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Thermal decoupling and small-scale structure in DM models with Yukawa-like interactions

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> L.v.d.A., Torsten Bringmann, Yaşar Goedecke [arXiv:1202.5456 [hep-ph]]

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Dark Matter

What do we know? $\textcircled{2}_{DM}$ \approx 0.23 \odot electically neutral non-baryonic collisionless Cold -> Large scale stucture

WIMPs are good candidates: motivation from particle physics $>$ right relic abundance comes out naturally (WIMP miracle)

DM with Yukawa-like interactions heavy DM interacts through light force carrier Φ repeated exchange of Φ -> Sommerfeld effect multiply cross-section by enhancement factor S resonances expected near bound state: $-$ off resonance S∼v⁻¹ − resonance S~v⁻² Φ Φ Φ χ χ $\overline{\mathbf{v}}$ $S(v)$ $\sigma_{XX} \rightarrow \sigma \sigma$ $\overline{\mathbf{v}}$ **g**χ From this result, we expect that the Sommerfeld enhancement will exhibit a series of resonances for speear bound state: where \sim fashion. The behaviour of the cross section close to $\frac{1}{2}$ \sim resonance \sim \sim \sim 1 2 5 10 20 50 100 1 10 100 1000 10^4 10^5 10^6 <u>(</u> 0.1 0.01 -10^{-3} -10^{-4} -10^{-5} Lattanzi, Silk (2009)

, where

nal solution is: №in(r) = Aeikinr + Be−ikinr + Be−ikinr + Be−ikinr + Be−ikinr + Be−ikinr + Be−ikinr + Be−ikinr

3

 m_{DM} (TeV)

Important interactions

annihilation self-scattering scattering

First part of talk

Second part of talk

Interplay between chemical and kinetic decoupling

In the conventional WIMP scenario, the collision term

the following \mathcal{S} , we can use \mathcal{S} , we can use \mathcal{S} to \mathcal{S} to \mathcal{S} to \mathcal{S} to \mathcal{S}

of the WIMP number density and "temperature" in this temperature in this temperature in this temperature in th regime, however, we need to solve the following coupled to solve the following coupled the following coupled to system of di↵erential equations for *y* and *Y* that follows

it clearly demonstrates that kinetic and chemical decou-

$\frac{1}{2}$ **cov**> enhanced for v→0 Sommerfeld enhanced *s*-wave annihilation, e.g., we then IN THE COLLISION OF THE COLLISION TERM calculate h*v*reli(2) simply by replacing *T* ! *T*. For a \sim some annihilation, we then \sim **EXAMPLE FOLLOWING SECTION OF A S** DENSITY AFTER KINETIC DECOUPLING calculate h*v*reli(2) simply by replacing *T* ! *T*. For a

DM velocity décreases **where the is valid in the faster after KD** $\begin{array}{ccc} \hline \end{array}$ h*v*reli = h*S*(*v*)0i*| T* =*T* ' 2 ⇡*T* at least unit is the time time time \mathbf{r} velocity decreases to to the i $\overline{}$ aster after RD annihilation rates, and in Eq. (1) can be completely neglected by the time time time \mathcal{L} **Example 12** DM velocity decrease is only governed by the expansion of the universe $\mathcal{L}_{\mathcal{A}}$ at leaster after KD is a transfer have grown large enough to trigger structure for the structure formation of the structure formation of the structure formation of the structure for th

¹ *^y*eq

Hx dx , (24)

y

roughly have *^v* ' *p/m* / *^x*1*/*² before kinetic decou-

the following \mathcal{L} is the following Section II \mathcal{L}

III. EVOLUTION OF DARK MATTER DENSITY AFTER KINETIC DECOUPLING

in Eq. (1) can be completely neglected by the time of kinetic decoupling, i.e. the further evolution of *f* is only governed by the expansion of the universe –

is qualitatively di↵erent and much more complex.

DM population depleted of lowest velocity particles *[* ⁰ *,* (27) *^v* ⇠ *^v*¯ ⌘ ^p3*T/m* fall into the Coulomb regime where cuss now in some detail, this part of the evolution history where λ is valid if velocities of the order of th DM population depleted of tiones velocity particles r *m* ⇡*T* , bleted *^v* ⇠ *^v*¯ ⌘ ^p3*T/m* fall into the Coulomb regime where

Sommerfeld enhanced *s*-wave annihilation, e.g., we then

tioned above. For a full understanding of the evolution

h*v*reli = h*S*(*v*)0i*|*

tioned above. For a full understanding of the evolution of the evolution $\mathcal{F}_{\mathbf{w}}$ of the MIMP number of the WIMP n regime, however, we need to solve the following coupled to solve the following coupled the following coupled to A. A new era of annihilation is qualitatively di↵erent and much more complex. Let us focus on the standard situation where *x*kd

^S(*v*) / *^v*¹; this is exactly the *^T* 1*/*²

and self-annihilation may start again. For the case of the cas Sommerfeld-enhanced annihilation rates, as we will discuss now in some detail, this part of the evolution history of the evolution history of the evolution history

relic density WIMP "temperature" *Y* ⁰ *^Y* ⁼ ¹ *^x g*0 ⇤S of the WIMP number density and "temperature" in this regime, we need to solve the following coupled to solve the following coupled to solve the following coupled to system of di↵erential equations for *y* and *Y* that follows

/ *^x*¹*/*² scaling men-

consistent description: set of coupled Boltzmann eq's ronsistent description: set of l ae update 3 *g*0 ⇤S d B 2*mc*(*T*) zma **Y** onsisterit description: set of coupled boltzmann eqs *x*cd; around and after kinetic decoupling, we thus have *Set of g*0 ⇤S *g*⇤^S *Hx sY* ^h*v*reli*[|] x*=*m*² */*(*s*2*/*3*y*) (28)

^S(*v*) / *^v*¹; this is exactly the *^T* 1*/*²

$$
\boxed{\frac{Y'}{Y} \;=\; -\frac{1-\frac{x}{3}\frac{g'_{*S}}{g_{*S}}}{Hx}sY\,\left<\sigma v_{\rm rel}\right|_{x=m_{\chi}^2/(s^{2/3}y)}\quad \frac{y'}{y}\;=\; -\frac{1-\frac{x}{3}\frac{g'_{*S}}{g_{*S}}}{Hx}\bigg[2m_{\chi}c(T)\left(1-\frac{y_{\rm eq}}{y}\right)-sY\left(\left<\sigma v_{\rm rel}\right>-\left<\sigma v_{\rm rel}\right>_{2}\right)_{x=m_{\chi}^2/(s^{2/3}y)}\bigg]}
$$

 (29)

g 0

have

⁰ *,* (27)

New era of annihilations

Part II: Small-scale problems of ACDM Cosmology Formation of dwarf galaxies and dwarf galaxies and

Puzzles in galaxy formation

"Missing satellite" problem in the Milky Way

Substructures in cold DM simulations much more numerous than observed number of Milky Way satellites!

slide reproduced with permission from Christoph Pfrommer

The cusp vs. core problem

J. van Eymeren, C. Trachternach, B. S. Koribalski, R.-J. Dettmar (2009)

observations of dwarf galaxies show core-like inner structure whereas a cusp is predicted from simulations

"The density profiles of all sample galaxies derived from the observed rotation curves (open grey triangles). Their inner slopes are measured by applying a least square fit to all data points within the innermost kpc (bold black lines). The fitted values of and the uncertainties are placed into the upper right corner of each panel. Note that the rotation curves of ESO 059-G001, NGC 4861, and NGC 5408 only contain two points in the inner 1 kpc. Therefore, no uncertainties can be given. The longdashed and dotted lines show the NFW and the ISO profiles, respectively, using the parameters of the minimum-disc case."

The "Too big to fail"-problem

6 *M. Boylan-Kolchin, J. S. Bullock and M. Kaplinghat*

most massive subhalos in simulations of MW sized halos are too dense to host observed brightest satellites!

Figure 3. Rotation curves for all subhalos with $V_{\text{infall}} > 30 \text{ km s}^{-1}$ and $V_{\text{max}} > 10 \text{ km s}^{-1}$, after excluding Magellanic Cloud analogs, in each of the six Aquarius simulations (top row, from left to right: A, B, C; bottom row: D, E, F). Subhalos that are at least 2σ denser than every bright MW dwarf spheroidal are plotted with solid curves, while the remaining subhalos are plotted as dotted curves. Data points with errors show measured V_{circ} values for the bright MW dSphs. Not only does each halo have several subhalos that are too dense to host any of the dSphs, each halo also has several massive subhalos (nominally capable of forming stars) with V_{circ} comparable to the MW dSphs that have no bright counterpart in the MW. In total, between 7 and 22 of these massive subhalos are unaccounted for in each halo.

Small-scale problems of ΛCDM Cosmology

missing satellites: simulations predict many more subhalos than number of galaxy satellites inferred from observed galaxy luminosities and HI mass functions

proposed solutions: increase gas entropy before collapse, suppress cooling efficiency, photo-evaporation, supernovae feedback, WDM...

Cusp/Core: observed cores of dSph and LSB galaxies in tension with cuspy internal density structure obtained by simulations.

proposed solutions: large velocity anisotropy, baryonic feedback, IDM, vdSIDM...

"too big to fail": most massive subhalos in simulations of MW sized halos too dense to host observed brightest satellites. proposed solutions: increased stochasticity of galaxy formation, low MW mass (WDM), vdSIDM...

Most solutions have shortcomings or only solve 1 or 2 problems at the same time

Self-scattering in structure formation

velocity dependent Self-Interacting DM is promising: [Loeb, Weiner (2011)], [Vogelsberger, Zavala, Loeb (2012)]

- avoids astrophysical constraints (unlike SIDM)
- produces cored subhalos without affecting inner density profiles on \bigcirc larger scales
- most massive subhalos are less dense and consistent with observations

2 benchmark models (σmax, vmax) solve:

cusp/core "too big to fail"

translated to (m_{χ}, m_{A}) , where V is a vector mediator

need m_{χ} > 600 GeV $m_{A'} = O((sub)$ MeV)

DM scattering off other particles

- freestreaming of WIMPs after kinetic decoupling creates cutoff in powerspectrum
- acoustic oscillations leads to similar cutoff
- cutoff scale is set by size of horizon at KD : late $KD \rightarrow high$ M_{cut}
- \odot M_{cut} = Max(M_{fs} , M_{ao}): only objects with M $\geq M_{\text{cut}}$ form
- scattering for
	- $>$ scalar mediator
		- $-$ scatters off Φ , μ^{\pm} and e^{\pm}
		- $-$ Saturation of T_{KD} ~ 0,1 MeV
		- ν's negligible:
			- |M_{Φν→Φν}|² ∝ m_ν²
	- vector mediator:
		- ν's contribute:
			- |MVν*→*V^ν| ² ∝ E^ν 2
		- $-$ T_{KD} can decrease to O(keV)!

Missing satellites and the cutoff mass

DM with vector mediator scattering off neutrino's: very late decoupling -> high M_{cut}

- \odot Lyman- α bounds: M_{cut} < 5.1 x 10¹⁰ M_o (m_{wdm} > 1 keV)
- **O** M_{cut} that can solve missing satellite problem inferred from N-body simulations with WDM

possibly solves also missing satellites problem!

[[]arXiv:1205.5809 [astro-ph.CO]]

More simulations and model building needed to confirm.

Conclusions

First consistent framework to describe interplay between chemical and kinetic decoupling

- possibility of new era of annihilations
- Small-scale problems of ΛCDM Cosmology can be solved by a DM model with:
	- $>$ velocity-dependent self-interactions mediated by (sub)MeV vector mediator
	- much later kinetic decoupling than in standard case follows naturally for vector mediator coupling to neutrinos

Need further model building and simulations to confirm.

Thank you for your attention!

Backup Slides

off resonance: S∼1/v

Kinetic decoupling temperature

off resonance resonance

bottom to top: $m_X = 100$ GeV 500 GeV 1 TeV 5 TeV

 $m_Φ = 100$ MeV 500 MeV 1 GeV 5 GeV

Smallest DM protohalos

 $m_Φ = 100 MeV$ 500 MeV 5 GeV

top to bottom: $m_X = 100$ GeV 500 GeV 1 TeV 5 TeV

off resonance: Mcut/M[⊙] ∼ 3 x 10-10 - 600 resonance: Mcut/M[⊙] ∼ 7 x 10-9 - 1100

The smallest protohaloes

Free streaming of WIMPs after *Particle DM and small-scale structure* 9 kinetic decoupling T. Bringmann, 2009

- washes out density fluctuations on small scales scales
(like baryonic oscillations) $\frac{1}{2}$ $\frac{1}{2}$ b Sciliations) :cillatione) #### ##### #
- translates to mass-scale M_{cut} of smallest gravitationally bound objects $"$ ""
"""" mass-so
""" "" \cdot , \cdot . \cdot . GUIS - r is nall $\overline{\mathbf{H}}$ ###### 4015 htc 1000 ntc awarany itationally $H \sim H \sim H \sim H$ $\overline{}$ $\overline{\$ nallect -######## ######## ; to mass-s α mooo oo

*M*fs*/M*

depends strongly on particle physics \Rightarrow not necessarily $M_{\rm cut} \sim 10^{-6} M_\odot$! # l dono !!!! !!!!! # ## $^{-\mathsf{o}}\mathsf{M}_\odot{}$ Higgsino (*Z^g <* 0*.*05) Gaugino (*Z^g >* 0*.*95) (10811000000)

damping mechanisms of the matter power spectrum after kinetic decoupling, viz. free