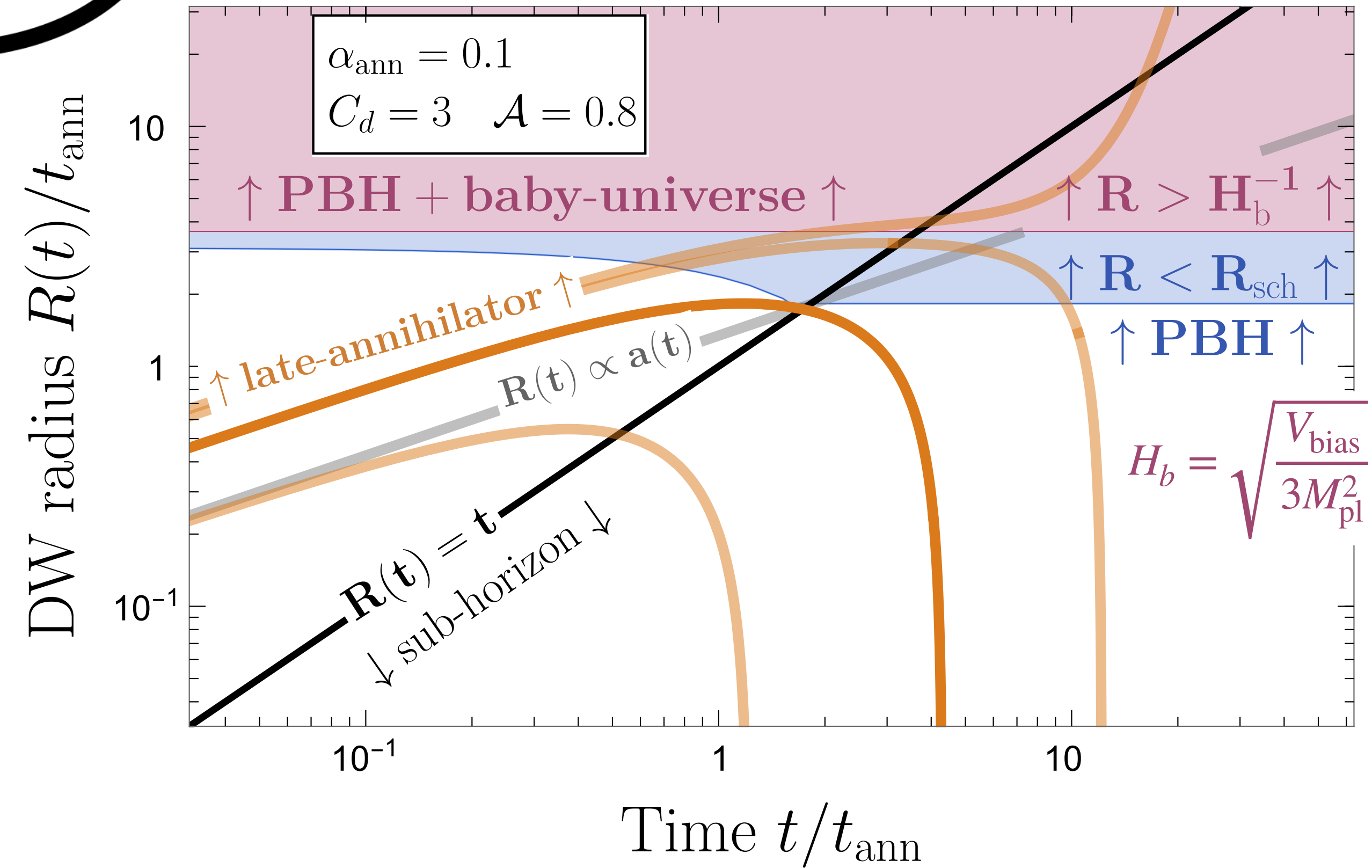
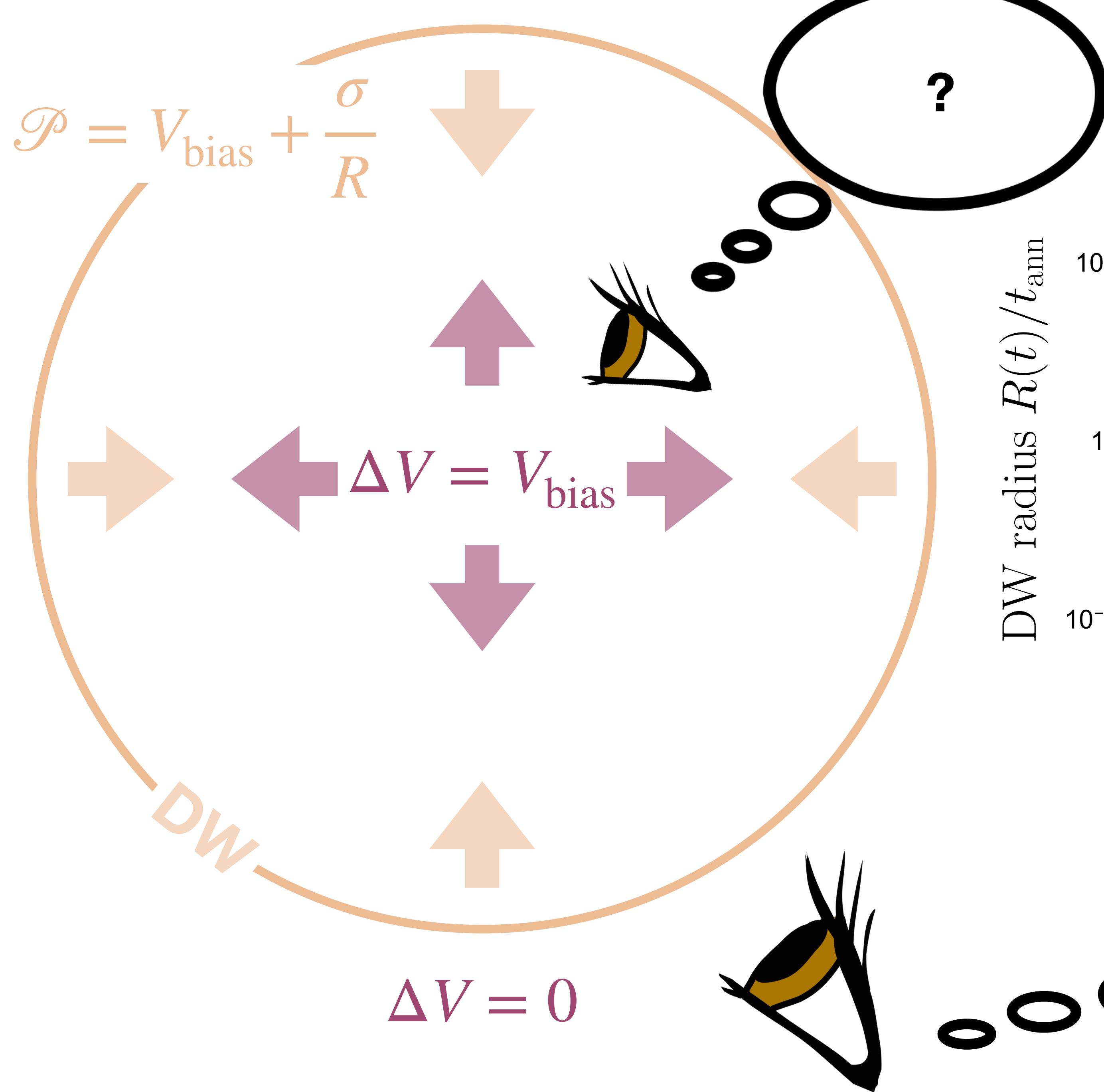


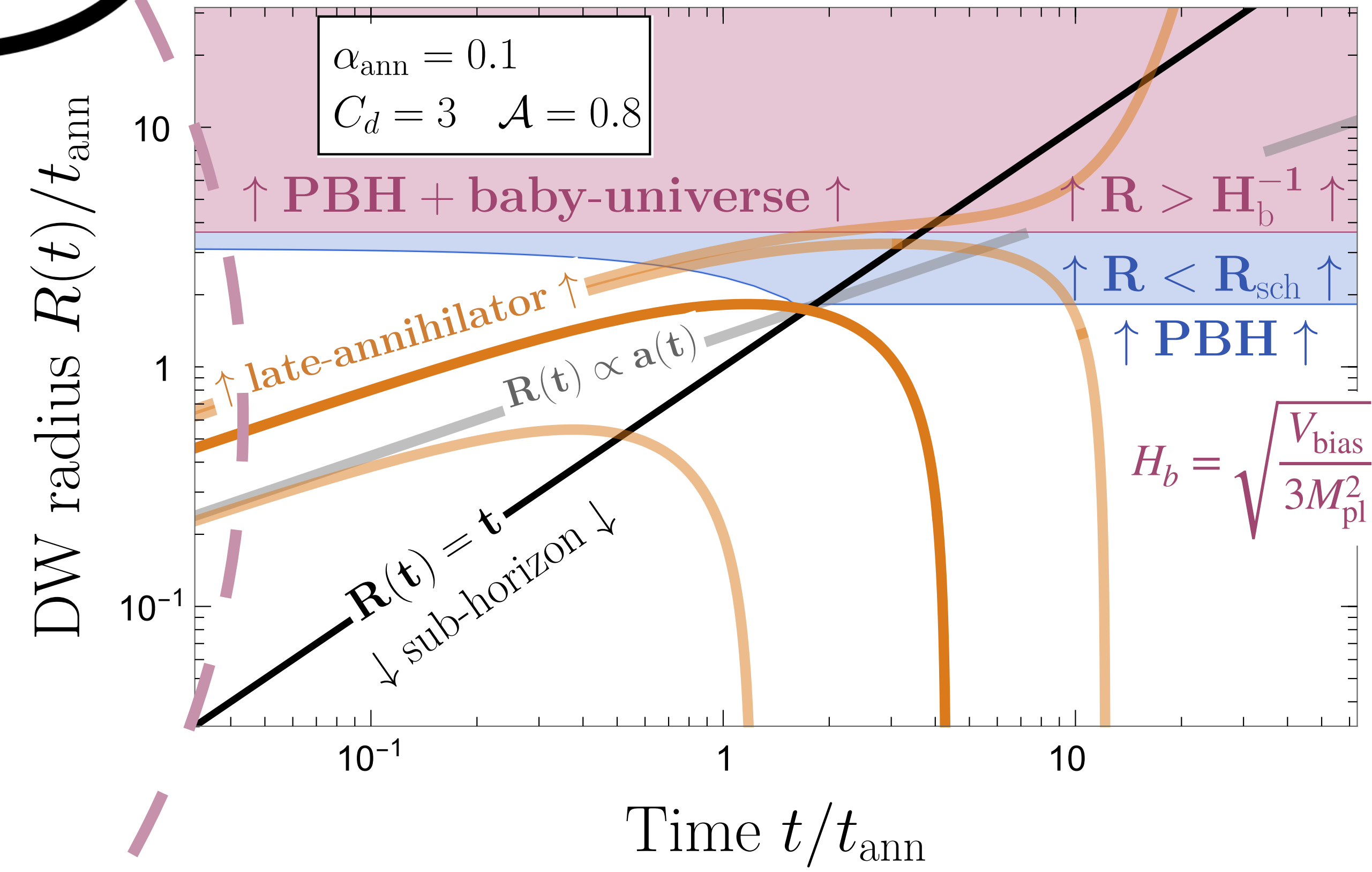
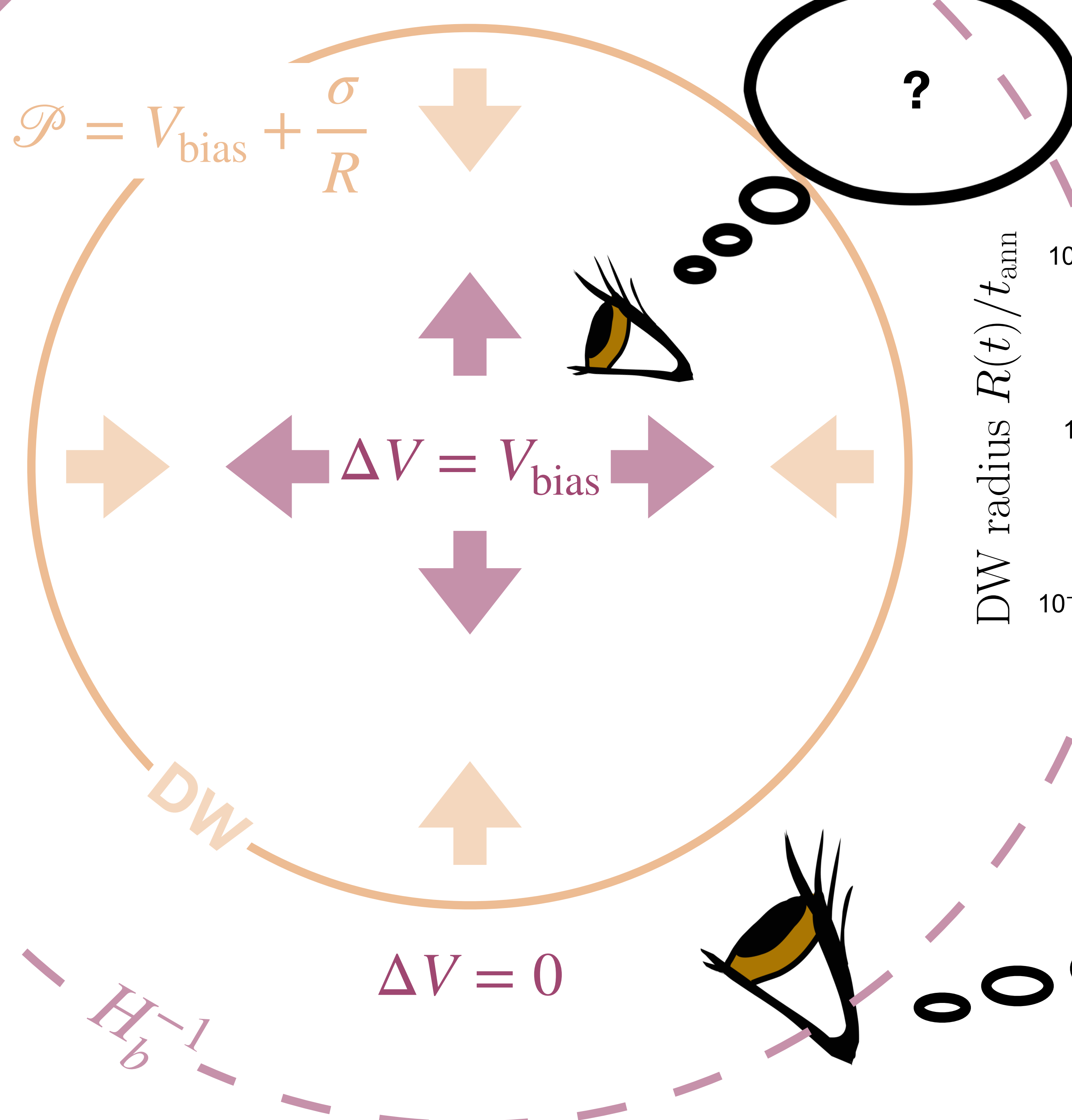
$\Delta V = 0$



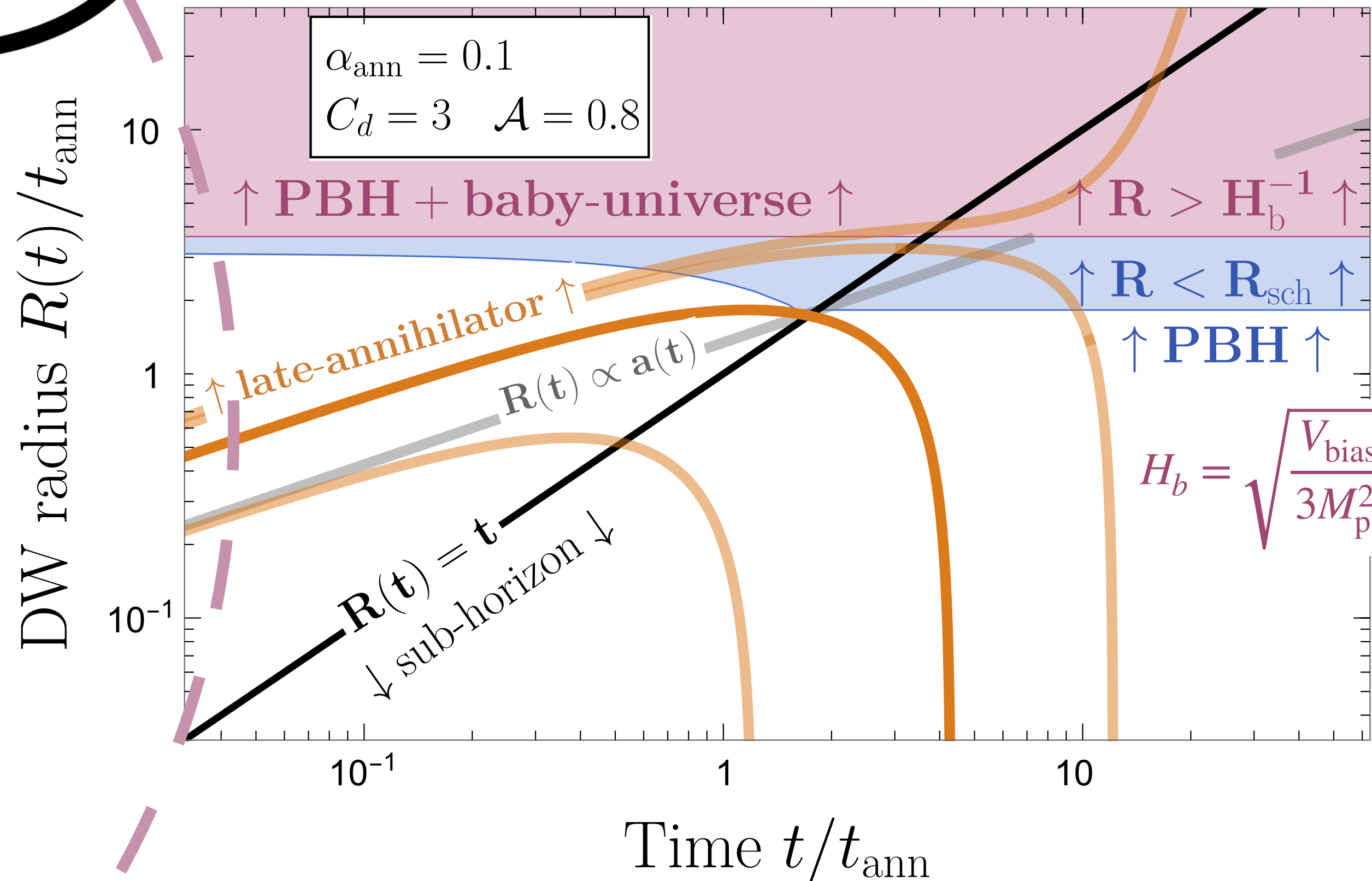
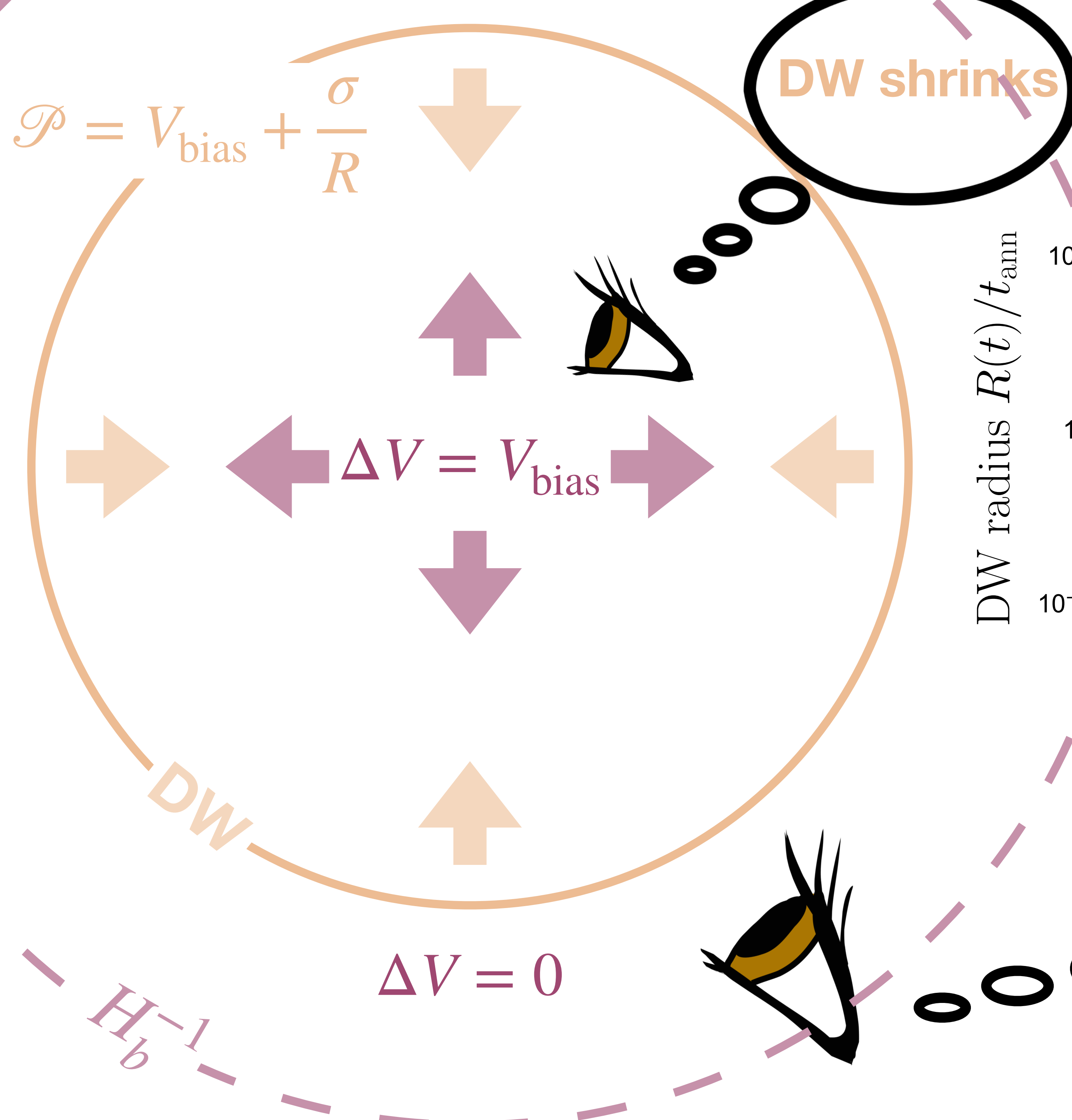
DW shrinks (in comoving coordinates)





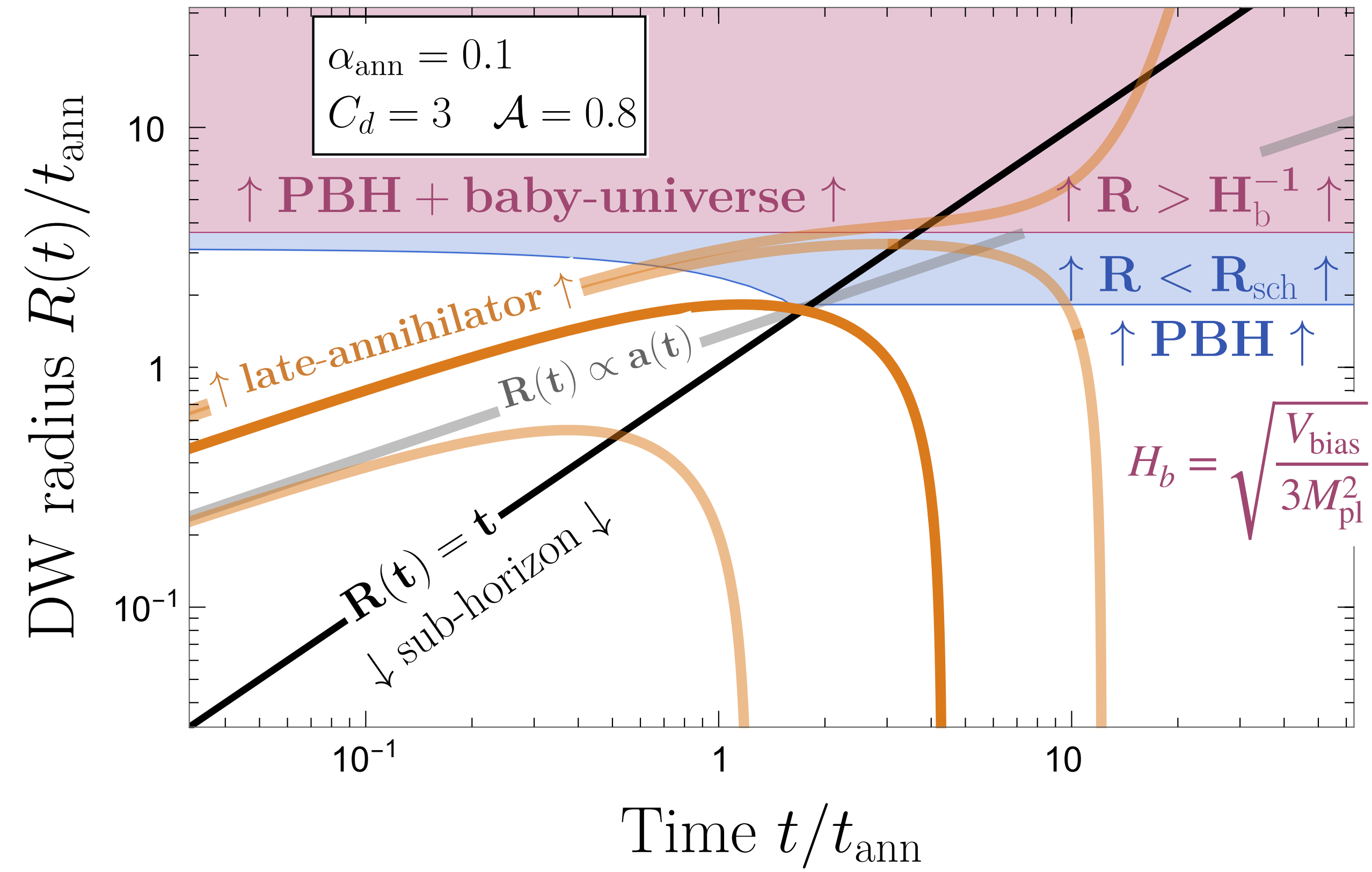
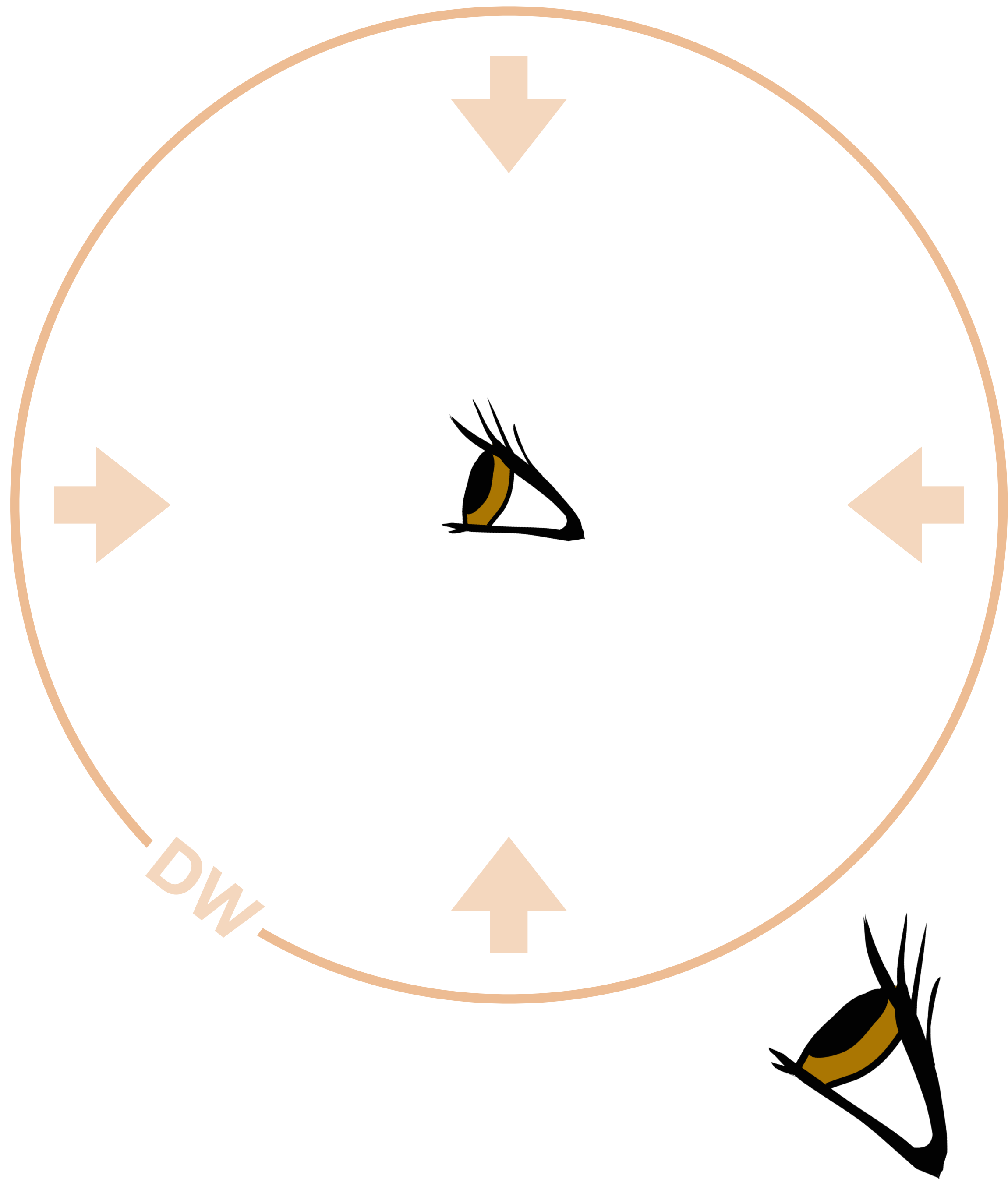


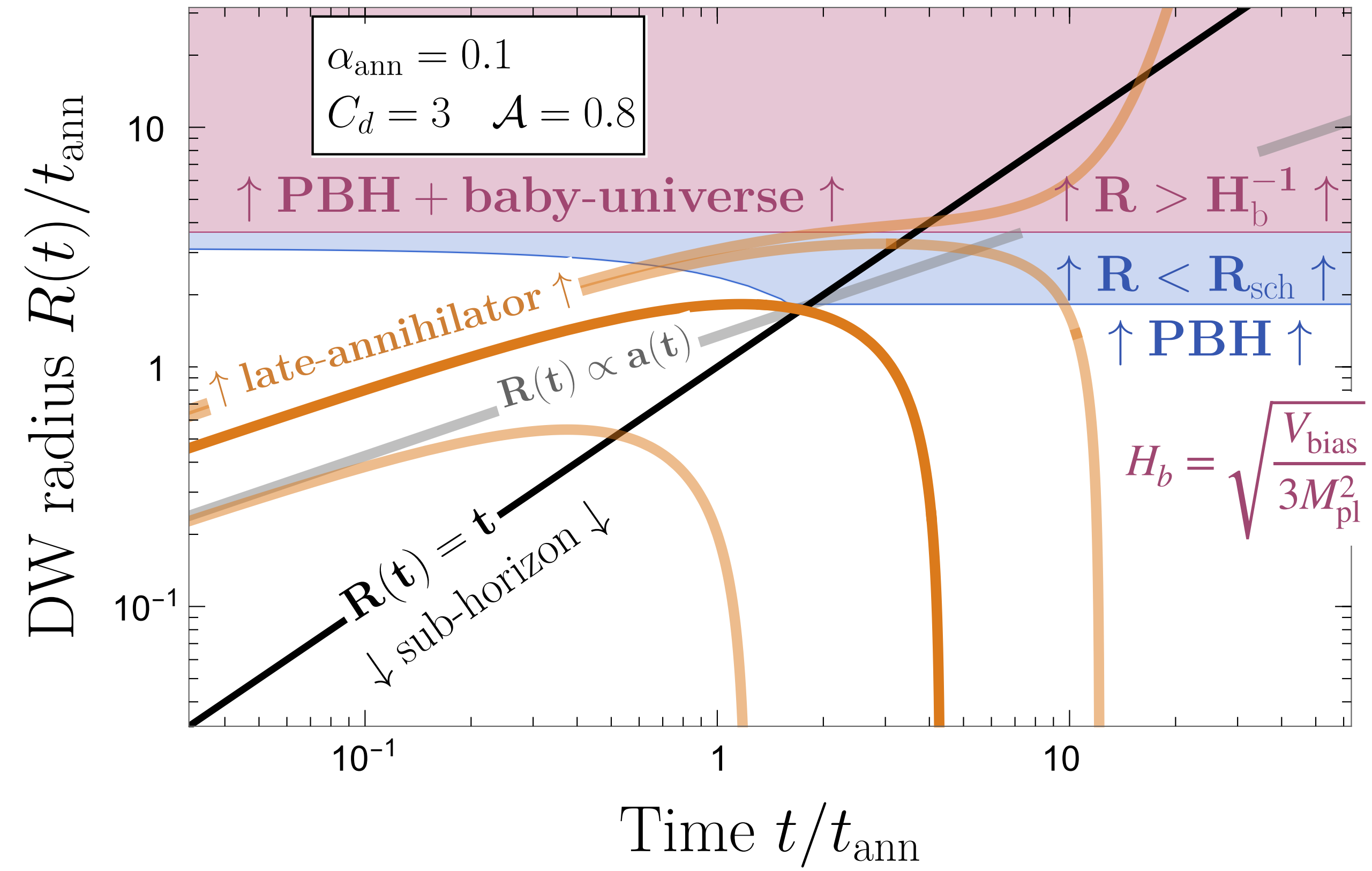
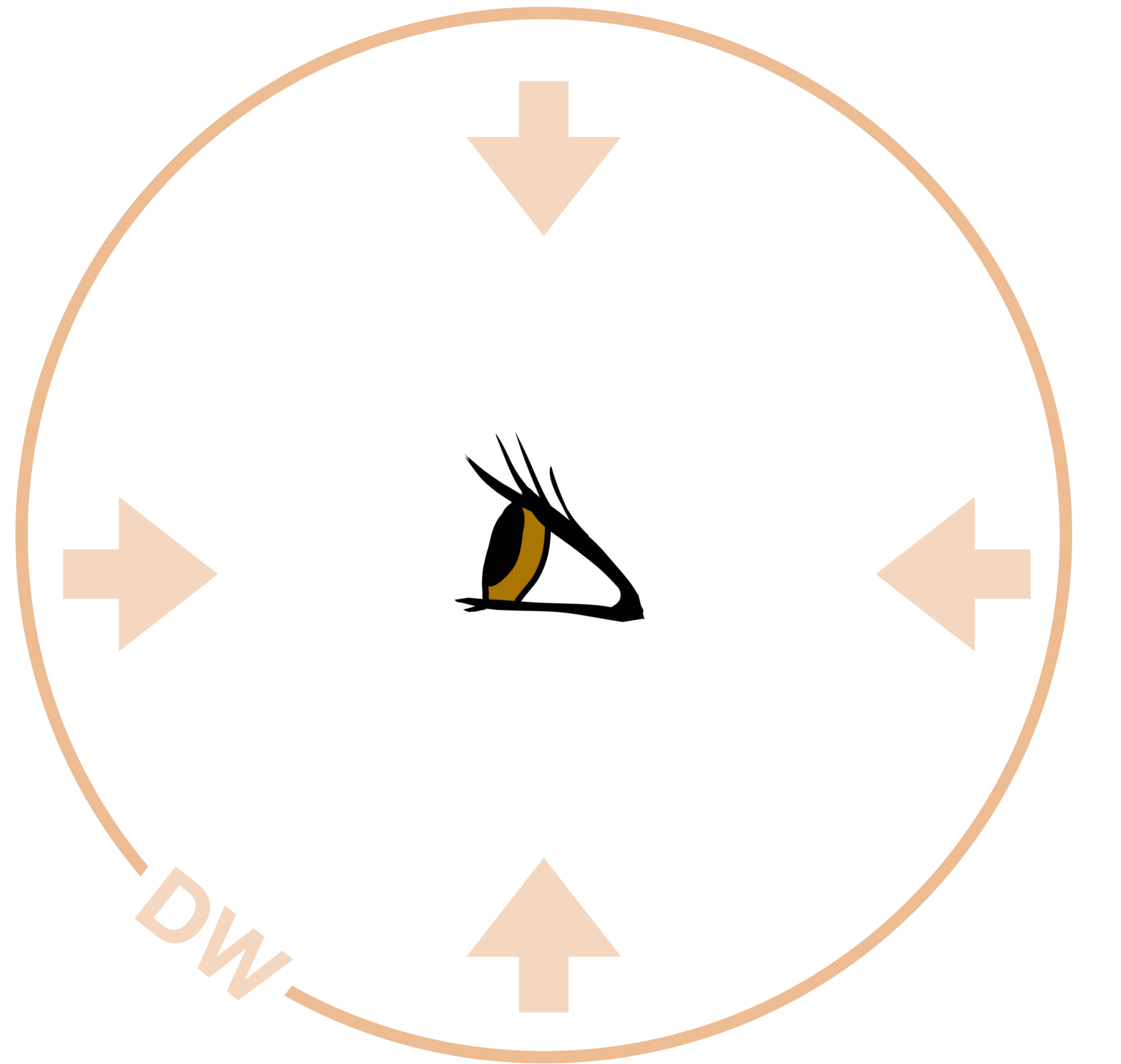
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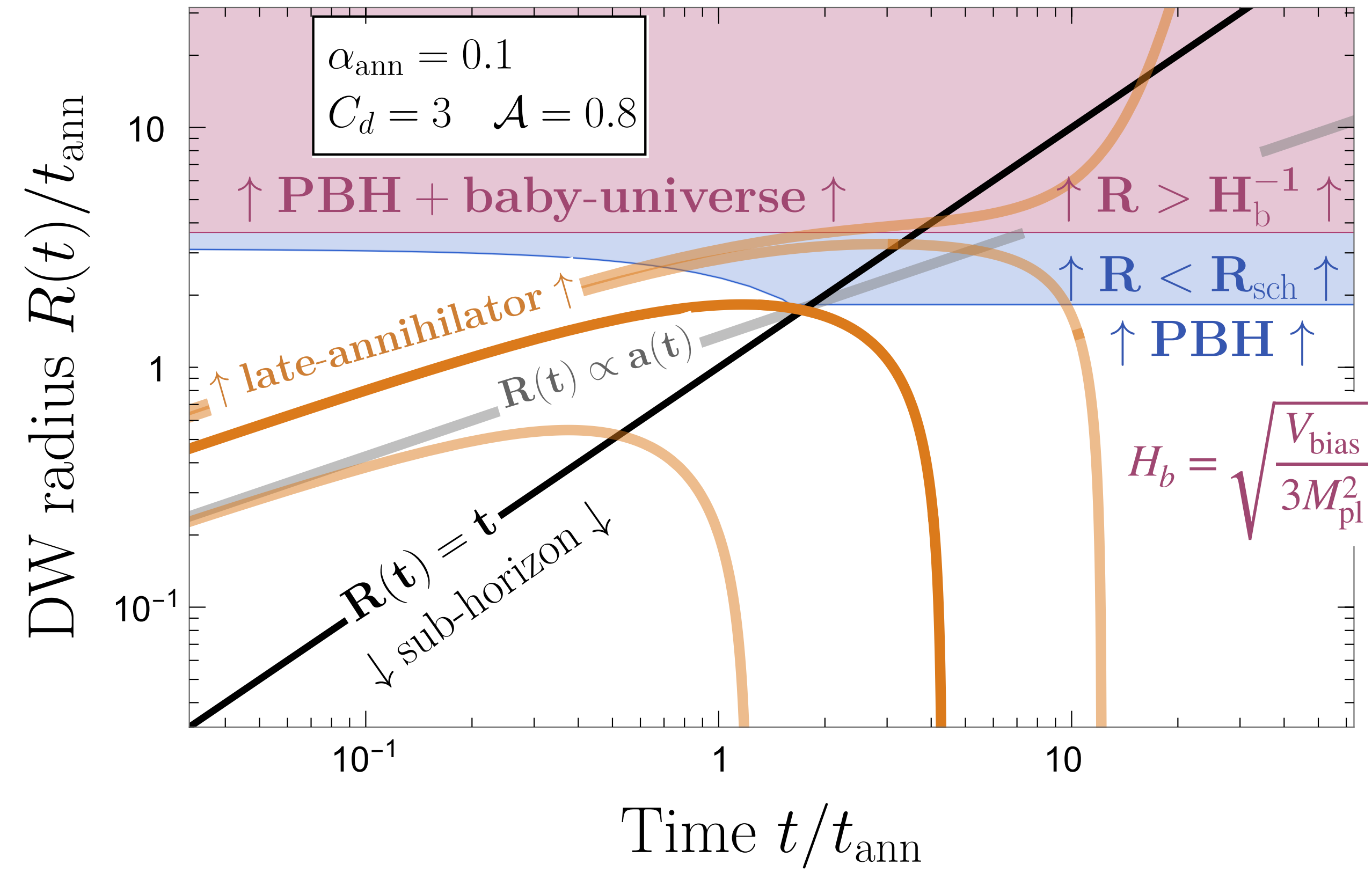
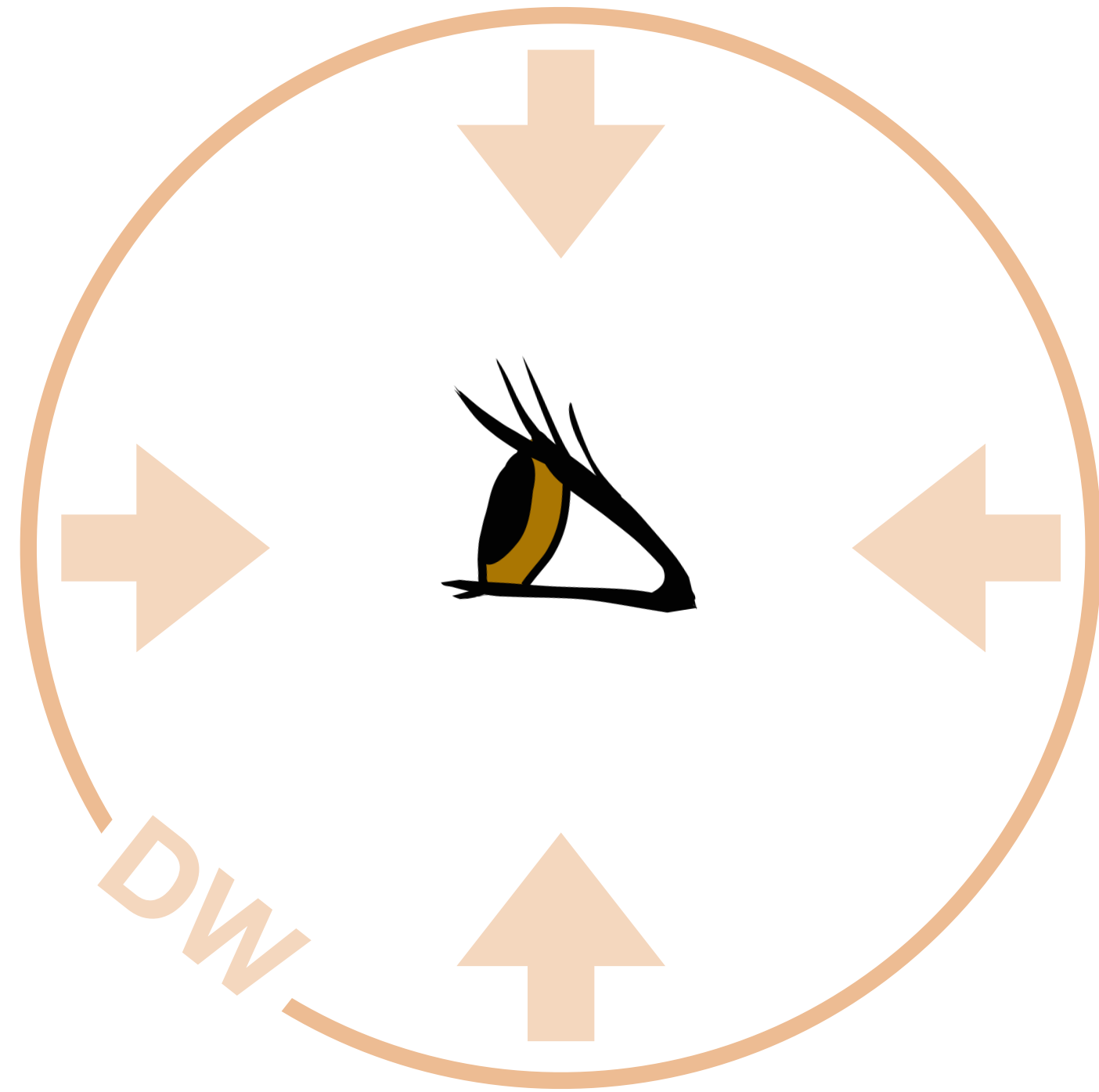


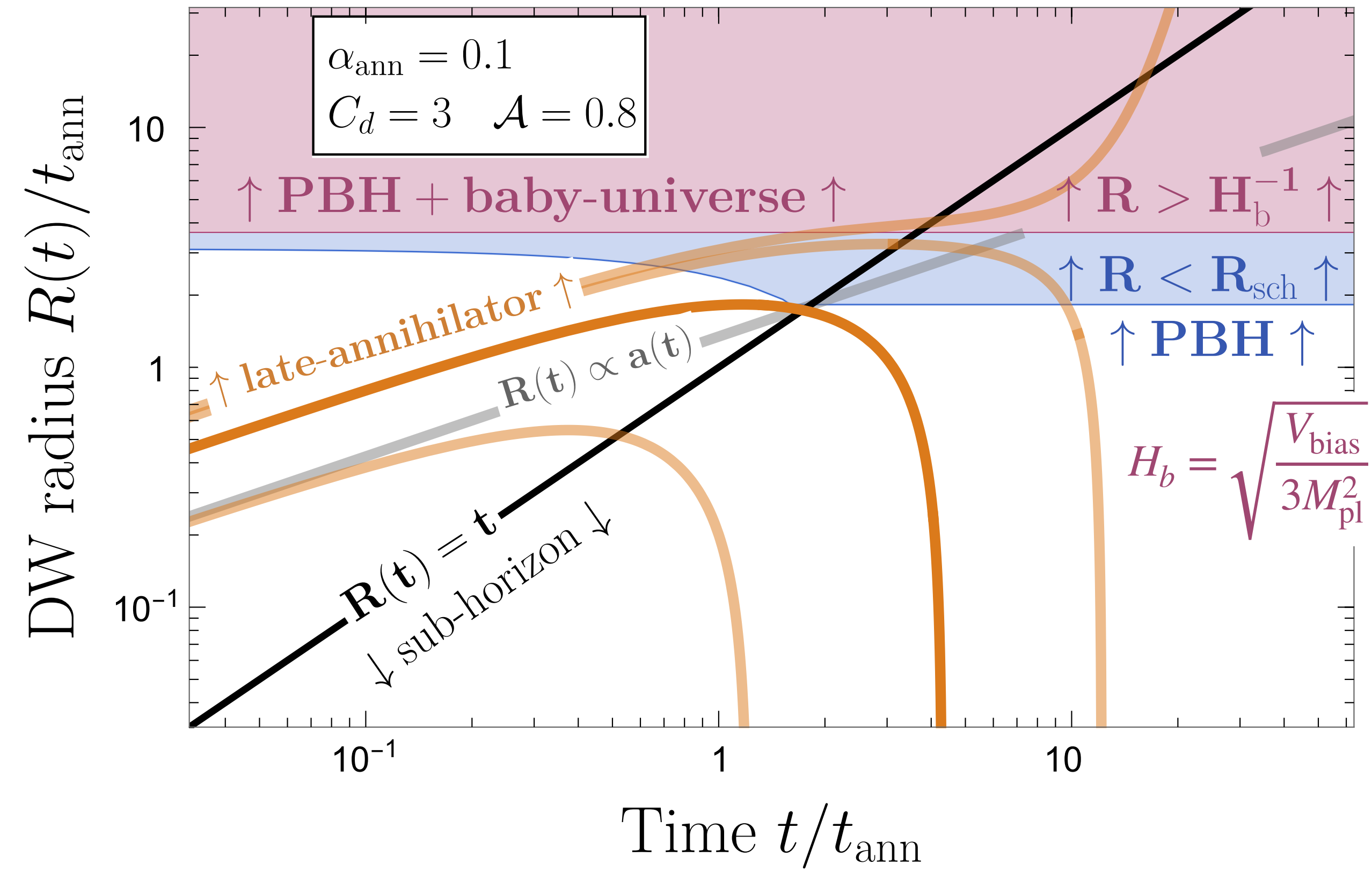
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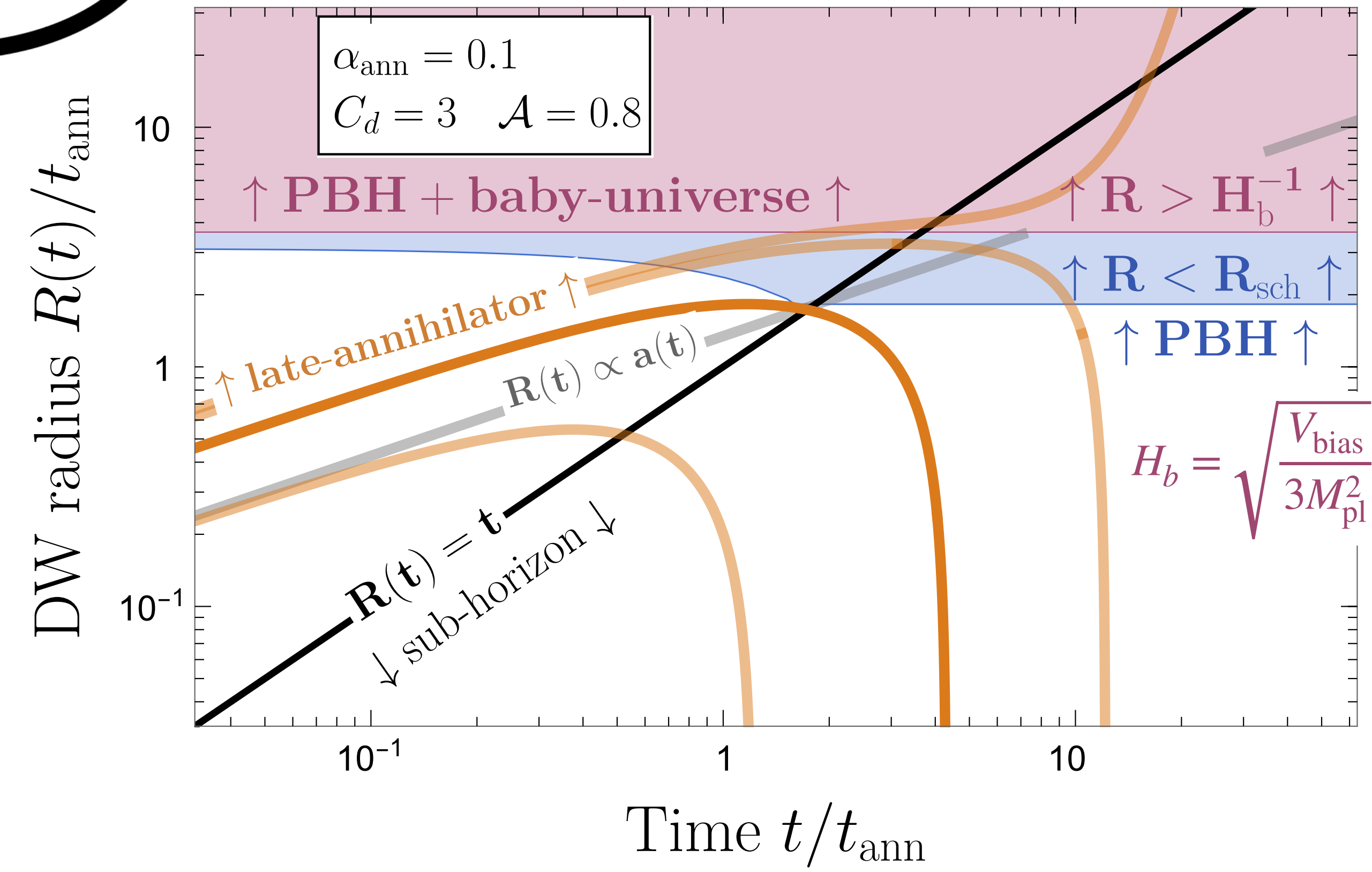
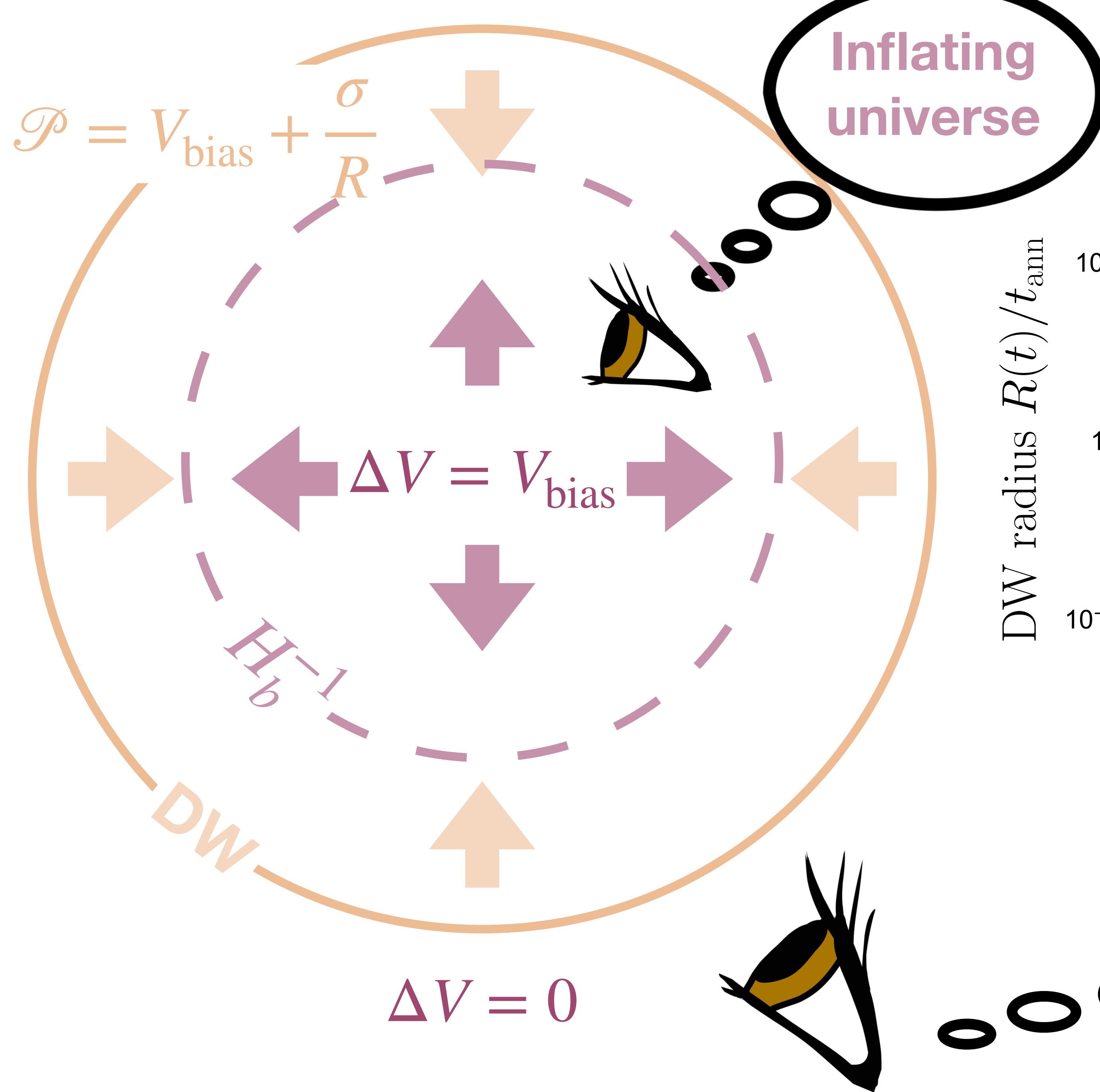






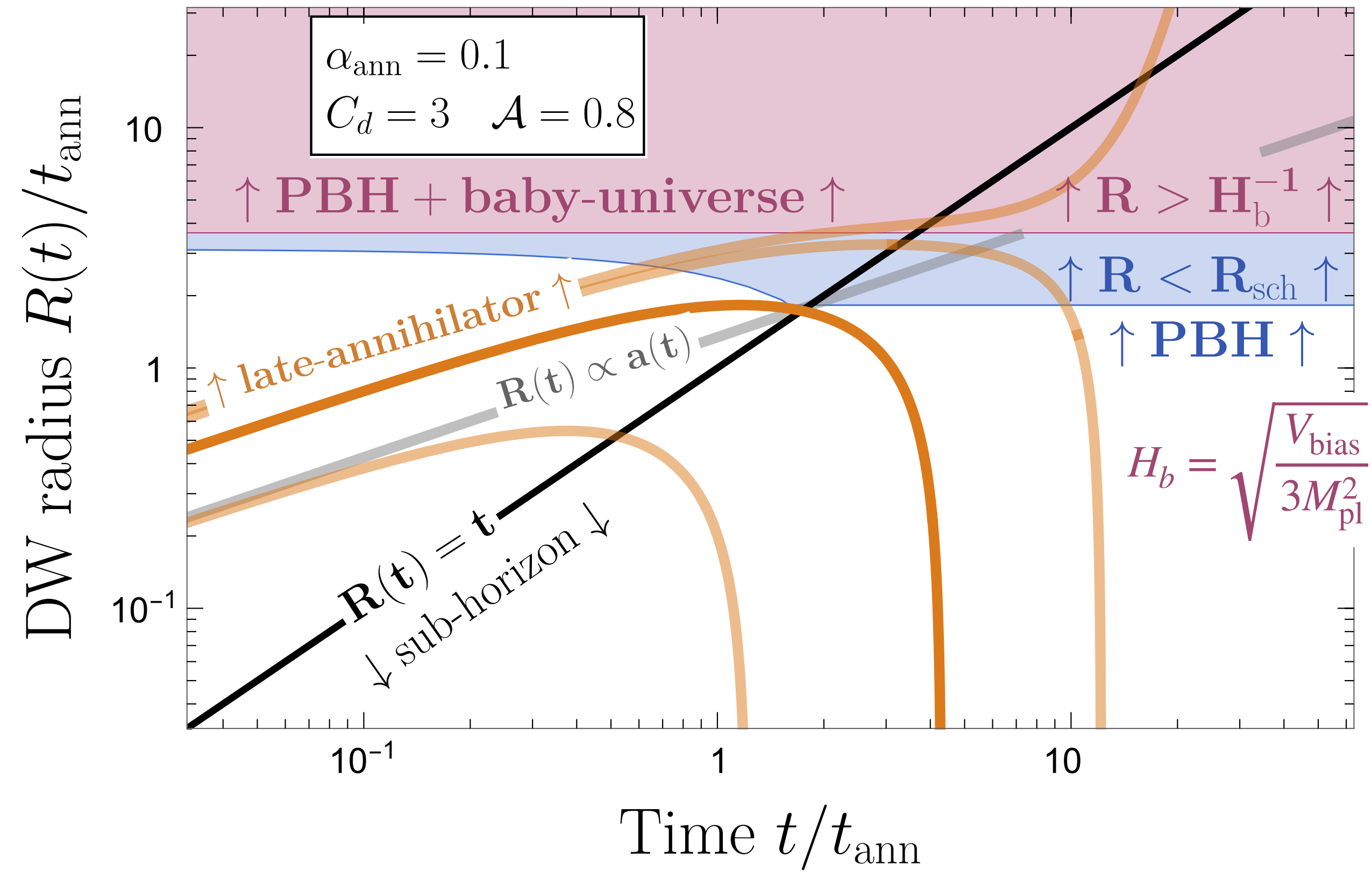
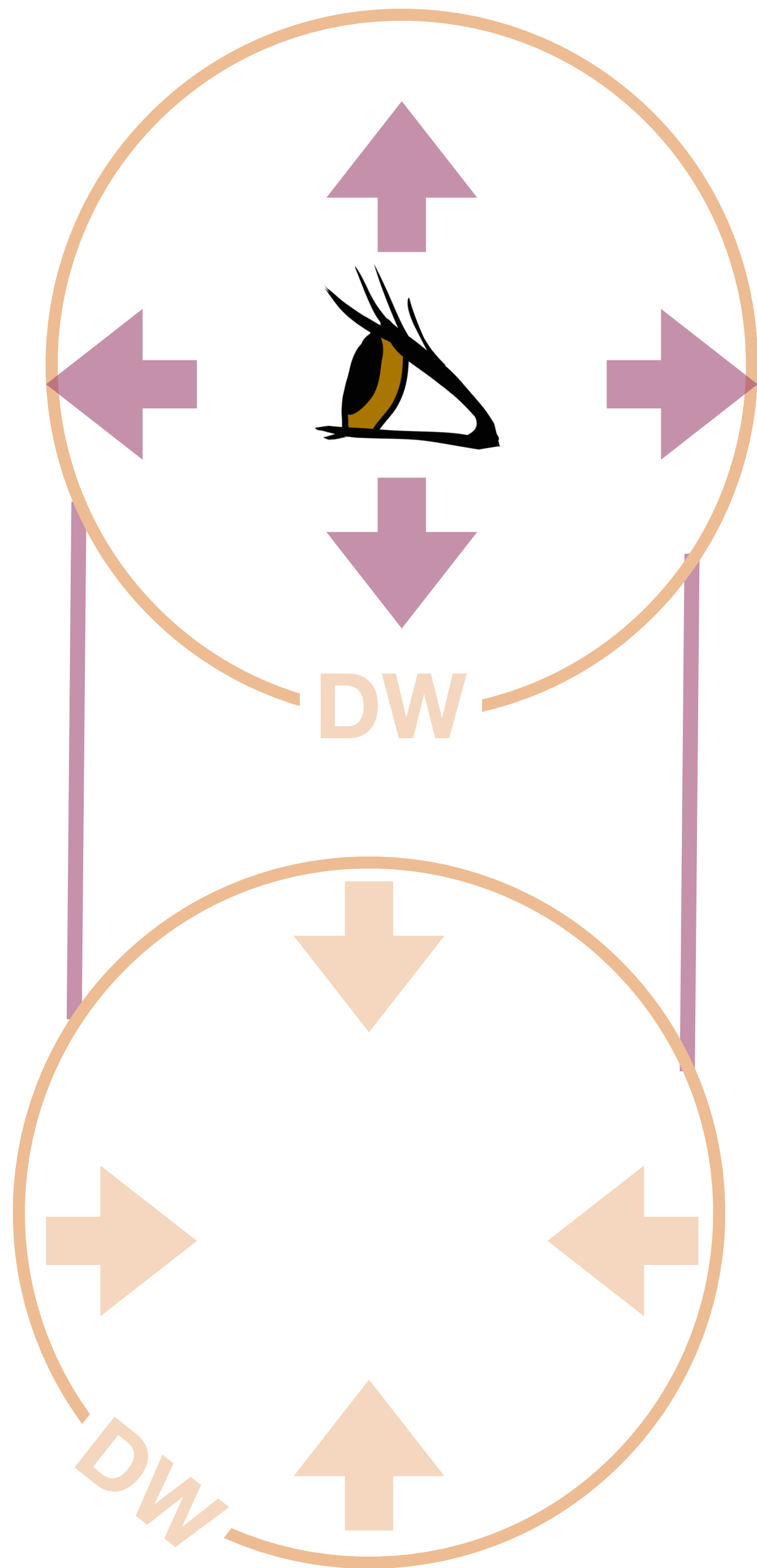


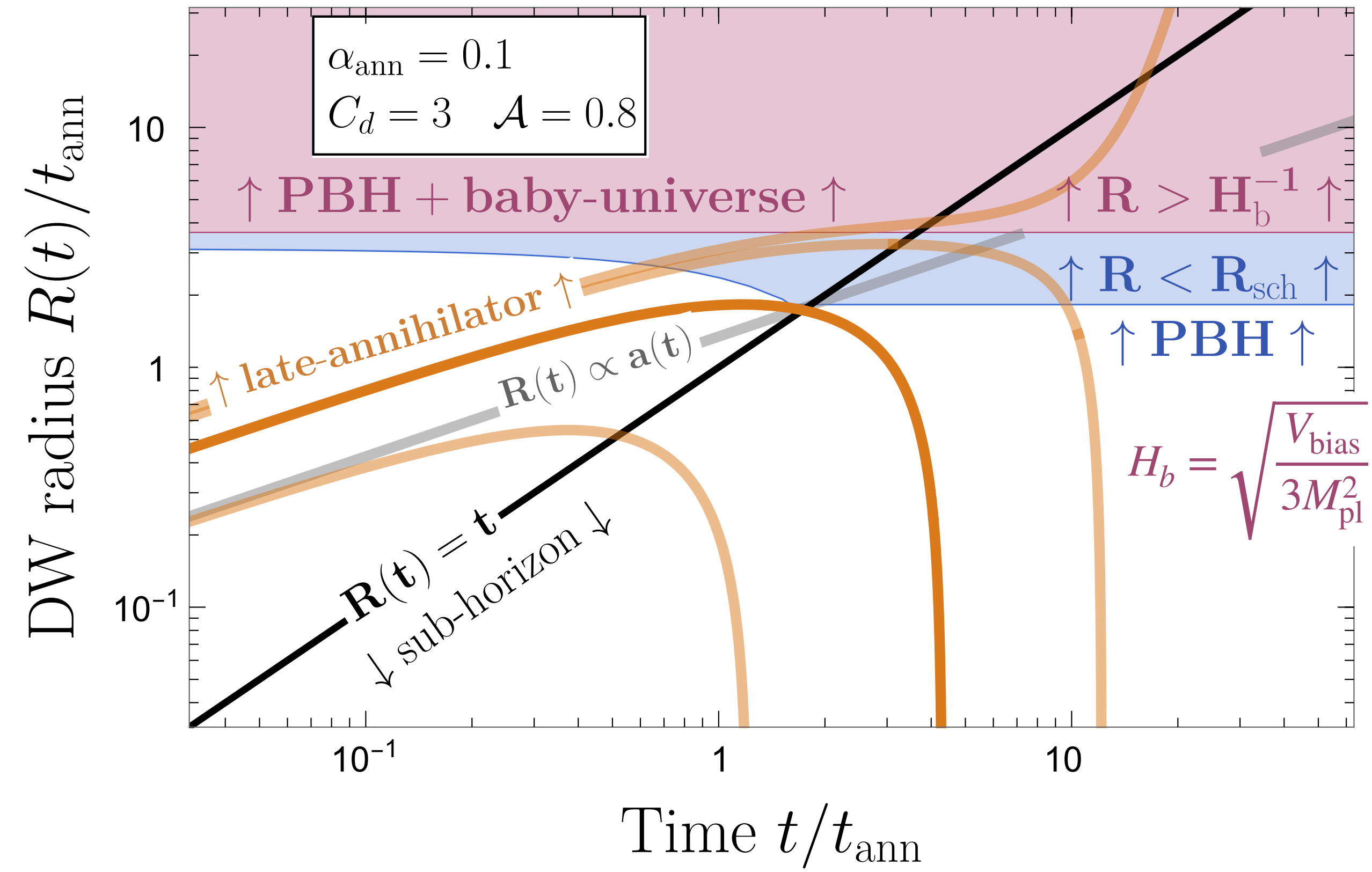
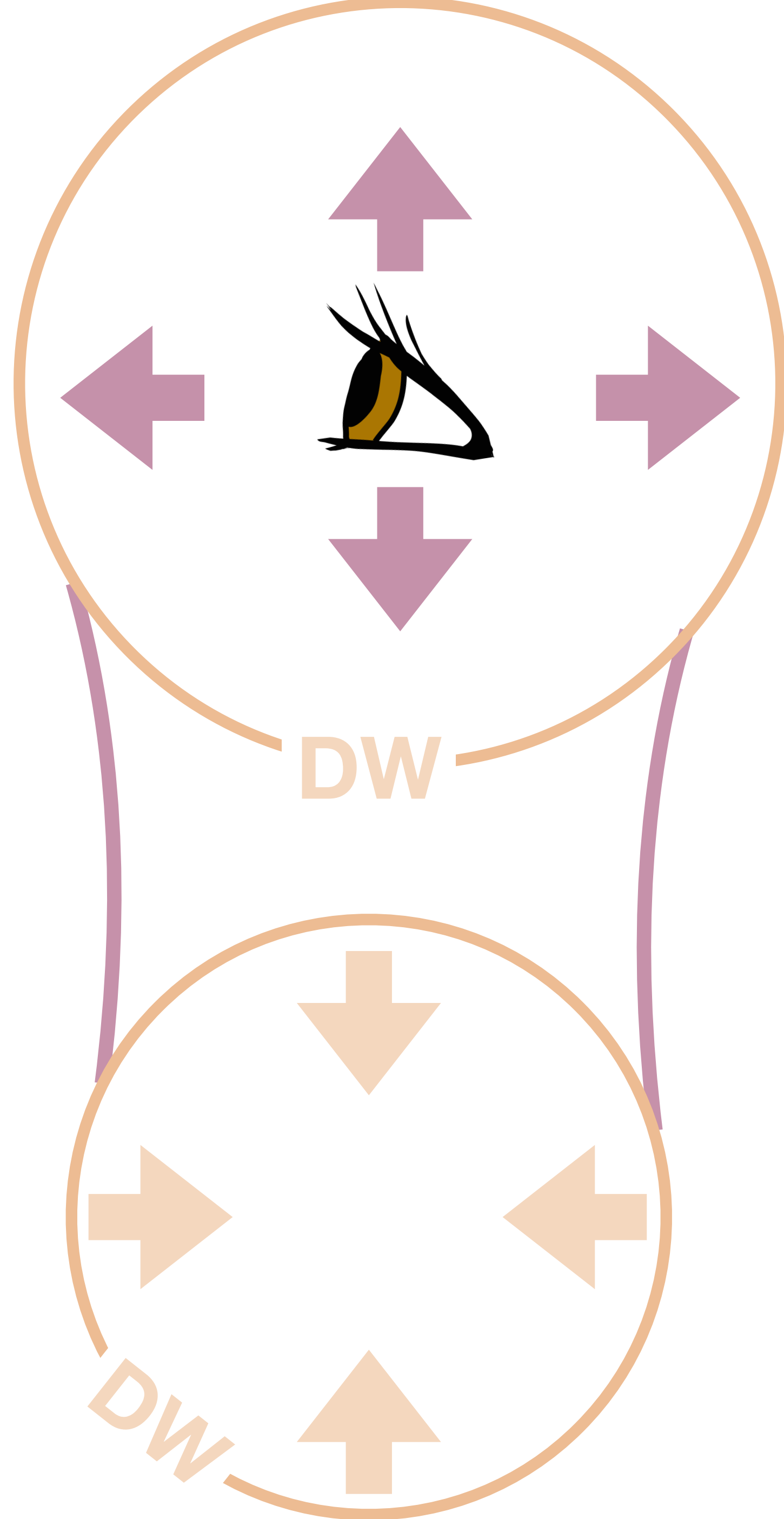


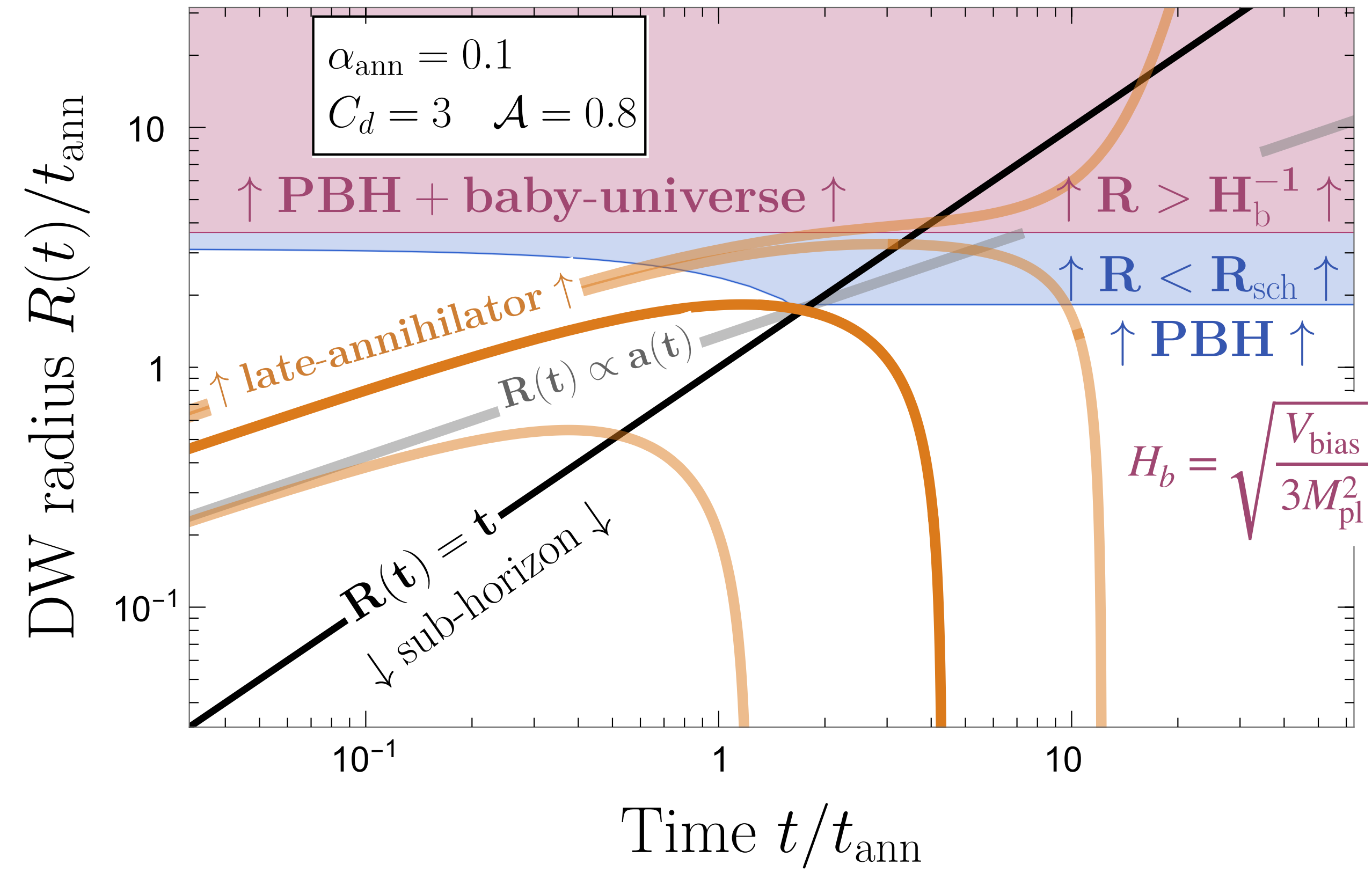
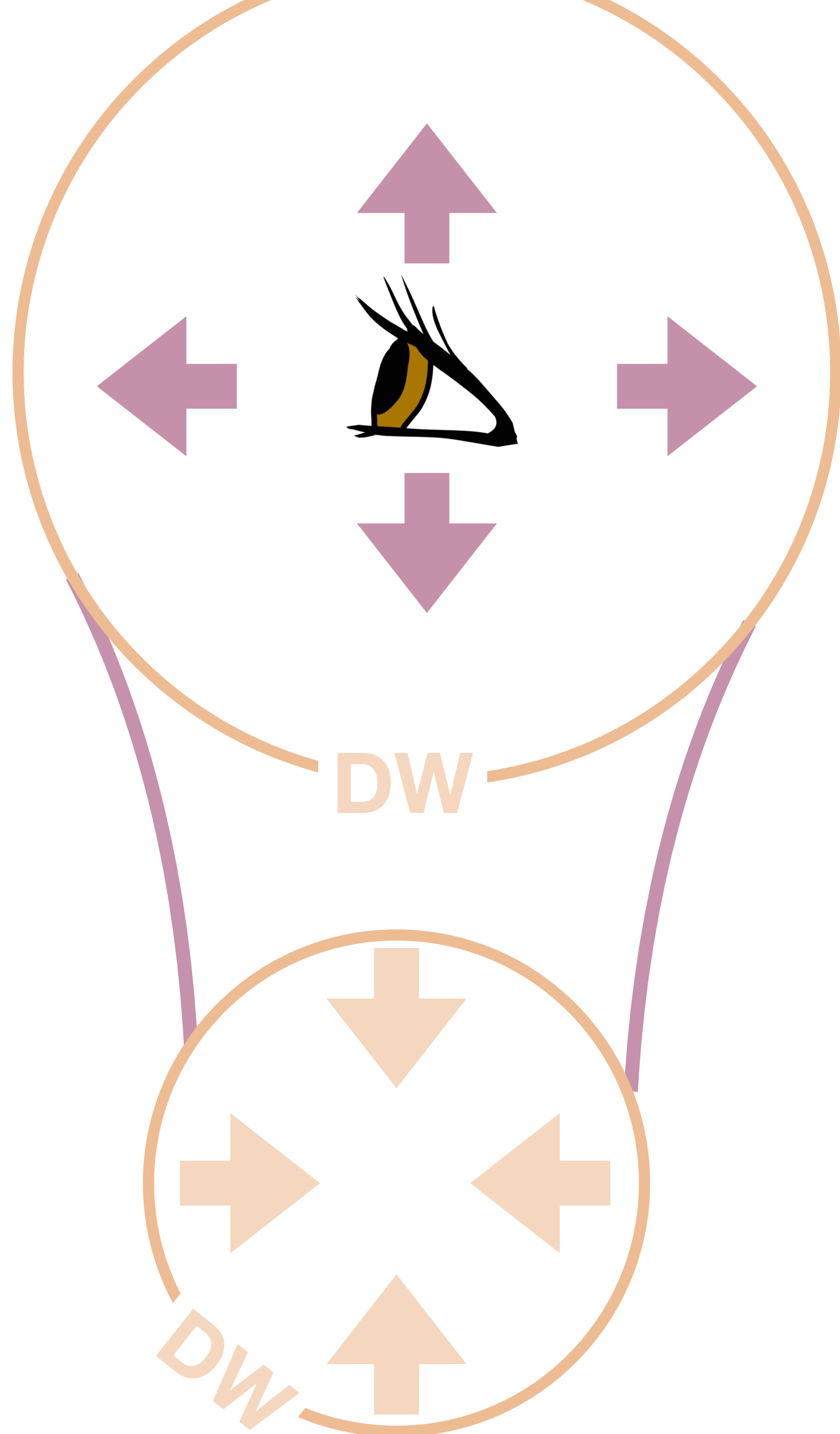


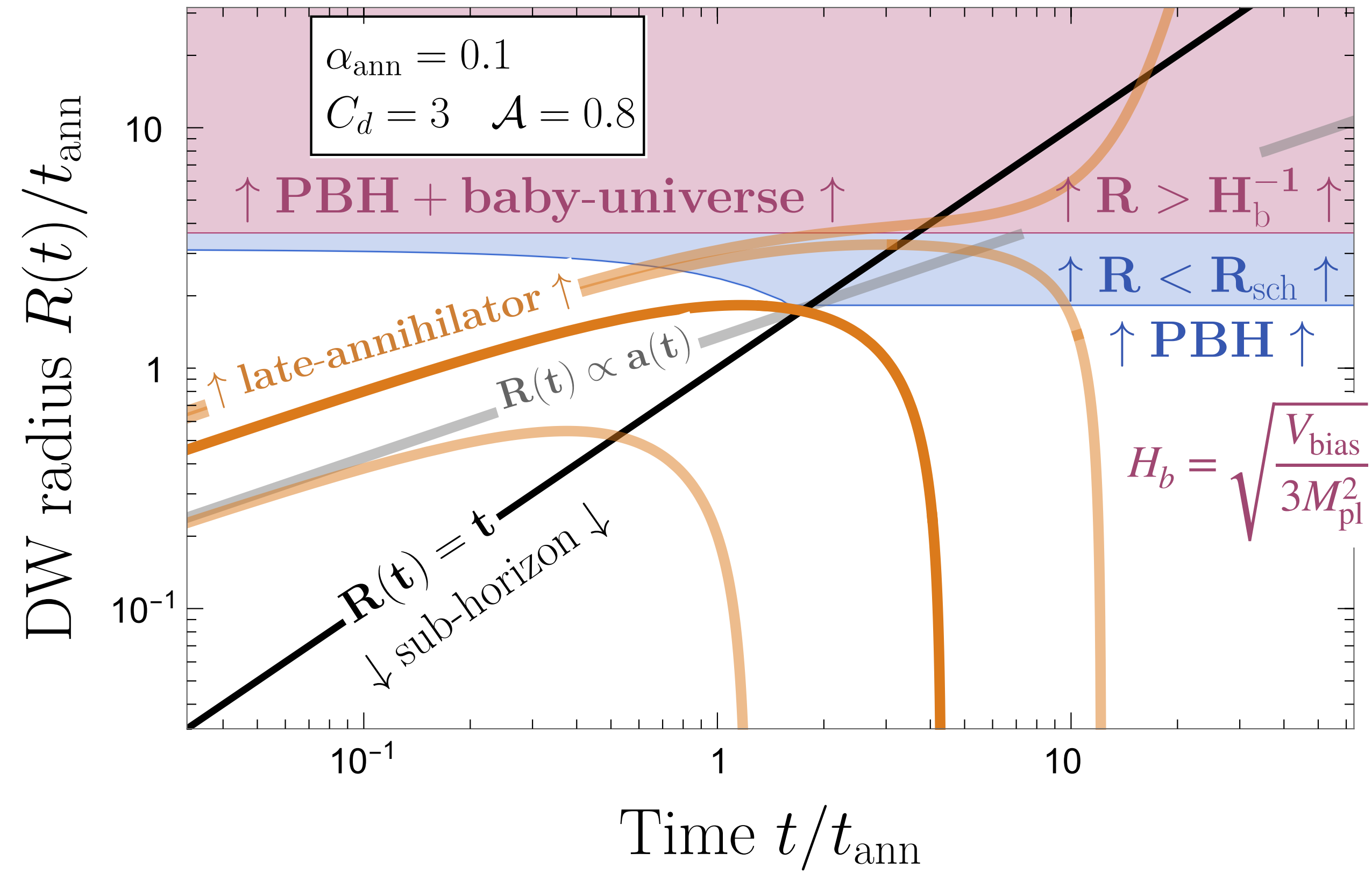
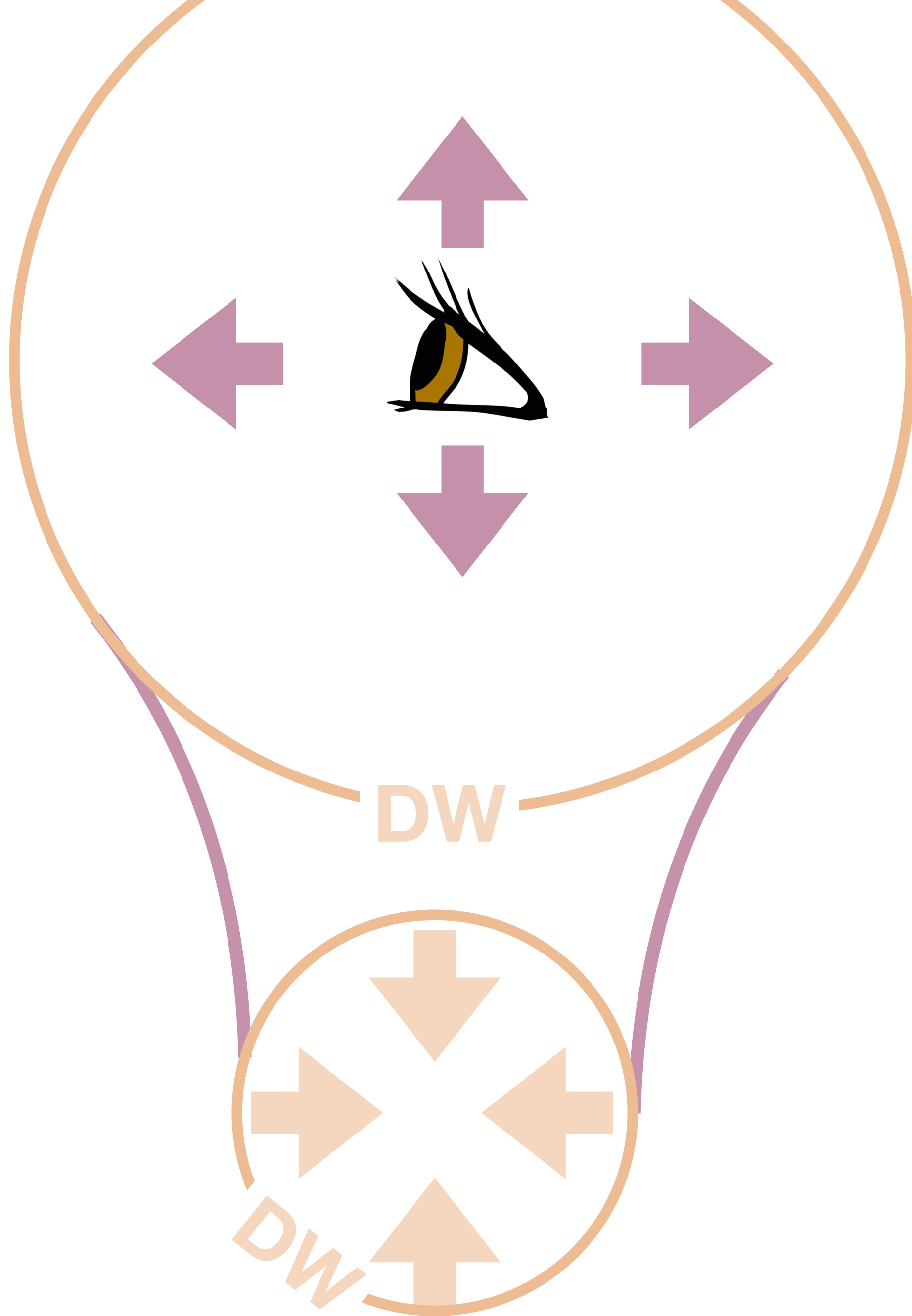
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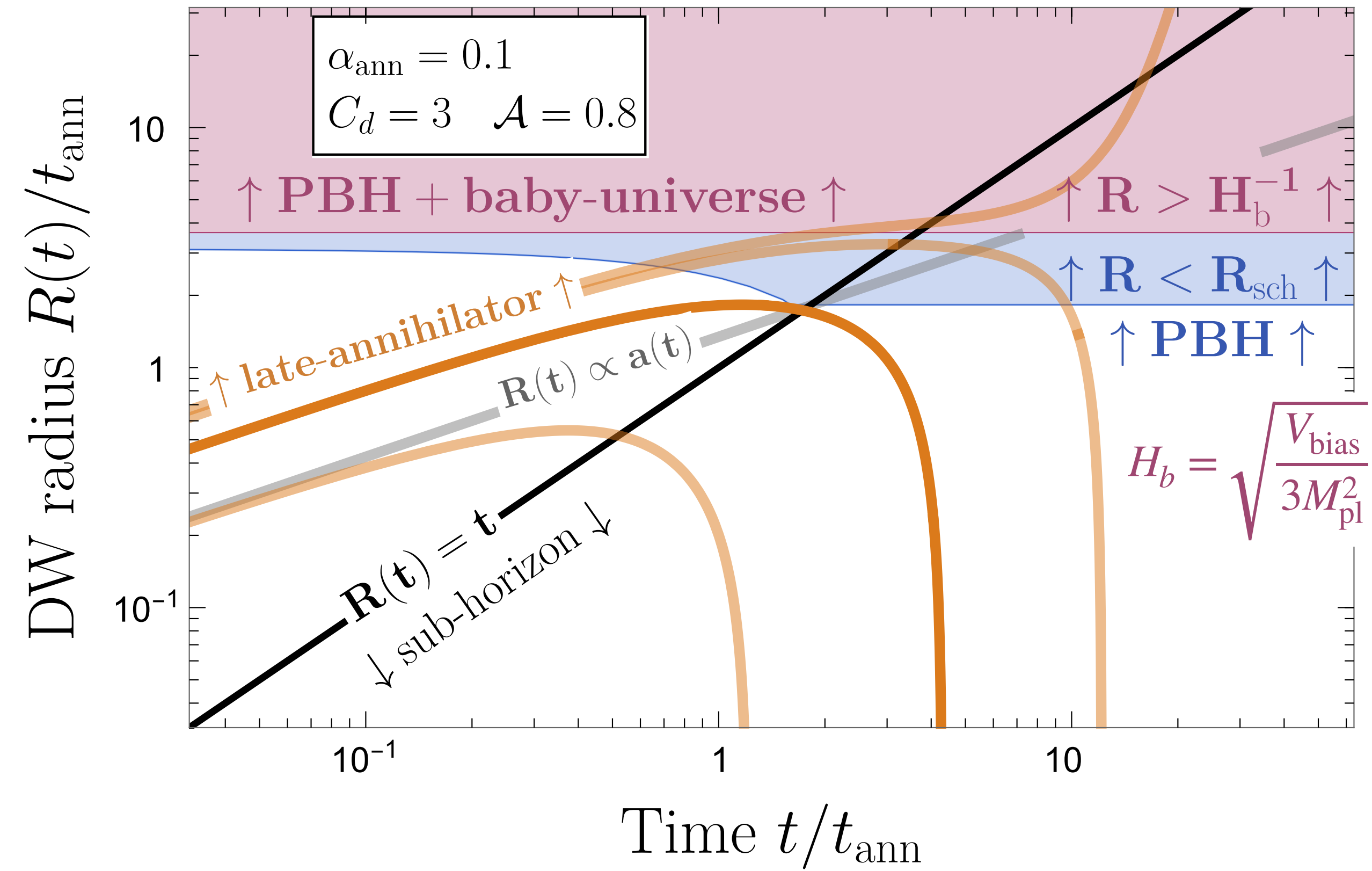
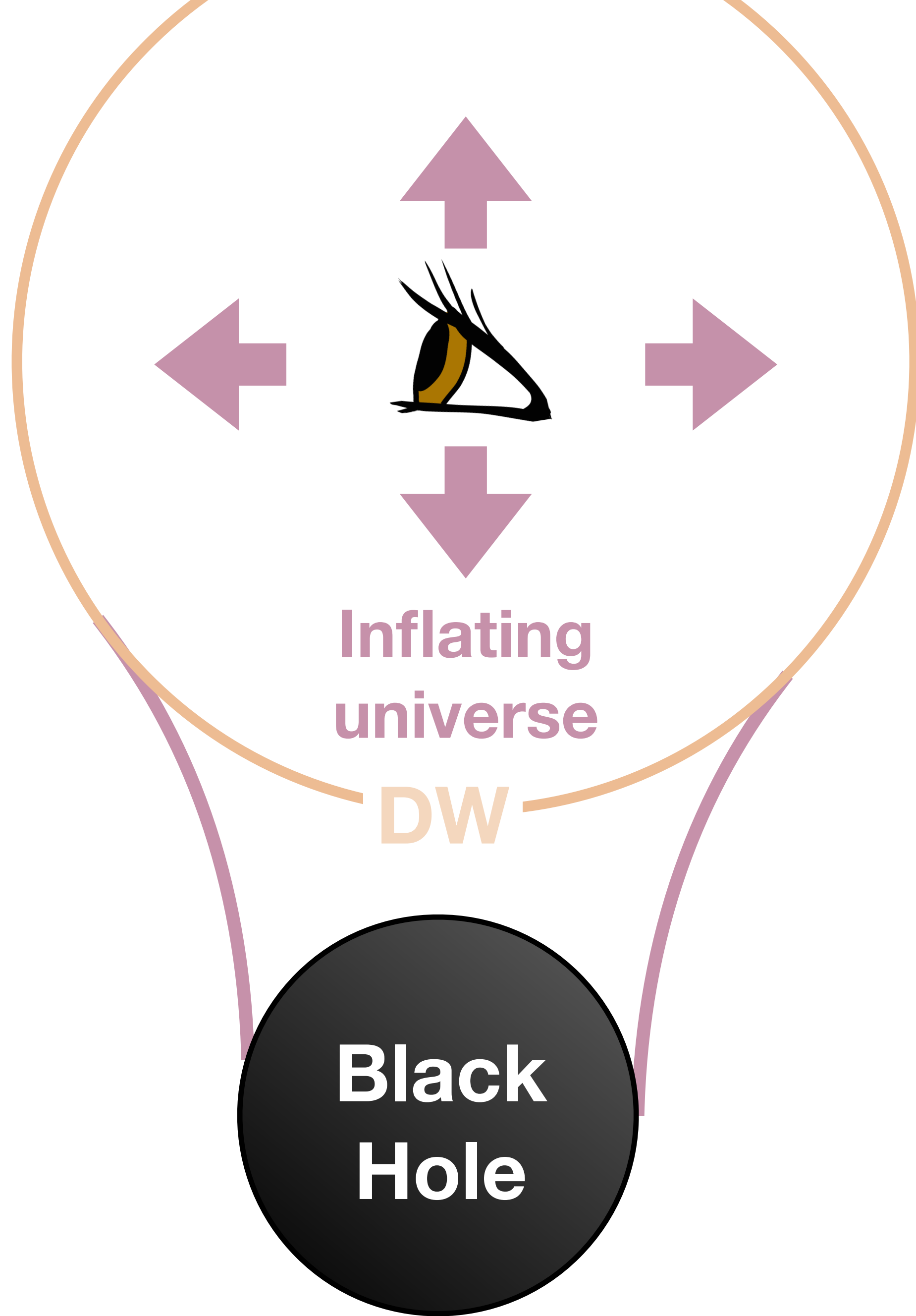




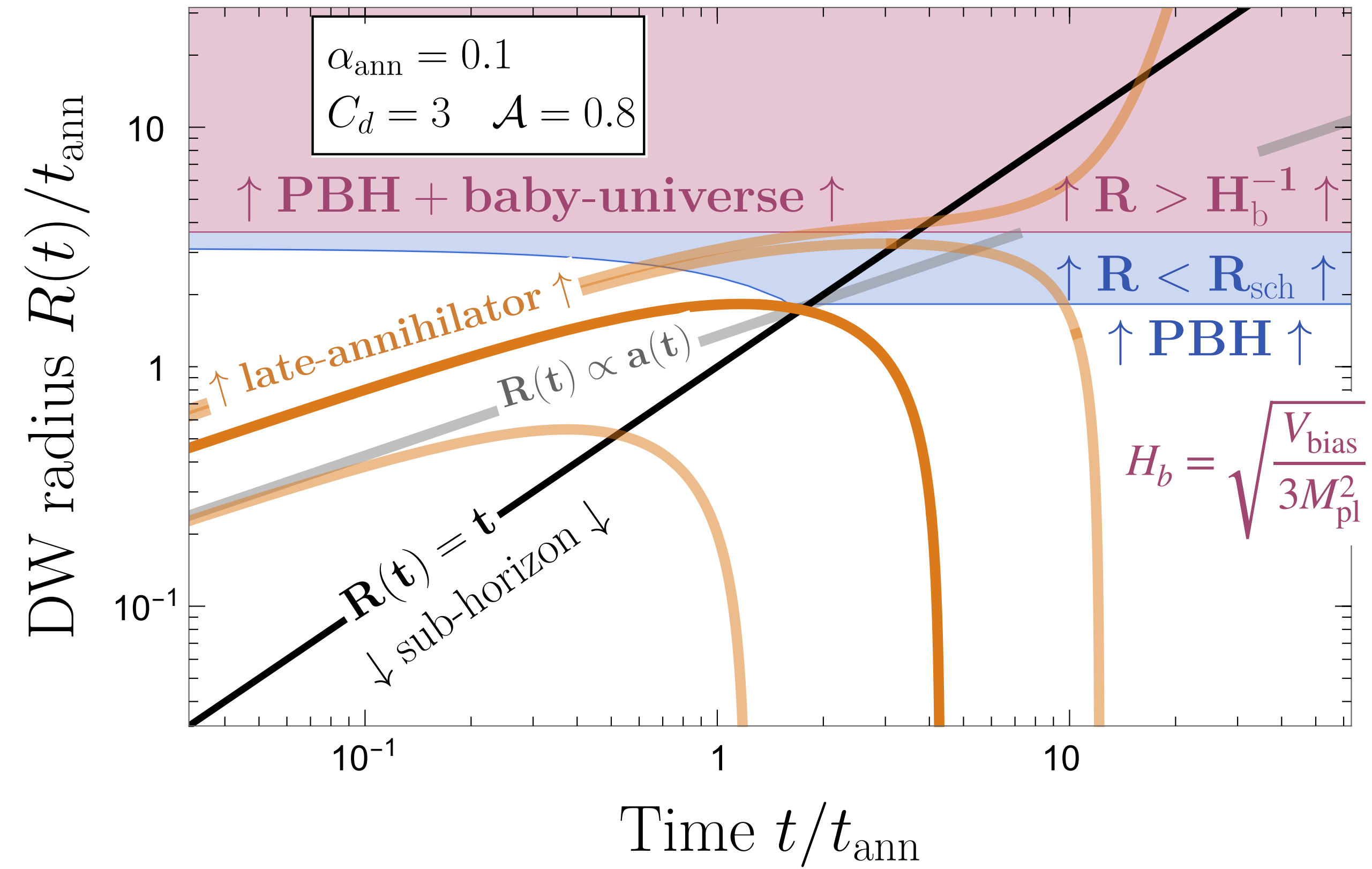
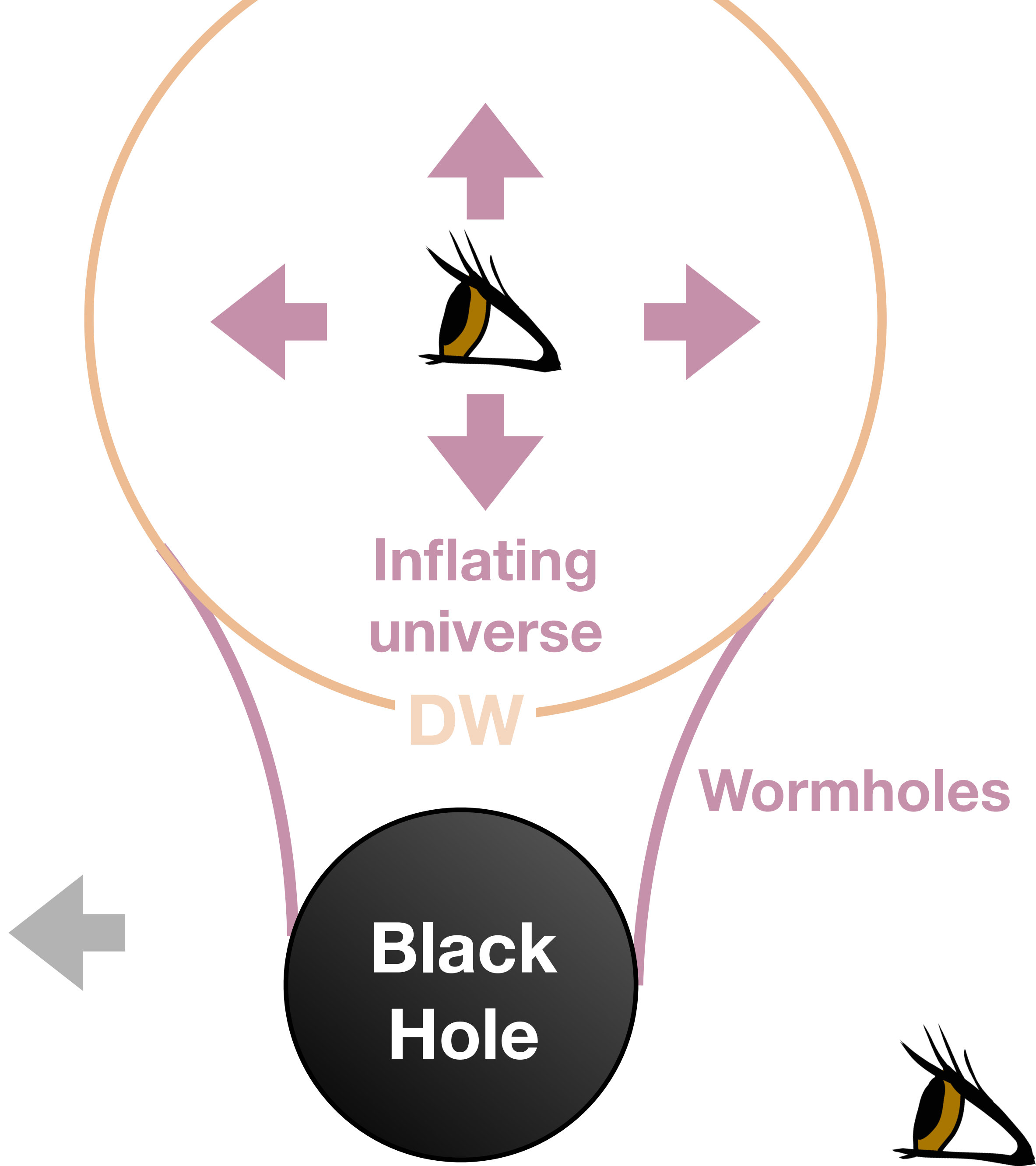






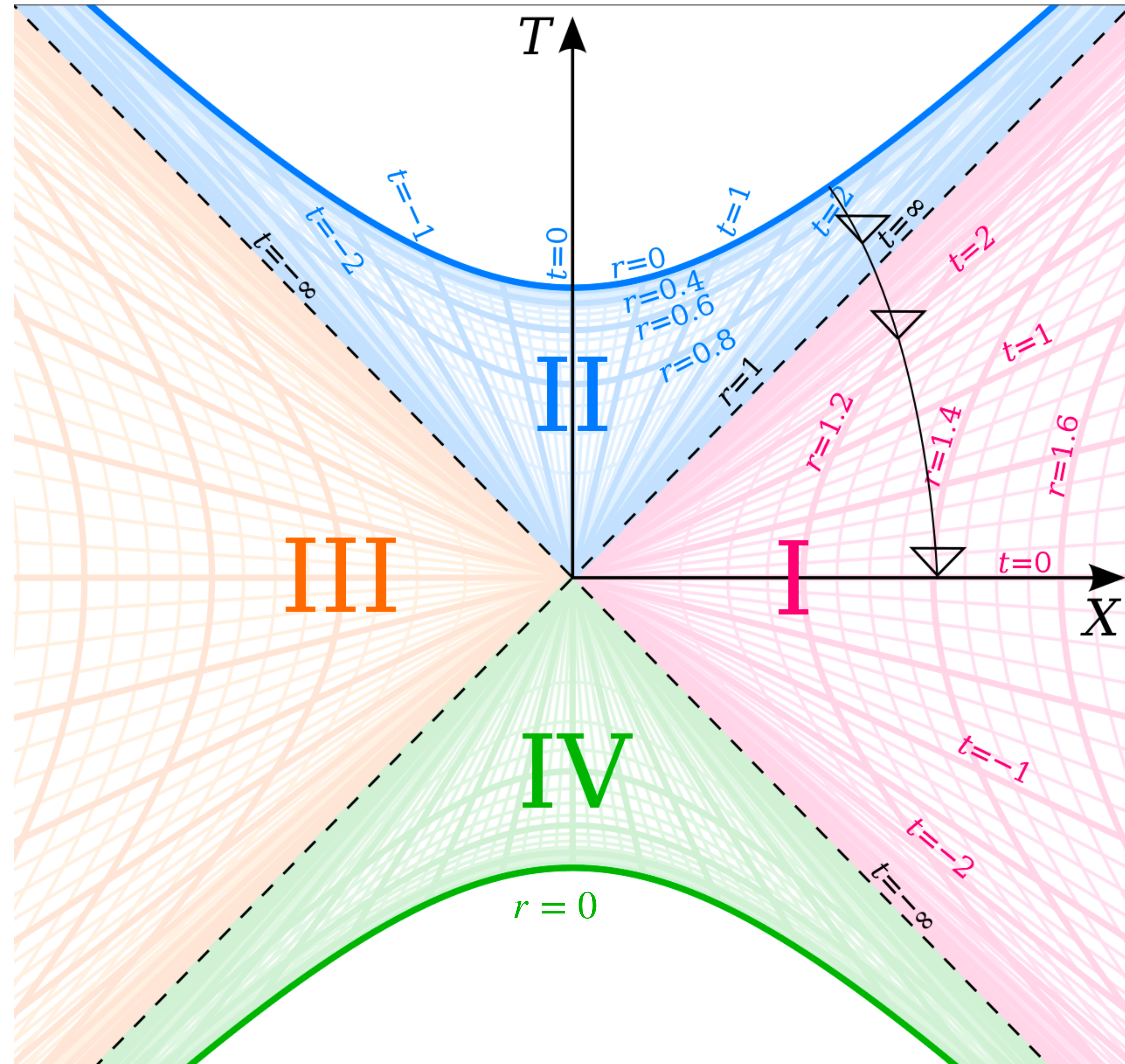






# Space-time diagram

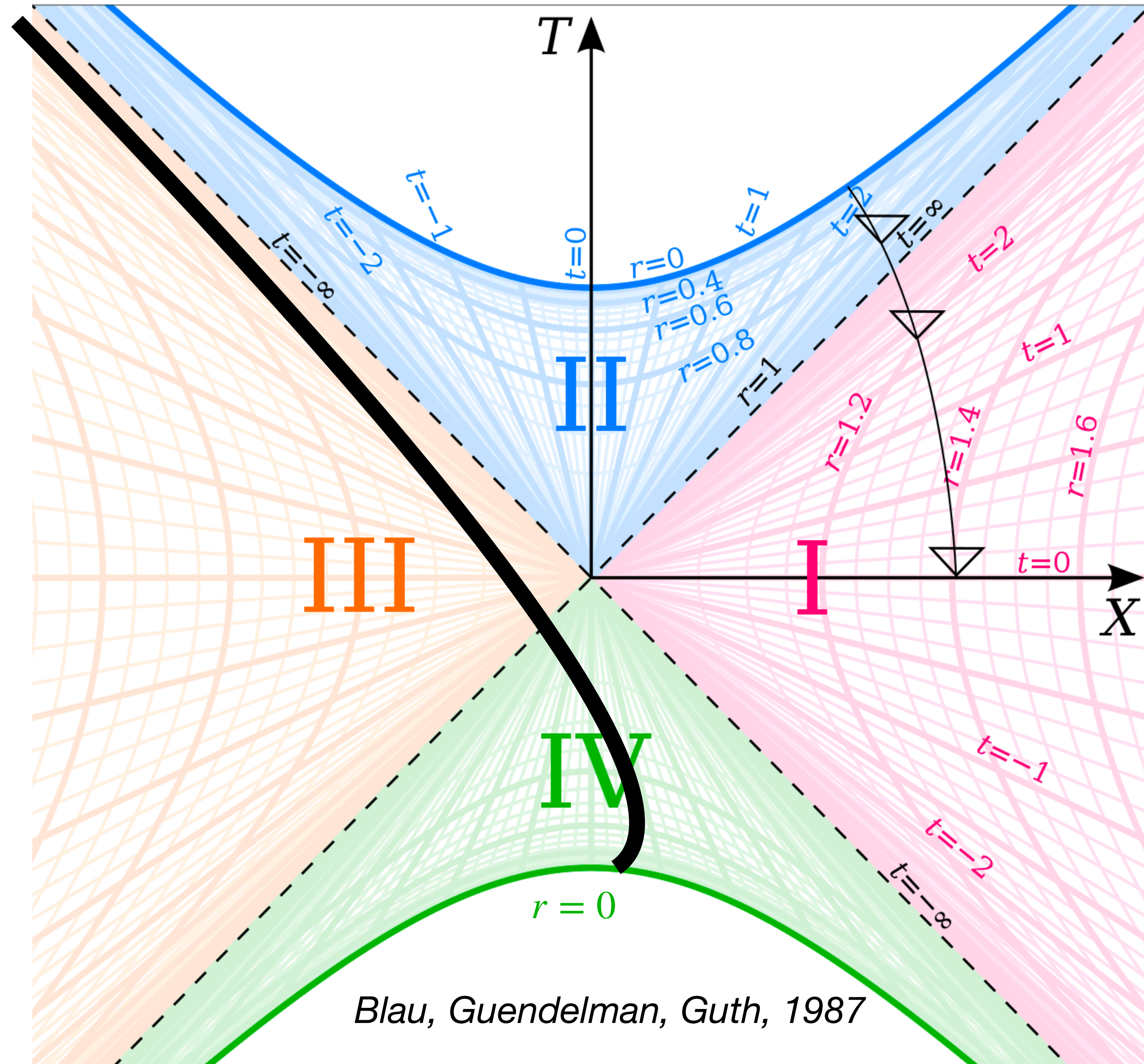
*Kruskal 1960 and Szekeres 1960*





# Space-time diagram

*Kruskal 1960 and Szekeres 1960*

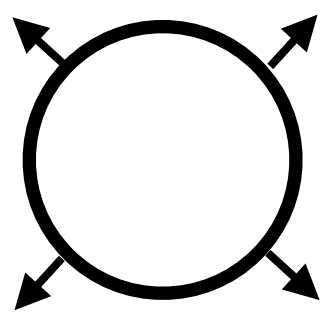
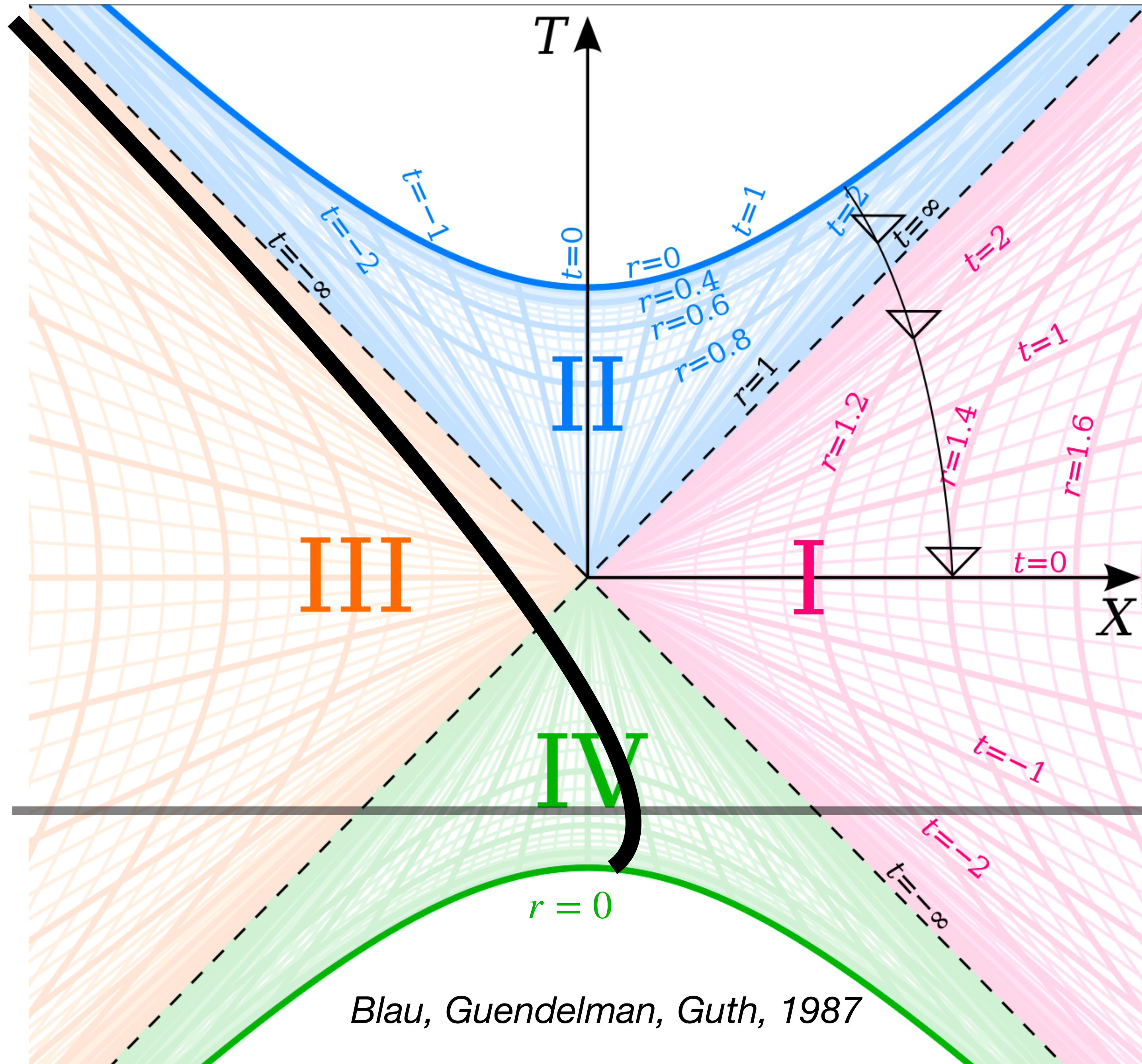


*Blau, Guendelman, Guth, 1987*



# Space-time diagram

*Kruskal 1960 and Szekeres 1960*



Expanding DW

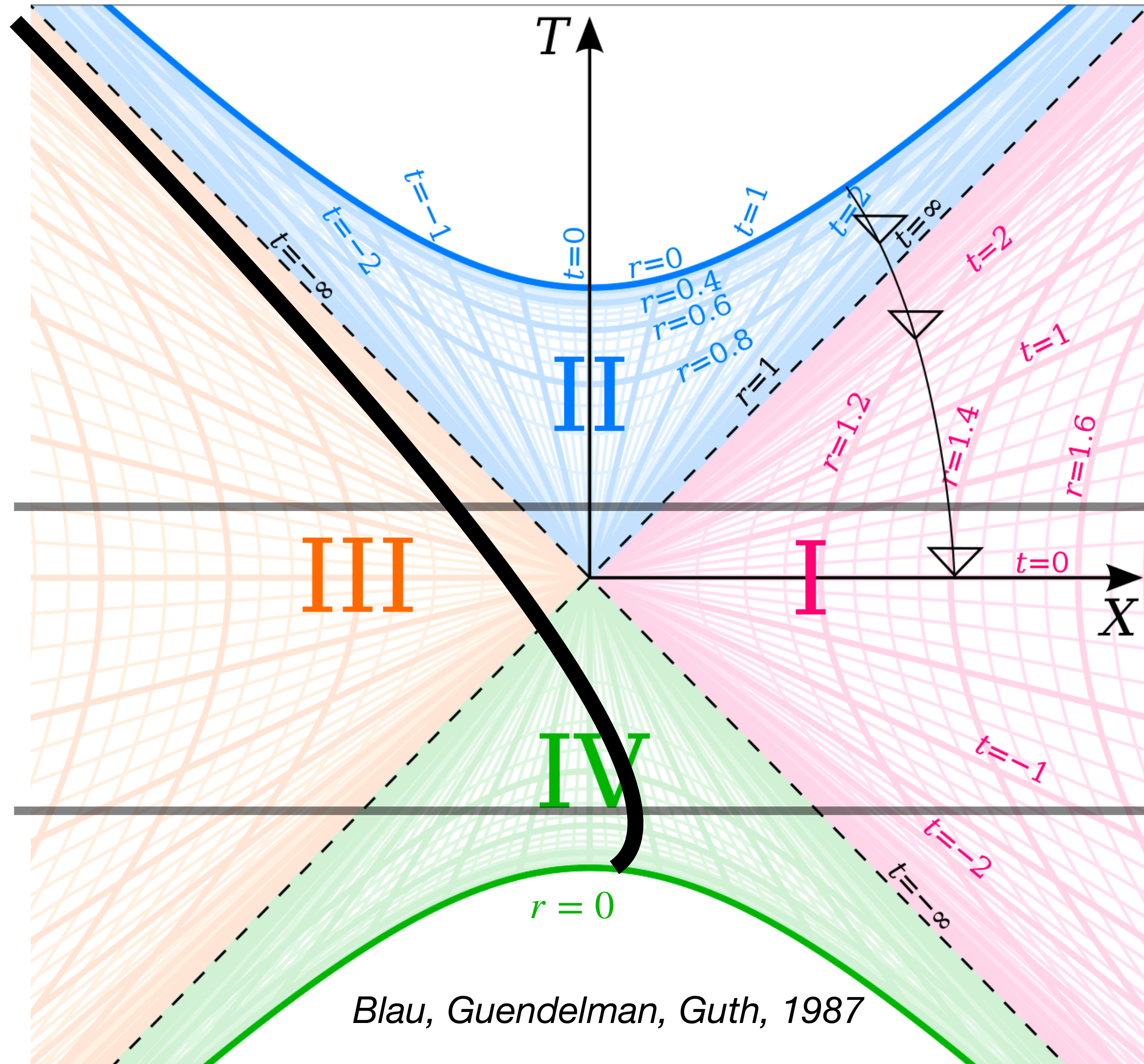
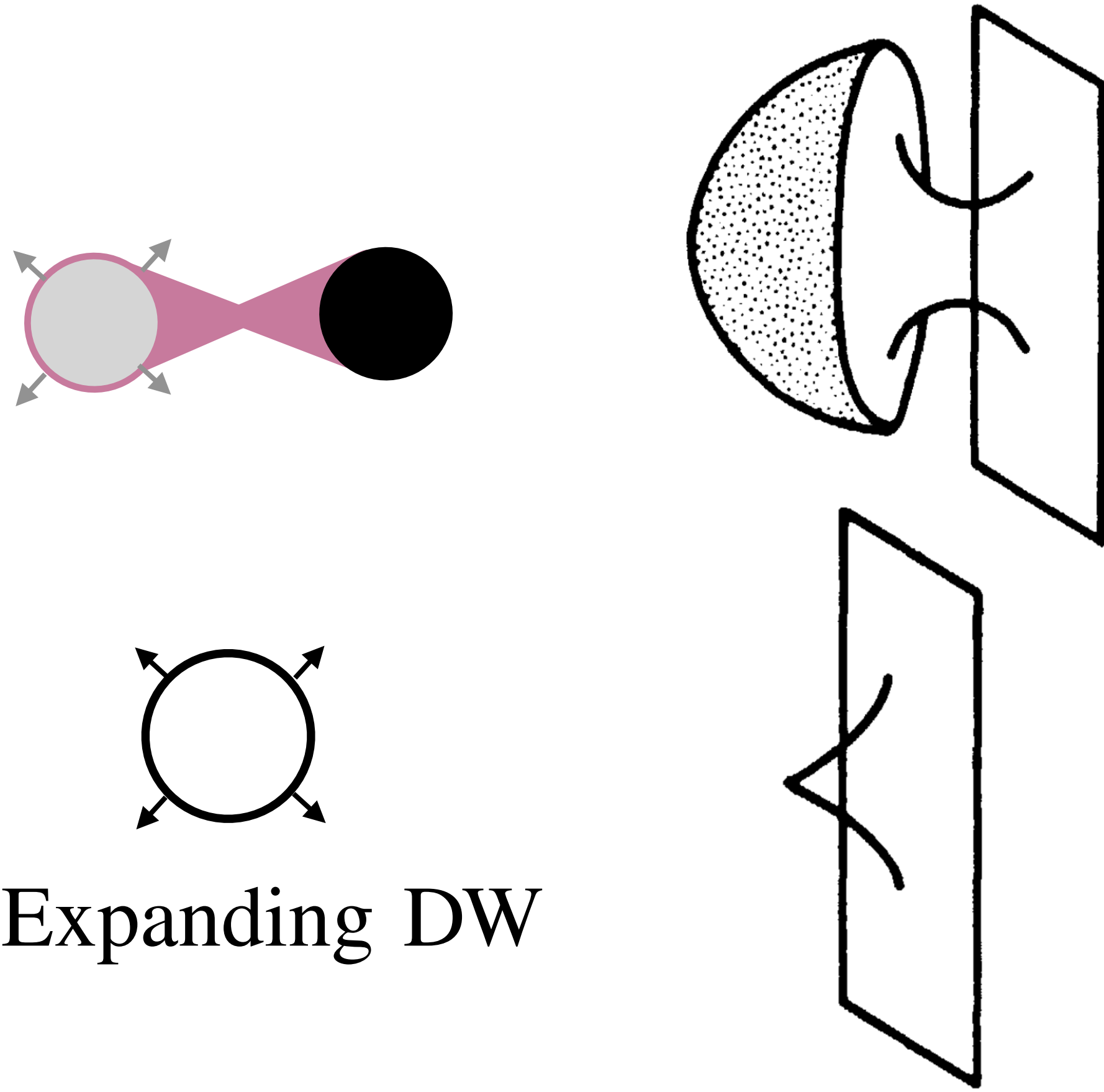


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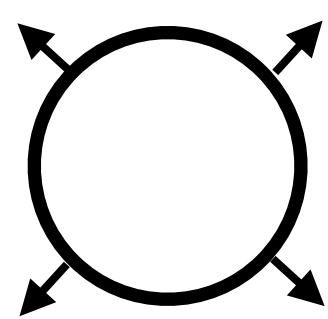
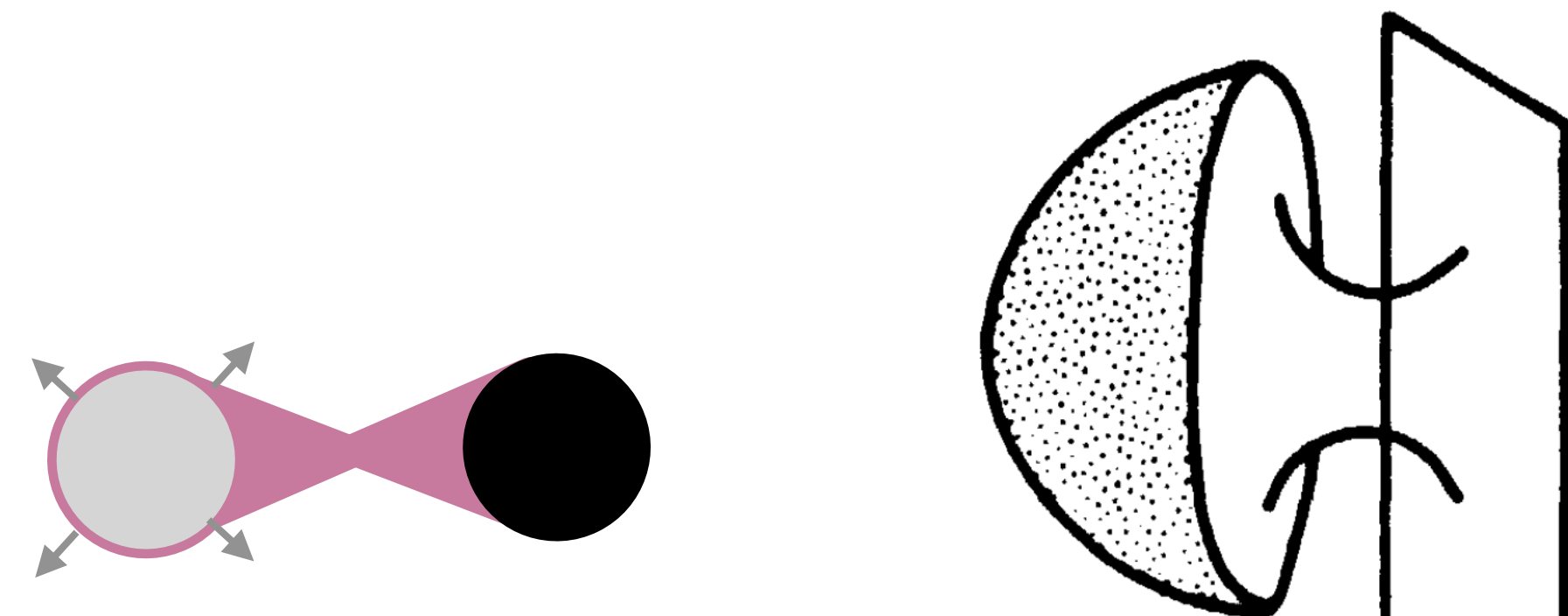
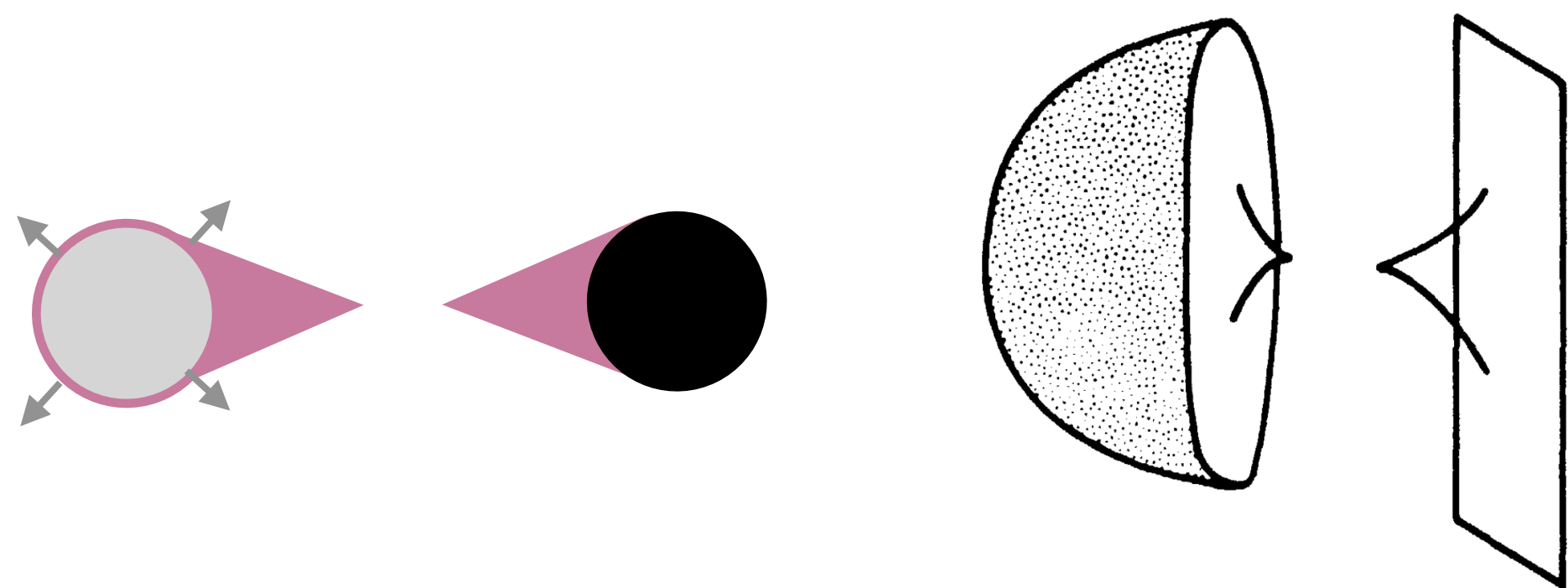
# Space-time diagram

*Kruskal 1960 and Szekeres 1960*



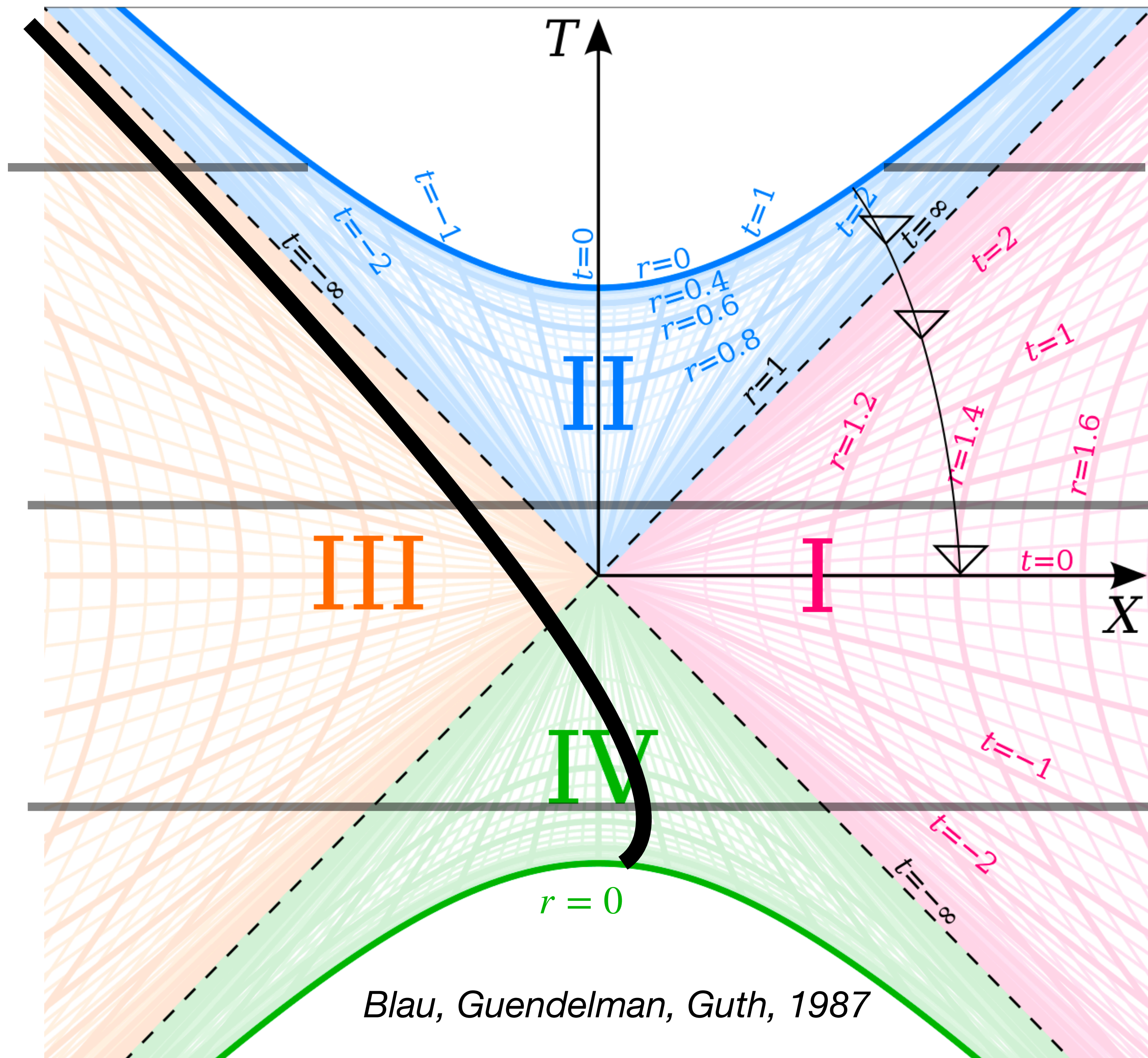


Space-time diagram



Expanding DW

Kruskal 1960 and Szekeres 1960



Blau, Guendelman, Guth, 1987



