DOUBLE DISK DARK MATTER

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OUTLINE

- Motivation and Basic Idea
- Constraints on Double-Disk and the Allowed Parameter Space
- Direct Detection and Solar Capture
- Conclusions and Outlook

WHAT DO WE KNOW ABOUT THE DARK MATTER? \mathbb{R} ⇤ˆ *QCD m^h* !*ⁿ*

n *m*^a**b** \rightarrow **m**^a

 $\Omega_{DM}h^2 = 0.12$

- DM is mostly collisionless. Self-interactions are (weakly) constrained
- The DM is most likely cold
- Most of the matter in the Milky Way, as well as in other Galaxies is dark, distributed in elliptical halos

Most of the constraints on the DM are derived assuming that the DM is single component. Can we have interesting signatures from a subdominant dissipative component of the DM?

SIGNALS OF DISSIPATIVE DARK MATTER

Expect that a dissipative DM component has a different spatial and velocity distribution than the dominant DM component

What can be affected?

- Direct detection (velocity distributions change)
- Stellar capture
- Indirect detection (diferent density profiles)
- Trajectories of stars

Even a subdominant DM component can lead to unusual effects

DARK GALACTIC DISK

What is the mechanism of a Galactic disk formation? *Vogelsberger, Torrey, Sijacki, Keres, Springel, Hernquist; 2011*

The baryonic matter collapses into a disk as it cools down. No Supernova or other stellar feedback is needed for disk formation.

Needed for disk formation in the dark sector:

- Cooling mechanism
- tcooling << tUniverse Even if tcooling ≃ tUniverse we can get interesting effects

COOLING DYNAMICS IN A VIRIAL CLUSTER

- \bullet Compton scattering. Cooling down of electrons when they scatter on cold CMB photons. Usually it is completely subdominant to other processes if z < 10. Not clear if Galaxies can form so early. This can change in the dark sector
- Bremsstrahlung radiation. Electrons scatter on protons in hot plasma. In the baryonic sector this is usually a dominant cooling mechanism for cooling all the way down to the temperatures ~ (0.1 … 0.01) B.
- Collisional cooling due to "molecular processes", for example $H + e^- \rightarrow H^- + \gamma$. These processes can cool dow some regions all te way down to O(100 K) and allow star formation. We will assume, that there are no such processes in the dark sector.

COOLING IN THE DARK

- Need a long range force in the hidden sector: neither Compton nor Bremsstrahlung are possible without this force. Assume $U(1)$ _D which leads to dissipative dynamics.
- Need a light DM component to allow a cooling which is fast enough, $t_{\text{Brem}} \propto m^{3/2}$, $t_{\text{Comp}} \propto m^3$. This is an electronlike DM component (C).
- \bullet In order to allow Bremsstrahlung we need also a protonlike heavy component (X).

HOW DOES DDDM COOL DOWN? Baric DDDI COOL D BAS DDDM COOL DO

Does it cool down fast enough Does it cool down fast enough?

parameter space. Points above the space of th
Points above the space of the sp

Compton-dominated

EFFICIENCY OF DARK COLING ⌦*DMh*² \overline{X} 0 \overline{Y} $\overline{$ 2*µ*² $\sqrt{2}$ \sqrt{G}

shrunk and constrain this ratio to be $\leq 2.5\%$ 3 error bars on the visible matter can be significantly

CONSTRAINTS ON SELF INTERACTIONS ˜ ⇤ˆ *QCD* ⌦*DMh*² " ⁰*.*¹² (41)

Bullet Cluster Constraints

Erecoil

max " ²*µ*²

*v*2

^X (42)

Zhe results are usually phrased as constraints on self-interactions cross ª *^z*⁰ sections. If we phrase them as constraints *on the faction of self-interacting DM, we get ≤ 30% can be self-interacting* ⇢p*z*q*dz* 9 B*z* \boldsymbol{u} $\frac{C}{2}$ *eracting*

Bounds from the Shapes of the Galactic Halos *Peter, Rocha, Balock, Kaplinghat; 2012 Basic idea: self-interacting DM forms for spherical haloes* ⌦*DM* À 0*.*05% (46) σ *m* $\lesssim 0.2$ barm $\frac{\overline{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\text{c}^{\text{C}}\$ *Hard to interpret in terms of multi-component DM, but 15% of SIDM is probably safe.*

ª *^z*⁰ B*z* ⇢p*z*q*dz* 9 **EXEQUAT CONSTRAINTS** B*z* COSMOLOGICAL CONSTRAINTS ON ´*z*⁰ ⇢p*z*q*dz* 9 \overline{a} $DDIDM$ Cyr ⁻*Racine, de Putter, Raccanelli, Sigurdson; 2013* M^d Mali
Mali
Mali *In the early Universe the DDDM* $\frac{1}{10^{-5}}$ (10⁻⁴ $\frac{1}{10^{-4}}$ $\frac{1}{10^{-3}}$ $\frac{1}{10^{-2}}$ $\frac{1}{10^{-6}}$ $\frac{1}{10^{-5}}$ $\frac{1}{10^{-4}}$ $\frac{1}{10^{-3}}$ $\xi = 0.3$ *In the early Universe the DDDM* is $\frac{1}{10^{-6}}$ $\frac{1}{10^{-3}}$ $\frac{1}{10^{-3}}$ $\frac{1}{10^{-2}}$ $\frac{1}{10^{-5}}$ $\frac{1}{10^{-5}}$ $\frac{1}{10^{-3}}$ $\frac{1}{10^{-3}}$ ⁻² 10⁻⁶ $\xi = 0.3$
 $m_D = 1 \text{ GeV}$
 $f_{\text{int}} = 5\%$ 10^{-1} $(\textit{similar to BAO})$ to dark acoustic os¹⁰⁻¹ $\frac{g}{\sqrt{\frac{B_{D}+r_{\text{w}}^2R_{M_{CQ_{D_{\text{w}}}}}}{f_{\text{int}}}}$ $\frac{m_{D}=1 \text{ GeV}}{10^{-1}}$ 10^{-1} 10^{-1} 10^{-1} *This should leave imprints on the CMB and Cooling* structure. The contribution of the large scaling structure. R_{M} 10^{-} $\epsilon_{\text{F}} = 0.3$ (46) $\epsilon_{\text{F}} = 0.3$ (47) $\epsilon_{\text{F}} = 0.3$ (47) $\epsilon_{\text{F}} = 0.3$ (47) $\epsilon_{\text{F}} = 0.3$ (47) $\epsilon_{\text{F}} =$ $\frac{1}{\alpha}$ uilibrium 10^{-6} 10^{-5} 10^{-3} **ML**
 E *DM*_D **am** Collection = Nutry Reserved 10-3 **almest no parameter** 10^{-1} 10^{-1} 10^{-1} 10^{-3} Non-Equilibrium Cooling eft fo 10^{-2} 10^{-2} $\mathfrak{m}^{\mathrm{CC}}$ $\begin{array}{c|c} 10^{-2} & \underline{\mathsf{f}} \\ \underline{\mathsf{g}} \\ \end{array}$ 10^{-4} $\partial^2 D^1 D^0 \partial^4 = 0.05 \partial^1 D^1 \partial^4 D^1 D^0 \partial^4 D^1 D^0 \partial^3 D^0$ $\sigma_{\mathcal{D}}$ À 0*.*2 E

For $\frac{10^{-3}}{m_e}$ (GeV)
 m_e (GeV)
 t_{cool} 10^{-3} 10^{-2} Ruled Out 95% C.I Cooling $n_D = 1$ GeV 10^{-1} 10^{-1} 10^{-1} 10^{-1} $f_{\text{max}} = 2\%$ $\frac{c}{2} = 2\%$ $= 0.05 \Omega_{\rm E}$ 10^{-4} 10^{-4} $\sqrt{2}$ 10^{-4} 10^{-6} 10^{-5} m_e (GeV)
 m_e 10^{-2} fasonable values! Printed by Wolfram Mathematica Student Edition Printed by Wolfram Mathematica Student Edition 10^{-3} 10^{-3} 10^{-3} $\Omega_{DM} \approx 0.25 \Omega_{DM}$ Equilibr 10^{-2} a_D Printed by Wolfram Mathematica Student Edition 10^{-4} \mathbf{v} Wolfram Mathematica Student Edition 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10⁻³*Planck*+*WMAP+BAO+* m_e (GeV) m_e (GeV) 10^{-3} $\Omega_{\rm ADM}^{\rm thermal} = 0.02 \Omega_{\rm DM}$ FIG. 15: PIDM parameter space where a galactic dark disk is likely to form superimposed on the cosmological constraints \mathcal{L} from the "Planck+WP+High-*l*+BAO+Lens" dataset. The red regions below the black dot-dashed line are ruled out at 95%

z " 2*, T^D* " *TCMB*{2 (43)

OVERVIEW OF THERMAL HISTORY OF DDDM

- A-priori we know nothing about the interactions of the hidden sector with the baryons. We assume that they interact at the weak scale, but this is not promised. Slightly below the EW scale the dark sector decouples from the visible sector.
- \bullet Below that scale the heavy component X freezes out.
- Below the freeze-out scale the recombination process between heavy particles start. This should not wash out the heavy symmetric component
- Below the mass of the light component C dark recombination process starts (X recombines with C). We should have enough light DM particles at this point.

CONSTRAINTS ON KINETIC MIXING ⇢p*z*q*dz* 9 B*z*

´*z*⁰

m^N

The dominant constraint on the kinetic mixing comes from a possibility *that afer the decoupling between the sectors, the light DM C might reequilibrate with the SM photons. The rate for CC*⇿ɣɣ ∼ *T, while the Hubble rate* ∼ *T² . This might have an impact on BBN. To avoid this we need the kinetic mixing* ≲ 10-9 *und constructive on the sectors, the light DM C might re-*⌦*DDDM* ⌦*DM* ave an impact on BBN. To avoid this

When does this happen? \overline{a} *m* does \mathbf{h} $\sum_{i=1}^n$

- If the dark EM and the hypercharge are embedded into one non-Abelian 變 group ⌦*DDDM* " 0*.*05 ⌦*DM* (48)
- No particles, which are charged simultaneously under the hypercharge and 變 the dark EM, while all other interactions are due to Yukawa-type $\frac{1}{2}$ couplings
- \bullet There are states, which are charged under both U(1), but they satisfy anomaly like conditions $\text{Tr}\ (Q_Y^mQ_L^n)$ $\binom{n}{D} = 0$

DDDM DIRECT DETECTION DIFFERS FROM CDM F **DETECTION** !*ⁿ*

m^h

The recoil energy in direct detection experiment varies from zero to maximal recoil energy ⌦*DMh*² = 0*.*12 (41)

> $E_{max}^{recoil} =$ $2\mu^2$ \overline{m}_N v_{λ}^2 $\begin{array}{c|c} Z & & \\ X & & \end{array}$

Dissipative DM tends to have smaller velocities than CDM ➪ expect smaller recoil energy than the CDM and weaker bounds than the bounds on the CDM.

RELEVANT VELOCITIES **BEIRY ANT VEI OCITHS** If the dissipative DM has enough time to collapse into a disk, it co-rotates

v
| <u>v</u>^{pe}critics in the contract with the contract with

I Naively we can get velocities For CDN the largest velocity between *vrel* and ¯*v*. as small as 10-7

For dissipative DM we will take ¯*^v* ⇠ ¹⁰⁴. ¯*^v* ⇠ ¹⁰⁵ or even 10⁶ can also

Andrey Katz (Harvard) DDDM October 23, 2013 20 / 27

10-⁴

around the GC with the baryonic disk, s.t. *|*~

¹⁰-⁶ ¹⁰-⁵ ¹⁰-⁴ ¹⁰-³ ¹⁰-² ¹⁰-⁴

 $t_{\rm cool} \leq t_{\rm U}$ $\frac{t}{t_{\rm U}}$ 10^{-4} **10**⁻⁵ **10**⁻⁵ **10**⁻⁴ **10**⁻³ **10**⁻² 10^{-3} 10^{-2} **0.100** $mc[GeV]$ **aD** $\epsilon = 0.05$, $m_X = 1$ GeV, $n_X = n_C = 7.3 \times 10^{-3}$ cm⁻³ 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3}

For CDM we usually have *m^N ^X* (42) $\bar{v} \approx |\vec{v}_{rel}| \approx 10^{-3}$ in the galactic frame, ~ \sim is the rotational velocity of the baryonic disk and the baryonic disk and the baryonic disk and thus \sim

2*µ*²

*v*2

n, times the ratio of the local DDDM density normalized by the normal cold dark matter

of the dissipative dark matter near the Sun is smaller than \mathcal{A}

ⁿ can be even larger. Even if the local density near the Sun is one order of magnitude above

Erecoil

1 If dissipative DM has enough time to collapse to a disk. The dark disk co-rotates with the $\frac{1}{2}$ baryonic disk around the Galactic Center. $k_{\text{max of a}}}$ to sellar set a distr τ_{loc} plot the construction of the construction of \mathbb{R}^3 \mathcal{L} In Fig. 2 we see that, if the dispersion is the dispersion is as small as small as small as small as small as

 $\overline{v} \sim |v_{\text{rel}}^{\oplus}| \lesssim 10^{-4}c$

 Γ big scattering Γ $\frac{1}{10^{-2}}$ **This is the smallest velocity** is that we consider

DISSIPATIVE DM AND DIRECT DETECTION to an experimental threshold are sensitive to DDDM scattering. The constraints on the cross sections for DDD scattering of the DDD scattering of the second scatteri . 104*c*, a large cross section of order the *Z*-exchange cross section is still allowed for DM $\frac{1}{\sqrt{2}}$

clear from the figure that for a heavy dark matter particle with matter particle with matter Γ relative velocition experiments to the above 104 to the direction of Sensitivity of various direct Recas detection experiments to the DM velocities

also be important for the DDM scenario, or in general, for the detection of any dark matter \mathbf{r} Recast of LUX results:

DM scenario. Yet from the discussions above, pushing direct direction thresholds lower could

In summary, due to the small velocity dispersion of \mathbb{R}^n

 \blacksquare As expected the hounds on dissingtive 100 1000 120 cold data with an exception ordinary cold data matter distribution with \mathbf{v} As expected the bounds on dissipative DM is weaker than on CDM

THE FIRST LOOK ON SOLAR CAPTURE

- The mean velocity is different from the CDM
- The DM is self-interacting, the self-capture is important
- The DM is partially asymmetric. The light component (C) must be asymmetric. The heavy component has both symmetric and asymmetric components
- Both free heavy particles and dark atoms can be captured
- \bullet In the dissipative regime the binding energy of the dark atoms is smaller than the solar temperature.

ASYMMETRIES AND SELF-INTERACTIONS *Nassym*(*t*) = *CNt .* In purely asymmetric case there is no annihilation, and therefore, of course

 $\frac{1}{\sqrt{2}}$ sluting accumunated in the bear ely symmetric asymptot[.]
-⇢*X* constant value. In partially asymmetric case the equilibrium is If the DM is purely asymmetric, it is linearly accumulated in the star. Purely symmetric asymptotes to a never reached.

- The capture in the young stars is 變 mostly the nuclear capture
- **When the amount of the captured** DM gets to some critical value, the exponential growth due to self capture is triggered

- tly the nuclear capture \bullet The exponential growth is brief, the effective cross section is saturated
	- **The capture further proceeds similar** to the nuclear capture, but with a different saturated cross-section.

SOLAR CAPTURE: RESULTS

Direct Detection and Solar Capture

Self Interactions and constraints and constraints and constraints and constraints and

Self Interactions and constraints

CONCLUSIONS AND OUTLOOK

- Partially dissipative DM is viable possible which can potentially lead to rich dynamics and interesting phenomenology
- Would be interesting to analyze DDDM with explicit simulations and further constrain it (or maybe find some hints for its existence)
- The direct bounds on the interactions of partially dissipative DM are relaxed compared to the bounds on CDM
- We get interesting bounds from the solar capture; the selfcapture effects are important