Cosmological searches for dark matter-baryon interactions

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Image credit: Budassi CIPANP 2018

Caveats of low-energy searches

- \triangleright DD has a ceiling.
- Masses << GeV are still \blacktriangleright poorly explored.
- > Assumptions about <u>local</u> astrophysics of DM.
- \triangleright Limited ability to pin down nature of the interaction. [see arXiv 1506.04454]

Cosmic microwave background [CMB]

3

With dark matter-proton scattering:

scattering à**drag force**à **suppression of small scales**

With dark matter-proton scattering:

VG and Boddy (2017), Boddy and VG (2018); Previous work: Chen et al (2002), Sigurdson et al (2004); Dvorkin et al (2014); etc.

Scattering in the early universe A. Boltzmann equations m^e **UC CHECH IS IN THE CUITY ONIVERSE** \sim Conttoring in the

Momentum transfer between baryon-photon fluid and DM affects perturbations and thermal history: w and the heavy parameter in the heavy day in the heavy day in the heavy of the heavy of the second in α below. In α is a below α below. In the second in α **OUR CALCULATIONS APPLY TO COLD DESIGNEED DURING MASS MUST MANUSCRET DURING CALCULATIONS CONTROLL AT A PRODUCT**
The redshift at a redshift at redshift affects perturbations and thermal history: helium. In our case of spin-independent search in the spin-

$$
\delta_{\chi} = -\theta_{\chi} - \frac{\dot{h}}{2}, \qquad \delta_{b} = -\theta_{b} - \frac{\dot{h}}{2}, \qquad T_{\chi} = -2\frac{\dot{a}}{a}T_{\chi} + 2R'_{\chi}(T_{b} - T_{\chi})
$$
\n
$$
\dot{\theta_{\chi}} = -\frac{\dot{a}}{a}\theta_{\chi} + c_{\chi}^{2}k^{2}\delta_{\chi} + R_{\chi}(\theta_{b} - \theta_{\chi}),
$$
\n
$$
\dot{\theta_{b}} = -\frac{\dot{a}}{a}\theta_{b} + c_{b}^{2}k^{2}\delta_{b} + R_{\gamma}(\theta_{\gamma} - \theta_{b}) + \frac{\rho_{\chi}}{\rho_{b}}R_{\chi}(\theta_{\chi} - \theta_{b})
$$
\n
$$
R_{\chi} = \frac{a c_{n} \rho_{b} \sigma_{0}}{m_{\chi} + m_{\text{H}}} \left(\frac{T_{b}}{m_{\text{H}}} + \frac{T_{\chi}}{m_{\chi}}\right)^{\frac{n+1}{2}} \mathcal{F}_{\text{He}}
$$

Gluscevic and Boddy (2017), Boddy and Gluscevic (2018),
Chen et al (2002), Sigurdson et al (2004): Dvorkin et al (2014): etc. Chen et al (2002), Sigurdson et al (2004); Dvorkin et al (2014); etc. 2), Sigurdson et al (20 Chen et al (2002), Sigurdson et al (2004); D Ω independent schemenden schemenden schemenden in the e Ω ection of Ω ection Ω of interactions is defined in the combination of α is defined by α is defined by

time; \overline{a} referred to the velocity divergence for the pho- \overline{b}

Data

Plot by E. Calabrese [for ACTPol] 7

Cosmological exclusion curves

v-independent DM scattering with proton: 95% confidence upper limit

VG and Boddy (2017)

High cross sections, down to mass ~keV!

exchange (and *µ^N* is the reduced mass of the DM–nucleon system); and *S*~ and *S*~*^N* are the DM spin and the nu-Non-relativistic EFT

momentum transfer is *|*~*q|*max=2*µ^N v*. Working to second order in momenta and velocities, various combinations of [*Fan et al, 2010; Fitzpatrick et al, 2012; Anand et al, 2013]*these four σ four σ four σ and σ the following 14 operators, 2 derived in Ref. [32]: σ

$$
O_1 = 1_X 1_N
$$

\n
$$
O_3 = \vec{S}_N \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{v}^{\perp}\right)
$$

\n
$$
O_4 = \vec{S}_X \times \vec{S}_N
$$

\n
$$
O_5 = \vec{S}_X \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{v}^{\perp}\right)
$$

\n
$$
O_7 = \vec{S}_N \cdot \vec{v}^{\perp}
$$

\n
$$
O_8 = -\left(\vec{S}_X \cdot \frac{i\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\right)
$$

\n
$$
O_{12} = \vec{S}_X \cdot \left(\vec{S}_N \cdot \vec{S}_N\right)
$$

\n
$$
O_{13} = \left(\vec{S}_X \cdot \vec{v}^{\perp}\right)
$$

\n
$$
O_{14} = \left(\vec{S}_X \cdot \frac{i\vec{q}}{m_N}\right)
$$

\n
$$
O_{15} = \left(\vec{S}_X \cdot \frac{i\vec{q}}{m_N}\right)
$$

$$
\mathcal{O}_9 = \vec{S}_{\chi} \cdot \left(\vec{S}_{N} \times \frac{i\vec{q}}{m_N} \right)
$$

\n
$$
\mathcal{O}_{10} = \vec{S}_{N} \cdot \frac{i\vec{q}}{m_N}
$$

\n
$$
\mathcal{O}_{11} = \vec{S}_{\chi} \cdot \frac{i\vec{q}}{m_N}
$$

\n
$$
\mathcal{O}_{12} = \vec{S}_{\chi} \cdot \left(\vec{S}_{N} \times \vec{v}^{\perp} \right)
$$

\n
$$
\mathcal{O}_{13} = \left(\vec{S}_{\chi} \cdot \vec{v}^{\perp} \right) \left(\vec{S}_{N} \cdot \frac{i\vec{q}}{m_N} \right)
$$

\n
$$
\mathcal{O}_{14} = \left(\vec{S}_{\chi} \cdot \frac{i\vec{q}}{m_N} \right) \left(\vec{S}_{N} \cdot \vec{v}^{\perp} \right)
$$

\n
$$
\mathcal{O}_{15} = \left(\vec{S}_{\chi} \cdot \frac{i\vec{q}}{m_N} \right) \left[\left(\vec{S}_{N} \times \vec{v}^{\perp} \right) \cdot \frac{i\vec{q}}{m_N} \right]
$$

Momentum transfer

 \Diamond Each operator -> cross section with a different dependence on relative particle velocity, different thermal history:

CMB observables

 \Diamond Each operator -> cross section with a different dependence on relative particle velocity, different thermal history:

Cosmological constraint on DM-baryon EFT

FIG. 3. The inferred upper limits on the DM–proton coupling control co *{O*1*, O*5*, O*8*, O*15*}*, chosen to represent all classes of relative velocity scalings of the cross section (indicated in the legend).

> 13 $\frac{1}{2}$

Other scattering scenarios

 $\sigma \sim \sigma_0$ Vⁿ Dvorkin+ (2014); Xu+ (2018);
Slatver+ (2018) Slatyer+ (2018)

Late-time: n <-2 Early-time: n≥-2

Late-time scattering: relative bulk velocity ry (13) and the problem of the set of the set

مر من در سال در سال در سال در سال 150 × for a nonzero percent arises from the interaction with baryons $[2010]$ z Tseliakhovitch and Hirata (2010)

Problem: non-linear equations pechlom: non linear equations for the DM and baryon density P fluctuations, and and divergence, expectively, and expectively, are given for a Fourier mode of a Fourier mode o Problem: non-linear equations my problem with α

$$
\dot{\delta}_{\chi} = -\theta_{\chi} - \frac{\dot{h}}{2}, \qquad \dot{\delta}_{b} = -\theta_{b} - \frac{\dot{h}}{2},
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$$

$$
R_{\chi} = \frac{a c_n \rho_b \sigma_0}{m_{\chi} + m_{\rm H}} \left(\frac{T_b}{m_{\rm H}} + \frac{T_{\chi}}{m_{\chi}}\right)^{\frac{n+1}{2}} \mathcal{F}_{\rm He}
$$
 Only for Vbulk << Vthermal

v-4 scattering: Planck limits

Boddy, VG, Poulin, + (coming up)

What about EDGES?

 2^x and 2^x and 2^x and 2^x The intensity of the observable $\overline{\mathbf{r}}$ *m*χ=0.3 GeV (red; roughly matching the most likely observed value⁵ $\mathop{\mathsf{ss}}\nolimits:$ **Is it in the sky? Is it c** Order of business: Is it in the sky? Is it cosmological? Is it DM?

EDGES: v-4 and millicharge

From CMB limits on momentum-transfer: EDGES cannot be 1% of millicharged DM, but could be 100% with some other v-4 interaction.

What's coming?

Data

Atacama Cosmology Telescope [ACT]

Fig. 5.— A 45 deg² subset of the map in full resolution in T showing ACTPol 149 GHz (top) and Planck 143 GHz (bottom), in equatorial Louis et al 2016

The Simons Observatory

ALMA

- A five year \$45M+ program to advance technology and infrastructure in preparation for CMB-S4.
- Will eventually lead to the merging of the ACT and POLARBEAR/Simons Array projects.
- Tentative plans include:

POLARBEAR/SIM

- Major site infrastructure
- New telescopes with space for more future telescopes.
- CMB-S4 class receivers with partially filled focal planes.

ACT

 \mathbf{A}

Forecasts

Large gain with next-stage CMB experiments.

Zack Li (Princeton)

Distinguishability?

DM-baryon scattering does NOT look like neutrino mass, DM annihilations, Neff, nor LCDM parameters, Zack Li (Prince†on)
once lensing is included in analyses.

[Li, VG, +, coming up]

What's coming?

Analysis

Work in progress

(with K. Boddy, Z. Li, M. Madhavacheril, the ACTPol collaboration)

- \triangleright Cross-correlation with large-scale structure.
- \triangleright Scattering with electrons (better sensitivity to lower mass).
- \triangleright Constrain specific well-motivated models.
- Ø **Ultimate goal: combine analyses of experimental and observational data, find and confirm the signal, robustly test DM physics.**

Summary

 \checkmark CMB and cosmology probe vast parameter space (sub-GeV mass and large cross sections).

Abundance of new data on the horizon: CMB, galaxy surveys, 21-cm experiments, direct detection, LHC, fixed targets, +

 \checkmark Synthesizing information is important to guide searches and will be essential post-discovery.