# THE COSMOLOGY OF DARK MATTER FREEZE-IN

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Cosmology from Home 2023 Based on work with Cora Dvorkin, Tongyan Lin, Saniya Heeba



# WHAT IS THE DARK MATTER?

## DARK MATTER MASS



(not to scale)

Many possibilities spanning 90+ orders of magnitude!

## DARK MATTER MASS



(not to scale)

## THERMAL DARK MATTER CANDIDATE: WIMPS (FREEZE-OUT)



## WIMP DIRECT DETECTION (MODEL DEPENDENT)



Akerib et al. Snowmass 2021 report

## WIMP (THERMAL FREEZE-OUT) INDIRECT DETECTION WINDOW



Low-mass bounds are driven by CMB constraint assuming s-wave cross section

## **BENEFITS OF WIMPS AS DARK MATTER**

- More than the second state of the second state
- Simple (not many new particles)
- Relic abundance independent of initial conditions as long as DM is in the bath
- $\widecheck$  Fine with early universe observables (BBN and  $N_{\rm eff}$ )
- **Markov** Relevant couplings can be experimentally probed

## BUT WE STILL HAVEN'T FOUND WIMPS

## PLAN OF ATTACK FOR GOING BEYOND WIMPS?

freeze-out while relativistic (neutrinos/warm dark matter)

- dark matter, SIMPs, ELDER, KINDER, etc.)
- dark photons, etc.)



if add auxiliary particles ("dark sectors") which make thermal histories richer with multiple temperatures, nontrivial kinetic and chemical decoupling (e.g. forbidden dark matter, cannibal

More make dark matter in a completely non-thermal way (axions,

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- ... more? Yes!!

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## FREEZE-IN VS. FREEZE-OUT



## FREEZE-IN VS. FREEZE-OUT



## FREEZE-IN AS A KEY SUB-GEV DARK MATTER BENCHMARK



From Snowmass Cosmic Frontiers topical report

- Freeze-in via a light mediator is the key milestone for many direct detection experiments
- Usual mediator is <u>dark photon</u> due to strong constraints on other light mediators
- Same combination of couplings predicts <u>both</u> the relic abundance and the signal strength — predictive!
- Uniquely accessible target for sub-MeV since freeze-in is "thermal-ish" and not subject to bounds from BBN

. . . . .

## MAKING SUB-MEV DARK MATTER FROM A THERMAL PROCESS



## PHOTONS CAN DECAY IN A MEDIUM TO WEAKLY COUPLED PARTICLES



This process can extinguish stars quickly if the final state is unhindered by the plasma (this is a stellar energy loss mechanism in the Standard Model through decay to neutrinos)

Light particles

Photon has an in-medium mass inside plasma ("plasmon"), phase space available for decays

Light particles

## PLASMON DARK MATTER FREEZE-IN



sub-MeV DM

This process makes dark matter efficiently in the early Universe, which is a hot, relativistic plasma!

sub-MeV DM



# CAN WE CONSTRAIN THIS WITH COSMOLOGY?

# DARK MATTER IS BORN "HOT" FROM FREEZE-IN

## **DEALING WITH NON-THERMAL PHASE SPACE**



 $m_{\chi} = 40 \text{ keV}$ 

## **DEALING WITH NON-THERMAL PHASE SPACE**

2

 $p_{\chi}/I_{\gamma}$ 



 $m_{\chi} = 40 \text{ keV}$ 



DM can optionally thermalize in its own sector if there are selfinteractions

5



## VELOCITY EFFECTS ON CLUSTERING (WARM DARK MATTER EXAMPLE)

Warm dark matter initial conditions:





 $\Omega_{\chi} = \frac{m_{\chi}}{94 \text{ eV}} \frac{11}{4} \left(\frac{T_{\chi}}{T_{\gamma}}\right)^3$ 

Lighter, Hotter

## PROBES OF STRUCTURE FORMATION ON SMALL SCALES



## **GRAVITATIONAL CLUSTERING AND PHASE SPACE**



## MAPPING WDM CONSTRAINTS TO FREEZE-IN CONSTRAINTS





## **DARK MATTER-BARYON DRAG APPARENT IN THE CMB**



### Photon-baryon fluid

## gravitational potential well

## Collisionless dark matter



### Photon-baryon fluid

### gravitational potential well

## Partly collisional dark matter



## **DM-BARYON SCATTERING AND PHASE SPACE**

 $(b\chi$ 

×.

More DM particles moving slower if DM does not thermalize, stronger v<sup>-4</sup> scattering effect seen in the CMB!





Dvorkin, Lin, KS 2011.08186



## **DM-BARYON DRAG RATE**



## DARK MATTER-BARYON DRAG EFFECT ON THE CMB



 $m_{\chi} = 35 \text{ keV}$ 







# ARE THERE ANY OTHER COSMOLOGICAL SIGNATURES OF FREEZE-IN?

## **PSEUDO-DIRAC DARK MATTER**

- ► If dark matter is charged under a new gauge group, e.g. dark U(1), with a massive gauge boson (dark photon with mass coming from Higgs-like mechanism), Dirac dark matter multiplet splits into multiple mass states  $\chi_1$ and  $\chi_2$  with small mass splitting  $\delta = m_2 - m_1$
- ► Couplings are off-diagonal (i.e. no state appears twice in vertex)
- Couplings, mass splitting, dark photon mass, dark Higgs mass are all inter-related in self-consistent way

 $\mathscr{L} \supset \frac{\kappa}{2} F'_{\mu\nu} F^{\mu\nu} + i g_{\chi} A'_{\mu} \chi_2 \gamma^{\mu} \chi_1$ 





## **PSEUDO-DIRAC DARK MATTER IS OFTEN INVOKED WHEN THERE ARE ANOMALIES**



<sup>~2000</sup> citations

DAMA/LIBRA annual modulation e.g. Tucker-Smith & Weiner (2001)  $\sim$ 1000 citations

XENON1T excess (photo I took at e.g. Baryakhtar et al. (2020) An et al. (2020)  $\sim 100$  citations







m

0

# **INELASTIC FREZE-IN**



Heeba, Lin, **KS** 2304.06072



## FREEZE-IN OF PSEUDO-DIRAC DARK MATTER



► Ground and excited state are produced symmetrically by fermionantifermion annihilation with extremely small branching fraction

► Mass splitting is too small to matter kinematically so we (mostly) reproduce

## HIGH DEGREE OF COMPLEMENTARITY WITH TERRESTRIAL EXPERIMENT



 $10^{1}$ Heeba, Lin, **KS** 2304.06072

## **COSMOLOGY OF THE META-STABLE EXCITED STATE**



 $\tau \sim 10^7 \text{ seconds} \times \left(\frac{m_{A'}}{1 \text{ GeV}}\right)^4 \left(\frac{100 \text{ MeV}}{\delta}\right)^5$ 

Same combination of couplings sets both the relic abundance and the dark matter decay rate!!!! Just like direct detection!

 All other processes are extremely suppressed/ rare due to small freeze-in couplings and low DM density

► Most of mass splitting energy goes into recoiling electron-positron pairs, ground state gets a velocity kick,  $v_{\rm kick} \sim \delta/m_{\chi}$ 

. . . . .

## **UNIVERSE AS A CALORIMETER FOR INELASTIC FREEZE-IN**

Electron-positron pairs from three-body decay can inject energy into tested by future probes (accelerator, PIXIE)



background environment! Lots of the parameter space is available and will be

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### **IMPACT OF THE INELASTIC THREE-BODY VELOCITY KICK** Heeba, Lin, **KS** 2304.06072

structure on characteristic length scales... complementary to electron calorimeter signatures!



Dark matter velocity kick from three-body decay can hinder the growth of

## **ASTROPHYSICAL SCATTERING SIGNATURES**



Exothermic scattering Endothermic scattering

- Relic excited state can be collisionally deexcited and populate the ground state
- Mass splitting could be below kinematic threshold for upscattering in a typical galactic environment, re-populating excited state
- These scattering channels convert between kinetic and mass energy, providing a way to heat and cool dark matter depending on the parameters and astrophysical environment



## WHAT HAPPENS TO GALAXY HALOS IF ONLY EXOTHERMIC SCATTERING IS POSSIBLE?



Vogelsberger, Zavala, KS, Slatyer MNRAS (2019)



Based on lighter mediator regime where Sommerfeld enhancement is possible, cross sections from KS & Slatyer (2015)



## DARK MATTER PARTICLES GET KICKED OUT OF THEIR HALOS, DENSITIES SMEARED



Vogelsberger, Zavala, KS, Slatyer MNRAS (2019)



## WHAT HAPPENS TO GALAXY HALOS IF YOU ADD BOTH EXO- AND ENDOTHERMIC SCATTERING?

CDM



z = 0.00



### Stephanie O'Neil and Saniya Heeba

Exothermic

Endothermic

O'Neil, Vogelsberger, Heeba, KS et al. (2022) Simulations done in the Born regime of scattering

# 

100 kpc Endothermic

z=0.00

z=0.50

CDM

## WHAT HAPPENS TO GALAXY HALOS IF YOU ADD ENDOTHERMIC SCATTERING?

z=2.10

z=1.00

z=1.75

O'Neil, Vogelsberger, Heeba, KS et al. (2022)

## MOST OF THE "ACTION" HAPPENS AFTER FORMATION OF HEAVIER HALOS (LATER IN **BOTTOM-UP STRUCTURE FORMATION) DUE TO KINETIC BARRIER TO UPSCATTERING!**

## THE UPSHOT: INELASTIC FREEZE-IN HAS A **COMPLETELY UNIQUE SET OF COSMOLOGICAL SIGNATURES!**

## SUMMARY

- Freeze-in is one of the simplest alternative thermal histories to WIMP freeze-out
- Despite the very small couplings (too small to be thermalized) dark matter made via freeze in can have a combination of signatures for
  - Direct detection
  - Suppressed clustering due to velocities
  - ► Altering CMB acoustic peaks
  - Injecting energetic electrons etc. during BBN, in spectral distortion era, into IGM
  - Accelerator searches
  - Exothermic and endothermic self-interactions in halos
- ► It's a big universe, lots of room for creativity!

