Structure formation with SIDM: Theory

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With

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In dark matter science, hope for the best…

• Let's hope we can find dark matter in the lab...

FERMI GAMMA-RAY SPACE TEI

…but prepare for the worst!

• Gravitational signatures might be all we can observe!

The many faces of interacting dark matter.

Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

Outline

• Interacting dark matter and acoustics relics: CMB and large-scale structure.

• Dissipative dynamics and interacting dark matter.

• Self-interacting dark matter and the substructure power spectrum.

Self-interacting DM and Acoustic Relics described by a Yukawa potential ↵*^X r* Acoustic Relics

• DM interactions will in general be mediated by a "new" force carrier. \mathbb{R} M interactions will in conoral be madieted by a "new" \bullet DN interactions wil

$$
\mathscr{L}_{\text{int}} = \begin{cases} g_X \bar{X} \gamma^\mu X \phi_\mu & \text{vector mediator} \\ g_X \bar{X} X \phi & \text{scalar mediator} \end{cases}
$$

• Two interesting cases for acoustic relics:

1) The mediator is light enough to be relativistic until late cosmological times. a vector interaction is both attractive (*X*^{\sim}) and repulsive (*X*^{\sim}). And repulsive (*X* or *X* or Thus, in the integrator is then enough to be relativistic until

2) The mediator is massive but also couples to a relativistic species (such as neutrinos) until late cosmological times. effective corresponding to the average of the average of the two. Th Δ) ine inequator is massive out also couples to a

• As long as the "dark radiation to dark matter" ratio is larger than unity \Rightarrow large sound speed (c²~1/3). the angular distribution over the scattering angle \mathcal{L} is important. However, to compare accompare across \mathcal{L} \bullet As long as the "dark radiation to dark matter" ratio is section and dependent mediators, independent of the strong end of the strong e

Carison et al. (1992)
Boehm, Fayet & Schaeffer (2001) The Purposes of al. (2012) end in the DM particle trajectories is spurious since the DM particle trajectories are unchanged. In the plasma literature, and DM particle trajectories are unchanged. In the plasma literature, $\frac{1}{2}$ and $\frac{1}{2}$ are the cross section of the transport cross section of the transport α are defined to parameter cross section of the transport α section of the transport α section of the transport α section of the transport of th Carlson et al. (1992) Boehm et al. (2002)

van den Aarssen et al. (2012) Cyr-Racine & Sigurdson (2013) Many more…

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Self-interacting DM and Cosmology: General Scenario

- We consider a model in which at least a fraction of the DM
	- 1. Couples to light, relativistic particles (either directly or via a massive messenger).

This leads to a non-vanishing sound speed and provides pressure support against gravitational collapse.

2. Has a relatively late epoch of kinematic decoupling $(z \ll z_{\rm BBN})$.

Such that cosmological scales can be affected.

Dark Matter "Sound"

Gravitationally-sourced acoustic waves

grate out the heavy mediator and model the interaction as a four-fermion vertex controlled by a dimensionfull

possible emission of *X* particle by neutrinos in the final state of kaon and *W* decay leads to upper bounds

on the value of *g*⌫. For a vector boson, we must have

coupling constant *^G*⌫ / *^g*²

Dark Acoustic Oscillations (DAO)

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Predictions for dark matter interacting with relativistic species Cold DM Interacting DM

Dark Acoustic Oscillations (DAO) matic decoupling, and *H*⁰ is the present-day Hubble conlations (DAO) at $\overline{}$ to as "dark proton" (mass *m*p). We assume that these thang (\Box) \Box \mathbf{u}

Shape of linear matter power spectrum depends on type of interaction one can further simplify the computation by the operation by noting the operation r often themselves power laws of momentum (see e.g. α

 $F = \frac{1}{10^{12}}$ $\frac{1}{10^{1}}$ $\frac{10^{2}}{10^{2}}$ $\frac{1}{10^{-2}}$ $\frac{1}{10^{-1}}$ $\frac{10^{0}}{10^{1}}$ $\frac{10^{0}}{10^{1}}$ $\frac{10^{1}}{10^{1}}$ dependence of the DM drag opacity ˙ ⁼ (⌦DR*h*²)*an*((2 + *ⁿ*)*/*3)(1 + *^z*) $k \in h/\text{Mpc}$ τ [Mpc] $-\dot{\kappa}_{\chi}(z_{\mathrm{drag}}) = \mathcal{H}(z_{\mathrm{drag}})$ *a*
 *C*yr-Racine, Sigurdson, Zavala +, arXi^{*,*} $\frac{10^{10}}{10^{12}}$ $\frac{10^{1}}{10^{0}}$ $\frac{10^{1}}{10^{2}}$ $\frac{10^{2}}{10^{2}}$ $\frac{10^{-2}}{10^{-2}}$ $\frac{10^{-1}}{10^{1}}$ $\frac{1}{10^{1}}$ $\begin{equation} k\ [h/\mathrm{Mpc}] \end{equation}$ $\begin{equation} \tau\ [\mathrm{Mpc}] \end{equation}$ to a decoupling temperature close to *T*DR ⇠ 1 keV (assuming ⇠ = 0*.*5). have \mathcal{X} \rightarrow \mathcal{X} \rightarrow \mathcal{X} and \mathcal{Y} and \mathcal{Y} and \mathcal{Y} and \mathcal{Y}

Cyr-Racine, Sigurdson, Zavala +, arXiv:1512.05344 , ↵*^l* = 1, and *b*_n = 0. *S*_n = 0. For complete and *d*ⁿ = 0. For complete and *d*ⁿ = 0. For complete are insensitive to a *a*ⁿ = 0. Complete and *d*ⁿ $\mathcal{L} = \mathcal{L} = \mathcal$ the well-known value of 4*/3, but we see that the wire see the see here* the set α

 $n=1$ $n = 2$ $n = 3$

 $n = 4$

CMB: lensed TT Spectrum

Cosmic Microwave Background: EE Spectrum *l*

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Cosmological Constraints: marginalized \overline{f}_{int}

Interacting DM: Allowed Fraction

Future: CMB Lensing BB Spectrum $\frac{1}{2}$ \mathbf{F} α charge power spectra in the atomic DM pccu um α and α distinguished a distinguished a distinction α ture: CMB Lensing BB Specti n each scan, we apply a low-pass and n

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Future constraints: CMB lensing with CMB-S4

$\frac{1}{2}$ Evidence for dark matter interactions in cosmological precision data?

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Lesgourgues et al., arXiv:1507.04351
Francis-Yan Cyr-Racine, Harvard

and

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 $\overline{}$ *Department of Physics, Stanford University, Stanford, CA 94305*

Abstract

Lesgourgues et al., arXiv:1507.04351

Evidence for dark matter interaction? The case of H_0

Riess et al. (2016)

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Evidence for dark matter interaction? The case Planck Coll. (2015) $e₁$

Francis-Yan Cyr-Racine, Harvard **22** & 20. 68 % and 95 % and 96 % and

Evidence for dark matter interaction? The problem with σ_{8} ? Köhlinger et al. (2017)

MEASUREMENTS OF THE TEMPERATURE AND E-MODE POLARIZATION OF THE CMB FROM 500 SQUARE DEGREES OF SPTPOL DATA

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Draft version July 31, 2017

ABSTRACT

the status of the lower than the previous best upper mint, and suggests that the EE damping tail is brighter than foregrounds to at least $\ell = 4100$ with modest source masking. Finally, we find We present measurements of the *E*-mode polarization angular auto-power spectrum (*EE*) and temperature-*E*-mode cross-power spectrum (*T E*) of the cosmic microwave background (CMB) using 150 GHz data from three seasons of SPTpol observations. We now report the *EE* and *T E* power spectra over the spherical harmonic multipole range $50 < \ell \leq 8000$, and detect the first nine acoustic peaks in the *EE* spectrum with high signal-to-noise. These measurements are the most sensitive to date of the *EE* and *TE* CMB angular polarization power spectra at $\ell > 1050$ and $\ell > 1475$, respectively. The observations cover 500 deg^2 of sky, a fivefold increase in area compared to previous SPTpol power spectrum releases, leading to more than a factor of two reduction in bandpower uncertainties. The additional sky coverage increases our sensitivity to the photon-diffusion damping tail of the CMB angular power spectra, which enables tighter constraints on Λ CDM model extensions such as primordial helium content Y_p and effective number of relativistic species N_{eff} . The volume of parameter space in the Λ CDM+ \hat{Y}_p , Λ CDM+ N_{eff} , and Λ CDM+ Y_p+N_{eff} models allowed by *Planck* temperature data is reduced by a factor of 2.7, 3.2, and 2.7, respectively, with the inclusion of SPTpol data. Furthermore, after masking all sources with unpolarized flux *>* 50 mJy we place a 95% confidence upper limit on residual polarized point-source power of $D_\ell = \ell(\ell + 1)C_\ell/2\pi < 0.10 \,\mu\mathrm{K}^2$ at $\ell = 3000$. This limit is a factor of four lower than the previous best upper limit, and suggests that the *EE* damping cosmological parameter constraints consistent with those for *Planck* temperature when fitting SPTpol

data at $\ell < 1000$. However, including SPTpol data at $\ell > 1000$ results in a preference for a higher value of the expansion rate $(H_0 = 71.2 \pm 2.1 \text{ km s}^{-1} \text{Mpc}^{-1}$) and a lower value for present-day density fluctuations ($\sigma_8 = 0.77 \pm 0.02$).

Lesgourgues et al., arXiv:1507.04351 See also: Chacko et al. (2016) Ko & Tang (2017)

Krall, Cyr-Racine & Dvorkin, arXiv:1705.08894

Francis-Yan Cyr-Racine, Harvard 8/2/17 27 Krall, Cyr-Racine & Dvorkin, arXiv:1705.08894

Can also make this work with partiallyinteracting dark matter

Cyr-Racine, Randall +, in prep.

Fix the cross section such that dark matter kinetic decoupling occurs near matter-radiation equality

- Adding extra radiation to increase the present-day Hubble rate generally lead to a larger amplitude of matter fluctuations.
- Weak lensing measurements give low values of $\sigma_{\rm g}$ (systematics?).
- Dark matter interacting with a relativistic species could provide a solution.
- Question: Does this mess up small-scale structure?
- Question: What about other consequences of coupling dark matter to light particles?

\mathbf{r} *z* Gyr *mXm^C m^X* + *m^C* nafti *µXC* ⌘ \mathbf{CS} *n*e dynami is the reduced mass. Substituting Eq. (B.20) into Eq. (B.9), we obtain the opacities $\overline{\mathbf{R}}$ $\sum_{i=1}^n \sum_{i=1}^n \sum_{i=1}^n \sum_{j=1}^n \sum_{i=1}^n \sum_{i=1}^n \sum_{i=1}^n \sum_{i=1}^n \sum_{j=1}^n \sum_{i=1}^n \sum_{i$ \sum *<u>Missingtive</u> t1Ve n*gmics π : Dissipative dynamics $\boldsymbol{\mathsf{X}}$ matter. Dissipative dynamics *Har* Discin sin ² rh matter Dissinative dynamics r: Dissipative dynamics ^p2⇡↵² ˙ *XC* = *a* $\overline{\mathbf{r}}$ *µ*[∞] ∞ *m Z C C X X* $\frac{1}{2}$ is the reduced mass $\sum_{i=1}^{n}$ into $\frac{1}{2}$, we obtain the opacities of opacities of opacities opacities of opacities of $\frac{1}{2}$ p2001, p2001, p2011, p2 <u>k</u> mat 6 ^p2⇡↵² *D* p*µXC m*^z
M^z *ipative* dynan *mCT*3*/*² \vec{A} dark matter: Dissipative dynami *mXm^C <u>Discinativ</u> mXT*3*/*² *C* \cdot k matter[,] Dissinative dynamics ation. Dissipative dynamics Dissipat *mXT*3*/*² \sqrt{C} dynamics er: Dissipative dynamics \mathbb{R}^n ynar inc_S *M* + *meracting dark matter: Dissipative dynamics matter: Dis x* sipative dynamic *n*free *^C* ln⇤*,* ˙ *CX* = *a* tter: Dissipa *n*free *^X* ln⇤*.* (B.28) ^p2⇡↵² *D* p*µXC mXT*3*/*² *ting dark matter: Di* 6 *D* p*µXC* $p^2 = 2^2$ *mCT*3*/*² *Interacting dark matter: Dissipative dynamics* For the Coulomb logarithm, we follow Ref. [81] and write *C C* For the Coulomb Could Have Co. For the Coulomb data matter. \overline{a} **3**/23/23/24 **For the Coulomb Luteracting dark m** *M*^{*Interac*} *^C* ln⇤*,* ˙ *CX* = *a ive dy ^X* ln⇤*.* (B.28) dark matter: $\frac{1}{2}$ **Theracting dark matures** *nC,* (B.29) For the Coulomb Could *E Interacting dark matter: Dissipative dyremative n*free *mCT*3*/*² *C native* dynamics a UU **g** dark matte Interacting dark matter: Dissipative dynamics α datk matter: Dis ative **c n natter: Dissi** *n*free *^X* ln⇤*.* (B.28) *nte* : Dissipativ *n*free Interacting dark matter: Dissipative dynamics *<u>auv</u> dvn m^X* + *m^C*

is the reduced mass . Substituting Eq. (B.20) into Eq. (B.20) into Eq. (B.20) into Eq. (B.9), we obtain the opacities of \mathbb{R} <u>I</u>IOWING energy diss *n*₂ *n*₂ *c*₁ *c*₁ *c*₁ *c*₁ *c*₂ *c*₁ *c*₂ *c*₂ *c*₂ *c*₂ *c*₂ *c*₂ *c*₂ matter is heated up to the virial ² rgy dissipat **i** *** ******* $\frac{2}{\pi}$ \mathbf{c} is nealed up ibly allowing energy dissipation: ded up to th *n*free *^C* ln⇤*,* ˙ *CX* = *a* $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ s heated $\frac{1}{2}$ p₂ $\frac{1}{2}$ $\frac{1}{$ *m*
M^{*X*} *M*₂ *n*atter is heated up to the virial α **b**² α *D***²** α **</sub>²** α **²** β *mXT*3*/*² *n* to the virial $\mathbf x$ heat *Fia*, the dark matter is heated up to the virial llowing en ˙ *XC* = *a n*atter *^C* ln⇤*,* ˙ *CX* = *a the dark matter is heated up to the virial* re, possibly allowing energy dissipation: but is heated *mXT*3*/*² *C* $r_{sination}$; *m^X* + *m^C* ing dark matter is neated up to the virial *n*g energy For the Coulomb logarithm, we follow Ref. [81] and write ˙ *XC* = *a F* ark matter is heated up to the virial bly allowing energy dissipation: p
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p*use in* 21 *m*
M^{*X*} *M C* • As halos form, the dark matter is heated up to the virial Ing energy dissipation. *r*ev dissipa *n*_{*i*} α *C C* α *C* $\$ temperature, possibly remperature, possibly allow hed rk matter is *n As* halos form, the dark matter is heated up to the virial \mathcal{L} temperature, possibly allowing energy dissipat *n*_{*n*} *n***_{***f***} ***c c*_{*n*} *c c*_{*n*} *c c c***_{***n***}** *c* *****c c***_{***n***}** *c***_{***n***}** *c c c c c c c c c c c c c c c c c c* 6 ^p2⇡↵² *D* p*µXC n*, the dark matter is heated up to the virial *X* \mathbf{Z} is a set \mathbf{Z} $\frac{1}{3}$ 1911 111
Iv 21101 ergy dissipation: ratur ϵ , possibly a *ng* energy dissipation: \sim for \sim m, the dark *n*ⁱs hooted up to the virial $-$ ten alos form, the da perature, po *n*₂ allowing energy dissination: For the dark matter is heated allowing energy dark mat *C* \overline{A} c halos form the dark matter is heated up to the virig $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$ and write $\frac{1}{\sqrt{2}}$ and write temperature, possibly allowing energy dissipation: **13 maros form, u
emnerature, nos** $\mathcal{B}(D)$ allowing energy dissipation: *n*free *COMPANY COMPANY COMPONY CONSIDIV* the dark matter is heat *n* Wing en *n* long and the usual contract the end in the loss in the value of the mean of the value of the usual contract of the value of the ρ ossibly allo *n*_c is naros form, are dark matter is neated up to the virial
temperature possibly allowing energy dissipation. • As halos form, the dark matter is heated up to the virial **C** ^{*C*} ^{*C* ^{*CX*} = *a*^{*x*} = *a*^{*x*}} temperature, possibly allowing energy dissipation: **C** ln i *C* ln i *CX* = *a*² = *a*² = *a*² = *a*² = *a*² = a² = a² = a²

C dark matter: The model matter fluctuations with this model. In section 7, we discuss the late-time astrophysical problem as the late-
In section 7, we discuss the late-time as the late-time astrophysical problem as the late-time astrophysical p arXiv:1702.05482

- Ingredients: $\mathcal C$
- A heavy $($ \sim 10 TeV) *X* particle (and its anti-particle)
- A light (~1 MeV) *C* particle $\overline{}$
- Λ megalogg $I(I)$ dork photon $f(x)$ from the lagrangian is proved. • A massless *U(1)* dark photon 4⇡

$$
\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \bar{X}\rlap{\,/}DX + \bar{C}\rlap{\,/}DC - m_X\bar{X}X - m_C\bar{C}C
$$

Key parameters:

• Key parameters:
$$
\alpha_D, m_X, m_C, f_{(XC)}
$$

 $\xi_0 \equiv (T_D/T_{CMB})|_{z=0}$

XC dark matter: Dissipative dynamics redshift would both make dissipation more ecient. As dark matter and baryons fall in to that the se choices are quite conservative since increasing the halo density or the benchmark \mathbf{r} redshift would both matter. Dissipative dynamics

- The main mechanisms for energy dissipation are Bremsstrahlung, inverse Compton scattering, collisional excitation and recombination, and finally, molecular excitation and recombination, and finally, molecular cooling. and recombination, and finally, molecular wohng.
a¹ α ¹/(2^{*n*}/²) ¹¹ is the mean molecular weight of the data plasma. *G*
 **Bremsstrahlung, inverse Compton scattering, collision

excitation and recombination and finally molecular** *s*
citation and recombination, and finally, molecular keV*,* (7.1) where *^µ* ⌘ ⇢DM*/*(2*nXmX*) ⇡ (1 +*f*(*XC*))¹ is the mean molecular weight of the dark plasma.
- Since the rate of collisional processes are very difficult to compute, we focus on Bremsstrahlung and inverse Compton: • Since the rate of collisional processes are very difficult to **S** Since the rate of collisional processes are very difficult to SHICE THE LATE OF CONSIDIAL PROCESSES ARE VERY CHARGIN TO compute, we focus on Dichissicaliting and in $\sqrt{2}$

$$
\Pi_{\text{Brem}} = \frac{16\alpha_D^3 \sqrt{2\pi T_C}}{(3m_C)^{3/2}} n_C^{\text{free}} (n_X^{\text{free}} + n_{\bar{X}}),
$$

$$
\Pi_{\rm Compt} = \frac{64\pi^3\alpha_D^2T_D^4}{135m_C^3}n_C^{\rm free}T_C.
$$

XC dark matter: Dissipative dynamics **D**issipa 135*m*³ *n*free *^C TC.* (7.3)

• We define an approximate cooling timescale: shed an *O*(1) fraction of their kinetic energy through radiative processes

$$
t_{\rm cool,C}\equiv\left(\frac{2(\Pi_{\rm Brem}+\Pi_{\rm Compt})}{3n_C^{\rm free}T_C}\right)^{-1}
$$

• At a minimum, this timescale must be shorter than the age of the Universe: For this radiative cooling of the *C* particles to have a significant impact on the structure of a diminimum, this unicscale must be shorter than the age of the Universe:

$$
t_{{\rm cool},C} < t_0
$$

As the *C* particles are dissipating their kinetic energy, they can scatter o↵ *X* and *X*¯

Tension between structure formation and cooling

- Structure formation favors a heavier *C* particle.
- On the other hand, dissipative dynamics requires *C* to be quite light.
- Dark disk formation might be possible but it is certainly contrived.

Agrawal, Cyr-Racine, Randall, Scholtz (2017)

Taking stock: Interacting dark matter and acoustics relics

- Cosmological measurements (CMB, large-scale structure, etc.) still have something to say about new interactions in the dark matter sector.
- Interacting dark matter can leave distinct imprints on observables.
- Are there hints in current data? Systematics?
- Important links to late-time effects (self-interaction, dissipation) See ETHOS work.

Probing SIDM via substructure lensing

Galaxy-scale Gravitational Lenses

Credits: Leonidas Moustakas

Direct Substructure Detection

• "Gravitational Imaging" of Perturbed Einstein Rings

 \mathbf{C} and detection of a dark-matter dominated satellite in the gravitational lens system of a data lens system. In the gravitatio Vegetti et al. *Nature*, (2012)

Direct Substructure Detection Figure 5. Initial subhalo search using ALMA Science Verification observations of SDP.81. Depicted are maps of linearized D from Equation (16) showing twice the difference in log marginalized posterior probability density between a smooth model without substructure and a model with a subhalo of mass M = 108.6Me, as a

• "Gravitational Imaging" of Perturbed Einstein Rings rovitotional Imaging". of Derturbed Einstein Dings t a l

Figure 6. Top left: the sky emission model in band 6 for the best-fit smooth lens parameters for the SDP.81 data. Top middle: the same for the perturbed model. Top right: the difference between the two models. The bottom panels show the same for band 7. The bright feature in the difference plots is mainly caused by the astrometric anomaly of the arc. In each row, the images have been scaled to the peak flux of the smooth model.

Hezaveh et al., (2016)

Direct Substructure Detection

• Constraints on the subhalo mass function

Hezaveh et al., (2016) (see also Vegetti et al. (2014) , Li et al. (2016)) differential number density of subhalos around SDP.81 derived using the non-

Substructure lensing: 2-point function

• Instead of describing lensing perturbations in terms of individual subhalo, look at the correlation function of the projected density field.

Substructure lensing: 2-point function

• Philosophy: in a CDM halo, many subhalos are encountered along any given line of sight.

Vogelsberger, Zavala, Cyr-Racine+, arXiv:1512.05349 F_{C} ind dengity paramatic projections F_{C} is the suppression of substructure, relative to the CDM models. The contracture to the CDM models. The C

10 Galaxy Lenses: Typical Scale

Galaxy-scale lenses probe the very inner part of their dark matter halo

Substructure lensing: 2-point function

- Philosophy: in a CDM halo, many subhalos are encountered along any given line of sight.
- By the central limit theorem, the fluctuations in the projected density field ***should*** be approximately Gaussian.
- My philosophy: even if the convergence field is not entirely Gaussian, looking at the substructure power spectrum is interesting.
- Key Question:

What will we learn about low-mass subhalos from measuring the substructure convergence power spectrum?

Substructure Convergence Power $Spectrum$ Here, *G* is the gravitational constant and *c* the speed of light. \overline{D} ou difficult \overline{D} ou difficult \overline{D} the Poisson equation equation equation \overline{D} (1707.04500) Substructure Convergence Power To obtain a general expression for the substructure \sim power spectrum ρ is small. $1-\frac{1}{\sqrt{2}}$ ou actual contrassement on the lens

Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590 Diaz Rivero, Cyr-Racine, & Dvorkin, arxiv:1/07.04590 Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

• Goal: Use the halo model to compute from first principle the substructure convergence power spectrum. $\overline{1}$ of the substructure convergence field substructure conver al: Use the halo model to compute from first princip e the halo model to compute from first principle

$$
\kappa_{\mathrm{sub}}(\mathbf{r}) = \sum_{i=1}^{N_{\mathrm{sub}}} \kappa_i(\mathbf{r} - \mathbf{r}_i, m_i, \mathbf{q}_i),
$$

$$
\xi_{\rm sub}(\mathbf{r}) \equiv \frac{1}{A} \int d^2 \mathbf{s} \int \prod_i d^2 \mathbf{r}_i \mathcal{P}_{\rm r}(\mathbf{r}_i)
$$

$$
\times (\kappa_{\rm sub}(\mathbf{s}) - \bar{\kappa}_{\rm sub})(\kappa_{\rm sub}(\mathbf{s} + \mathbf{r}) - \bar{\kappa}_{\rm sub})
$$

= ¯*n*sub*|*˜*i*(k)*|*

$$
P_{\rm sub}(\mathbf{k}) = \int d^2 \mathbf{r} \, e^{-i\mathbf{k} \cdot \mathbf{r}} \xi_{\rm sub}(\mathbf{r})
$$

^A⇠sub(r) = ^X

*^d*²^s *^d*²r*ii*(^s ^r*i*)*i*(^s ⁺ ^r ^r*i*)*P*r(r*i*)

2

Substructure Convergence Power Spectrum where *J*0(*x*) is the 0th order Bessel function. DUCCULUIL
Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590 P_{max} arror, cyr alleme, α D roman, latenties. We can be considered.

• As in the standard halo model, there are two distinct contributions to the overall power spectrum:

$$
P_{\text{sub}}(k) = P_{1\text{sh}}(k) + P_{2\text{sh}}(k)
$$

1-subhalo term
2-subhalo term 2-subhalo term

$$
P_{1sh}(k) = \frac{(2\pi)^2 \bar{\kappa}_{sub}}{\langle m \rangle \Sigma_{\rm crit}} \int dm \, d\mathbf{q} \, m^2 \, \mathcal{P}_{\rm m}(m) \, \mathcal{P}_{\rm q}(\mathbf{q}|m) \qquad P_{2sh}(k) = \frac{(2\pi)^2 \bar{\kappa}_{sub}^2}{\langle m \rangle^2} P_{\rm ss}(k) \left[\int dm \, d\mathbf{q} \, m \, \mathcal{P}_{\rm m}(m) \, \mathcal{P}_{\rm q}(\mathbf{q}|m) \right] \times \left[\int dr \, r J_0(k \, r) \hat{\kappa}(r, \mathbf{q}) \right]^2 \times \int dr \, r J_0(k \, r) \hat{\kappa}(r, \mathbf{q}) \left[\int m \, d\mathbf{q} \, m \, \mathcal{P}_{\rm m}(m) \, \mathcal{P}_{\rm q}(\mathbf{q}|m) \right] \tag{29}
$$

(the subscript *i* has been dropped since it is now super-

fects on lensing observables such as the lensing potential,

*dr rJ*0(*k r*)ˆ(*r,* q)

The amplitude of the 1-subhalo term is approximately

Substructure Power Spectrum: tNFW

As a warm up, let's consider a population of truncated \bullet NFW subhalos.

Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

Substructure Power Spectrum: tNFW tNFW subhalos (solid blue; same fiducial model as in Fig. 3) and the substructure Power Spe (dotted-dashed gray) and *k*scale (solid gray), as well as \mathcal{L} die regel \mathcal{L} and \mathcal{L} matter scenarios: \mathcal{L} WHICH WE W

• The power spectrum depends mostly on three quantities: U sing the CDM scenario as our baseline, we found that \mathcal{U}

Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590 *k* . *k*

Substructure Power Spectrum: truncated cored profile

Let's now consider an SIDM-inspired truncated cored \bullet profile:

Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

Substructure Power Spectrum: truncated cored profile

Key probe of the inner subhalo density profile: asymptotic \bullet slope.

Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

Measuring the substructure power spectrum: cartoon

Measuring the substructure power spectrum: cartoon

Measuring the substructure power spectrum: cartoon

• There is definitely signal in the lensing residual!

Interacting dark matter and substructure: Conclusions

- The n-point functions of the projected density field allow for a more general description of dark matter substructure.
- For CDM, 2-point function should dominate, but other npoint function are also present.
- Within the halo model, the substructure power spectrum mostly depends on the abundance of substructure, their truncation, and their inner density profile.
- In principle, it appears possible to measure the substructure convergence power spectrum.
- Significant challenges for lens and source modeling.