From Dark Particle Physics to the Matter Distribution of the Universe

Aspen Particle Physics conference, March 21 2017

Francis-Yan Cyr-Racine

Postdoctoral Fellow

Department of Physics, Harvard University

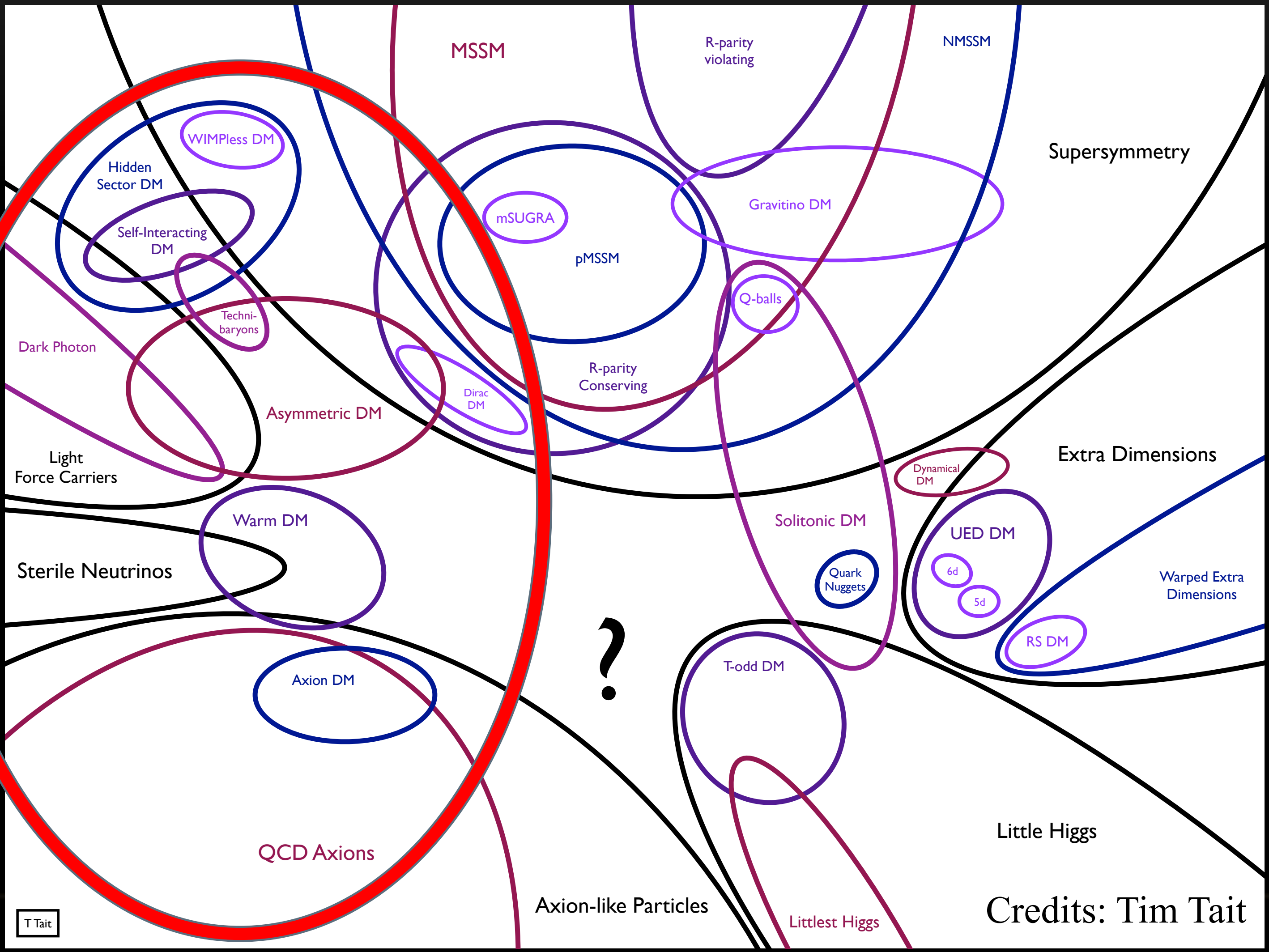
With contributions from:
Jesús Zavala, Mark Vogelsberger
Kris Sigurdson, Torsten Bringmann,
Christoph Pfrommer

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).

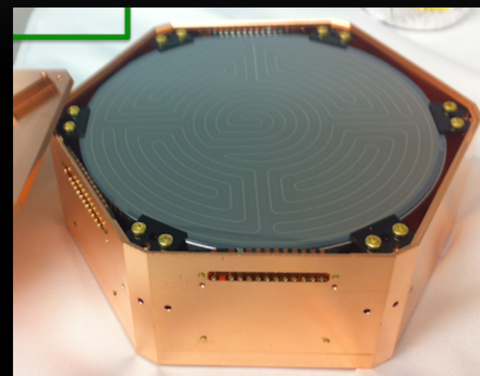
"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

Dark Matter: Possible Ideas

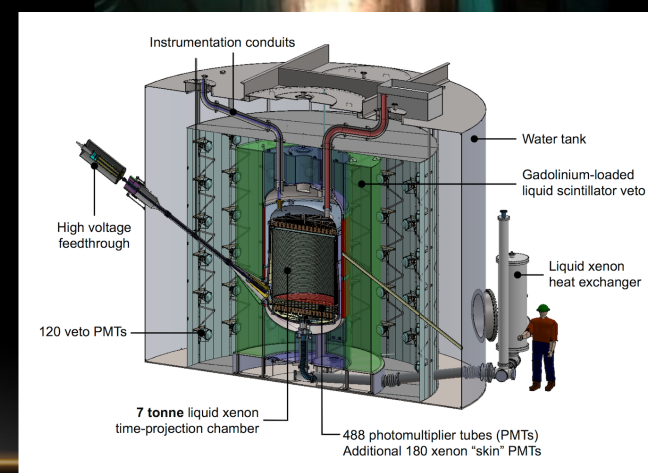


In dark matter science, hope for the best…

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



Xe
XENON
Dark Matter Project

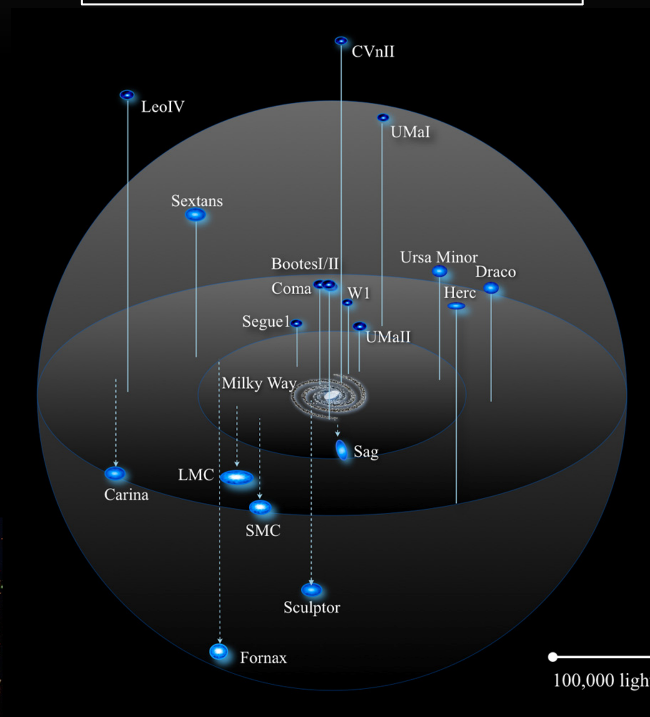


…but prepare for the worst!

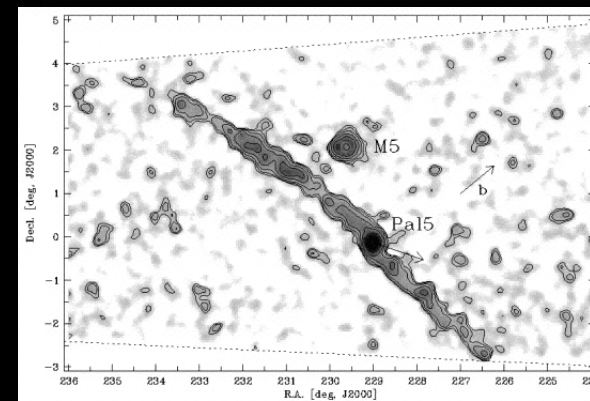
- Gravitational signatures might be all we can observe!

Gravitational Lensing

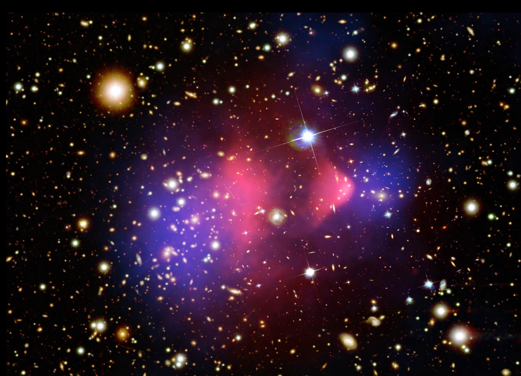
Dwarf galaxies



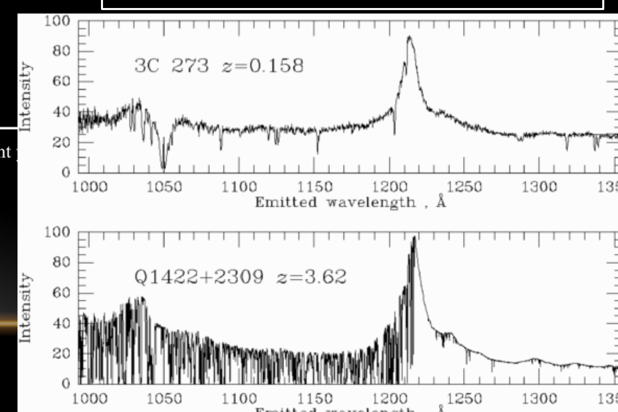
Stellar Streams



Merging Clusters

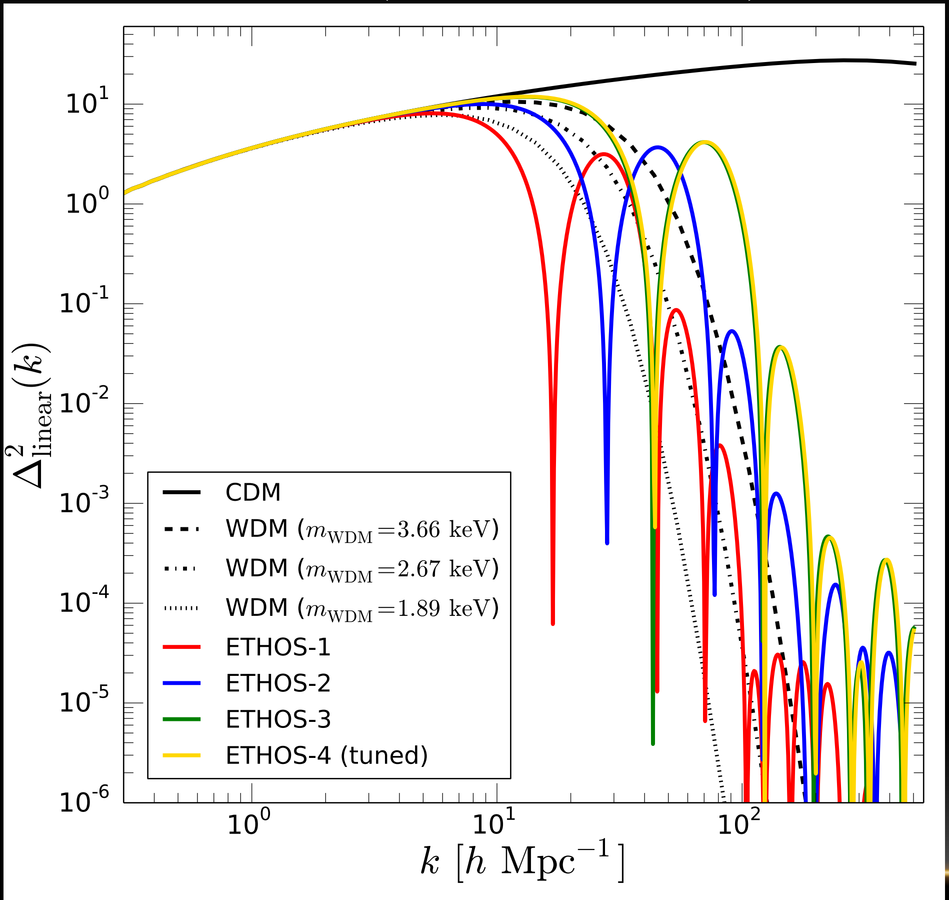


Lyman-alpha forest

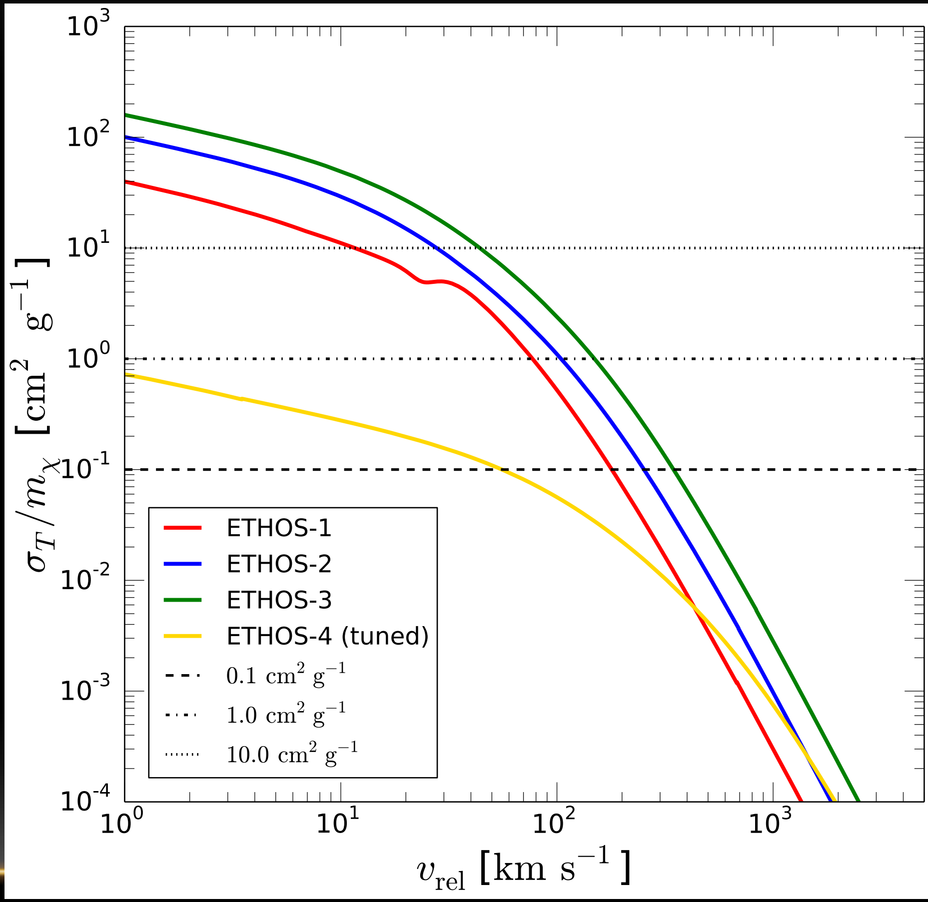


Which kind of DM physics can we probe?

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



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

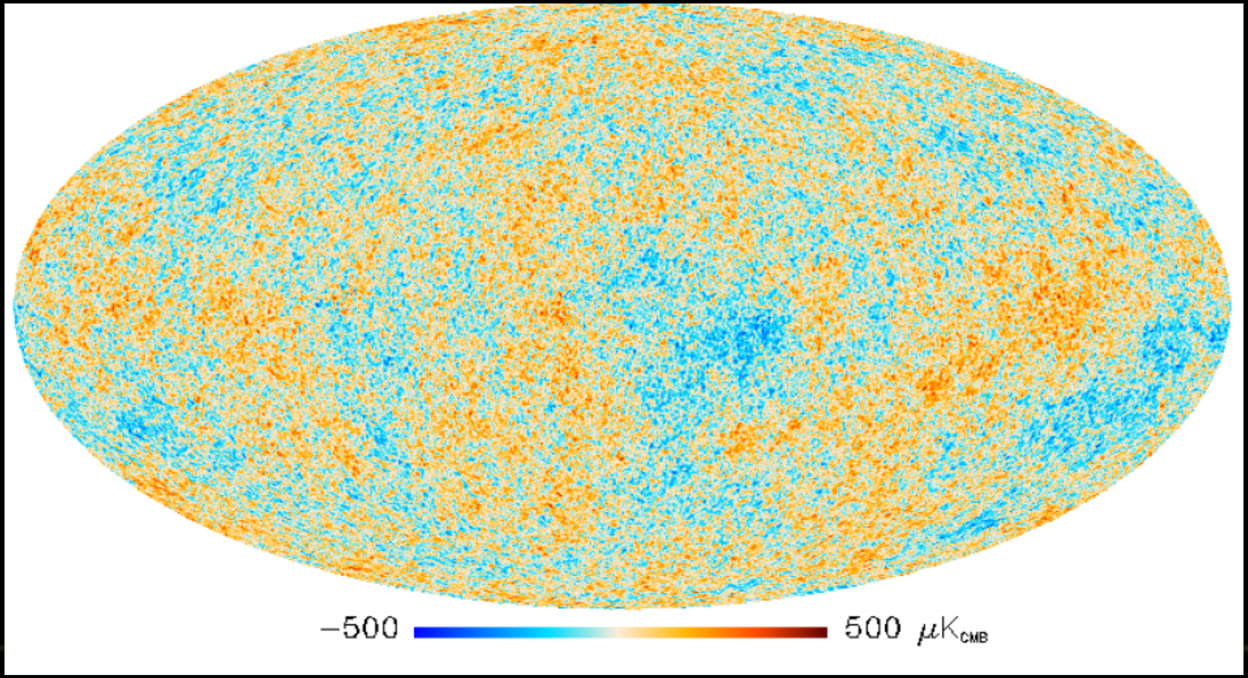


Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

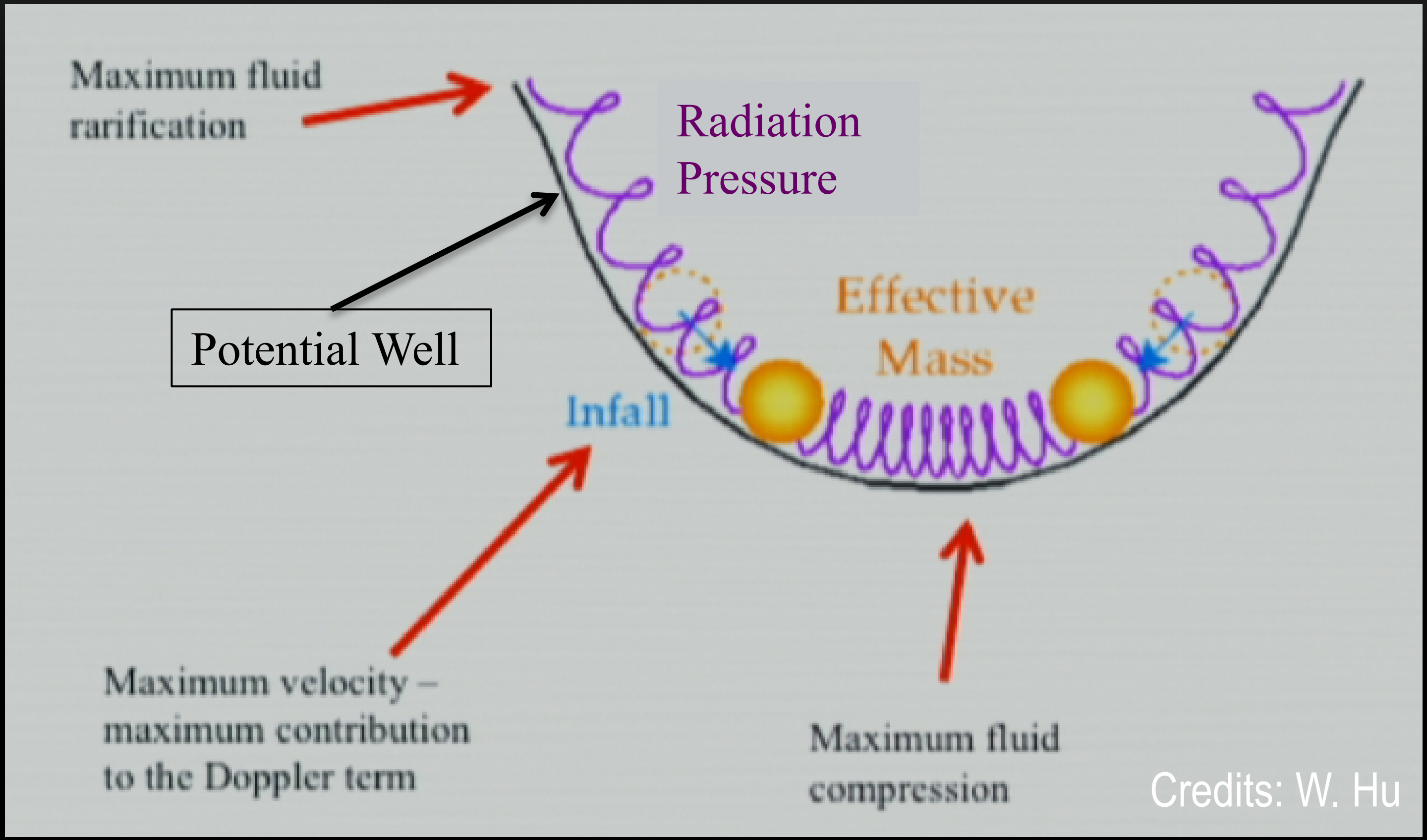
But small scales are messy…

Is there anything we can do with large scales?

Let's consider the CMB.

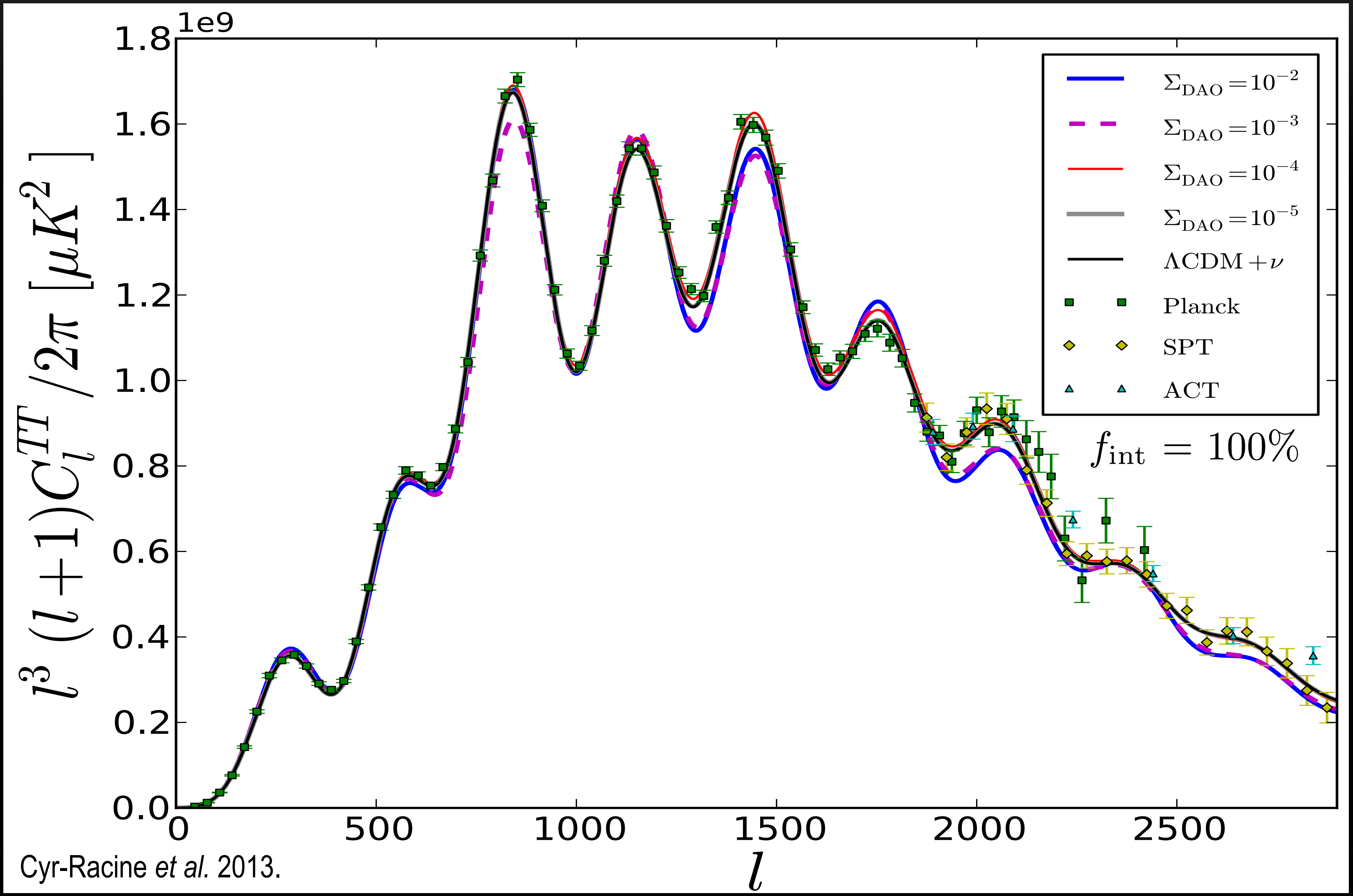


Probing the dark matter transfer function: Cosmic microwave background

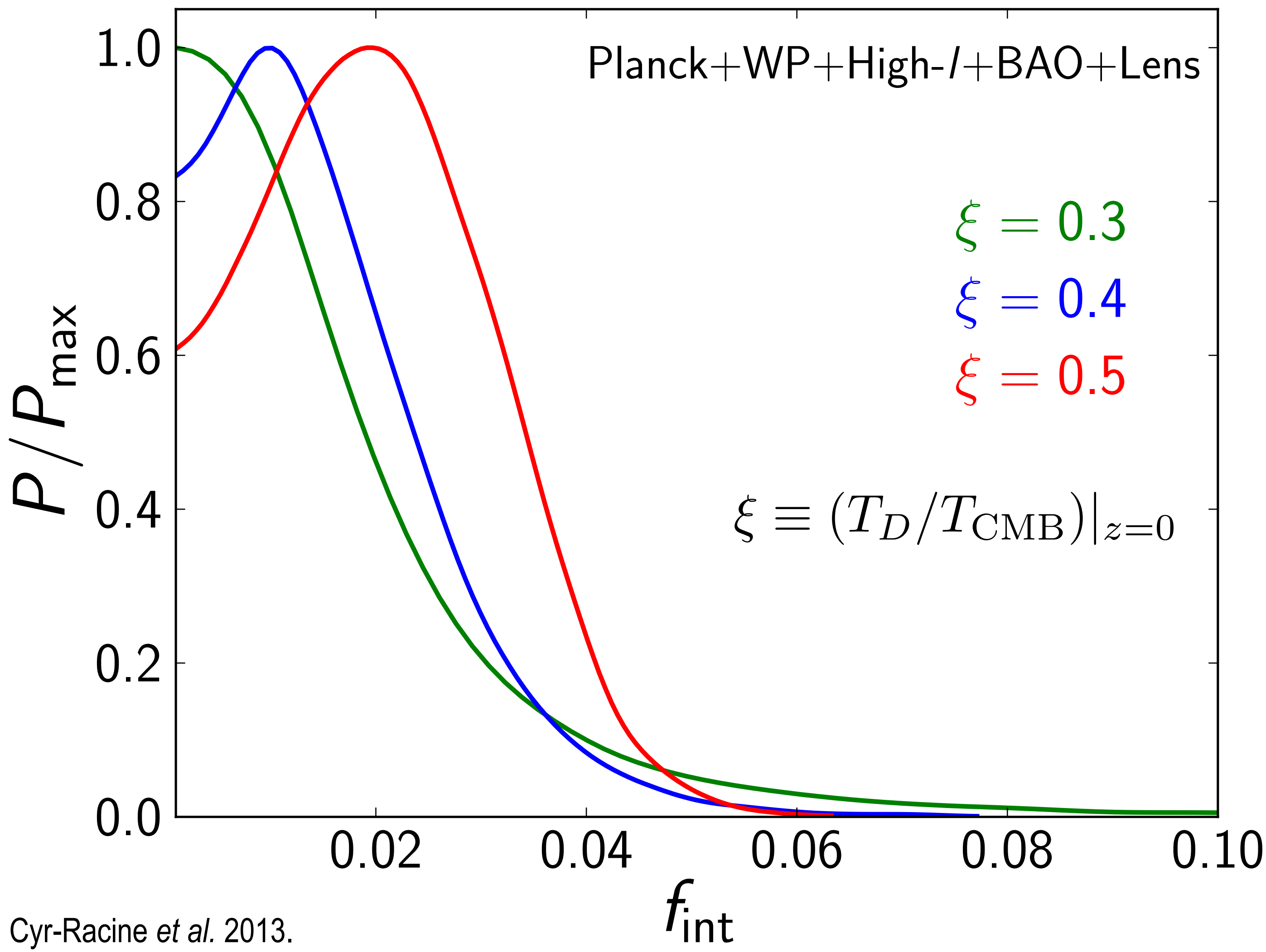


Dark matter is needed to source the gravitational potential

Linear regime: Cosmic microwave background



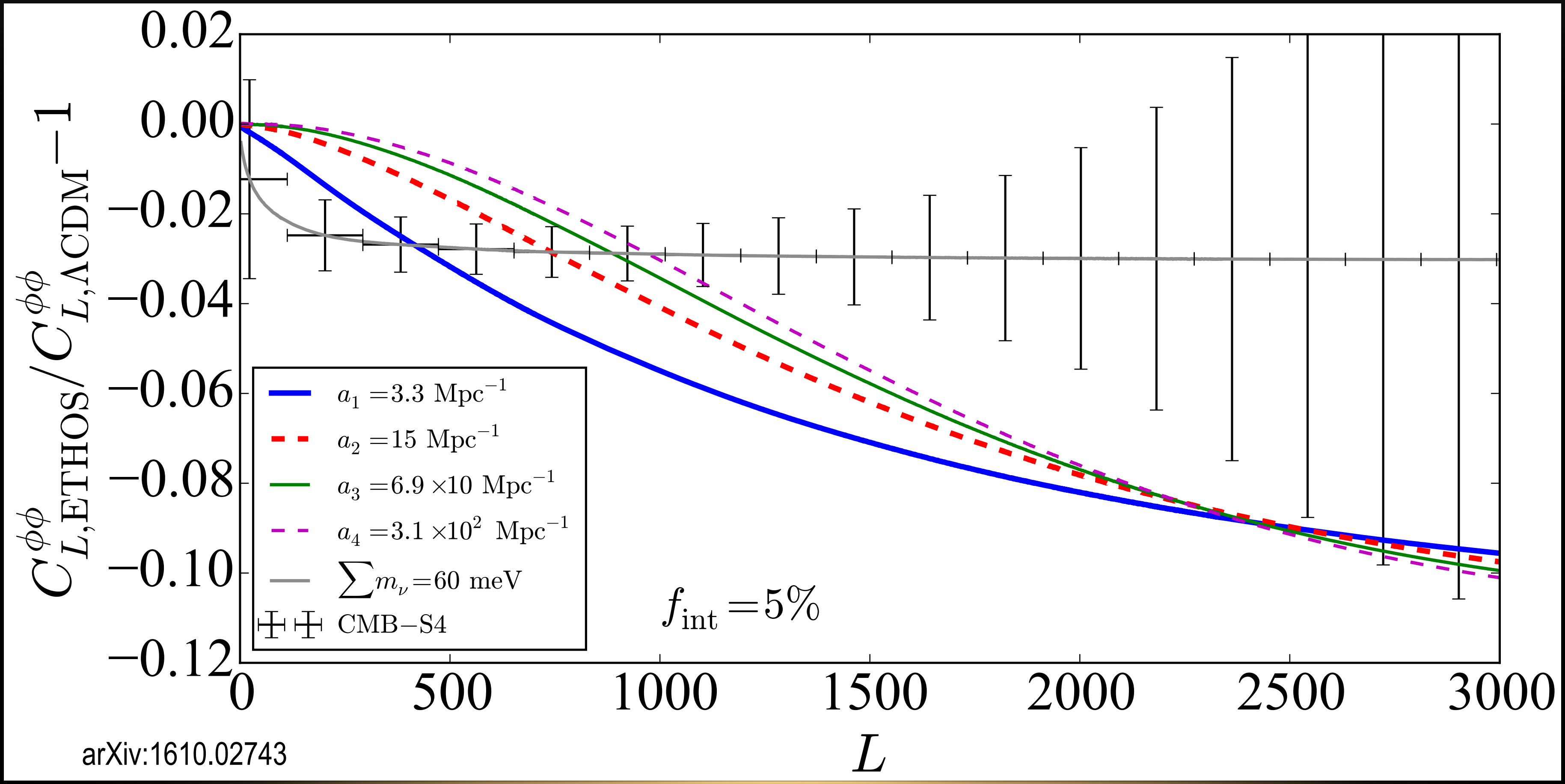
Linear regime: Cosmic microwave background



Cyr-Racine *et al.* 2013.

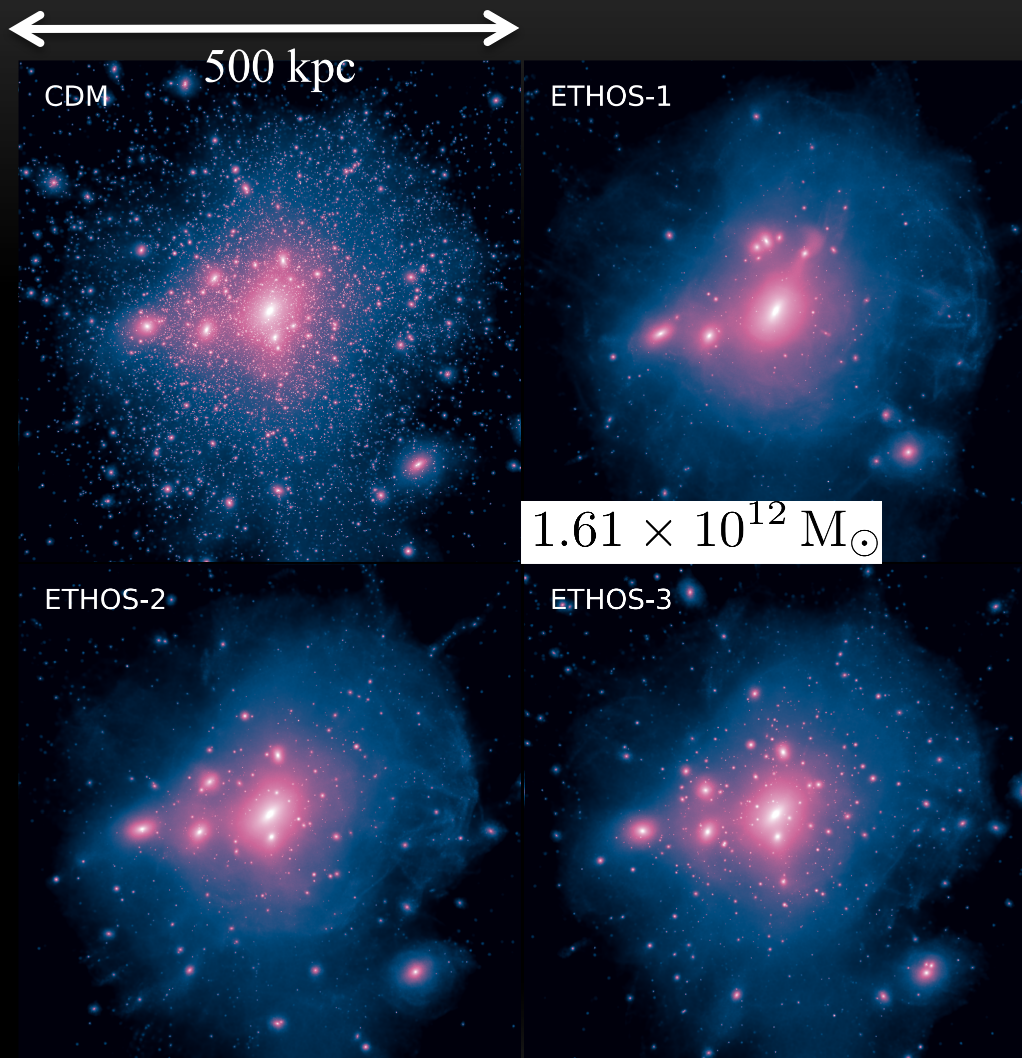
Linear regime: Cosmic microwave background

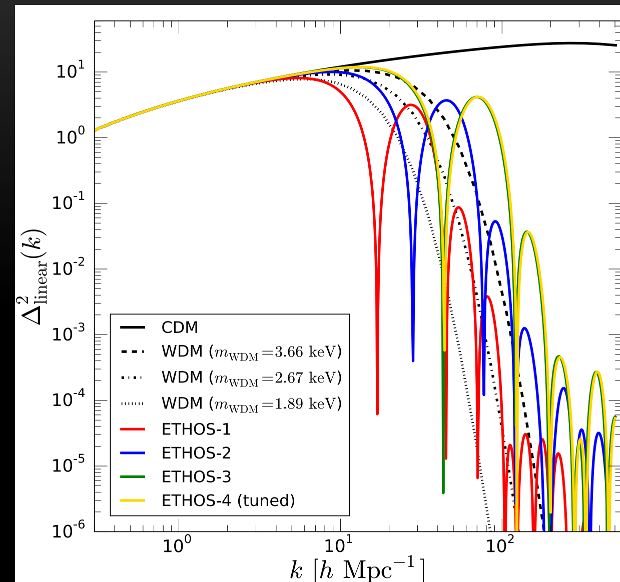
- The next frontier is to constrain subdominant DM component

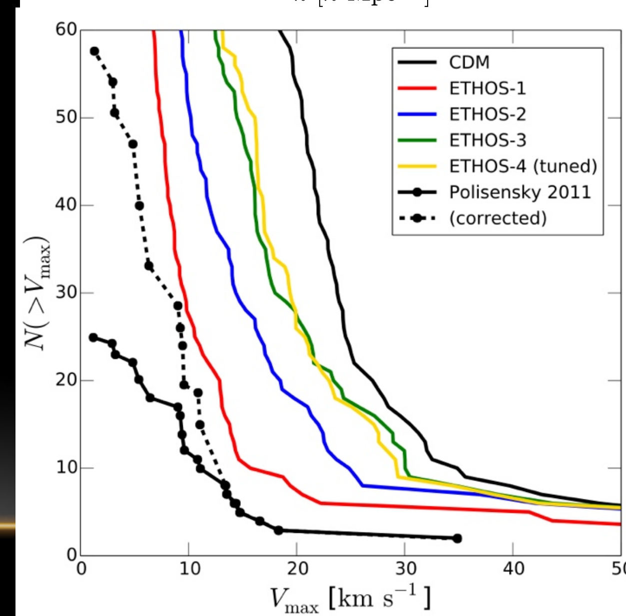


Let's now focus on small, non-linear scales

Simulations: Subhalo mass function



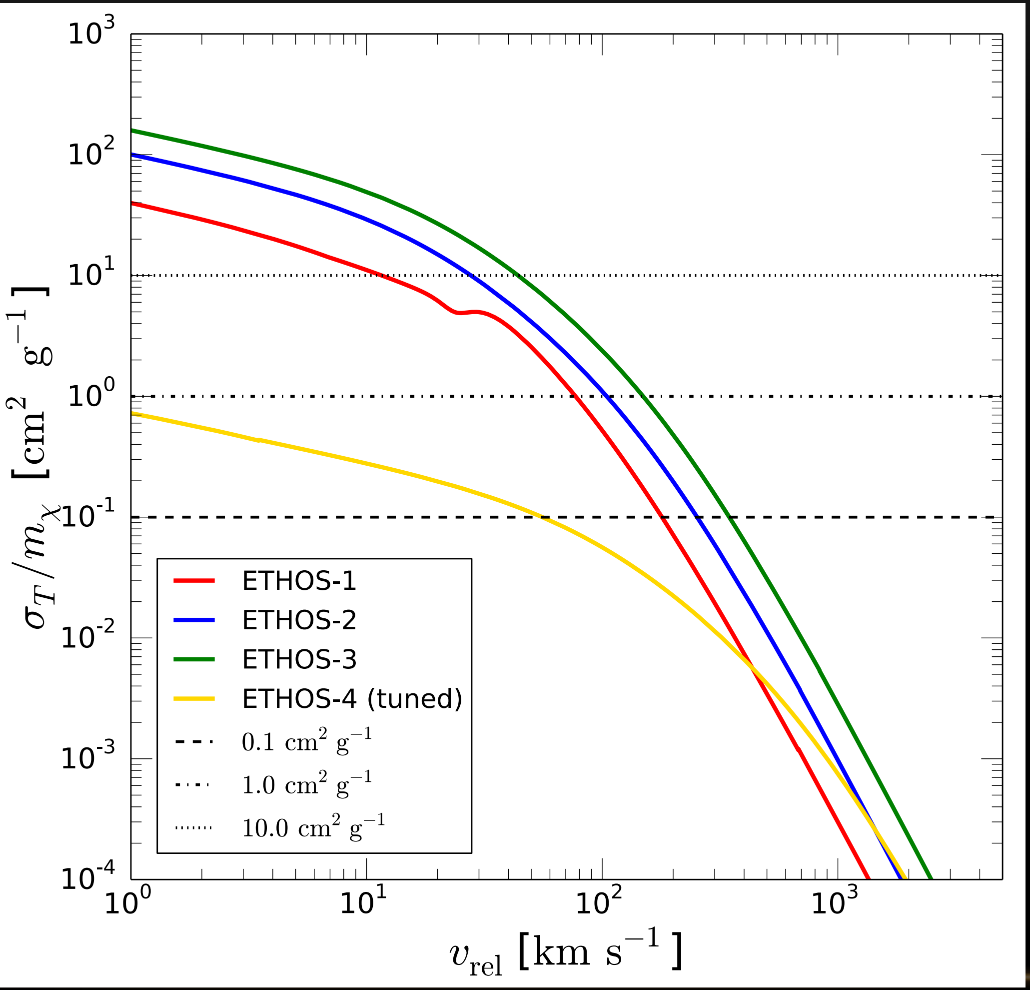




Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

2) Changing the dynamic of structure formation: self-interaction

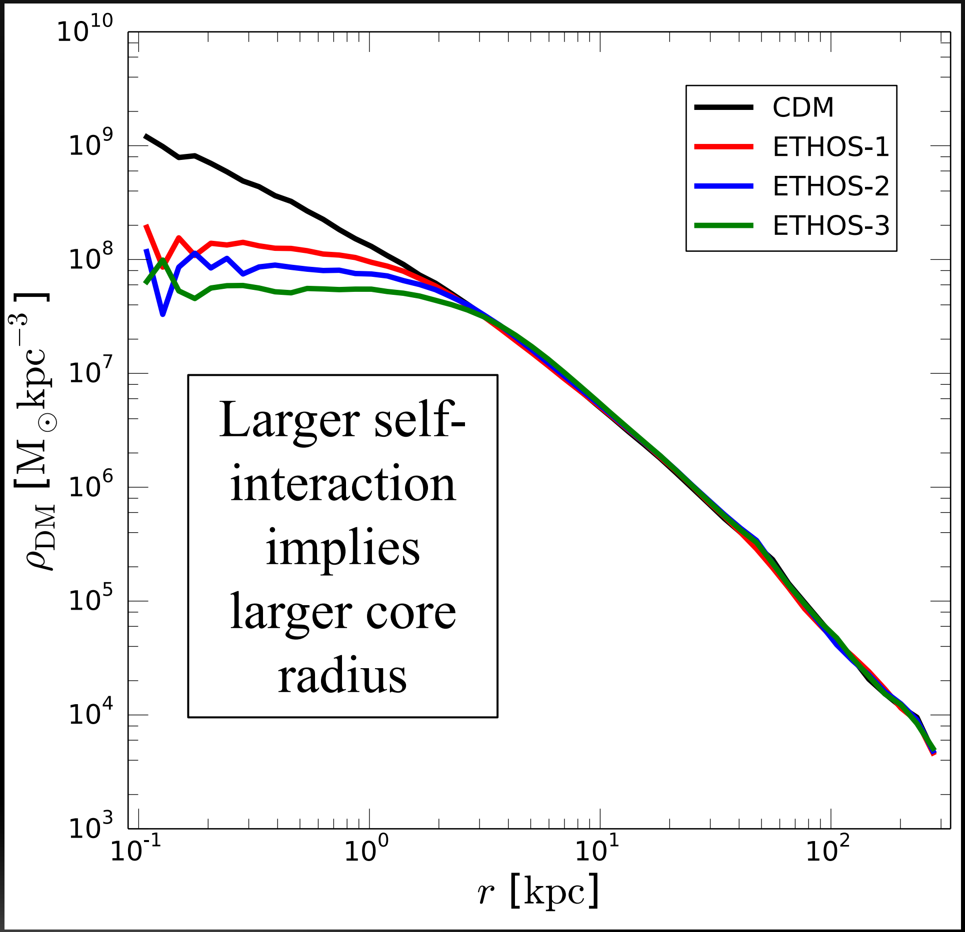
Self-interaction cross section over DM mass



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

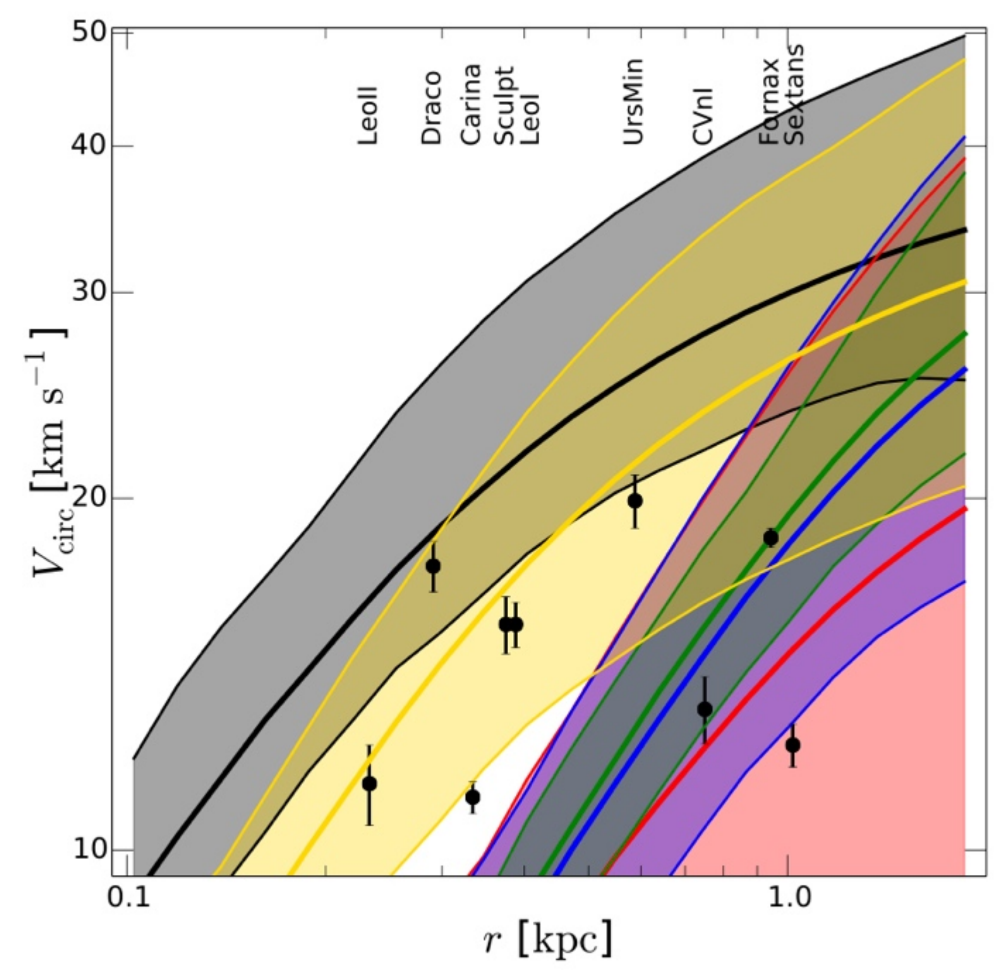
2) Changing the dynamic of structure formation: self-interaction

Example:
The density profile of collapsed DM objects develops a constant density core.



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

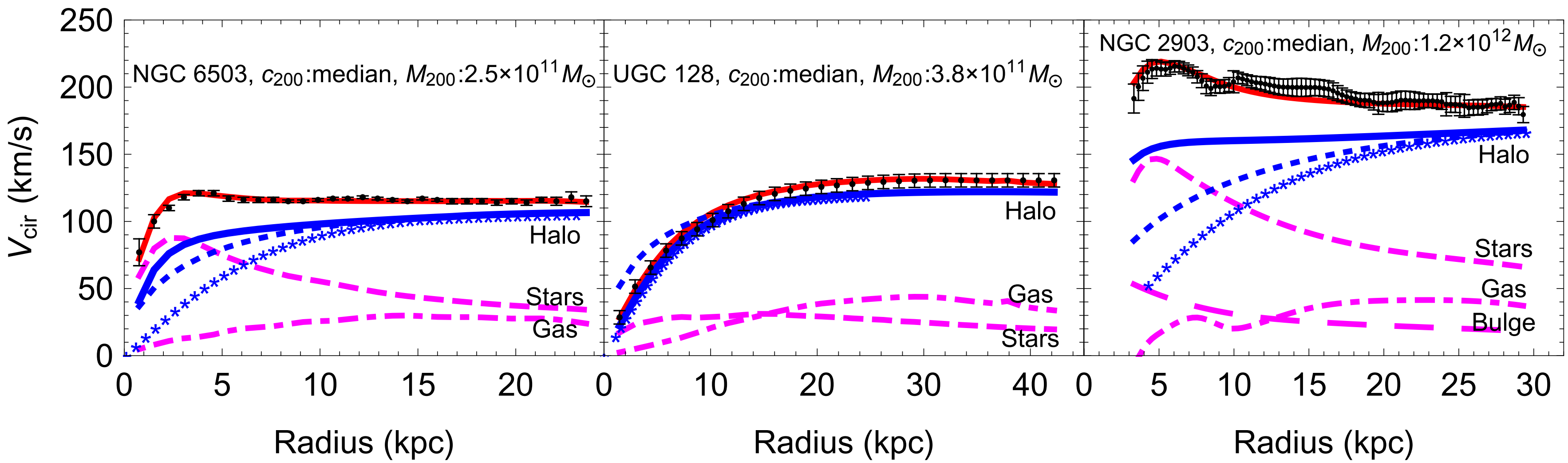
Self-interaction: Velocity profile of local dwarfs



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

Self-interaction: Interplay with baryons

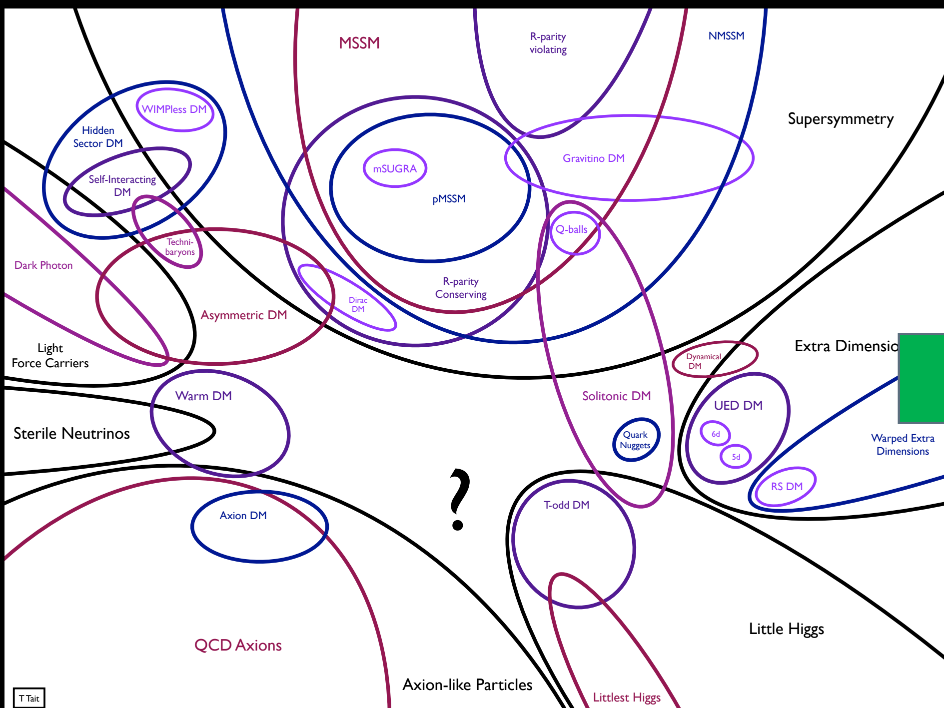
- Unlike CDM, SIDM can thermalize and equilibrate with the baryons.



Kamada, Kaplinghat, Pace and Yu, arXiv:1611.02716

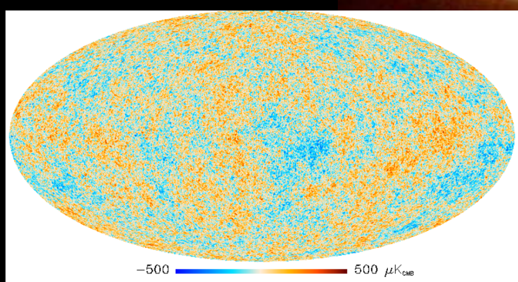
From Dark Matter Physics to Predictions

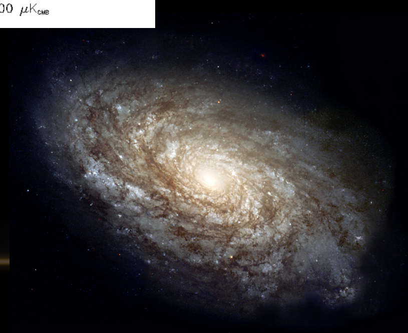
- So far, we have focused on making structure-formation predictions in relevant dark matter models.

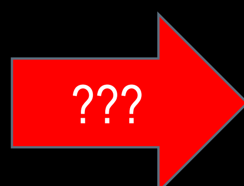


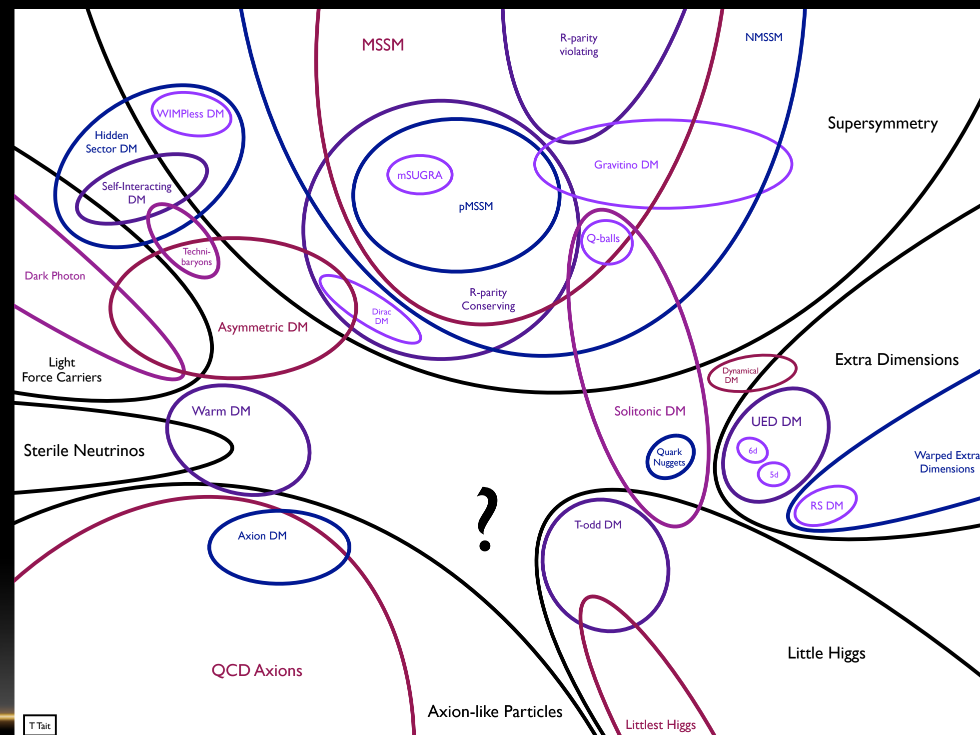
From Observations to Dark Matter Physics

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









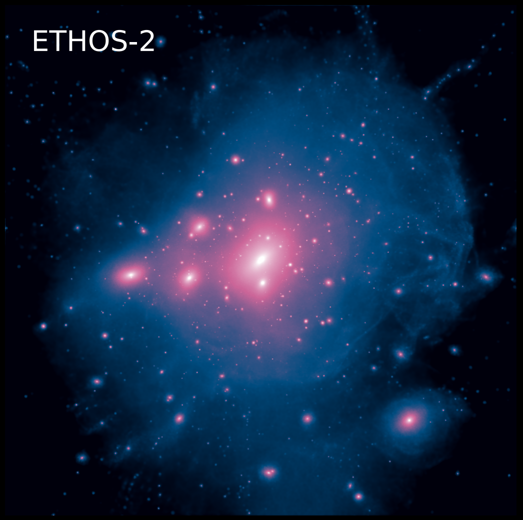
NEEDED:

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.

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

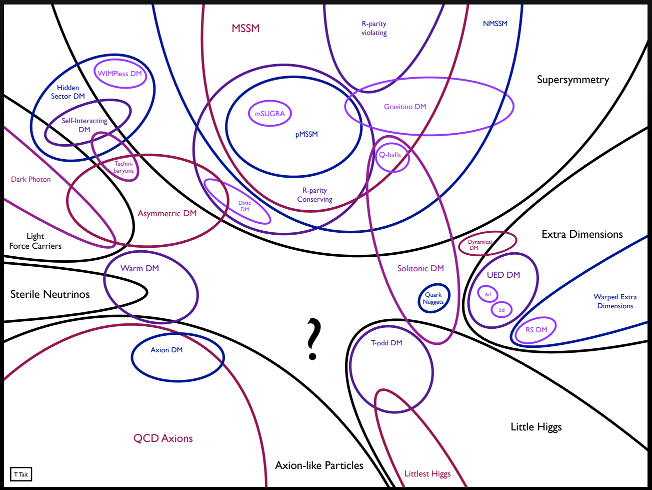


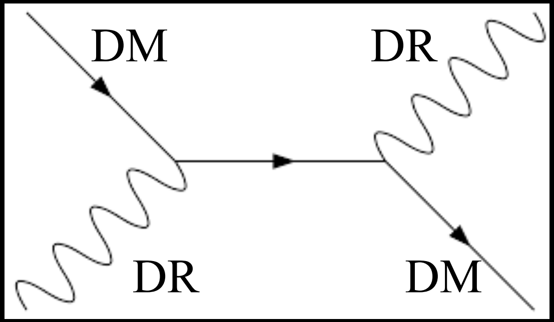
- All dark matter particle models that map to a given effective ETHOS model can be constrained at the same time.

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

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

DR opacity

Angular coefficients

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

Classification of dark matter theories according to their structure formation properties

- Structure of the opacity terms:

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

Envelope Function

Opacity Coefficients

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

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:

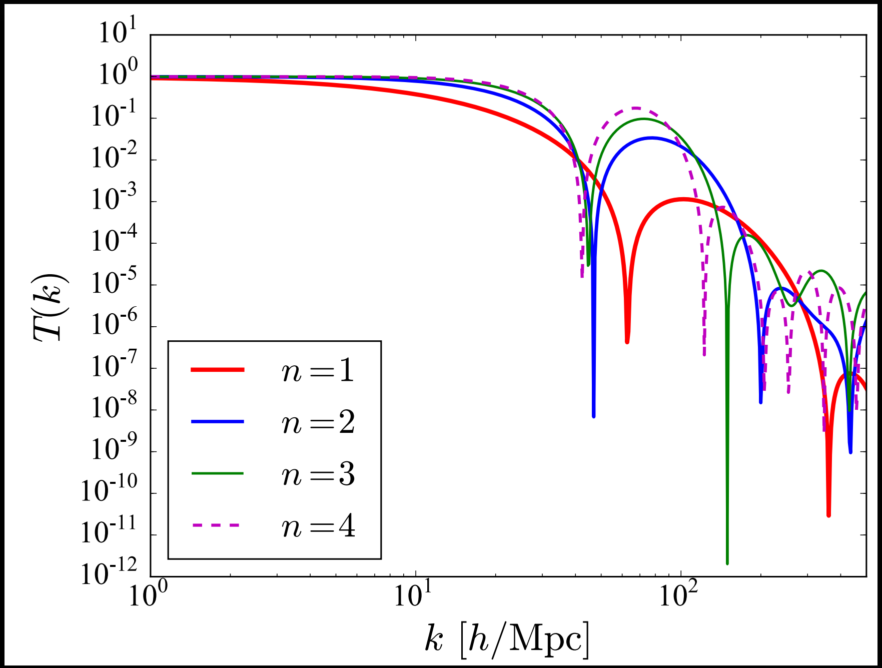
$$a_0 \longrightarrow \sum |\mathcal{M}|^2 \propto \frac{1}{p_{\rm DR}^2}$$

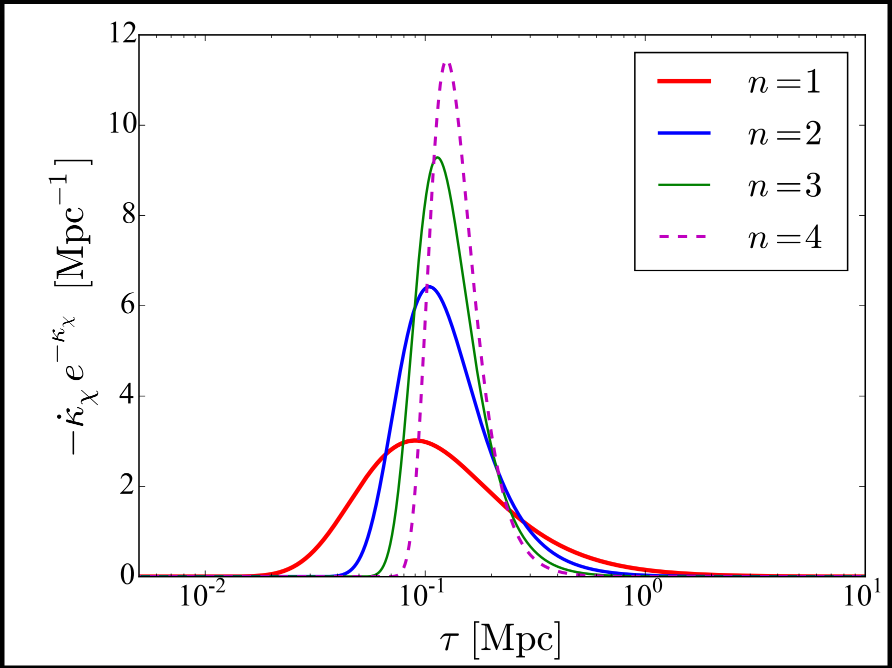
$$a_2 \longrightarrow \sum |\mathcal{M}|^2 \propto \text{const.}$$

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

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

Application Shape of linear matter power spectrum for different *n*





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

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

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.

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

ETHOS -- Next Step: Make it an actual "effective" theory

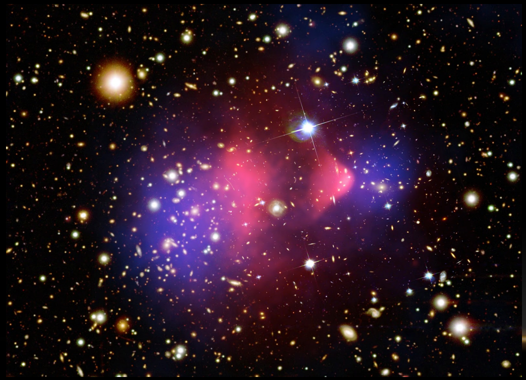
- ETHOS
  - Early times: perturbative density fluctuations.
  - Near collapse time: k-modes strongly-coupled, need simulations.
  - After virialization: new degrees of freedom (halos??) What is the effective description here?

- QCD
  - High T: perturbative in the quarks.
  - Near T_c: strongly-coupled, need Lattice computation.
  - $T \ll T_c$: new degrees of freedom (mesons, hadrons), chiral Lagrangian.

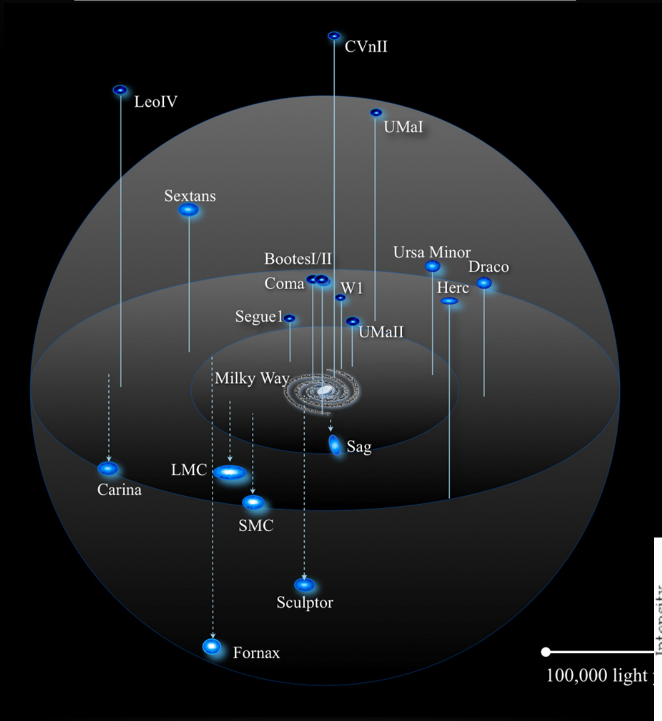
Ultimate goal: Combine constraints

Gravitational Lensing

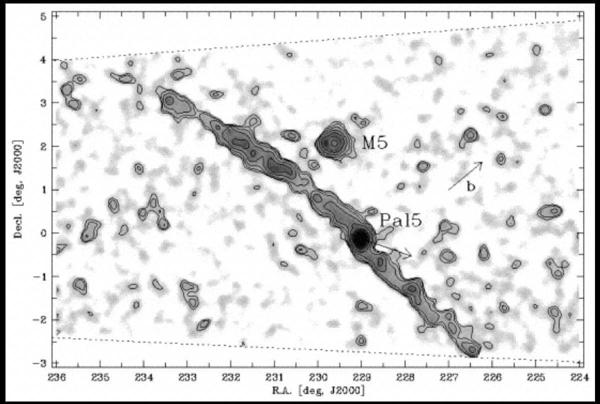
Merging Clusters



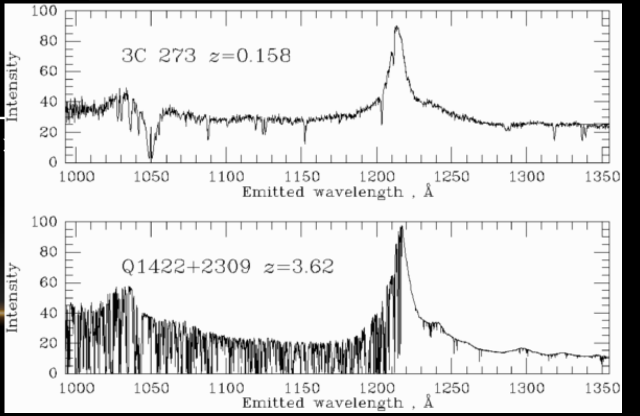
Dwarf galaxies



Stellar Streams



Lyman-alpha forest



Take-Home Message

- In the most pessimistic scenario, gravitational signatures of DM might be all we have access to.
- Important clues about DM physics lie on small-scales.
- 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.
- Much work remains to be done to make ETHOS an actual effective theory and use it as a common language to describe observations.