Primordial Black Holes in dwarf galaxies and in the high-z Universe

Savvas M. Koushiappas

Non-baryonic dark matter

Mon. Not. R. astr. Soc. (1974) 168, 399-415.

BLACK HOLES IN THE EARLY UNIVERSE

B. J. Carr and S: W. Hawking

(Received 1974 February 25)

SUMMARY

The existence of galaxies today implies that the early Universe must have been inhomogeneous. Some regions might have got so compressed that they underwent gravitational collapse to produce black holes. Once formed, black holes in the early Universe would grow by accreting nearby matter. A first estimate suggests that they might grow at the same rate as the Universe during the radiation era and be of the order of 1015 to 1017 solar masses now. The observational evidence however is against the existence of such giant black holes. This motivates a more detailed study of the rate of accretion which shows that black holes will not in fact substantially increase their original mass by accretion. There could thus be primordial black holes around now with masses from 10^{-5} g upwards.

<u>T</u>

Axions **Neutrinos** WIMP's Flavor-mixed dark matter Q-balls **Monopoles** Planck relics **Primordial black holes** Quark nuggets Shadow matter Mirror matter

Cosmic strings **Wimpzillas** Colour droplets D-matter Krypton **CHAMPs** Brane World Dark Matter Pyrgons MeV dark matter

…

Fundamental questions about primordial black holes

- When and how are they form?
- When and how can we infer their existence?

What would it take to establish their existence?

- Direct observation (e.g., gravitational waves)
- Indirect observation (e.g., effects in the early universe, CMB, energetic backgrounds, lensing, **stellar dynamics**, **merger rates**, etc….

PRL 119, 041102 (2017) PHYSICAL REVIEW LETTERS week ending veek ending

28 JULY 2017

Dynamics of Dwarf Galaxies Disfavor Stellar-Mass Black Holes as Dark Matter

Savvas M. Koushiappas^{1,2,*} and Abraham Loeb^{2,†}

¹Department of Physics, Brown University, 182 Hope St., Providence, Rhode Island 02912, USA ²Institute for Theory and Computation, Harvard University, 60 Garden Street, Cambridge, Massachusetts 02138, USA (Received 5 April 2017; revised manuscript received 12 May 2017; published 24 July 2017)

 $\frac{1}{1111}$ PHYSICAL REVIEW LETTERS arXiv:1708.07380

systems with stars of mass ms ∼ 1 M[⊙] and black holes of

Maximum Redshift of Gravitational Wave Merger Events

indirect detection experimental search S as well as α the Dark Energy Survey [37,38]. Savvas M. Koushiappas^{*}

Department of Physics, Brown University, 182 Hope St., Providence, Rhode Island 02912, USA and Institute for Theory and Computation, Harvard University, 60 Garden Street, Cambridge, Massachusetts 02138, USA

 Λ here ρ parameter space of axiom data matter is also showed the second the second theorems. Also showed the shock of a with onomy Department, Harvard Oniversity, 60 p_{max} \overline{A} and \overline{A} evidence of any major disruption reserve of any matrices.
Astronomy Department, Harvard University, 60 Garden Street, Cambridge, Massachusetts 02138, USA S egue 1 to demonstrate the effect of primordial black the effect. Call black the effect of S and S (Received 24 August 2017) $d_{\mathcal{B}}$ matter because it is well studied, although a similar studied, although a similar studied, although a similar studied, although a similar studied of \mathcal{B} 6 Abraham Loeb†

PRL 119, 041102 (2017) PHYSICAL REVIEW LETTERS week ending veek ending

28 JULY 2017

Dynamics of Dwarf Galaxies Disfavor Stellar-Mass Black Holes as Dark Matter

Savvas M. Koushiappas^{1,2,*} and Abraham Loeb^{2,†}

¹Department of Physics, Brown University, 182 Hope St., Providence, Rhode Island 02912, USA ²Institute for Theory and Computation, Harvard University, 60 Garden Street, Cambridge, Massachusetts 02138, USA (Received 5 April 2017; revised manuscript received 12 May 2017; published 24 July 2017)

Dwarf galaxies — state of the art constraints on $\langle \sigma v \rangle$

<u>1</u>

10²⁴ see also ApJ 801, 74 (2014) & Ackermann et al., PRD 89, 042001 (2014) & 1503.02641Geringer-Sameth, Koushiappas & Walker, PRD 91, 083535 (2015),

<u>1</u>

Reticulum II in gamma-rays

 $A \rightarrow \infty$ first look at the gamma-ray signal \mathcal{A} first look at the gamma-ray signal \mathcal{A}

PRL 115, 081101 & ApJL 808 L36 (2015)

the earlier it collapses, the <u>higher its density</u>. Small scales collapse first. The smaller the perturbation

Dark matter halos contain **high density dark matter** substructure

The spectrum of dark matter subhalo properties originates from the host assembly history — a random realization set by initial conditions.

Koushiappas, Zentner & Walker, PRD 69, 043501 (2004), but see also Baltz, Tayor & Wai, ApJ 659, L125 (2006), Kuhlen, Diemand & Madau , arXiv:0805.4416

The spectrum of dark matter subhalo properties originates from the host assembly history — a random realization set by initial conditions.

> These two may have the **same mass**, but different history

Koushiappas, Zentner & Walker, PRD 69, 043501 (2004), but see also Baltz, Tayor & Wai, ApJ 659, L125 (2006), Kuhlen, Diemand & Madau , arXiv:0805.4416

The spectrum of dark matter subhalo properties originates from the host assembly history — a random realization set by initial conditions.

The spectrum of dark matter subhalo properties originates from the host assembly history — a random realization set by initial conditions.

Koushiappas, Zentner & Walker, PRD 69, 043501 (2004), but see also Baltz, Tayor & Wai, ApJ 659, L125 (2006), Kuhlen, Diemand & Madau , arXiv:0805.4416

Koushiappas, Zentner & Walker, PRD 69, 043501 (2004), but see also Baltz, Tayor & Wai, ApJ 659, L125 (2006), Kuhlen, Diemand & Madau , arXiv:0805.4416

Dwarf galaxies

- High mass-to-light ratio (i.e., dark matter dominated, very few stars)
- No known astrophysical background (no gas, stars are old)

Dwarf galaxies: reconstructing the gravitational potential well

 $n(r) \propto f(\mathbf{v})$ (Newton) Stellar kinematics ${\bf v} \propto f'(\sigma_{\perp})$ (Jeans)

- High mass-to-light ratio (i.e., dark matter dominated, very few stars)

- No known astrophysical background (no gas, stars are old)

Dwarf galaxies: reconstructing the gravitational potential well

- High mass-to-light ratio (i.e., dark matter dominated, very few stars)
- No known astrophysical background (no gas, stars are old)

Dwarf galaxies: reconstructing the gravitational potential well Assuming dynamic equilibrium and spherical symmetry, these Dwart galaxies: reconstructing the gravitational pot (Binney & Tremaine 2008), *3.1. Dark Matter Density* ν(*r*)*u*² econstructing the grav *f* (*s*) ν(*s*) *^s*² *ds,* (14)

!

ν(*r*)*u*²

^r(*r*) " + 2β*a*(*r*)*u*²

^r(*r*)

⁼ [−]*d*^Φ

⁼ [−]*GM*(*r*)

s
2 *ds*, (14)
2 *ds*, (14)

. (15)

*^r*² *,*

 \mathcal{A} suming dynamic equilibrium and spherical symmetry, these symmetry, these symmetry, these symmetry, these symmetry, these symmetry, the symmetry

Equation (11) has the general solution (van der Marel 1994;

$$
\frac{1}{v(r)} \frac{d}{dr} [v(r)\overline{u_r^2}(r)] + 2 \frac{\beta_a(r)\overline{u_r^2}(r)}{r} = -\frac{d\Phi}{dr} = -\frac{GM(r)}{r^2}
$$

$$
\beta_a(r) = 1 - \frac{2u_\theta^2(r)}{\overline{u_r^2}(r)} \qquad M(r) = 4\pi \int_0^r s^2 \rho(s)ds
$$

$$
\sigma^2(R) \Sigma(R) = 2 \int_R^\infty \left(1 - \beta_a(r) \frac{R^2}{r^2}\right) \frac{v(r) \overline{u_r^2}(r) r}{\sqrt{r^2 - R^2}} dr
$$

M(*r*) = 4π THE ASTROPHYSICAL JOURNAL, 801:74 (18pp), 2015 March 10
THE ASTROPHYSICAL JOURNAL, 801:74 (18pp), 2015 March 10 THE ASTROPHYSICAL JOURNAL, 801:74 (18pp), 2015 March 10

© 2015. The American Astronomical Society. All rights reserved.

^f (*r*) ⁼ ² *^f* (*r*1) exp \$# *^r*

ν(*r*) =

force the inferious from the dark matter of the data matter dark matter halo.

The Astrophysical Journal, 801:74 (18pp), 2015 March 10 Geringer-Sameth, Koushiappas, & Walker

In order to accurately quantify uncertainties in the spatial

scale radius *rs*, with α specifying its sharpness. For (α*,* β*,* γ) =

"cusps" (γ *>* 1), or halos with "cores" of uniform central den-

 $s_{\rm 0}$, as are usually inferred from observations of real distributions of real distributions of real distributions of $r_{\rm 0}$

3. RECONSTRUCTING THE DARK MATTER POTENTIAL

WITH STELLAR KINEMATICS

*b*² + *x*2).

*b*² + *x*2, the distance from

^α"(β−^γ)*/*^α *.* (7)

 $\sqrt{2}$

 \mathbf{R}

 \mathbf{I}

 \mathbf{I}

 \mathbf{f}

 \mathcal{L}

 $\mathbf{1}$

 \parallel

 \mathcal{L}

 \mathbf{r}

slope *d* log ρ*/d* log *r*|*^r*≪*rs* = −γ and outer logarithmic slope

d log ρ*/d* log *r*|*^r*≫*rs* = −β. The transition happens near the

scale radius *rs*, with α specifying its sharpness. For (α*,* β*,* γ) = \overline{a}

line-of-sight velocity dispersion σ(*R*), according to (Binney &

DWARF GALAXY ANNIHILATION AND DECAY EMISSION PROFILES FOR DARK MATTER EXPERIMENTS

ALEX GERINGER-SAMETH^{1,2}, SAVVAS M. KOUSHIAPPAS¹, AND MATTHEW WALKER² ALEX GERINGER-SAMETH^{1,2}, SAVVAS M. KOUSHIAPPAS¹, AND MATTHEW WALKE
¹ Department of Physics, Brown University, Providence, RI 02912, USA; alexgs@cmu.edu, koushiappas@br
² McWilliams Center for Cosmology, Department *Received 2014 August 4; accepted 2014 December 19; published 2015 March 4*
² *ALEX GERINGER-SAMETH^{1,2}, SAVVAS M. KOUSHIAPPAS¹, AND MATTHEW WALKER²
¹ Department of Physics, Brown University, Providence, RI 02912, USA; alexgs@cmu.edu, koushiappas@brown.edu
Conter for Cosmology, Department of* t_{rel} and t_{rel} are t_{rel} and t_{rel} a ² McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, Pittsburgh, Patagoge Channel and the SALE (SON, alcagoge Channel and the SALE (SON, alcagoge Channel and the SALE (SON, alcagoge Chann to observe the profiles of the profiles stellar density $\frac{1}{2}$, and $\frac{1}{2}$, and

Gamma-ray searches for dark matter annihilation and decay in dwarf galaxies rely on an understanding of the

^β*a*(*s*)*s*−¹ *ds*%

)⁵*/*² *,* (17)

Dwarf galaxies: reconstructing the gravitational potential well **Society (Eq. 1)**

Fig. 1.— Projected velocity dispersion profiles for eight bright dSphs, from Magellan/MMFS and MMT/Hectochelle data. Over-plotted are

Dwarf galaxies: **Dark matter** dominated systems with few stars

Primordial black hole

Dwarf galaxies: **Dark matter** dominated systems with few stars

Dwarf galaxies: **Dark matter** dominated systems with few stars **Primordial black hole** $m_{\text{BH}} \approx 30 M_{\odot}$ $m_{\text{s}} \approx 1 M_{\odot}$

Dwarf galaxies: **Primordial black hole** dominated systems with few stars

relaxation time to Hubble time is ∼0.01. Thus, mass

hole masses mBH. The deficit increases as fDM and mBH increase. Right: Projected stellar surface density of Segue 1. Data points

place in Segue 1 by the present epoch [The quoted present epoch [The quoted present]

for two reasons: first, Plummer profiles are known to be

acceptable fits to the present-day distribution of stars in

dwarf galaxies, and second, a Plummer profile has an inner

core. Anything steeper than a cored profile such as

Plummer will exhibit even more severe effects of mass

segregation [an exponential profile can also be used (see

radial shells by using the virial theorem and the diffusion

coefficient for weak scattering of stars off black holes (see

also Ref. [46]). The differential equation that governs the

evolution of radial mass shells as a function of time is then

We follow Brandt [28] and calculate the evolution of

stars is described by a Plummer profile. This is justified

for two reasons: first, Plummer profiles are known to be

acceptable fits to the present-day distribution of stars in

dwarf galaxies, and second, a Plummer profile has an inner

 \mathbb{R}^2

sdvs: ð2Þ

core. Anything steeper than a cored profile such as

Plummer will exhibit even more severe effects of mass

segregation [an exponential profile can also be used (see

Ref. [48]), with similar results].

radial shells by using the virial theorem and the diffusion

coefficient for weak scattering of stars off black holes (see

also Ref. [46]). The differential equation that governs the

^s i&: ð3Þ

evolution of radial mass shells as a function of time is then

We follow Brandt [28] and calculate the evolution of

Ref. [48]), with similar results].

 $B_{\rm eff}$ is the Coulomb \sim 10 is the Coulomb \sim

2

 ϵ change of KE

¼

2

$$
\frac{dE_s}{dt} = \sqrt{\frac{2}{\pi}} \frac{1}{\sigma_s^3} \int_0^\infty m_s \langle \Delta E \rangle_s v_s^2 e^{-v_s^2/2\sigma_s^2} dv_s
$$

holes to reach equipartition is treed to reach equipartition is trelax $\mathcal{L}_{\mathcal{L}}$

$$
\frac{dE_s}{dt} = \frac{\sqrt{96\pi}G^2m_s\rho_{\text{BH}}\ln\Lambda}{[\langle v_s^2 \rangle + \langle v_{\text{BH}}^2 \rangle]^{3/2}}[m_{\text{BH}}\langle v_{\text{BH}}^2 \rangle - m_s\langle v_s^2 \rangle]
$$

holes to reach equipartition is treed to reach equipartition is trelax $\mathcal{L}_{\mathcal{L}}$

 \overline{a}

^p ^σBH, ^σ²

 \mathbf{L}

 \vert $\overline{}$

r 1

 \mathbb{R}^n

^s ⁱ ^þ ^hv²

 $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$, the half light radius is isomorphism.

 \mathbf{B}

[28] T. D. Brandt, Astrophys. J. Lett. 824, L31 (2016). T. D. Brandt, Astrophys. J. Lett. $824, L31$ (2016)

segregation are minimal and thus provide a conservative

[29] T. S. Li, J. D. Simon, A. Drlica-Wagner, K. Bechtol, M. Y.

equipartition soon as the black holes establish a collisional

 $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$, the half light radius is isomorphism.

[28] T. D. Brandt, Astrophys. J. Lett. 824, L31 (2016). \overline{T} D \overline{D} and \overline{D} attended \overline{N} \overline{S} attended \overline{S} T. D. Brandt, Astrophys. J. Lett. $824, L31$ (2016)

segregation are minimal and thus provide a conservative

[27] Y. Akrami, F. Kuhnel, and M. Sandstad, arXiv:1611.10069.

[29] T. S. Li, J. D. Simon, A. Drlica-Wagner, K. Bechtol, M. Y.

 $\frac{1}{\sqrt{2}}$

\$

 \overline{a}

^p ^σBH, ^σ²

 \mathbf{L}

 \vert $\overline{}$

r 1

 \mathbb{R}^n

 $\frac{1}{2}$

 $r_{\rm h}$ (pc) 40

 \Box

^s ⁱ ^þ ^hv²

erfor hans handels

 \mathbf{B}

1 þ

 $\sigma = 5$ km s⁻¹

 $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$, the half light radius is isomorphism.

 $\rho = 0.5 M_{\odot} pc^{-3}$

ms $\overline{}$

velocity dispersion unknown | Dark matter distribution unknown Use 1/2-light radius of the central cluster only

 $\mathcal{F}_{\mathcal{A}}$, and $\mathcal{F}_{\mathcal{A}}$ fig. 1.1, and $\mathcal{F}_{\mathcal{A}}$ is 3000 M $\mathcal{F}_{\mathcal{A}}$ star cluster by 30 M $\mathcal{F}_{\mathcal{A}}$

dark matter in black holes. If, for example, the fraction of the fraction of the fraction of the fraction of t

therein). At an age of 3 Gyr (left panel), MACHOS (lef T. D. Brandt, Astrophys. J. Lett. $824, L31$ (2016)

segregation are minimal and thus provide a conservative

[29] T. S. Li, J. D. Simon, A. Drlica-Wagner, K. Bechtol, M. Y.

$$
t_{\rm r} = \frac{E_s}{dE_s/dt}
$$

$$
t_{\rm r} = \frac{E_s}{dE_s/dt}
$$

$$
t_{\rm r} = \frac{E_s}{dE_s/dt}
$$

Dwarfs with smallest relaxation time

Segue 1 Boötes II Segue II Wilman 1 Coma Berenices Canes Venatici II

$$
t_{\rm r} = \frac{E_s}{dE_s/dt}
$$

Dwarfs with smallest relaxation time

Segue 1

Boötes II Segue II Wilman 1 Coma Berenices Canes Venatici II

⃝^C 2011. The American Astronomical Society. All rights reserved. Printed in the U.S.A.

A COMPLETE SPECTROSCOPIC SURVEY OF THE MILKY WAY SATELLITE SEGUE 1: THE DARKEST GALAXY[∗]

JOSHUA D. SIMON¹, MARLA GEHA², QUINN E. MINOR³, GREGORY D. MARTINEZ³, EVAN N. KIRBY^{4,8}, JAMES S. BULLOCK³, Manoj Kaplinghat³, Louis E. Strigari^{5,8}, Beth Willman⁶, Philip I. Choi⁷, Erik J. Tollerud³, and Joe Wolf³

Local Group

[∼]30 mag arcsec−2. Deeper, wide-field photometric surveys of

Stream. The Astrophysical Journal, 801:74 (18pp), 2015 March 10

© 2015. The American Astronomical Society. All rights reserved. \heartsuit 2015. The American Astronomical Society. All rights reserved. The Astrophysical Journal, 801:74 (18pp), 2015 March 10 doi:10.1088/0004-637X/801/2/74 THE ASTROPHYSICAL JOURNAL, 801174 (18pp), 20
© 2015. The American Astronomical Society. All rights reserved. (e.g., Toomre & Toomre 1972). Detecting such features in the

doi:10.1088/0004-637X/801/2/74

DWARF GALAXY ANNIHILATION AND DECAY EMISSION PROFILES FOR DARK MATTER EXPERIMENTS $\overline{\text{PUCP}}$ and the galaxies the galaxies theory the DWARF GALAXY ANNIHILATION AND DECAY EMISSION PROFILES FOR DARK MATTER EXPERIMENTS

ALEX GERINGER-SAMETH^{1,2}, SAVVAS M. KOUSHIAPPAS¹, AND MATTHEW WALKER² magnitudes fainter and likely below the SDSS detection limit of ¹ Department of Physics, Brown University, Providence, RI 02912, USA; alexgs@cmu.edu, koushiappas@brown.edu 2McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA; mgwalker@andrew.cmu.edu

Received 2014 August 4; accepted 2014 December 19; published 2015 March 4

Koushiappas & Loeb PRL 119, 041102 (2017)

 \vert Look at the evolution of the whole stellar population in Segue 1 $\begin{bmatrix} 1 & \text{Eos} \\ \text{Eos} & \text{Eos} \end{bmatrix}$

 $\overline{1}$

 \perp

BHⁱ [−] mshv²

 \mathbf{B}

 \mathbf{r}

which based on the virial theorem can be written as

 $t = \frac{1}{2}$ and N is the system is dominated by

by black holes (as is the case here), then stars will reach

equipartition soon as the black holes establish a collisional

 $\overline{}$

$$
\frac{dr}{dt} = \frac{4\sqrt{2}\pi G f_{\text{DM}} m_{\text{BH}}}{\sigma} \ln \Lambda \left(\alpha \frac{M_s}{\rho_{\text{DM}} r^2} + 2\beta r \right)^{-1}
$$

Koushiappas & Loeb PRL 119, 041102 (2017) and a total mass από το προσωπικού του προσωπικού του προσωπικού του προσωπικού του προσωπικού του προσωπικού τ
Στην αποτελεία στην αποτελεία στην αποτελεία στην απόταση της προσωπικού του προσωπικού του προσωπικού του π

Equipartition leads to the depletion of stars from the center of the dwarf

Koushiappas & Loeb PRL 119, 041102 (2017)

Evolution of density profile when 1% of dark matter is in 20 solar mass black holes

$$
\frac{\delta \rho_s}{\rho_s} = \frac{r^3(t)}{r^3(0)} - 1
$$

Primordial black hole constraints from the whole stellar population of Segue 1

function of black hole mass mass mass mBH. The solid (dashed) black hole mass $\mathcal{L}(\mathcal{A})$

lower values of β simply imply a higher normalization of

than the currently measured value of the Plummer scale

radius. Any other choice would lead to stronger constraints

on black hole dark matter (we confirmed this assumption

by repeating the analysis for a suite of initial scale radii of a

Plummer profile as well as by assuming an isothermal

sphere or a Hernquist profile as the initial distribution. All

these options led to stronger constraints to black hole dark

matter). We assume that the dark matter distribution is

described by a generalized NFW profile [49], whose

 $p_{\rm max}$

Ref. [50] are given by the median values obtained by the

MCMC analysis of Geringer-Sameth et al. [50]. The

median value of the profile parameters does not necessarily

correspond to the median value of the density at all radii.

We repeated the calculation by assuming the median of the median of

The stars are initially distributed in a Plummer profile

 $\mathbf{1}$

Both of these consistent with current observations

Ruled out

Both of these consistent with current observations

Ruled out

Fokker-Planck treatment of the same problem

How to distinguish primordial from baryonic black holes

PHYSICAL REVIEW LETTERS

Maximum Redshift of Gravitational Wave Merger Events

Savvas M. Koushiappas^{*}

4 Department of Physics, Brown University, 182 Hope St., Providence, Rhode Island 02912, USA 5 and Institute for Theory and Computation, Harvard University, 60 Garden Street, Cambridge, Massachusetts 02138, USA

6 Abraham Loeb†

7 Astronomy Department, Harvard University, 60 Garden Street, Cambridge, Massachusetts 02138, USA (Received 24 August 2017)

 Future generations of gravitational wave detectors will have the sensitivity to detect gravitational wave events at redshifts far beyond any detectable electromagnetic sources. We show that if the observed event 11 rate is greater than one event per year at redshifts z ≥ 40, then the probability distribution of primordial density fluctuations must be significantly non-Gaussian or the events originate from primordial black holes. The nature of the excess events can be determined from the redshift distribution of the merger rate.

14 DOI:

15 The discovery of gravitation and merging pairs of gravitation pairs and merginal waves from merging pairs o

Koushiappas & Loeb, arXiv:1708.07380

non-Gaussianity in the primordial density fluctuation $\mathcal{L}_{\mathcal{A}}$

- Black holes must be formed.
- Black holes must find a way to get close enough so that gravitational waves can take-over as the dominant energy loss mechanism.

- Black holes must be formed.
- Black holes must find a way to get close enough so that gravitational waves can take-over as the dominant energy loss mechanism.

the integral of the rate of black hole mergers per redshift

of mass *M* at *z*, h✏(*M,z*)i is the eciency of converting

the denominator is to convert the rest frame rate to the

The integral integral in Equation (2) is performed from a mini-from a mini-from a min-from a min-fro

the integral of the rate of black hole mergers per redshift

interval,

(1967).

[19] R. E. Angulo, V. Springel, S. D. M. White, A. Jenkins, C. M. Baugh, and C. S. Frenk, MNRAS 426, 2046 (2012),

(2010), 1005.2416.

volume per redshift interval and the (1 + *z*) factor in Koushiappas & Loeb, arXiv:1708.07380

The integral integral in Equation (2) is performed from a mini-from a mini-from a min-from a min-fro

the integral of the rate of black hole mergers per redshift

the integral of the rate of black hole mergers per redshift

Rate of black hole merger events velocities between baryons and dark matter [44]) and a $\begin{bmatrix} 3 & 3 & 3 \end{bmatrix}$. The shaded area represents represent the shaded area represents in $\begin{bmatrix} 3 & 3 & 3 \end{bmatrix}$

everything in between these two extreme cases. We define maximum redshift **zmax** such that the ob-Define maximum redshift

 $\overline{3}$, the minimum mass is the largest (including relative relat

Koushiappas & Loeb, arXiv:1708.07380

Rate of black hole merger events velocities between baryons and dark matter [44]) and a $\begin{bmatrix} 3 & 3 & 3 \end{bmatrix}$. The shaded area represents represent the shaded area represents in $\begin{bmatrix} 3 & 3 & 3 \end{bmatrix}$

everything in between these two extreme cases. Define maximum redshift

 $\overline{3}$, the minimum mass is the largest (including relative relat

Things to take away

1. Black holes as dark matter lead to a depletion of stars in the center and the appearance of a ring in the projected stellar surface density profile.

2. Current observations rule out the possibility that more than 4% of the dark matter is composed of black holes with mass of few tens of solar masses.

3. Next generation of large aperture telescopes could improve these constraints.

4. Future gravitational wave detectors will be sensitive to events from high redshifts. A detection of events with redshift greater than 40 must be due to either primordial black holes or the presence of non-gaussianity in the spectrum of primordial fluctuations.