# From Dark Particle Physics to the Matter Distribution of the Universe

Warsaw workshop on Non-Standard Dark Matter, June 2nd 2016


Francis-Yan Cyr-Racine

Postdoctoral Fellow

Center for the Fundamental Laws of Nature, Harvard University

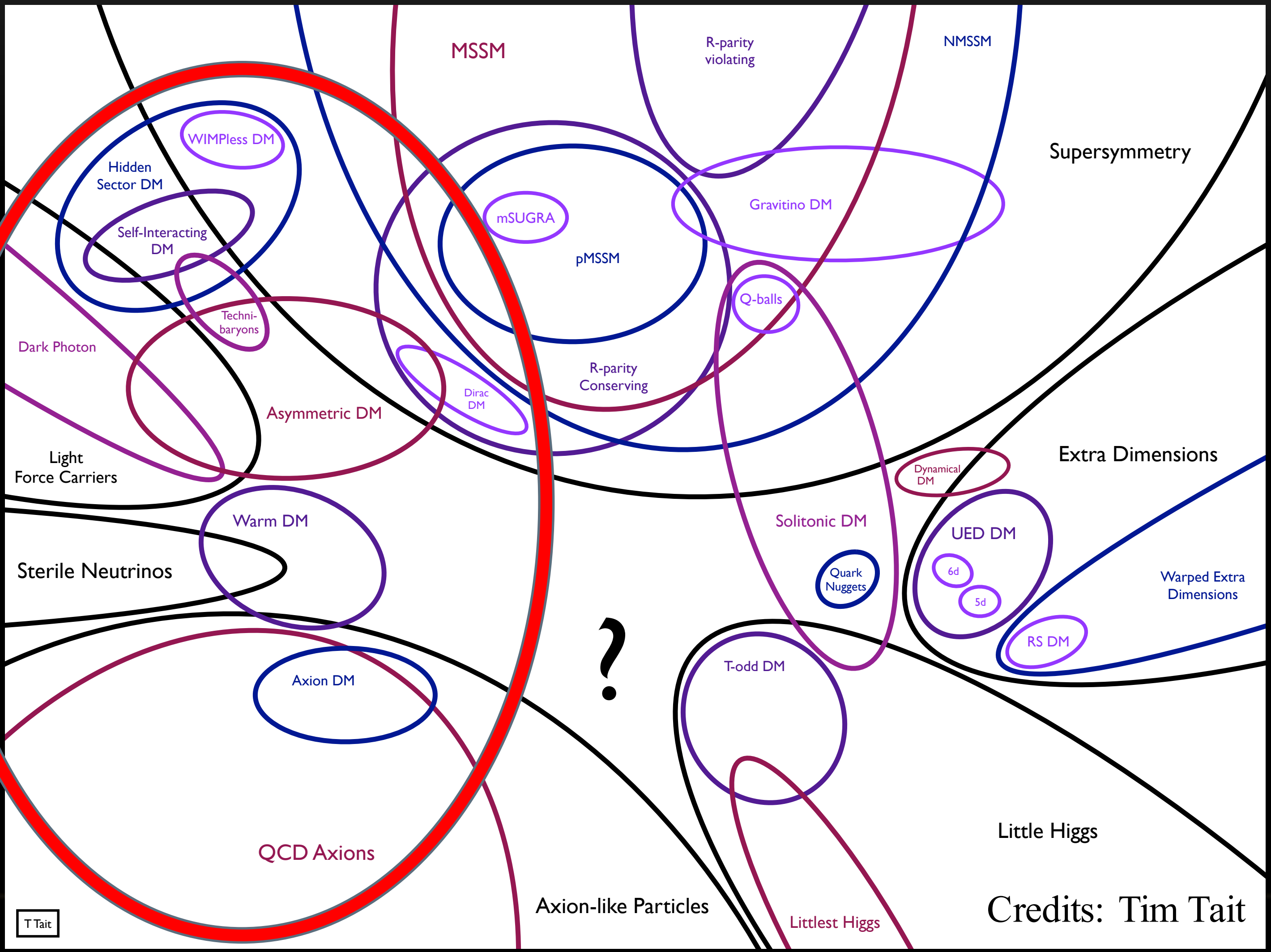

With contributions from:
Jesús Zavala, Mark Vogelsberger
Kris Sigurdson, Torsten Bringmann,
Christoph Pfrommer

# Dark Matter: what is it, and what it isn't

- Dark matter is primarily an astrophysical and cosmological problem.
- It is not primarily a particle physics problem, although it can easily be accommodated within many extensions of the Standard Model.
- Consensus: some kind of new particle(s).


"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

# Dark Matter: Possible Ideas




Credits: Tim Tait

# Non-Standard Dark Matter: A Case Study

## SELF-INTERACTING DARK MATTER


ERIC D. CARLSON
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138

MARIE E. MACHACEK
Department of Physics, Northeastern University, Boston, MA 02115

AND

LAWRENCE J. HALL
Department of Physics, University of California; and Theoretical Physics Group, Physics Division,
Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, CA 94720



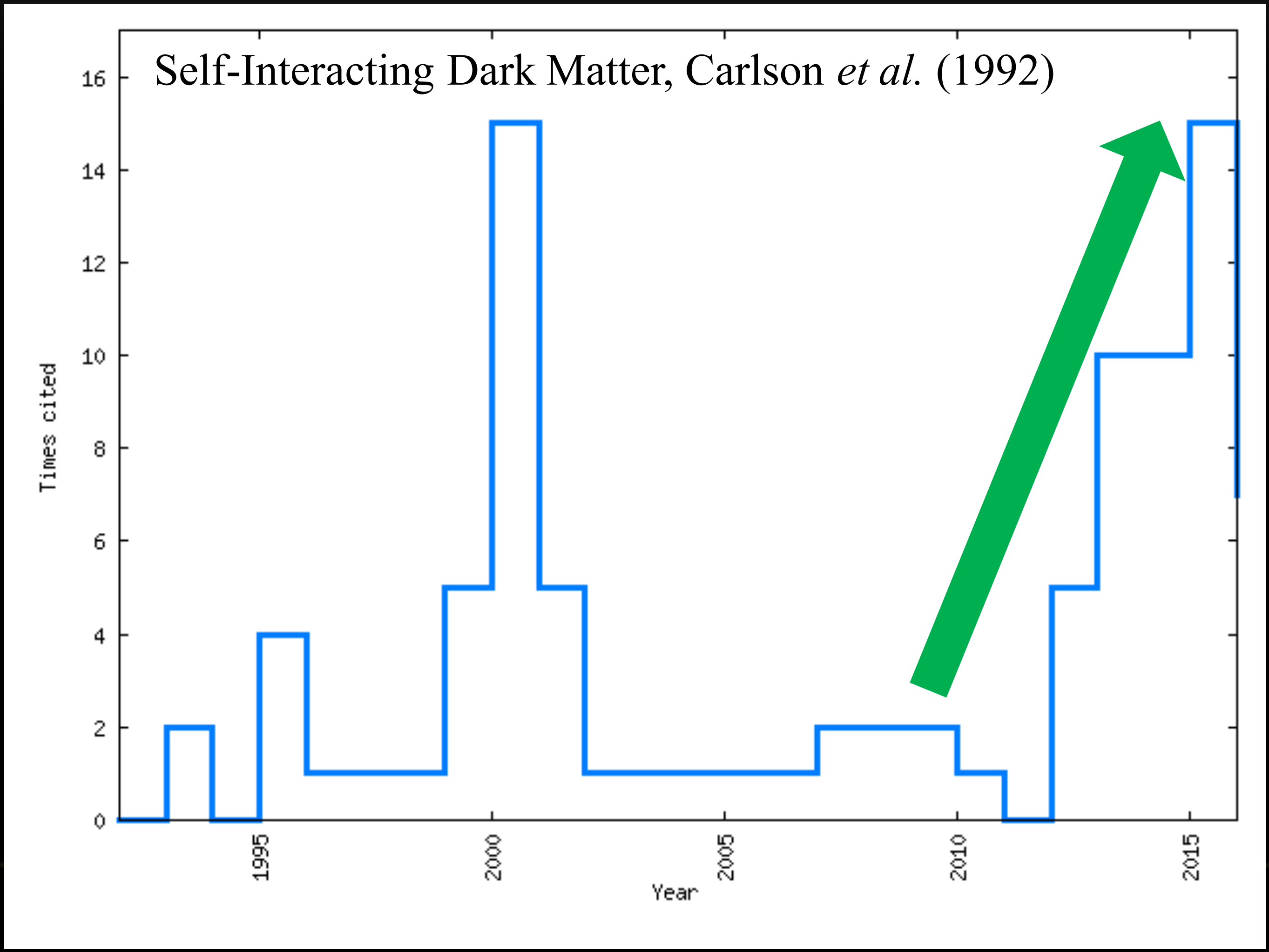
*Received 1992 March 17; accepted 1992 April 20*



### ABSTRACT

A new type of dark matter is considered. As with cold dark matter, when the dark matter is nonrelativistic it does not couple to the electron-photon plasma, so its entropy per comoving volume is fixed. The new feature is that there is a cosmological era where number-changing reactions keep the dark matter in chemical equilibrium so that the chemical potential vanishes. This has several interesting consequences: during this era the dark matter cannibalizes its rest mass to keep warm, its temperature dropping only logarithmically with scale. The energy density and density perturbations of the dark matter also have unusual scale dependences, modified by logarithms compared to usual cold dark matter. We have done a general study of such self-interacting dark matter to identify the interesting ranges for its mass, coupling, and entropy. There are two consequences of this scheme which are particularly noteworthy. The unusual evolution of energy density and density perturbations allows for the possibility of decreasing the predicted anisotropies in the cosmic microwave background by a factor of 2 or more. This dark matter allows a completely new scheme for processing density perturbations. The theory introduces a new cosmological mass scale: the Jeans mass when the number-changing processes decouple. Perturbations on this supercluster scale are the first to go nonlinear. Unlike hot dark matter, density perturbations on galactic scales are not negligible.

# Non-Standard Dark Matter: A Case Study

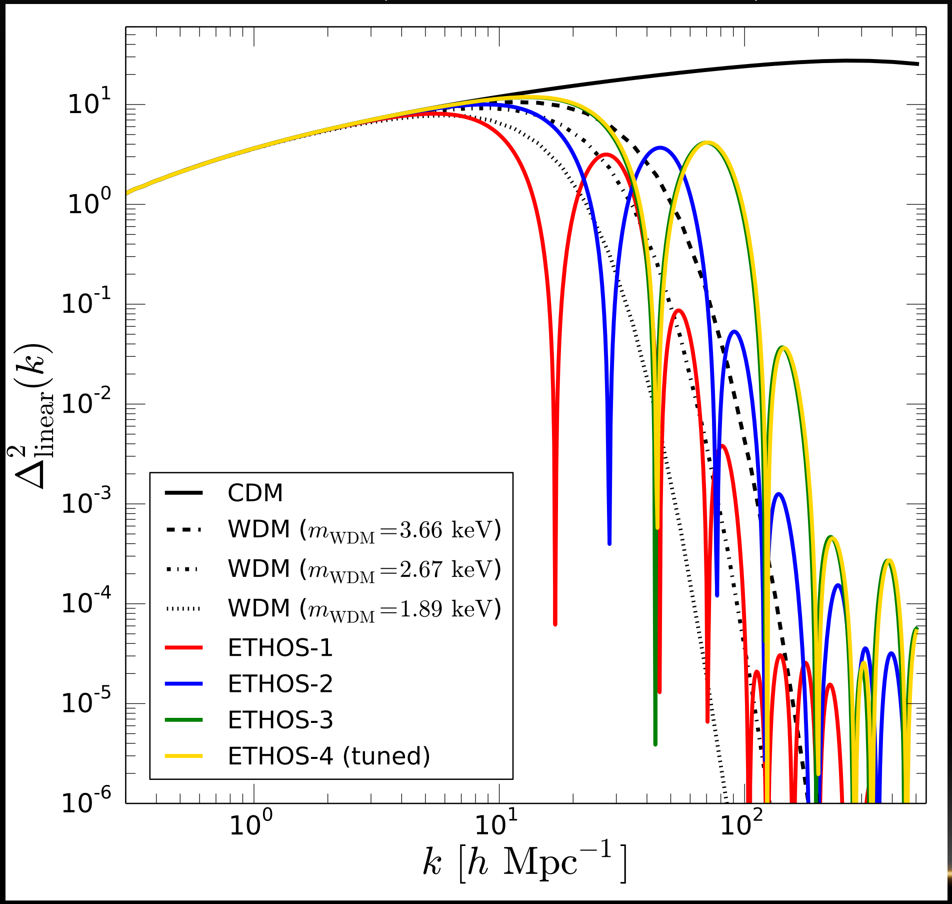


# Dark Matter: The score so far…

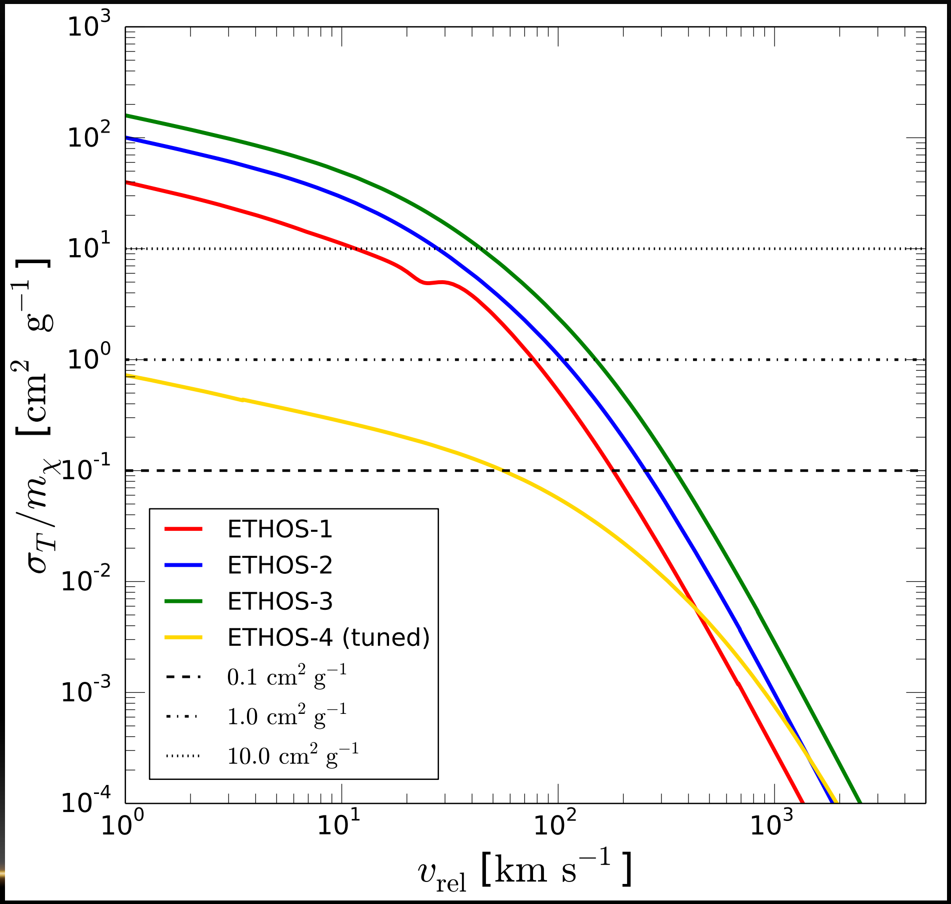
- We have used cosmological and astrophysical observations to establish the existence of dark matter.
- We would now would like to use similar (more precise!) observations to characterize the properties of dark matter.
- Need to classify and parametrize dark matter models with respect to their structure formation properties (ETHOS), rather then their intrinsic particle properties.

# Which kind of DM physics can we probe?

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



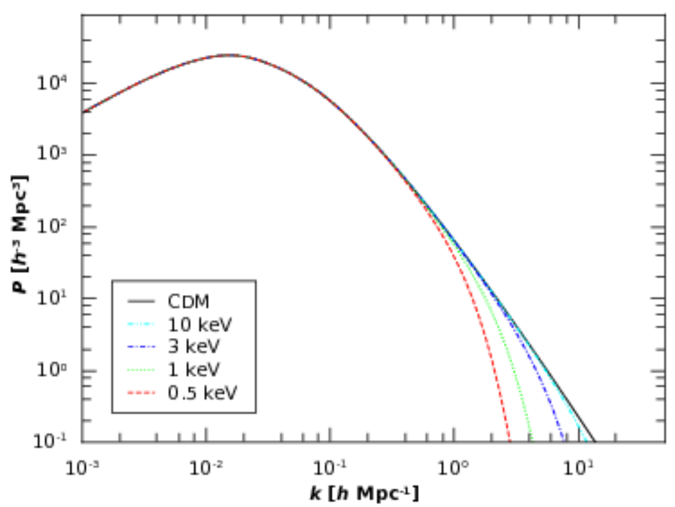

2) Physics affecting the dynamics of structure formation (self-interaction)



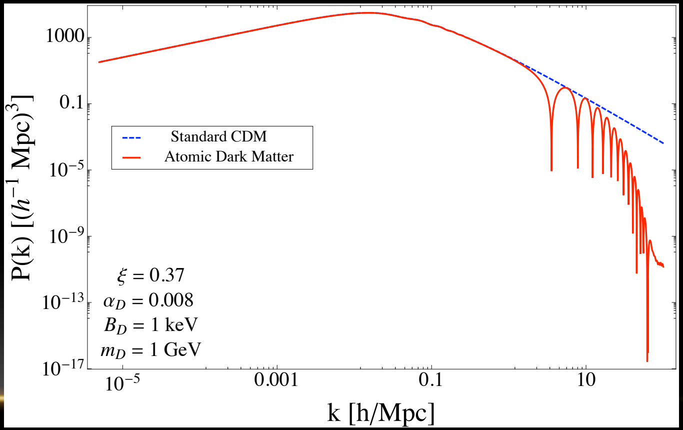

Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

# 1) Changing the Dark Matter Transfer Function: Two possible approaches

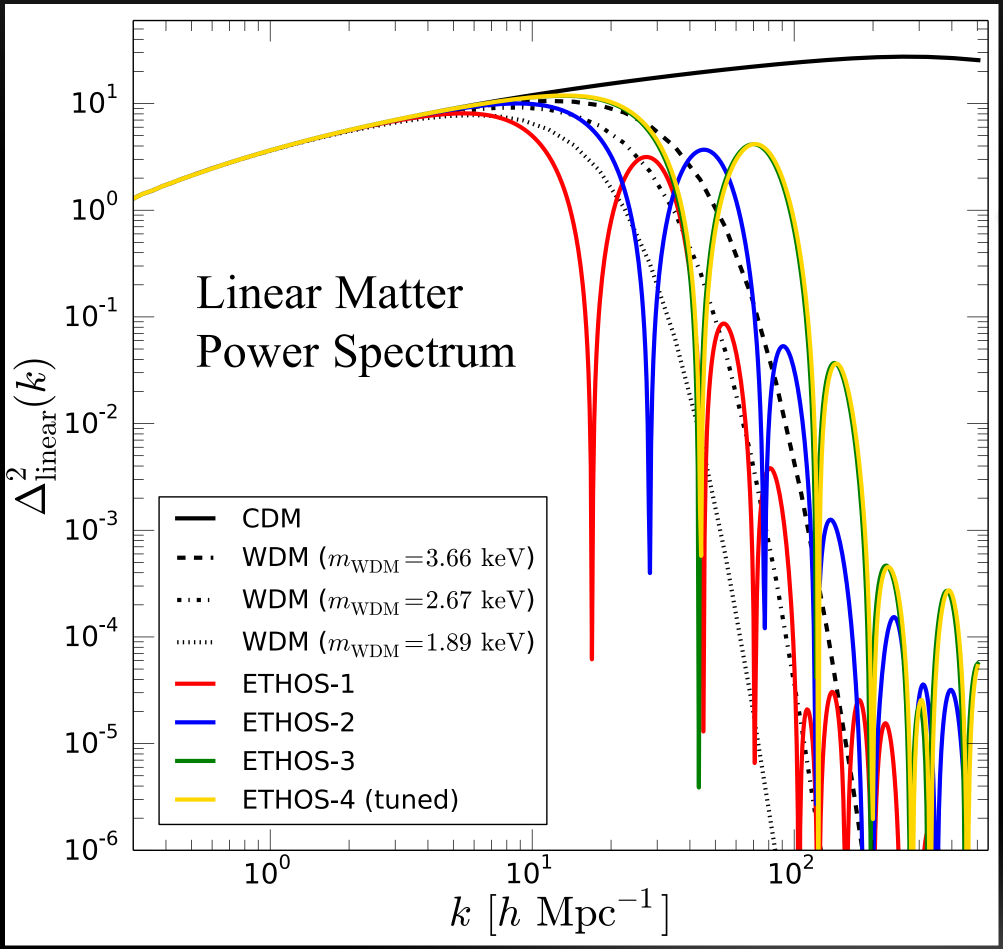
- Dark Matter is itself relativistic at early times (Warm dark matter)




- Dark Matter is coupled to relativistic degrees of freedom at early times.

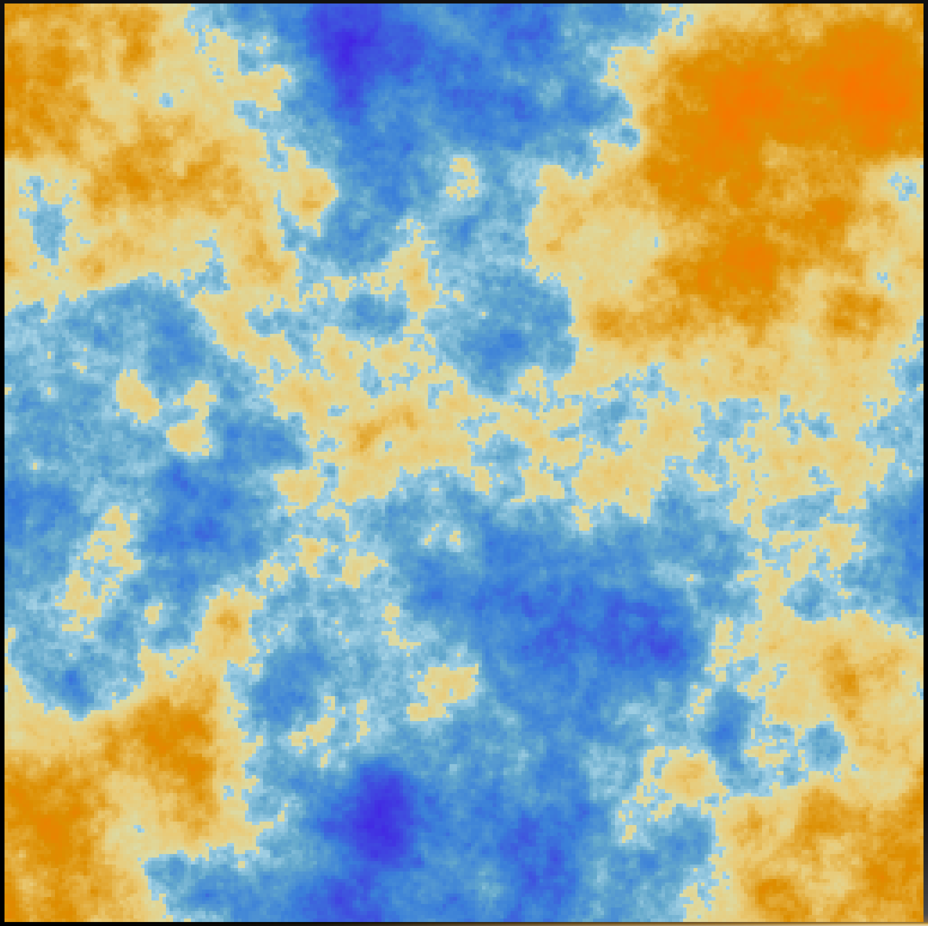


# Important: On sub-galactic scales, the DM transfer function is largely unconstrained!

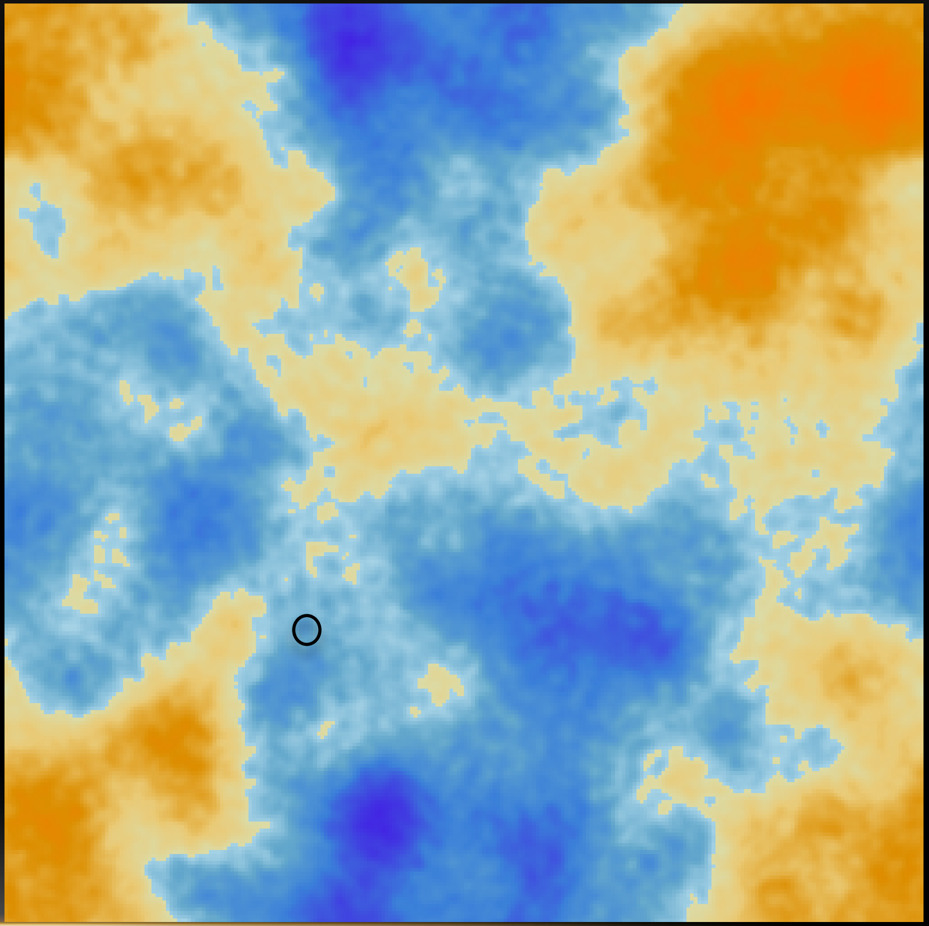



# Predictions for late-decoupling dark matter

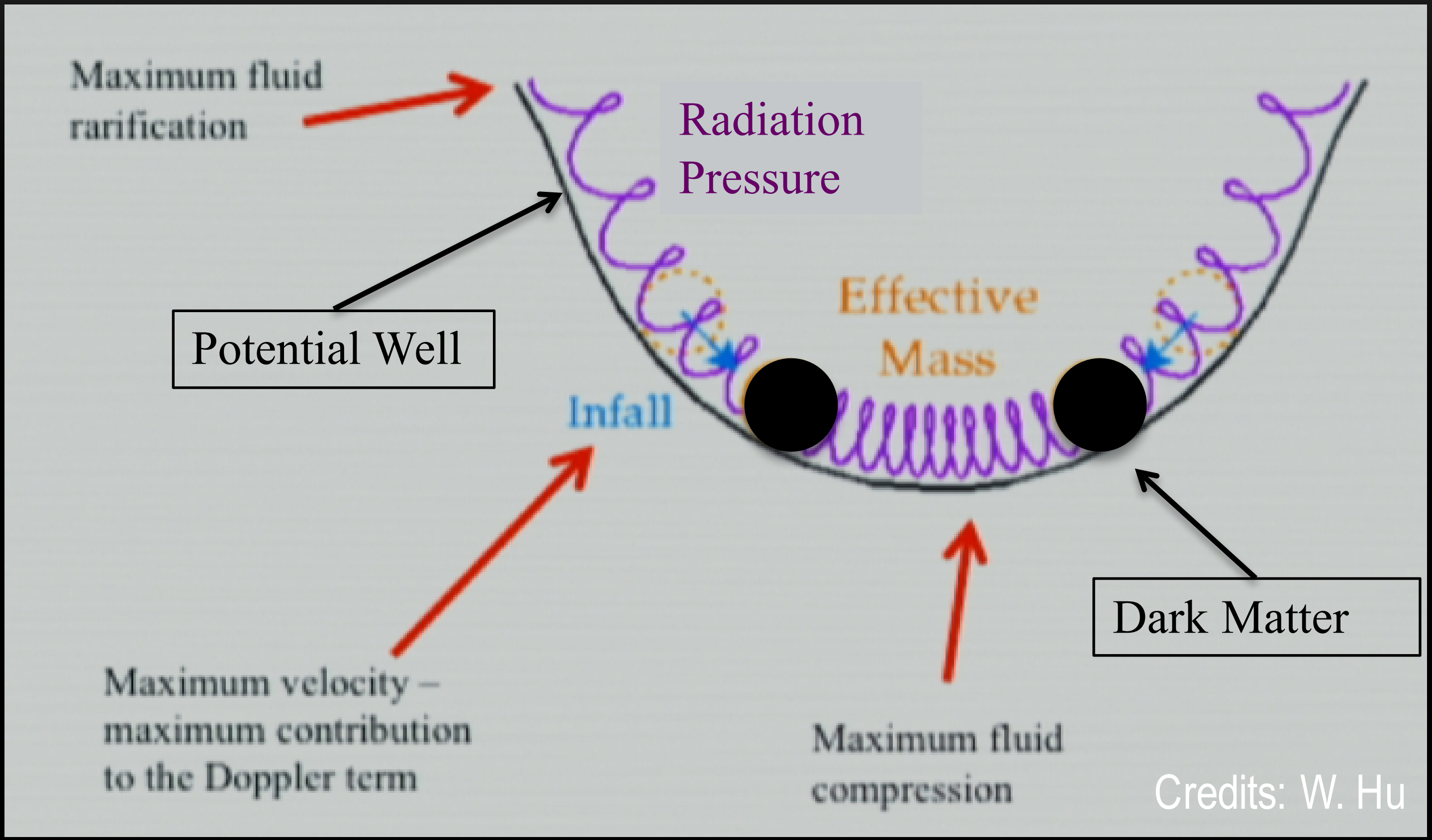
Cold DM



Late-decoupling DM

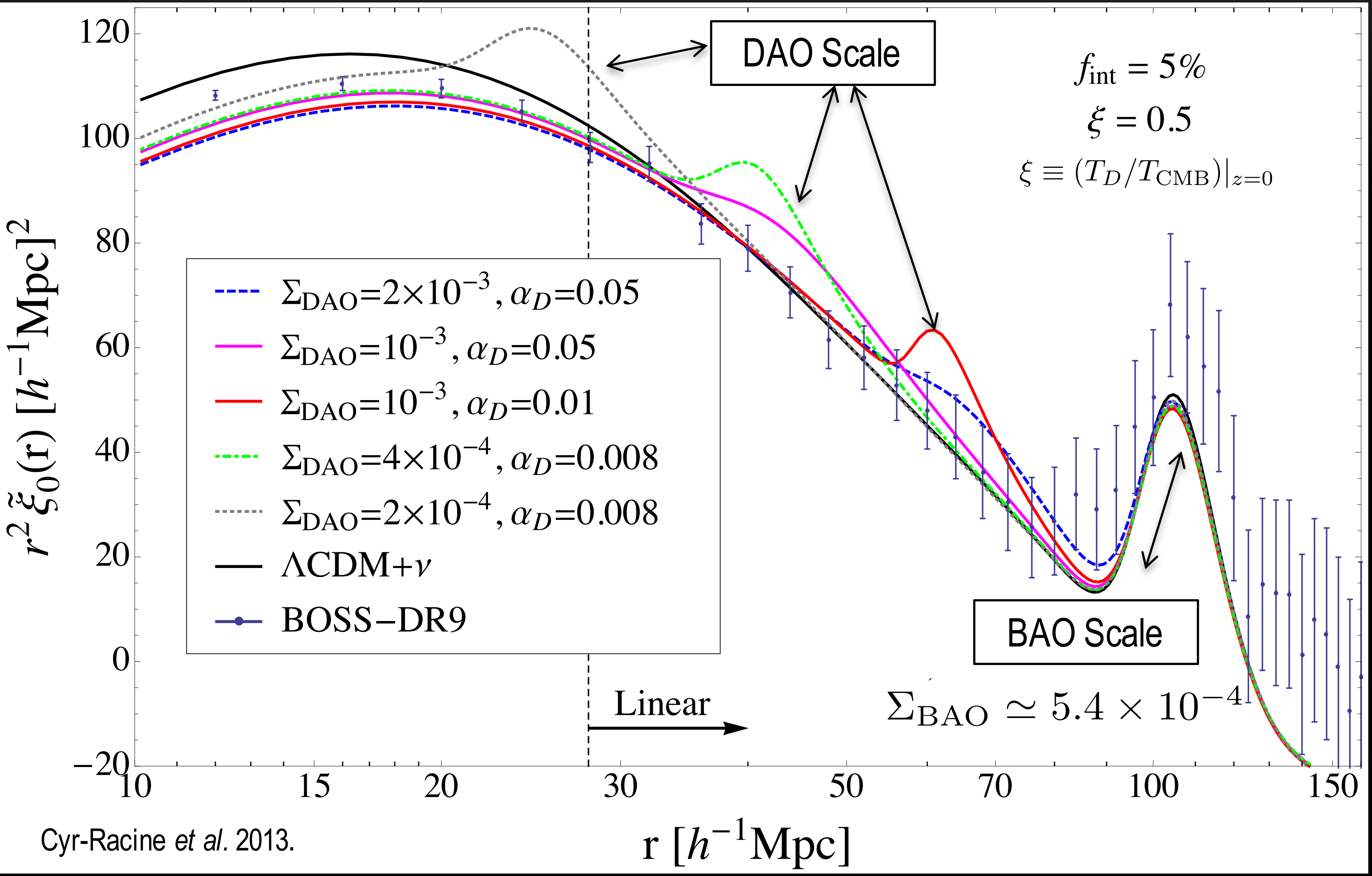


# Relevant Physics: Dark Matter “Sound”



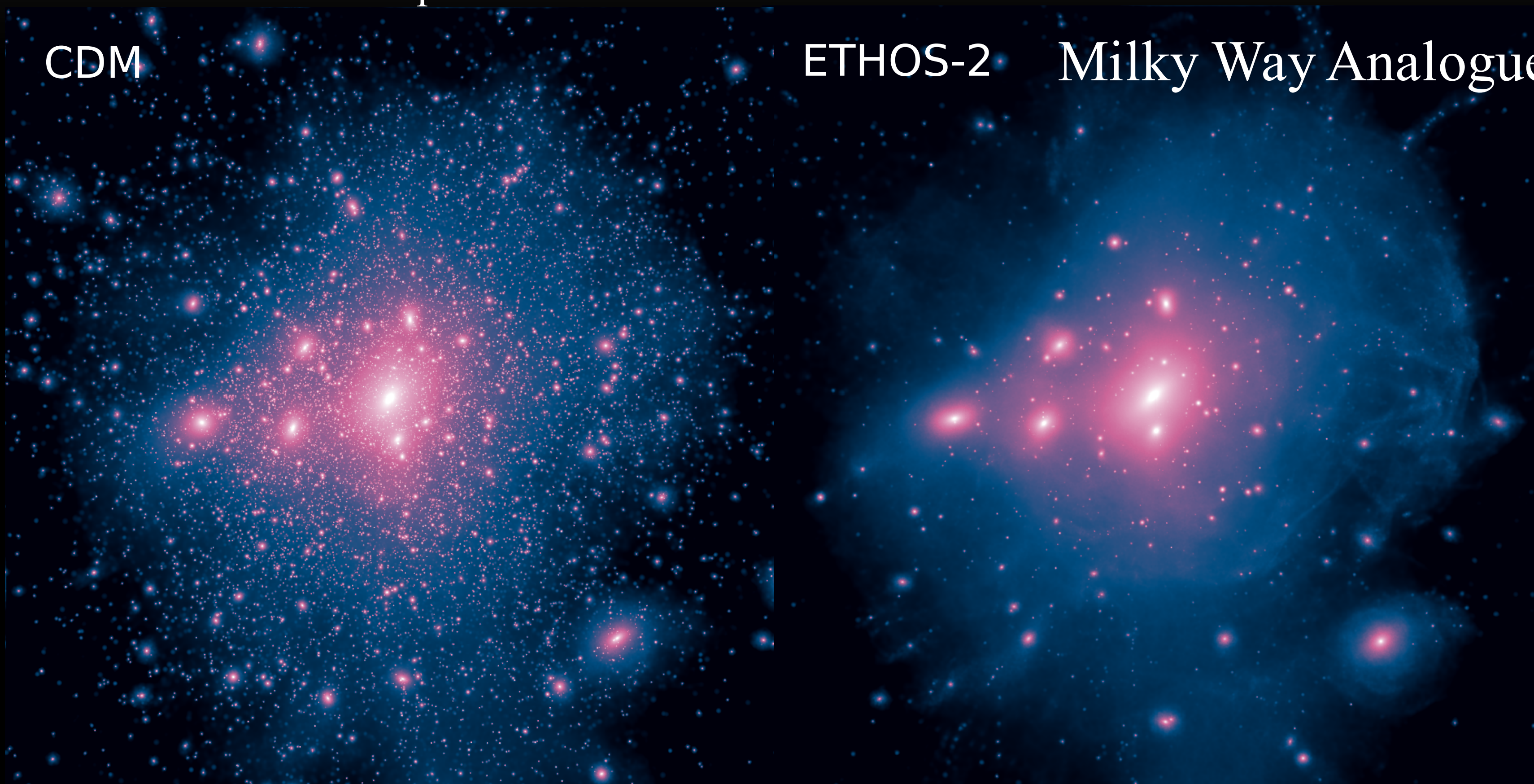

Gravitationally-sourced acoustic waves

# Dark Acoustic Oscillations (DAO)



# Changing the dark matter transfer function really matters for small-scale structures!

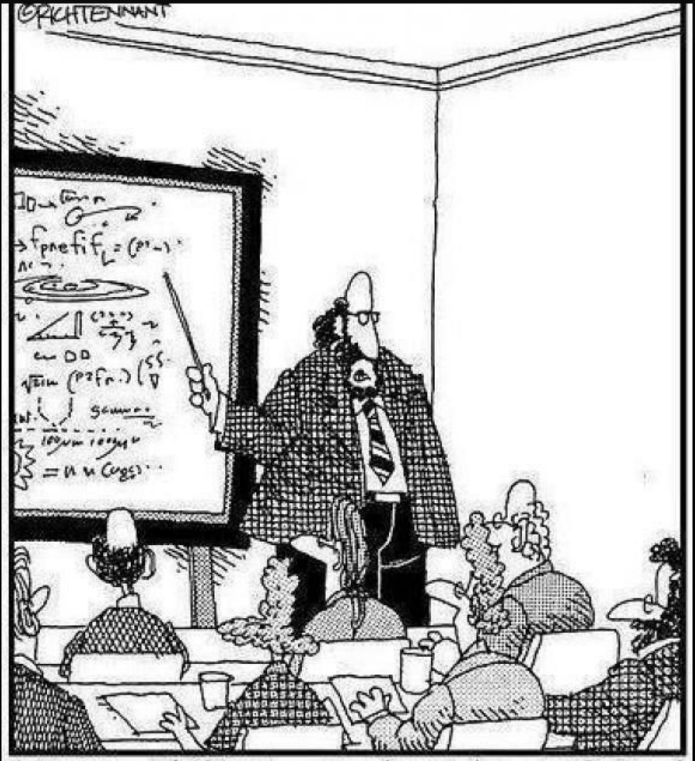
500 kpc




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

# Many more possibilities for dark matter physics to be relevant to structure formation!

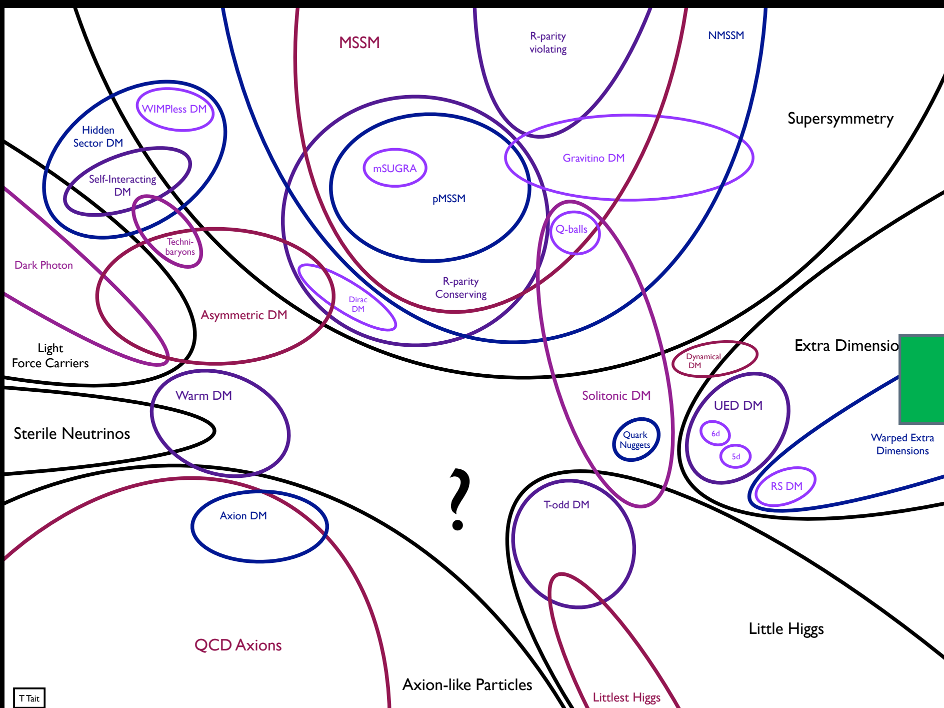
- Dark matter decay/annihilation.
- Phase transition/condensation.
- < insert you favorite model here >
- Etc.




"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

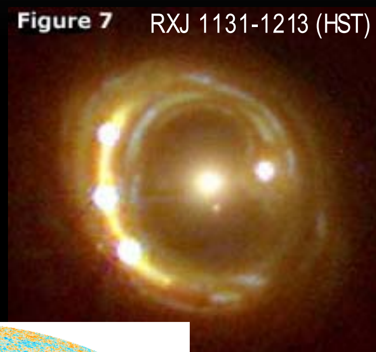
# From Dark Matter Physics to Predictions

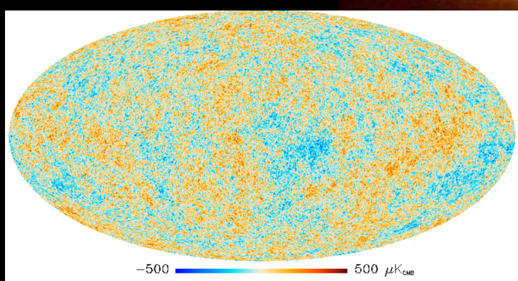
- So far, we have focused on making structure-formation predictions in relevant dark matter models.



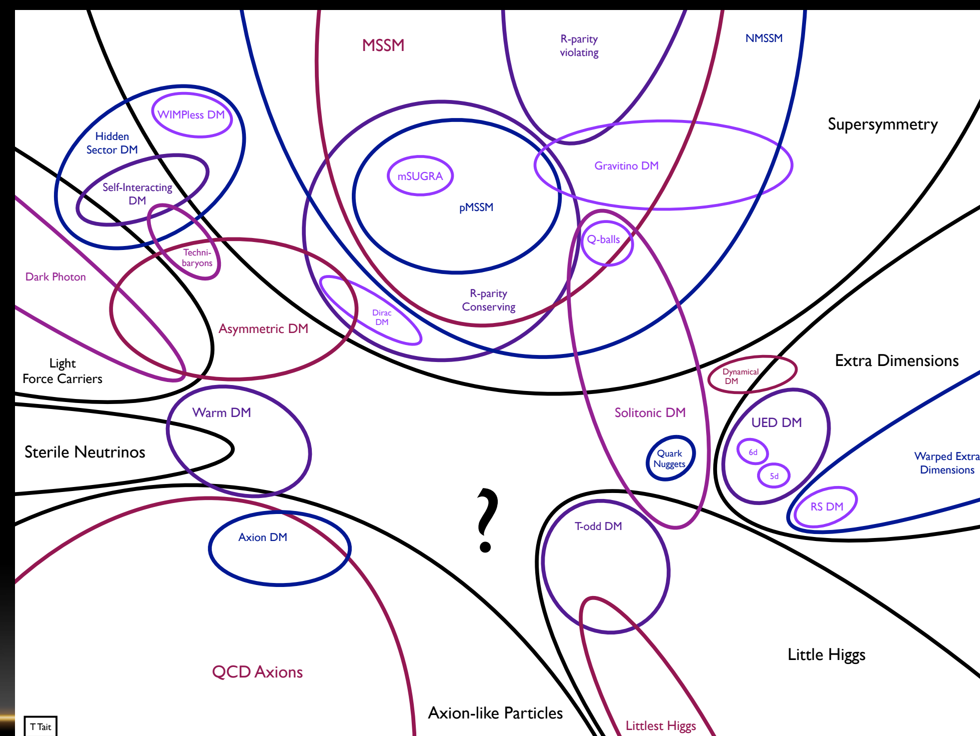

# From Observations to Dark Matter Physics

- How do we infer the physics of dark matter from observations?




???



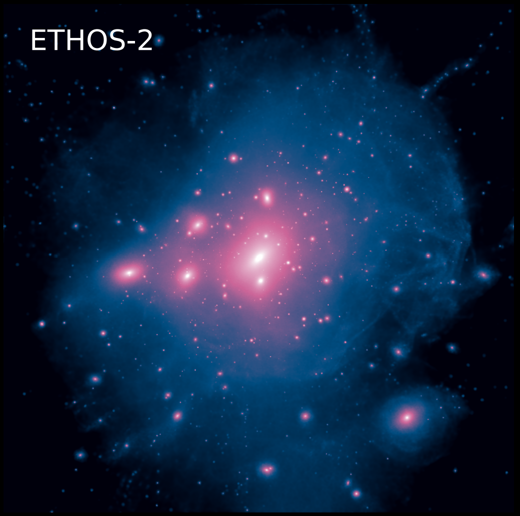
# NEEDED:

A classification of dark matter theories according to their structure formation properties.

# ETHOS: the Effective THeory Of Structure formation

- ETHOS allows the classification of dark matter theories according to their structure formation properties rather than their intrinsic particle properties.

$$\Xi_{\rm ETHOS} = \left\{ \omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{ \frac{\langle \sigma_T \rangle_{v_{M_i}}}{m_\chi} \right\} \right\}$$

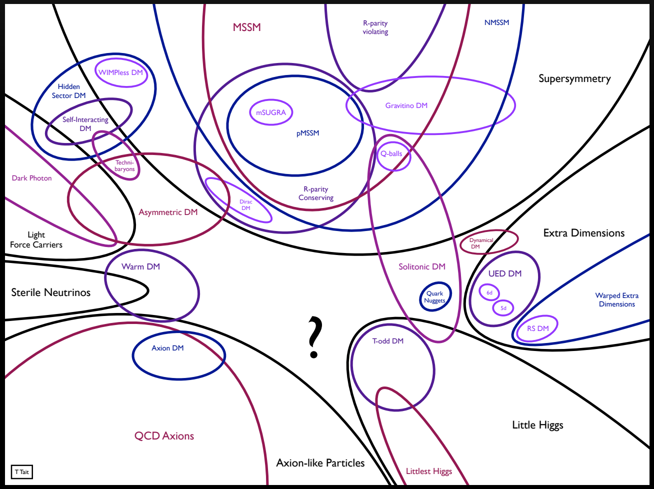


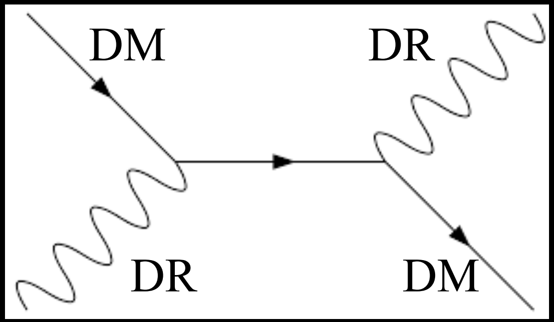

- All dark matter particle models that map to a given effective ETHOS model can be constrained at the same time.

Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349
Cyr-Racine, Sigurdson, Zavala +, arXiv:1512.05344

# ETHOS: First Step

- In the first paper, we are primary concerned with dark matter having significant interactions with relativistic species.
- These models are well-motivated in the context of self-interacting dark matter.
- These models are characterized by a non-CDM matter power spectrum and self-interaction at late times inside halos.




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

# Classification of dark matter theories according to their structure formation properties

- Where does the particle physics of DM enter the problem?

Dark Matter Equations

$$\dot{\delta}_\chi + \theta_\chi - 3\dot{\phi} = 0,$$
$$\dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = \dot{\kappa}_\chi \left[\theta_\chi - \theta_{\rm DR}\right]$$

DM drag opacity

Dark Radiation Equations

$$\dot{\delta}_{\rm DR} + \frac{4}{3}\theta_{\rm DR} - 4\dot{\phi} = 0,$$
$$\dot{\theta}_{\rm DR} + k^2(\sigma_{\rm DR} - \frac{1}{4}\delta_{\rm DR}) - k^2\psi = \dot{\kappa}_{\rm DR-DM}\,(\theta_{\rm DR} - \theta_\chi),$$
$$\dot{\Pi}_{{\rm DR},l} + \frac{k}{2l+1}\left((l+1)\Pi_{{\rm DR},l+1} - l\Pi_{{\rm DR},l-1}\right) = \left(\alpha_l \dot{\kappa}_{\rm DR-DM} + \beta_l \dot{\kappa}_{\rm DR-DR}\right)\Pi_{{\rm DR},l},$$

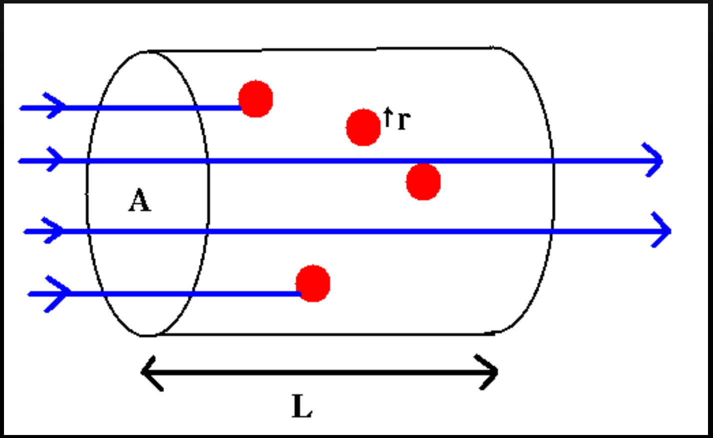
DR opacity

Angular coefficients

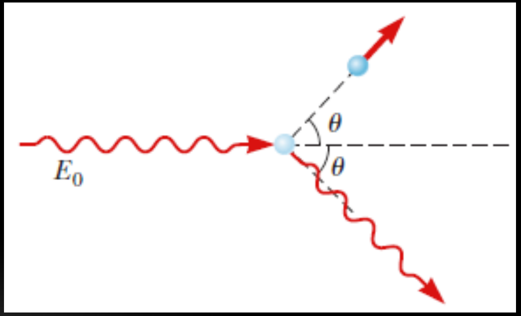
Cyr-Racine, Sigurdson, Zavala +, arXiv:1512.05344

# Where does the particle physics of DM enter the problem?

- Dark Matter drag opacity




- Dark radiation opacity
- Angular dependence of the scattering cross section
- Dark Matter sound speed $c_\chi^2$



# Classification of dark matter theories according to their structure formation properties

- Structure of the opacity terms:

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

Envelope Function

Opacity Coefficients

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

Momentum Conservation

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

# What does $a_n$ mean?

- The index $n$ is directly related to the momentum dependence of the scattering:

$$a_n \longrightarrow \sum |\mathcal{M}|^2 \propto \left(\frac{p_{\rm DR}}{m_\chi}\right)^{n-2}$$

- For example:

$$a_0 \longrightarrow \sum |\mathcal{M}|^2 \propto \frac{1}{p_{\rm DR}^2}$$

$$a_2 \longrightarrow \sum |\mathcal{M}|^2 \propto \text{const.}$$

$$a_4 \longrightarrow \sum |\mathcal{M}|^2 \propto p_{\rm DR}^2$$

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

# ETHOS Parametrization: P(k)

- We propose a simple parametrization that completely specifies the shape of the linear matter power spectrum.

DR Opacity Coefficients

$$\left\{\omega_{\rm DR}, \{a_n, \alpha_l\}, \{b_n, \beta_l\}, \{d_n, m_\chi, \xi\}\right\} \to P_{\rm lin.,\ matter}(k)$$

DM Opacity Coefficients

DM Temperature Evolution: only important for sound speed term.

$\xi = (T_{\rm DR}/T_{\rm CMB})|_{z=0}$

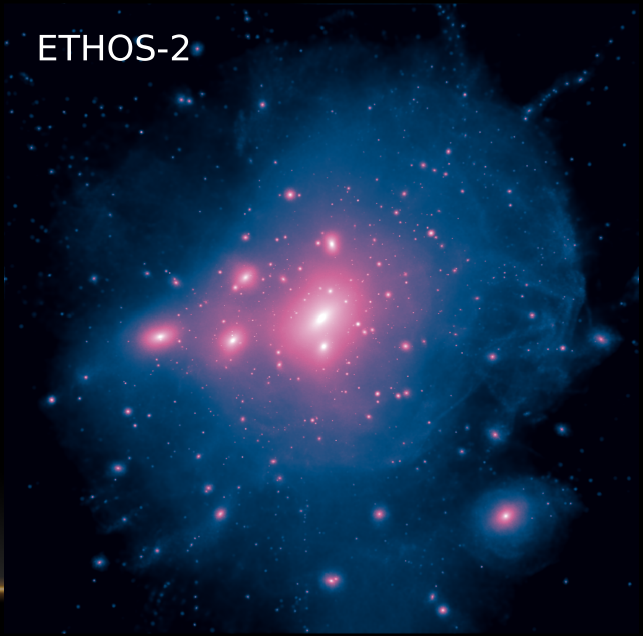
$\omega_{\rm DR} \equiv \Omega_{\rm DR} h^2$

https://bitbucket.org/franyancr/ethos_camb.

# ETHOS: Brief Summary

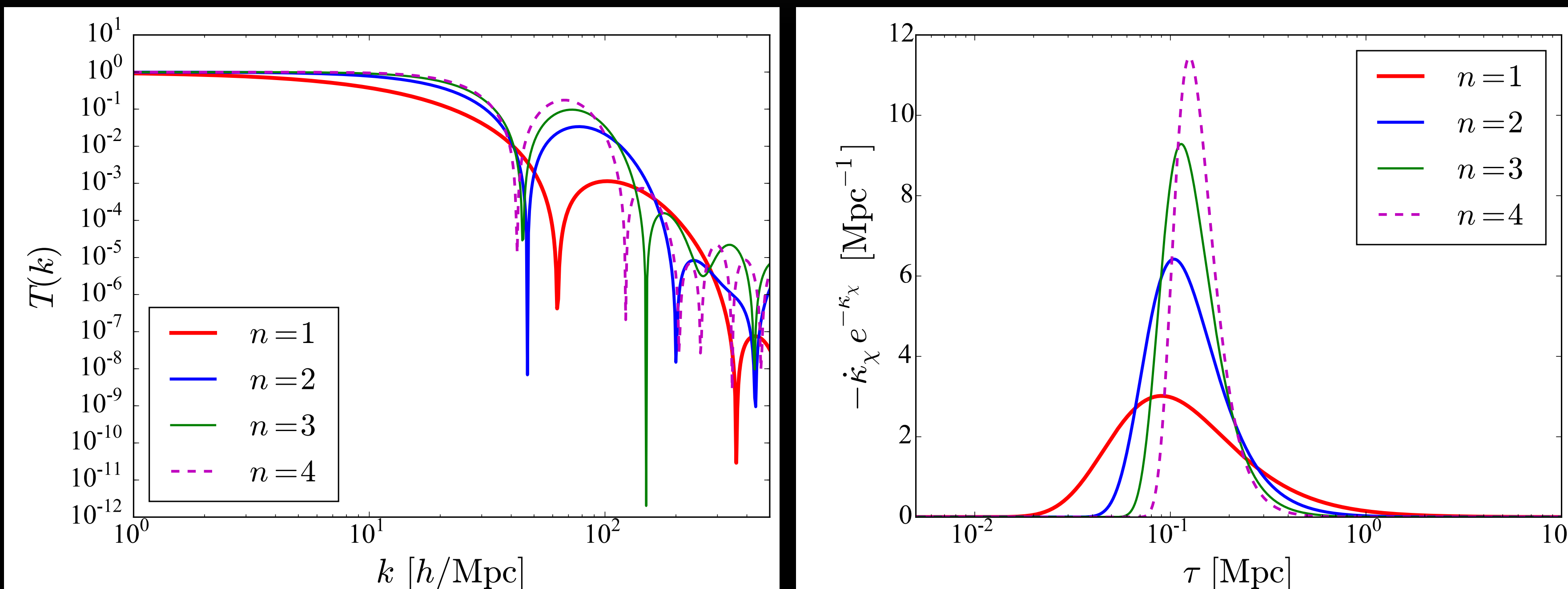
- Starting from first principles, we have identified where the key DM physics enters the evolution of cosmological perturbations.
- We have proposed a simple parametrization for the generic case of DM-DR interaction.

$$\Xi_{\rm ETHOS} = \left\{ \omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{ \frac{\langle \sigma_T \rangle_{v_{M_i}}}{m_\chi} \right\} \right\}$$



# Applications

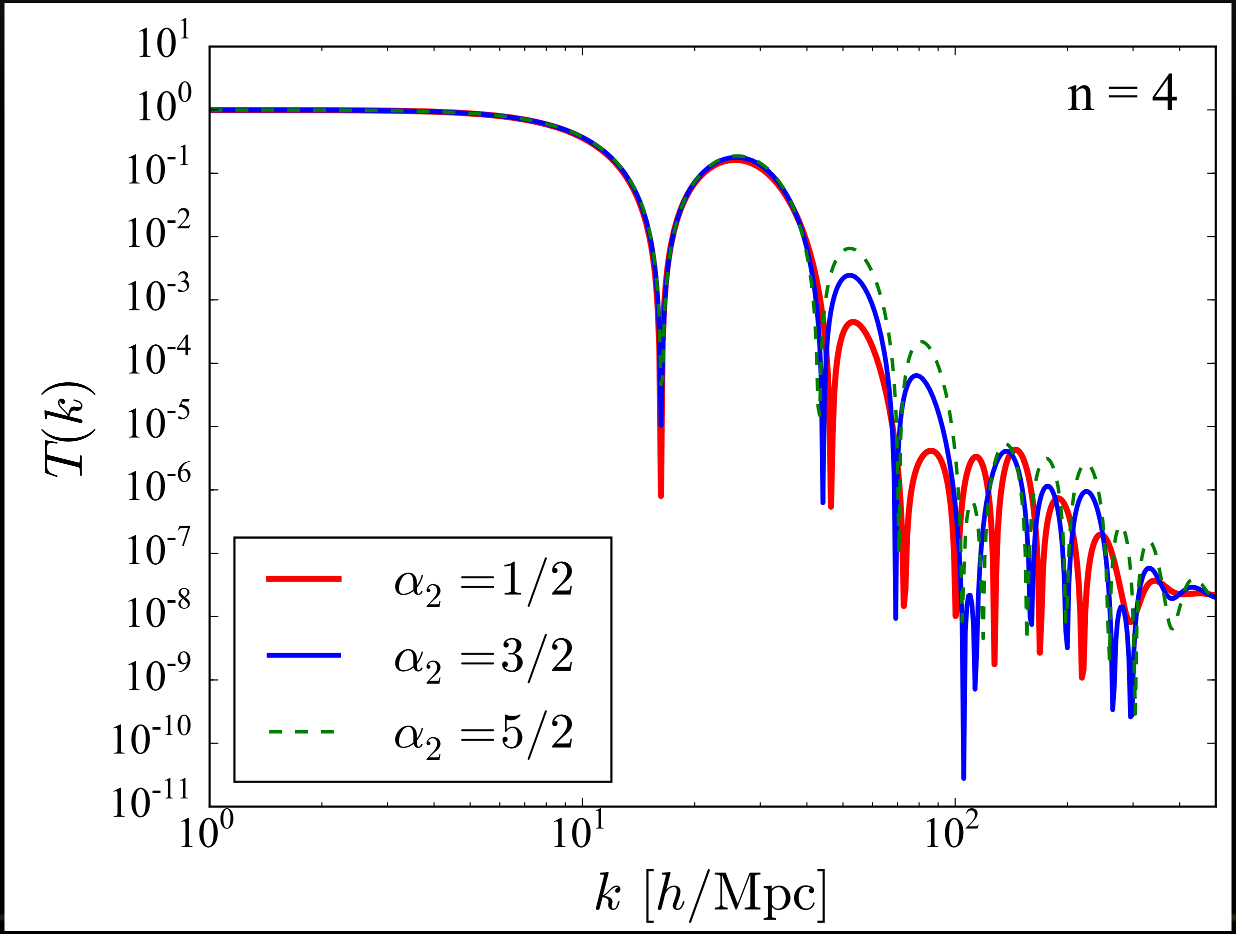
# Application I: Shape of linear matter power spectrum for different *n*




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

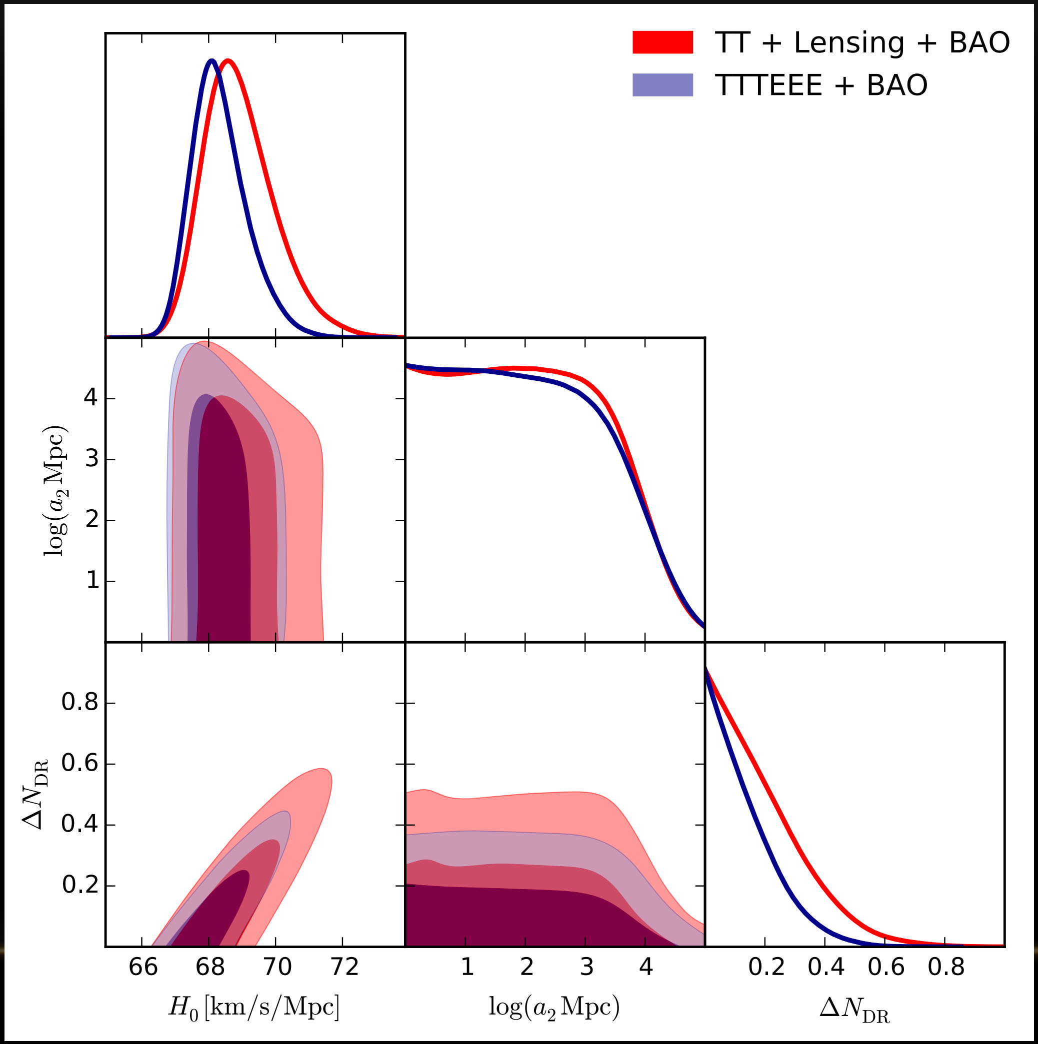
Cyr-Racine, Sigurdson, Zavala +, arXiv:1512.05344

# Application I: Shape of linear matter power spectrum for different $\alpha_l$

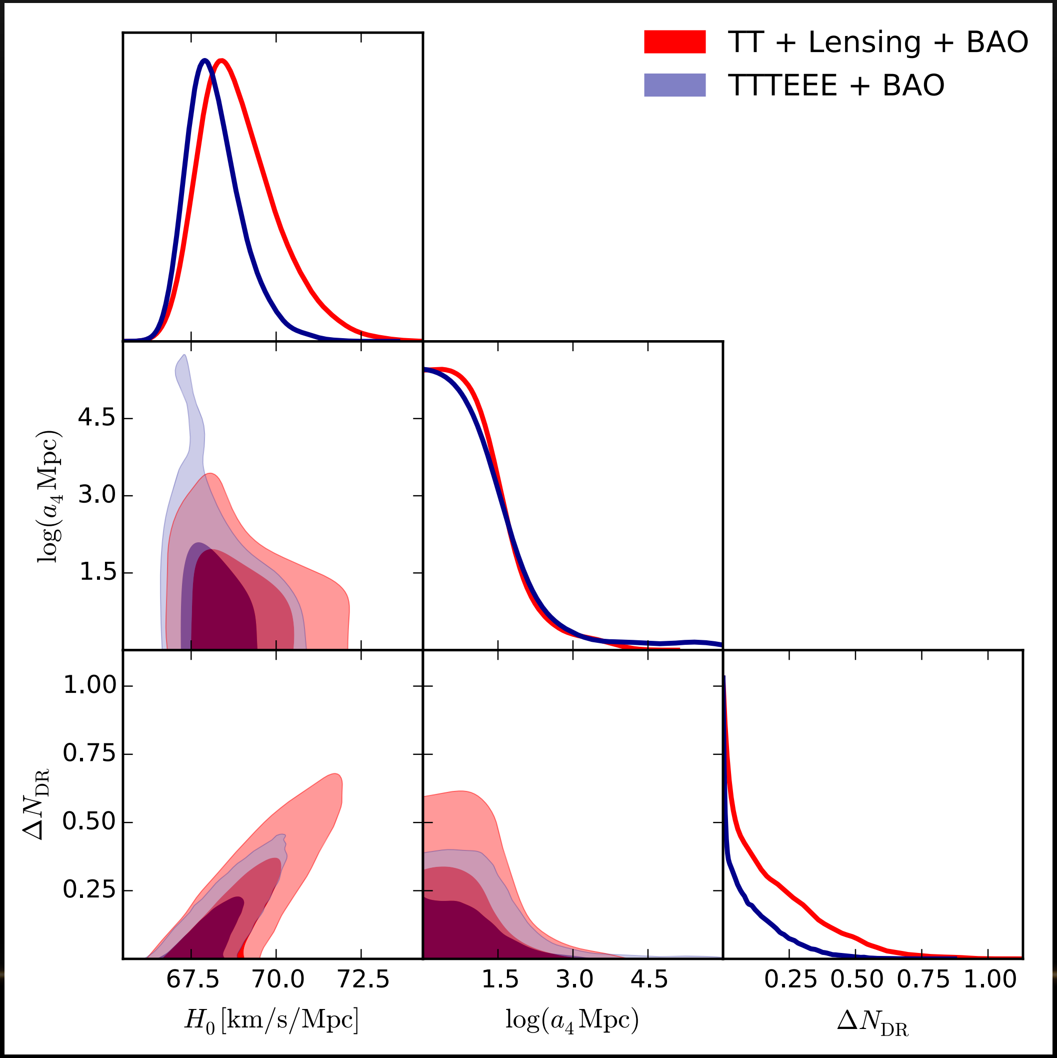



Cyr-Racine, Sigurdson, Zavala +, arXiv:1512.05344

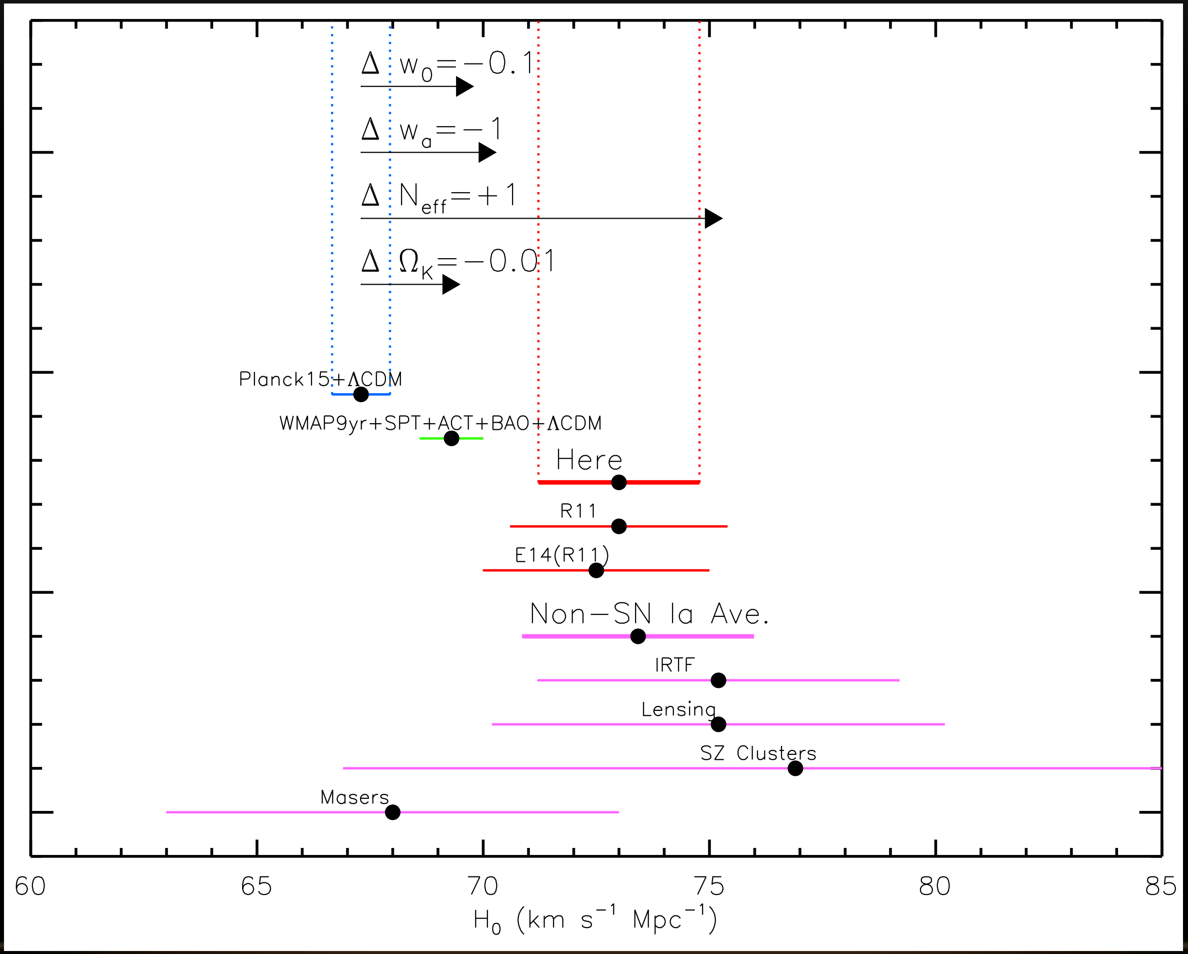
# Application II: parametrization for cosmological constraints from Planck



# Application II: parametrization for cosmological constraints from Planck

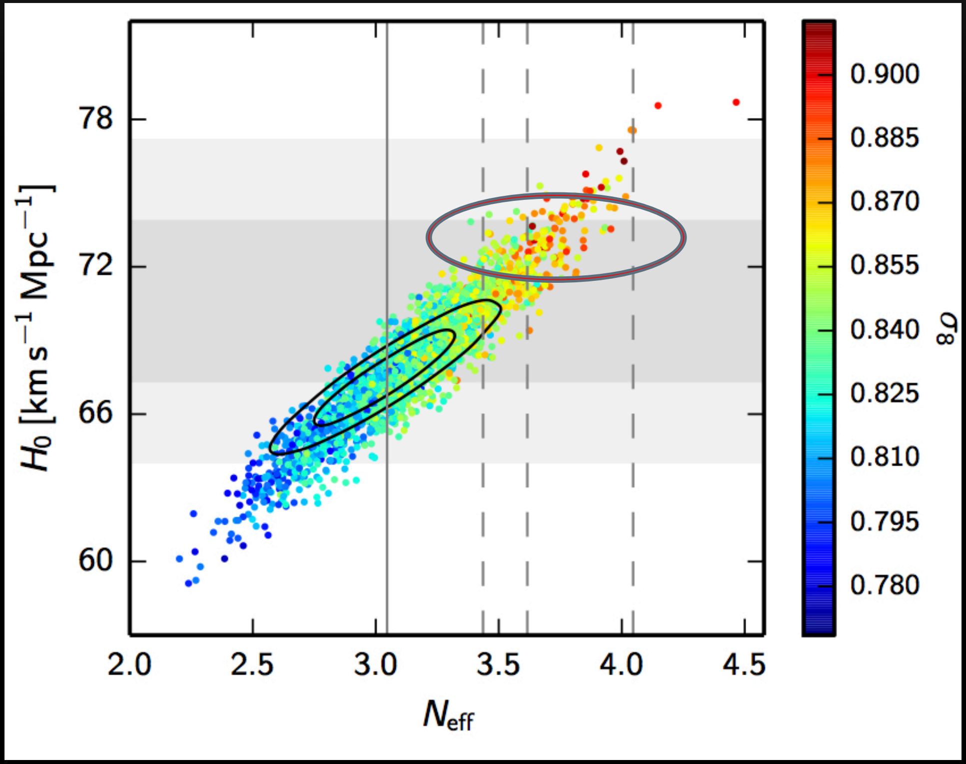


# Application III: Addressing tension in our cosmological model?




Riess et al. (2016)

# Application III: Addressing tension in our cosmological model?




Planck Collaboration XIII (2015)

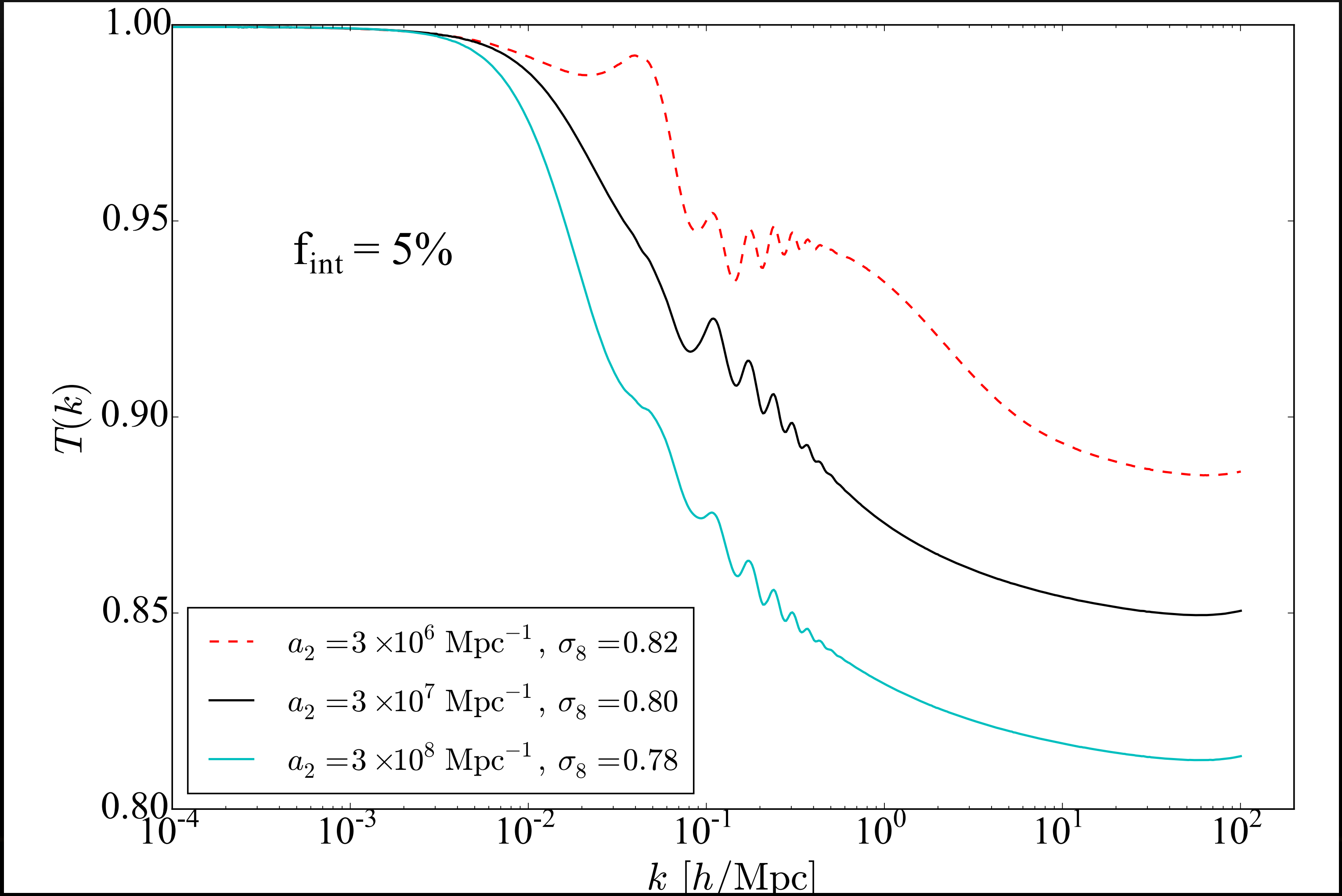
$\boldsymbol{\sigma}_8 \sim 0.88$

Meanwhile, LSS favors a lower value of $\boldsymbol{\sigma}_8$

$$\sigma_8(\Omega_{\rm m}/0.3)^{0.17} = 0.81 \pm 0.03$$

Mantz et al. (2014)

# Application III: Addressing tension in our cosmological model?



# ETHOS: Advantages and Future Work

- ETHOS provides a way to systematically parametrize deviations from the standard cold dark matter scenario.
- Our current implementation can capture many relevant cases, but we plan to expand it to capture more possible dark matter physics such as decay, annihilation, etc.

$$\Xi_{\rm ETHOS} = \left\{ \omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{ \frac{\langle \sigma_T \rangle_{v_{M_i}}}{m_\chi} \right\} \right\}$$

# Take-Home Message

- From an astrophysical perspective, there is a need to classify and parametrize dark matter models with respect to their structure formation properties.
- We have taken a first step in this direction with the ETHOS framework.
- We can now start to systematically investigate how the different relevant DM physics affects structure formation.
- Can now use the ETHOS framework to put model-independent constraints on DM physics.