Title: CMB Constraints on Sommerfeld-Enhanced Dark Matter

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Abstract: Dark matter (DM) annihilation around the redshift of last scattering can alter the recombination history of the universe, broaden the last scattering surface, and influence the observed temperature and polarization fluctuations of the cosmic microwave background (CMB). Unlike other indirect astrophysical signals of DM annihilation, these CMB signatures are free of the significant uncertainties inherent in modeling galactic physics, and provide an independent method to test and constrain models of dark matter. Recently measured anomalous excesses of 10-1000 GeV electron and positron cosmic rays have motivated DM models with large annihilation cross sections when the relative velocity of the annihilating particles is low. We have calculated in detail the efficiency with which energy from DM annihilation is deposited into the photon-baryon plasma around the redshift of last scattering, for an array of annihilation channels, allowing precise predictions of the effect of DM annihilation on the CMB. I will discuss CMB constraints for specific annihilation channels, which can strongly limit the allowed parameter space for DM models fitting the excesses measured by PAMELA and/or Fermi. I will also describe degeneracies between the effect of DM annihilation and changes to the cosmological parameters, and their implications. In particular, DM annihilation could alter the apparent value of the scalar spectral index n_s as measured by WMAP.

CMB constraints on Sommerfeld-enhanced DM annihilation

Tracy Slatyer – Harvard University
New Lights on Dark Matter
Perimeter Institute, 11 June 2009

arXiv:0906.1197 with Douglas Finkbeiner & Nikhil Padmanabhan

Outline

- Heating and ionization of the IGM by dark matter annihilation around z ~ 1000 modifies the cosmic microwave background (CMB).
- New work: detailed calculation of the energy absorption efficiency – can constrain specific models.
- Models that fit cosmic-ray excesses are close to WMAP5 limits, well above expected Planck limits (factor of ~10).

Why look at DM annihilation during recombination?

- Free of present-day astrophysical uncertainties – fairly well understood physics

- Not as sensitive to spectrum of annihilation products, compared to cosmic-ray signals – depends mostly on total power (in electrons and photons)

- Especially sensitive to models with boosted annihilation at low velocities

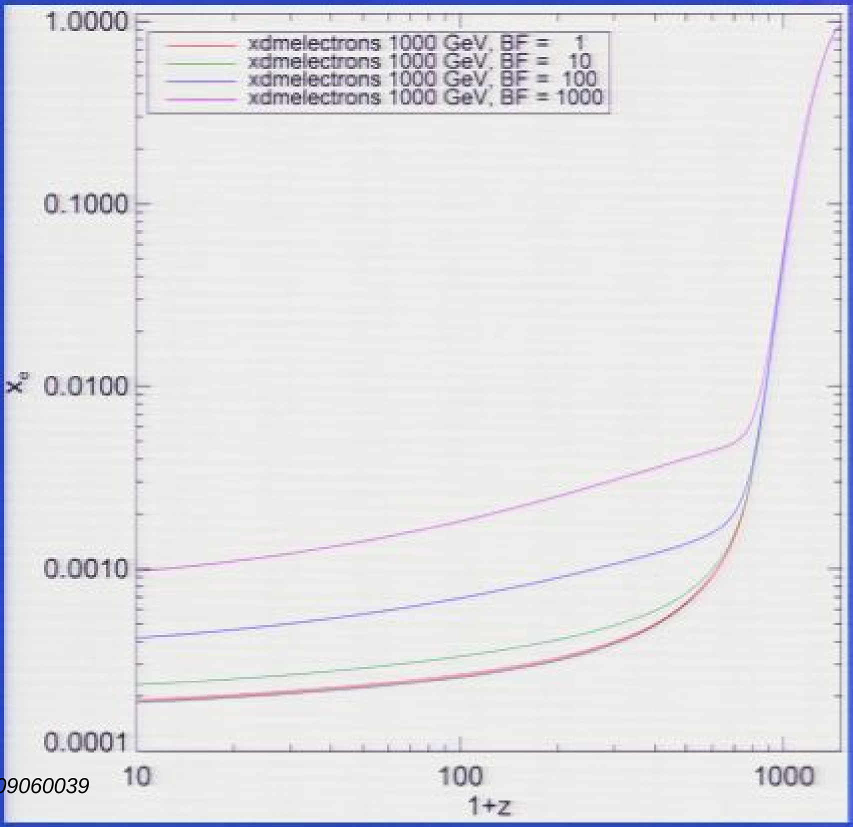
WIMP annihilation at z ~ 1000

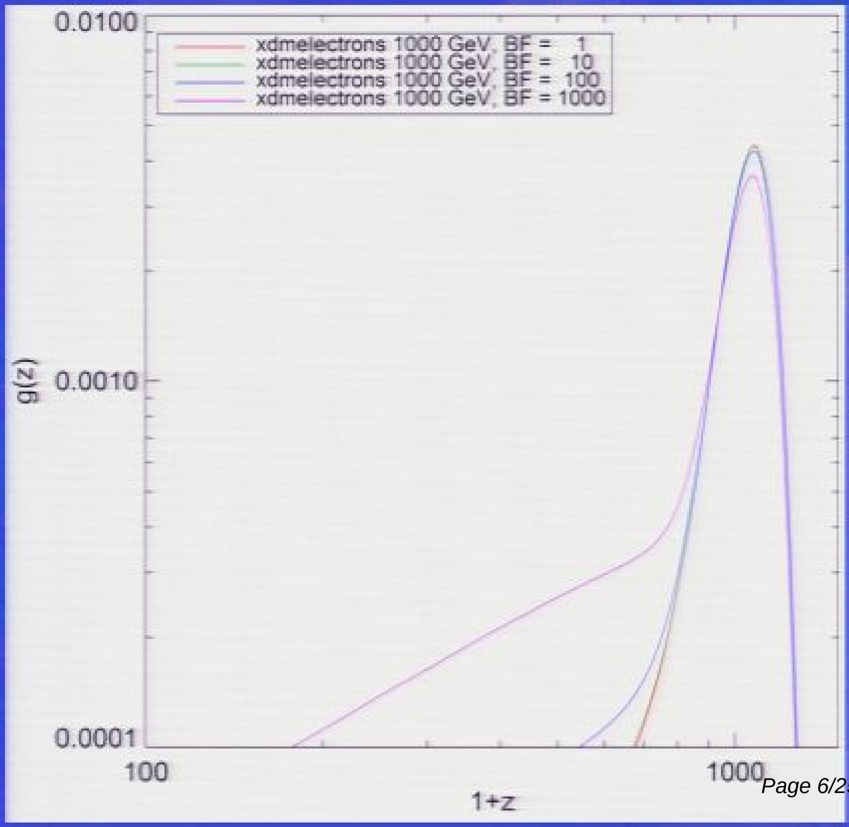
Chen and Kamionkowski 04, Finkbeiner and Padmanabhan 05

- WIMP annihilation injects high energy particles: e^+e^-, γ, ν, p.
- Energy injected in neutrinos and protons largely escapes.
- e^+e^- with $E < 1$ MeV and photons with $E < 1$ keV efficiently heat and ionize the IGM.
- Higher energy photons, e^+e^- must first lose their energy (by redshifting, downscattering, pair production, etc).

Effects on the ionization history

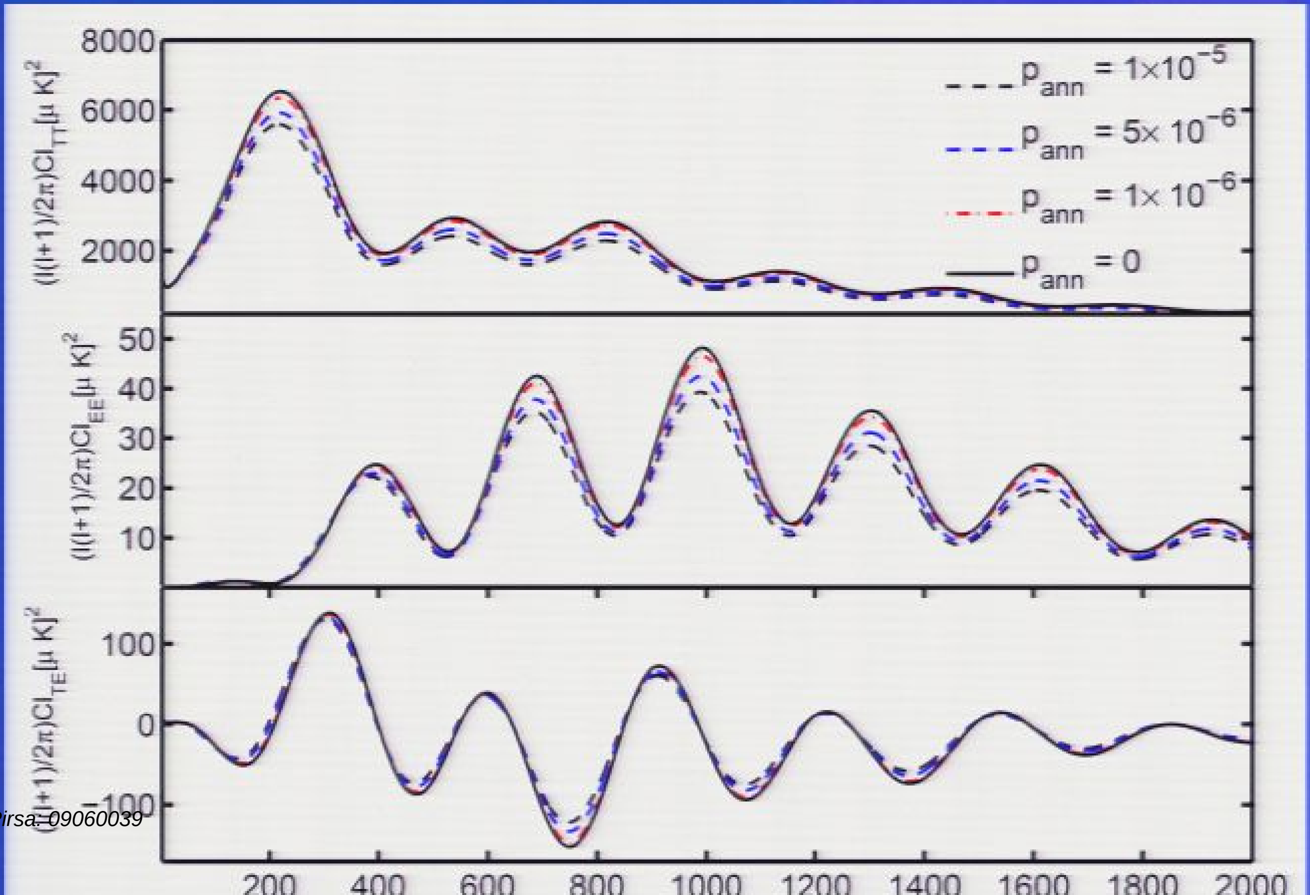
- Additional residual ionization
- Broader surface of last scattering





Effects on the CMB

- Broadening of last scattering surface suppresses temperature fluctuations, modifies polarization fluctuations in CMB



TT, EE, TE angular power spectra for different values of the energy injection from DM annihilation.

(Galli et al, 0905.0003)

$$f\frac{<\sigma v>}{m} \equiv p_{ann}$$

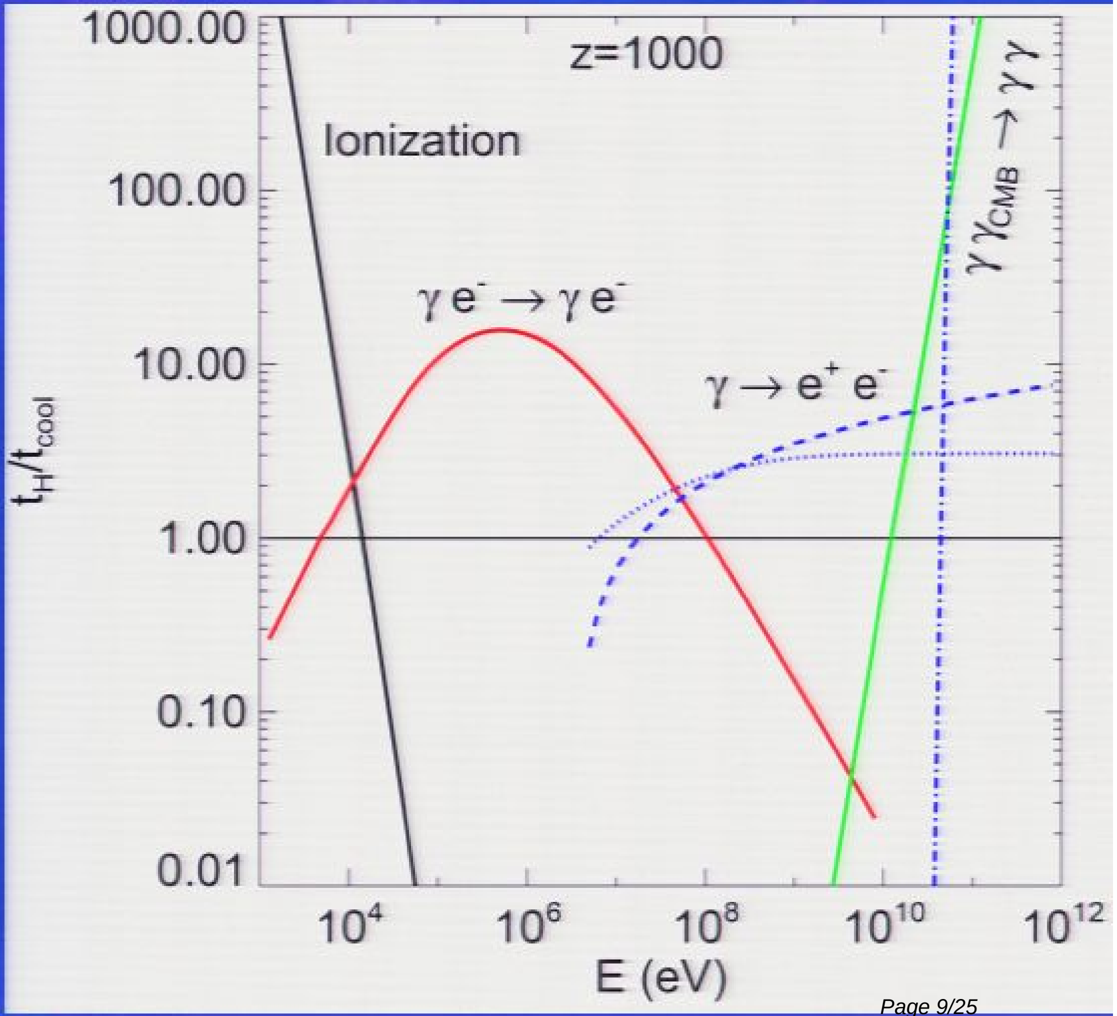
Electron energy losses

- In order of decreasing energy:
  - Inverse Compton scattering
  - Ionization and excitation (on H/He/He^+)
  - Collisional heating
  - Positron annihilation
- All fast compared to a Hubble time – can ignore redshifting.
- Most energy converted to gamma rays via ICS or annihilation, small fraction promptly deposited by low-energy processes.

Photon energy losses

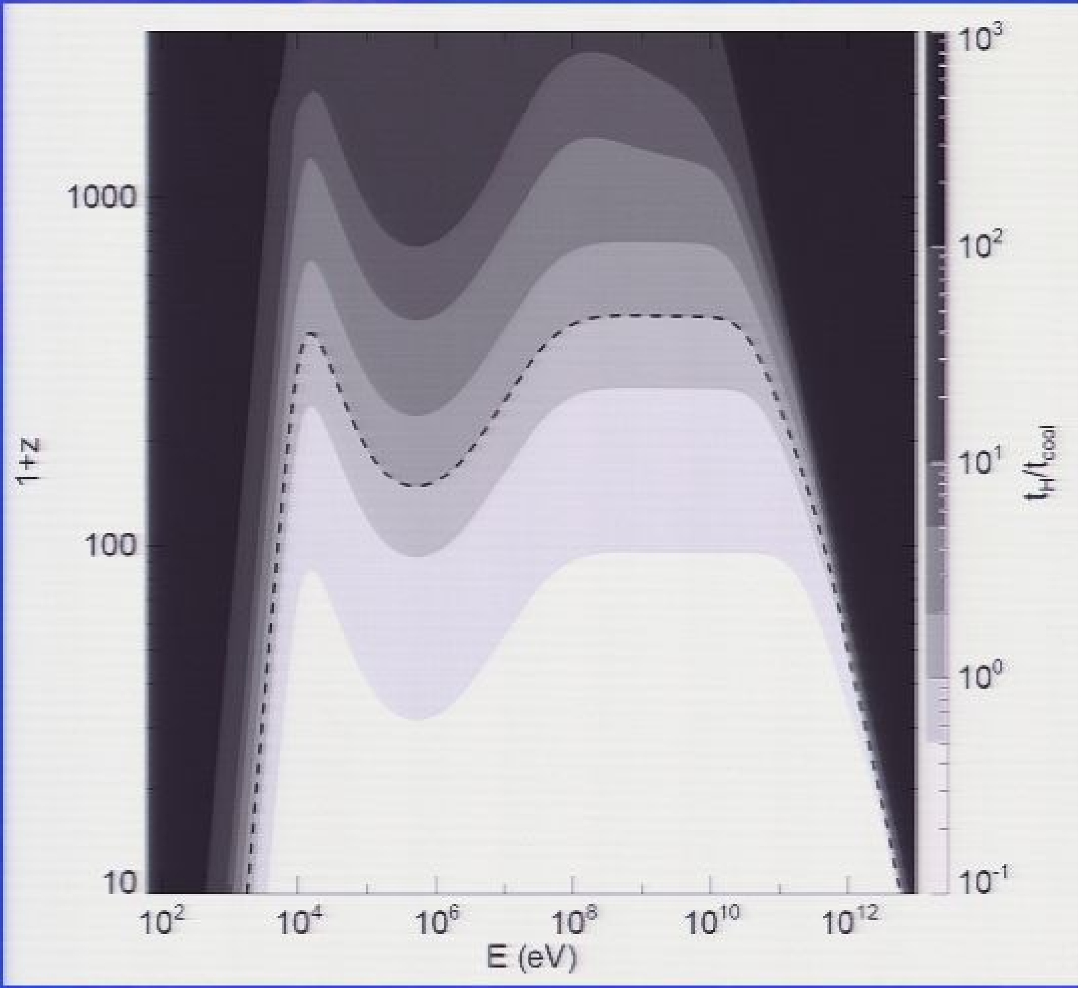
- In order of decreasing energy:
  - Pair production on CMB.
  - Downscattering on CMB.
  - Pair production on gas.
  - Compton scattering.
  - Photoionization of gas.

(Note: previous work had a factor of ~3 error in cooling times.)



The "transparency window(s)"

- $t_{cool} << t_H$ at energies > 100 GeV, <1 keV at z ~ 1000.
- At intermediate energies, $t_{cool} \sim t_H$.
- Dominant processes are pair production on gas, Compton scattering.
- Universe becomes more transparent at lower z.



The on-the-spot approximation

- Some fraction "f" of energy from WIMP annihilation is promptly deposited, heating and ionizing the IGM.
- Remainder of energy is redshifted away – unabsorbed photons may appear in diffuse gamma backgrounds today.
- Assume "f" is independent of redshift.
- Previous work then constrains $f <\sigma v> / M$.

Beyond the on-the-spot approximation

- WIMP annihilations at much earlier redshifts ($z \sim 2000+$) can heat/ionize gas at $z \sim 1000$.
- Universe becomes more transparent at later redshifts.
- Define effective efficiency $f(z)$:

  $\varepsilon(z)$ = energy deposited to the IGM by DM annihilation per baryon per second, at redshift z

  $$= f(z)\, 2\, M_{DM} \langle \sigma v \rangle (1+z)^3 (n_{DM})_0^2 / (n_{baryon})_0$$

Calculating the energy absorption

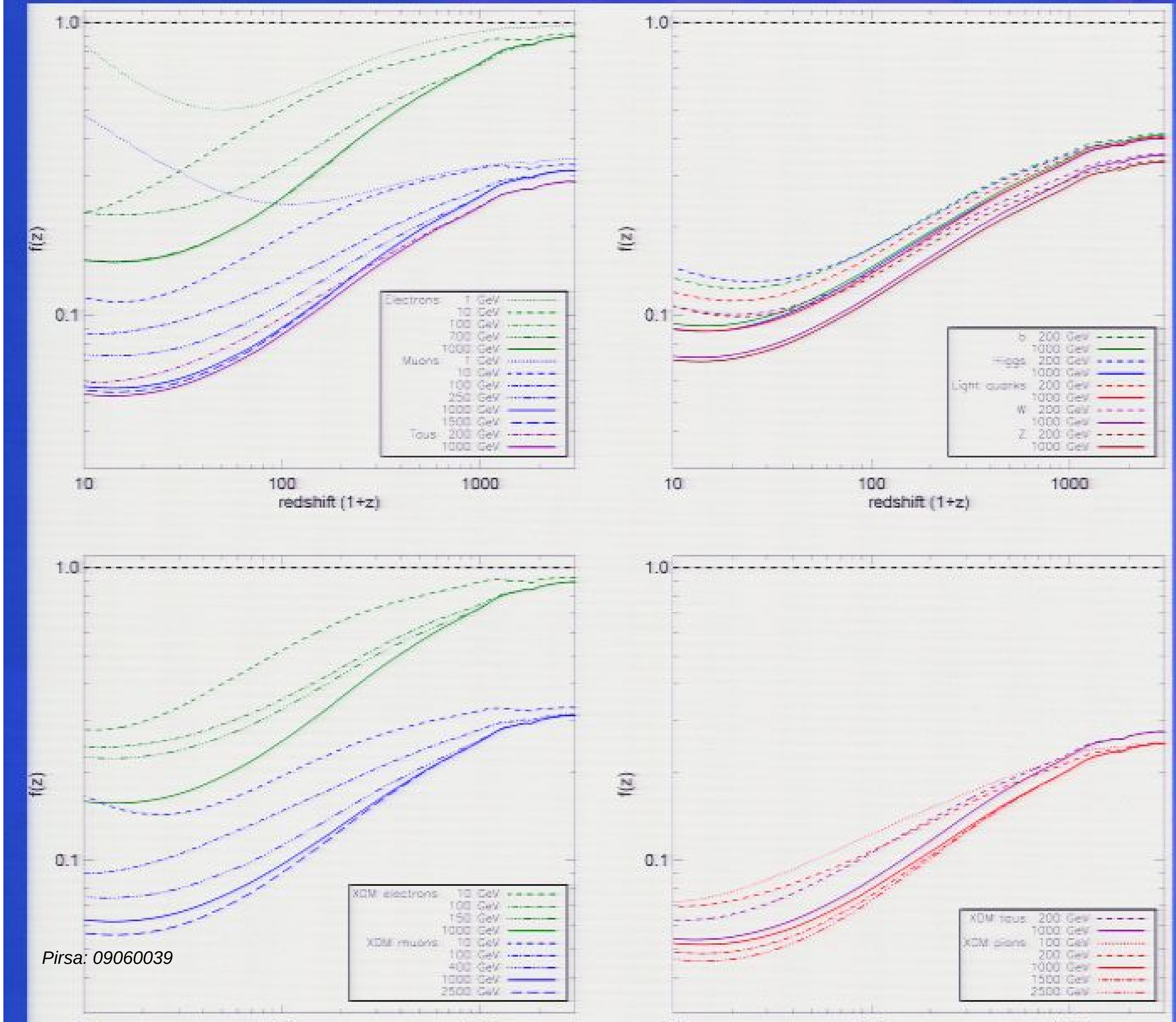
- Inject photons and electrons from DM annihilation at each timestep (dlnz = 1/1000)

- Energy in electrons => γ-rays, + prompt ionization/heating.

- Low-E photons promptly ionize/heat gas, high-E photons cascade to lower energies (pair production + ICS)

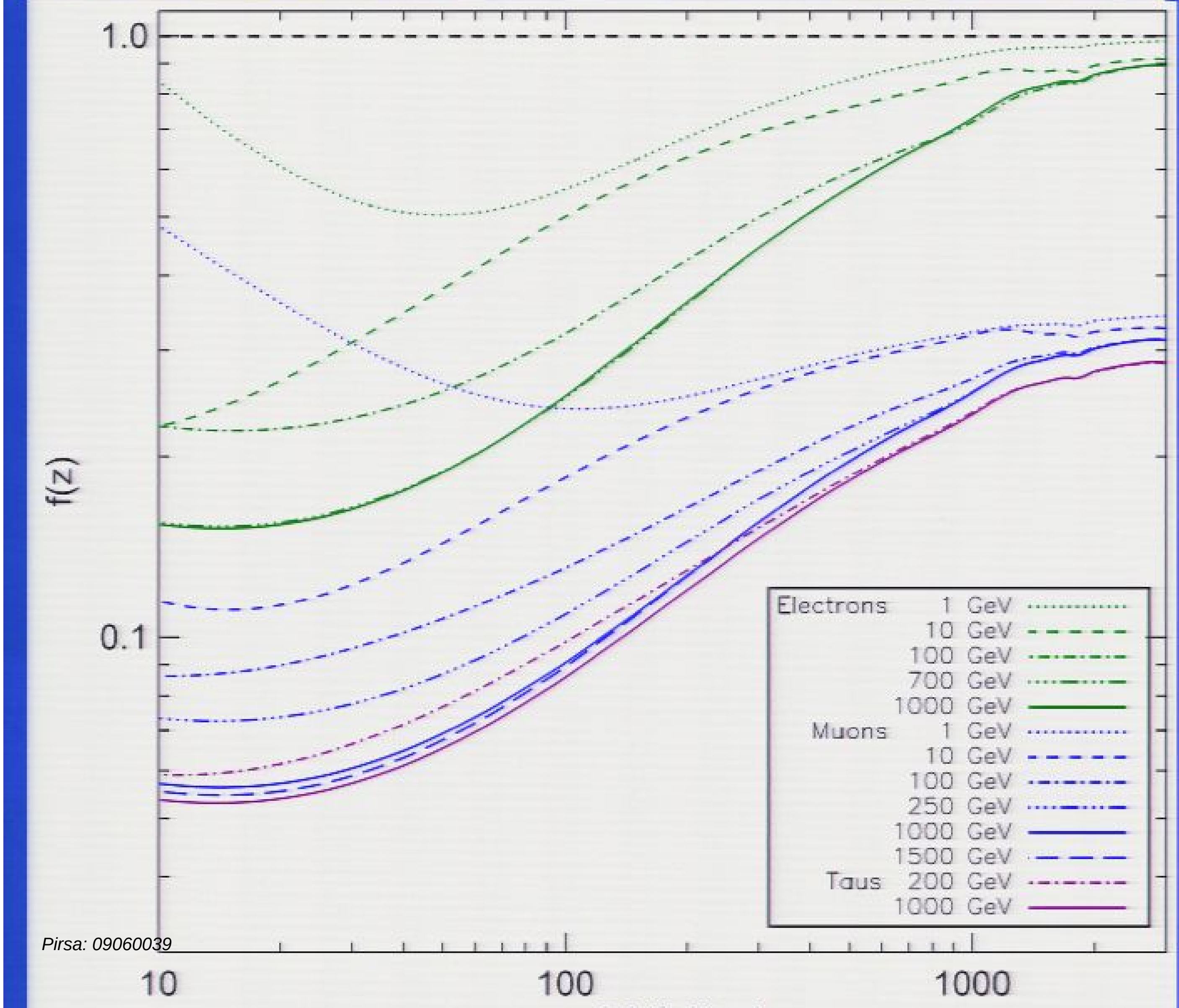
- Evolve photon spectra in semi-transparent window w.r.t. z
  - Pair production cascades
  - Photon-photon scattering
  - Compton scattering +ICS of upscattered electrons
  - Redshifting

f(z) for specific annihilation channels



Channel	DM mass (GeV)	$f_{\rm mean}$
Electrons	1	0.92
$\chi\chi \to e^+e^-$	10	0.84
	100	0.69
	700	0.70
	1000	0.70
Muons	1	0.32
$\chi\chi \to \mu^+\mu^-$	10	0.31
	100	0.26
	250	0.25
	1000	0.24
	1500	0.24
XDM electrons	10	0.88
$\chi\chi \to \phi\phi$	100	0.73
followed by	150	0.70
$\phi \to e^+e^-$	1000	0.70
XDM muons	10	0.32
$\chi\chi \to \phi\phi$	100	0.27
followed by	400	0.25
$\phi \to \mu^+\mu^-$	1000	0.25
	2500	0.24
XDM pions	100	0.22
$\chi\chi \to \phi\phi$	200	0.21
followed by	1000	0.20
$\phi \to \pi^+\pi^-$	1500	0.20
	2500	0.20
W bosons	200	0.29
$\chi\chi \to W^+W^-$	300	0.29
	1000	0.28
Z bosons	200	0.28
$\chi\chi \to ZZ$	1000	0.27
Higgs bosons	200	0.34
$\chi\chi \to h\bar{h}$	1000	0.32
b quarks	200	0.35
$\chi\chi \to b\bar{b}$	1000	0.33
Light quarks	200	0.34

f(z) for specific annihilation channels



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b quarks	[illegible]	0.35
$\chi\chi \to b\bar{b}$	1000	0.33
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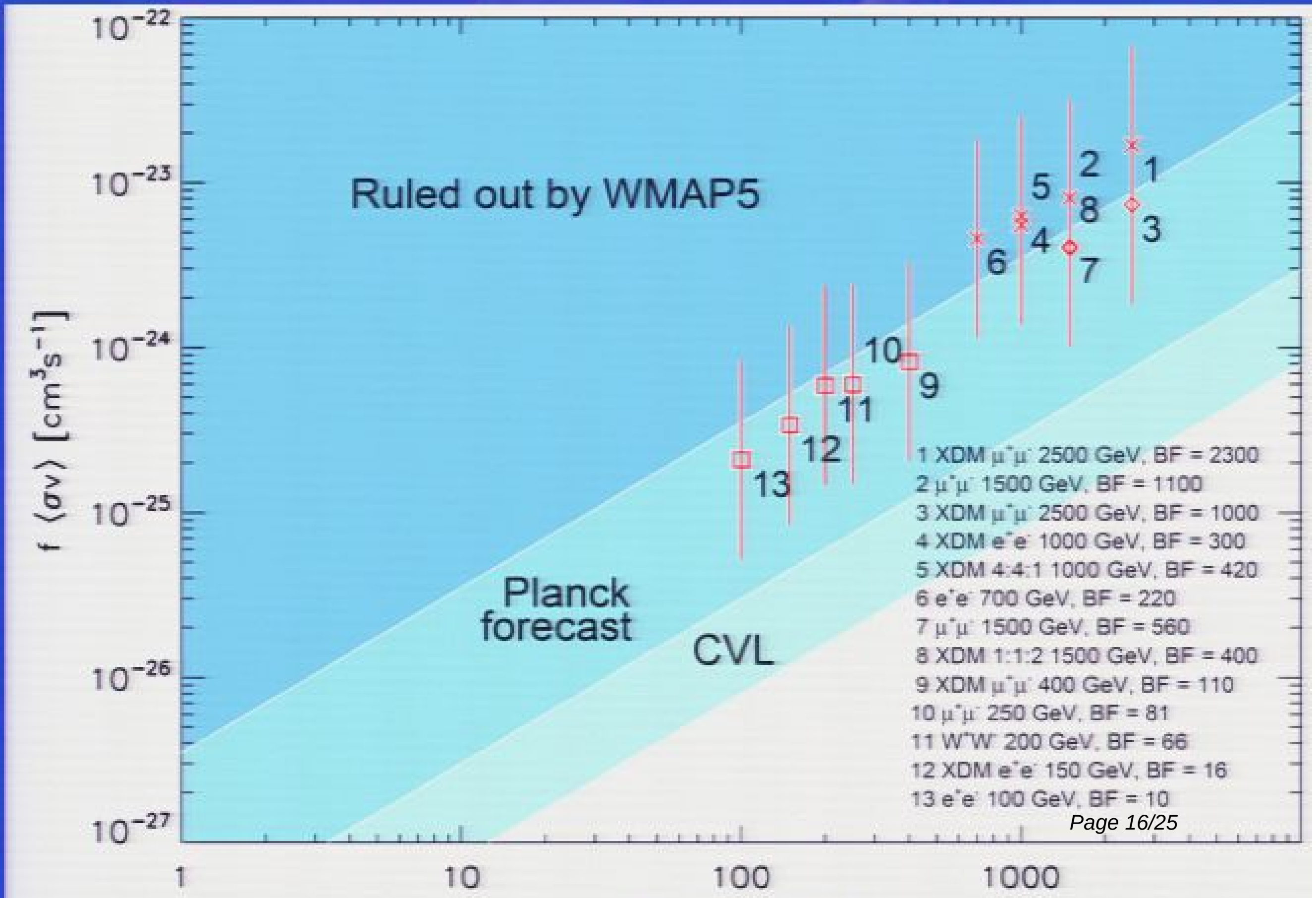
Constraints on DM models

Galli et al 0905.0003; Cholis et al 0811.3641

- Average f over z=800-1000, compare specific DM annihilation channels to constraints on f <σ v>.

- WMAP5: models that fit PAMELA / ATIC / Fermi are close to 95% confidence limit – but with large uncertainties.

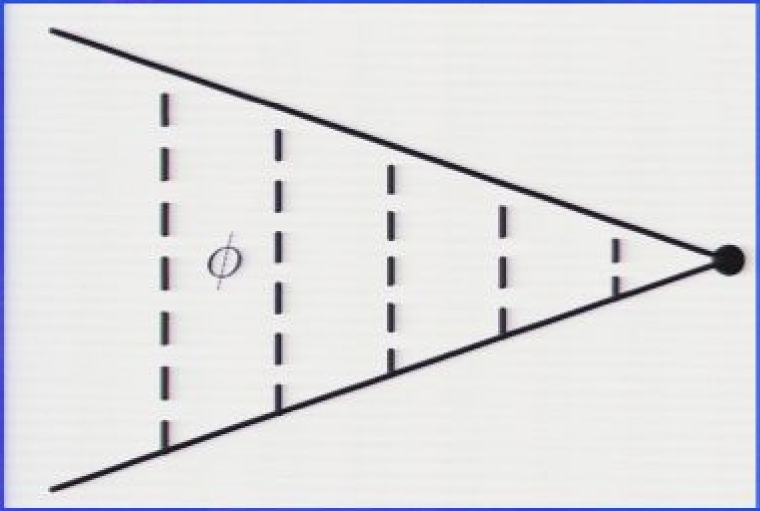


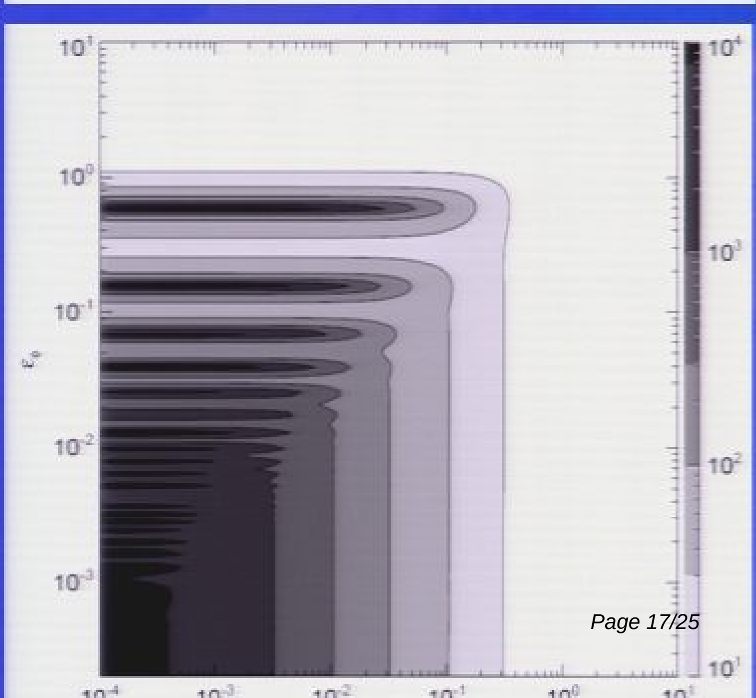
- Planck can test these models

Sommerfeld enhancement

Sommerfeld 1931, Hisano et al 2005, Cirelli et al 2007, March-Russell et al 2008

- Nonperturbative boost to annihilation at low velocities.
- Attractive force mediated by exchange of light particle (relative to DM)
- Proposed to explain large annihilation xsec in Galactic halo, relative to freezeout





Sommerfeld enhancement at z ~ 1000

- For Yukawa potential, non-resonant enhancement scales as $\alpha/(v/c)$ until $v/c \sim m_V/m_{DM}$, then saturates at $\sim \alpha/(m_V/m_{DM})$.
- DM velocity at z~1000 is VERY small, $v/c \sim 10^{-8}$.
- Compare to $v/c \sim 10^{-4}$-10^{-3} in present-day Galactic halo, near the Earth.
- Enhancement either much greater at z~1000, or already saturated.

CMB constraints on Sommerfeld-enhanced models

- Cross section required for PAMELA / ATIC / Fermi ~ maximum saturated cross section allowed by WMAP5.
- If Sommerfeld-enhanced models fit cosmic-ray excesses => enhancement MUST be saturated by v/c ~ 10^{-4}-10^{-3}.
- Consistency check: enhancement provides z-independent boost around redshift of recombination, so assuming constant $<\sigma v>$ justified.

Lower limit on the force carrier mass?

- For Yukawa potential, small mediator masses are disfavored: $m_V/m_{DM} > \sim 10^{-4}$ (e.g. $m_V << \sim 100$ MeV disfavored, for a 1 TeV WIMP). Relevant for collider searches.
- Resonant enhancement delays saturation to lower velocities for given m_V: limits on m_V can only get stronger.
- Light force carriers still allowed in more complicated scenarios?

Modifying the apparent cosmological parameters

Finkbeiner and Padmanabhan 05

- Adding new parameter for DM annihilation changes best-fit cosmological parameters.

- Effect can be estimated semi-analytically:

$$C_l = 4\pi A \int_0^\infty d(\ln k)\, k^{n_s} D^2(k) T^2(k)$$

$$D(k) = \int dz\, g(z) \exp\left(-\frac{k^2}{k_D^2(z)}\right)$$

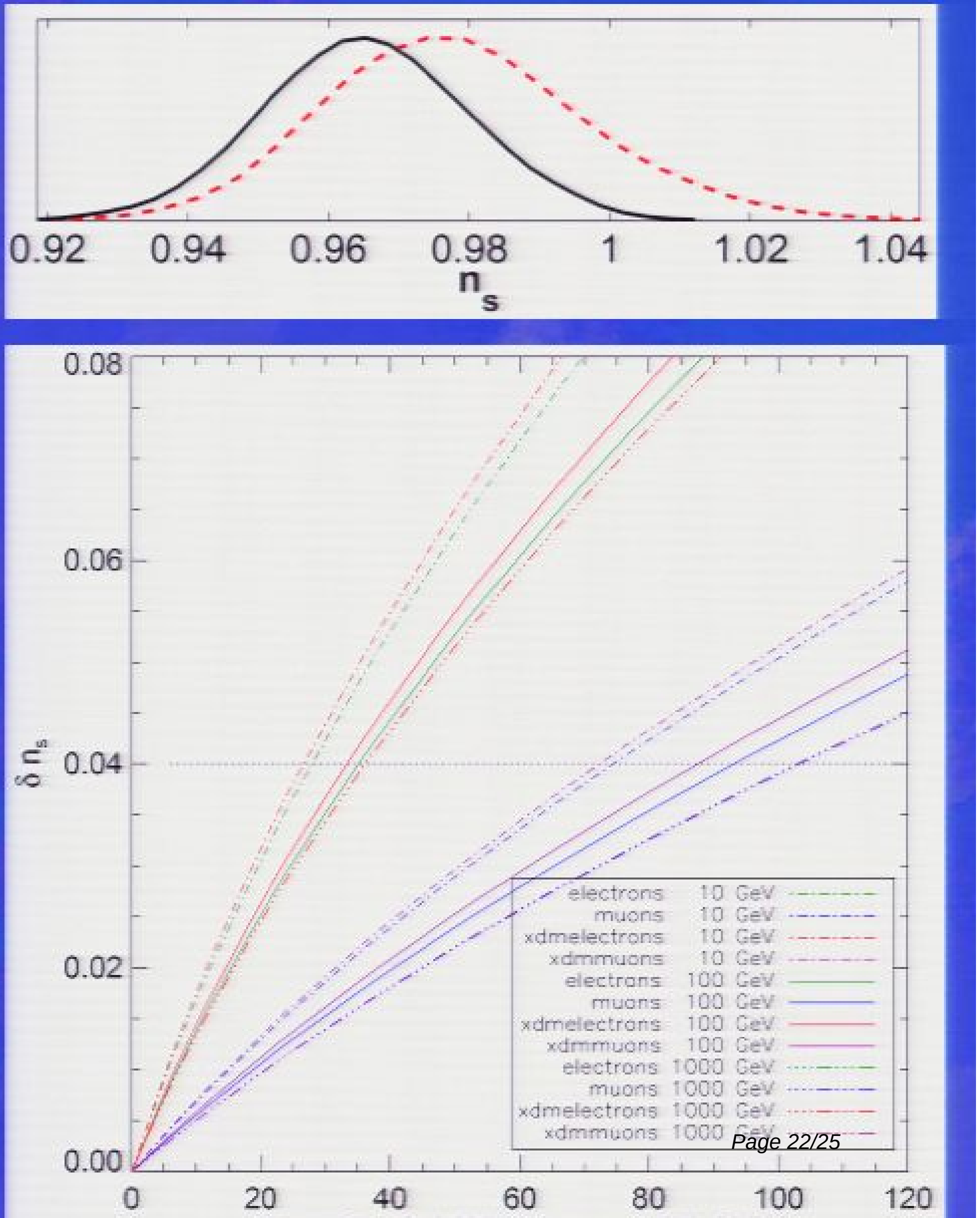
$$\frac{1}{k_D^2} = \int_z^\infty dz\, \frac{c}{H^2(z)} \frac{1}{6(1+R)\tau'(z)} \left[\frac{R^2}{(1+R)} + \frac{16}{15}\right]$$

For scales relevant to l > 50 in the CMB, $D(k)/(D(k))_0$ is well fitted by a power law, $A_\cdot k^{\alpha}$.

Effects on n_s

(Galli et al, 0905.0003)

- Effects of DM annihilation on temperature anisotropy can be nearly exactly compensated by increasing n_s, amplitude.
- In presence of DM annihilation: n_s, σ_8 appear smaller than their true values.
- Polarization measurements break degeneracy.



Future directions

- Detailed likelihood analysis for the cosmological parameter values and the energy injection from DM annihilation, using our accurate expressions for f(z).
- Update constraints with further cosmic-ray data.
- Explore Sommerfeld-enhanced models other than the simple Yukawa-potential scenario – very light force carriers still allowed?
- Extend detailed energy absorption calculation to decaying dark matter?

Conclusions

- First detailed calculation of f(z) for WIMP annihilation allows direct comparison of models to CMB constraints.
- Cross sections + annihilation channels which fit cosmic-ray anomalies lie close to WMAP5 95% limits (but fits have large astrophysical uncertainties).
- Broad range of DM explanations for cosmic-ray excesses can be ruled out by Planck at 95% confidence at the factor of 10 level.
- Sommerfeld-enhanced models which fit cosmic-ray data: enhancement is ~saturated at $v/c \sim 10^{-3}$-10^{-4}. For the simplest (Yukawa potential) case, force carriers with $m_V << 10^{-4}\ m_{DM}$ are disfavored.
- DM annihilation may mean true values of n_s, σ_8 are higher than previously thought.

Constraints on DM models

Galli et al 0905.0003; Cholis et al 0811.3641

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