

CDM in crisis?

solutions beyond the concordance model

Open Problems in Cosmology

CDM in crisis?

solutions beyond the concordance model



observations theory 100

Keck telescopes (Mauna Kea)

Jaguar Cray XT (Oak Ridge National Lab), Top #1 June 2010

Open Problems in Cosmology

CDM in crisis?

Computational Cosmology

CDM in crisis?

Computational Cosmology

simulation of cosmic structure formation – initial conditions



I. primordial matter density field



















- the cusp-core problem
- satellite galaxies
- bulge-less disk galaxies
- the Council of Giants
- speeding bullets
- El Gordo
- Hubble tension
- Iiving on the EDGES
- the nature of dark matter?
- the nature of dark energy?



the nature of dark energy?

the cusp-core problem

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ACDM claims central density cusps: $\rho_{central}^{DM}(r) \propto r^{\alpha}$; $\alpha < 0$



(dark matter halo 'Aquarius-A', Springel et al. 2008)

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ACDM claims central density cusps:
$$\rho_{central}^{DM}(r) \propto r^{\alpha}$$
; $\alpha < 0$

Navarro, Frenk & White (1996): a universal density profile!?

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{\left(r/r_s\right)\left(1 + r/r_s\right)^2}$$





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Navarro, Frenk & White (1996): a universal density profile!?



ACDM claims central density cusps:
$$\rho_{central}^{DM}(r) \propto r^{\alpha}$$
; $\alpha < 0$

e.g.,

Navarro, Frenk & White (1996, 1997):	α = -1
Moore (1999):	$\alpha = -1.5$
Ghigna (2000):	α = -1.5
Fukushige & Makino (2001):	$\alpha = -1.5$
Dahle, Hannestad, Sommer-Larsen (2003):	$\alpha = -(0.9-1.6)$
Power et al. (2003):	$\alpha = -1.2$
Ricotti (2003):	$\alpha = -(1-1.4)$
Fukushige, Kawai & Makino (2004):	α < -1.5
Tasitsiomi et al. (2004):	$\alpha = -1.2$
Hayashi et al. (2004):	$lpha \approx$ -1.0
Diemand, Moore & Stadel (2004):	α = -1.16
Navarro et al. (2004):	$\alpha = \alpha(r)$
Caimmi, Marmo & Valentinuzzi (2005):	α = -1
Reed et al. (2005):	$\alpha = -1.4$
Diemand et al. (2005):	α = -1.2

• • •









possible solutions

- "stationary": (e.g. re-interpretation)
 - triaxial halo
- non-circular motions (bulge, bar, disk, ...)

- ...

• dynamical:

(e.g. adjusting CDM)

- adiabatic contraction
- bar-DM interactions
- baryonic feedback
- ...
- tinkering with fundamental physics (gravity, WDM, cDE, VDE, ...)

possible solutions

- "stationary": (e.g. re-interpretation)
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_ ...

• dynamical:

(e.g. adjusting CDM)

- adiabatic contraction
- bar-DM interactions
- baryonic feedback

- ...

original $\rho(r) \neq \text{present-day } \rho(r)$ due to **baryonic processes**

• tinkering with fundamental physics (gravity, WDM, cDE, VDE, ...)



possible solutions: baryonic processes are very complex



Open Problems in Cosmology

possible solutions: baryonic processes are very complex





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satellites: missing?

quantitative comparison...





satellites: missing?

and even problematic in the field in general...



- not (yet) discovered (e.g. observational problem)
- missing physics: (e.g. modeller problem)
 - baryonic feedback

— ...

• tinkering with fundamental physics (gravity, WDM, cDE, VDE, ...)



- not (yet) discovered (e.g. observational problem)
- missing physics: (e.g. modeller problem)
 baryonic feedback
 ...
- tinkering with fundamental physics (gravity, WDM, cDE, VDE, ...)

- not (yet) discovered (e.g. observational problem)
- missing physics: (e.g. modeller problem) – baryonic feedback



- not (yet) discovered (e.g. observational problem)
- missing physics: (e.g. modeller problem) – baryonic feedback



. . .

- not (yet) discovered (e.g. observational problem)
- missing physics: (e.g. modeller problem) – baryonic feedback

dwarf galaxy (w/ dark matter halo) photons from first objects gas has been heated

— . . .

- not (yet) discovered (e.g. observational problem)
- missing physics: (e.g. modeller problem) – baryonic feedback



• Kim, Peter & Hargis (2018) "There is no MSP!"

There is No Missing Satellites Problem

Stacy Y. Kim^{1,2,*} Annika H. G. Peter^{1,2,3}, and Jonathan R. Hargis⁴ ¹Department of Astronomy, The Ohio State University, ¹J0 W. 18th Are., Columbus, OH 45210, USA ²Center for Cosmology and Astro-Particle Physics, The Ohio State University, ¹D1 W. Woodruff Are., Columbus, OH 45210, USA ³Department of Physics, The Ohio State University, ³D1 W. Woodruff Are., The Ohio State University, ³D1 W. Woodruff Are., Columbus, OH 45210, USA and ⁴Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA (Datest: June 14, 2018)

A critical challenge to the cold dark matter (CDM) paradigm is that there are fewer satellites observed around the Milky Way than found in simulations of dark matter substructure. We show that there is a match between the observed satellite counts corrected by the detection efficiency of the Sloan Digital Sky Survey (for luminosities $L \gtrsim 340 L_{\odot}$) and the number of luminous satellites predicted by CDM, assuming an empirical relation between stellar mass and halo mass. The "missing satellites problem", cast in terms of number counts, is thus solved. We also show that warm dark matter models with a thermal relic mass smaller than 4 keV are in tension with satellite counts, putting pressure on the sterile neutrino interpretation of recent X-ray observations. Importantly, the total number of Milky Way satellites depends sensitively on the spatial distribution of satellites, possibly leading to a "too many satellites" problem. Measurements of completely dark halos below 10° M_{\odot} , achievable with substructure lensing and stellar stream perturbations, are the next frontier for tests of CDM.

I. INTRODUCTION

One outstanding problem for the cold dark matter (CDM) paradigm is the missing satellites problem (MSP). When originally formulated, the MSP highlighted the discrepancy between the number of satellites predicted in CDM simulations, numbering ~10 [1–3]. Since then, increasingly sensitive surveys have pushed the observed ant the Milky Way (MW), numbering ~10 [1–3]. Since then, increasingly sensitive surveys have pushed the observed satellite count to ~50 (e.g., Ref. [4– 6]). Simultaneously, however, improved resolution in numerical simulations has also increased the number of predicted satellites (e.g., [7]).

COOT dicted satellites (e.g., [7]). A crucial step towards resolving the MSP is to correct for those satellites that have not yet been detected. Only a fraction of the MW's virial volume has been surveyed [8]. The Sloan Digital Sky Survey (SDSS), by which ultra-faint dwarfs with luminosities as low as 340 L₀ (Segue I) were discovered, overed only about a third of the sky. For the faintest dwarfs, SDSS was complete to ~10% of the MW's virial radius [9, 10]. The observed count is thus a lower bound on the luminous MW satellites.

Fully resolving the MSP requires that the completeness-corrected galaxy count match the predicted *luminous* satellite abundance. This depends on the physics of an additional key component: baryons. There is growing evidence that not all dark matter subhalos host an observable galaxy. Galaxy evolution models [11] and star-formation histories of ultra-faint dwarfs [12] indicate that feedback processes and reionization prevent star formation. In fact, subhalos below $\sim 10^{\circ} M_{\odot}$ are inefficient in forming a luminous component [13, 14]. In CDM, most MW subhalos are dark. In this work, we compare completeness corrections of

the observed MW luminous galaxy population to theoretical predictions for the luminous galaxy population. We use an analytic approach to highlight specific physics, and provide a roadmap for future MW-based DM constraints. Our completeness correction is inspired by Refs. [8, 15–17], which used simulations or Bayesian techniques to estimate that the MW hosts hundreds of luminous satellites. We calculate the total number of luminous galaxies down to 340 L_☉ based on the satellites observed hy SDSS. For comparison, we predict the number of luminous satellites expected in CDM based on empirical scaling relations between halos and galaxies.

Successful dark matter models control produce just enough dark matter subhalos to match the corrected galaxy count—they must produce enough *luminous* galaxies. This places stringent constraints on warm dark matter (WDM) and sterile neutrino models, competitive with Lyman-a forest constraints [18].

Successful galaxy formation models must produce enough luminous galaxies to match the corrected galaxy count. This has implications for the mass threshold for the subhalos that host the faintest galaxies, the redshift of reionization, and the tidal stripping of subhalos.

II. COMPLETENESS CORRECTIONS

The total number of luminous satellites within the MW virial radius ($R_{\rm vir}$ = 300 kpc) can be extrapolated from

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- Kim, Peter & Hargis (2018) "There is no MSP!"
- Sales, Wetzel & Fattahi (2022) "There is no MSP!"

Baryonic solutions and challenges for cosmological models of dwarf galaxies

Laura V. Sales^{1,*}, Andrew Wetzel², and Azadeh Fattahi³

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ABSTRACT

Galaxies and their dark-matter halos have posed several challenges to the Dark Energy plus Cold Dark Matter (ACDM) cosmological model. These discrepancies between observations and theory intensify for the lowest-mass (dwarf) galaxies. ACDM predictions for the number, spatial distribution, and internal structure of low-mass dark-matter halos have historically been at odds with observed dwarf galaxies, but this is partially expected, because many predictions modeled only the darkmatter component. Any robust ACDM prediction must include, hand-in-hand, a model for galaxy formation to understand how baryonic matter populates and affect dark-matter halos. In this article, we review the most notable challenges to ACDM regarding dwarf galaxies, and we discuss how recent cosmological numerical simulations have pipointed baryonic solutions to these challenges. We identify remaining tensions, including the diversity of the inner dark-matter content, planes of satellites, stellar morphologies, and star-formation quenching. Their resolution, or validation as actual problems to ACDM, will likely require both refining galaxy formation models and improving numerical accuracy in simulations.

Baryonic matter constitutes only ~ 17% of the total mass budget in the Universe¹ but it dominates what we call galaxies in observations. Therefore, modeling the effects of baryons is unavoidable to achieve a successful cosmological galaxy formation theory to compare against observations^{3,4}. The relevant physical processes in galaxies interact non-linearly with each other and also may back-react onto the (dominant) dark-matter component through gravity. Thus, cosmological numerical simulations have emerged as powerful tools to follow the assembly of galaxies within dark-matter halos^{4,5}.

In this Review, we focus on theoretical insights from cosmological baryonic simulations within ACDM on the formation of low-mass (dwarf) galaxies, with stellar masses $M_{\rm ex} \leq 10^{9} \, M_{\odot}$. Other theoretical approaches, such as analytical/semi-analytical methods^{6,7} and semi-empirical/forward-modeling techniques⁸⁻¹³ are also immensely valuable and complementary; though we refer the reader to the references above. Furthermore, in this review we focus only on cold dark matter (OMM) as a viable dark-matter nodel. However, some tensions and challenges with observations might be mitigated, sometimes arguably more naturally, by changing the underlying nature of dark matter or modifying the law of gravity. We refer the reader to¹⁸⁻¹⁰ for a discussion of these approaches.

The physics of dwarf galaxy formation

The formation of dark-matter structures in ACDM is a process relatively well understood, where halos form from the hierarchical

growth of high-density fluctuations in an otherwise homogeneous early Universe. Halos assemble 'hierarchically': low-mass halos collapse first and then merge to form more massive ones. Because CDM is assumed collisionless, only the effects of gravity are important to study the formation of dark-matter structures. Baryons, on the other hand, which initially were primordial gas, but then (in part) converted to stars and metals, decoupled early from the dark matter; modeling their evolution requires a complex network of physical processes, including hydrodyamics and the cooling and heating of gas, in addition to gravity. We refer to these as 'baryonic processes'.

Several haryonic processes are essential to form realistic galaxies within ACDM. An important aspect of their combined effects is a suppression of the efficiency of star formation, achieved from a combination of stellar feedback channels, including superiova explosions^{17–23} and radiation and winds from young stars^{32,12}. The extragalactic UV background, which drives cosmic reionization, suppresses gaseous accretion into galaxies and, on the extreme scales of ultra-faint dwarf galaxies ($M_{\perp} \lesssim 10^4$ M_{\odot} see ref.¹⁴), cosmic reionization is thought to halt star formation entriely, making such present-day galaxies 'fossils' of reionization^{56–31}. Although these processes all affect massive galaxies like the Milky Way (MW), dwarf galaxies, with their shallower dark matter potentials and fewer number of stars, are particularly susceptible to the physics of stellar feedback and reionization. Four dwarf galaxies are particularly sensitive laboratories for testing galaxy formation models.

- Kim, Peter & Hargis (2018) "There is no MSP!"
- Sales, Wetzel & Fattahi (2022) "There is no MSP, but many others!"

Baryonic solutions and challenges for cosmological models of dwarf galaxies

Laura V. Sales^{1,*}, Andrew Wetzel², and Azadeh Fattahi³

¹Department of Physics and Astronomy, University of California, Riverside, CA 92507, USA ²Department of Physics and Astronomy, University of California, Davis, CA 95616, USA ³Institute for Computational Cosmology, Department of Physics, Durham Univ., South Road, Durham, DH1 3LE, UK ⁶-mail: Bales@ucr.edu

ABSTRACT

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cosmic reionization, suppresses gaseous accretion into galaxies and, on the extreme scales of ultra-kint dwarf galaxies $(M_s \lesssim 10^5 M_{\odot})$; see ref.¹⁴), cosmic reionization is thought to halt star formation entirely, making such present-day galaxies risosils' of reionization^{26,21}. Although these processes all affect massive galaxies like the Milky Way (MW), dwarf galaxies, with their shallower dark matter potentials and fewer number of stars, are particularly susceptible to the physics of stellar feedback and reionization's four sear particularly sensitive laboratories for testing galaxy formation models.

$[\Lambda CDM Tensions with Dwarf Galaxies]$

No tension	Uncertain	Weak tension	Strong tension
Missing satellites	M_{\star} - $M_{\rm halo}$ relation	Too big to fail	Diversity of rotation curves
	Core-cusp	Diversity of dwarf sizes	Satellite planes
		Quiescent fractions	
s of ultra-faint dwarf galaxies ing such present-day galaxies (by Way (MW), Warf galaxies, ptible to the physics of stellar g galaxy formation models.			

- the cusp-core problem
- satellite galaxies:
 - missing?, too big too fail?, planar distribution?
- bulge-less disk galaxies
- the Council of Giants
- speeding bullets
- El Gordo
- Hubble tension
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- the nature of dark matter?
- the nature of dark energy?













Boylan-Kolchin et al. (2011)







- baryonic physics
- tinkering with DM particle (WDM, self-interacting, ...)

baryonic physics



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satellites: planar distribution?

M31 satellite galaxies



- environmental effects, i.e. Local Group is a very special place:
 - binary system
 - situated in filament towards Virgo cluster
- dynamical effects, e.g. radial alignment of orbits, ...
- how to (best) define planes?

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Gillet et al. 2015)

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possible solutions

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• Sales, Wetzel & Fattahi (2022) "one of the most pressing problems!"

ACDM Tensions with Dwarf Galaxies			
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observed





• "angular momentum catastrophe"



conservation of angular momentum

angular momentum crisis?

• "angular momentum catastrophe"





conservation of angular momentum



- proper numerical modelling
- baryonic effects



- proper numerical modelling
- baryonic effects



simulation code specifically designed to conserve angular momentum...

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Our Corner of the Universe

All Bright Galaxies Nearer Than 20 Million Light Years

> Marshall L. McCall York University Toronto, Canada www.physics.yorku.ca

> > (c) Marshall McCall

https://www.youtube.com/watch?v=VzL7xGzfNlU







- no explanation as of now!
- currently investigating using cosmological simulations...

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Bullet cluster (IE 0657-558)



Bullet cluster (IE 0657-558)

speeding bullets?



• simulations volumes simply too small (i.e. cosmic variance)?



• simulations volumes simply too small (i.e. cosmic variance)?



- possible solutions
 - simulations volumes simply too small (i.e. cosmic variance)?



• simulations volumes simply too small: Jubilee simulation!



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Hubble tension

• independent measurements of H_0



Hubble tension





Freedman (2017)

Hubble tension



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Experiment to Detect the Global EoR Signature (EDGES)



EDGES antenna in western Australia (photo credit: Judd Bowman/ASU)

Experiment to Detect the Global EoR Signature (EDGES)



EDGES antenna in western Australia (photo credit: Judd Bowman/ASU)



detection of neutral hydrogen
























Experiment to Detect the Global EoR Signature (EDGES)



EDGES antenna in western Australia (photo credit: Judd Bowman/ASU)

- the signal has been observed
- the signal agrees with the general expectation, but
- the signal is twice as strong:
 - either the spin-temperature is lower than expected
 - or the CMB photons are hotter than expected
 - or there exist an additional radiation field (PBHs?)

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• the nature of dark matter?

the nature of dark energy?

we have not found the dark matter particle (yet)...

we have not found the dark matter particle (yet)... ... or did we!?

Did LIGO detect dark matter?

Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Elv D. Kovetz, Alvise Raccanelli, and Adam G. Riess¹ ¹Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $10 M_{\odot} \lesssim M_{\rm bh} \lesssim 100 M_{\odot}$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they can radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will then rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the 2-53 Gpc⁻³ yr⁻¹ rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

The nature of the dark matter (DM) is one of the most longstanding and puzzling questions in physics. Cosmological measurements have now determined with exquisite precision the abundance of DM 1. 2. and we know from a combination of observations and numerical

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simulations quite a bit about its distribution in Galactic halos. Still, the nature of the DM remains a mystery. Given the efficacy with which weakly-interacting massive particles-for many years the favored particle-theory explanation-have eluded detection, it may be warranted to consider other possibilities for DM. Primordial black holes (PBHs) are one such possibility 3.4. Here we consider whether the two $\sim 30 M_{\odot}$ black holes detected by LIGO 5 could plausibly be PBHs. There is a window for PBHs to be DM if the BH mass is in the range $10 M_{\odot} \lesssim M \lesssim 100 M_{\odot}$ 6, 7. Lower masses are excluded by microlensing surveys 8, and higher masses would disrupt wide binaries 7, 9, 10. It has been ar-

gued that PBHs in this mass range are excluded by cosmic microwave background (CMB) constraints 11, 12. However, these constraints require modeling of several complex physical processes, including the accretion of gas onto a moving BH, the conversion of the accreted mass to a luminosity, the self-consistent feedback of the BH radiation on the accretion process, and the deposition of the radiated energy as heat in the photon-baryon plasma. A significant (and difficult to quantify) uncertainty should therefore be associated with this upper limit, and it seems worthwhile to examine whether PBHs in this mass range could have other observational consequences.

In this Letter, we show that if DM consists of $\sim 30 M_{\odot}$ BHs, then the rate for mergers of such PBHs falls within the merger rate inferred from GW150914. In any galactic halo, there is some small chance that two BHs will undergo a hard scatter and in so doing lose energy to a soft gravitational wave (GW) burst and thereby become

gravitationally bound. This binary will then merge via emission of GWs in less than a Hubble time. Below we first estimate roughly the rate of such mergers and then present the results of more detailed calculations. We then discuss uncertainties in the calculation and some possible ways to distinguish PBHs from BH binaries from more traditional astrophysical sources.

Consider two PBHs that approach each other with some impact parameter on a hyperbolic orbit, with relative velocity v_{phb}. When the PBHs deflect each other, there is a time-varying quadrupole moment and thus GW emission. The PBH pair becomes gravitationally bound if the GW emission is greater than the initial kinetic energy. The cross section for this process is 13, 14,

$$\begin{split} \sigma &= 2^{3/7} \pi \left(\frac{85 \pi}{6 \sqrt{2}}\right)^{2/7} R_s^2 \left(\frac{v_{\text{pbh}}}{c}\right)^{-18/7} \\ &= 1.37 \times 10^{-14} M_{30}^2 \, v_{\text{pbh}-200}^{-18/7} \, \text{pc}^2, \end{split} \tag{6}$$

where $R_s = 2GM_{\rm pbh}/c^2$ is the Schwarzschild radius, M_{30} the PBH mass in units of $30 M_{\odot}$, and $v_{\rm pbh-200}$ the relative velocity in units of 200 km sec⁻¹.

We begin with a rough but simple and illustrative estimate of the rate per unit volume of such mergers. Suppose that all DM matter in the Universe resided in Milky-Way like halos of mass $M = M_{12} \, 10^{12} \, M_{\odot}$ and uniform mass density $\rho = 0.002 \rho_{0.002} M_{\odot} \text{ pc}^{-3}$ with $\rho_{0.002} \sim 1$. The rate of mergers per halo, assuming a uniform-density halo of volume $V = M/\rho$, would then be

$$N \simeq (1/2)V(\rho/M_{\text{pbh}})^2 \sigma v$$

 $\simeq 3.10 \times 10^{-12} M_{12} \rho_{0.002} v_{\text{obb}-200}^{-11/7} \text{ yr}^{-1},$ (2)

where the relative velocity $v_{pbh-200}$ is specified by a characteristic halo velocity. The mean cosmic DM mass density is $\rho_{\rm dm} \simeq 3.6 \times 10^{10} M_{\odot} {\rm Mpc}^{-3}$, and so the spatial

we have not found the dark matter particle (yet)... ...or did we!?

Simeon Bird Dias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Mar black holes? Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Admended Black holes? ¹Department of Physics and Astronem Ban Apple University, 3400 N. Charles St., Baltin D., MD 21218, USA

may detected by LIGO may be a signature We consider the possibility that the black-hole (BH) bit of dark matter. Interestingly enough, there remains a window for masses $10 M_{\odot} \lesssim M_{\rm bh} \lesssim 100 M_{\odot}$ e primordial black holes (PBHs) r ay constitute the dark matter. If two BHs in a galactic pass sufficiently close, they can rac ate enough energy in gravitational waves to become gravhalo itationally bound. The bound BHs will then rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the 2-53 Gpc⁻³ yr⁻¹ rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

The nature of the dark matter (DM) is one of the most longstanding and puzzling questions in physics. Cosmological measurements have now determined with exquisite precision the abundance of DM 1. 2. and we know from a combination of observations and numerical simulations quite a bit about its distribution in Galactic halos. Still, the nature of the DM remains a mystery. Given the efficacy with which weakly-interacting massive particles-for many years the favored particle-theory explanation-have eluded detection, it may be warranted to consider other possibilities for DM. Primordial black holes (PBHs) are one such possibility 3.4.

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Here we consider whether the two $\sim 30 M_{\odot}$ black holes detected by LIGO 5 could plausibly be PBHs. There is a window for PBHs to be DM if the BH mass is in the range $10 M_{\odot} \lesssim M \lesssim 100 M_{\odot}$ [6], [7]. Lower masses are excluded by microlensing surveys 8, and higher masses would disrupt wide binaries 7, 9, 10. It has been argued that PBHs in this mass range are excluded by cosmic microwave background (CMB) constraints 11, 12. However, these constraints require modeling of several complex physical processes, including the accretion of gas onto a moving BH, the conversion of the accreted mass to a luminosity, the self-consistent feedback of the BH radiation on the accretion process, and the deposition of the radiated energy as heat in the photon-baryon plasma. A significant (and difficult to quantify) uncertainty should therefore be associated with this upper limit, and it seems worthwhile to examine whether PBHs in this mass range

In this Letter, we show that if DM consists of $\sim 30 M_{\odot}$ BHs, then the rate for mergers of such PBHs falls within the merger rate inferred from GW150914. In any galactic halo, there is some small chance that two BHs will undergo a hard scatter and in so doing lose energy to a soft gravitational wave (GW) burst and thereby become

could have other observational consequences.

gravitationally bound. This binary will then merge via emission of GWs in less than a Hubble time. Below we first estimate roughly the rate of such mergers and then present the results of more detailed calculations. We then discuss uncertainties in the calculation and some possible ways to distinguish PBHs from BH binaries from more traditional astrophysical sources.

Consider two PBHs that approach each other with some impact parameter on a hyperbolic orbit, with relative velocity v_{phb}. When the PBHs deflect each other, there is a time-varying quadrupole moment and thus GW emission. The PBH pair becomes gravitationally bound if the GW emission is greater than the initial kinetic energy. The cross section for this process is 13, 14,

$$\begin{split} \sigma &= 2^{3/7} \pi \left(\frac{85 \pi}{6 \sqrt{2}}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7} \\ &= 1.37 \times 10^{-14} M_{30}^2 v_{\rm pbh-200}^{-18/7} \, {\rm pc}^2, \end{split} \tag{2}$$

where $R_s = 2GM_{\rm pbh}/c^2$ is the Schwarzschild radius, M_{30} the PBH mass in units of $30 M_{\odot}$, and $v_{\rm pbh-200}$ the relative velocity in units of 200 km sec⁻¹.

We begin with a rough but simple and illustrative estimate of the rate per unit volume of such mergers. Suppose that all DM matter in the Universe resided in Milky-Way like halos of mass $M = M_{12} \, 10^{12} \, M_{\odot}$ and uniform mass density $\rho = 0.002 \rho_{0.002} M_{\odot} \text{ pc}^{-3}$ with $\rho_{0.002} \sim 1$. The rate of mergers per halo, assuming a uniform-density halo of volume $V = M/\rho$, would then be

$$N \simeq (1/2)V(\rho/M_{\rm pbh})^2 \sigma v$$

 $\simeq 3.10 \times 10^{-12} M_{12} \rho_{0.002} v_{\rm pbh}^{-11/7} {}_{200} {\rm yr}^{-1},$ (2)

where the relative velocity $v_{pbh-200}$ is specified by a characteristic halo velocity. The mean cosmic DM mass density is $\rho_{\rm dm} \simeq 3.6 \times 10^{10} M_{\odot} {\rm Mpc}^{-3}$, and so the spatial arXiv:astro-ph/9605094v3 21 May 1996

I. INTRODUCTION

A period of "inflation" or accelerated expansion in the early universe is an attractive idea in modern cosmology. Acceleration of the scale factor could drive the universe towards homogeneity, isotropy and spatial flatness. However it is the ability of quantum fluctuations in the fields driving inflation to produce a nearly scale-invariant spectrum of quantum fluctuations that provides the most powerful test of the inflationary paradigm and may allow us to constrain the physics involved. Cosmological observations allow us to measure the amplitude and tilt of the primordial density and, possibly, gravitational wave spectra on scales that would have left the horizon during inflation.

The first inflationary models such as the old and the new inflationary universe scenario presumed that inflation began in the false vacuum state after the high temperature phase transitions in the early universe [1,2]. Later it was proposed that all possible initial conditions should be considered without necessarily assuming initial thermal equilibrium, and see whether some of these conditions may lead to inflation. This scenario was called chaotic inflation [3]. For many years the idea of chaotic initial conditions seemed too radical, since it implied a considerable deviation from the idea of the hot Big Bang. It was argued that for a successful realization of inflationary theory one should satisfy so-called "thermal constraints" [4]. However, gradually it was understood that the assumption of thermal initial conditions is neither natural nor helpful for inflationary theory [5]. As a re-

Juan García-Bellido*, Andrei Linde[†] and David Wands^{‡*} *Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, U.K. [†]Physics Department, Stanford University, Stanford CA 94305-4060, USA [‡]School of Mathematical Studies, University of Portsmouth, Portsmouth PO1 2EG, U.K. (May 15, 1996)

Density Perturbations and Black Hole Formation in Hybrid Inflation

We investigate the recently proposed hybrid inflation models with two stages of inflation. We show that quantum fluctuations at the time corresponding to the phase transition between the two inflationary stages can trigger the formation of a large number of inflating topological defects. In order to study density perturbations in these models we develop a new method to calculate density perturbations in a system of two scalar fields. We show that density perturbations in hybrid inflation models of the new type can be very large on the scale corresponding to the phase transition. The resulting density inhomogeneities lead to a copious production of black holes. This could be an argument against hybrid inflation models with two stages of inflation. However, we find a class of models where this problem can be easily avoided. The number of black holes produced in 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 post-inflationary reheating occurs via black hole evaporation.

PACS numbers: 98.80.Co SU-ITP-96-20, SUSSEX-AST 96/5-1, RCG-96/07, astro-ph/9605094

sult, most of the models investigated now belong to the class of chaotic inflation, which provides the most general framework for the development of inflationary cosmology.

The simplest models of chaotic inflation include theories with potentials $V(\phi)$ such as $m^2 \phi^2/2$ or $\lambda \phi^4/4$. Inflation occurs in these theories at $\phi > M_{\rm P}$. However, one may also consider chaotic inflation near $\phi = 0$ in models with potentials which could be used for implementation of the new inflation scenario, such as $-m^2\phi^2/2 + \lambda\phi^4/4$ [6]. For brevity, one may call inflation in such models "new inflation", to distinguish it from inflation at large ϕ , but strictly speaking these models also belong to the general class of chaotic inflation models: the original new inflationary universe scenario based on the theory of high temperature phase transitions have never been successfully implemented in realistic theories.

The simplest models of chaotic inflation such as the model $m^2 \phi^2/2$ have many advantages, including natural initial conditions near the Planck density and the existence of the regime of eternal self-reproduction of the universe [5]. Normalizing the mass scale by the fluctuations in the microwave background observed by COBE [7] gives $m \simeq 2 \times 10^{13}$ GeV and the energy density at the end of inflation is $V(\phi) \simeq (10^{16} \,\text{GeV})^4$. At this energy gravitational waves contribute about 10% of the microwave background fluctuations. The tilt of the density perturbation spectrum in this model is $n - 1 \simeq -0.03$.

However, inflation occurs in such models only for $\phi \gtrsim M_P$. It is quite possible to have inflation at $\phi > M_P$ in models with polynomial potentials, but in string theory and supergravity one often encounters potentials

- the cusp-core problem
- satellite galaxies:
 - missing?
 - too big too fail?
 - planar distribution?
- bulge-less disk galaxies
- the Council of Giants
- speeding bullets
- El Gordo
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proper modelling of baryonic physics!?

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CDM in crisis?

solutions beyond the concordance model

Alternative Cosmologies

- Warm Dark Matter
- MOdified Newtonian Dynamics
- Lemaitre-Tolman-Bondi void models
- Quintessence models
- Modified gravity f(R) models
- ...

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$$\lambda_{f} \approx a \int_{0}^{t_{eq}} \frac{v}{a} dt$$

$$v(z) = 0.04371 (1+z) \left(\frac{\Omega_{X} h^{2}}{0.15}\right)^{1/3} \left(\frac{g_{X}}{1.5}\right)^{-1/3} \left(\frac{m_{X}}{keV}\right)^{-4/3} km/s$$

S

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$$43/4 = 10.75; \quad g^{*} = \text{at decoupling of X}$$

(Bode et al. 2001; Viel et al. 2013)

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ratio between photon and WDM degrees of freedom

(Bode et al. 2001; Viel et al. 2013)

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*suppression of P(k)...

(Bode et al. 2001; Viel et al. 2013)







warm dark matter suppresses small-scale structure



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$$R_{S} = 0.31 \left(\frac{\Omega_{X}}{0.3}\right)^{0.15} \left(\frac{h}{0.65}\right)^{1.3} \left(\frac{m_{X}}{keV}\right)^{-1.15} h^{-1} Mpc$$
$$M_{S} = 3.49 \times 10^{9} \left(\frac{\Omega_{X}}{0.3}\right) \left(\frac{R_{S}}{h^{-1} Mpc}\right)^{3} h^{-1} M_{\odot}$$

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the formation of objects with mass $M \le M_S$ will be suppressed











(courtesy C. Power)



(courtesy C. Power)



(CLUES collaboration, http://www.clues-project.org)

warm dark matter suppresses small-scale structure leaving LSS in place

Mon. Not. R. Astron. Soc. 345, 1285-1290 (2003)

Top-down fragmentation of a warm dark matter filament

Alexander Knebe, ^{1*} Julien E. G. Devriendt, ² Brad K. Gibson¹ and Joseph Silk² ¹Centre for Astrophysics & Supercomputing, Swinburne University, PO Box 218, Mail # 31, Hawthorn, Victoria, 3122, Australia ²Astrophysics, Oxford University, Keble Road, Oxford OX1 3RH

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ABSTRACT

We present the first high-resolution *N*-body simulations of the fragmentation of dark matter filaments. Such fragmentation occurs in top-down scenarios of structure formation, when the dark matter is warm instead of cold. In a previous paper, we showed that warm dark matter (WDM) differs from the standard cold dark matter (CDM) mainly in the formation history and large-scale distribution of low-mass haloes, which form later and tend to be more clustered in WDM than in CDM universes, tracing the filamentary structures of the cosmic web more closely. Therefore, we focus our computational effort in this paper on *one* particular filament extracted from a WDM cosmological simulation and compare in detail its evolution to that of the same CDM filament. We find that the mass distribution of the haloes forming via fragmentation within the filament is broadly peaked around a Jeans mass of a few $10^9 M_{\odot}$, corresponding to a gravitational instability of smooth regions with an overdensity contrast around 10 at these redshifts. Our results confirm that WDM filaments fragment and form gravitationally bound haloes in a top-down fashion, whereas CDM filaments are built bottom-up, thus demonstrating the impact of the nature of the dark matter on dwarf galaxy properties.

Key words: methods: numerical – cosmology: miscellaneous – cosmology: theory – dark matter – large-scale structure of Universe.



warm dark matter suppresses small-scale structure leaving LSS in place

Mon. Not. R. Astron. Soc. 380, 93-103 (2007)

doi:10.1111/j.1365-2966.2007.12053.x

Discreteness effects in simulations of hot/warm dark matter

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ABSTRACT

In hot/warm dark matter (HDM/WDM) universes the density fluctuations at early times contain very little power below a characteristic wavelength related inversely to the particle mass. We study how discreteness noise influences the growth of non-linear structures smaller than this coherence scale in N-body simulations of cosmic structure formation. It has been known for 20 yr that HDM simulations in which the initial uniform particle load is a cubic lattice exhibit artefacts related to this lattice. In particular, the filaments which form in such simulations break up into regularly spaced clumps which reflect the initial grid pattern. We demonstrate that a similar artefact is present even when the initial uniform particle load is not a lattice, but rather a glass with no preferred directions and no long-range coherence. Such regular fragmentation also occurs in simulations of the collapse of idealized, uniform filaments, although not in simulations of the collapse of infinite uniform sheets. In HDM or WDM simulations all selfbound non-linear structures with masses much smaller than the free streaming mass appear to originate through spurious fragmentation of filaments. These artificial fragments form below a characteristic mass which scales as $m_p^{1/3}k_{peak}^{-2}$, where m_p is the N-body particle mass and k_{peak} is the wavenumber at the maximum of $k^3 P(k) [P(k)]$ is the power spectrum]. This has the unfortunate consequence that the effective mass resolution of such simulations improves only as the cube root of the number of particles employed.

Key words: neutrinos - methods: N-body simulations - methods: numerical - dark matter.











warm dark matter simulations are not as easy as they appear...
 ...and actually requires novel simulation techniques



Alternative Cosmologies

• Warm Dark Matter

MOdified Newtonian Dynamics

- Lemaitre-Tolman-Bondi void models
- Quintessence models
- Modified gravity f(R) models
- ...

MOND





*actually, Fritz Zwicky already needed DM to explain stability of galaxy clusters in 1933

MOND





- Milgrom (1983, 1984):
 - Newtonian accelerations

$$F = m g_N(r)$$
 with $g_N = \frac{GM(< r)}{r^2}$

 $m g_N = m a$

- Milgrom (1983, 1984):
 - modified accelerations

$$F = m g_N(r) \qquad \text{with} \qquad g_N = \frac{GM(\langle r)}{r^2}$$
$$m g_N = m a \mu(a/a_0) \qquad \text{with} \qquad \mu(x) = \begin{cases} x \quad ; x <<1\\ 1 \quad ; x >>1 \end{cases}$$

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• or modified forces

$$g_N = g \,\mu(|g|/a_0)$$

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• or modified forces

$$g_N = g \ \mu(|g| / a_0) \qquad \longrightarrow \qquad g = \begin{cases} g_N & ; g_N << a_0 \\ \sqrt{g_N a_0} & ; g_N >> a_0 \end{cases}$$

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$$g_N = g \ \mu(|g|/a_0) \qquad \xrightarrow{\text{proposed dependence}} g = \begin{cases} g_N & ; g_N << a_0 \\ \sqrt{g_N a_0} & ; g_N >> a_0 \end{cases}$$

m g = m a

Tully-Fisher relation! (...and flat rotation curves)

- Milgrom (1983, 1984):
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• or modified forces

$$g_{N} = g \ \mu(|g|/a_{0}) \qquad a_{0} \approx 1.2 \times 10^{-8} \, cm/s^{2}$$
$$\mu(x) = x \left(1 + x^{2}\right)^{-1/2}$$

- Milgrom (1983, 1984):
- modified accelerations

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• or modified forces

$$g_{N} = g \,\mu(|g|/a_{0}) \qquad a_{0} \approx 1.2 \times 10^{-8} \, cm/s^{2} \quad \approx cH_{0}$$
$$\mu(x) = x \left(1 + x^{2}\right)^{-1/2}$$

MOND as modified gravity

$$\nabla \cdot \left(g \, \mu(|g|/a_0) \right) = -4\pi G \rho$$

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very complicated to develop numerical solvers:

- Brada & Milgrom (1999)
- Nipoti, Londrillo & Ciotti (2007)
- Tiret & Combes (2007)
- Llinares, Knebe & Zhao (2008)

(cosmological setting!)

Angus et al. (2012)Candlish, Smith & Fellhauer (2015)

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MOND as modified gravity

0

0

0.25

0.5

lcos(curl, g_N)l

0.75

$$\nabla \cdot \left(g \,\mu(|g|/a_0) \right) = -4\pi G\rho$$

- non-linear: $\rho = \rho_1 + \rho_2 \implies g \neq g_1 + g_2$
- $g \rightarrow g + \nabla \times h \implies g\mu(|g|/a_0) = g_N + \nabla \times h$ • non-intuitive: z=0.000 z=0.355 $\nabla \times h$ z=0.973 6 z=1.948 z=3.215 ----z=5.000 - - - - -5 Probability (Llinares et al. 2008) g_N 3 $g\mu(|g|/a_0)$ 2

1

Cosmology with MOND

• 2nd Friedmann equation:
$$\ddot{R} = -\frac{4\pi G}{3} \left(\rho + \frac{3p}{c^2}\right) R$$

- Cosmology with MOND
 - 2^{nd} Friedmann equation: \ddot{R}

MOND

- Cosmology with MOND
 - 2nd Friedmann equation:

$$\ddot{R} = -\frac{4\pi G}{3} \left(\rho + \frac{3p}{c^2} \right) R$$

$$\downarrow g \rightarrow \sqrt{g_N a_0}$$

$$\ddot{R} = -\sqrt{\frac{4\pi G a_0}{3}} \left(\rho + \frac{3p}{c^2} \right) R$$

$$\downarrow p = 0; \rho \propto R^{-3}$$

$$\ddot{R} = -\frac{1}{R} \sqrt{\frac{\Omega_{m,0}}{2} H_0^2 a_0}$$

- Cosmology with MOND
 - 2nd Friedmann equation:

$$\ddot{R} = -\frac{1}{R} \sqrt{\frac{\Omega_{m,0}}{2}} H_0^2 a_0$$

spherical top-hat collapse in MONDian Universe...

MOND

- Cosmology with MOND
 - growth of density perturbations:



MOND

- Cosmology with MOND
 - number density evolution of objects:



Alternative Cosmologies

- Warm Dark Matter
- MOdified Newtonian Dynamics
- Lemaitre-Tolman-Bondi void models
- Quintessence models
- Modified gravity f(R) models
- •••

