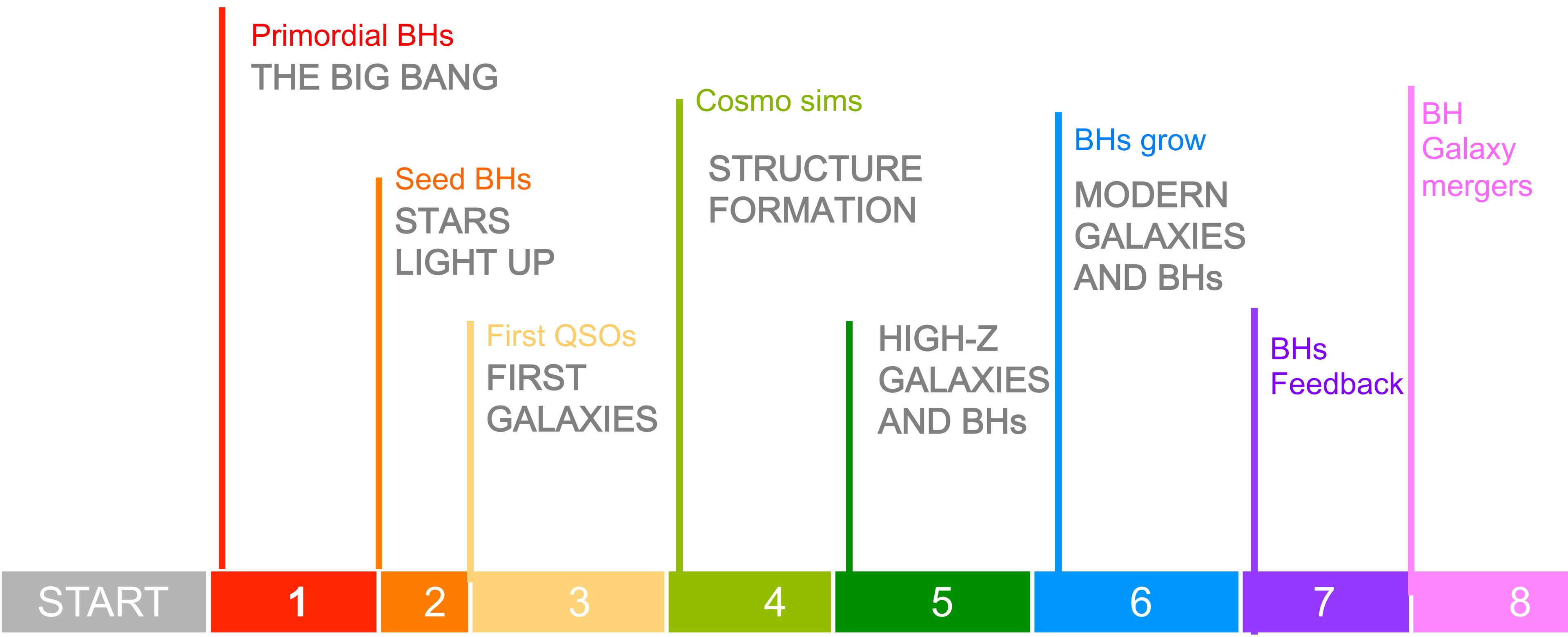
A journey through 13.8 billion years:

BHs across cosmic history



1

Primordial Black Holes

THE BIG BANG

INGREDIENTS + CONDITIONS = $M_{BH} \sim 10^{-5}$g – $10^{5}M_{\odot}$

Density Inhomogeneities @inflation

Radiation dominated

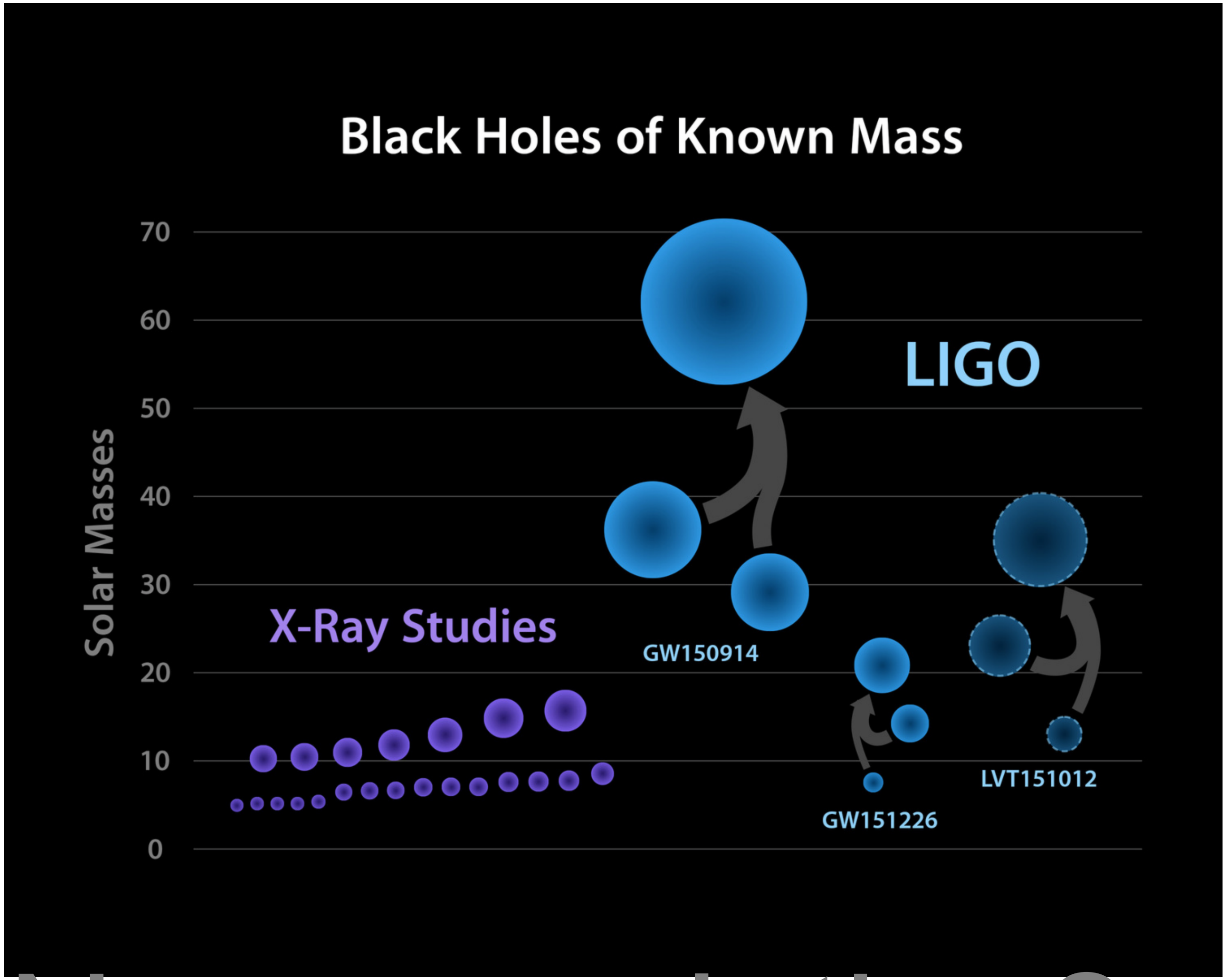
Up to All DM

Only speculate

Only speculate

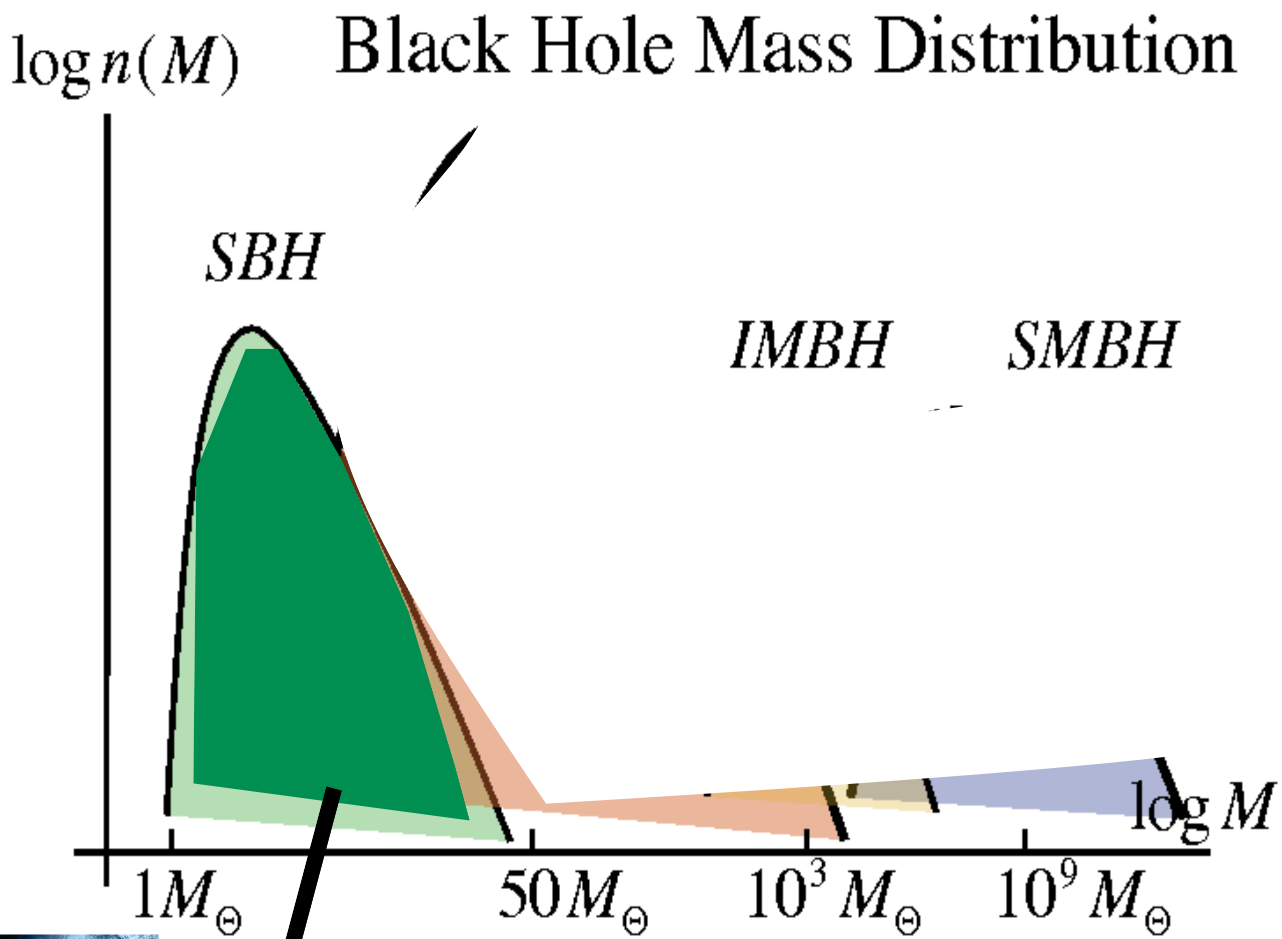
Only speculate

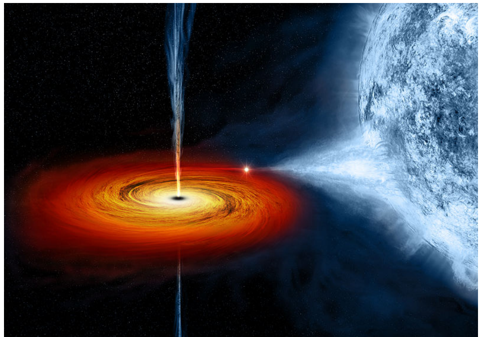
Merging BHs @LIGO



New population?

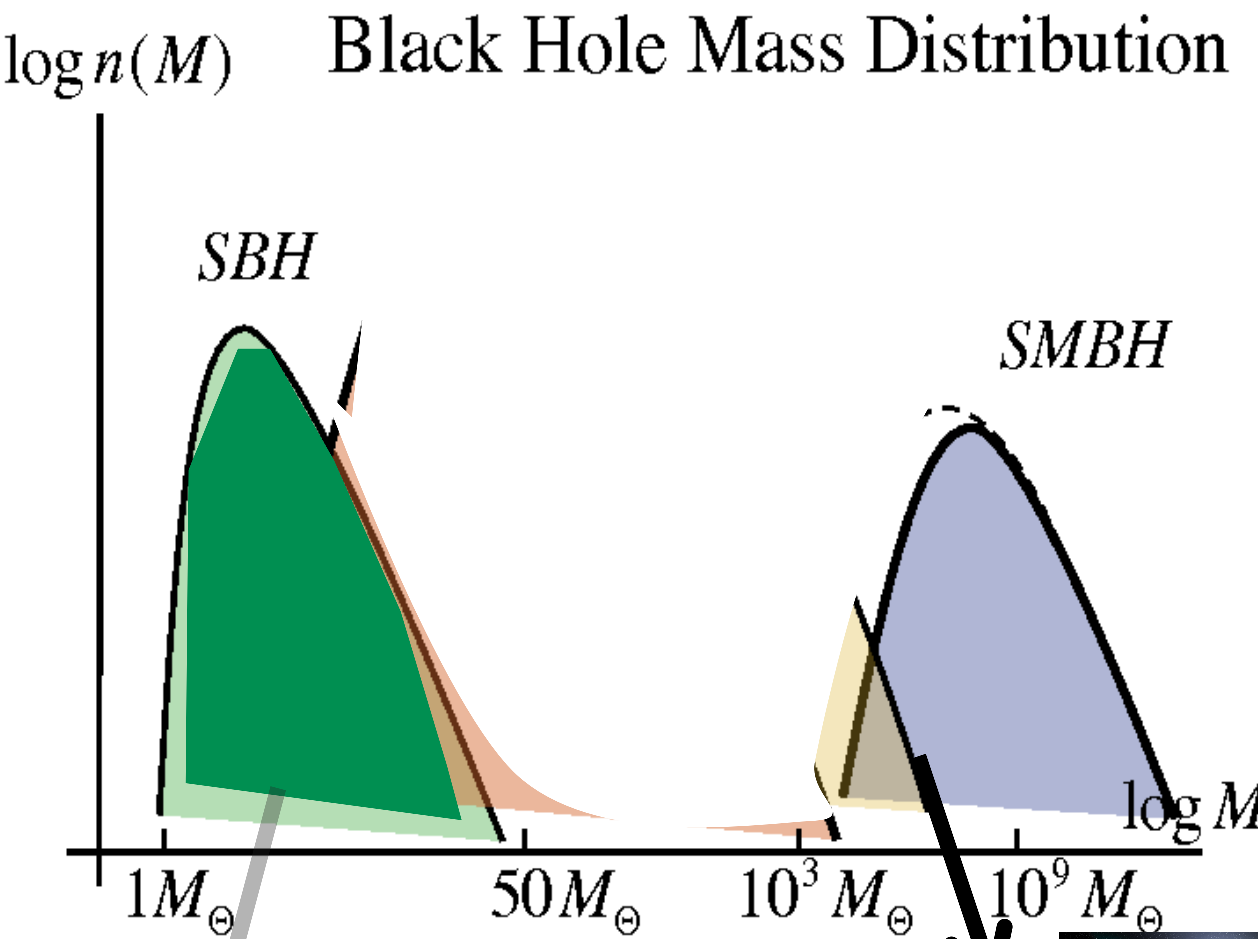
BHs: evidence for stellar mass black holes



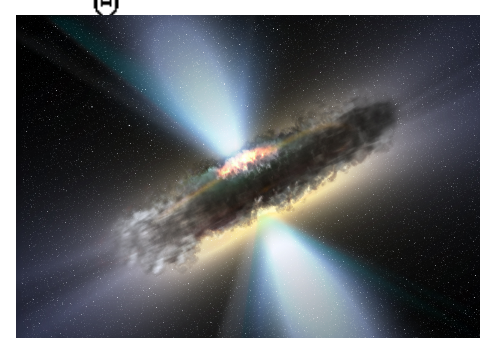


e.g Cygnus X-1
BH birth, LIGO binaries

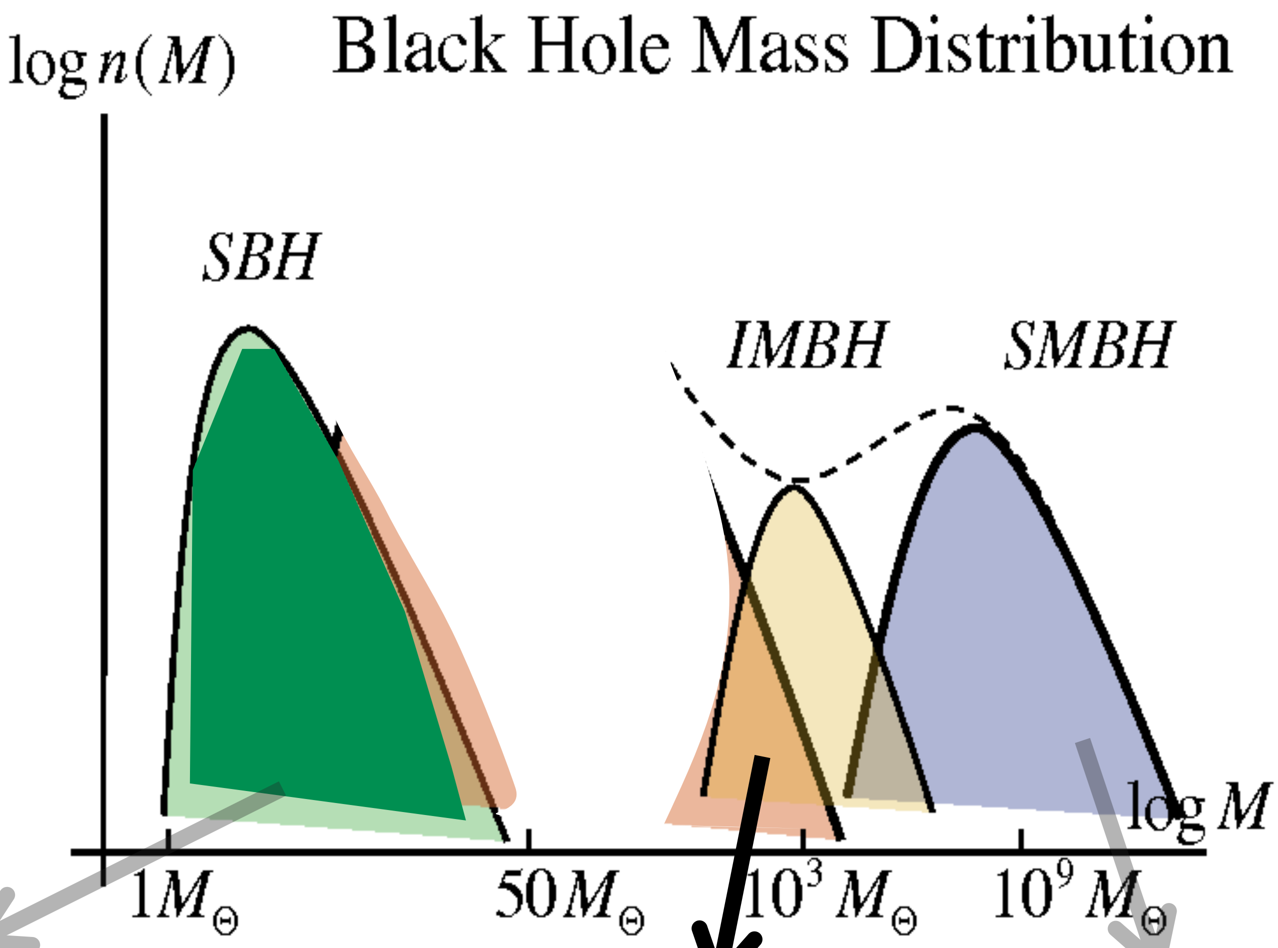
BH: evidence for supermassive black holes



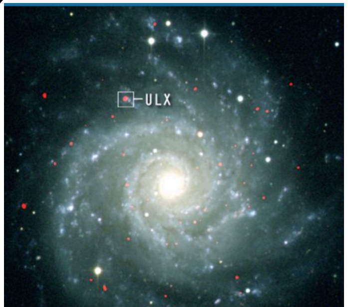
e.g. Milky Way
QSOs
up to 10^{10} $M_\odot$



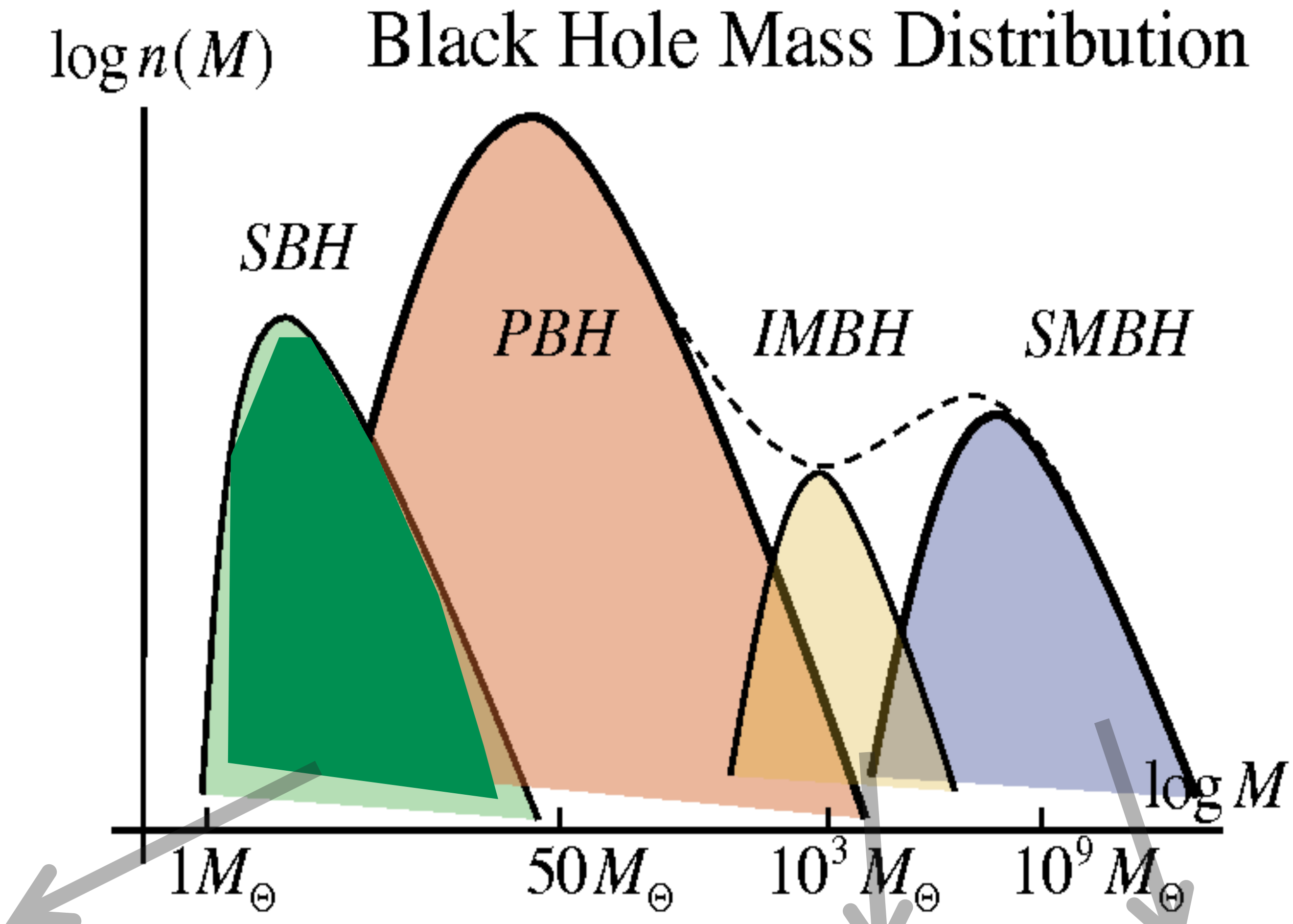
BH: mild evidence for intermediate black holes

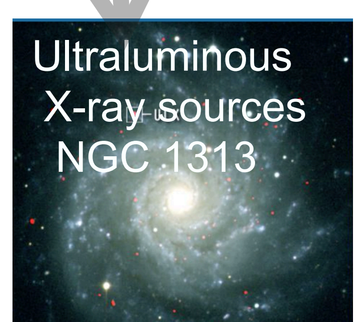


Ultraluminous
X-ray sources
NGC 1313



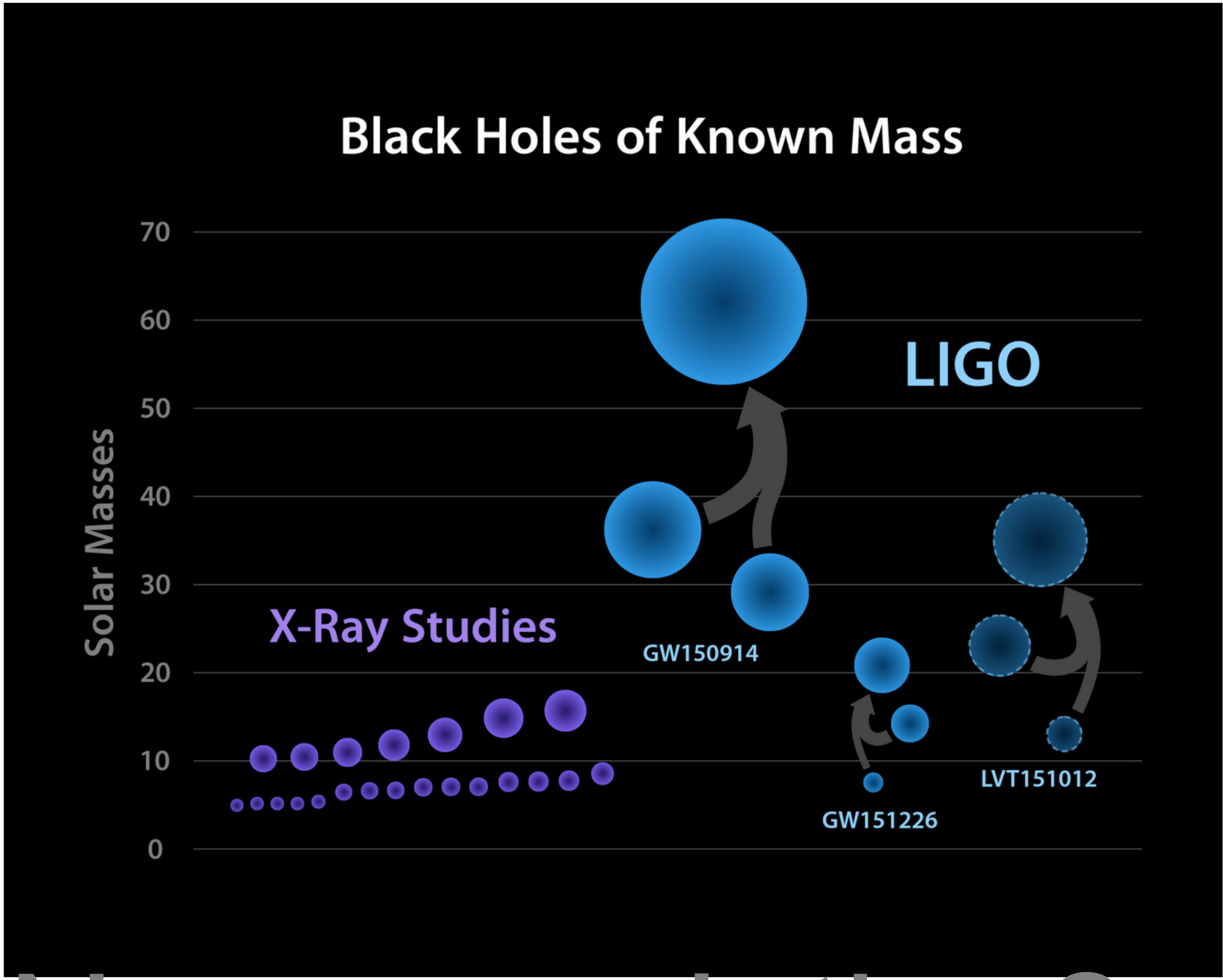
BH: primordial black holes: not yet ruled out





Merging BHs @LIGO

PBHs?



New population?

Merging BHs @LIGO

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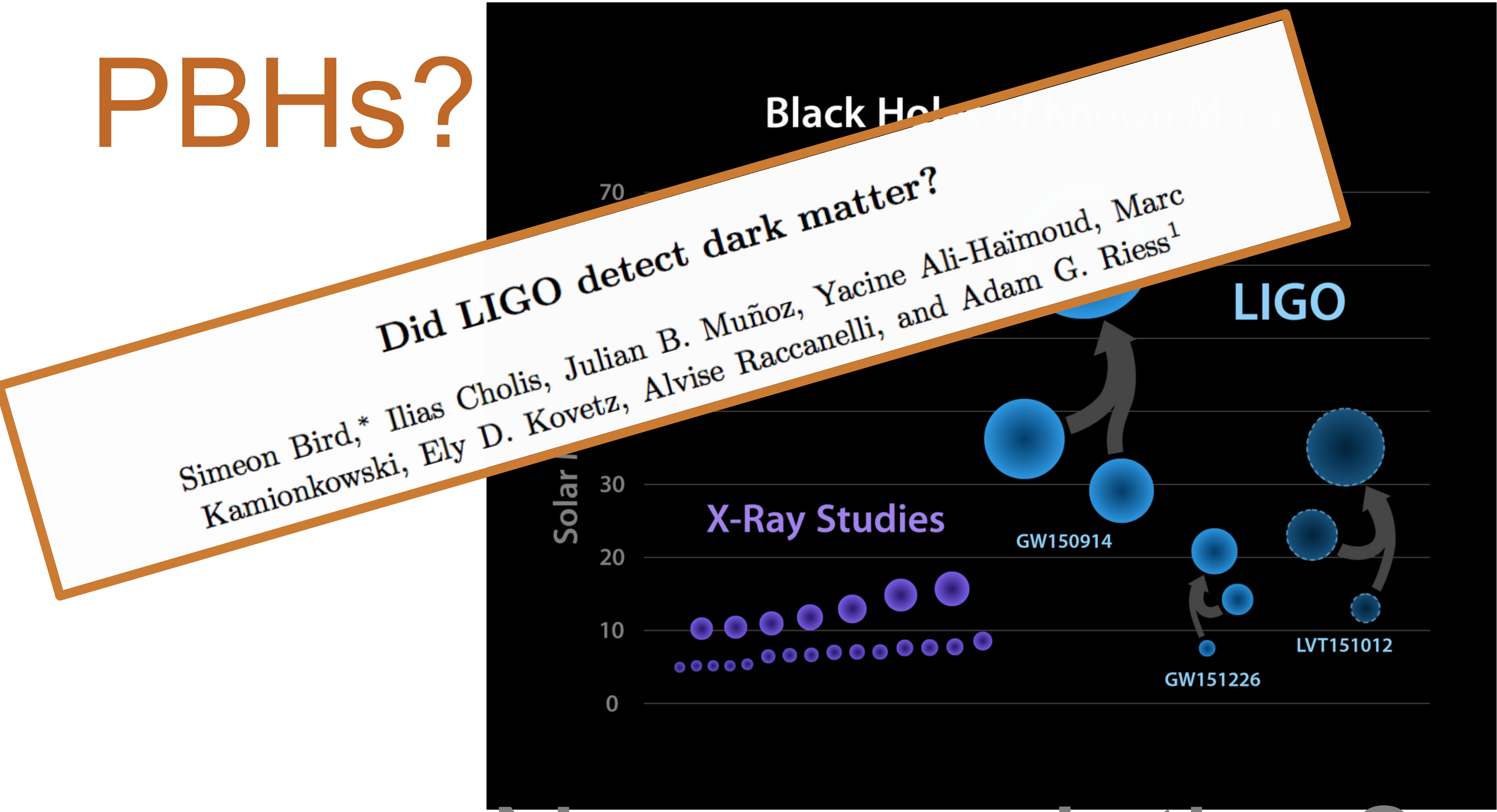


Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

New population?

Primordial BHs

Hawking Radiation

$$T_{BH} \propto \frac{1}{M_{BH}}$$

Gravity + thermodynamics = quantum gravity?

Early Universe that cannot otherwise be probed

Primordial BHs

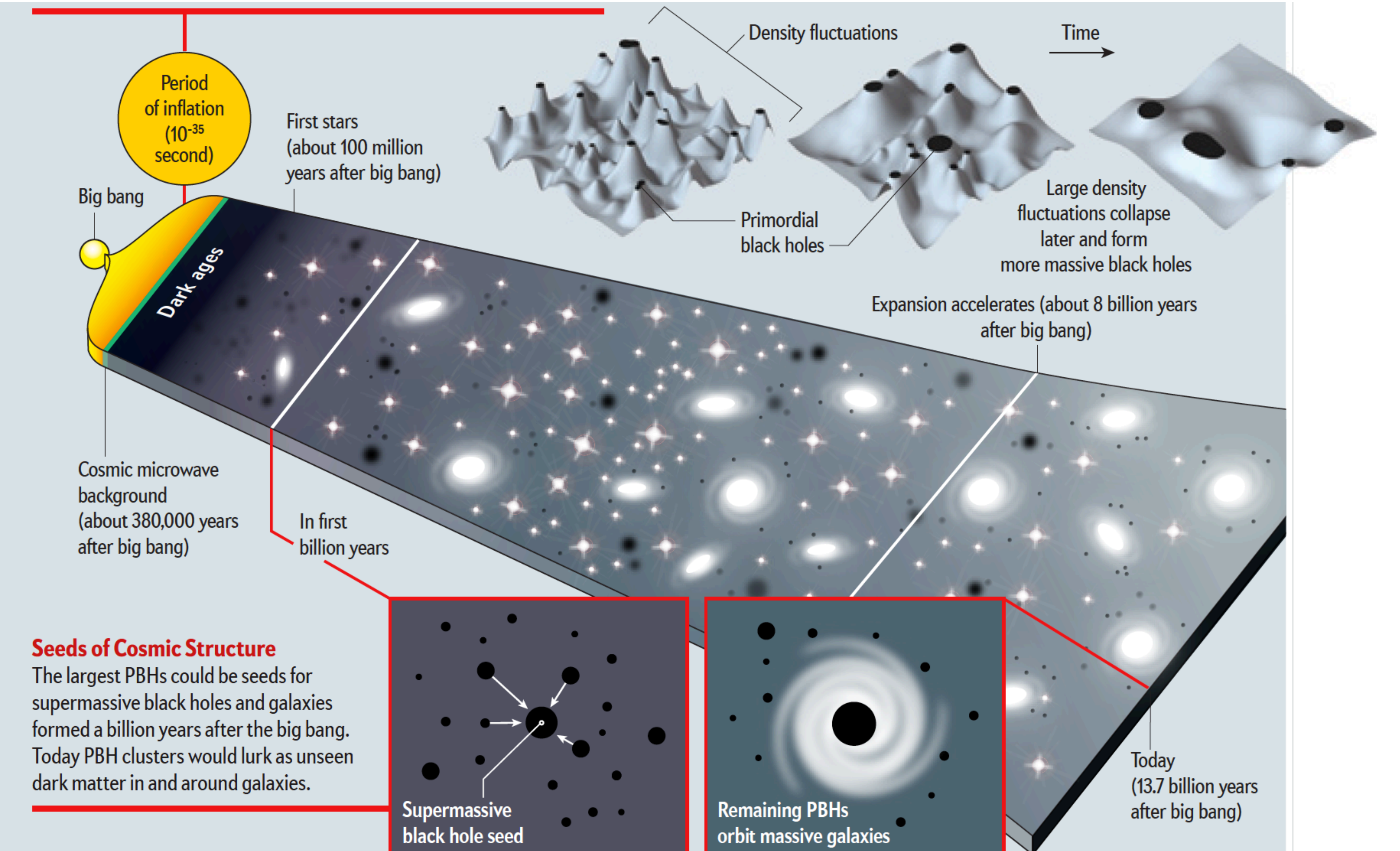
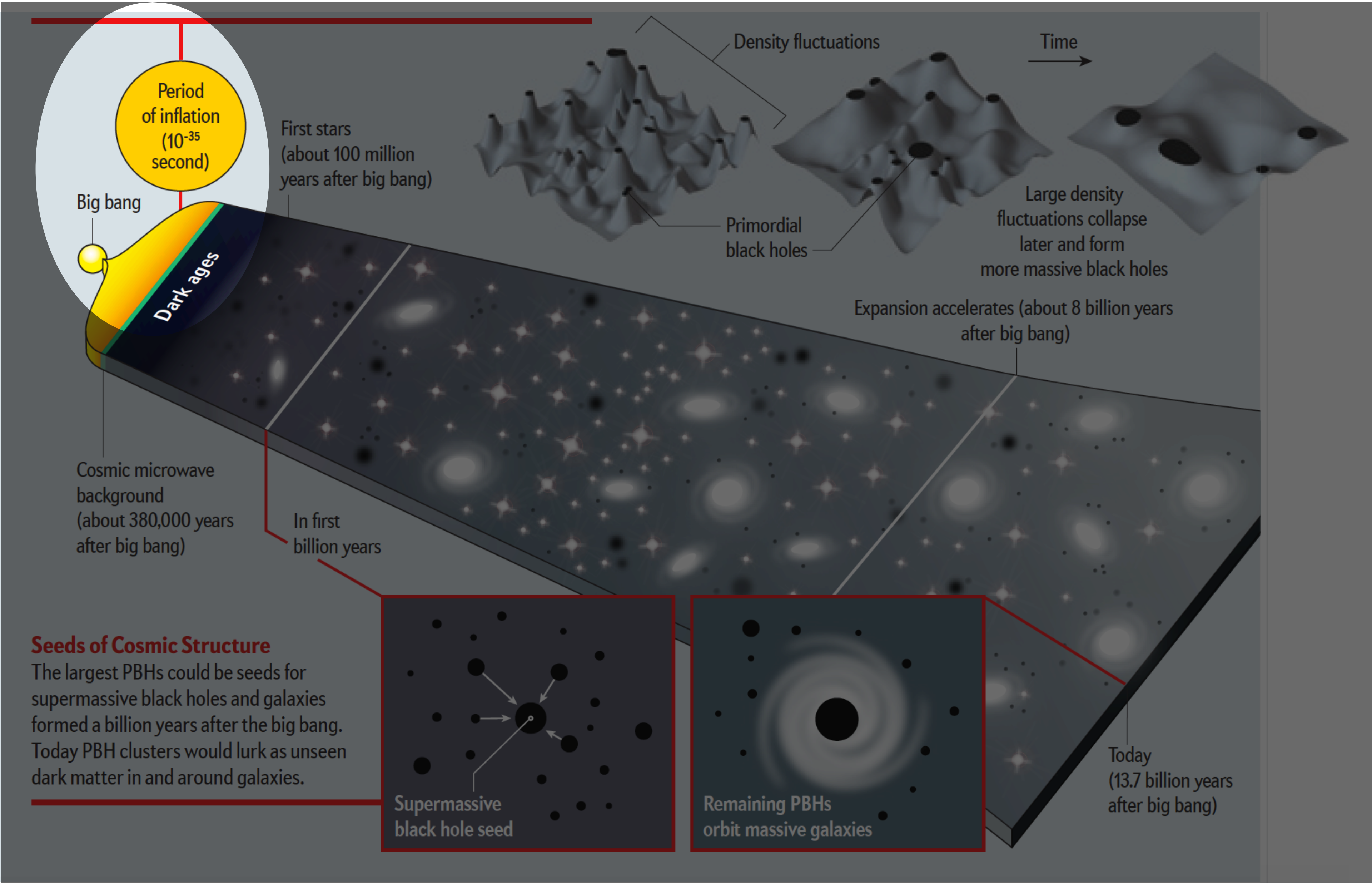


Image: Garcia-Belllido & Clesse in Scientic American

Primordial BHs

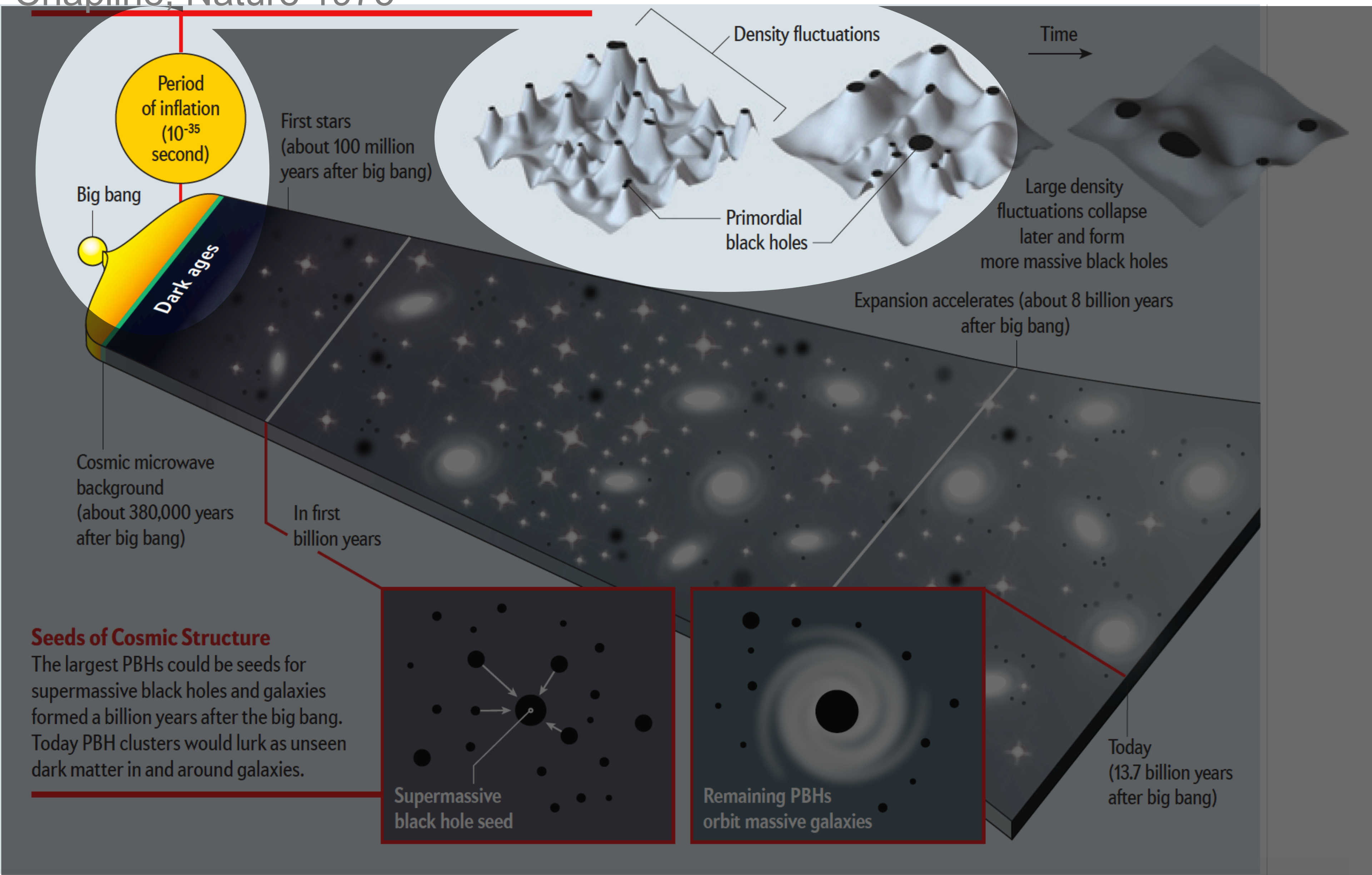


Seeds of Cosmic Structure

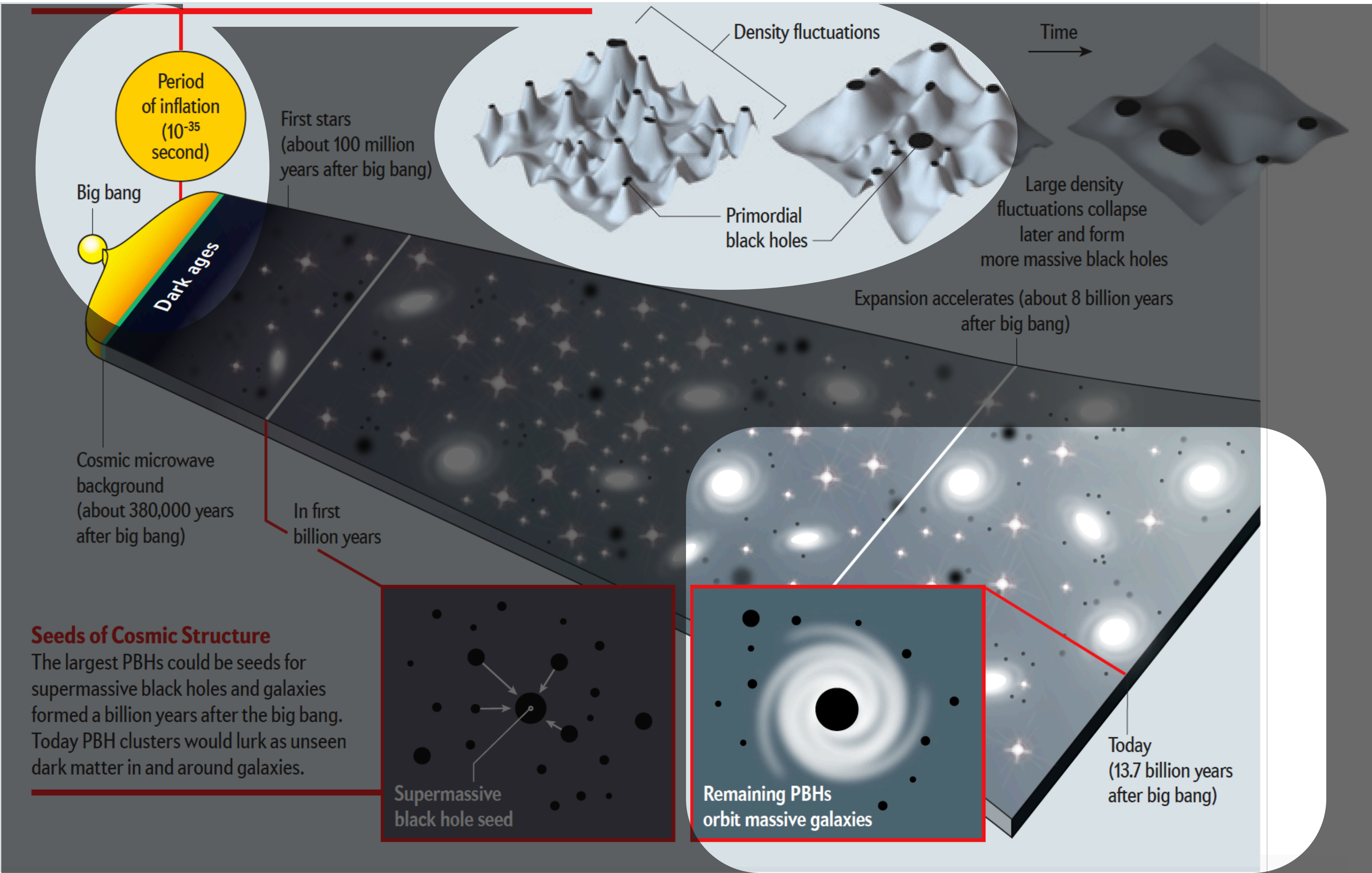
The largest PBHs could be seeds for supermassive black holes and galaxies formed a billion years after the big bang. Today PBH clusters would lurk as unseen dark matter in and around galaxies.

Primordial BHs

Chapline, Nature 1975



Primordial BHs

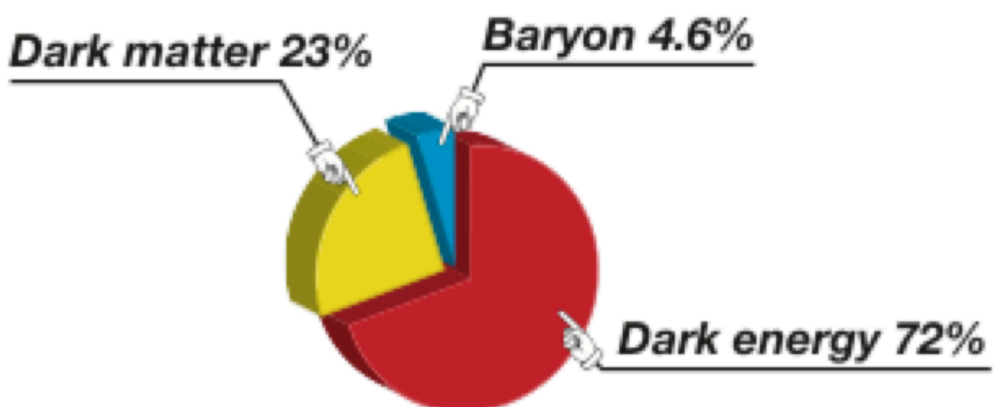


Review by Carr, Kuhnel & Sandastad 17, ‘Primordial BHs as Dark Matter’

30 years and yet no evidence of WIMPS…

Cosmic Microwave Background

$$\Omega_{DM} = 0.27$$



[WMAP collaboration]

IEW D VOLUME 54, NUMBER 10 15 NOVEMBER 1996

Density perturbations and black hole formation in hybrid inflation

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and Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom

. The resulting density inhomogeneities lead to a copious production of black holes.

for certain values of parameters these black holes may constitute the dark matter in the Universe.

quantum fluctuations at the time corresponding to the phase transition between the two inflationary stages can

these models can be made extremely small, but in general it could be sufficiently large to have important cosmological and astrophysical implications. In particular, for certain values of parameters these black holes may constitute the dark matter in the Universe. It is also possible to have hybrid models with two stages of inflation where the black hole production is not suppressed, but where the typical masses of the black holes are very small. Such models lead to a completely different thermal history of the Universe, where postinflationary reheating occurs via black hole evaporation. [S0556-2821(96)00522-X]

PACS number(s): 98.80.Cq

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Massive primordial black holes from hybrid inflation as dark matter and the seeds of galaxies

Sébastien Clesse[1,*] and Juan García-Bellido[2,†]
[1]*Namur Center of Complex Systems (naXys), Department of Mathematics, University of Namur,*

These PBHs could have acquired large stellar masses today, via merging, the model passes both the constraints from CMB distortions and microlensing. the tail of the PBH mass distribution could be responsible for the seeds of supermassive black holes at the center of galaxies, as well as for ultraluminous x-ray sources.

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DOI: 10.1103/PhysRevD.92.023524 PACS numbers: 98.80.Cq

What are primordial BHs?

$R_s = 2GM/c^2 = 3\ (M/M_\odot)$ km

→ $\rho_s = 10^{18} (M/M_\odot)^{-2}$ g/cm^3

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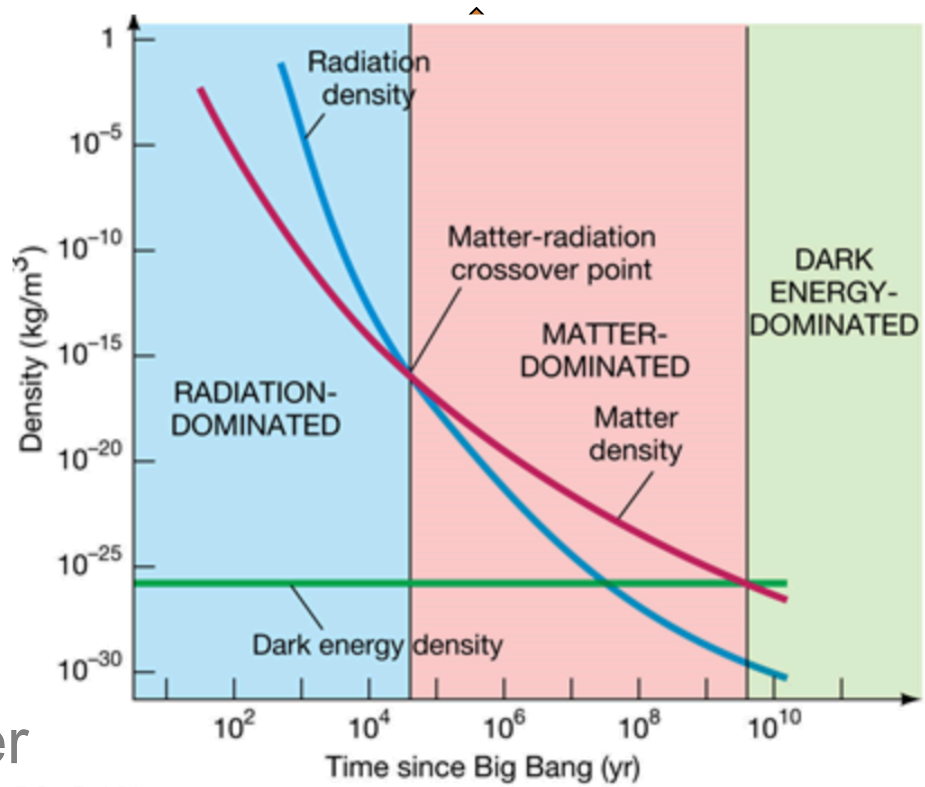
Cosmological density:

Radiation dominated:
$\rho \sim a(t)^{-4}$
$a(t) \sim t^{1/2}$



$a(t) = 1/(1+z)$, scale parameter

What are primordial BHs?

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Cosmol

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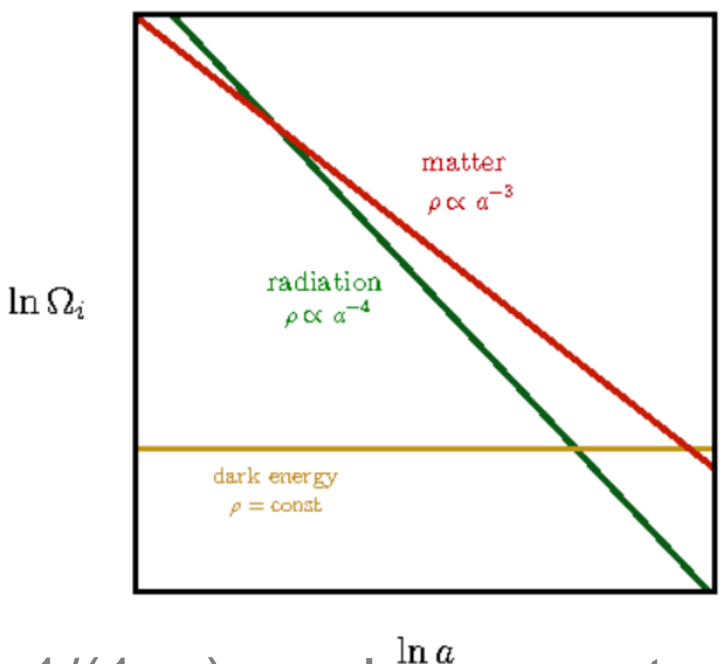

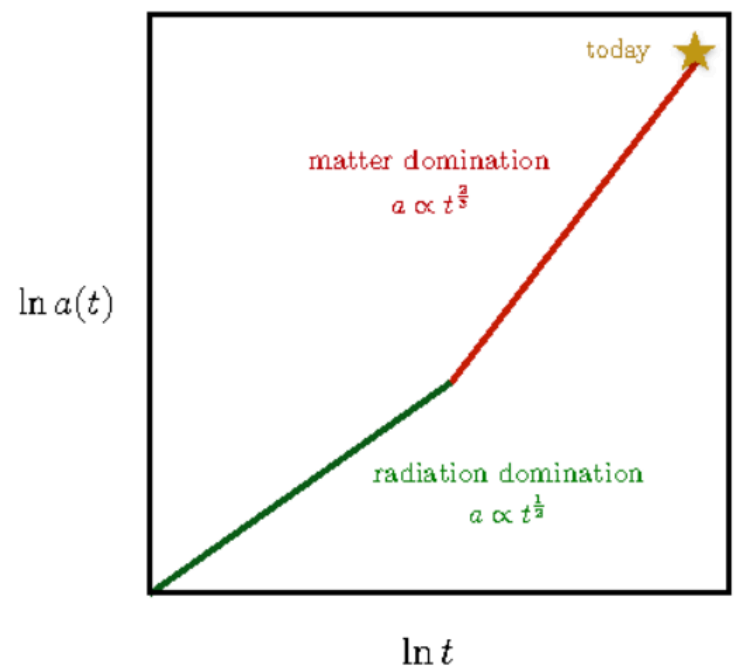

a(t)=1/(1+z), scale parameter

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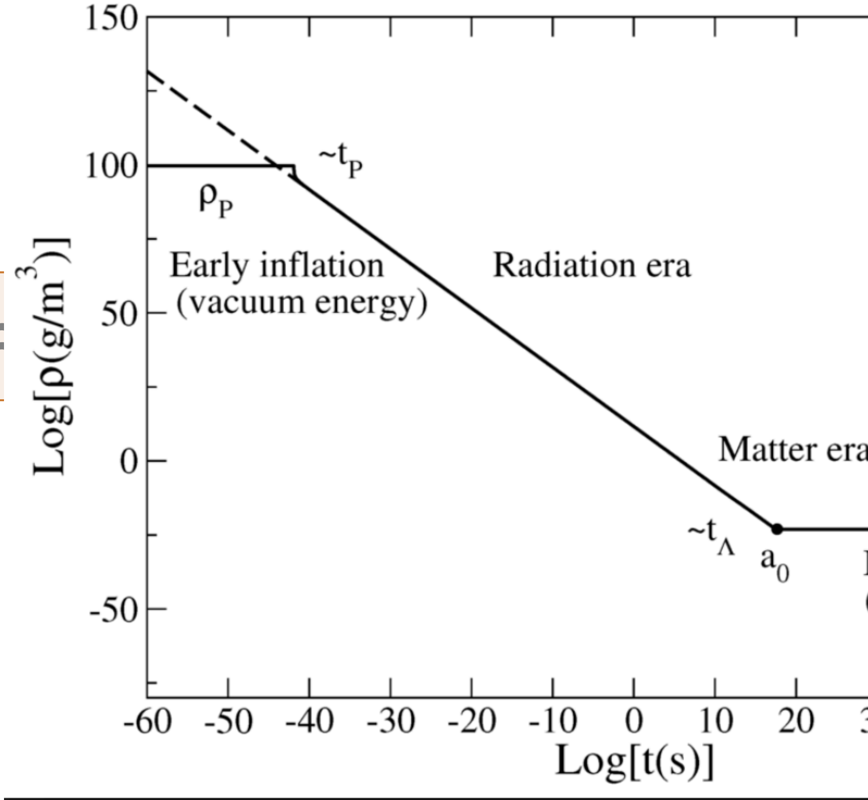
$\rho \approx (1/\ t^2)$



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$\rho_s = 10^{18} (M/M_\odot)^{-2}$ g/cm^3

Cosmological density:

Radiation dominated:
$\rho \sim a^{-4}$
$a(t) \sim t^{1/2}$

$\rho \approx (1/Gt^2) \approx 10^6 (t/1s)^{-2}$ g/cm^3

During rad era $c_s = c/\sqrt{3}$

$R_s \sim R_{jeans} \sim R_h$

What are primordial BHs?

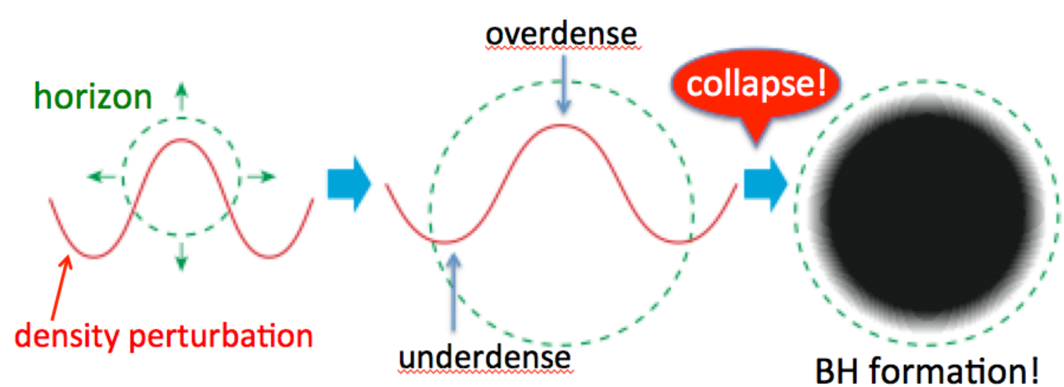
Collapsed relativistic matter: Radiation
PBH have horizon mass at time of formation

$M_{PBH} = c^3t/G =$

- 10^{-5}g @$t=10^{-43}$s (min)
- 10^{15} g $t=10^{-23}$s (evap.
- $10^5\ M_\odot$ $t= 1$s (max)

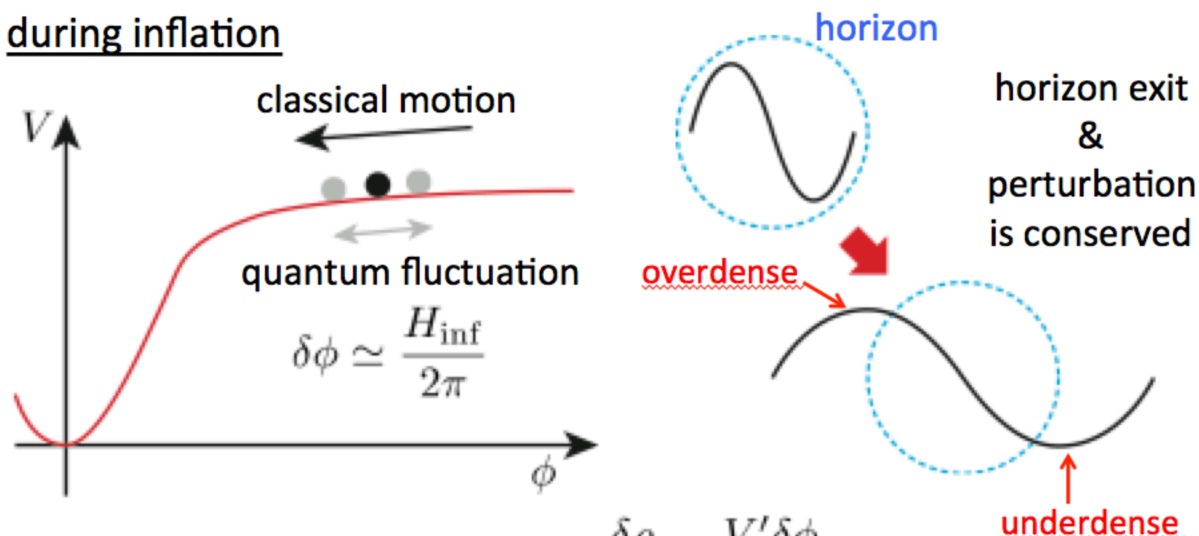
Huge range of masses

need large inhomogeneities to collapse



What are primordial BHs?

PBH form from primordial inhomogeneities
@Inflation

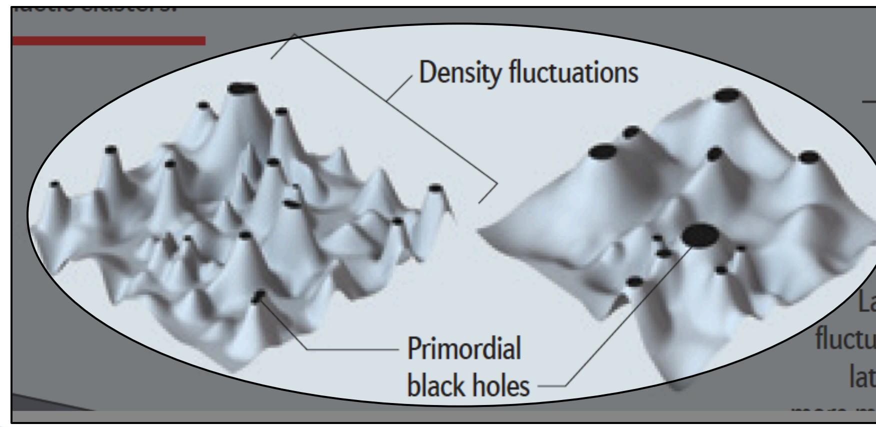


Density perturbation of ϕ : $\frac{\delta\rho}{\rho} \simeq \frac{V'\delta\phi}{V}$

Overdense regions can then stop expanding and recollapse

What are primordial BHs?

PBH form from primordial inhomogeneities @Inflation



Form in the quasi-linear regime (δ_c > 20-40%)

$$M = kM_H(\delta-\delta_c)^\gamma$$

Critical collapse rad. era (GR sims)

See Carr, Kuhnel, Sandstadt+17

What are primordial BHs?

PBH form from primordial inhomogeneities
@Inflation

Other models:

- Pressure reduction/phase transition

(QCD: 1 M_{sun} or e+-e- annih. $10^5 M_{sun}$) (e.g. Kholopov &Polnarev80,Jedamizid 97)

- Cosmic strings (e.g. Polnarev&Zemboricz88,Hawking 89, Branderberger Wichozki98

- Bubble collisions (e.g.Crawford & Schramm82, La& Steinhardt89)

Collapsed fraction and relics

$\Omega_{PBH} \sim \beta\Omega_r(1+z) \sim \beta t^{-1/2}$

given $M = c^3 t/G$

$\Rightarrow \quad \Omega_{PBH}/\Omega_{DM} \sim (M/1M_\odot)^{-1/2} (\beta/10^{-9})$

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β = fraction of mass in the universe in PBHs

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β = fraction of mass in the universe in PBHs

$\Omega_r = 10^{-4}$ density in CMB and $\Omega_{DM} = 0.27$

$(1+z) \rightarrow$ radiation $\sim(1+z)^4/$ matter$\sim(1+z)^3$

Collapsed fraction and relics

$\Omega_{PBH} \sim \beta\Omega_r(1+z) \sim \beta t^{-1/2}$

given $M = c^3 t/G$

$\Rightarrow$ $f = \Omega_{PBH}/\Omega_{DM} \sim (M/1M_\odot)^{-1/2}\,(\beta/10^{-9})$

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Collapsed fraction and relics

$\Omega_{PBH} \sim \beta\Omega_r(1+z) \sim \beta t^{-1/2}$

given $M = c^3 t/G$

⇒ $f = \Omega_{PBH}/\Omega_{DM} \sim (M/1M_\odot)^{-1/2}\,(\beta/10^{-9})$

β = fraction of mass in the universe in PBHs

$\Omega_r = 10^{-4}$ density in CMB and $\Omega_{DM} = 0.27$

A very small value of β can give all the DM
Tiny collapsed fraction during rad. era may produce all the DM

Collapsed fraction and relics

Example:

Take QCD era:

$t=10^{-5}$ s

$M_{PBH} \sim M_h \sim 1\ M_\odot$

$\beta = 10^{-9} \rightarrow \Omega_{pbh}/\Omega_{DM}=1$

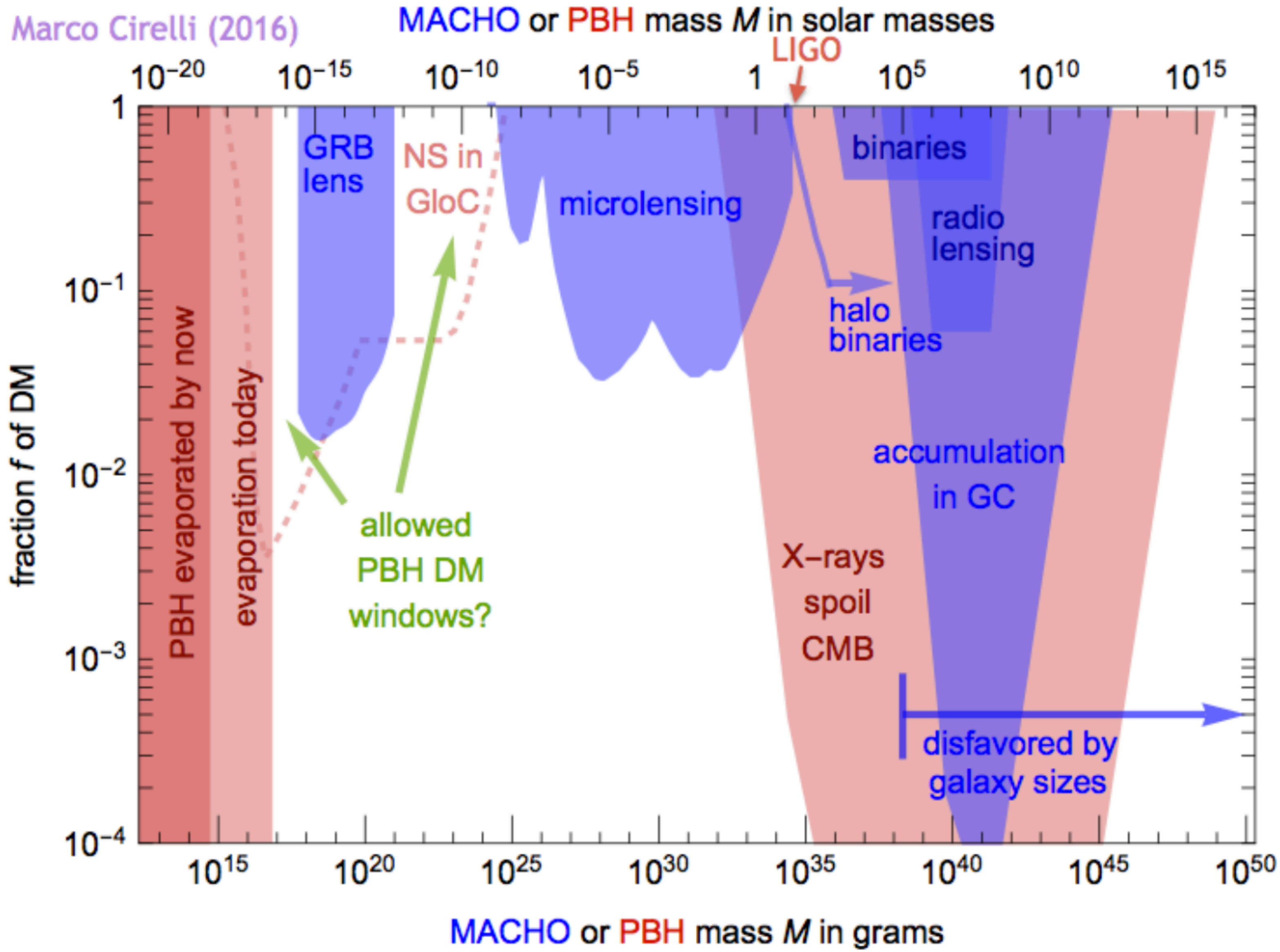
all the DM is made of PBH

Why do we care about PBH

- Physics on scales otherwise inaccessible by observations
- The dark matter can be made of PBH
- Produce MACHO, IMBH, ULX
- Perhaps the seed for SMBHs

Astrophysical constraints:

See Carr, Kuhnel, Sandstadt+17 and refs



Astrophysical constraints:

Microlensing:

- Initial MACHO results: observed 17 events and claimed these were consistent with compact objects with mass 0.5 Msun contributing to 20% of halo mass (Alcock et al. 2000)

- Later these constraints revisited by EROS, OGLE etc.. And attributed to self-lensing or clumping of the halo.

- More with Kepler…

Limits on Fig. are from null detections.

Astrophysical constraints:

Dynamical constraints:

- Unbinding of soft binaries in the halo
- Disk heating and instability
- Stability of tidal streams
- Heating of stars in dwarf gal. (ultra-faint dwarfs)

Astrophysical constraints:

GW constraints

Primordial binaries (Sasaki et al. 16)

Binary formation by capture in mini halos (Bird et al.16, Kovetz17)

Astrophysical constraints:

GW constraints

Binary formation
 by capture in
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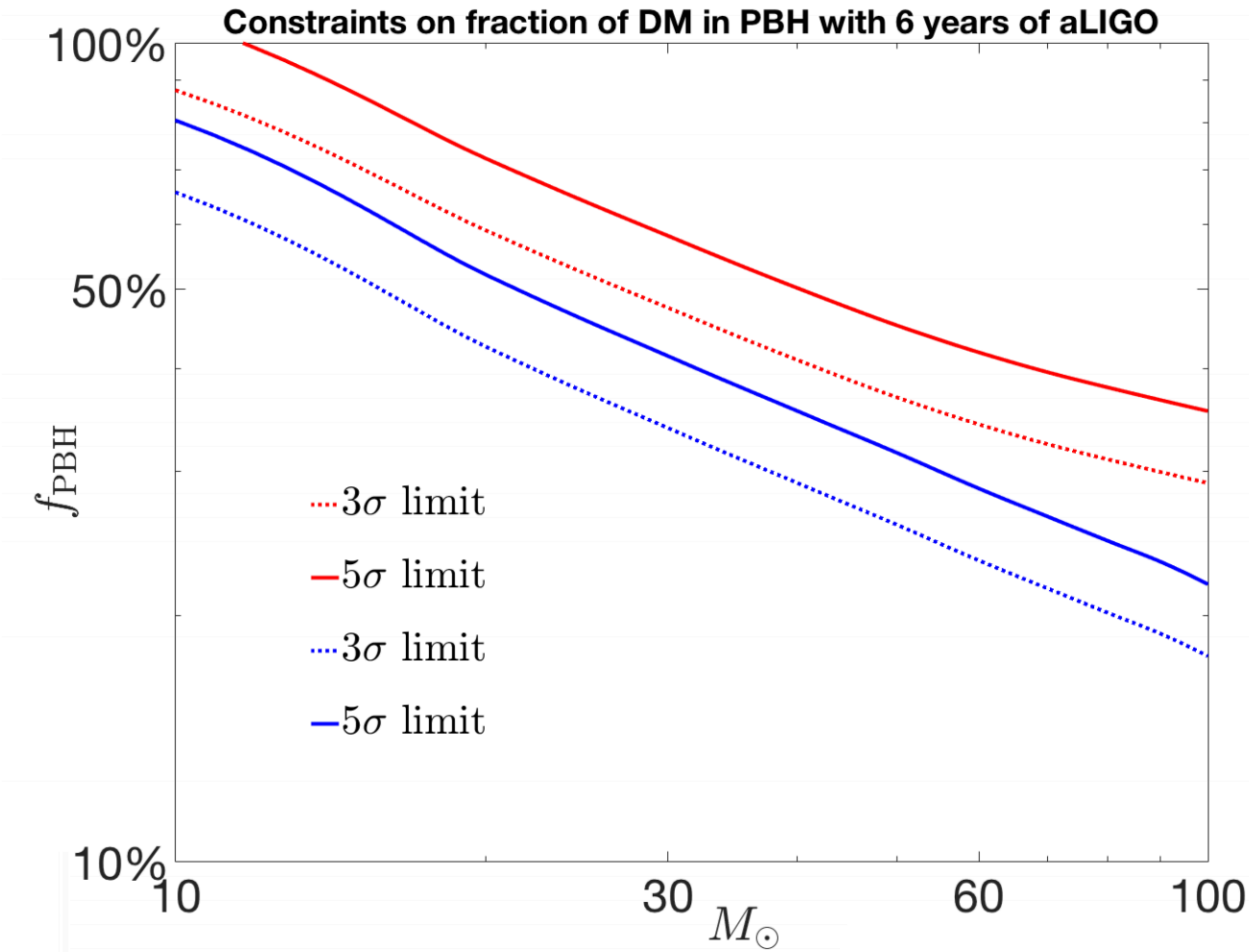

Astrophysical constraints:

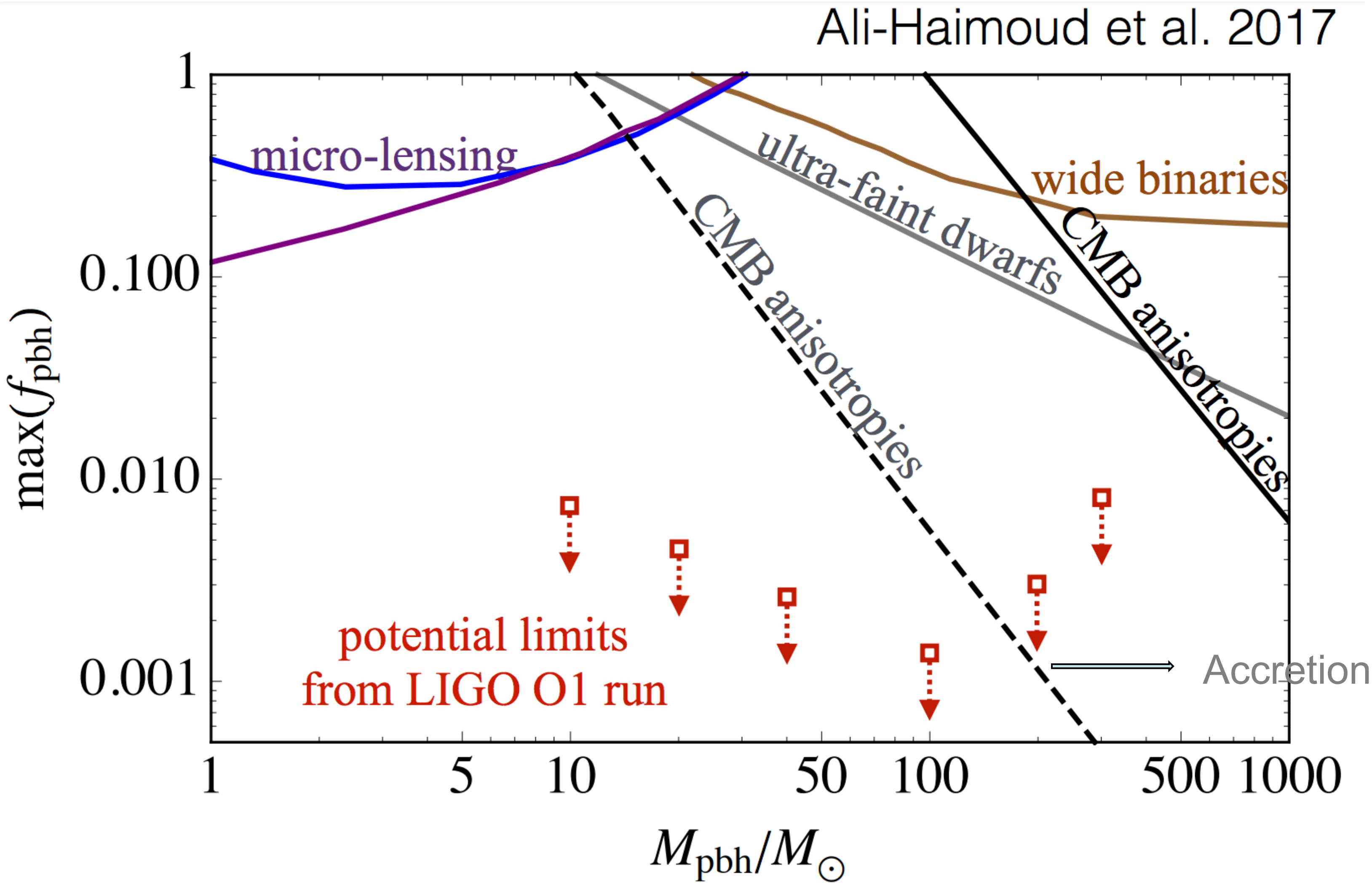

FIG. 7. Potential upper bounds on the fraction of dark matter I n PBHs as a function of their mass (red arrows). These bounds need to confirmed by numerical simulations. For comparison we also show the microlensing limits from the EROS [21] (purple) and MACHO [20] (blue) collaborations limits from wide Galactic binaries [22], ultrafaint dwarf galaxies [25], and CMB anisotropies [24].

SURVEY MONKEY I:

https://www.surveymonkey.com/r/MSVVHXK