Structure formation with SIDM: Theory

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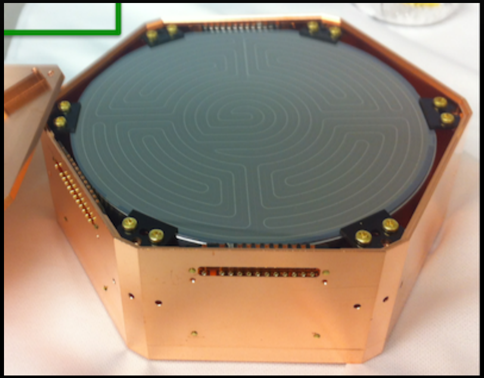
Chuck Keeton, Leonidas Moustakas
Kris Sigurdson, Jesús Zavala, Mark Vogelsberger,
Torsten Bringmann, Christoph Pfrommer

In dark matter science, hope for the best…

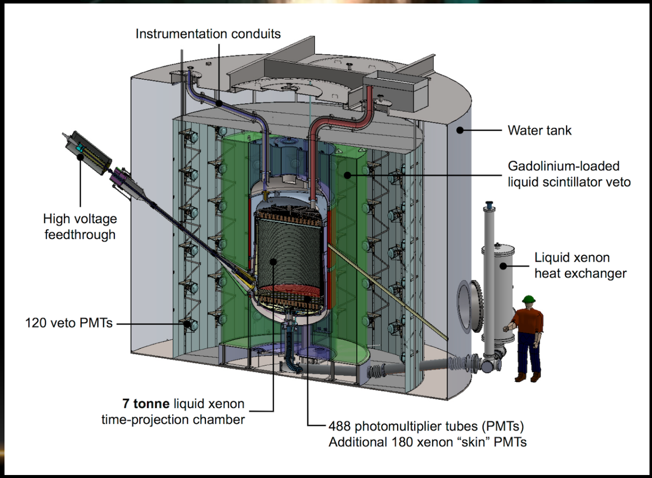
- Let’s hope we can find dark matter in the lab…



Xe

XENON

Dark Matter Project

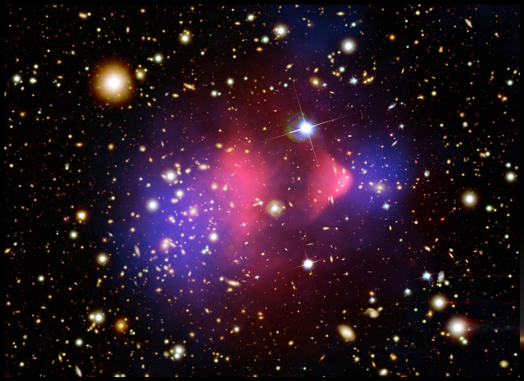


…but prepare for the worst!

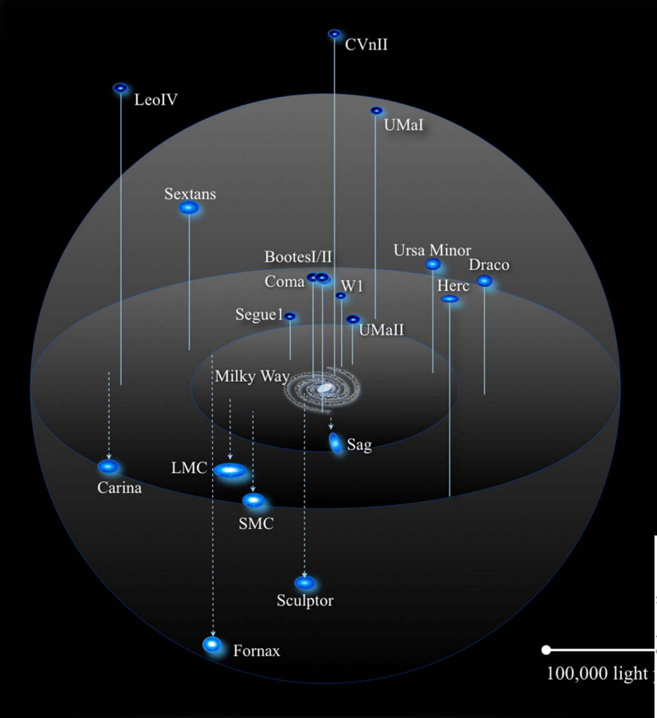
- Gravitational signatures might be all we can observe!

Gravitational Lensing

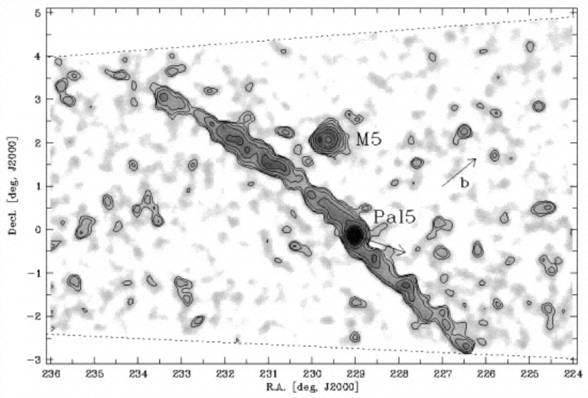
Merging Clusters



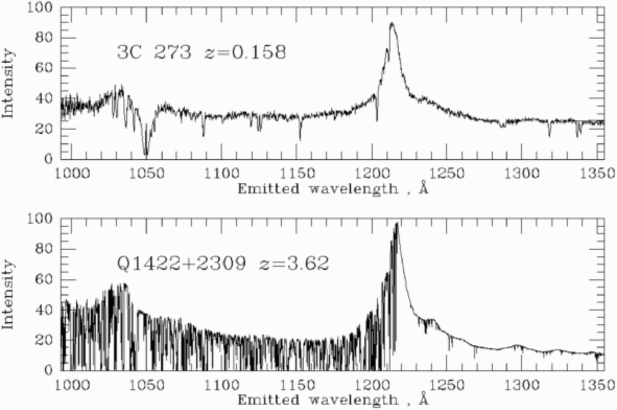
Dwarf galaxies



Stellar Streams

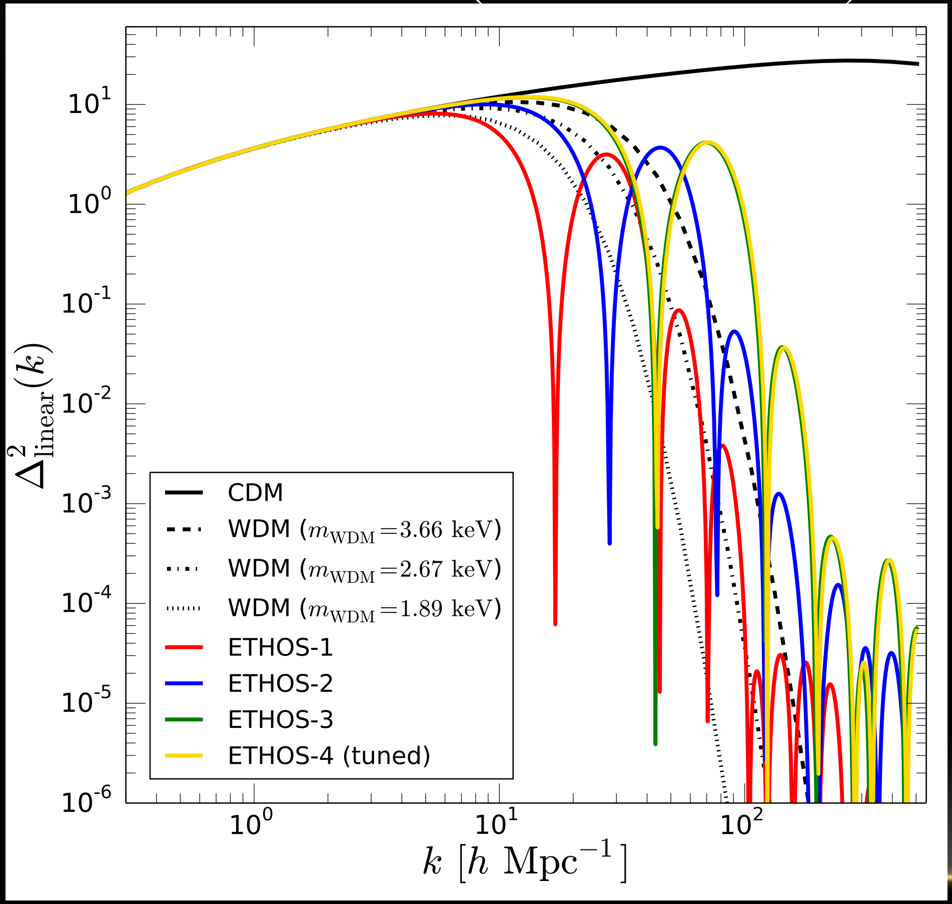


Lyman-alpha forest

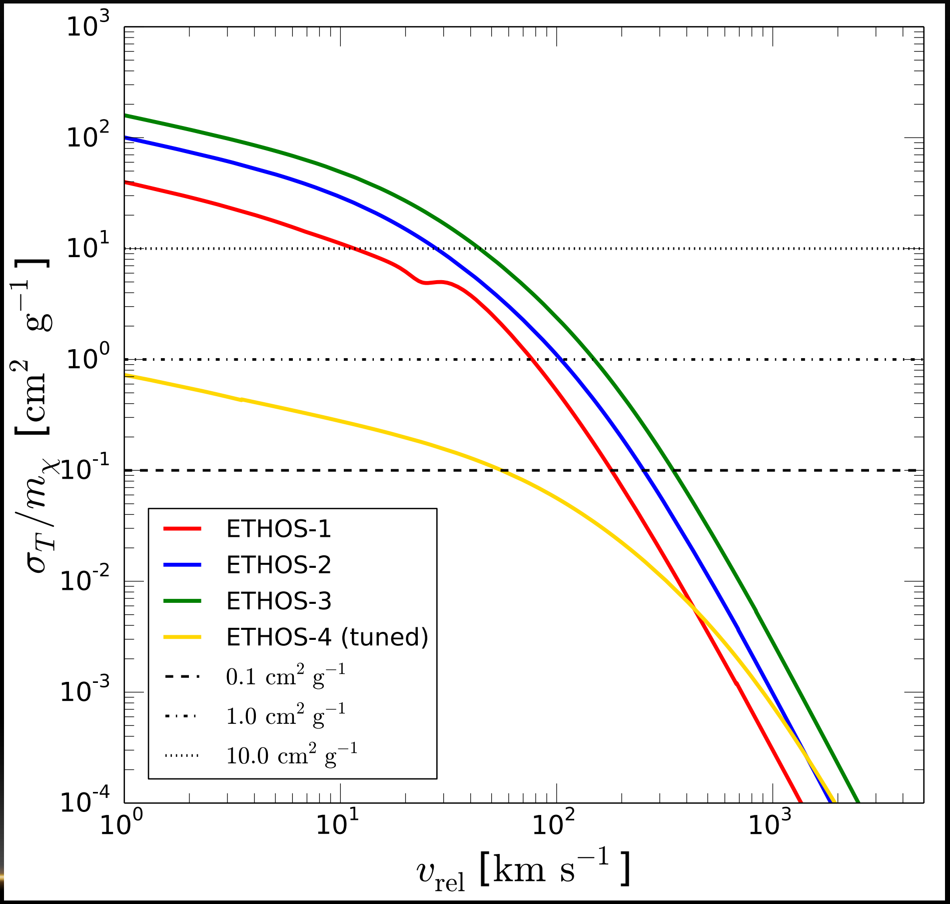


The many faces of interacting dark matter…

1) Interactions affecting the DM transfer function (initial conditions)



2) Interaction affecting the dynamics of structure formation (self-interaction)



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

- DM interactions will in general be mediated by a "new" force carrier.

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

- Two interesting cases for acoustic relics:

  1) The mediator is light enough to be relativistic until late cosmological times.

  2) The mediator is massive but also couples to a relativistic species (such as neutrinos) until late cosmological times.

- As long as the "dark radiation to dark matter" ratio is larger than unity => large sound speed ($c^2 \sim 1/3$).

Carlson et al. (1992)
Boehm, Fayet & Schaeffer (2001)
Boehm et al. (2002)
Boehm & Schaeffer (2005)

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

Self-interacting DM and Cosmology: General Scenario

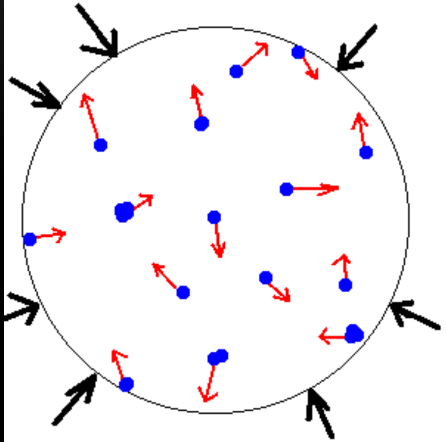
- We consider a model in which at least a fraction of the DM

  1. Couples to light, relativistic particles (either directly or via a massive messenger).

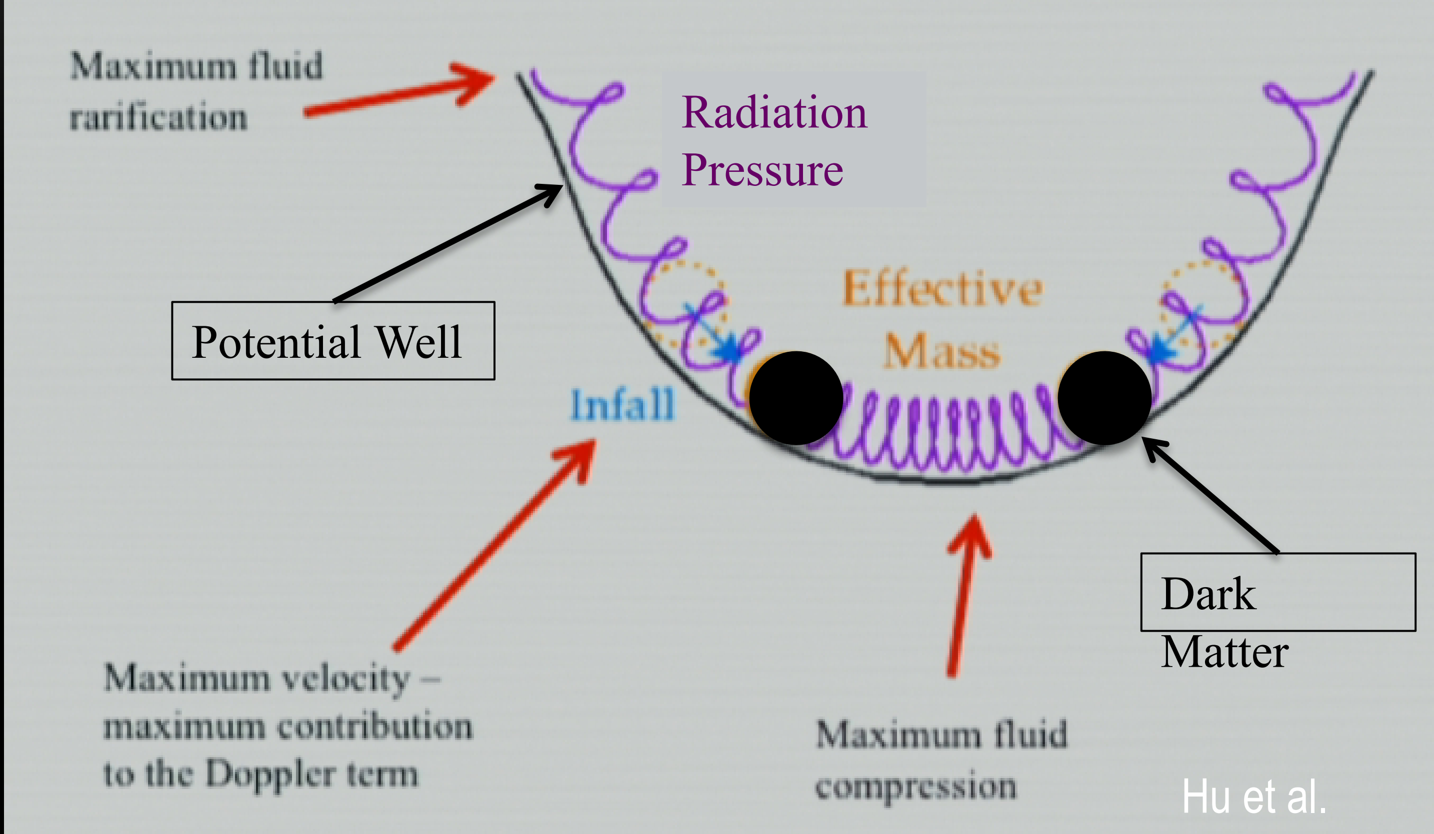
     This leads to a non-vanishing sound speed and provides pressure support against gravitational collapse.

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

     Such that cosmological scales can be affected.

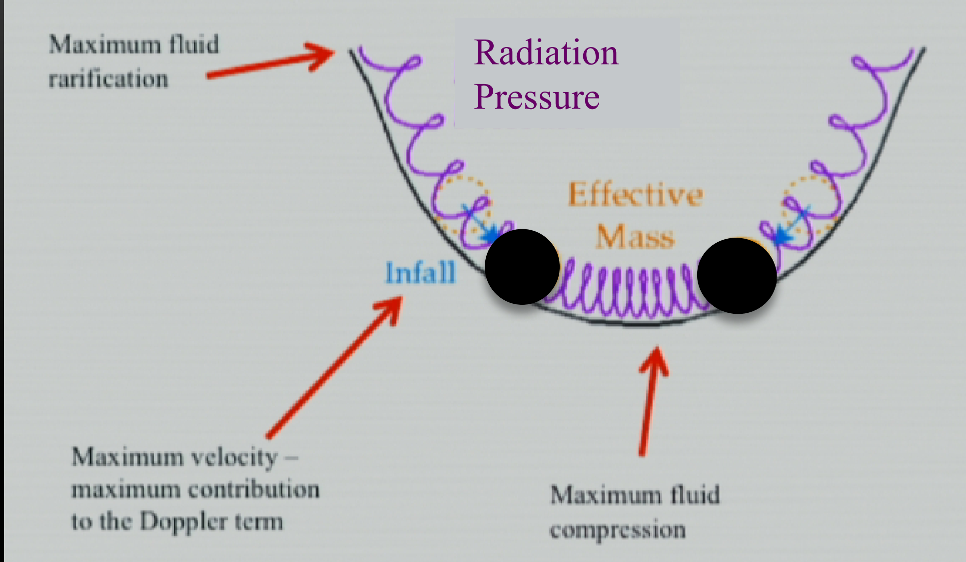


Dark Matter "Sound"



Hu et al.

Gravitationally-sourced acoustic waves



Hu et al.

gravitational potentials

Pressure term

$$\dot{\delta}_{\rm DM} = 3\dot{\phi} - \theta_{\rm DM}$$

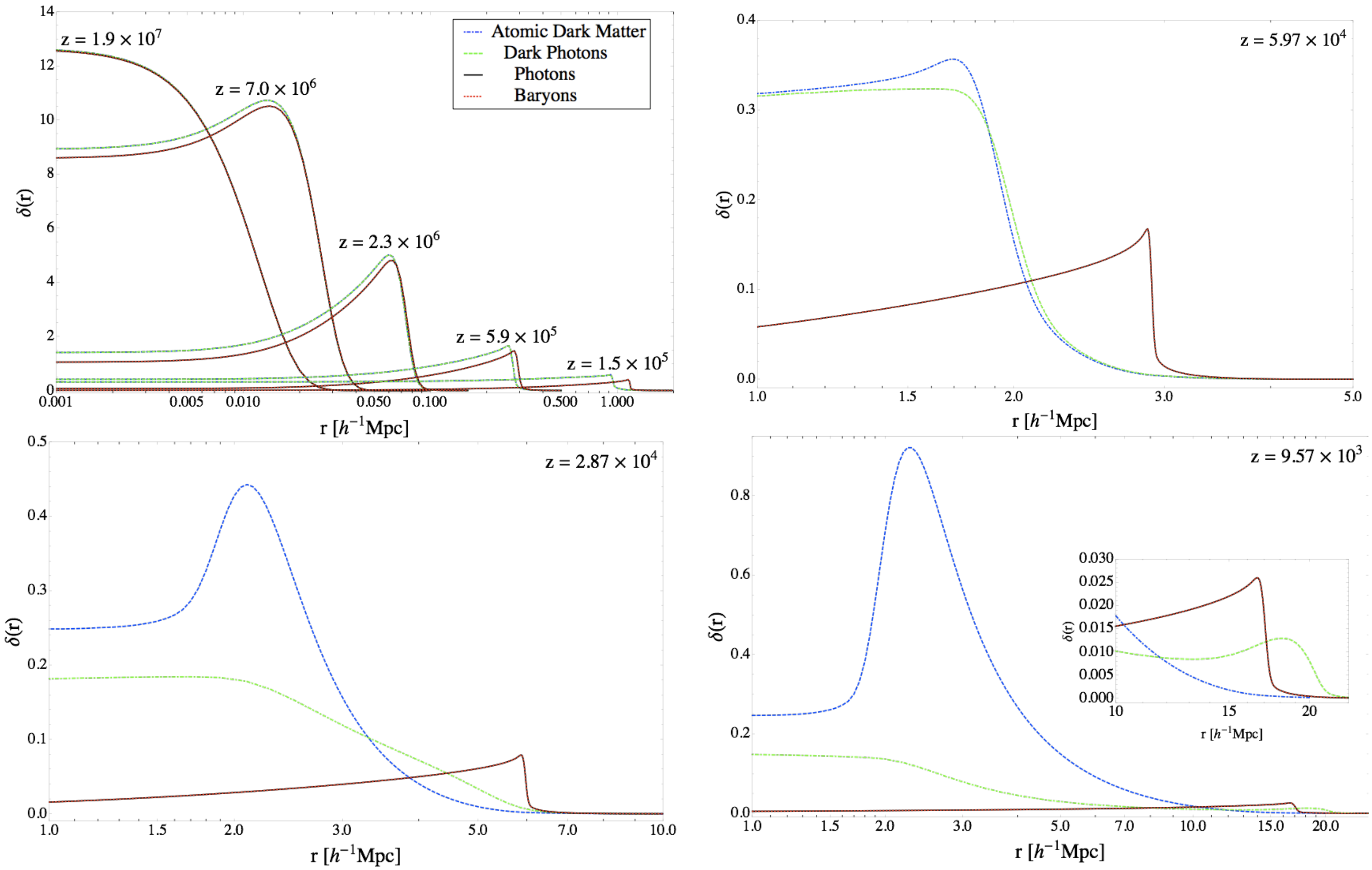
$$\dot{\theta}_{\rm DM} + \frac{\dot{a}}{a}\theta_{\rm DM} - c^2_{\rm DM}k^2\delta_{\rm DM} - k^2\psi = \Gamma_{\rm DM}(\theta_{\rm REL} - \theta_{\rm DM})$$

Sound speed

Collision term

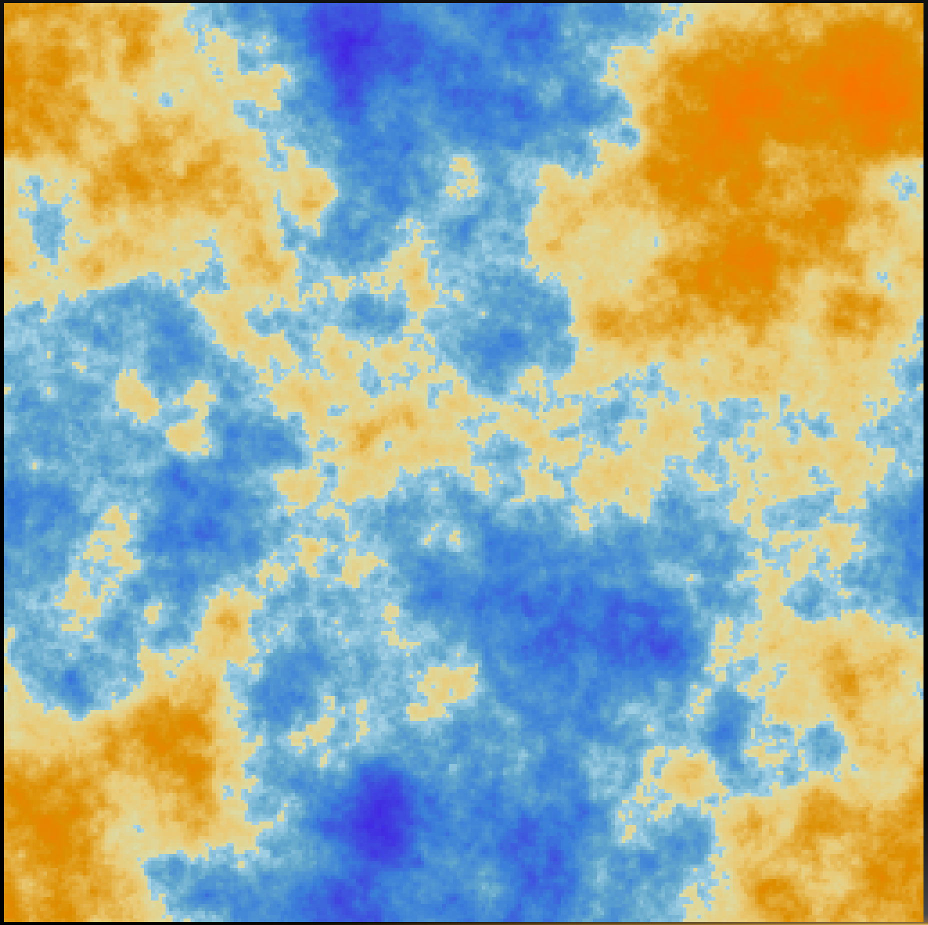
Momentum transfer rate

Dark Acoustic Oscillations (DAO)

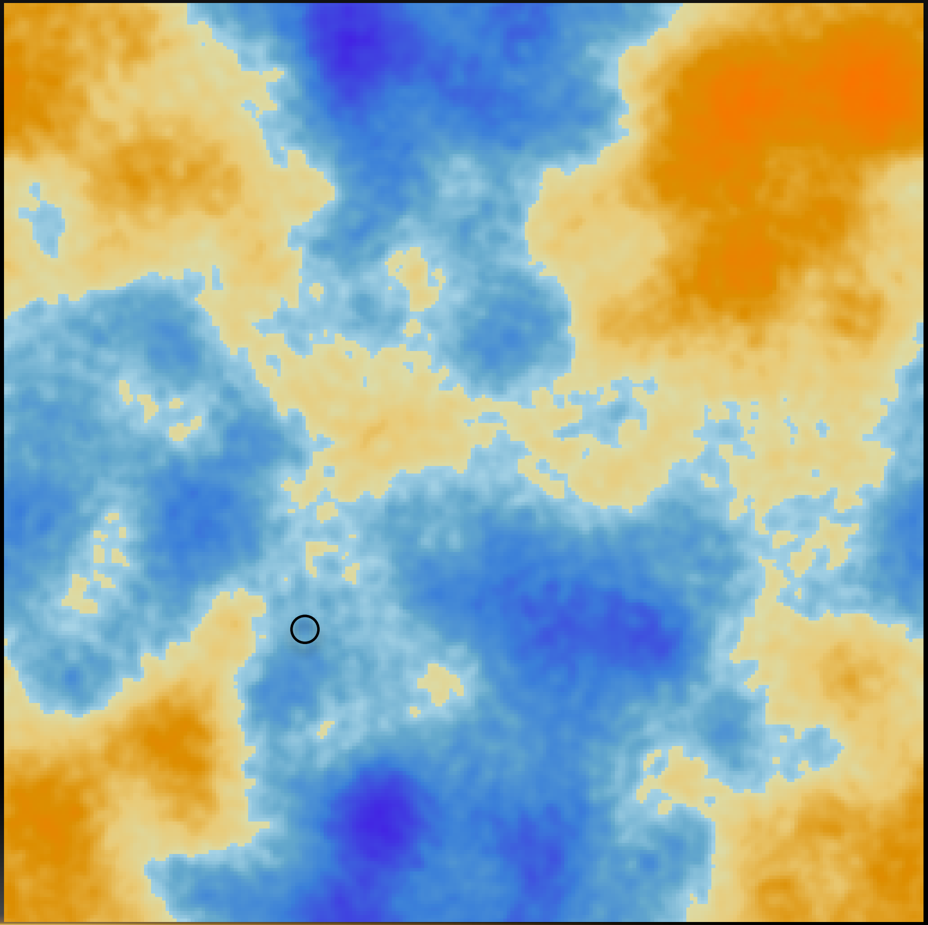


Predictions for dark matter interacting with relativistic species

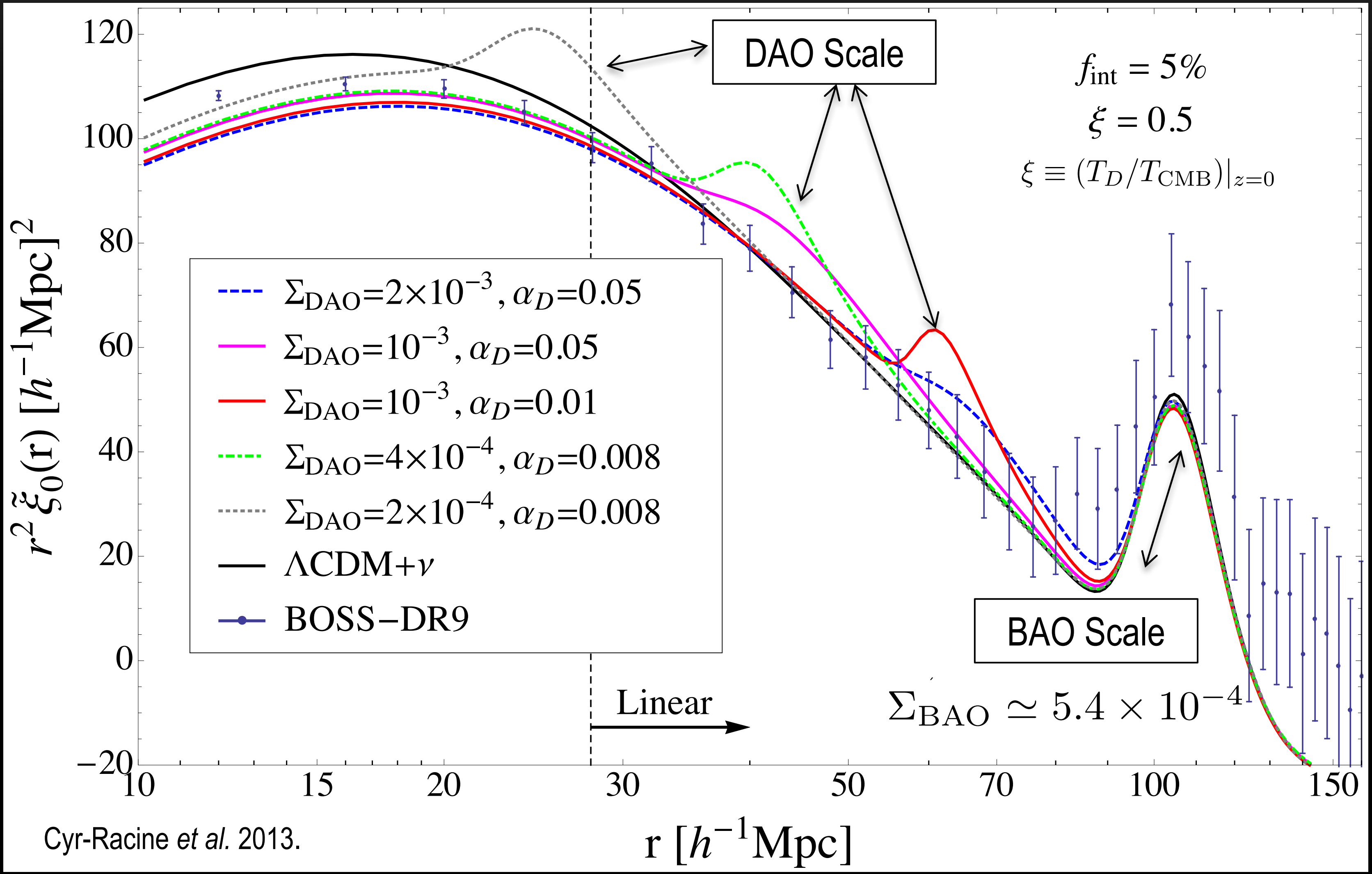
Cold DM



Interacting DM



Dark Acoustic Oscillations (DAO)

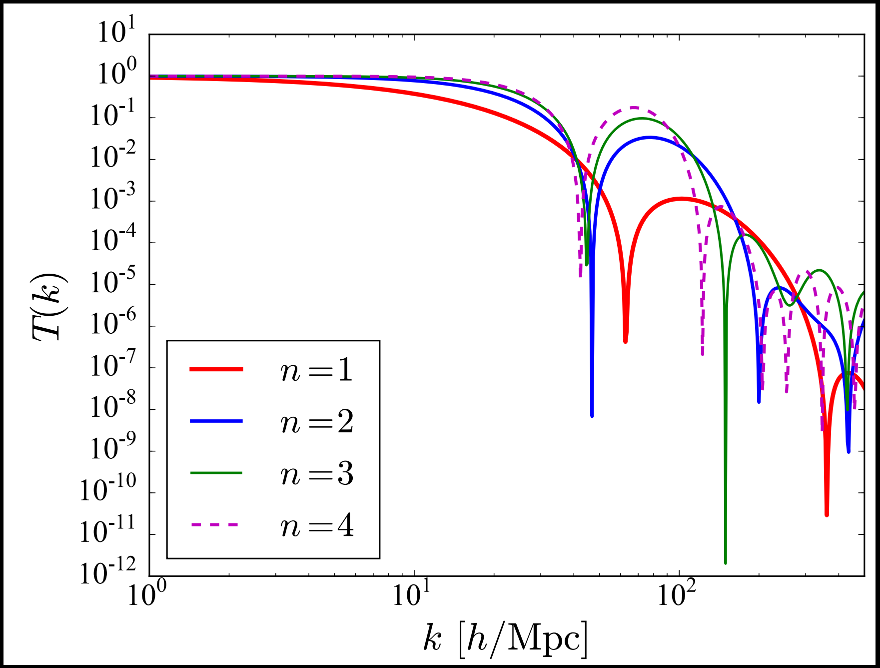


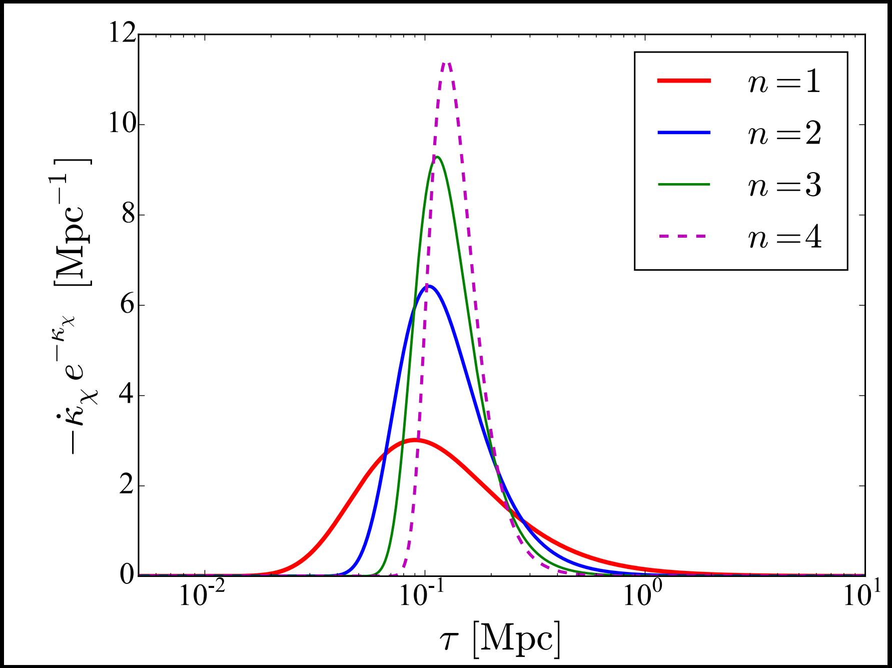
Cyr-Racine *et al.* 2013.

Shape of linear matter power spectrum depends on type of interaction

DM opacity:

$$\dot{\kappa}_\chi = -(\Omega_{\rm DR}h^2)x_\chi(z)\sum_n \left(\frac{2+n}{3}\right) a_n \frac{(1+z)^{n+1}}{(1+z_{\rm D})^n}$$

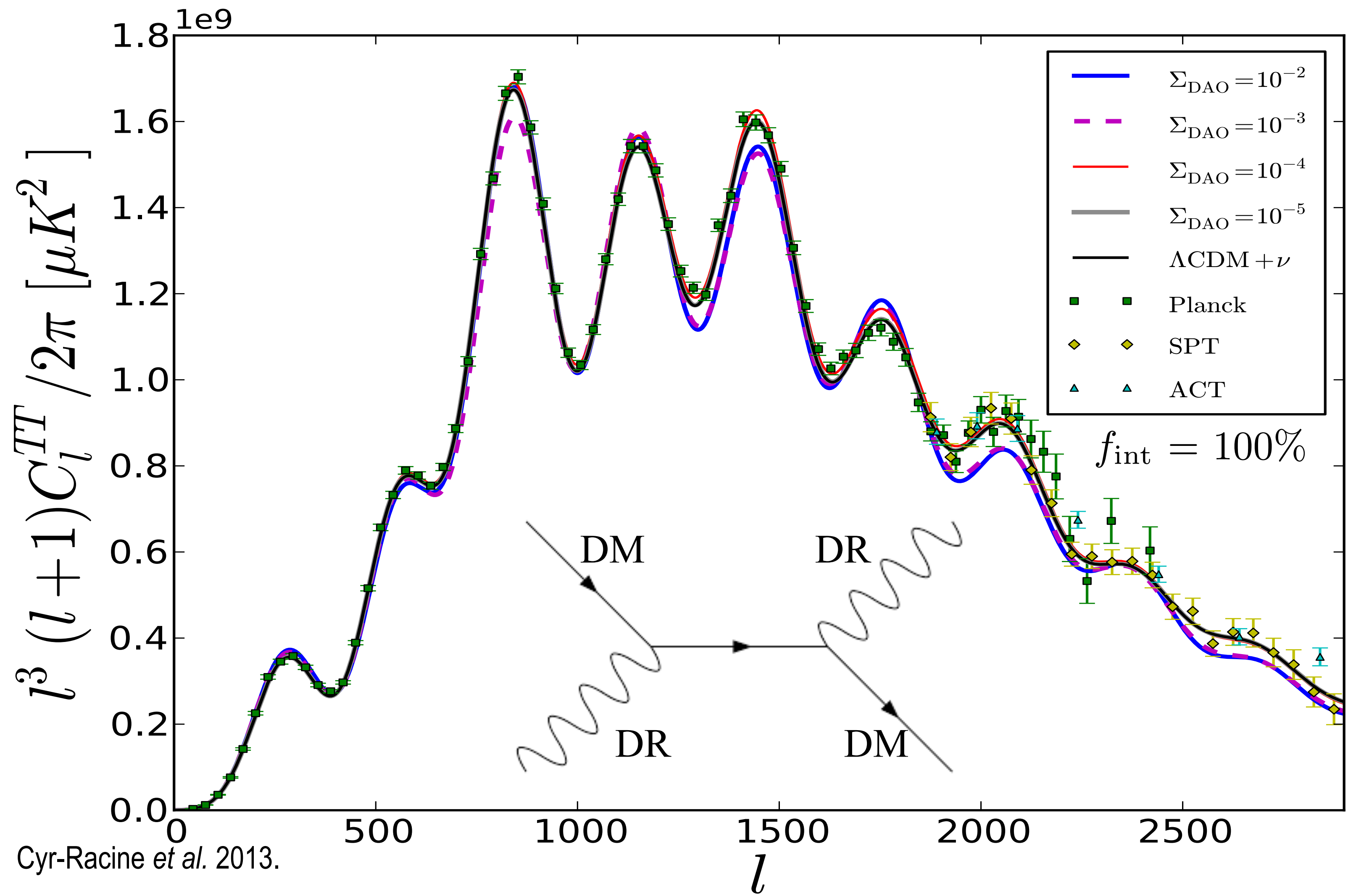




$$-\dot{\kappa}_\chi(z_{\rm drag}) = \mathcal{H}(z_{\rm drag})$$

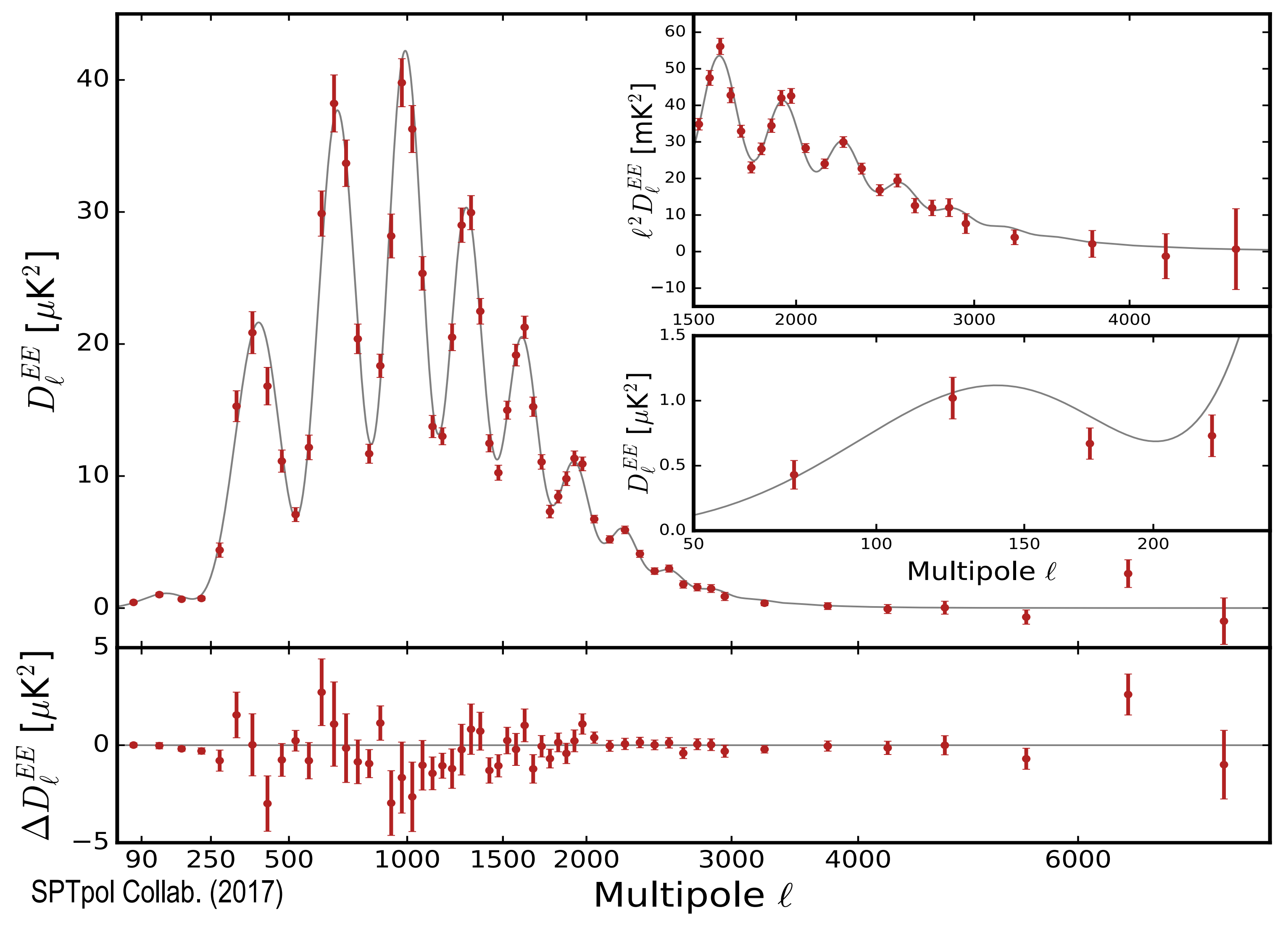
Cyr-Racine, Sigurdson, Zavala +, arXiv:1512.05344

CMB: lensed TT Spectrum



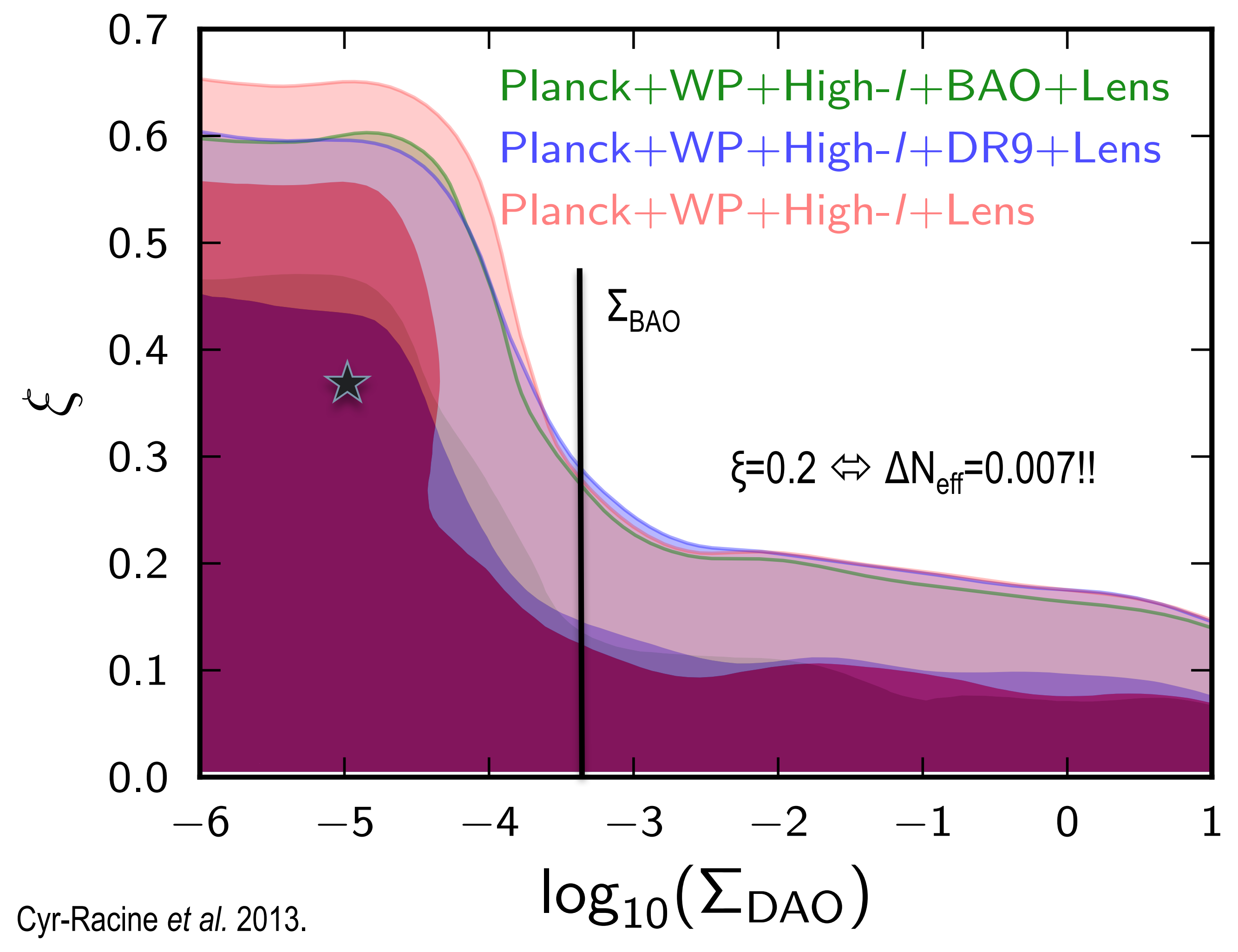
Cyr-Racine *et al.* 2013.

Cosmic Microwave Background: EE Spectrum



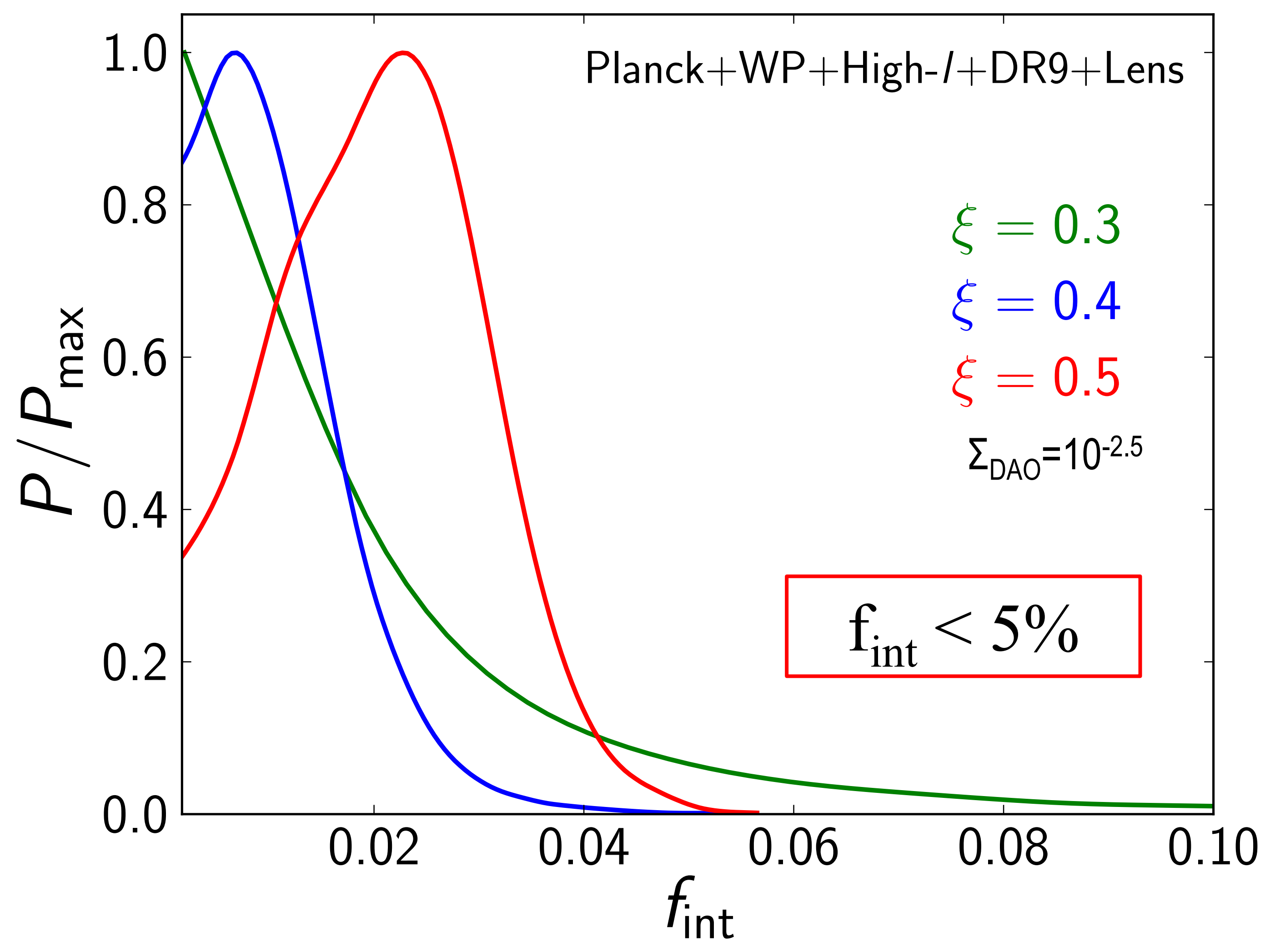
SPTpol Collab. (2017)

Cosmological Constraints: marginalized f_{int}

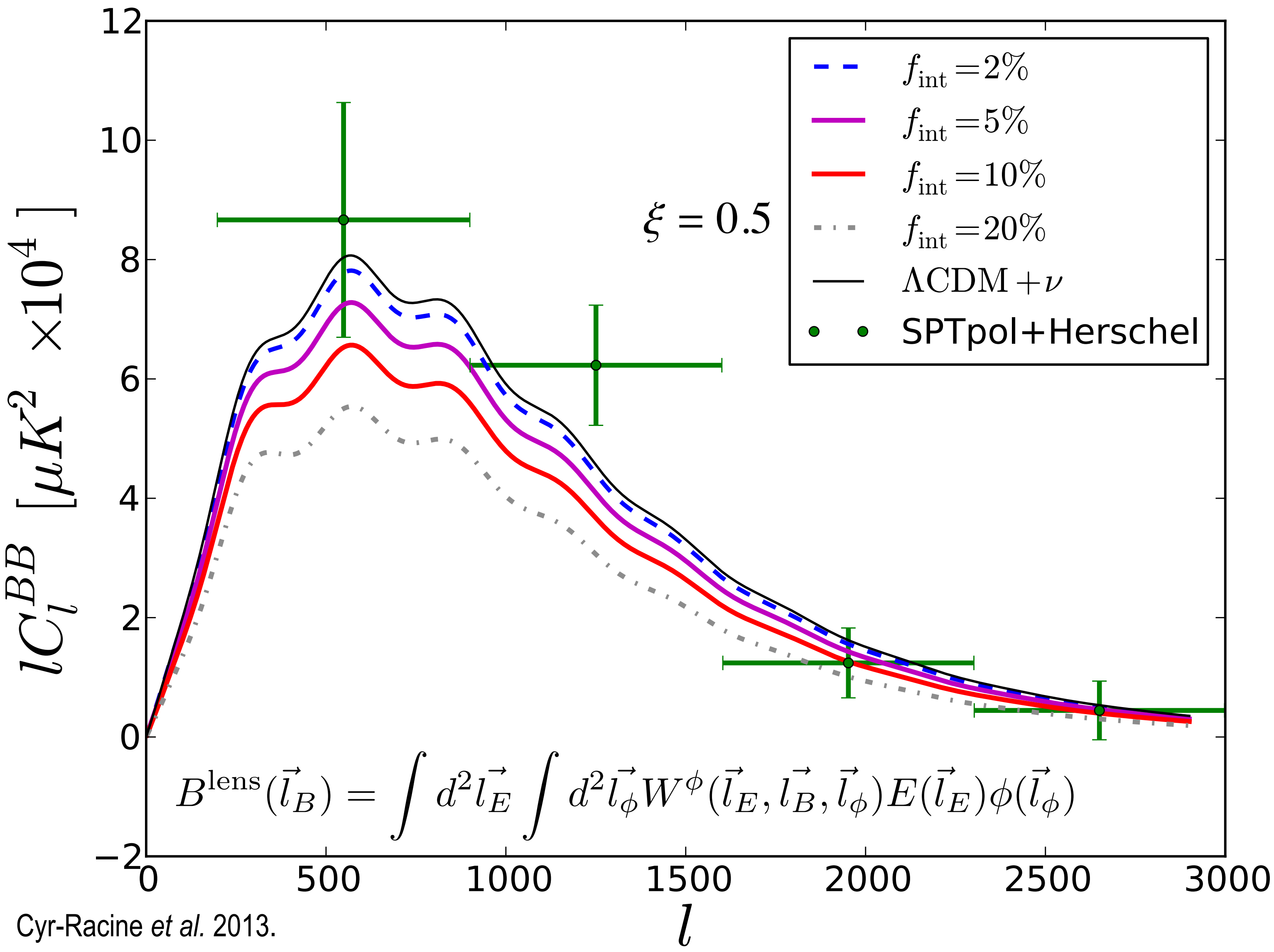


Cyr-Racine *et al.* 2013.

Interacting DM: Allowed Fraction



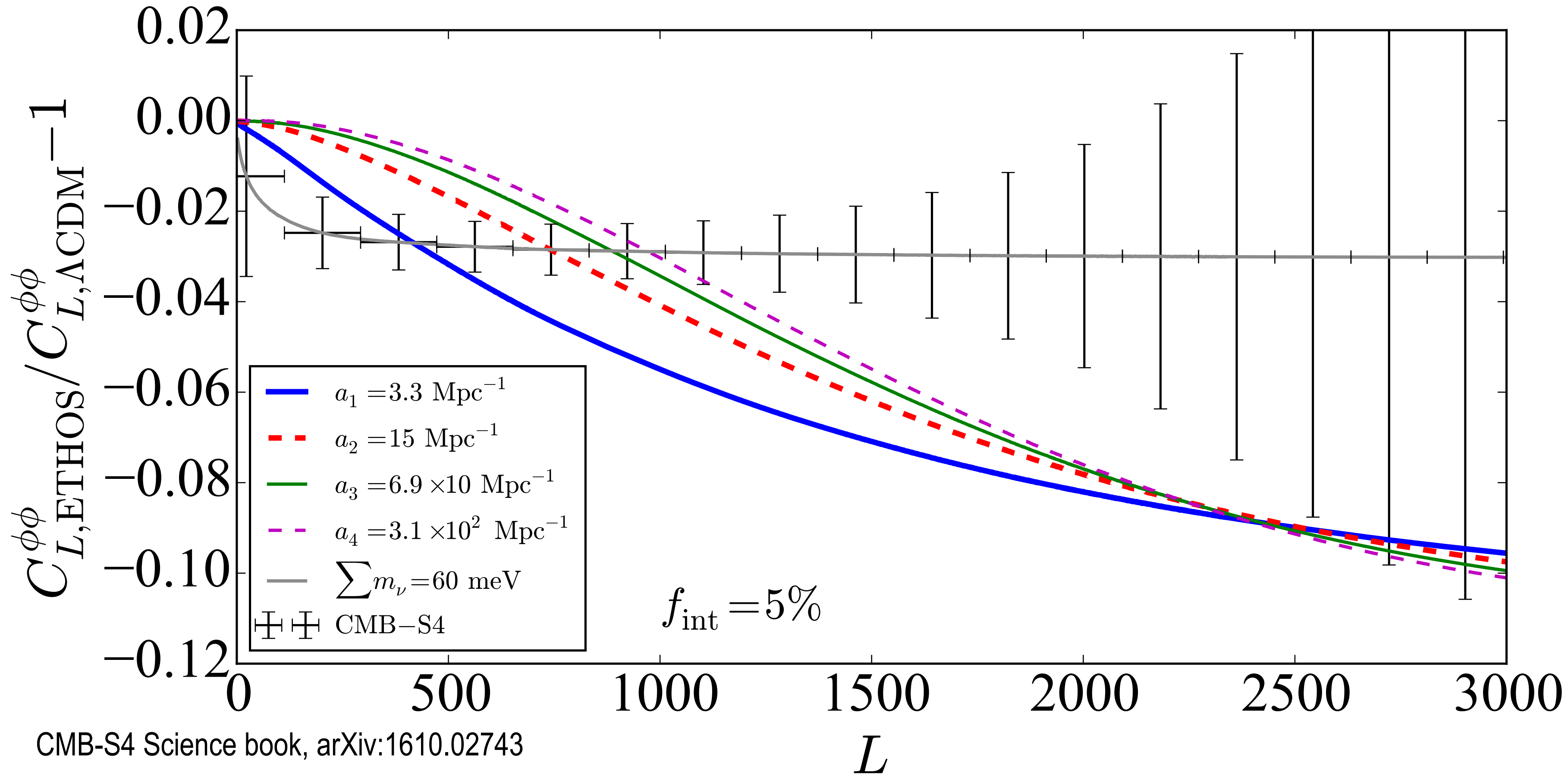
Future: CMB Lensing BB Spectrum



$$B^{\rm lens}(\vec{l}_B) = \int d^2\vec{l}_E \int d^2\vec{l}_\phi W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi)E(\vec{l}_E)\phi(\vec{l}_\phi)$$

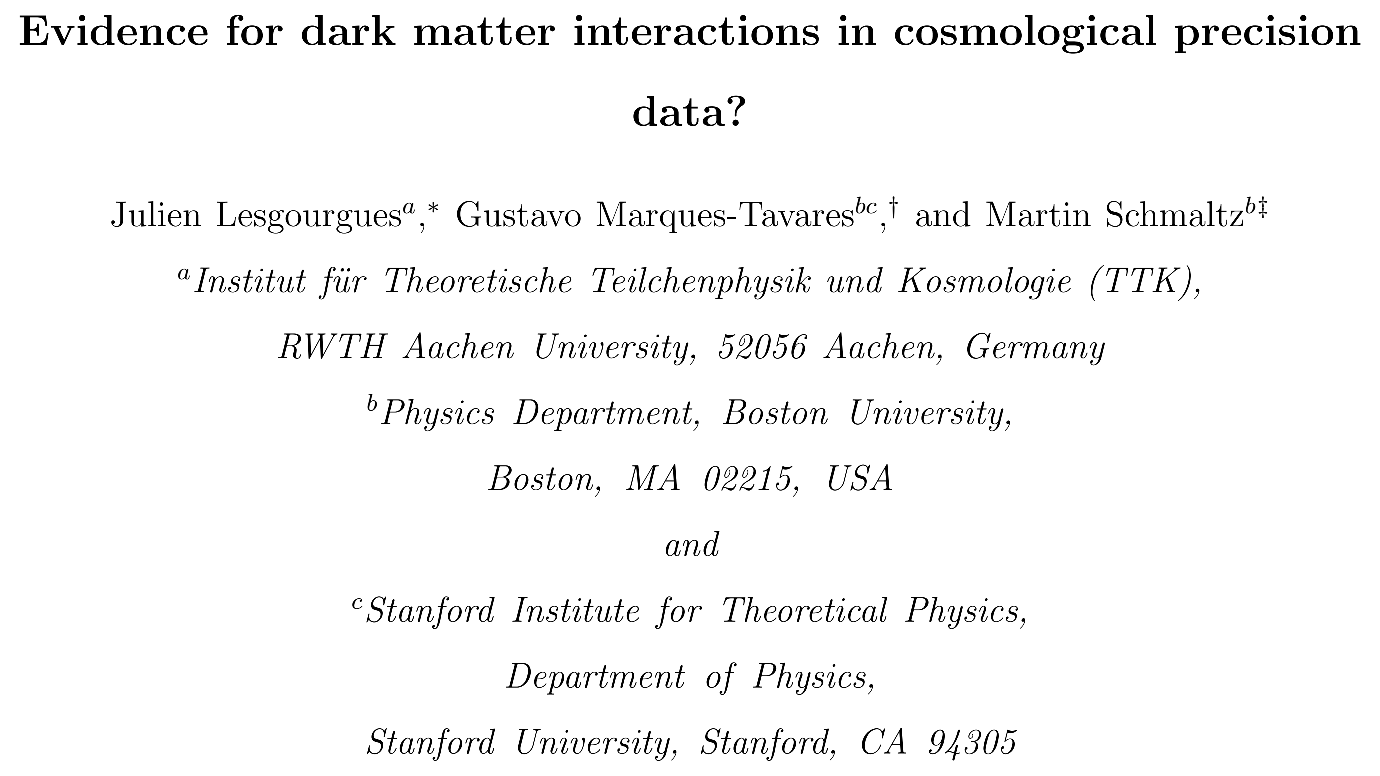
Cyr-Racine *et al.* 2013.

Future constraints: CMB lensing with CMB-S4



CMB-S4 Science book, arXiv:1610.02743

Evidence for dark matter interaction?



Evidence for dark matter interactions in cosmological precision data?

Julien Lesgourgues[a],[*] Gustavo Marques-Tavares[bc],[†] and Martin Schmaltz[b‡]

[a]*Institut für Theoretische Teilchenphysik und Kosmologie (TTK),*
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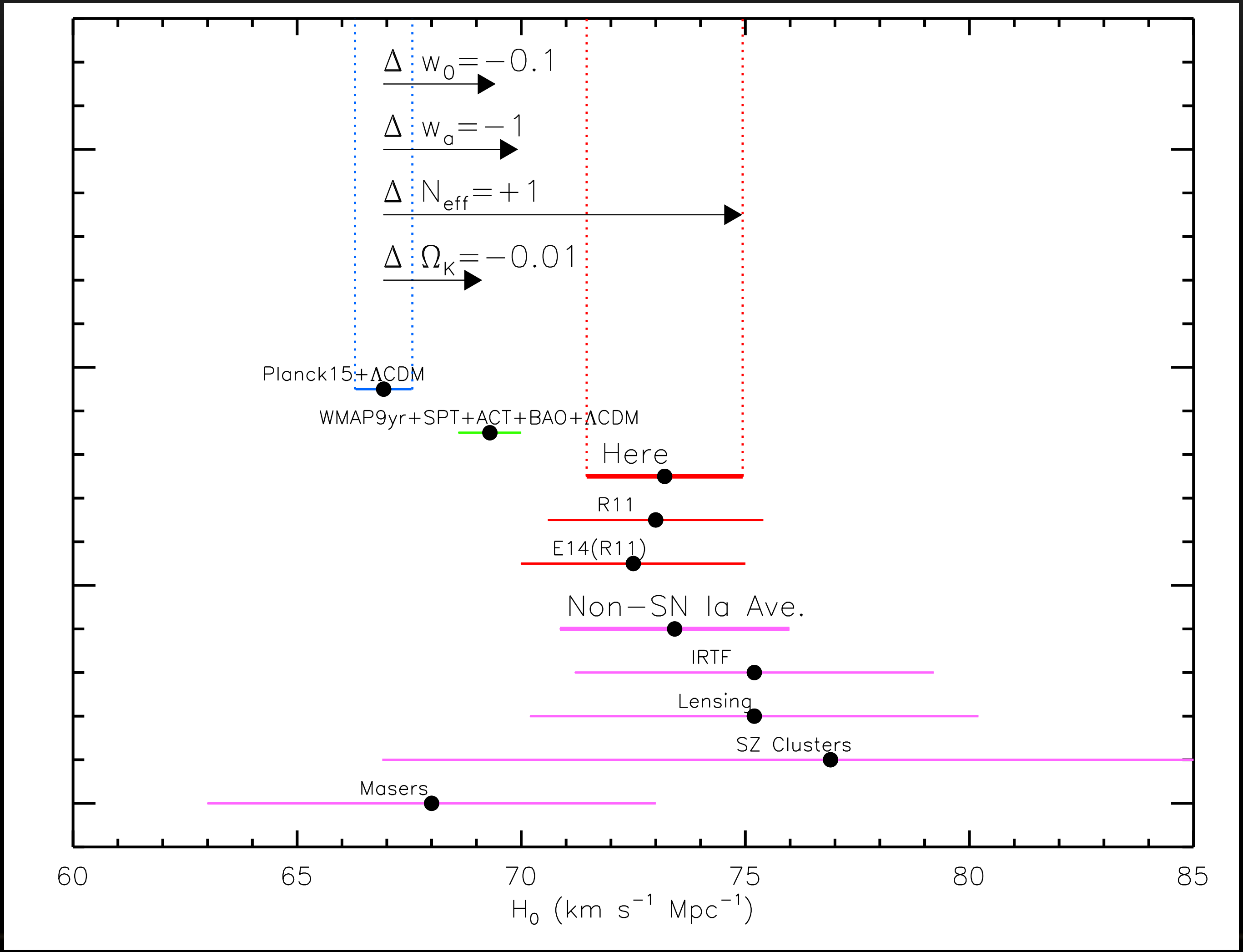
iv:1610.02743

Lesgourgues et al., arXiv:1507.04351

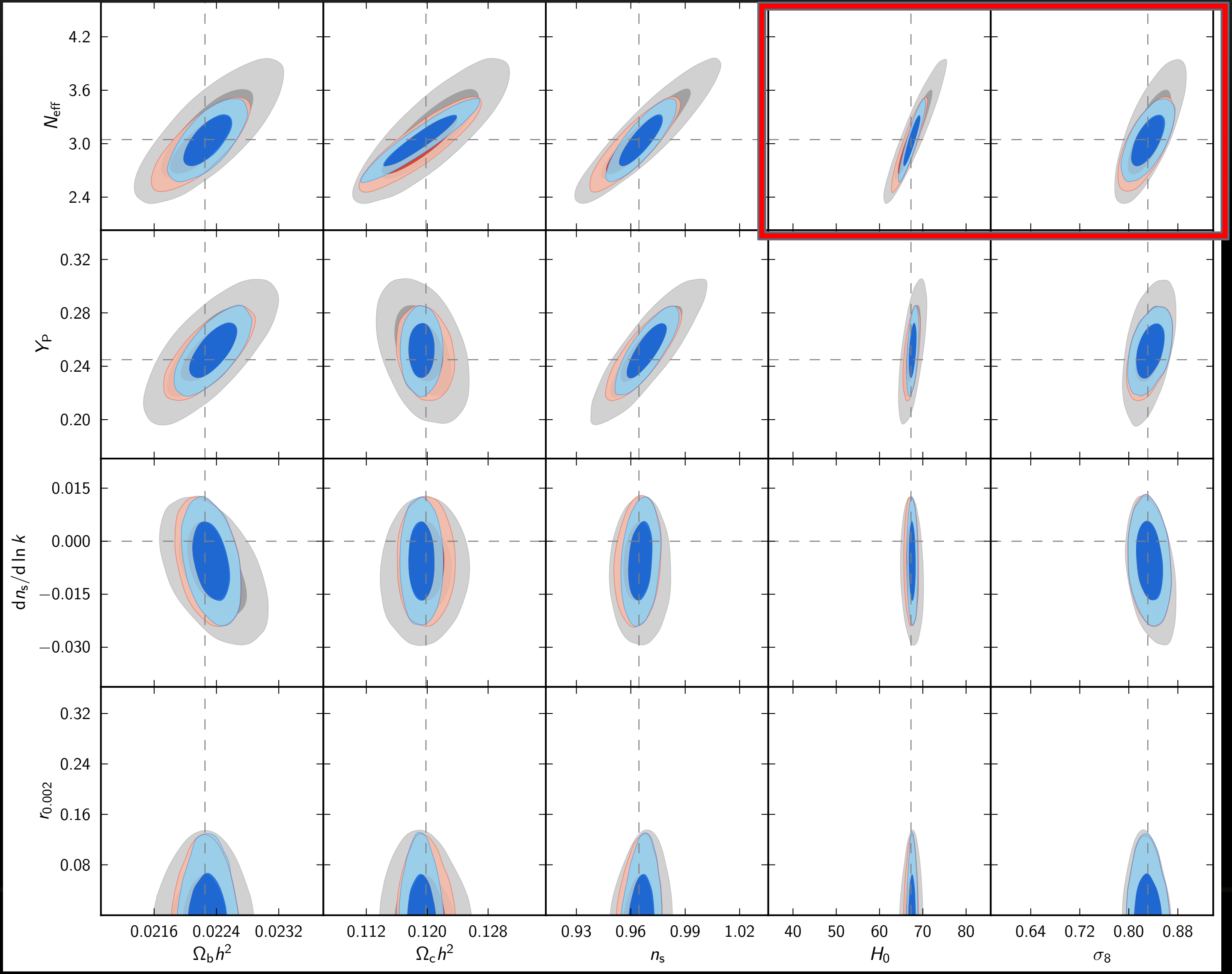
Evidence for dark matter interaction? The case of H_0



Riess et al. (2016)

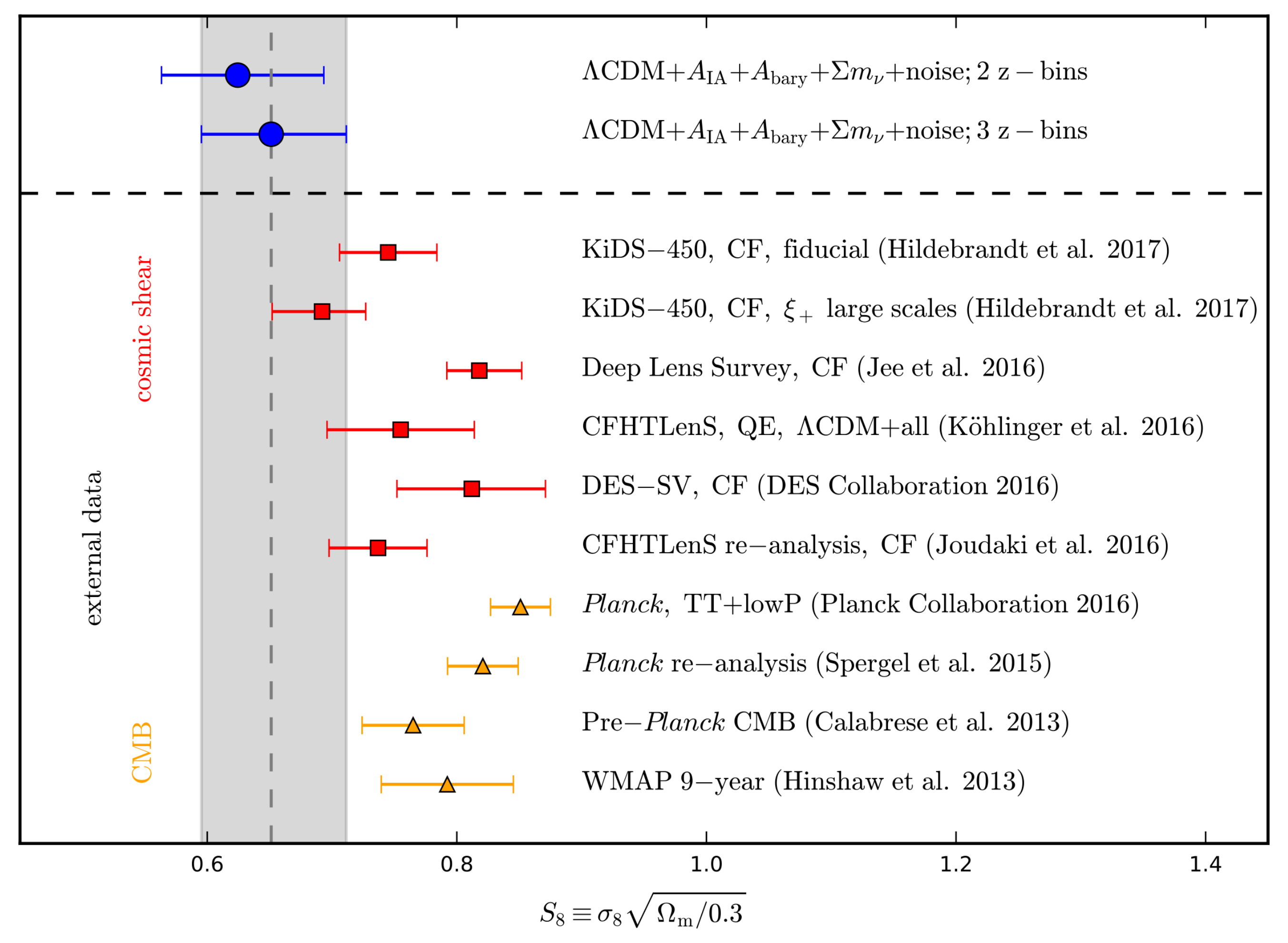
Evidence for dark matter interaction? The case of H_0

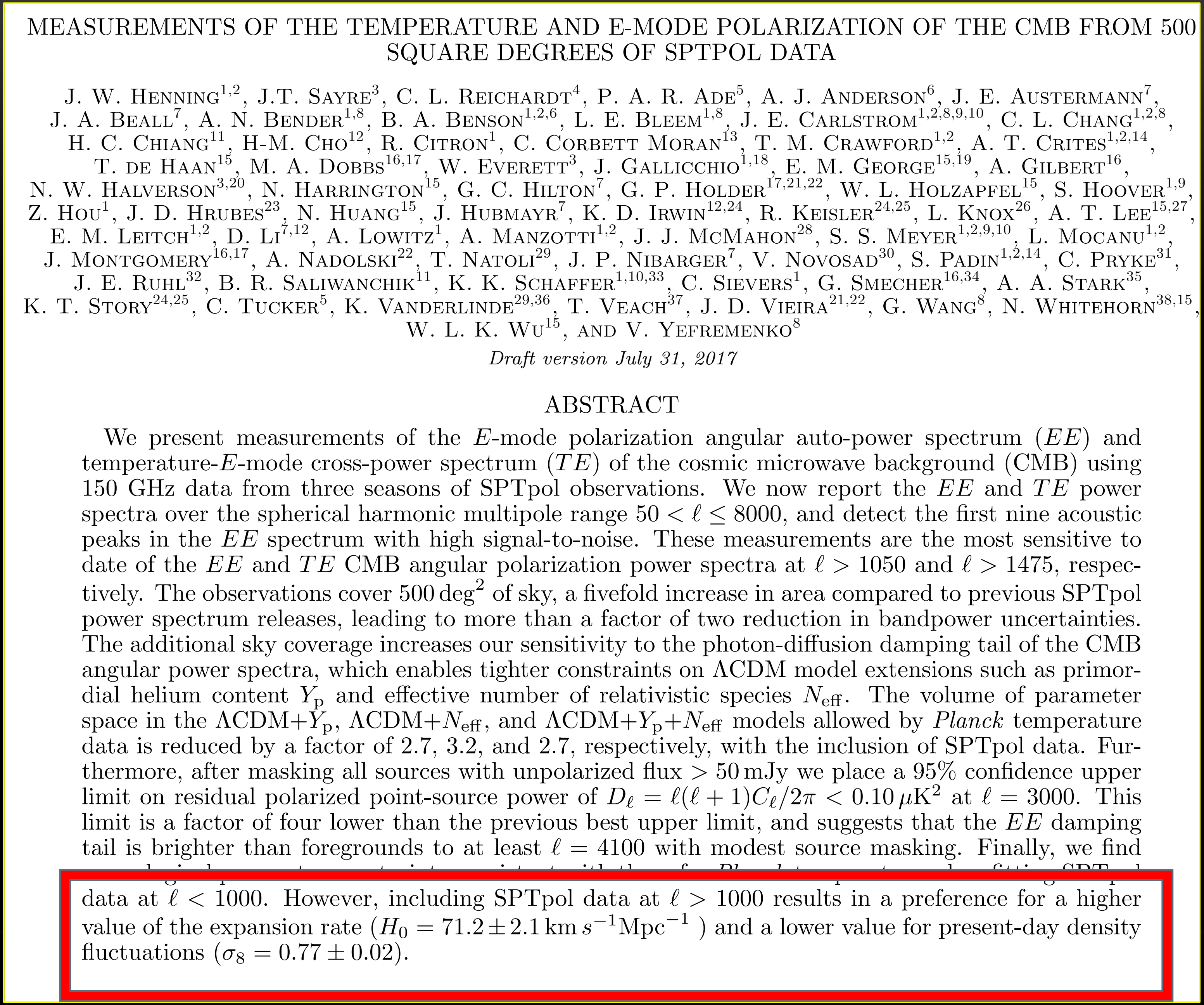
Planck Coll. (2015)



Evidence for dark matter interaction? The problem with $\boldsymbol{\sigma}_8$?

Köhlinger et al. (2017)





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

J. W. Henning[1,2], J.T. Sayre[3], C. L. Reichardt[4], P. A. R. Ade[5], A. J. Anderson[6], J. E. Austermann[7], J. A. Beall[7], A. N. Bender[1,8], B. A. Benson[1,2,6], L. E. Bleem[1,8], J. E. Carlstrom[1,2,8,9,10], C. L. Chang[1,2,8], H. C. Chiang[11], H-M. Cho[12], R. Citron[1], C. Corbett Moran[13], T. M. Crawford[1,2], A. T. Crites[1,2,14], T. de Haan[15], M. A. Dobbs[16,17], W. Everett[3], J. Gallicchio[1,18], E. M. George[15,19], A. Gilbert[16], N. W. Halverson[3,20], N. Harrington[15], G. C. Hilton[7], G. P. Holder[17,21,22], W. L. Holzapfel[15], S. Hoover[1,9], Z. Hou[1], J. D. Hrubes[23], N. Huang[15], J. Hubmayr[7], K. D. Irwin[12,24], R. Keisler[24,25], L. Knox[26], A. T. Lee[15,27], E. M. Leitch[1,2], D. Li[7,12], A. Lowitz[1], A. Manzotti[1,2], J. J. McMahon[28], S. S. Meyer[1,2,9,10], L. Mocanu[1,2], J. Montgomery[16,17], A. Nadolski[22], T. Natoli[29], J. P. Nibarger[7], V. Novosad[30], S. Padin[1,2,14], C. Pryke[31], J. E. Ruhl[32], B. R. Saliwanchik[11], K. K. Schaffer[1,10,33], C. Sievers[1], G. Smecher[16,34], A. A. Stark[35], K. T. Story[24,25], C. Tucker[5], K. Vanderlinde[29,36], T. Veach[37], J. D. Vieira[21,22], G. Wang[8], N. Whitehorn[38,15], W. L. K. Wu[15], and V. Yefremenko[8]

Draft version July 31, 2017

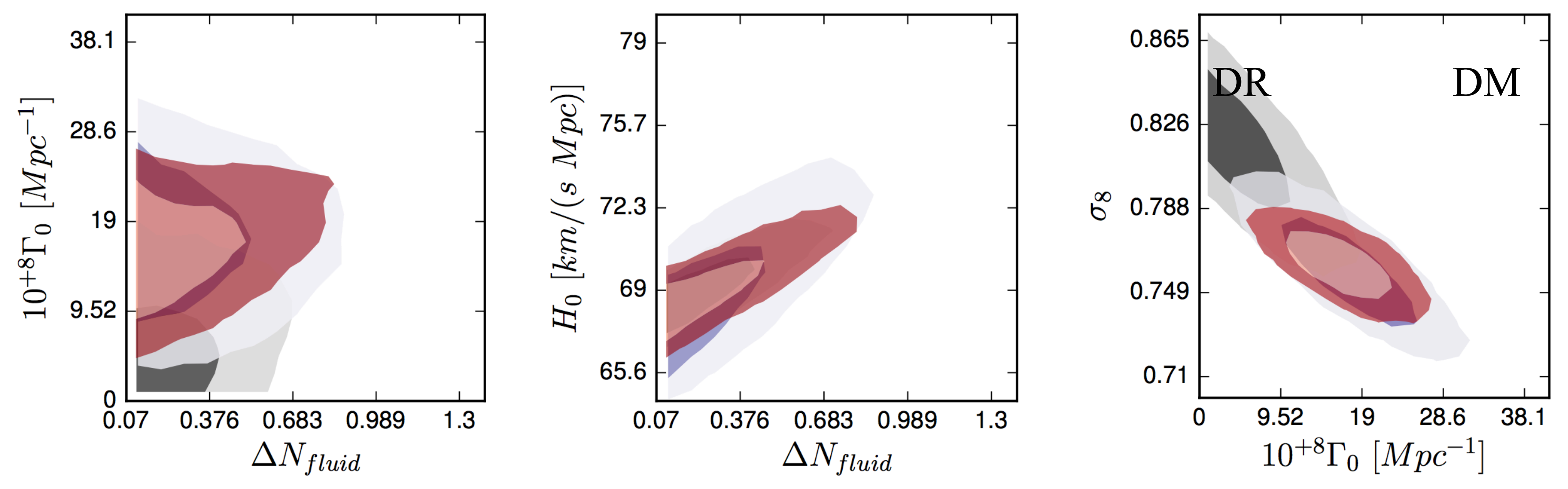
ABSTRACT

We present measurements of the E-mode polarization angular auto-power spectrum (EE) and temperature-E-mode cross-power spectrum (TE) of the cosmic microwave background (CMB) using 150 GHz data from three seasons of SPTpol observations. We now report the EE and TE 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 $500\,\mathrm{deg}^2$ 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 ΛCDM model extensions such as primordial helium content Y_p and effective number of relativistic species N_eff. The volume of parameter space in the $\Lambda\mathrm{CDM}+Y_\mathrm{p}$, $\Lambda\mathrm{CDM}+N_\mathrm{eff}$, and $\Lambda\mathrm{CDM}+Y_\mathrm{p}+N_\mathrm{eff}$ 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 $> 50\,\mathrm{mJy}$ 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 tail is brighter than foregrounds to at least $\ell = 4100$ with modest source masking. Finally, we find [illegible] data at $\ell < 1000$. However, including SPTpol data at $\ell > 1000$ results in a preference for a higher value of the expansion rate ($H_0 = 71.2 \pm 2.1\,\mathrm{km}\,s^{-1}\mathrm{Mpc}^{-1}$) and a lower value for present-day density fluctuations ($\sigma_8 = 0.77 \pm 0.02$).

SPTpol collab. (2017)

Evidence for dark matter interaction?

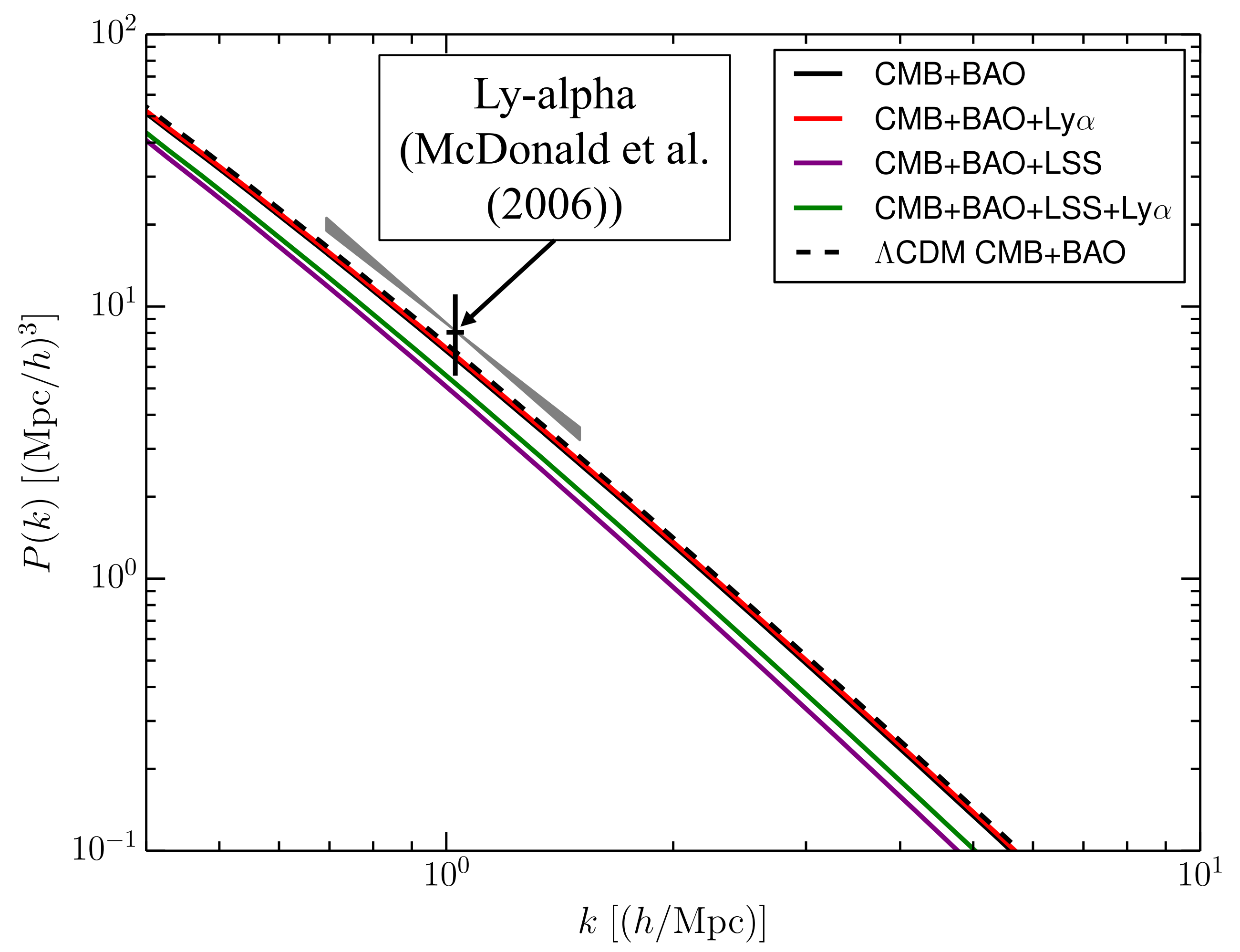
DM DR



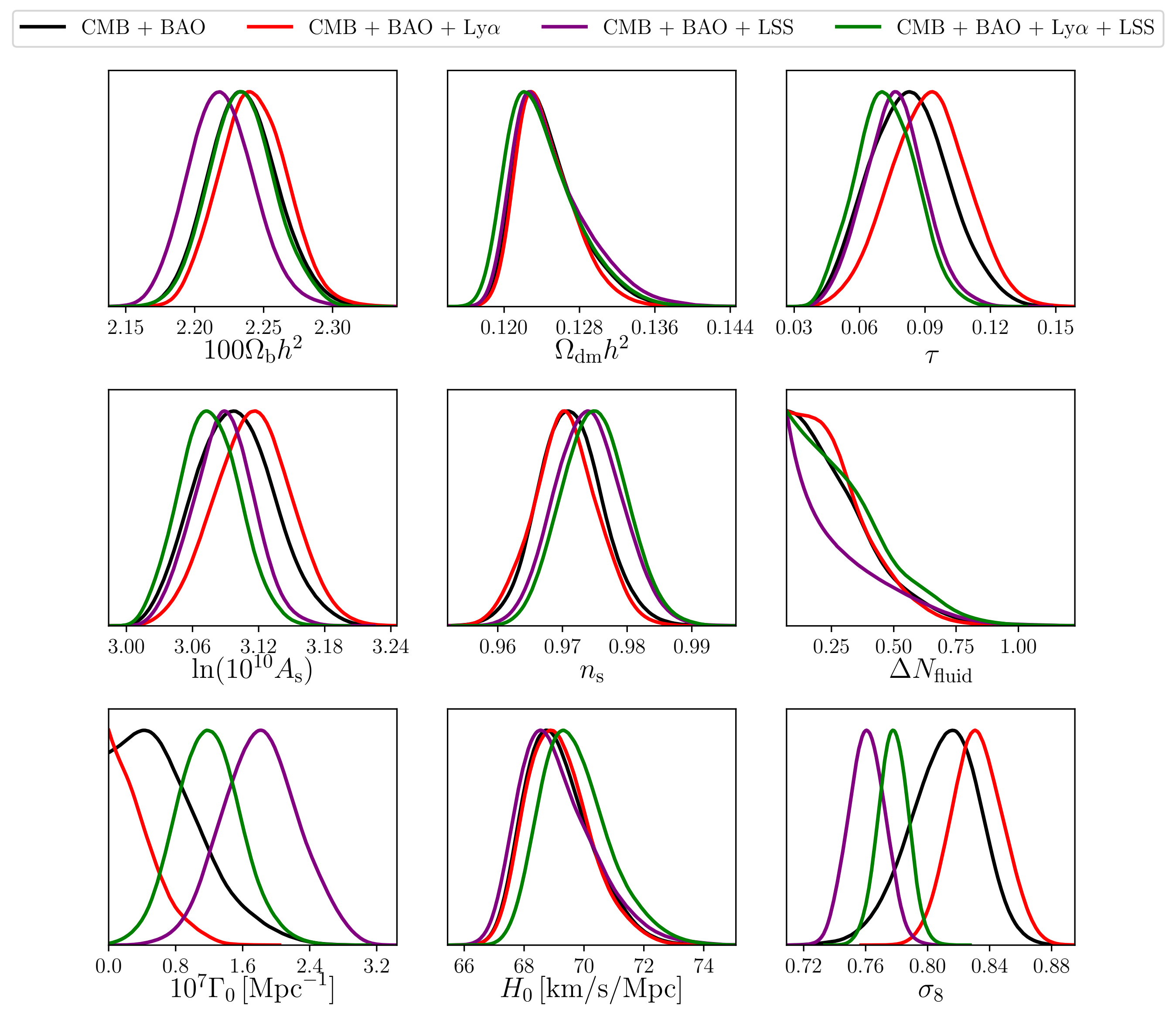
Lesgourgues et al., arXiv:1507.04351
See also: Chacko et al. (2016)
Ko & Tang (2017)

Evidence for dark matter interaction?

Krall, Cyr-Racine & Dvorkin, arXiv:1705.08894

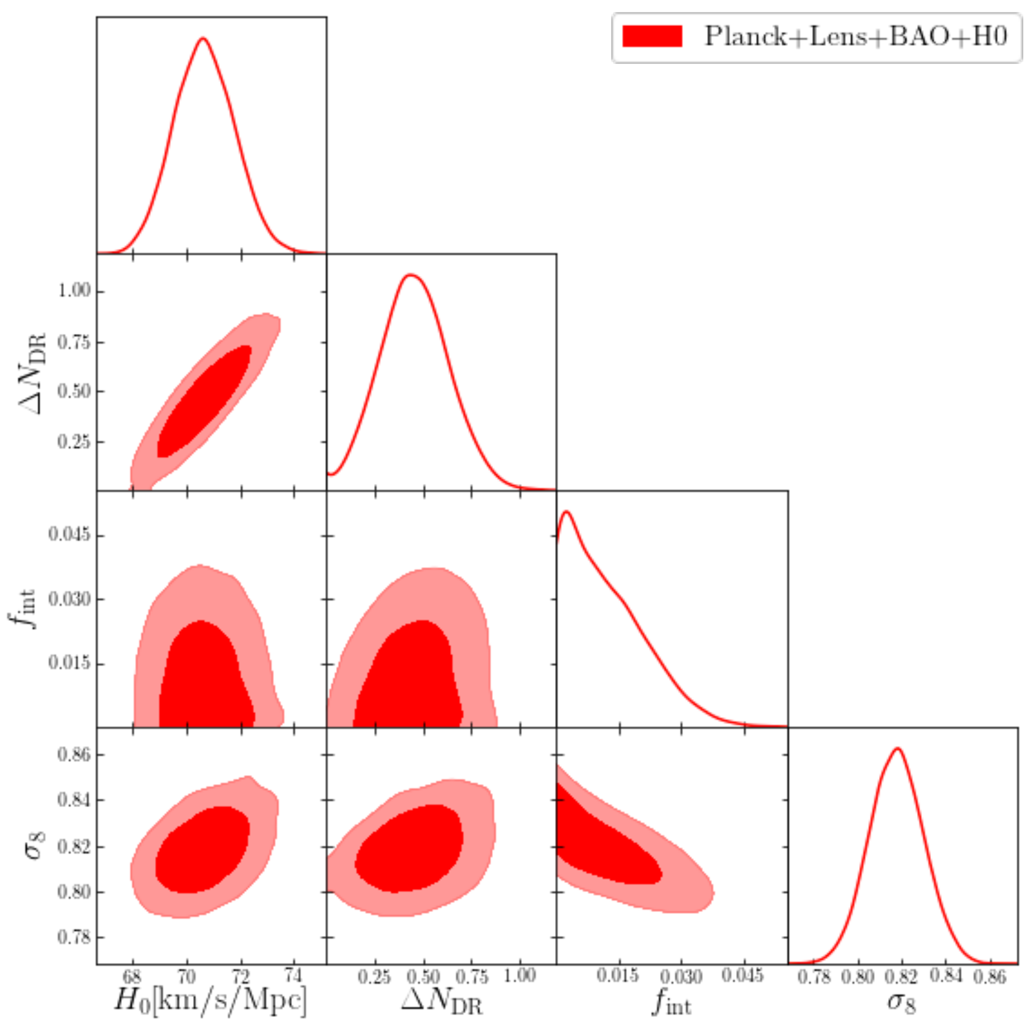


Evidence for dark matter interaction?



Krall, Cyr-Racine & Dvorkin, arXiv:1705.08894

Can also make this work with partially-interacting dark matter



Cyr-Racine, Randall +, in prep.

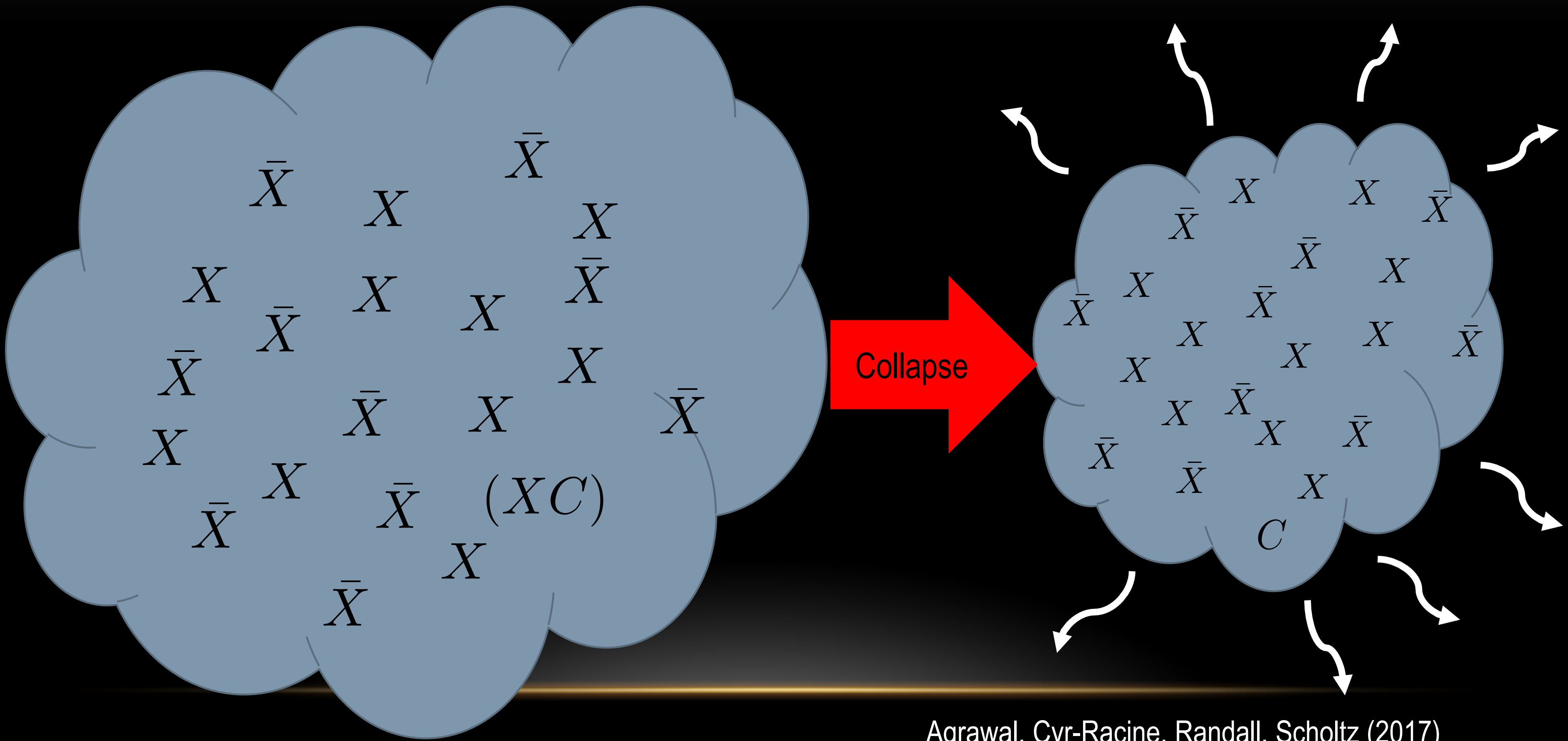
Fix the cross section such that dark matter kinetic decoupling occurs near matter-radiation equality

Evidence for dark matter interaction?

- 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 $\boldsymbol{\sigma}_8$ (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?

Interacting dark matter: Dissipative dynamics

- As halos form, the dark matter is heated up to the virial temperature, possibly allowing energy dissipation:



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

XC dark matter: The model

arXiv:1702.05482

- Ingredients:
  - A heavy (~10 TeV) *X* particle (and its anti-particle)
  - A light (~1 MeV) *C* particle
  - A massless *U(1)* dark photon

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \bar{X}\not{D}X + \bar{C}\not{D}C - m_X\bar{X}X - m_C\bar{C}C$$

- Key parameters:

$$\alpha_D, m_X, m_C, f_{(XC)}$$

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

XC dark matter: Dissipative dynamics

- The main mechanisms for energy dissipation are Bremsstrahlung, inverse Compton scattering, collisional excitation and recombination, and finally, molecular cooling.
- Since the rate of collisional processes are very difficult to compute, we focus on Bremsstrahlung and inverse Compton:

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

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

XC dark matter: Dissipative dynamics

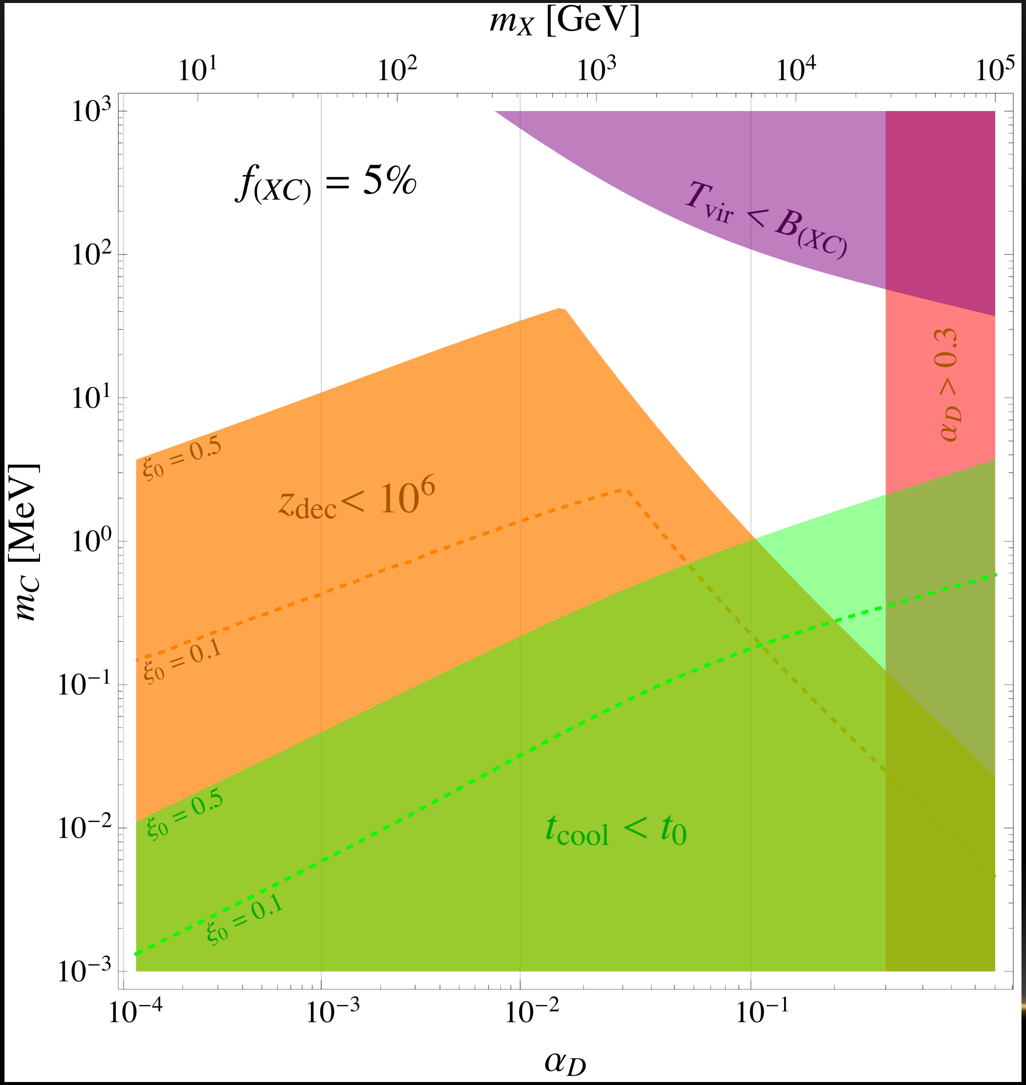
- We define an approximate cooling timescale:

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

- At a minimum, this timescale must be shorter than the age of the Universe:

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

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.

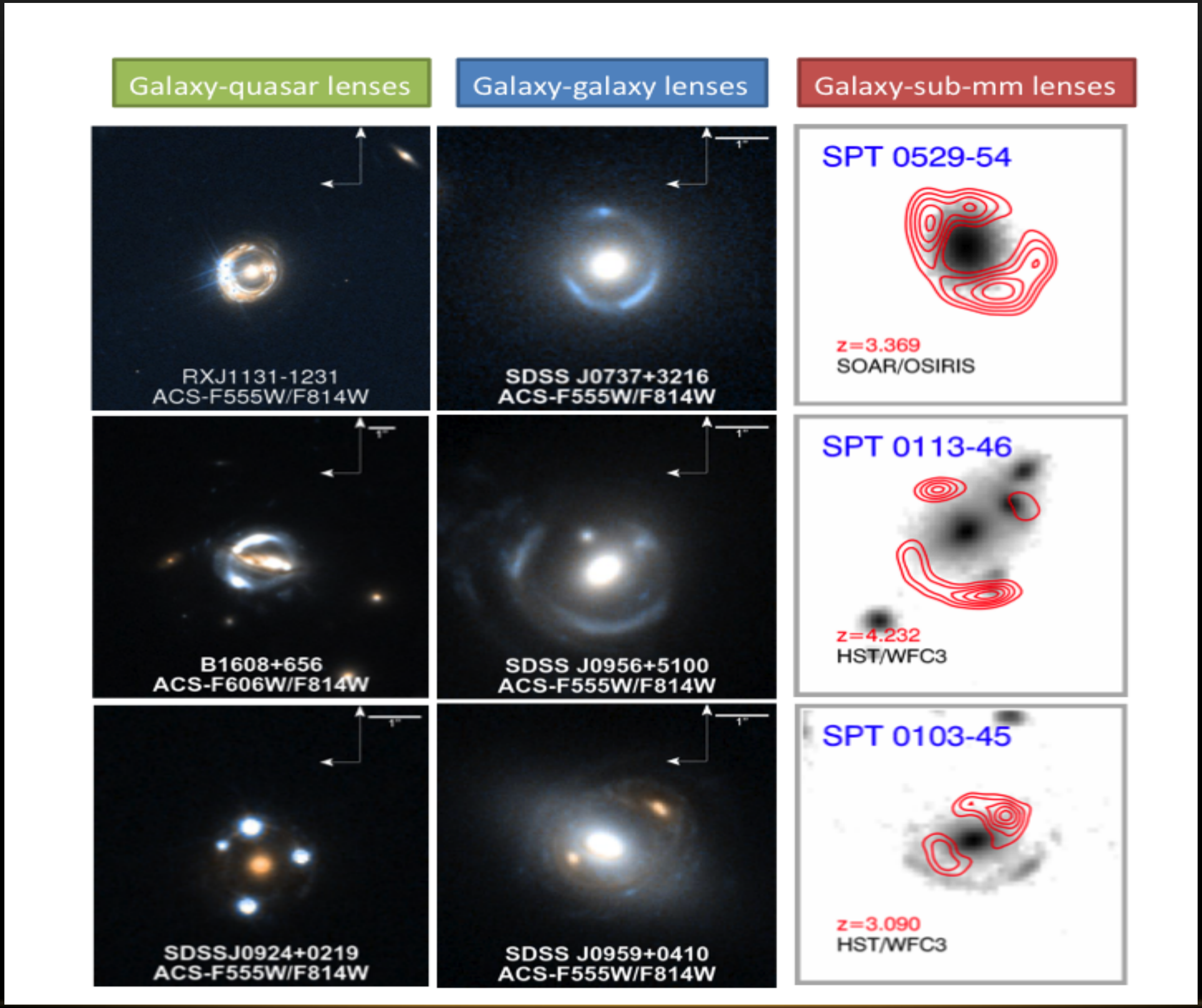
Agrawal, Cyr-Racine, Randall, Scholtz (2017)

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

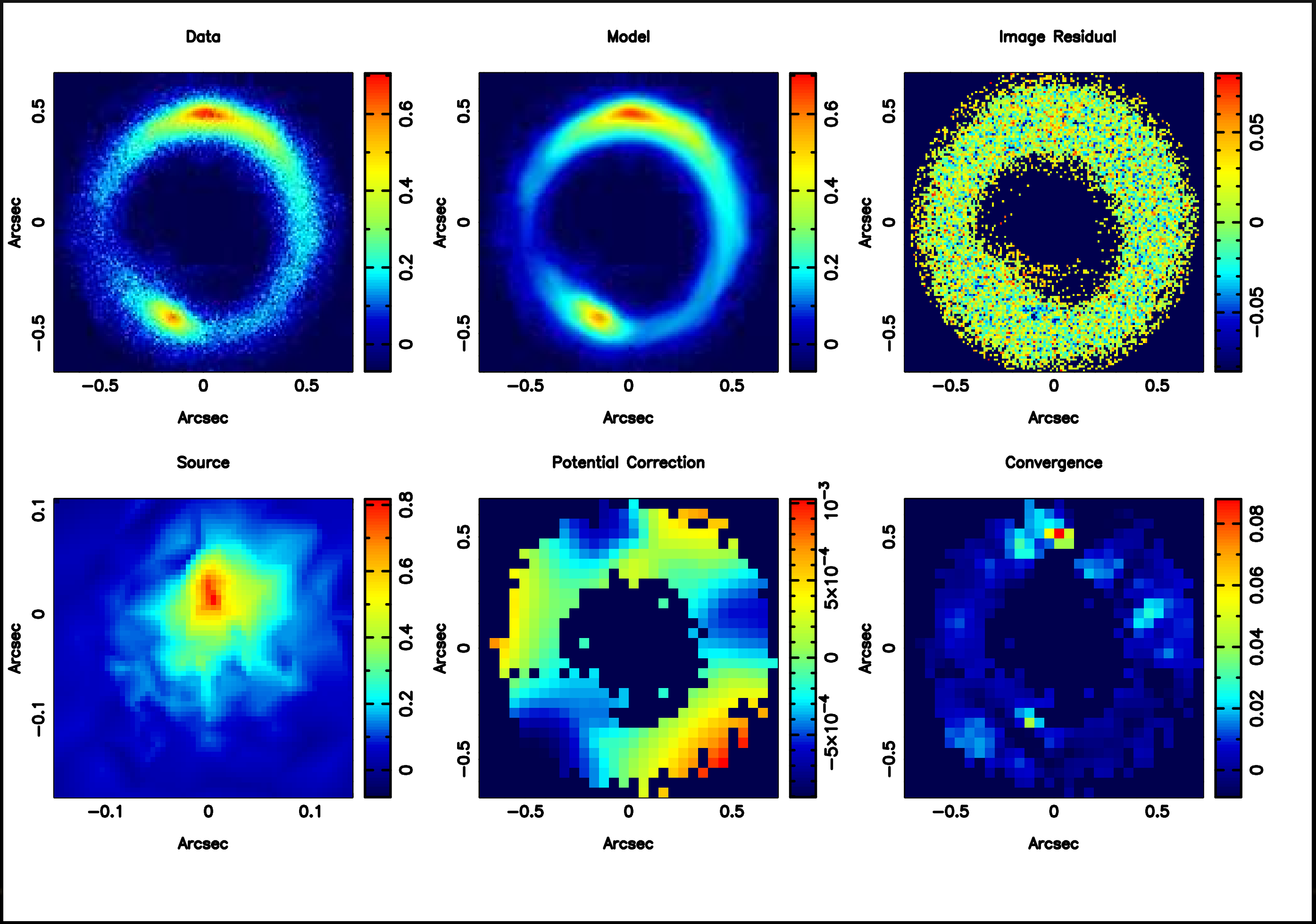
Galaxy-scale Gravitational Lenses



Credits: Leonidas Moustakas

Direct Substructure Detection

- "Gravitational Imaging" of Perturbed Einstein Rings



Vegetti et al. *Nature*, (2012)

Direct Substructure Detection

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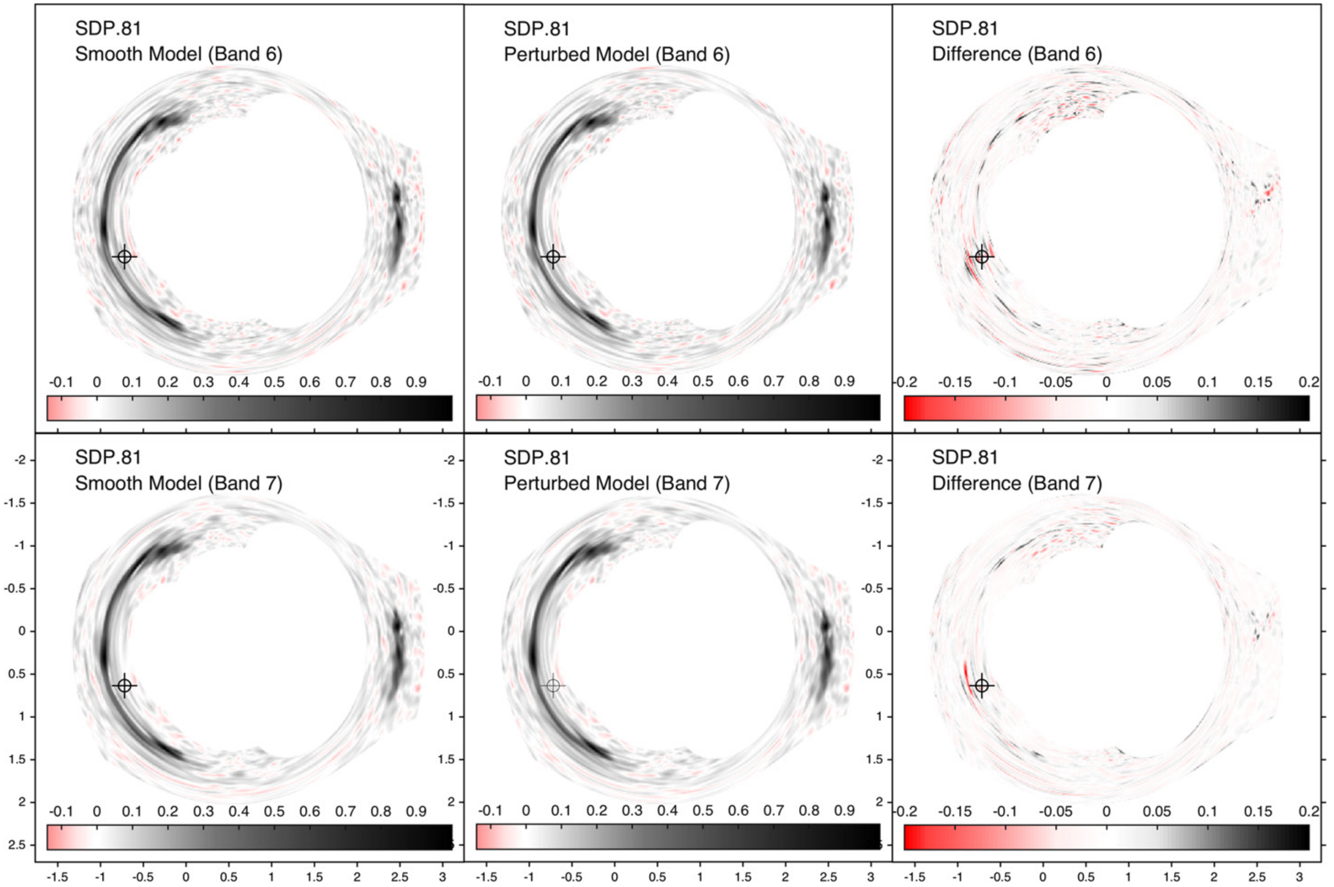
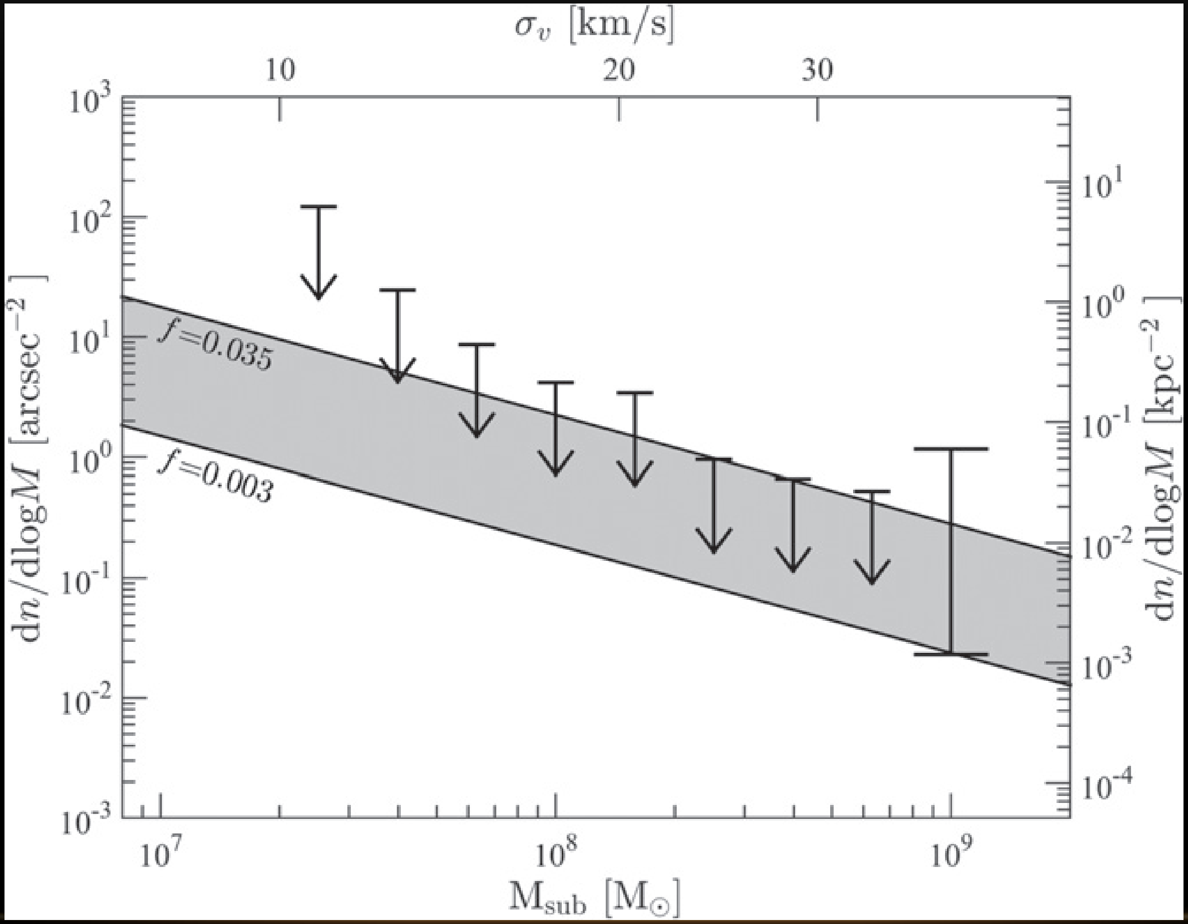


Figure 6. Top left: the sky emission model in band 6 for the best-fit smooth lens parameters for the SDP.81 data. Top middle: the same for the perturbed model. Top right: the difference between the two models. The bottom panels show the same for band 7. The bright feature in the difference plots is mainly 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

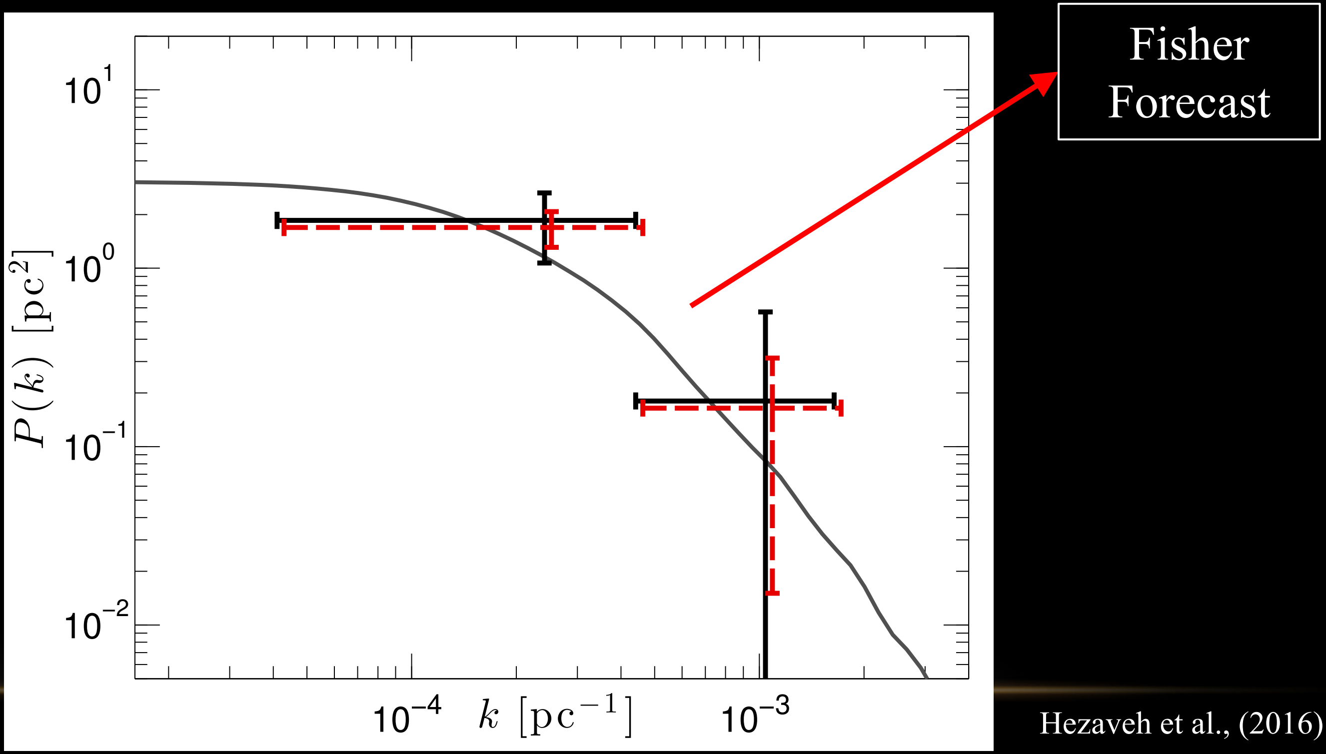
- Constraints on the subhalo mass function



Hezaveh et al., (2016) (see also Vegetti et al. (2014), Li et al. (2016))

Substructure lensing: 2-point function

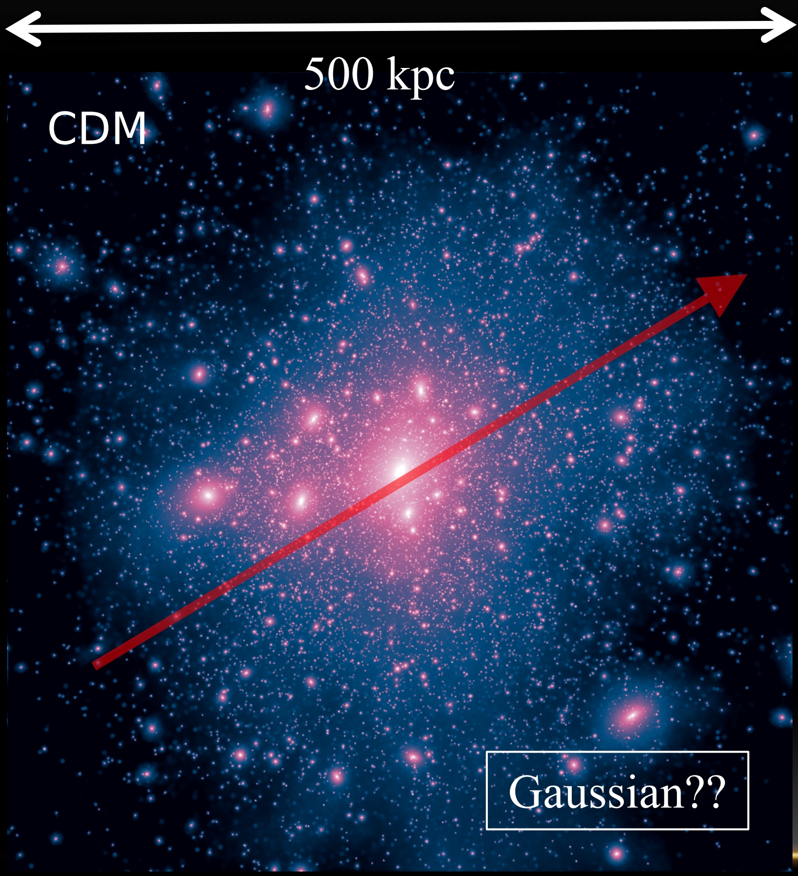
- Instead of describing lensing perturbations in terms of individual subhalo, look at the correlation function of the projected density field.



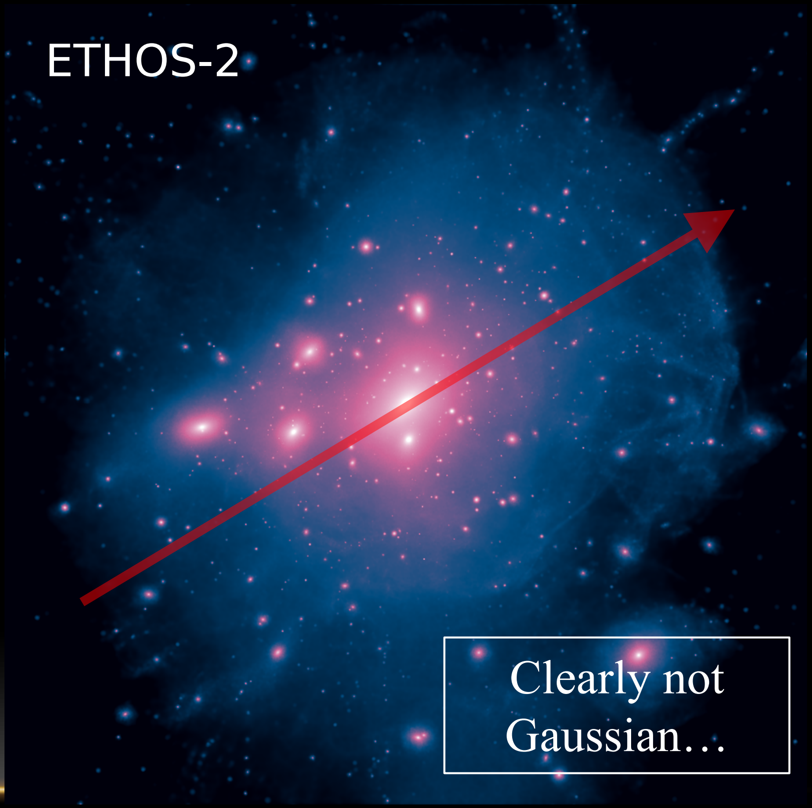
Hezaveh et al., (2016)

Substructure lensing: 2-point function

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



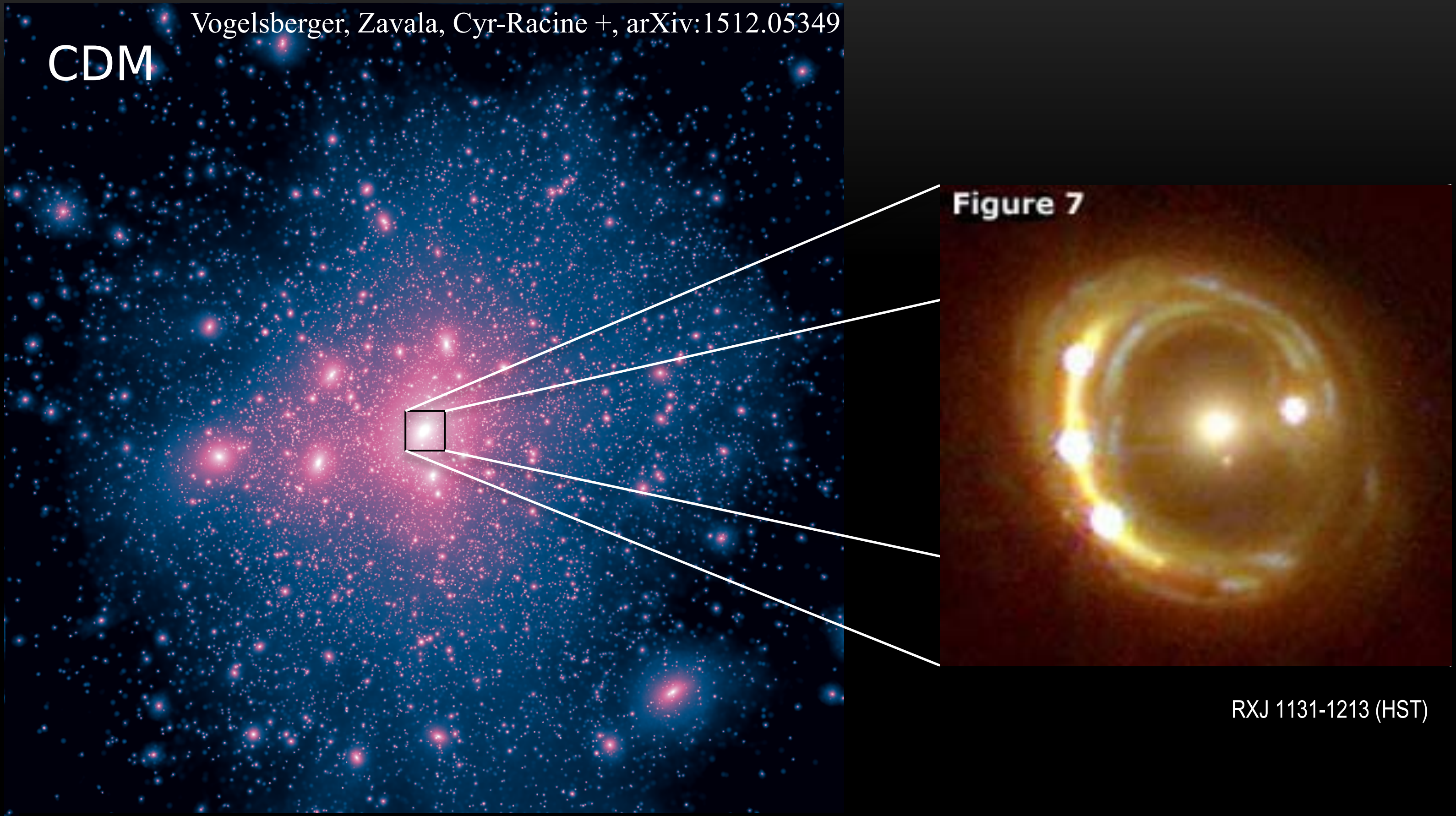
Gaussian??



Clearly not Gaussian…

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

Galaxy Lenses: Typical Scale



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

RXJ 1131-1213 (HST)

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

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

- Goal: Use the halo model to compute from first principle the substructure convergence power spectrum.

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

$$\begin{aligned}\xi_{\rm sub}(\mathbf{r}) \equiv \frac{1}{A}\int d^2\mathbf{s}\int\prod_i d^2\mathbf{r}_i\mathcal{P}_{\rm r}(\mathbf{r}_i)\\ \times\left(\kappa_{\rm sub}(\mathbf{s})-\bar{\kappa}_{\rm sub}\right)\left(\kappa_{\rm sub}(\mathbf{s}+\mathbf{r})-\bar{\kappa}_{\rm sub}\right)\end{aligned}$$

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

Substructure Convergence Power Spectrum

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

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

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

1-subhalo term

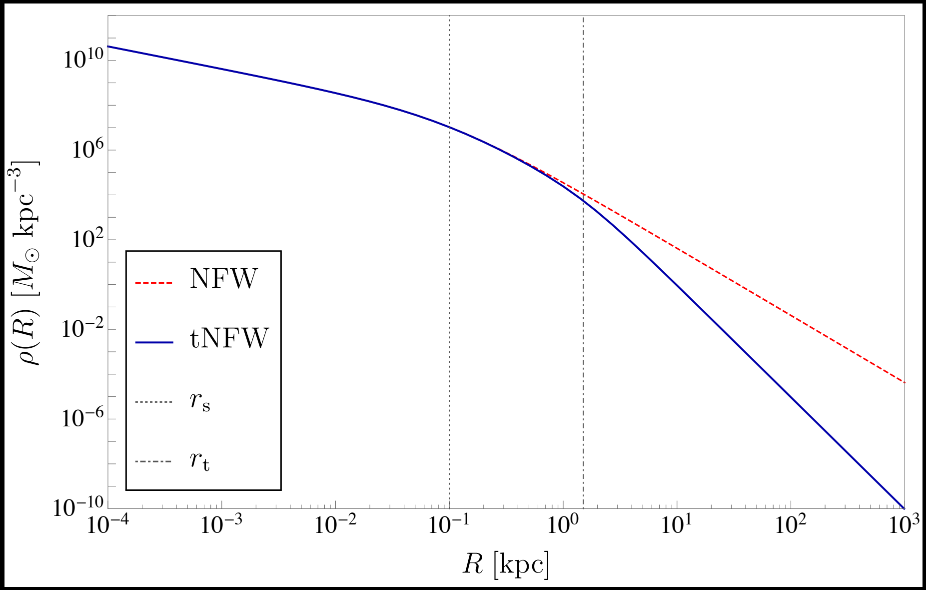
2-subhalo term

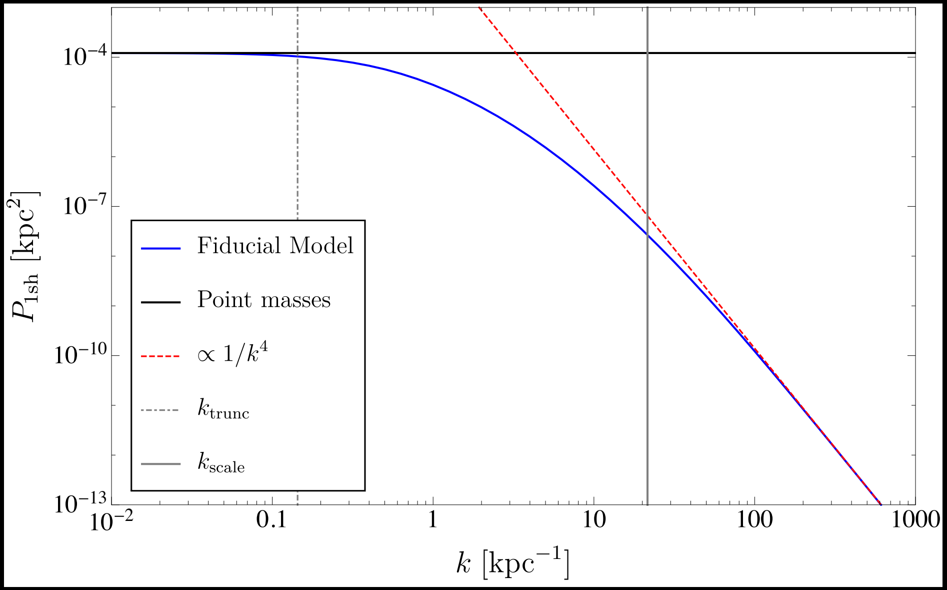
$$P_{\rm 1sh}(k) = \frac{(2\pi)^2\bar{\kappa}_{\rm sub}}{\langle m\rangle\Sigma_{\rm crit}}\int dm\, d\mathbf{q}\, m^2\, \mathcal{P}_{\rm m}(m)\, \mathcal{P}_{\rm q}(\mathbf{q}|m) \times\left[\int dr\, r J_0(k\, r)\hat{\kappa}(r,\mathbf{q})\right]^2$$

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

Substructure Power Spectrum: tNFW

- As a warm up, let’s consider a population of truncated NFW subhalos.

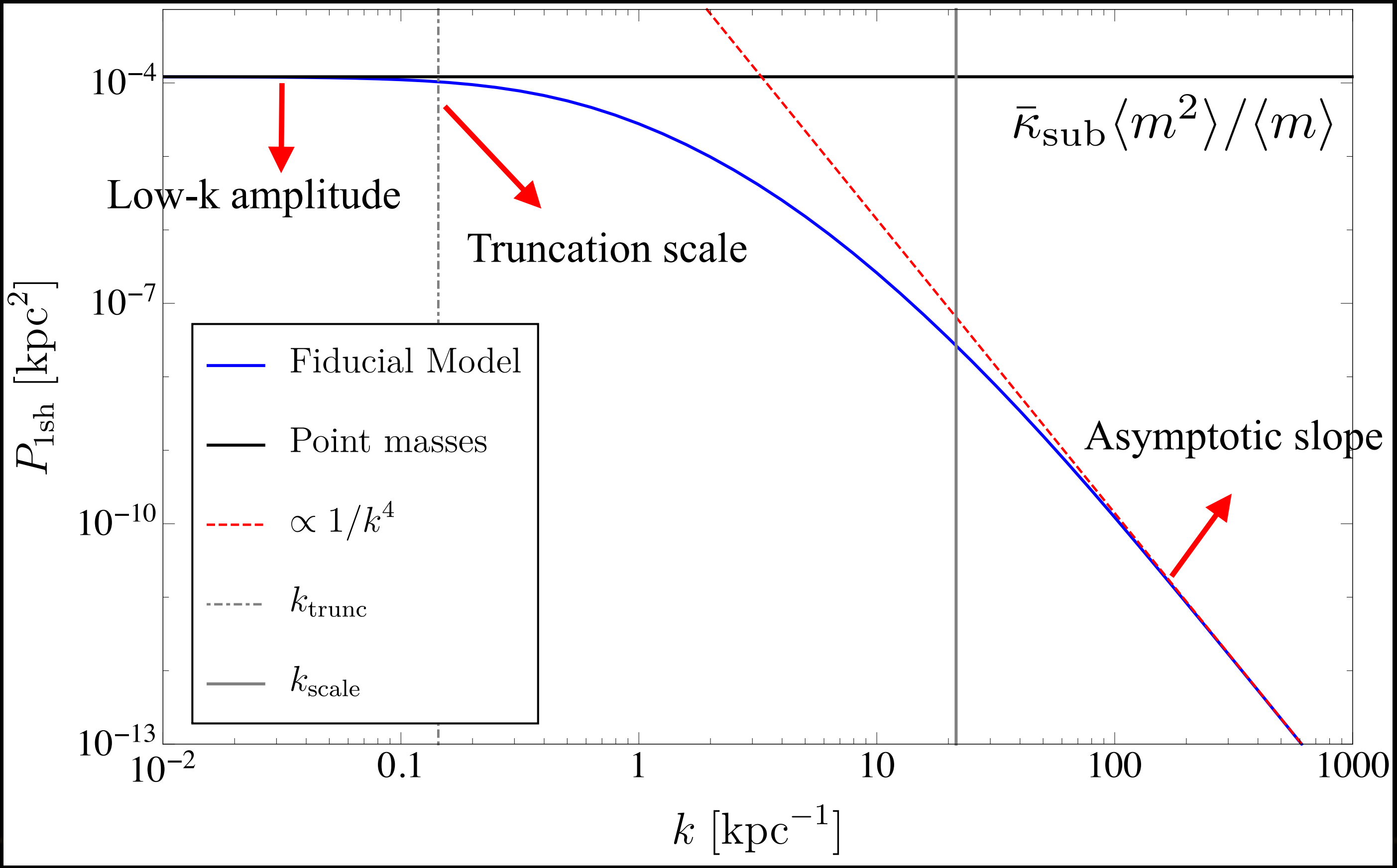




Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

Substructure Power Spectrum: tNFW

- The power spectrum depends mostly on three quantities:



Low-k amplitude

Truncation scale

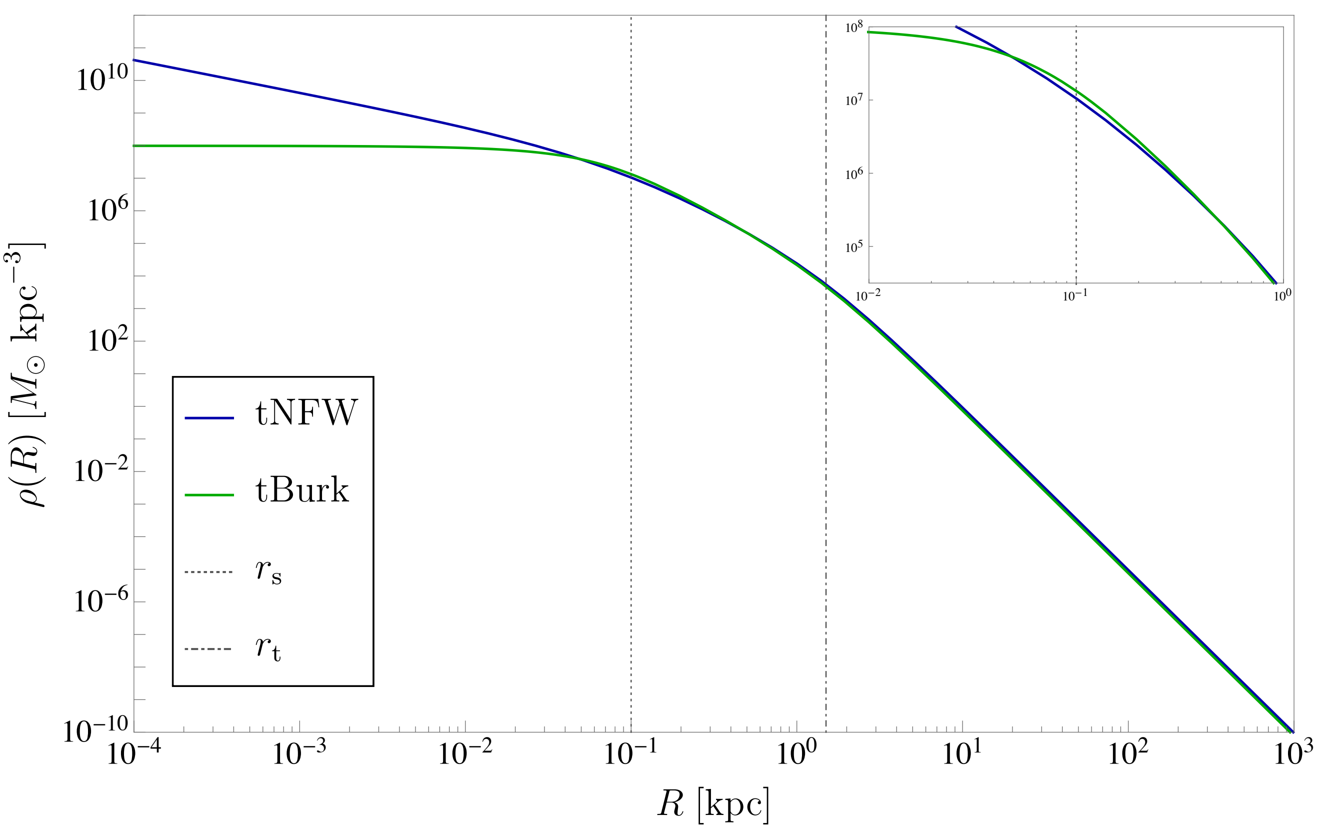
Asymptotic slope

$\bar{\kappa}_{\mathrm{sub}}\langle m^2\rangle/\langle m\rangle$

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

Substructure Power Spectrum: truncated cored profile

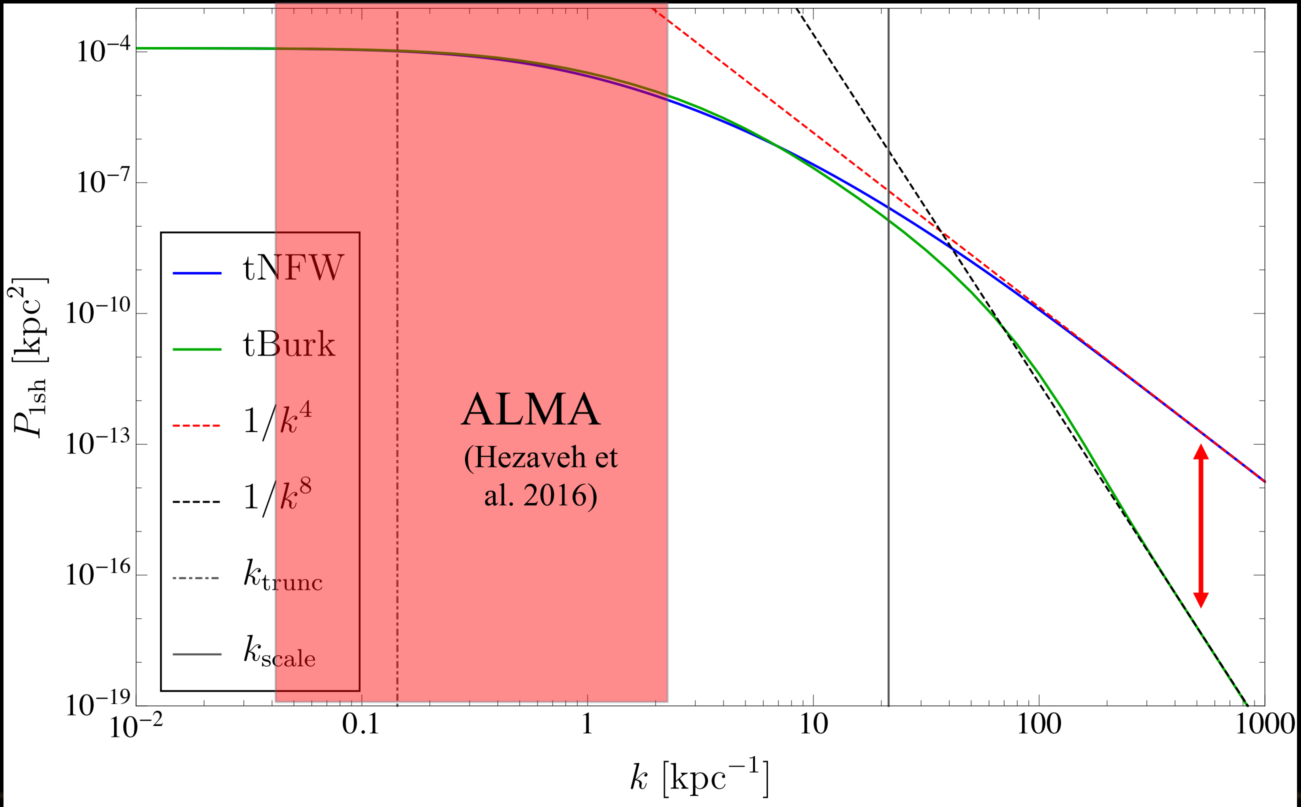
- Let’s now consider an SIDM-inspired truncated cored profile:



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

Substructure Power Spectrum: truncated cored profile

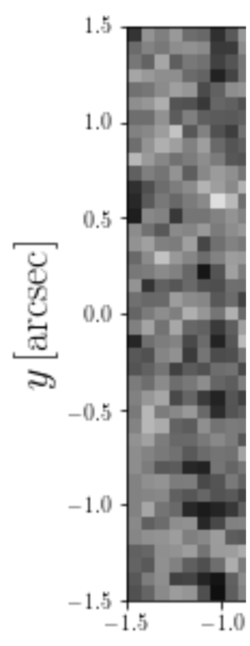
- Key probe of the inner subhalo density profile: asymptotic slope.

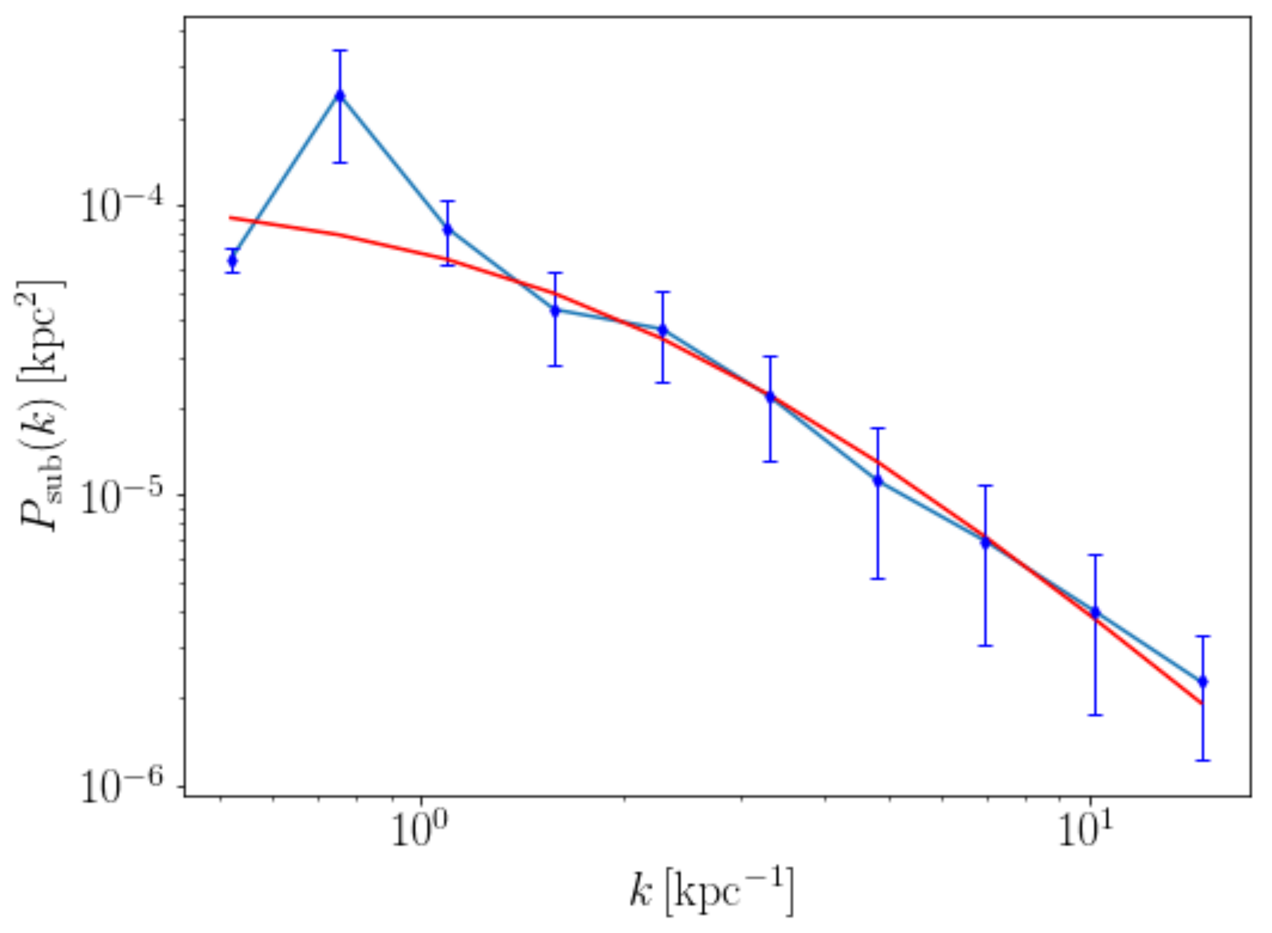


Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

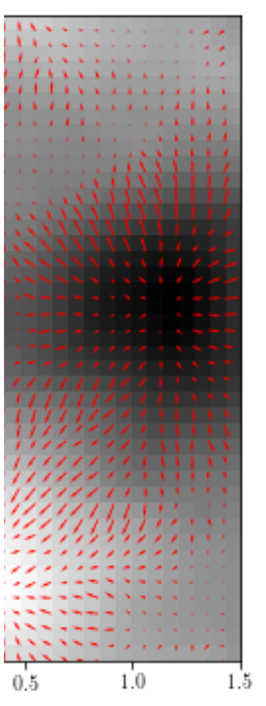
Measuring the substructure power spectrum: cartoon

Substruc





ection field



Measuring the substructure power spectrum: cartoon

Fiducial image

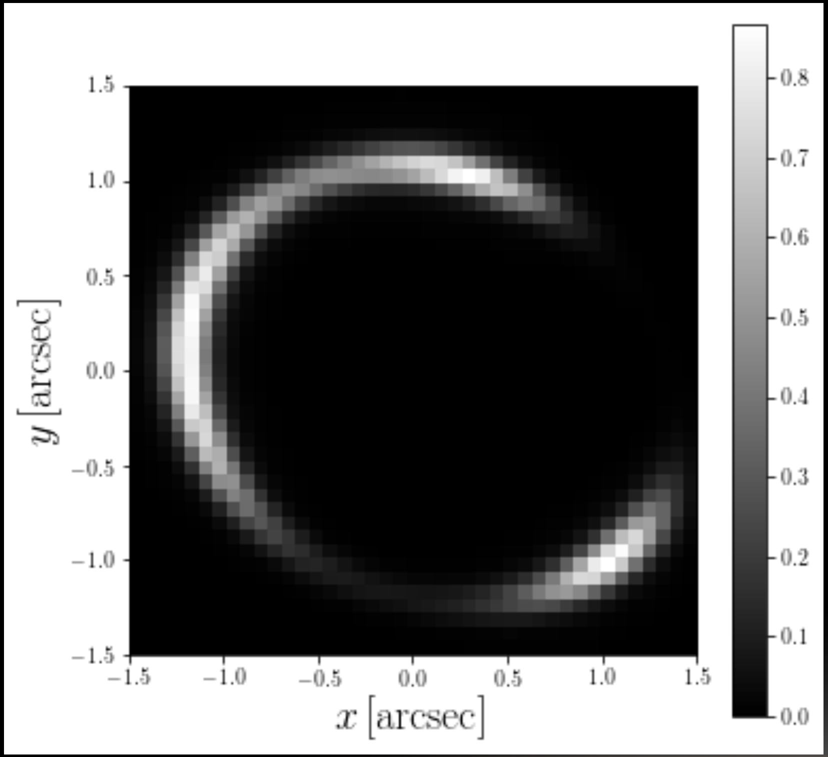
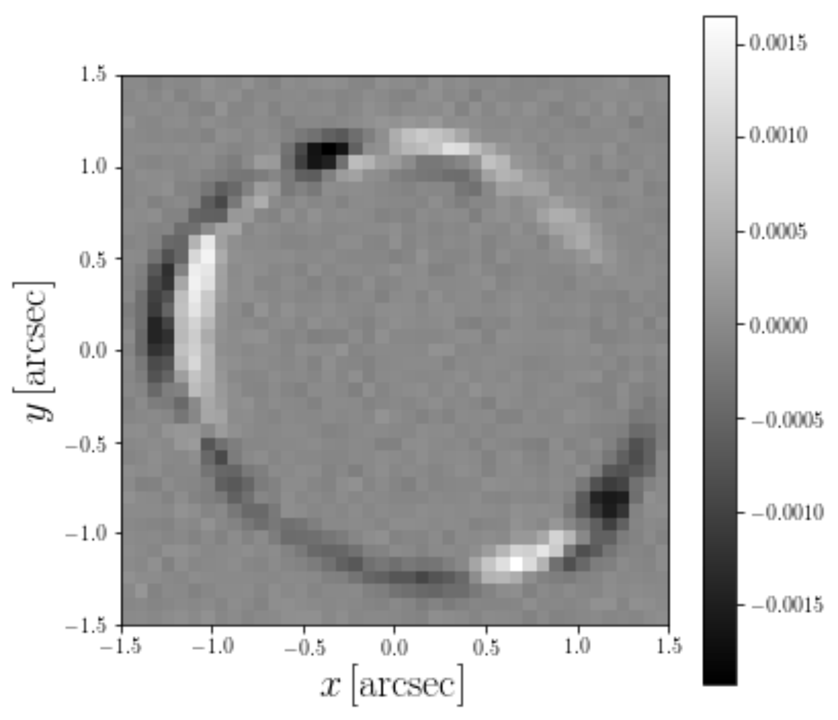
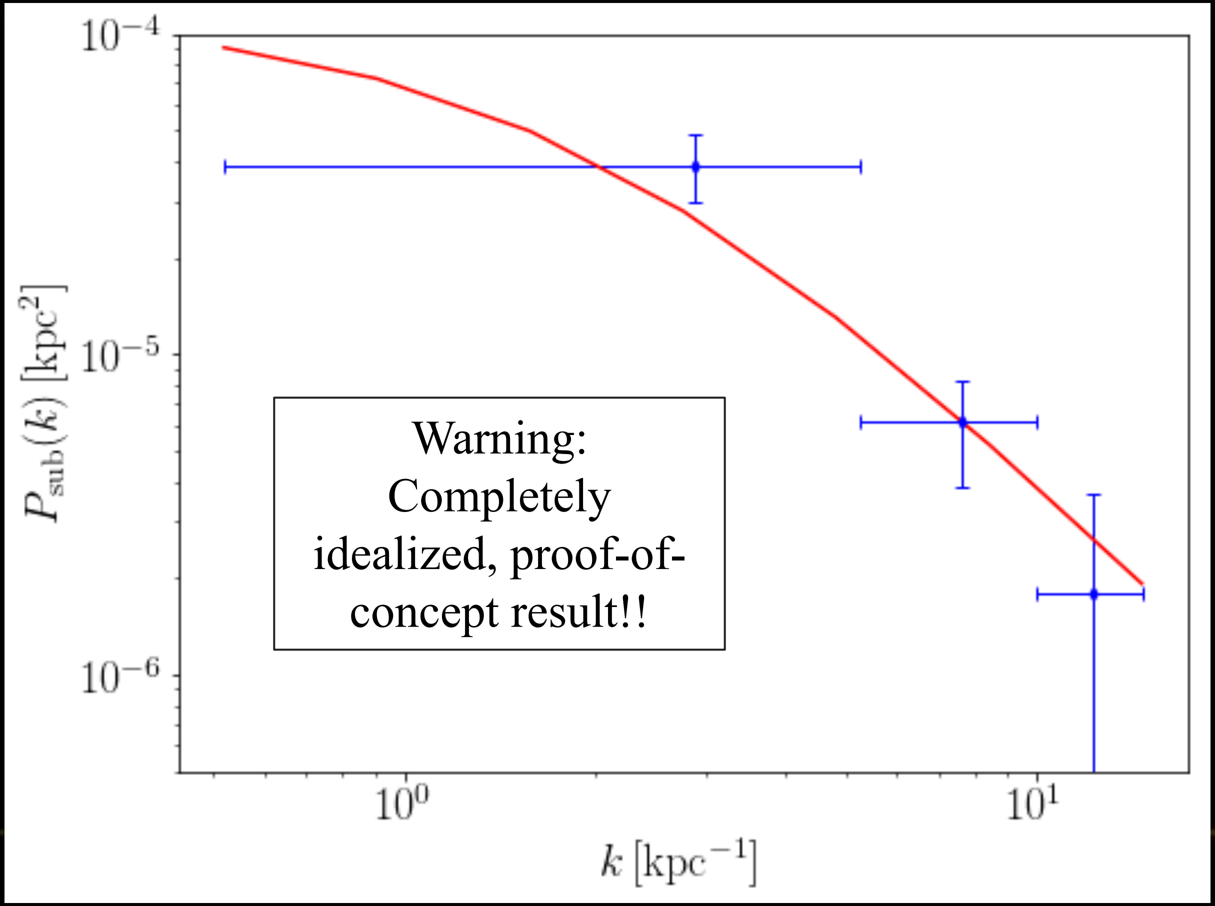


Image residuals



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 n-point 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.