Probing Dark Matter with the CMB and Large-Scale Structure

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References:

- **C. Dvorkin, K. Blum and M. Zaldarriaga, PRD (2013)**
- **K. Blum, C. Dvorkin and M. Zaldarriaga (in preparation)**
- **C. Dvorkin, K. Blum and M. Kamionkowski (to appear)**

Outline

- Effect of **WIMP Dark Matter** Annihilation on the CMB:

✧ Homogeneous scenario: suppressed CMB temperature and polarization fluctuations at l>100, enhanced polarization at large scales.

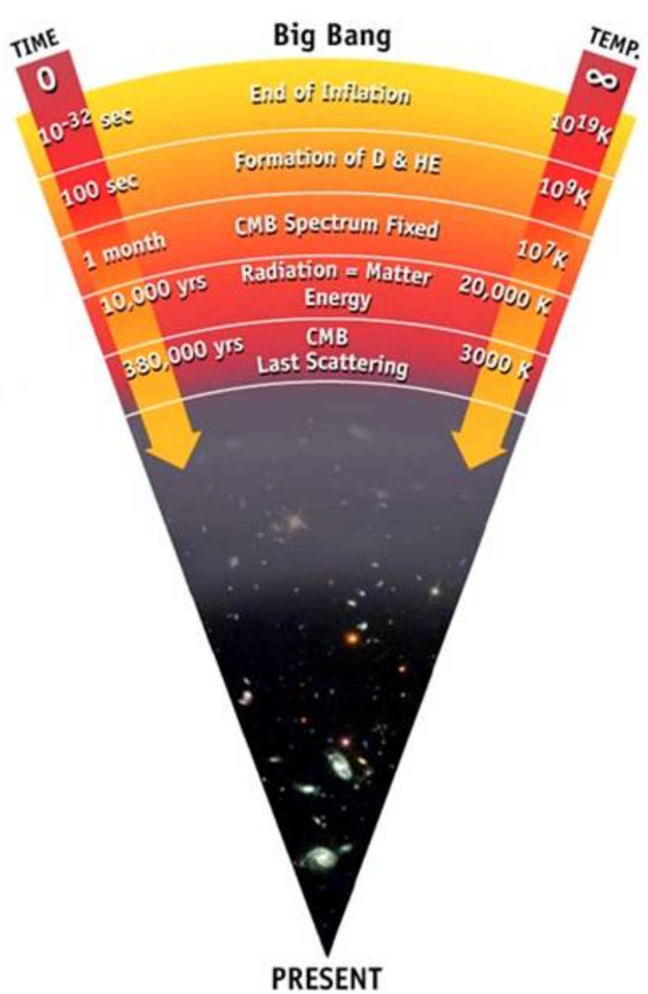
✧ Inhomogeneous scenario:
- Boosted electron perturbations: source of Non-Gaussianity.

  Recombination Bispectrum: important to understand in order to disentangle non-linear evolution from exotic physics/primordial Non-Gaussianity.

- Other effects: enhanced matter temperature fluctuations – key observable: 21 cm radiation field; CMB B-mode polarization.

- Effect of **Dark Matter-baryon interactions** on the CMB and the LSS.

Cosmic History

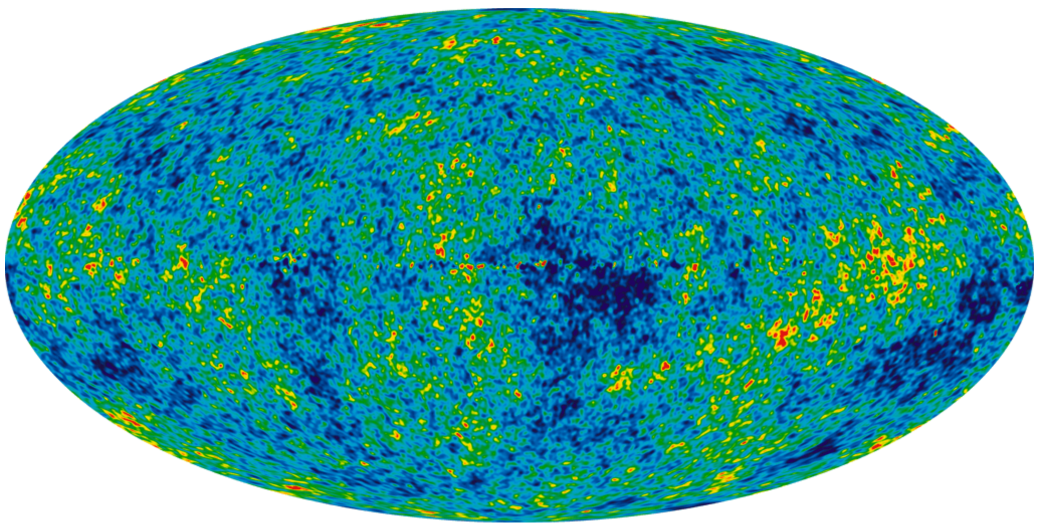


- The universe began as a hot and dense plasma of particles in thermal equilibrium.
- Recombination ($z \approx 1100$): $p^+ + e^- \rightarrow H$
  Universe becomes transparent to CMB photons.

  Photons mainly freestream.
- Radiation from first stars and quasars reionizes the universe ($z \approx 10$-20) and $\sim 10\%$ of the photons re-scatter.
- We observe these photons at $T \approx 2.725$ K.

CMB Anisotropies

"Snapshot" of the Early Universe



Gaussian random fluctuations: $\Delta T \approx 100 \mu K$

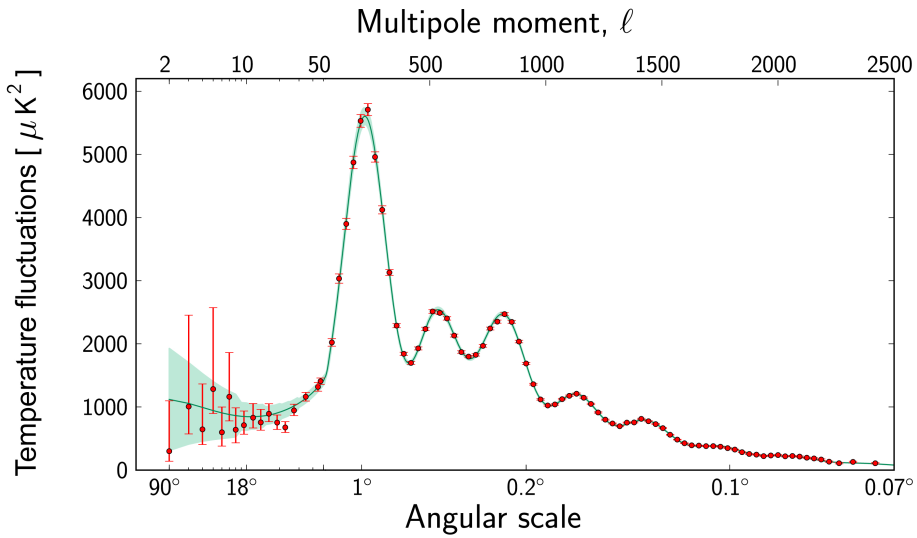
CMB Power Spectrum

Power spectrum: contains all the information for a Gaussian, isotropic field.

$$\Delta T\left(\hat{\mathbf{n}}\right) = \sum_{\ell m} T_{\ell m} Y_{\ell m}\left(\hat{\mathbf{n}}\right)$$

$$\langle T_{\ell m} T^{*}_{\ell' m'} \rangle = C_{\ell}^{TT} \delta_{\ell\ell'} \delta_{mm'}$$

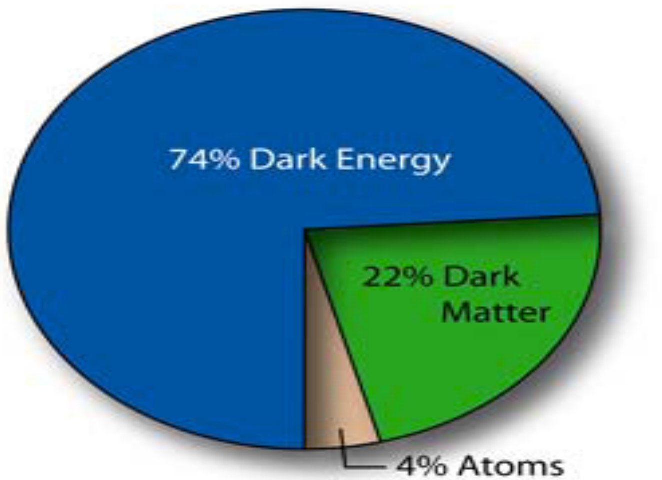
It has been **predicted** and **measured** with good precision.



Planck collaboration (2013)

ΛCDM: the "Standard" Model of Cosmology

Homogeneous background

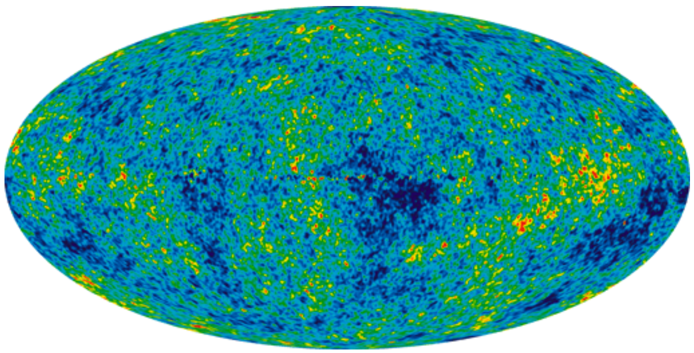


$$\Omega_b h^2, \Omega_c h^2, \Omega_\Lambda, \tau, \theta$$

- Baryonic matter: 4%
- Cold dark matter: 22%
- Dark energy: 74%

Λ? CDM?

Perturbations



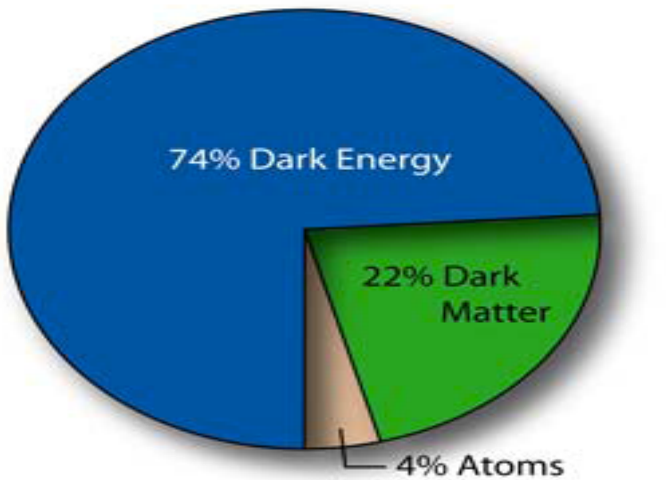
$$A_s, n_s$$

- Nearly scale-invariant
- Gaussian

Origin?

ΛCDM: the "Standard" Model of Cosmology

Homogeneous background



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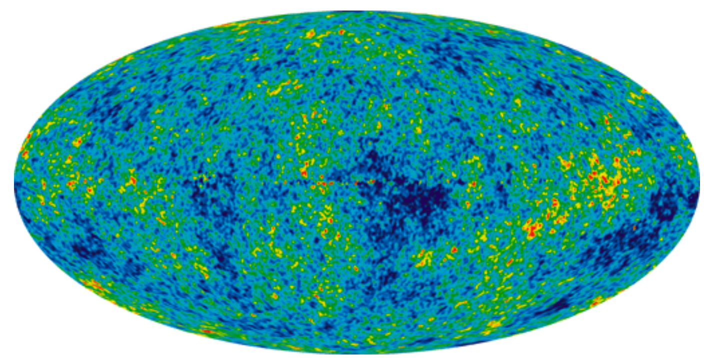

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- Nearly scale-invariant
- Gaussian

Origin?

WIMP Dark Matter Annihilation

- Thermal production of DM: $\langle \sigma v \rangle \sim 3 \times 10^{-26} cm^3/s$ (WIMP)
- Annihilation rate: $\Gamma \propto n^2 \langle \sigma v \rangle$ (*n* depends on the model of DM distribution)

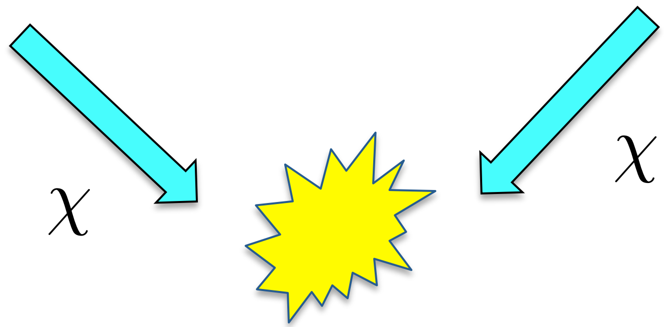
Dark matter annihilation should leave a **signature in the CMB**.

At z$\sim$1000, when the CMB decouples, the homogeneous DM density is

$$n(z = 1000) = n_{today}(1+z)^3 \sim n_{today} \times 10^9$$

CMB: less uncertainties than other astrophysical probes (independent of the DM distribution)!

WIMP Dark Matter Annihilation



$$W^{\pm}, Z, b\bar{b}, h$$

FINAL PRODUCTS

$$p\bar{p}, \nu\bar{\nu}, e^{\pm}, \gamma$$

Energy Injection in the CMB

FINAL PRODUCTS

$p\bar{p}, \nu\bar{\nu}, e^{\pm}, \gamma$

- **Heat the plasma**
- **Ionize neutral hydrogen**
- **Excite H atoms**

Shull and van Steenberg, ApJ (1985)
Chen and Kamionkowski, PRD (2004)

Energy injected into the plasma per unit volume, per unit time:

$$\frac{dE}{dtdV} = n_{pairs} P_{ann} E_{ann} f(z)$$

Number of DM particle pairs

Annihilation probability per unit time

Energy released per annihilation

Fraction of energy absorbed by the plasma (depends on the model)

Slatyer, Padmanabhan and Finkbeiner (2009)

Energy Injection in the CMB

FINAL PRODUCTS

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- **Heat the plasma**
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Shull and van Steenberg, ApJ (1985)
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Energy injected into the plasma per unit volume, per unit time:

$$\frac{dE}{dtdV} = \rho_\chi^2 \left[\frac{f(z)\langle\sigma v\rangle}{m_\chi} \right]$$

(Majorana particle)

Standard Recombination

The three-level atom model: consider only three energy levels of hydrogen atom; ground state (n=1), first excited state (n=2) and the continuum (n>2).

Peebles (1968)
Z'eldovich et al. (1968)

BOTTLENECKS

- Ground state recombinations are ineffective
- Lyman-alpha photons are re-captured

EFFICIENT RECOMBINATION PROCESSES

- Two-photon process, 2s→1s
- Redshifting off-resonance: $R \sim H/(n_H \lambda_\alpha^3)$

Seager, Sasselov, Scott (2000)

Standard Recombination

Effective Boltzmann equation for the free electron density:

$$\frac{\partial n_e}{\partial t} + 3Hn_e = C_H \left[-\alpha_H n_e^2 + \beta_H (n_H - n_e) e^{-E_{2s}/kT_M} \right]$$

Standard Recombination

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$$\frac{\partial n_e}{\partial t} + 3Hn_e = C_H \left[-\alpha_H n_e^2 + \beta_H (n_H - n_e) e^{-E_{2s}/kT_M} \right]$$

Recombination rate

Standard Recombination

Effective Boltzmann equation for the free electron density:

$$\frac{\partial n_e}{\partial t} + 3Hn_e = C_H \left[-\alpha_H n_e^2 + \beta_H (n_H - n_e) e^{-E_{2s}/kT_M} \right]$$

Recombination rate **Ionization rate**

DM Annihilation at Recombination

Effective Boltzmann equation for the free electron density:

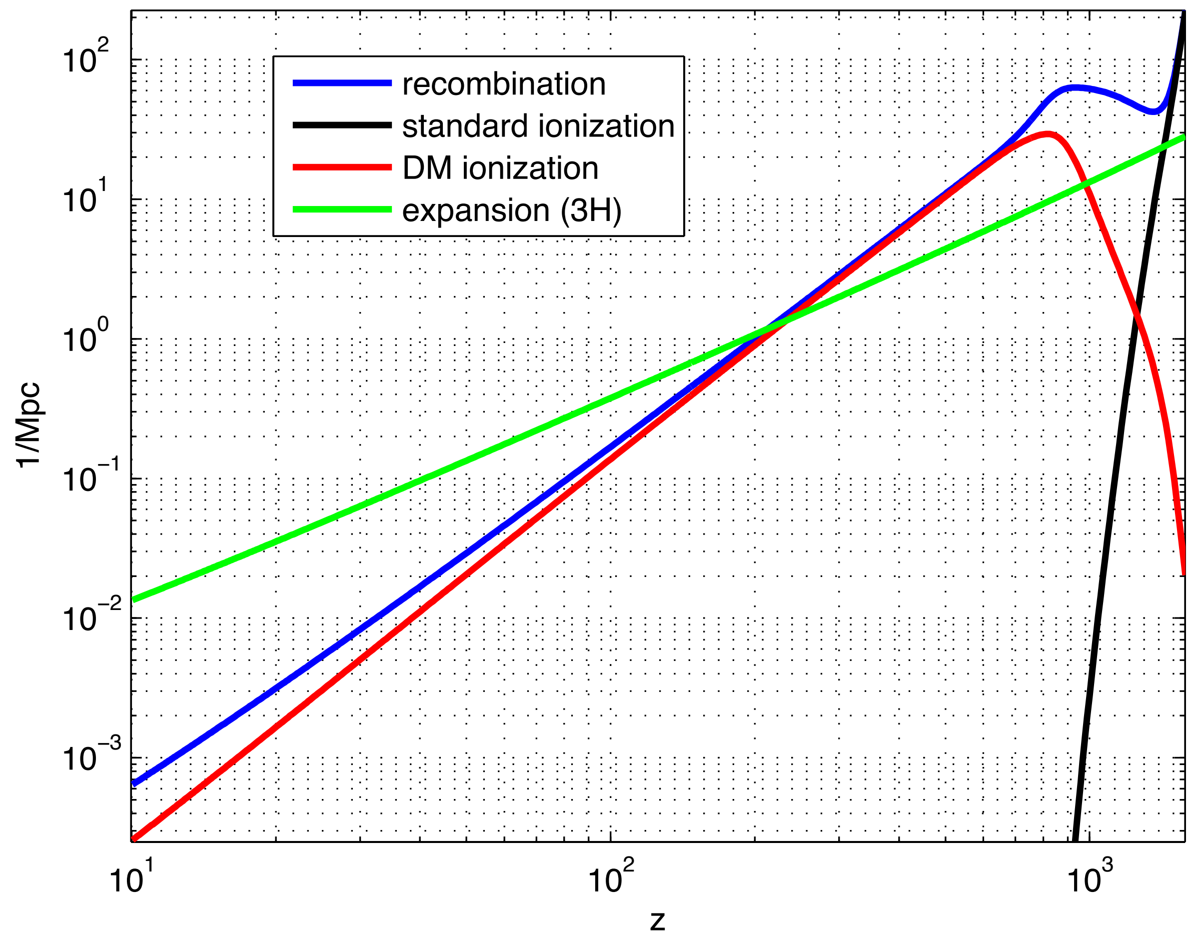
$$\frac{\partial n_e}{\partial t} + 3Hn_e = C_H \left[-\alpha_H n_e^2 + \beta_H (n_H - n_e) e^{-E_{2s}/kT_M} \right] + I_\chi$$

Recombination rate **Ionization rate**

Dark matter ionization rate:

$$I_\chi = \frac{n_H - n_e}{3n_H} \frac{dE}{dV\,dt} \frac{1}{n_H \epsilon_H} \left(1 + \frac{4}{3}(1 - C_H) \right)$$

Time scales (Recombination, Ionization, Expansion)



Ionization "floor"

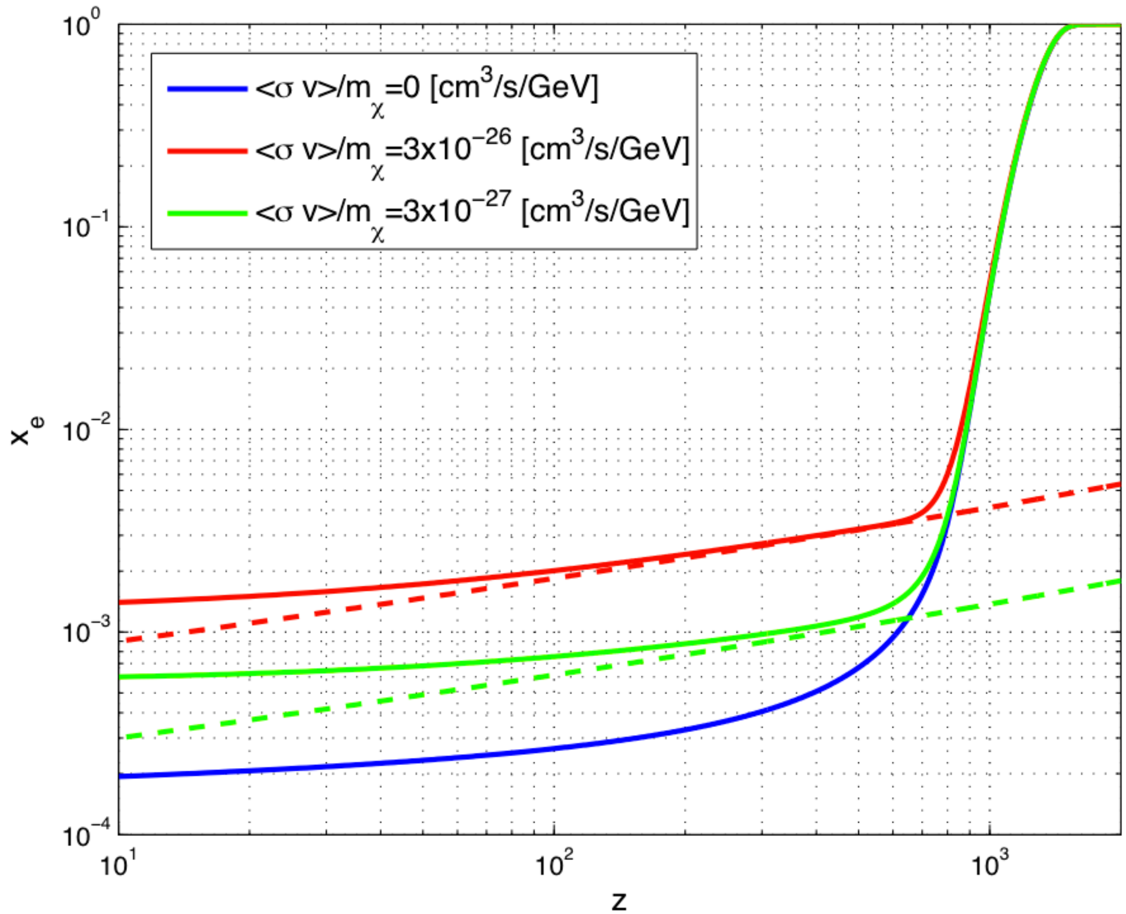
At 200<z<600, there is a competing effect between recombination and ionization from DM annihilations: $R_s \approx I_\chi$

Quasi-equilibrium solution for the free electron fraction: $x_e = n_e/n_H$

$$x_e^{floor} = 3 \times 10^{-3} \left(\frac{z}{1000}\right)^{1/3} \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26} cm^3/s}\right)^{1/2} \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)^{-1/2}$$

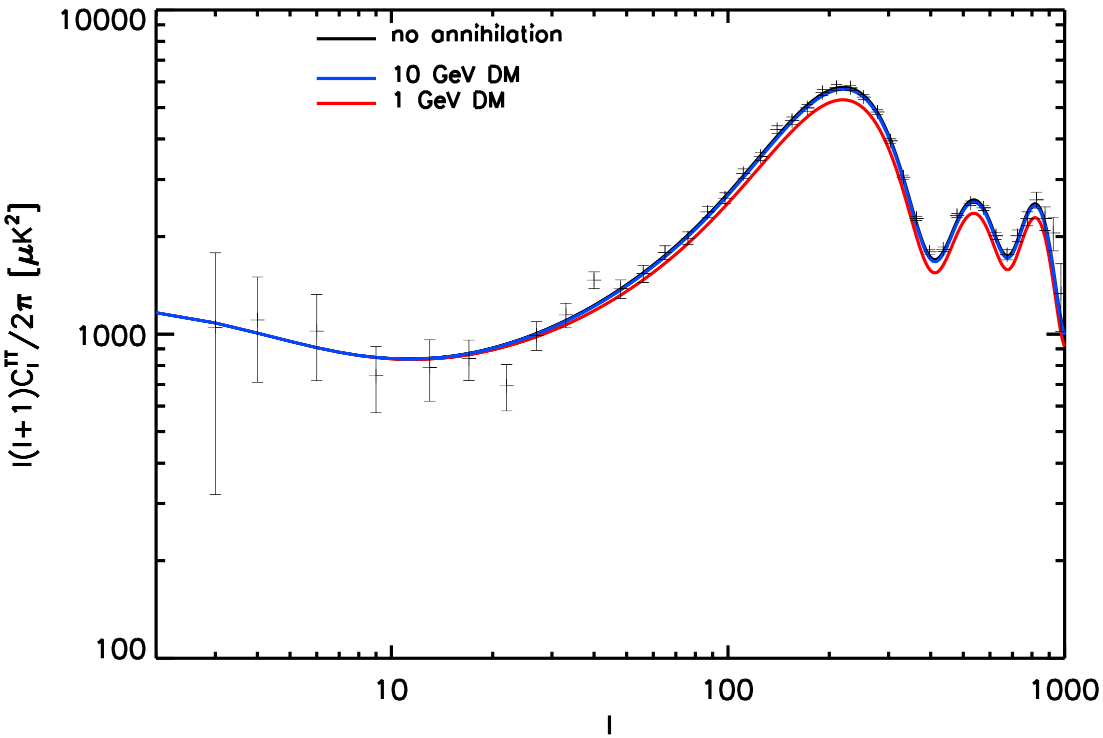
Dark matter can easily dominate the ionization fraction after recombination

Free electron fraction evolution



Effect on the CMB Temperature

A higher ionization suppresses the CMB temperature fluctuations



Degeneracy:

$$C_\ell \to e^{-2\Delta\tau} C_\ell$$

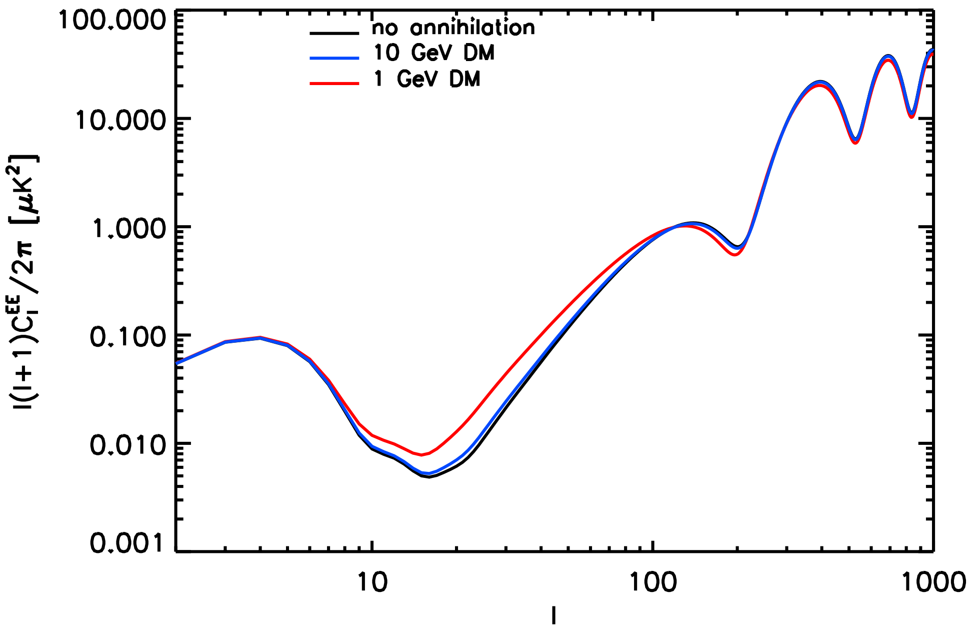
$$A_s \to e^{2\Delta\tau} A_s$$

Padmanabhan and Finkbeiner (2005)

Current CMB constraints are $\mathcal{O}(1)$ GeV ⟶ Complementary to direct detection searches, that are most sensitive to $m_\chi \gtrsim 10$ GeV, due to kinematical considerations.

Effect on the CMB Polarization

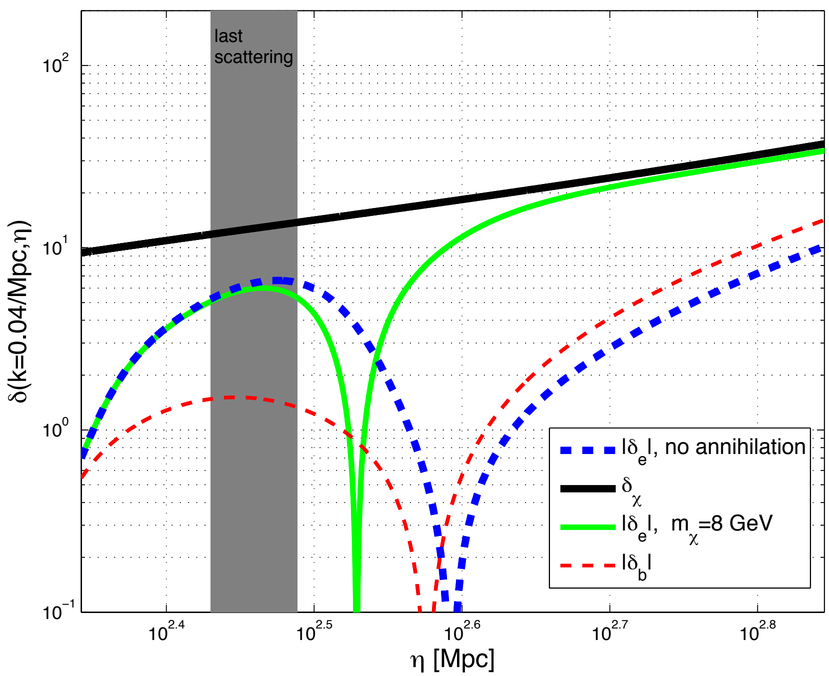
A higher ionization enhances the polarization fluctuations at large scales



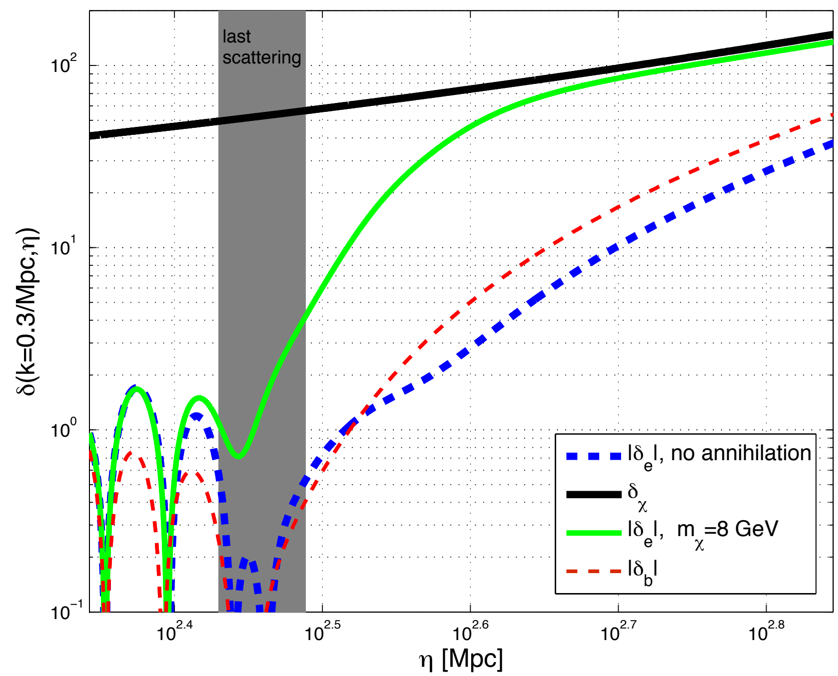
- Screening of the observed spectrum at l>100
- Re-scattering of photon generates extra polarization at large scales

Dark Matter Annihilation Inhomogeneous scenario

There are growing ionization modes that track the collapse of matter overdensities.



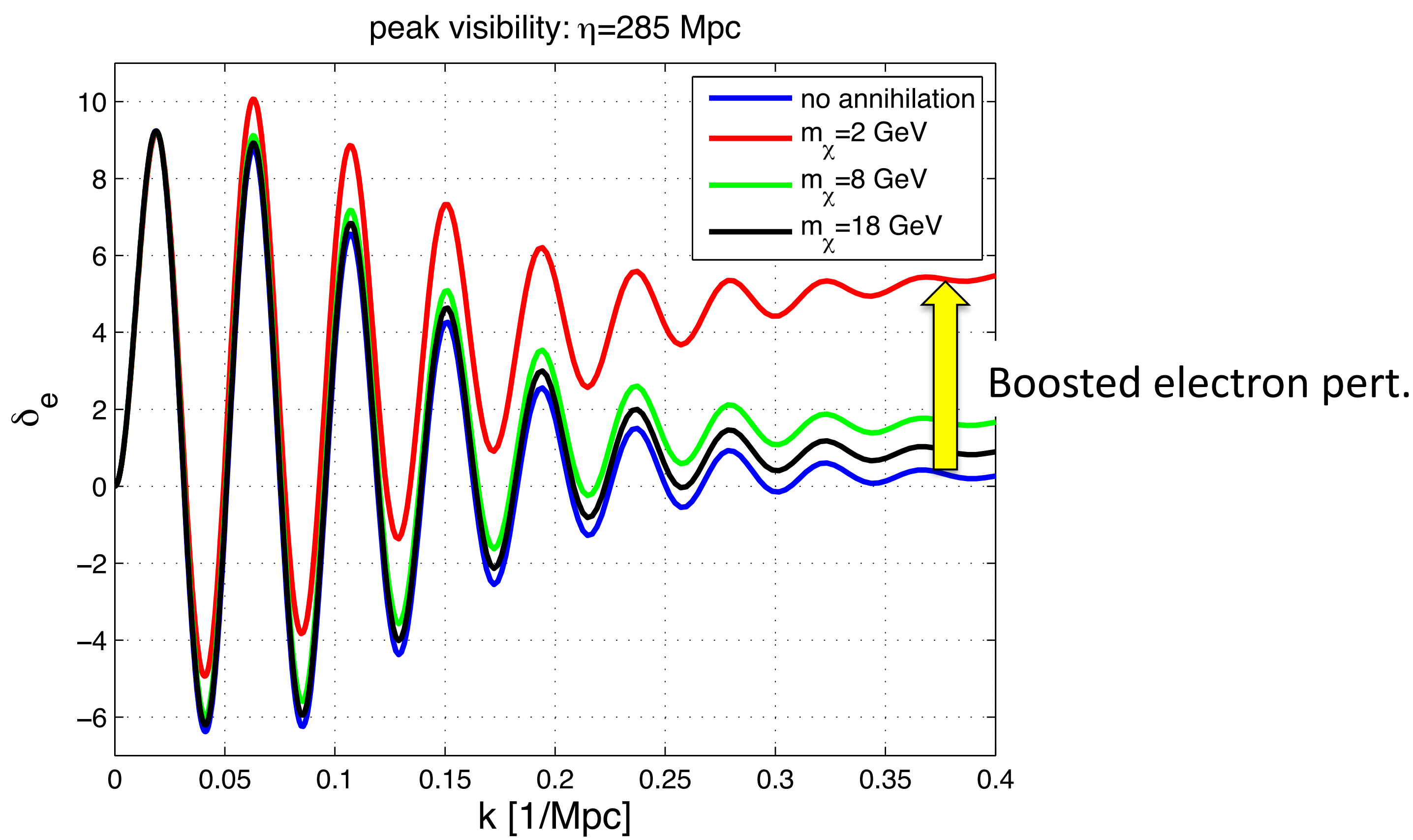
k=0.04 Mpc^{-1}



k=0.3 Mpc^{-1}

C. Dvorkin, K. Blum, and M. Zaldarriaga (2013)

Comparison to standard first order electron perturbations



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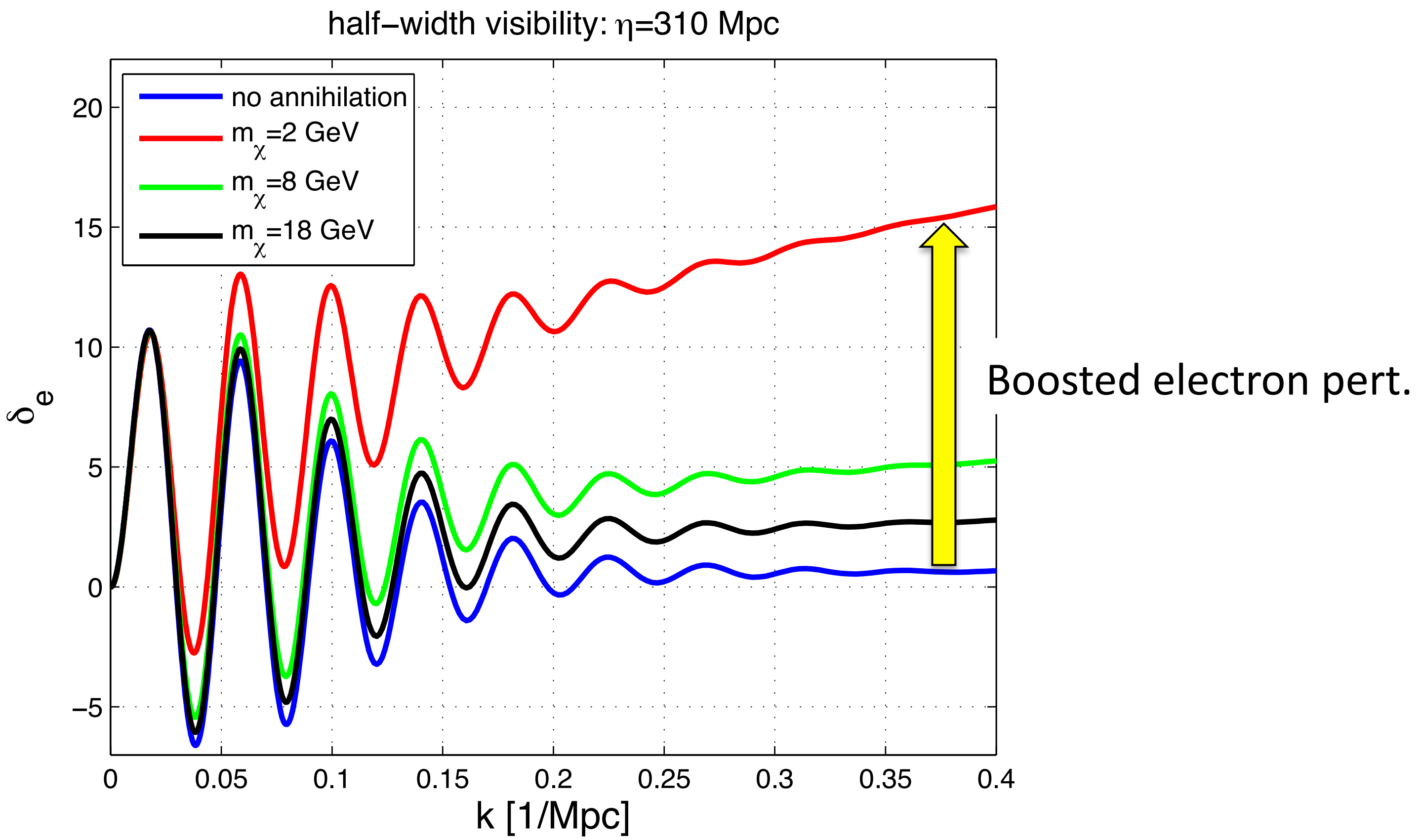


C. Dvorkin, K. Blum, and M. Zaldarriaga (2013)

Can we observe electron density perturbations in the CMB?

CMB Bispectrum: probe of electron density perturbations

- **From perturbed visibility: anisotropic optical depth.**
- **From perturbed diffusion damping, sound speed, etc.**

Senatore, Tassev and Zaldarriaga (2009)
Khatri and Wandelt (2009)

Can we observe electron density perturbations in the CMB?

CMB Bispectrum: probe of electron density perturbations

- **From perturbed visibility: anisotropic optical depth.**

The first and second order anisotropies today are given by the line of sight solutions to the Boltzmann equation:

$$\Theta^{(1)}(\vec{k},\eta_0,\hat{n}) = \int_0^{\eta_0} d\eta e^{ik\mu_k(\eta-\eta_0)} g(\eta) S^{(1)}(\vec{k},\eta,\hat{n}),$$ *Seljak and Zaldarriaga (1996)*

$$\Theta^{(2)}(\vec{k},\eta_0,\hat{n}) = \int_0^{\eta_0} d\eta e^{ik\mu_k(\eta-\eta_0)} g(\eta) S_{\delta g}(\vec{k},\eta,\hat{n})$$

$$S_{\delta g}(\vec{k},\eta,\hat{n}) = \int \frac{d^3q}{(2\pi)^3}\delta_e(\vec{k}-\vec{q},\eta)\left(\Theta_0^{(1)}(\vec{q},\eta) + \mu_q v_b^{(1)}(\vec{q},\eta) - \frac{1}{2}\mathcal{P}_2(\mu_q)\Pi^{(1)}(\vec{q},\eta) - \Theta^{(1)}(\vec{q},\eta,\hat{n})\right)$$

Can we observe electron density perturbations in the CMB?

CMB Bispectrum: probe of electron density perturbations

- **From perturbed visibility: anisotropic optical depth.**

$$B^{\ell_1\ell_2\ell_3} = \frac{4}{\pi^2}\sqrt{(2\ell_1+1)(2\ell_2+1)(2\ell_3+1)}\begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ 0 & 0 & 0 \end{pmatrix}\int d\eta g(\eta)\left(f_{\ell_1}(\eta)g_{\ell_2}(\eta) + \mathrm{perm}\right)$$

$$f_\ell(\eta) = (-1)^l \int dk k^2 P(k)\Theta^{(1)}_\ell(k,\eta_0)\sum_{l',l''}(2l'+1)(2l''+1)\begin{pmatrix} \ell & \ell' & \ell'' \\ 0 & 0 & 0 \end{pmatrix}^2 i^{l+l'+l''} j_{l'}[k(\eta_0-\eta)]$$
$$\times\left(\delta_{l''1}\frac{\theta_b^{(1)}(k,\eta)-\theta_\gamma^{(1)}(k,\eta)}{3k} + \delta_{l''2}\frac{\Pi^{(1)}(k,\eta)}{10} - (1-\delta_{l''0})(1-\delta_{l''1})\Theta^{(1)}_{l''}(k,\eta)\right)$$

New anisotropies generated by electron perturbations:

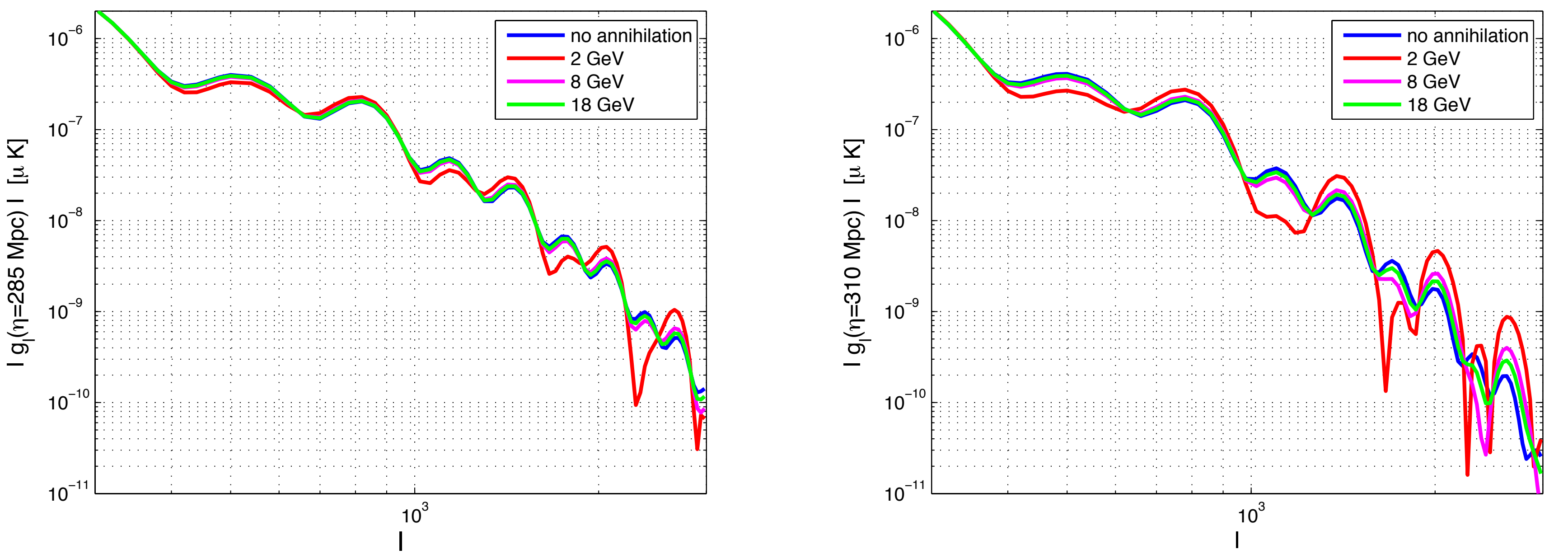
$$g_\ell(\eta) = \int dk k^2 P(k)\Theta^{(1)}_\ell(k,\eta_0) j_\ell[k(\eta_0-\eta)]\delta_e(k,\eta)$$

Can we observe electron density perturbations in the CMB?

Signal-to-noise $\sim$ 0.5 for Planck; polarization will have more information (work in progress).

at peak visibility

at half-maximum visibility



The main boost in the electron perturbations by DM annihilation occurs on small scales, l>3000 (challenging to observe).

C. Dvorkin, K. Blum, and M. Zaldarriaga (2013)

Perturbed Harmonic Oscillator

Solve the perturbed Boltzmann equation up to second order in the tight coupling limit ($k\dot{\tau} >> 1$) and identify the physical processes:

$$c_s^2 = \frac{1}{3(1+R)}$$

$$\boxed{\ddot{\Theta}_0 + \underbrace{k^2 c_s^2 \left(1 - R\partial_\eta \left[\frac{R}{\dot{\tau}(1+R)}\right]\right)}_{w^2} \Theta_0 - \underbrace{\frac{k^2 c_s^2}{\dot{\tau}} \left(\frac{16}{15} + \frac{R^2}{1+R}\right)}_{iw} \dot{\Theta}_0 = S_{k_D} + S_{c_s}}$$

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Silk damping

$$S_{k_D} = -\frac{k^2 c_s^2}{\dot{\tau}} \int \frac{d^3q}{(2\pi)^3} \left(\frac{16}{15} \mathcal{P}_2 \left(\hat{k} \cdot \hat{q}\right) + \frac{R^2}{1+R} \frac{q}{k} \mathcal{P}_1 \left(\hat{k} \cdot \hat{q}\right)\right) \delta_e(\vec{k} - \vec{q})\, \dot{\Theta}_0^{(1)}(\vec{q}),$$

Perturbed Harmonic Oscillator

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Sound speed

$$S_{c_s} = -k^2 c_s^2 \int \frac{d^3q}{(2\pi)^3} \frac{q}{k} \mathcal{P}_1 \left(\hat{k} \cdot \hat{q}\right) R\partial_\eta \left(\frac{R}{\dot{\tau}(1+R)} \delta_e(\vec{k} - \vec{q})\right) \Theta_0^{(1)} (\vec{q})$$

Perturbed Harmonic Oscillator

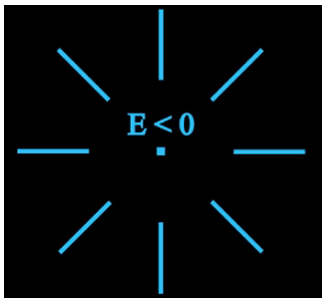
- Solution with WKB Green's function:

$$\theta_0^{(2)}(\vec{k},\eta) \approx \int_0^{\eta} d\eta' G(k,\eta,\eta') \left(S_{k_D}(\vec{k},\eta') + S_{c_s}(\vec{k},\eta') \right)$$

$$G(k,\eta,\eta') = \frac{\sin\left(k \int_{\eta'}^{\eta} d\eta'' c_s(\eta'')\right)}{k c_s(\eta)} e^{-k^2/k_D^2}$$

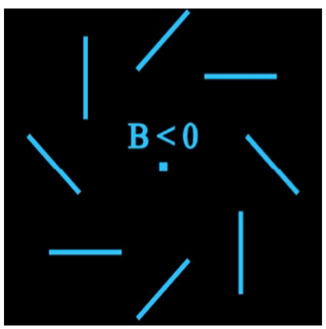
CMB polarization: E-B decomposition

Represent CMB polarization on the sky by a traceless symmetric tensor Π_{ab}



E-mode: "curl-free" field

$$\Pi_{ab} = \left(\nabla_a \nabla_b - \frac{1}{2} g_{ab} \nabla^2\right) \phi$$



B-mode: "divergence-free" field

$$\Pi_{ab} = \left(\frac{1}{2} \epsilon_{ac} \nabla^c \nabla_b + \frac{1}{2} \epsilon_{bc} \nabla^c \nabla_a\right) \phi$$

This is the analog of the gradient/curl decomposition of a vector field

Generation of B-modes

Polarization is a spin-2 field: $(Q \pm iU)(\hat{\mathbf{n}}) \rightarrow e^{\mp i2\Psi}(Q \pm iU)(\hat{\mathbf{n}})$

$$(Q \pm iU)(\hat{\mathbf{n}}) = -\sum_{\ell m}(E_{\ell m} \pm iB_{\ell m})_{\pm 2}Y_{\ell m}(\hat{\mathbf{n}})$$

- Scalar sources + linear evolution ➡ E-modes
- Tensor sources or non-linear evolution ➡ B-modes

Generation of B-modes

Polarization is a spin-2 field: $(Q \pm iU)(\hat{\mathbf{n}}) \to e^{\mp i2\Psi}(Q \pm iU)(\hat{\mathbf{n}})$

$$(Q \pm iU)(\hat{\mathbf{n}}) = -\sum_{\ell m} (E_{\ell m} \pm iB_{\ell m})_{\pm 2} Y_{\ell m}(\hat{\mathbf{n}})$$

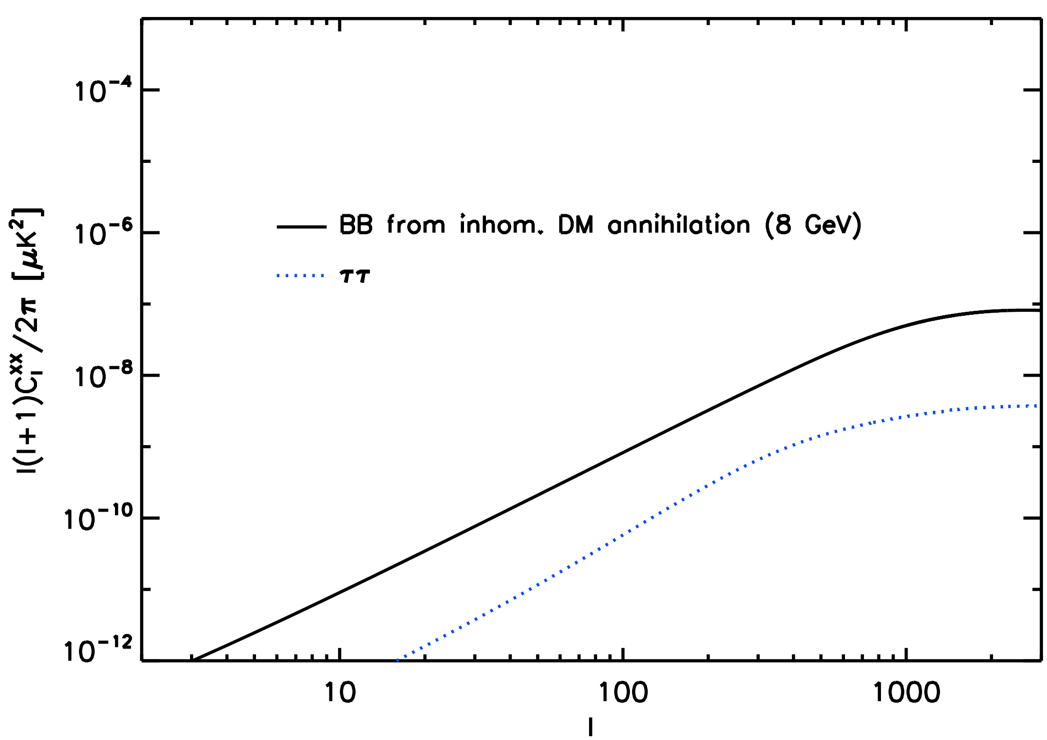
- Scalar sources + linear evolution ➡ E-modes
- Tensor sources or non-linear evolution ➡ B-modes

Electron perturbations: the optical depth is a function of position in the sky. The amplitude of the E-mode field is modulated by $\Delta\tau(\hat{\mathbf{n}})$. Regions with higher optical depth will have lower observed peaks.

$$\Delta (Q \pm iU)(\hat{\mathbf{n}}) = -\Delta\tau(\hat{\mathbf{n}})\,(Q \pm iU)^{(rec)}(\hat{\mathbf{n}})$$

Screening generates B-modes

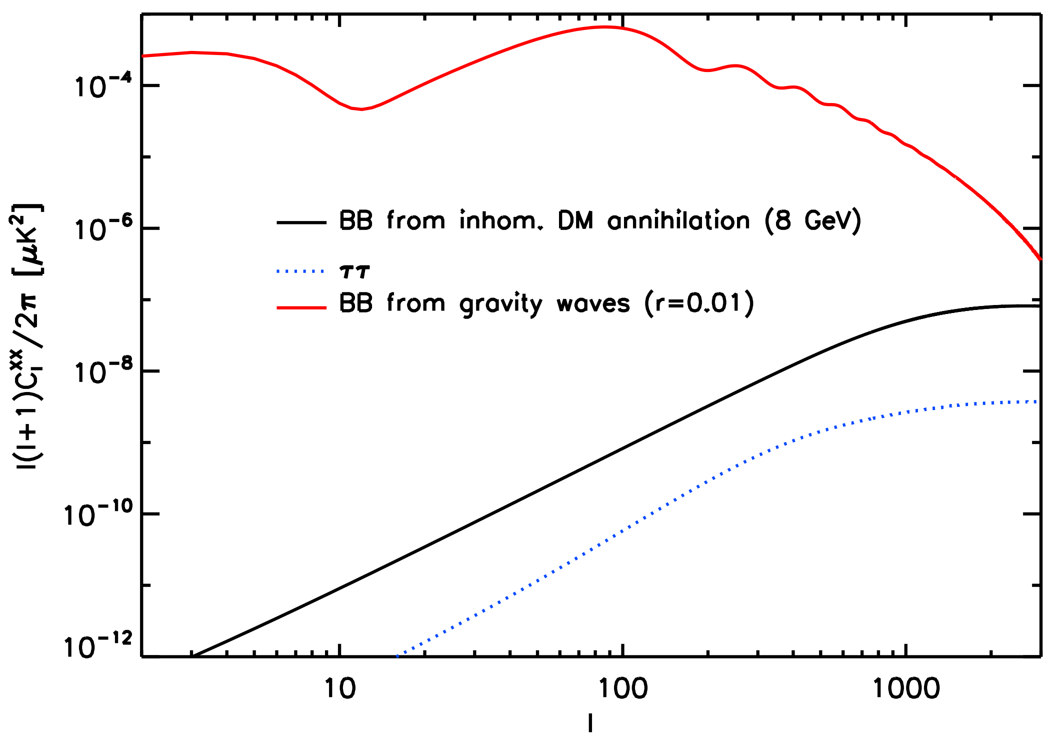
New channel for B-mode polarization



- E-mode fluctuations modulated by τ perturbations generate B-mode polarization with nearly the same wavelength as the τ fluctuations.
- Plateau at small scales dictated by matter fluctuations.
- B-mode amplitude scales as m_χ^{-1} .
- Other sources of B-modes: gravitational lensing, patchy reionization.

C. Dvorkin, K. Smith (2009)
C. Dvorkin, W. Hu, K. Smith (2009)

New channel for B-mode polarization



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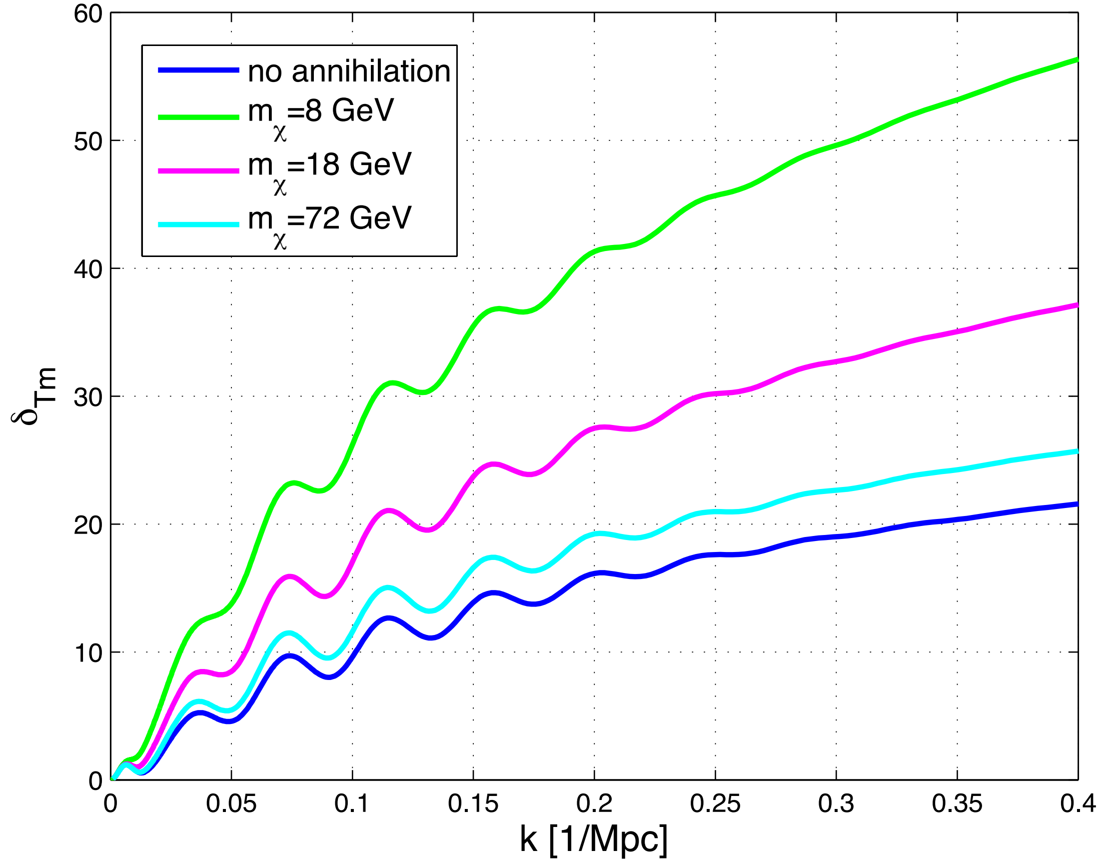
- Relevant scales for gravity waves: ($\ell < 10$, $\ell \sim 50$). B-mode from inhomogeneous DM is unlikely to be a contaminant.

Enhanced Matter Temperature fluctuations at late times



There should be more information in the 21 cm radiation field (future work).

Beyond the WIMP paradigm

- It has been pointed out that Dark Matter self-interactions can significantly affect small-scale structure. *Spergel and Steinhardt (2000); Wandelt et al. (2000)*

- Baryon processes such as star formation, supernova feedback, gas accretion, etc. can have important effects, but these processes are partially understood theoretically and poorly constrained observationally.

- Goal: to use observational probes of the statistical properties of the CMB and matter fluctuations (where the theory is under better control) in order to know how much interaction between baryons and Dark Matter can occur today, consistent with these observational constraints.

Linear Cosmological Perturbations with Dark Matter-Baryon Interactions

C. Dvorkin, K. Blum and M. Kamionkowski (to appear)

$$\dot{\delta}_c = -\theta_c - \frac{1}{2}\dot{h}$$

$$\dot{\theta}_c = -\frac{\dot{a}}{a}\theta_c + c_c^2 k^2 \delta_b + \boxed{R_c(\theta_b - \theta_c)}$$

$$\dot{\delta}_b = -\theta_b - \frac{1}{2}\dot{h}$$

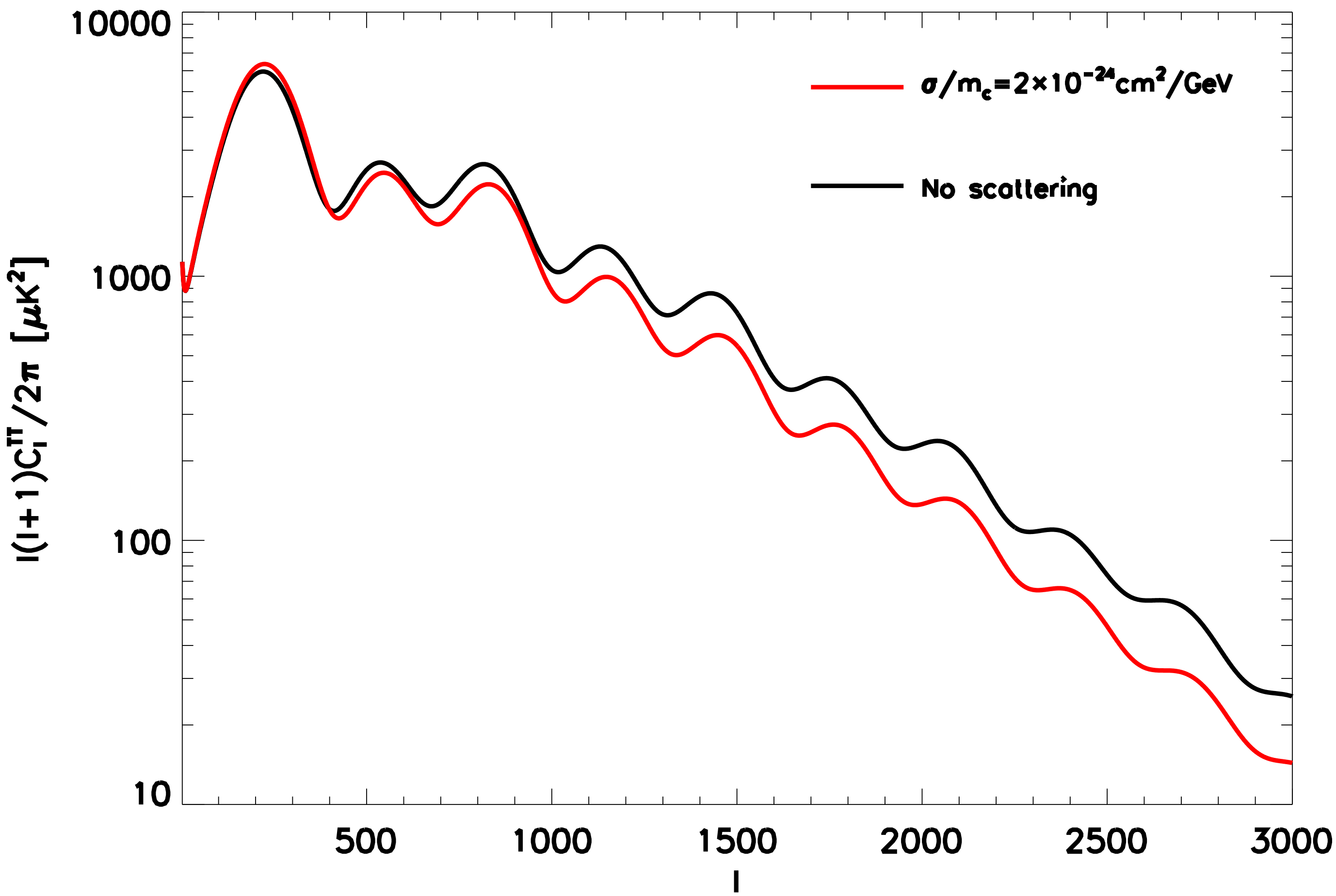
$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + \boxed{\frac{\rho_c}{\rho_b} R_c(\theta_c - \theta_b)} + R_\gamma(\theta_\gamma - \theta_b)$$

Dark Matter-baryon momentum exchange rate:

$$R_c = \frac{c_n a \rho_b \sigma}{m_c + m_b}\left(\frac{T_b}{m_b} + \frac{T_c}{m_c}\right)^{\frac{n+1}{2}}$$ with $\sigma(v) = \sigma v^n$

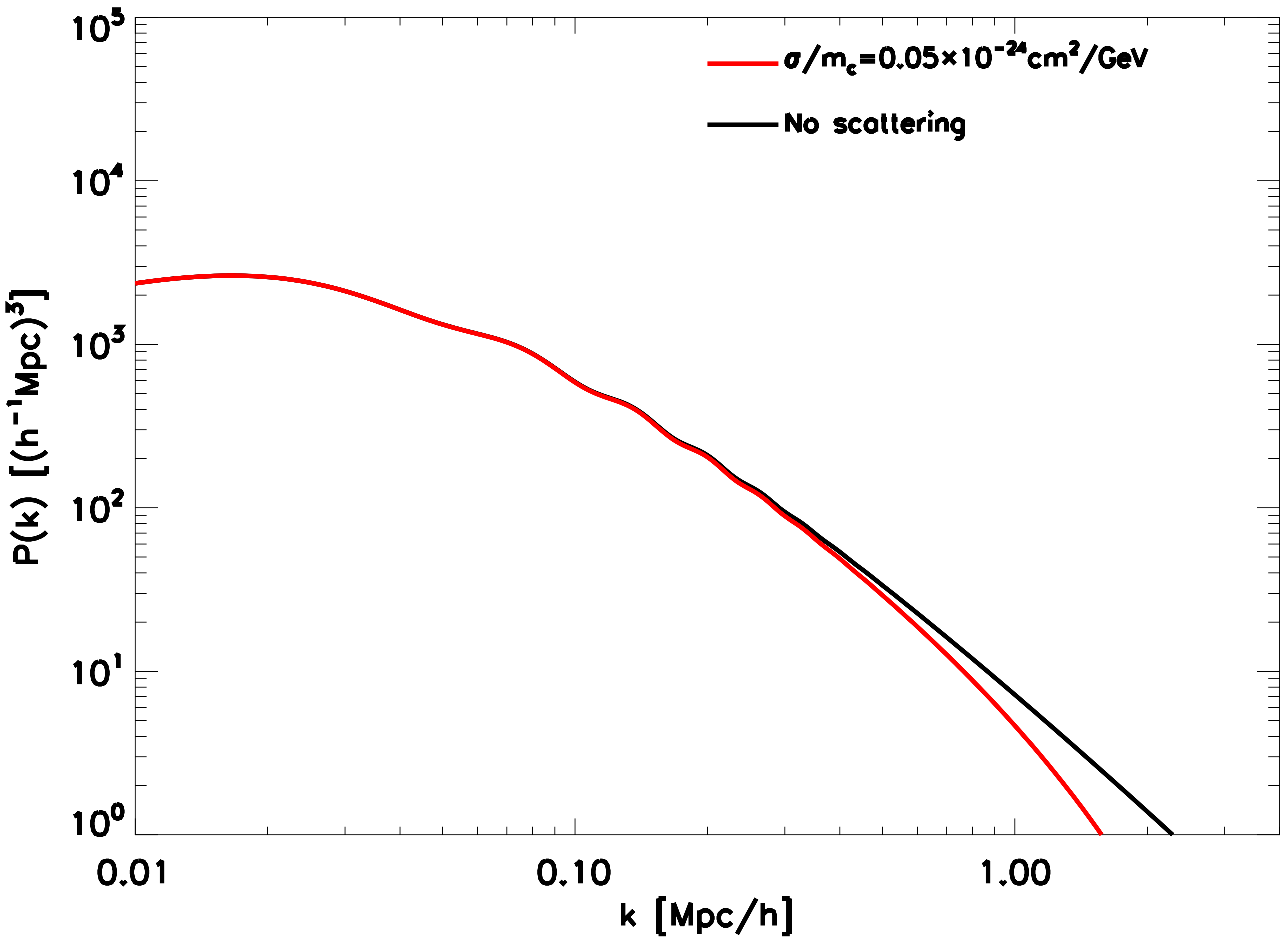
$R_c \propto \sigma/m_c$ for $m_c >> m_b$ $\quad$ $R_c \propto \sigma/m_c^{(n+1)/2}$ for $m_c << m_b$

Imprints on the CMB Power Spectrum



C. Dvorkin, K. Blum and M. Kamionkowski (to appear)

Effect on the Matter Power Spectrum



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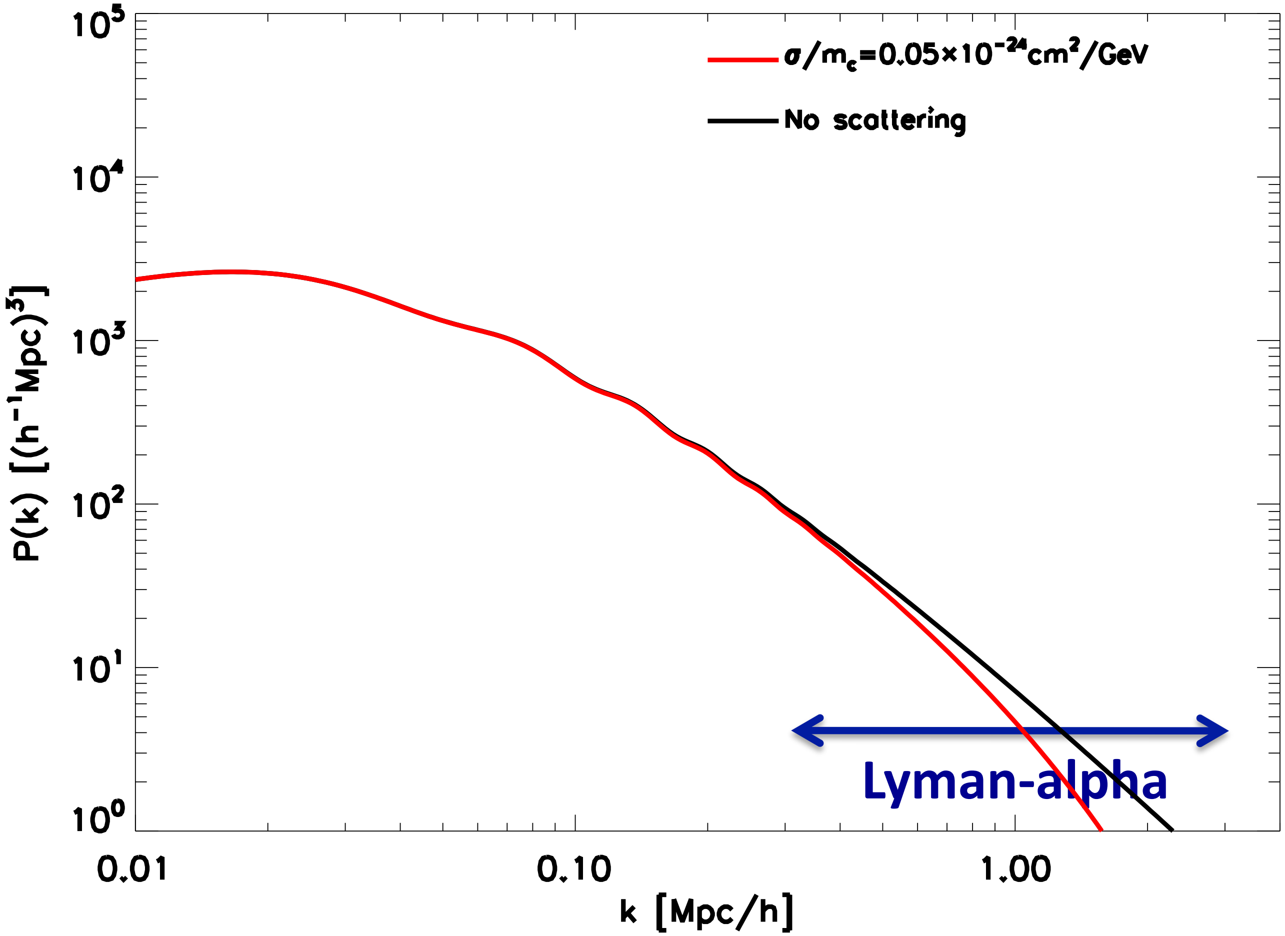


C. Dvorkin, K. Blum and M. Kamionkowski (to appear)

Lyman-alpha forest

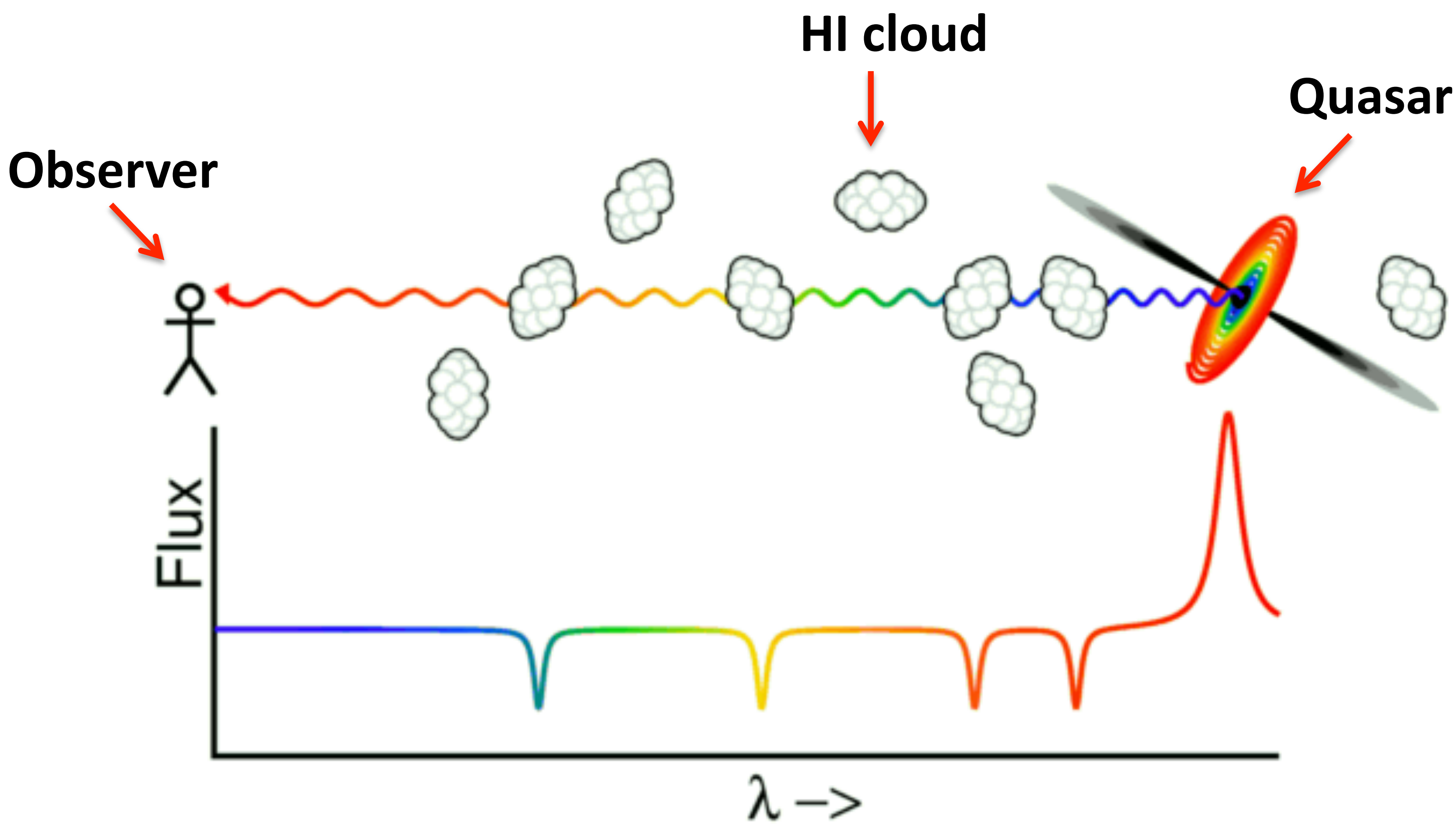
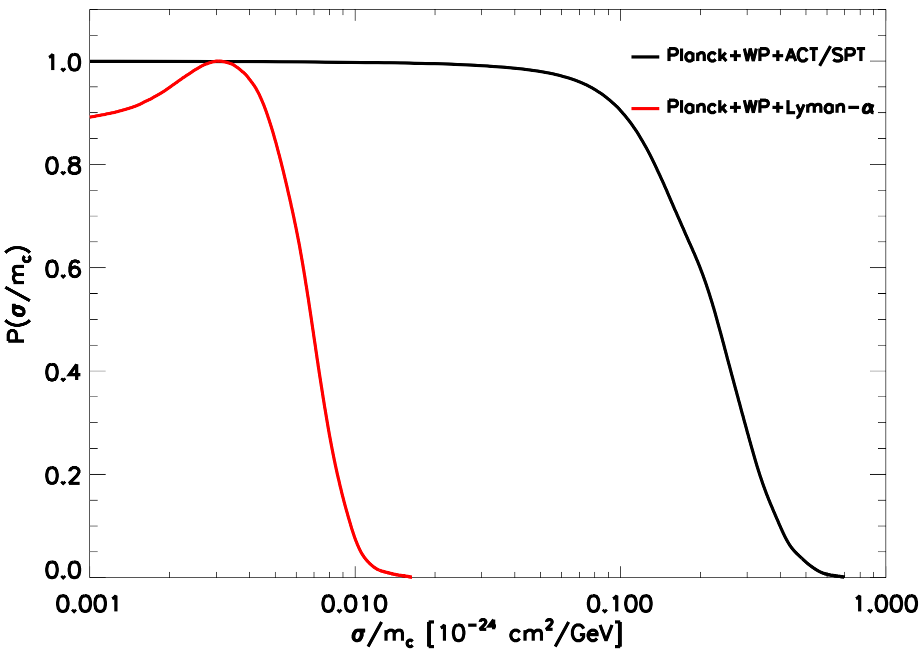


Image credit: E. Wright

Constraints from the CMB (Planck) + Lyman-alpha measurements (SDSS)

McDonald, Seljak, et al.



C. Dvorkin, K. Blum and M. Kamionkowski (to appear)

CMB data from Planck + Ly-alpha flux power spectrum measurements at z~3 from the SDSS constrain:

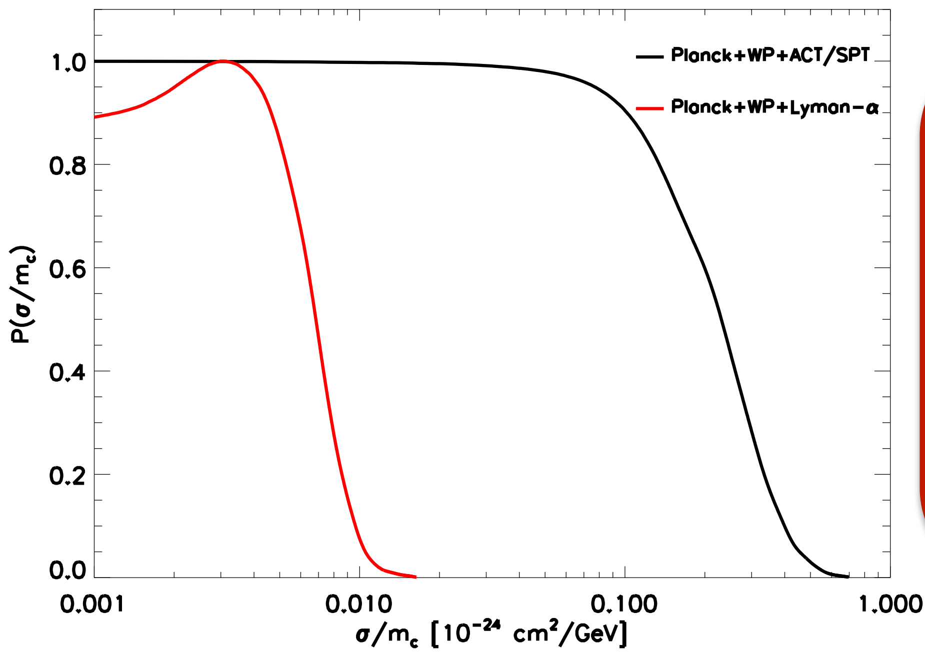
$$\sigma/m_c < 8 \times 10^{-27} cm^2/GeV$$

(at the 95% CL).

Two orders of magnitude below the ballpark of the proposed DM self-interactions cross-section:

$$8 \times 10^{-25} < \frac{\sigma/cm^2}{m_c/GeV} < 8 \times 10^{-22}$$

Minimal mean free path for baryons scattering on Dark Matter in the Milky Way



$$\rho_c \approx 0.4\ GeV/cm^3$$

$$\lambda = \left(\frac{\rho_c \sigma}{m_c}\right)^{-1}$$

$$\lambda \gtrsim 120\ Mpc$$

C. Dvorkin, K. Blum and M. Kamionkowski (to appear)

Conclusions

- WIMP Dark matter annihilation leads to growing ionization modes that track the collapse of dark matter overdensities (boosted by 1 to 2 orders of magnitude at small scales relative to standard model).

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- • Enhanced matter temperature fluctuations at late times (natural observational tool: 21 cm radiation – future work).
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- Dark Matter-baryon interactions suppress the CMB and matter fluctuations. CMB data from Planck + Ly-alpha forest measurements from the Sloan Digital Sky Survey put very tight constraints.