Hunting for Dark Matter with Cosmology

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Outline

- CMB and Dark Matter overview.

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

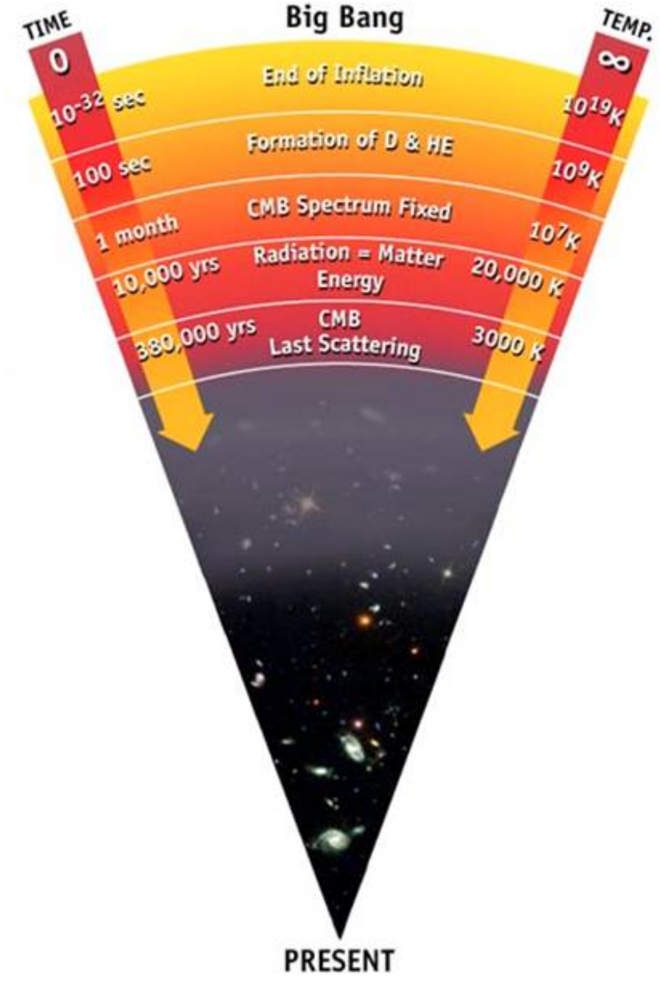
- Homogeneous scenario.
- Inhomogeneous scenario: boosted electron perturbations.

CMB non-gaussianity from recombination:
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

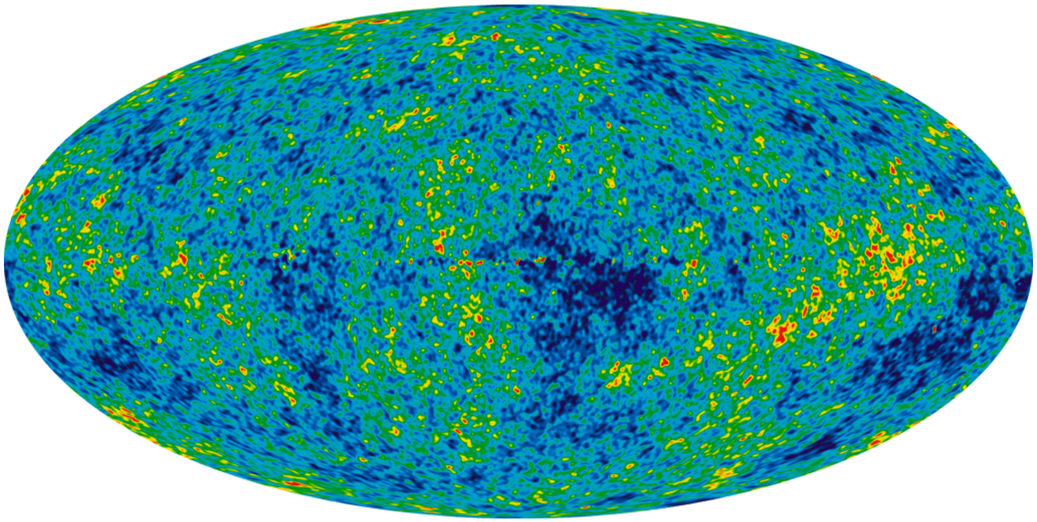


- The universe began as a hot and dense plasma of particles in thermal equilibrium.
- Recombination (z $\approx$1100): $p^+ + e^- \to H$
  Universe becomes transparent to CMB photons.

  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: $\Delta T \approx 100 \mu K$

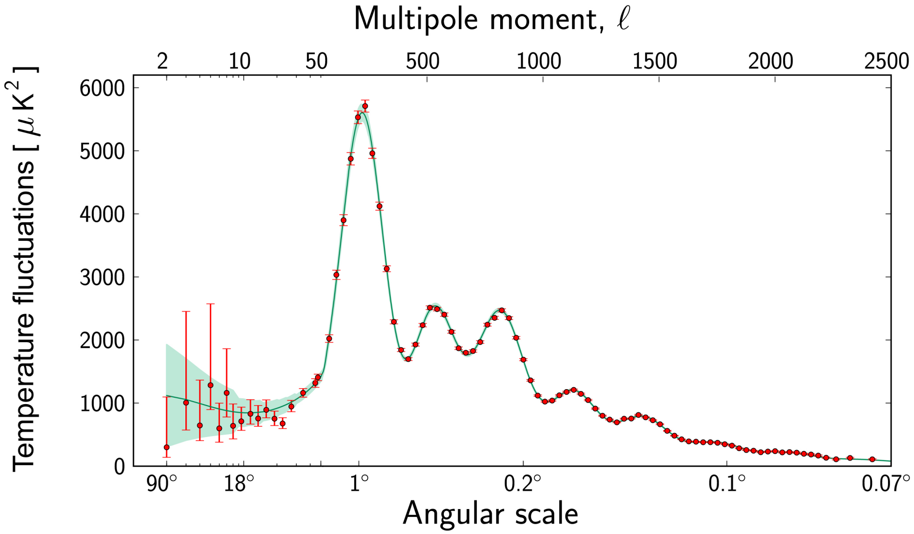
CMB Power Spectrum

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

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

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

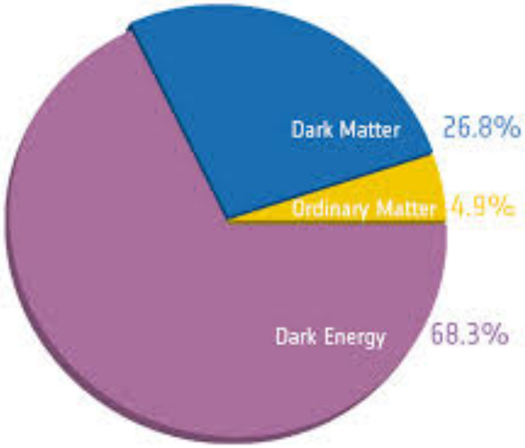
It has been **predicted** and **measured** with good precision.



Planck collaboration (2013)

ΛCDM: the "Standard" Model of Cosmology

Homogeneous background

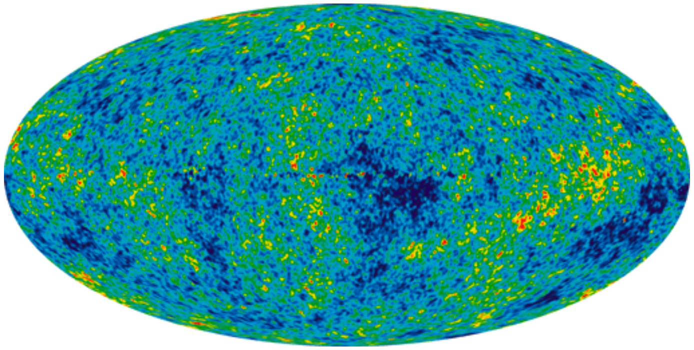


$$\Omega_b h^2, \Omega_c h^2, \Omega_\Lambda, \tau, \theta$$

- Baryonic matter: 5%
- Cold dark matter: 27%
- Dark energy: 68%

Λ? CDM?

Perturbations



$$A_s, n_s$$

- Nearly scale-invariant
- Gaussian

Origin?

ΛCDM: the "Standard" Model of Cosmology

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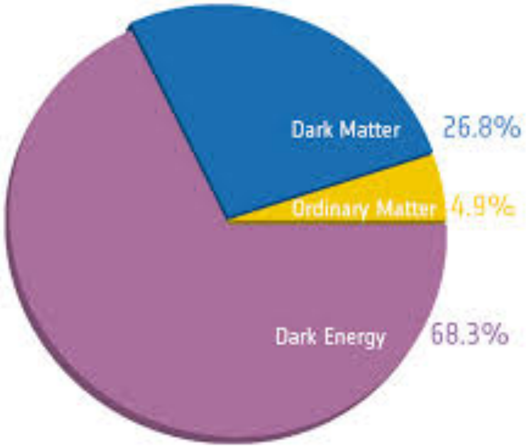

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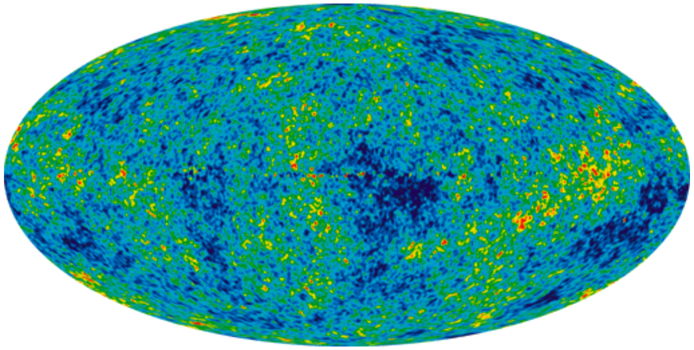

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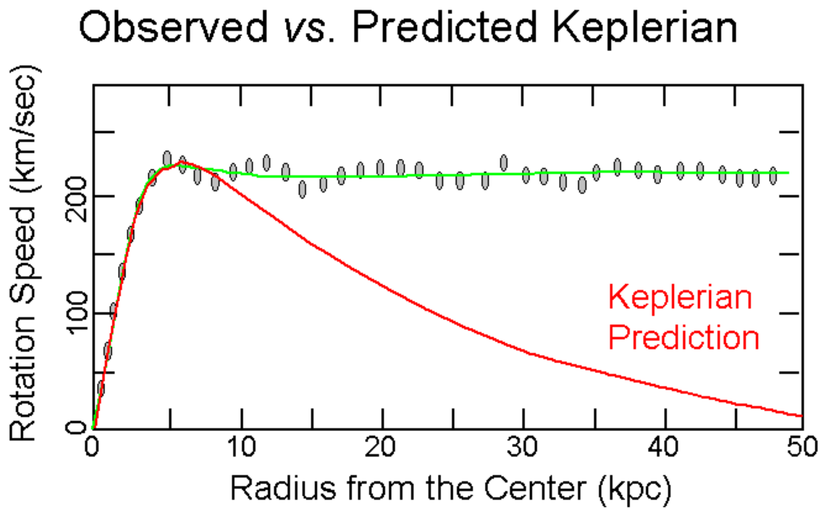
- Gaussian

Origin?

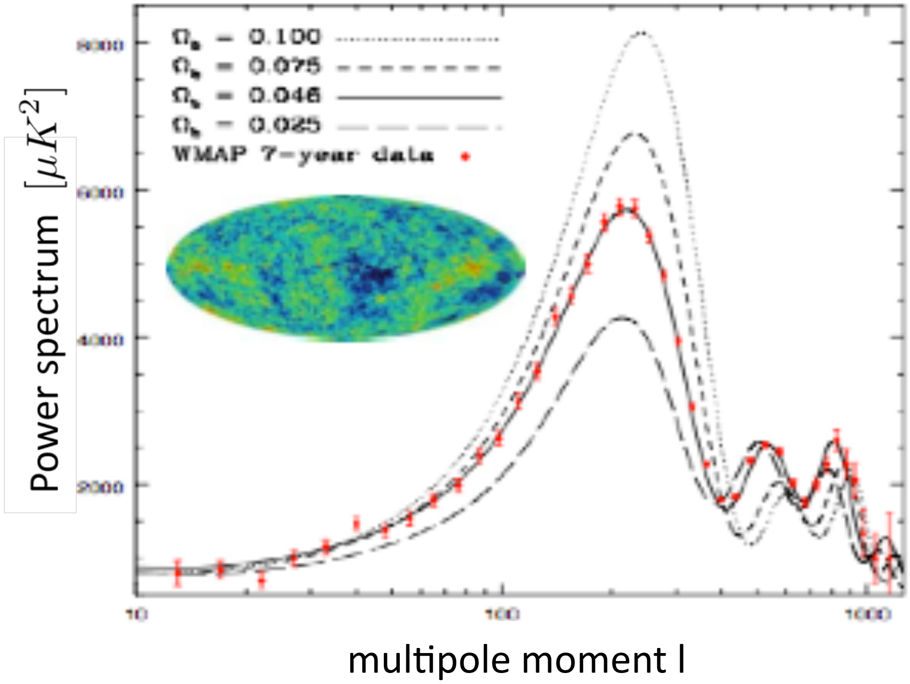
Evidence for Dark Matter

Overwhelming evidence for Dark Matter:
Galactic scales
Cluster scales
Cosmic Microwave Background

Galaxy rotation curves



The cosmic microwave background



Gravitational lensing

Looking for Dark Matter off the beaten track

Where do Dark Matter interactions matter?

Some well known avenues:

Excess high energy cosmic/gamma rays;
Missing energy at colliders;
Nucleon recoil deep underground;
…

Important to look for new processes

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)

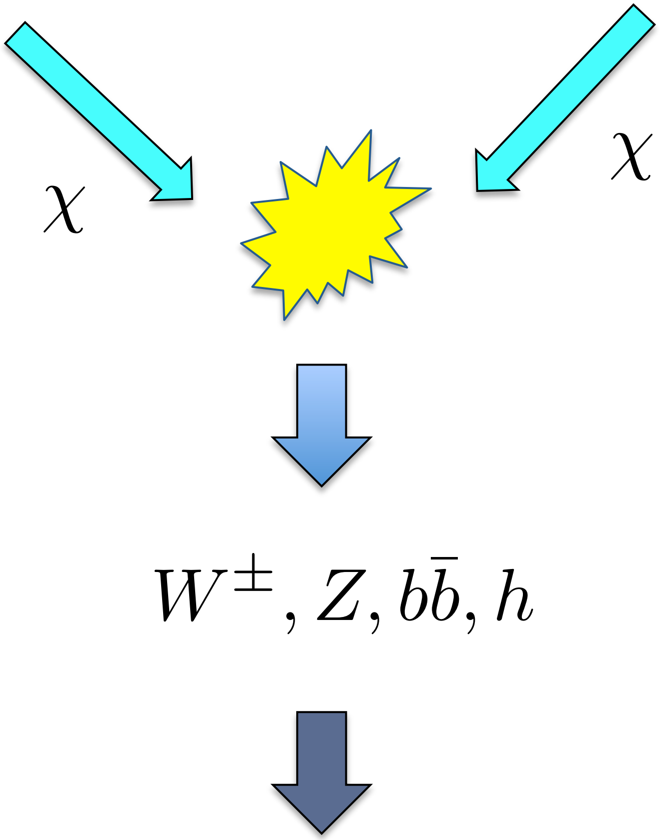
Dark matter annihilation should leave a **signature in the CMB**.

At z∼1100, when the CMB decouples, the homogeneous DM density is

$$n(z=1100) = n_{today}(1+z)^3 \sim n_{today} \times 10^9$$

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:

$$\frac{dE}{dtdV} = \underbrace{n_{pairs}}_{\text{Number of DM particle pairs}} \underbrace{P_{ann}}_{\text{Annihilation probability per unit time}} \underbrace{E_{ann}}_{\text{Energy released per annihilation}} \underbrace{f(z)}_{\text{Fraction of energy absorbed by the plasma (depends on the model)}}$$

Slatyer, Padmanabhan and Finkbeiner (2009)

Energy Injection in the CMB

FINAL PRODUCTS

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

→

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

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

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

(Majorana particle)

Standard Recombination

Peebles, ApJ (1968)
Z’eldovich and Sunyaev, JETP (1969)

Effective Boltzmann equation for the free electron density:

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

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Ionization rate

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Effective Boltzmann equation for the free electron density:

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

Recombination rate **Ionization rate**

DM Annihilation at Recombination

Effective Boltzmann equation for the free electron density:

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

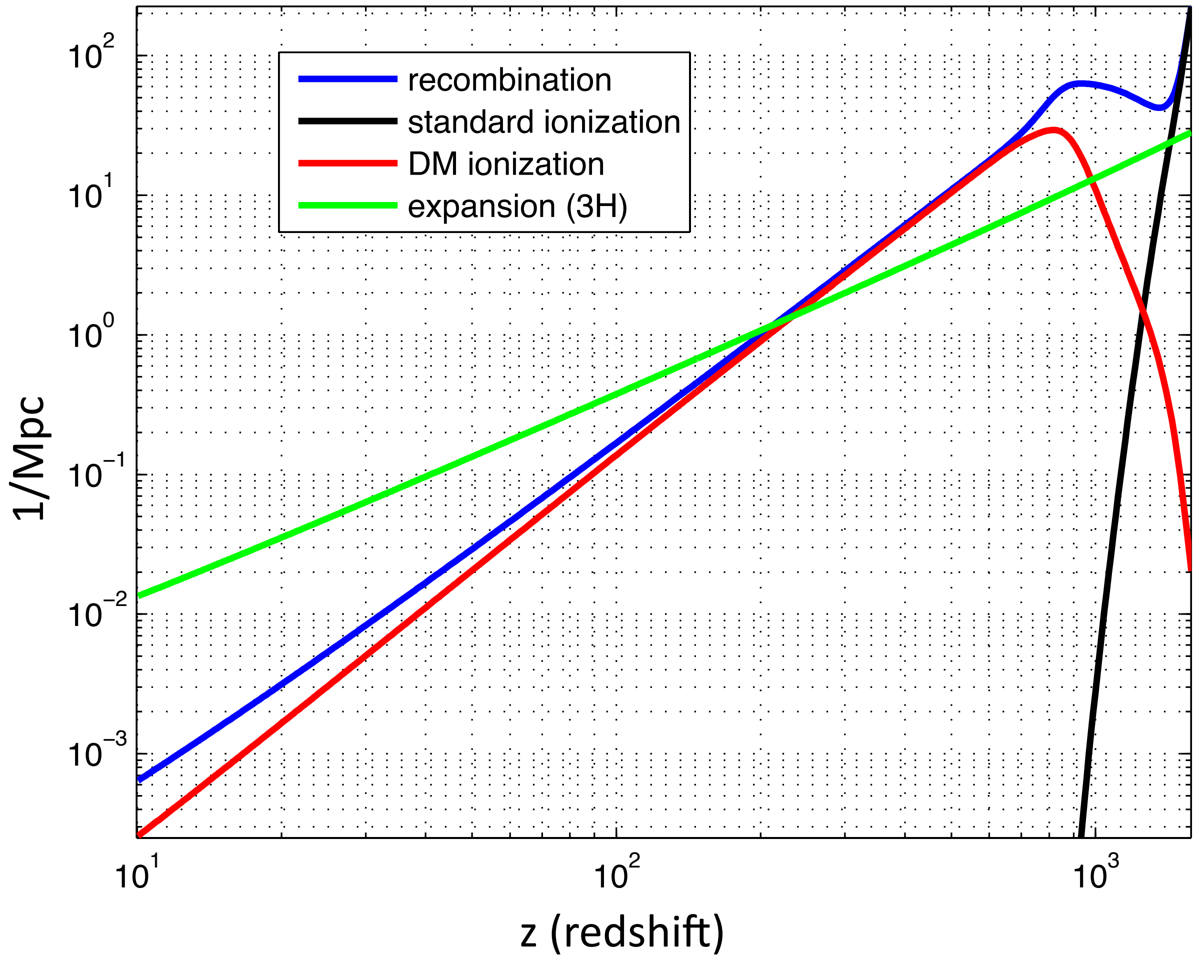
Recombination rate

Ionization rate

Dark matter ionization rate:

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

Time scales (Recombination, Ionization, Expansion)



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

Ionization "floor"

At 200<z<600, there is a competing effect between recombination and ionization from DM annihilation.

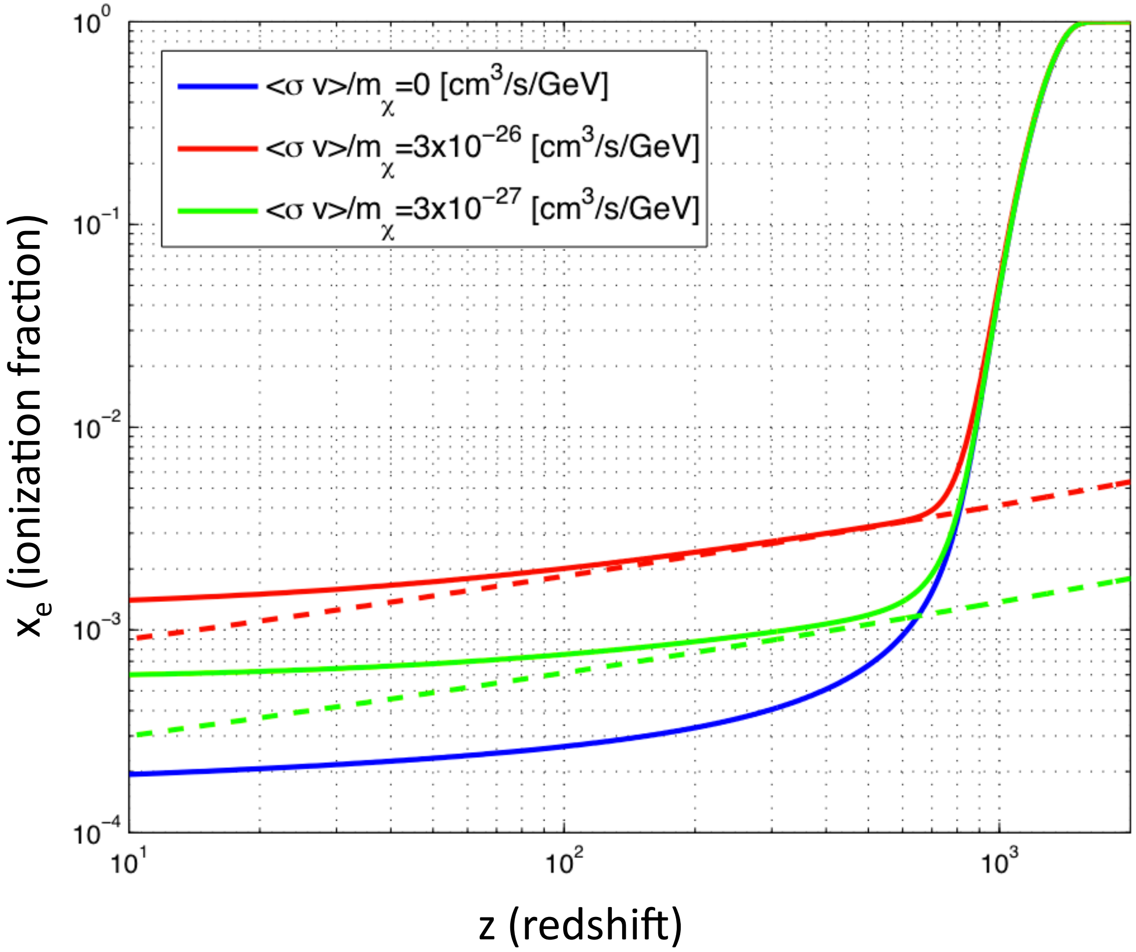
Quasi-equilibrium solution for the free electron fraction: $x_e = n_e/n_H$

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

Dark matter can easily dominate the ionization fraction after recombination

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

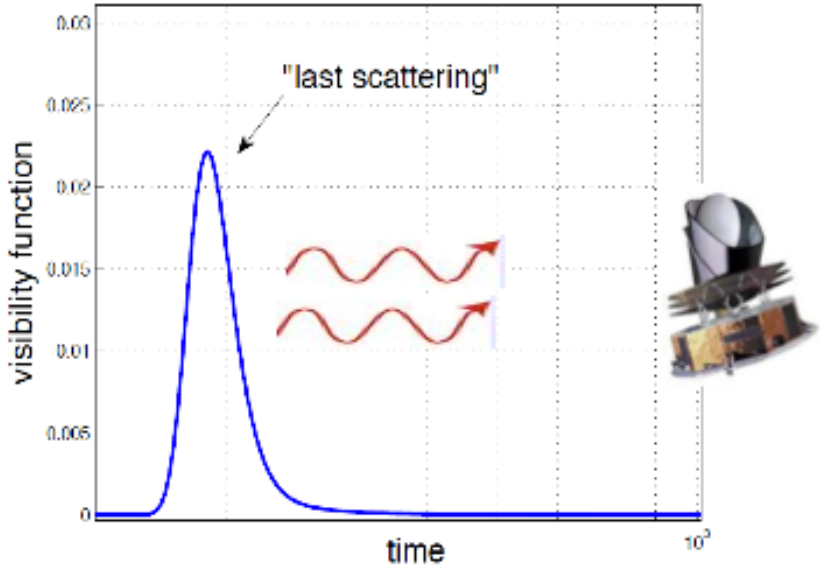
Free electron fraction evolution



Thomson scattering

"Visibility function": probability that a photon last scattered at a time η.

$$g(\eta) = -e^{-\tau(\eta)}\dot{\tau}(\eta)$$



- Dark matter annihilation injects energy into the plasma.
- Ionizes hydrogen.

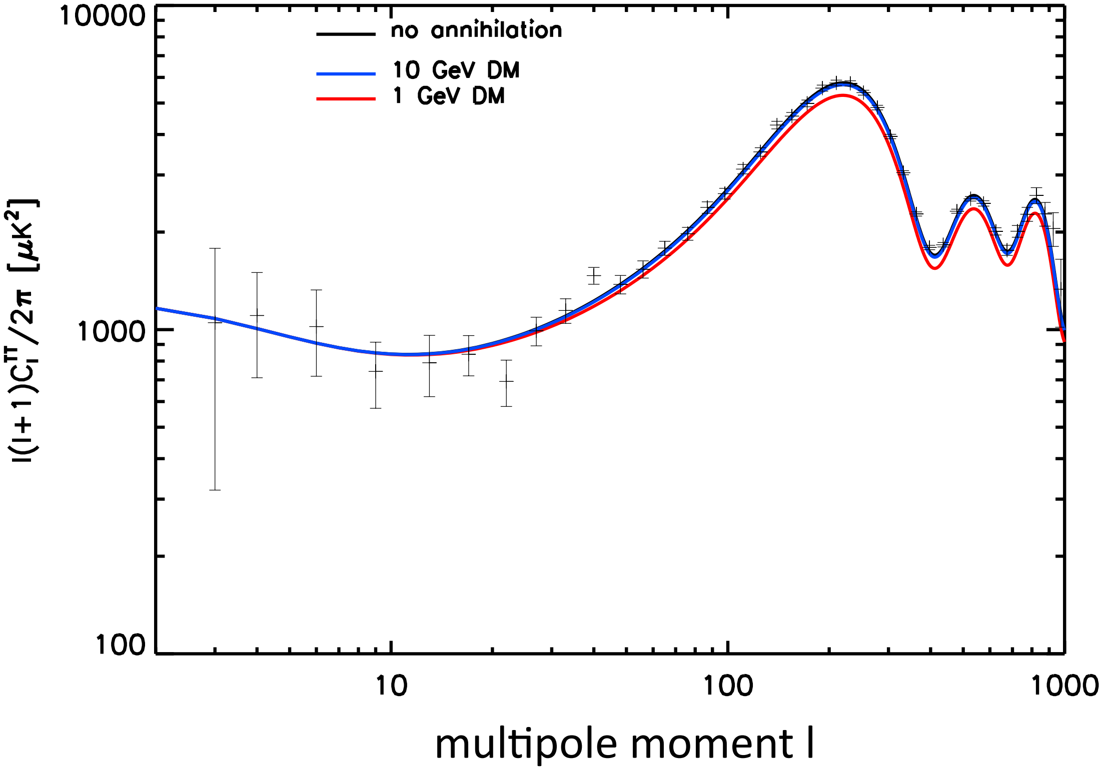
- Excess Thomson scattering:

$$T^{\rm obs}(\hat{\mathbf{n}}) \rightarrow T^{\rm rec}(\hat{\mathbf{n}})e^{-\Delta\tau},$$

with $\Delta\tau(\eta) = c\sigma_T \int_{\eta}^{\eta_0} d\eta' a(\eta') n_e(\eta')$

Effect on the CMB Temperature

A higher ionization suppresses the CMB temperature fluctuations



Degeneracy:

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

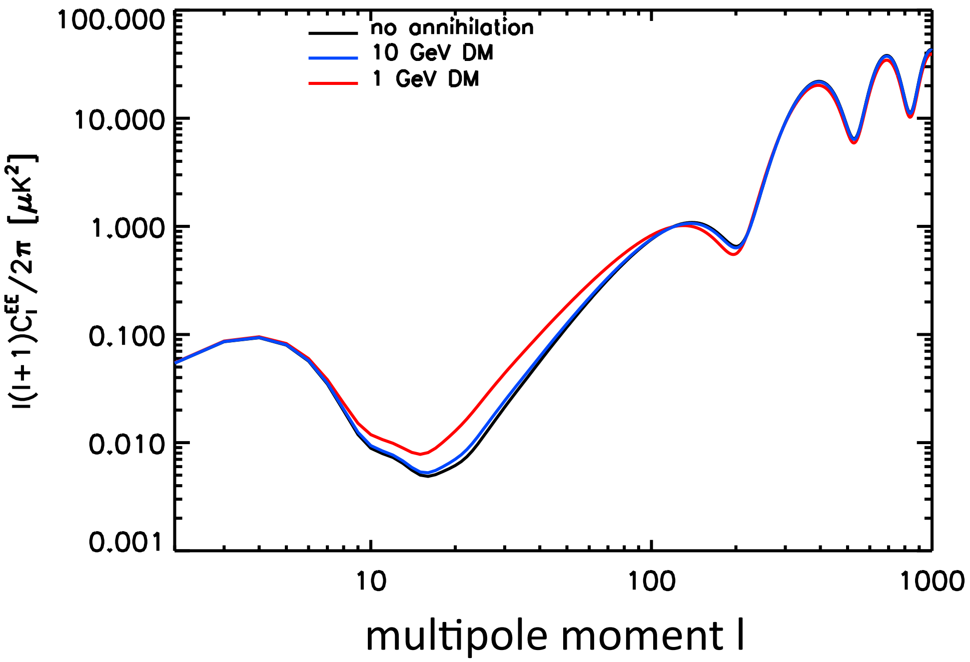
$$A_s \to e^{2\Delta\tau} A_s$$

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

Markov Chain Monte Carlo technique

The MCMC algorithm samples the parameter space evaluating the **likelihood of the data**, given each proposed parameter set.

$$\mathcal{L}(\mathbf{x}|\mathbf{p}) = \frac{1}{(2\pi)^{N/2}\sqrt{\det\mathbf{C}(\mathbf{p})}}\exp\left[-\frac{1}{2}\mathbf{x}^{\dagger}[\mathbf{C}(\mathbf{p})]^{-\mathbf{1}}\mathbf{x}\right]$$

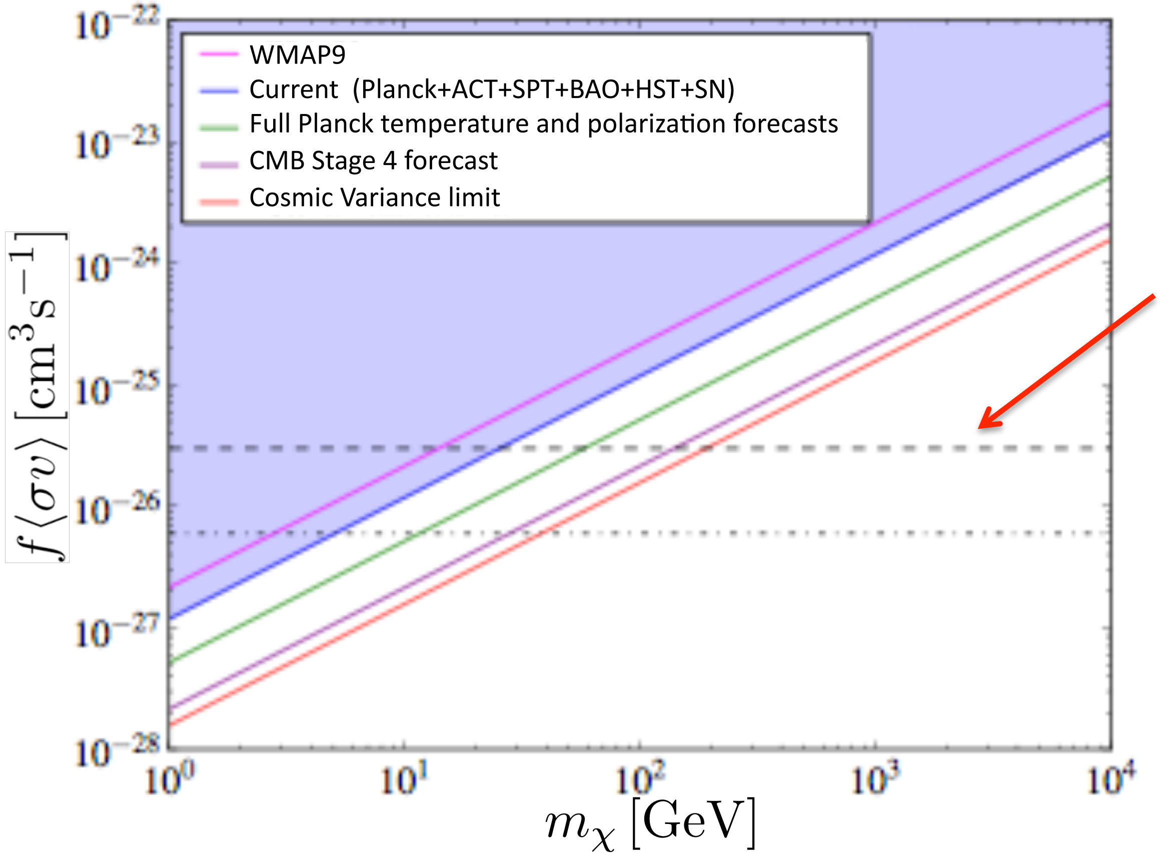
Data **Model** **Covariance**

The posterior distribution is obtained using Bayes' Theorem:

$$\mathcal{P}(\mathbf{p}|\mathbf{x}) = \frac{\mathcal{L}(\mathbf{x}|\mathbf{p})\mathcal{P}(\mathbf{p})}{\int d\mathbf{p}\mathcal{L}(\mathbf{x}|\mathbf{p})\mathcal{P}(\mathbf{p})}$$

Likelihood Prior probability density

Current and Future Dark Matter Annihilation Constraints from the CMB



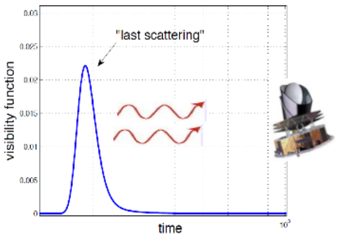
Thermal cross section

- Planck polarization data: coming this year.
- CMB “Stage IV” experiment is being planned now!

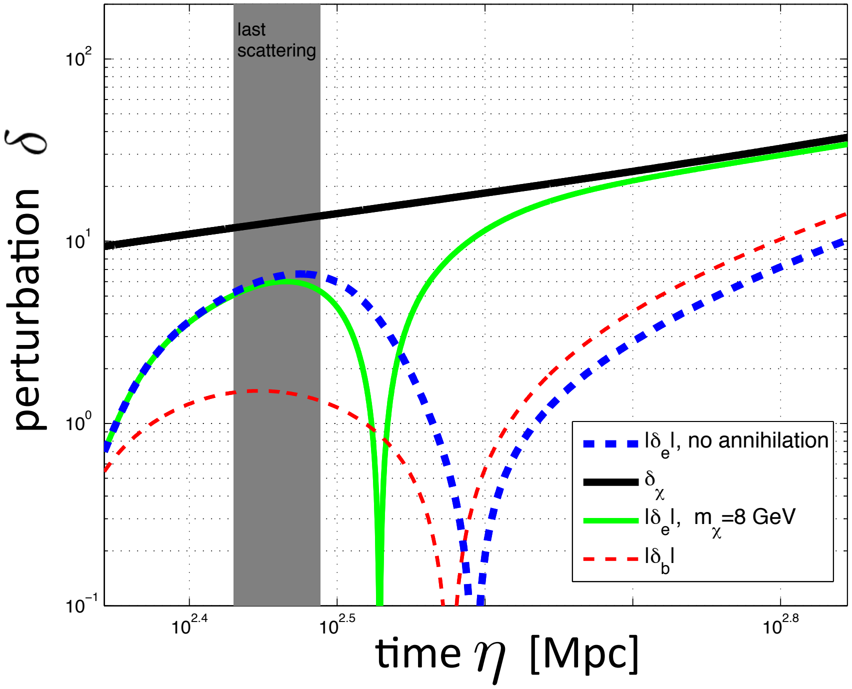
W. Wu, J. Errard, C. Dvorkin, C. L. Kuo, A. Lee, et al., ApJ (2014)

Dark Matter Annihilation
Inhomogeneous scenario

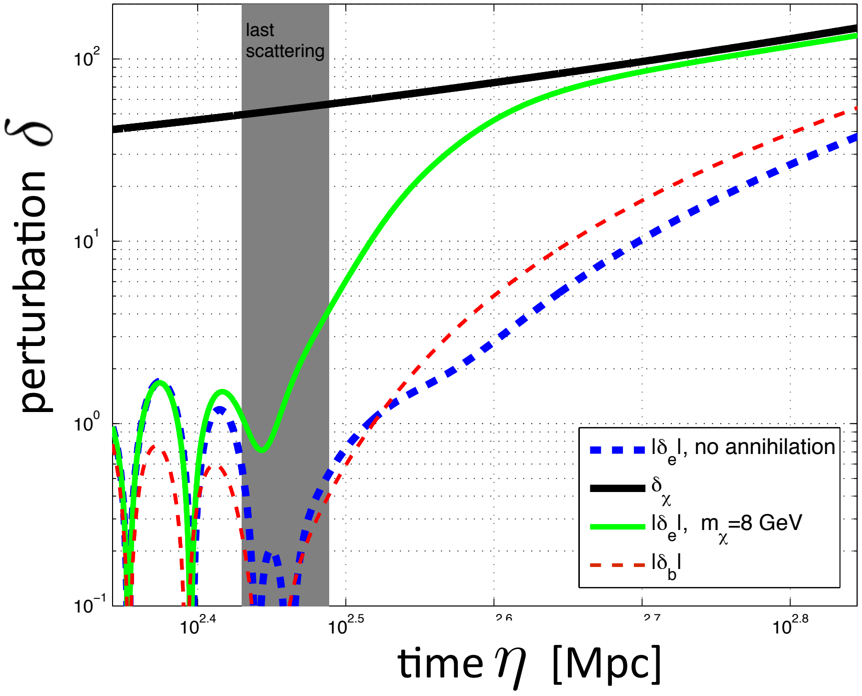
There are growing ionization modes that track the collapse of matter overdensities.



k=0.04 Mpc^{-1}

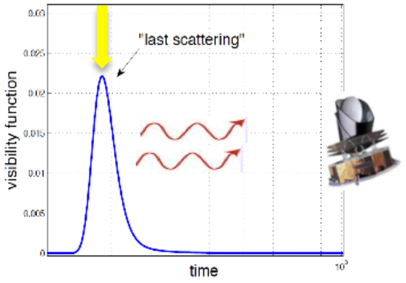


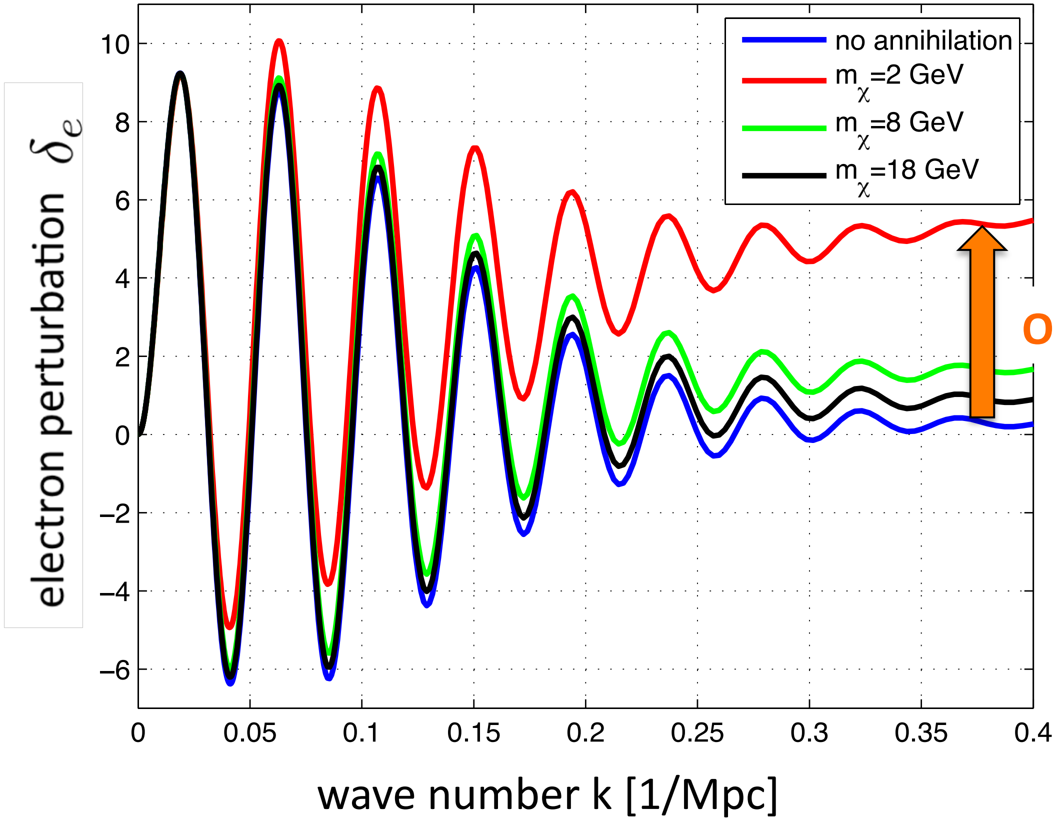
k=0.3 Mpc^{-1}



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

Comparison to standard first order electron perturbations





Order of magnitude boost!

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

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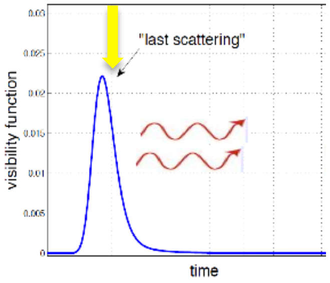

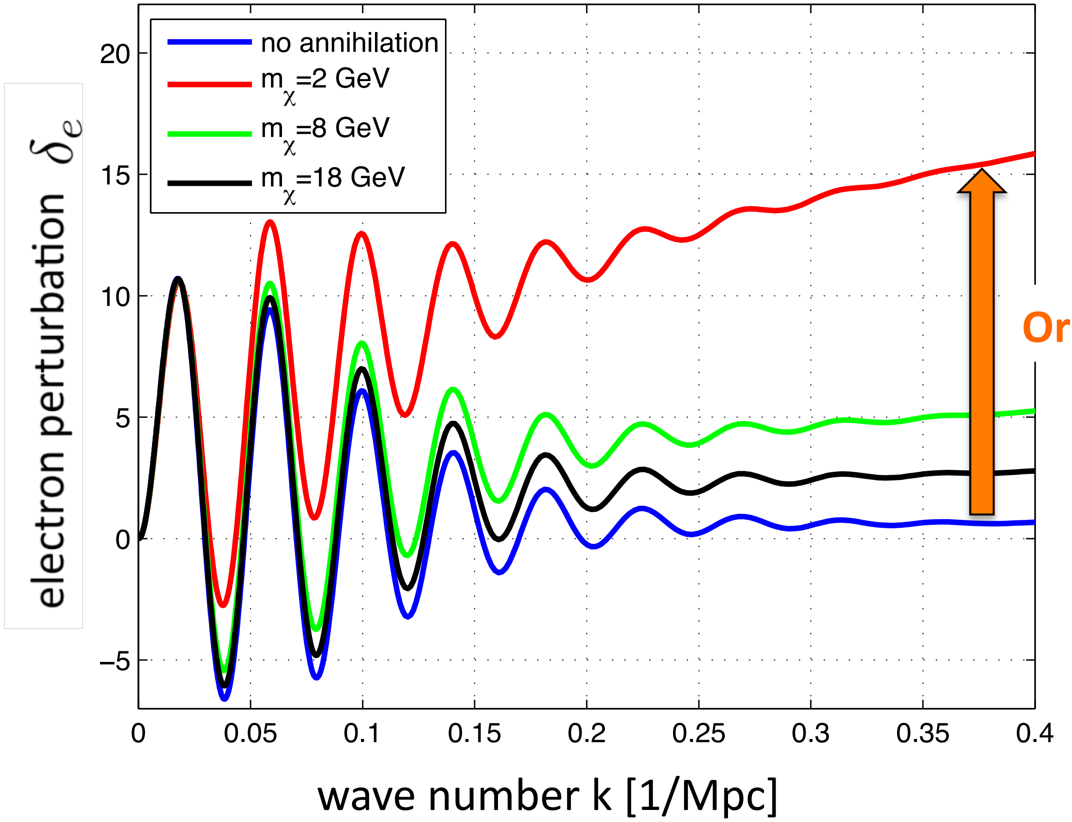

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C. Dvorkin, K. Blum, and M. Zaldarriaga, Phys. Rev. D (2013)

Can we observe electron density perturbations in the CMB?

CMB Non-Gaussianity at Recombination

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

CMB Non-Gaussianity

$$B^{\ell_1\ell_2\ell_3}_{m_1m_2m_3} = \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle$$

Probe of the physics of inflation

Maldacena, JHEP 0305 (2003) 013

Acquaviva et al., Nuclear Physics B 667 (2003) 119

CMB Non-Gaussianity

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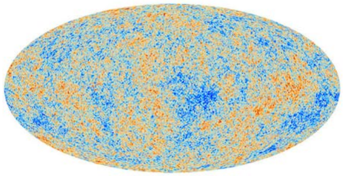

***Planck XXIV* (2013)**

$$f_{NL}^{local} = 2.7 \pm 5.8 \;\; (68\%\,\mathrm{C.L.})$$
$$f_{NL}^{equil} = -42 \pm 75 \;\; (68\%\,\mathrm{C.L.})$$
$$f_{NL}^{ortho} = -25 \pm 39 \;\; (68\%\,\mathrm{C.L.})$$

“f_{NL}”: effective amplitude of the non-Gaussian signal

$f_{NL}^{feature}$: all models analyzed have less than 3 sigma significance.

Model-independent formalism to constrain features in the inflationary potential from CMB observations by means of a principal component analysis.

C. Dvorkin and W. Hu, PRD (2010a)
C. Dvorkin and W. Hu, PRD (2010b)
C. Dvorkin and W. Hu, PRD (2011)
P. Adshead, W. Hu, C. Dvorkin and H.V. Peiris, PRD (2011)
P. Adshead, C. Dvorkin, W. Hu and E. Lim, PRD (2012)

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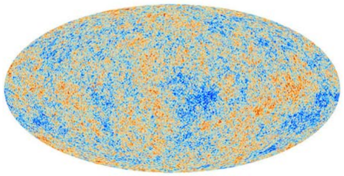

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$f_{NL}^{feature}$: all models analyzed have less than 3 sigma significance.

Should vanish for single-field inflation

Creminelli & Zaldarriaga, M.2004, JCAP, 0410, 006

CMB Non-Gaussianity

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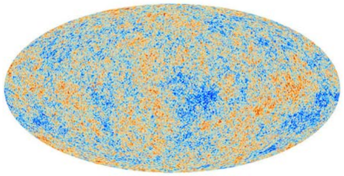

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$f_{NL}^{feature}$: all models analyzed have less than 3 sigma significance.

Well in the ballpark of the effects we discuss here.

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.**

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.**

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

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

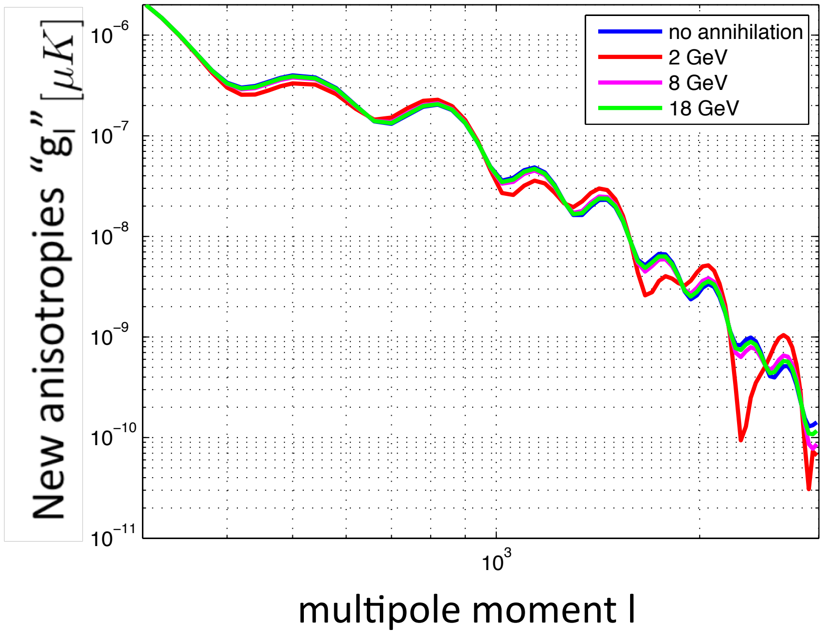
New anisotropies generated by electron perturbations:

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

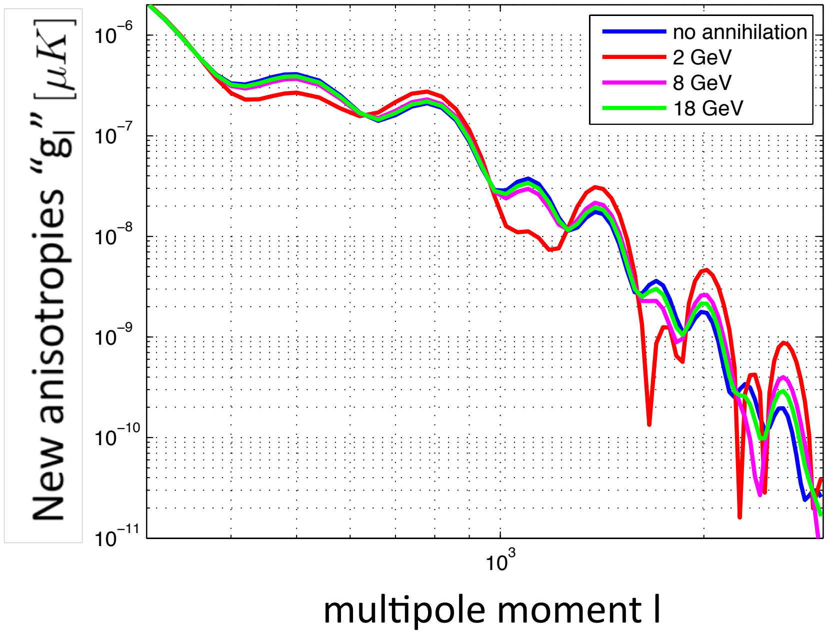
Can we observe electron density perturbations in the CMB?

Signal-to-noise ~ 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, Phys. Rev. D (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:

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

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

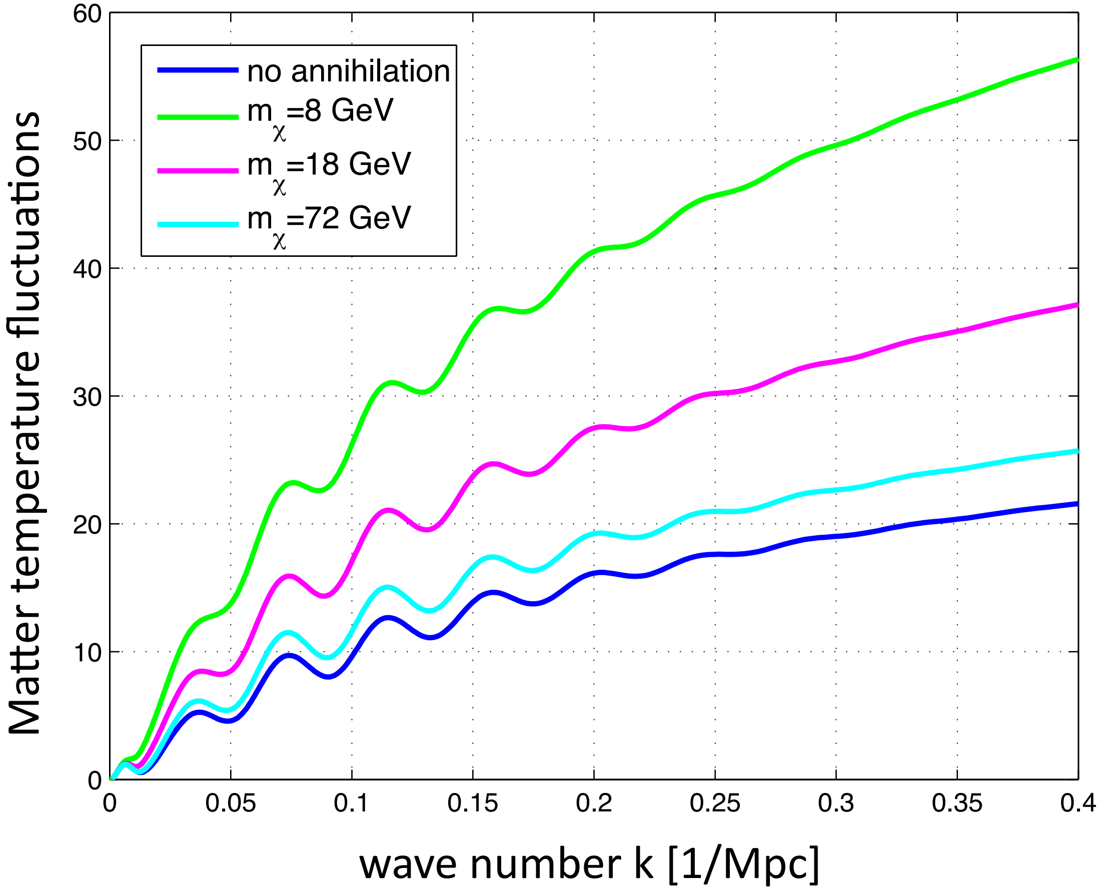
Sound speed

Silk damping

- Solution given by WKB's Green function.

C. Dvorkin, K. Blum, and M. Zaldarriaga, in preparation

Enhanced Matter Temperature fluctuations



Current and future 21 cm experiments: LOFAR, MWA, PAPER, SKA, etc, etc..

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 and Dark Matter-Baryon interactions can significantly affect small-scale structure.

Spergel and Steinhardt (2000);
Cyburt, Fields, Pavlidou and Wandelt (2002)

- 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.

Small-scale issues

- "Missing Satellite problem":

Does CDM predict too many Satellite Galaxies?

- "Cuspy halo problem":

Do CDM models predict halos with density cores that are too dense compared to observations?

Possible solutions:

- Baryonic physics;
- Self-interacting Dark Matter;
- Dark Matter-Baryon Interactions;

…

Dark Matter-Baryon Interactions

Goal: to use observational probes of the CMB and matter fluctuations (where the theory is under better control) to know how much interaction between baryons and Dark Matter can occur today.

C. Dvorkin, K. Blum and M. Kamionkowski, Phys. Rev. D (2013)

Dark Matter-Baryon Interactions

C. Dvorkin, K. Blum and M. Kamionkowski, Phys. Rev. D (2013)

$$\dot{\delta}_\chi = -\theta_\chi - \frac{1}{2}\dot{h}$$

$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + \boxed{R_\chi \left(\theta_b - \theta_\chi\right)}$$

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

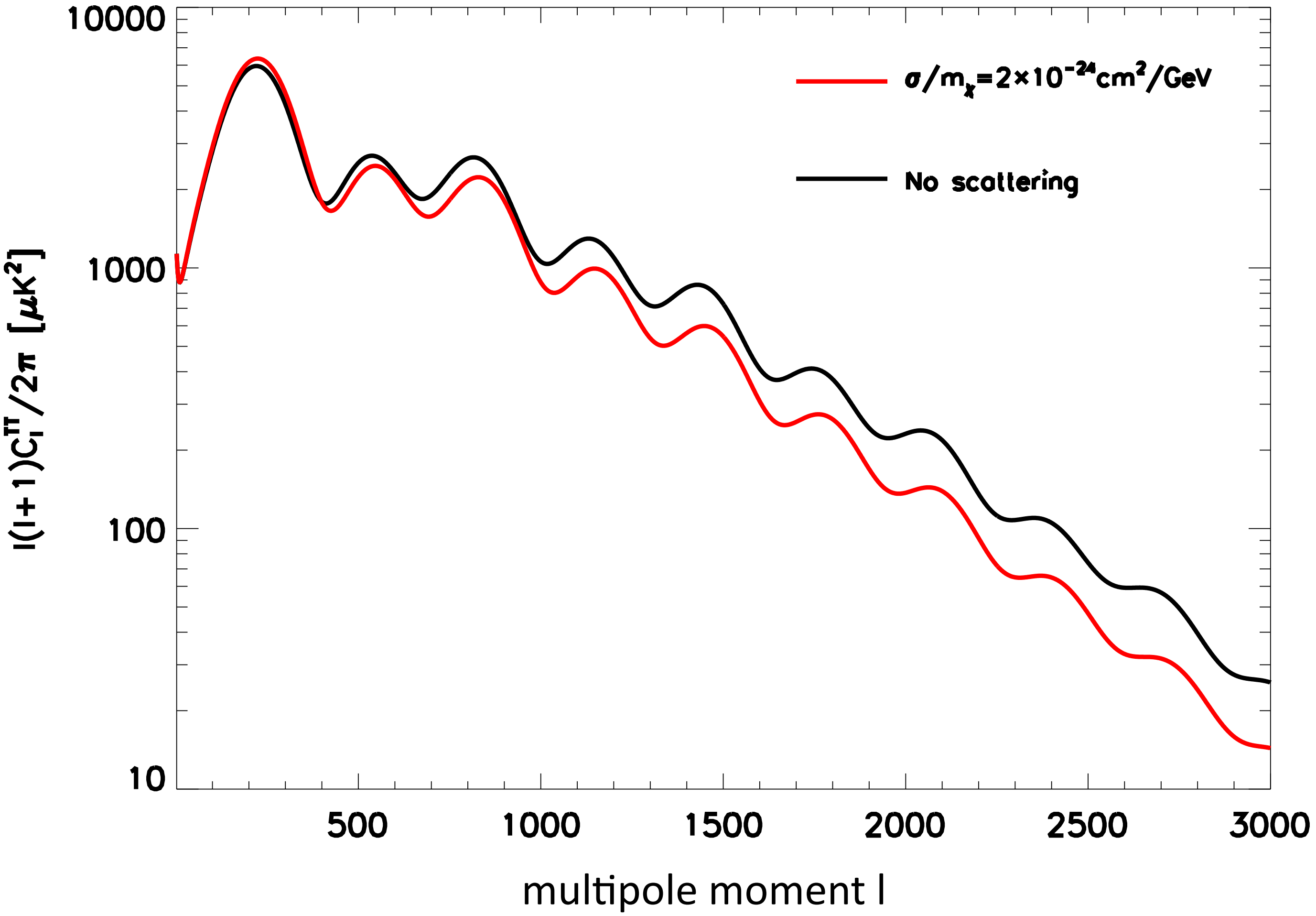
$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + \boxed{\frac{\rho_\chi}{\rho_b} R_\chi \left(\theta_\chi - \theta_b\right)} + R_\gamma \left(\theta_\gamma - \theta_b\right)$$

Dark Matter-baryon momentum exchange rate:

$$R_\chi = \frac{a \rho_b \sigma_0}{m_\chi + m_H} c_n \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} + \frac{V_{\mathrm{RMS}}^2}{3}\right)^{\frac{n+1}{2}}$$ with $\sigma(v) = \sigma_0 v^n$

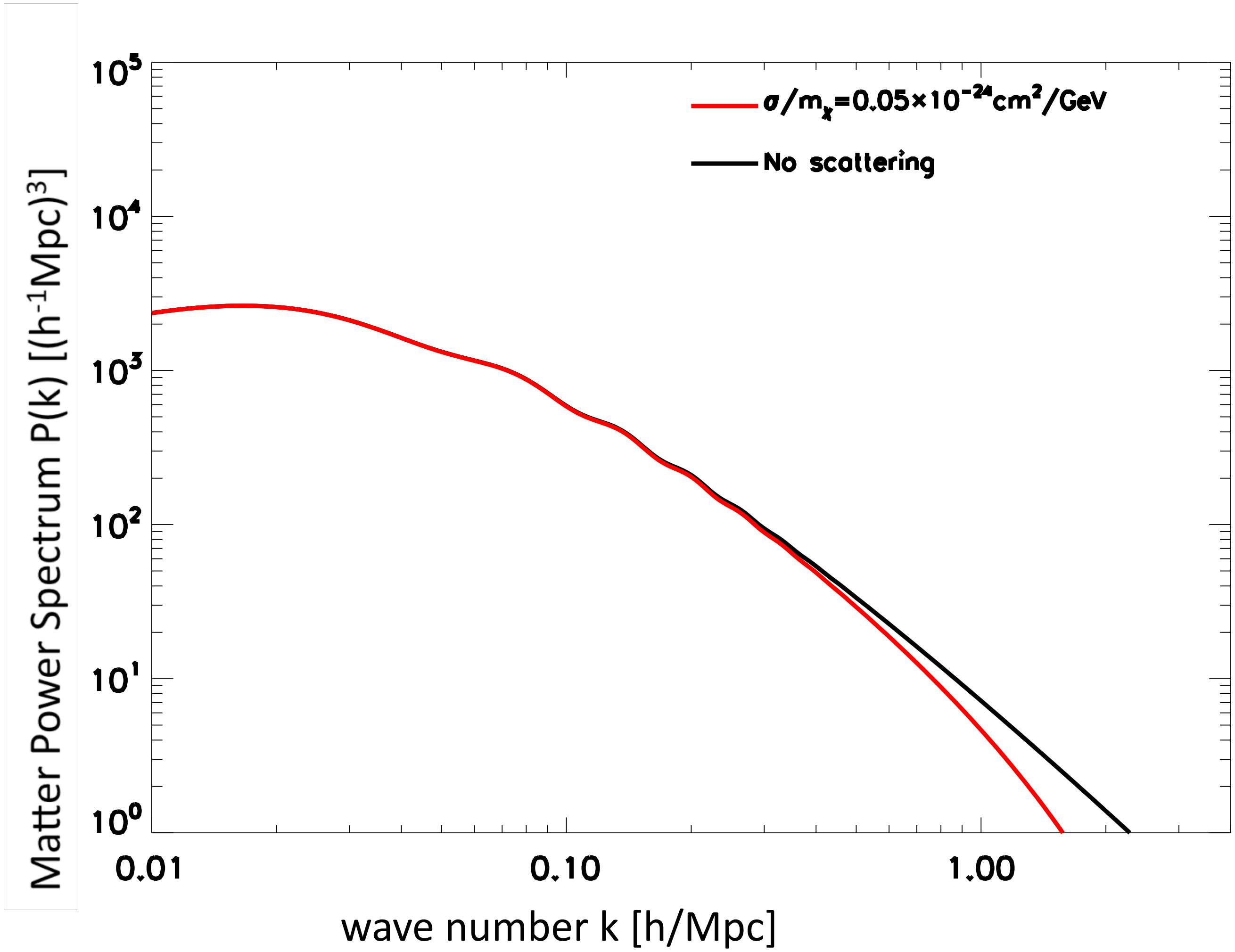
$R_\chi \propto \sigma_0 / m_\chi$ for $m_\chi >> m_H$ $R_\chi \propto \sigma_0 / m_\chi^{(n+1)/2}$ for $m_\chi << m_H$

Imprints on the CMB Power Spectrum



C. Dvorkin, K. Blum and M. Kamionkowski, Phys. Rev. D (2013)

Effect on the Matter Power Spectrum



C. Dvorkin, K. Blum and M. Kamionkowski, Phys. Rev. D (2013)

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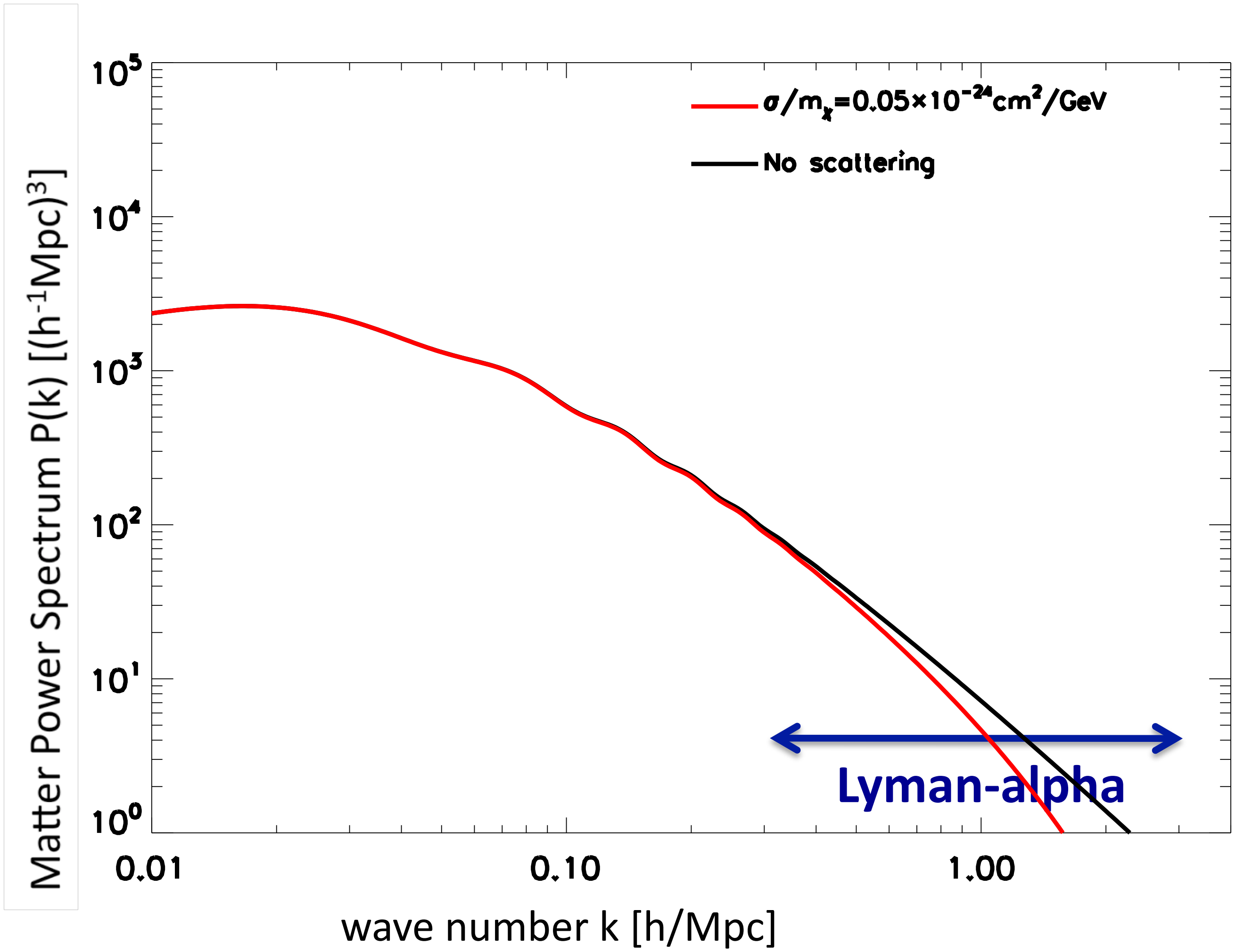


C. Dvorkin, K. Blum and M. Kamionkowski, Phys. Rev. D (2013)

Lyman-alpha forest

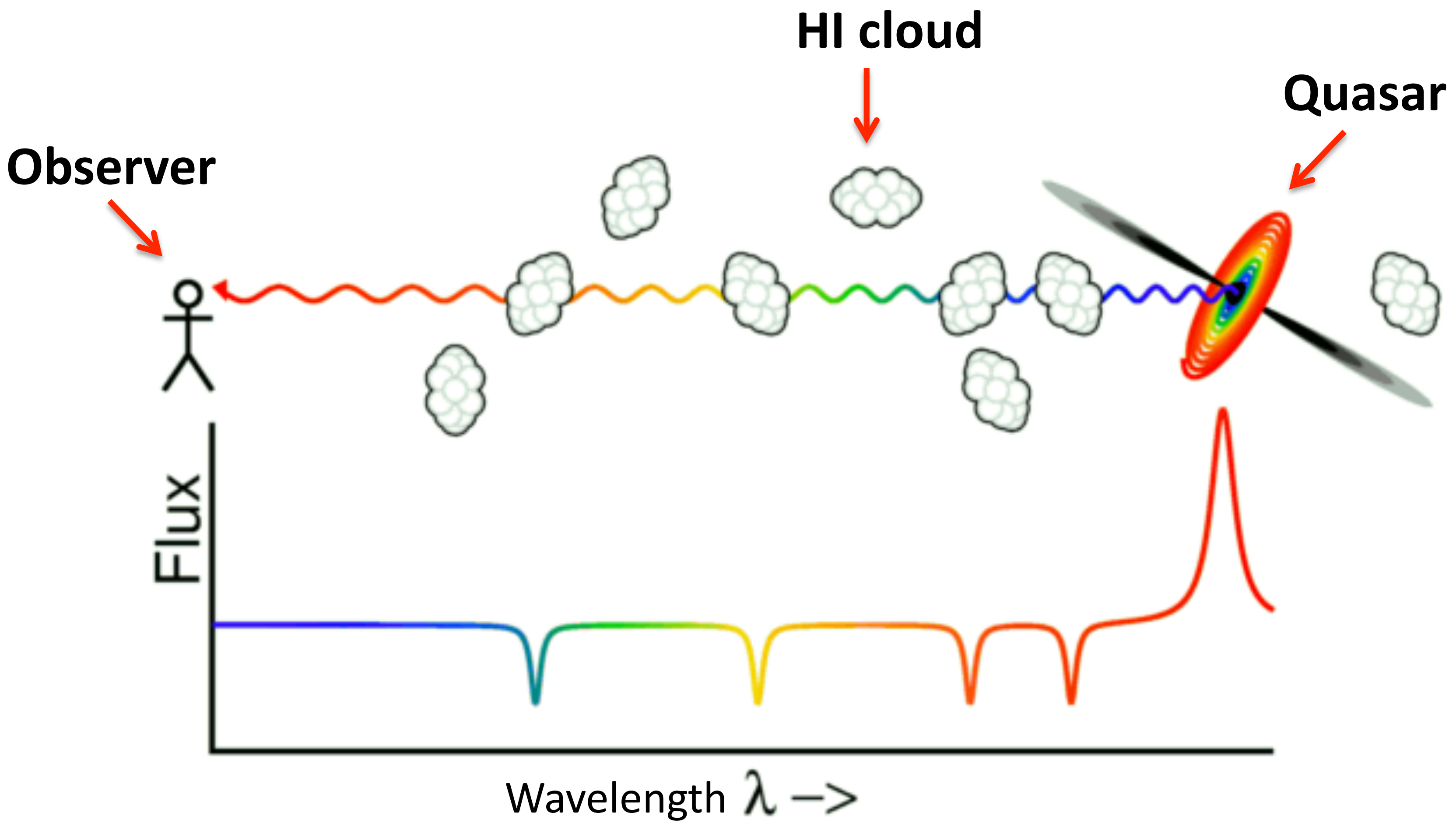
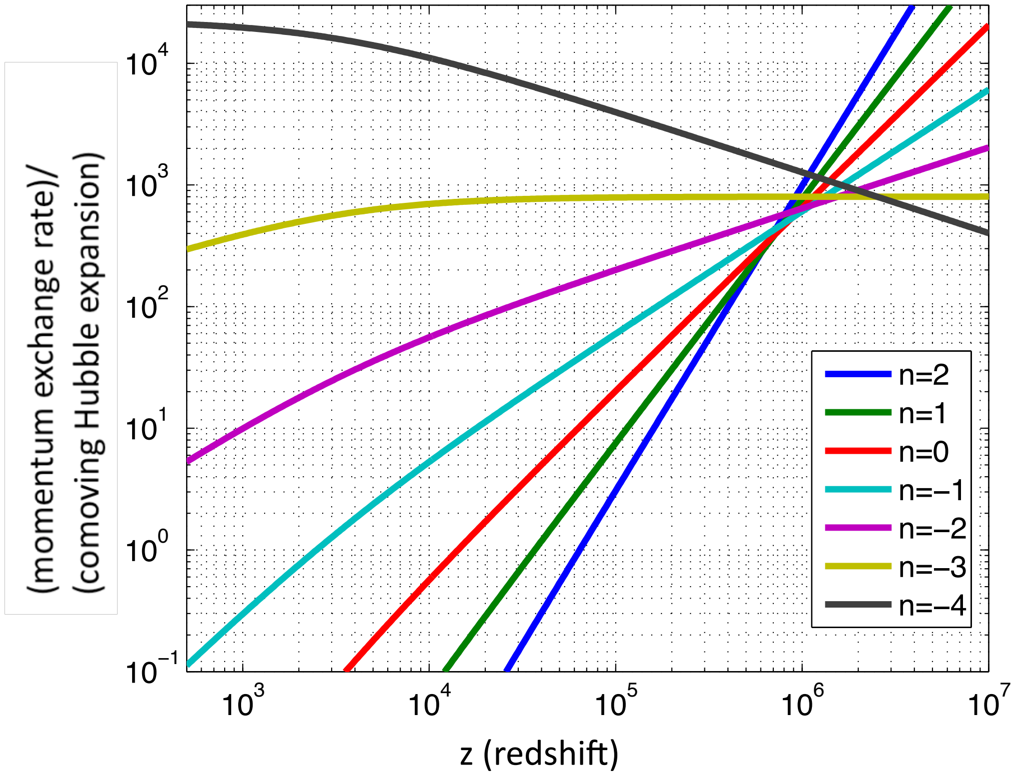


Image credit: E. Wright

Constraining Dark Matter-Baryon Scattering with Cosmology



All the curves ($\sigma(v) = \sigma_0 v^n$) are normalized to satisfy a mean free path of $\sim$ 1 Mpc in a system like the Milky Way, with $\rho_\chi \simeq 0.4\ GeV/cm^3$, and $v \approx 220\ km/s$.

C. Dvorkin, K. Blum and M. Kamionkowski, Phys. Rev. D (2013)

Likelihood analysis

MODEL: $\mathbf{p} = \left\{ \Omega_b h^2, \Omega_c h^2, \theta, \tau, A_s, n_s, \frac{\sigma}{m_\chi} \right\}$

$$\mathcal{L}(\mathbf{x}|\mathbf{p}) = \frac{1}{(2\pi)^{N/2}\sqrt{\det \mathbf{C}(\mathbf{p})}} \exp\left[-\frac{1}{2} \mathbf{x}^\dagger [\mathbf{C}(\mathbf{p})]^{-\mathbf{1}} \mathbf{x} \right]$$

- CMB temperature data (Planck satellite)

+

- Lyman-alpha data (Sloan Digital Sky Survey)

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

Mean free path: $\lambda = \left(\frac{\rho_\chi \sigma}{m_\chi}\right)^{-1}$ $(\text{with}\ \ \rho_\chi \approx 0.4\,\text{GeV/cm}^3)$

n	CMB (95%CL, cm^2/g)	CMB + Lyman-α (95%CL, cm^2/g)	λ (MW)
-4	1.8×10^{-17}	1.7×10^{-17}	27 Gpc
-2	3.0×10^{-9}	6.2×10^{-10}	738 Mpc
-1	1.6×10^{-5}	1.4×10^{-6}	313 Mpc
0	0.12	3.3×10^{-3}	138 Mpc
+2	1.3×10^{5}	9.5×10^{3}	46 Mpc

(**CMB data**: from **Planck**; **Ly-alpha data**: from the **Sloan Digital Sky Survey**)

A baryon in the halo of a galaxy like our Milky Way does not scatter from Dark Matter particles during the age of the Universe.

C. Dvorkin, K. Blum and M. Kamionkowski, Phys. Rev. D (2013)

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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- Using CMB data from Planck + Ly-alpha forest measurements from the Sloan Digital Sky Survey, we conclude that a baryon in the halo of a Galaxy like our Milky Way does not scatter from Dark Matter particles during the age of the Universe.