Primordial black holes as dark matter in galaxies

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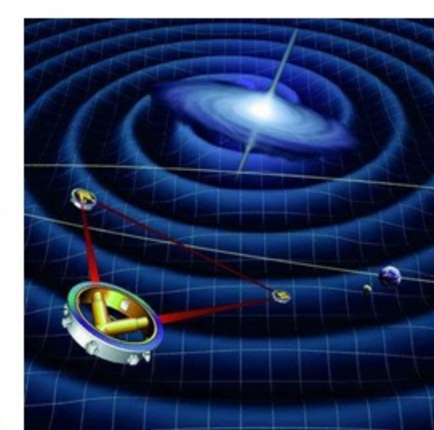
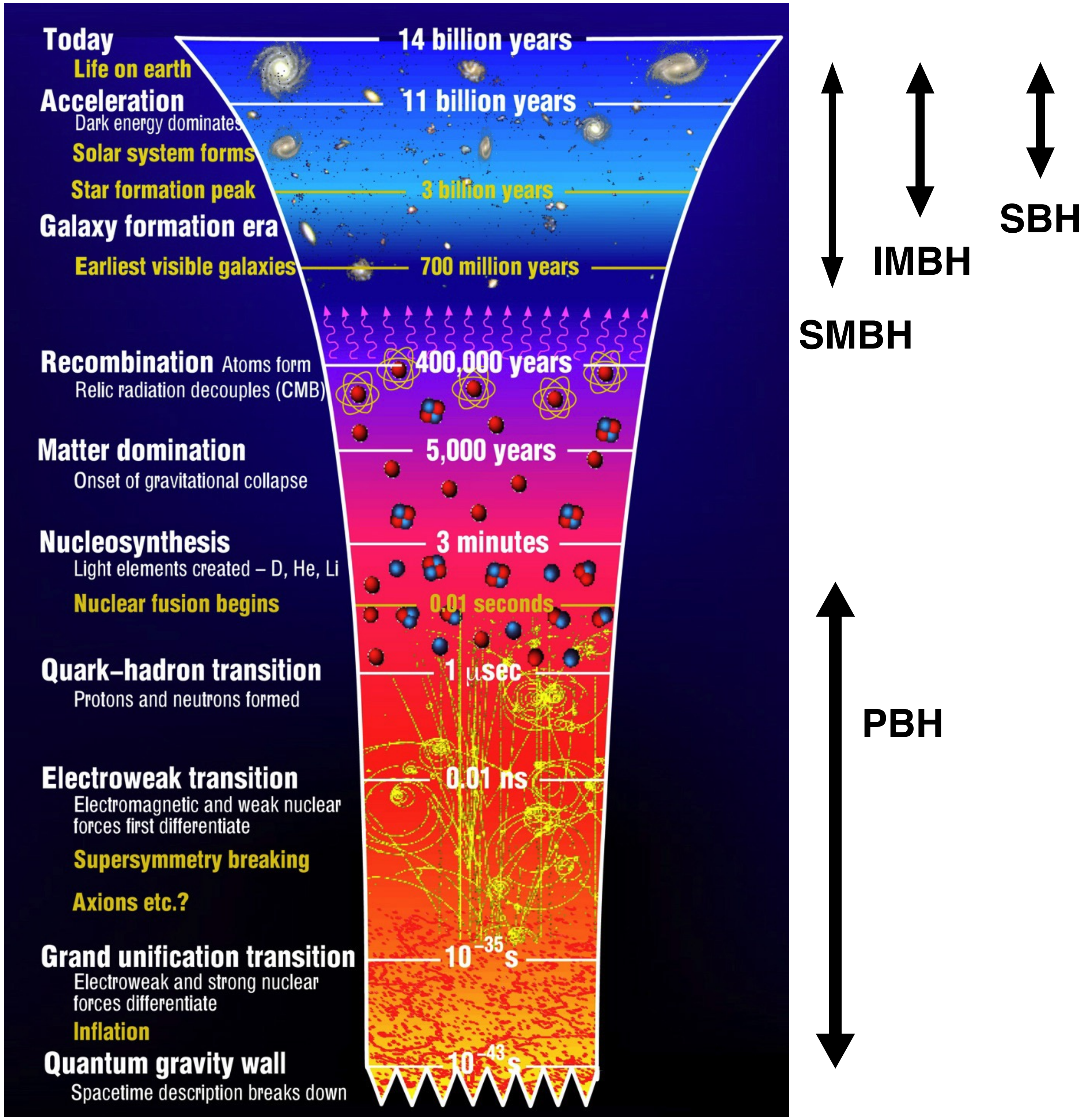


Black holes:
Types

- Stellar black hole (**SBH**)
  - –
- Intermediate-mass black hole (**IMBH**)
  - –
- Supermassive black hole (**SMBH**)
  - –
- Primordial black hole (**PBH**)
  - –



credits: ctc uk

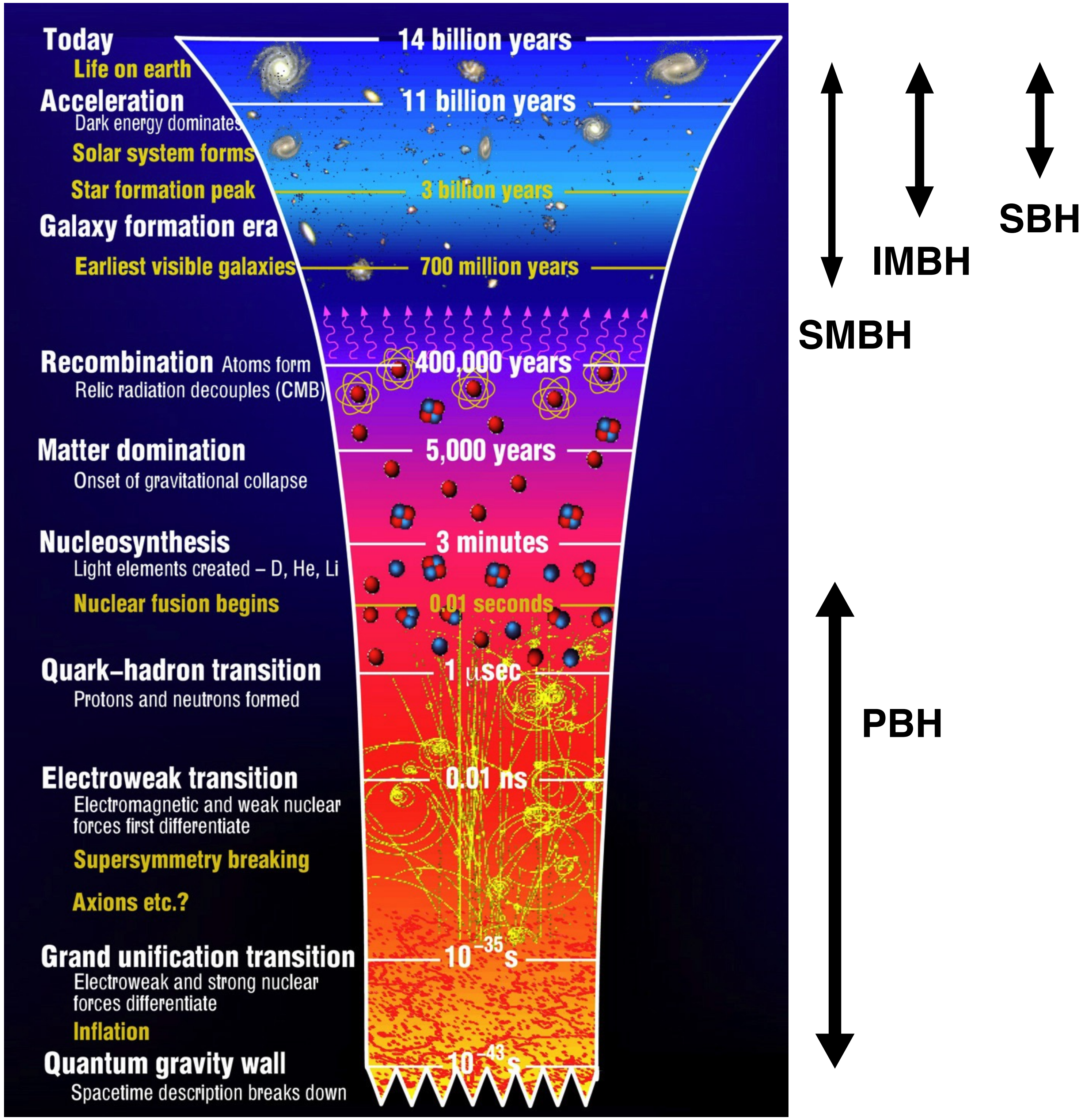
Black holes:
Origins

- Stellar black hole (**SBH**)
  Galaxy fortmation era

- Intermediate-mass black hole (**IMBH**)
  Galaxy fortmation era

- Supermassive black hole (**SMBH**)
  Galaxy fortmation era

- Primordial black hole (**PBH**)
  Early Universe



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Black holes:
Observed or theoretically predicted?

- Stellar black hole (**SBH**)
  -
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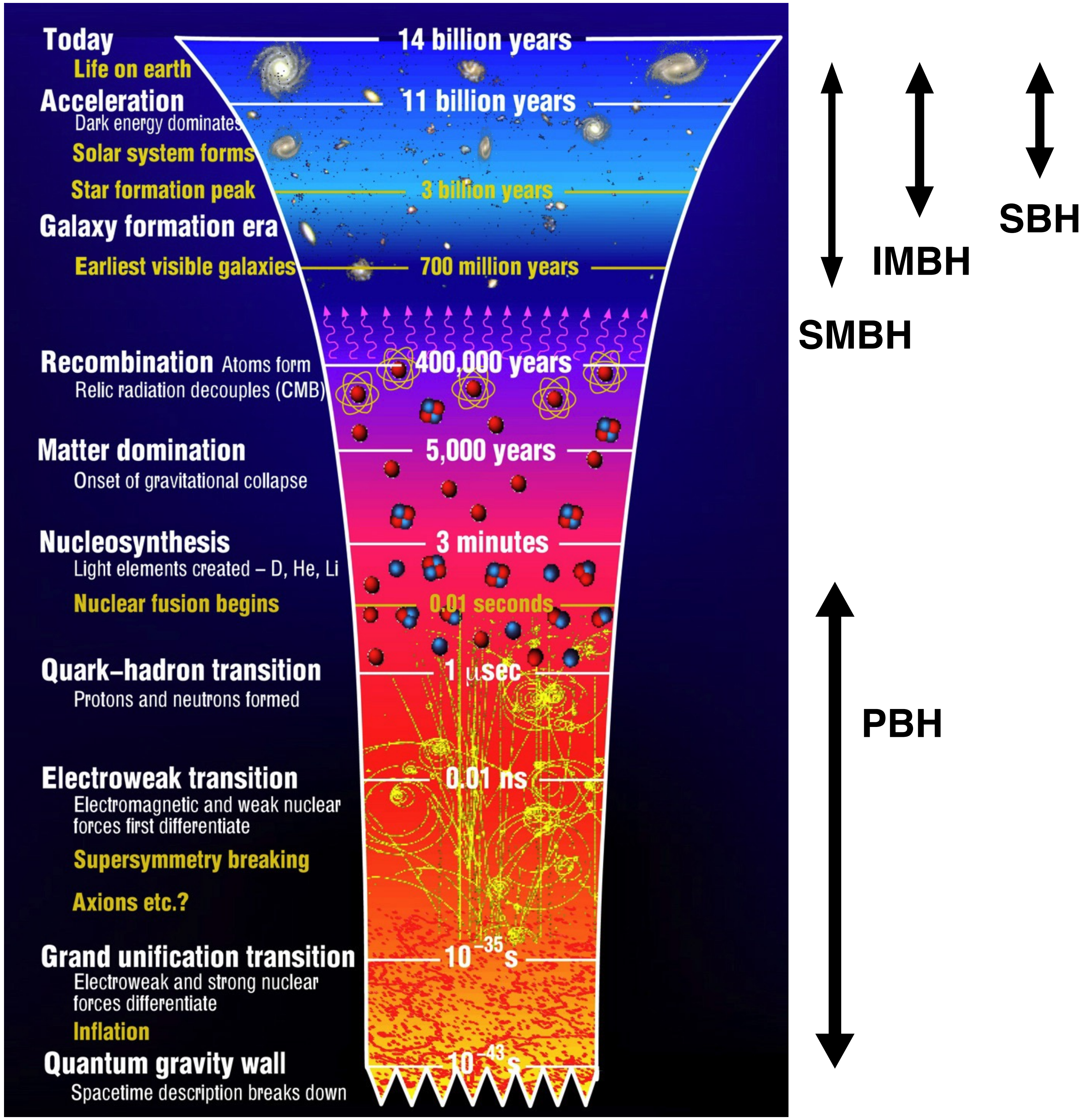

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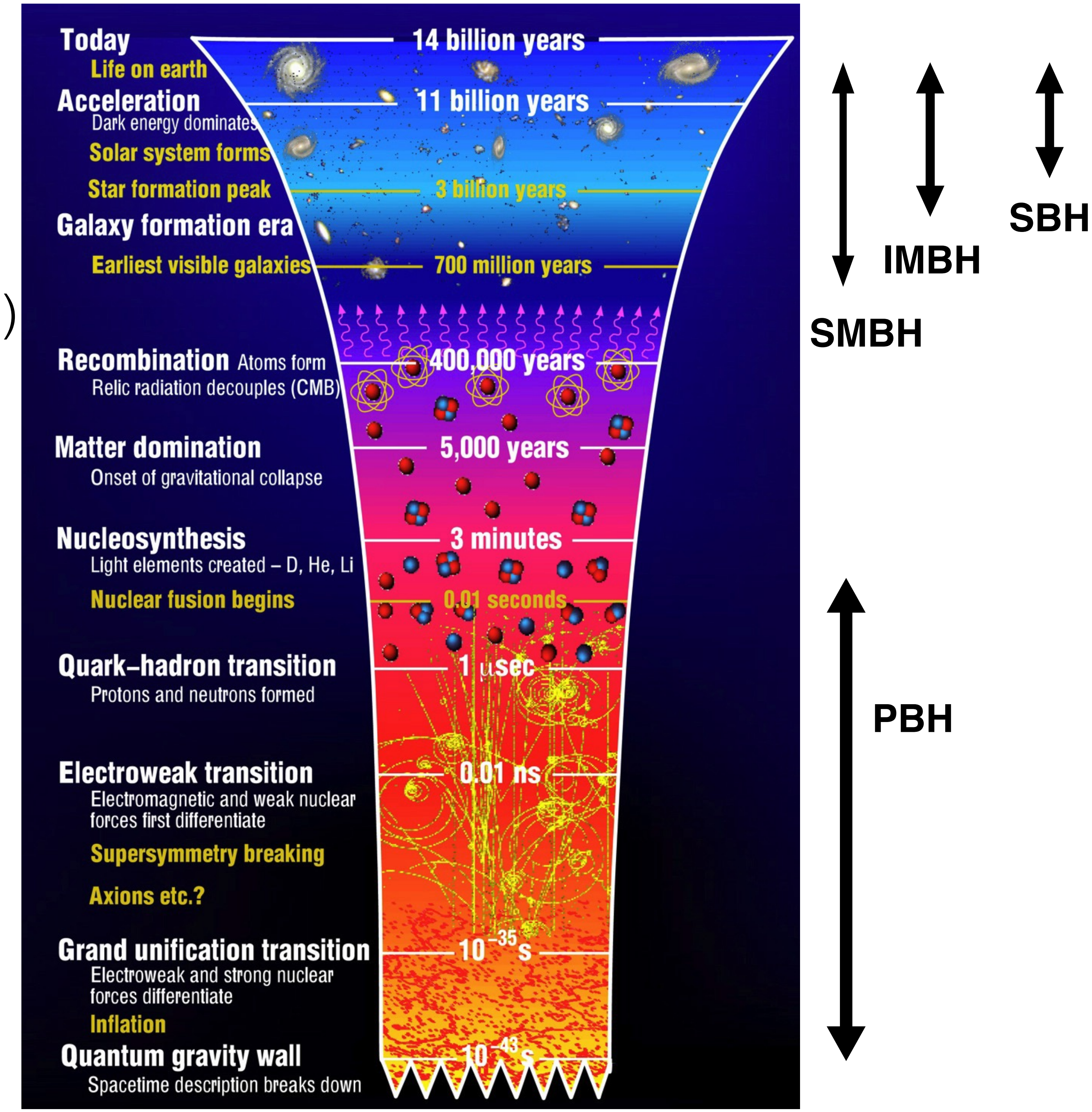

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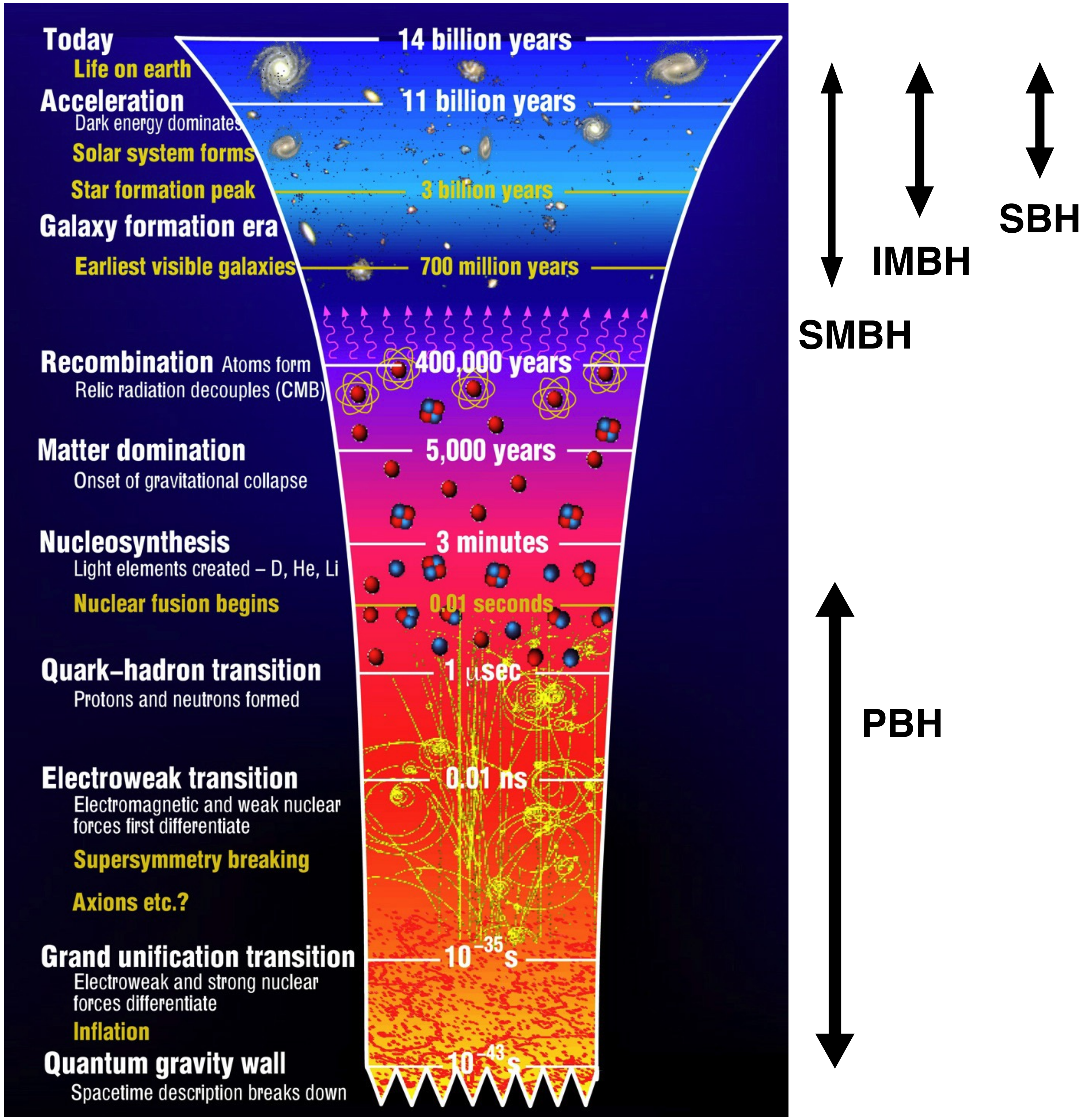

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Black holes:
Mass range

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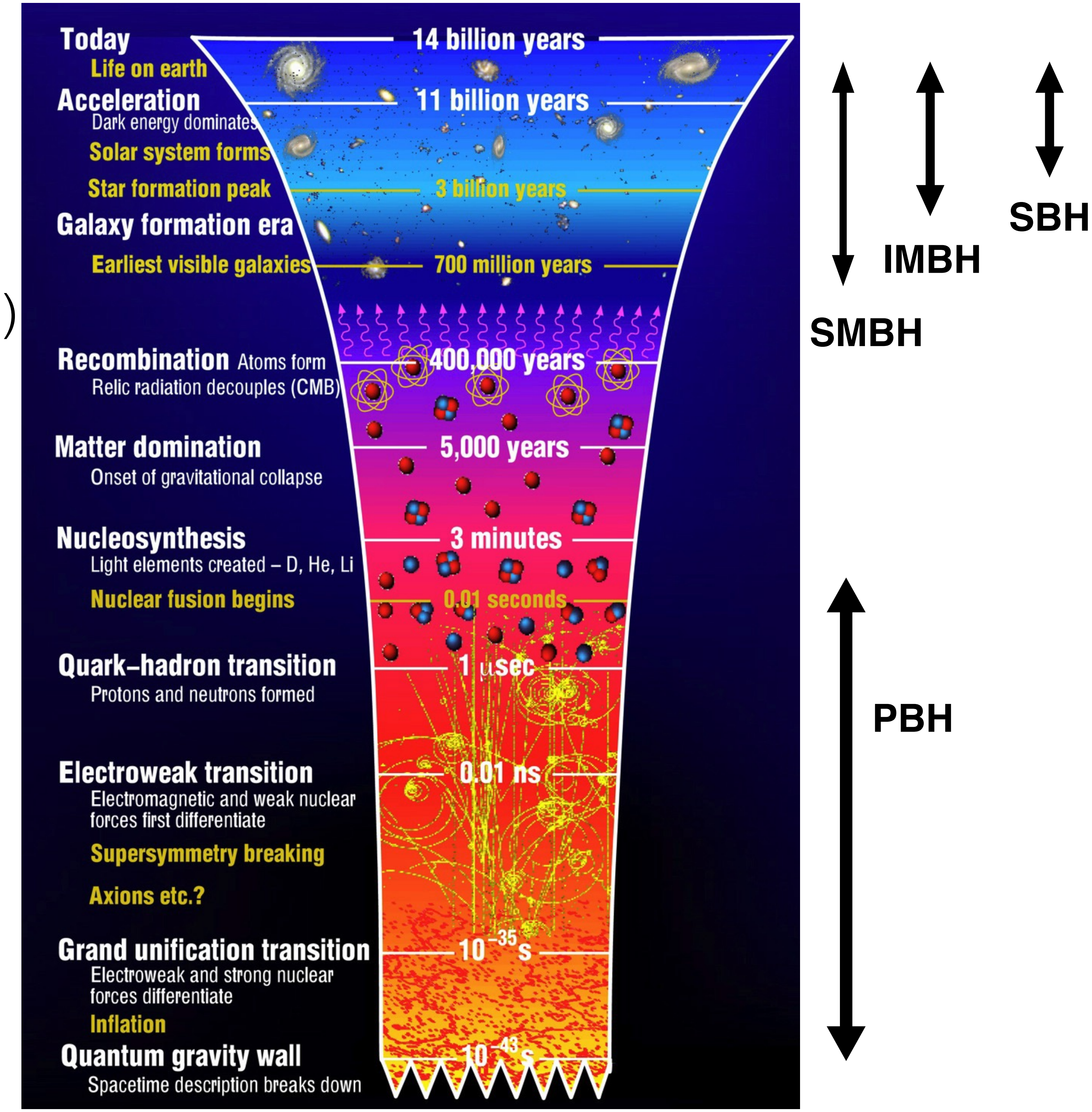

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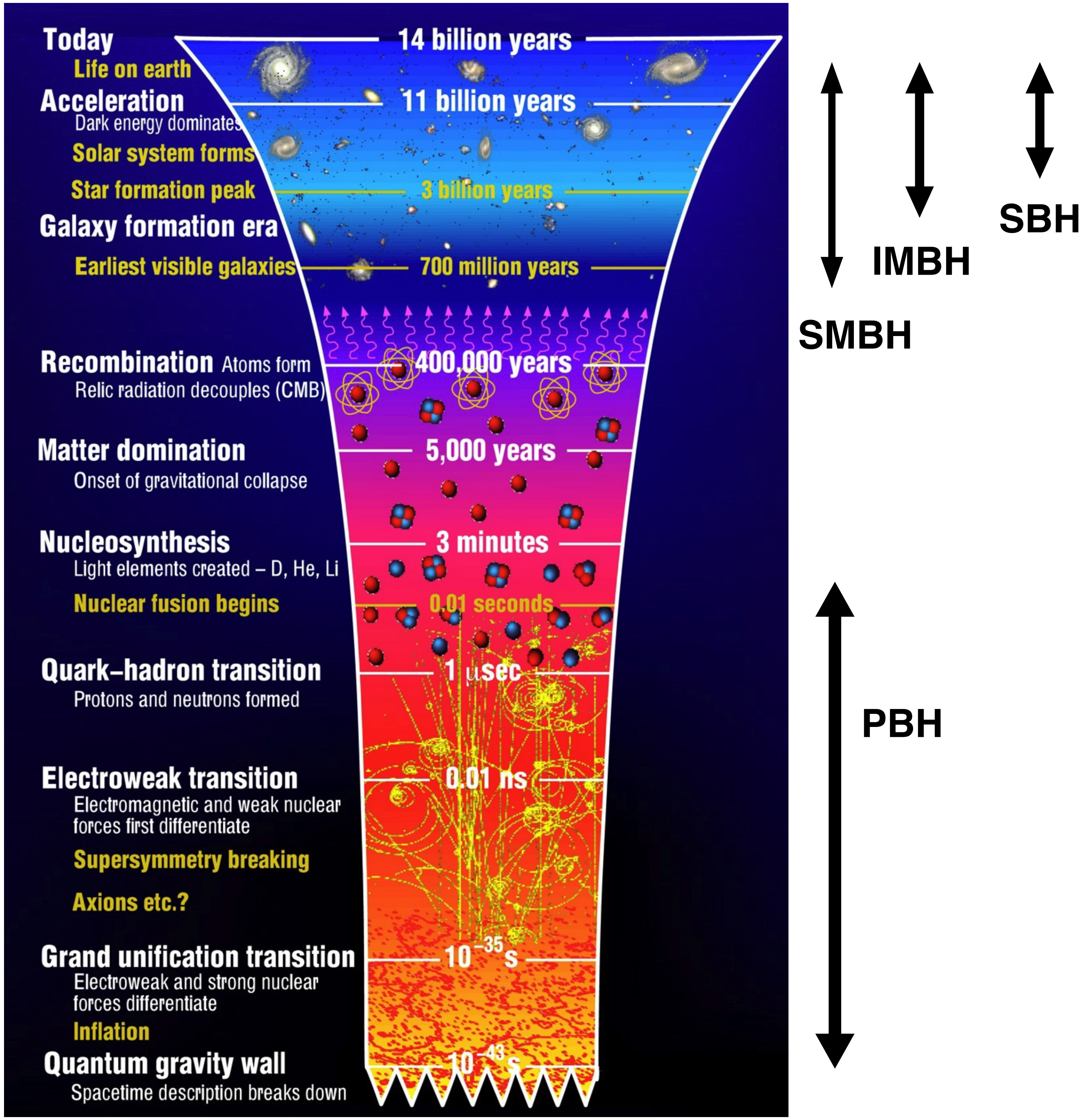
Black holes:
Mass range

- Stellar black hole (**SBH**)
  10 - 30 $M_\odot$
- Intermediate-mass black hole (**IMBH**)
  10^3 - 10^5 $M_\odot$
- Supermassive black hole (**SMBH**)
  10^6 - 10^9 $M_\odot$
- Primordial black hole (**PBH**)
  ? - ? $M_\odot$



credits: ctc uk

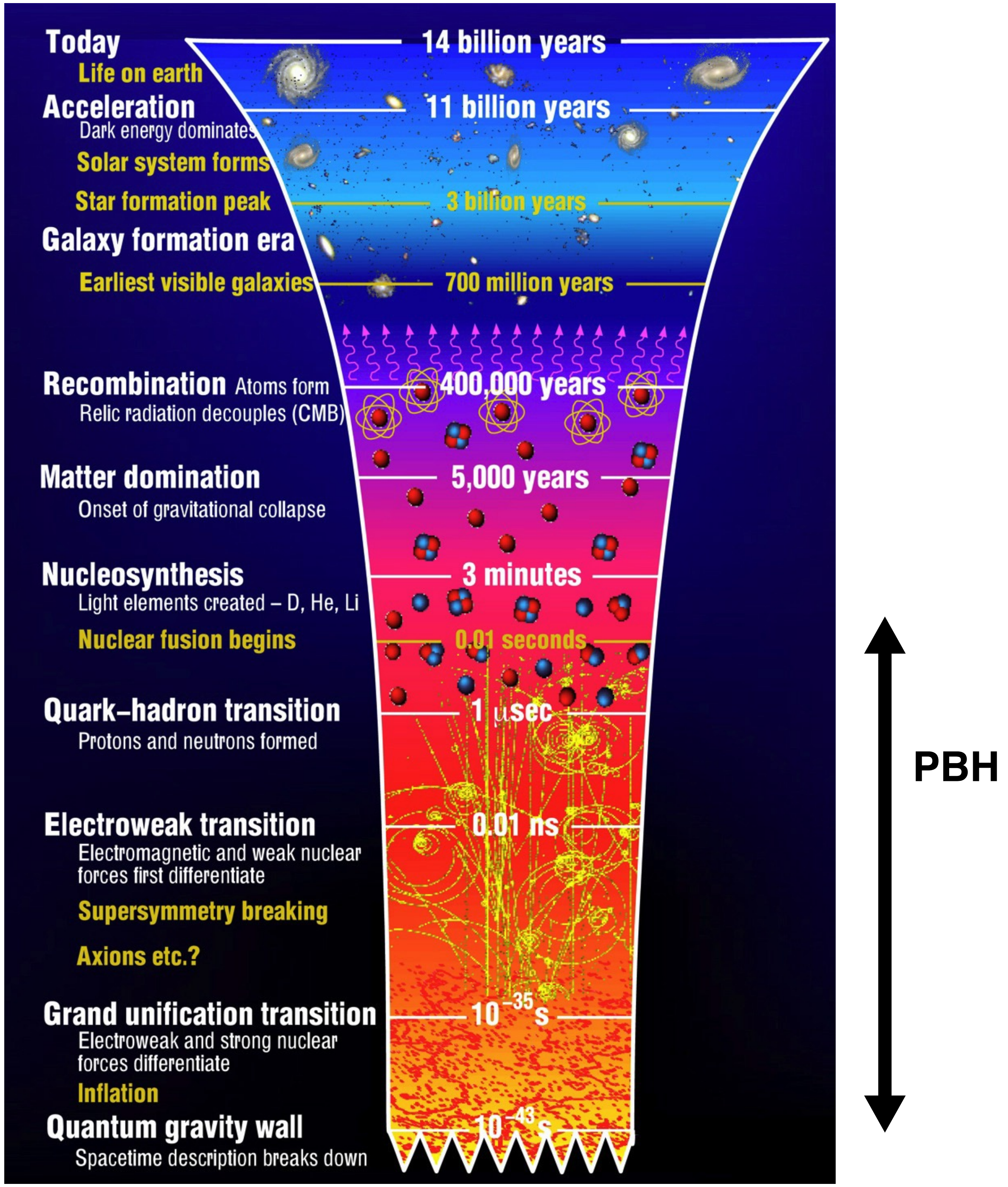
Primordial black holes: Formation

Early Universe epochs:

- Primordial black hole (**PBH**): **? - ? $M_\odot$**

$$M_{PBH} \sim 5\times10^{-19}\left(\frac{t}{10^{-23}s}\right)M_\odot$$

- Primordial black hole (**PBH**): **10^{-33} - 10^{5} $M_\odot$**



Carr & Hawking 1971

credits: ctc uk

Primordial black holes: Evaporation

- Primordial black hole (**PBH**): **10^{-33} - 10^{5} $M_\odot$**

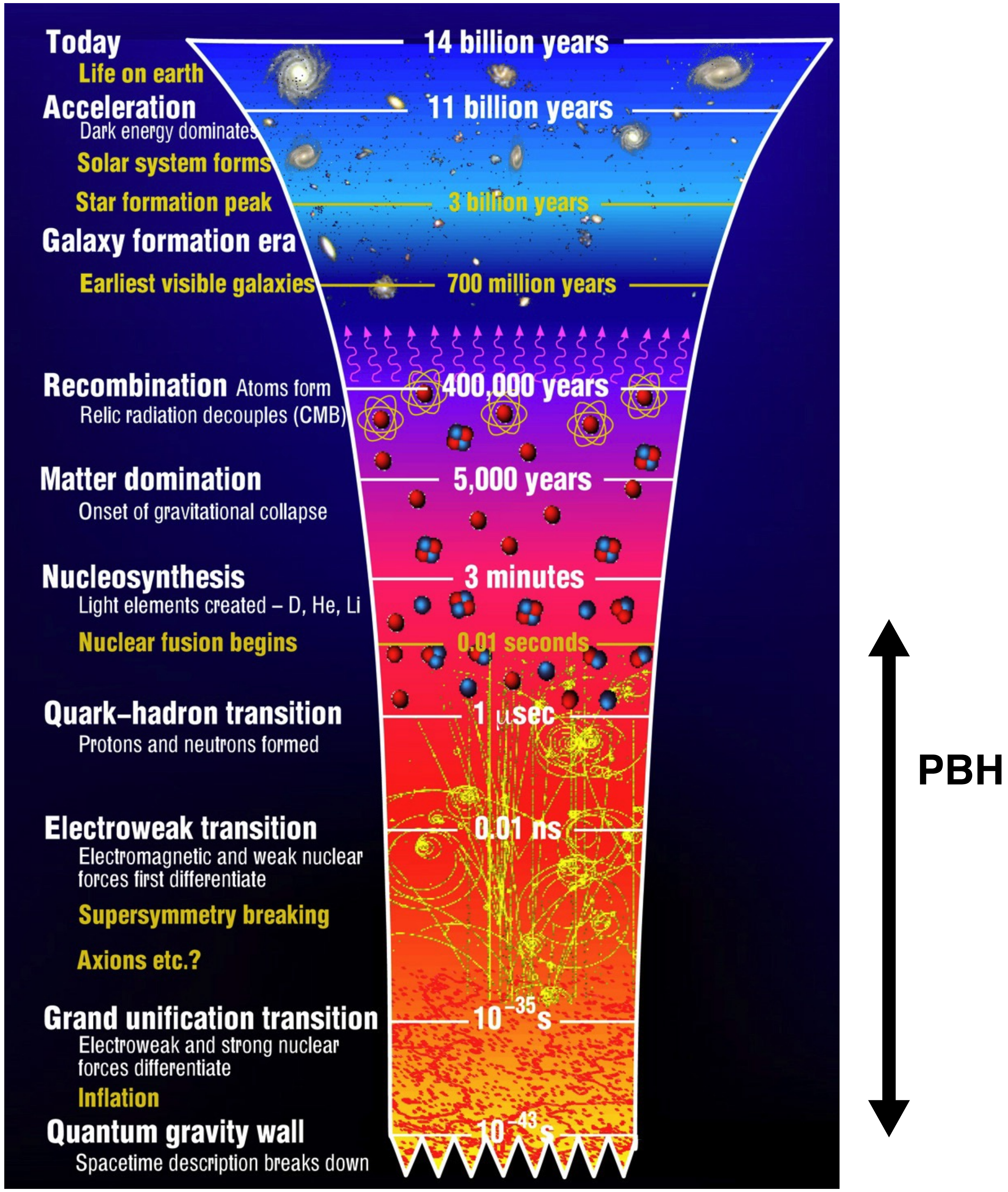
$$T_{evap}^{1/3} = 1.5 \times 10^{18} \frac{M_{PBH}}{M_\odot} Gyr$$

$$T_{evap} \geq 14 Gyr$$

$$\rightleftharpoons$$

$$M_{PBH} \geq 10^{-18} M_\odot$$

- Primordial black hole (**PBH**): **10^{-18} - 10^{5} $M_\odot$**



Hawking 1974

credits: ctc uk

Black holes:
Mass range

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  10 - 30 $M_\odot$
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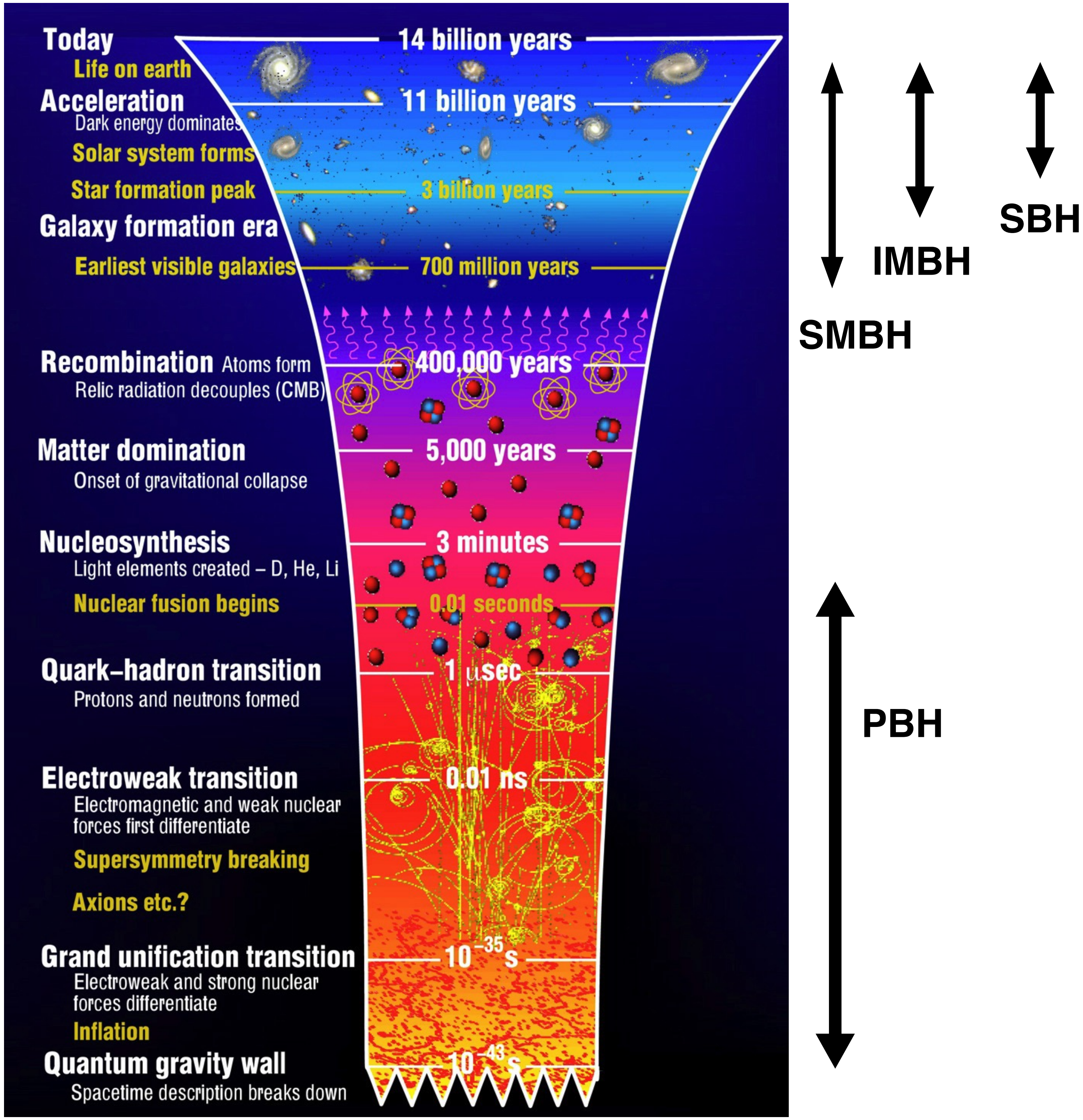

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Nature of cold dark matter

Cold dark matter candidates:

- Microscopic → WIMPs such as **Neutralinos**
- Macroscopic → MACHOs such as **PBHs**

Nature of cold dark matter

Cold dark matter candidates:

- Microscopic → WIMPs such as **Axions**
- Macroscopic → MACHOs such as **PBHs**

Nature of cold dark matter

Cold dark matter candidates:

- Microscopic → WIMPs such as **Axions**
- Macroscopic → MACHOs such as **PBHs**

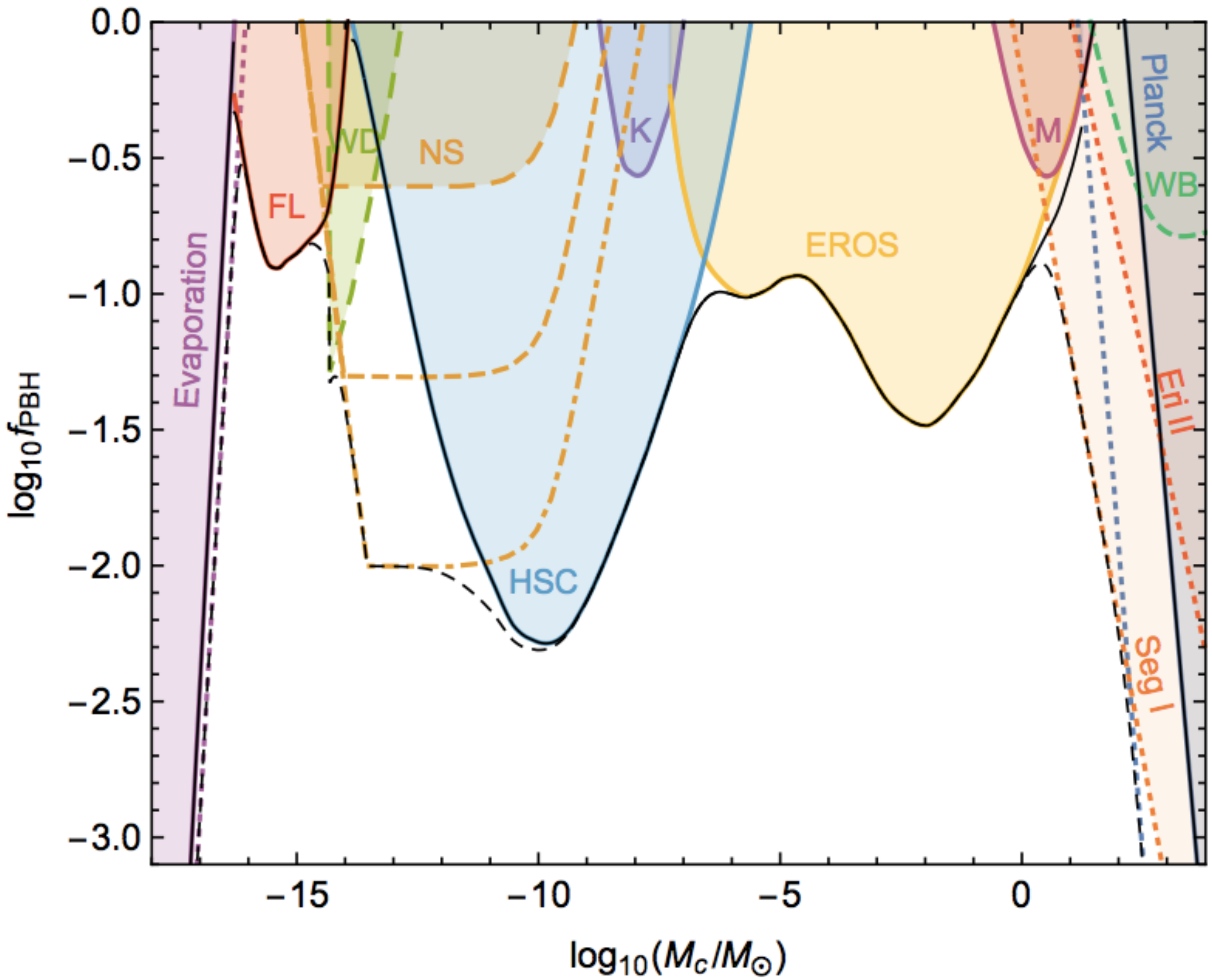
DM being composed of PBHs

$$f = \Omega_{PBH}/\Omega_{DM}$$

Primordial black holes: Mass windows

Two classes of constraints:

- relatively robust —
- less firm - - -



Carr et al. 2017

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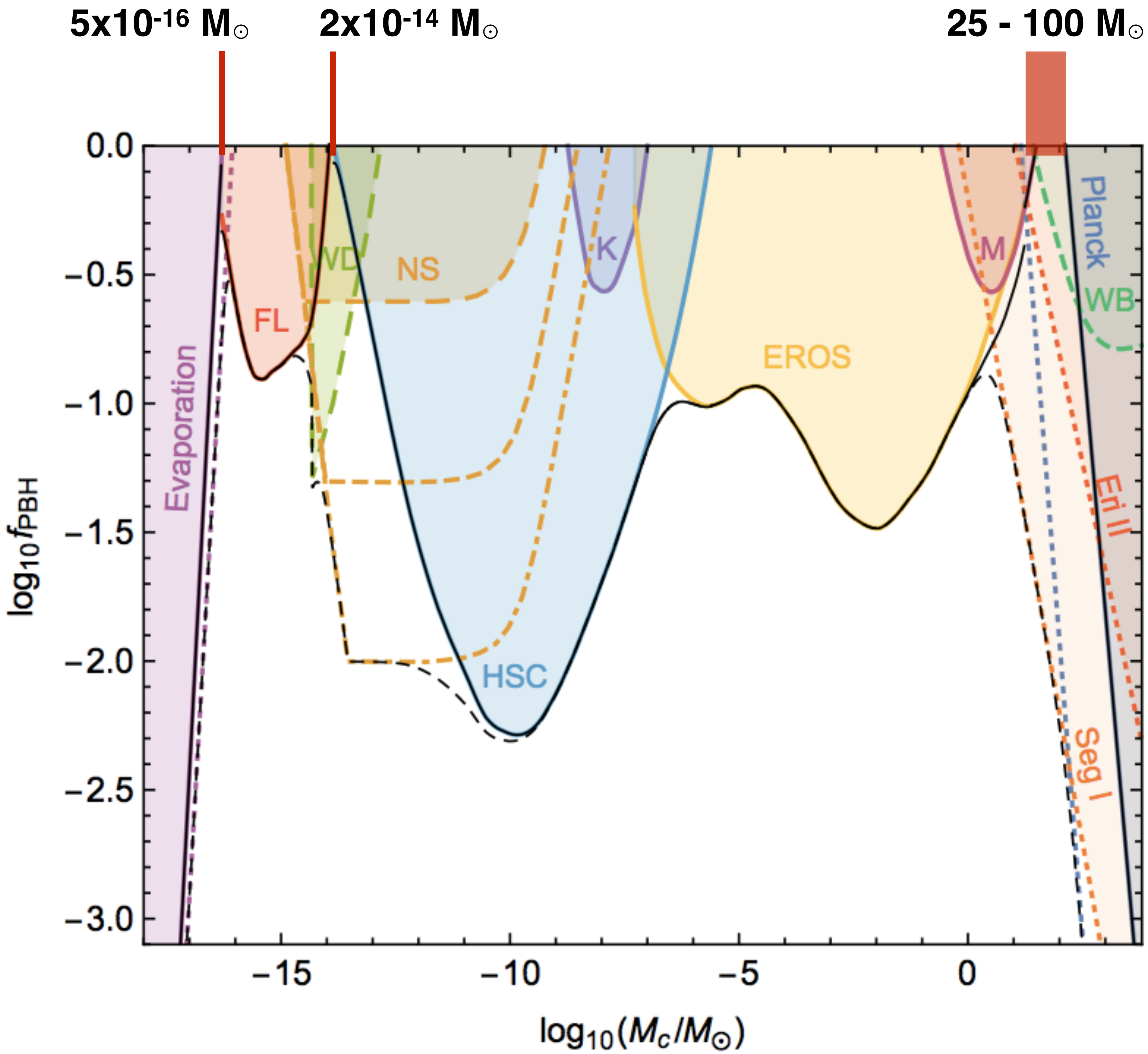
3 mass windows!



Carr et al. 2017

Primordial black holes: Mass windows

Two classes of constraints:

- relatively robust —
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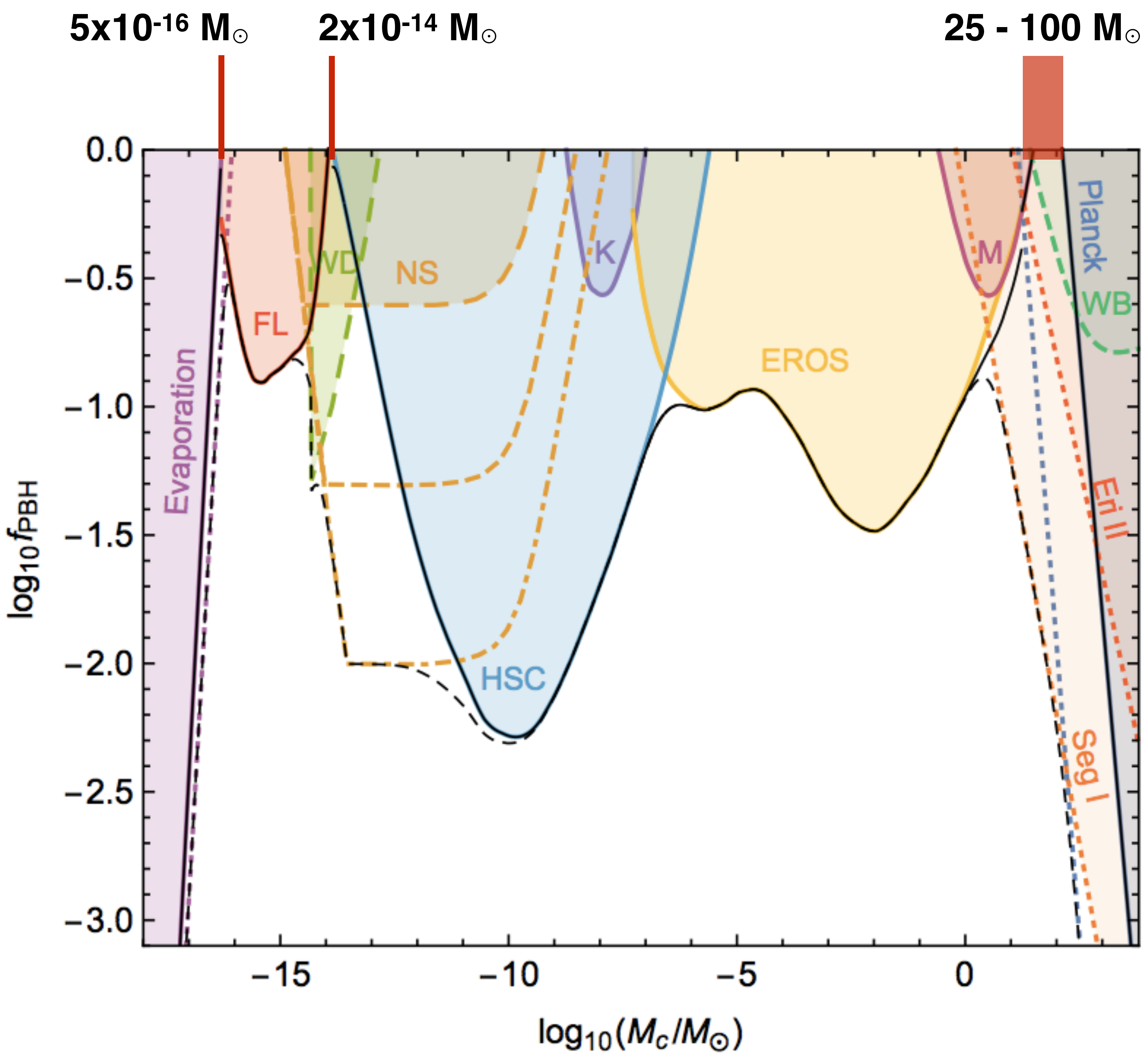
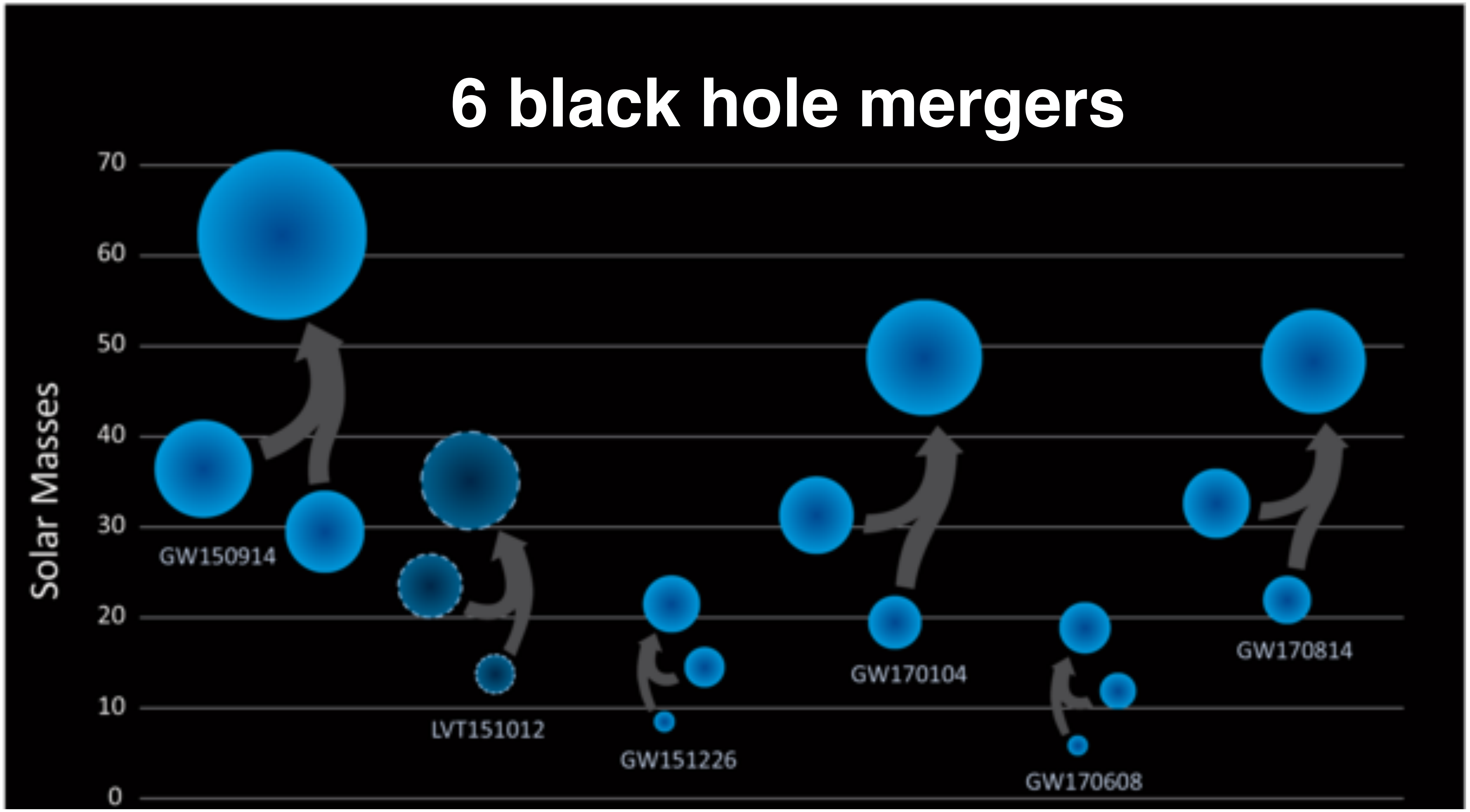
3 mass windows!

- Primordial black hole (**PBH**): **25 - 100 M$_\odot$**



Carr et al. 2017

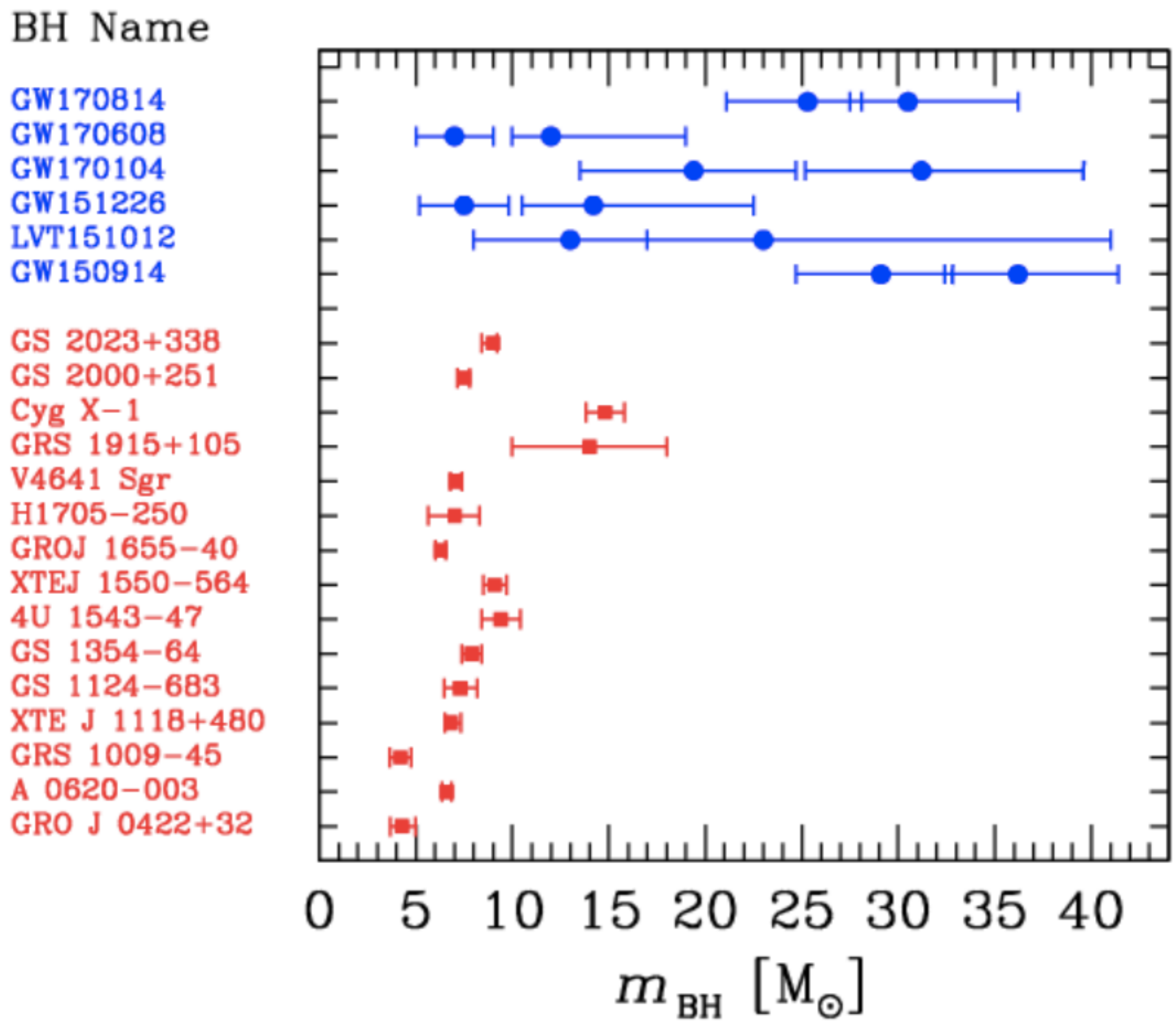
LIGO black holes: Detections



- Stellar black hole (**SBH**): **10 - 30 M**$_{\odot}$
- Primordial black hole (**PBH**): **25 - 100 M**$_{\odot}$

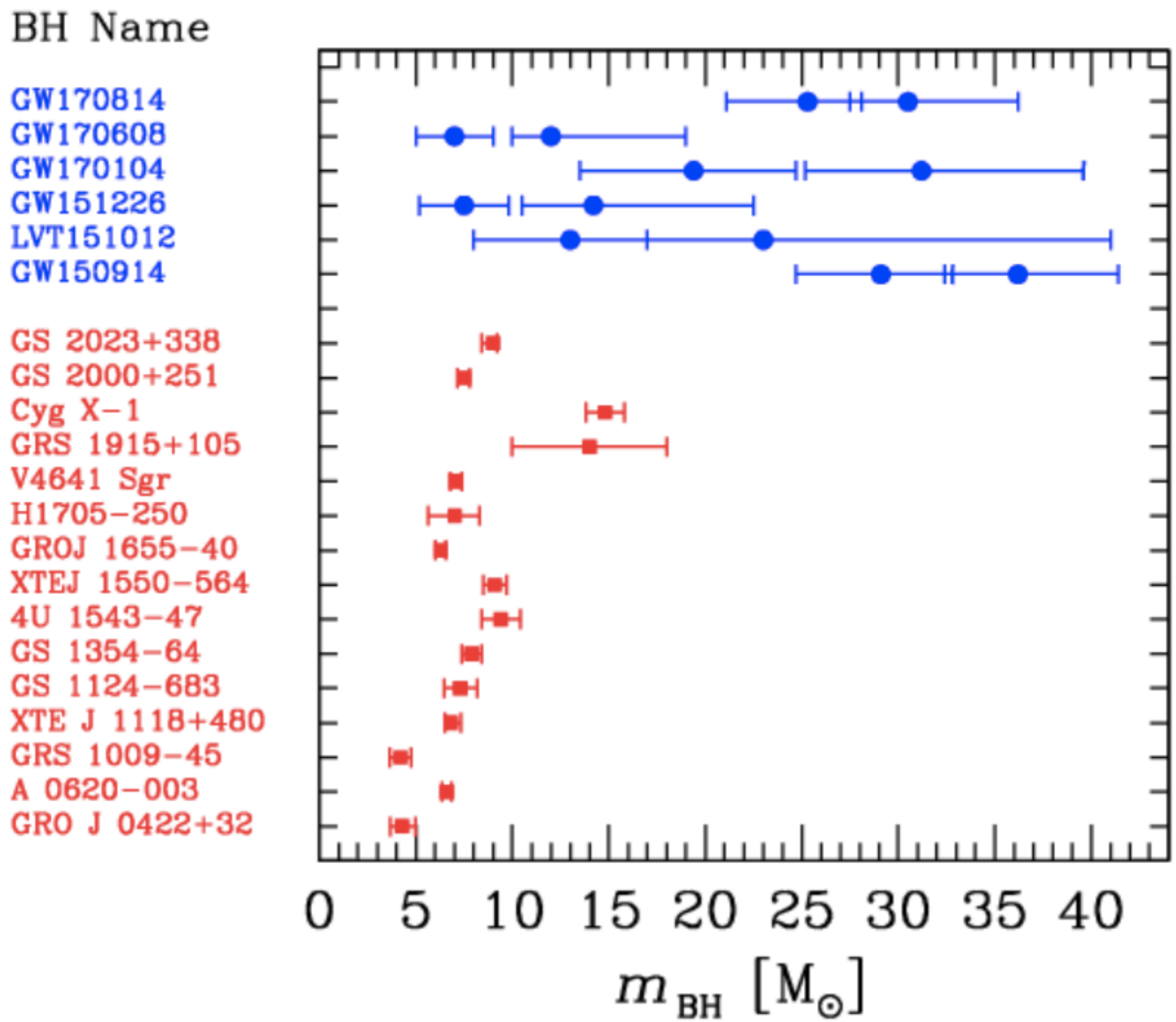
credits: LIGO caltech

LIGO black holes:
Stellar or Primordial?



Mapelli 2018

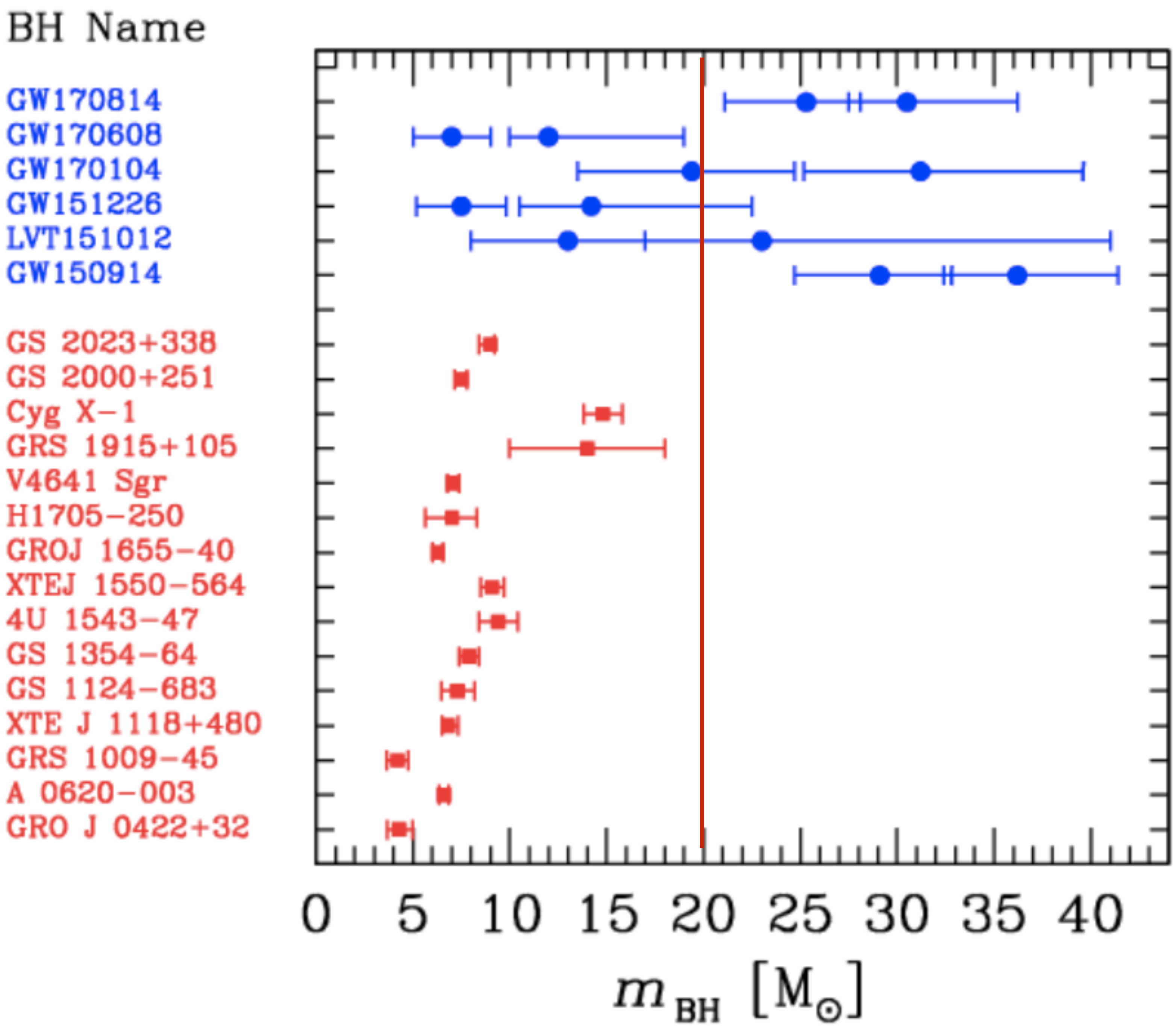
LIGO black holes:
Stellar or Primordial?



Mapelli 2018

LIGO black holes:
Stellar or Primordial?

Observed SBHs < 20 $M_\odot$



Mapelli 2018

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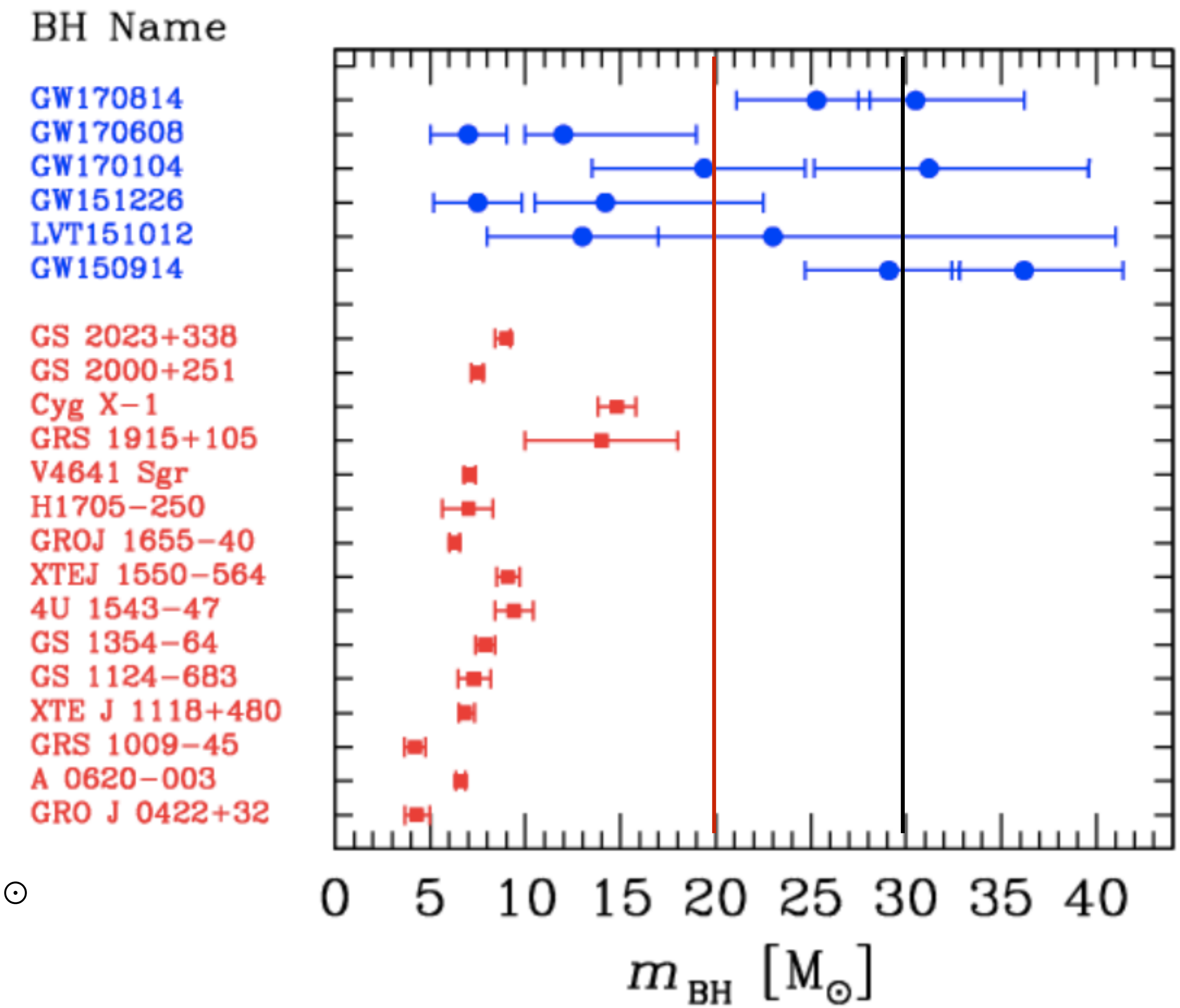

Observed SBHs < 20 $M_\odot$

Theoretical models < 30 $M_\odot$

Mapelli 2018

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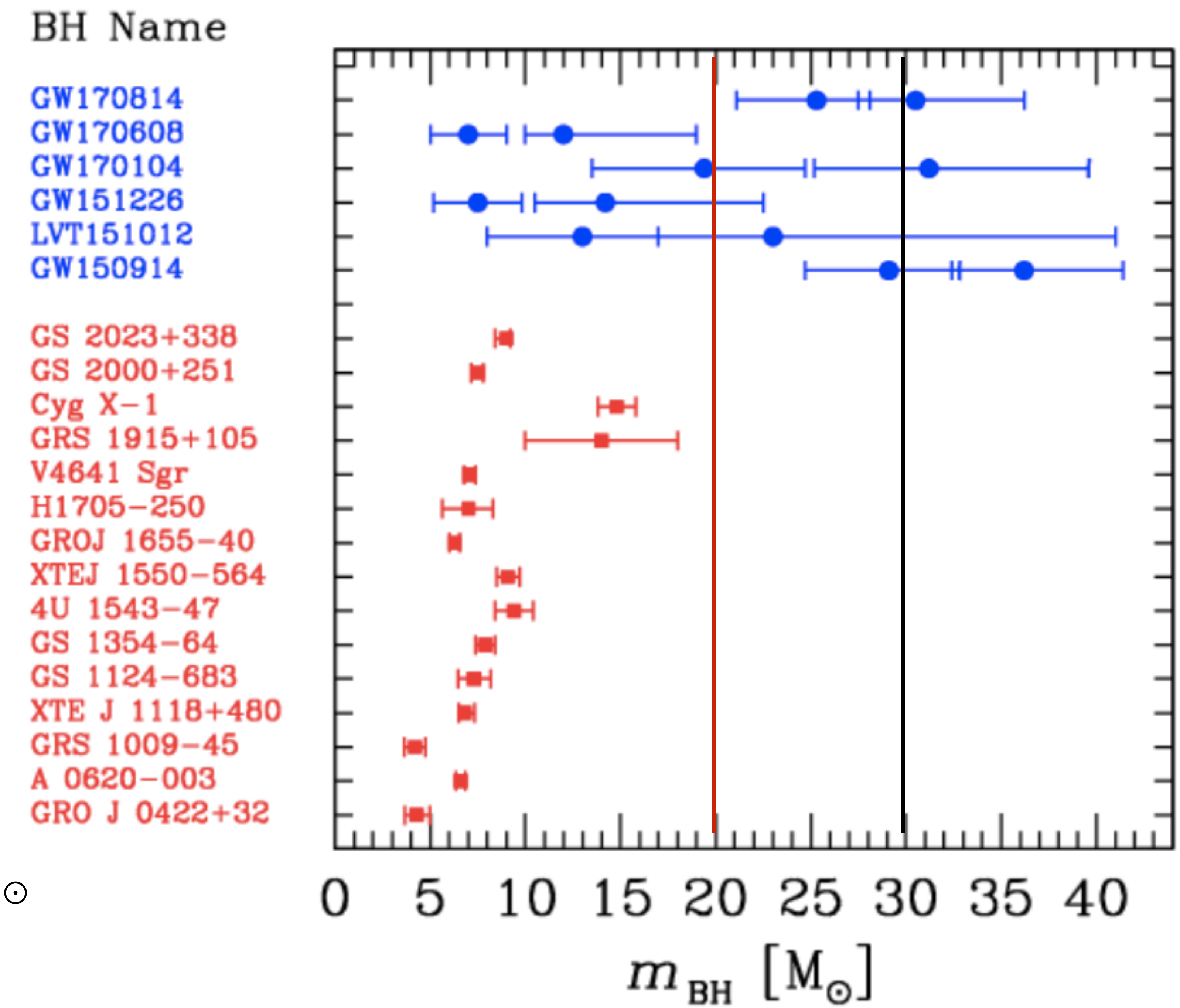
Stellar or Primordial?



Observed SBHs < 20 $M_\odot$

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LIGO black holes could be primordial!

Mapelli 2018

Primordial black holes as dark matter: Hypothesis

DM being composed of PBHs

$$f = \Omega_{PBH} / \Omega_{DM}$$

Mass window ~ **25-100 $M_\odot$**

LIGO detection ~ 10-50 $M_\odot$

Primordial black holes as dark matter: Hypothesis

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Mass window ~ **25-100 $M_{\odot}$**

LIGO detection ~ 10-50 $M_{\odot}$

What happened in galaxies?

Dark matter theories

- **Cold Dark Matter**
- **Warm Dark Matter**
- **Fuzzy (Ultralight) Dark Matter**
  (Hu et al. 2000, Hui et al. 2016)
- **Self-Interacting Dark Matter**
  (Spergel & Steinhardt 2000)

Core-cusp problem

Astrophysical constraints:

- **Large-scale constraints**
  e.g. CMB

- **Small-scale constraints**
  e.g. Number of satellite galaxies, Dark matter density profile

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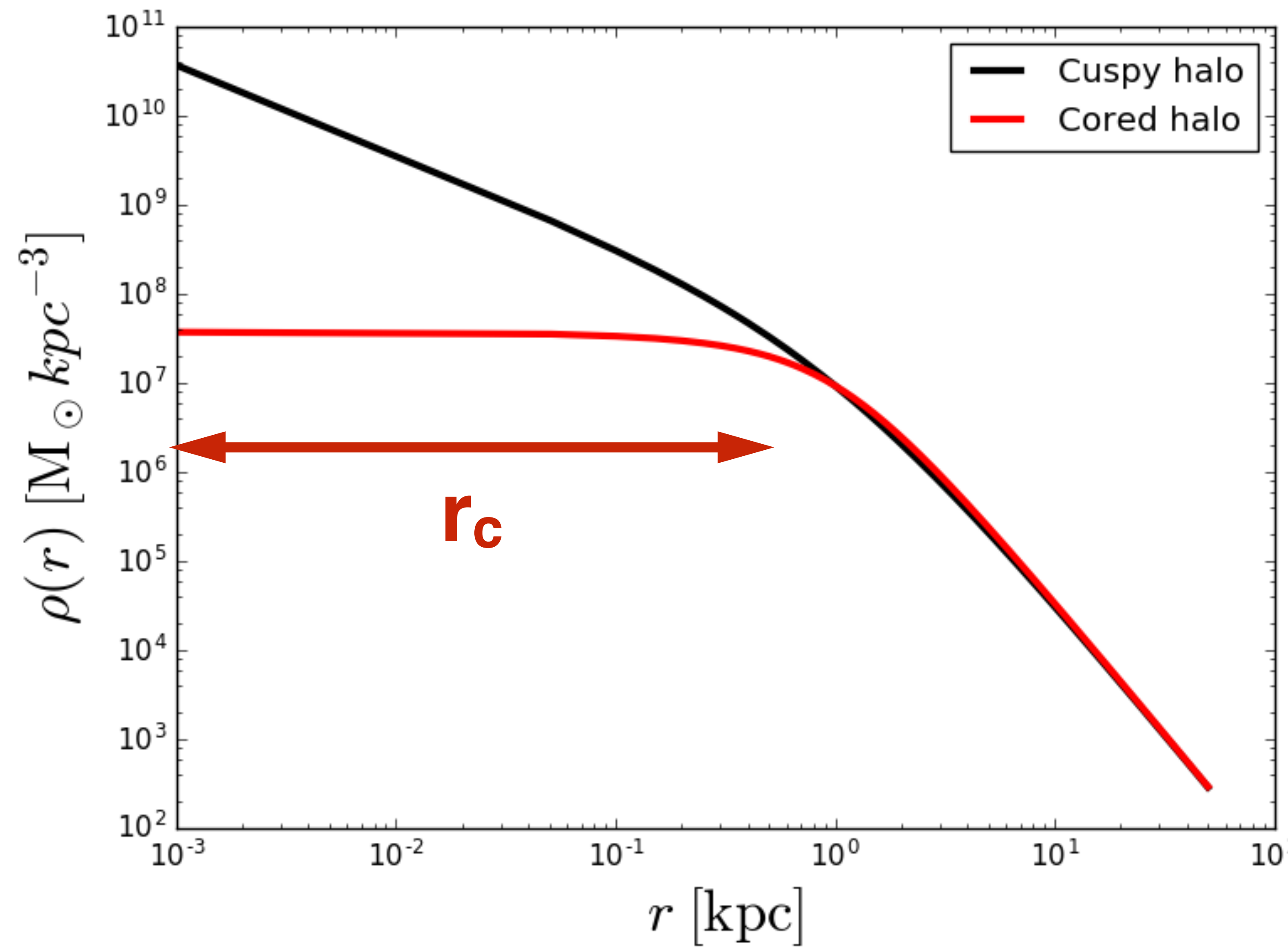

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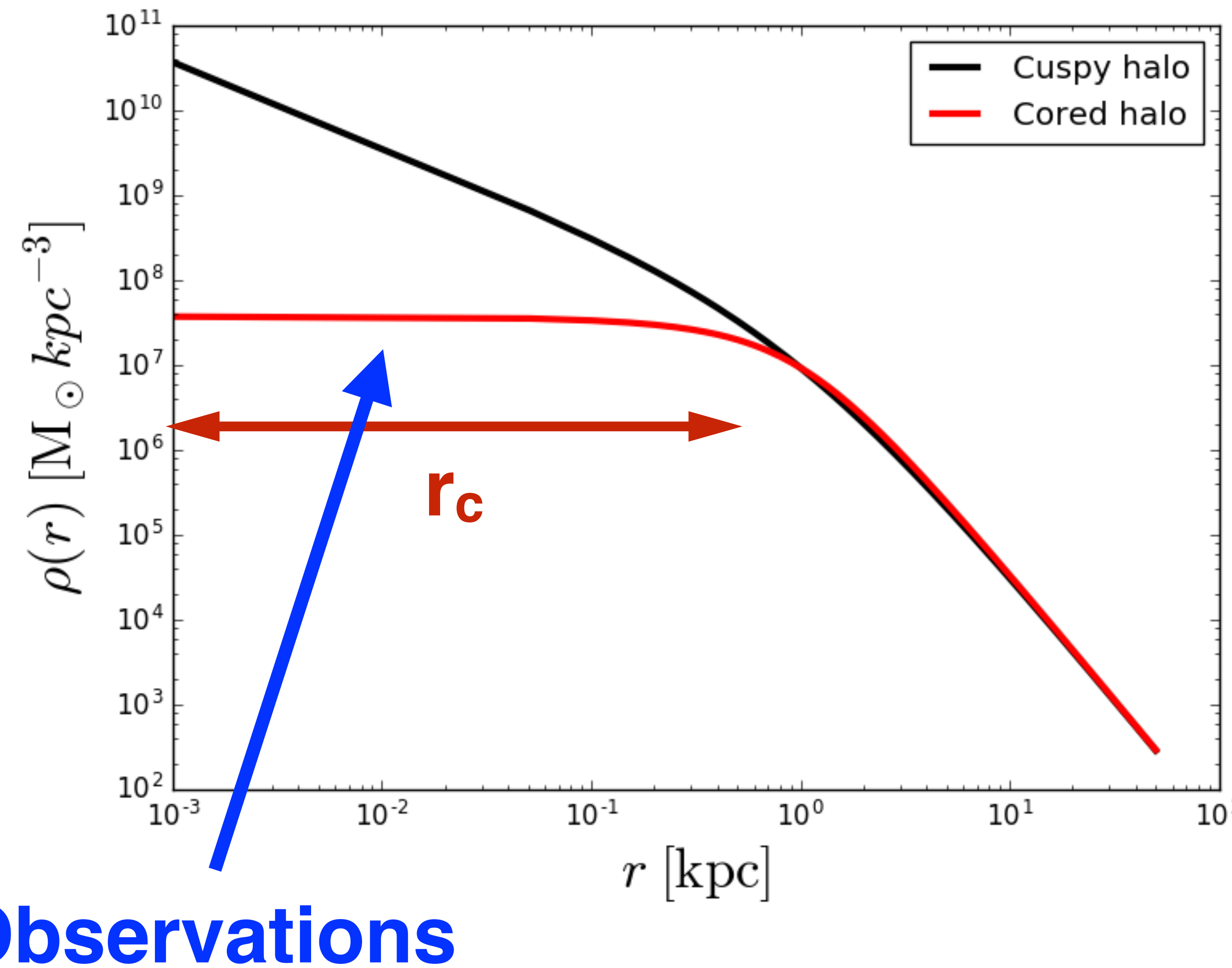

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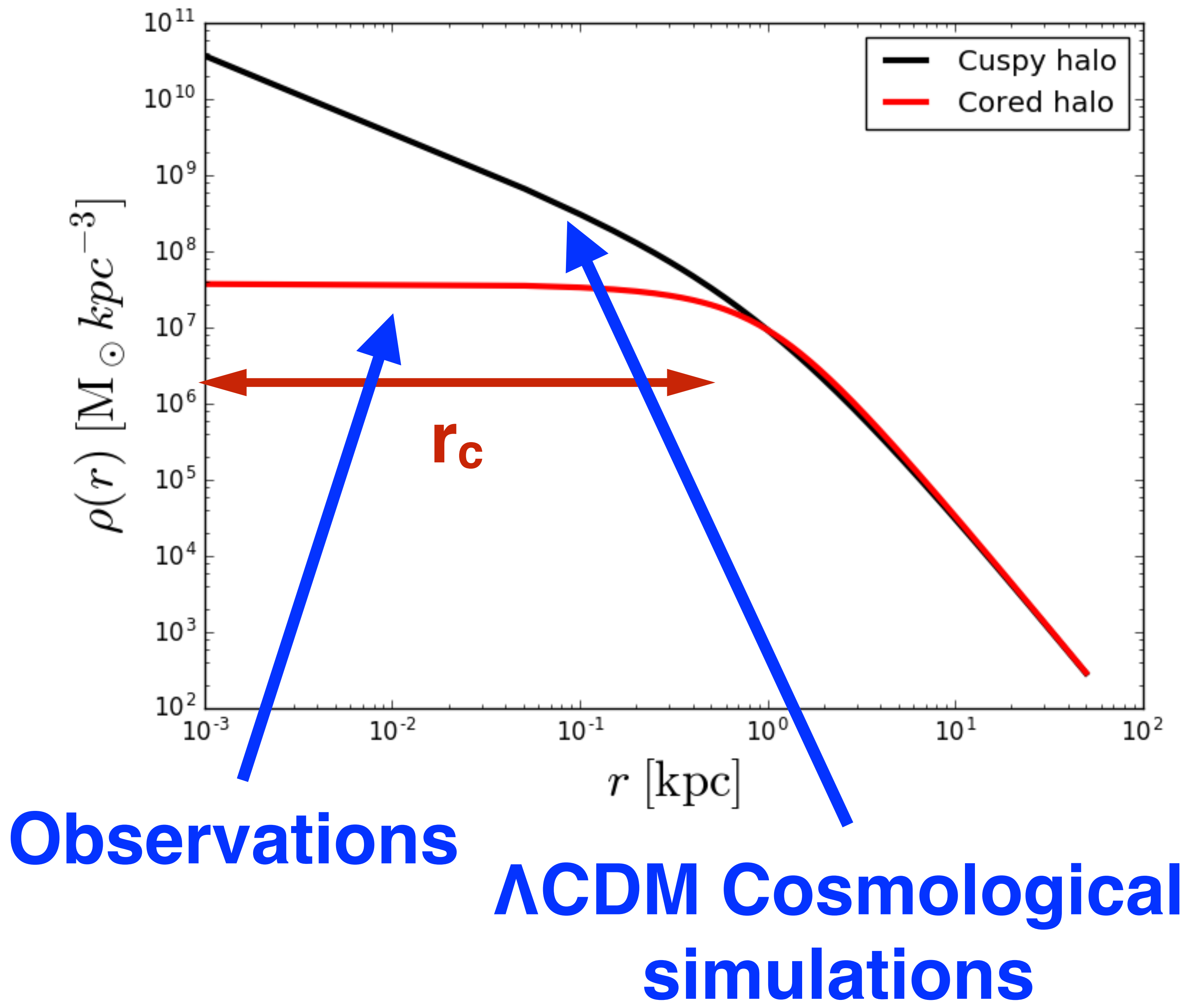
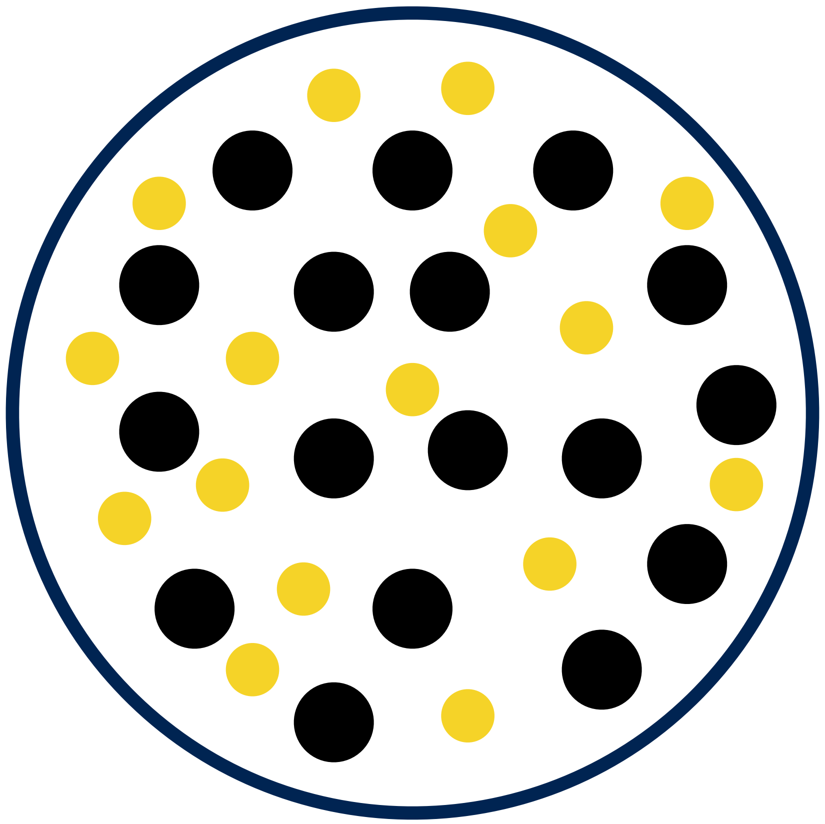


Core-cusp problem

- **Cold Dark Matter** — **Cusp**
- **Warm Dark Matter** (Colin et al. 2000; Bode et al. 2001) — **Core**
- **Fuzzy Dark Matter** (Hu et al. 2000; Hui et al. 2017) — **Core**
- **Self-Interacting Dark Matter** (Vogelsberger et al. 2012) — **Core**
- **Primordial Black Holes as dark matter** (Boldrini et al. in prep.) — **??**

PBHs as DM galaxies

Galaxy halo composed of PBH and DM particles



$f_m = M_{PBH}/M_{DM}$

- ● 25-100 $M_\odot$ PBHs
- ● 1 $M_\odot$ DM

Two-body relaxation

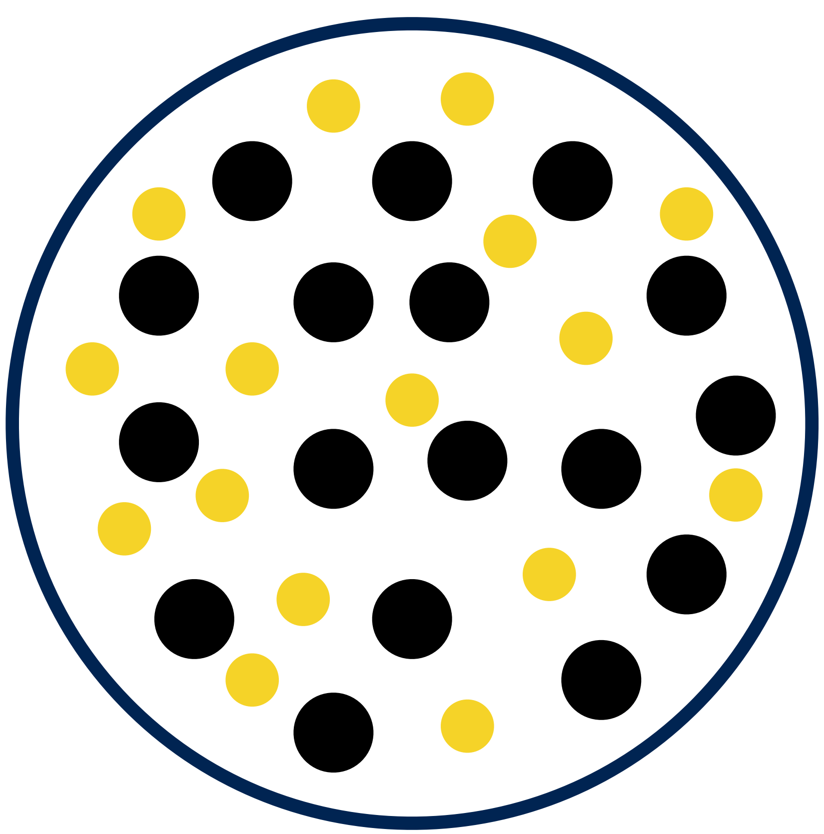
Scattering DM by PBHs

↓

Two-body relaxation

↓

Mass segregation



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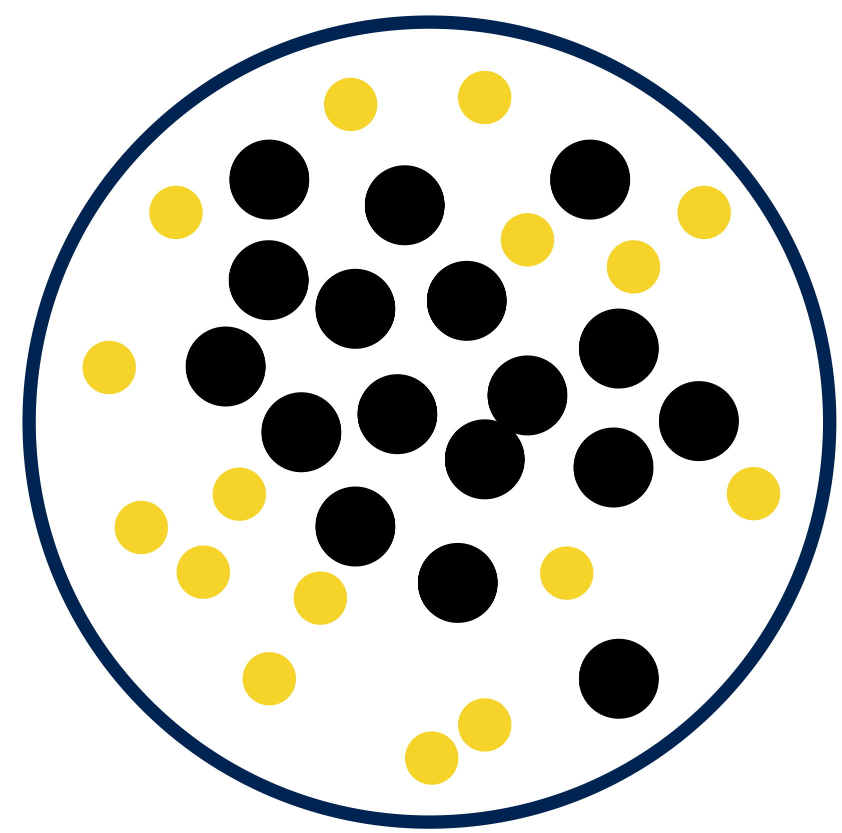
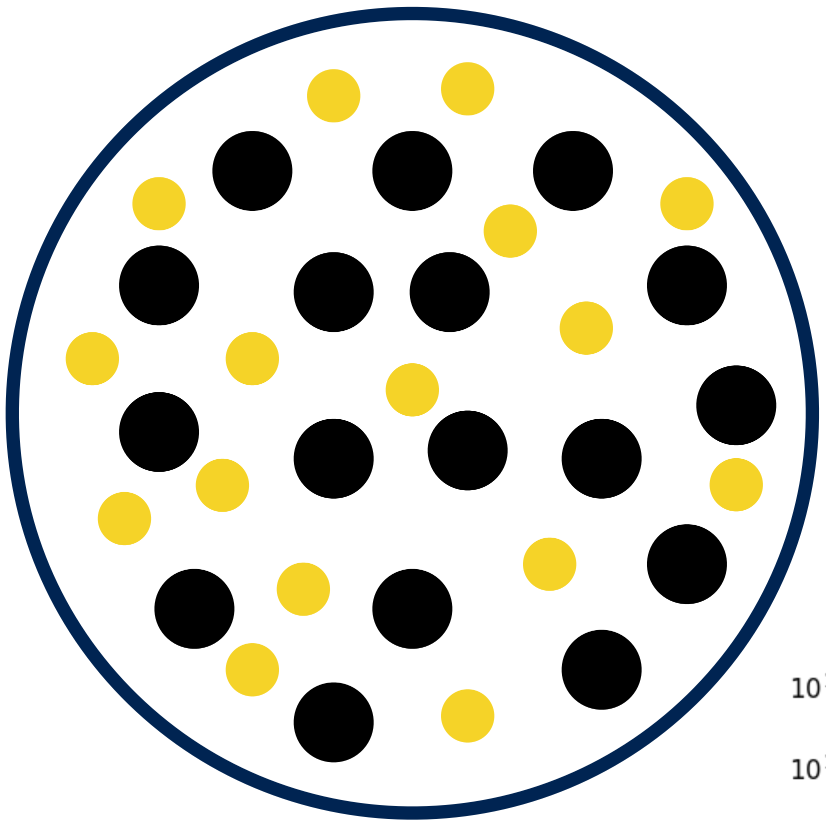


Cusp-to-core transition



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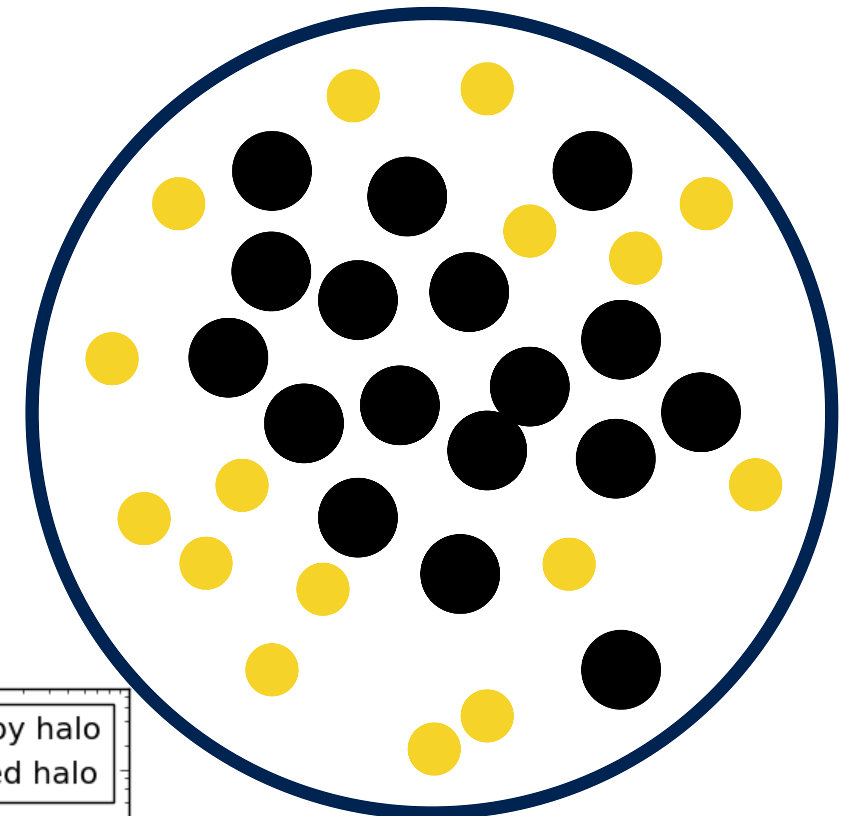

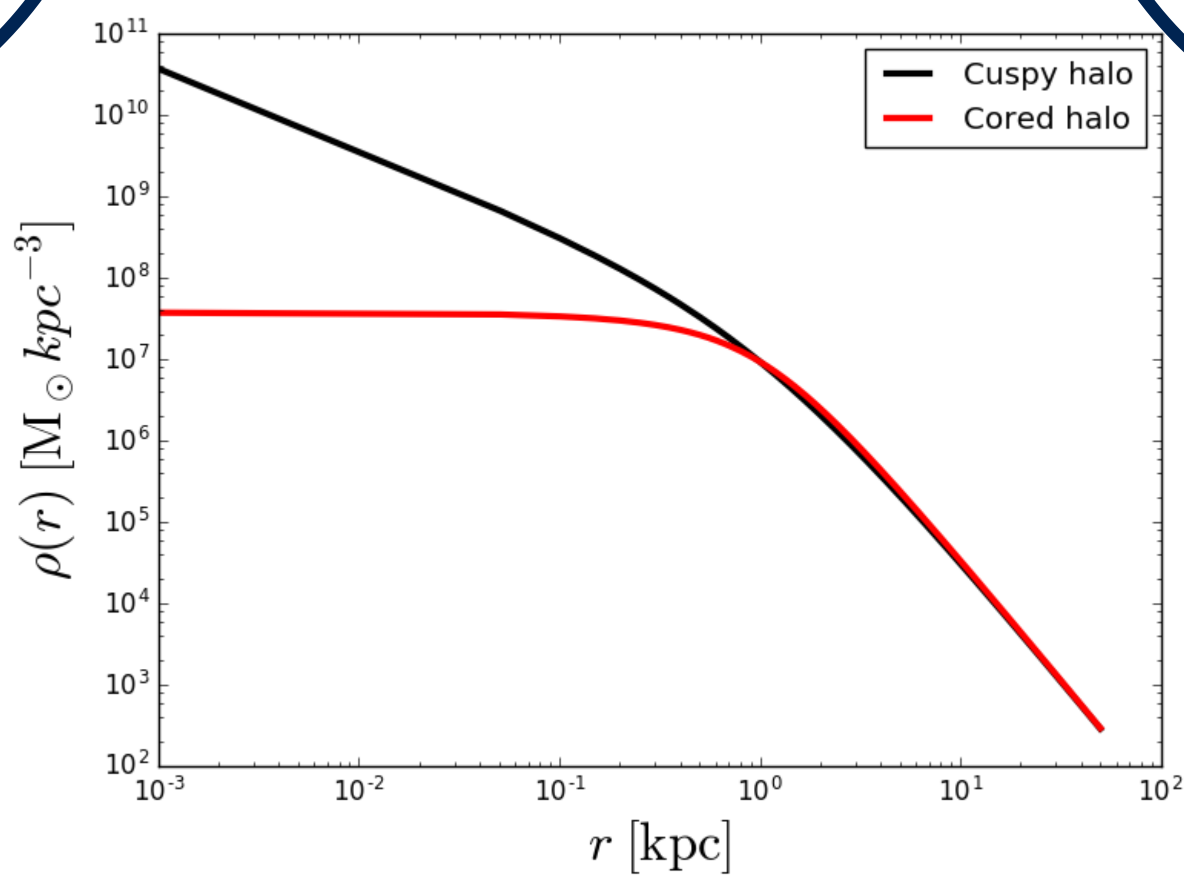

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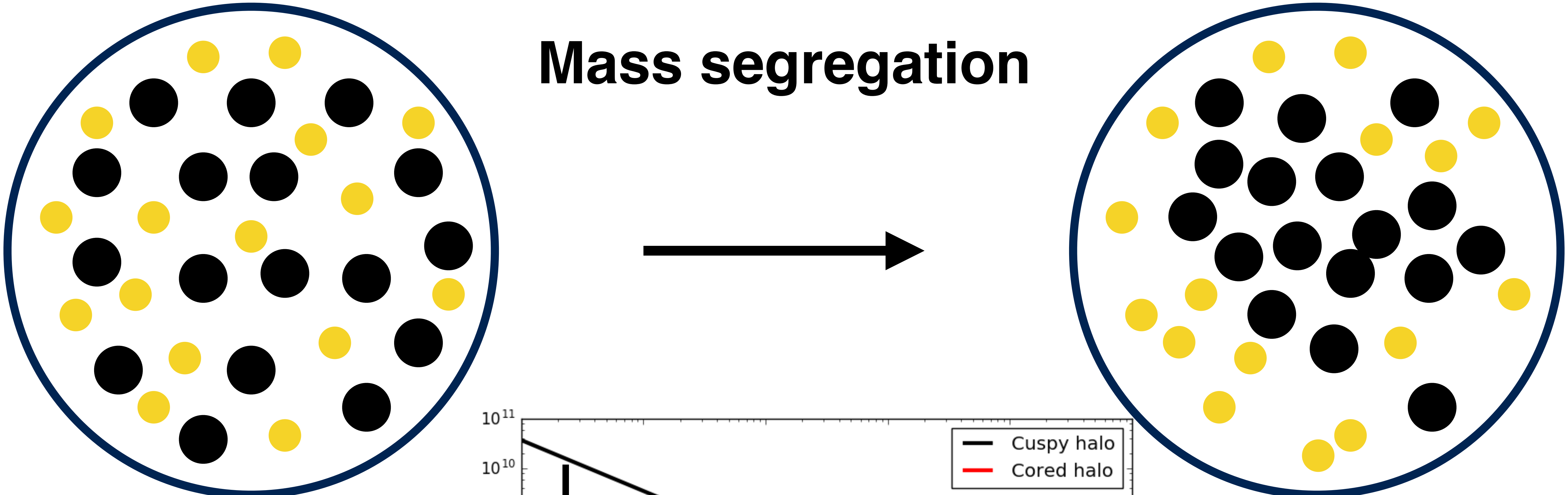
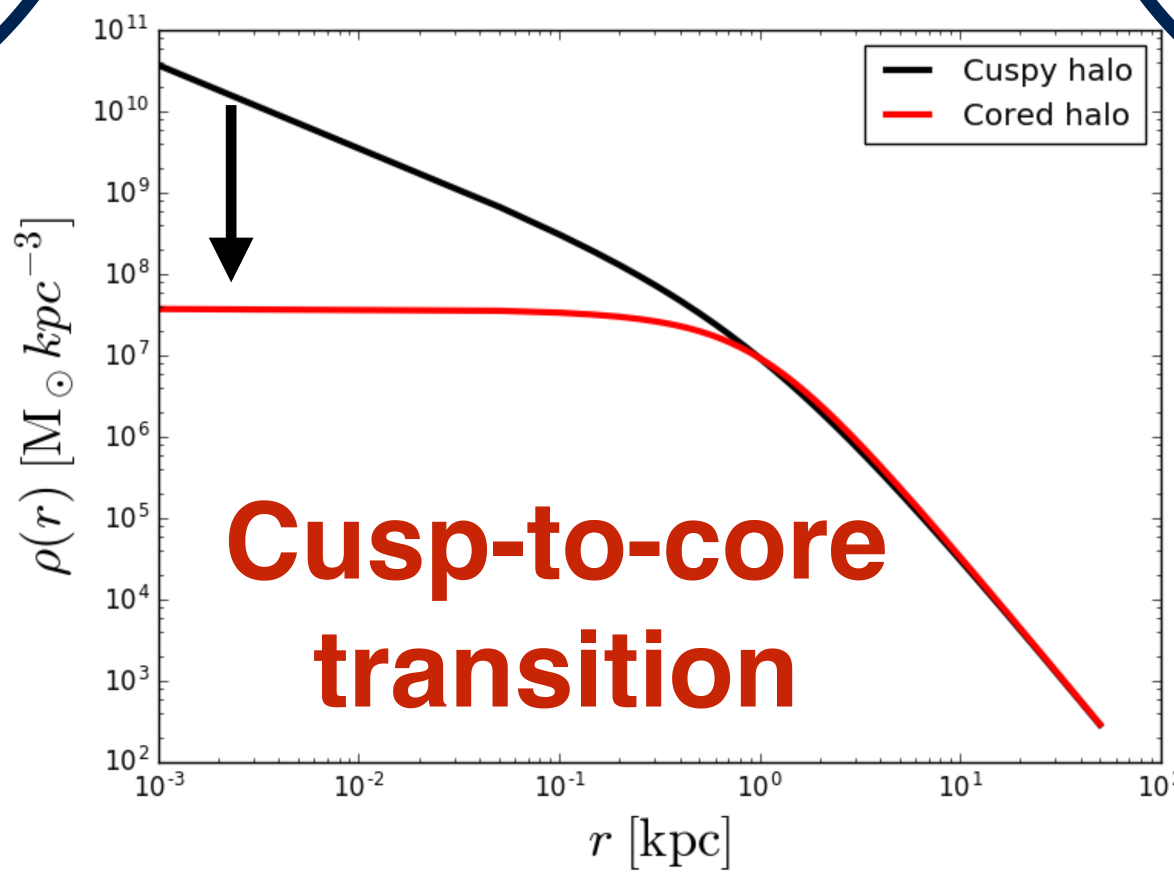
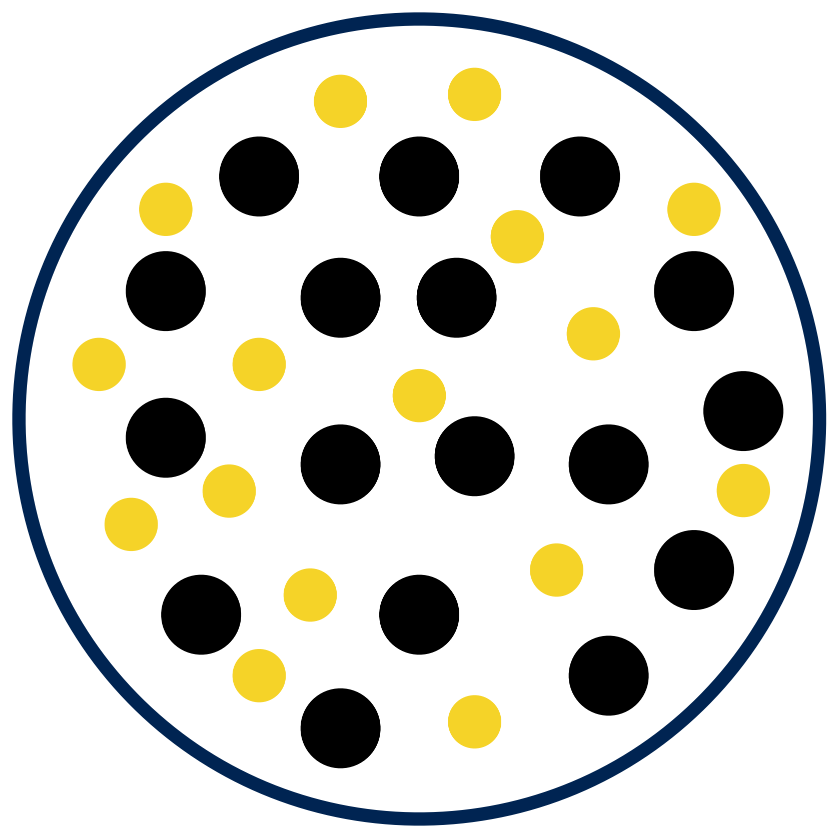




Simulations

Nbody:

- Gravitational Vlasov Poisson
- Spherical
- Collisionless



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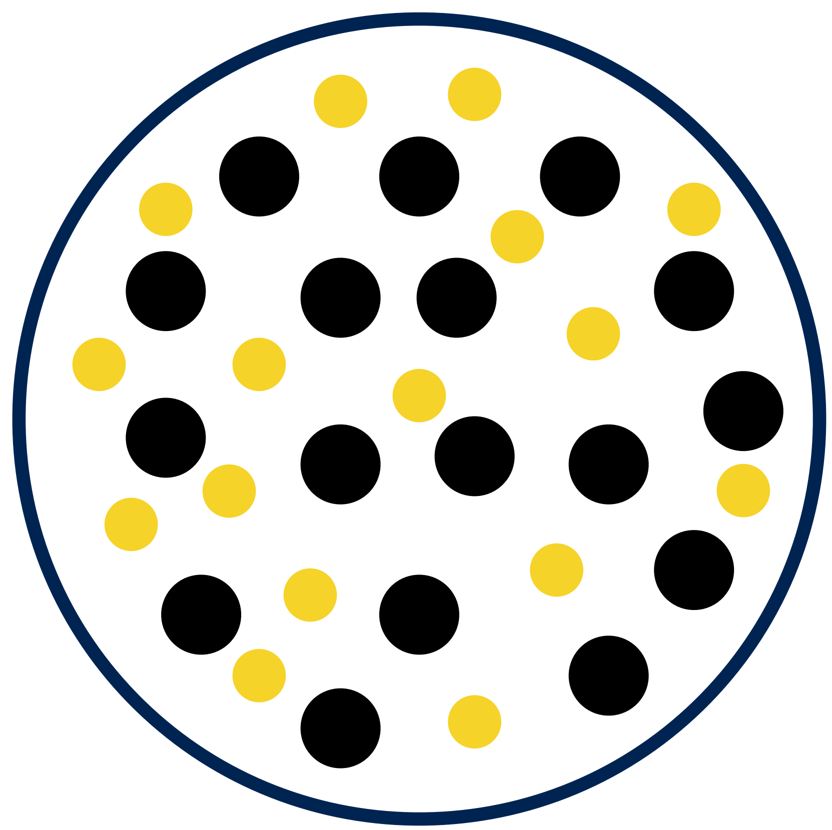


$f_m = M_{PBH}/M_{DM}$

Gothic:

- Tree code
- Softened
- GPU

● **25-100 $M_\odot$ PBHs**

● **1 $M_\odot$ DM**

Miki & Umemura 2016

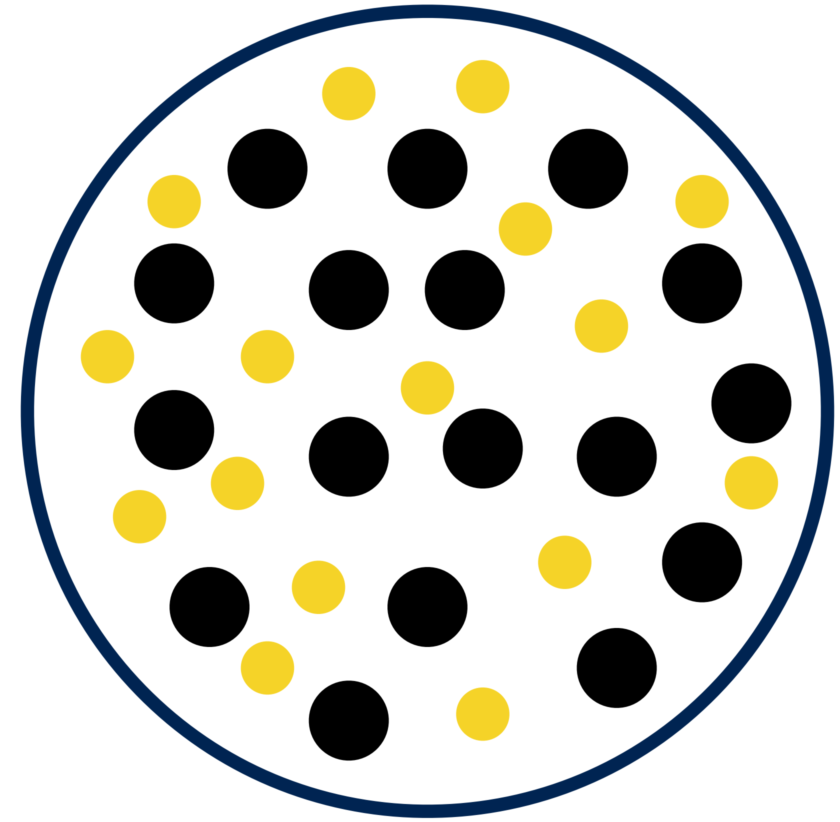
PBH & DM halo density profiles

Following NFW profile:

$$\rho = \rho_0 \left(\frac{r}{r_s}\right)^{-1} \left(1 + \frac{r}{r_s}\right)^{-2}$$

ρ_{DM}

ρ_{PBH}



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Navarro et al. 1996

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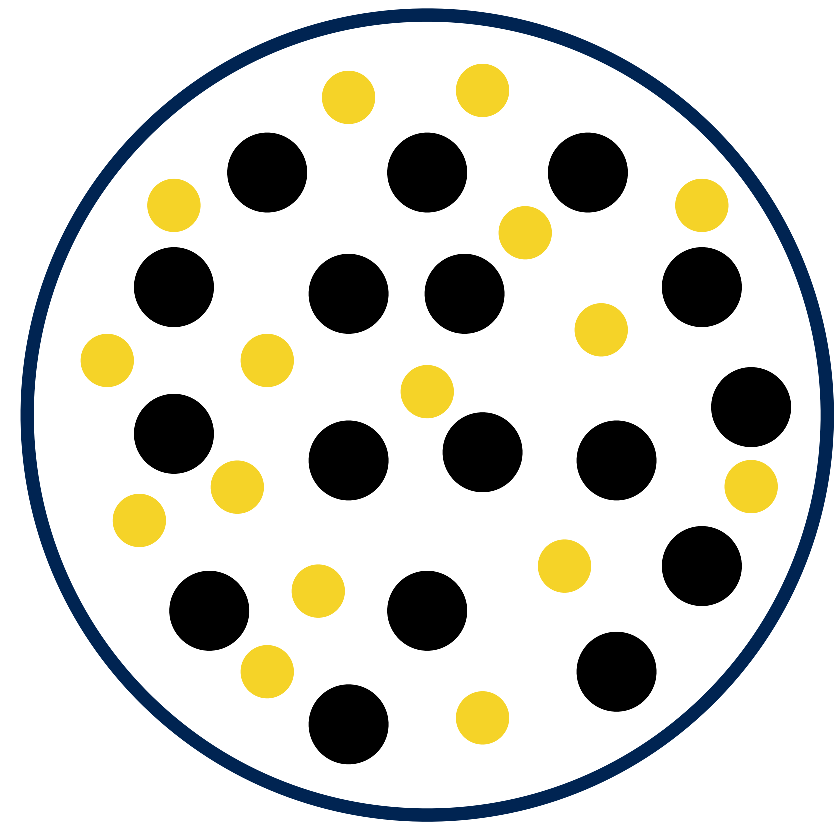
→ ρ_{DM}

→ ρ_{PBH}



- $r_s^{PBH} = r_s^{DM}$
- $r_s^{PBH} = r_s^{DM} / 2$

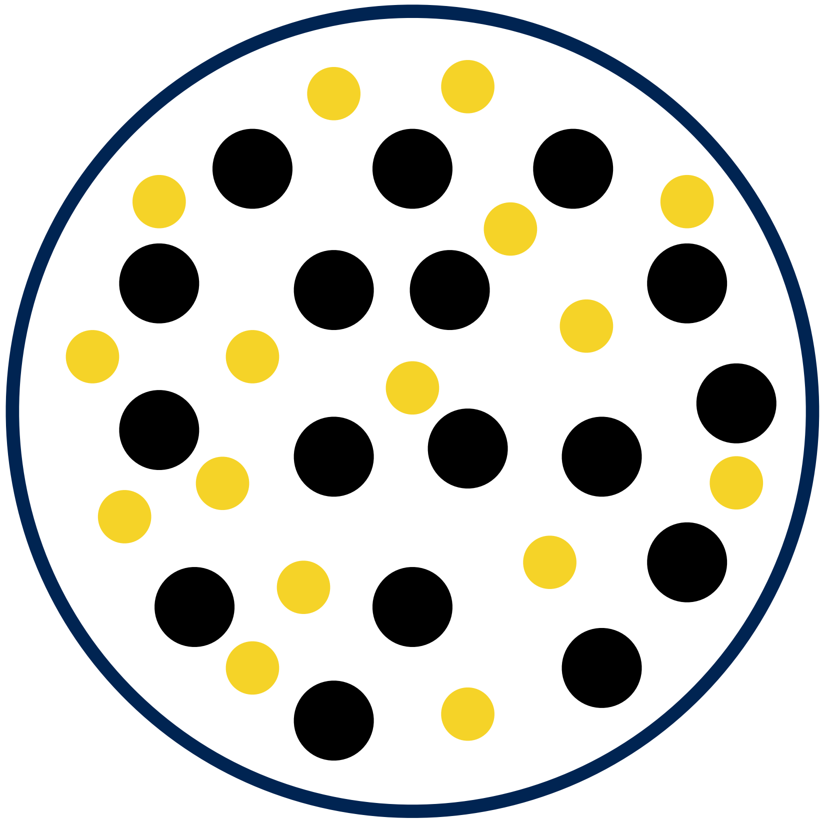
$f_m = \mathbf{M_{PBH}} / \mathbf{M_{DM}}$

Navarro et al. 1996

PBH-DM halo relaxation time

Relaxation time approximation:

$$T_{relax} \sim \frac{M_h}{\ln(M_h)}$$



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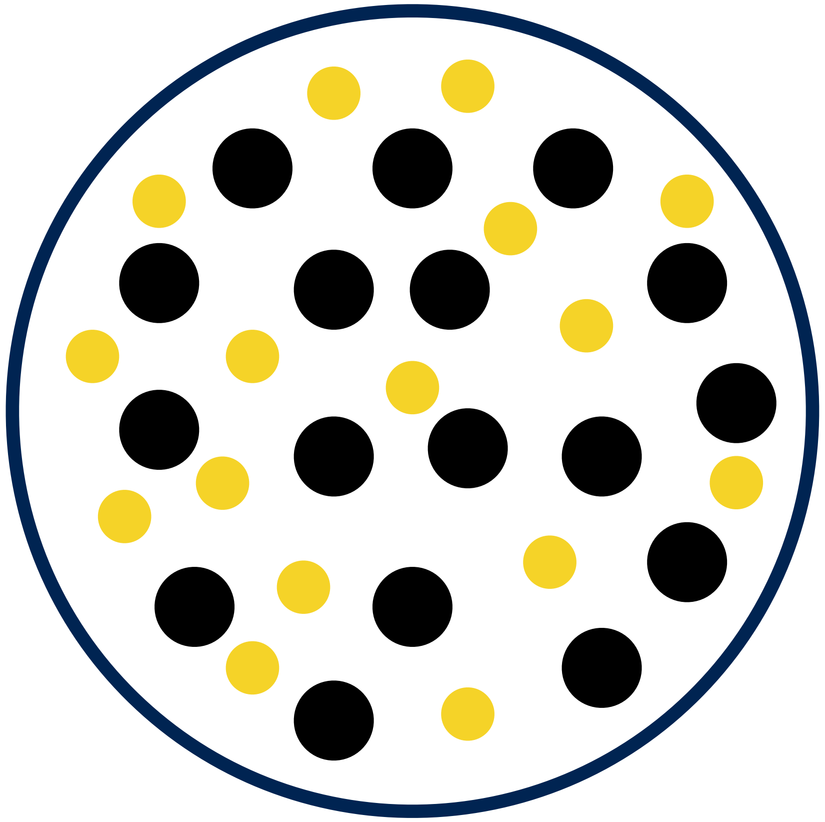
Dwarf galaxies 10^7 - 10^9 $M_\odot$:

$10^8\ M_\odot$ halo ~ 9 $T_{relax}(10^7\ M_\odot)$

$10^9\ M_\odot$ halo ~ 78 $T_{relax}(10^7\ M_\odot)$



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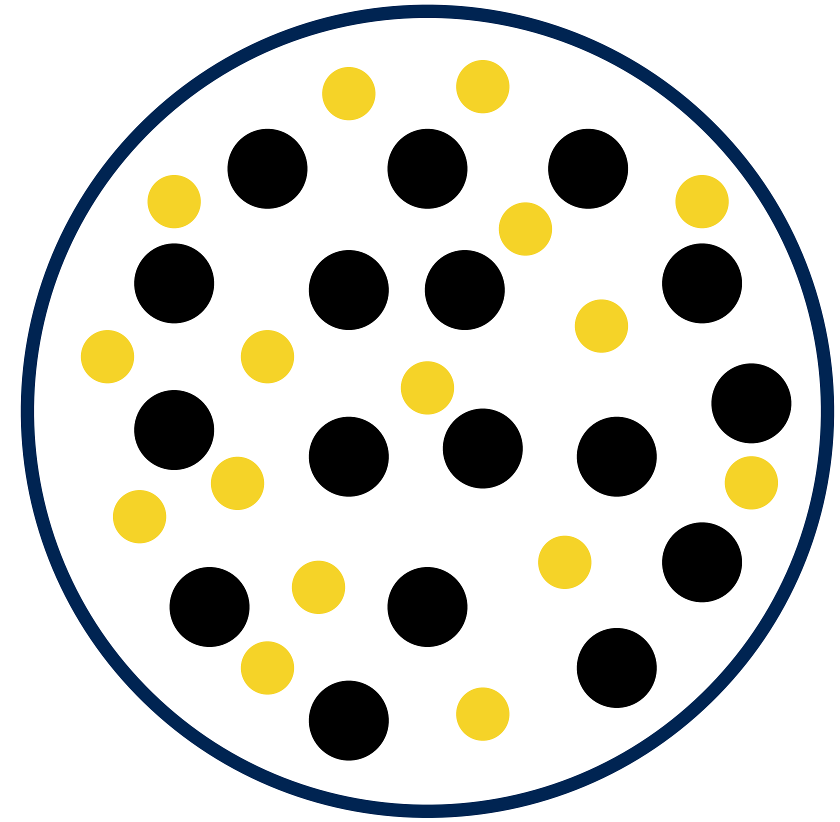

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$10^8\ M_\odot$ halo ~ 9 $T_{relax}(10^7\ M_\odot)$

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PBH-DM halo mass : $10^7\ M_\odot$

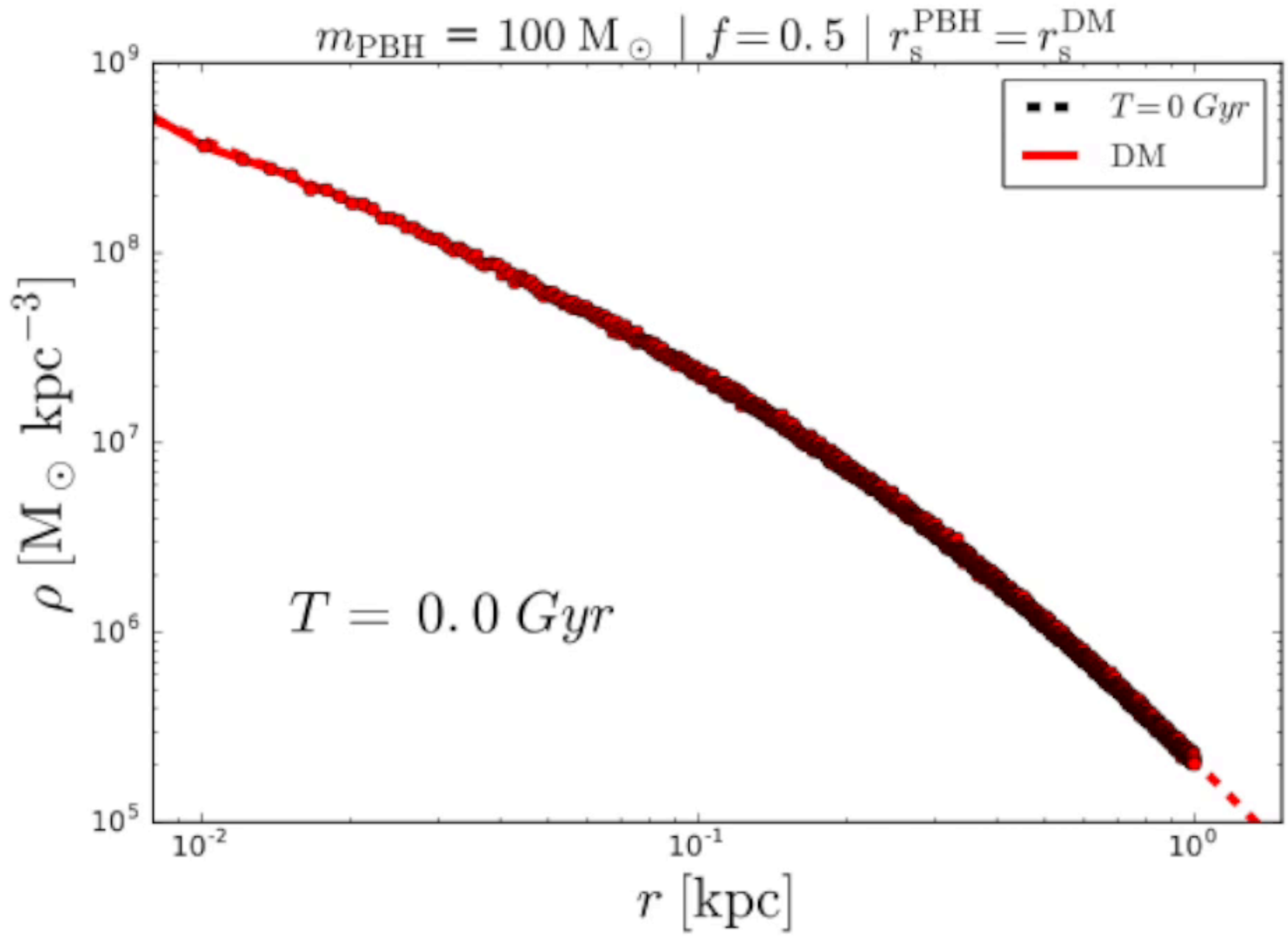
Navarro et al. 1996

Simulation

Parameters:

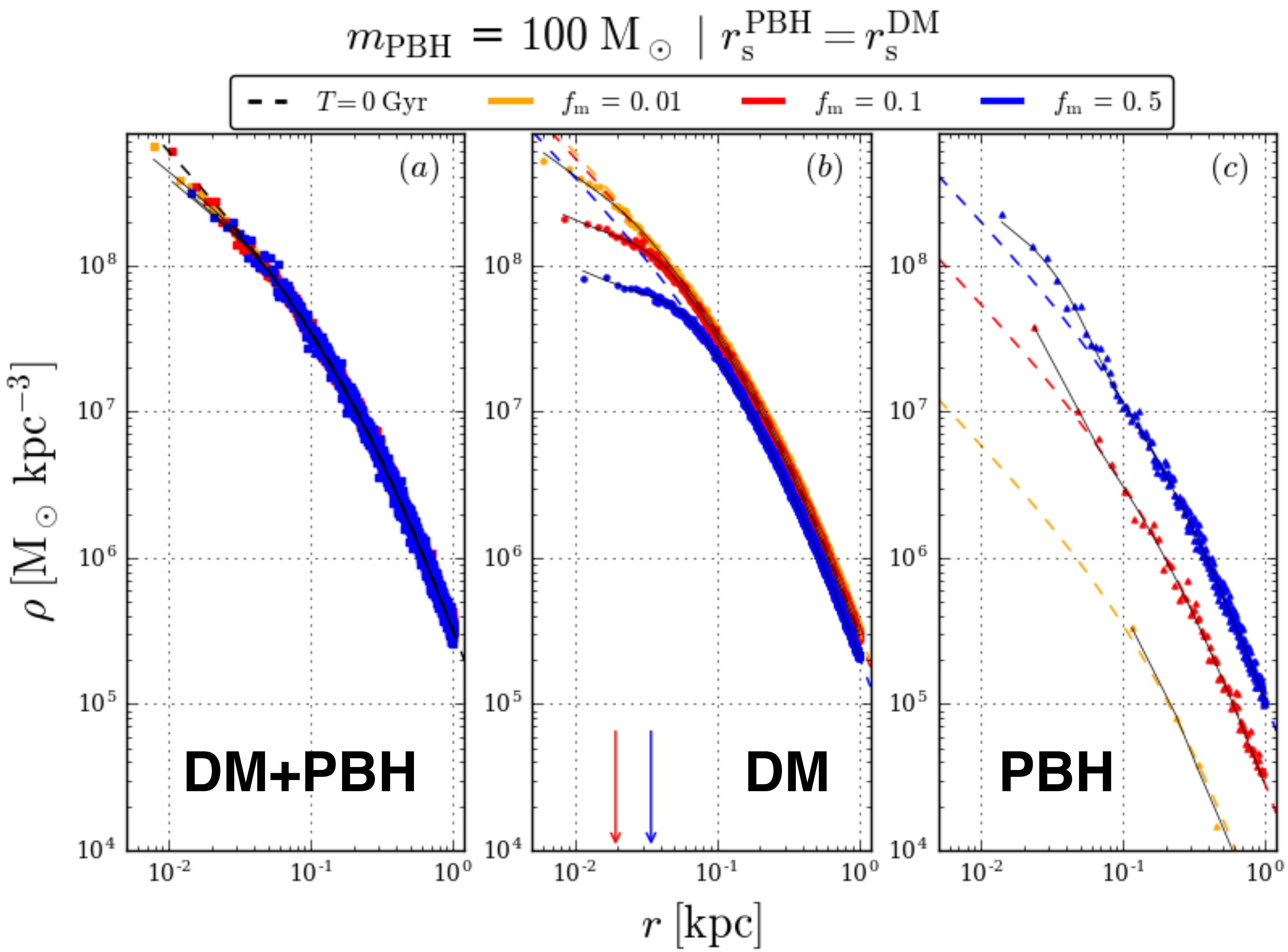
- Mass fraction f_m = [0.5, 0.1, 0.01]
- PBH mass m_{PBH} = [25, 50, 100] $M_\odot$ & m_{DM} = 1 $M_\odot$
- Halo mass $M_h = 10^7\ M_\odot$
- r_s^{PBH} = [1, 0.5] r_s^{DM}
- T_s = 11 Gyr (z=2)

Results



Boldrini et al. in prep.

Density profiles evolution



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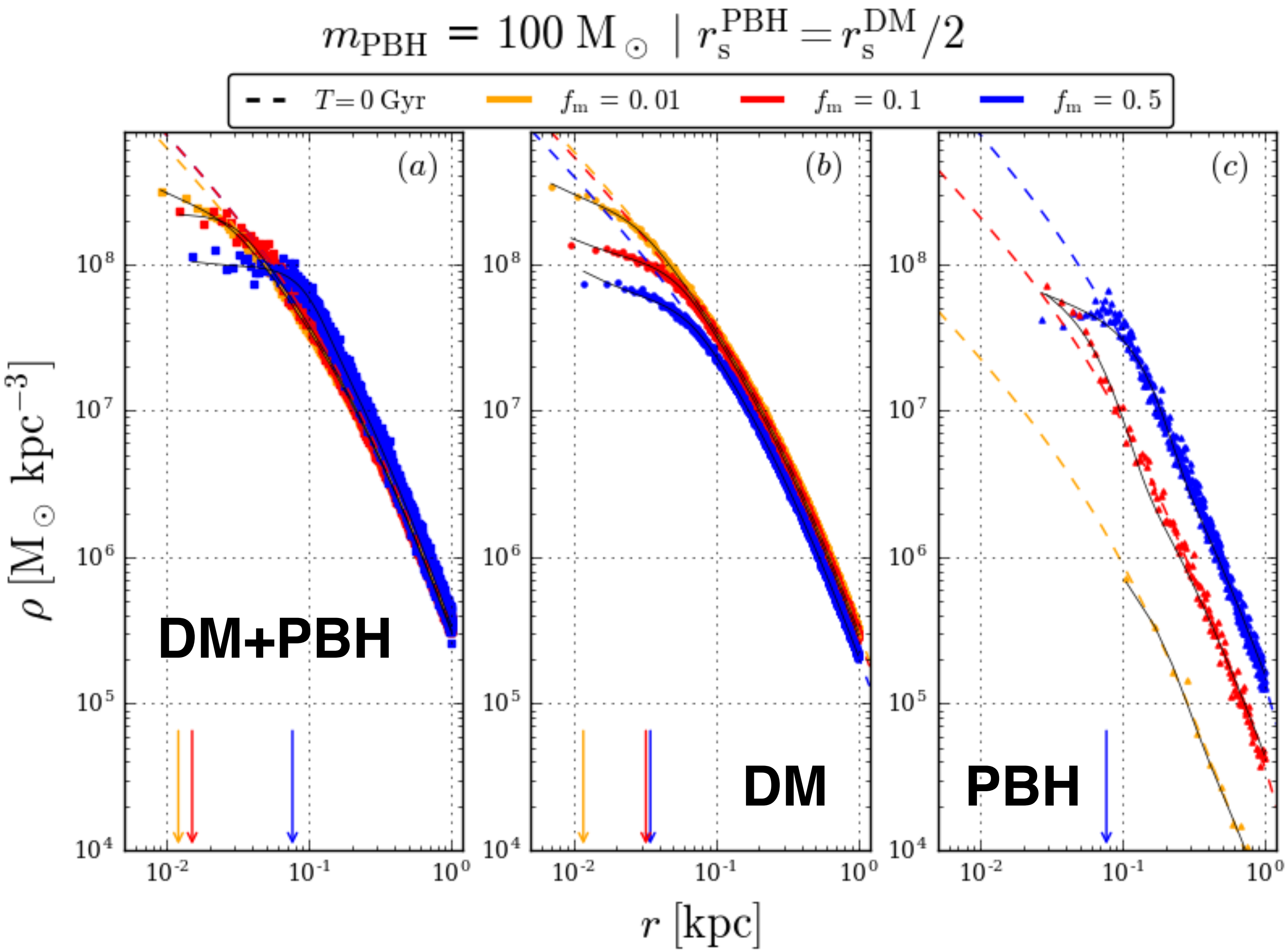


Multiples cores!

Boldrini et al. in prep.

Core fits

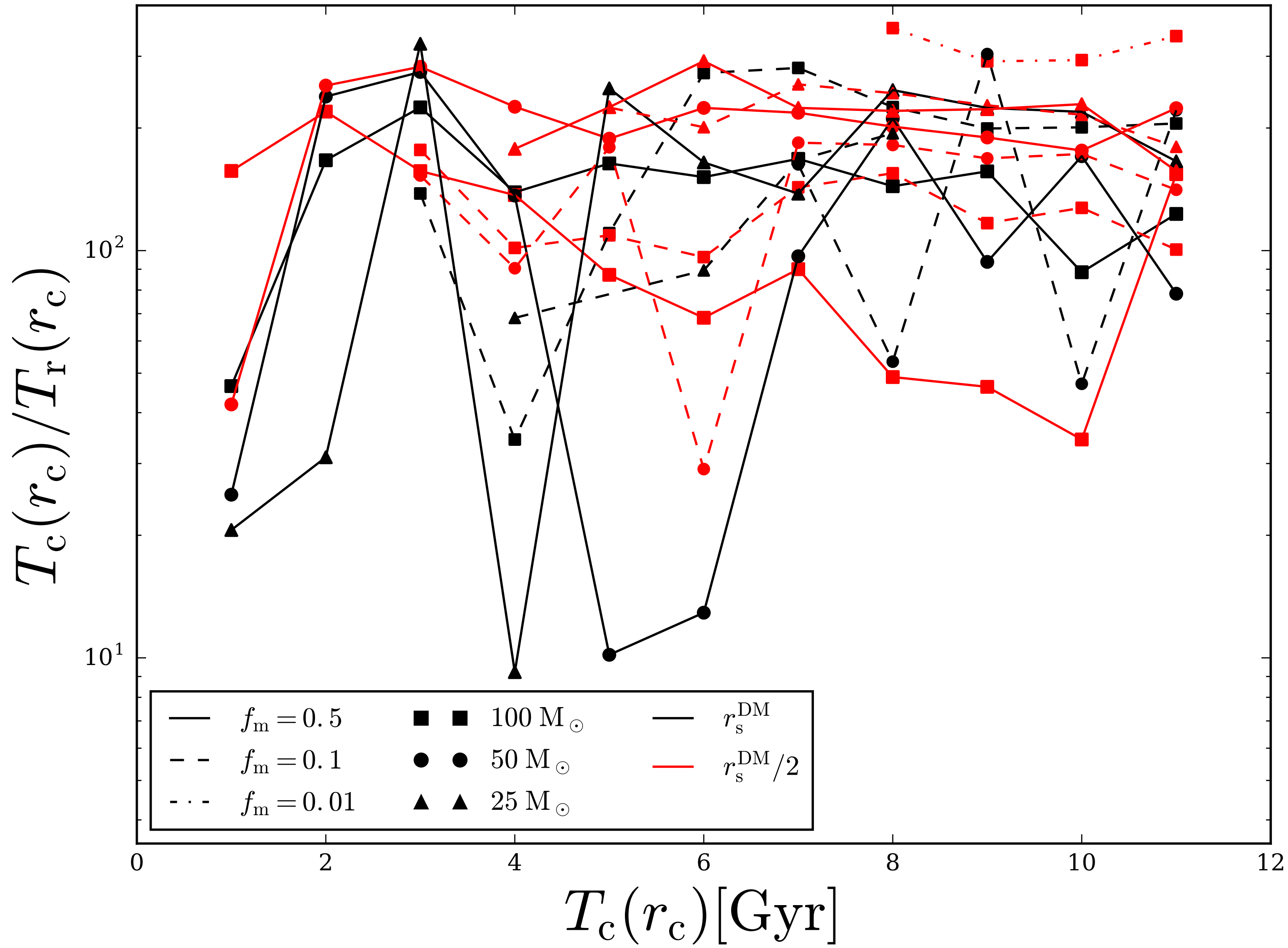
f_m	r_s^{PBH}/r_s^{DM}	m_{PBH} [$M_\odot$]	CCT	r_c [pc]	χ^2/ν
0.5	1	25	○	17.6	1.01
0.5	1	50	○	31.28	1.02
0.5	1	100	○	34.32	1.0
0.1	1	25	○	10.01	1.01
0.1	1	50	○	14.48	1.0
0.1	1	100	○	19.33	1.03
0.01	1	25	×	-	-
0.01	1	50	×	-	-
0.01	1	100	×	-	-
0.5	1/2	25	○	19.7	1.05
0.5	1/2	50	○	22.48	0.99
0.5	1/2	100	○	34.63	1.06
0.1	1/2	25	○	15.1	1.02
0.1	1/2	50	○	21.55	1.02
0.1	1/2	100	○	32.23	1.01
0.01	1/2	25	×	-	-
0.01	1/2	50	×	-	-
0.01	1/2	100	○	11.73	0.99

Boldrini et al. in prep.

Time ratio

Relaxation time:

$$T_{relax} = \frac{v^3}{8\pi(n_d m_d{}^2 + n_p m_p{}^2) G^2 \ln\left(\frac{r_{200}}{\varepsilon}\right)}$$



Binney & Tremaine 2008

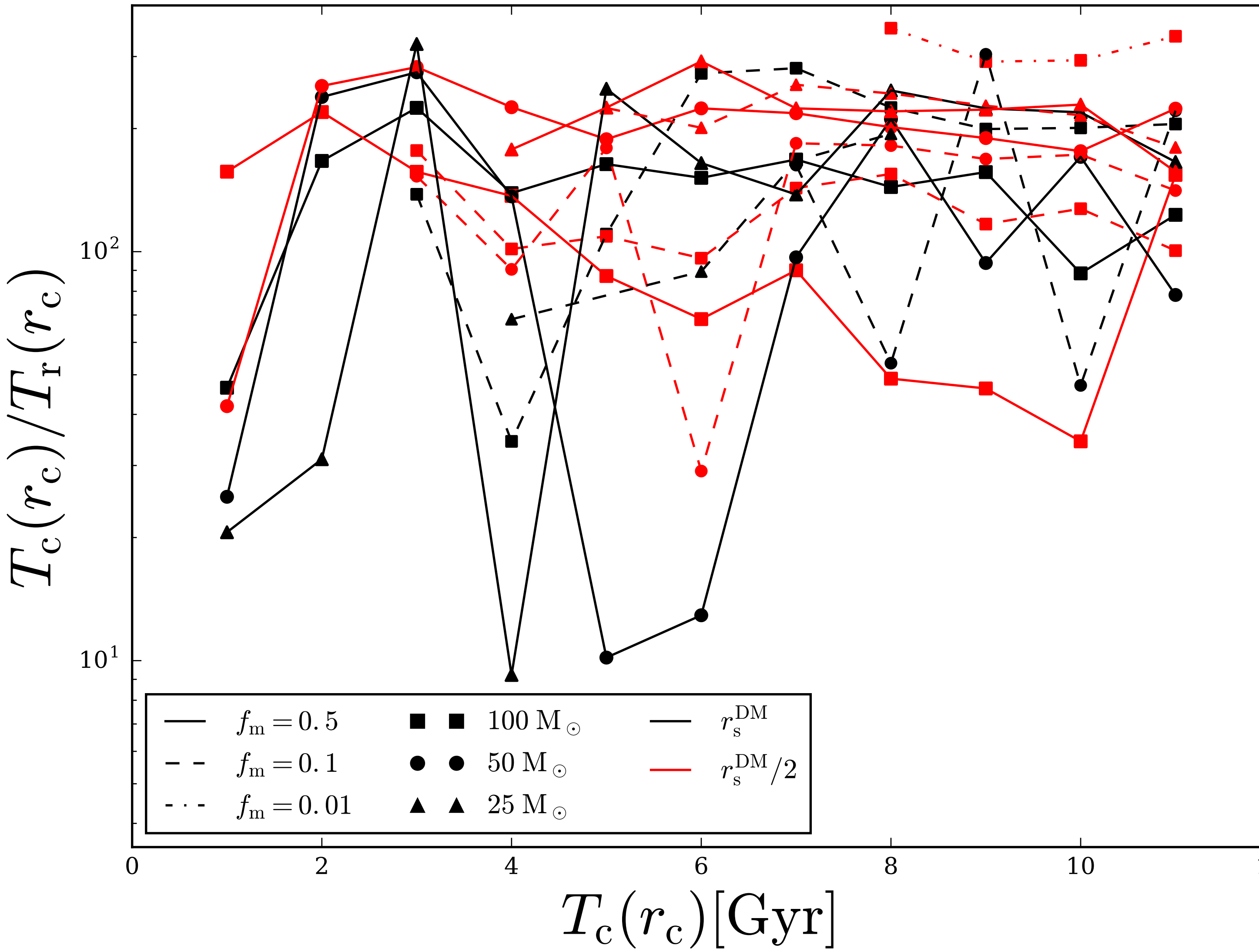
Boldrini et al. in prep.

Time ratio

Relaxation time:

$$T_{relax} = \frac{v3}{8\pi(n_d m_d{}^2 + n_p m_p{}^2)G^2 \ln\left(\frac{r_{200}}{\varepsilon}\right)}$$

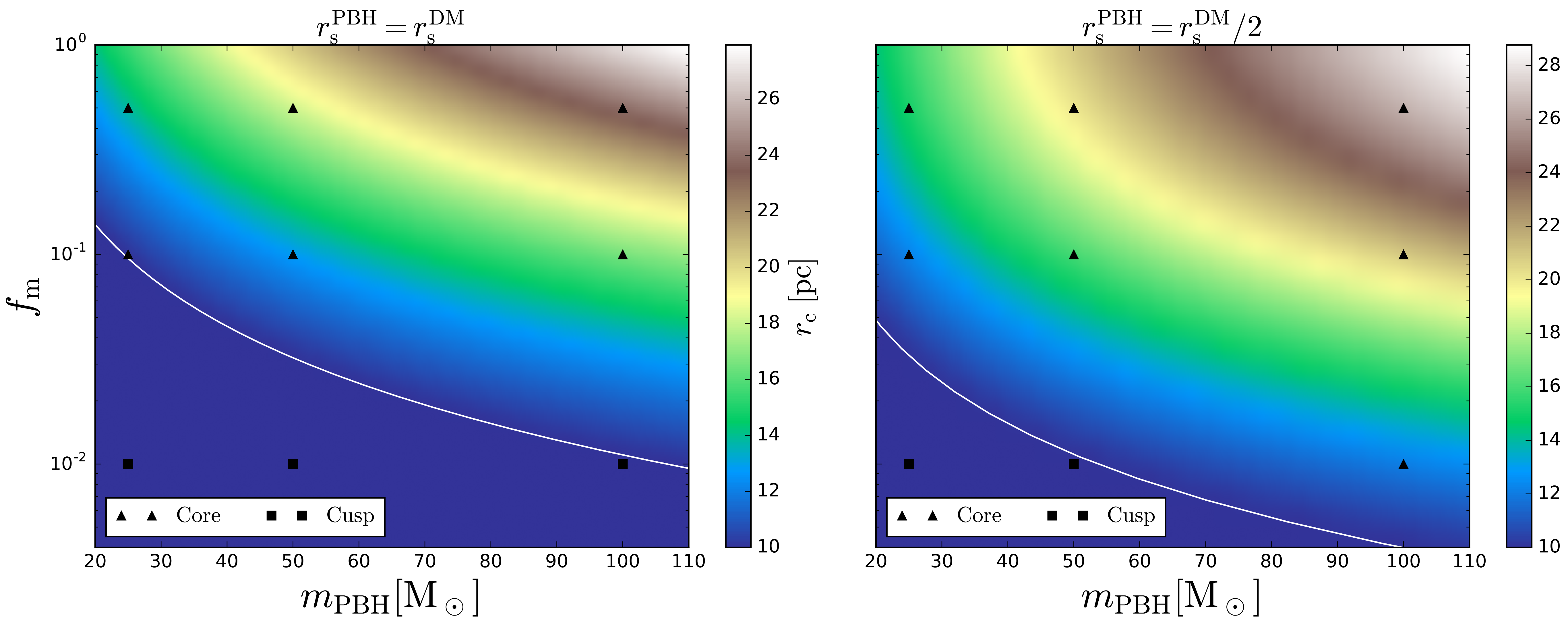
$$\frac{T_c(r_c)}{T_{relax}(r_c)} \sim O(100)$$



Binney & Tremaine 2008

Boldrini et al. in prep.

Core formation: Size



Boldrini et al. in prep.

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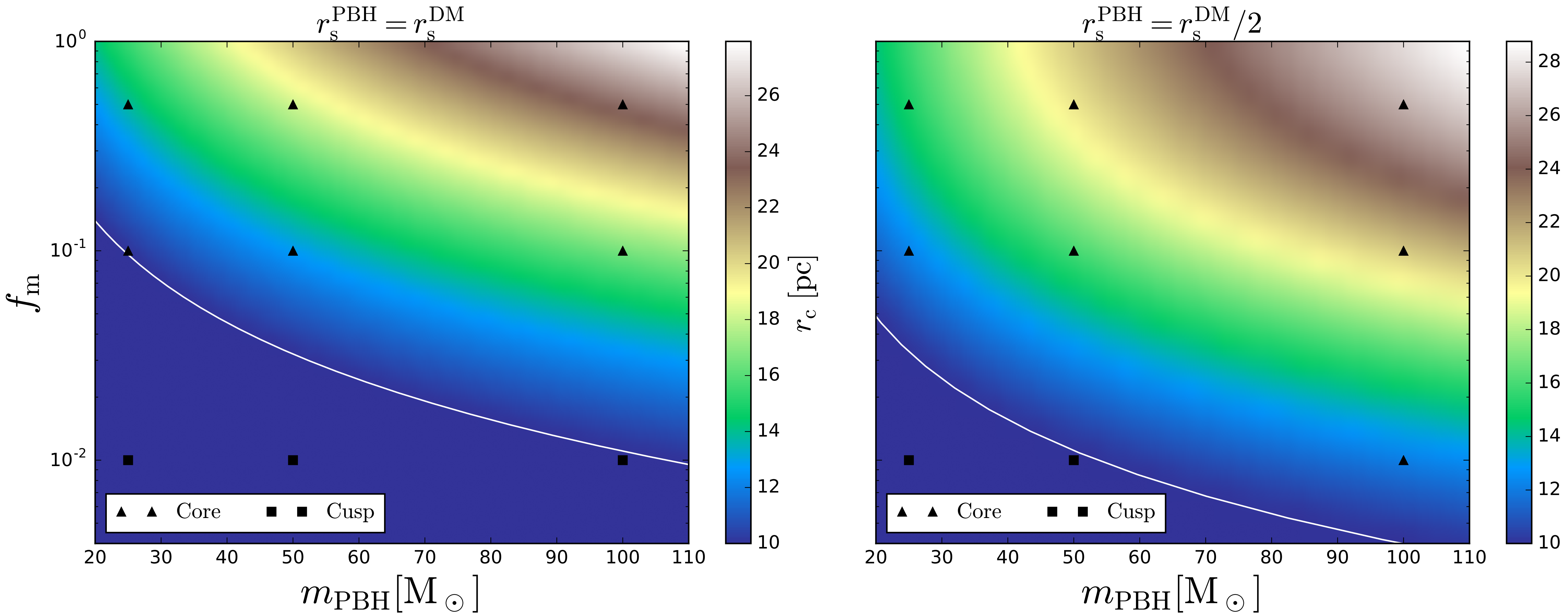
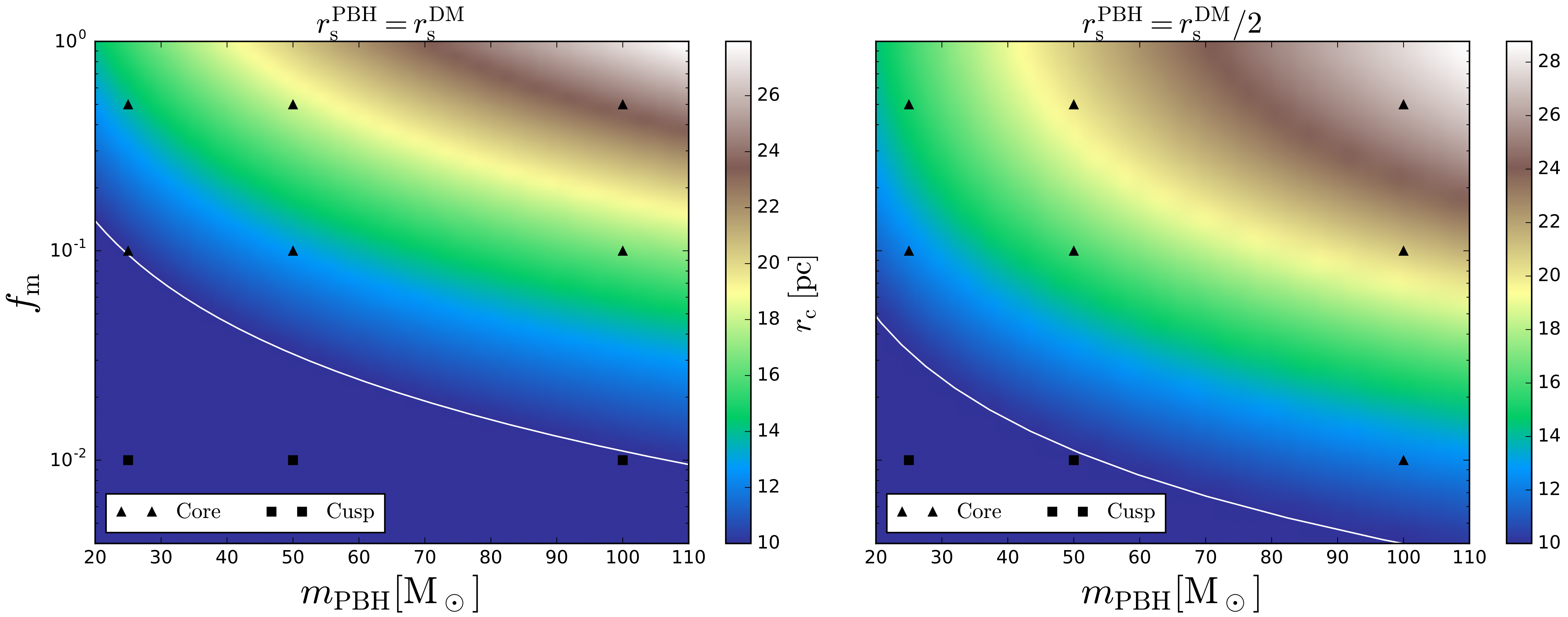


Higher mass and higher density region for PBH generated larger core size

Boldrini et al. in prep.

Core formation: Size

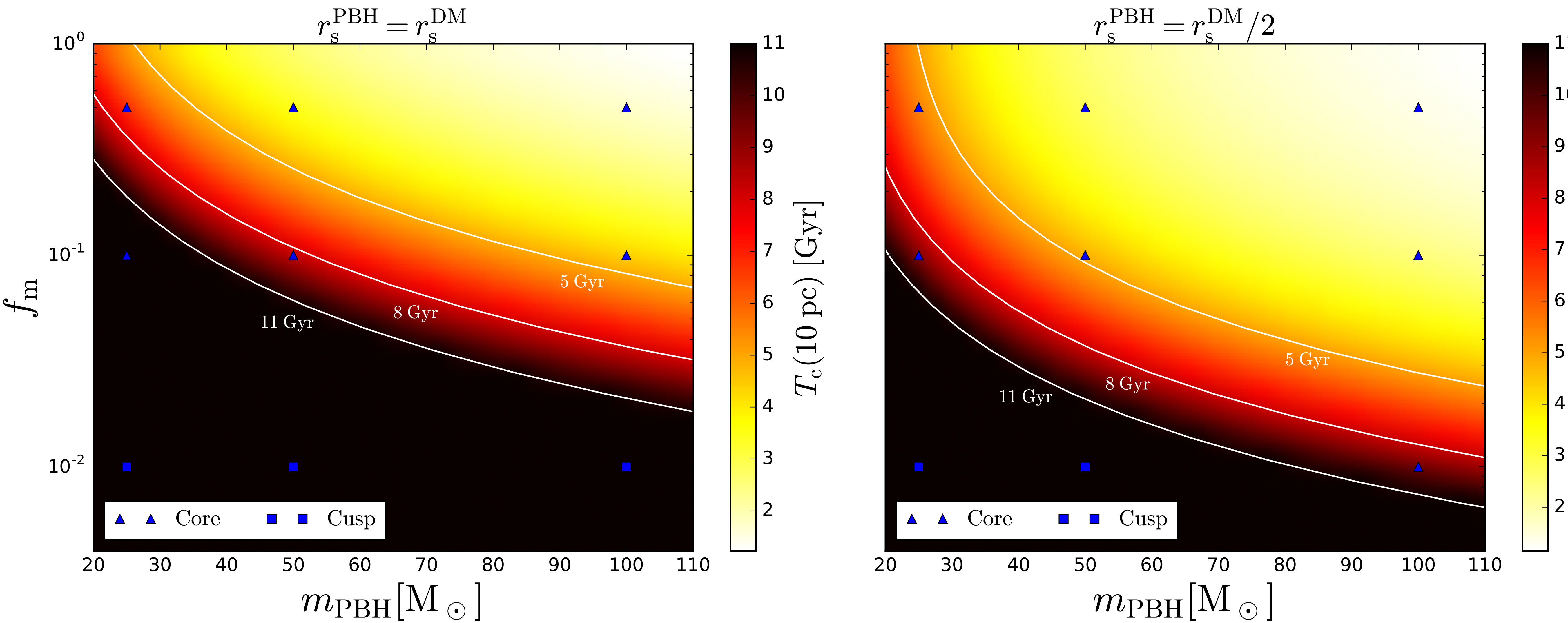


At least 1% of DM can be PBHs

depending on initial PBH distribution

Boldrini et al. in prep.

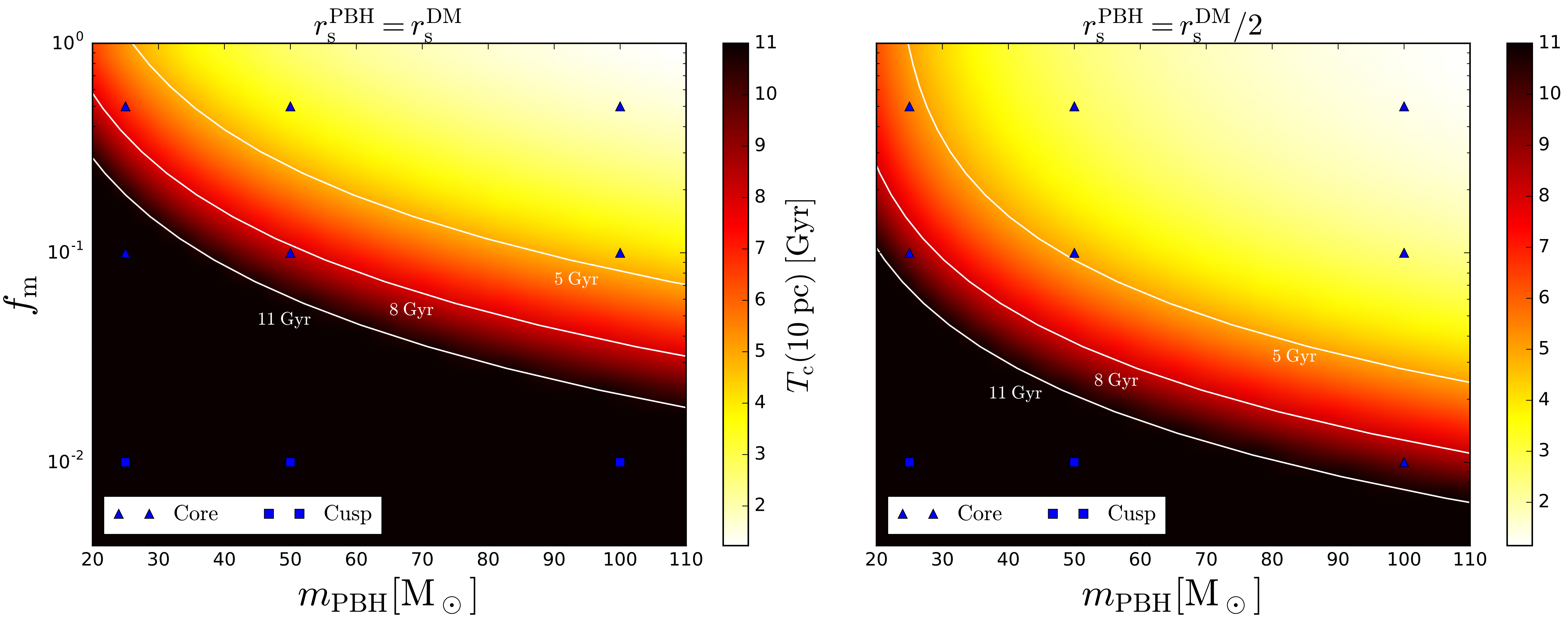
Core formation: Transition time



The transition takes between 1 and 8 Gyr to occur

Boldrini et al. in prep.

Core formation: Transition time



The transition takes between 1 and 8 Gyr to occur

Boldrini et al. in prep.

Prospects

- **Hierarchical Galaxy Formation**

→ Low mass galaxy mergers

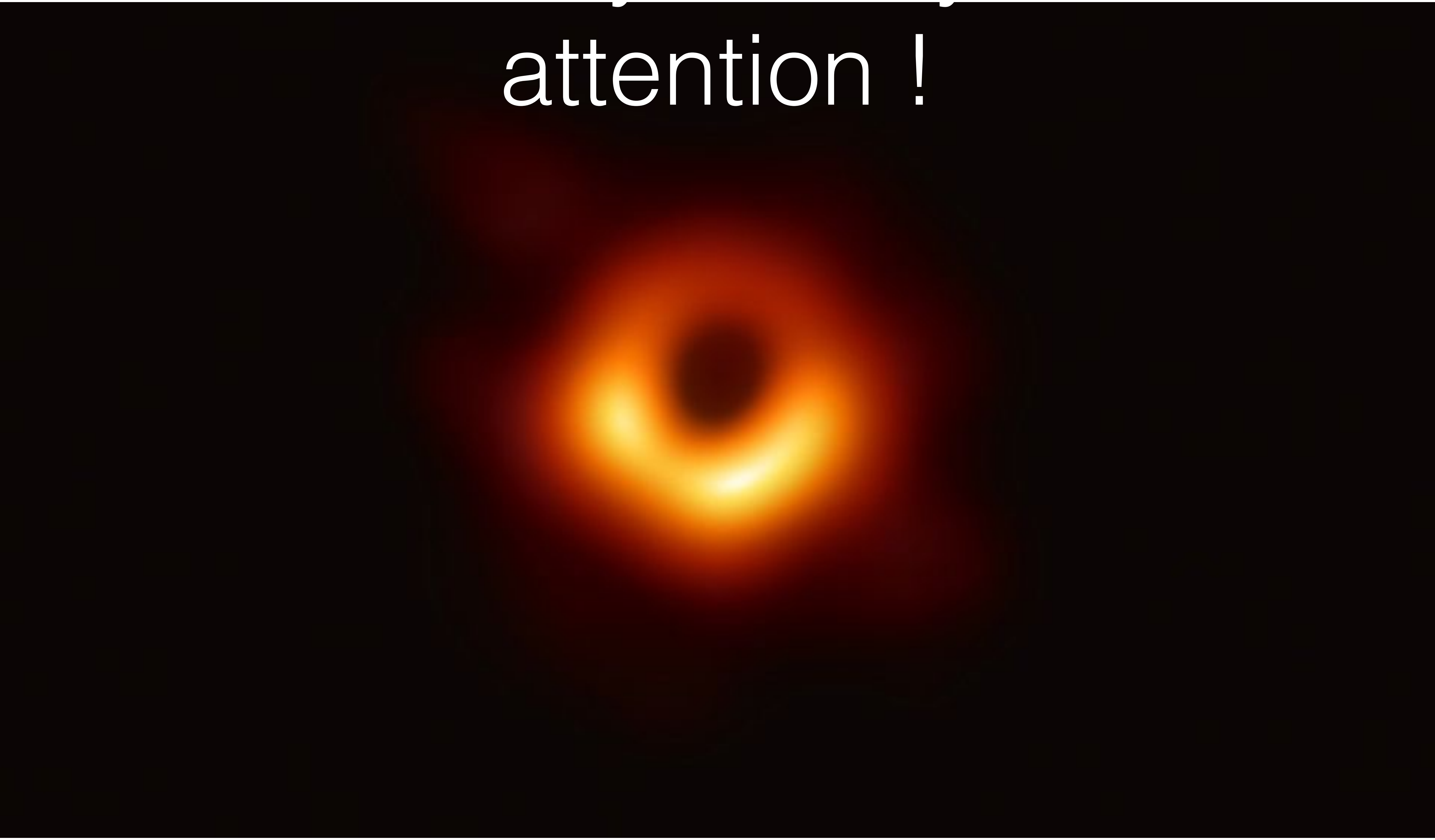
→ Merger of cored halos yields a cored halo (Boylan-Kolchin & Ma 2004)

→ Massive cored galaxies

Boldrini et al. in prep.

Prospects

- **Hierarchical Galaxy Formation**
  - → Low mass galaxy mergers
  - → Merger of cored halos yields a cored halo (Boylan-Kolchin & Ma 2004)
  - → Massive cored galaxies
- **Observations**
  - → Multiple cores
  - → What will observations be? (Boldrini et al. in prep)


attention !

Questions?