Joint ILIAS-CAST-CERN Axion Training

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PHOTON-AXION CONVERSION AS A MECHANISM FOR SUPERNOVA DIMMING: LIMITS FROM CMB SPECTRAL DISTORTION

Alessandro MIRIZZI

Dip.to di Fisica and Sez. INFN, BARI (Italy)

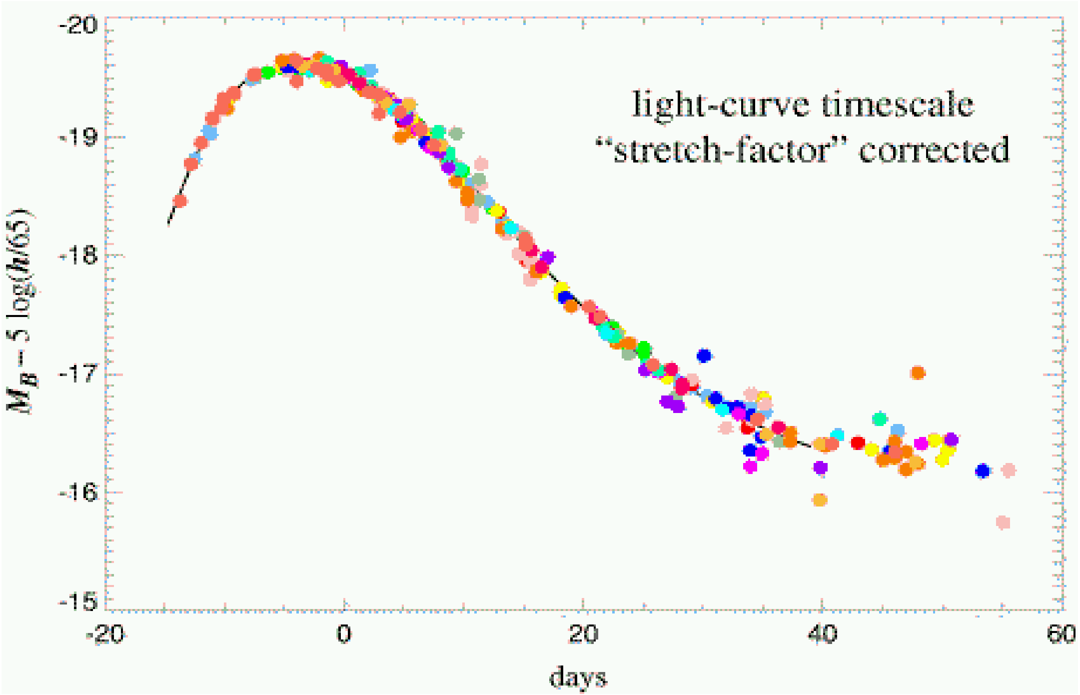
Based on: A.M., G.G. Raffelt, and P.D. Serpico, PRD 72, 023501 (2005).

[astro-ph/0506078]

OUTLINE

- **SNe Ia dimming**
- **Dark energy and cosmic acceleration**
- **Photon-axion conversion**
- **Achromaticity constraints**
- **QSO constraints**
- **CMB constraints**
- **Conclusions**

SUPERNOVAE IA



(Calal/Tololo Sample, Kim et al. 1997)

A SN Ia is the thermonuclear explosion of a carbon-oxigen white dwarf in a binary when the rate of mass transfer from the companion star is high.

SNe IA as cosmological standard candles.

The peak-luminosity of SNe IA can be used as an efficient distance indicator.

LUMINOSITY DISTANCE

Distance estimates from SNe Ia light curves are derived from the luminosity distance

$$d_L = \left(\frac{L}{4\pi F} \right)^{1/2}$$

- *L* intrinsic luminosity
- *F* observed flux

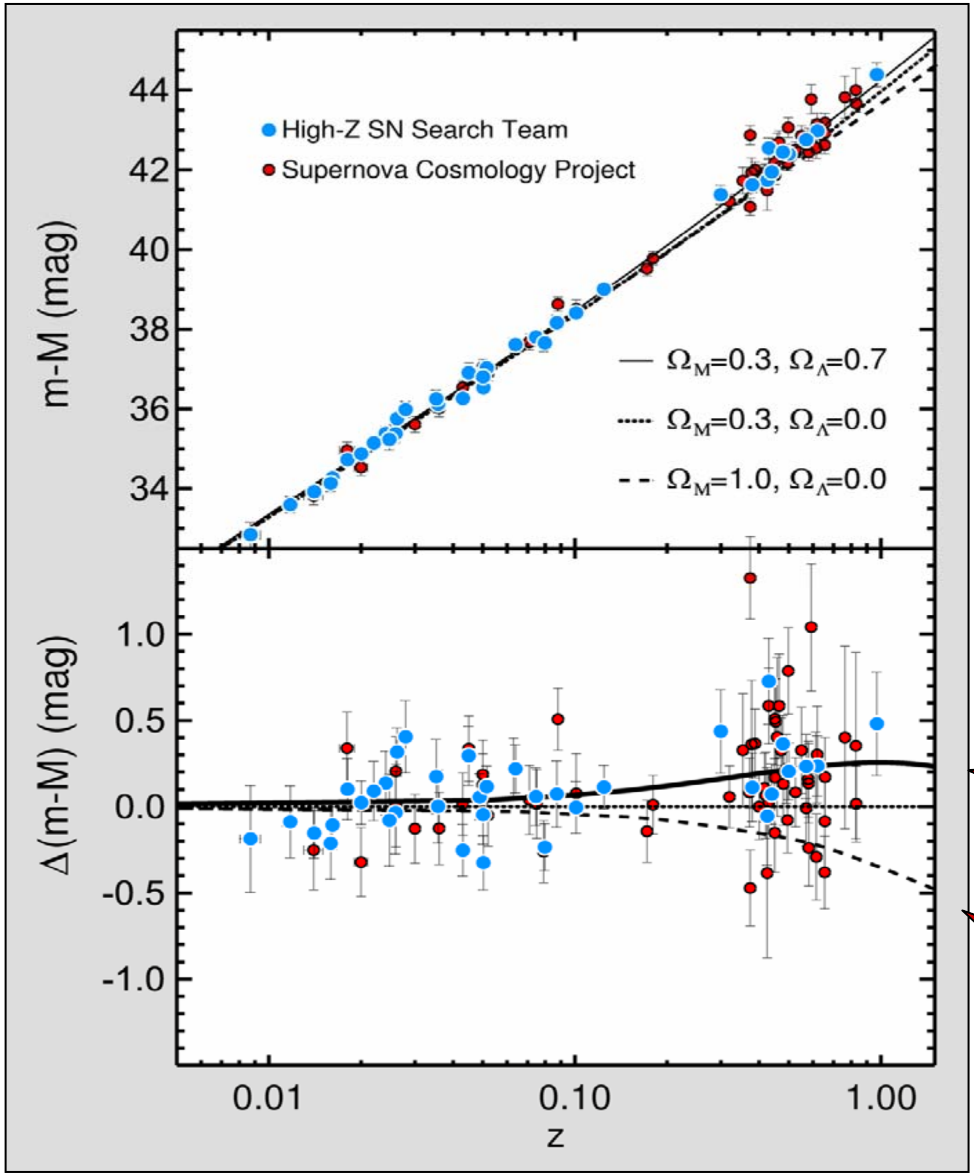
It depends on the cosmological parameters

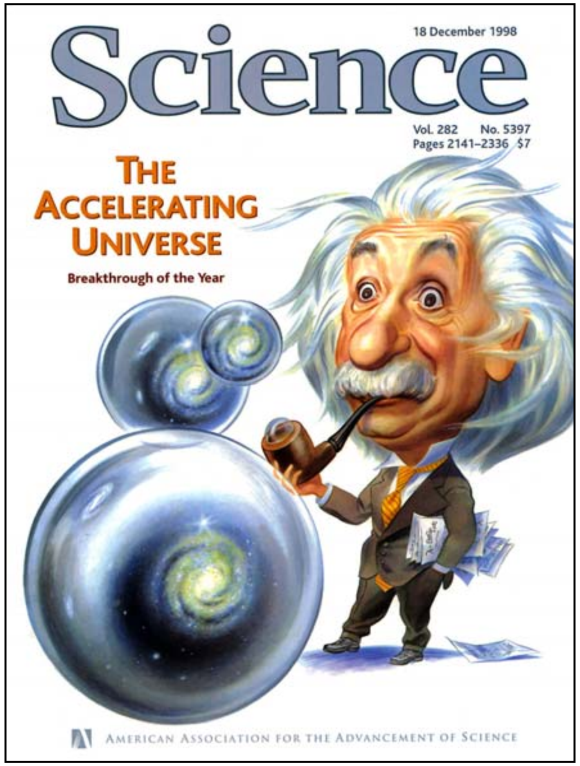
The luminosity distance is often expressed in terms of the **magnitude**

$$m = M + 5 \log_{10} \left(\frac{d_L}{Mpc} \right) + 25$$

M is the absolute magnitude (value at 10 pc)

HUBBLE DIAGRAM





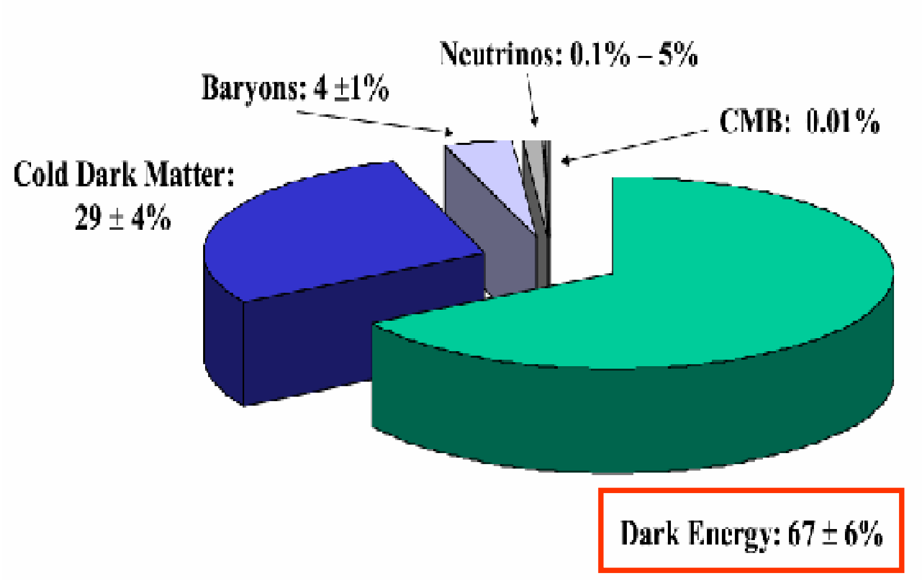
Accelerated expansion (Ω_M = 0.3, Ω_Λ = 0.7)

Decelerated expansion (Ω_M = 1)

SNe Ia at 0.3 ≲ z ≲ 1.7 appear fainter than expected for a decelerating Universe

MATTER AND ENERGY IN THE UNIVERSE: A STRANGE RECIPE

SNe Ia data interpreted as a consequence of a cosmic acceleration due to a cosmological constant Λ. In a flat Universe [Ω=1] $\Omega_\Lambda \approx 0.7$ and $\Omega_m \approx 0.3$.



The condition for acceleration is $w \equiv \frac{p}{\rho} < -\frac{1}{3}$ **Equation of state**

The pure **cosmological constant** case, where the density is a pure vacuum density, corresponds to **w=-1**

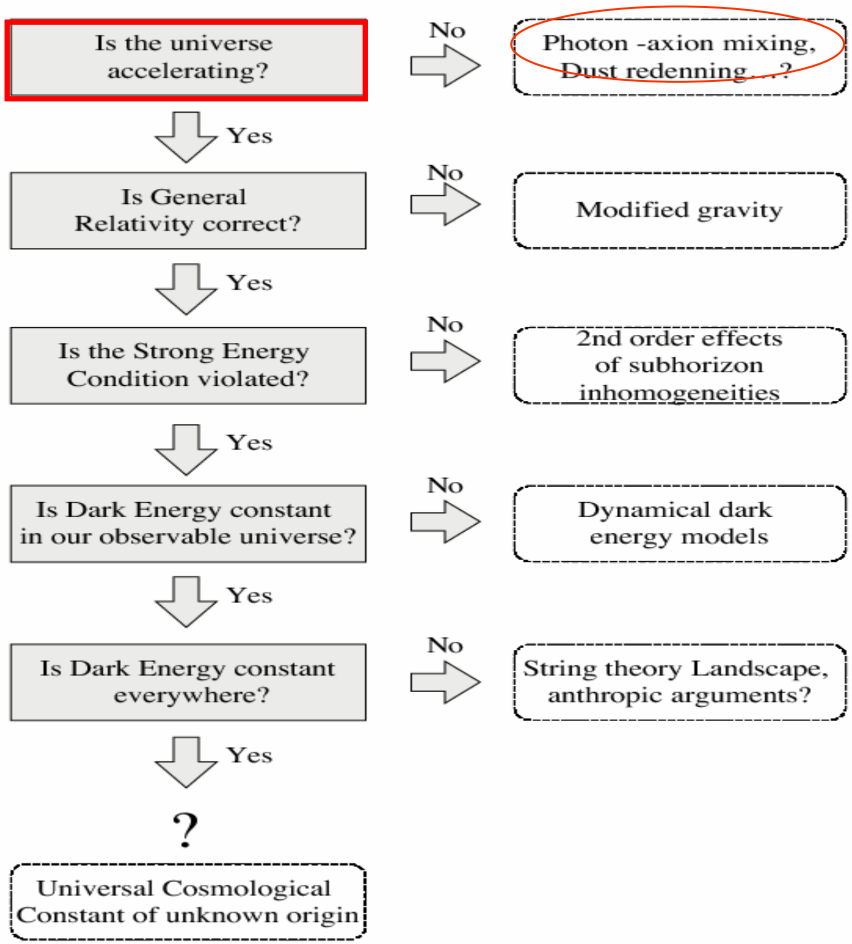
IS THERE REALLY DARK ENERGY?

The nature of Dark Energy is still very much a mystery.

e.g. if we have a cosmological constant $\rho_\Lambda \approx 10^{-12}$ eV^4 → What is the physics associated to such a small scale?

Wide-ranging theoretical investigations of alternative scenarios

Photon-axion mixing into intergalactic magnetic field dims SN photon flux



R. Bean, S. Carroll, M. Trodden, astro-ph/0510059

PHOTON-AXION MIXING AND SN DIMMING/ SOME REFERENCES

- C. Csaki, N. Kaloper, and J. Terning, PRL **88**, 161302 (2002).
- C. Deffayet, D. Harari, J.P. Uzan, and M. Zaldarriaga, PRD **66**, 043517 (2002).
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- E. Mortsell and A. Goobar, JCAP **0304**, 003 (2003).
- B.A. Bassett, ApJ **607**, 661 (2004).
- B.A. Bassett, and M. Kunz, PRD **69**, 101305 (2004).
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- L. Ostman and E. Mortsell, JCAP **0502**, 005 (2005).

[….]

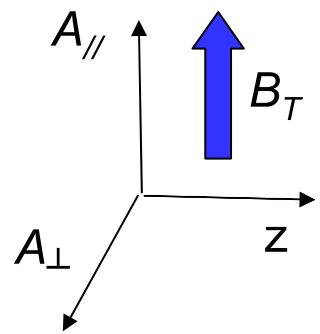
PHOTON-AXION MIXING

Axions and photons oscillate into each other in an external magnetic field due to the interaction term

$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \vec{E} \cdot \vec{B} a$$

For propagation in the z-direction and very relativistic axions, one obtains a "Schrödinger equation"

$$\left[\omega + \begin{pmatrix} \Delta_\perp & \Delta_R & 0 \\ \Delta_R & \Delta_\parallel & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix} - i\partial_z \right] \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0$$



If one ignores a possible Faraday rotation effect (Δ_R=0), $A_\perp$ decouples, and the lower part represents a 2 × 2 mixing problem

$$\left[\omega + \begin{pmatrix} \Delta_{pl} & \Delta_{a\gamma} \\ \Delta_{a\gamma} & \Delta_{a} \end{pmatrix} - i\partial_z \right] \begin{pmatrix} A_{\parallel} \\ a \end{pmatrix} = 0$$

Photon-axion mixing

where

- $\Delta_{pl} = -\frac{\omega_{pl}^2}{2\omega}$; $\omega_{pl}^2 = \frac{4\pi\alpha n_e}{m_e}$ **plasma frequency**
- $\Delta_{a\gamma} = \frac{g_{a\gamma}|B_T|}{2}$
- $\Delta_a = -\frac{m_a^2}{2\omega}$

The solution follows from the diagonalization through the rotation angle

$$\vartheta = \frac{1}{2}\arctan\left(\frac{2\Delta_{a\gamma}}{\Delta_{pl} - \Delta_a}\right)$$

PHOTON-AXION CONVERSION PROBABILITY

The probability for a photon emitted in a state $A_{\square}$ to convert into an axion after travelling a distance ***s*** is given by

$$P_0\left(\gamma \rightarrow a\right) = \left|\left\langle A_{\square}(0) \middle| a(s)\right\rangle\right|^2 = \sin^2(2\vartheta)\ \sin^2(\Delta_{osc} s/2)$$

$$= \left(\Delta_{a\gamma} s\right)^2 \frac{\sin^2(\Delta_{osc} s/2)}{(\Delta_{osc} s/2)^2}$$

with

$$\Delta_{osc} = \sqrt{\left(\Delta_{pl} - \Delta_a\right)^2 + 4\Delta_{a\gamma}^2}$$

oscillation wavenumber

- After the propagation over many random *B*-field domains (*r* » *s*, with *s* the domain size) one obtains an inchoerent average over magnetic field configurations and photon polarization states

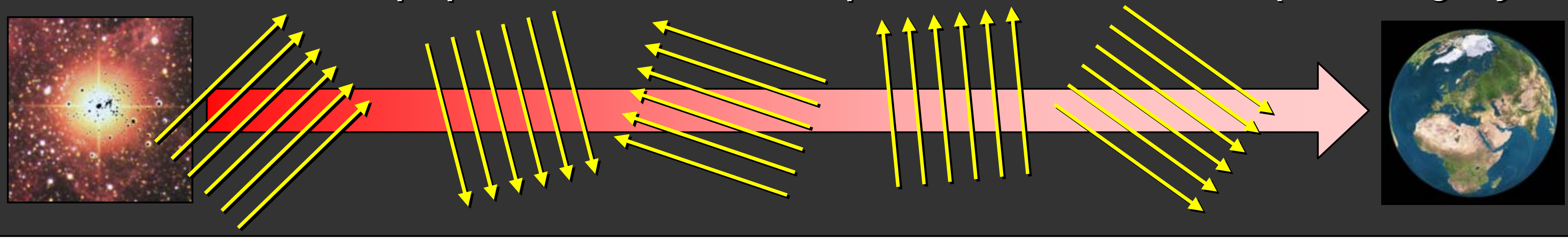
$$P_{\gamma \rightarrow a}(r) = \frac{1}{3}\left[1 - \exp\left(-\frac{3P_0 r}{2s}\right)\right]$$

random B

For r/s $\rightarrow \infty$ the conversion probability saturates to 1/3.

DIMMING OF SUPERNOVAE WITHOUT COSMIC ACCELERATION

Axion-photon-oscillations in intergalactic B-field domains dim photon flux
- Effect grows linearly with distance
- Saturates at equipartition between photons and axions (unlike grey dust)



TYPICAL VALUES

- Path length: $r \sim H_0^{-1} \sim 10^3$ Mpc
- Domain size: $s \sim 1$ Mpc
- Field strength: $B \sim 1$ nG
- a-γ coupling: $g_{a\gamma} \sim 10^{-10}$ GeV^{-1}
- Plasma density: $n_e \lesssim 10^{-7}$ cm^{-3}
- Photon energy: $\omega \sim 1$ eV
- Axion mass: $m_a < 10^{-16}$ eV

$$\frac{\Delta_{a\gamma}}{Mpc^{-1}} = 0.15 g_{10} B_{ng}$$

$$\frac{\Delta_a}{Mpc^{-1}} = -7.7\times10^{28}\left(\frac{m_a}{1\,eV}\right)^2\left(\frac{\omega}{1\,eV}\right)^{-1}$$

$$\frac{\Delta_{pl}}{Mpc^{-1}} = -11.1\left(\frac{\omega}{1\,eV}\right)^{-1}\left(\frac{n_e}{10^{-7}\,cm^{-3}}\right)$$

After a distance ***r***, photon-axion conversion has reduced the number of photons emitted by the source and thus the flux ***F*** to the fraction

$$P_{\gamma\to\gamma} = 1 - P_{\gamma\to a}$$

Therefore, the luminosity distance becomes

$$d_L \to d_L / (P_{\gamma\to\gamma})^{1/2}$$

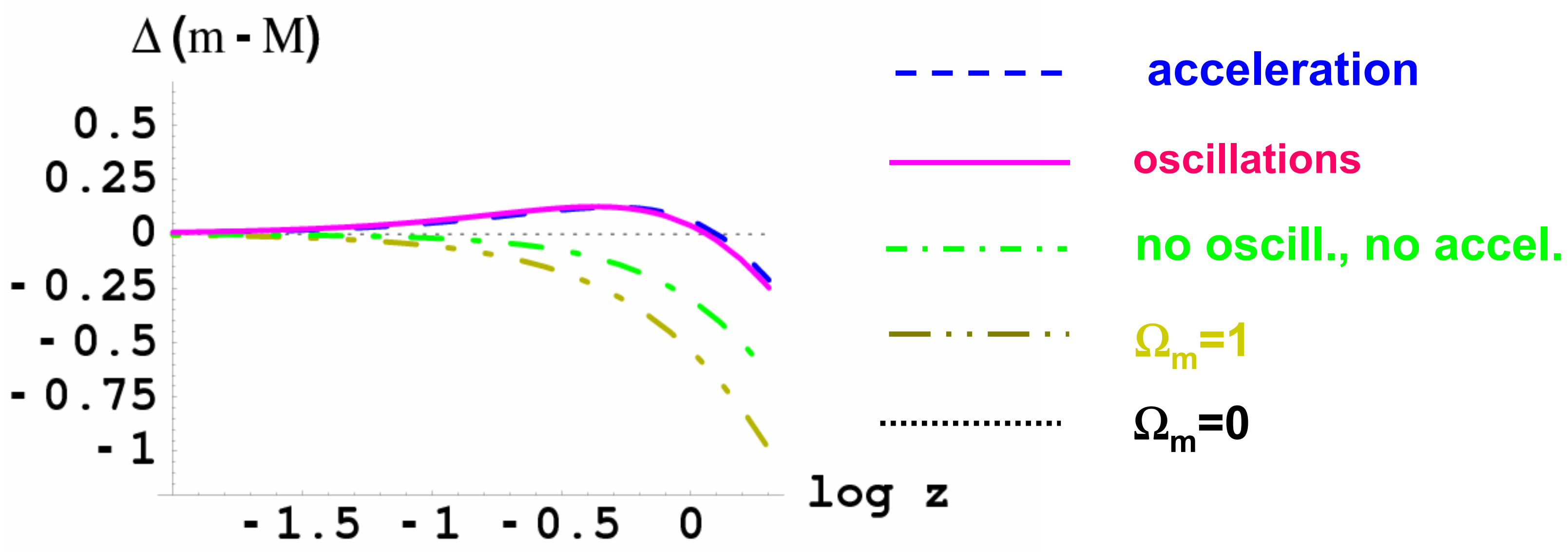
and the magnitude

$$m \to m - \frac{5}{2}\log_{10}\left(P_{\gamma\to\gamma}\right)$$

Distant SNe Ia would eventually saturate ($P_{\gamma\to\gamma}$=2/3), and hence appear $(3/2)^{1/2}$ times further away than they really are. This corresponds to a maximum dimming ~ 0.4 mag.

● CKT I

[*C. Csaki, N. Kaloper, and J. Terning, " Dimming Supernovae without Cosmic Acceleration," PRL* ***88****, 161302 (2002).*]



Oscillation model in CKT I:

Ω_m=0.3 ; Ω_s=0.7 → **NO COSMOLOGICAL ACCELERATION**

w=p/ρ=-1/3

BUT: They neglect plasma density effects (Δ_{pl}=0)

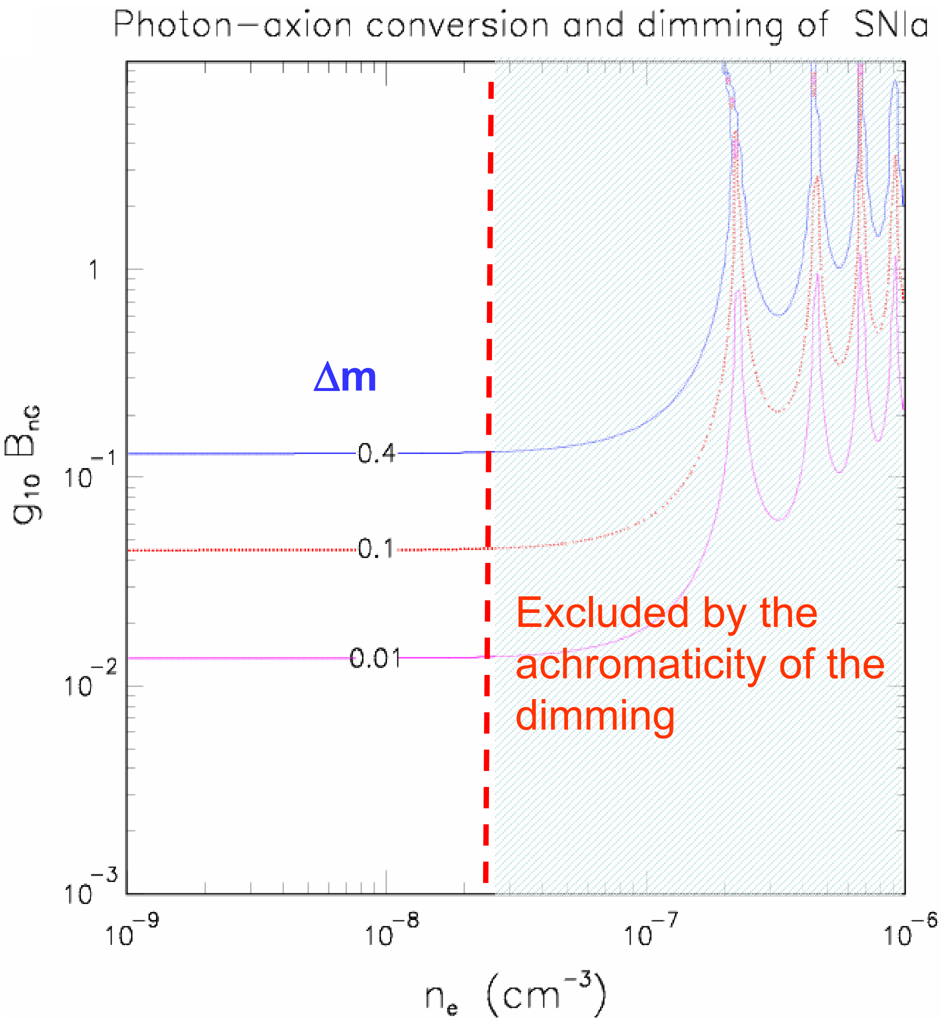
$$\vartheta = -\frac{1}{2} arctg(-2\frac{\Delta_{a\gamma}}{\Delta_a}) \simeq -\frac{1}{2} arctg(40\frac{\omega}{1eV}) \simeq \frac{\pi}{4}$$

$$\Delta_{osc} \simeq 2\Delta_{a\gamma}$$

The oscillation is achromatic

- **CKT II**

[*C. Csaki, N. Kaloper, and J. Terning, "Effects of the intergalactic plasma on supernova dimming via photon axion oscillations," PLB* ***535****, 33 (2002).*]



When $\Delta_{pl} \neq 0$, chromaticity depends sensitively on assumed values and distribution of the plasma density n_e and B [*C. Deffayet, D. Harari, J.P. Uzan, and M. Zaldarriaga, PRD* ***66****, 043517 (2002).*]

CKT II: Any value of $n_e \lesssim 2.5 \times 10^{-8}\ cm^{-3}$ garantees the required achromaticity of the dimming ($\lesssim$ 3% level between B and V bands)

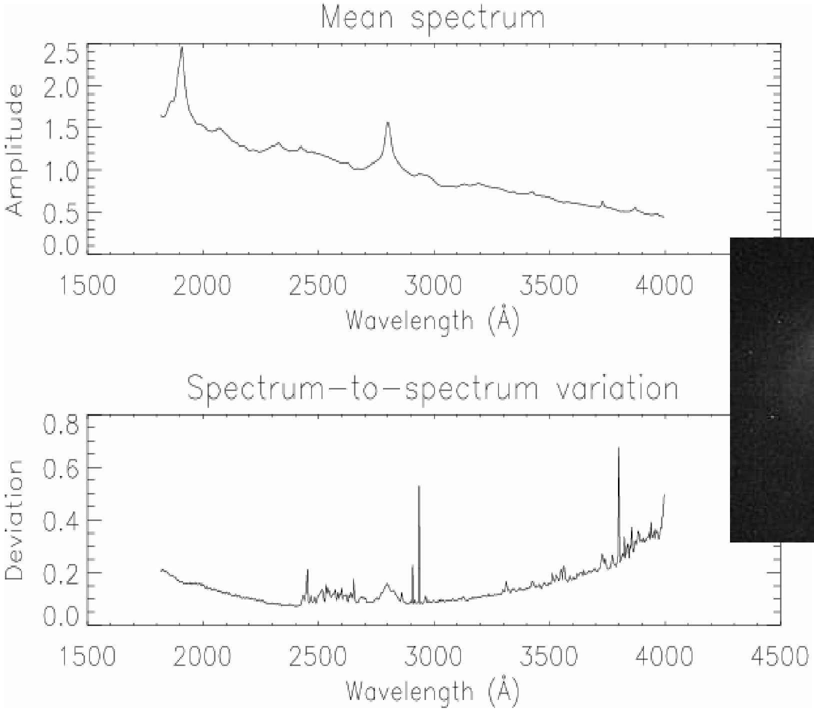
PHOTON-AXION CONVERSION AND QSO SPECTRA

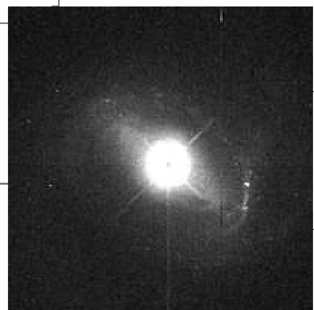
[*L. Ostman and E. Mortsell, "Limiting the dimming of distant type Ia supernovae", JCAP* ***0502****, 005 (2005).*]

An effect of photon-axion oscillations is an energy-dependent dispersion added to the quasar spectra.

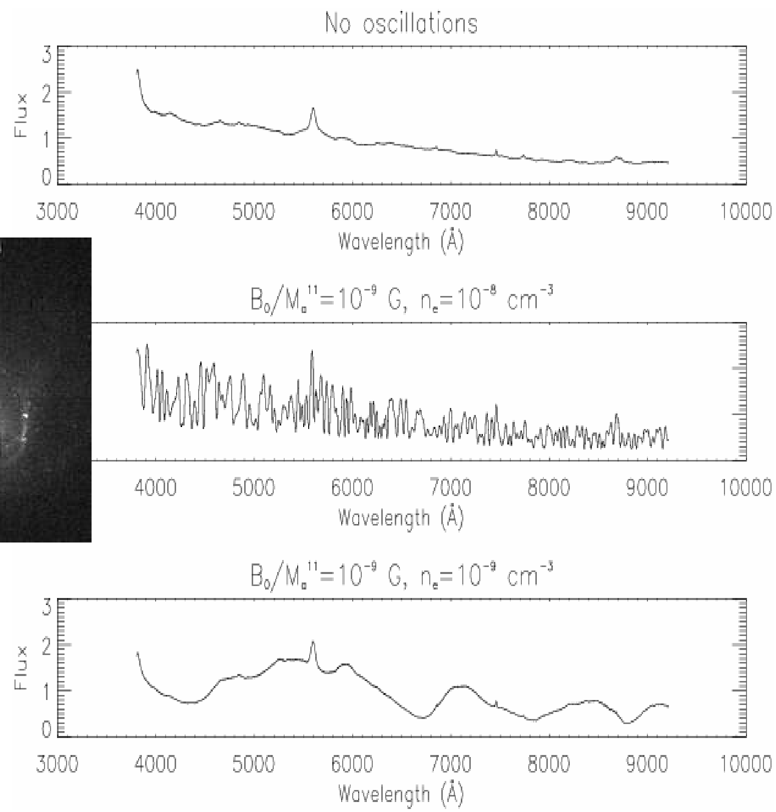
By comparing the dispersion in observed QSO spectra with the dispersion induced by γ-a oscillations is possible to constraint the photon-axion parameter space.

No γ-a conversion

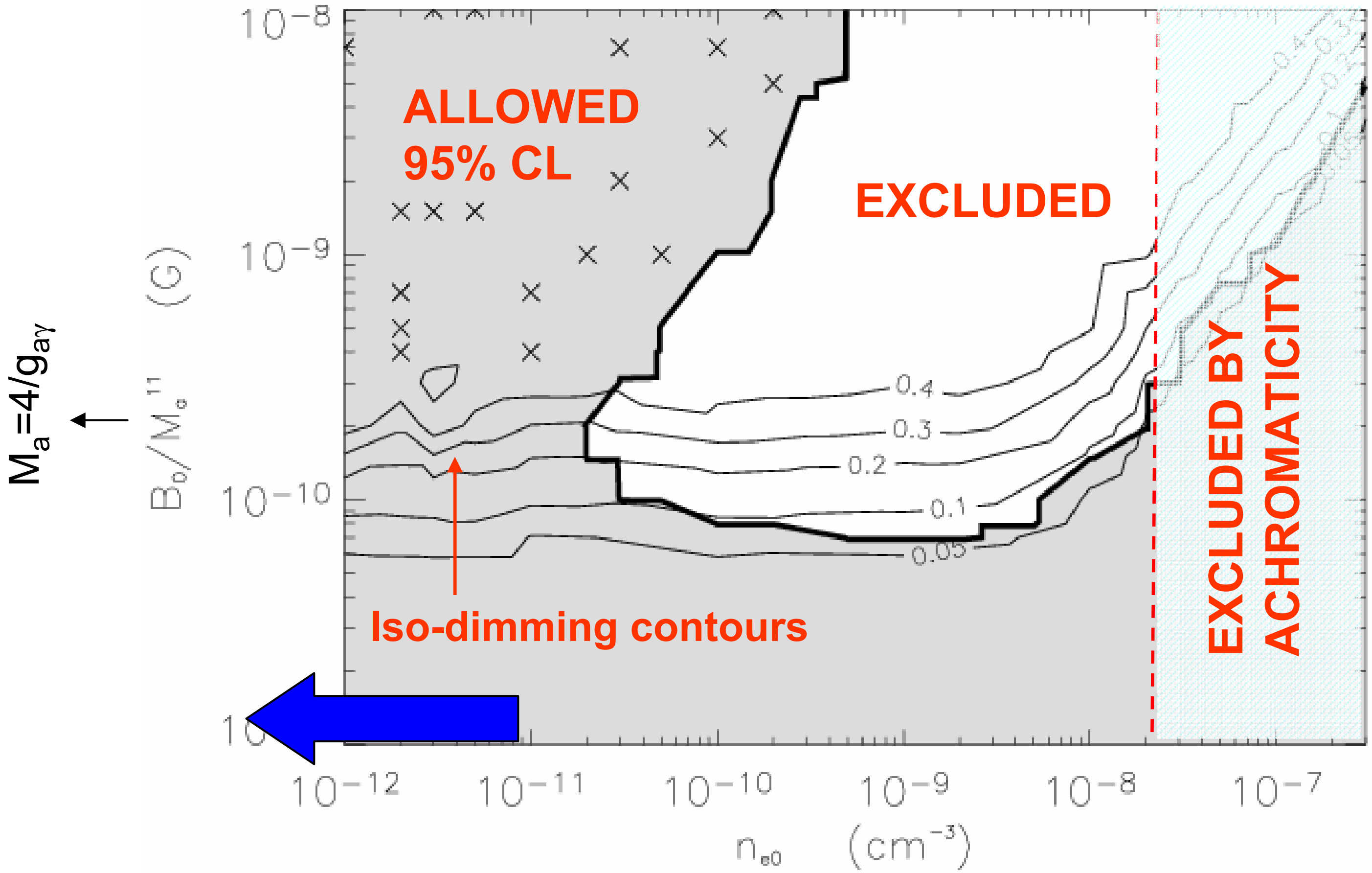




γ-a conversion



QSO CONSTRAINTS



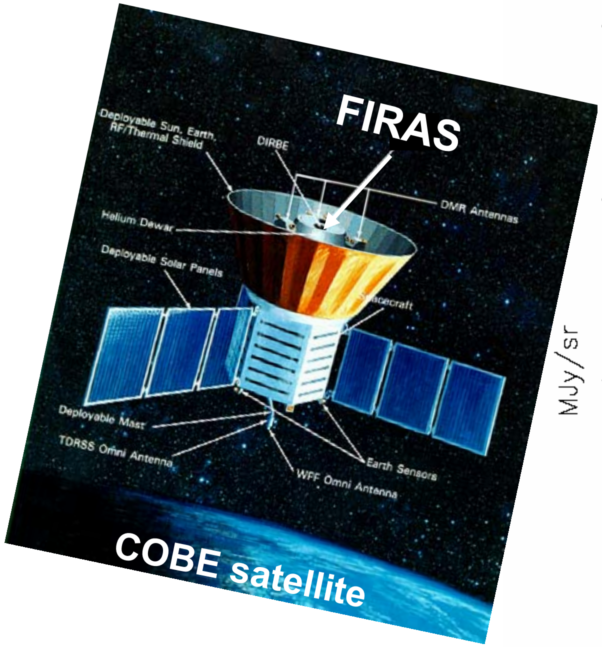
A small-n_e parameter region ($n_e \lesssim 10^{-11}$ cm^{-3}) is left open by the dispersion in QSO spectra.

HOW TO CLOSE THIS WINDOW?

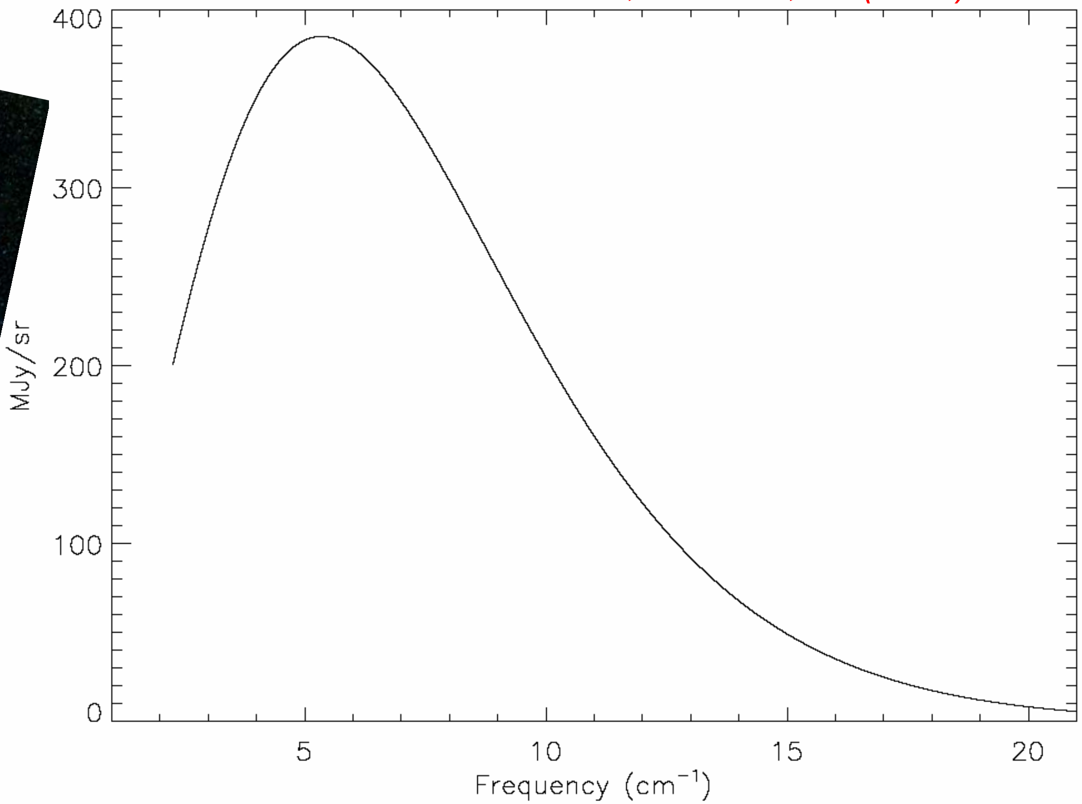
CONSTRAINTS ON PHOTON-AXION CONVERSION FROM CMB

Photon-axion conversion should leave their imprint on the cosmic microwave background (CMB) photons.

Appreciable distrortions to the blackbody spectrum of the CMB may appear, considering that CMB data are have an accuracy of one part on 10^4-10^5.



FIRAS DATA - *Fixen et al., APJ 473,576(1996)*



In the presence of γ-a conversion, the CMB blackbody spectrum

$$\Phi^0(\omega,T) = \frac{\omega^3}{2\pi^2}[\exp(\omega/T)-1]^{-1}$$

$\omega \sim 10^{-4}$ eV

T= 2.725 +/- 0.002 K

would convert into a deformed spectrum given by

$$\Phi(\omega,T) = \Phi^0(\omega,T)P_{\gamma\to\gamma}(\omega)$$

We compare the measured spectrum [FIRAS DATA - *Fixen et al., APJ 473,576(1996)*] with a blackbody deformed by photon-axion oscillation. We build the function (*)

$$\chi_\nu^2(T,\lambda) = \frac{1}{N-1}\sum_{i,j=1}^{N}\Delta\Phi_i(\sigma^2)_{ij}^{-1}\Delta\Phi_j$$

λ=($g_{a\gamma}$B, n_e)

where

$$\Delta\Phi_i = \Phi_i^{\exp} - \Phi^0(\omega_i,T)P_{\gamma\to\gamma}(\omega_i,\lambda)$$

$$\sigma_{ij}^2 = \rho_{ij}\sigma_i\sigma_j$$

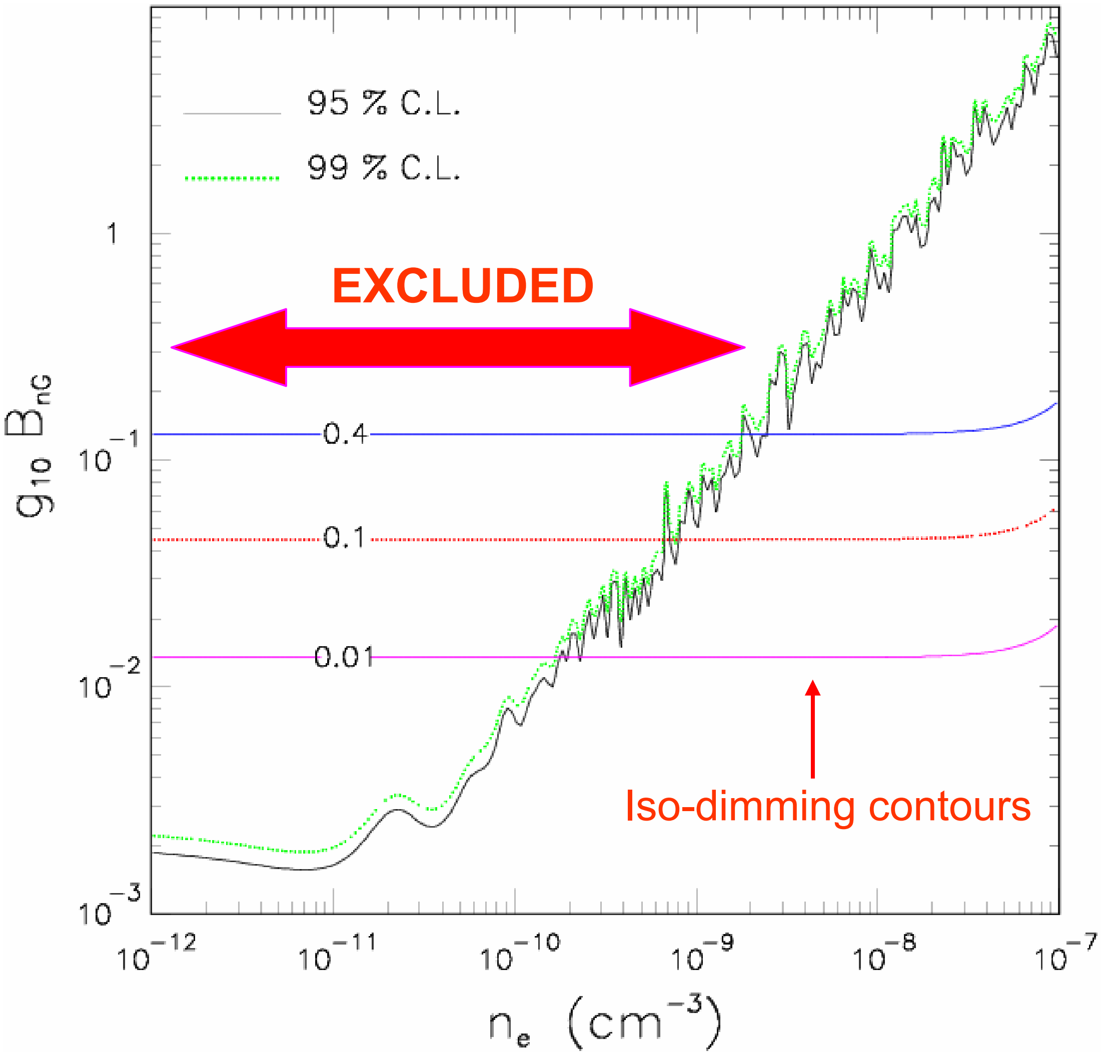
i-th residual

covariance matrix

We minimize the χ^2 for each point λ=($g_{a\gamma}$B, n_e) in the parameter space with respect to *T*.

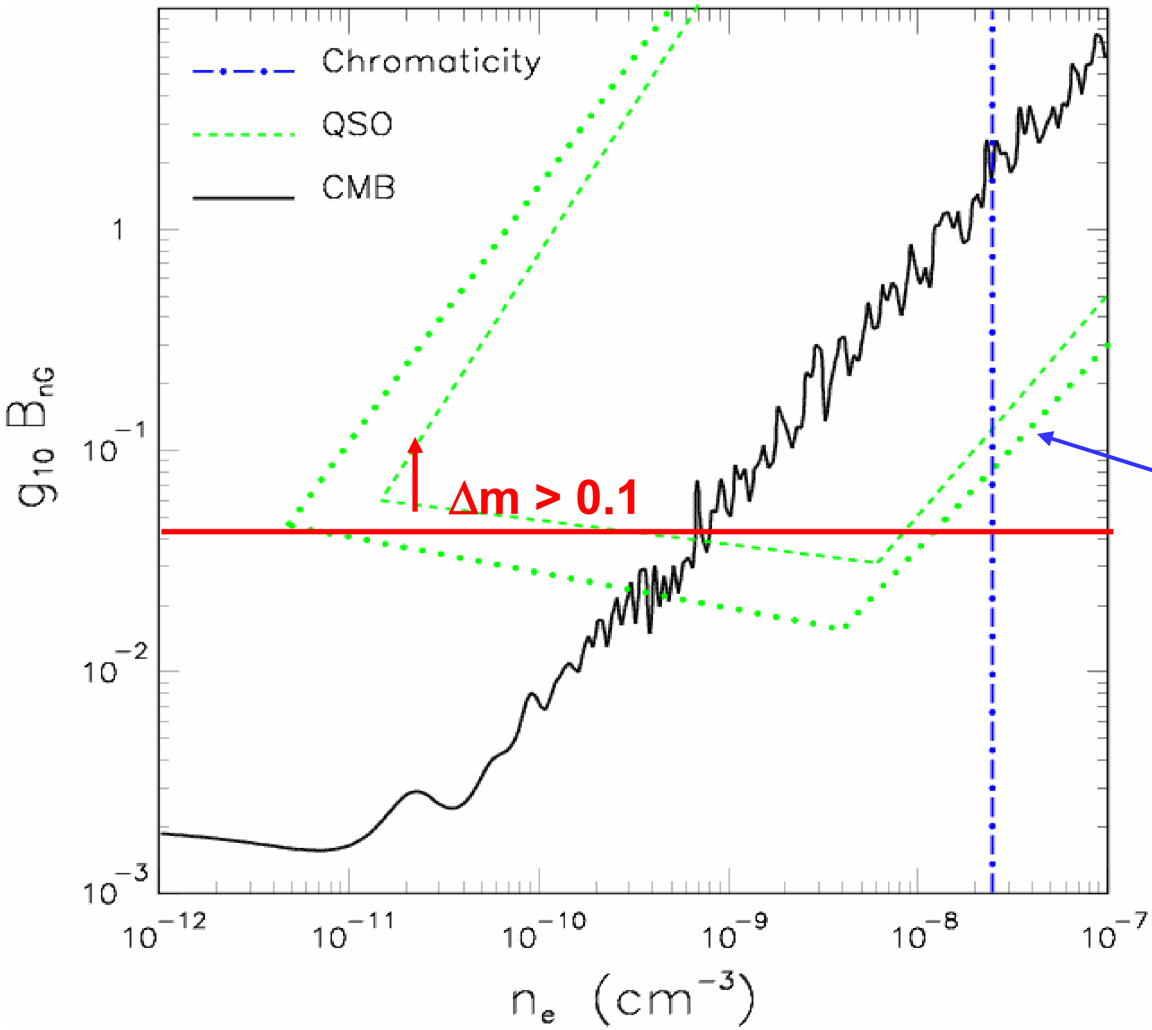
*(*) A.M., G.G.Raffelt, and P.D. Serpico, PRD **72**, 023501 (2005).*

CMB CONSTRAINTS



The entire region for $n_e \lesssim 10^{-9}$ cm^{-3} is excluded for SN dimming

COMBINING CMB+QSO+CHROMATICITY CONSTRAINTS



Intrinsic dispersion of 5% in QSO spectra

COMBINING CMB + QSO CONSTRAINTS, THE PHOTON-AXION CONVERSION SHOULD BE EXCLUDED AS THE LEADING EXPLANATION OF SN DIMMING

CONCLUSIONS

Axion-photon mixing has been proposed as an alternative mechanism to explain the apparent dimming of distant SNe Ia without introducing cosmic acceleration.

- **We have studied the effects of this mechanism on Cosmic Microwave Background (CMB) photons.**
- **We have shown that photon-axion conversion would induce relevant distortions to the CMB blackbody spectrum, allowing to put significant constraints on this model.**
- **Combining these results with the limits coming from the dispersion on QSO spectra and from the achromaticity, this scenario can only play a subleading role for SN Ia dimming.**