Two-Component Dark Matter

N-body Simulations with Two-Component Dark Matter — Zoomlandia — 02/06/24

> M.V. Medvedev KU, IAS, Princeton U, MIT

supported by NSF via PHY-2010109

-- Next Decade: A paradigm shift? --

- History & Motivation
- Models (SIDM, etc)
- Overview of 2cDM | physics

-
- ‣ cosmology
- ‣ understanding

Historically first small scale problems where $\mathbf n$ is the mass with the mass with the observed wit rotation of gas in large spiral galaxies. The structure of dark 0.4×10^{-1} Isothermal: *r,=2.5* kpc mand of the selection of Isothermal: *r,=4.6* kpc **THSMIDAILY IIISL SHIGH SCAIC PRODIC**

• core/cusp problem $\overline{}$ e/cusp problem when the contract of the contra

Evidence against dissipationless dark matter from observations of galaxy haloes

THERE are two different types of missing (dark) matter: the unseen matter needed to explain the high rotation velocities of atomic hydrogen in the outer parts of spiral galaxies¹ \cdot^2 , and the much larger amount of (non-baryonic) matter needed to prevent the universe from expanding forever¹ (producing either a 'flat' or a 'closed' Universe)³. Several models have been proposed to provide the dark matter required within galaxy haloes for a flat universe, r, and the dark matter required which gainx) haves for a flat difference,
of which cold dark matter (CDM) has proved the most successful $r_c = 5.5 \text{ kpc}$ \rightarrow at reproducing the observed large-scale structure of the Universe⁴⁻ ⁶. CDM belongs to a class of non-relativistic particles that interact primarily through gravity, and are named dissipationless because they cannot dissipate energy (baryonic particles can lose energy by emitting electromagnetic radiation). Here I show that the modelled small-scale properties of CDM^{7-9} are fundamentally incompatible with recent observations¹⁰⁻¹³ of dwarf galaxies, which are thought to be completely dominated by dark 8 10 12 matter on scales larger than a kiloparsec. Thus, the hypothesis that dark matter is predominantly cold seems hard to sustain. $\frac{1}{2}$ do the dark matt

Ben Moore*

Department of Astronomy, University of California, Berkeley, California 94720, USA

r;;:

² , where *rg* is the distance from the centre of the halo 18•

NATURE · VOL 370 · 25 AUGUST 1994

r,=4.4 kpc

 r_g

r,=6.1 kpc

¹ Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
² Institut d'Astrophysique, 98 bis Boulevard Arago, F-75014 Paris, France ANATOLY KLYPIN, ANDREY V. KRAVTSOV, AND OCTAVIO VALENZUELA

matter universe. If the zero-point of the Tully-Fisher relation is set by the properties of our Milky Way system, we find that standard CDM predicts too many haloes and results in a B -band luminosity density of the Universe that is a factor of 2 too high. The only apparent solution to this problem is to assume that many haloes remain observationally undetectable. We also compute the gas mass-luminosity relation for

WHERE ARE THE MISSING GALACTIC SATELLITES?

ANATOLY KLYPIN, ANDREY V. KRAVTSOV, AND OCTAVIO VALENZUELA Astronomy Department, New Mexico State University, Box 30001, Department 4500, Las Cruces, NM 88003-0001 $\frac{1}{\sqrt{2}}$ circ)^B 1200(^V circ/10

observed around our Galaxy. The di†erence is even larger if we consider the abundance of satellites in

 $\sum_{i=1}^{N}$ matter satellites with circular velocity of the matter than 1 and mass instituto de Astronomia, Apartado Postal 877, 22900 Ensenada, Mexico andre do restronomia, reparado 1 estas erry, 223 es Ensendida, momeo
Received 1999 January 18; accepted 1999 April 15 FRANCISCO PRADA

simulated galaxy groups similar to the Local Group. The models predict \sim 300 satellites inside a 1.5 Mpc radius, while only \sim 40 satellites are observed in the Local Group. The observed and predicted VDFs cross at \approx 50 km s⁻¹, indicating that the predicted abundance of satellites with $V_{\text{circ}} \gtrsim 50$ km s⁻¹
is in reasonably good agreement with observations. We conclude therefore that unless a large fraction is in reasonably good agreement with observations. We conclude, therefore, that unless a large fraction of the Local Group satellites has been missed in observations, there is a dramatic discrepancy between observations and hierarchical models, regardless of the model parameters. We discuss several possible chs and incraremear models, regardless of the moder parameters. We discuss several possibility

explanations for this discrepancy including identifies with the high-velocity clouds with the high-velocity clouds of some satellites with the high-velocity clouds with the high-velocity clouds with the high-velocity cloud

Historically first small scale problems

• substructure problem (missing satellites)

1993MNRAS.264..201K

Downloaded from https://academic.oup.com/mnras/article/264/1/201/1075745 by Institute for Advanced Study user on 04 December 2023

AND

Mon. Not. R. Astron. Soc. 264, 201-218 (1993)

The formation and extending the September 1999 September β and astronomical M-10 c.

G. Kauffmann,¹ S. D. M. White¹ and B. Guiderdoni²

Too big to fail? The puzzling darkness of massive Milky Way subhaloes

Michael Boylan-Kolchin,^{*}† James S. Bullock and Manoj Kaplinghat

Department of Physics and Astronomy, Center for Cosmology, University of California, 4129 Reines Hall, Irvine, CA 92697, USA

Accepted 2011 May 2. Received 2011 April 20; in original form 2011 February 28

ABSTRACT

We show that dissipationless Λ cold dark matter simulations predict that the majority of the most massive subhaloes of the Milky Way are too dense to host any of its bright satellites (L_V) 10^5 L_(c)). These dark subhaloes have peak circular velocities at infall of *V*_{infall} = 30–70 km s⁻¹ and infall masses of (0.2–4) × 10¹⁰ M_{\odot}. Unless the Milky Way is a statistical anomaly, this implies that galaxy formation becomes effectively stochastic at these masses. This is in marked contrast to the well-established monotonic relation between galaxy luminosity and halo circular velocity (or halo mass) for more massive haloes. We show that at least two (and typically four) of these massive dark subhaloes are expected to produce a larger dark matter annihilation flux than Draco. It may be possible to circumvent these conclusions if baryonic feedback in dwarf satellites or different dark matter physics can reduce the central densities of massive subhaloes by order unity on a scale of 0.3–1 kpc. of massive subhardes by order IDOWNLOADED FROM HTMLP or ADVANCED STRANGER FOR A CARDEMIC STRANGER S

Key words: Galaxy: halo – galaxies: abundances – cosmology: theory – dark matter.

Figure 2. Subhaloes from all six Aquarius simulations (circles) and VL-II (triangles), colour-coded according to *V*infall. The grey-shaded region shows the 2σ confidence interval for possible hosts of the bright MW dwarf spheroidals (see Fig. 1). 100 must halo both the hosts of the bright in we dward $F1g. 1$).

1 1 C 1 *td***** that do not. These subhaloes all have central densities that are too $c_{c1} = 1 + 1 + \mathbf{M} \mathbf{W}^T \mathbf{1}$ of $c_1 = 1 + 1 + 1 + 1 + 1 + 1 + 1$ high to host any of the bright MW dwarf spheroidals; they also have higher values of both V_{max} and V_{infall} , on average. region is almost exactly the same as 6.5 [×] ¹⁰⁶ *< ^M*300/M[⊙] *<* ³ [×] $10⁷$. Many of the subhaloes lie in the range that is consistent at the 2σ level with the dwarfs, but there are a large number of subhaloes

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

LETTERS

the hosts of the nine bright (*LV ⊙*) MW dwarf spheroidal galaxies. We have sphered galaxies and galaxies. We have

we have verified that the this approach gives that the correct mass to be the corre

 $\mathcal{L}(\mathcal{$

Historically first small scale problems Downloaded from https://academic.oup.com/mnrasl/article/415/1/L40/965196 by Institute for Advanced Study user on 04 December 2023 To **E** Distortcally to die die Galaxies of the MW and MW surements of the dwarfs' masses. Walker et al. (2009) and Wolf et al. (2009) and Wolf et al. (2009) and Wolf e

of *R*1*/*² and *M*1*/*² from Wolf et al. (2010).

• too-big-to-fail problem Mon. Not. R. Astron. Soc. 415, L40-L44 (2011) doi:10.1111/j.1745-3933.2011.01074.x the hosts of the nine bright (*LV ⊙*) MW dwarf spheroidal galaxies.
In the nine bright (*LV ⊙) MW dwarf spheroidal galaxies*. of *R*1*/*² and *M*1*/*² from Wolf et al. (2010). observed values of *M*¹*/*² are effectively measurements of the dark -pig-to-rail propierri

Historically first small scale problems

- core/cusp problem
- substructure problem (missing satellites)
- too-big-to-fail problem

log halo mass

log radius

Current tensions

- core-cusp need collisions
- missing satellites may be gone
	-
	-
	- -
		- Sionial Turnsbucks
- WIMP miracle **gone(?)** (blame: direct detection exp)

- History & Motivation
- Models (SIDM, etc)
- Overview of 2cDM | physics

-
- ‣ cosmology
- ‣ understanding

Early DM models

Self-Interacting Dark Matter (SIDM) *Spergel & Steinhardt, 1999*

elastic scattering in the dark sector

Two-component DM (2cDM) with flavor mixing

MVM, 2000

works simultaneously for Core/Cusp & Missing satellites

"Fuzzy" Dark Matter

de Broglie wave length ~ 1 kpc core, m~ 1e-22 eV

Hu, et al, 1999

Annihilating Dark Matter *Kamionkowski, et al, 2008*

changes late structure formation

Boosted Dark Matter

"Lorenz-boosted"

ETHOS *changes the initial power spectrum and late structure formation Vogelsberger, 2015*

Necib, et al, 2017

Other DM models

any inelastic/multi-component DM models were originally *motivated by desire to reconcile DAMA/Libra data with other Direct Detection experiments (Edelweiss, XENON,...)*

...more...

hanges initial power spectrum

postulate two or more states "heavy+light" or "excited+ground states" and inelastic interactions between them

inelastic, multicomponent models are almost equivalent from the point of view of simulations (except for fluid DM)

- History & Motivation
- Models (SIDM, etc)
- Overview of 2cDM | physics

-
- ‣ cosmology
- ‣ understanding

x

Бруно Понтекори

$$
\begin{pmatrix}\n\left| \text{flavor}_1 \right\rangle \\
\left| \text{flavor}_2 \right\rangle\n\end{pmatrix} = \begin{pmatrix}\n\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta\n\end{pmatrix}\n\begin{pmatrix}\n\left| \text{mass}_{heavy} \right\rangle \\
\left| \text{mass}_{light} \right\rangle\n\end{pmatrix}
$$

A flavor-mixed particle

B. Pontekorvo Zh. Teor. Exp Fiz (1957); Soviet JETP (1958)

Interactions do not care about propagation (mass) eigenstates; Propagation does not care about interaction (flavor) eigenstates.

A flavor-mixed particle

Flavor is a quantum property that allows a particle to have several masses altogether, at the same time and vice versa

Schrödinger equation

$$
i\partial_t \begin{pmatrix} m_h(x,t) \\ m_l(x,t) \end{pmatrix} = \left[\begin{pmatrix} -\partial_{xx}^2/2m_h & 0 \\ 0 & -\partial_{xx}^2/2m_l - \Delta m \end{pmatrix} + \begin{pmatrix} m_h \phi(x) & 0 \\ 0 & m_l \phi(x) \end{pmatrix} + \begin{pmatrix} V_{hh} & V_{hl} \\ V_{lh} & V_{ll} \end{pmatrix} \right] \begin{pmatrix} m_h(x,t) \\ m_l(x,t) \end{pmatrix}
$$

Here

Illustrative model

MVM, J Phys A 2010

$$
\begin{pmatrix} V_{hh} & V_{hl} \\ V_{lh} & V_{ll} \end{pmatrix} = U \begin{pmatrix} V_1 & 0 \\ 0 & 0 \end{pmatrix} U^{\dagger}
$$

No flavor mixing case

With flavor mixing

Quantum evaporation

MVM, J Phys A 2010; JCAP 2014

Particle gradual escape from a gravitational potential (in "elastic" collisions) without changing particle's identity

"Munchausen effect"

Baron von Munchausen lifted himself (and his horse) out of the mud by pulling on his own pigtail.

> It is one of the "true" stories from "*The Surprising Adventures of Baron Munchausen*" by Rudolph Raspe

0

V↵↵ 000

1

cos2 ∪ cos2
2 ∪ cos2 ∪ c

$$
|mm\rangle \equiv \left(\begin{array}{c} hh \\ hl \\ lh \\ ll \end{array}\right) \equiv \left(\begin{array}{c} h_1 h_2(\mathbf{x}_1, \mathbf{x}_2, t) \\ h_1 l_2(\mathbf{x}_1, \mathbf{x}_2, t) \\ l_1 h_2(\mathbf{x}_1, \mathbf{x}_2, t) \\ l_1 l_2(\mathbf{x}_1, \mathbf{x}_2, t) \end{array}\right)
$$

The interaction matrix is diagonal interaction matrix is diagonal in the flavor basis, in the flavor basis, is
The flavor basis, is diagonal in the flavor basis, in the flavor basis, is diagonal in the flavor basis, in th

A =

$$
U_2 \equiv U \otimes U = \begin{pmatrix} \cos^2 \theta & -\cos \theta & \sin \theta & -\cos \theta & \sin^2 \theta & \sin^2 \theta \\ \cos \theta & \sin \theta & \cos^2 \theta & -\sin^2 \theta & -\cos \theta & \sin \theta \\ \cos \theta & \sin \theta & -\sin^2 \theta & \cos^2 \theta & -\cos \theta & \sin \theta \\ \sin^2 \theta & \cos \theta & \sin \theta & \cos^2 \theta & \cos^2 \theta \end{pmatrix}
$$

cfion $\overline{}$ Because each interaction involves two flavor-mixed particles, the system is described by a $\frac{1}{2}$ = $\mathbf{r} \cap \mathbf{r} \neq \mathbf{r}$ \mathbf{B} is the system interaction in variable particles, the system is described by a system in \overline{C} \overline{C} \overline{c} cos2 ∪ sin ∑ cos2 ∪ cos2 ∪
Cos2 ∪ cos2 **JIND Darucles** Technical: Interaction of 2-comp particles

two-particle wave-function, which has four components in the flavor and mass bases: α and α and α and α

Wave-functions	$ ff\rangle \equiv \begin{pmatrix} \alpha\alpha \\ \alpha\beta \\ \beta\alpha \\ \beta\beta \end{pmatrix} \equiv \begin{pmatrix} \alpha_1\alpha_2(\mathbf{x}_1, \mathbf{x}_2, t) \\ \alpha_1\beta_2(\mathbf{x}_1, \mathbf{x}_2, t) \\ \beta_1\alpha_2(\mathbf{x}_1, \mathbf{x}_2, t) \\ \beta_1\beta_2(\mathbf{x}_1, \mathbf{x}_2, t) \end{pmatrix}$ \n	
Mixing	$ ff\rangle = U_2 mm\rangle$	$U_2 \equiv$

 \overline{a}

$$
V = U_2^{\dagger} \tilde{V} U_2 = \left(\begin{array}{ccc} A & E & E & D \\ E & C & D & F \\ E & D & C & F \\ D & F & F & B \end{array} \right)
$$

$$
A = \frac{1}{8} [3V_{\alpha\alpha} + 2V_{\alpha\beta} + 3V_{\beta\beta} + 4(V_{\alpha\alpha} - V_{\beta\beta})\cos 2\theta + (V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta})\cos 4\theta],
$$

\n
$$
B = \frac{1}{8} [3V_{\alpha\alpha} + 2V_{\alpha\beta} + 3V_{\beta\beta} - 4(V_{\alpha\alpha} - V_{\beta\beta})\cos 2\theta + (V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta})\cos 4\theta],
$$

\n
$$
C = \frac{1}{8} [V_{\alpha\alpha} + 6V_{\alpha\beta} + V_{\beta\beta} - (V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta})\cos 4\theta],
$$

\n
$$
D = \frac{1}{4} [V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta}] \sin^2 2\theta,
$$

\n
$$
E = -\frac{1}{4} [V_{\alpha\alpha} - V_{\beta\beta} + (V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta})\cos 2\theta] \sin 2\theta,
$$

\n
$$
F = -\frac{1}{4} [V_{\alpha\alpha} - V_{\beta\beta} - (V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta})\cos 2\theta] \sin 2\theta,
$$

Interaction	$\tilde{V} = \begin{pmatrix}\nV_{\alpha\alpha} & 0 & 0 & 0 \\ 0 & V_{\alpha\beta} & 0 & 0 \\ 0 & 0 & V_{\beta\alpha} & 0 \\ 0 & 0 & 0 & V_{\beta\beta}\n\end{pmatrix}$ \n
-------------	---

Since trace is invariant under a unitary transformation, Tr(*V*) = *V*↵↵ + 2*V*↵ + *V*; also useful (MM, JCAP 2014)

lh 0

equation
$$
i\hbar\partial_t |mm(x_1,x_2,t)\rangle = (H^{\text{free}} + H^{\text{grav}} + V) |mm(x_1,x_2,t)\rangle
$$

0 *H*free

hl 0 0

 \overline{a}

de Statte

conversion

ⁱ@*^t [|]mm*(*x*1*, x*2*, t*)ⁱ = (*H*free ⁺ *^H*grav ⁺ *^V*)*|mm*(*x*1*, x*2*, t*)i*.* (11)

*H*free

BB@

0 *H*free

hl 0 0

*^x*1*x*¹ */*2*m^h* @²

particle is redshifted in this repeating the contraction of the amplitude of the ampli $t \sim$ collocities; colloquially speaking, the potential well. The potential well were t *I Technical: 2-comp 2-particle dynamics* 0 *H*free *hh* 000 1 Fig. 1 illustrates such a particle. The bold red and blue curves represent heavy and light mass eigenstates represent to the curve of \sim will restrict further study to one-dimensional motion of \mathbf{r} Z -C The evolution of the system at hand in the system at hand is described by the system at hand is described by t
The system at hand is described by the system at hand is described by the system at hand is described by the s Technical: 2-comp 2-particle dynamics

 $\overline{}$

Here the free particle Hamiltonian, and the free particle Hamiltonian, and the free particle Hamiltonian, and

 $S_{\rm{S}}$ is the mass basis, \sim $S_{\rm{S}}$ is the mass basis, \sim $S_{\rm{S}}$ is the mass basis, \sim

in which are constructed in the cost α and α and α sin α and α and α sin α sin α sin α sin α

$$
H^{\text{free}} = \begin{pmatrix} H^{\text{free}}_{hh} & 0 & 0 & 0 \\ 0 & H^{\text{free}}_{hl} & 0 & 0 \\ 0 & 0 & H^{\text{free}}_{lh} & 0 \\ 0 & 0 & 0 & H^{\text{free}}_{ll} \end{pmatrix} \qquad H^{\text{free}}_{hl} = - \frac{H^{\text{free}}_{hl}}{H^{\text{free}}_{lh}} = - \frac{H^{\text{free}}_{hl}}{H^{\text{free}}
$$

ergy is conserved: the light eigenstate climbs up the light eigenstate climbs up the potential and loses energy (
In the potential and loses energy (e.g., a mass leads to be possible energy (e.g., a mass leads to be possib

$$
H_{hh}^{\text{free}} = -\partial_{x_1x_1}^2/2m_h - \partial_{x_2x_2}^2/2m_h,
$$

\n
$$
H_{hl}^{\text{free}} = -\partial_{x_1x_1}^2/2m_h - \partial_{x_2x_2}^2/2m_l - \Delta m,
$$

\n
$$
H_{lh}^{\text{free}} = -\partial_{x_1x_1}^2/2m_l - \partial_{x_2x_2}^2/2m_h - \Delta m,
$$

\n
$$
H_{ll}^{\text{free}} = -\partial_{x_1x_1}^2/2m_l - \partial_{x_2x_2}^2/2m_l - 2\Delta m.
$$

\n0
\n0
\n
$$
H_{hh}^{\text{grav}} = m_h\phi(x_1) + m_h\phi(x_2),
$$

\n
$$
H_{hl}^{\text{grav}} = m_h\phi(x_1) + m_h\phi(x_2),
$$

\n
$$
H_{lh}^{\text{grav}} = m_l\phi(x_1) + m_h\phi(x_2),
$$

\n
$$
H_{ll}^{\text{grav}} = m_l\phi(x_1) + m_l\phi(x_2),
$$

\n
$$
H_{ll}^{\text{grav}} = m_l\phi(x_1) + m_l\phi(x_2),
$$

$$
V = U_2^{\dagger} \tilde{V} U_2 = \begin{pmatrix} \frac{A}{E} & \frac{E}{C} & \frac{D}{D} & \frac{E}{F} \\ \frac{E}{D} & \frac{D}{C} & \frac{E}{F} & \frac{E}{B} \end{pmatrix}
$$

 $H_{ll}^{\text{grav}} = m_l \phi(x_1) + m_l \phi(x_2),$

satisfies energy conservation, where Because each interaction involves two flavor-mixed par-Schrödinger equation

eigenstates are related as before, *|ff*i = *U*² *|mm*i, where the unitary matrix is

Complete evaporation of 2-comp. particles

(MM, JCAP 2014)

 $|h\rangle$ + $|l\rangle$ → $|l\rangle$ + $|l\rangle$

- History & Motivation
- Models (SIDM, etc)
- Overview of 2cDM | physics

-
- ‣ cosmology
- ‣ understanding

Substructure 2cDM physics

Core heating does not change halo mass. Thus, SIDM *without baryons* cannot resolve the satellite problem.

*i*nelastic: $|h\rangle + |l\rangle$ → $|l\rangle + |l\rangle$

MVM, ArXiv 2000; J Phys A 2010; JCAP 2014

-
- *"kick" velocity:* ½*mv2kick ~ ∆mc2*

if vkick ≫ *vescape, dwarf halos destroyed*

log halo mass

Substructure in simulations

MM, PRL 2014

Core-cusp 2cDM physics

collisional (inelastic) heating + temperature equilibration

log radius

log radius

Core formation via collisions. Self-Interacting DM (SIDM): Spergel & Steinhardt, PRL 1999

CDM, collisionless halo profile

Core-cusp in simulations

MM, PRL 2014

Summary: theory confirmed

MVM+ : **2cDM** simulations

MVM+, PRL 2014; MNRAS 2019, 2022

Theory confirmed

cross-sections

Key: cross-sections part of the Schr¨odinger equation with a given scattering potential *V* (*r*) and *S*(*l*) partial *S*-matrix amplitudes of the processes (*siti*) ! (*s^f t^f*) for a given *l*. The elastic

scattering [i.e, (*siti*) ! (*siti*)] cross-sections and the conversion [i.e., (*siti*) ! (*s^f t^f*), where

where P *l* are P *l* are R are radial functions being the solutions being the solutions being the solutions being the radial functions R

$$
\sigma_{(s_it_i)\to(s_it_i)} = \frac{\pi}{k_i^2} \sum_{l=0}^{\infty} (2l+1) \left| 1 - S_{(s_it_i)(s_it_i)}^{(l)} \right|^2
$$

$$
\sigma_{(s_it_i)\to(s_f t_f)} = \frac{\pi}{k_i^2} \sum_{l=0}^{\infty} (2l+1) \left| S_{(s_it_i)(s_f t_f)}^{(l)} \right|^2,
$$

$$
\sigma_{i\to f}(v)=\left\{\begin{array}{c}\sigma_0\\ \sigma_0\end{array}\right.
$$

, (2.13)

pheres" (*s*-wave scattering)

ation-like

um conversion probability

ford-like

$$
\sigma_{(s_it_i)\to(s_it_i)} = \frac{\pi}{k_i^2} \sum_{l=0}^{\infty} (2l+1) \left| 1 - S^{(l)}_{(s_it_i)(s_it_i)} \right|^2,
$$

$$
S_{(s_it_i)\to(s_jt_f)} = \frac{\pi}{k_i^2} \sum_{l=0}^{\infty} (2l+1) \left| S^{(l)}_{(s_it_i)(s_f t_f)} \right|^2,
$$

 $\begin{array}{cc} \frac{1}{2} (v/v_0)^{a_s} & \text{for scattering,} \ \frac{1}{2} (p_f/p_i) (v/v_0)^{a_c} & \text{for conversion} \end{array}$

natural: a_s=a_c

2cDM σ(v)-simulations bidden processes with negative final kinetic energy *Eⁱ*0*j*⁰ *<* 0. is the Heaviside function that screens out kinematically for-Our implementation ensures that the probability of the vast

2cDM-σ(v) -- Profiles (MW-like) $\overline{}$ implementation ensures that the probability of the vaster that the vaster that the vaster of the vaster the vaster of the vas \angle CDIVI-O(V)

bidden processes with negative final kinetic energy *Eⁱ*0*j*⁰ *<* 0.

• The velocity-dependent cross-section is parametrized as

power *a^c* = 0 (the third row). This trend, however, seems to (Todoroki & MM, 2019,2020,2022)

2cDM summary

- Substructure Problem
- TBTF problem
- Core/cusp problem across halo mass scales from dwarfs to clusters
- Radial distribution of dwarfs (problem?)

$$
\sigma(v) \sim 1(?)...0.1...0.01
$$

(a_s, a_c) = (0,0), (-2,-2) -- natural
Δm/m ~ 10⁻⁸ $\Leftrightarrow v_k \sim 50-100$ km/s

Some 2cDM models* *simultaneously resolve*:

(Todoroki & MM, 2019,2020,2022)

- History & Motivation
- Models (SIDM, etc)
- Overview of 2cDM | physics

-
- ‣ cosmology
- ‣ understanding

2

d⇢

$$
v_{th}^2 = \frac{4\pi G \rho_0 R^{\beta}}{\beta(3-\beta)} r
$$

M˙ = *l*ution $\vec{\Lambda}$

 $M_0 = (1 - \xi)At$ $\sqrt{ }$

 i nitial halo mass

assume profile

= *vth,*⁰

 $\frac{1}{2}$

,

Substructure evaporation ⇣ *r R* **2** ⌘ ² *^a* are used. If the velocity is approximated as *^v* ⇠ *^vth*, Eq. (C11) can be expressed in a *dM*˙ $rac{1}{2}$ ⇣ *r R* **r** C₁ Mass loss of a halo The mass loss rate per unit volume can be written

compact form as a series of the compact of The grate to yield the total halo mass-loss $M = \frac{1}{\lambda+3} \frac{m}{m} \left[\frac{1}{n_0 \beta} \left(\frac{1}{3-\beta}\right)^2 - \left(\frac{1}{R}\right)^2\right]^{M-3}$ integrate to yield the total halo mass-loss $\dot{M}=$ $\frac{3-\beta}{2}$ $\lambda + 3$ $\sigma_0 v_0$ *m* $\sqrt{ }$ $\begin{array}{ccc} \text{A} & \text{B} & \text{C} & \text{A} & \text{A} & \text{A} & \text{A} \end{array}$ the interval of [R, *rc*], the above equation can be generalized as

⇣ *r*

⌘

$$
\rho(r) = \rho_0 \left(\frac{r}{R}\right)^{-\beta} \hspace{1cm} v_{th}^2 = \frac{4\pi G \rho_0 R^{\beta}}{\beta (3-\beta)} r
$$

mass-loss per radius
$$
\frac{d\dot{M}}{dr} = 4\pi r^2 \dot{\rho} = 4\pi r^2 \dot{\rho}_0 \left(\frac{r}{R}\right)^{\lambda = 1 - \frac{5}{2}\beta + a(1 - \frac{\beta}{2})}
$$

$$
\dot{\rho} = -(n\sigma v)\rho = -\rho^2 \left(\frac{\sigma}{m}\right)v = \rho_0 \left(\frac{r}{R}\right)^{-2\beta} \frac{\sigma_0}{m} \left(\frac{v}{v_0}\right)^a v
$$

integrate to yield the total halo mass-loss
$$
\dot{M} = \frac{3 - \beta}{\lambda + 3} \frac{\sigma_0 v_0}{m} \left[\frac{G}{v_0 \beta} \left(\frac{4\pi \rho_0}{3 - \beta} \right)^{1/3} \right]^{\alpha + 1} \left(\frac{r_c}{R} \right)^{\lambda + 3} M^{1 + \frac{2}{3}(\alpha + 1)}
$$

\n*just a constant* approximately constant
\nsolution $\dot{M} = -|A|M^{\xi}$
\n
$$
M_0 = \left[(1 - \xi)At + M^{1 - \xi} \right]^{1/(1 - \xi)}
$$
\n*inital halo mass*
\n*final halo mass*

 $2-\beta$

or the ISO case.

⌘+3 *just a constant* 2, we have ⇠ *>* 0 in general. We then proceed as

d(*M/V*)

d⇢

⌘

⇣ *r*

✓ *v*

◆*^a*

the source of the source of
The source of the source

ا المستخدم المستخدم المستخدم
المستخدم المستخدم المستخدم

assume profile hydrostatic balance yields

Substructure evaporation **the contract of the contract DStructure evaporation** h ructure i¹*/*(1⇠) **ULL** h **I** le eval i¹*/*(1⇠)

mapping of old to new *M*₂ 2 *M* \overline{O} |

which is a mass distribution function. In particular, the mass distribution function \mathcal{L}

New mass function given the old one $f(M_0)$ is $f(M_0) = f(M_0(M, t)) \equiv f(M, t)$.

Evaporation resolves substructure & TBTF problems Shape of mass function tells: index a_c (conversion) and σ_0/m

$$
\text{If } a \text{ is a point of } a \text{ is a point of } M_0 = \begin{cases} \left(M^{-2/3} - \frac{2}{3}At\right)^{-3/2}, & a = 0\\ M e^{At}, & a = -1\\ \left(M^{2/3} + \frac{2}{3}At\right)^{3/2}, & a = -2 \end{cases}
$$

Now the cumulative mass function can be obtained by and similarly for the velocity function

$$
f(M_0)=f(M_0(M,t))\equiv f(M,t)
$$

V

Do halos evaporate completely? (e.g., relic neutrinos from big band) and some dark matter candidates because of the candidates because of the internal \sim **Do nalos ev** The composition at *t >* 0 is described by *nh*(*t*) and *nl*(*t*), which are governed by equawo naios evaporate connoieteiv is unit system. Here *v* is the relative velocity of two interacting eigenstates which are comparable *ⁿ*˙ *^h* ⁼ (*hhv*) *ⁿ*² *^h* (*hlv*) *nhnl,* (5.1a) α *n***h** α *l* α *l* α *l* α *l* α *n* α *l* α *n* $\$ where we also assumed, for simplicity, that the particle density, that the particle density is uniform throughout th

These assumptions are very natural for non-relativistic mixed particles such as neutrinos α

 $\dot{n}_h = -\eta$ abundance evolution eqns. produce evolution equal $\dot{n}_1 = -(\sigma_{11}v) n_1^2 - (\sigma_{11}v) n_1 n_1$

$$
\dot{n}_l\,=\,-
$$

tions

for heavy and light eigenstates if *m^h* ' *ml*. Here also *hh* is the total cross-section of the

abundance evolution eqns.
$$
\dot{n}_h = -(\sigma_{hh}v) n_h^2 - (\sigma_{hl}v) n_h n_l,
$$

$$
\dot{n}_l = -(\sigma_{hl}v) n_h n_l,
$$

$$
\text{then} \quad \frac{d\,n_h}{d\,n_l} = \frac{\sigma_{hh}\,n_h}{\sigma_{hl}\,n_l} + 1
$$

$$
\frac{n_{l,\infty}}{n_{l,0}} = \left[1 - \frac{n_{h,0}}{n_{l,0}}(1 - R)\right]^{\frac{1}{1 - R}}
$$

Poseble when **n** *n***₂₂** , (5.4b), (5.4 Complete evenoration is possible when

$$
\boxed{\frac{n_{l,0}}{n_{h,0}} \leq 1 - \frac{\sigma_{hh}}{\sigma_{hl}}}
$$

J Phy:
J ; JCAP MM, J Phys A 2010; JCAP 2014

where we also assumed, for simplicity, that the particle density is uniform that the particle density is uniform

Do halos evaporate completely?
\nabundance evolution eqns.
$$
\dot{n}_h = -(\sigma_{hh}v)\frac{n_h^2}{n_h} - (\sigma_{hl}v)n_hn_l,
$$
\n
$$
\dot{n}_l = -(\sigma_{hl}v)n_hn_l,
$$
\nthen
$$
\frac{dn_h}{dn_l} = \frac{\sigma_{hh}n_h}{\sigma_{hl}n_l} + 1
$$
\nSolution
$$
\frac{n_h(l)}{n_{h,0}} - \left(\frac{n_{l,0}/n_{h,0}}{1-R}\right)\left(\frac{n_l(l)}{n_{l,0}}\right) + \left(1 - \frac{n_{l,0}/n_{h,0}}{1-R}\right)\left(\frac{n_l(l)}{n_{l,0}}\right)^R
$$
\n
$$
R = \sigma_{hl,l}/\sigma_{hl}
$$
\n
$$
\frac{n_{l,\infty}}{n_{l,0}} = \left[1 - \frac{n_{h,0}}{n_{l,0}}(1-R)\right]^{\frac{1}{1-R}}
$$
\nis possible when\n
$$
\frac{n_{l,0}}{n_{h,0}} \leq 1 - \frac{\sigma_{hh}}{\sigma_{hl}}
$$
\nMM, J Phys A 2010; JCAP 2014

$$
\text{asymptotically} \quad n_h(\infty) \to 0, \ n_l(\infty) \to n_{l,\infty}
$$

*nl,*⁰

processes *hh* ! *hl, lh, ll* and *hl* is the total cross-section of the processes *hl, lh* ! *ll*, hence

then

Message 1

Wide parameter region allowed: $\sigma(v) \sim 1...0.1...0.01$ – consistent with all constraints $\Delta m/m \sim 10^{-8} \Leftrightarrow v_k \sim 50\text{-}100 \text{ km/s}$

SUBSTRUCTURE

theory with $\sigma(v)$ can explains TBTF and *missing* and *non-missing* satellites

simulations vs data - fit well

(Todoroki & MM, 2019,2020,2022)

σ0/m and index as (scattering) *rc* ' σ_0 /*m* and index a_s (scattering)

✓ *r*

✓ *v*

◆*^a*

number of interactions per particle m rticle *Nint* = *nvt^H* = ⇢vir *m* $t \cdot 1$

> Scattering resolves core-cusp problem Core size tells: *m* $\n *pro*\n$ $\int\limits_{0}^{\pi} f(x) \, dx$ *ndex a_s (sc* $\frac{1}{2}$ *rc* \mathbf{u} g \mathbf{P} $\frac{1}{2}$ ◆*^a ^a*+1 ² (*a*+3)

Cusp softening **0** *t*H*v*⁰ ◆ *a*+1 ² ✓*r^c*

er of interactions per particle
\n
$$
N_{int} = n\sigma vt_H = \rho_{\text{vir}} \frac{\sigma_0}{m} t_{\text{H}} v_0 \left(\frac{V_{\text{vir}}}{v_0}\right)^{a+1} \left(\frac{r_c}{R_{\text{vir}}}\right)^{a+1-\frac{\beta}{2}(a+3)}
$$

$$
\rho_{\text{vir}} = \frac{(3 - \beta)M_{\text{vir}}}{4\pi R_{\text{vir}}^3}
$$

$$
V_{\text{vir}}^2 = GM_{\text{vir}}/R_{\text{vir}}
$$

$$
N_{\text{vir}} \equiv \rho_{\text{vir}} \frac{\sigma_0}{m} V_{\text{vir}} t_{\text{H}}
$$

*r*0

m

*v*0

1*/*2

*r*0

——————
प्राप्तविद्यालय
प्राप्तविद्यालय

m

*v*0

$$
\simeq \left[\left(\frac{\text{a few}}{N_{\text{vir}}} \right) \left(\frac{V_{\text{vir}}}{v_0} \right)^{-a} \right]^{-\xi} \propto \sigma_0^{\xi}
$$

*r*0

*v*0

m

(3)*v*²

*r*0

$$
\xi = \frac{2}{\beta(a+3) - 2(a+1)}
$$

core radius

Message 2

Resolves core-cusp problem. Core size tells: $σ₀/m$ and indexes a_s , a_c

Wide parameter region allowed: $\sigma(v) \sim 1...0.1...0.01$ – consistent with all constraints $\Delta m/m \sim 10^{-8} \Leftrightarrow v_k \sim 50\text{-}100 \text{ km/s}$

PROFILES

core sizes from fits to simulated halos

(Todoroki & MM, 2019,2020,2022)

Message 3

DISTRIBUTION of SATELLITES

Wide parameter region allowed: $\sigma(v) \sim 1...0.1...0.01$ – consistent with all constraints $\Delta m/m \sim 10^{-8} \Leftrightarrow v_k \sim 50\text{-}100 \text{ km/s}$

Resolves substructure radial distribution Shape of function depends on all parameters

(Todoroki & MM, 2019,2020,2022)

"inelastic recoil"

 $\Delta m/m \sim 10^{-7} - 10^{-8}$

example, $m \sim$ tens GeV, $\Delta E \sim$ few keV

direct detection

2cDM predictions

indirect detection

"γ-ray annihilation

(MVM, JPhysA 2010; JCAP, 2014; PRL 2014)

2cDM vs other inelastic $h \epsilon$ r in Ω

Thus, in this case the overlap is negligible, in this case the overlap is negligible, in this case the overlap
Thus, in this case the overlap is negligible, in this case of the overlap is negligible, in this case of the o

Not a problem for 2cDM: conversions do not occur before structure formation starts (needed to separate mass states)

2

~2

excited, inelastic, exothermal, dark photon, boosted...
early universe "catastrophe" when the come well-separate can relate that mass excited inelastic, exothermal, dark photon, boosted...

~2

⇠ *O*(1)*.* (6.13)

(MM, JCAP 2014)

Outcomes

too many collisions gravithermal collapse

collisions uninteresting

 $0.1 < \sigma/m <$ few cm²/g

small mass splitting: Y. Zhang, Phys. Dark Univ. 15 (2017) K. Schutz, T.R. Slatyer, JCAP 01 (2015) 021 J. Kopp et al. JHEP 12 (2016) 033 M. Baumgart et al. JHEP 0904:014,2009

What about low-degeneracy? Boosted DM => See recent KC, et al paper.

2cDM model parameters be conserved in all processes. The energy-momentum conservation in elastic scattering is trivial, so we show that the divisions are divisions in which a heavy eigenstate is a heav

 $\theta = \pi/4.$

vne ean simplify by makings assamptions.

other, and also that $\frac{1}{2}$ second, scattering channels $\frac{1}{2}$ and $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ assumptions: then, we can have the most "minimal" model then, we can have the most "minimal" model fy by makings assumptions: then, we can have the most "minimal" model one can simplify by makings assumptions: then, we can have *the most "minimal" model*

$$
V = U_2^{\dagger} \tilde{V} U_2 = \begin{pmatrix} A & E & E & D \\ E & C & D & F \\ E & D & C & F \\ D & F & F & B \end{pmatrix} \qquad V_{\beta\beta} = -V_{\alpha\alpha} \qquad V = V_{\alpha\alpha} \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}
$$

can have the most "mini
\n
$$
V = V_{\alpha\alpha} \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}
$$

Next decade:

A paradigm shift?

CDM Inelastic DM

- Collisionless
- Single species
- Cold

Need: · Data!

- Self-interacting
- Multi-species
- Exothermal/Endothermal
- "Non-minimal"
- LSS evolution with z
- Ly-alpha forest imprint
- Early universe (?)

❖ Cosmological observations ❖ Indirect detection ❖ Direct detection

• Comprehensive realistic simulations w. baryons

- -
	-
	-
-
- Theory

FOR ATTENTION WE THANK

THE END OF PRESENTATION THIS IS

end of presentation