Non-minimal cold dark matter particles and the CMB

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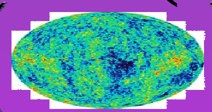
Plan

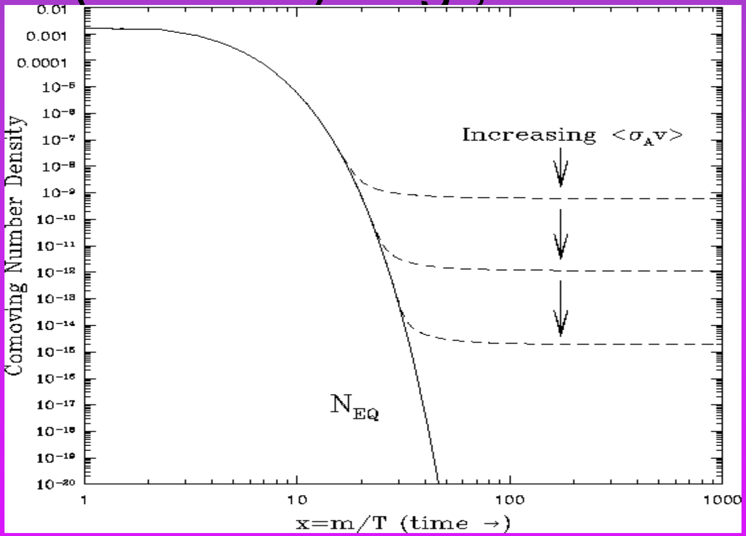
- Review of standard weakly interacting massive particle scenario
- (Possible) problems with CDM on small scales
- Self-interacting dark matter
- WIMPs from charged-particle decay (Sigurdson, MK; Sigurdson, Caldwell, Doran, Kurylov, MK)
- “How dark is `dark’?” Dark-matter dipole moments

What do we know?

- Compelling cosmological evidence that nonbaryonic (non SM) dark matter exists.
- $\Omega_d h^2 \Big($  $\Big) = 0.113$
- Dark matter must be ‘dark’ matter.
- But empirically, know little else….

Good news: cosmologists don't need to "invent" new particle:

- Weakly Interacting Massive Particles (WIMPS). e.g.,neutralinos



(e.g., Jungman, MK, Griest 1996)

$$\Omega_\chi h^2 \approx \frac{3\times 10^{-27}\, cm^3/\mathrm{sec}}{\langle \sigma v\rangle}$$

- Axions

$m_a \sim 10^{-(3\text{-}6)}$ eV

arises in Peccei-Quinn solution to strong-CP problem

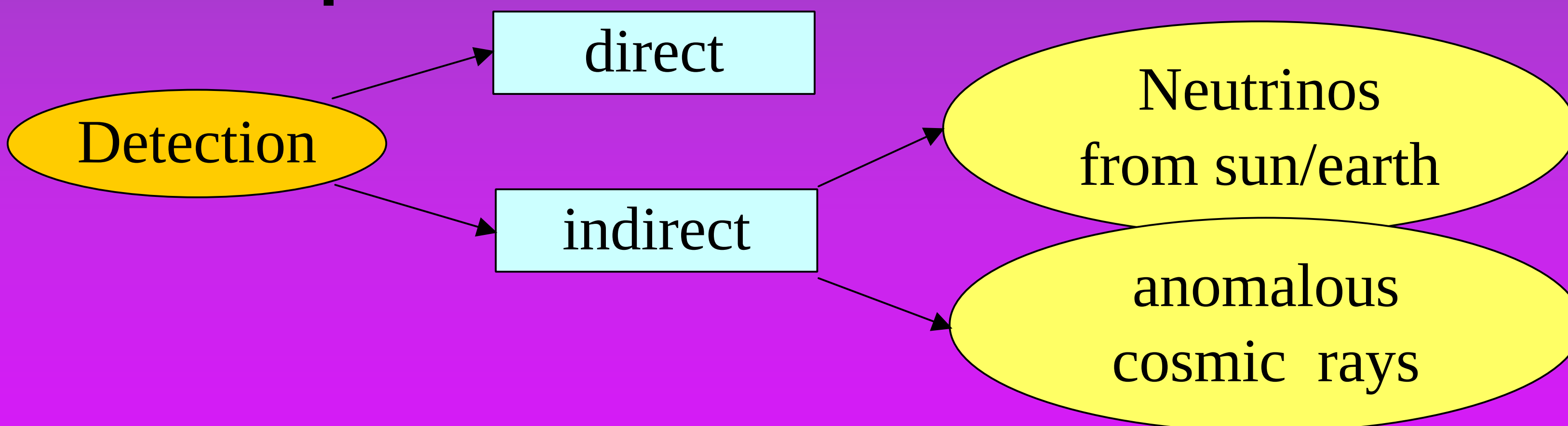
(e.g., Raffelt 1990; Turner 1990)

WIMPs

Relic Density: $\Omega_\chi h^2 \approx (3\times10^{-26}\ cm^3/sec / \sigma_{\chi\chi\to sm})$

Annihilation cross section $\sigma_{\chi\chi\to sm}$ of Weak Interaction strength gives right answer

Prospects for detection:



WIMP candidate motivated by SUSY:

Lightest Neutralino, LSP in MSSM

Typical WIMP-WIMP elastic scattering cross section ~10^{-40} cm^2 and mass 10-1000 GeV; for halo density ~GeV/cm^3 and velocity ~300 km/sec, mean-free time for WIMP scattering is at least $10^{13}/H_0$; thus, WIMPs act as collision-***free*** dark matter.

Axion-axion cross section far smaller, so also collisionless.

Problem 1: Halo cusps

N-body simulations show "cusp", $\rho \sim 1/r$, for small r for collisionless halos (Navarro, Frenk, White 1996; Moore et al. 1997); however, rotation curves for (at least some, maybe most) galaxies show dark-matter cores.

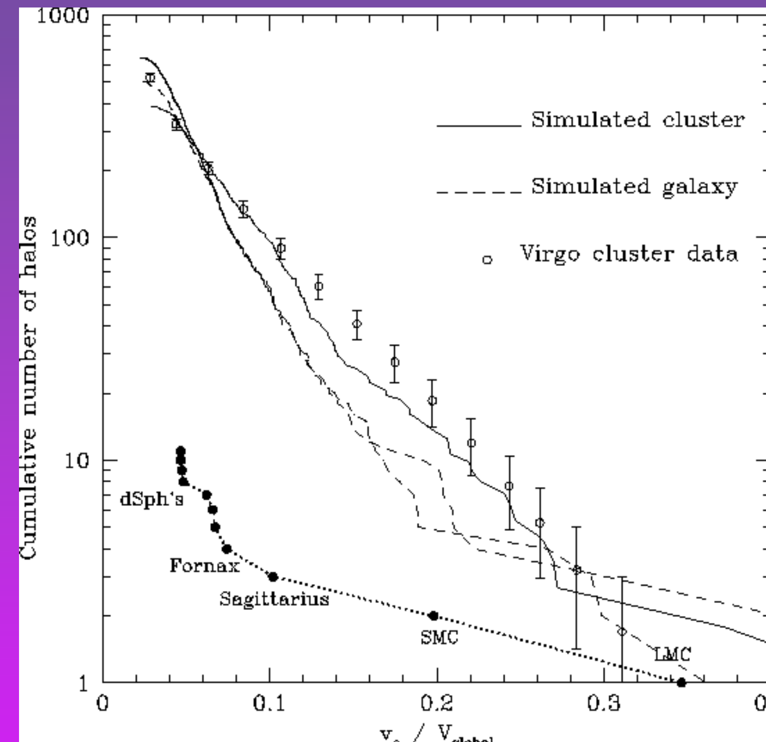
Problem 2: Halo substructure

N-body simulations show more than 10 times as many dwarf galaxies in typical galactic halo than are observed in Milky Way (Moore et al. 1999; Klypin et al. 1999)

Cluster

galactic
halo

300 kpc



The self-interacting dark matter solution (Spergel & Steinhardt 1999):

Hypothesize that dark matter can elastically scatter from itself

Small self-interaction leads to energy transport that reduces sharp subgalactic features like cusp and substructure.

Requires X-sections ~13 OoM bigger than WIMP

Now ruled out by lensing, dynamics, and x-ray observations of elliptical galaxies.

Lesson from SIDM

Clever observations and arguments can constrain interactions of dark-matter particles

Another possible resolution:

Power suppression on small scales from inflation with broken scale invariance

MK&Liddle, PRL 84, 4525 (2000)

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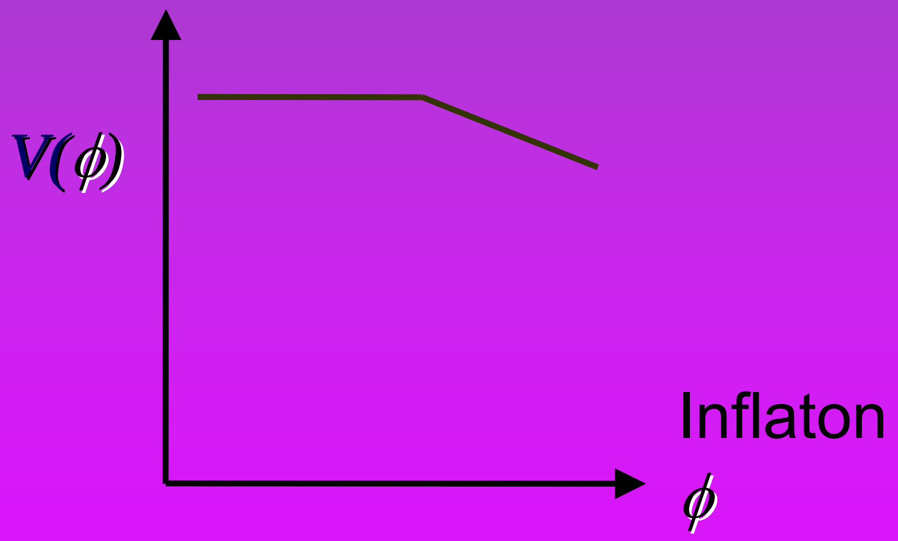
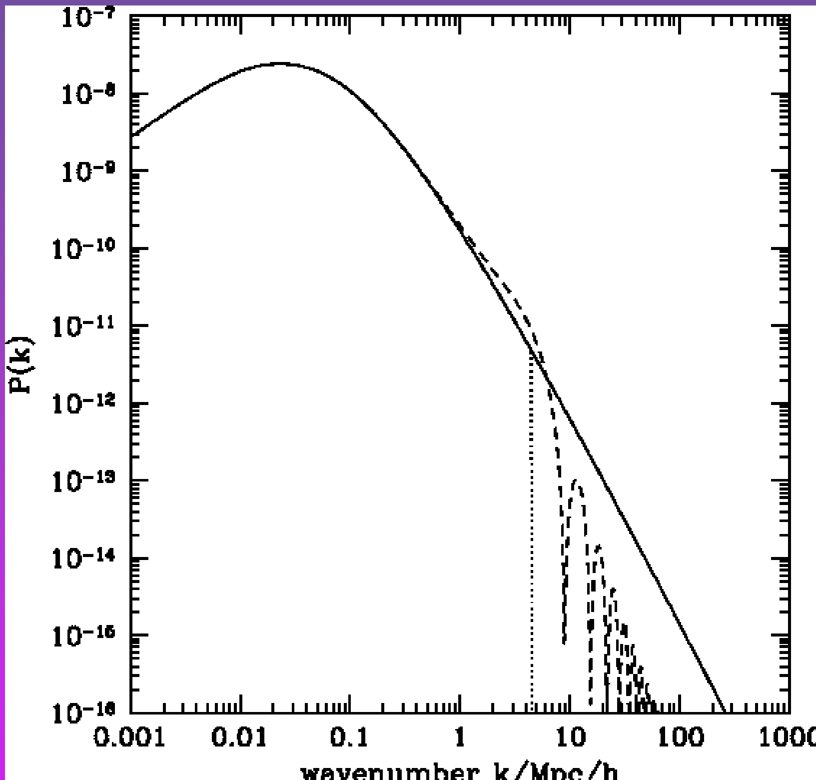
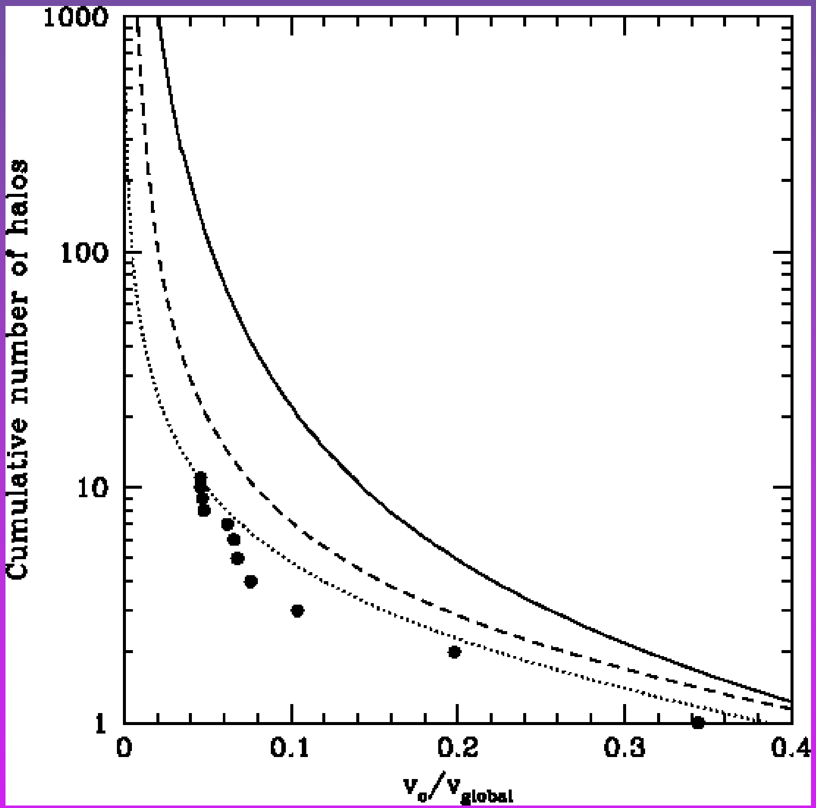
Yokoyama, PRD, 2000





P(k)
wavenumber k/Mpc/h
10−7
10−8
10−9
10−10
10−11
10−12
10−13
10−14
10−15
10−16
0.001
0.01
0.1
1
10
100
1000



Cumulative number of halos
v_c/v_{global}
1000
100
10
1
0
0.1
0.2
0.3
0.4

ad hoc

BSI

What about cusps?

May be astrophysical solutions to this problem
As well (e.g., Binney, Dehnen, Silk;
Katz, Weinberg; Sellwood, Milosavljevic)

WIMPs from Charged-Particle Decay

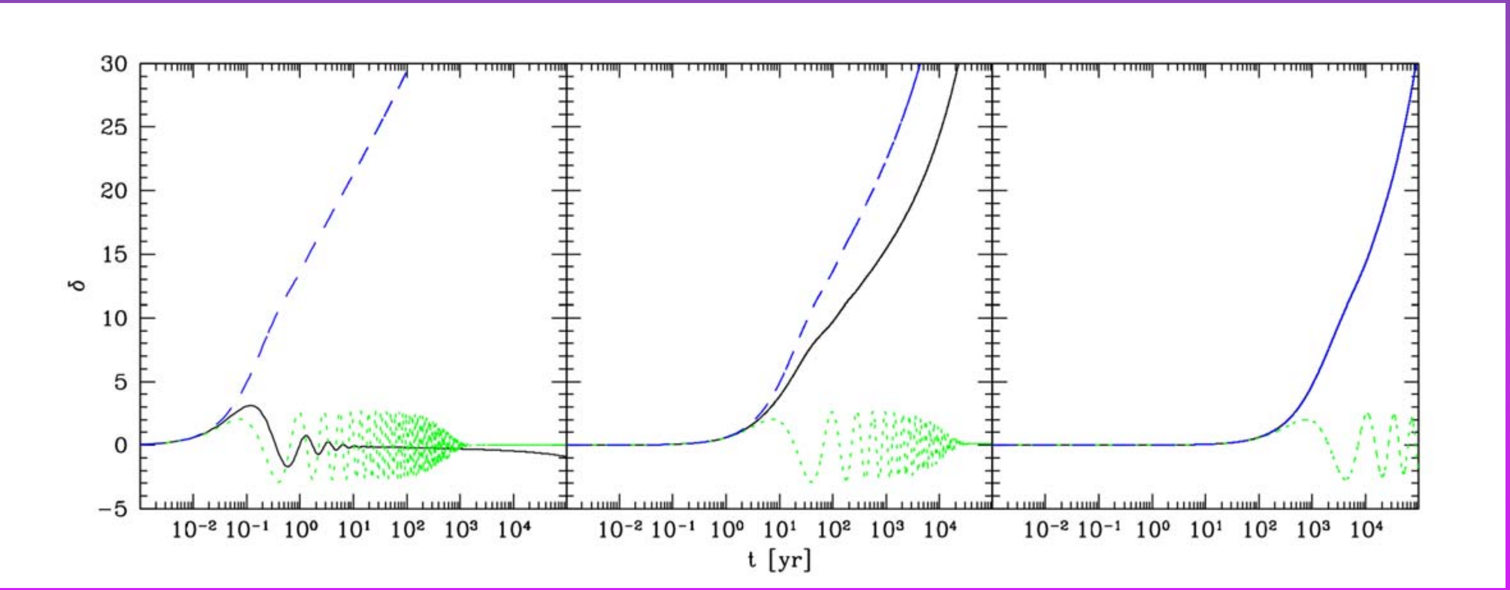
(Sigurdson & MK, PRL 2004)

$$\phi^{\pm} \longrightarrow \chi + \ldots$$

Charged particles: couple to baryon-photon fluid, have pressure, so growth of structure suppressed. Growth of modes that enter horizon while dark matter is charged is suppressed

If charged particle has lifetime ~3.5 yr, power on <Mpc suppressed

Effect of Charged NLDP?



k= 30 Mpc^{-1} 3 Mpc^{-1} 0.3 Mpc^{-1}

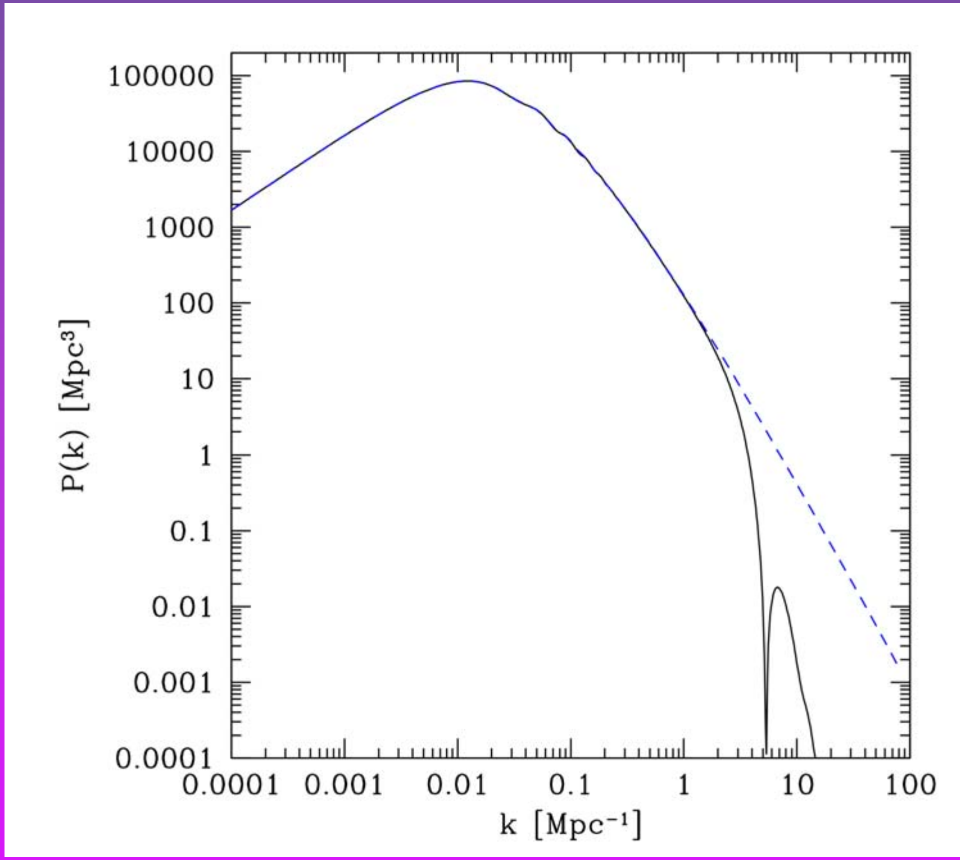
Dark Matter (Standard Case)
Dark Matter (w/Charged NLDP)

$\tau = 3.5\ \mathrm{yr}$

Charged Matter (Baryons+NLDP)

f_ϕ = fraction of DM that is initially charged

If $f_\phi = 1$



K. Sigurdson and MK

Phys. Rev. Lett. **92**, 171302 (2004) [astro-ph/0311486]

Small Scale Structure Problem

- Can solve this problem with charged-decay for lifetimes of order years.

- Long lifetime. Weak coupling?

SuperWIMPS

J. Feng et al. (2003)

$$\tilde{e} \longrightarrow \tilde{G} + e$$
$$e^1 \longrightarrow G^1 + e$$

- Measurements of small-scale *P(k)* can lead to cosmologically interesting lifetimes.

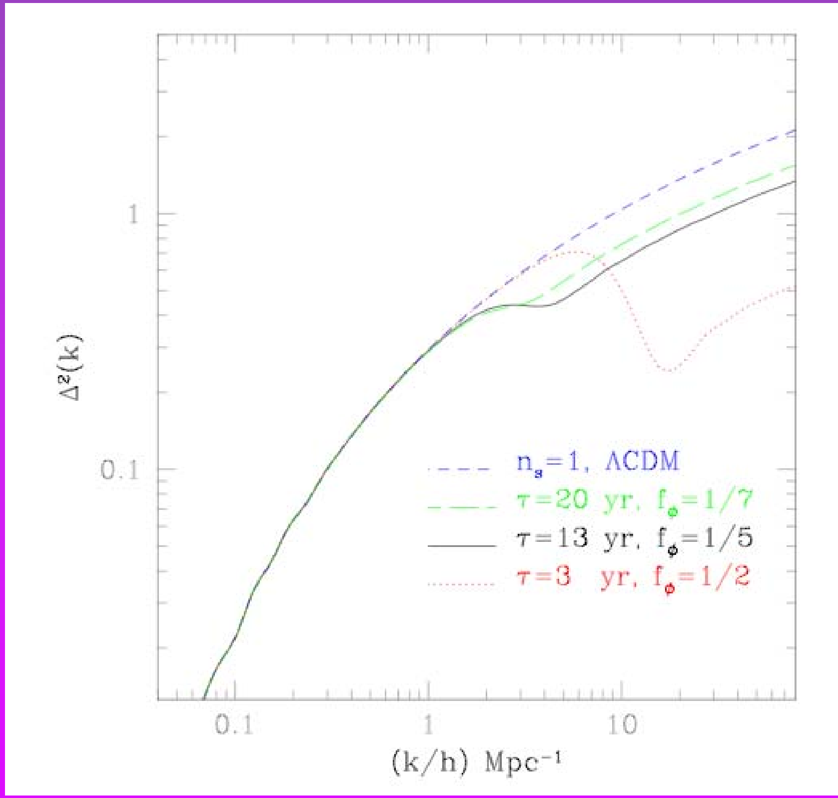
Can charged-particle decay mimic Running of spectral index?

(Profumo, Sigurdson, Ullio, MK, PRD 2005, astro-ph/0410714)

$$f_\phi < 1$$

$$\Delta^2(k) = k^3 P(k)/2\pi^2$$

Suppression by a factor $(1 - f_\phi)^2$ in the linear power spectrum.



21-cm Fluctuations

- Measurement of linear-regime *P(k)* with 21-cm spin-flip transition during the “Cosmic Dark Ages”, at redshifts z=30-200 may discriminate between running of spectral index, and charged-particle decay

How Dark is "Dark"? How weak must coupling of DM to photon be?

- Charge? No.

  A. Gould et al. (1990)

- Millicharge?

  S. L. Dubovsky *et al.* (2004)

  S. Davidson *et al.* (2000)

- What about a neutral particle with magnetic or electric dipole moments?

Kris Sigurdson, Michael Doran, Andriy Kurylov, Robert R. Caldwell, Marc Kamionkowski   Phys. Rev. D70 (2004) 083501 [astro-ph/0406355]

Effective Interaction

The effective interaction Lagrangian:

$$\mathcal{L}_{\gamma\chi} = -\frac{i}{2}\bar{\chi}\sigma_{\mu\nu}(\mathcal{M} + \gamma_5\mathcal{D})\chi F^{\mu\nu}$$

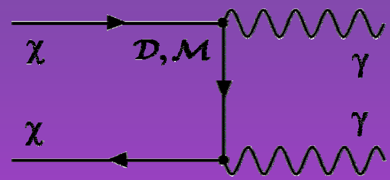
In the nonrelativistic limit:

$$\mathcal{M}\overrightarrow{S} \cdot \overrightarrow{B} \qquad\qquad \mathcal{D}\overrightarrow{S} \cdot \overrightarrow{E}$$

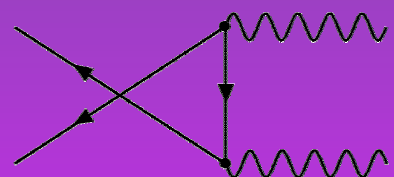
Constraints From

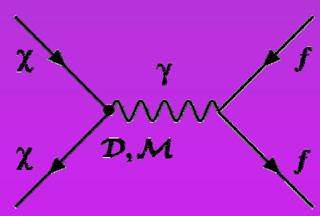
- Cosmological Relic Abundance
- Direct Detection
- Cosmology (CMB and LSS)
- Precision Standard Model
- Production at Accelerators
- Gamma Rays

Relic Abundance



$$\sigma_{\chi\bar{\chi}\to 2\gamma} v \;=\; (\mathcal{D}^4 + \mathcal{M}^4) m_\chi^2 / 2\pi$$



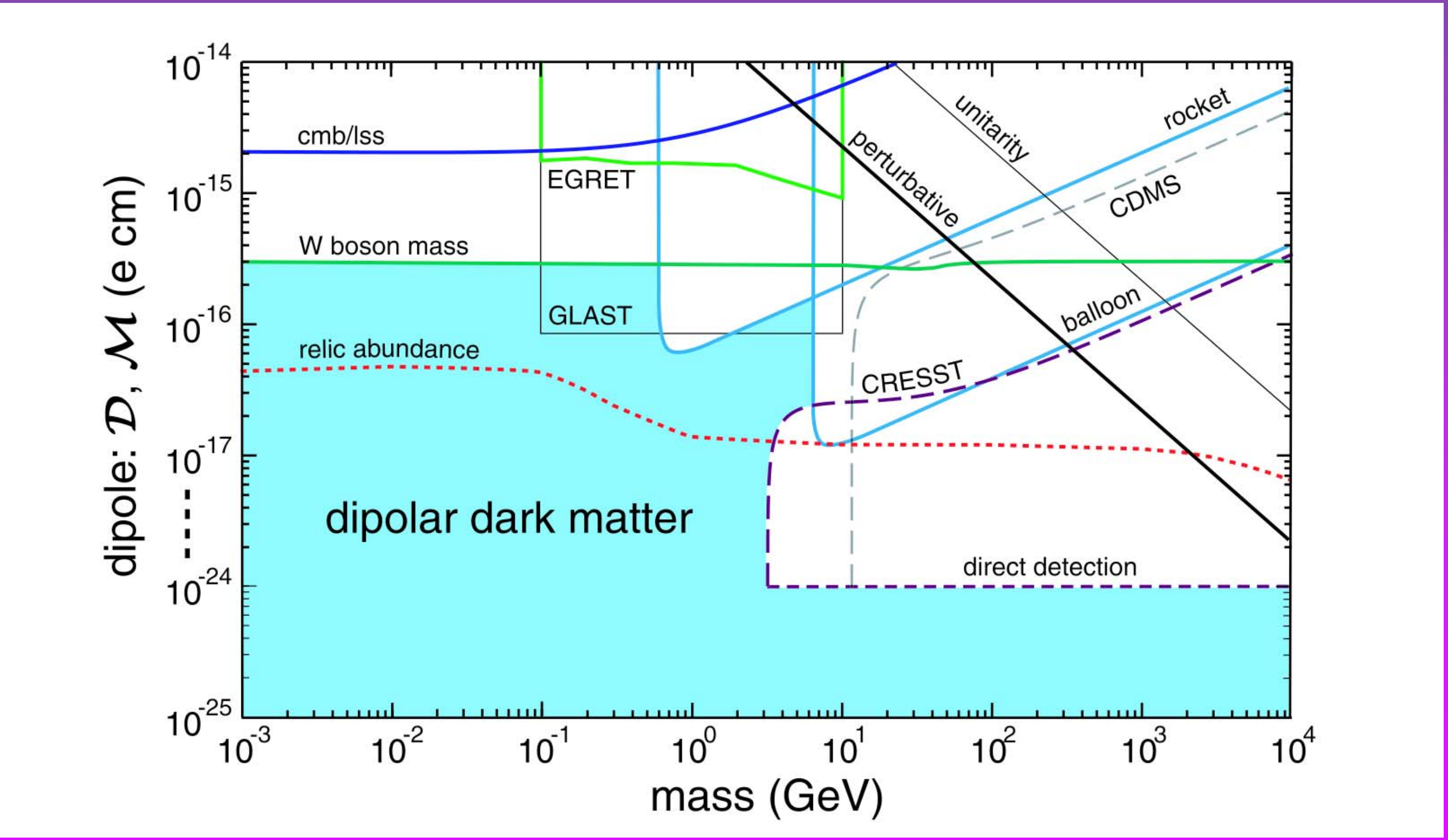


$$\sigma_{\chi\bar{\chi}\to f\bar{f}} v \;=\; N_{\rm eff}\,\alpha(\mathcal{D}^2 + \mathcal{M}^2)$$

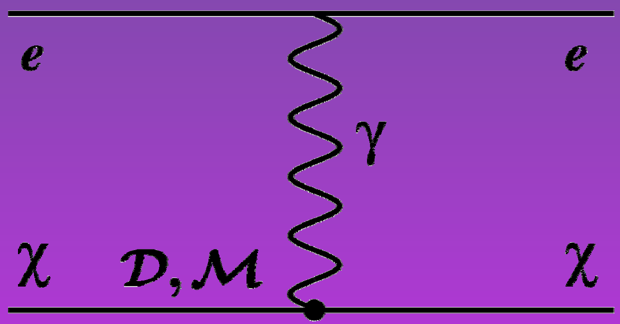
Standard Cosmological Freeze-out Calculation

$$\mathcal{M} \sim 10^{-6}\mu_B \qquad \mathcal{D} \sim 10^{-17}\ \mathrm{e\ cm}$$

Constraints



Direct Detection



$$\frac{d\sigma}{d\Omega} = \frac{Z^2 e^2 \left(\mathcal{D}^2 + \mathcal{M}^2\right)}{8\pi^2 v^2 (1 - \cos\theta)}$$

$$v \sim 10^{-3}\, c$$

$$\mathcal{D}_{17} = \mathcal{D}/(10^{-17}\mathrm{e\ cm})$$

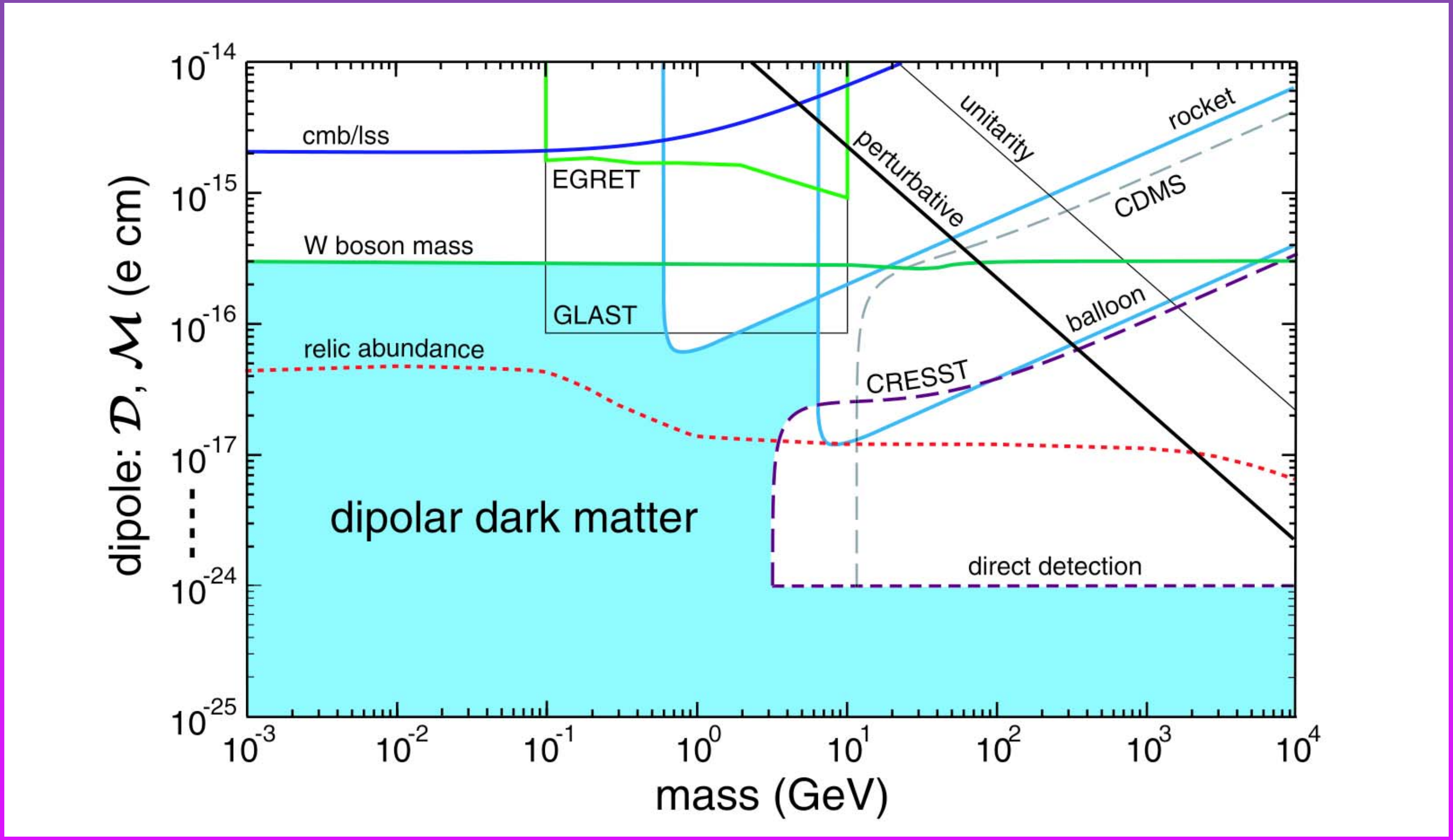
$$\sigma \sim 6.4 \times 10^{-32} Z^2 (\mathcal{D}_{17}^2 + \mathcal{M}_{17}^2)\ \mathrm{cm}^2$$

CDMS (Soudan):

$$\sigma \lesssim 10^{-42}\ \mathrm{cm}^2 \text{ at } m_\chi = 10\ \mathrm{GeV}$$

$$\left(\mathcal{D}_{17}^2 + \mathcal{M}_{17}^2\right)^{1/2} \lesssim 10^{-7}$$

Constraints



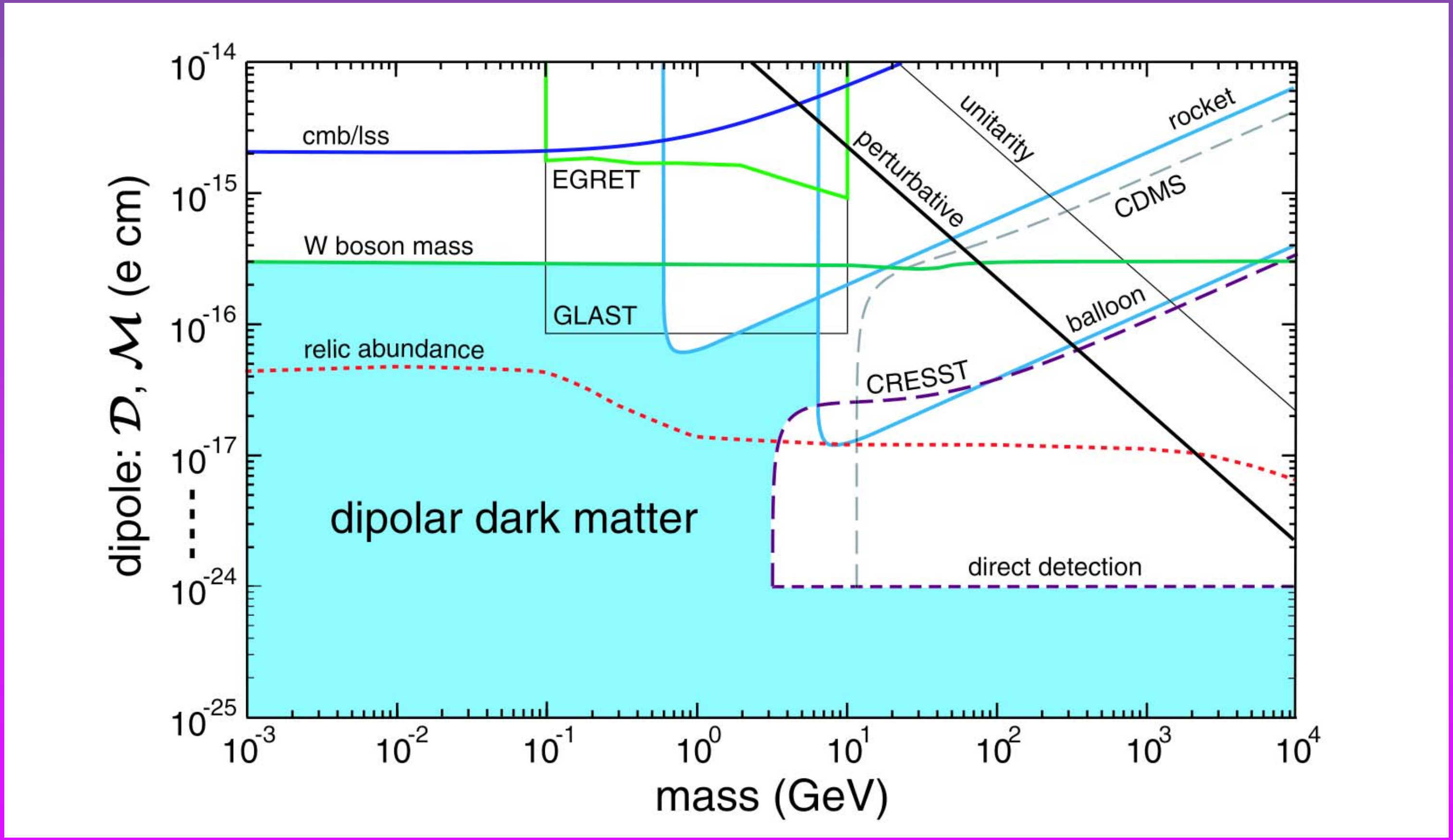
Direct Detection

But… if the dipole strength is too large dipolar dark matter (DDM) will scatter in the atmosphere and the rock above the detector and arrive at the detector with an energy below the detection threshold.

$$\mathcal{D}^2 + \mathcal{M}^2 > \frac{\frac{1}{2} m_\chi v^2 - \frac{1}{4} \frac{m_\chi m_d}{\mu[m_\chi, m_d]^2} E_{\rm th}}{\frac{e^2}{2\pi} L \sum_i f_i Z_i^2 \frac{\mu[m_\chi, m_i]^2}{m_i^2} [1 + (m_i/2m_\chi)^{1/2}]}$$

Strongest constraints from shallowest experiment with a null result. Balloon and Rocket experiments.

Constraints

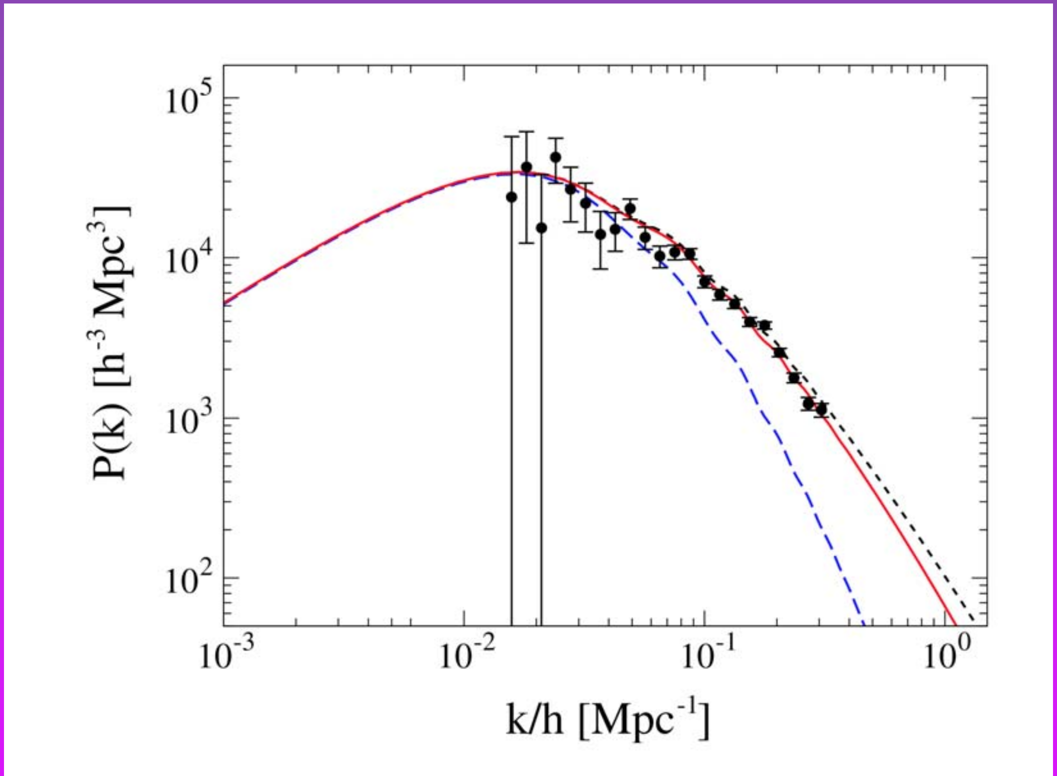


Effects on the Matter Power Spectrum

Black 1.0×10^{-16} e cm

Red 1.4×10^{-15} e cm

Blue 5.0×10^{-15} e cm

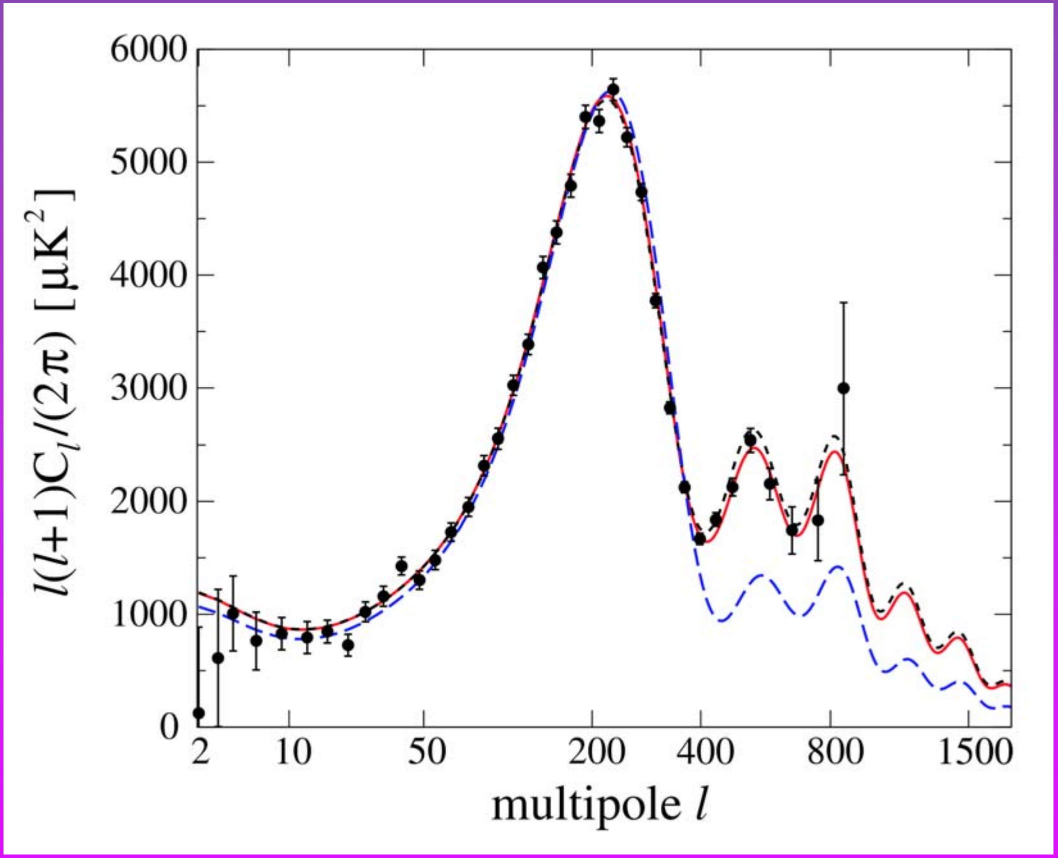


Effects on the CMB

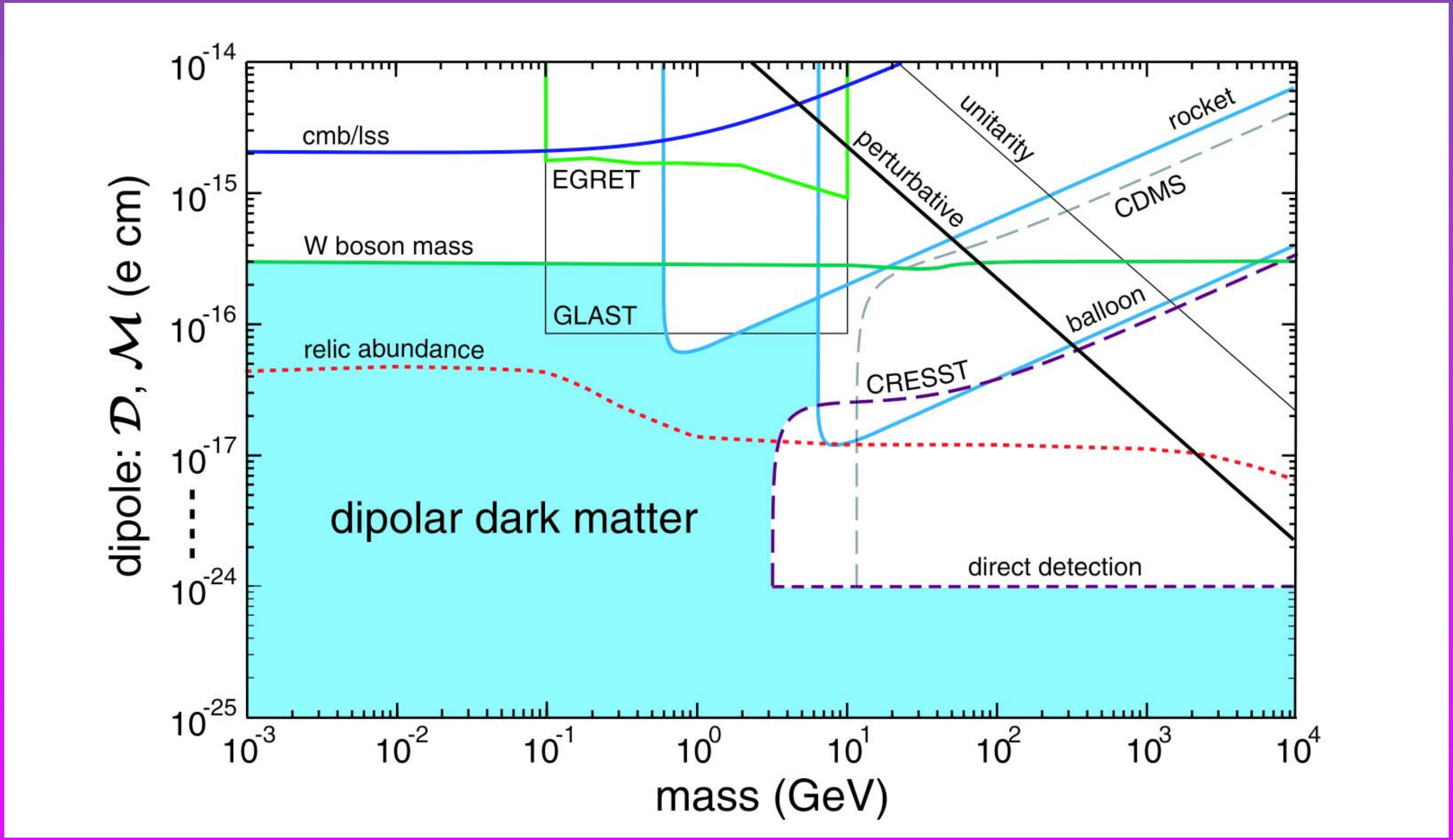
Black 1.0×10^{-16} e cm

Red 1.4×10^{-15} e cm

Blue 5.0×10^{-15} e cm

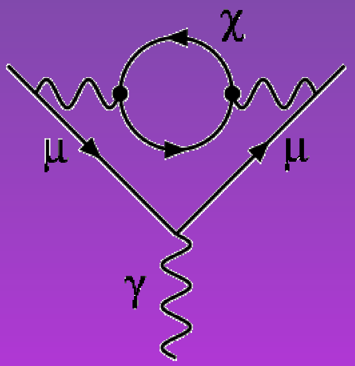


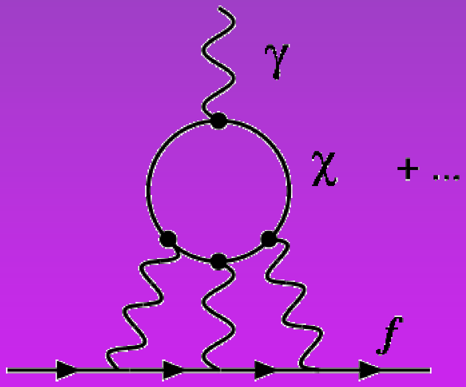
Constraints



Precision Standard Model

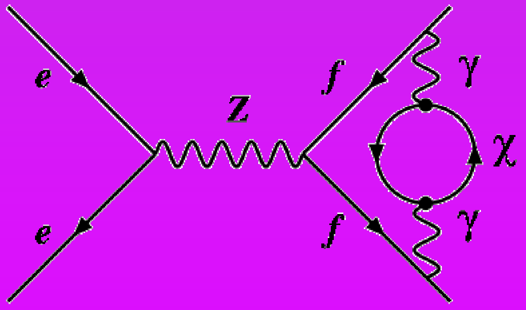
Muon g-2





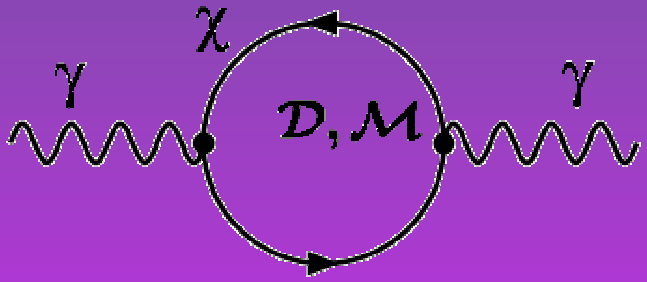
Standard Model EDMs

Z-Pole



Precision Standard Model

Strongest Constraint:

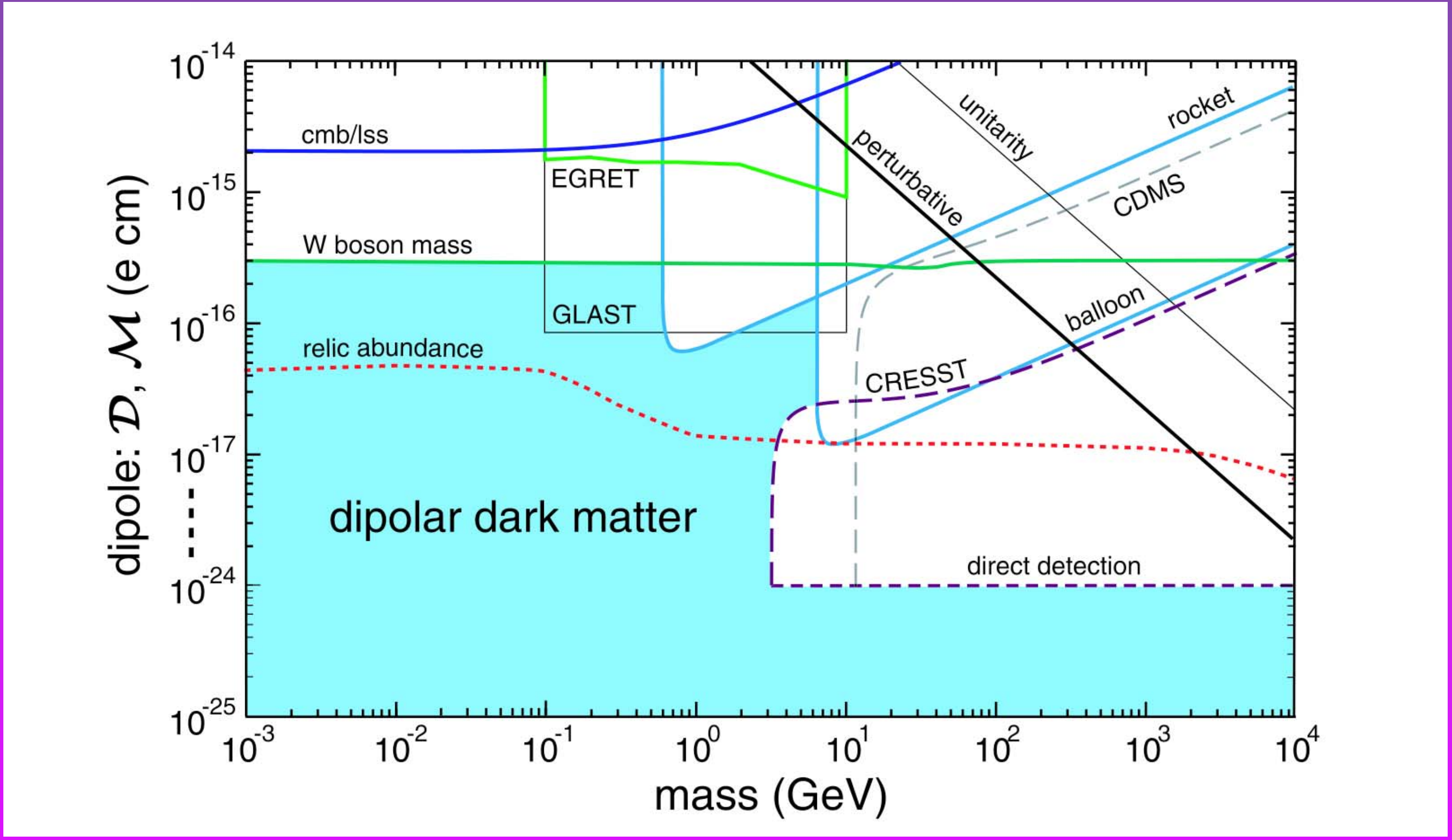


$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{(1 - m_W^2/m_Z^2)(1 - \Delta r)}$$

$$\Delta r^{SM} = 0.0355 \pm 0.0019 \pm 0.0002 \qquad \Delta r^{New} < 0.003$$

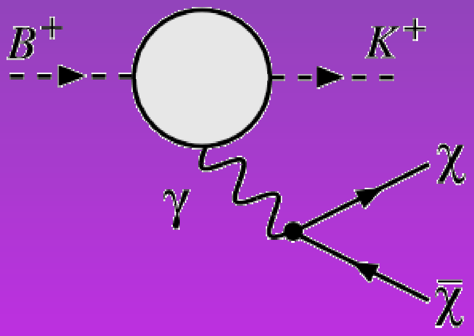
$$(\mathcal{D}^2 + \mathcal{M}^2)^{1/2} \lesssim 3 \times 10^{-16}\ e\ \mathrm{cm}$$

Constraints



Production at Accelerators

B^+ and K^+ decays:



Look for missing energy

$$\mathcal{D} \lesssim 3.8 \times 10^{-14}\ e\ \mathrm{cm}$$

LEP, Tevatron? Tricky.

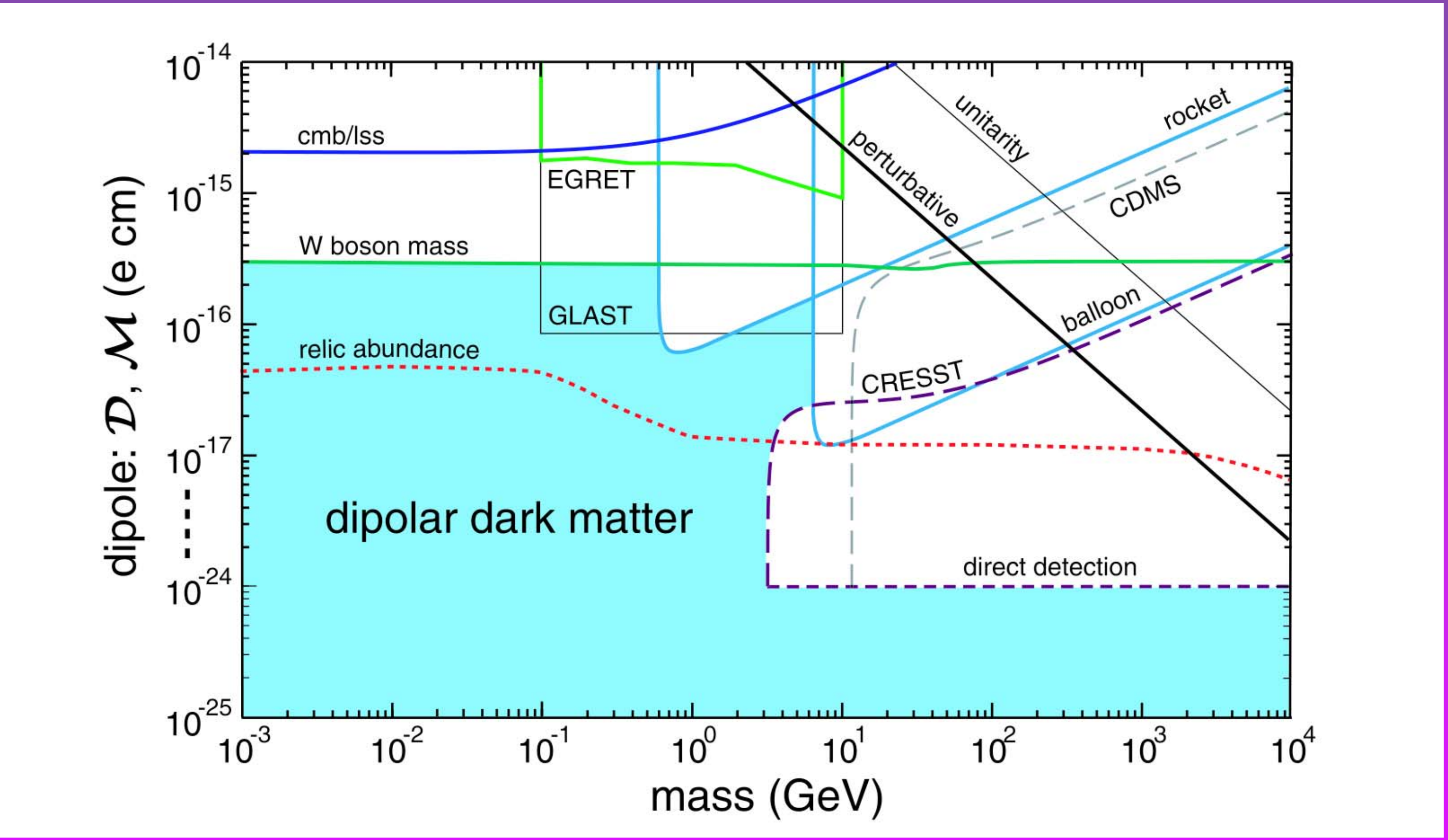
Perturbation theory breaks down when $\mathcal{D}E_{process} \gtrsim 1$

Need the full theory not the effective theory

Gamma Rays

- Annihilation at the Galactic center could produce a nearly monoenergetic line.
- EGRET Constraints
- Possible GLAST signal

Constraints



Dipolar Dark Matter?

- Dipolar Dark Matter: A phenomenologically viable dark-matter candidate with a mass between an MeV and a GeV and predominantly dipole interactions.

Particle Decays and the CMB

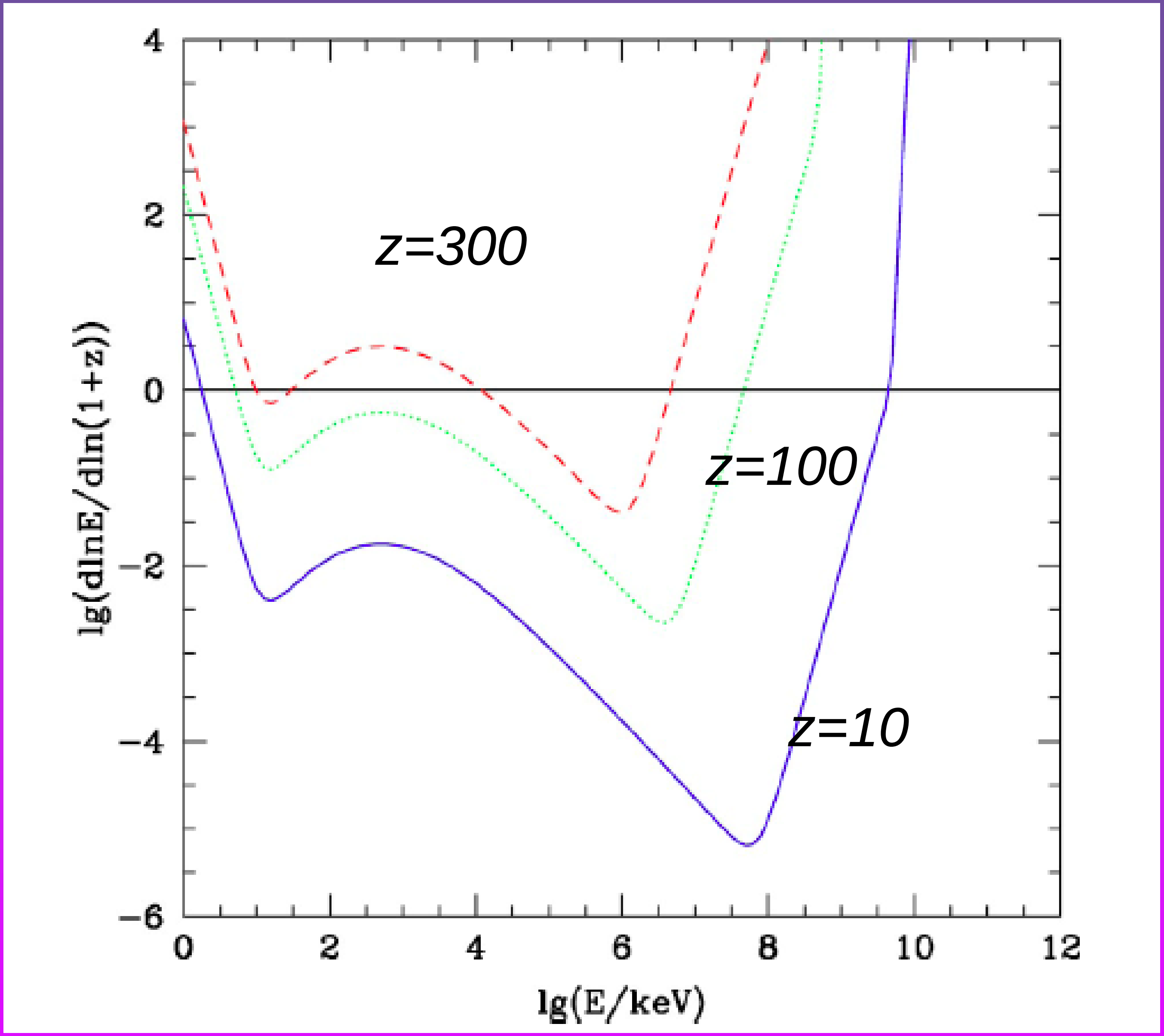
Xuelei Chen and MK, PRD 70, 043502 (2004)
also, Kasuya, Kawasaki, Sugiyama (2004)
and Pierpaoli (2004)

- Speculation: early reionization from WMAP due to decaying particles rather than early stars
- Can we constrain dark-matter decay channels and lifetimes from the CMB and elsewhere?

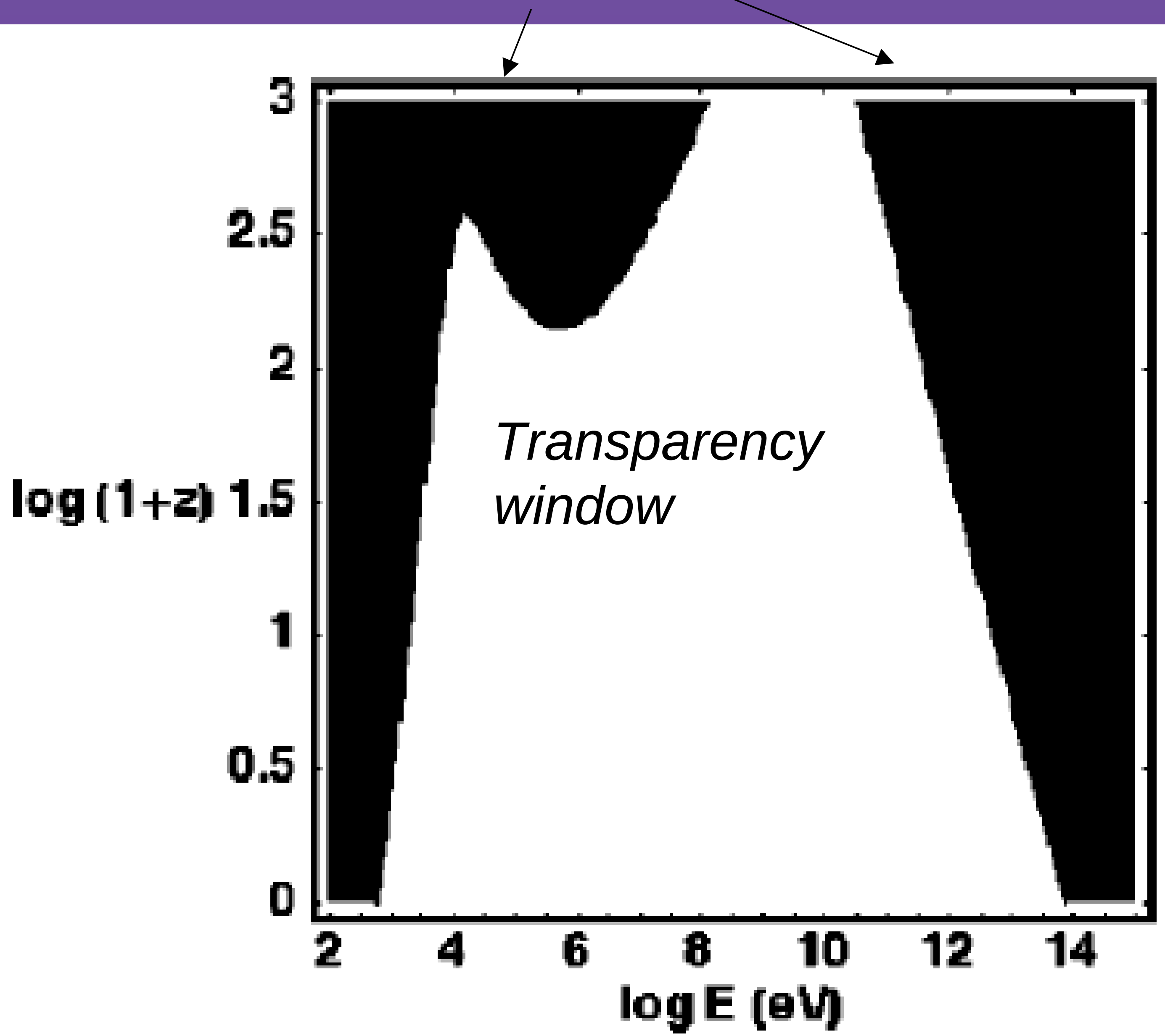
Decays to photons with E>13.6 eV

- Energy loss processes include photoionization, Compton scattering, pair production from electrons, nuclei, background photons, and scattering from background photons

Photon energy loss rate per Hubble time



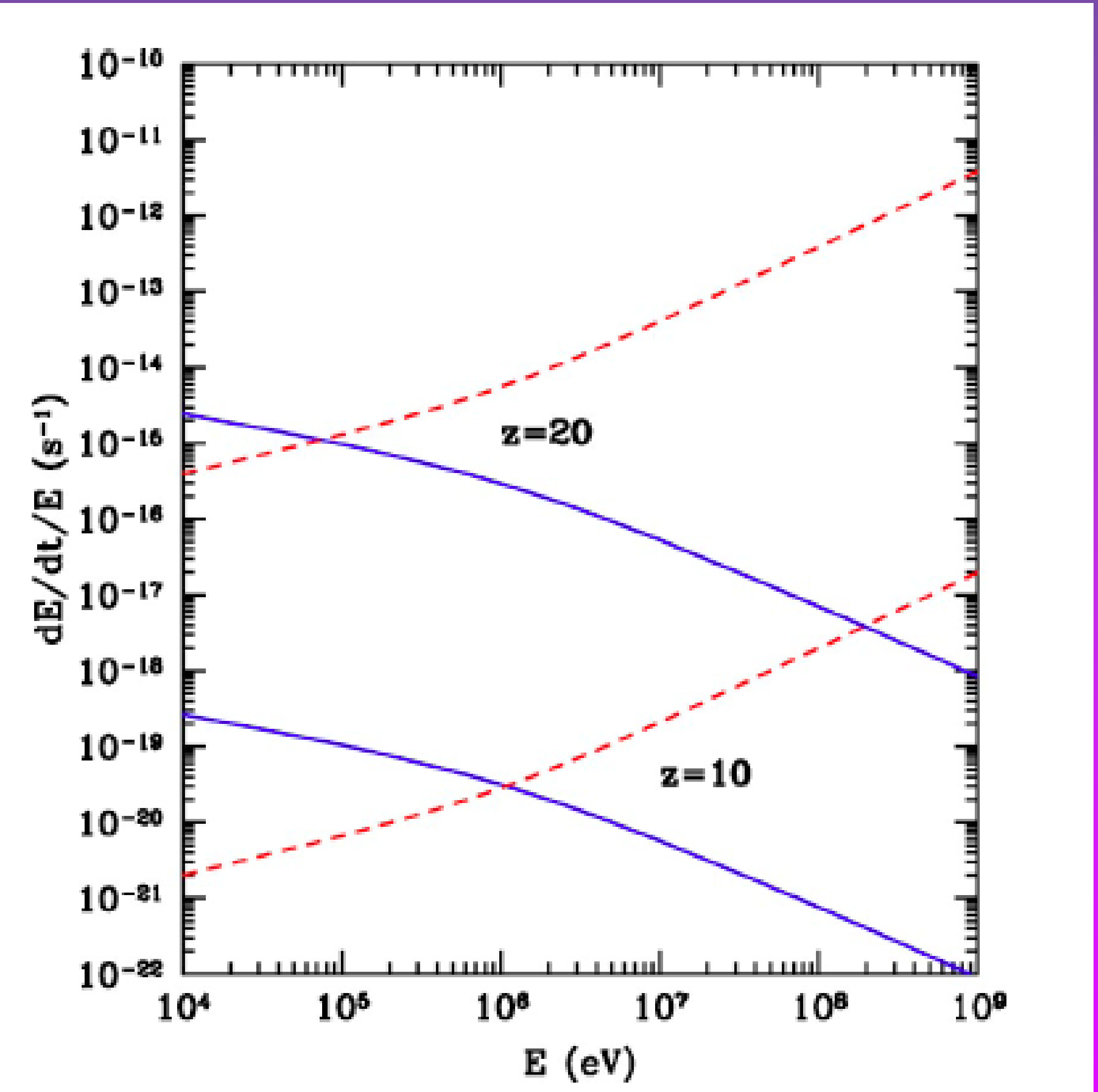
Photons absorbed by IGM



Particles decay to electrons

- Energy lost by ionization or inverse-Compton scattering CMB
- Energy generally deposited in IGM unless GeV<E<50 TeV, when upscattered CMB photon in transparency window

Electron energy-loss rate



Inverse Compton

ionization

IGM optical depth, temperature, and ionization for long-lived decaying particle

Depends only on energy-injection rate

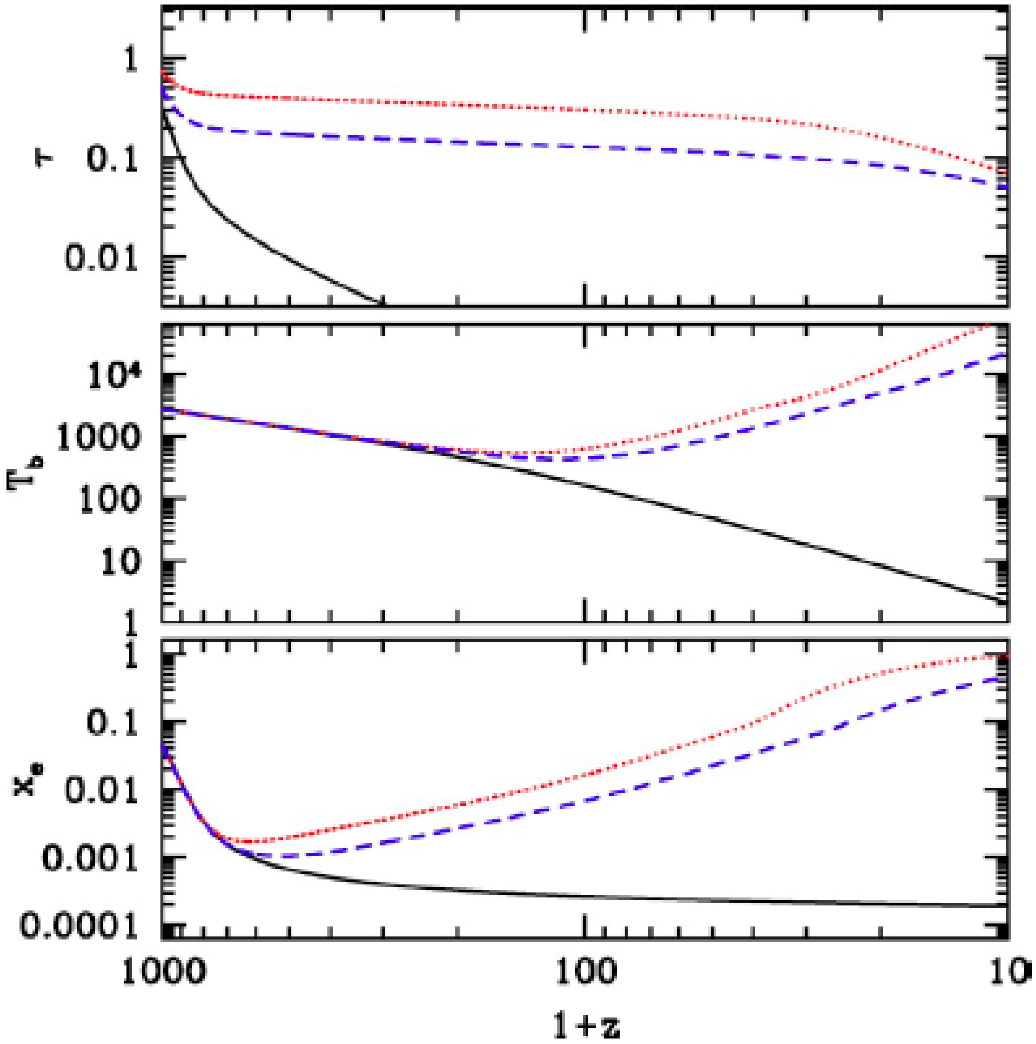


FIG. 4. The optical depth, IGM temperature, and ionization fraction as a function of redshift for standard recombination with no reionization (black solid line) and a decaying-particle model with two-particle decay with $\Gamma_X \ll H_0$ and $\xi \equiv \chi_i f_X \Gamma = 2.4 \times 10^{-23}$ s^{-1}, $\tau = 0.4$ (red dotted line), and 0.6×10^{-23} s^{-1}, $\tau = 0.17$ (blue dashed line).

Ionization induced by particle decays ionizes IGM and affects CMB power spectra

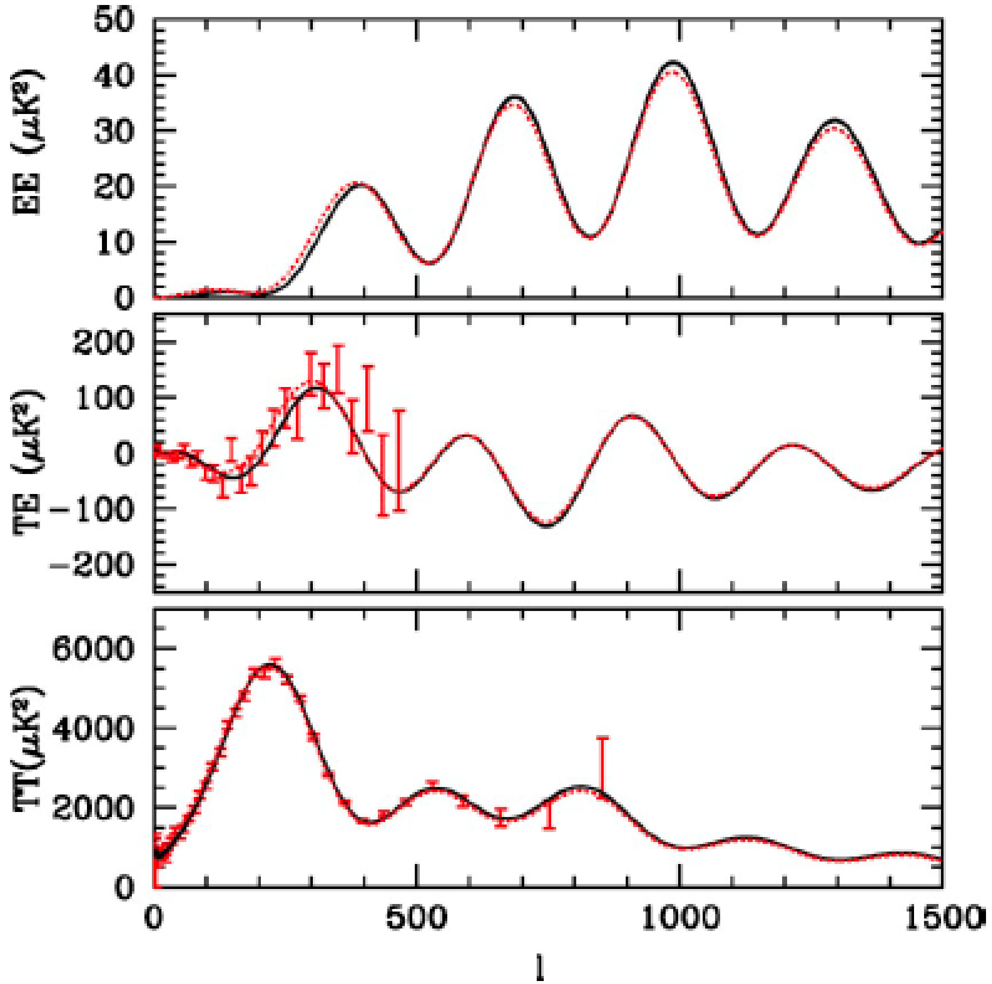


FIG. 5. The CMB temperature and polarization power spectrum $l(l+1)C_l/(2\pi)$ for decaying particles with lifetimes greater than the age of the Universe. The data points with error bars are the binned data given by the WMAP team [44]. No particle decay (black solid line); long-lived particle decay with $\xi = 2.4 \times 10^{-23}\ s^{-1}$, red dotted line; and $0.6 \times 10^{-23}\ s^{-1}$, (blue dashed line).

again for l<100

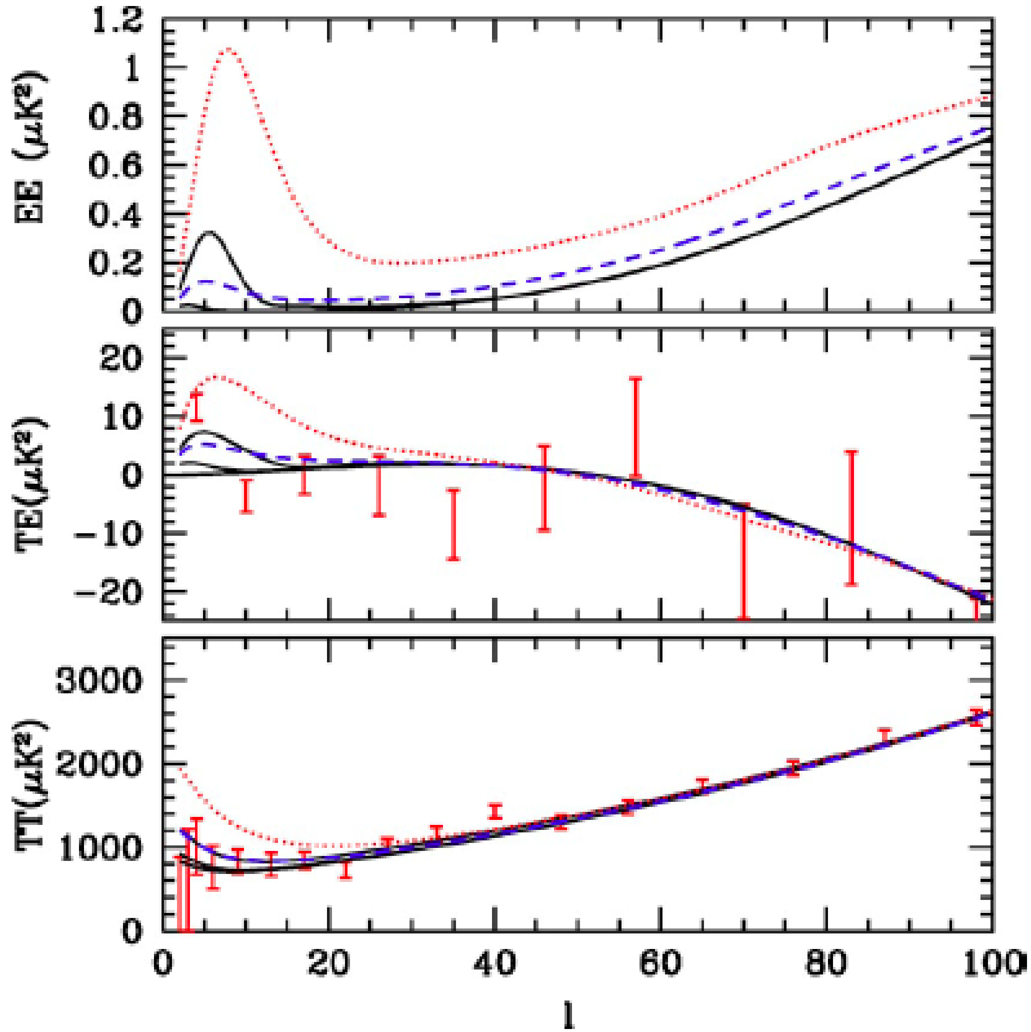


FIG. 6. Same as the previous figure, but for $l<100$: $\xi=2.4 \times 10^{-23}\ s^{-1}$ (red dotted line) and $0.6\times 10^{-23}\ s^{-1}$ (blue dashed line). We also plotted three curves for the no-particle-decay case (black solid line) which are almost indistinguishable except for the TE polarization; from top to bottom they are $\tau=0.17$, step-function reionization at $z<7$, and no reionization.

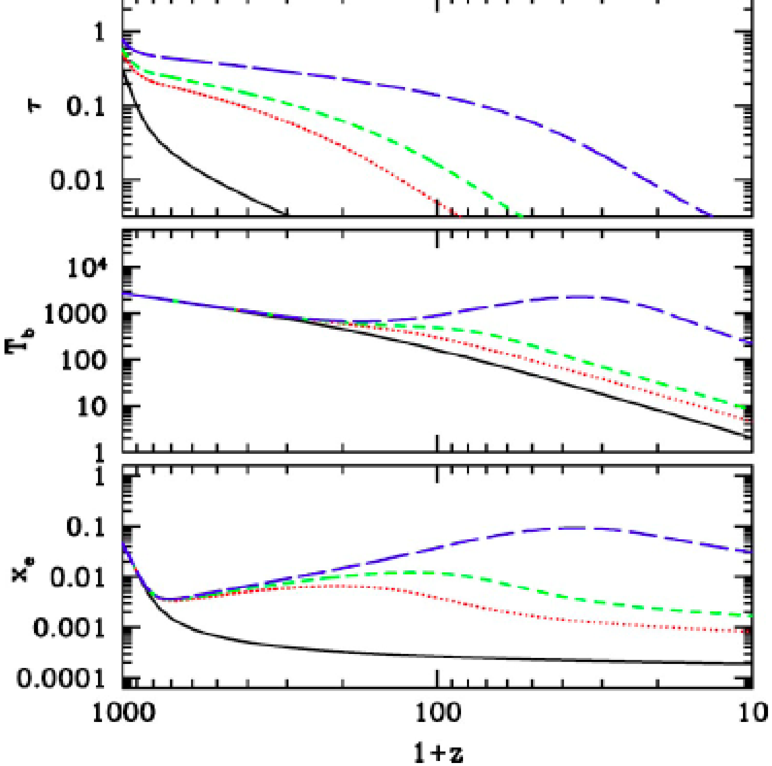


FIG. 7. The optical depth, IGM temperature, and ionization fraction for the standard no-reionization model (black solid line) and particle-decay-only models, all with $\chi=0.3$, and $\Gamma_X=10^{-14}\ \mathrm{s}^{-1}$, $f_X(z_{\mathrm{eq}})=0.5\times10^{-8}$ (red dotted line); $\Gamma_X=0.5\times10^{-14}\ \mathrm{s}^{-1}$, $f_X(z_{\mathrm{eq}})=10^{-8}$ (green short dashed line); and $\Gamma_X=10^{-15}\ \mathrm{s}^{-1}$, $f_X(z_{\mathrm{eq}})=5\times10^{-8}$ (blue long dashed line).

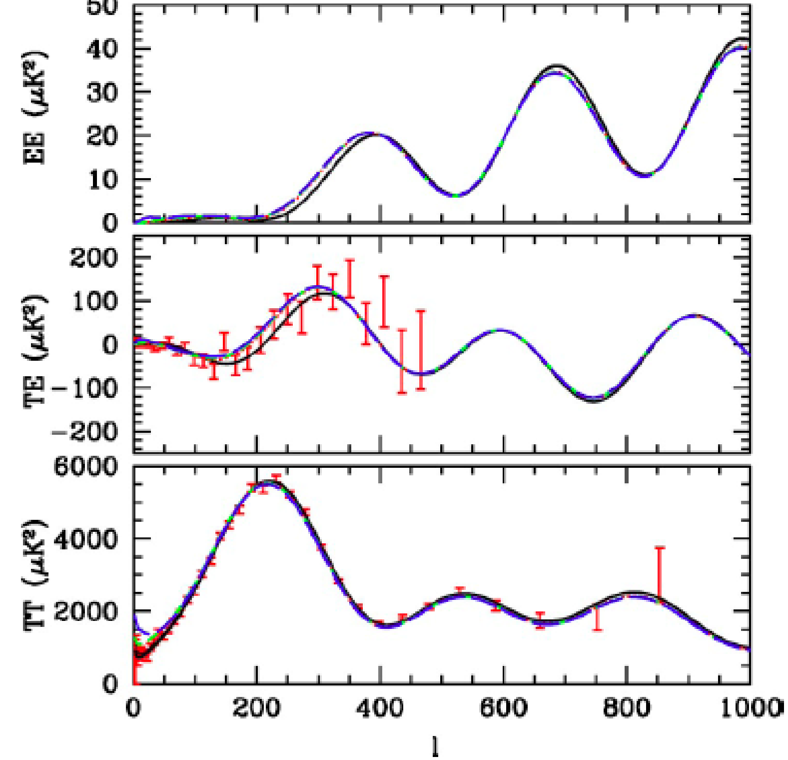


FIG. 8. The CMB temperature and polarization power spectrum. Same models as the previous figure.

redshift and then starts to decrease again. The peak position depends on the lifetime. The models plotted in Fig. 7 have $\Gamma_X^{-1}=10^{14}$ s, 2×10^{15} s, and 10^{15} s, which correspond to the

And for short-lived particles; now depends on energy-injection rate and lifetime.

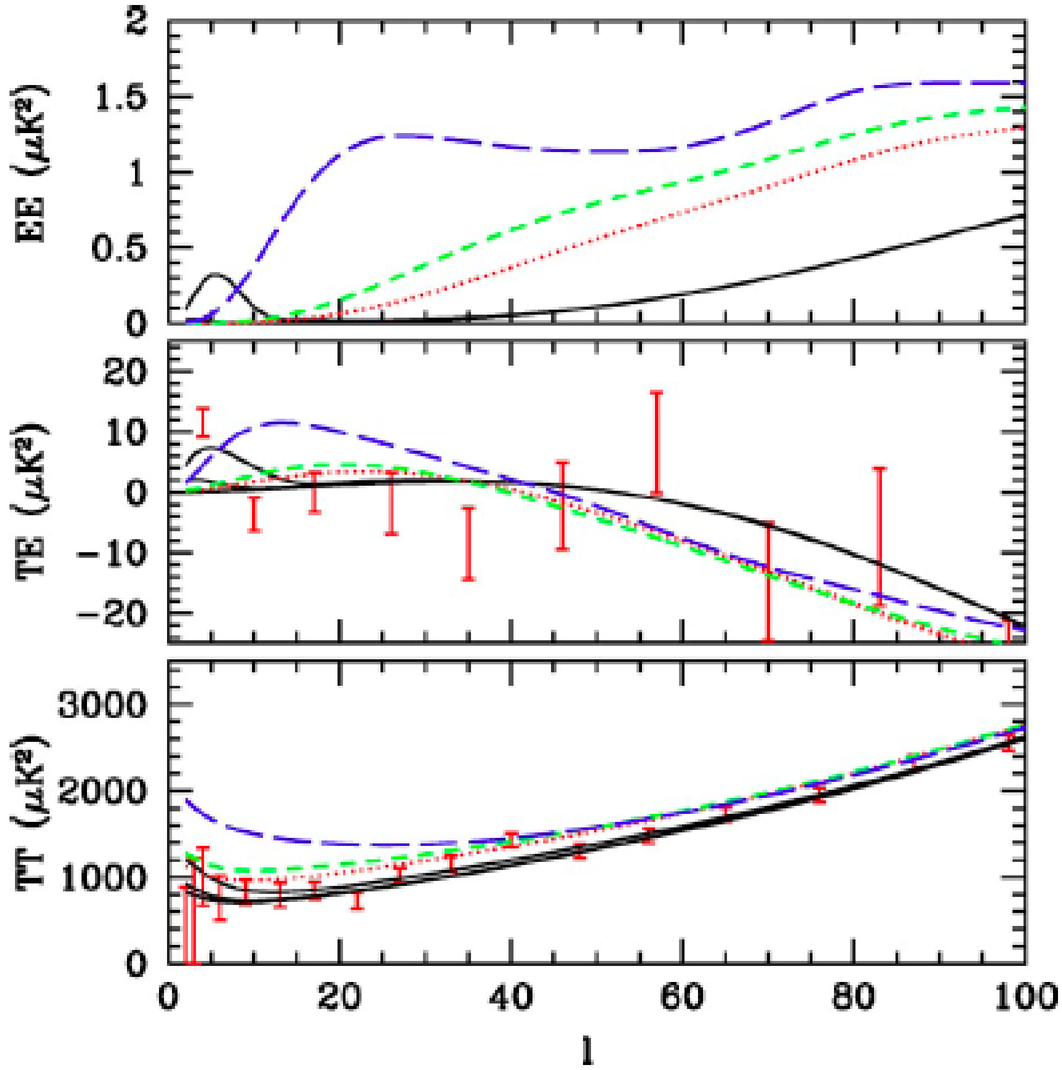


FIG. 9. Low-l CMB temperature and polarization power spectrum. Same models as Fig. 8. The three black solid lines (almost indistinguishable except for the TE polarization) are, from top to bottom, for $\tau = 0.17$, step function reionization at $z < 7$, and no reionization.

Constraints from CMB to decays where energy absorbed in IGM

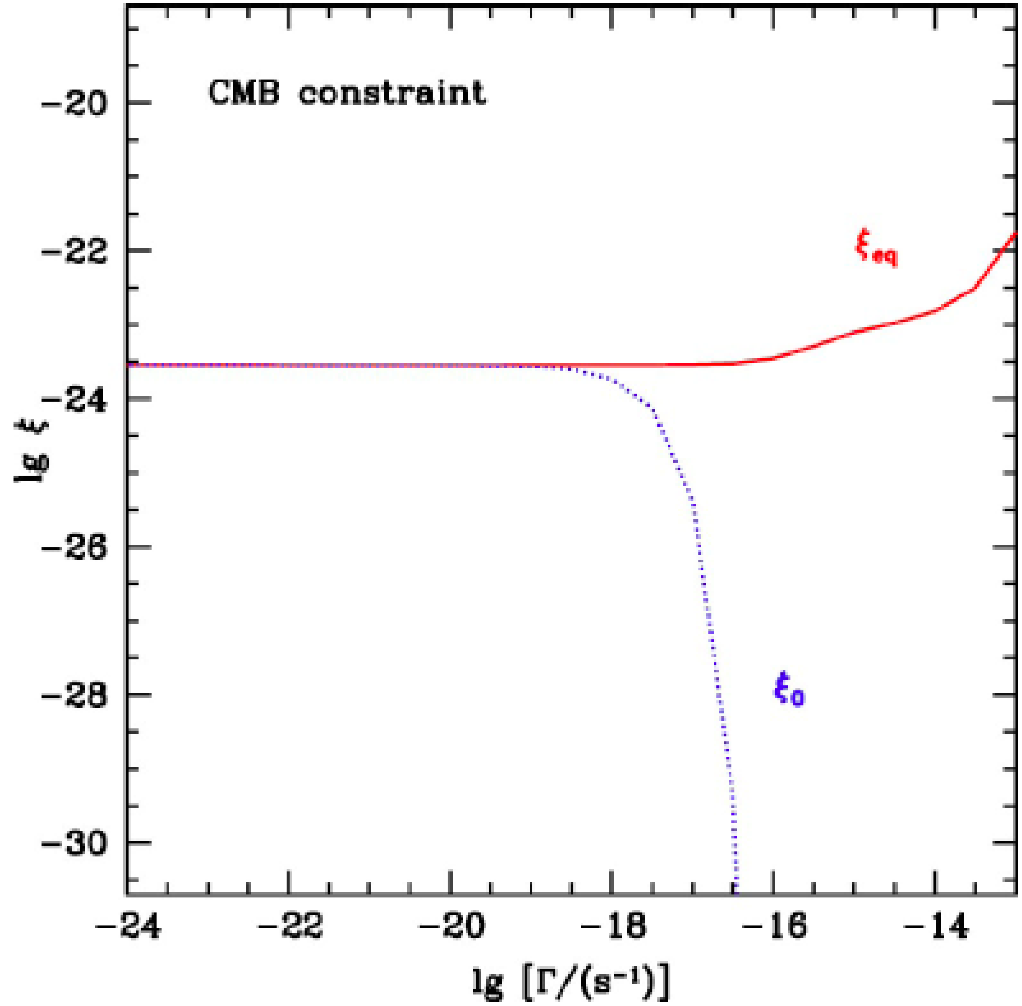


FIG. 12. WMAP 1σ constraints on decaying particles. Plotted are $\xi \equiv \chi f_X \Gamma_X$, where $f_X = \Omega_X / \Omega_b$. The red solid curve shows constraint on the value at matter radiation equality ξ_{eq}; the blue dotted curve shows constraint on the value today ξ_0. Note that the WMAP constraint applies if the injected photon or electron energy does not fall in the transparency windows shown in Fig. 2 and Sec. II.

Constraints from diffuse backgrounds for decays in transparency window

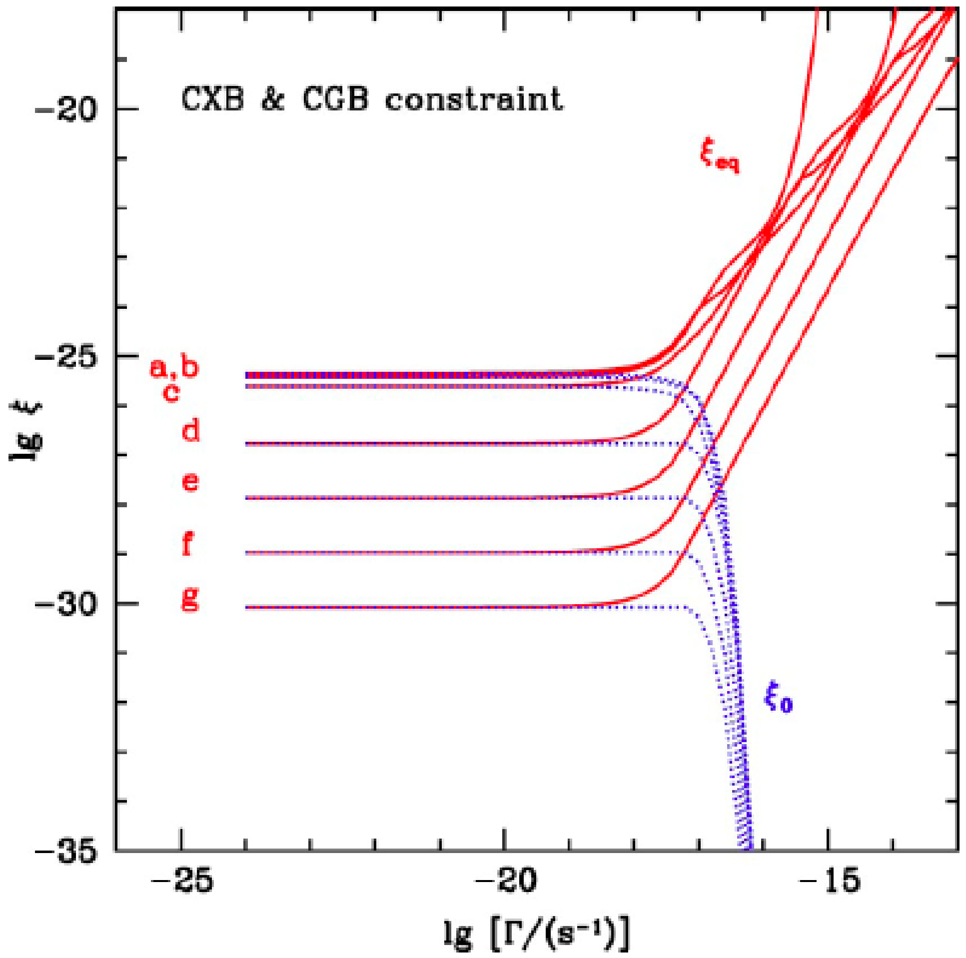
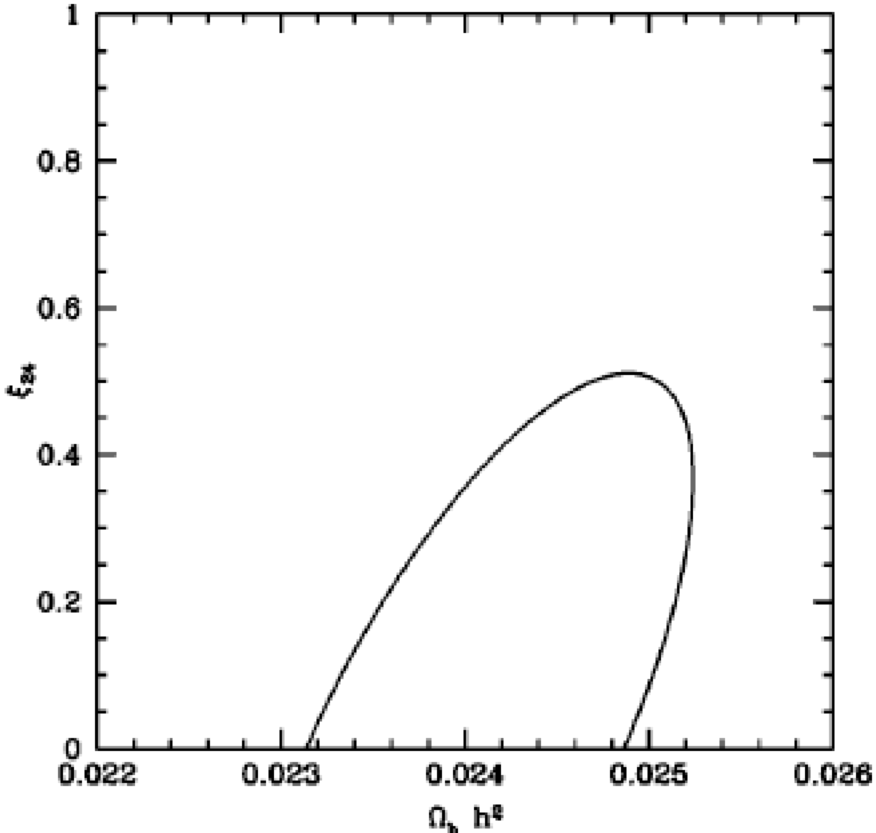


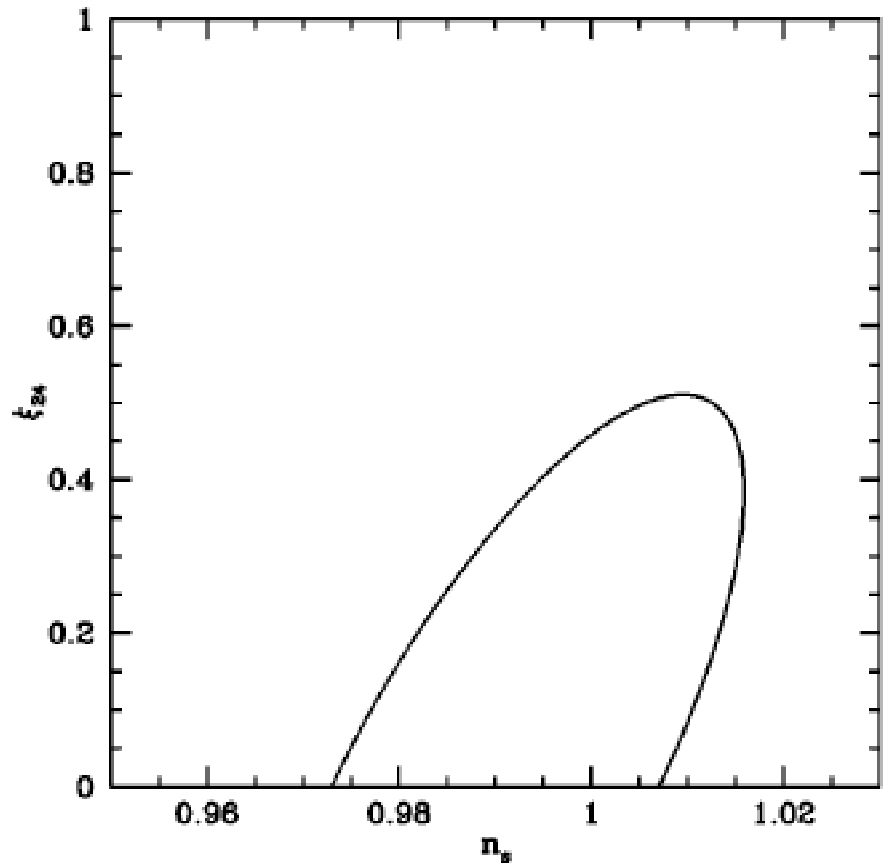
FIG. 13. Constraint of ξ based on diffuse x-ray and γ-ray background. The red solid curve shows constraint on the value at matter radiation equality ξ_{eq}; the blue dotted curve shows constraint on the value today ξ_0. The curves are for photon energy (a) 100 keV, (b) 1 MeV, (c) 10 MeV, (d) 100 MeV, (e) 1 GeV, (f) 10 GeV, (g) 100 GeV. Note that the x-ray and γ-ray constraints do not apply for photon and electron injection energies that fall outside the transparency windows.

Covariance with cosmological parameters



Baryon density

Spectral index



Summary

- Self-interacting dark matter more tightly constrained than one might have thought
- dark matter from charged-particle decay may account for dwarf-galaxy dearth
- Or mimic running of spectral index
- Couplings to photons tightly constrained
- CMB provides new constraints to dark-matter decays for decay products that heat IGM rather than propagate undisturbed