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

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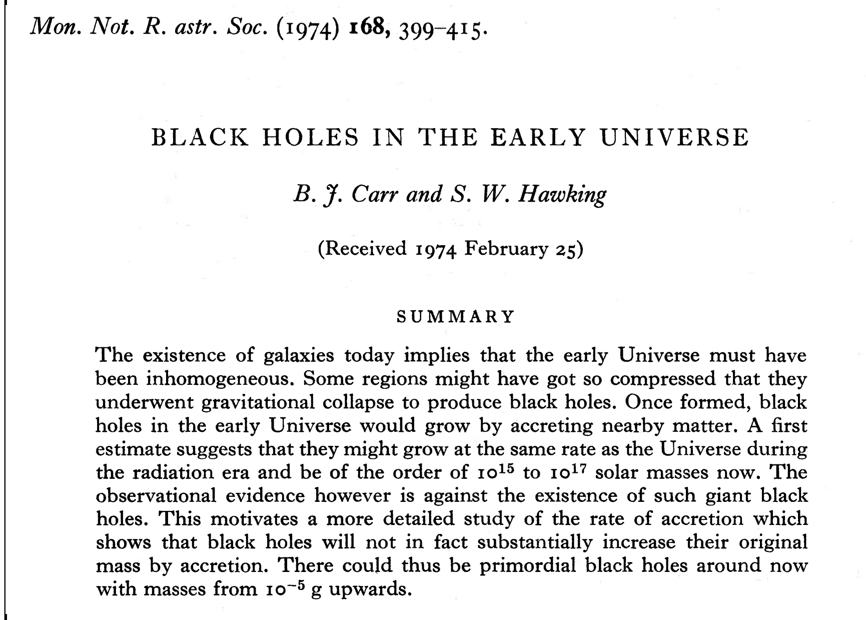
UNITED STATES OF AMERICA

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 10^{15} to 10^{17} 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.

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 28 JULY 2017

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

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(Received 5 April 2017; revised manuscript received 12 May 2017; published 24 July 2017)

PHYSICAL REVIEW LETTERS arXiv:1708.07380

Maximum Redshift of Gravitational Wave Merger Events

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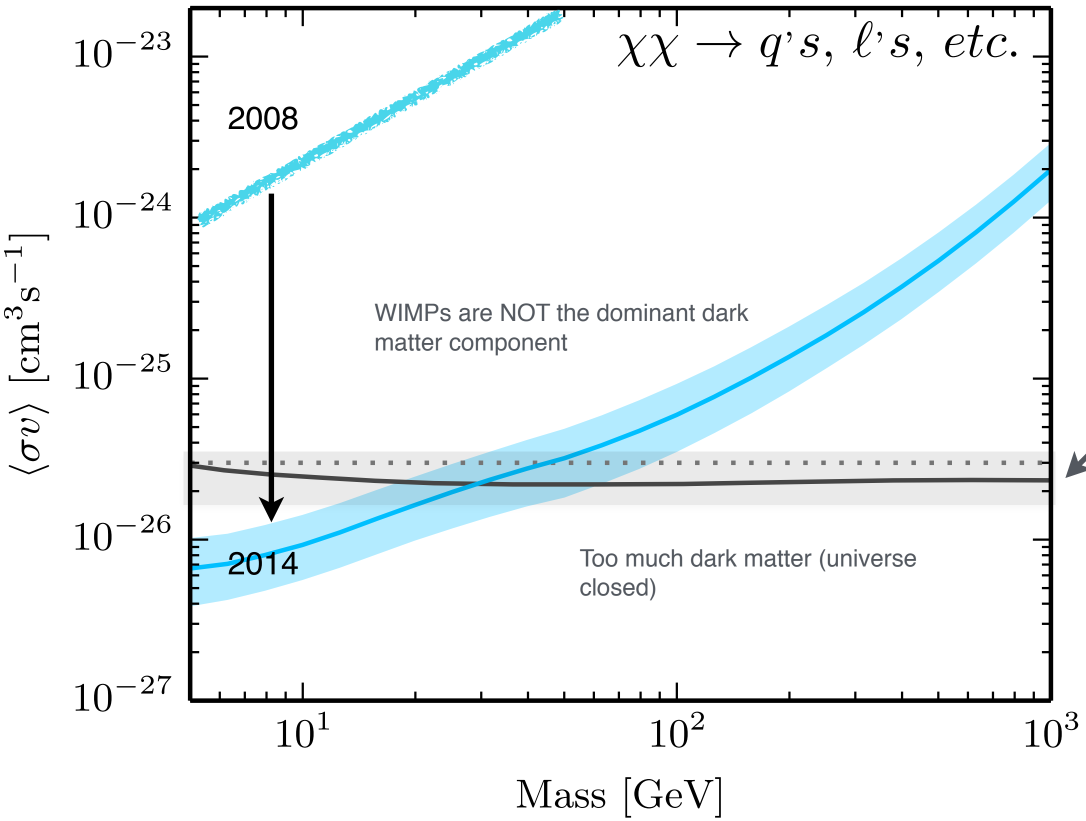
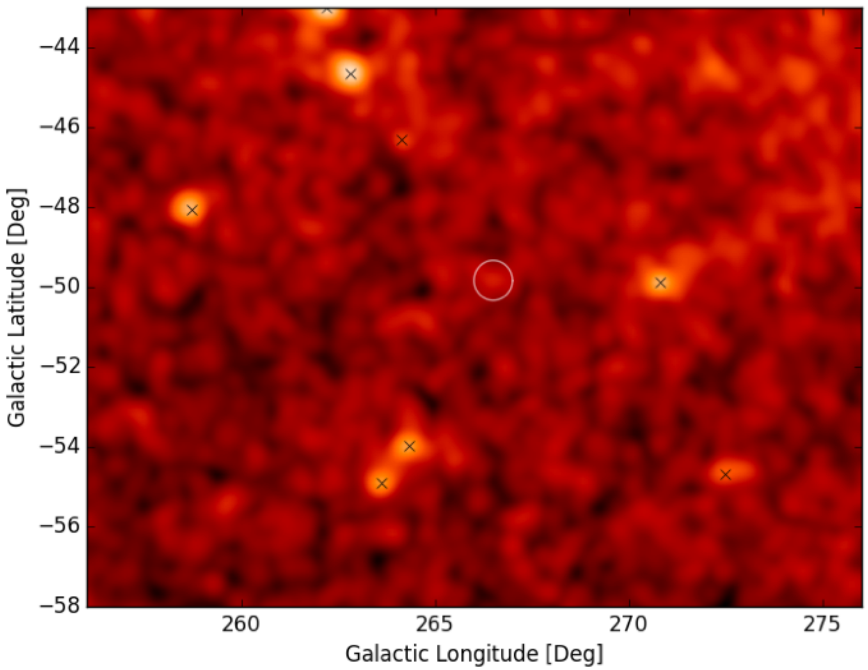
Dwarf galaxies — state of the art constraints on $\langle \sigma v \rangle$



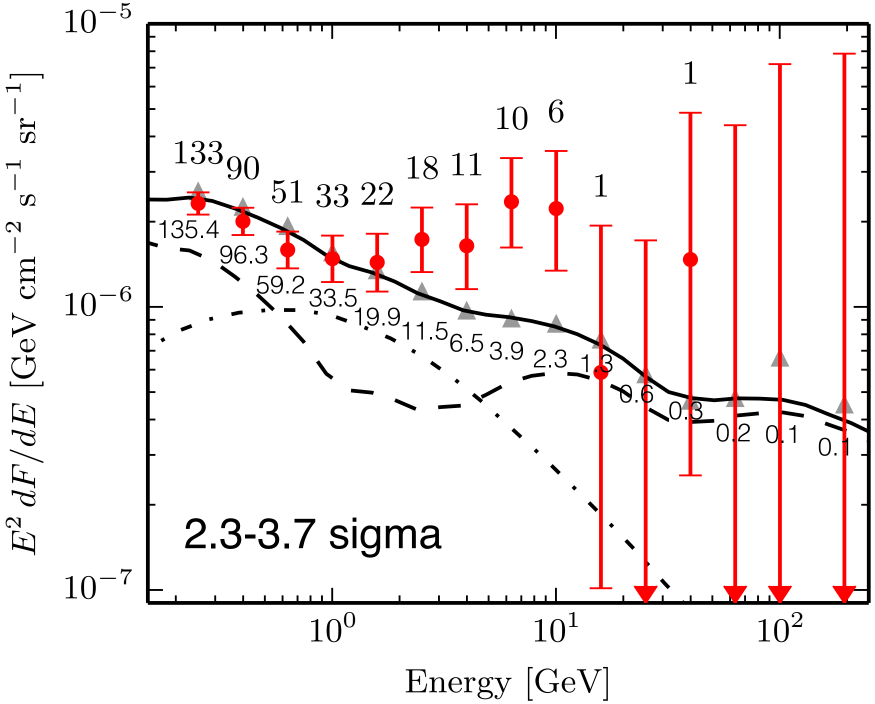
This value reproduces our observed Universe.

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

Reticulum II in gamma-rays



Pass7R



PRL 115, 081101 & ApJL 808 L36 (2015)

The structure of substructure

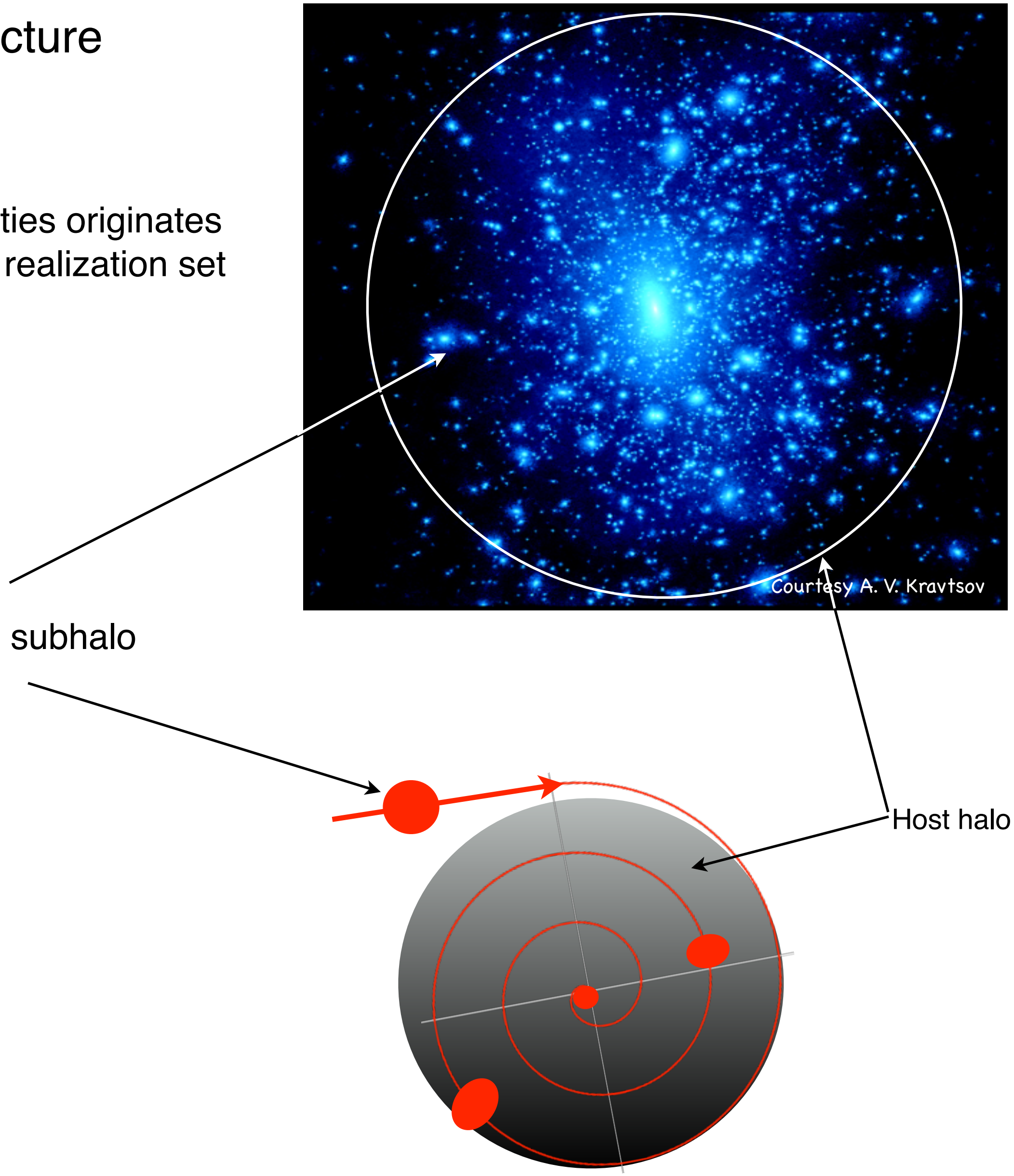

Courtesy A. V. Kravtsov

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

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

The structure of substructure

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



Courtesy A. V. Kravtsov

Accreted subhalo

Host halo

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

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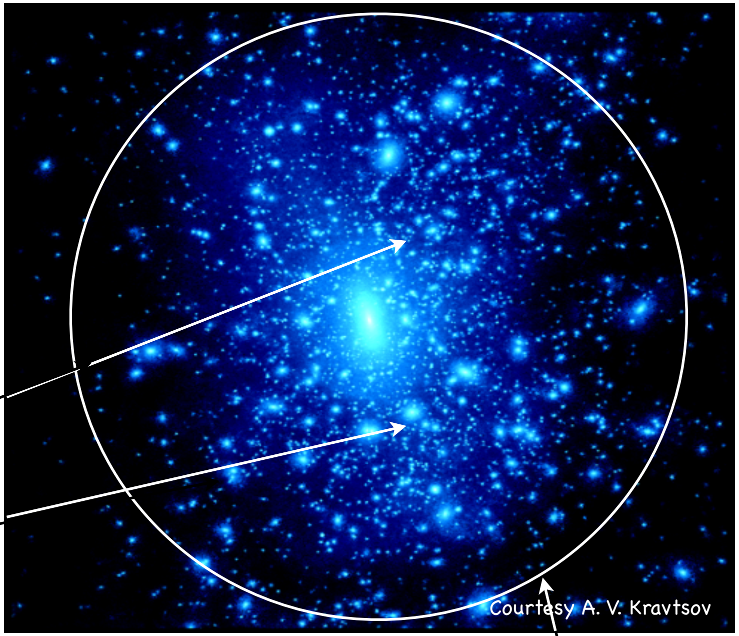
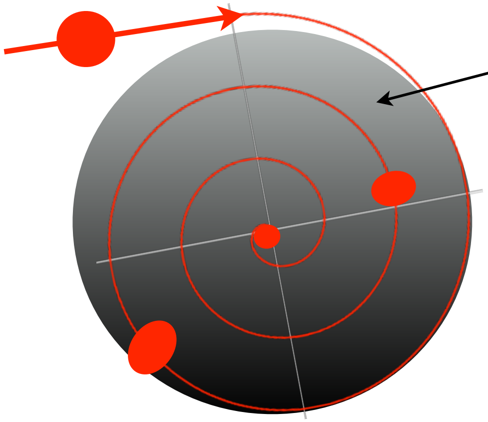


Courtesy A. V. Kravtsov

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



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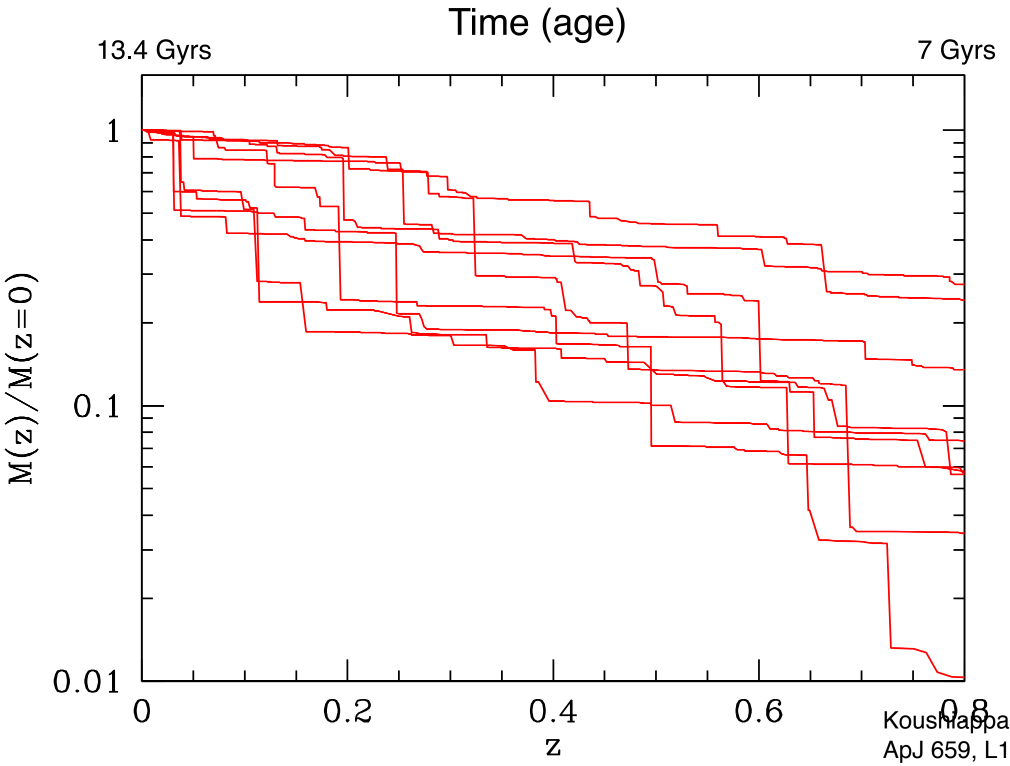

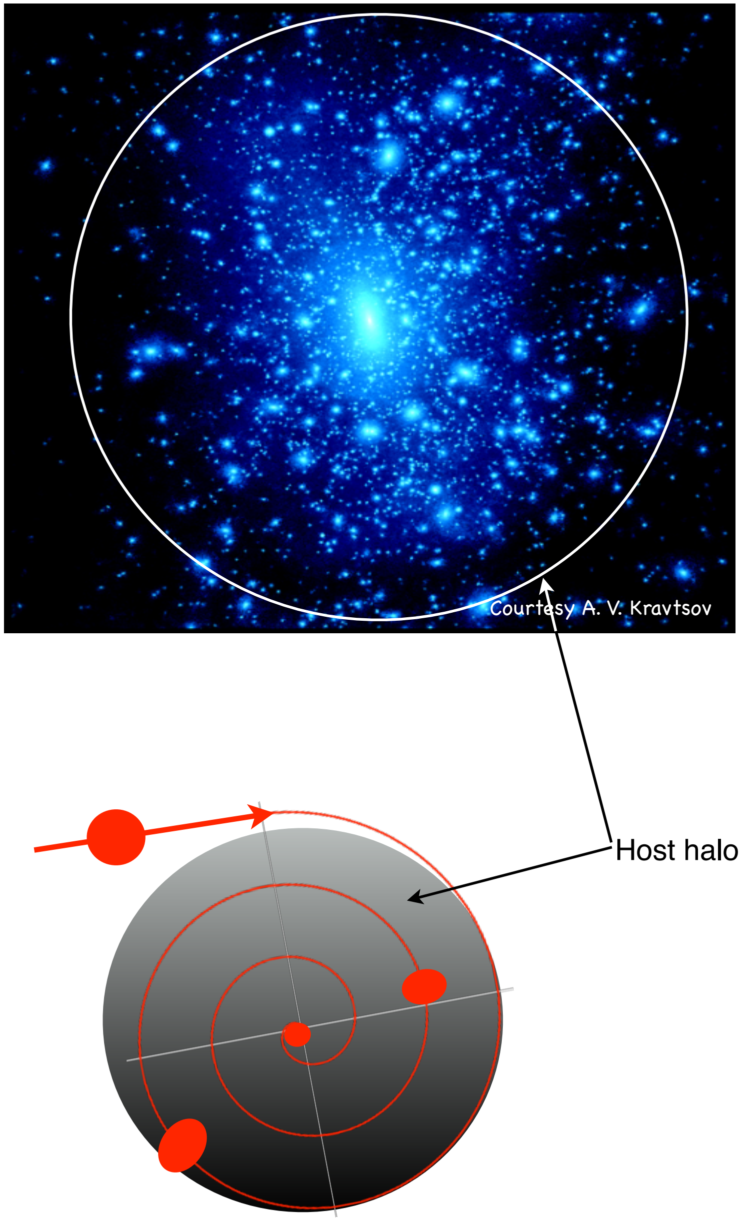

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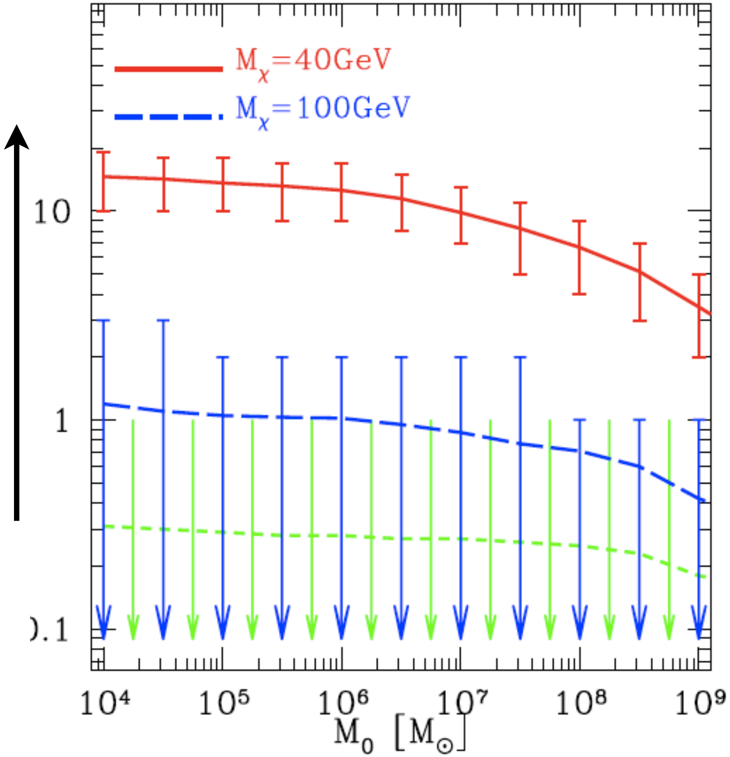
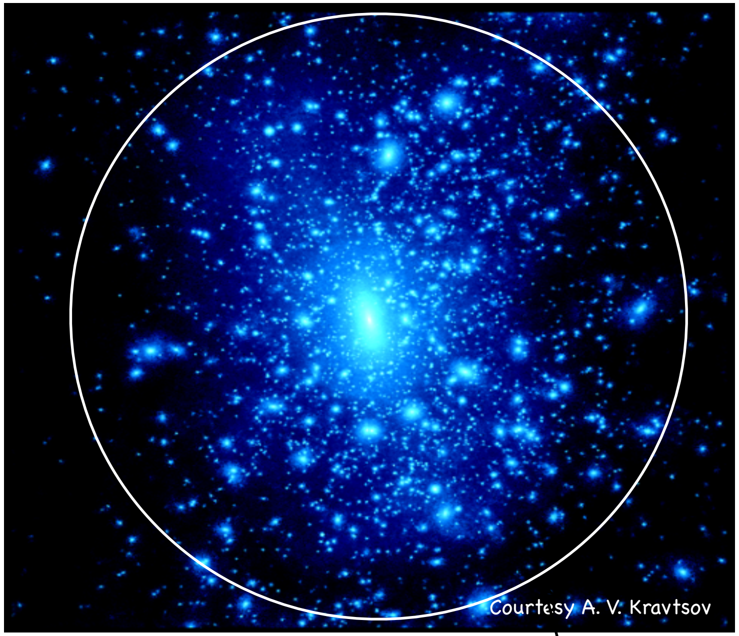
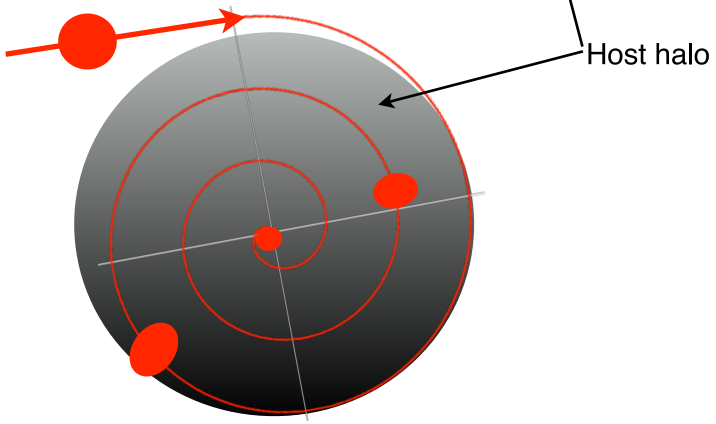


How many greater than some luminosity threshold

Mass of subhalo


Courtesy A. V. Kravtsov



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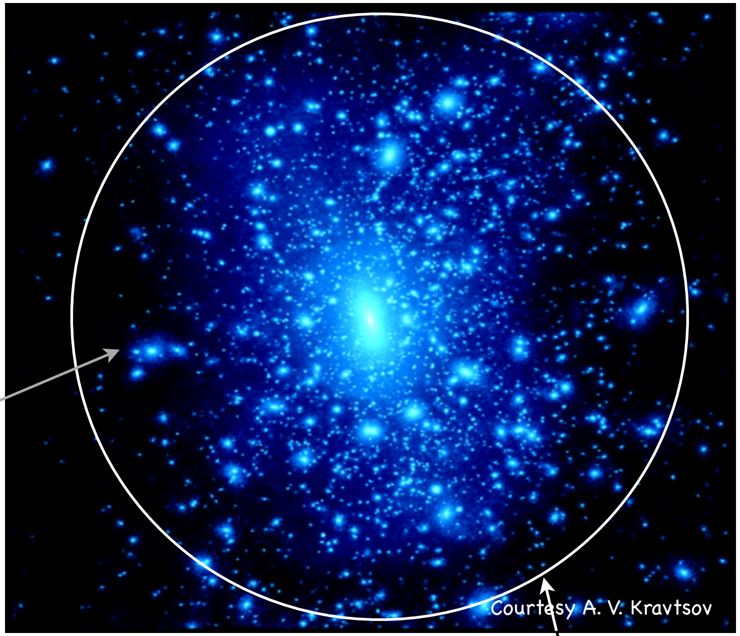
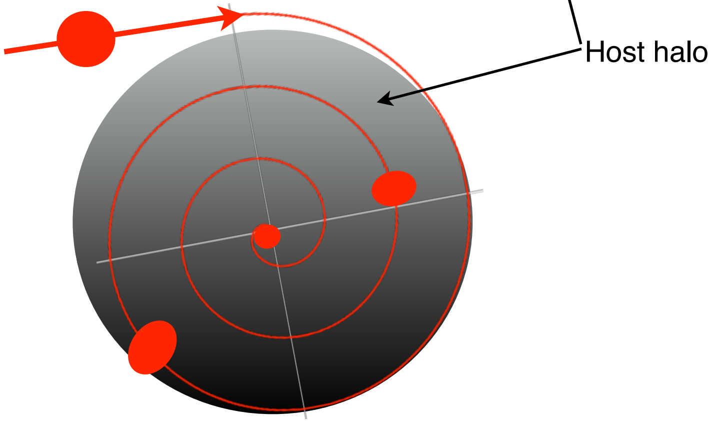
The structure of substructure


Courtesy A. V. Kravtsov

If these dark matter potential wells contain stars we call them **dwarf galaxies**



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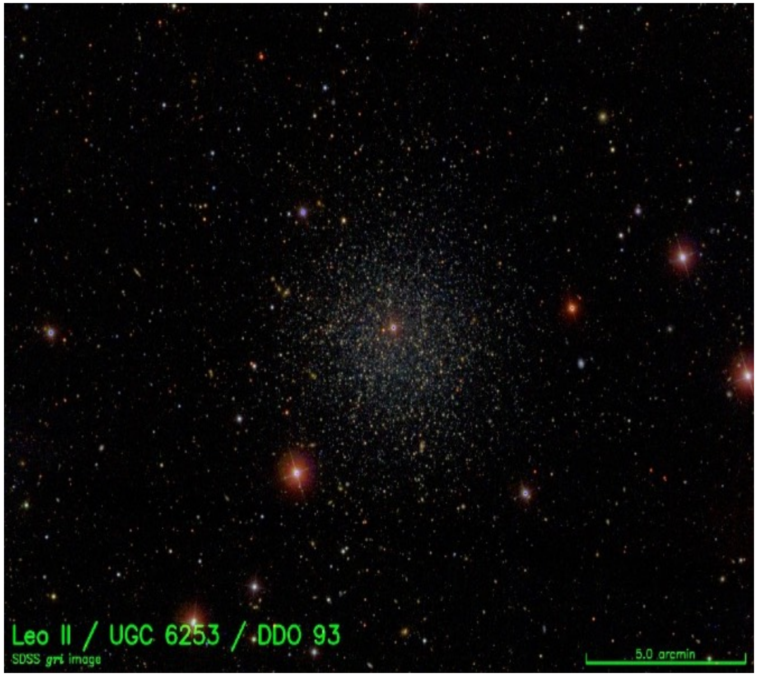
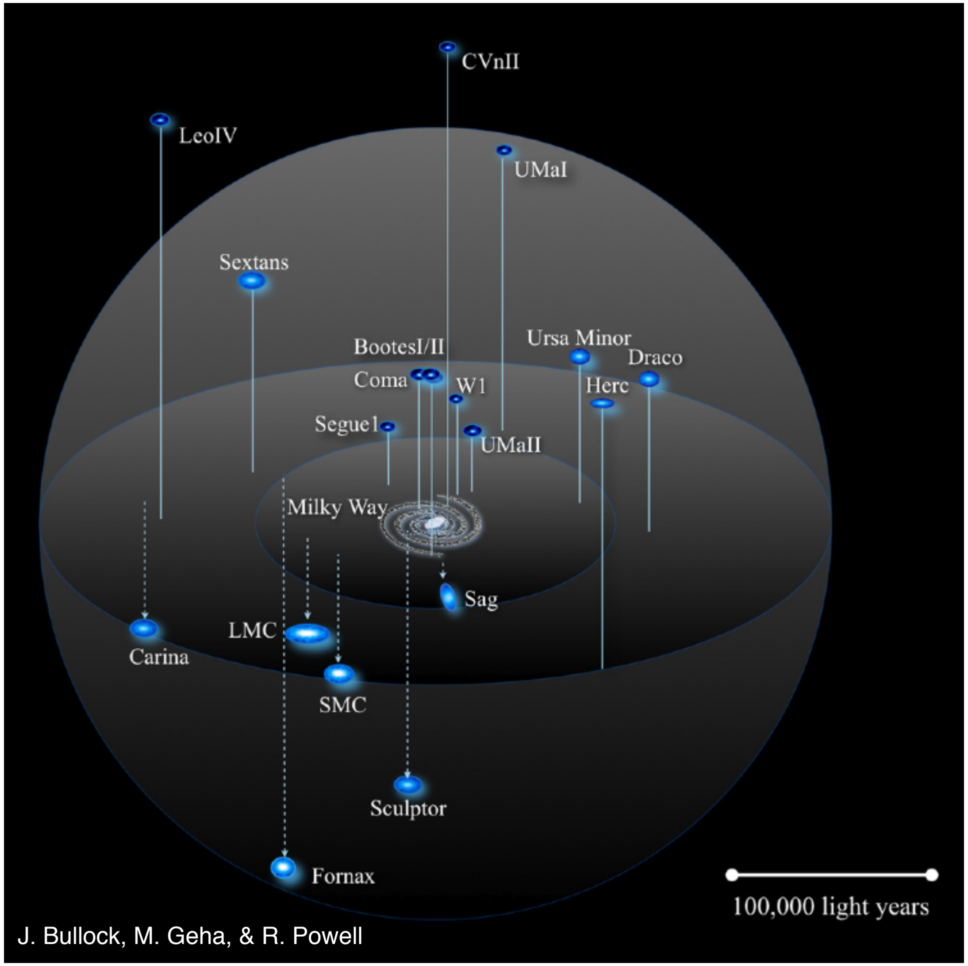
Dwarf galaxies

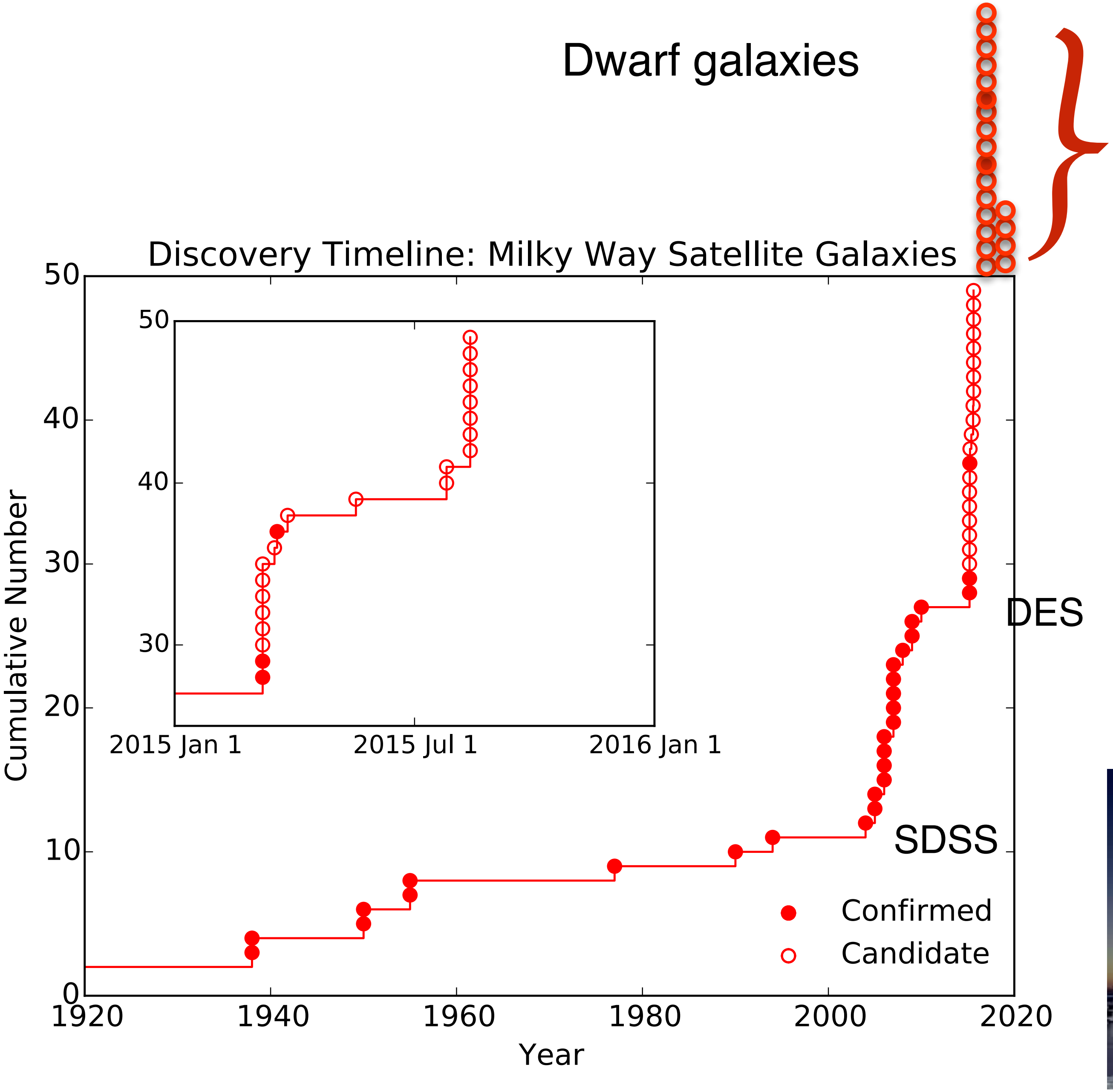




J. Bullock, M. Geha, & R. Powell

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

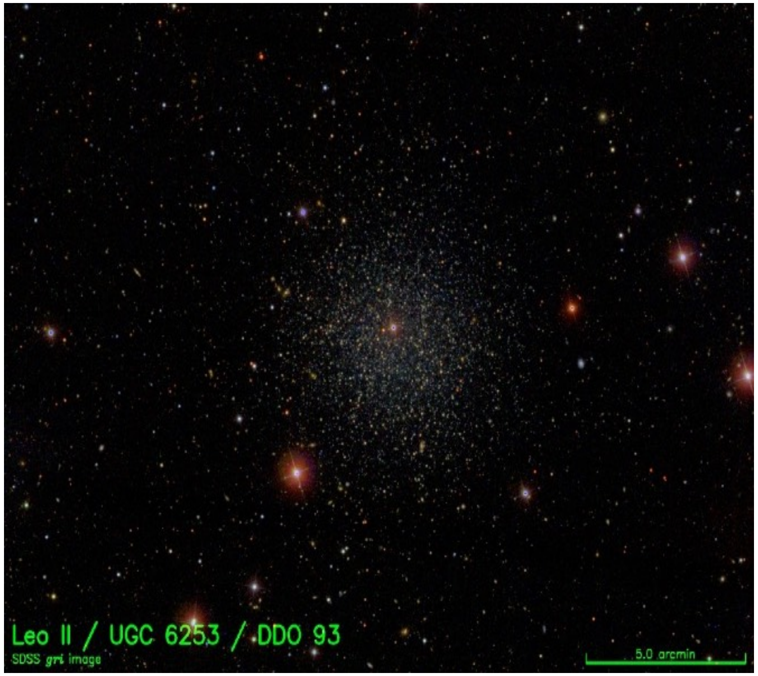
Dwarf galaxies



December 15, 2017 new DES dwarfs according to my secret reliable DES source!

From Keith Bechtol’s talk TAUP 2015

Dwarf galaxies: reconstructing the gravitational potential well



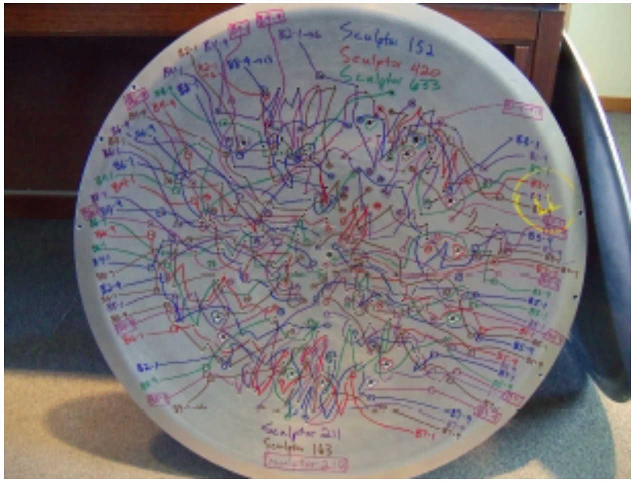
$n(r) \propto f(\mathbf{v})$ (Newton)

$\mathbf{v} \propto f'(\sigma_\perp)$ (Jeans)

Stellar kinematics

- 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



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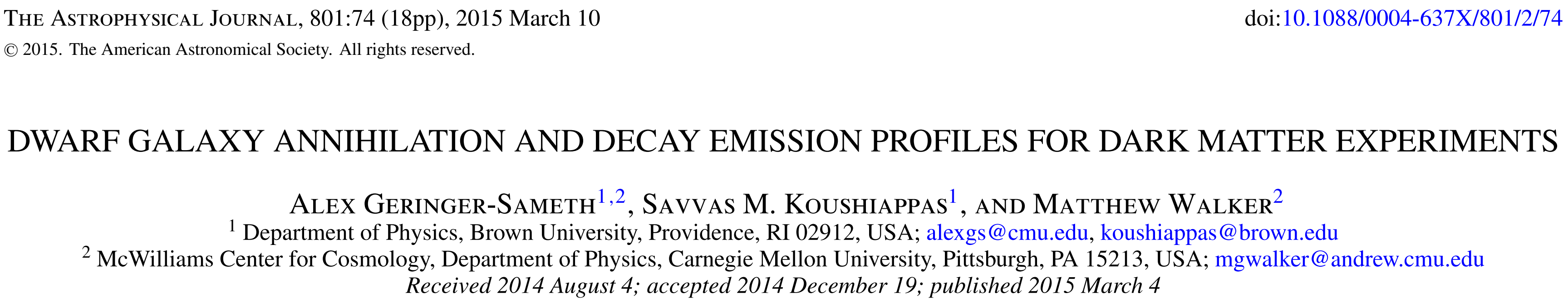
Dwarf galaxies: reconstructing the gravitational potential well

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

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

$$\Big\downarrow$$

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



THE ASTROPHYSICAL JOURNAL, 801:74 (18pp), 2015 March 10
doi:10.1088/0004-637X/801/2/74

DWARF GALAXY ANNIHILATION AND DECAY EMISSION PROFILES FOR DARK MATTER EXPERIMENTS

ALEX GERINGER-SAMETH[1,2], SAVVAS M. KOUSHIAPPAS[1], AND MATTHEW WALKER[2]
[1] Department of Physics, Brown University, Providence, RI 02912, USA; alexgs@cmu.edu, koushiappas@brown.edu
[2] McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA; mgwalker@andrew.cmu.edu

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Dwarf galaxies: reconstructing the gravitational potential well

Plummer vs Flexible profile for stars

Dark matter distribution

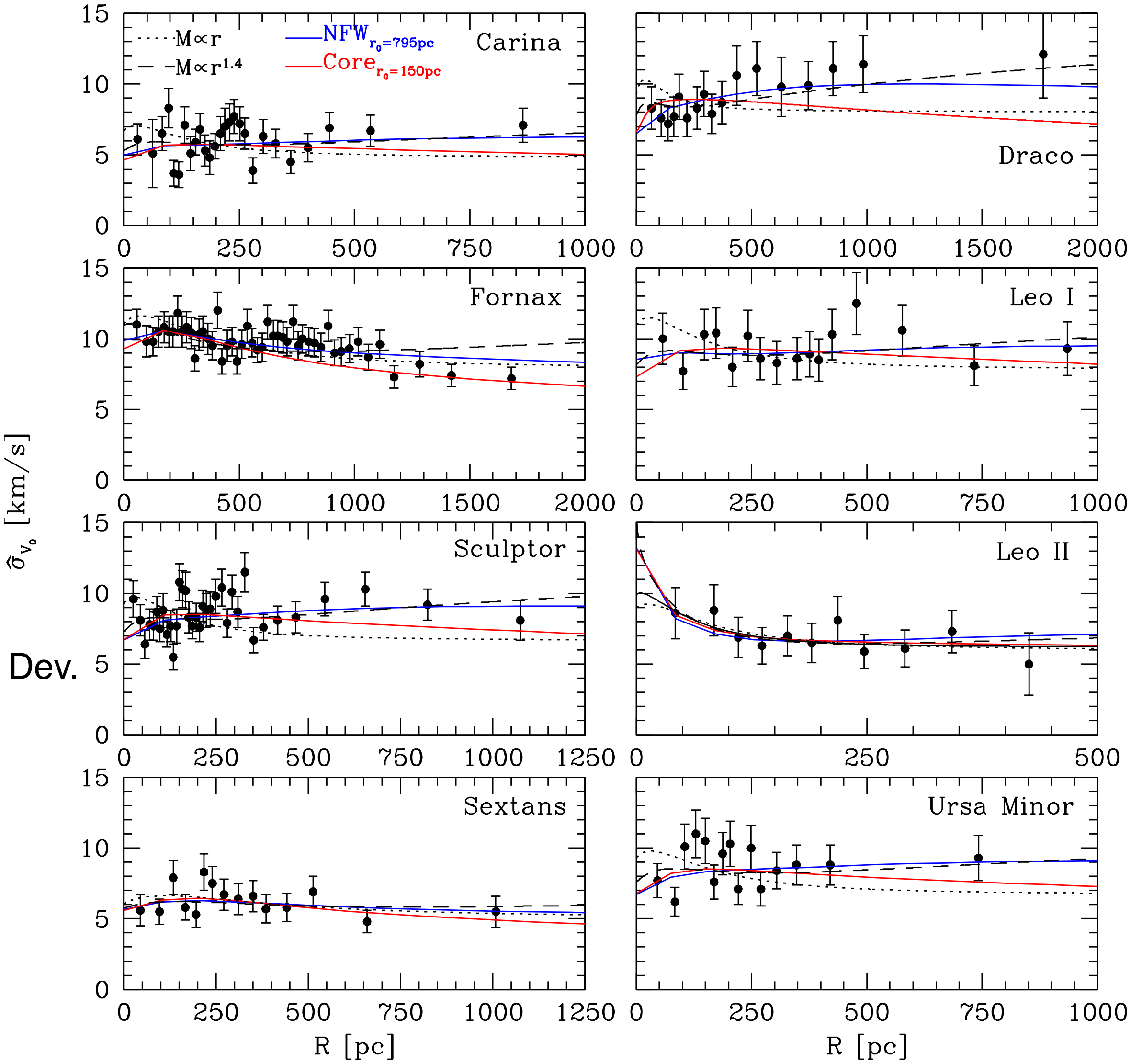
Artificial vs no artificial truncation

Anisotropies in vel. disp.

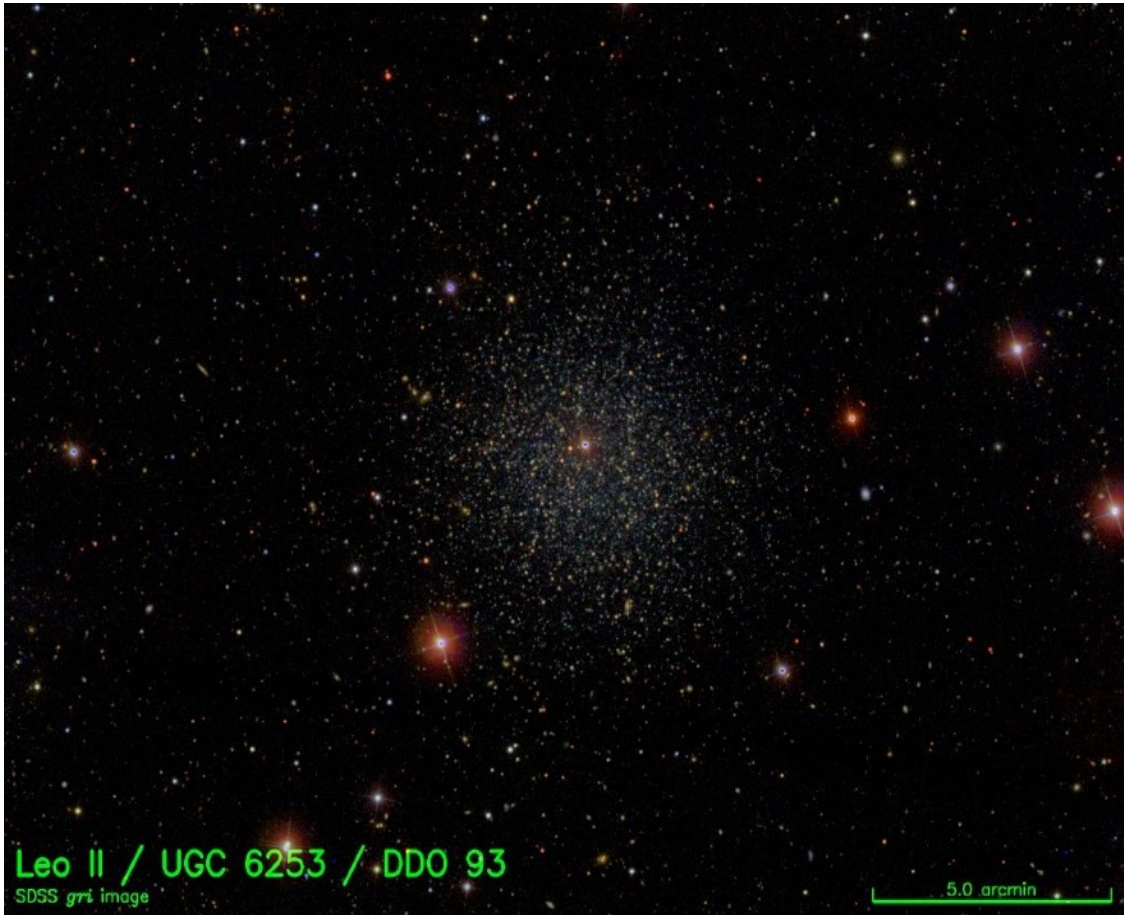
Assumptions on the distribution

Quoted errors are percentiles vs Std. Dev.

Membership probabilities

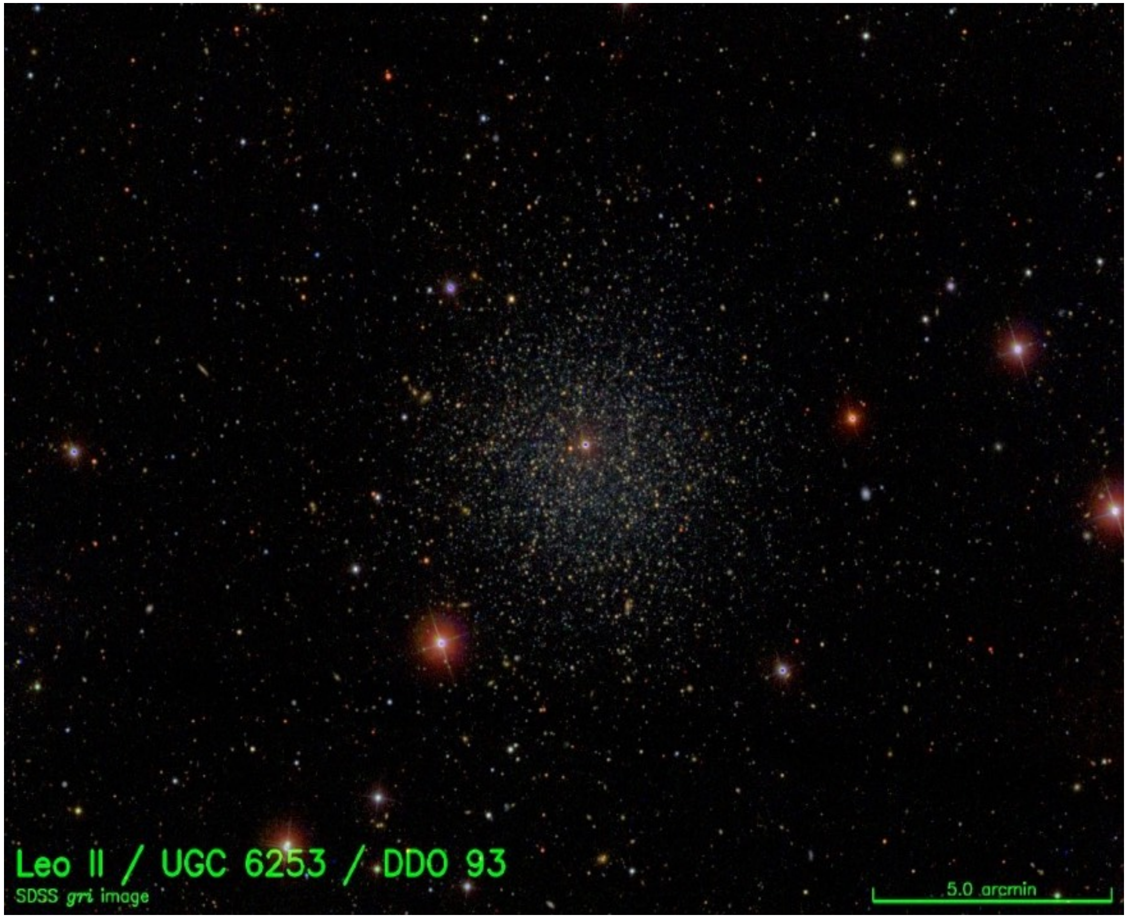


Dwarf galaxies: **Dark matter** dominated systems with few stars



Primordial black hole

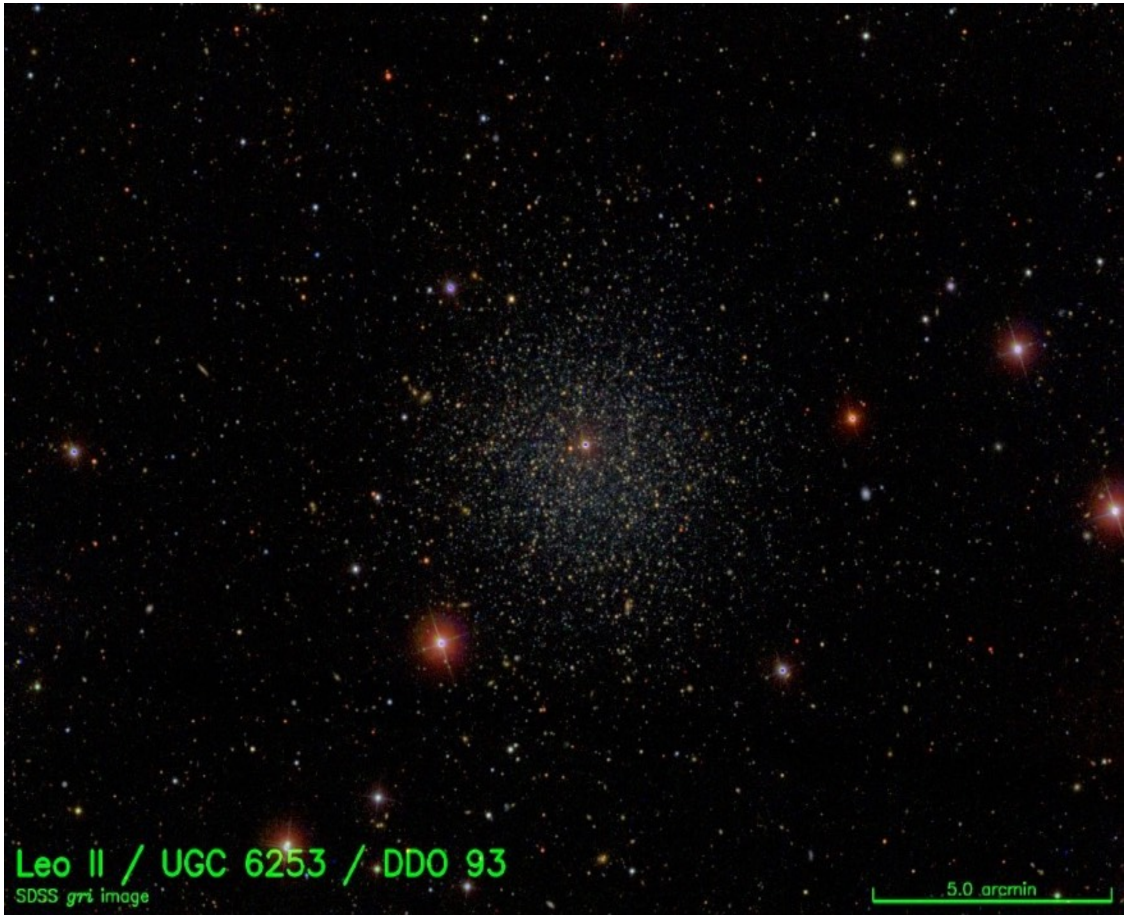
Dwarf galaxies: ~~Dark matter~~ dominated systems with few stars



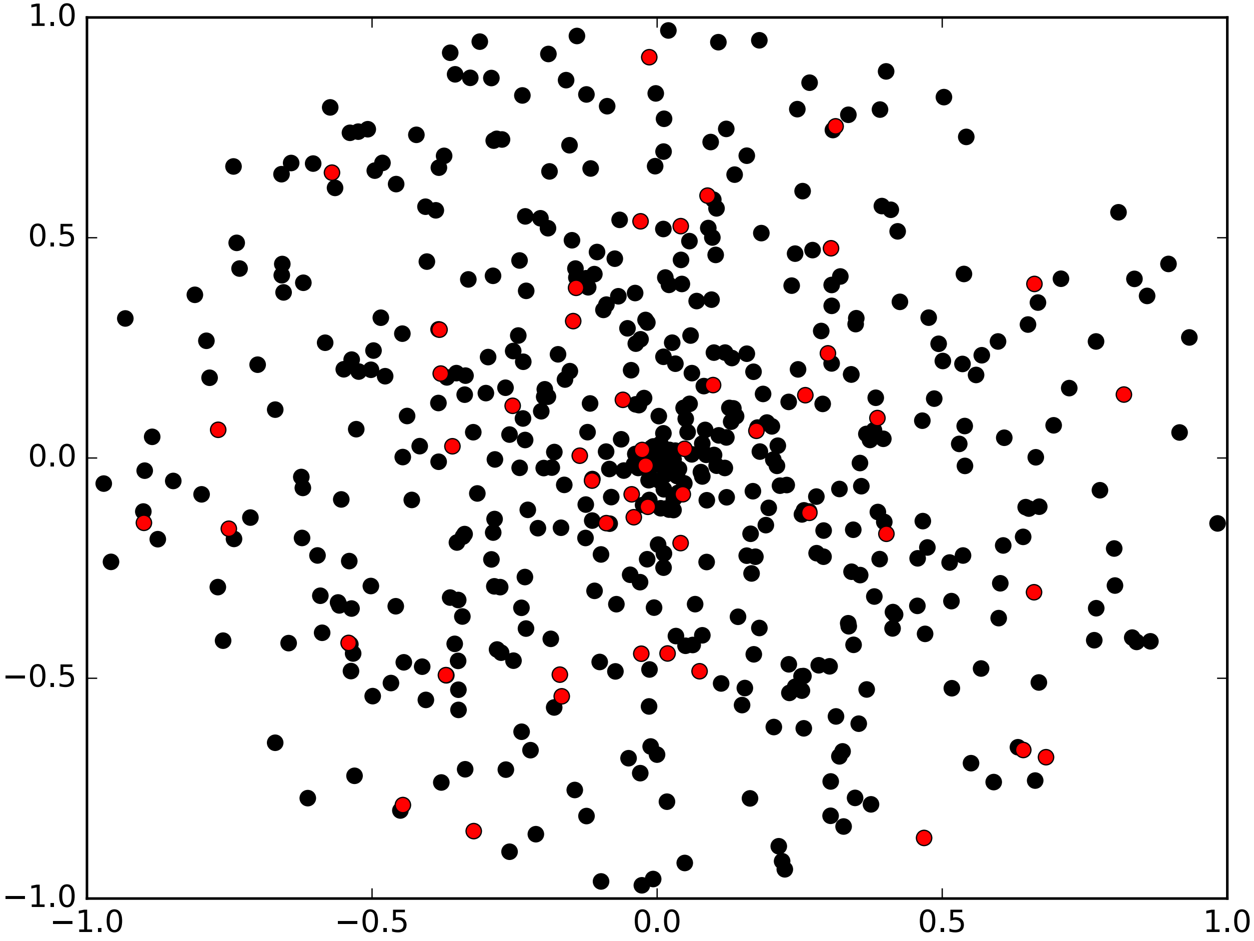
Primordial black hole

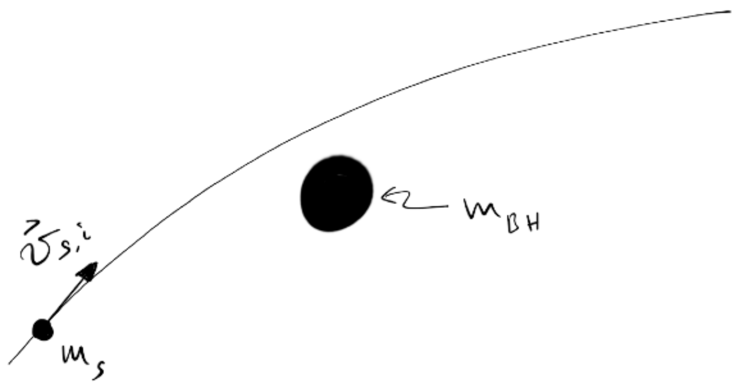
Dwarf galaxies: ~~**Dark matter**~~ dominated systems with few stars

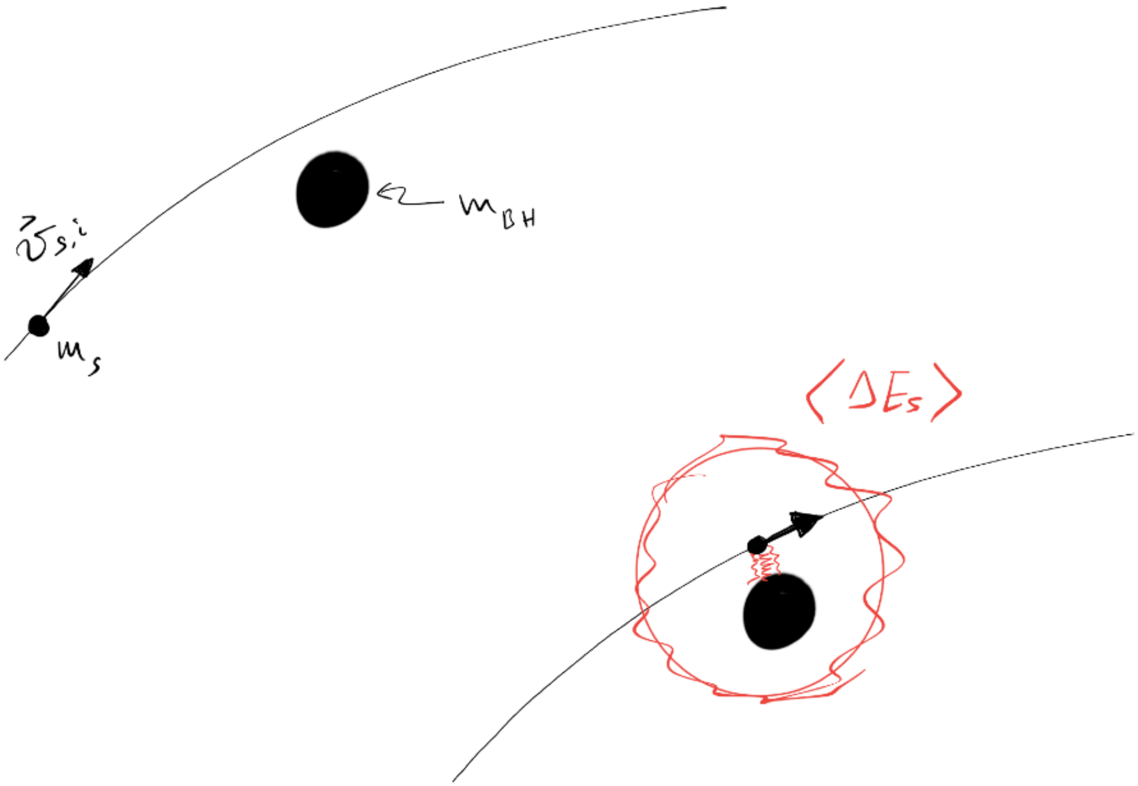
$m_{\mathrm{BH}} \approx 30 M_{\odot}$ $m_{\mathrm{s}} \approx 1 M_{\odot}$

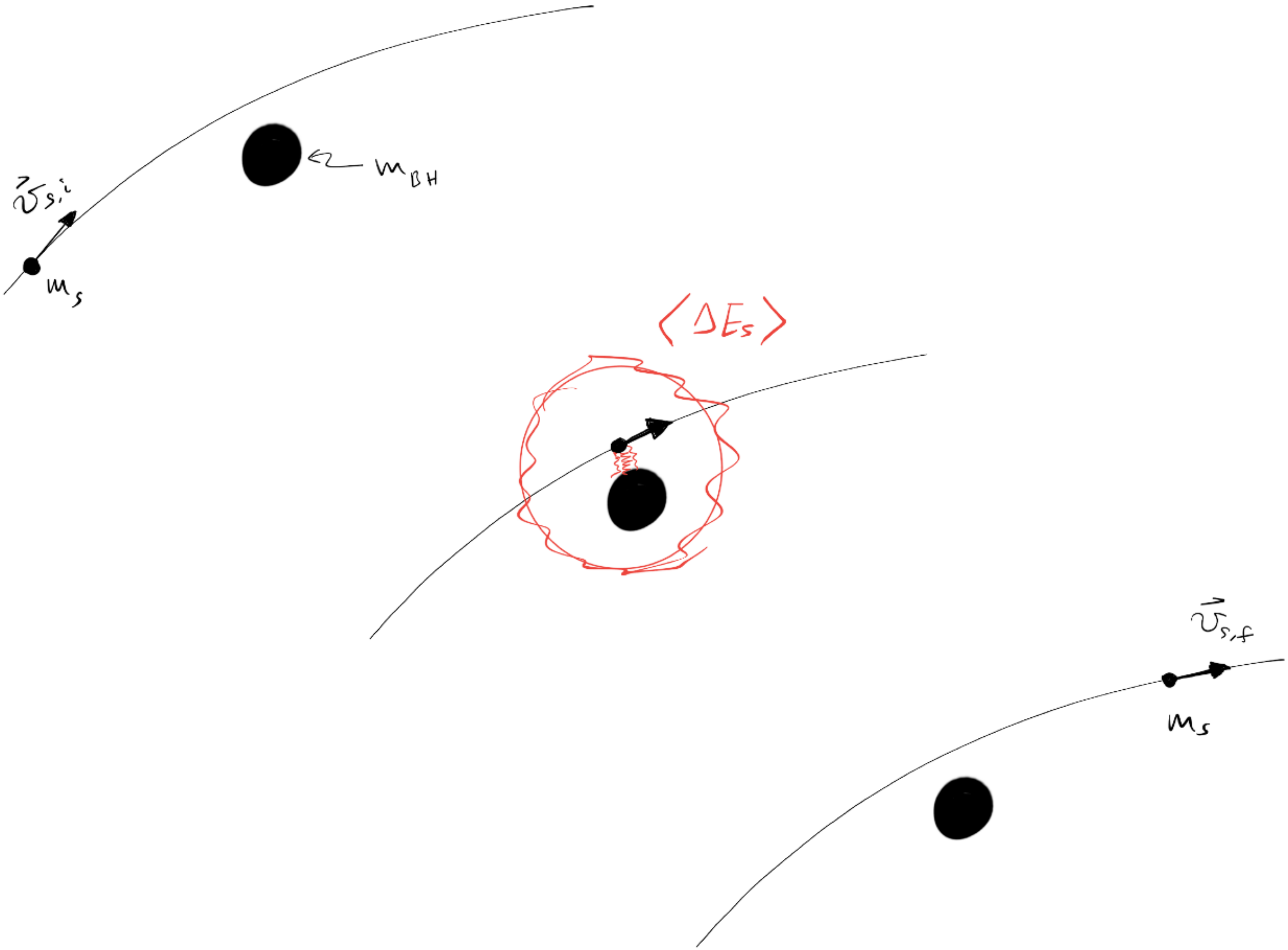


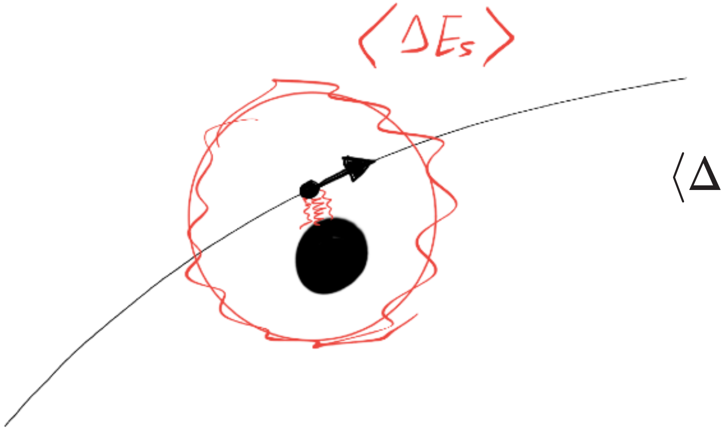
Dwarf galaxies: **Primordial black hole** dominated systems with few stars




$\vec{v}_{s,i}$
m_s
m_{BH}


$\vec{v}_{s,i}$
m_s
m_{BH}
$\langle \Delta E_s \rangle$


$\vec{v}_{s,i}$
m_s
m_{BH}
$\langle \Delta E_s \rangle$
$\vec{v}_{s,f}$
m_s



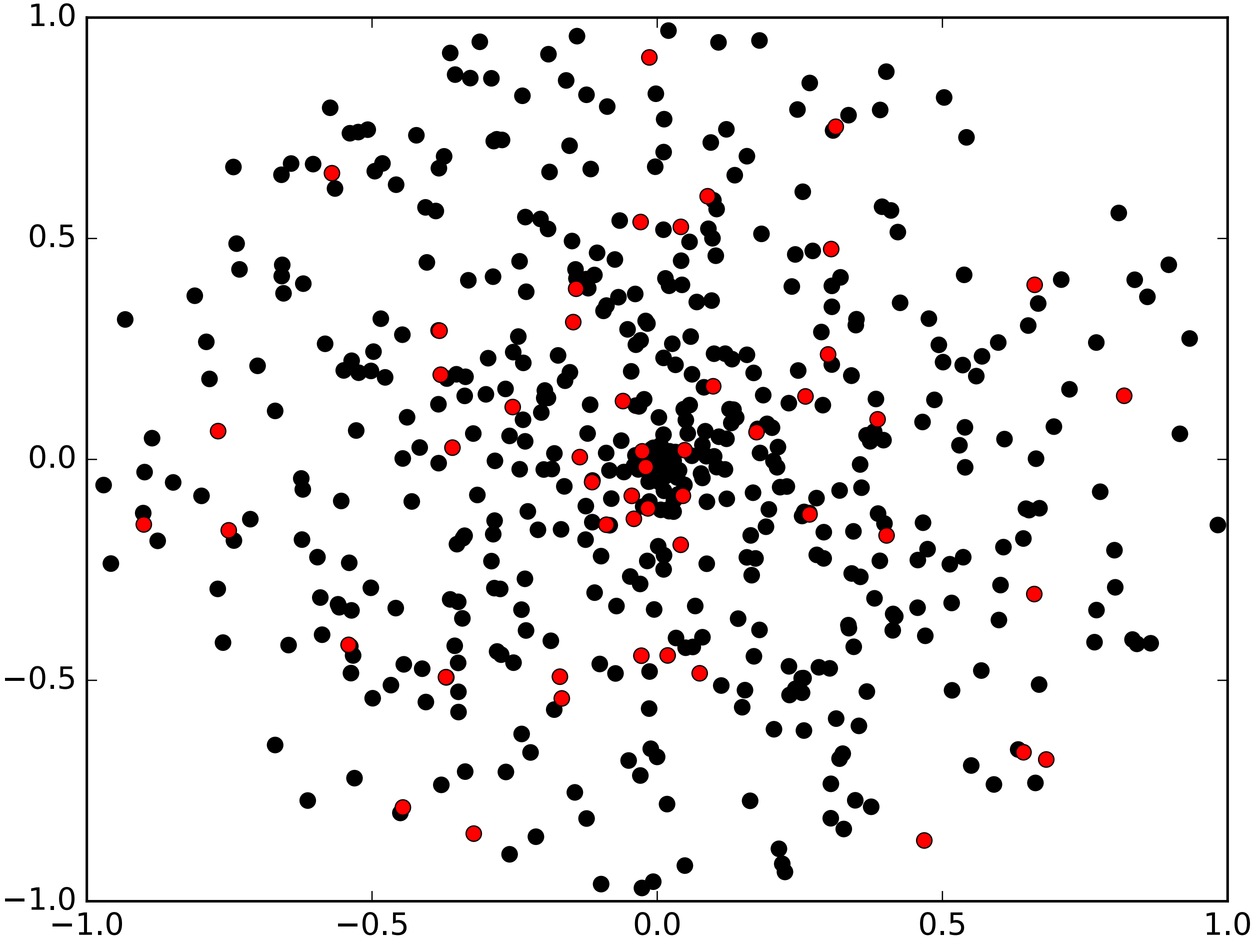
Single interaction

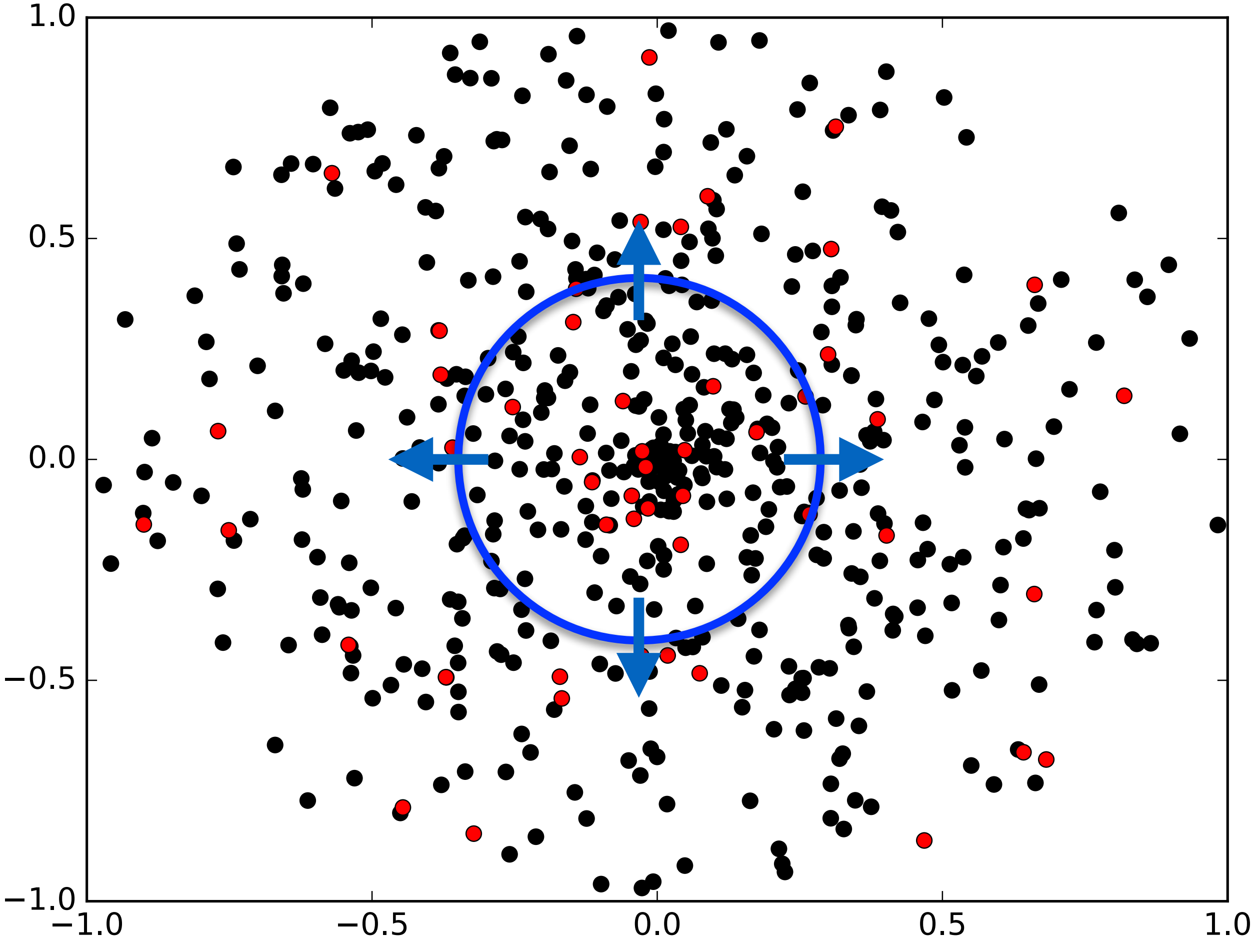
$$\langle \Delta E \rangle_s = v_s \langle \Delta v_{s,\parallel} \rangle + \frac{1}{2} \langle (\Delta v_{s,\parallel})^2 \rangle + \frac{1}{2} \langle (\Delta v_{s,\perp})^2 \rangle$$
$$= \frac{4\pi G^2 m_{\mathrm{BH}} \rho_{\mathrm{BH}} \ln \Lambda}{v_s}$$
$$\times \left[-\frac{m_s}{m_{\mathrm{BH}}} \mathrm{erf}(X) + \left(1 + \frac{m_s}{m_{\mathrm{BH}}} \right) X \mathrm{erf}'(X) \right]$$

Mean change of KE

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

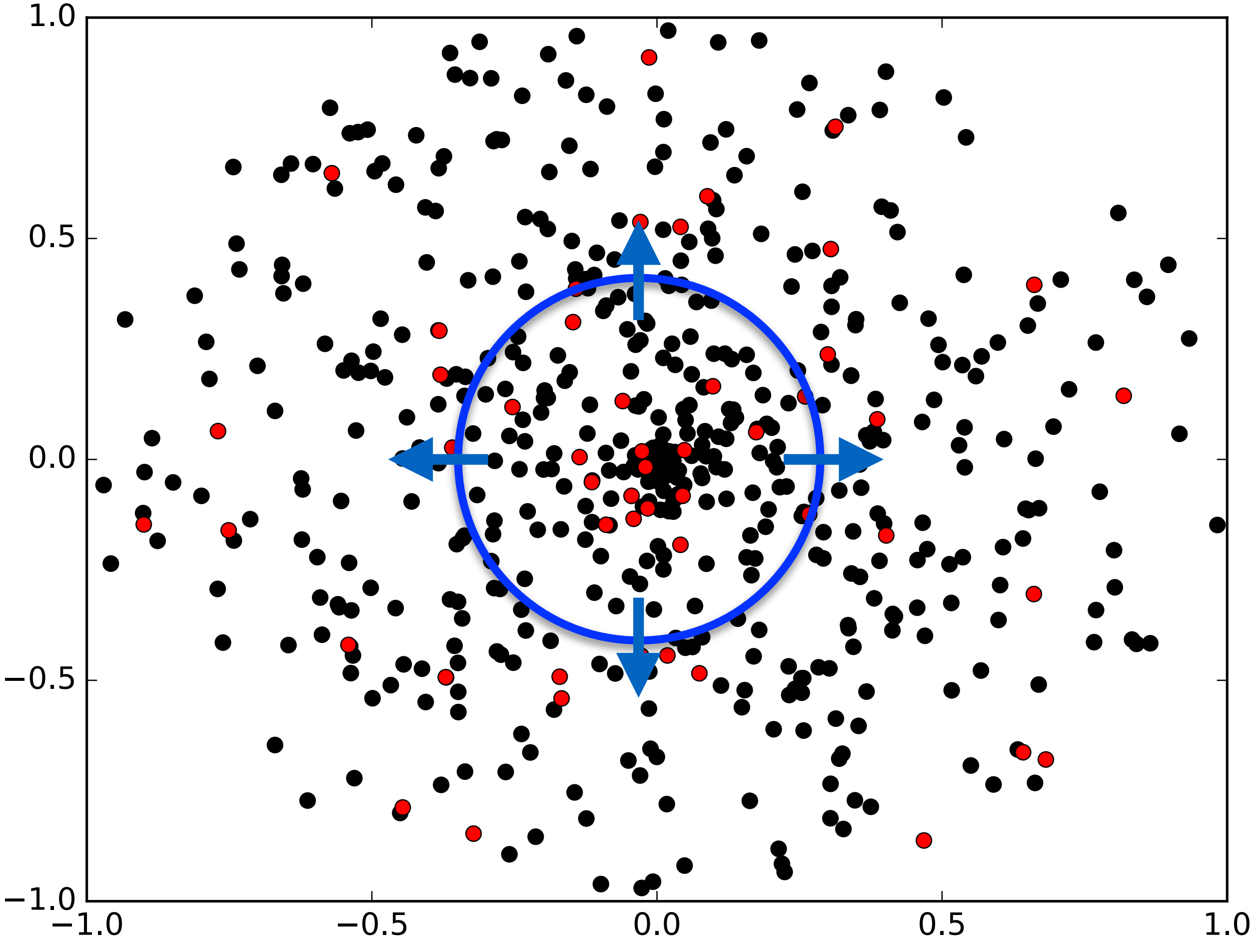
$$\frac{dE_s}{dt} = \frac{\sqrt{96\pi} G^2 m_s \rho_{\mathrm{BH}} \ln \Lambda}{\left[\langle v_s^2 \rangle + \langle v_{\mathrm{BH}}^2 \rangle \right]^{3/2}} \left[m_{\mathrm{BH}} \langle v_{\mathrm{BH}}^2 \rangle - m_s \langle v_s^2 \rangle \right]$$


1.0
0.5
0.0
−0.5
−1.0
−1.0
−0.5
0.0
0.5
1.0



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

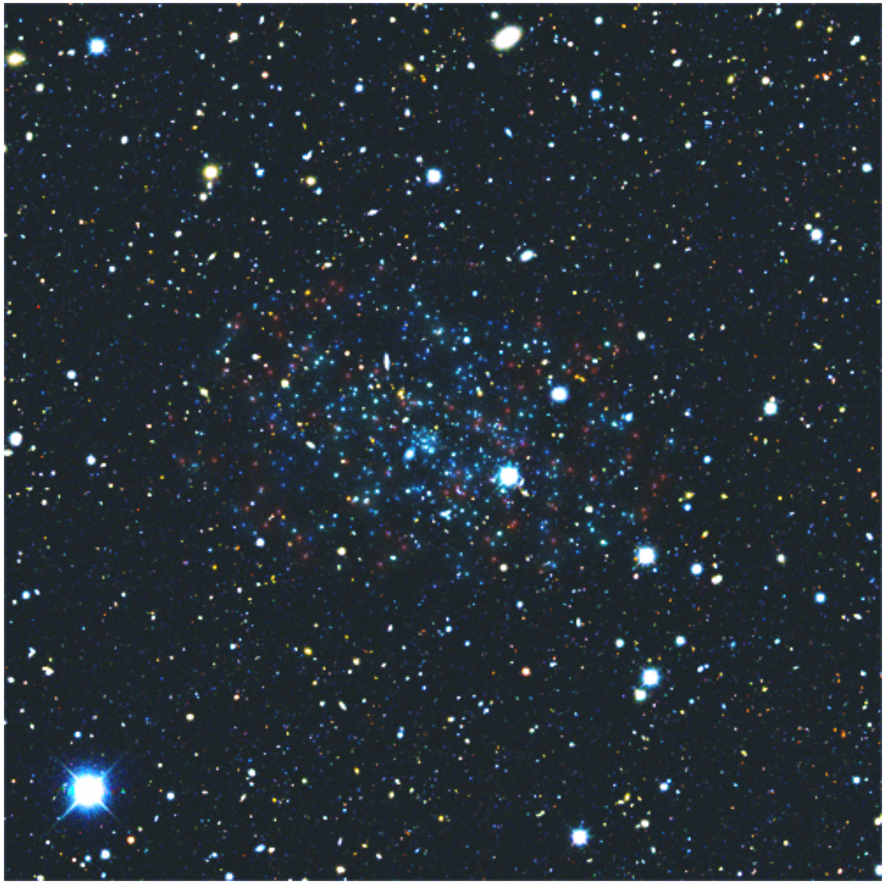
T. D. Brandt, Astrophys. J. Lett. **824**, L31 (2016)

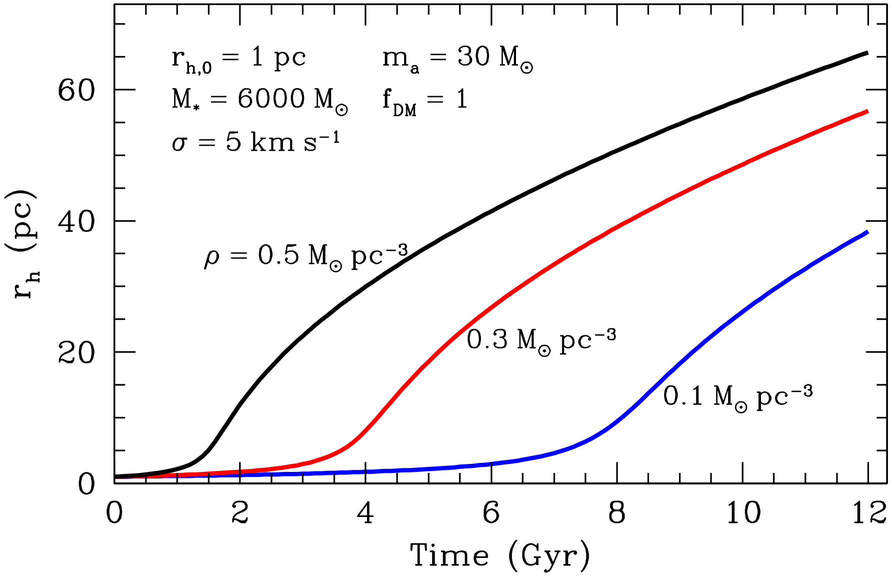


Look at the evolution of the half-light radius $$\frac{dr}{dt} = \frac{4\sqrt{2}\pi G f_{\mathrm{DM}} m_{\mathrm{BH}}}{\sigma} \ln \Lambda \left(\alpha \frac{M_s}{\rho_{\mathrm{DM}} r^2} + 2\beta r \right)^{-1}$$

T. D. Brandt, Astrophys. J. Lett. **824**, L31 (2016)

Eridanus II





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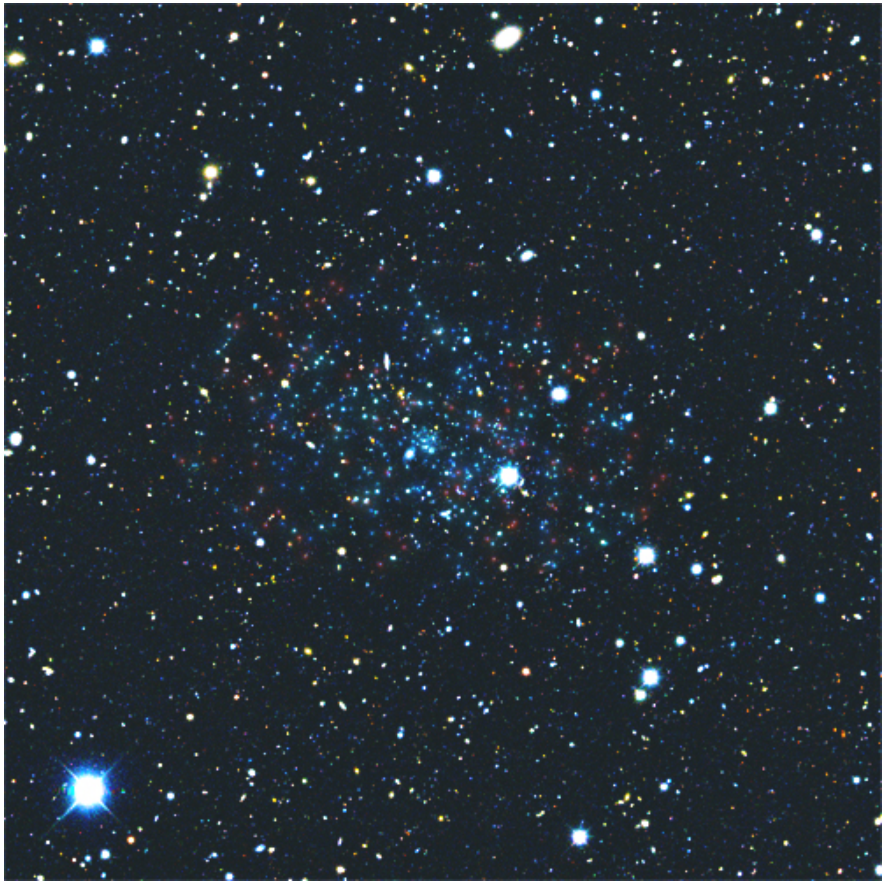
T. D. Brandt, Astrophys. J. Lett. **824**, L31 (2016)

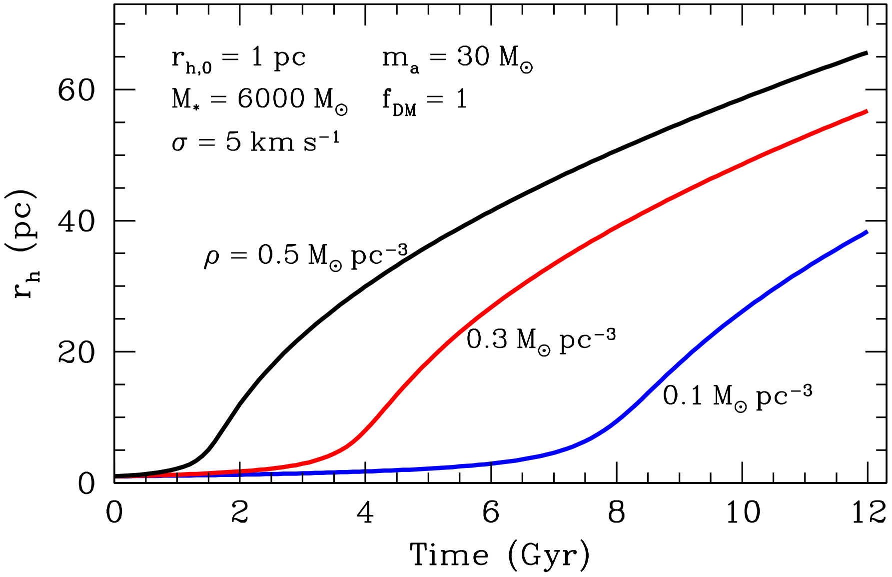
Eridanus II

Velocity dispersion unknown

Dark matter distribution unknown

Use 1/2-light radius of the central cluster only





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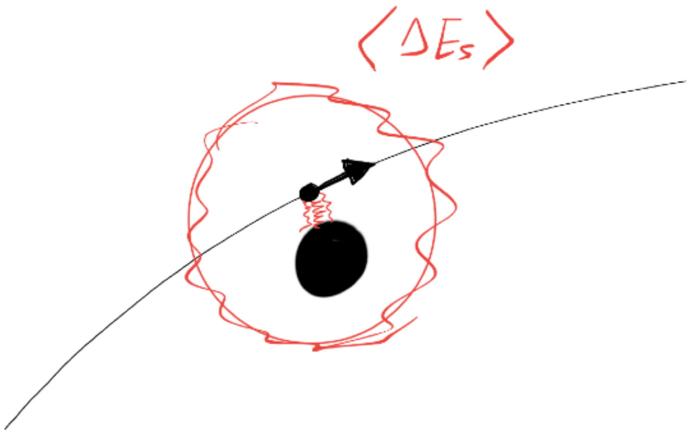
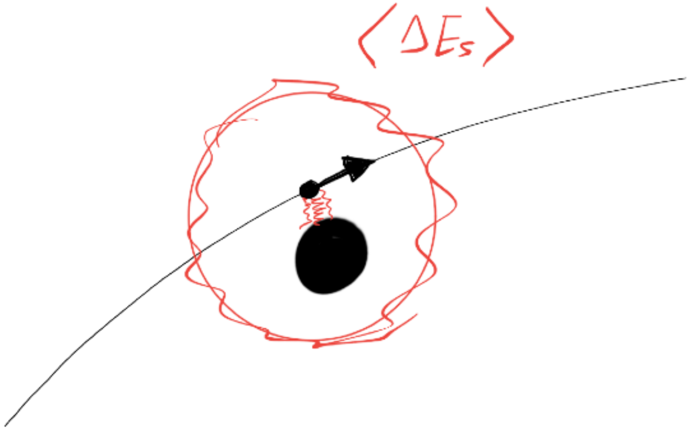


Time over which equipartition takes place

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



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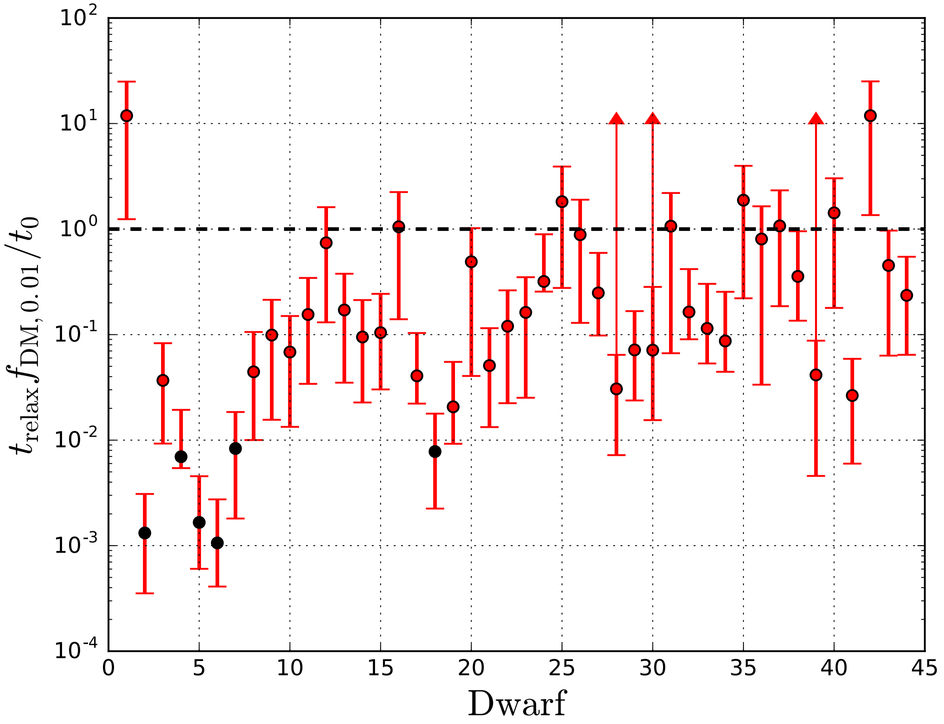
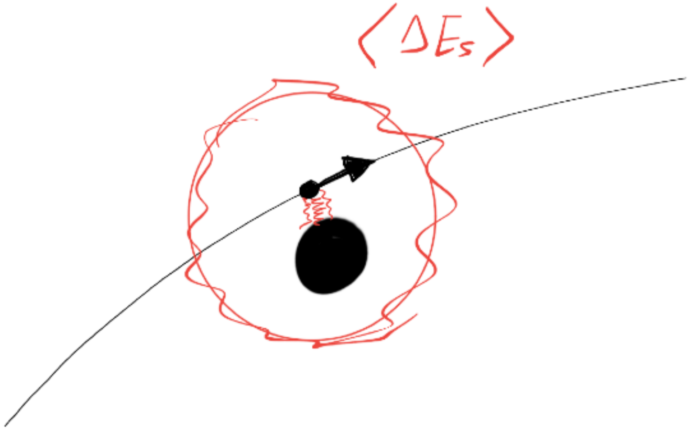


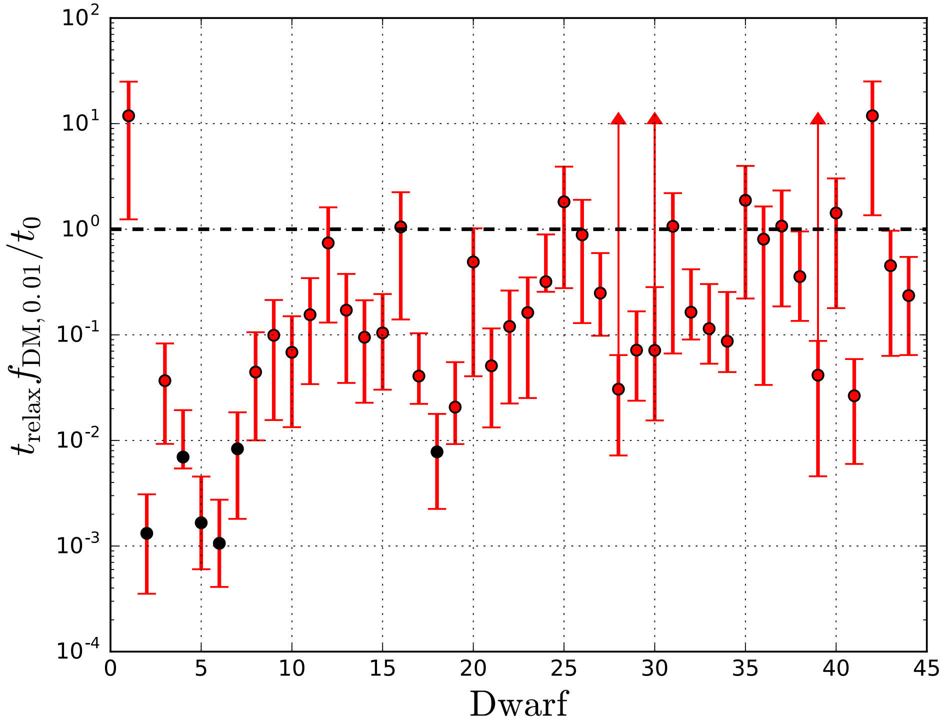


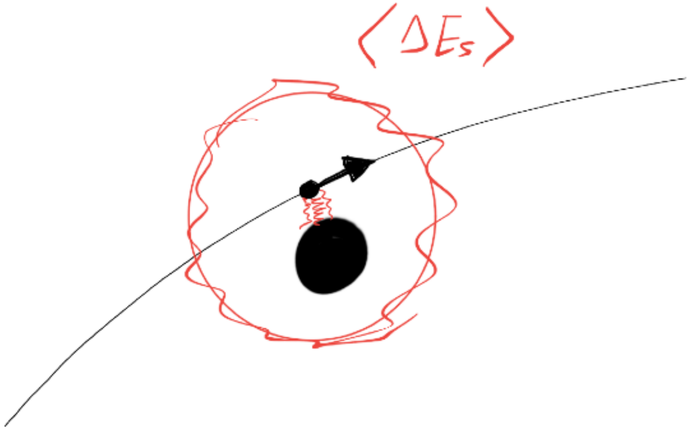
Time over which equipartition takes place

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

Dwarfs with smallest relaxation time

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





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Segue 1

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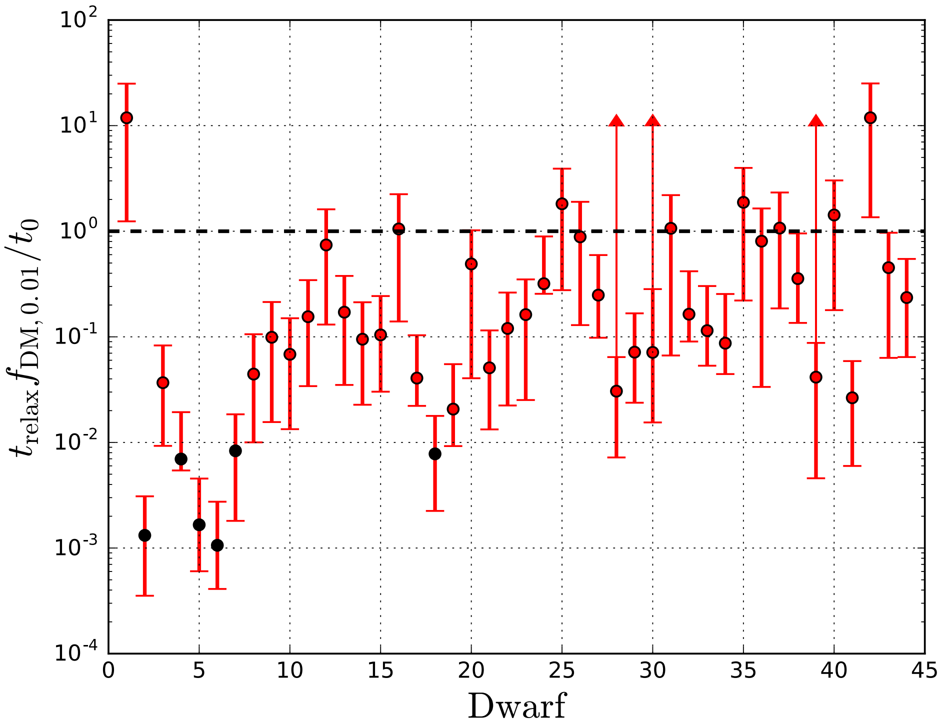
Coma Berenices

Canes Venatici II



The Astrophysical Journal, 733:46 (20pp), 2011 May 20 doi:10.1088/0004-637X/733/1/46

A COMPLETE SPECTROSCOPIC SURVEY OF THE MILKY WAY SATELLITE SEGUE 1: THE DARKEST GALAXY*

Joshua D. Simon[1], Marla Geha[2], Quinn E. Minor[3], Gregory D. Martinez[3], Evan N. Kirby[4,8], James S. Bullock[3], Manoj Kaplinghat[3], Louis E. Strigari[5,8], Beth Willman[6], Philip I. Choi[7], Erik J. Tollerud[3], and Joe Wolf[3]

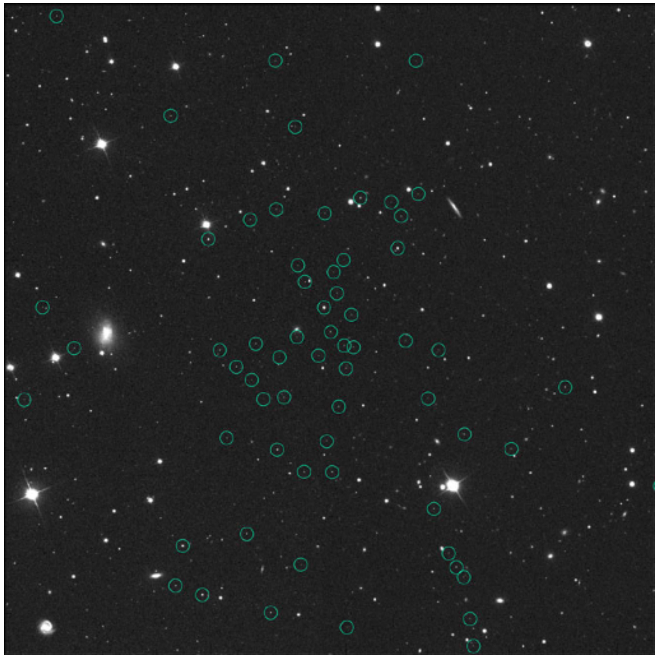


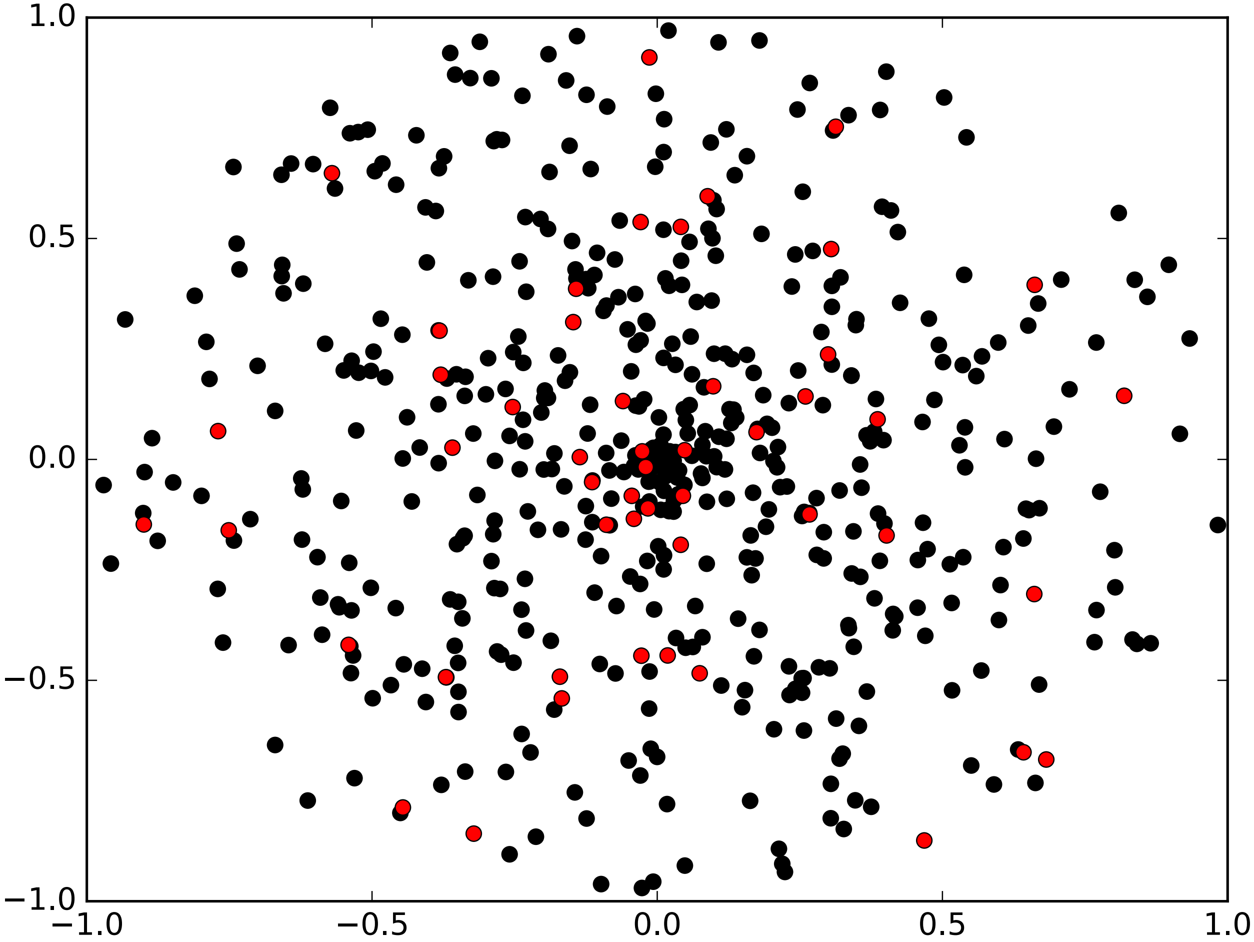
Table 1
Summary of Properties of Segue 1

Row	Quantity	Value
(1)	R.A. (J2000) (h m s)	10:07:03.2 ± $1^{\mathrm{s}}.7$
(2)	Decl. (J2000) (° ′ ″)	+16:04:25 ± 15″
(3)	Distance (kpc)	23 ± 2
(4)	M_V	$-1.5^{+0.6}_{-0.8}$
(5)	L_V ($L_\odot$)	340
(6)	ϵ	$0.48^{+0.10}_{-0.13}$
(7)	$\mu_{V,0}$ (mag arcsec^{-2})	$27.6^{+1.0}_{-0.7}$
(8)	r_{eff} (pc)	29^{+8}_{-5}
(9)	V_{hel} (km s^{-1})	208.5 ± 0.9
(10)	V_{GSR} (km s^{-1})	113.5 ± 0.9
(11)	σ (km s^{-1})	$3.7^{+1.4}_{-1.1}$
(12)	Mass ($M_\odot$)	$5.8^{+8.2}_{-3.1} \times 10^5$
(13)	M/L_V ($M_\odot/L_\odot$)	3400
(14)	Mean [Fe/H]	−2.5

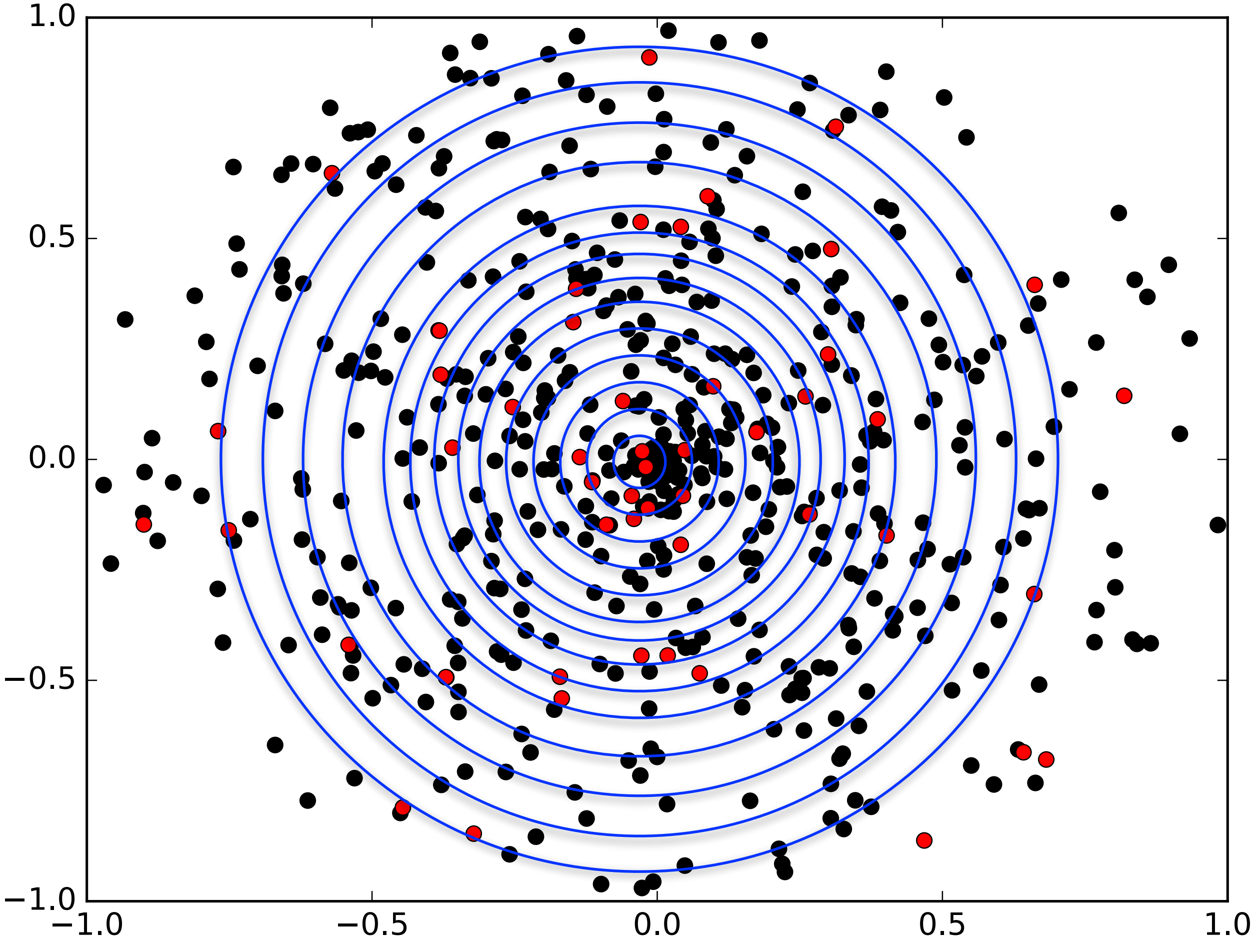
The Astrophysical Journal, 801:74 (18pp), 2015 March 10 doi:10.1088/0004-637X/801/2/74

DWARF GALAXY ANNIHILATION AND DECAY EMISSION PROFILES FOR DARK MATTER EXPERIMENTS

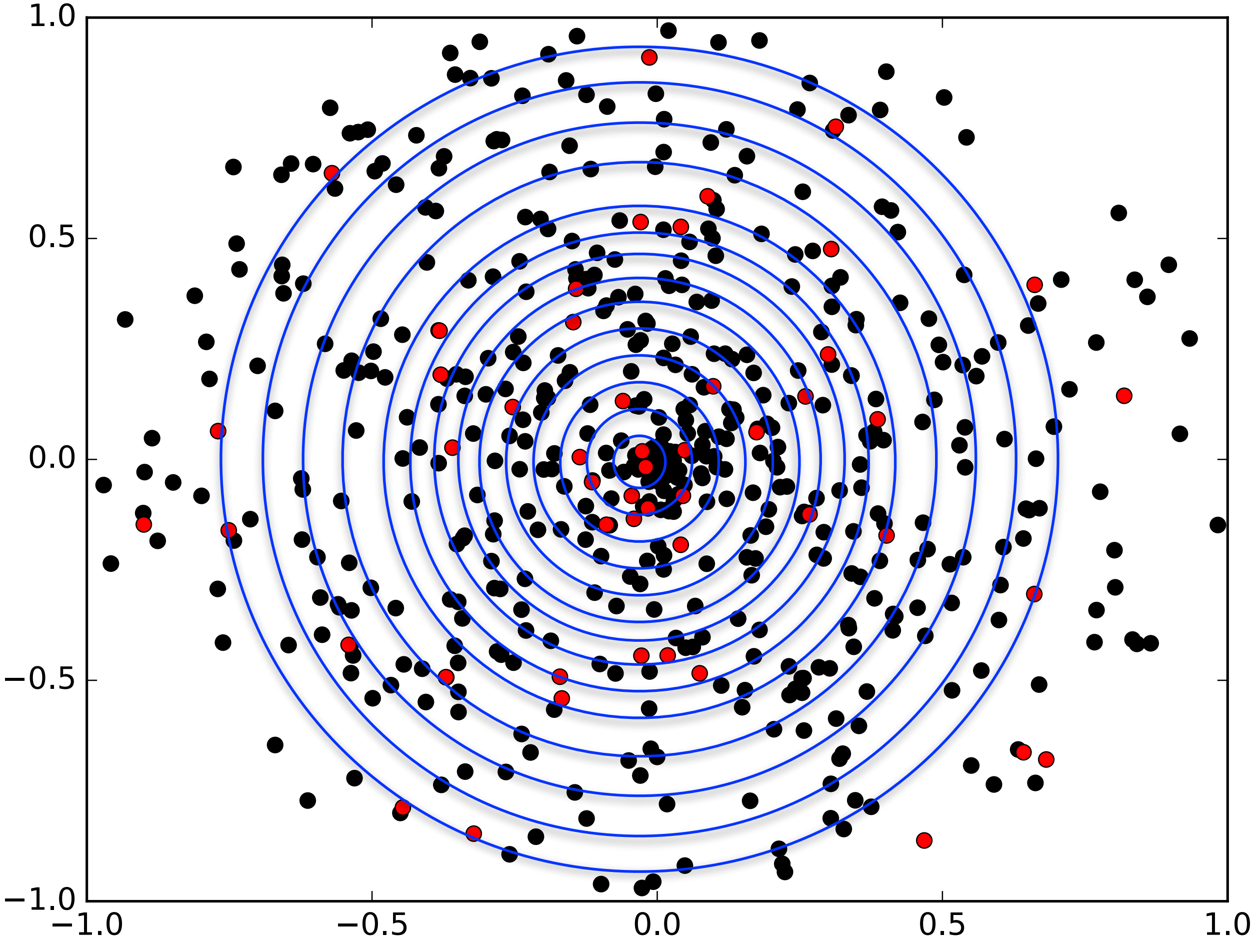
Alex Geringer-Sameth[1,2], Savvas M. Koushiappas[1], and Matthew Walker[2]



Koushiappas & Loeb PRL 119, 041102 (2017)



Koushiappas & Loeb PRL 119, 041102 (2017)

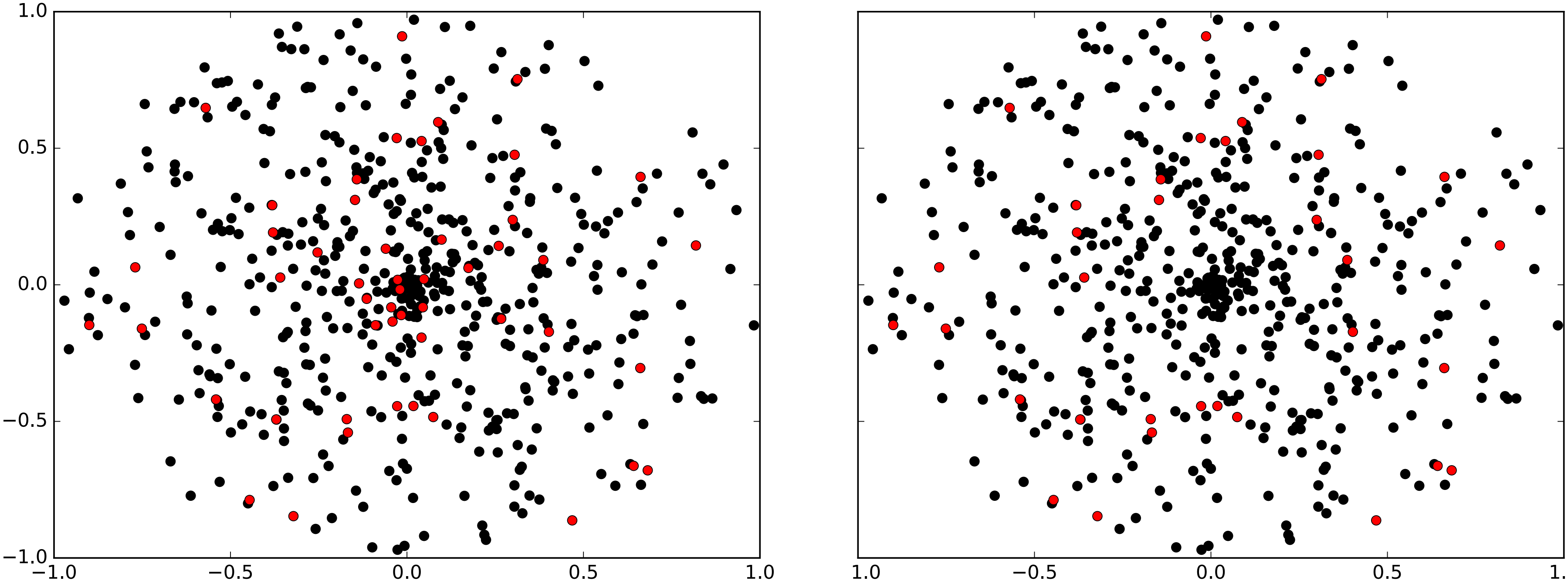


Look at the evolution of the whole stellar population in Segue 1

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

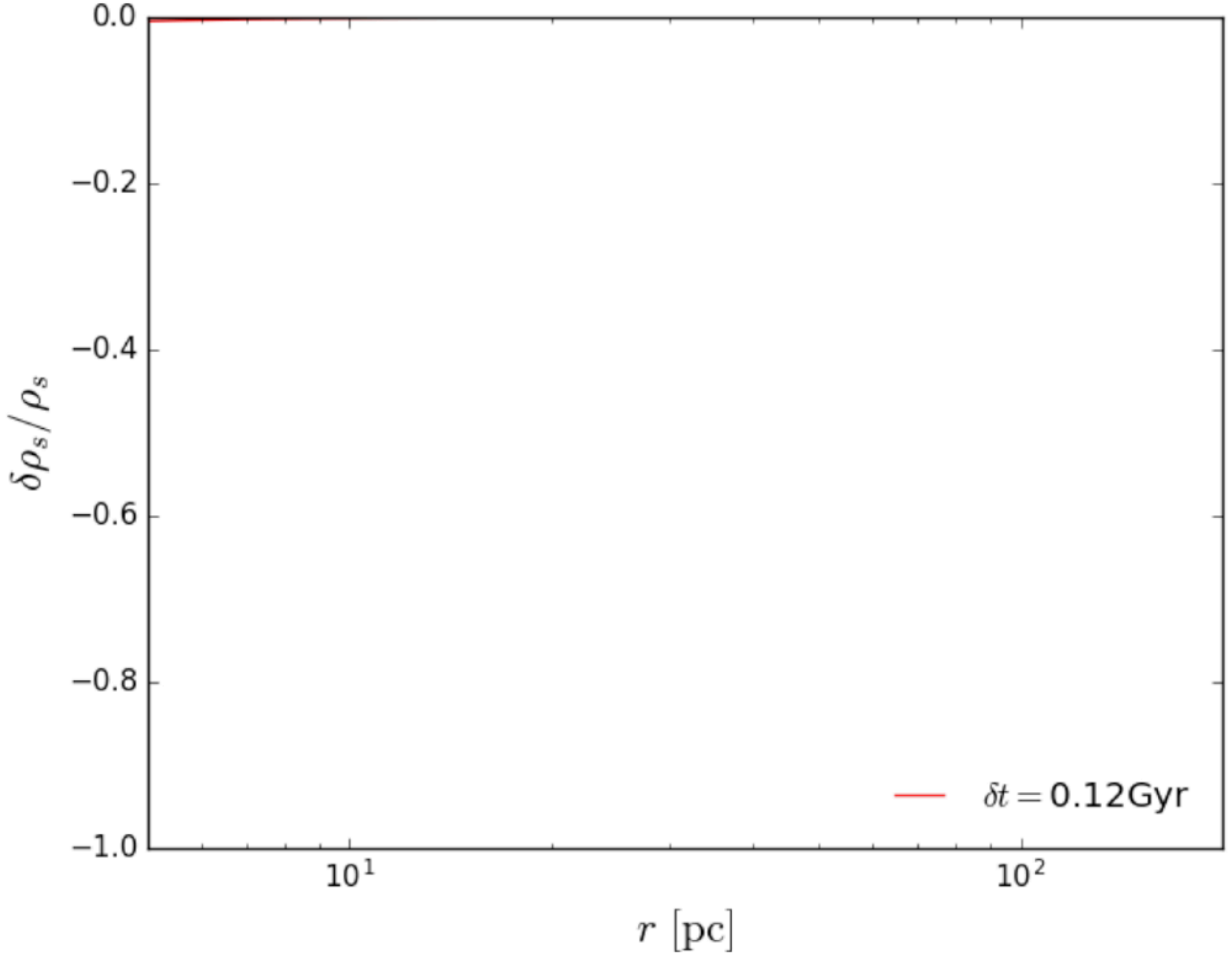
Koushiappas & Loeb PRL 119, 041102 (2017)

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



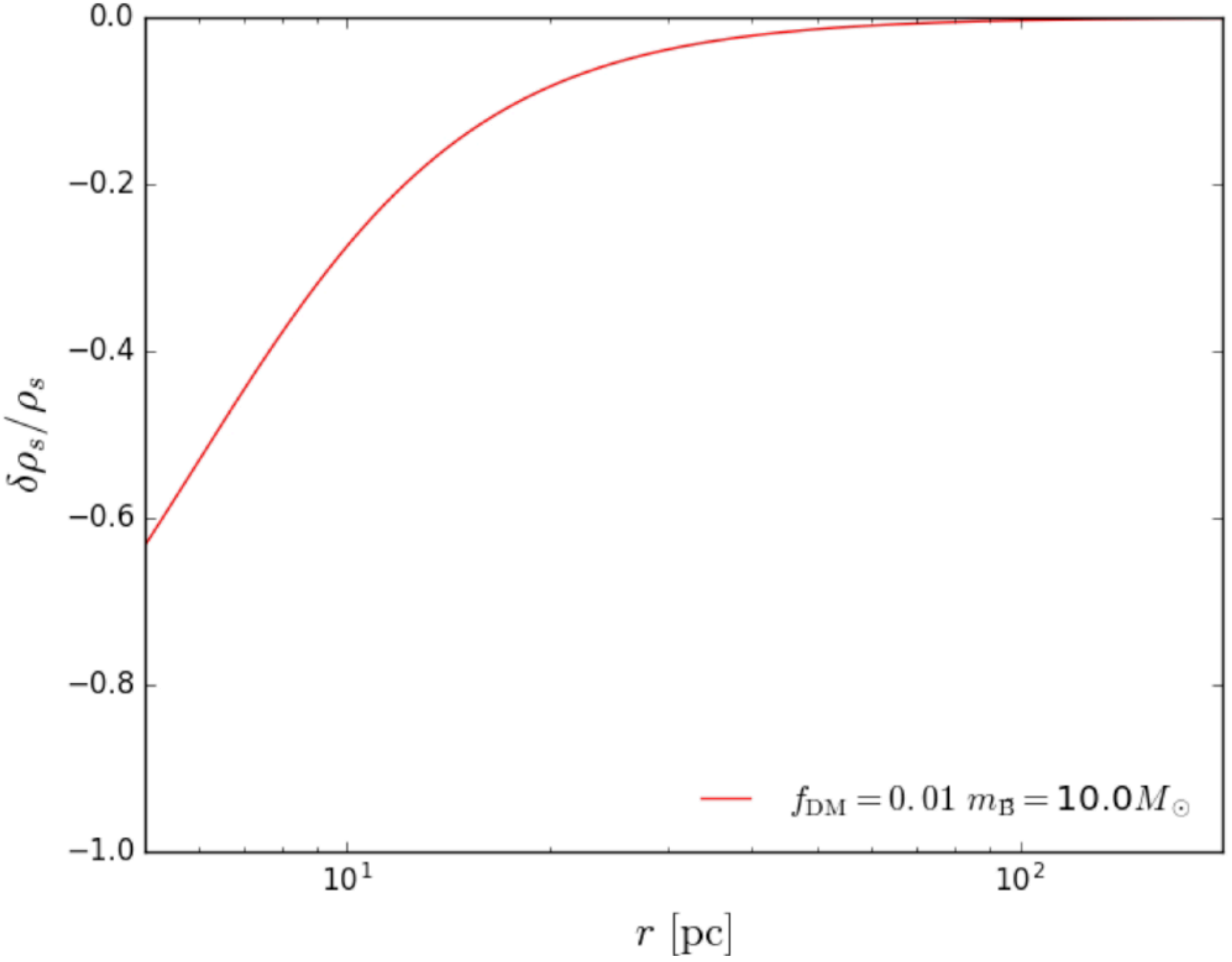
Koushiappas & Loeb PRL 119, 041102 (2017)

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



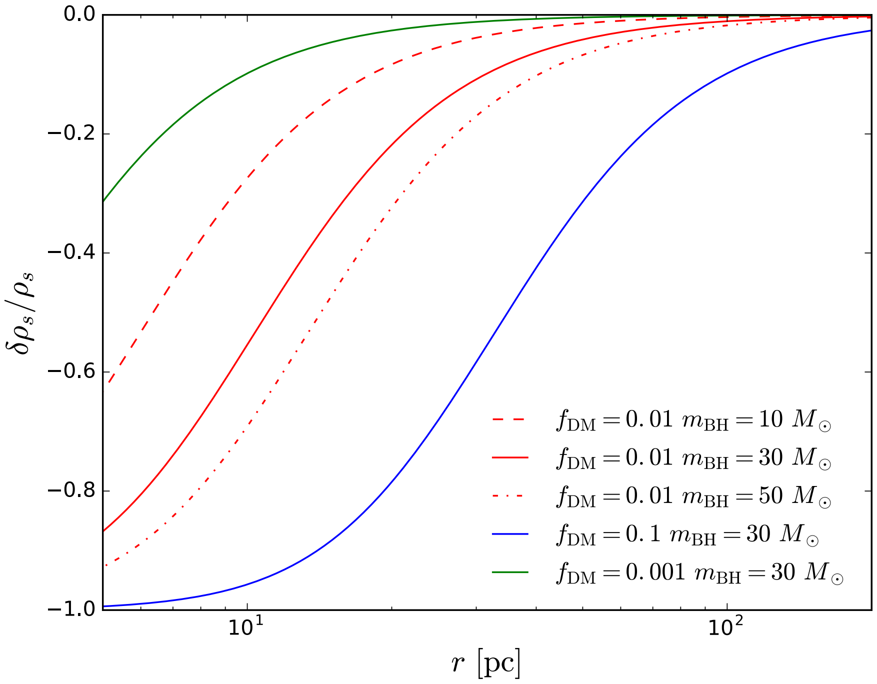
Koushiappas & Loeb PRL 119, 041102 (2017)

Evolution of density profile over 12 Gigayears



Koushiappas & Loeb PRL 119, 041102 (2017)

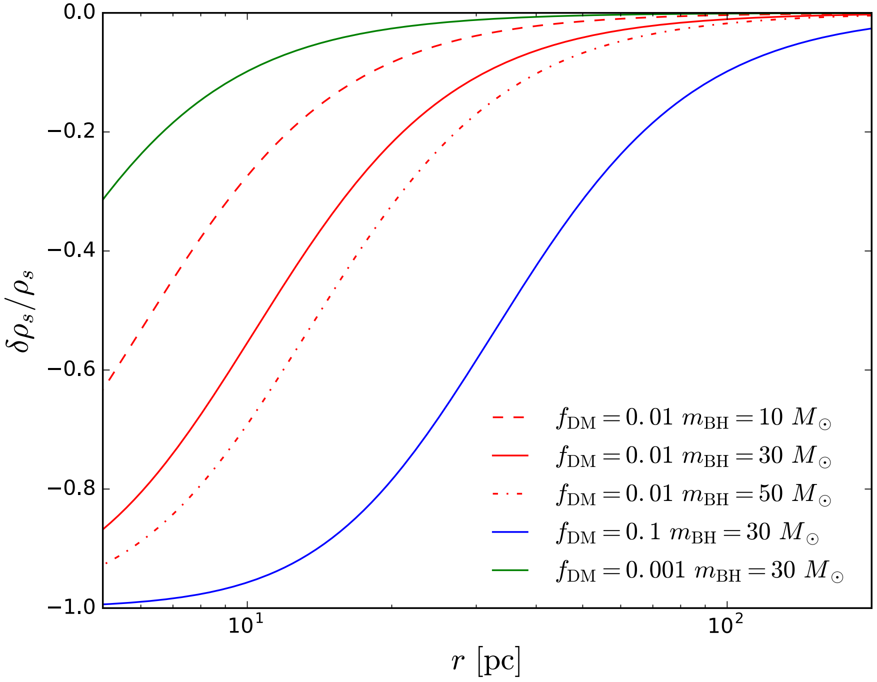
Depletion of stars in the inner regions



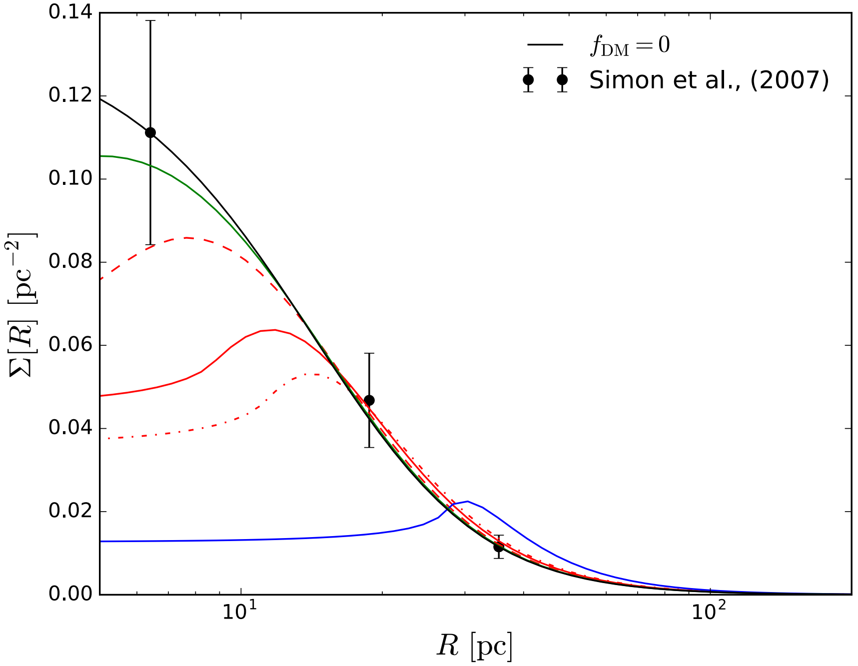
$$\frac{\delta\rho_s}{\rho_s} = \frac{r^3(t)}{r^3(0)} - 1$$

Koushiappas & Loeb PRL 119, 041102 (2017)

Depletion of stars in the inner regions



Prediction of a **stellar ring** in projection



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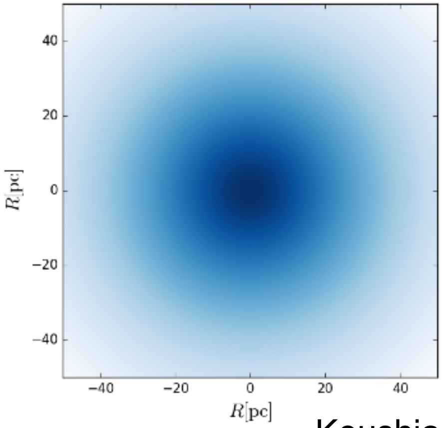
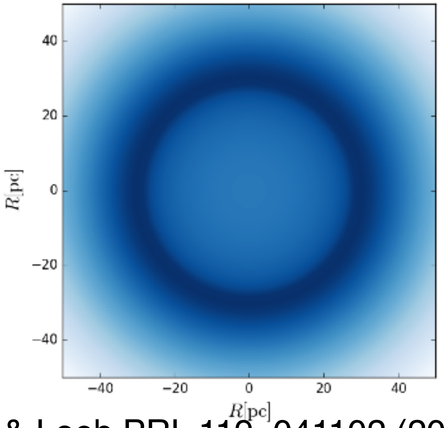
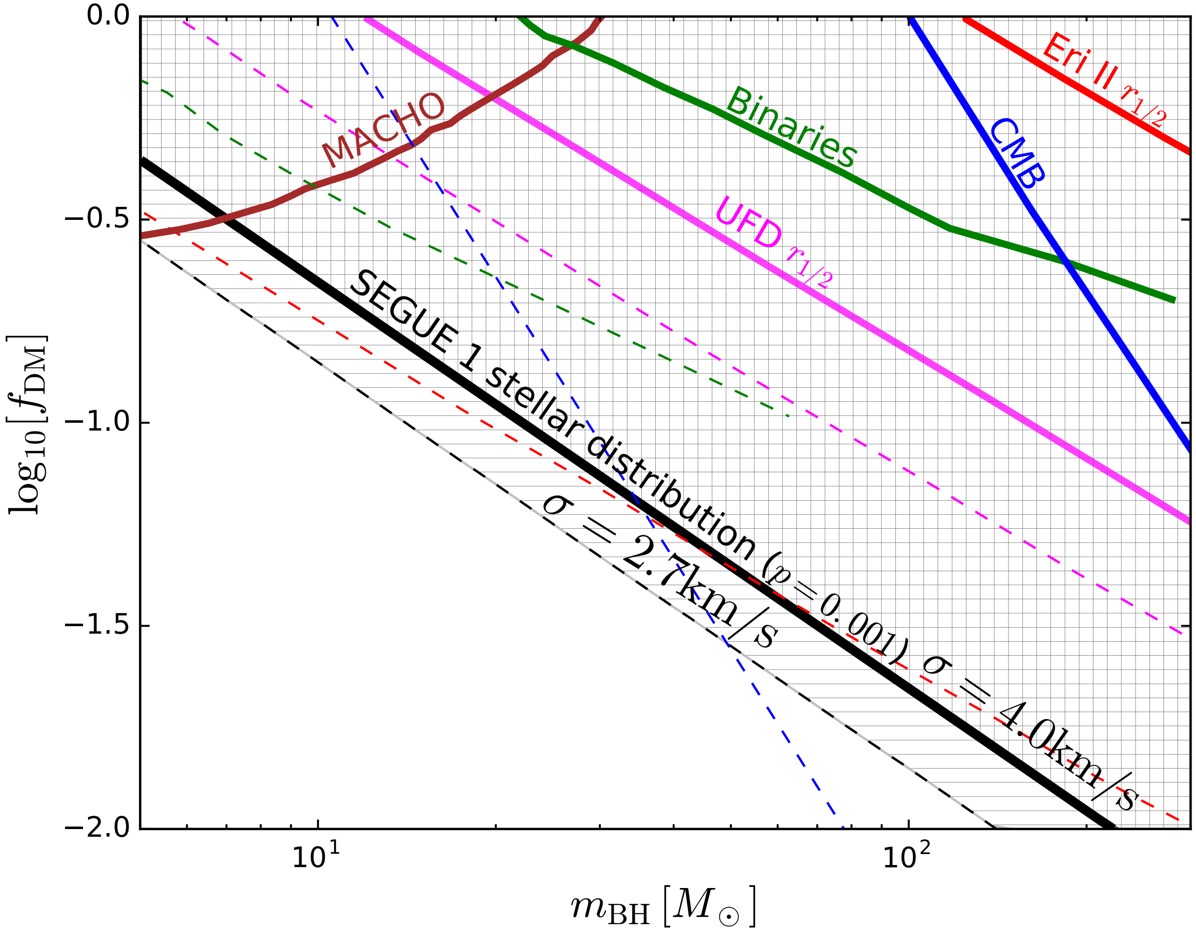


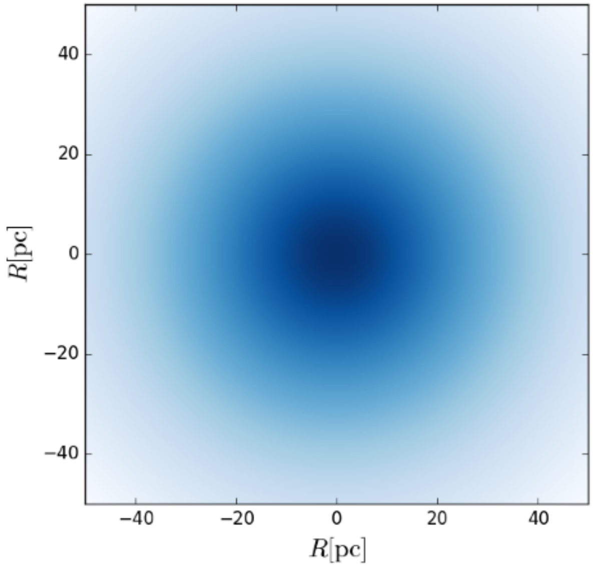


Koushiappas & Loeb PRL 119, 041102 (2017)

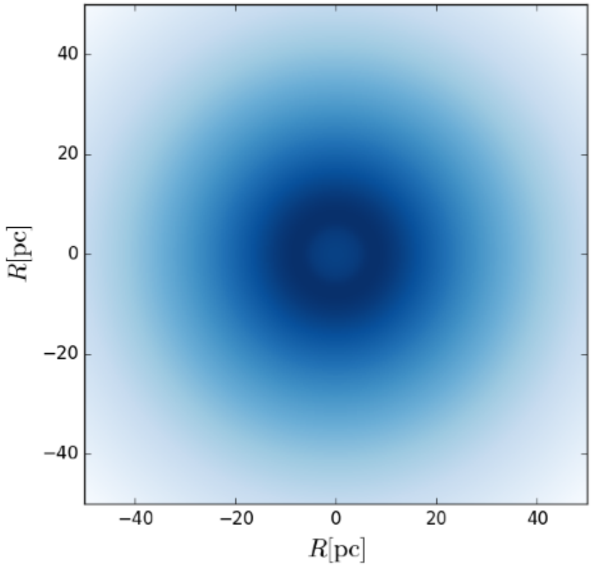
Primordial black hole constraints from the whole stellar population of Segue 1



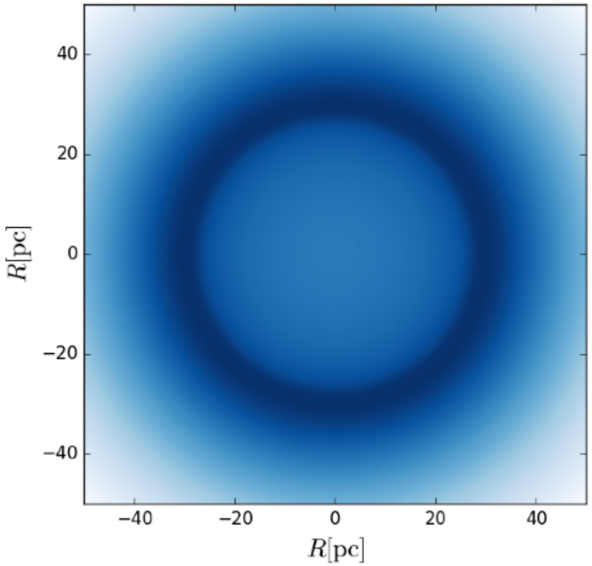
No black holes



1% dark matter in
10 solar mass black holes

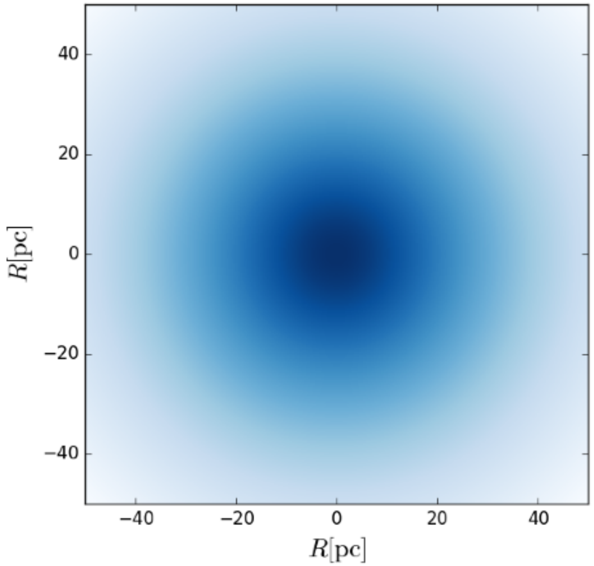


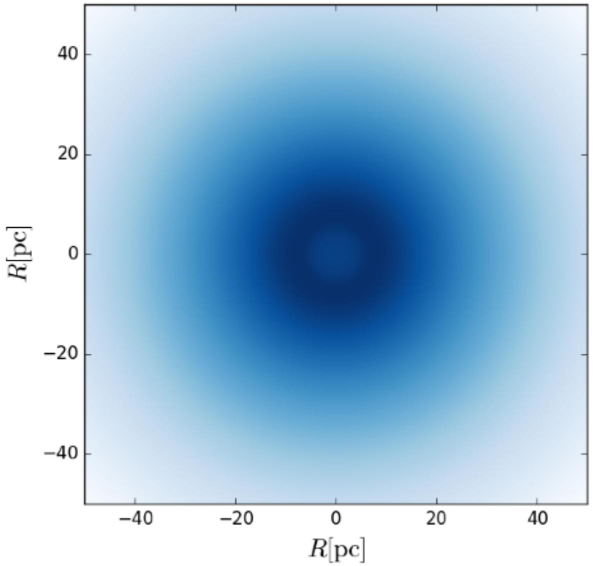
10% of dark matter in
30 solar mass black holes



Both of these consistent with current observations

Ruled out


No black holes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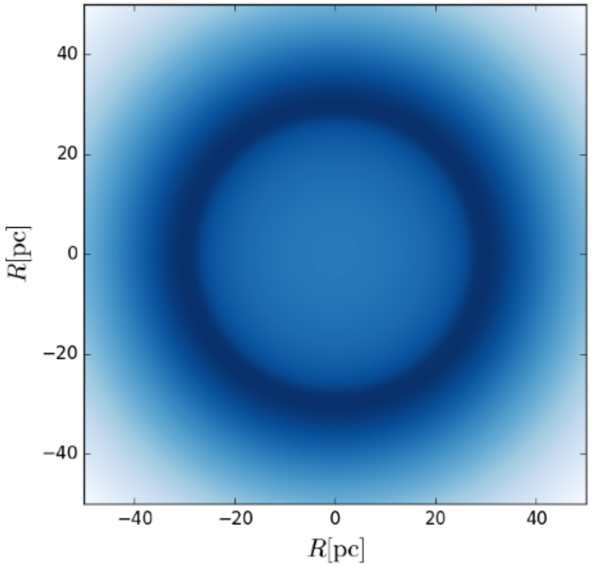
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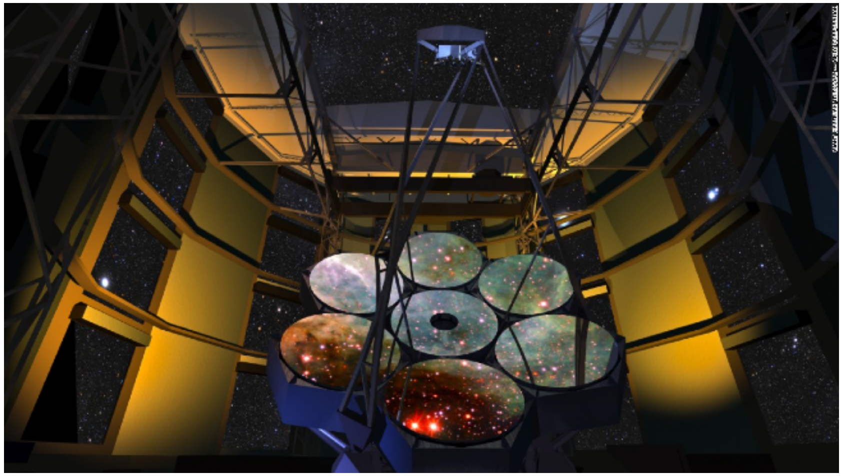
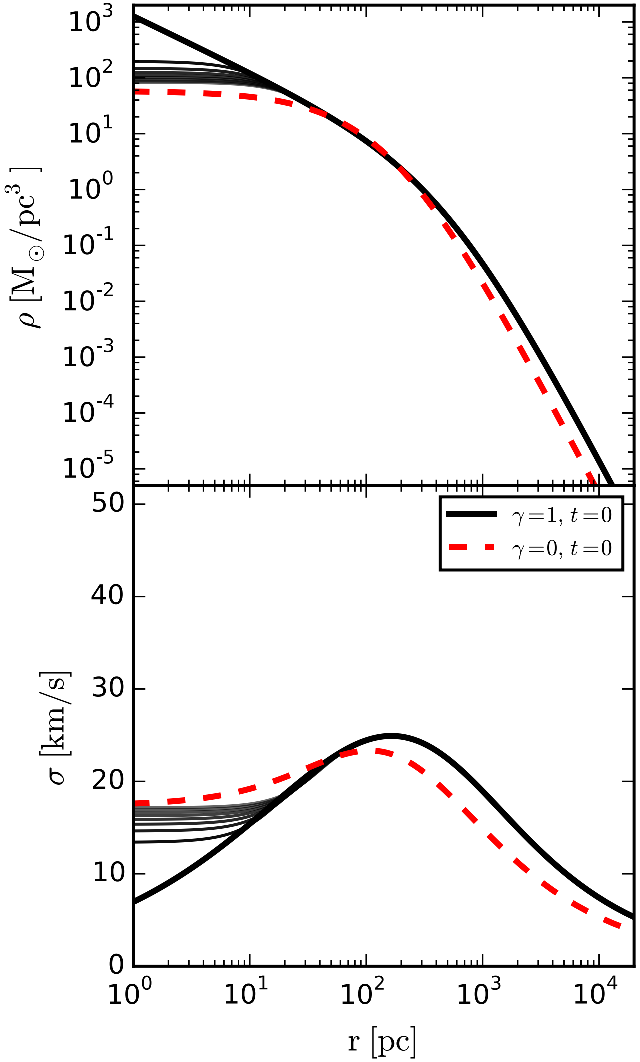
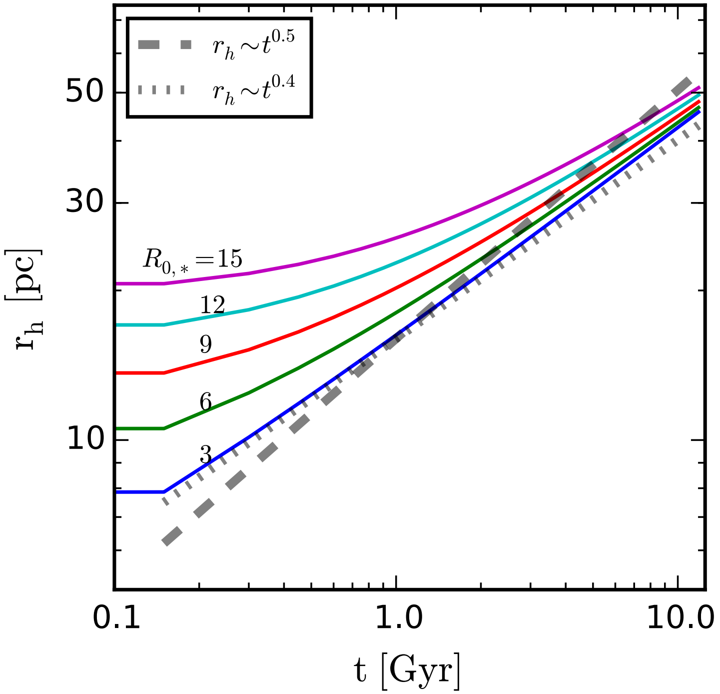
GIANT MAGELLAN
TELESCOPE



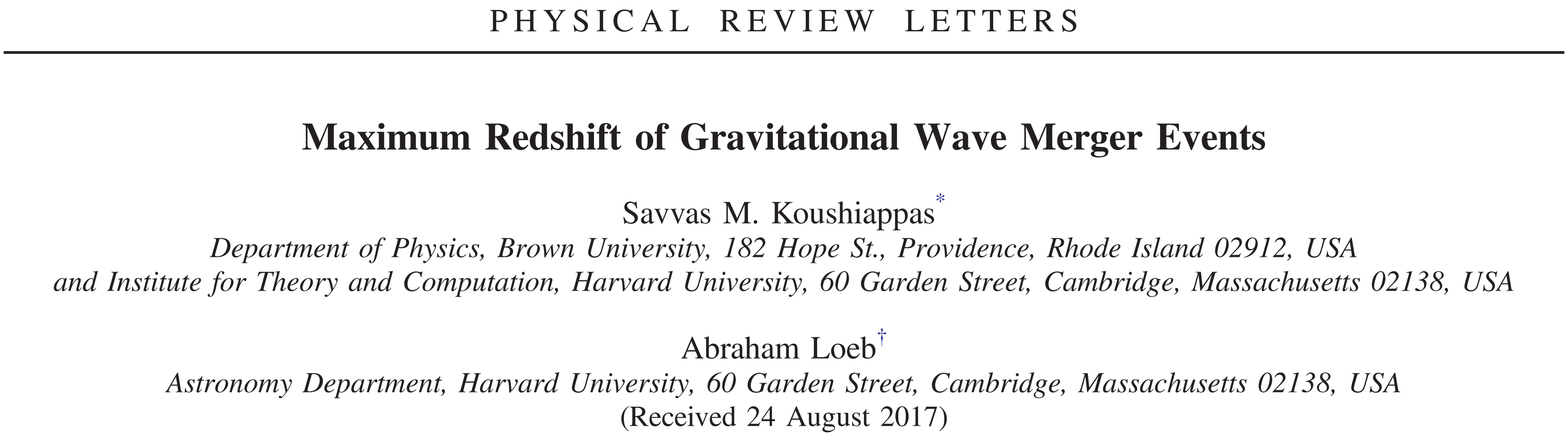
Fokker-Planck treatment of the same problem



1. **arXiv:1710.05032 [pdf, other]**
Primordial Black Holes as Dark Matter: Constraints From Compact Ultra-Faint Dwarfs
Qirong Zhu, Eugene Vasiliev, Yuexing Li, Yipeng Jing



How to distinguish primordial from baryonic black holes



PHYSICAL REVIEW LETTERS

Maximum Redshift of Gravitational Wave Merger Events

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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

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Astronomy Department, Harvard University, 60 Garden Street, Cambridge, Massachusetts 02138, USA

(Received 24 August 2017)

Koushiappas & Loeb, arXiv:1708.07380

Rate of black hole merger events

- 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.

Koushiappas & Loeb, arXiv:1708.07380

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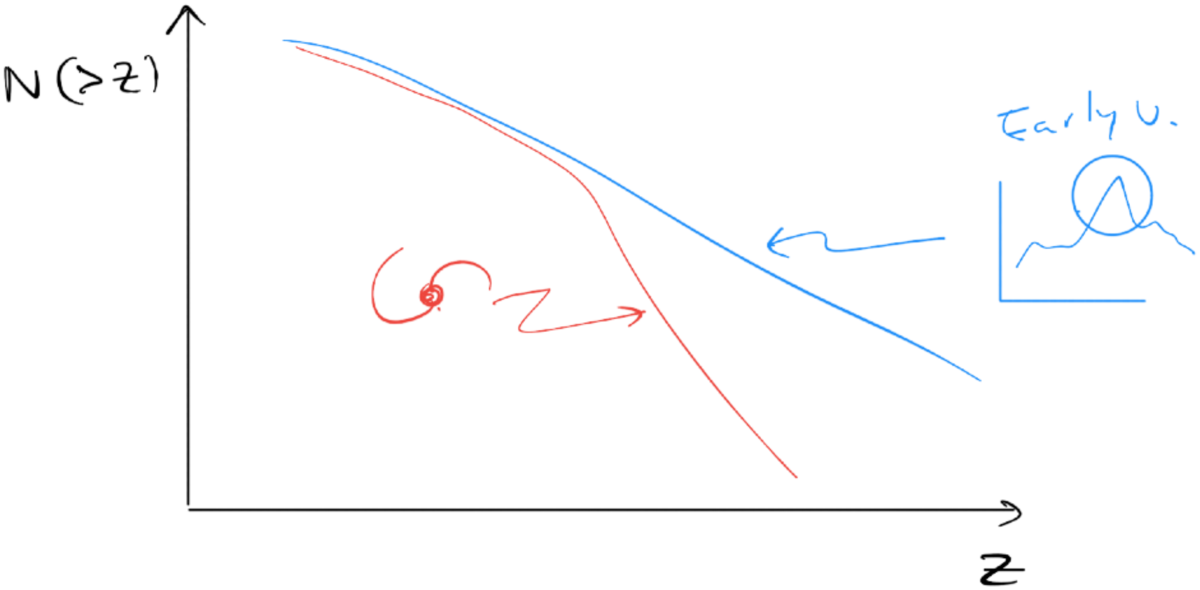

Koushiappas & Loeb, arXiv:1708.07380

Rate of black hole merger events

$$\mathcal{N}(>z) = \int_z^\infty \frac{d\mathcal{R}}{dz}\, dz$$

Fraction of gas that cools to form black holes

Rate of gas inflow

$$\frac{d\mathcal{R}}{dz} \equiv \int_{M_{\min}(z)}^{\infty} \frac{dN}{dM\,dV} C_{\mathrm{NG}}(M,z) \frac{\langle \epsilon(M,z) \rangle}{(1+z)} \frac{\dot{M}_{\mathrm{g}}(M,z)}{2m_{\mathrm{BH}}} \frac{dV}{dz}\, dM$$

Minimum halo mass where gas can cool

Dark matter halo mass function

Effects of non-gaussianity on halo mass function

Black hole mass (monochromatic)

Comoving volume

Integral is over all dark matter halo masses

Koushiappas & Loeb, arXiv:1708.07380

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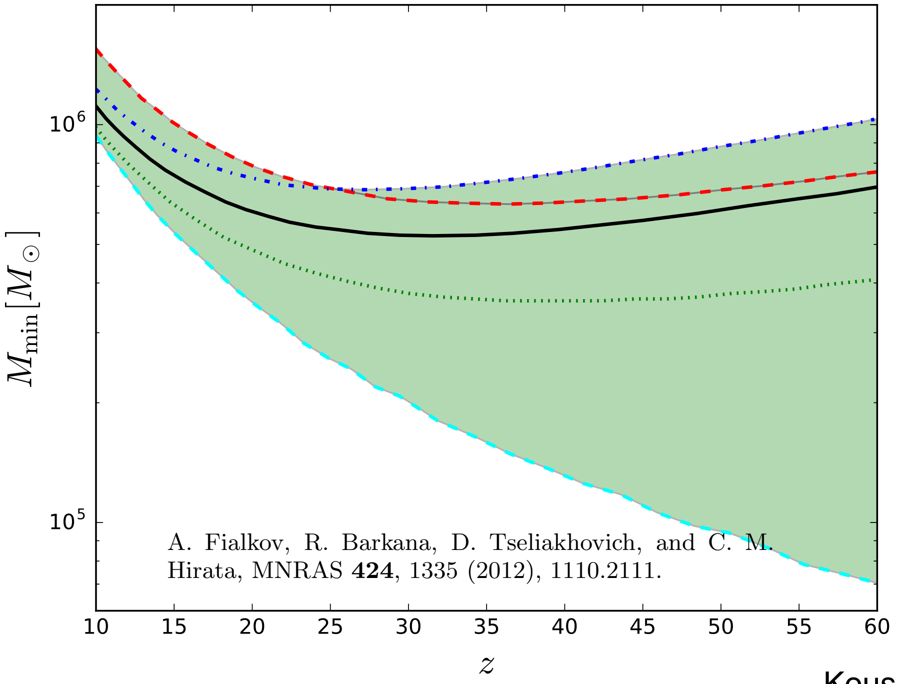

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Koushiappas & Loeb, arXiv:1708.07380

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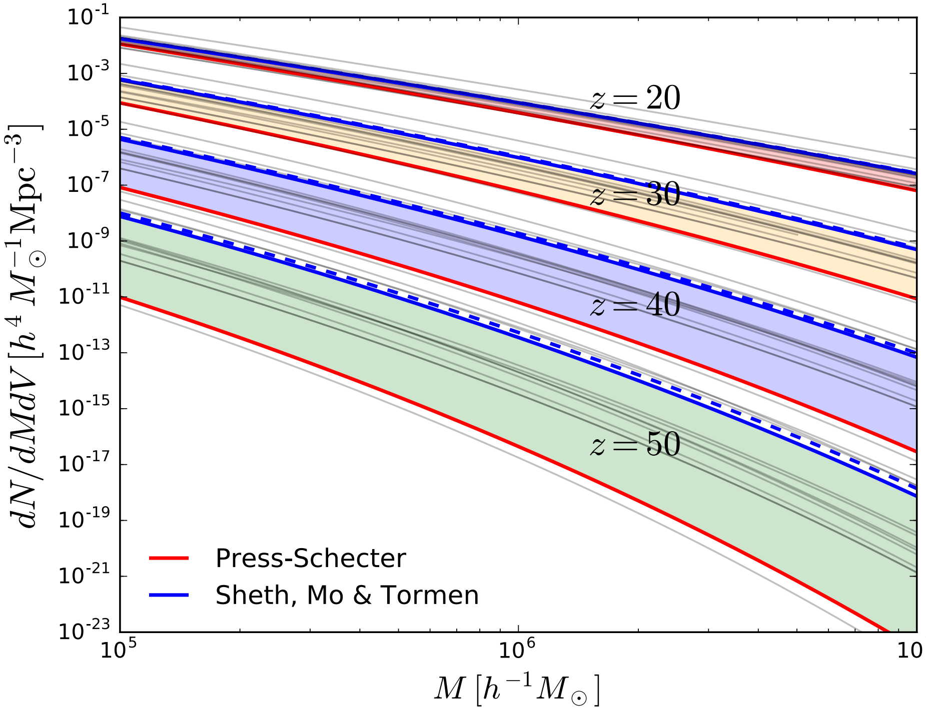
Dark matter halo mass function

Effects of non-gaussianity $f_{\rm NL} = 43$ on halo mass function



S. Matarrese, L. Verde, and R. Jimenez, ApJ **541**, 10 (2000), astro-ph/0001366.

Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, F. Arroja, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, et al., A&A **594**, A17 (2016), 1502.01592.

Koushiappas & Loeb, arXiv:1708.07380

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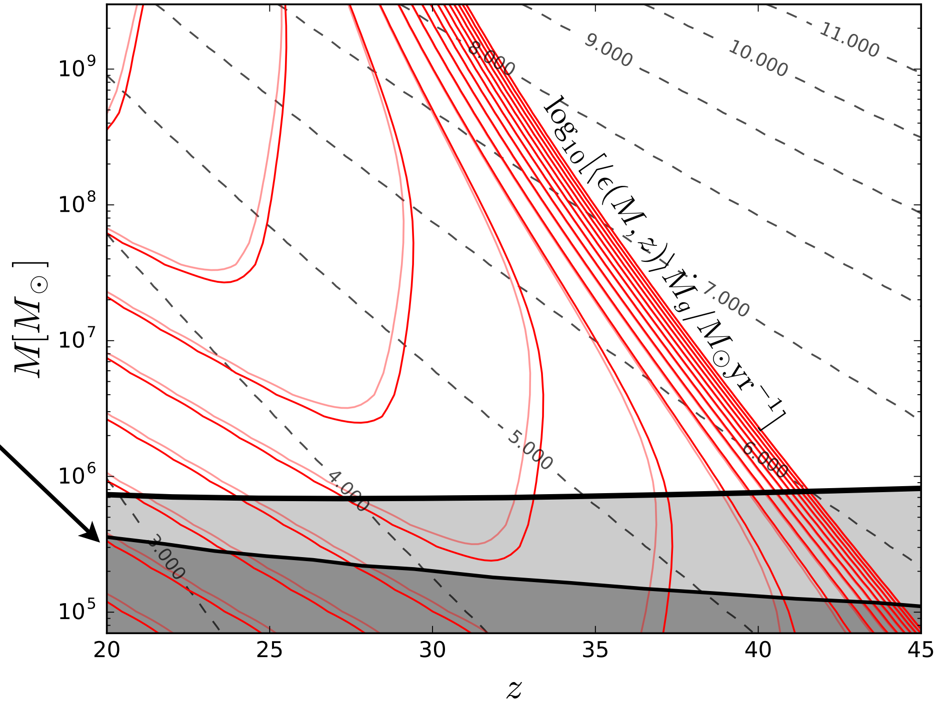

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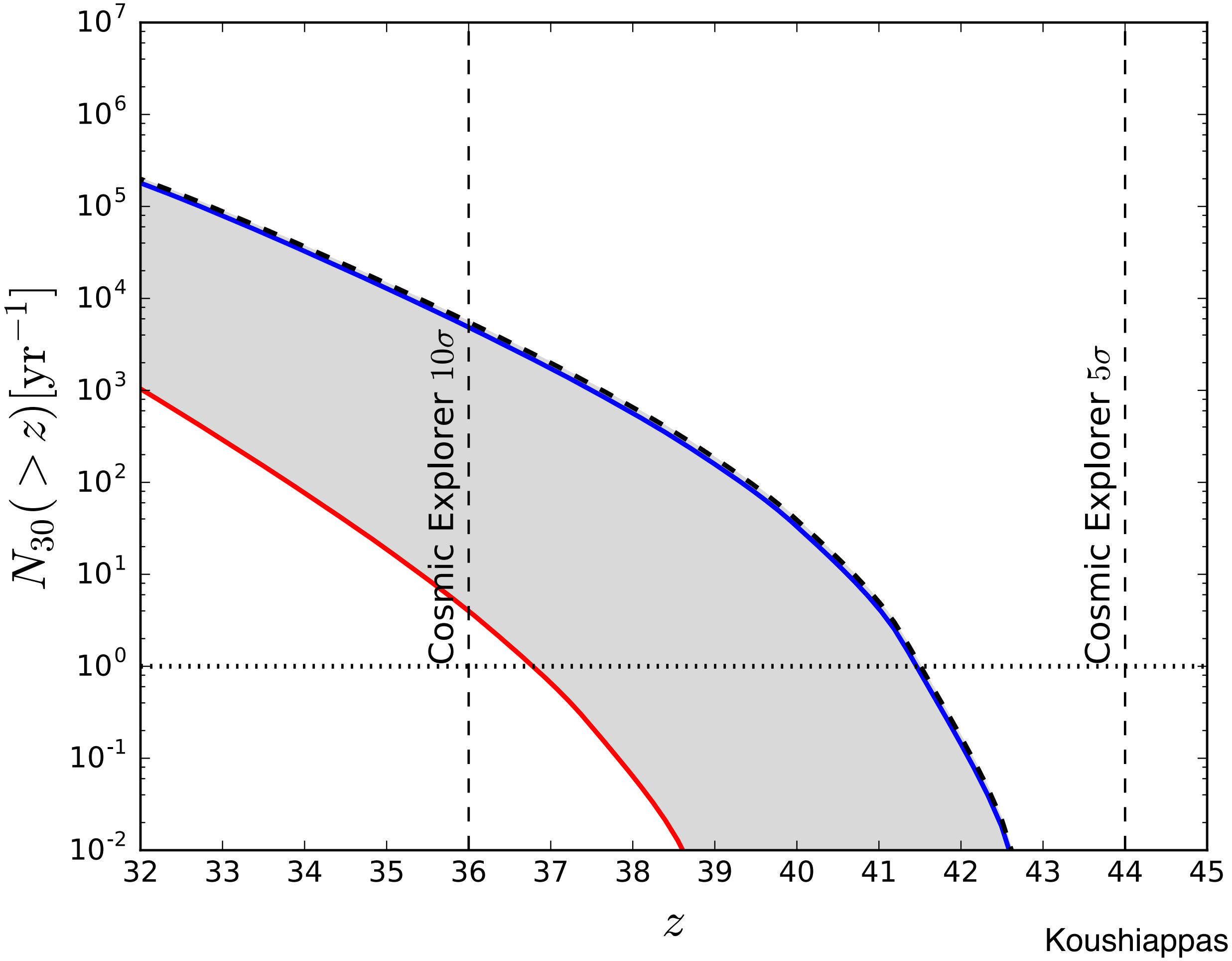
E. Neistein and A. Dekel, MNRAS **388**, 1792 (2008), 0802.0198.
T. Goerdt, D. Ceverino, A. Dekel, and R. Teyssier, MNRAS **454**, 637 (2015), 1505.01486.
G. Sun and S. R. Furlanetto, MNRAS **460**, 417 (2016), 1512.06219.

Rate of black hole merger events

Define maximum redshift

$$\mathcal{N}(z = z_{\rm max}) = 1\,{\rm yr}^{-1}$$



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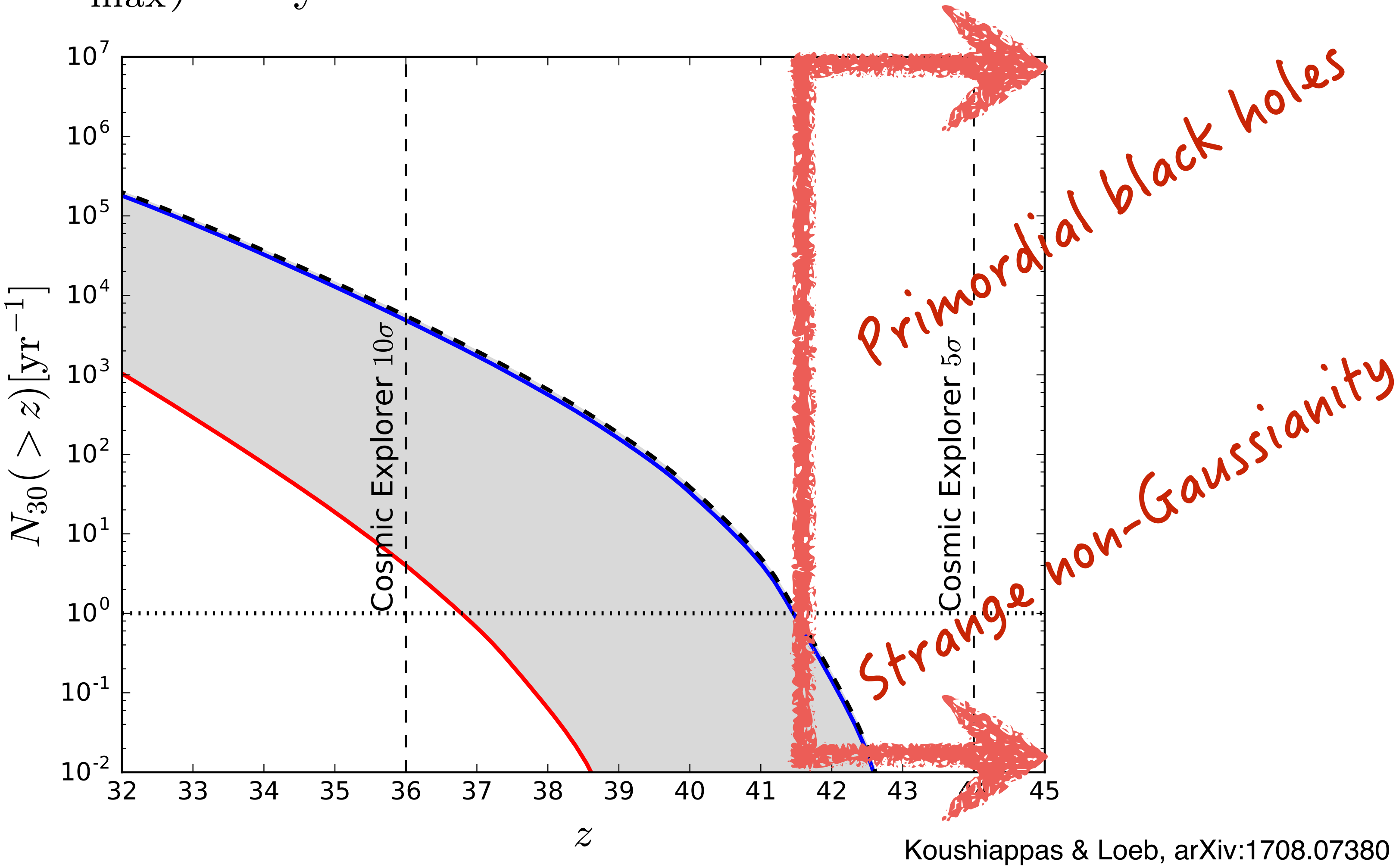

Koushiappas & Loeb, arXiv:1708.07380

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.