A Hidden Microwave Background ?
- signatures of photon-WISP oscillations in the CMB -

Javier Redondo

Deutsches Elektronen Synchrotron (DESY)

5th Workshop on Axions, WIMPs and WISPs (DURHAM 2009)

based on PRL 101, 131801 (2008), JCAP 0903, 026 (2009) and arXiv:0905.4865

in collaboration with Joerg Jaeckel, Alessandro Mirizzi, Andreas Ringwald and Guenter Sigl

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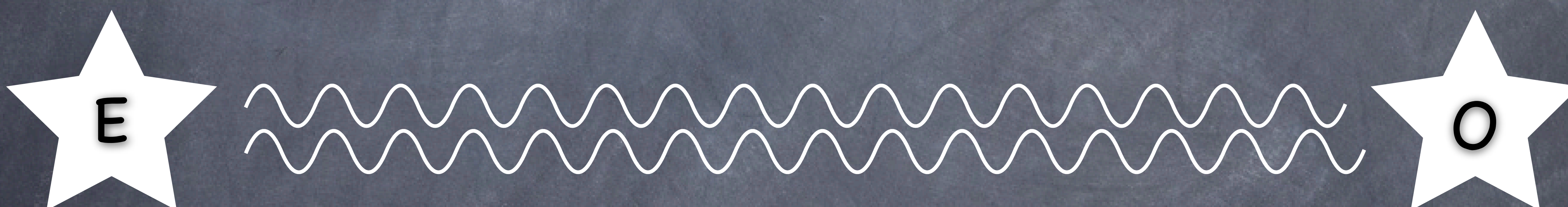
Photon Oscillations and the WISP Zoo

Weakly interacting slim particles (WISPs) can (and will) mix with photons

$$\mathcal{L}_{\rm mass} = \begin{pmatrix} \gamma \\ \phi \end{pmatrix}^T \begin{pmatrix} 0 & \delta \\ \delta & m_\phi^2 \end{pmatrix} \begin{pmatrix} \gamma \\ \phi \end{pmatrix} \xrightarrow{R(\theta)} \mathcal{M}^2 = \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix},$$

A photon emitted by E is a combination of two different waves propagating at different speeds ... the beating of the two waves produces oscillations



$$|\gamma\rangle(L) = \cos\theta e^{\imath \frac{m_1^2}{2\omega} L}|\gamma_1\rangle + \sin\theta e^{\imath \frac{m_2^2}{2\omega} L}|\gamma_2\rangle$$

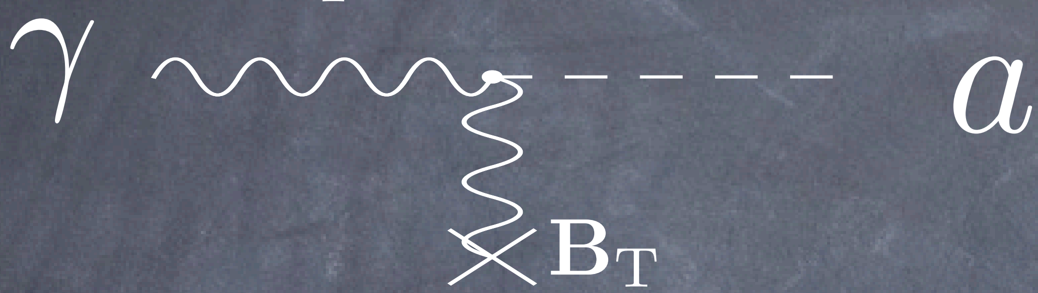
After a length L the photon-WISP conversion probability is given by

$$P(\gamma \to \phi) = \sin^2 2\theta \sin^2 \frac{\Delta L}{2\omega} = \frac{4\delta^2}{m_\phi^4 + 4\delta^2} \sin^2 \frac{(m_\phi^4 + 4\delta^2)^{1/2} L}{2\omega}$$

Photon Oscillations and the WISP Zoo

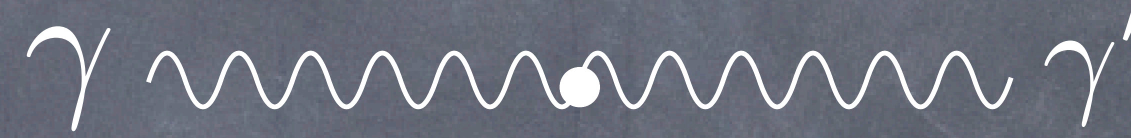
Axion-like Particles

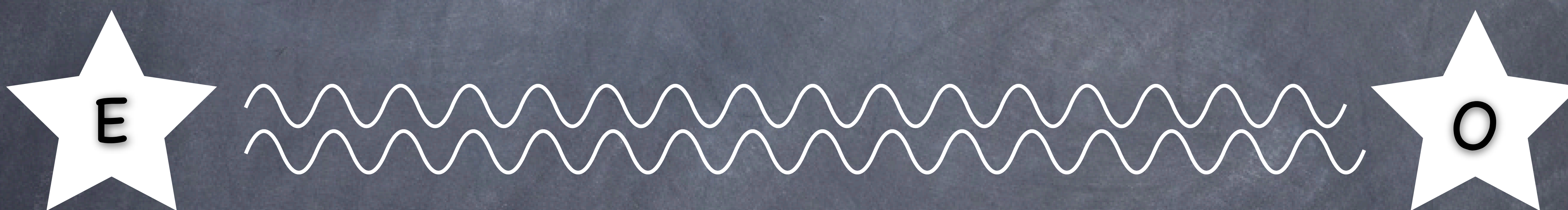
$$\mathcal{L}_{\rm I} = g\frac{1}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a \rightarrow \delta = gB_{\rm T}\omega$$



Hidden Photons

$$\mathcal{L}_{\rm I} = -\frac{\chi}{2}F_{\mu\nu}B^{\mu\nu}a \rightarrow \delta = \chi m_{\gamma'}^2$$





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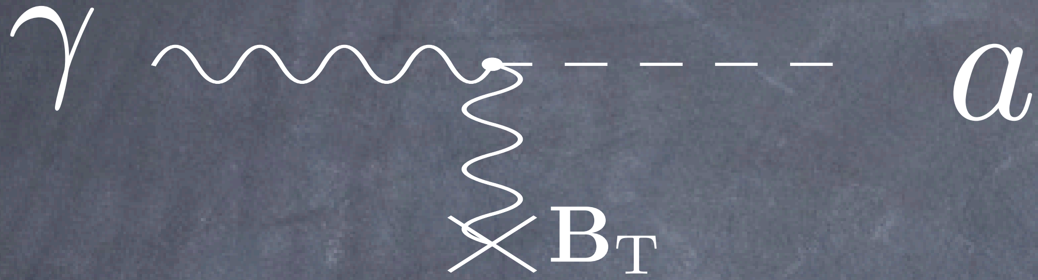

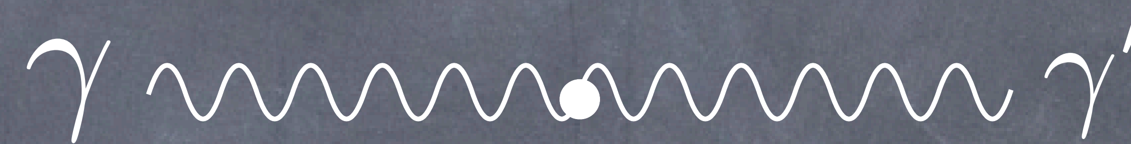

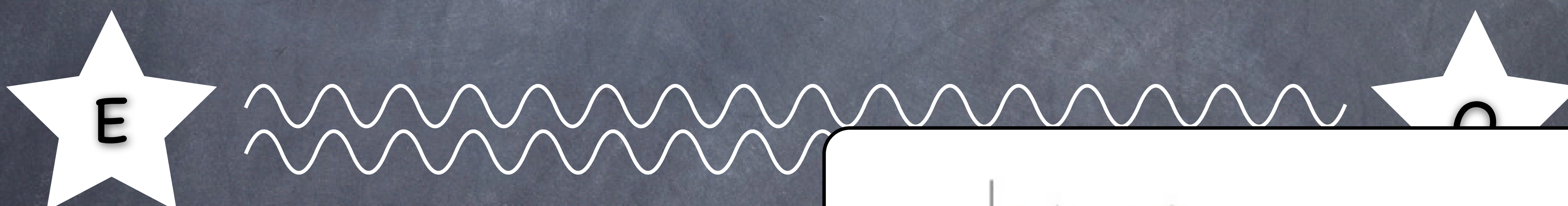

$$|\gamma\rangle(L) = \cos\theta e^{i\frac{m_1^2}{2\omega}L}$$

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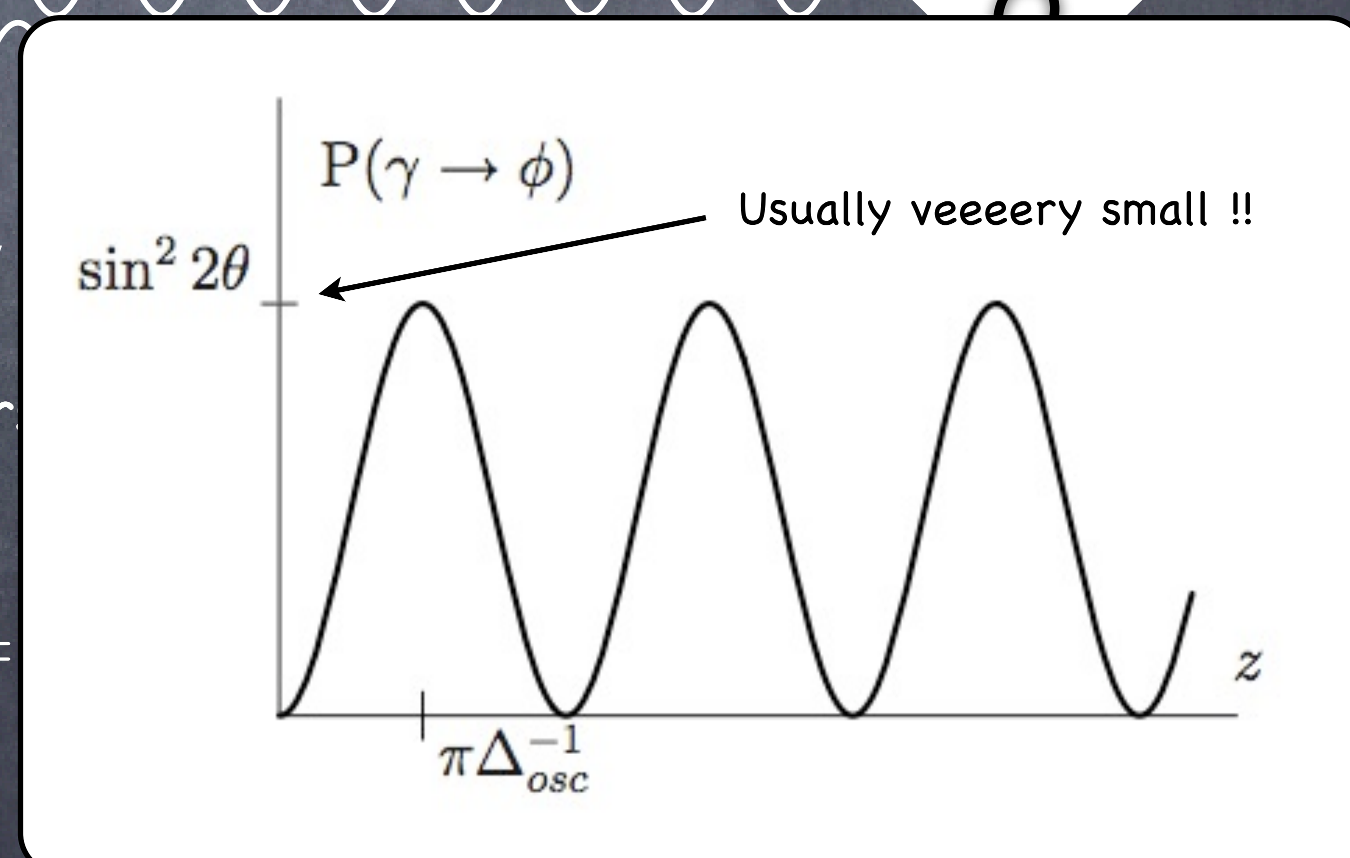
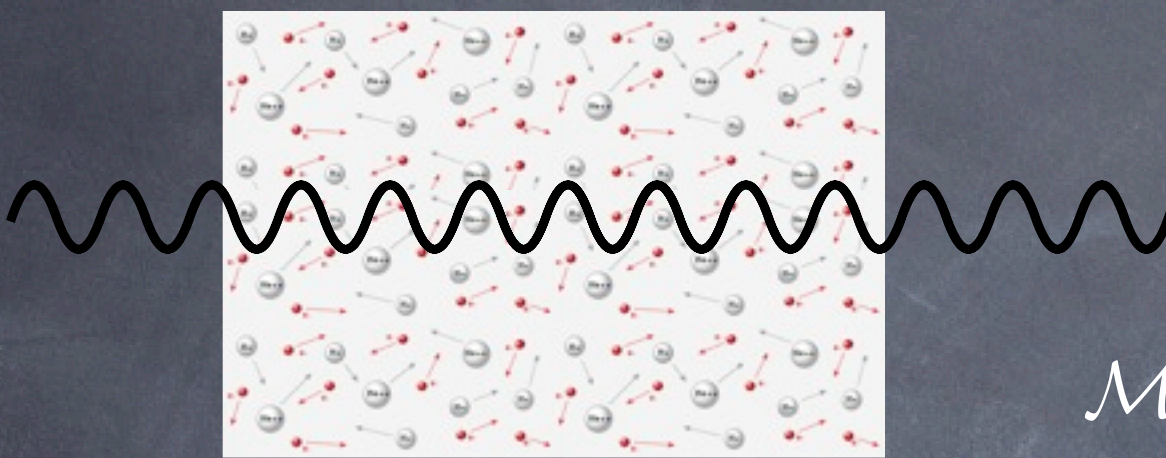


Photon Oscillations in a medium : Resonance

In a medium photons get an ``effective" mass (index of refraction)



$$m_\gamma^2 \equiv -2\omega^2(n-1)$$

$$\mathcal{M}^2 = \begin{pmatrix} m_\gamma^2 & \delta \\ \delta & m_\phi^2 \end{pmatrix} \to \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix},$$

In the oscillation probability, the mass squared difference is what matters

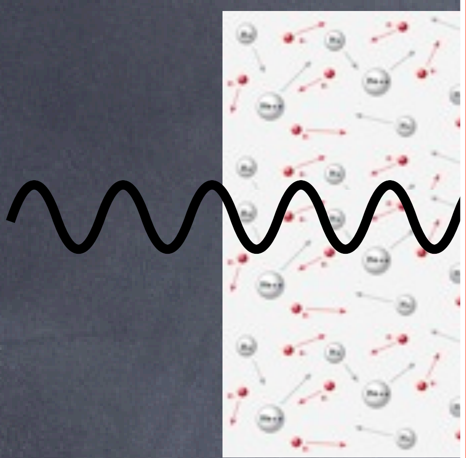
$$P(\gamma\to\phi) = \sin^2 2\theta \sin^2\frac{\Delta L}{2\omega} = \frac{4\delta^2}{(m_\phi^2 - m_\gamma^2)^2 + 4\delta^2}\sin^2\frac{((m_\phi^2 - m_\gamma^2)^2 + 4\delta^2)^{1/2} L}{2\omega}$$

In a suitable medium $m_\gamma^2 = m_\phi^2$ the amplitude of the Photon oscillations is **1**

$$P(\gamma\to\phi) = \sin^2\frac{\delta L}{\omega} \sim \left(\frac{\delta L}{\omega}\right)^2$$

Photon Oscillations in a medium : Resonance

In a medium p



RECIPE FOR A PHOTON OSCILLATION EXPERIMENT

Longest possible distances ...

Homogeneous backgrounds (that we can tune?) ...

Intense and controlled source ...

Small photon frequencies ...

$1)$

$\begin{matrix} 0 \\ m_2^2 \end{matrix} \Big) ,$

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RECIPE FOR A PHOTON OSCILLATION EXPERIMENT

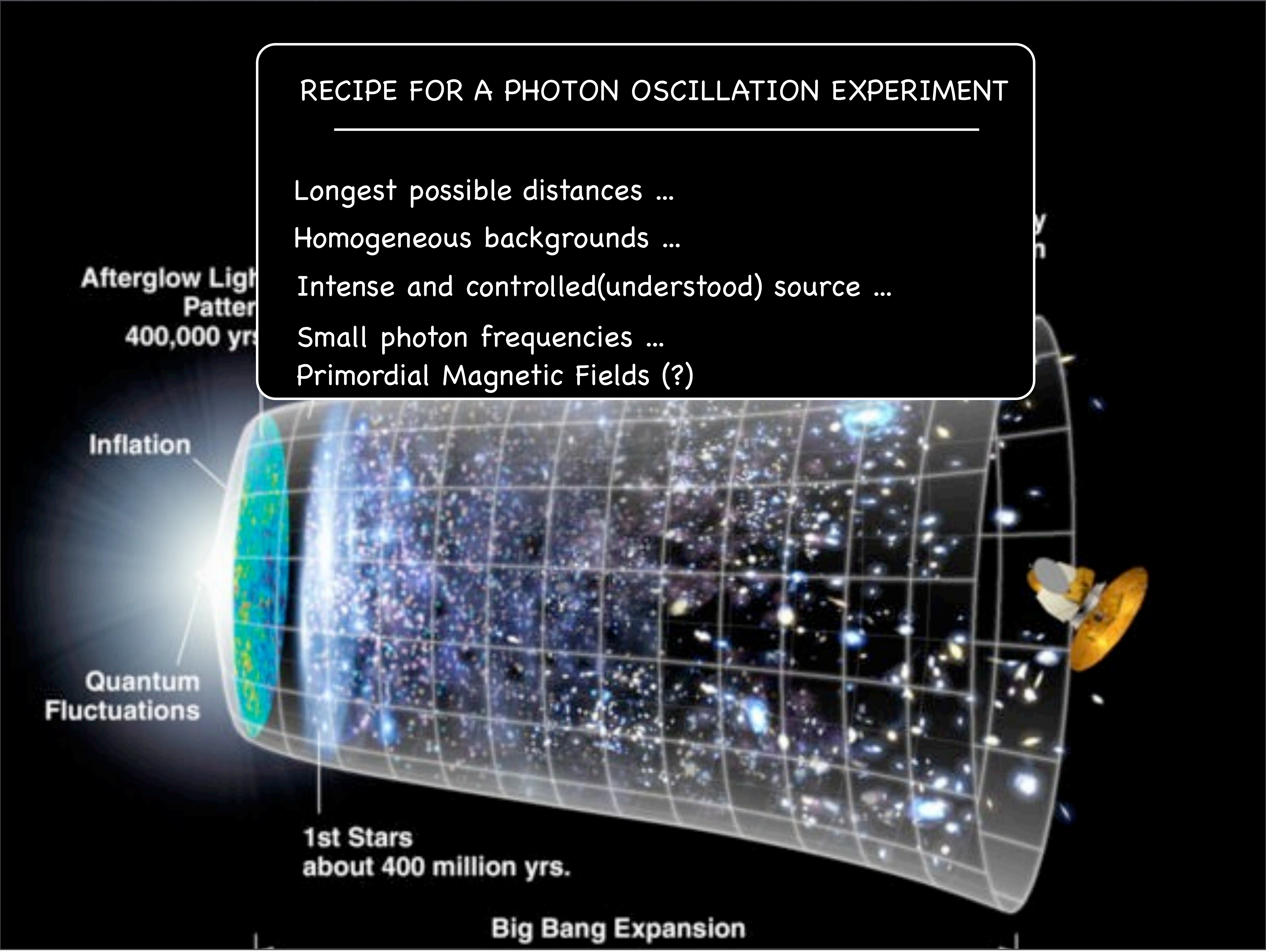
Longest possible distances ...

Homogeneous backgrounds ...

Intense and controlled(understood) source ...

Small photon frequencies ...

Primordial Magnetic Fields (?)

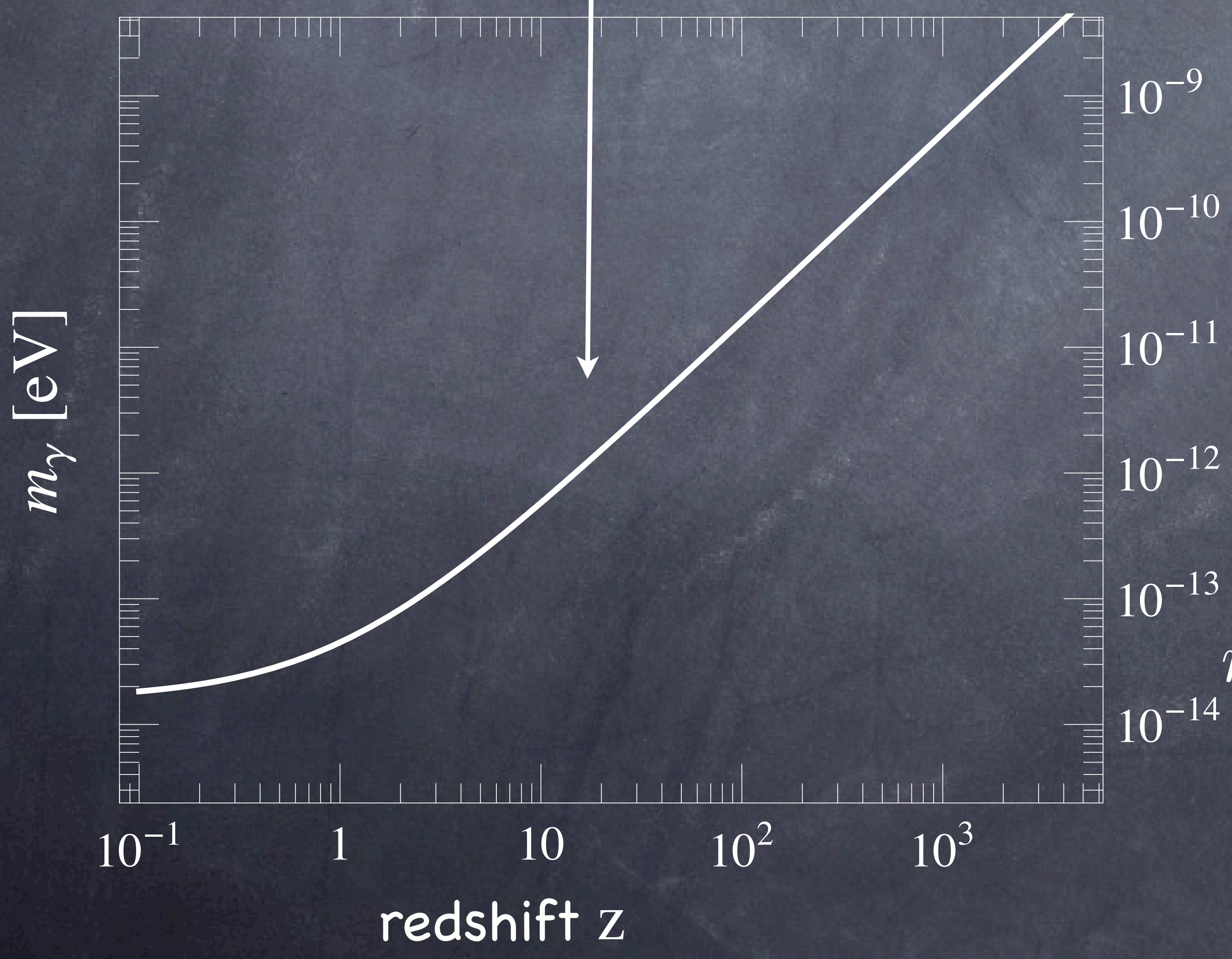


Photon effective mass during the universe expansion

Two contributions : free electrons and neutral atoms (H for simplicity)

$$m_\gamma^2 = -2\omega^2(n-1) = \omega_P^2 - 2\omega^2(n_H - 1) - 2\omega^2(n_{...} - 1)$$

$$m_\gamma^2 = (1.6 \times 10^{-14}\,\mathrm{eV})^2(1+z)^3 X_e \left(1 - 0.0073\left(\frac{\omega}{\mathrm{eV}}\right)^2\left(\frac{1-X_e}{X_e}\right)\right),$$



$$\omega_P^2 = \frac{4\pi\alpha}{m_e} n_{e,\mathrm{free}}$$

$$n_H - 1 \simeq 13.6 \times 10^{-5} \frac{n_{e,\mathrm{bound}}}{n_*}$$

$$n_{e,\mathrm{total}} \approx n_{\mathrm{baryon}} \equiv \eta\, n_\gamma$$
$$\approx (2 \times 10^{-14}\mathrm{eV})^2(1+z)^3$$

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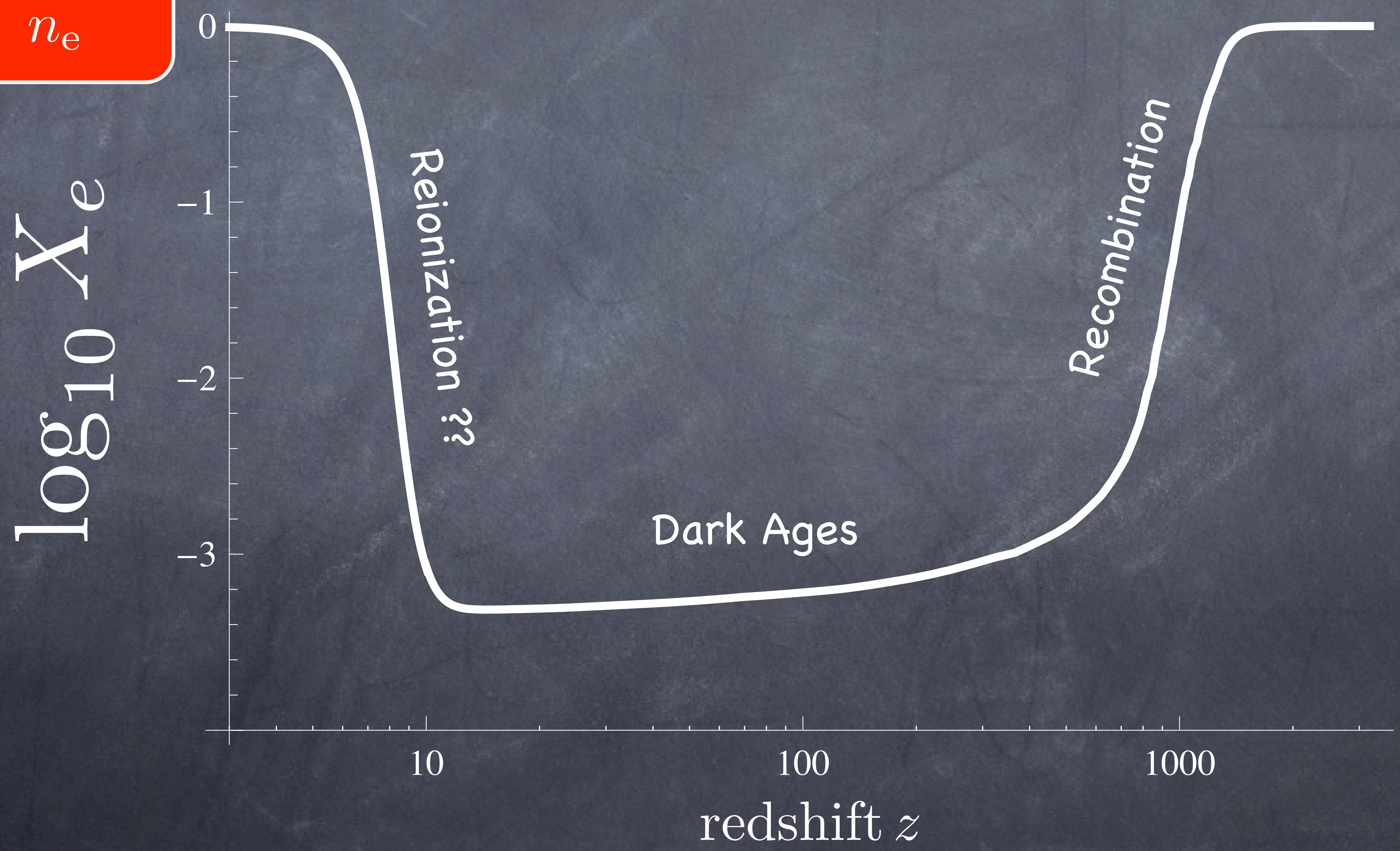
$$X_e = \frac{n_{\rm e,free}}{n_{\rm e}}$$

H IONIZATION HISTORY



S. Seager [arXiv:9909275]

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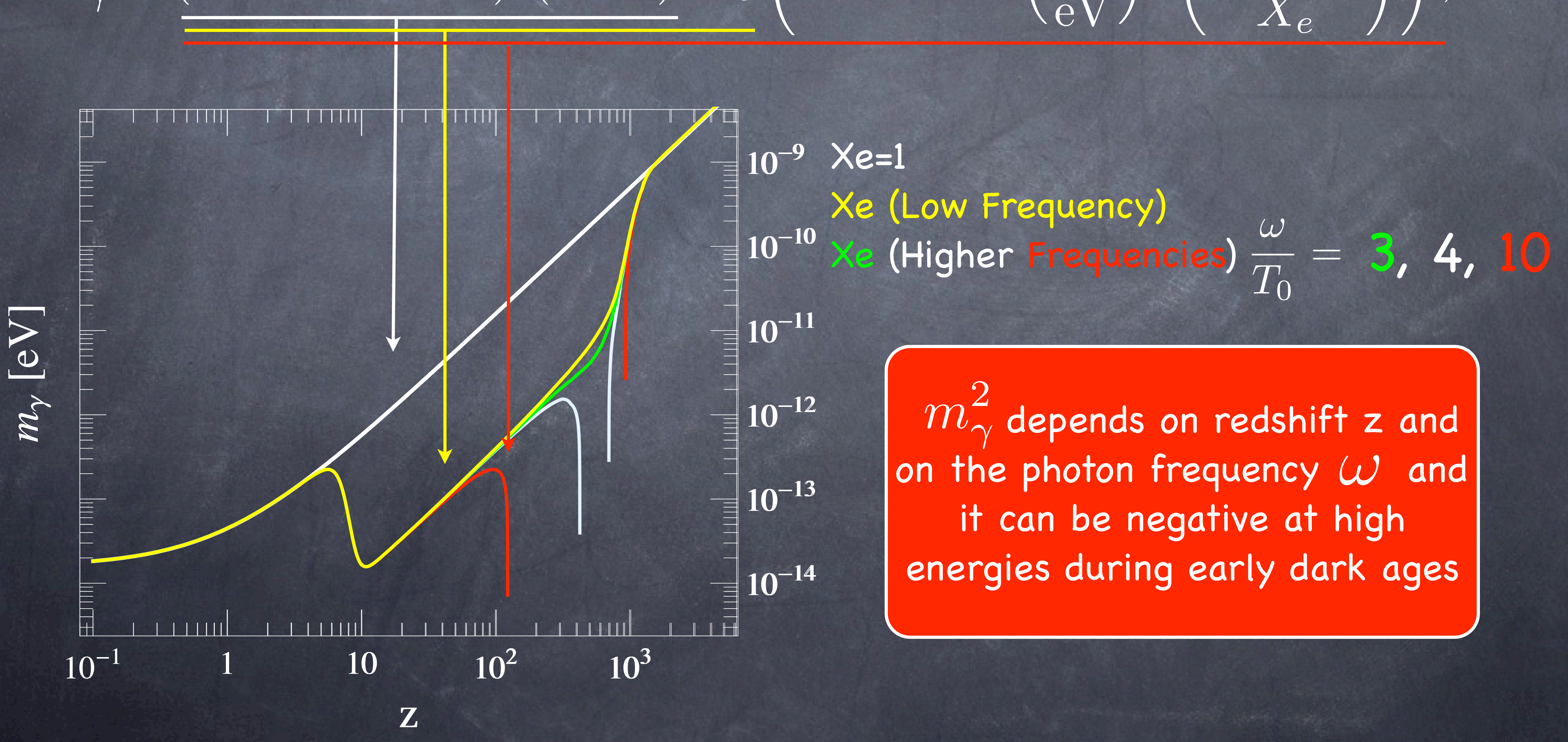


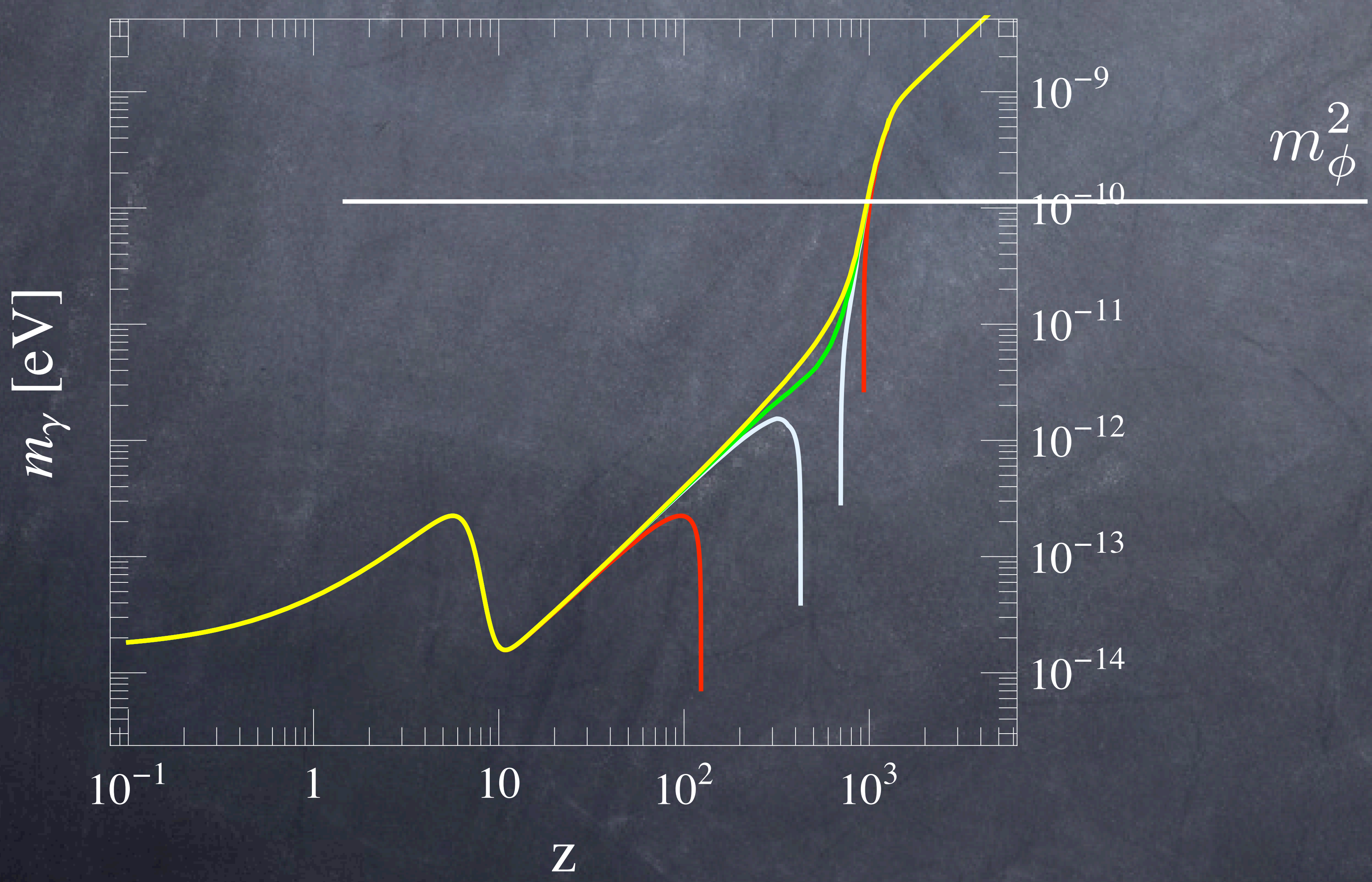
m_γ^2 depends on redshift z and on the photon frequency ω and it can be negative at high energies during early dark ages

Photon effective mass during the universe expansion : Resonances

Two contributions : free electrons and neutral atoms (H for simplicity)

$$m_\gamma^2 = -2\omega^2(n-1) = \omega_P^2 - 2\omega^2(n_H - 1) - 2\omega^2(n_{...} - 1)$$

Because of the interplay of redshift and frequency, many crossing points (resonances) are possible $(m_\gamma^2 = m_\phi^2)$ depending on the WISP mass



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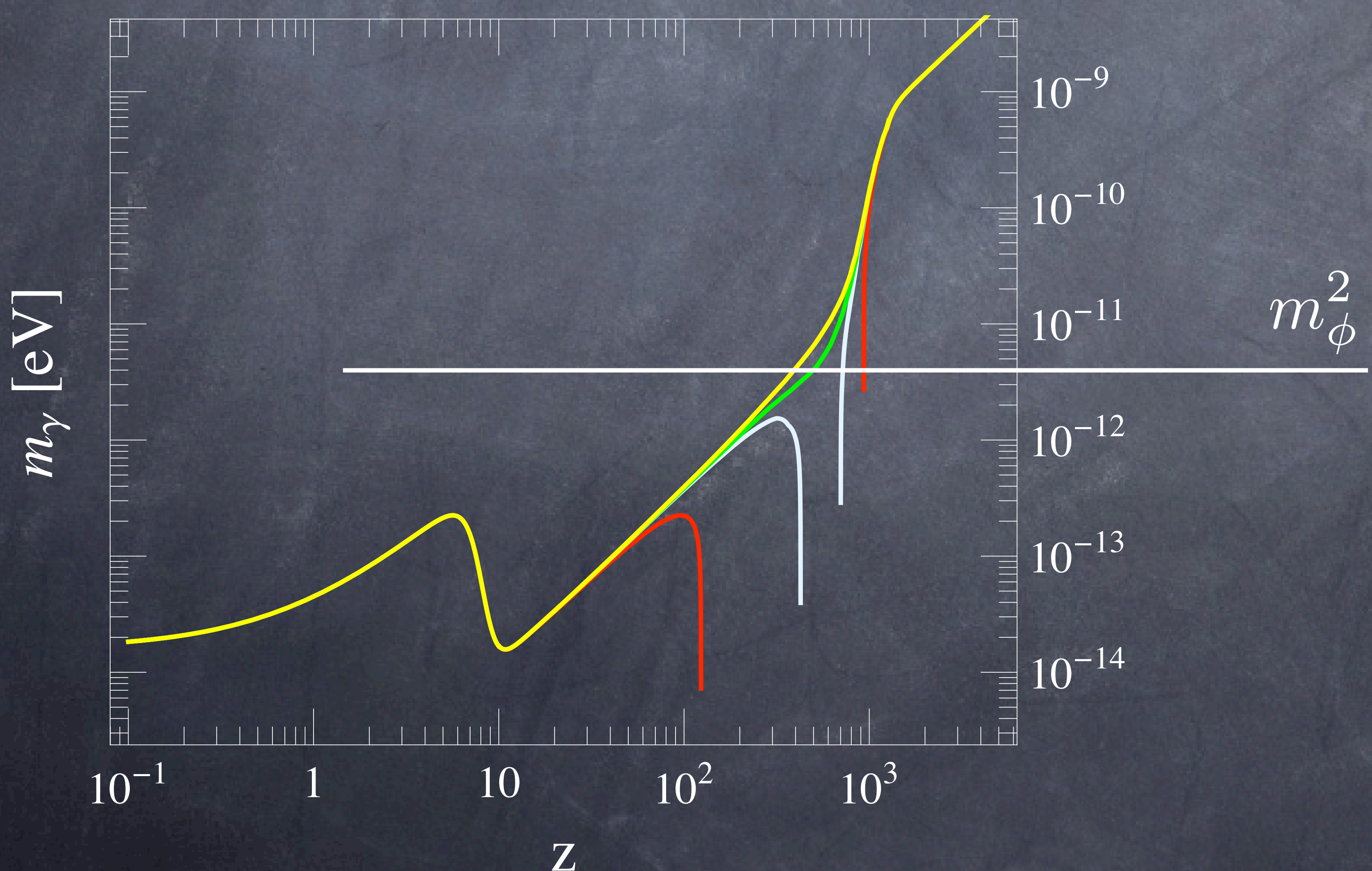

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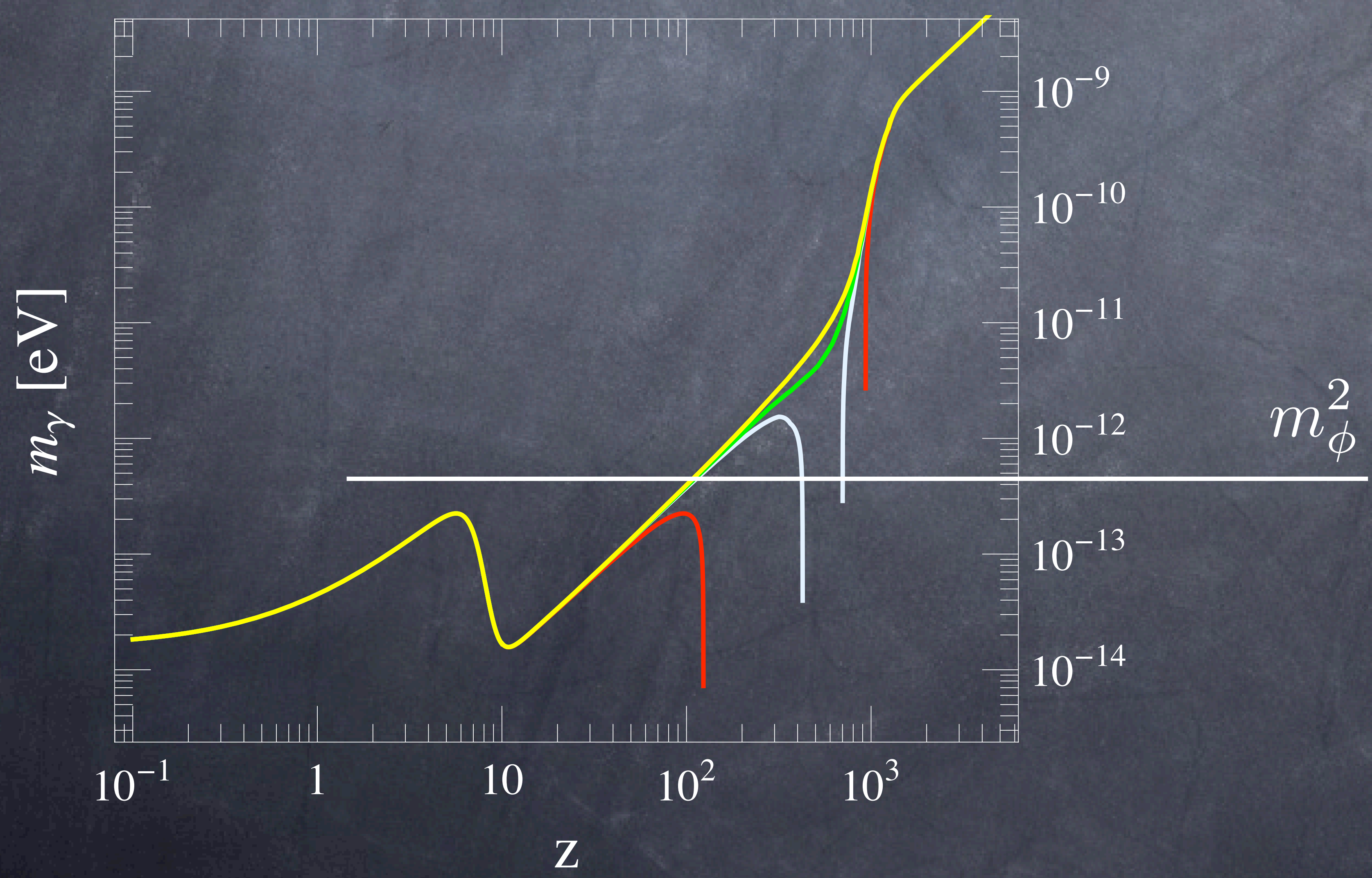

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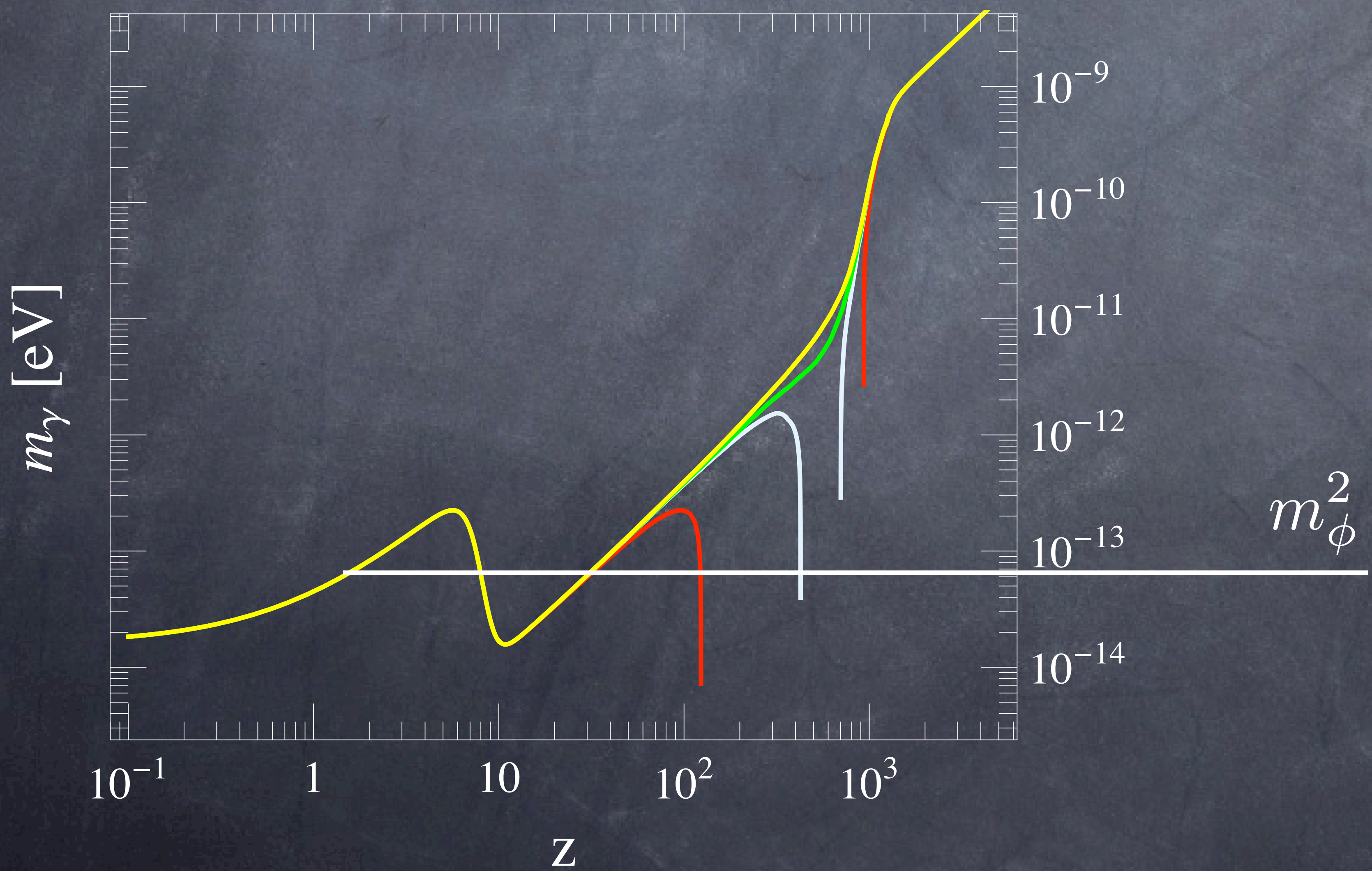

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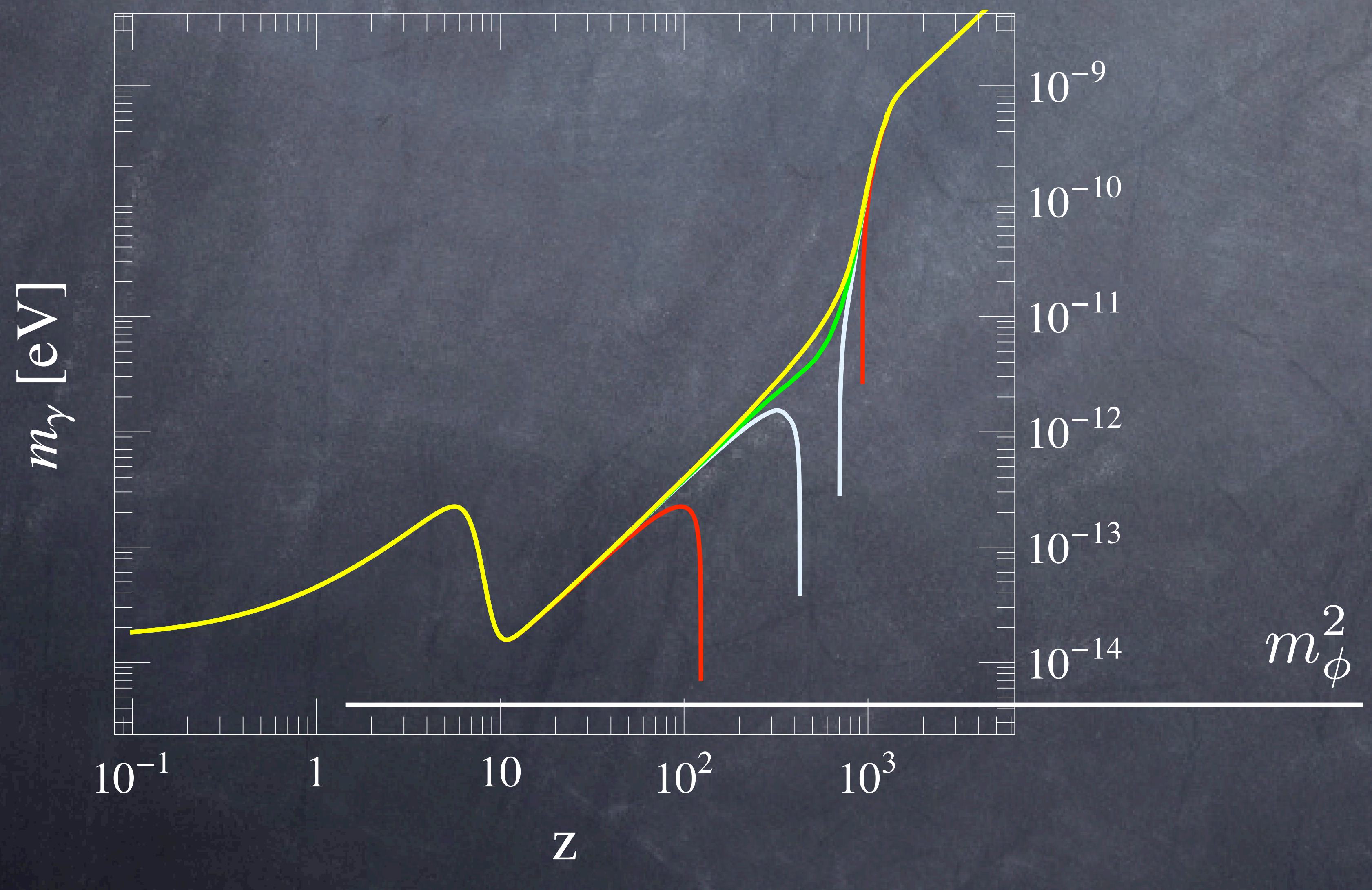


Photon Oscillations in a varying medium : Resonance

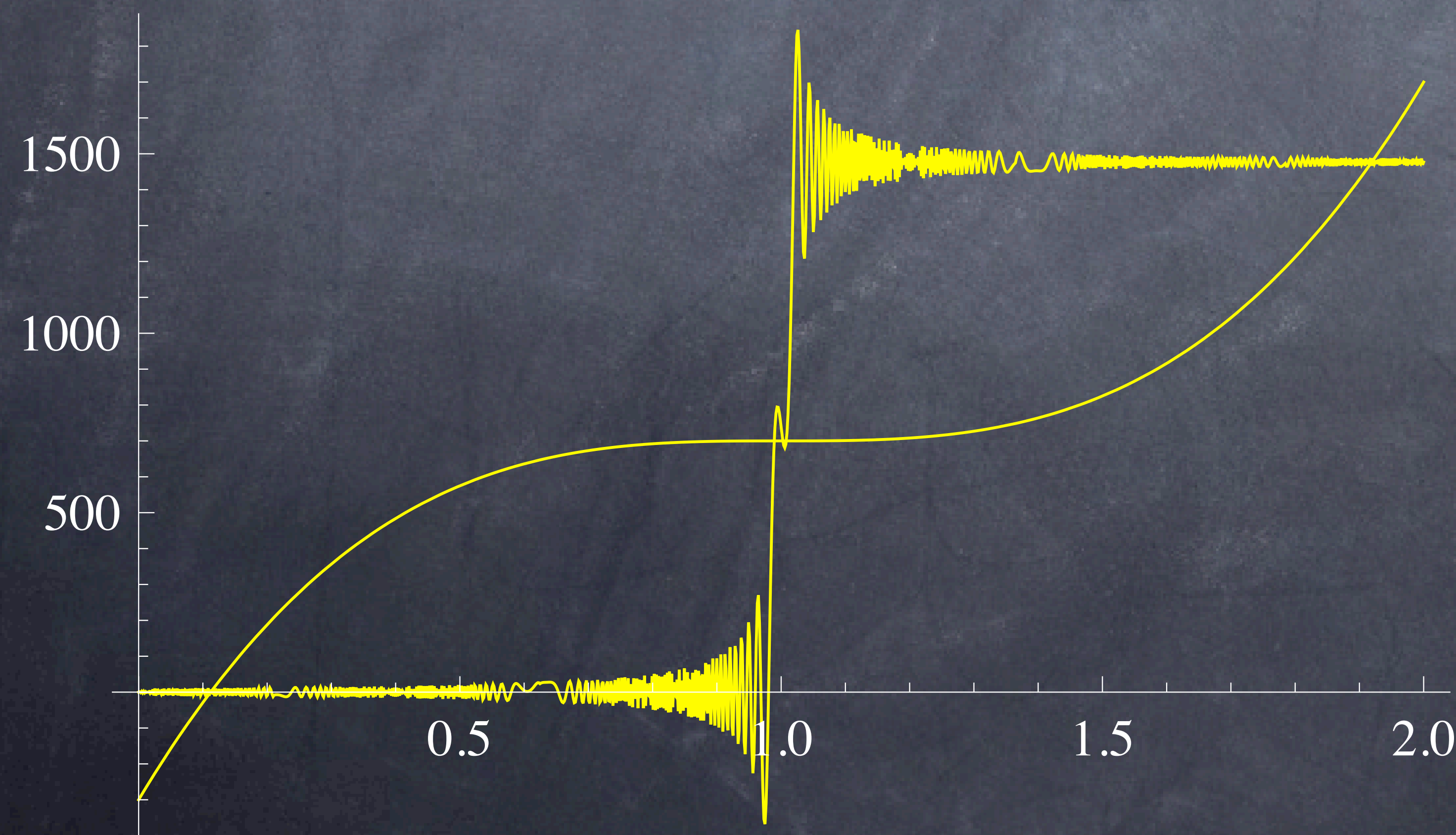
At first order in the conversion probability in a varying medium is

$$P(\gamma \to \phi) = \left| \int dt\, \frac{\delta(t)}{2\omega} e^{i \int^t dt' \frac{m_\phi^2 - m_\gamma^2(t')}{2\omega}} \right|^2$$

Raffelt & Stodolsky
PRD 37, 1237 (1988)

If the argument is huge, many oscillations cancel out and the most relevant contribution is the resonance, where this integral has a saddle point

$$\lim_{k\to\infty} \int dt f(t) e^{ikg(t)} = f(t_r) \left(\frac{2\pi}{k g''(t_r)} \right)^{1/2} e^{i\pi/4} \quad ; \quad g'(t_r) = 0$$



$$P(\gamma \to \phi) = \pi \frac{\delta}{\omega} \delta \left| \frac{dm_\gamma^2}{dt} \right|^{-1}_{t=t_r}$$

$$= \frac{\text{Resonance width}}{\text{Res. oscillation length}}$$

WISPs are produced during the resonance, before and after they are essentially decoupled

Photon Oscillations in a varying medium : Resonance

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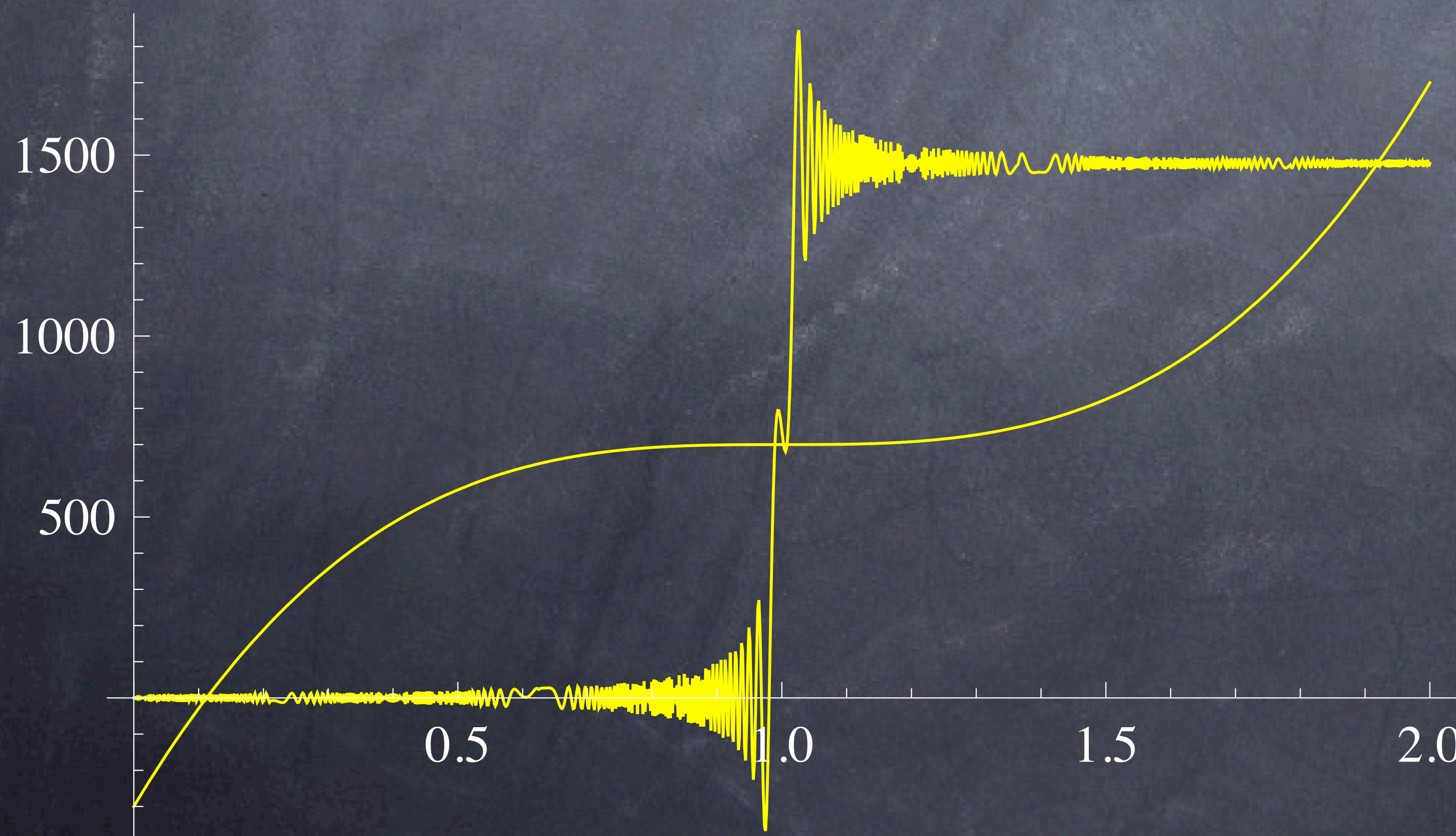

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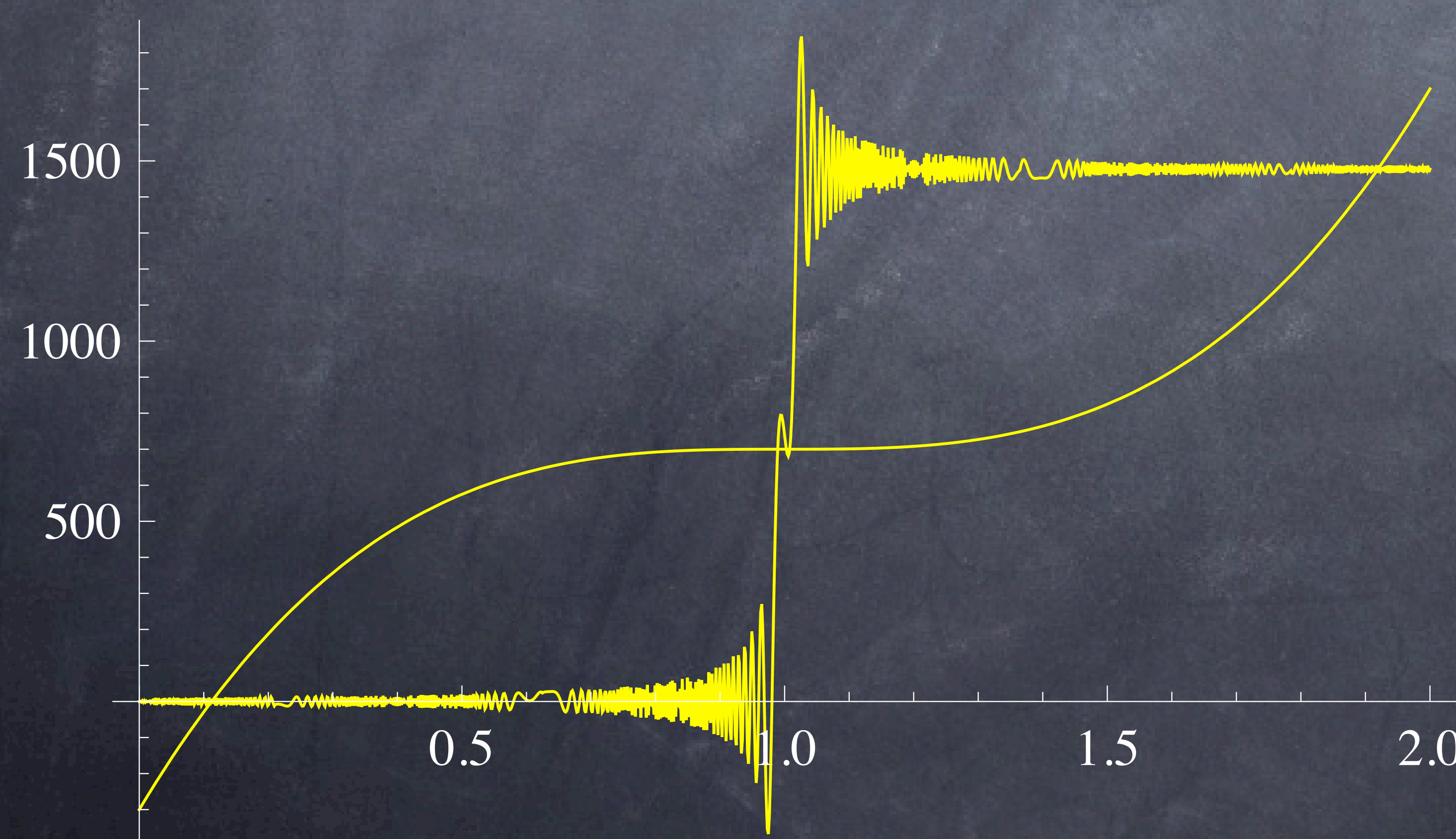

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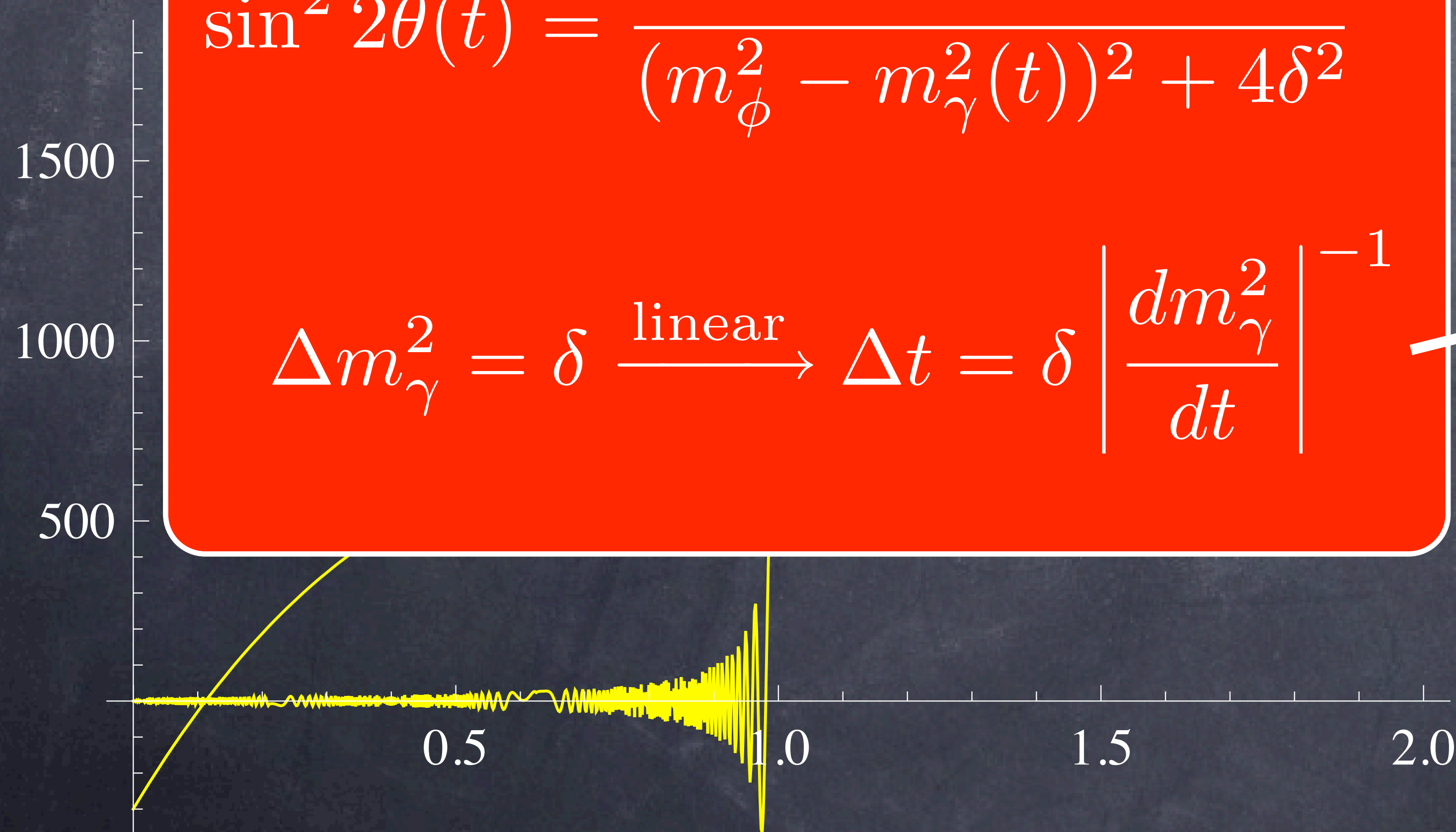
$$\Delta m_\gamma^2 = \delta \xrightarrow{\text{linear}} \Delta t = \delta\left|\frac{dm_\gamma^2}{dt}\right|^{-1}$$



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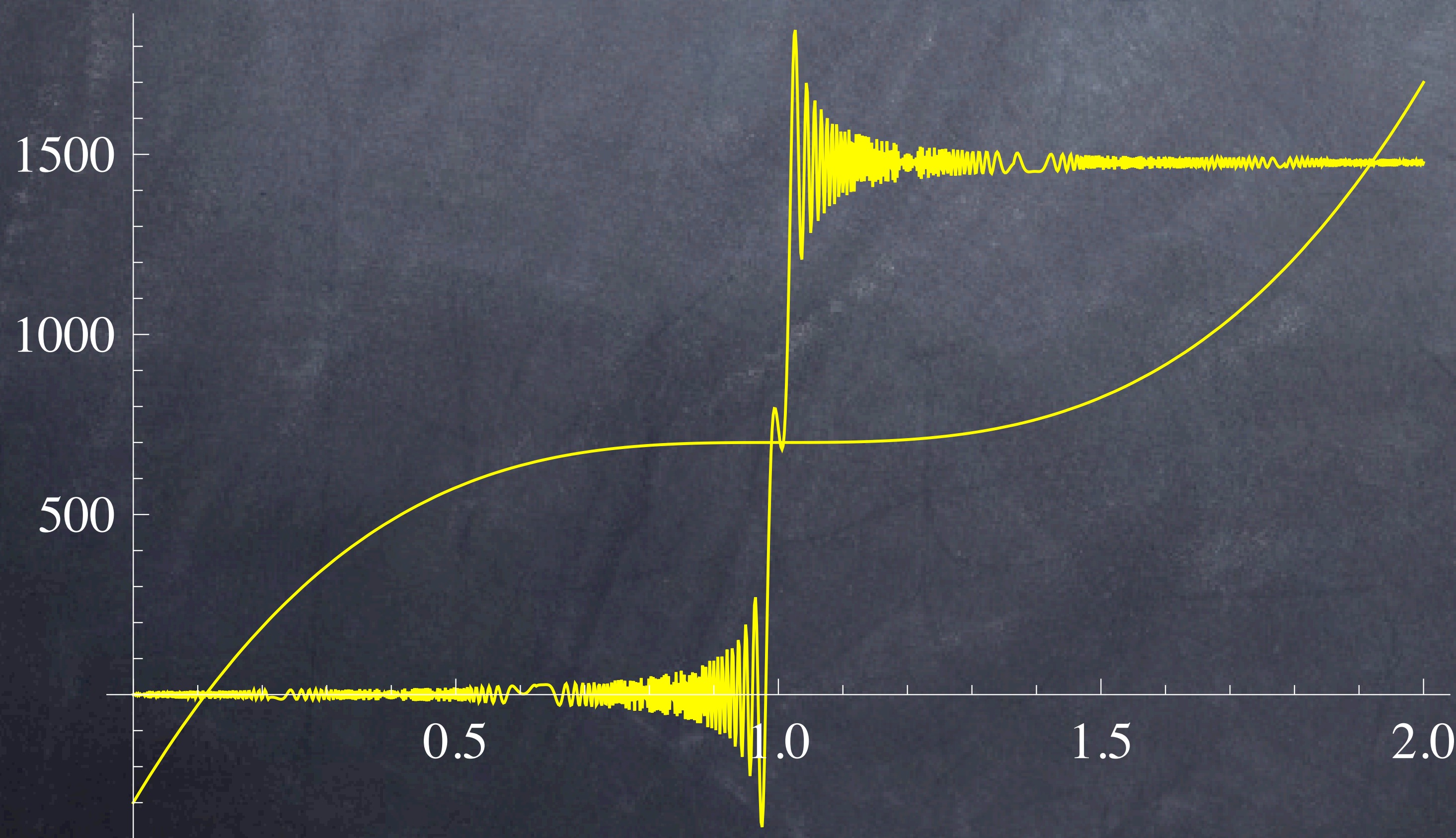

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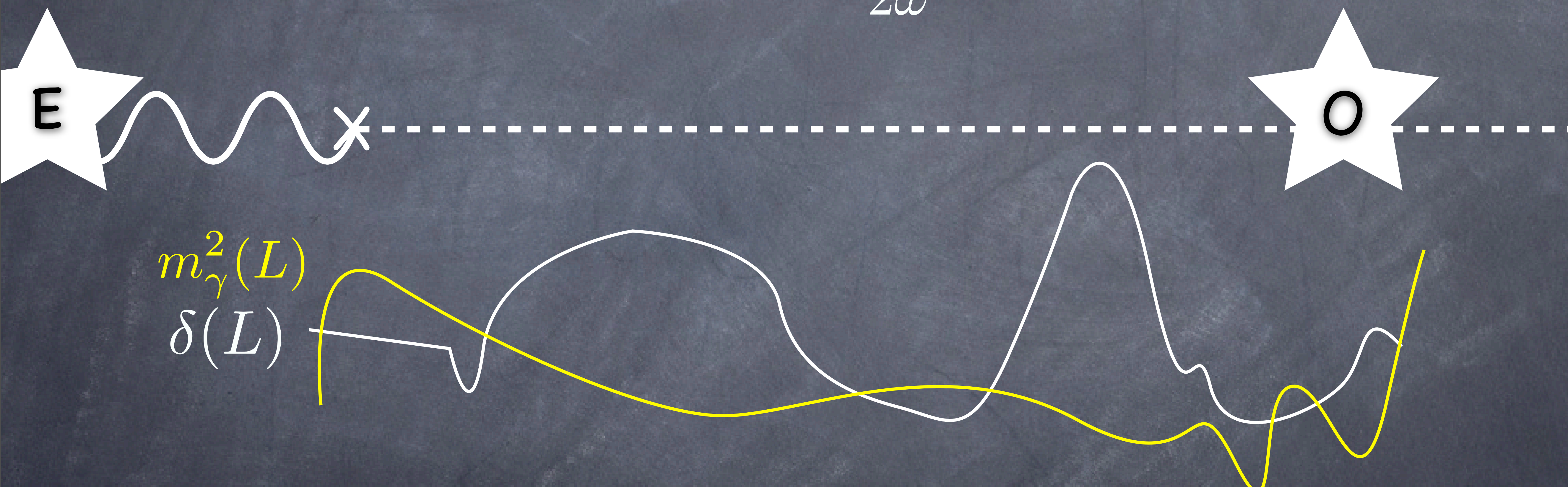
WISPs are produced during the resonance, before and after they are essentially decoupled

At zero order in the mixing, photons and WISPs are propagation eigenstates, and the mixing can be treated as a interaction vertex

The photon WISP transition can happen at any point between E and O

$$dA(\gamma \to \phi) = dL \frac{\delta(L)}{2\omega} \ \ e^{\imath\psi(L)}$$



$$\psi(L) = \int^L dL' \frac{m_\phi^2 - m_\gamma(L)^2}{2\omega}$$

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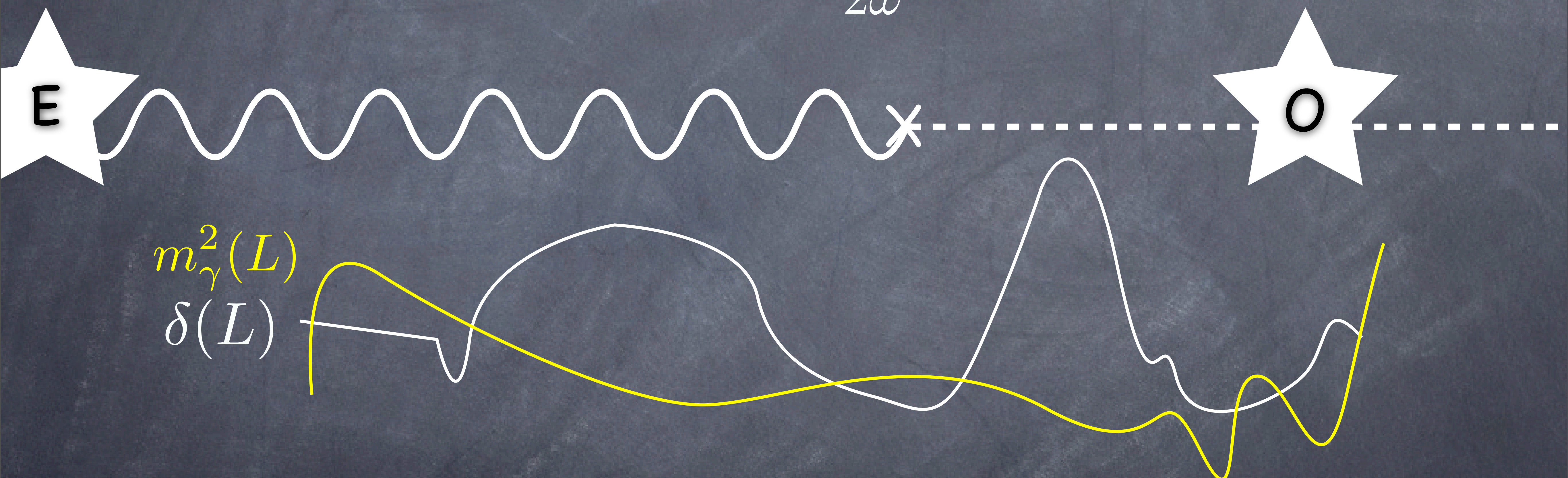

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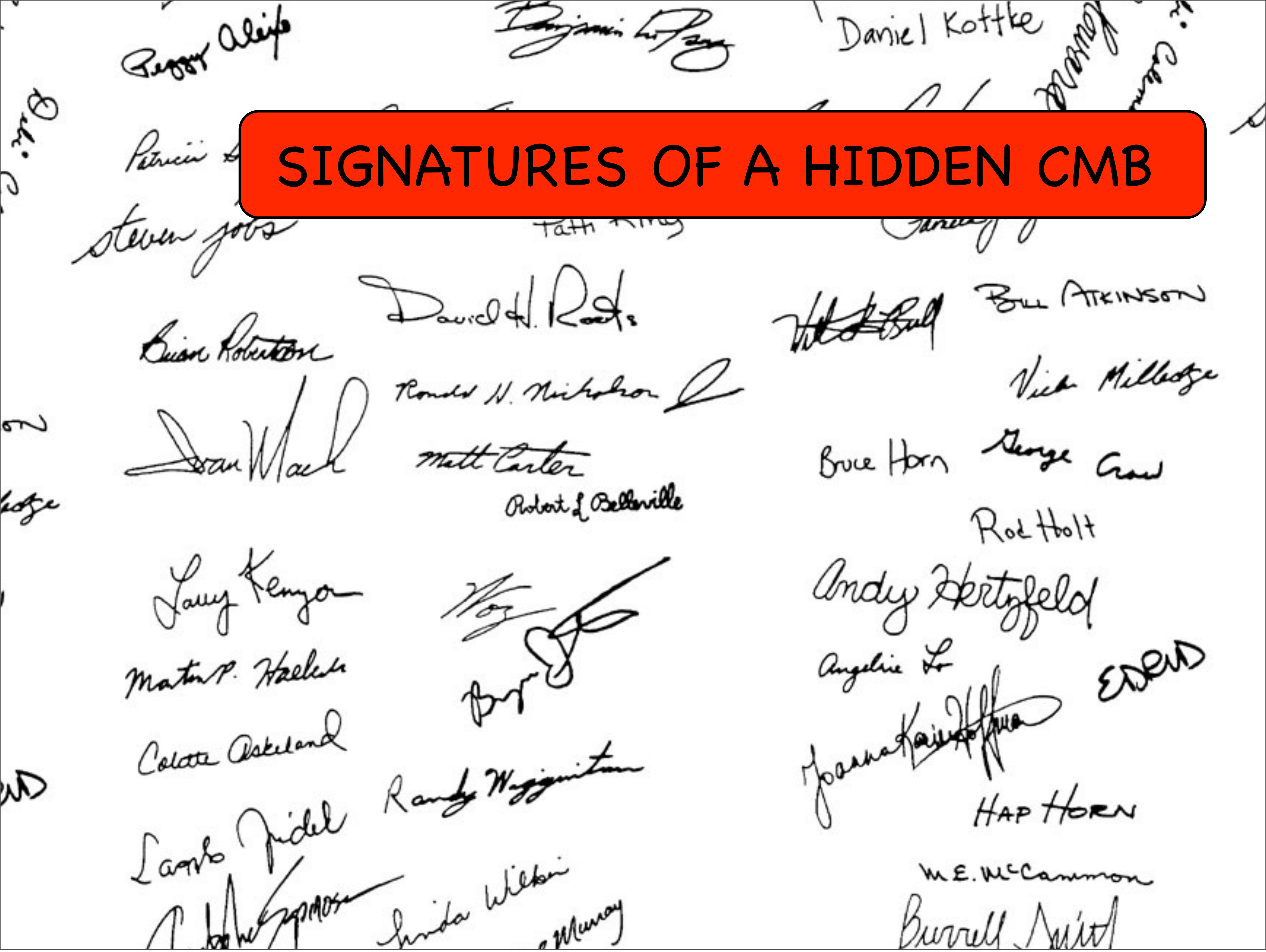
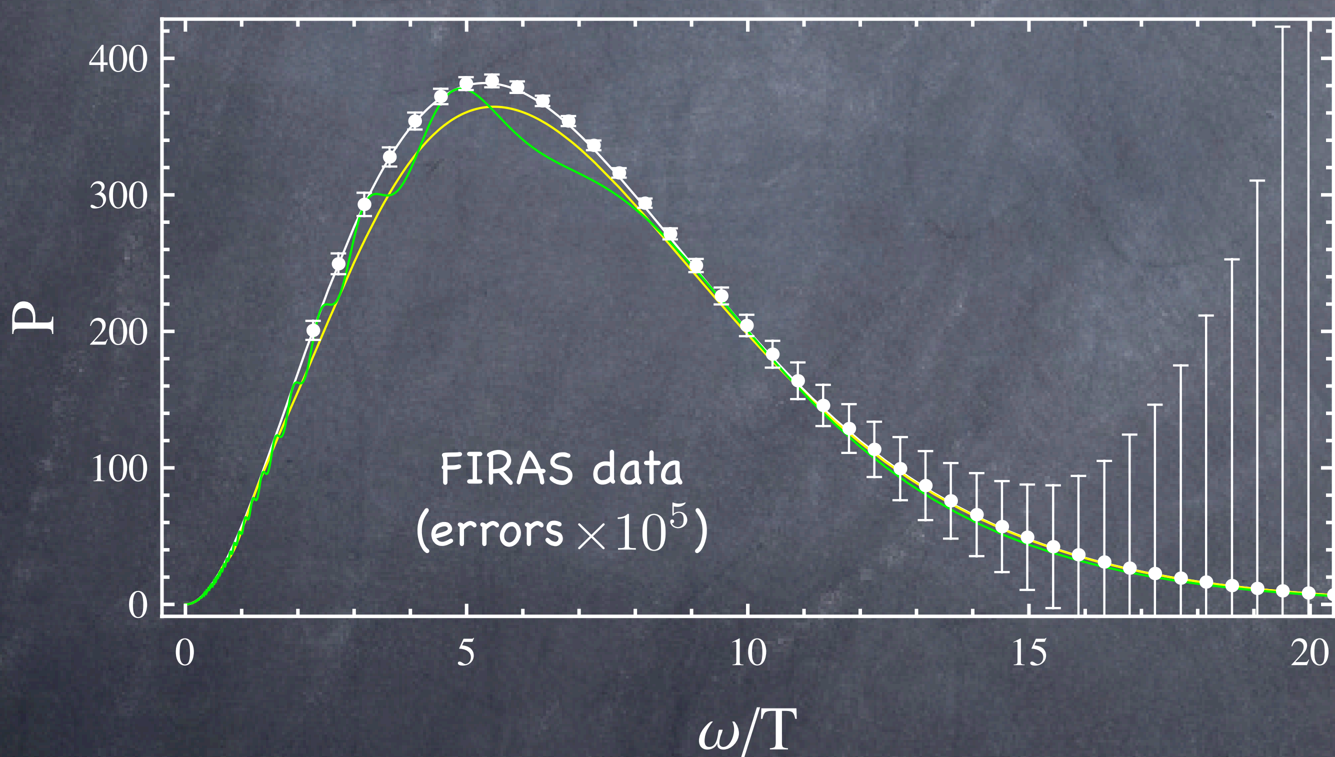
SIGNATURES OF A HIDDEN CMB

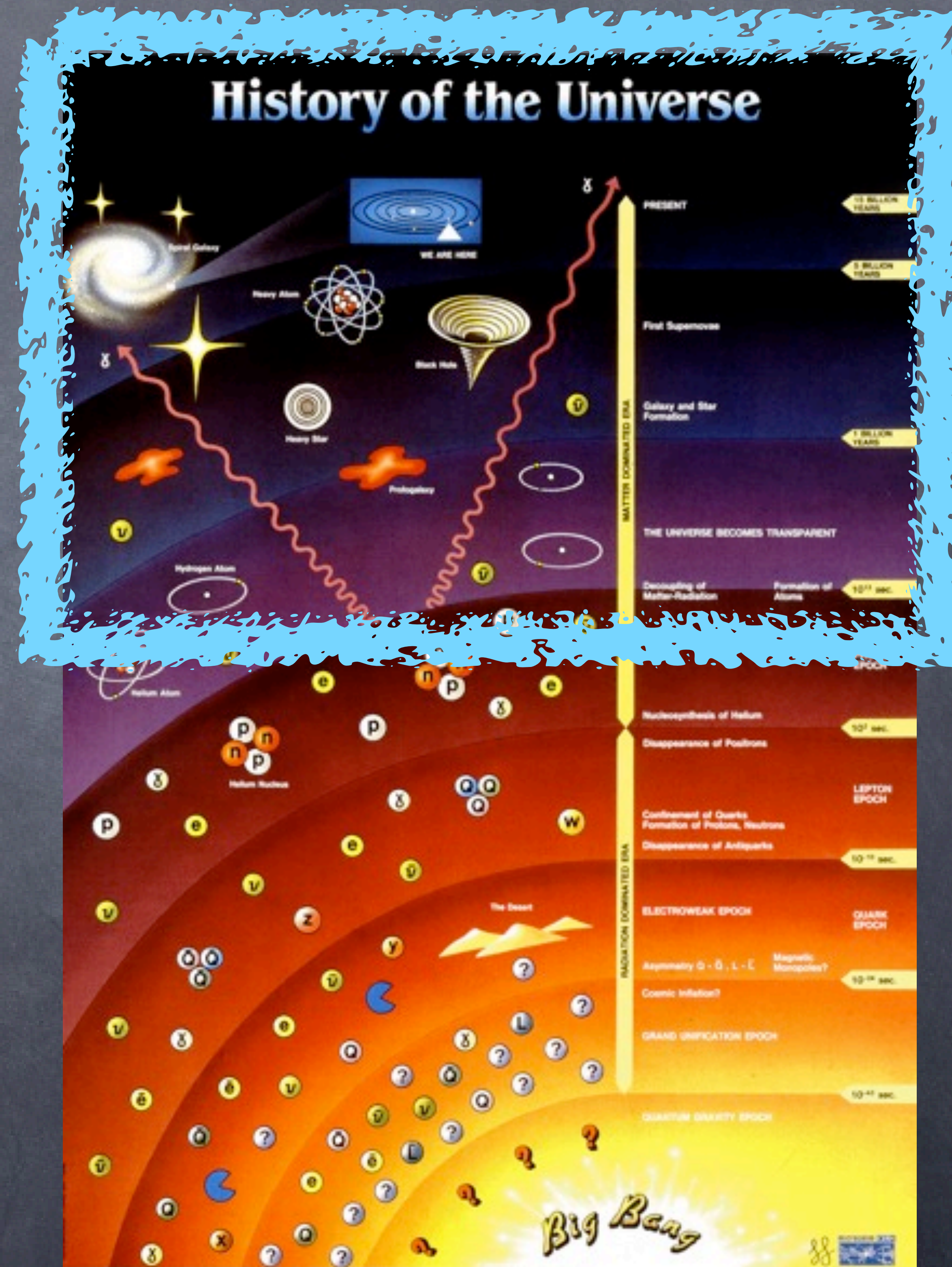


Resonance AFTER Recombination

After the resonance, the primordial plasma cannot process the CMB distortions

FIRAS on COBE measured the CMB spectrum with 10^4 accuracy!





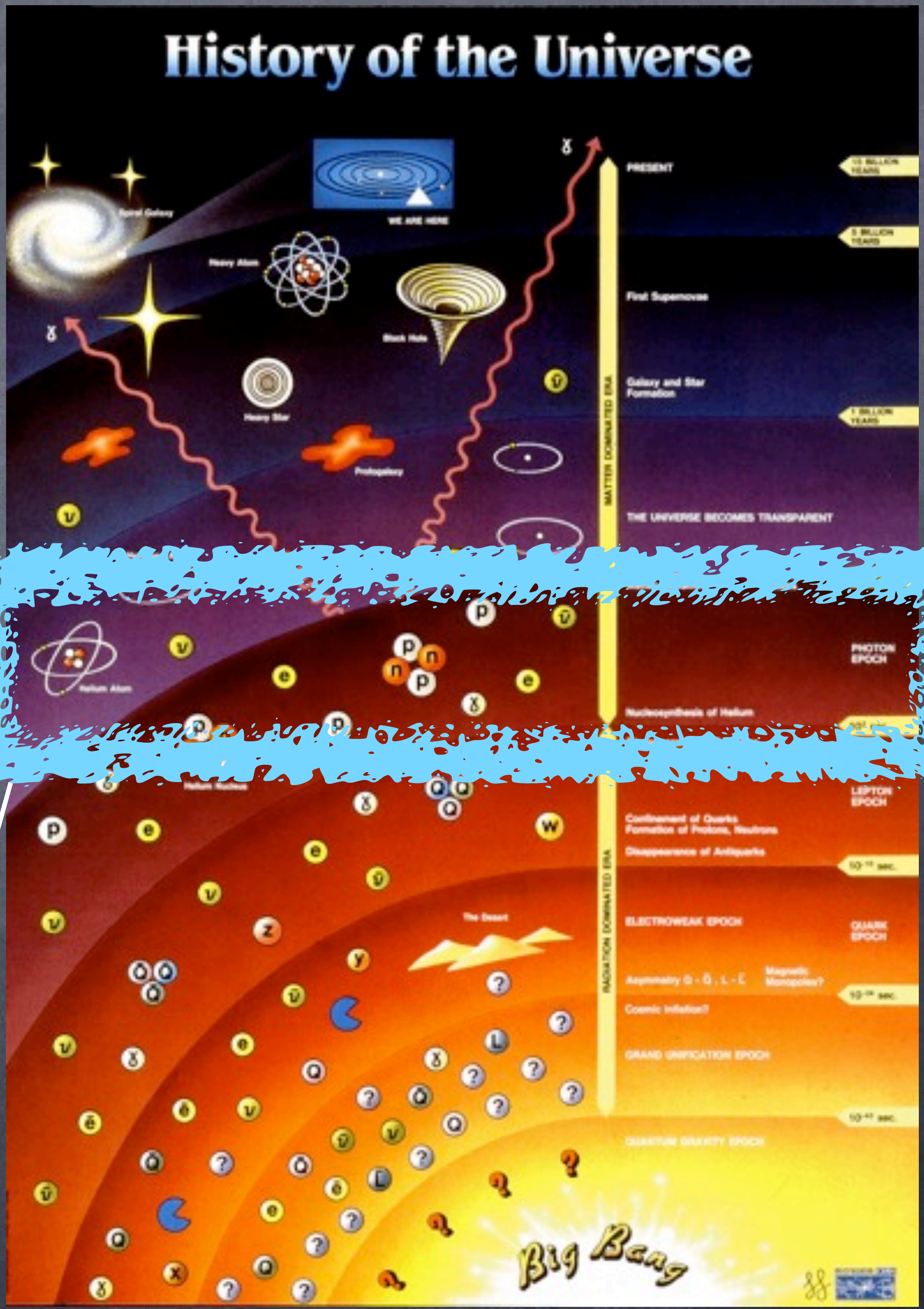
Photon oscillations into WISPs are frequency dependent and they leave their imprint on the CMB spectrum

SIGNATURES OF THE FORMATION OF A HIDDEN CMB: spectral distortions II

Resonance BEFORE Recombination (after BBN)

After the resonance, the primordial plasma can process the CMB distortions

Three periods determined by the response of the plasma to CMB distortions



Compton Scattering of direction fast

DIRECTION AND POLARIZATION AVERAGE

Compton Scattering of energy fast

KINETICAL EQUILIBRIUM REGAINED

$$\mu - \mathrm{distortion}$$

Double Compton Scattering effective

RECREATION OF A BB SPECTRUM

Resonance BEFORE Recombination (after BBN)

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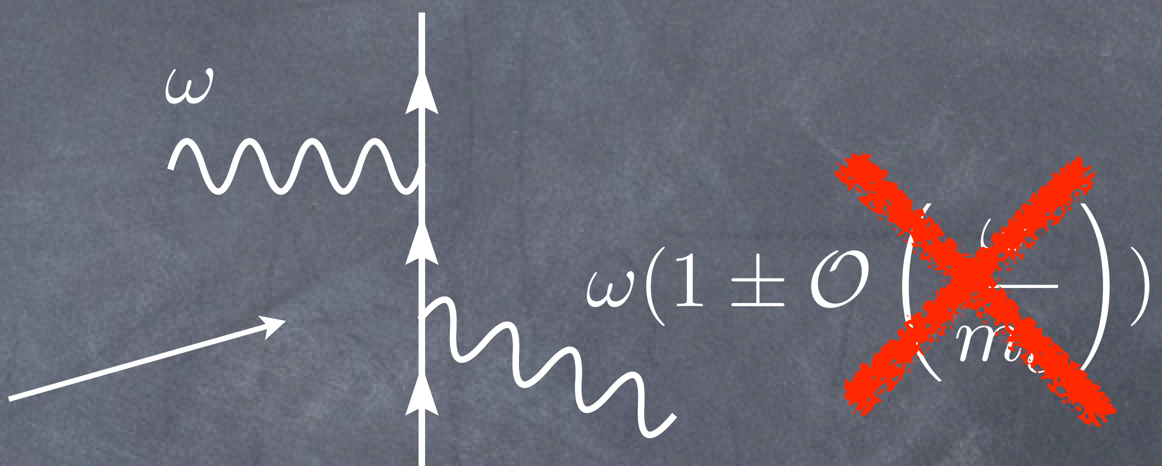

Compton Scattering of direction fast

DIRECTION AND POLARIZATION AVERAGE

Compton Scattering of energy fast

KINETICAL EQUILIBRIUM REGAINED

$$\mu - \text{distortion}$$

Double Compton Scattering effective

RECREATION OF A BB SPECTRUM

SIGNATURES OF THE FORMATION OF A HIDDEN CMB: spectral distortions II

Resonance BEFORE Recombination (after BBN)

After the resonance, the primordial plasma can process the CMB distortions

Three periods determined by the response of the plasma to CMB distortions

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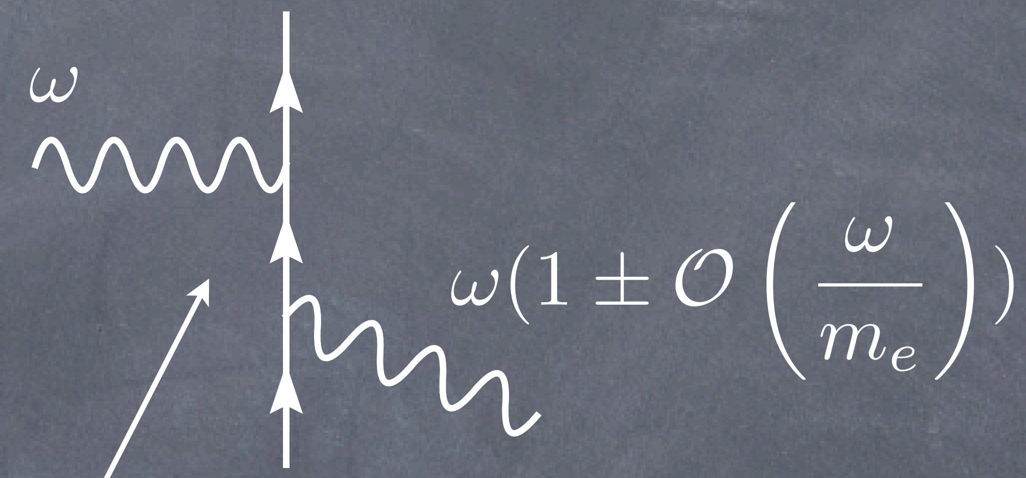
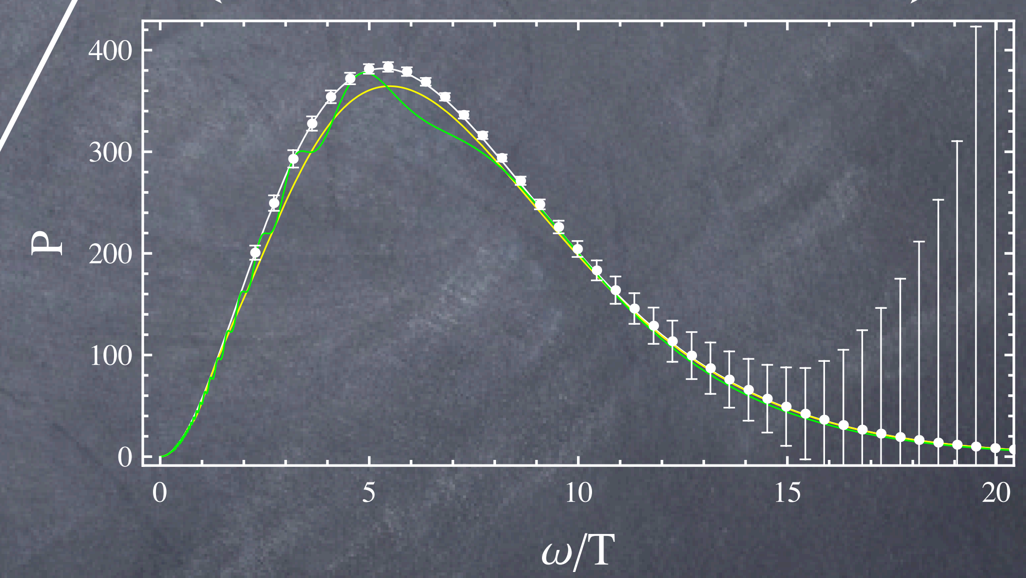


Photons can redistribute up and down



but photon number is conserved !

$$f \to \frac{1}{e^{\frac{\omega}{T'}+\mu} - 1}$$

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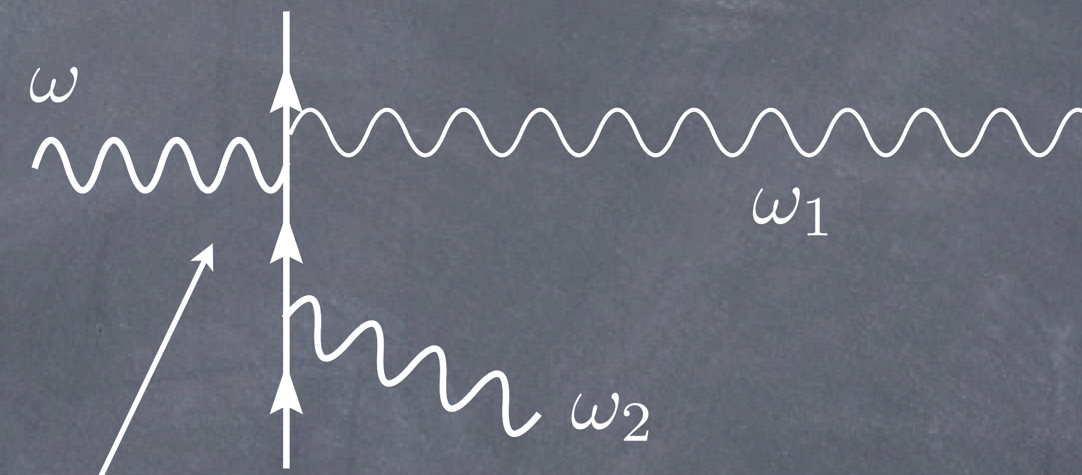

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RECREATION OF A BB SPECTRUM

NOW photon number is NOT conserved !

$$f \to \frac{1}{e^{\frac{\omega}{T'}+\mu} - 1}$$

$\mu \to 0$

(Double Compton erases the chemical potential away)

Other signatures?

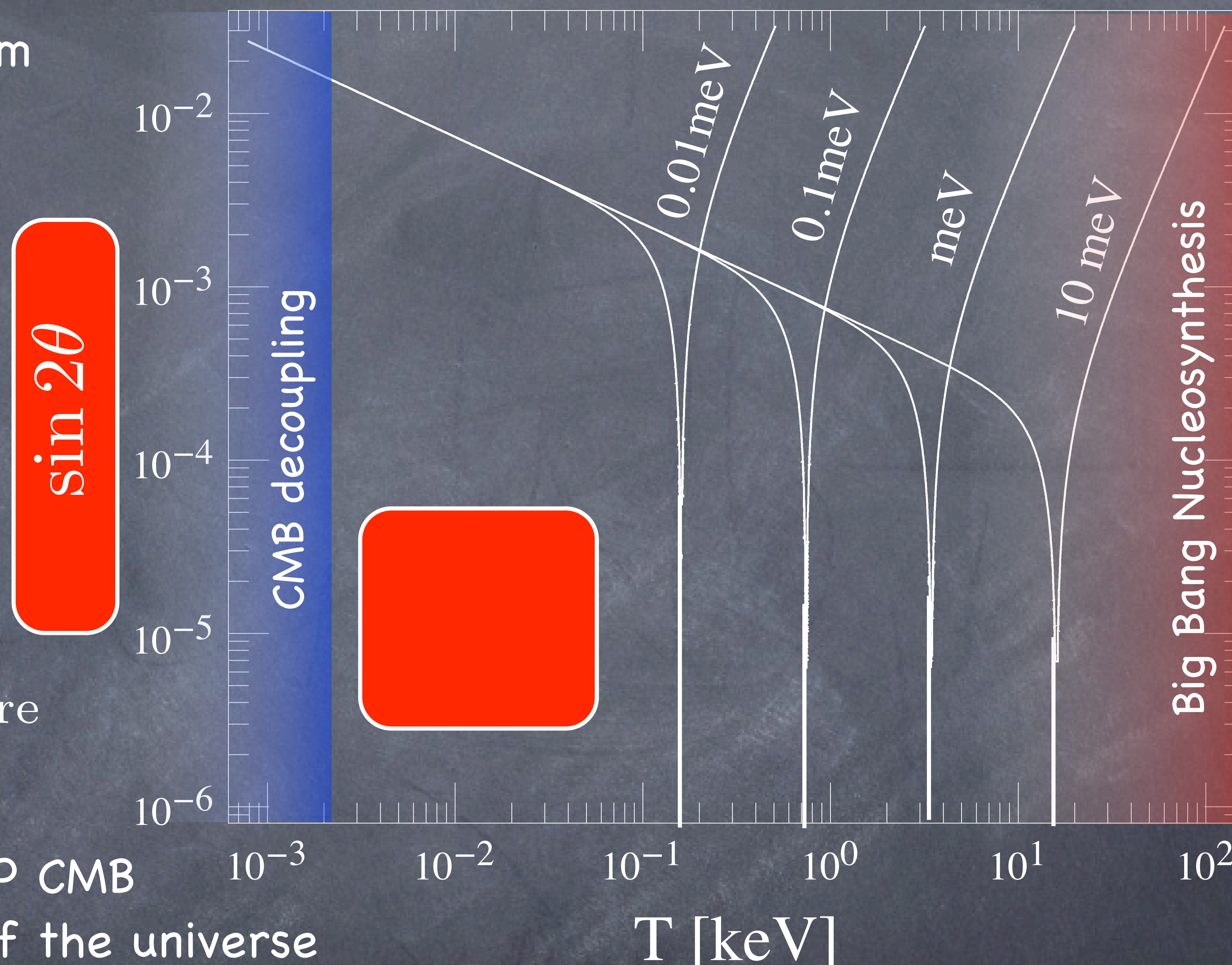
SIGNATURES OF THE FORMATION OF A HIDDEN CMB: Hidden Energy Matters

Oscillations transfer energy from photons to WISPS

$$x \equiv \frac{\rho_\phi}{\rho_\gamma}$$

Double Compton restores a BlackBody for photons at a different Temperature

$$T^{\text{after}} = (1-x)^{1/4} T^{\text{before}}$$



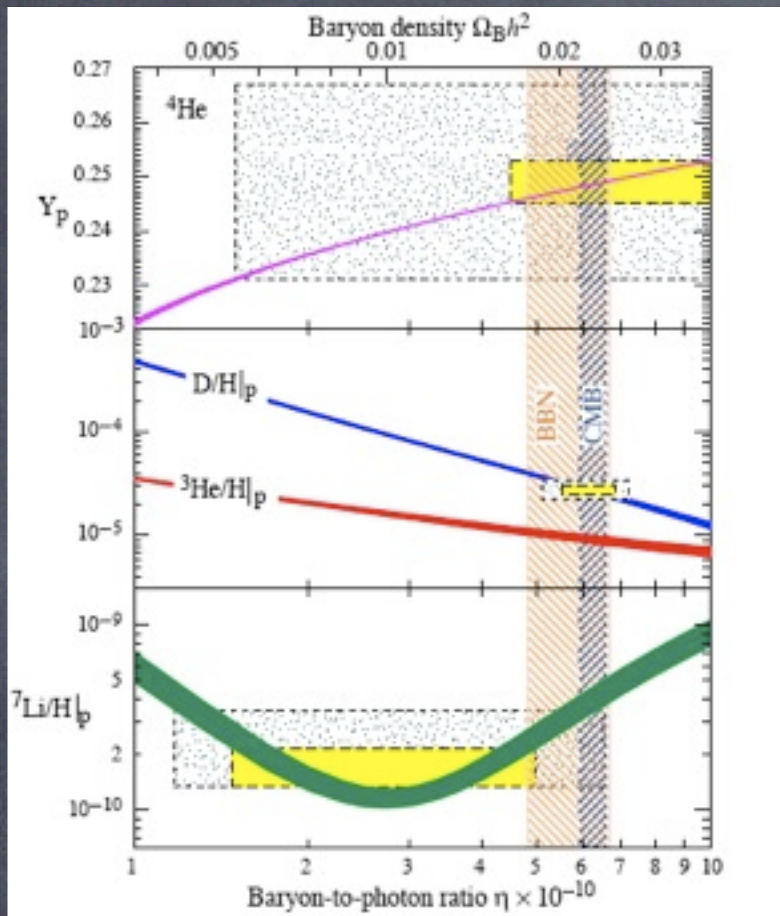
The energy stored in the WISP CMB contributes to the expansion of the universe as if they were additional neutrinos

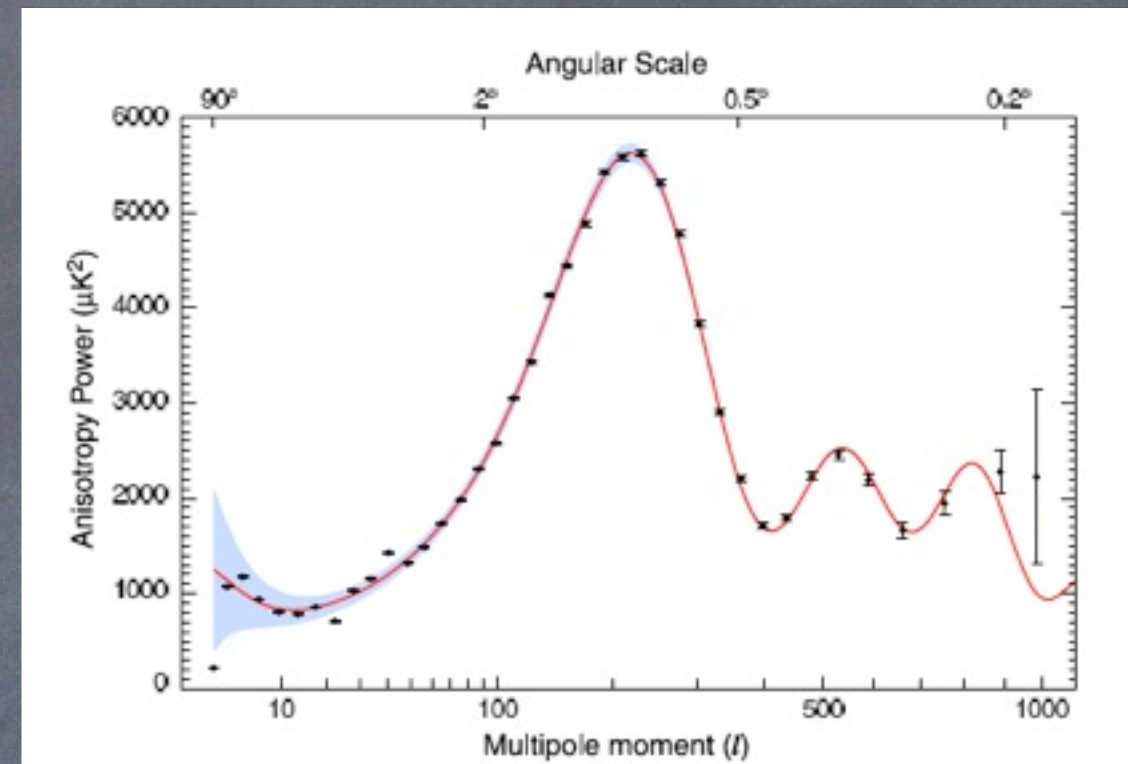
$$N_\nu^{\text{eff}}(x) = \frac{N_\nu}{1-x} + \frac{8}{7}\frac{x}{1-x}\left(\frac{11}{4}\right)^{4/3}$$

The number of effective neutrinos is both measured at BBN and at the CMB decoupling!

SIGNATURES OF THE FORMATION OF A HIDDEN CMB: Hidden Energy Matters

BBN vs CMB(+others...)





BBN results (PDG)

CMB results (Steigman)

(WMAP5+otherCMB+LSS+SN+HST)

Assume $N_\nu = 3.046$

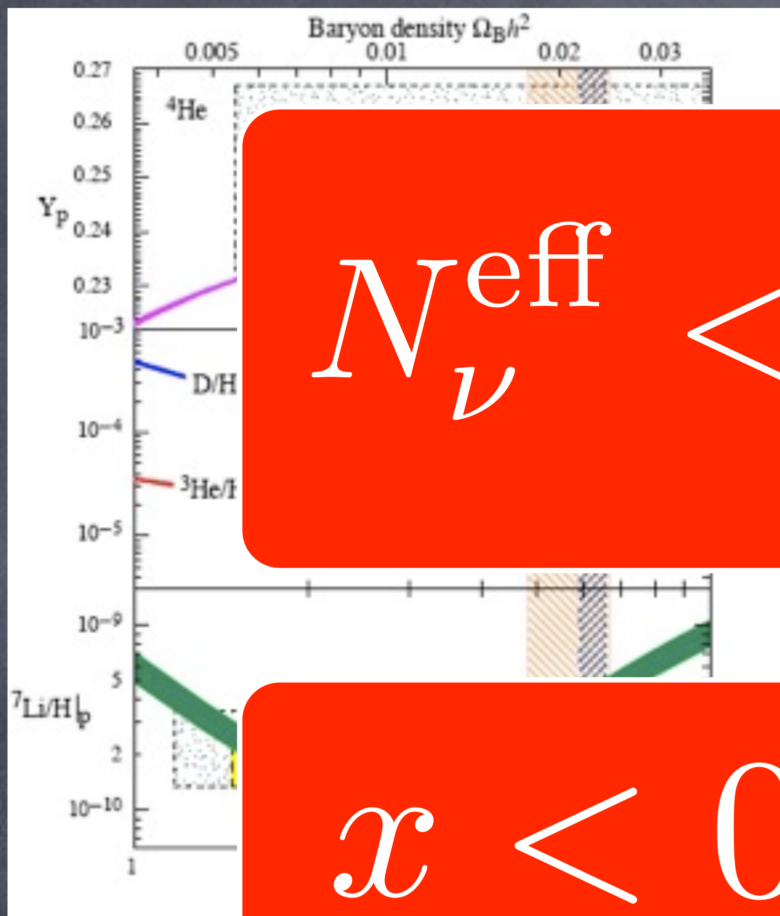
$$\eta^{\rm BBN} = 5.7^{+0.8}_{-0.9} \times 10^{-10}$$

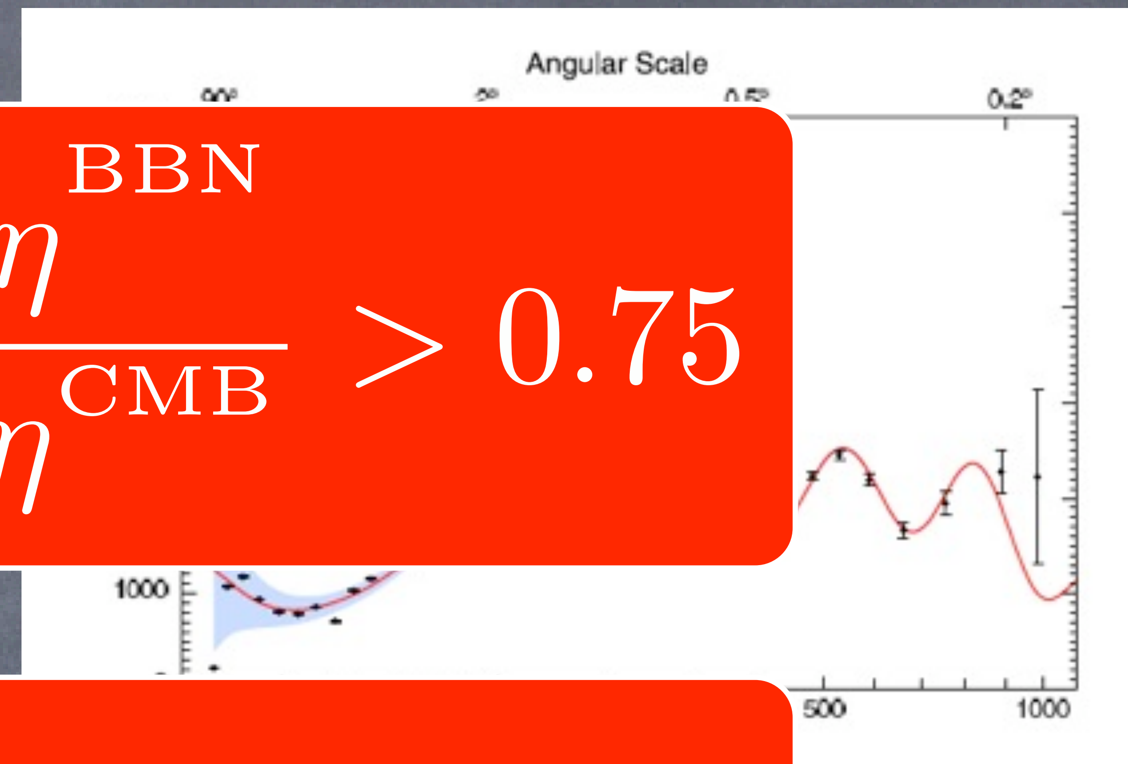
$$\eta^{\rm CMB} = 6.14^{+0.3}_{-0.25} \times 10^{-10}$$

$$N_\nu^{\rm eff} = 2.9^{+2.0}_{-1.4}6$$

SIGNATURES OF THE FORMATION OF A HIDDEN CMB: Hidden Energy Matters

BBN vs CMB(+others...)





$$N_\nu^{\rm eff} < 4.8 \qquad \frac{\eta^{\rm BBN}}{\eta^{\rm CMB}} > 0.75$$

$$x < 0.2 \qquad x < 0.32$$

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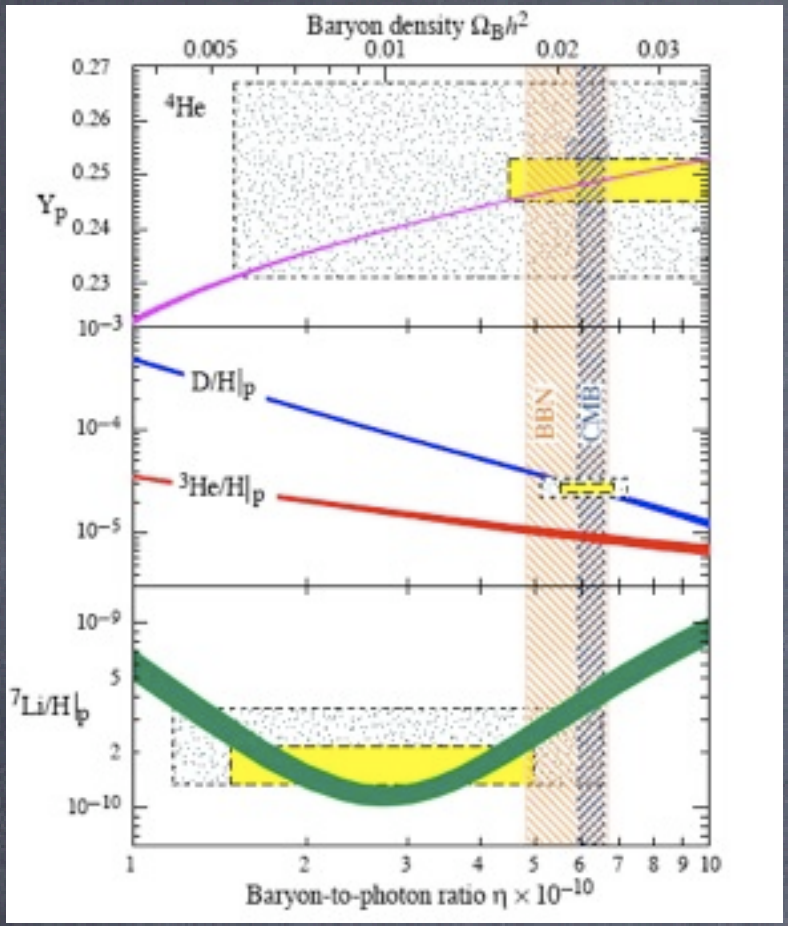
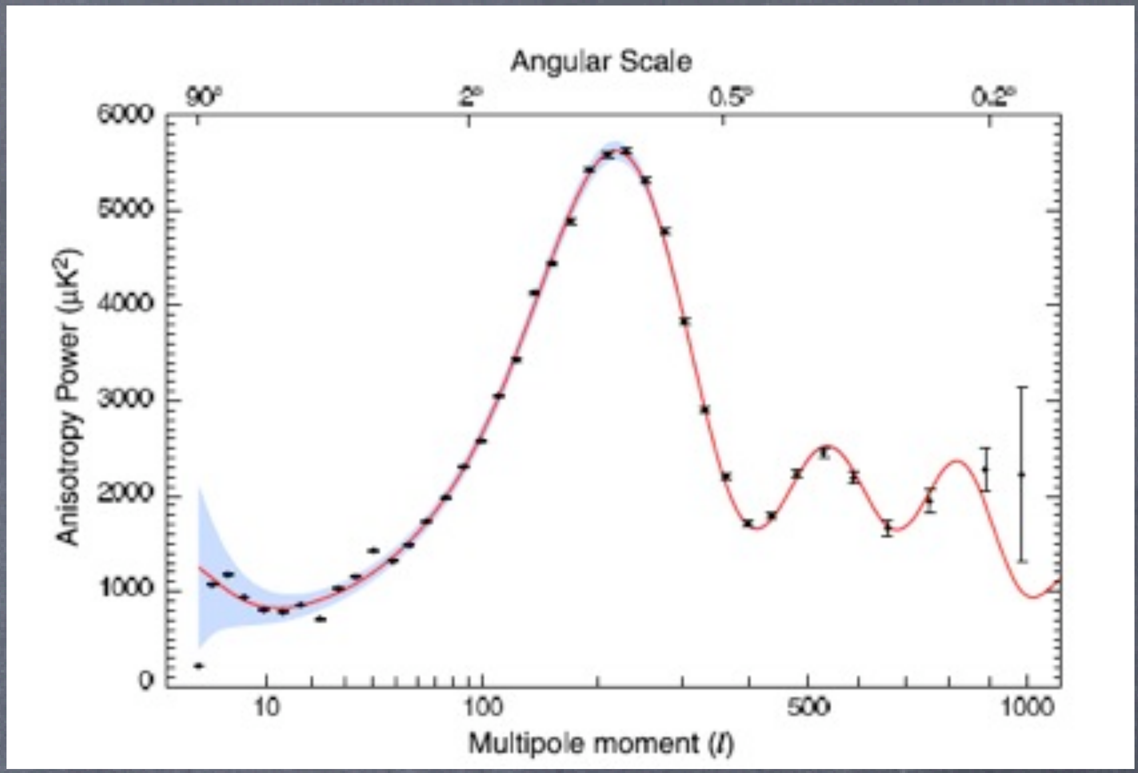
BBN vs CMB(+other +SDSS+Ly-alpha)





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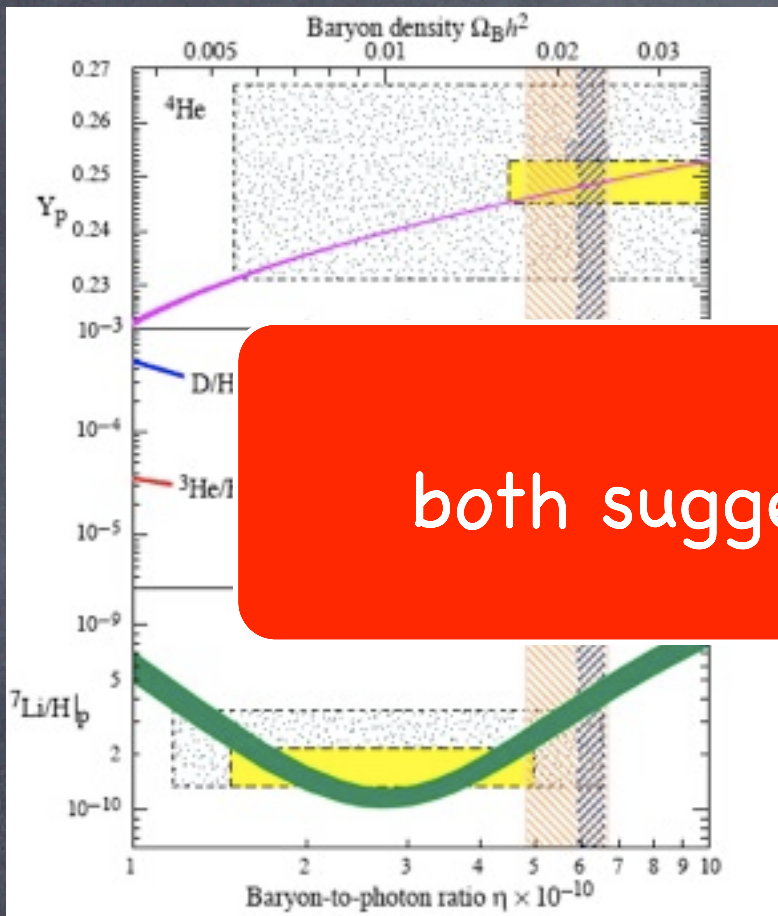
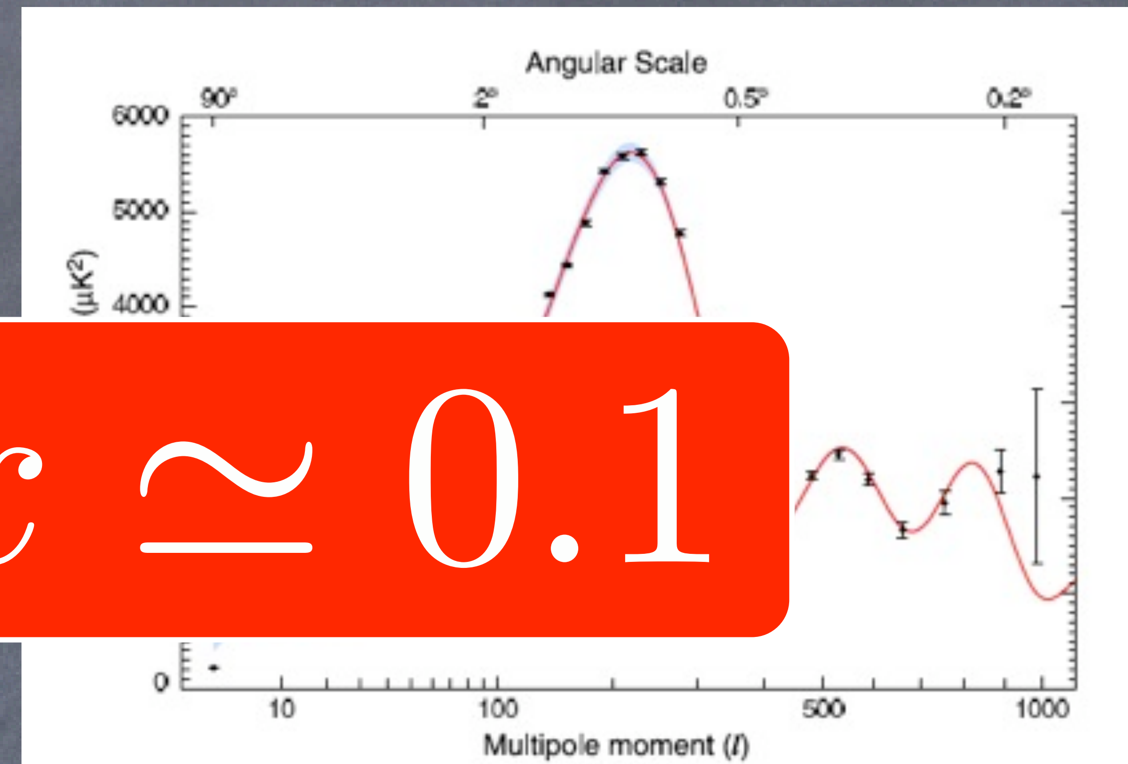
BBN vs CMB(+other +SDSS+Ly-alpha)





both suggest ... $x \simeq 0.1$

BBN results (PDG)

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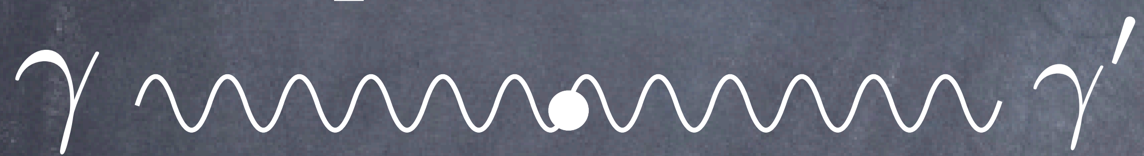
HIDDEN PHOTONS

At first order in δ the resonant conversion probability in a varying medium is

$$P(\gamma \to \phi) = \pi \frac{\delta^2}{m_\phi^2 \omega H(z_r)} \left| \frac{d \log m_\gamma^2}{d \log(1+z)} \right|^{-1}_{z=z_r}$$

Hidden Photons

$$\mathcal{L}_\mathrm{I} = -\frac{\chi}{2} F_{\mu\nu} B^{\mu\nu} a \to \delta = \chi m_{\gamma'}^2$$



$$P(\gamma \to \gamma') = \frac{\pi \chi^2 m_\gamma^2}{3 H \omega} \Big|_{z_\mathrm{res}}$$

Simple case, Xe = 1

$$m_\gamma^2 = (2 \times 10^{-14}\,\mathrm{eV})^2 (1+z)^3 \qquad |...| = 3 \qquad H \propto (1+z)^{(2,3/2)} (\mathrm{RD}, \mathrm{MD})$$

$$P(\gamma \to \gamma')(RD) = \chi^2 \frac{\mathrm{const.}}{\omega / T}$$

Low energy photons oscillate easier
Larger distortions at low energies

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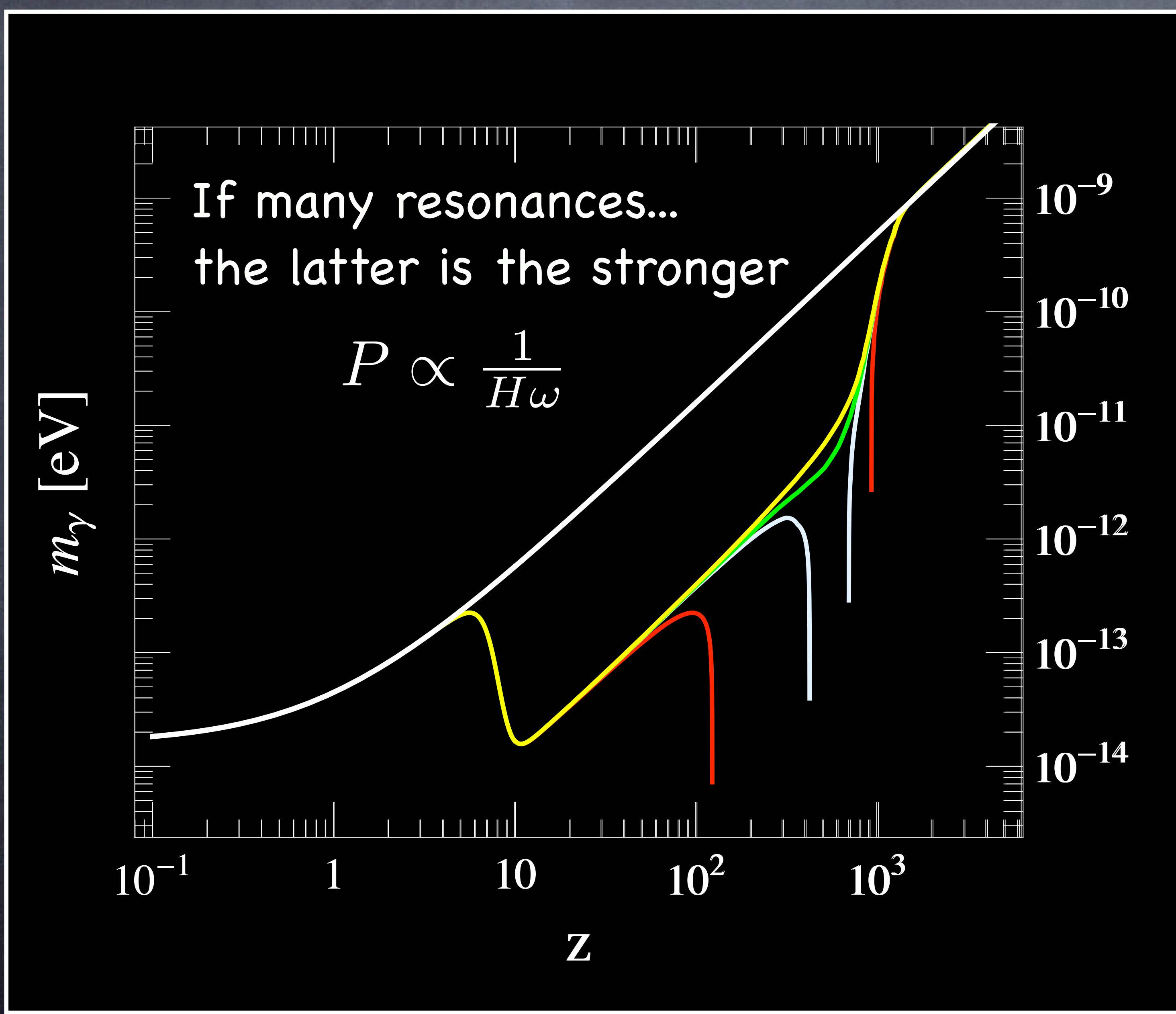

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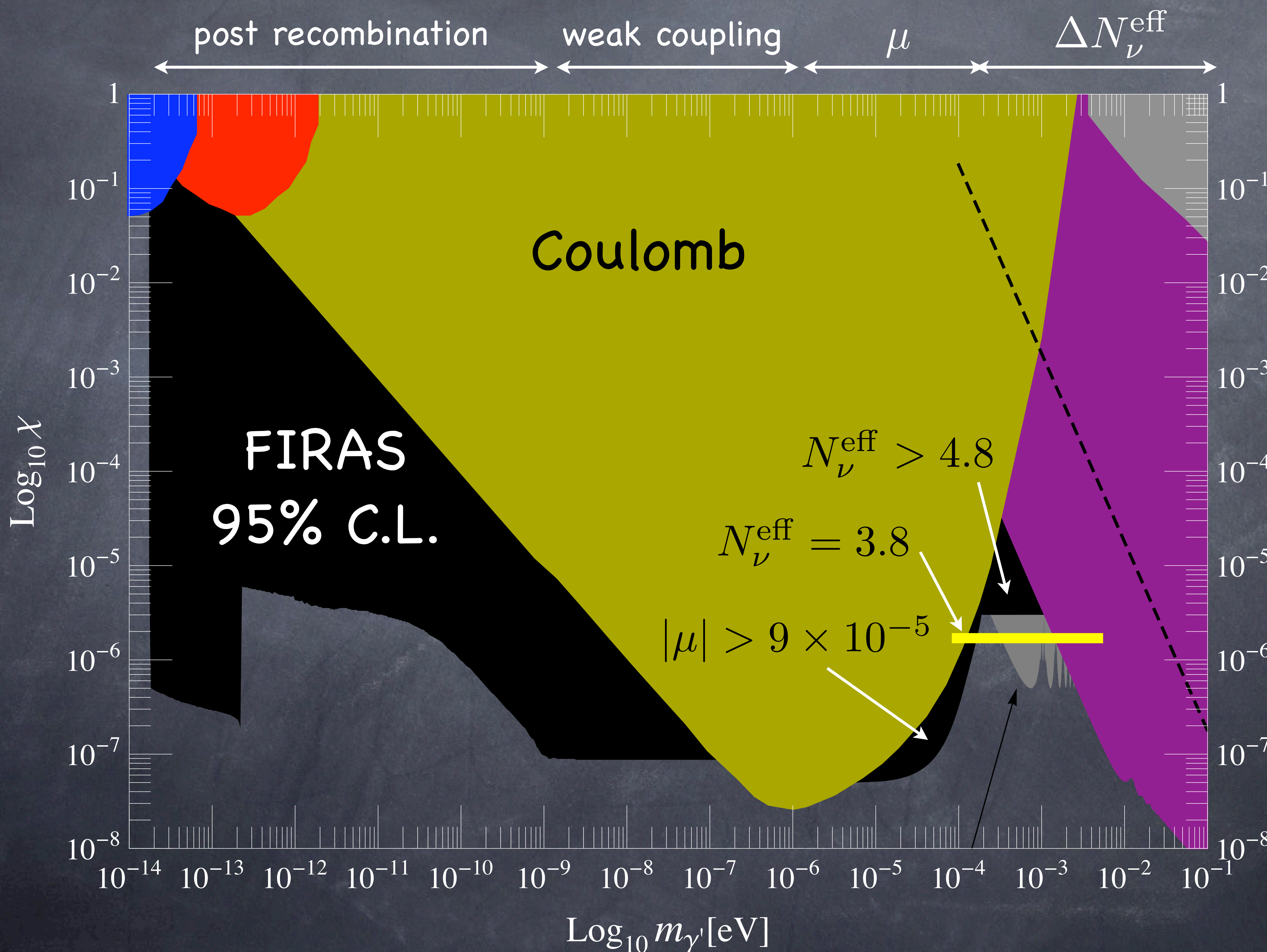

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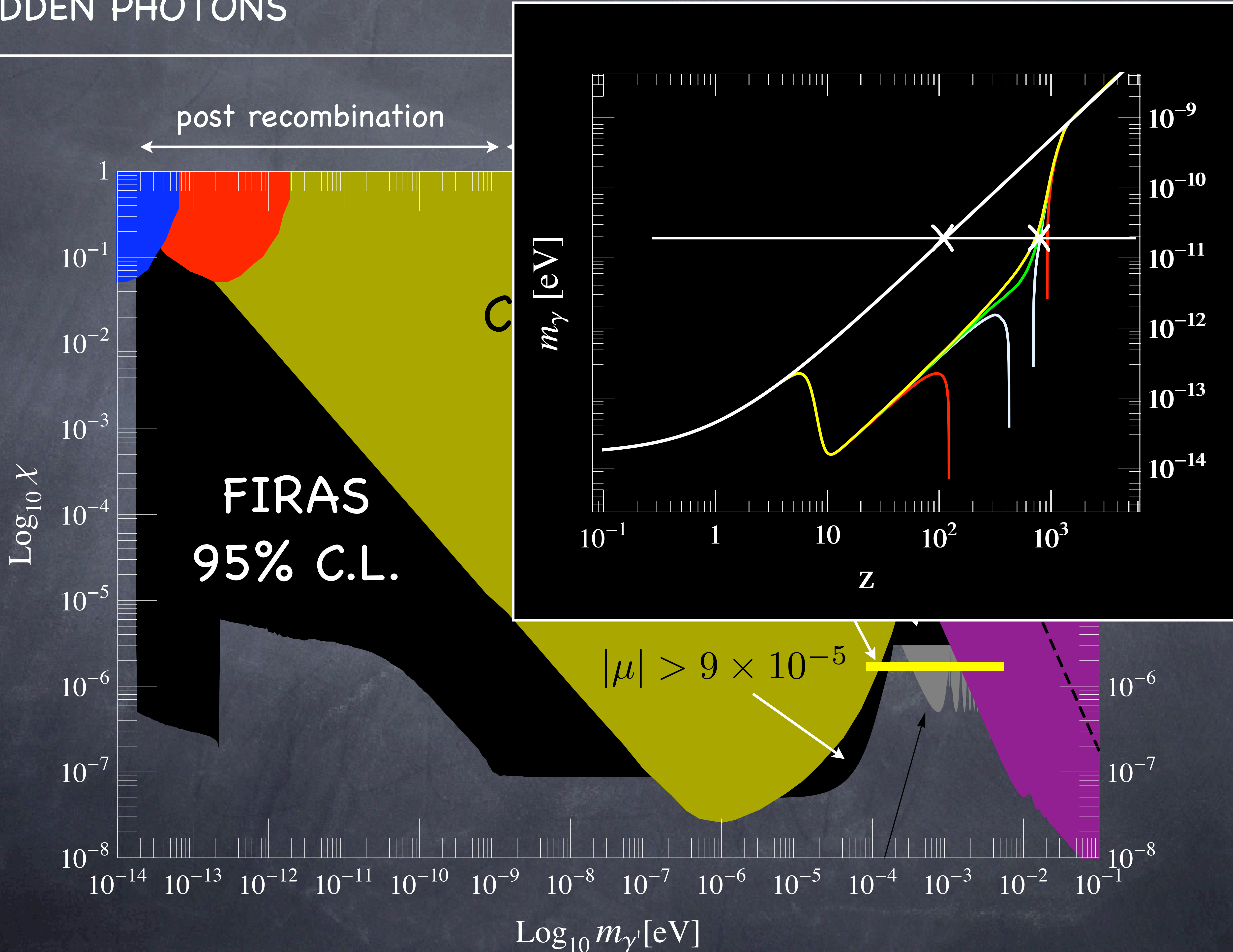

AXION-LIKE PARTICLES

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$$P(\gamma \to a) = \left. \frac{\pi (g B_{\rm T} \omega)^2}{3 H \omega} \right|_{z_{\rm res}}$$

Primordial Magnetic Field ``Frozen"

$$B_T = B_{T,0}(1+z)^2$$

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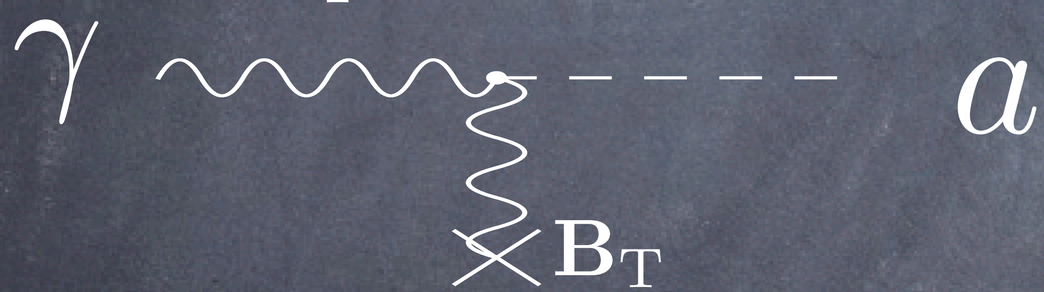
Axion-like Particles

$$\mathcal{L}_\mathrm{I} = g \frac{1}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} a \to \delta = g B_\mathrm{T} \omega$$



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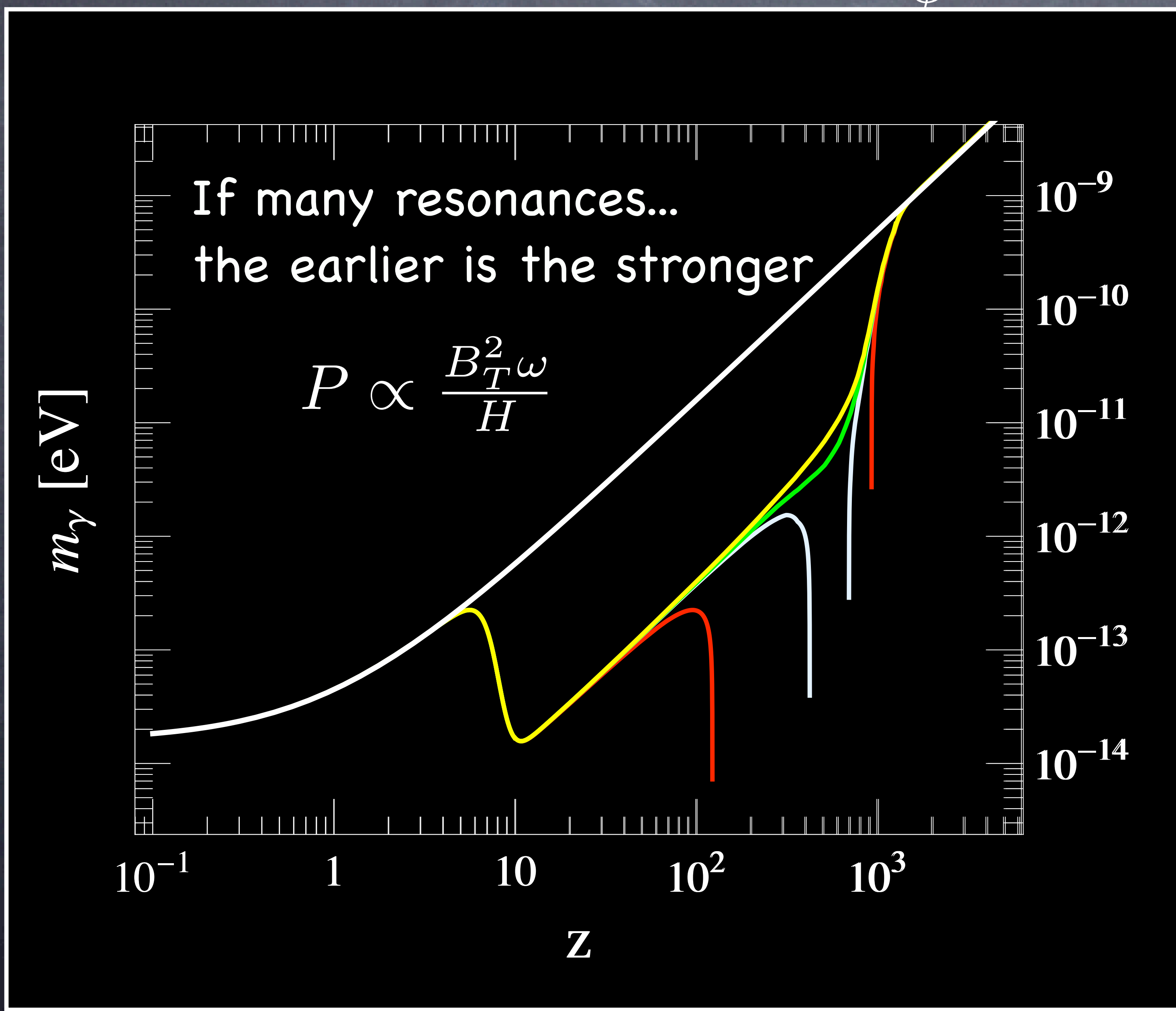

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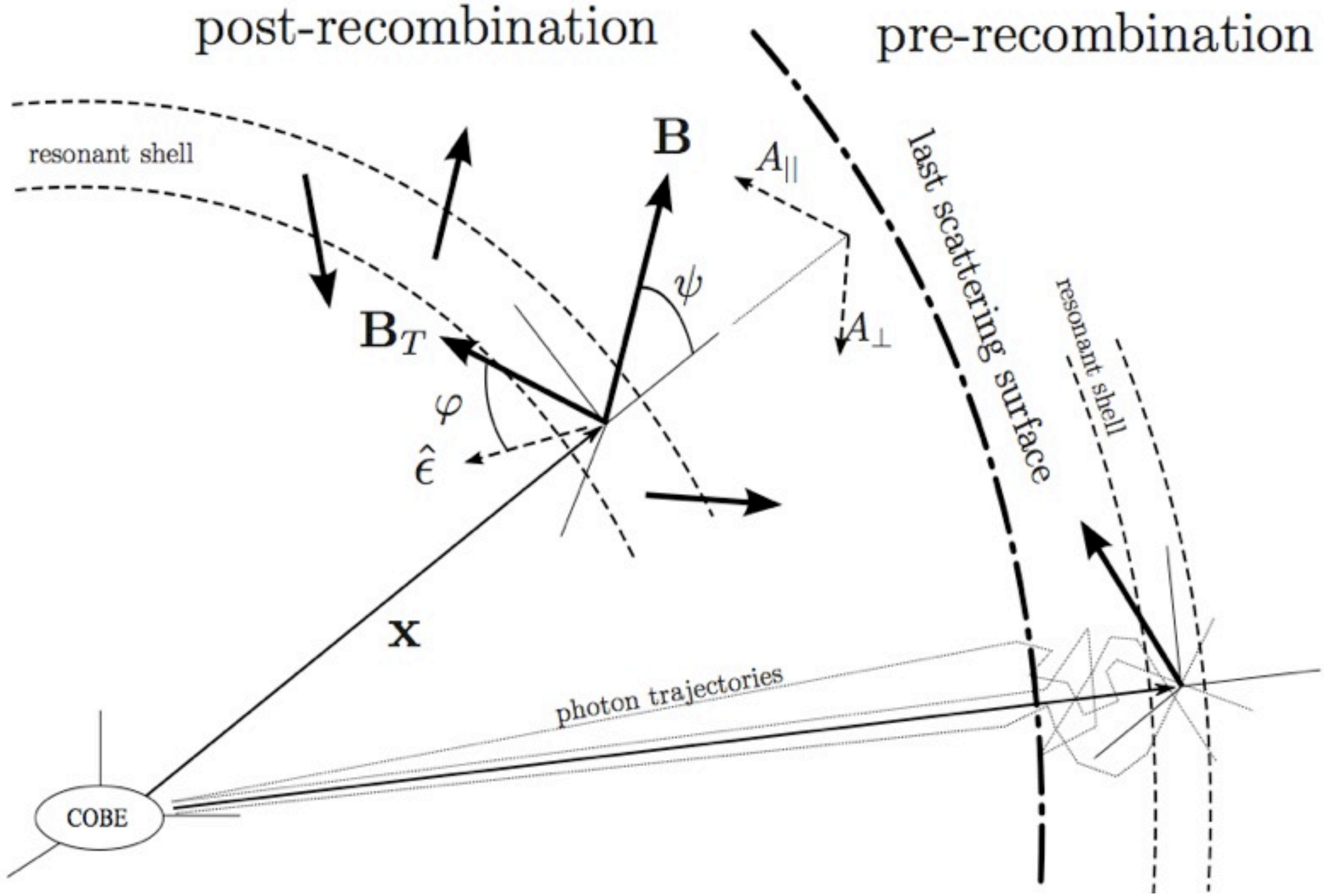
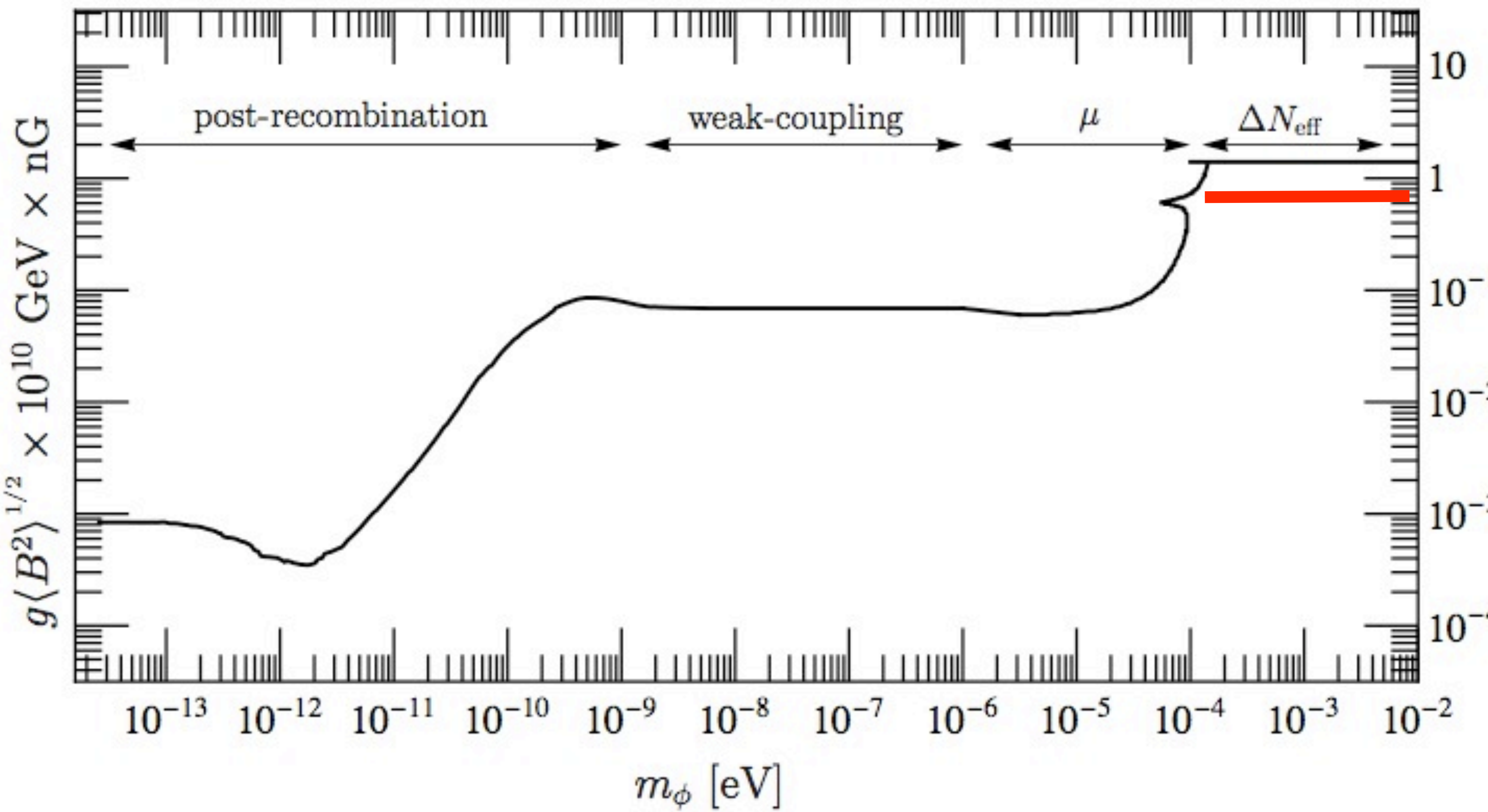


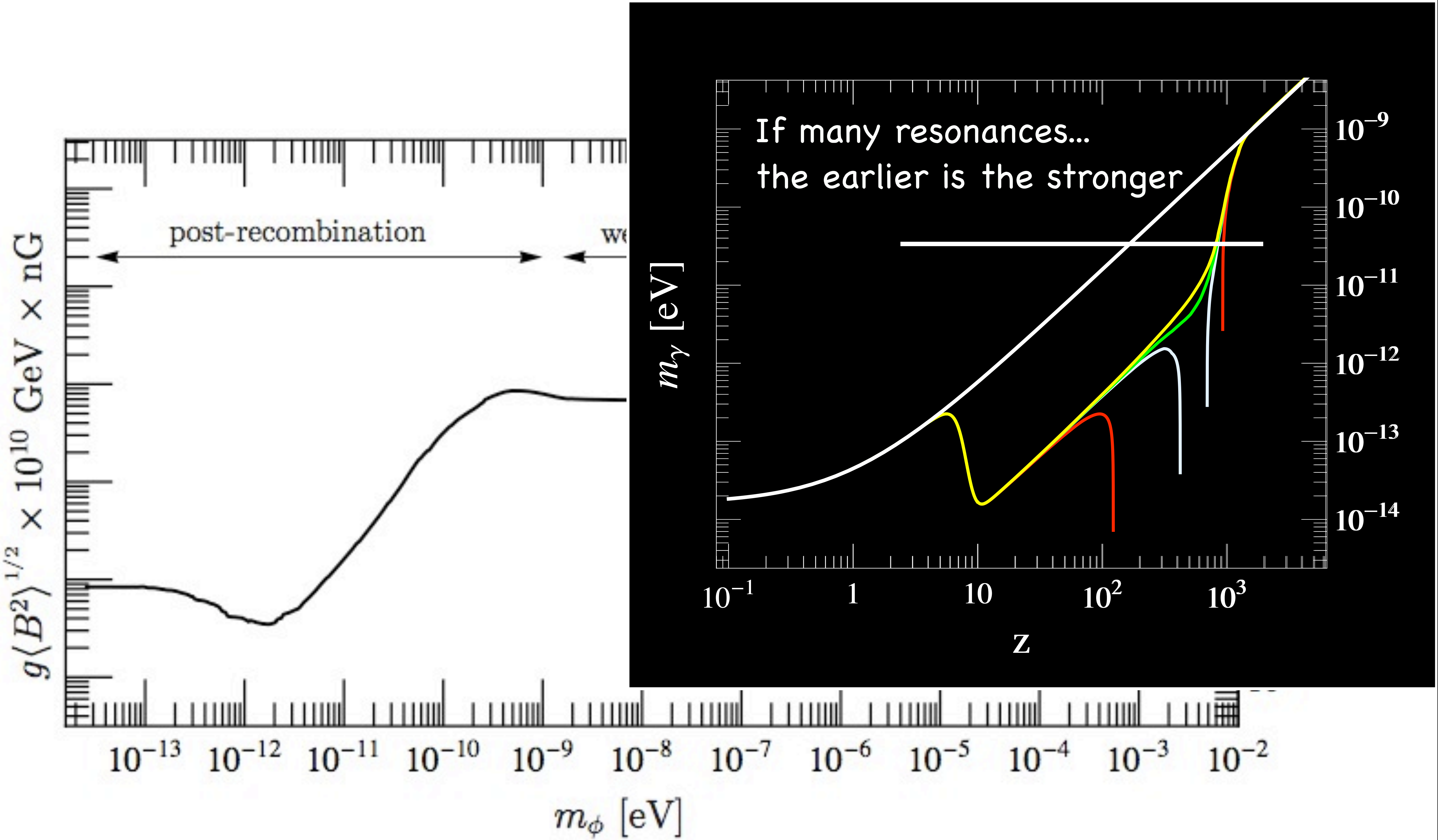
Resonances after recombination produce not only spectral distortions but also anisotropies and polarization (work in progress)

Resonances before recombination will lost polarization signatures due to Compton scattering ...

AXION-LIKE PARTICLES



AXION-LIKE PARTICLES



Conclusions

- Resonant photon oscillations of the CMB can create a Hidden CMB

- Signatures are distortions of the spectrum, enhanced baryon to photon ratio and effective neutrinos (CMB vs BBN)
*(first hint? points to meV masses)

- Axion Like particles require Primordial Magnetic Fields B
* If discovered -> Strong Bounds on g

$$B \sim 10^{-7}\mathrm{G} \rightarrow g < 10^{-13,-15}\mathrm{GeV}^{-1}$$

* If an ALP is discovered-> bounds on B

$$g \sim 10^{-11}\mathrm{GeV}^{-1} \rightarrow B \lesssim \mathrm{nG}$$

* Work in progress for polarization and anisotropies

-Other WISPs can be equally constrained

THANK YOU!