Cosmological Signatures of Interacting Dark Matter

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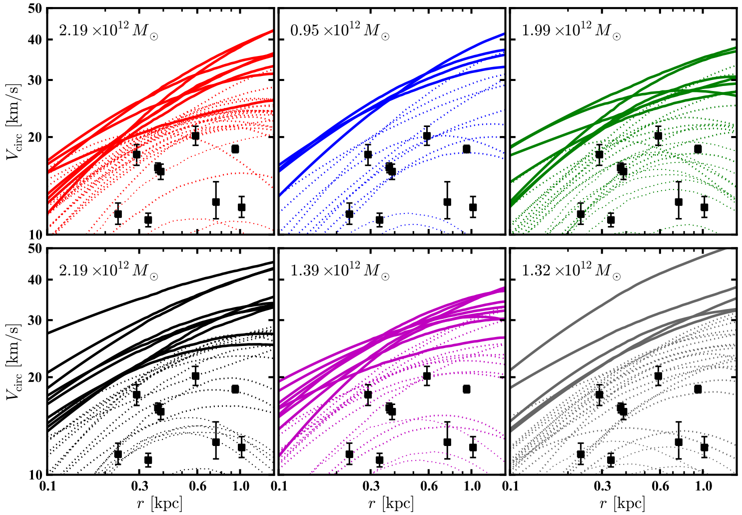
Self-interacting DM and Astrophysics

- In the last decade, self-interacting DM has been mostly discussed in the context of astrophysics.

"Too Big to Fail" Problem

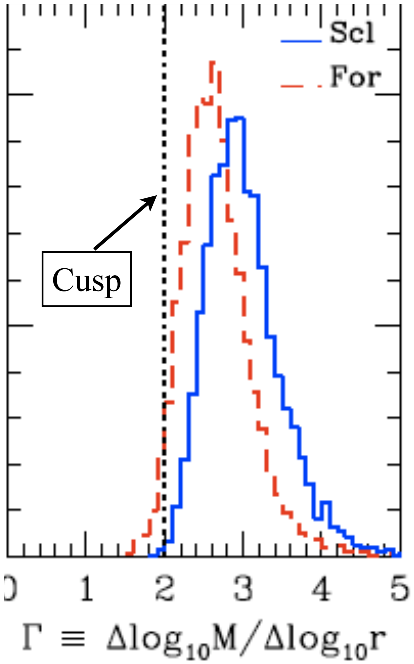


Boylan-Kolchin *et al. (2012)*

"Merging Cluster"

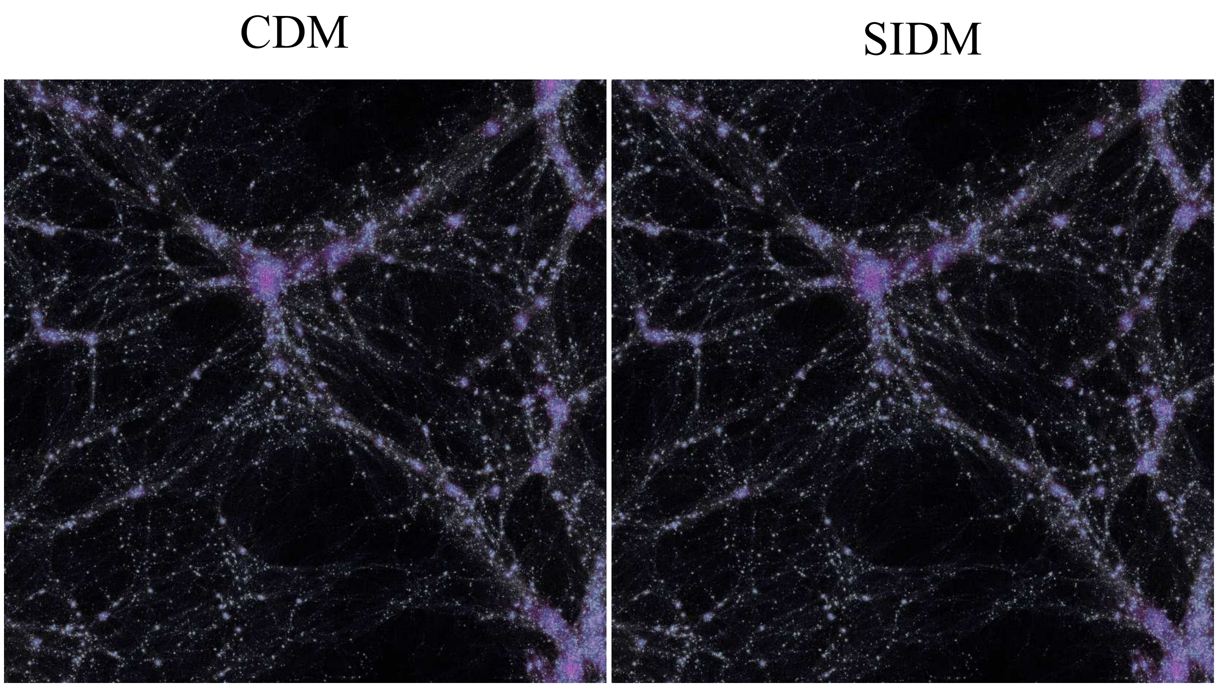
Mahdavi *et al.* (2007)
Dawson *et al.* (2012)

"Core-Cusp" Problem



Walker & Penarrubia *(2011)*

Self-interacting DM and ~~Astrophysics~~ Cosmology



Rocha *et al.* (2012)

Self-interacting DM and Cosmology

While nonstandard dark matter is believed to affect mostly small astrophysical scales, can it also lead to any telltale cosmological signatures (CMB, P(k), weak lensing, etc)?

Key Questions:

- Which properties does interacting DM need to have in order to affect cosmological observables?
- What are the relevant parameters describing these properties that can be constrained with cosmological data?

Self-interacting DM and Cosmology

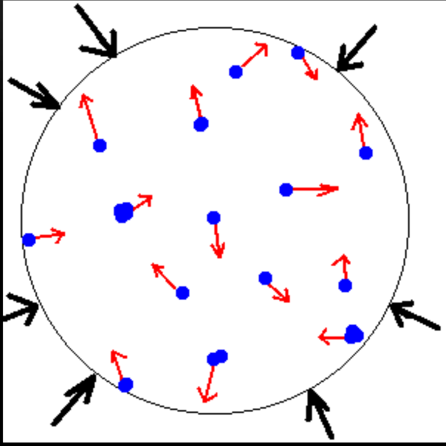
- We need at least a fraction of the DM to:
  1. Couple to a light , relativistic p[illegible]es, or be itself a relativistic parti[illegible]imes (e.g. Warm DM).

     This leads to a no[illegible]d speed that provides pres[illegible]inst gravitational collapse[illegible]

  2. Ha[illegible]ely late epoch of kinematic deco[illegible]ng.

     Such that cosmological scales can be affected.

Not Exhaustive!



Self-interacting DM and Cosmology

- Interacting DM models affect cosmological observables in two ways:
  1. Modifications to the background cosmology.
  2. Modification to the evolution of DM fluctuations.

$$H^2 = \frac{8\pi G}{3}\rho_{\rm tot}$$

gravitational potentials

Pressure term

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

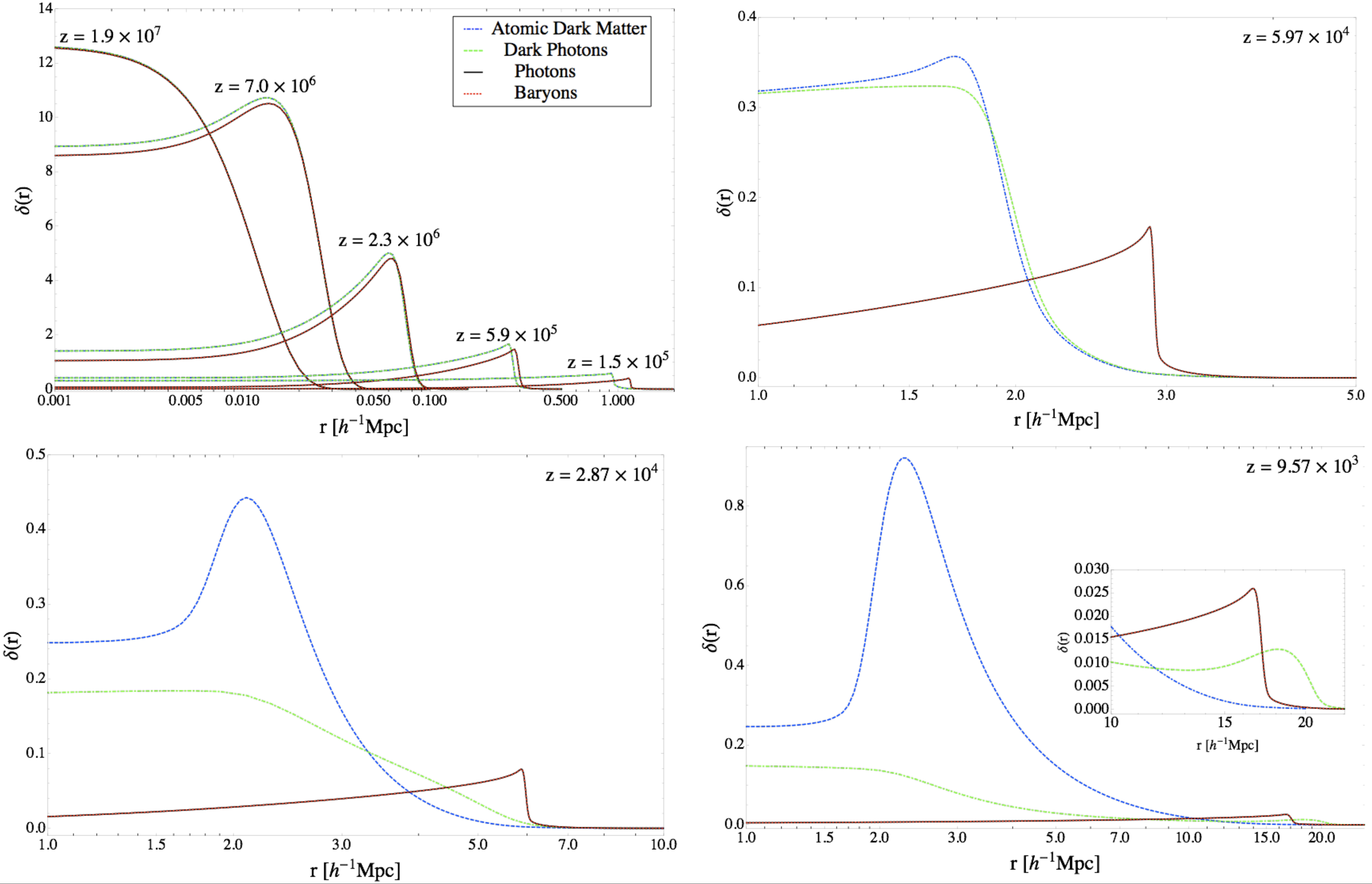
$$\dot{\theta}_{\rm DM} + \frac{\dot{a}}{a}\theta_{\rm DM} - c_{\rm DM}^2 k^2 \delta_{\rm DM} - k^2\psi = \Gamma_{\rm DM}(\theta_{\rm REL} - \theta_{\rm DM})$$

Sound speed

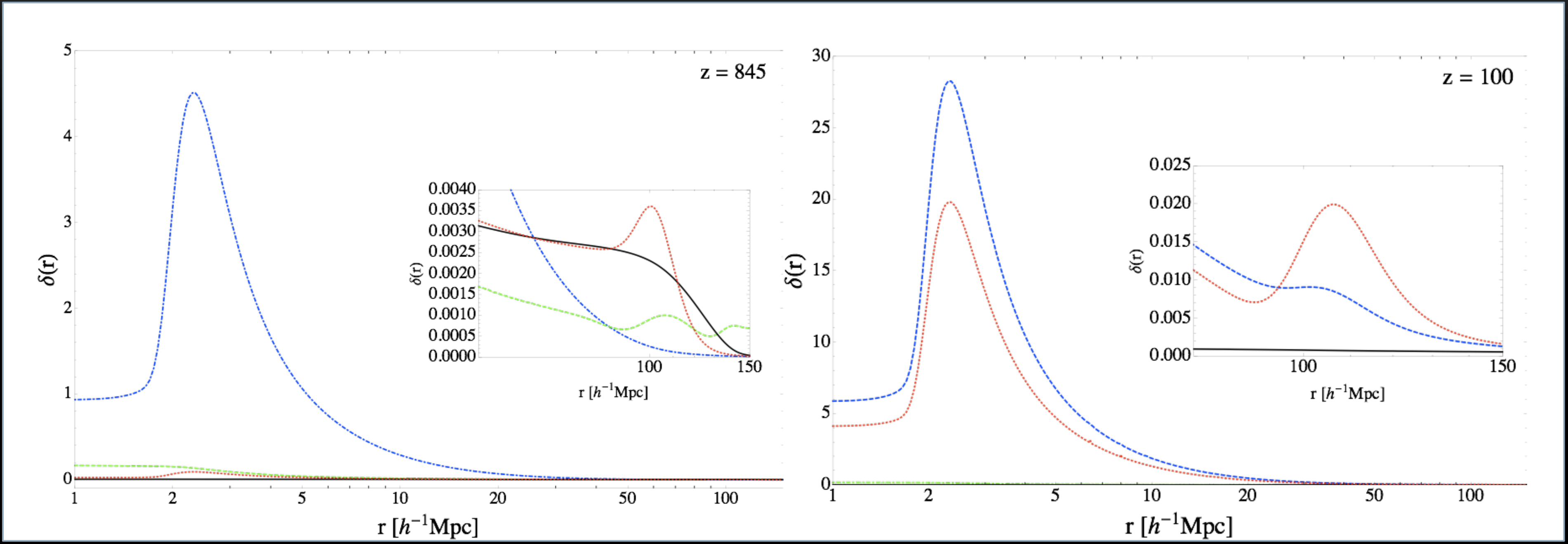
Collision term

Momentum transfer rate

Generic Signature: Dark Acoustic Oscillation (DAO)

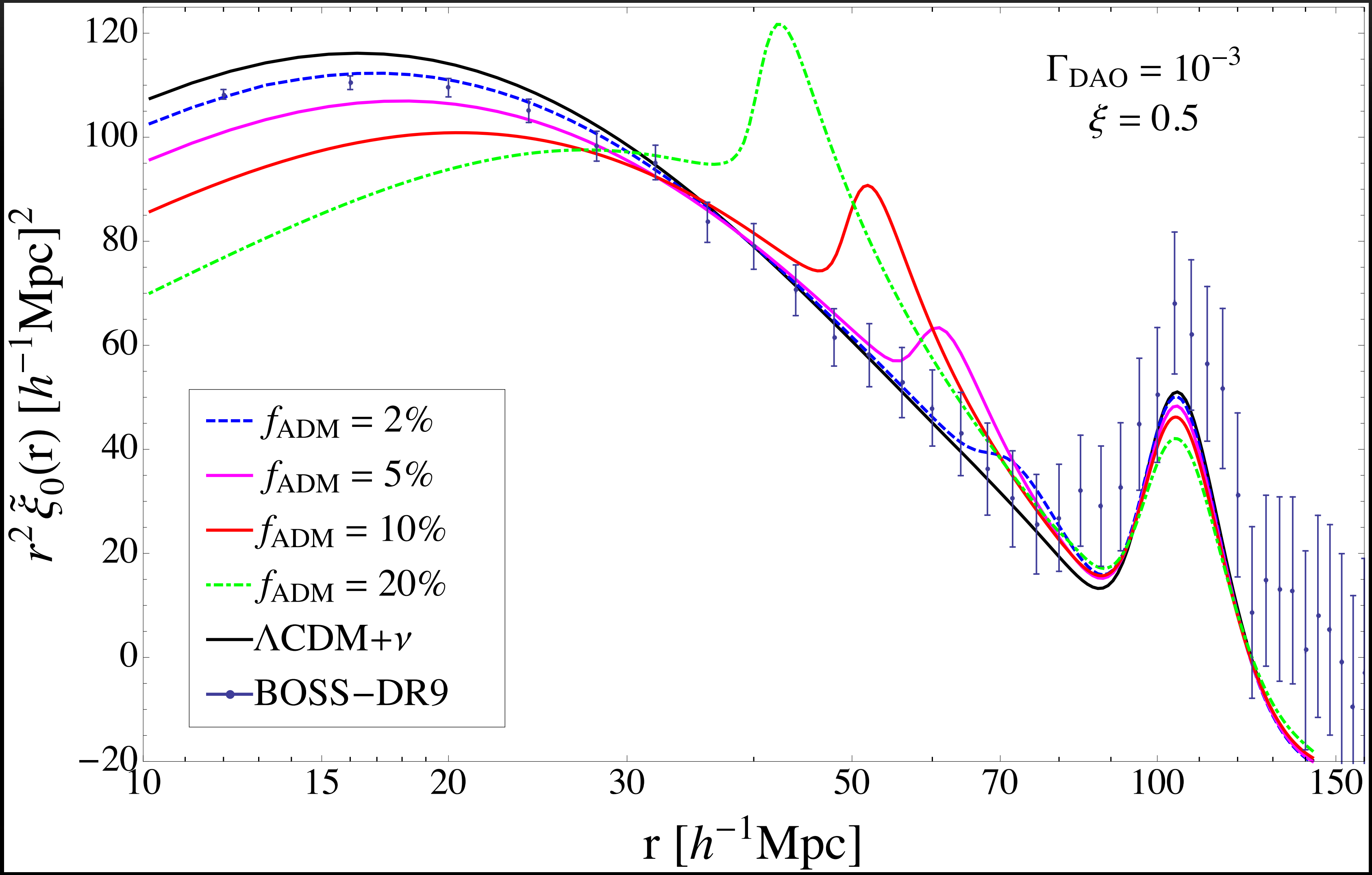


Generic Signature: Dark Acoustic Oscillation (DAO)



- A new "DAO" scale corresponding to the size of the "dark" sound horizon at kinetic decoupling emerges in the dark-matter density field.
- On smaller scales, the interaction of dark matter with the dark radiation suppresses the amplitude of fluctuations.

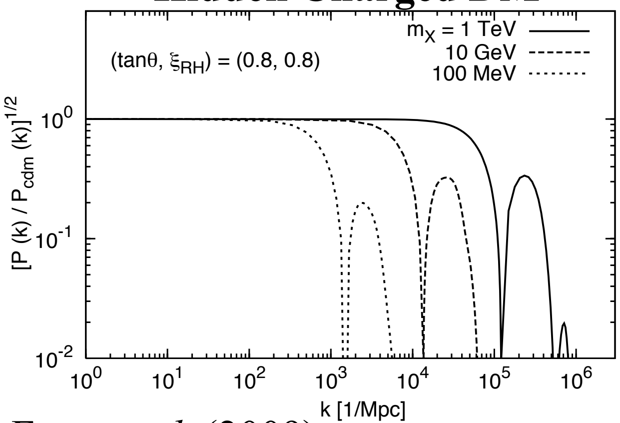
DAO Scale



$\Gamma_{DAO} = 10^{-3}$
$\xi = 0.5$
$f_{ADM} = 2\%$
$f_{ADM} = 5\%$
$f_{ADM} = 10\%$
$f_{ADM} = 20\%$
ΛCDM+ν
BOSS−DR9
$r^2\,\tilde{\xi}_0(r)\ [h^{-1}\mathrm{Mpc}]^2$
r $[h^{-1}\mathrm{Mpc}]$
120
100
80
60
40
20
0
−20
10
15
20
30
50
70
100
150

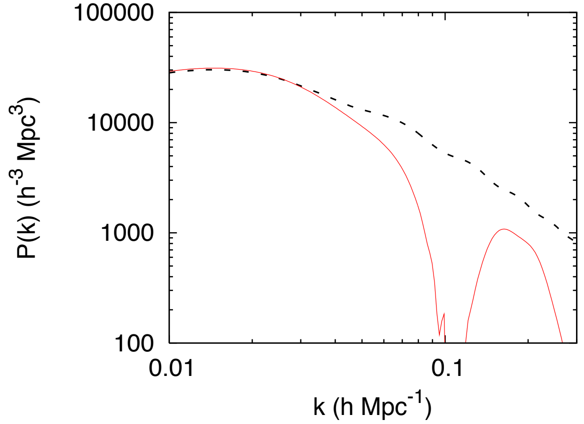
Interacting DM and Cosmology

Hidden Charged DM



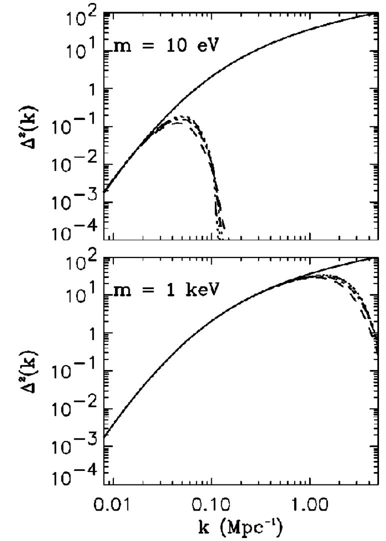
Feng *et al.* (2009)

Neutrino-DM Interaction



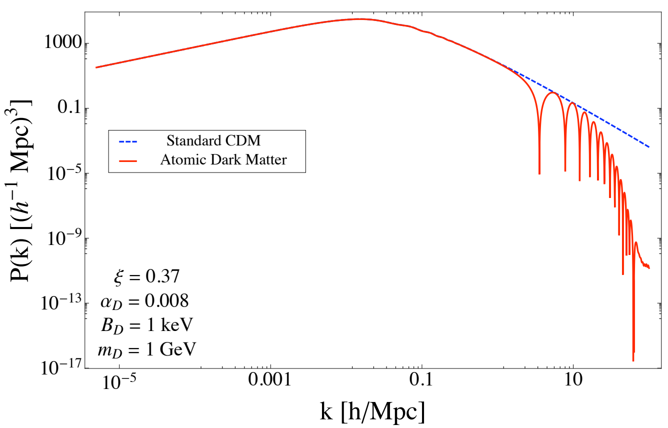
Serra *et al.* (2009)

Interacting Warm DM



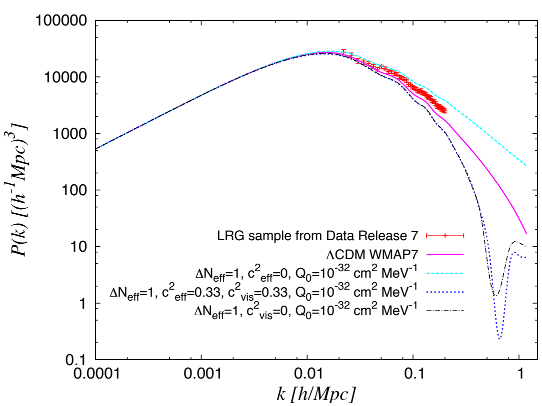
Hannestad and Scherrer (2000)

Atomic DM



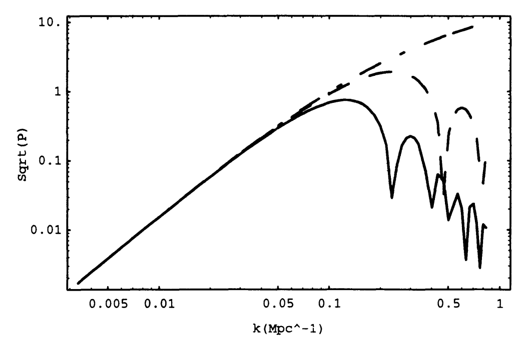
Cyr-Racine & Sigurdson (2012)

DM-DR Interaction



Diamanti *et al.* (2012)

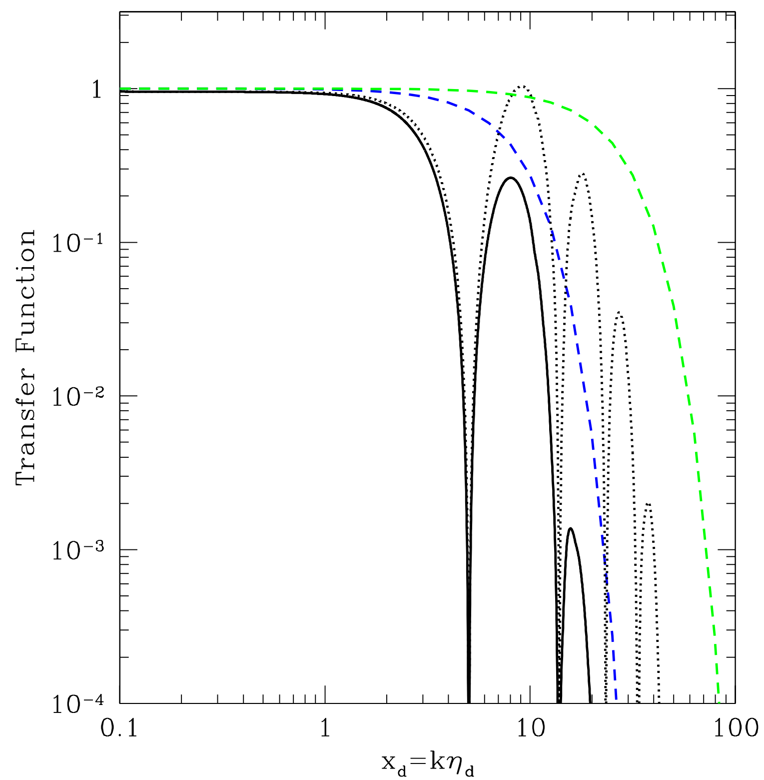
"Cannibal" DM



Machacek (1994); De Laix *et al.*(1995).

But wait, what about WIMPs ?

Kinematic decoupling is too early…sound horizon is too small.



$$T_d = \left(\frac{M_\sigma^4 M}{M_{pl}}\right)^{1/4} \approx 10 \text{ MeV} \left(\frac{M_\sigma}{100 \text{ GeV}}\right)\left(\frac{M}{100 \text{ GeV}}\right)^{1/4}$$

Loeb and Zaldarriaga (2005); Bertschinger (2006).

Partially-Interacting Dark Matter (PIDM)

- Assume that only a fraction f_{ADM} of DM is interacting.
- A useful toy model is a mixture of Atomic Dark Matter and Cold Dark Matter.
- Can lead to interesting galactic-scale phenomenon (e.g. DDDM, Fan *et al. (2013)*.)
- Useful complementarity between the "small" astrophysical scales and the "large" cosmological scales

What do cosmological data actually say about dark matter interactions??

Atomic Dark Matter

FYCR, K. Sigurdson, Phys. Rev. D 103515 (2013)

- Postulate a new U(1) gauge force in the (hidden) Dark Sector.
- The dark matter is made of two oppositely-charged fermions (dark 'electron' and dark 'proton').
- The Dark Sector is neutral overall (no long-range force).
- The Model is fully described by 4 parameters:

$$\alpha_D, B_D, m_D, T_D \qquad (\xi \equiv T_D/T_{SM})$$

$$\frac{m_D}{B_D} \geq \frac{8}{\alpha_D^2} - 1$$

This model has a very rich phenomenology despite its minimal set of ingredients.

Which parameters really affect the cosmological observables?

1. A quantity determining the momentum transfer rate between the dark radiation and the DM:

$$\Gamma_{\rm DAO} \equiv \alpha_D \left(\frac{B_D}{\rm eV}\right)^{-1} \left(\frac{m_D}{\rm GeV}\right)^{-1/6}$$

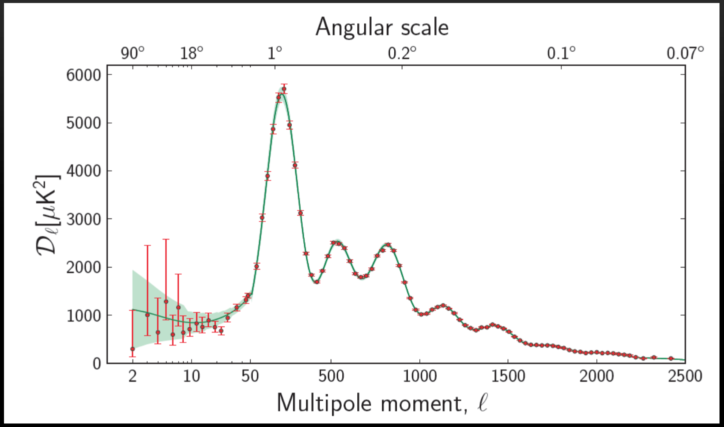
2. The amount of dark radiation in the Universe:

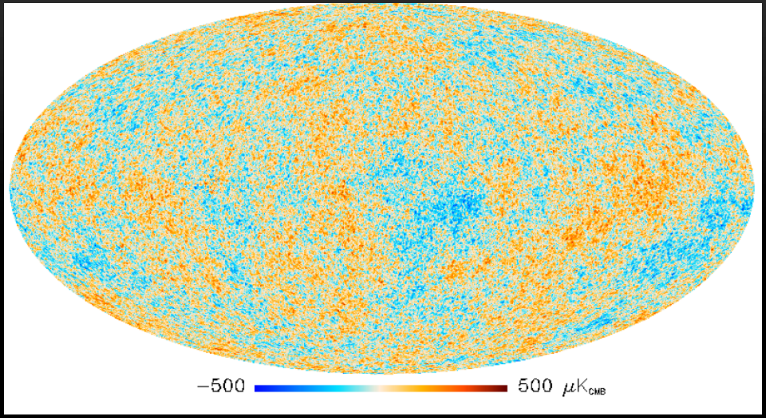
$$\xi \equiv \left.(T_D/T_{\rm CMB})\right|_{z=0}$$

3. The fraction of interacting DM:

$$f_{\rm ADM}$$

Cosmic Microwave Background



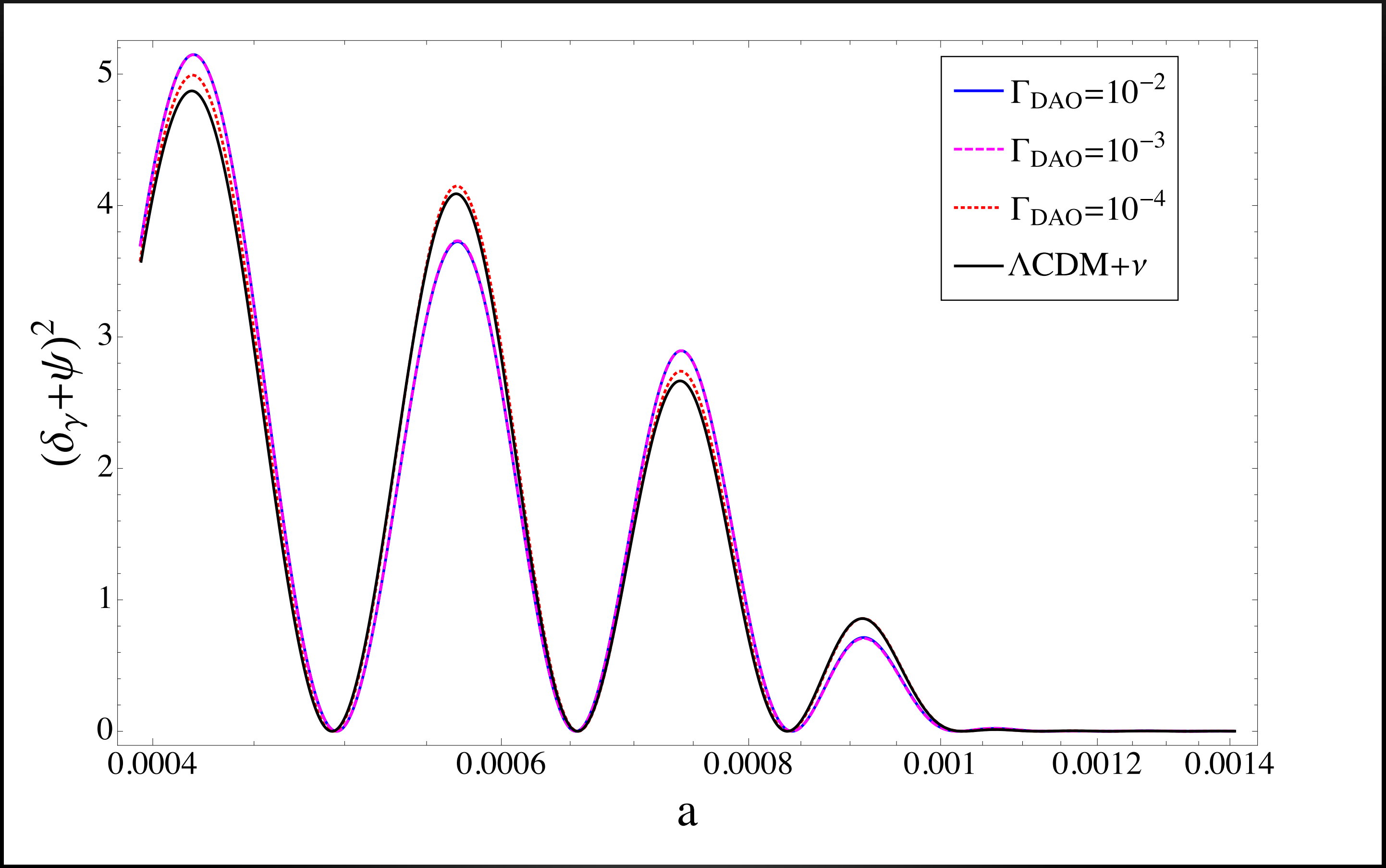


- Advantages of CMB:
  1. "Simulations" do include baryons!
  2. Linear physics.
  3. Clean and well-understood probe.
- Drawback:
  1. Only explores a limited range of scales (l<3000).

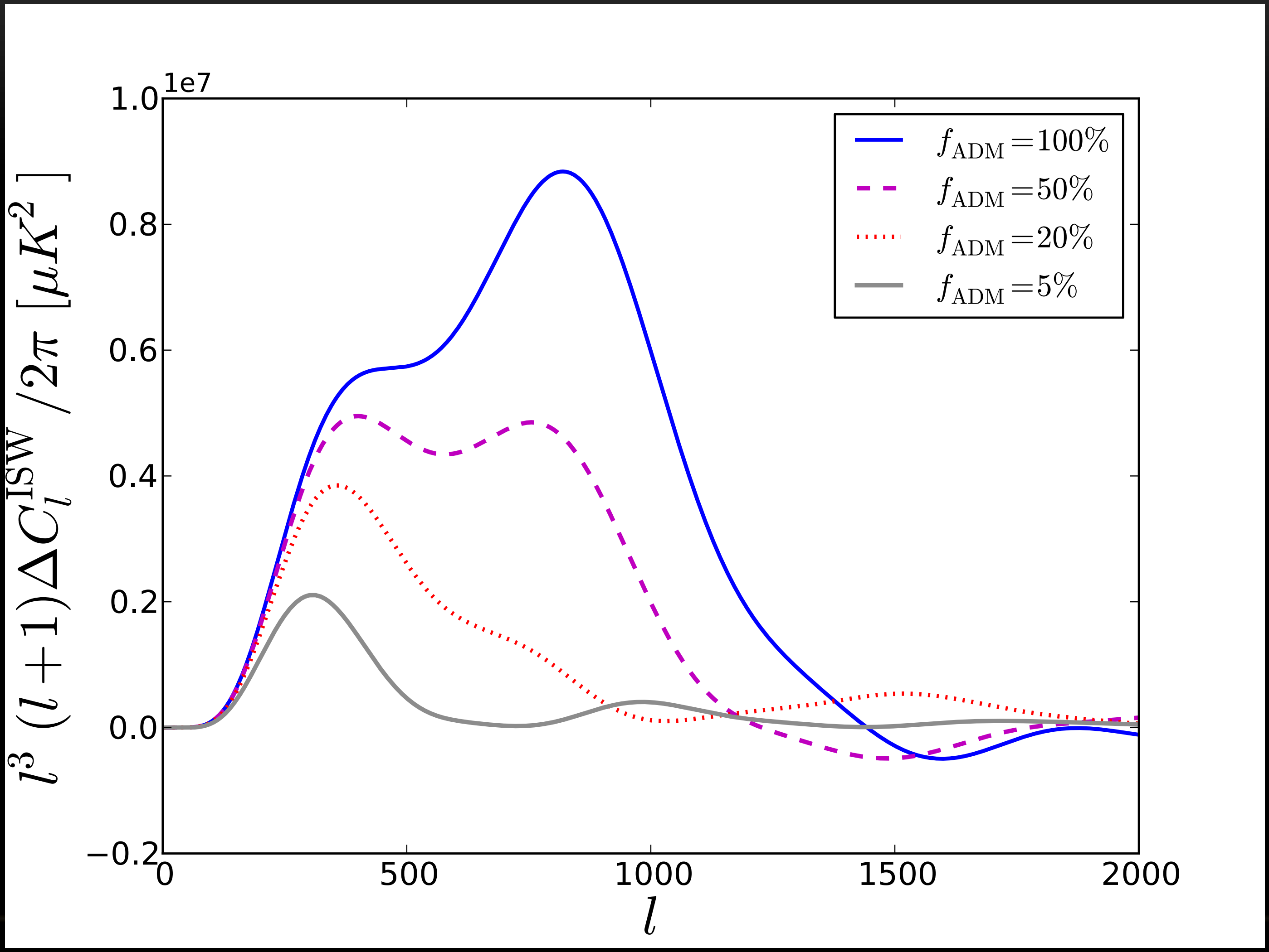
Cosmic Microwave Background

- There are 2 types of effects that can allow us to distinguish an interacting dark matter scenario from a ΛCDM:
  - The smoother DM distribution on small scales lead to shallower DM gravitational potentials.
    - Modified ratio of even and odd TT peaks
    - Modified CMB lensing
  - The dark radiation is not free-streaming at early time and therefore does not behave like neutrinos.
    - Modified amplitudes and phase in temperature and polarization spectra.
    - Modified shear stress close to CMB last scattering modify TT and EE spectra.
    - Stronger early Integrated Sachs-Wolfe effect .

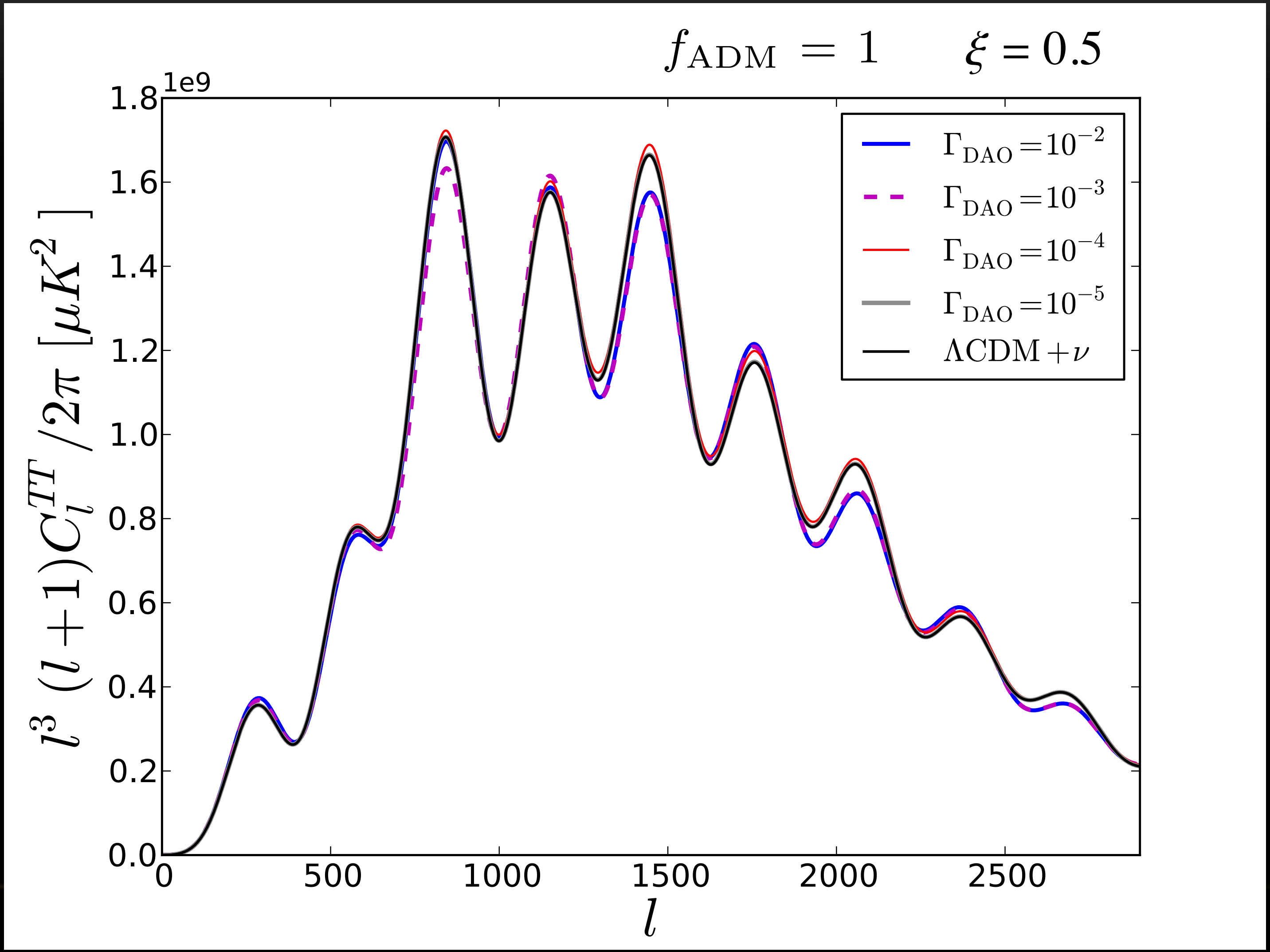
Ratio of Odd to Even TT Peaks



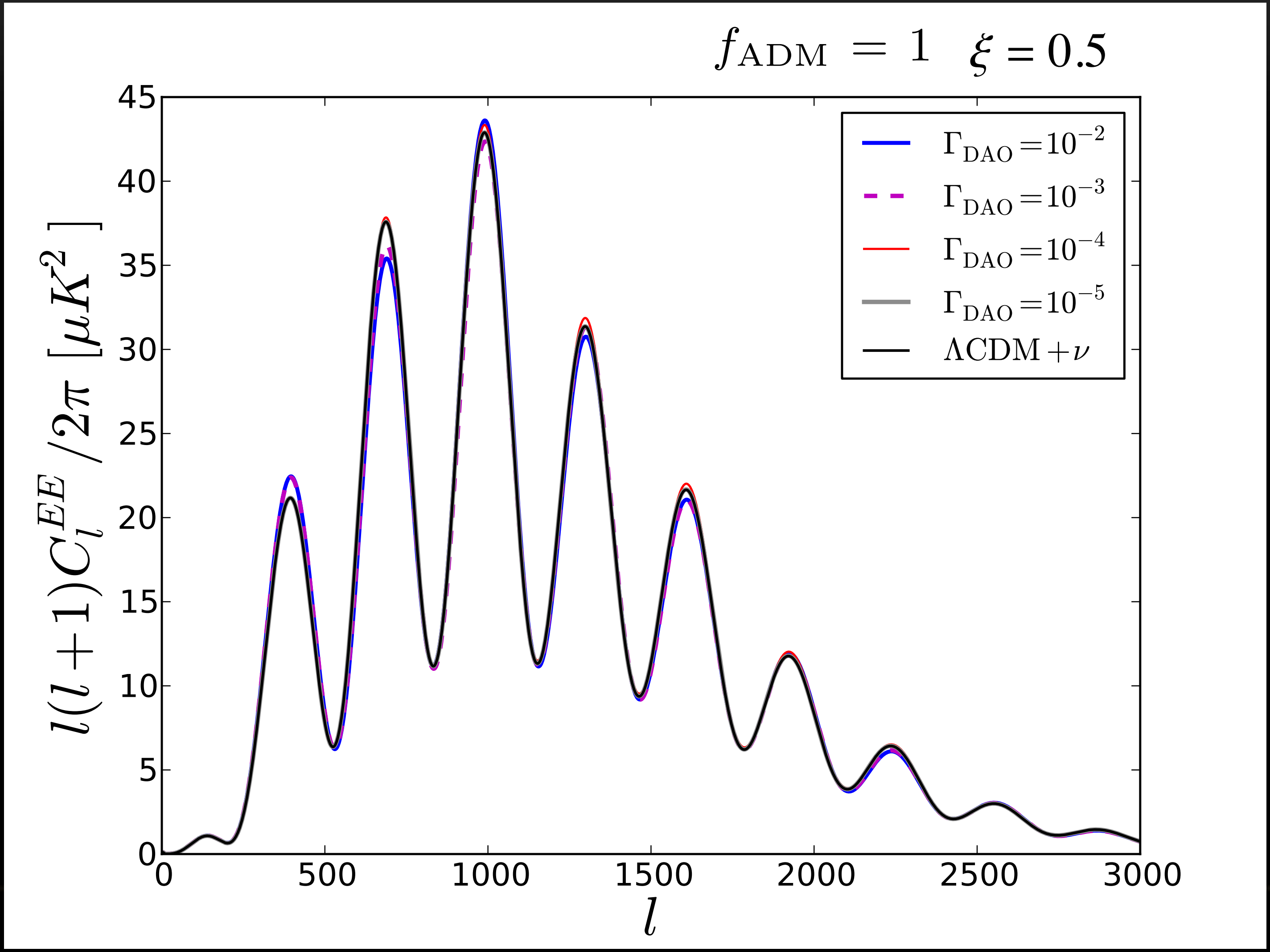
Early Integrated Sachs-Wolfe Effect



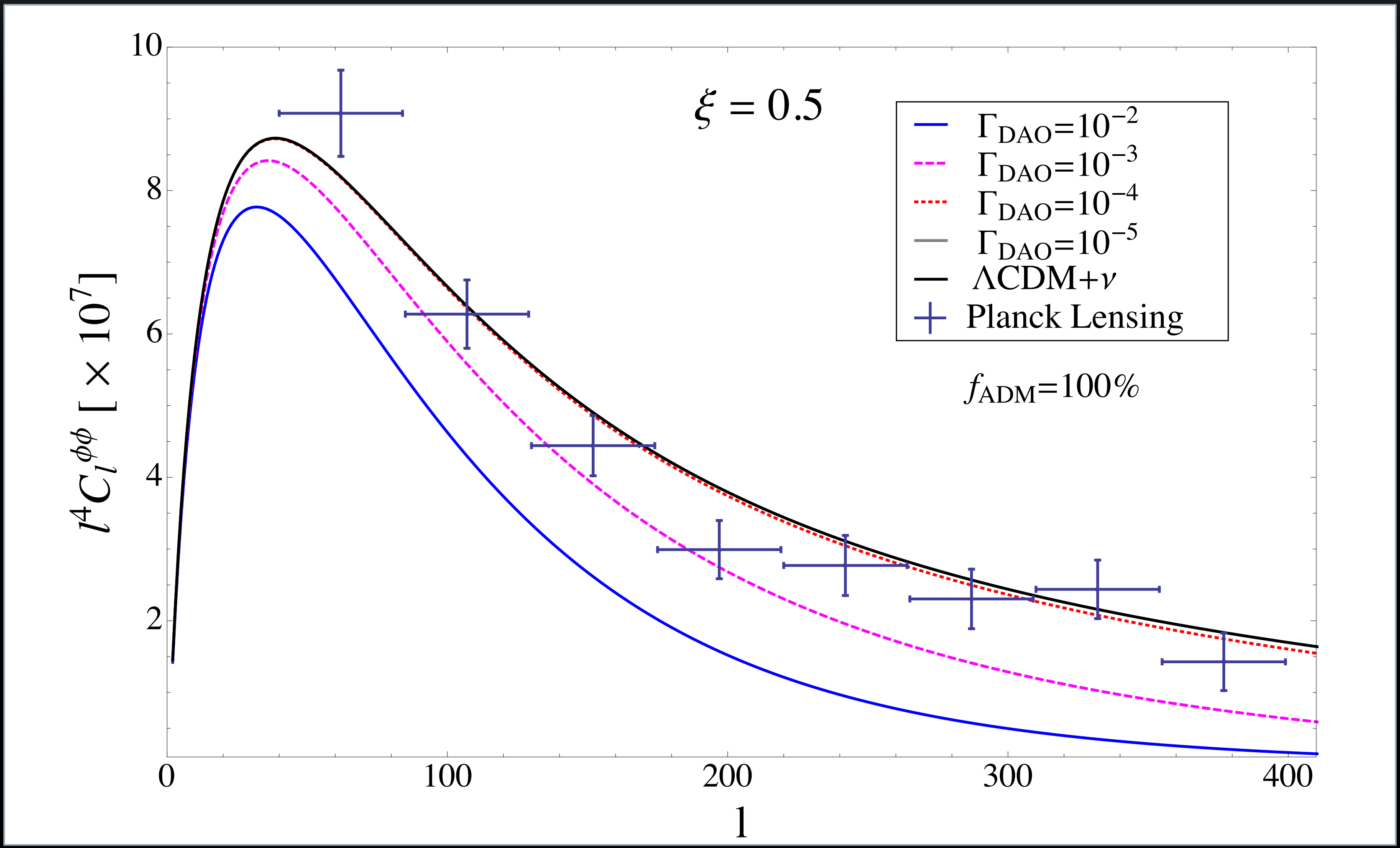
Cosmic Microwave Background: TT Spectrum (no lensing)



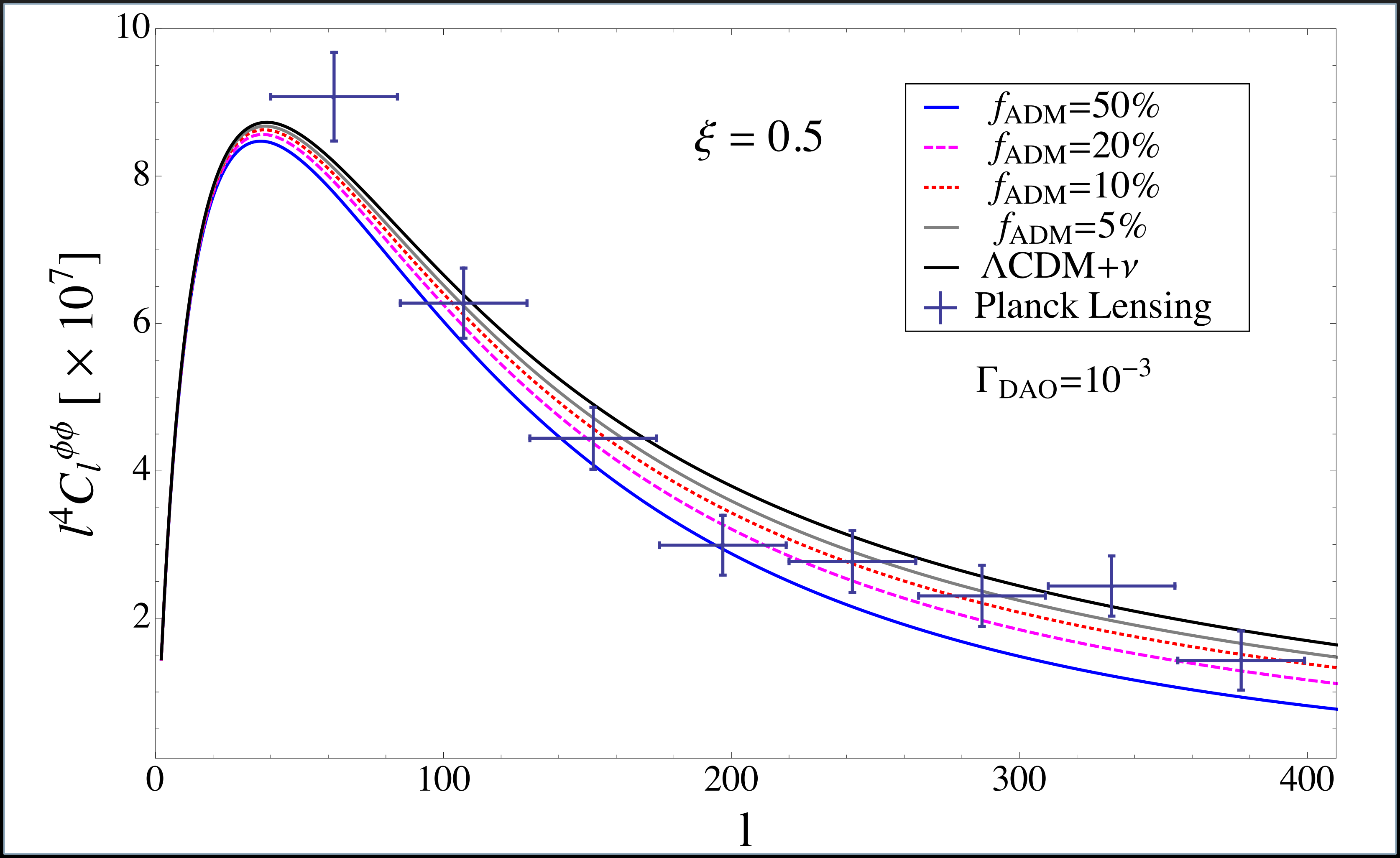
Cosmic Microwave Background: EE Spectrum (no lensing)



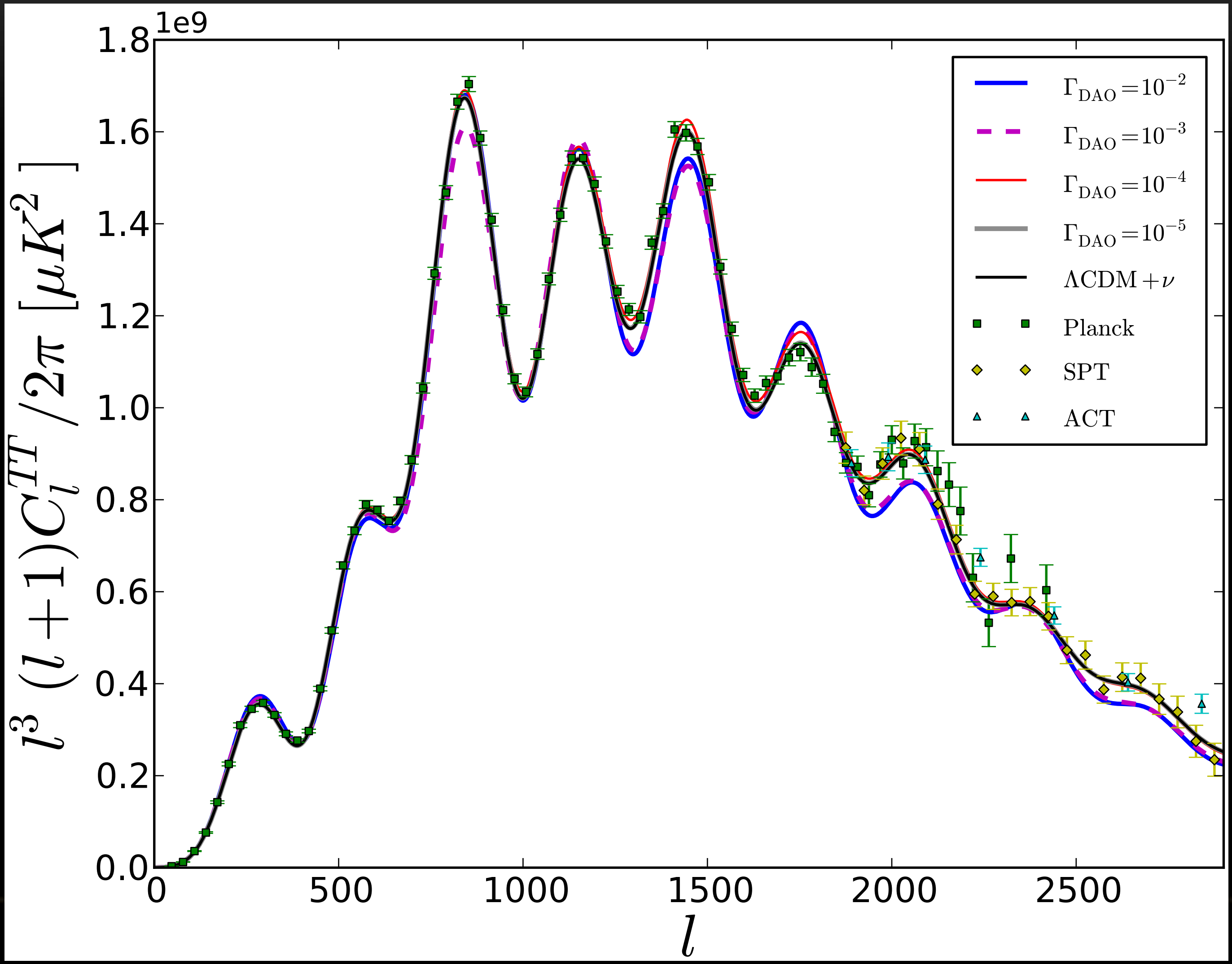
Cosmic Microwave Background: Lensing Spectrum



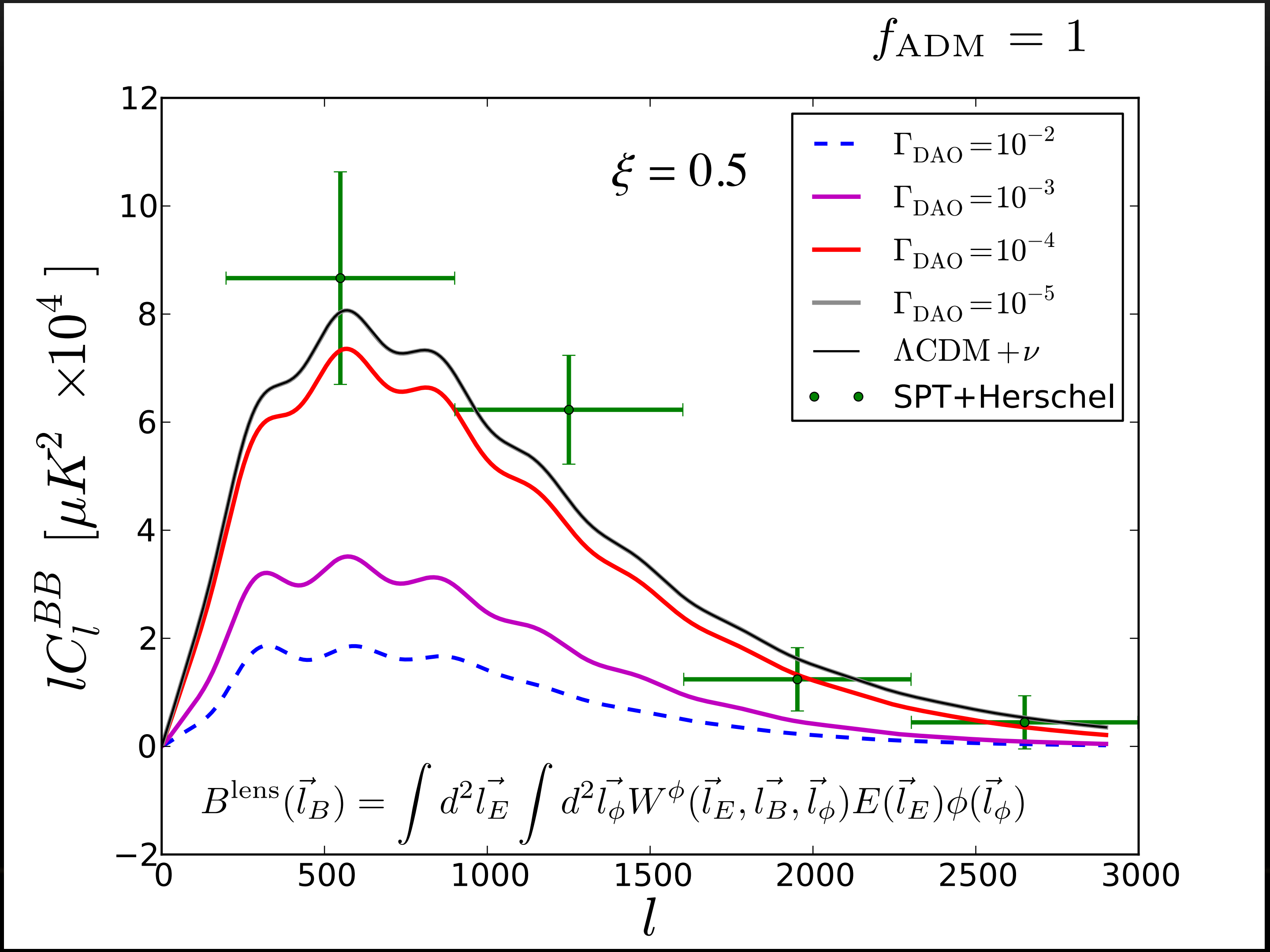
Cosmic Microwave Background: Lensing Spectrum



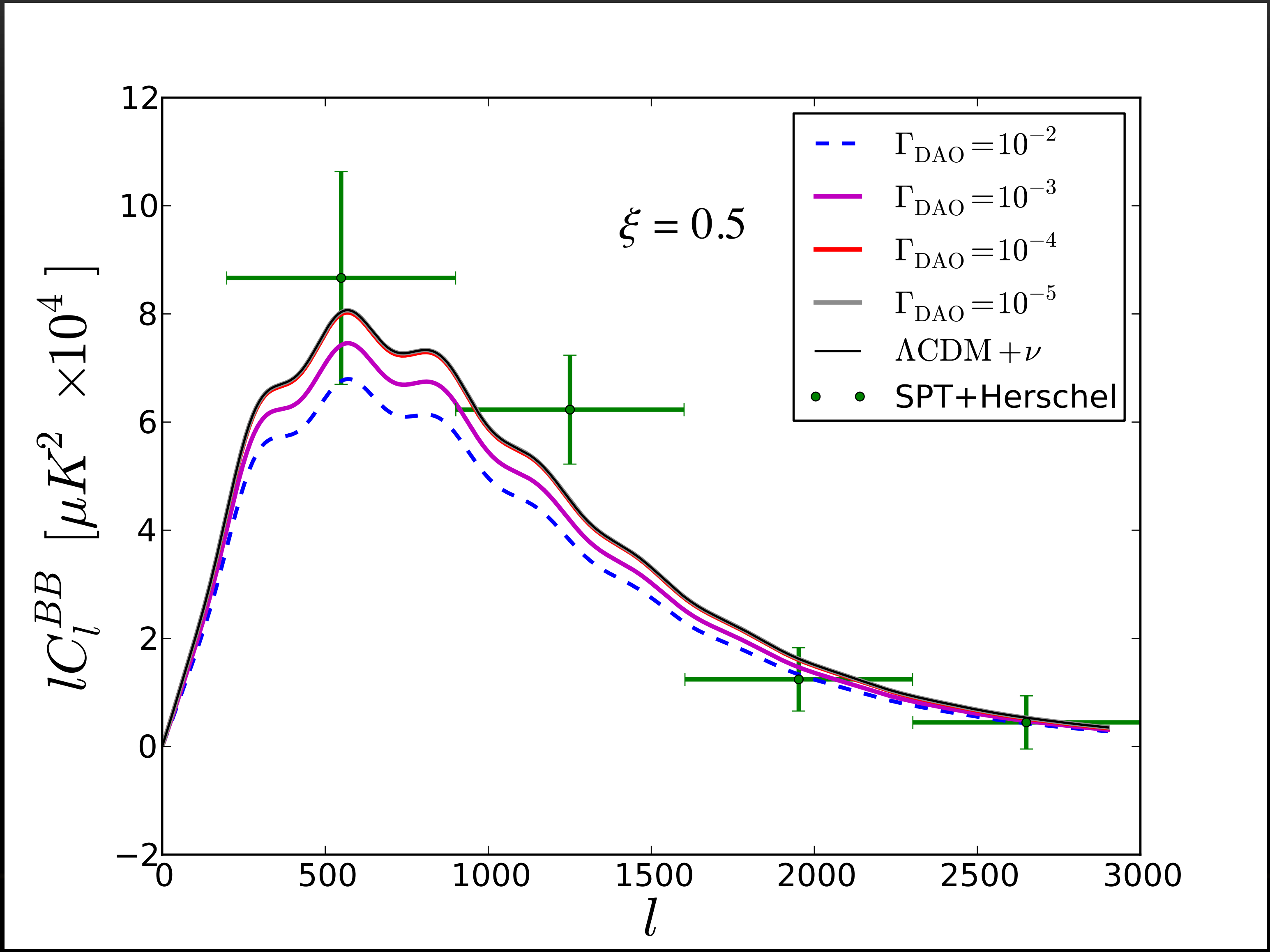
CMB lensed TT Spectrum



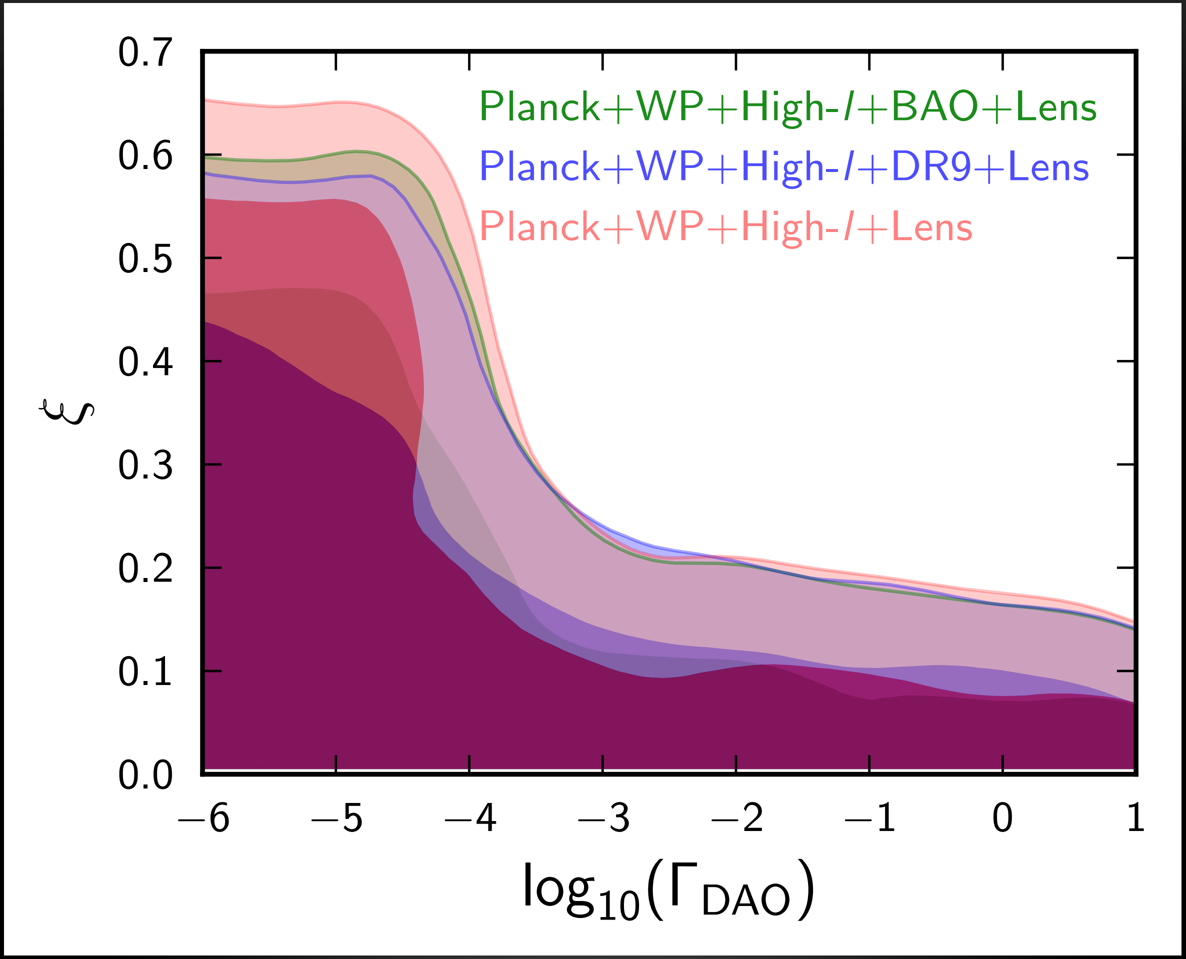
Cosmic Microwave Background: Lensing BB Spectrum



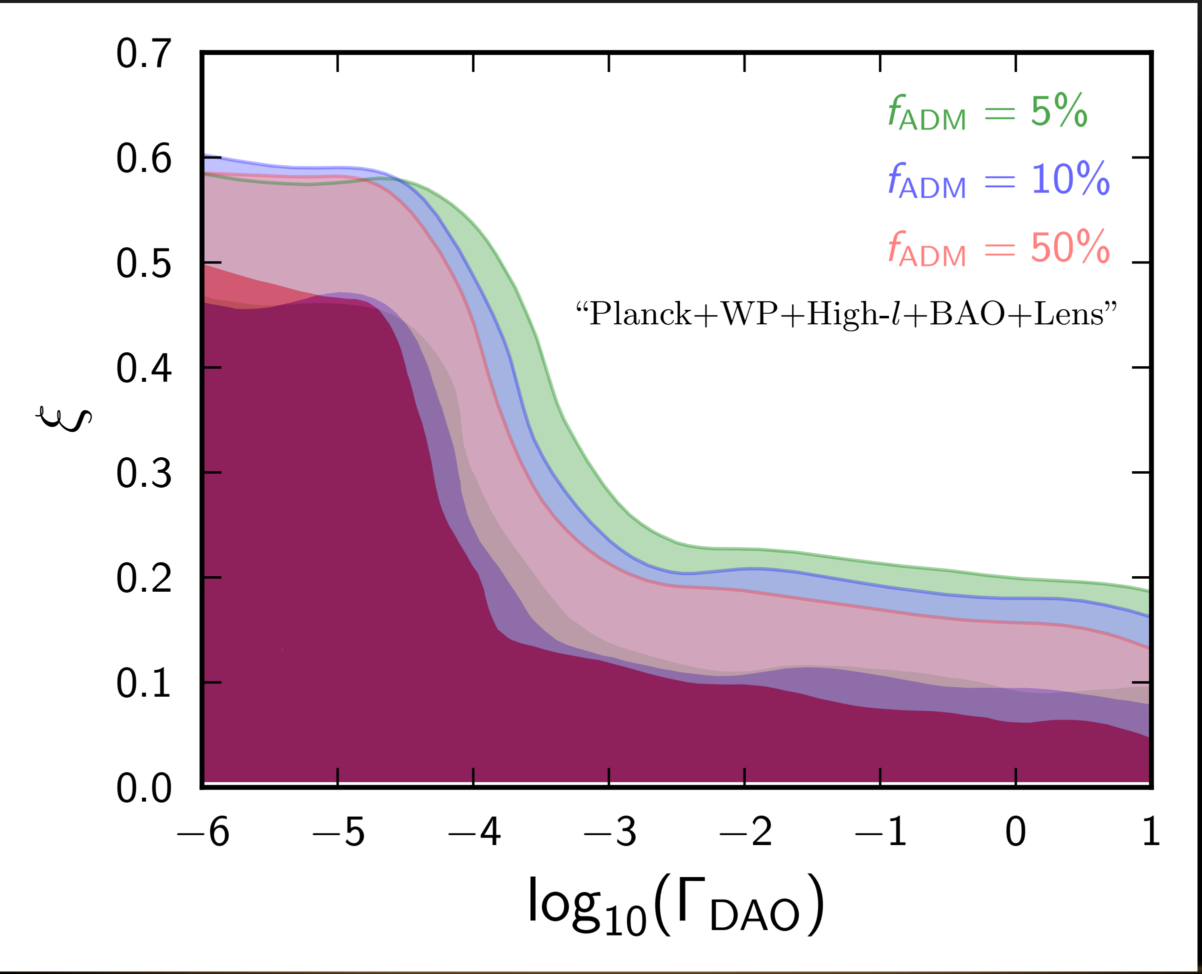
CMB Lensing BB Spectrum, $f_{ADM} = 5\%$



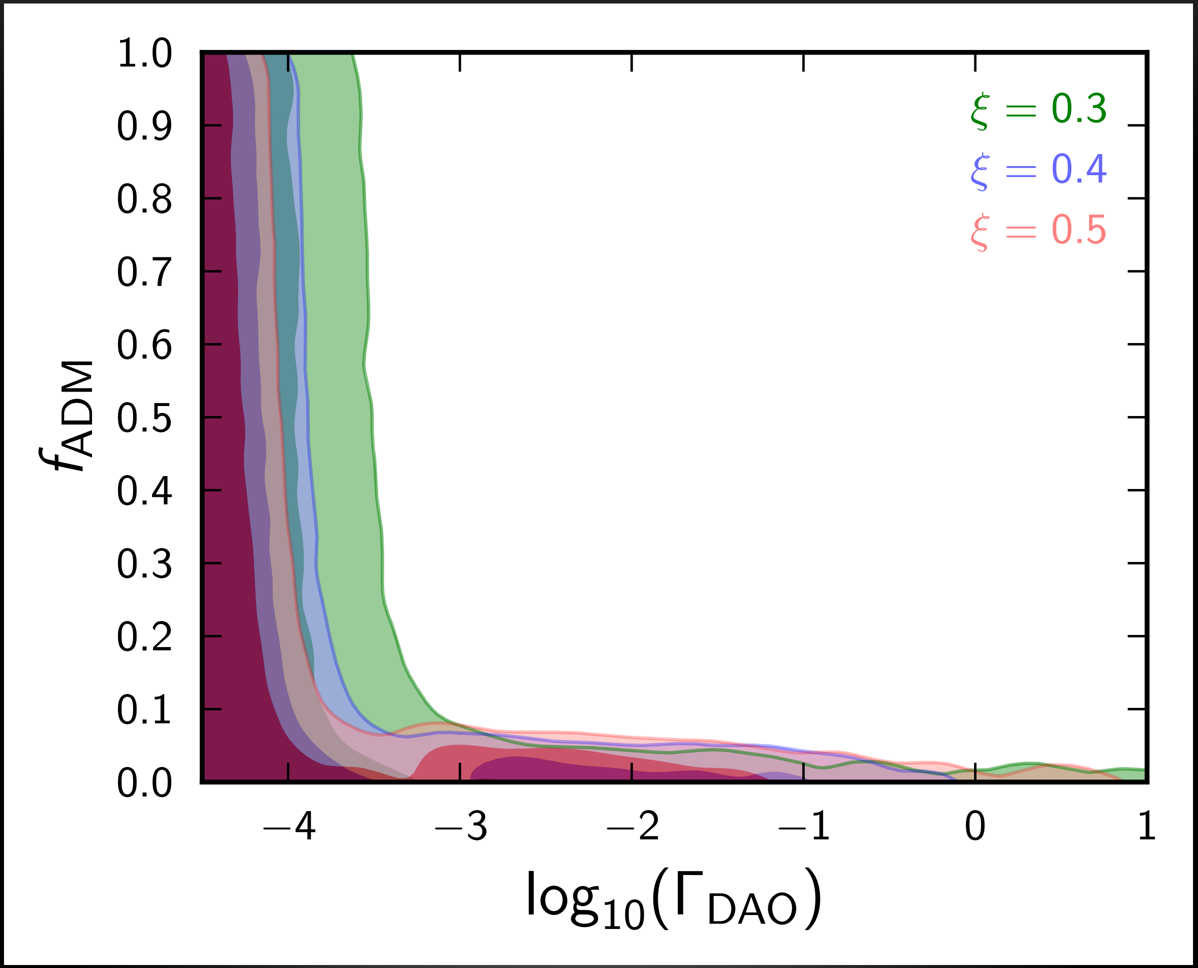
Cosmological Constraints: free f_{ADM}



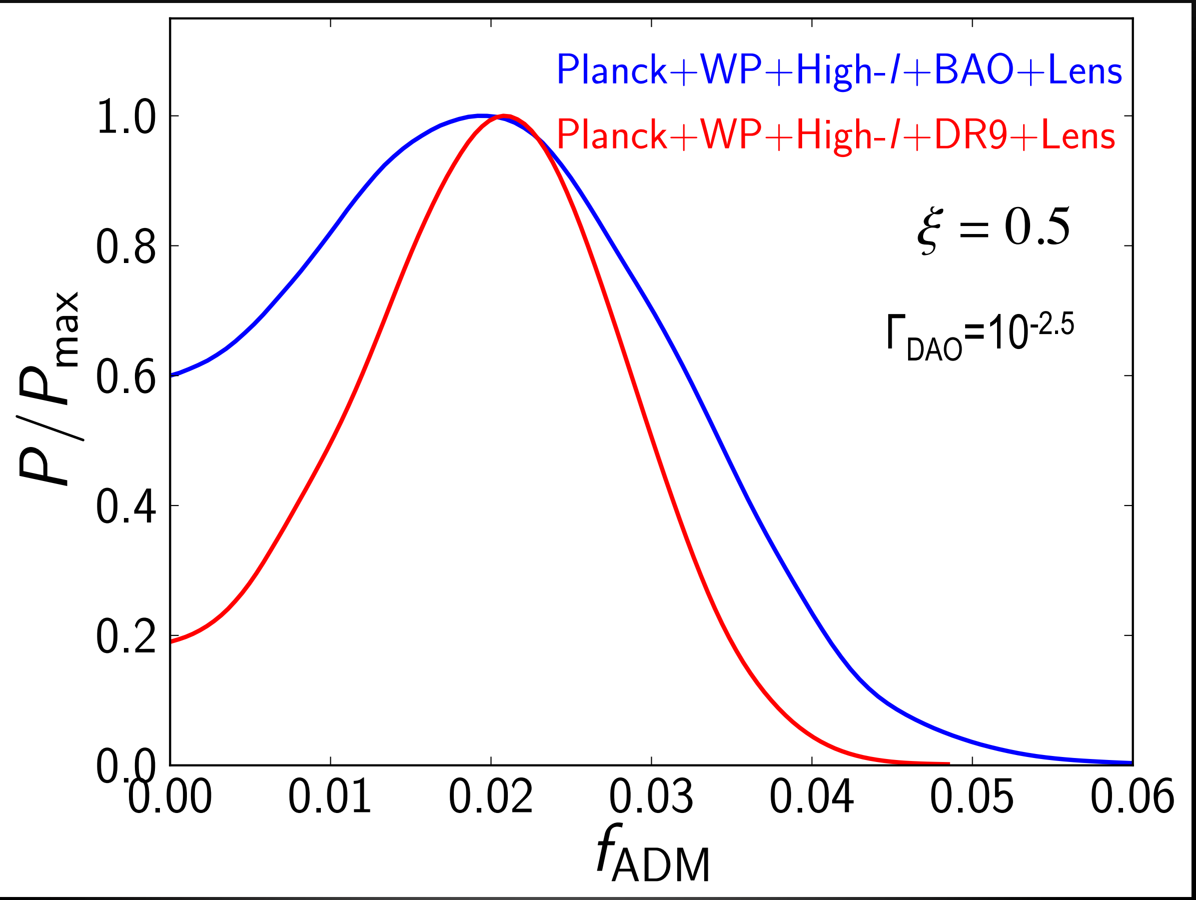
Cosmological Constraints: fixed f_{ADM}



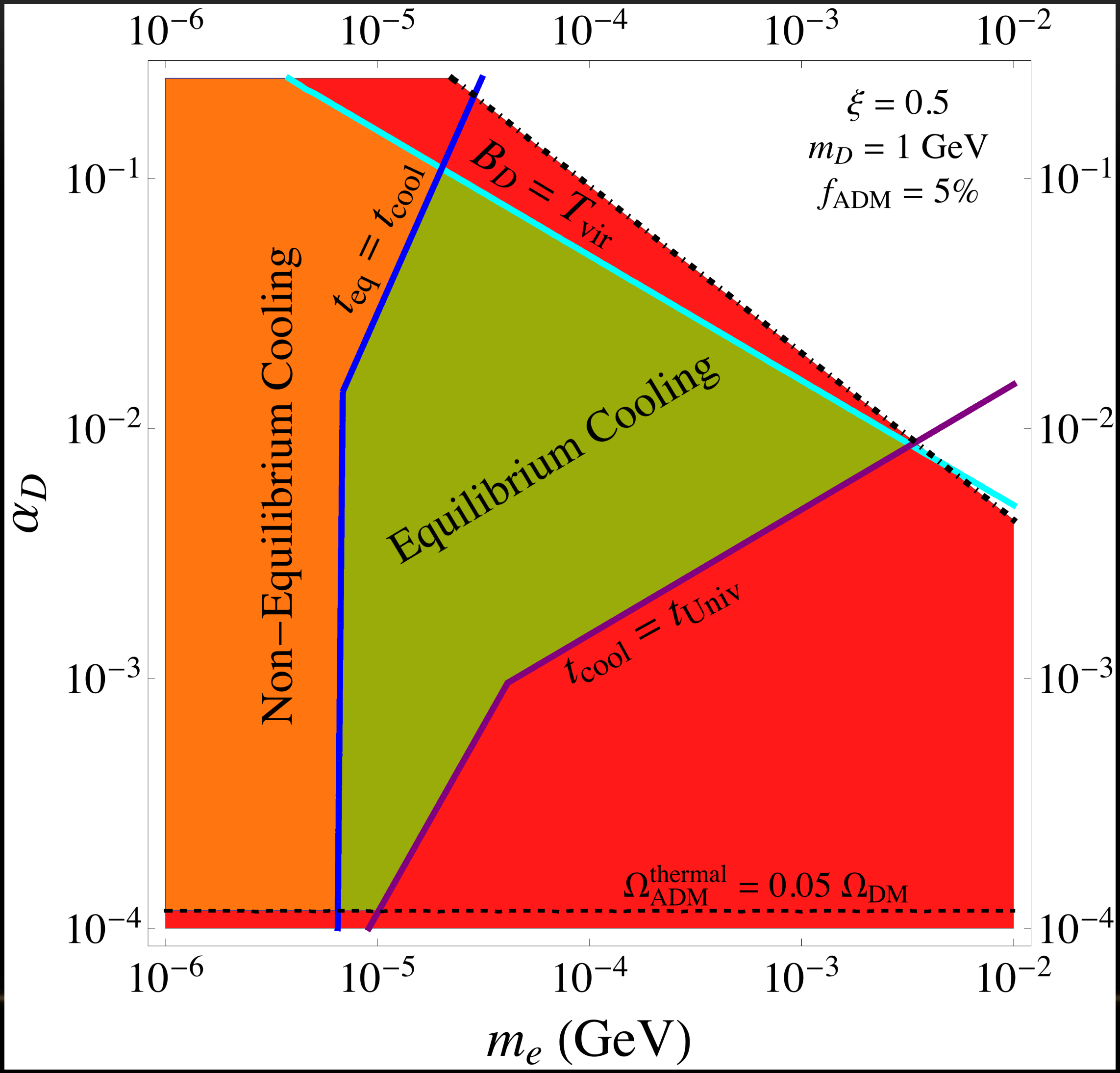
Cosmological Constraints on f_{ADM}



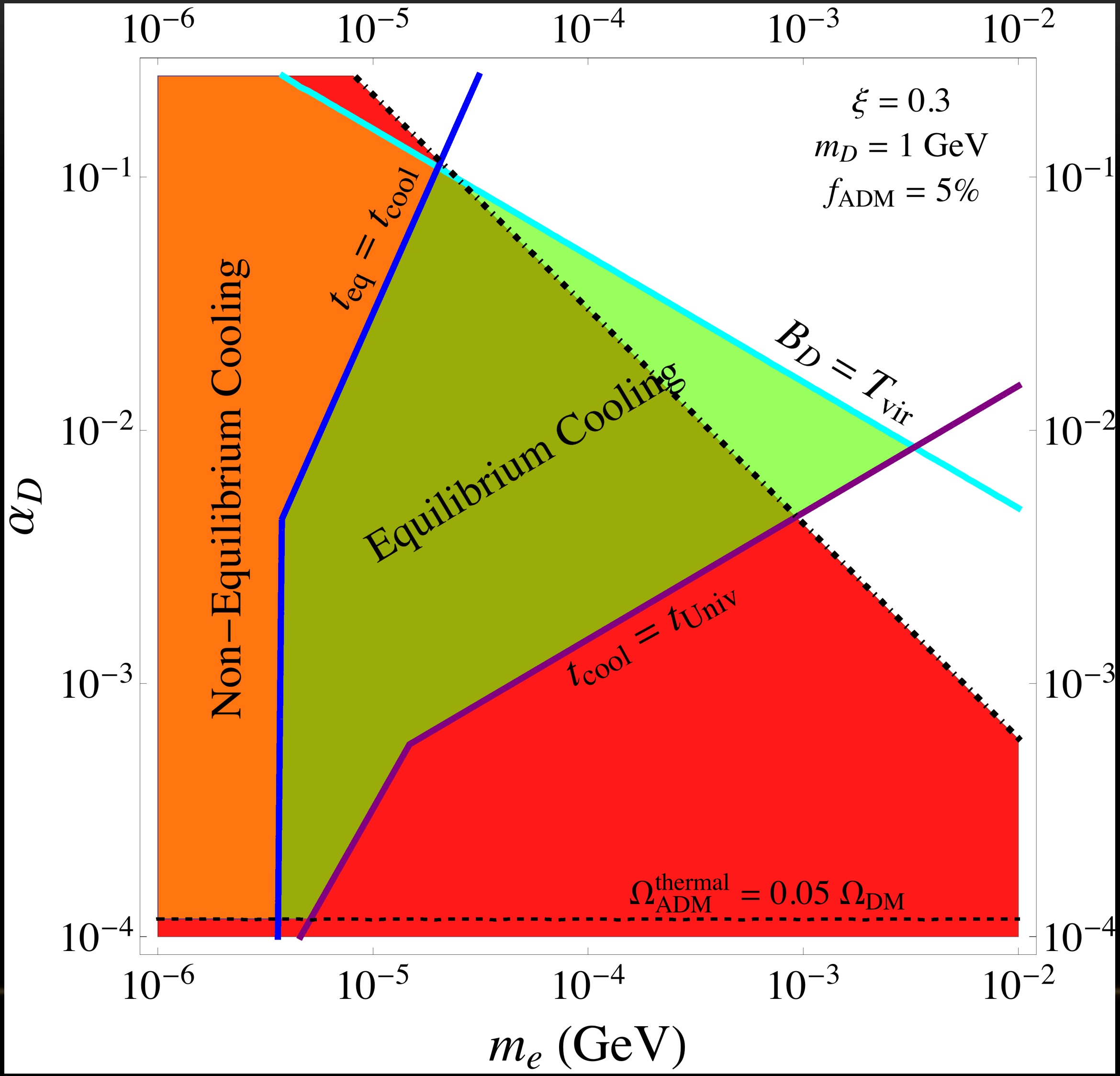
Interacting DM: Allowed Fraction



Constraints on Double-Disk DM



Constraints on Double-Disk DM



Conclusions

- This is a unique time for “cosmological” interacting dark matter.
- Current data already put strong constraints on interacting dark matter.
- CMB lensing B-mode and lensing reconstruction will provide even stronger constraints/hints of interacting DM in the near future (Planck, ACTpol, STPpol, PolarBear. etc.)
- The complementarity between the cosmological and astrophysical properties of DM might help us pinpoint its nature.

Challenges and Future Directions

- Non-linearity
- CMB lensing
- Weak lensing
- Small-astrophysical scales?