Constraints on sub-eV physics beyond the SM from cosmological distance measurements

Tasos Avgoustidis

(DAMTP/CTC, University of Cambridge)

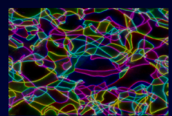
Based on:

Arxiv:1004.2053

Arxiv:0902.2006 (JCAP)

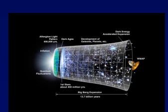
with C. Burrage, J. Redondo, L. Verde & R. Jimenez

Outline

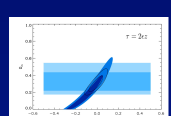


Sub-eV Physics beyond the SM:

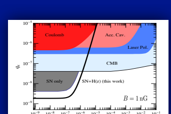
ALPs & MCPs in Field & String Theory



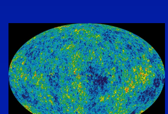
Cosmological Distance Measures



Method & Constraints



Implications for Couplings & Masses



Forecasts & Outlook

The QCD Axion

QCD allows for a CP-violating term:

$$\mathcal{L}_{\not{CP}} = \frac{\alpha_s}{4\pi}\,\theta\,\mathrm{tr}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Parameter θ constrained experimentally:

$$\boxed{|\bar{\theta}| \lesssim 10^{-10}}$$

unnaturally small

<u>*Peccei-Quinn*</u>: Promote θ to a dynamical field, the axion a, with shift symmetry $a \to a + \mathrm{const}$:

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\alpha_s}{4\pi f_a} a\,\mathrm{tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\alpha}{8\pi f_a} a\,F_{\mu\nu}\tilde{F}^{\mu\nu} + \mathcal{L}_{\mathrm{int}}[\partial_\mu a/f_a, \psi]$$

coupling to EM

Non-trivial potential around $\langle a \rangle = 0$, axion is a PNG boson with parametrically small mass:

$$m_a \simeq 0.6\,\mathrm{meV} \times \left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right)$$

Axions in String Theory

Axion-Like Particles (ALPs) arise in String Theory as 0-modes of antisymmetric tensor fields

- *Type II*: bosonic action for a D*p*-brane has two contributions

RR q-form

$$S_p = -T_p \left(\int \underbrace{d^{p+1}\xi \, e^{-\phi} \sqrt{\det(g + B + 2\pi\alpha' F)}}_{\text{DBI piece: includes } F_{\mu\nu}F^{\mu\nu}} + i \int \underbrace{\sum_q C_q \wedge e^{B + 2\pi\alpha' F}}_{\text{WZ piece: includes } aF_{\mu\nu}\tilde{F}^{\mu\nu}} \right)$$

Axion decay const set by the string scale: $f_a \sim \dfrac{M_s}{g_s} \sim 10^{4-17}\,\mathrm{GeV}$

- *Heterotic*:

$aF_{\mu\nu}\tilde{F}^{\mu\nu}$

$$S_H = \frac{2\pi M_s^8}{g_s^2} \int d^{10}x \sqrt{-g} R - \frac{M_s^6}{2\pi g_s^2} \int \frac{1}{4} \mathrm{tr} F \wedge \star F - \frac{M_s^4}{g_s^2} \int \frac{1}{2} \mathrm{tr} H \wedge \star H + \ldots$$

with axion decay const of order $f_a = \dfrac{\alpha_{YM} M_P}{2\pi\sqrt{2}} \sim 10^{16}\,\mathrm{GeV}$

Other sub-eV particles

- *Hidden U(1)* fields, coupling to photons via:

$$\mathcal{L}_{\rm mix} = \frac{\chi}{2 e g_h} F_{\mu\nu} X^{\mu\nu}$$

Mixing parameter $10^{-17} \lesssim \chi \lesssim 10^{-5}$

- *Hidden matter* charged under theses U(1)s

Small (unquantised) charge $\epsilon \sim \chi g_h$

aka Mini-Charged Particles (MCPs)

- *Chameleons* can couple to (ordinary) photons

Constraints on these particles come predominantly from low-E experiments (lasers, microwave cavities, torsion balances,...)

Here we will constrain ALPs (& MCPs) by comparing cosmological distance measurements

Distance Measures in Cosmology

- *Luminosity distance*:

$$\boxed{d_L(z) = (1+z)\frac{c}{H_0}\int_0^z dz' \left[\Omega_m(1+z)^3 + \Omega_V(1+z)^{3(1+w)}\right]^{-1/2}}$$

Inferred from *standard candles*, notably Ia SNae

- *Ang. diameter distance* related through Etherington relation:

(from *standard rulers*)

$$\boxed{d_L(z) \stackrel{?}{=} (1+z)^2 d_A(z)}$$

If photon number conservation is violated, there will be a mismatch in the above due to a non-trivial "opacity" τ :

$$d_{L,obs}(z) = d_{L,true}(z)\, e^{\tau(z)}$$

This can happen if photons are converted to ALPs along line of sight

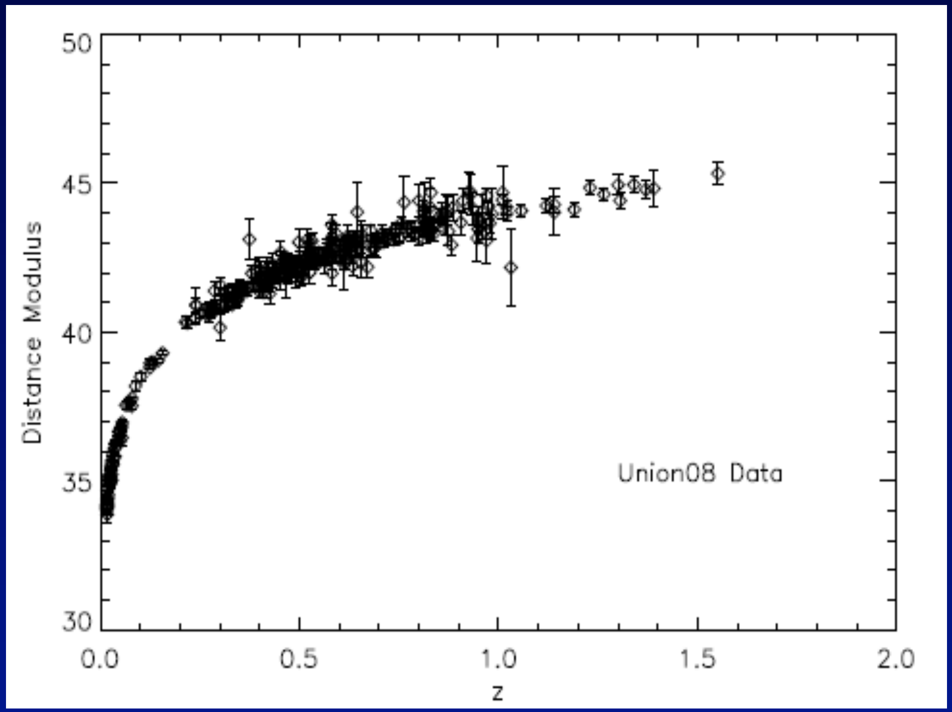
Constraining opacity & ALPs

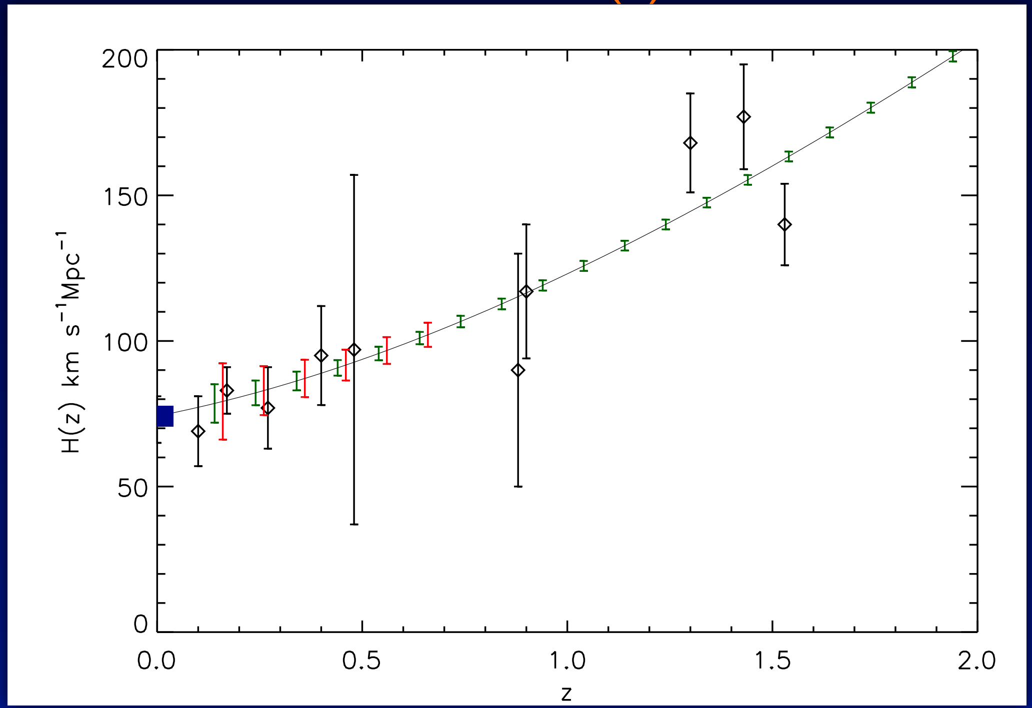
$$d_{L,obs}(z) = (1+z)^2 e^{\tau} d_A(z)$$

Measure from SN observations

constrain

Predict from H(z) data





Any ALP coupling to photons via $\frac{1}{4M} F_{\mu\nu} F^{\mu\nu} \phi$ or $\frac{1}{8M} \epsilon_{\mu\nu\kappa\lambda} F^{\mu\nu} F^{\kappa\lambda} \phi$ will produce non-trivial opacity.

Can constrain jointly ALP coupling and cosmological parameters by using SN and H(z) (or BAO) data.

Method

Run likelihood analysis for flat ΛCDM models in (τ, Ω_m, H_0)

Constrain opacity parameter(s) by marginalising over cosmologies:

$$P(\tau|S,E) = \int_{\Omega_m}\int_{H_0} P(\tau,\Omega_m,H_0|S)\,P(\Omega_m,H_0|E)\,\mathrm{d}\Omega_m \mathrm{d}H_0$$

$$d_{L,obs}(z) = (1+z)^2 e^{\tau} d_A(z)$$

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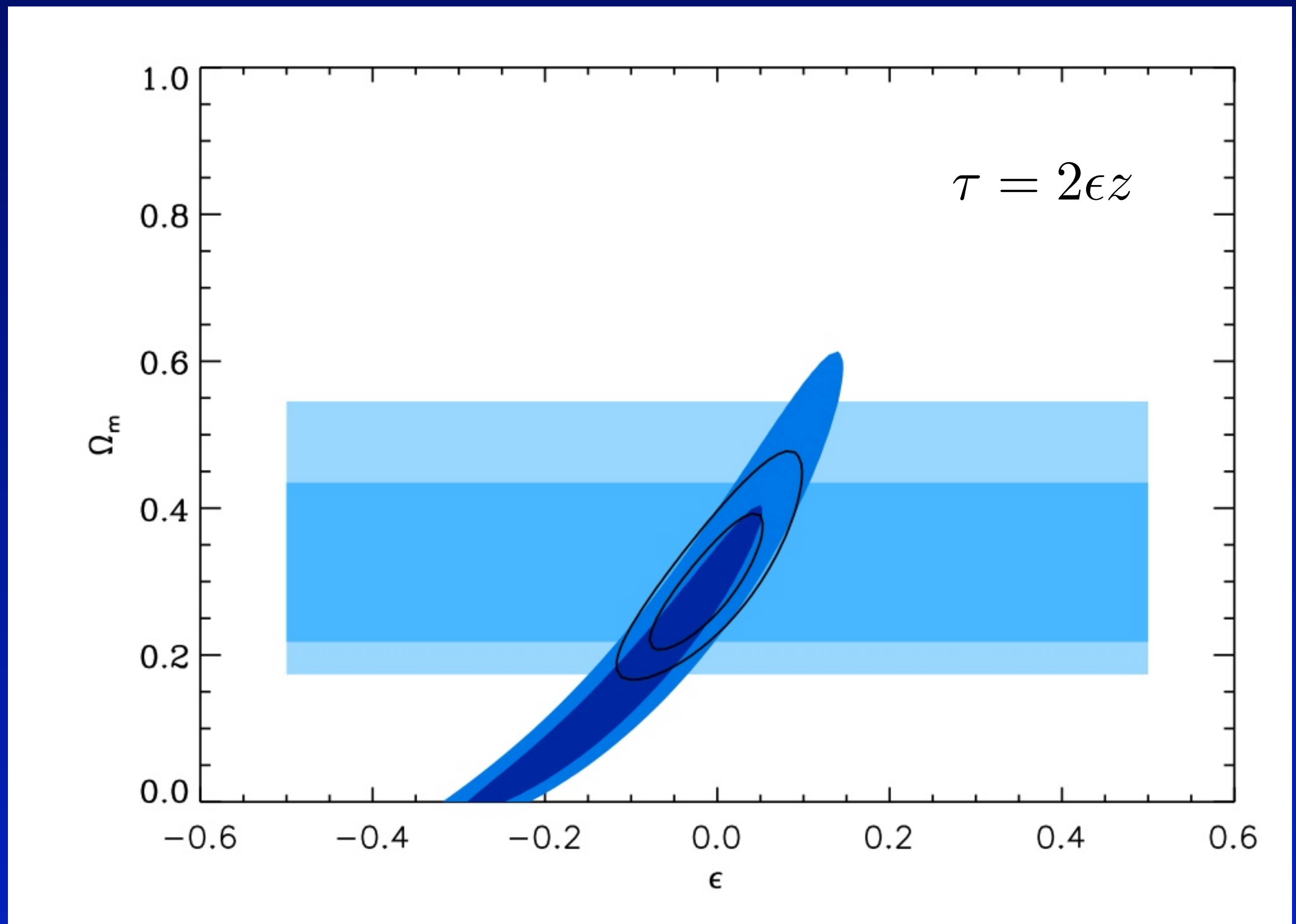

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$$d_{L,obs}(z) = (1+z)^2 e^{\tau} d_A(z)$$

•For ALPs: $$e^{-\tau} \equiv \mathcal{P}(z) = A + (1-A) \exp\left(-\frac{P}{H_0 L} \frac{H(z) - H_0}{\Omega_m H_0}\right)$$

Initial SN flux mix: $A = \frac{2}{3}\left(1 + \frac{I_\phi}{I_\gamma}\right)$

Photon-axion conversion probability

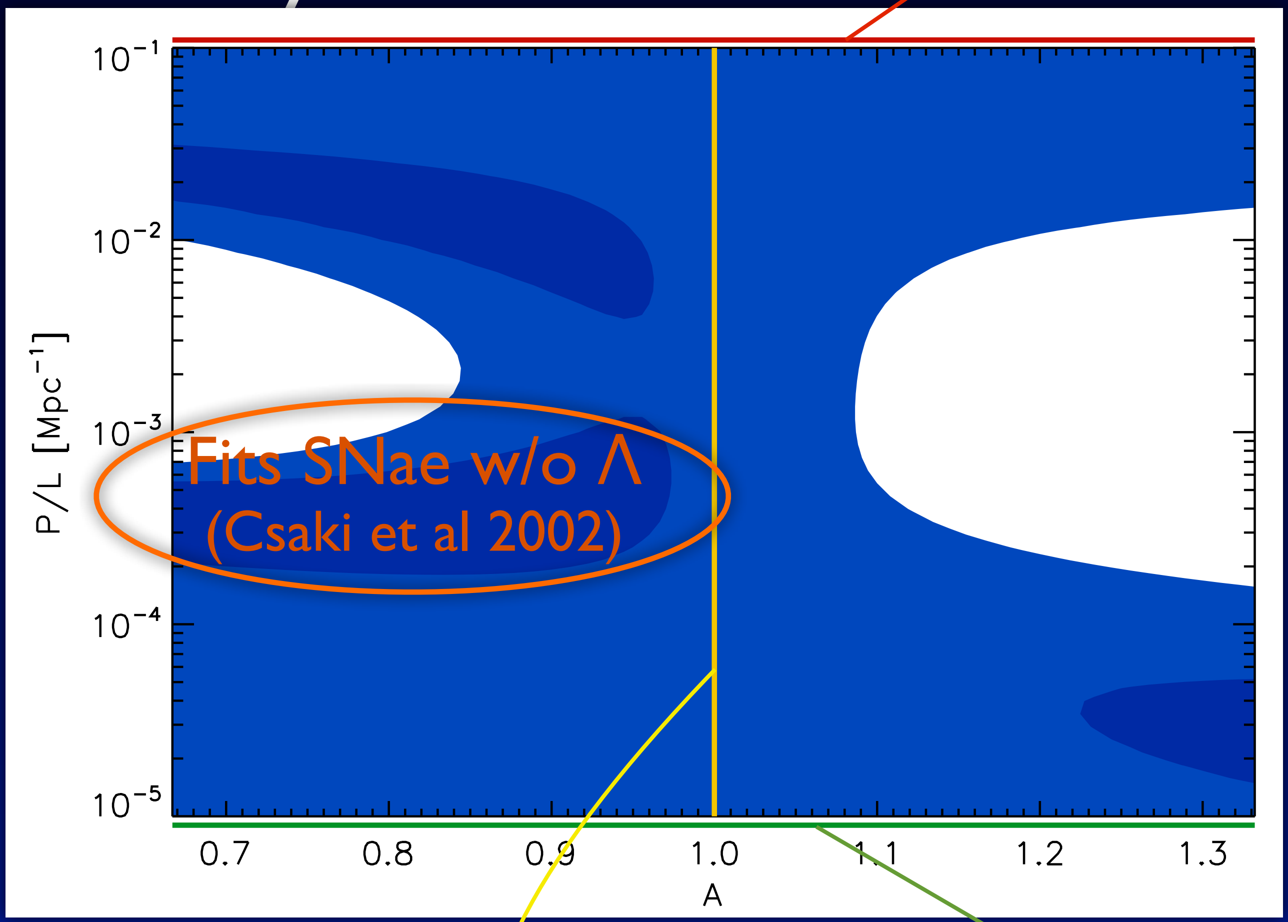
•For MCPs: $$e^{-\tau} \equiv \mathcal{P}(z) = \exp\left(-\kappa y(z)\right)$$

Rate of $\gamma \to \psi\bar{\psi}$

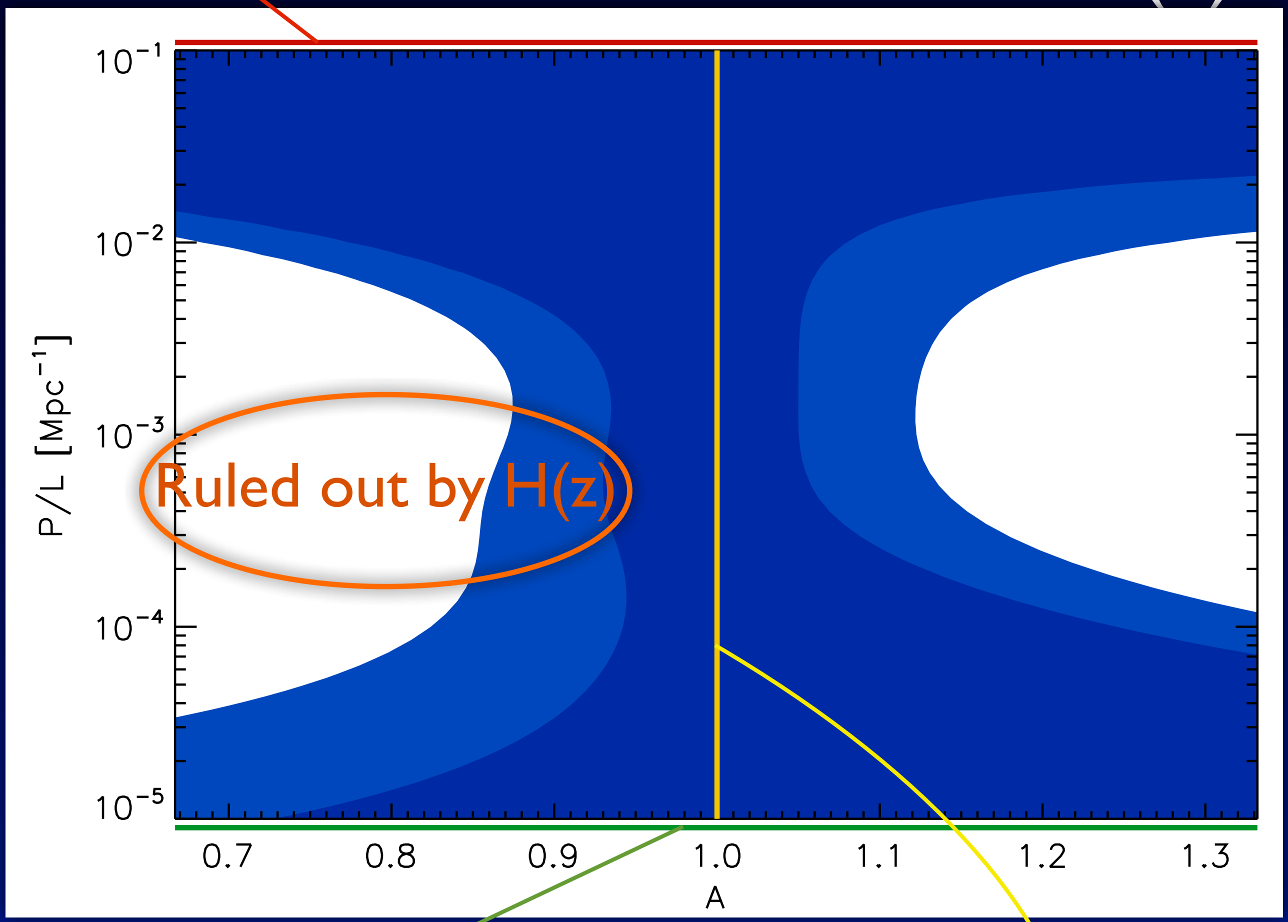
Axion-Like Particles (incl. Chameleons)

Rapid photon-axion thermalization

SN only



SN + H(z)



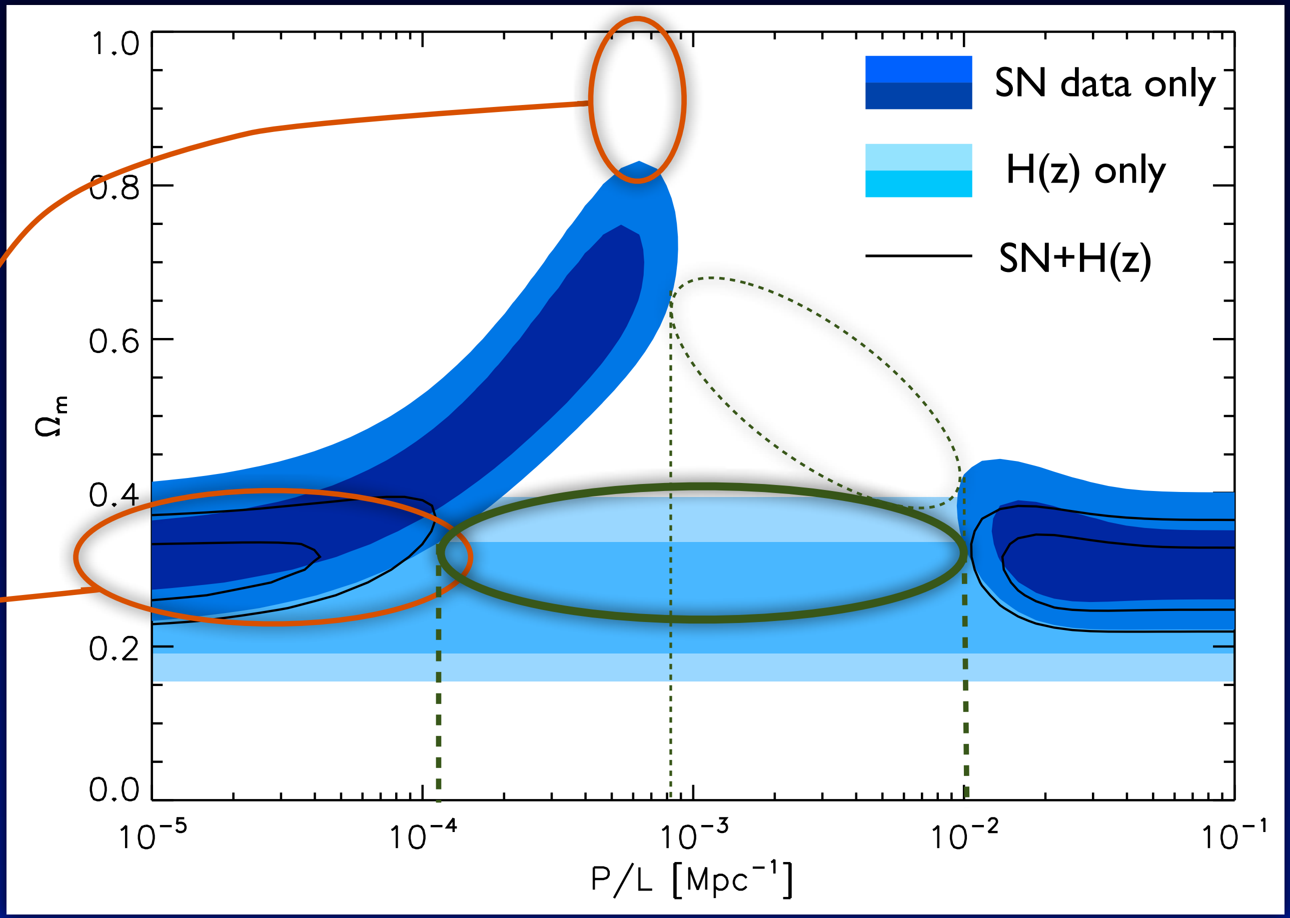
No photon-axion mixing

Flux thermalised at SN:
no propagation effect

Simplest ALPs (A=2/3)

If ALPs have no other interactions than 2-photon couplings, then they do NOT contribute to SN luminosity (i.e. A≃2/3)

Λ=0 excluded at >3σ



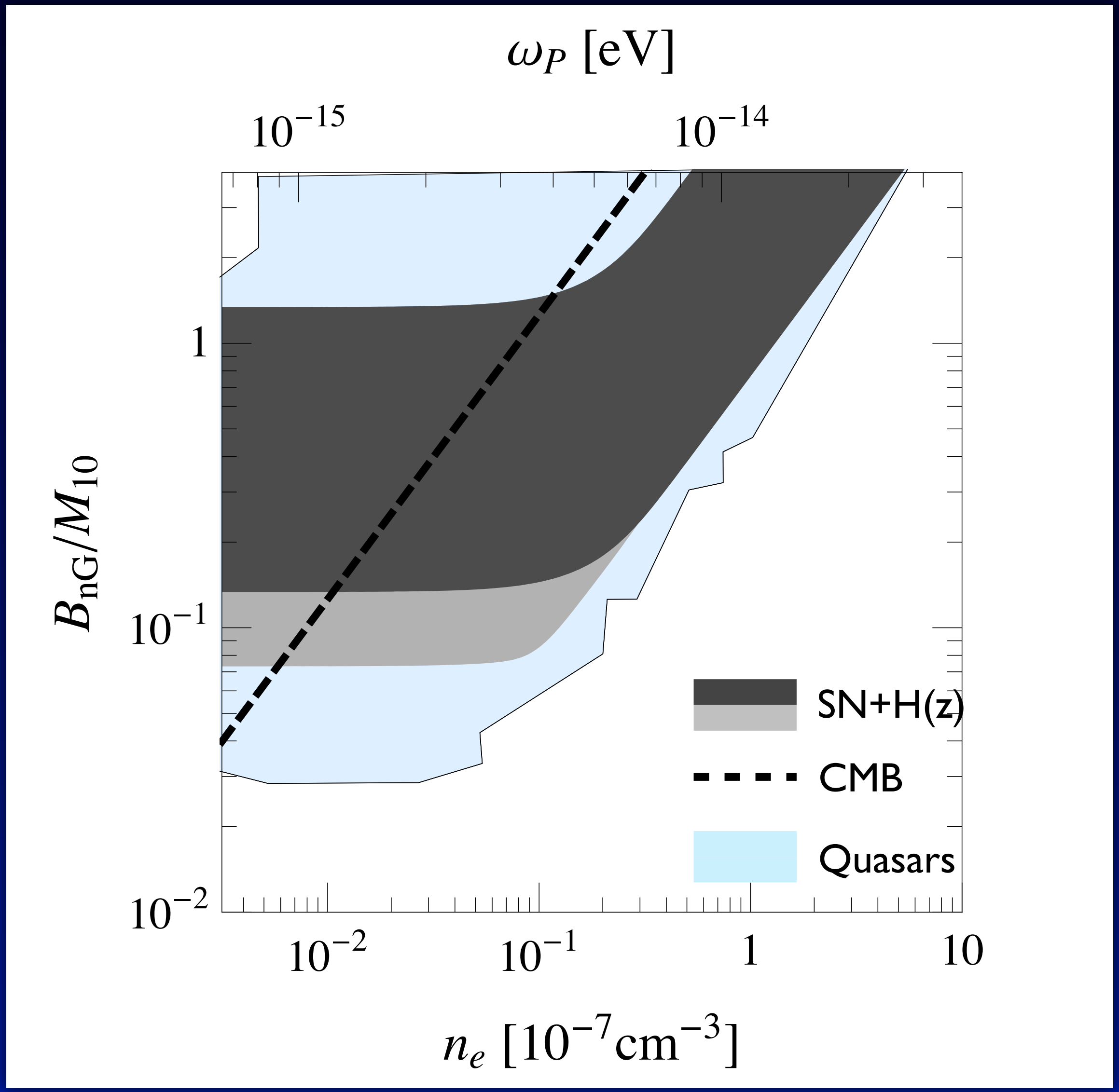
Degeneracy broken by H(z) data

Excludes this range of P

This constraint on P translates into a constraint on the axion-photon coupling scale M, intergalactic magnetic field B and the electron density

Constraining the Axion Coupling

The photon-axion conversion probability P, depends on the combination B/M and on the electron number density:

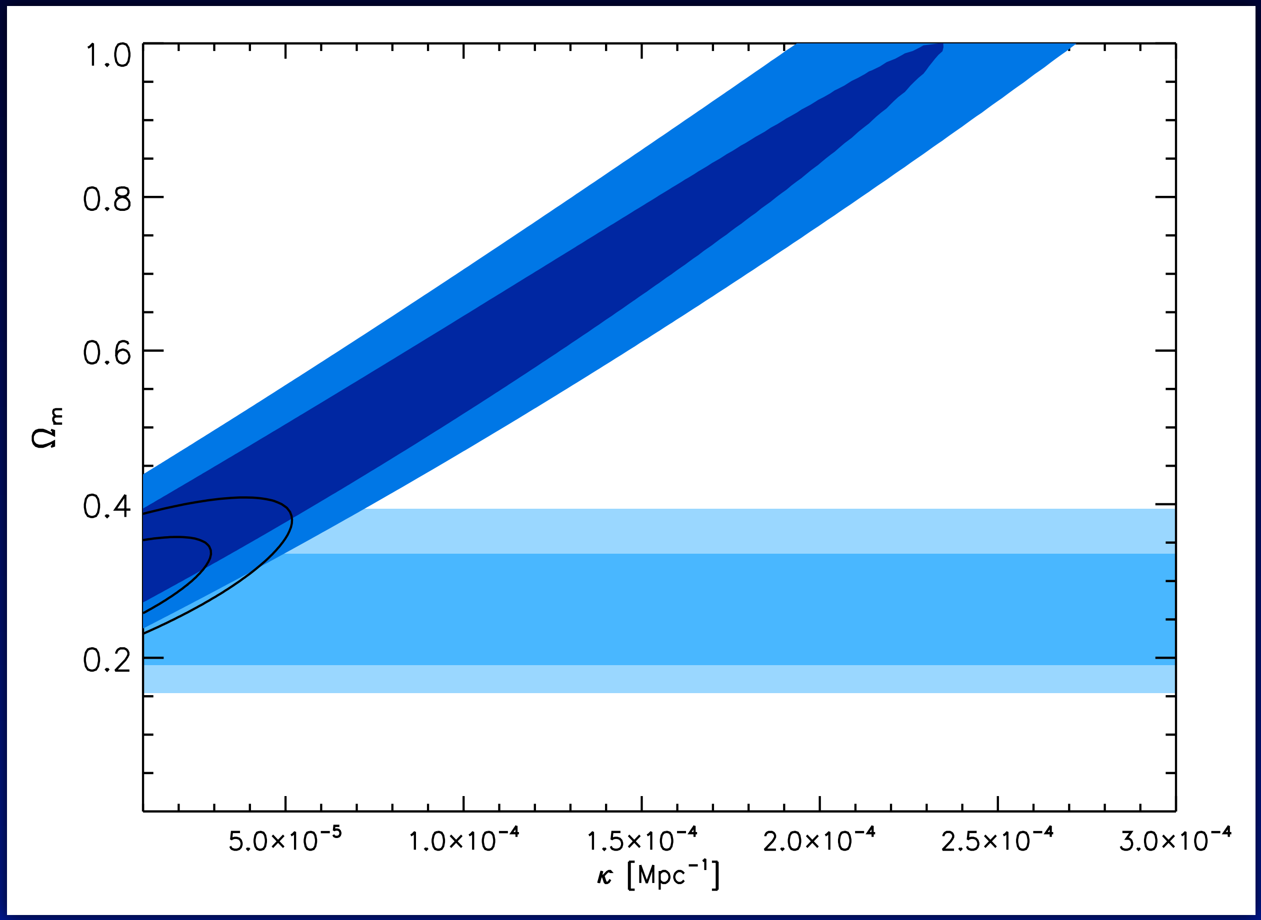


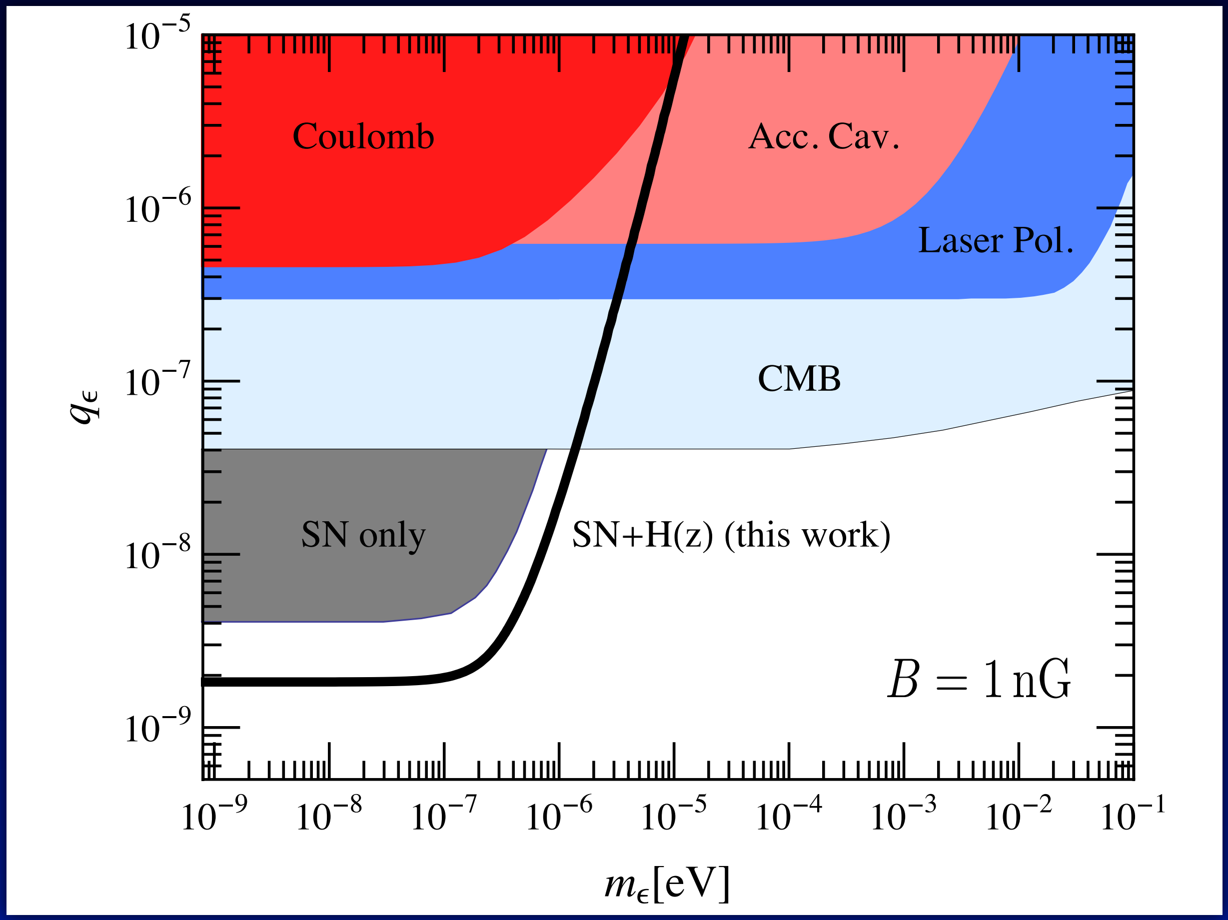
Bounds from cosmological distances already competitive with CMB and Quasar bounds

Stronger constraints on axion-photon coupling will be placed as intergalactic magnetic fields are better understood and observational data improve

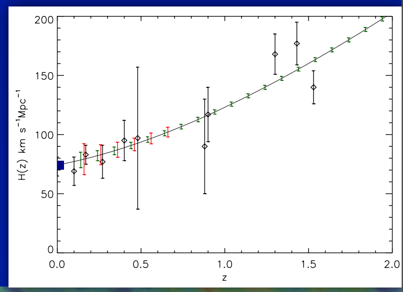
Mini-Charged Particles

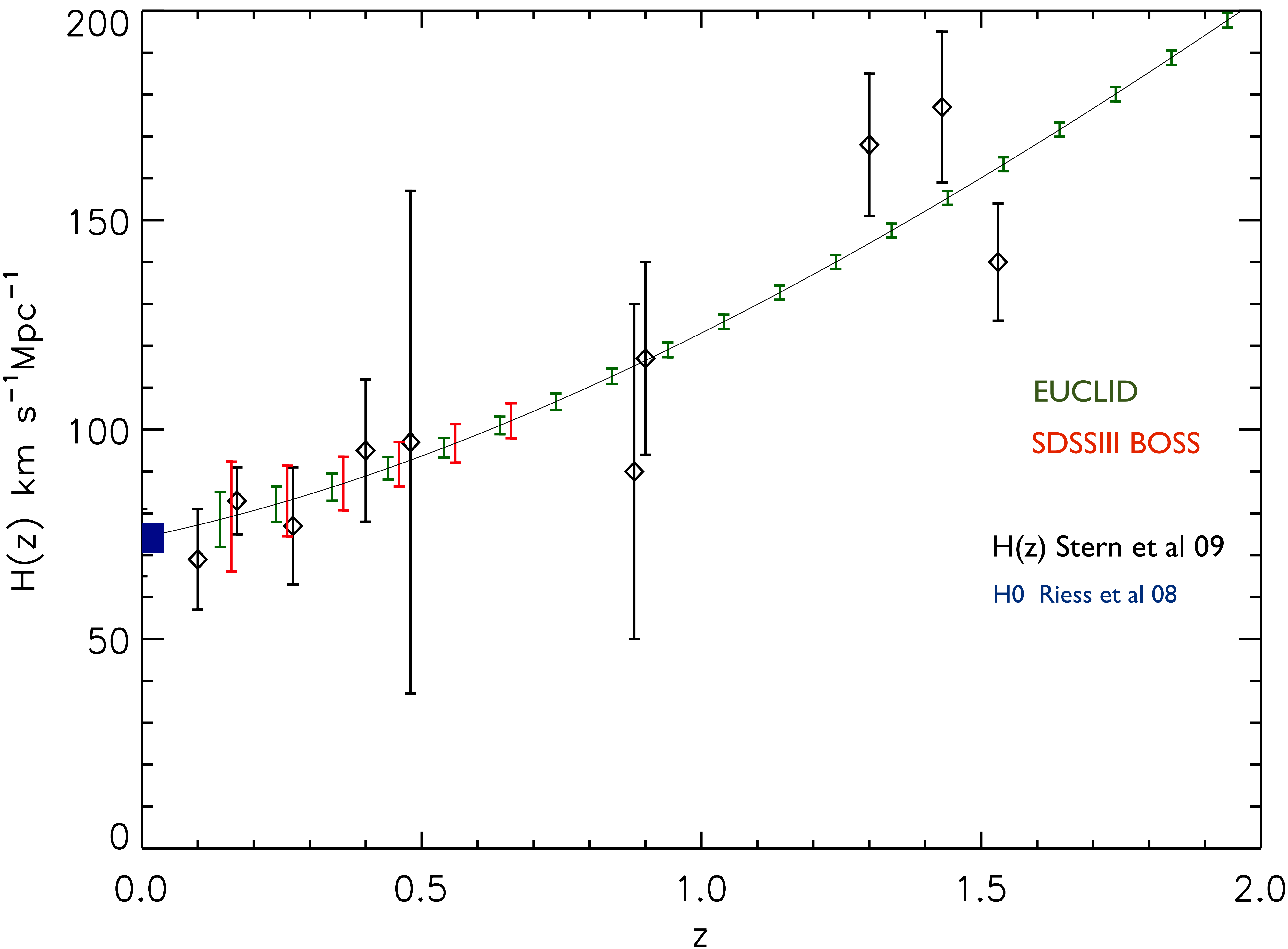
For MCPs ψ the rate κ of the $\gamma \to \psi\bar{\psi}$ process depends on the MCP charge and mass, as well as the magnetic field:





- Constraints from cosmology competitive with lab experiments
- H(z) significantly improves constraints
- Expect dramatic improvement with future H(z)/BAO data

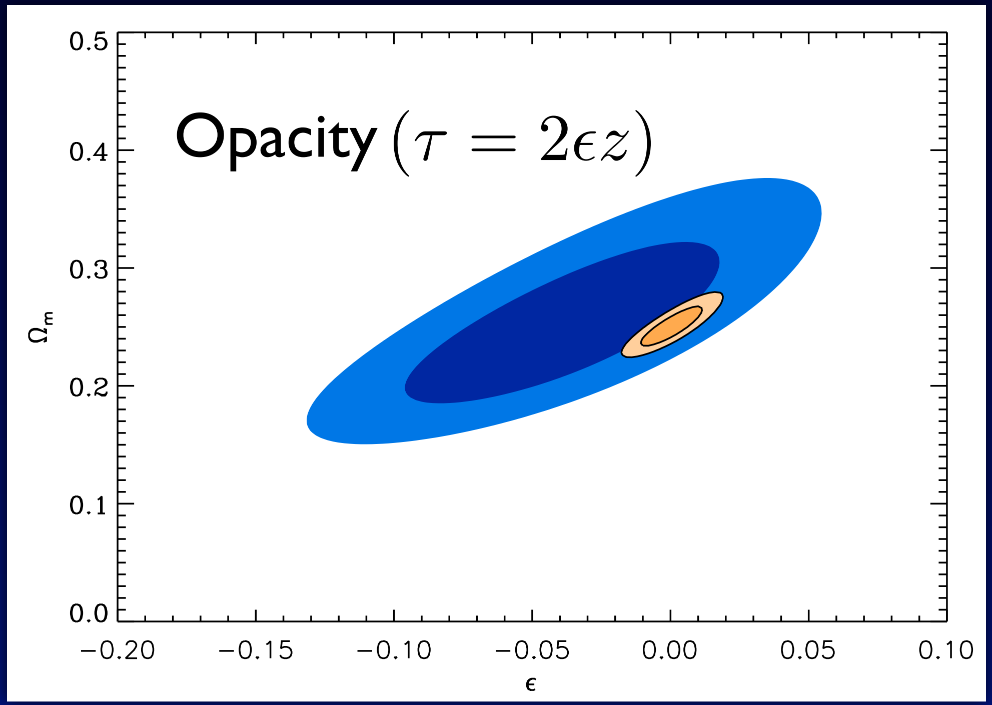


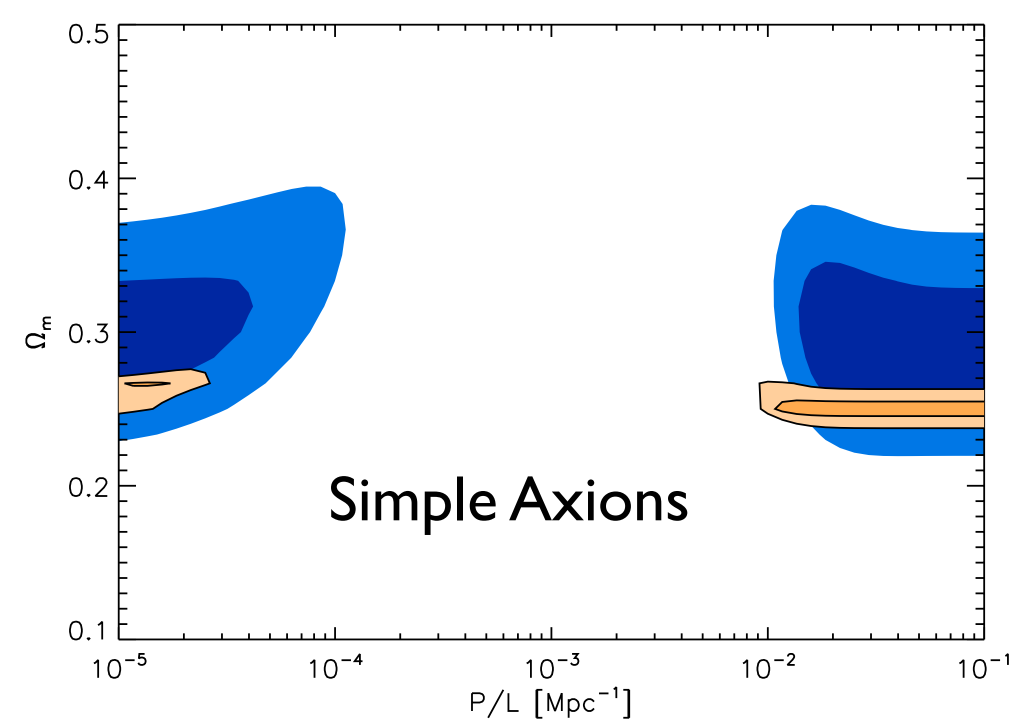


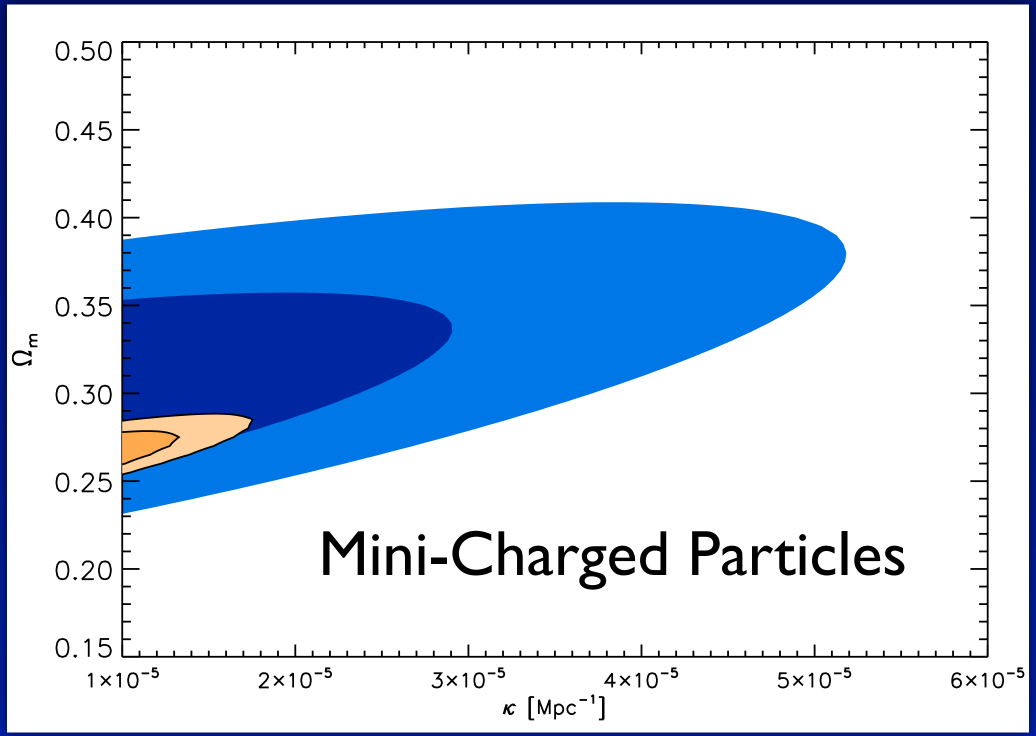
H(z) km s^{-1}Mpc^{-1}
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
z
EUCLID
SDSSIII BOSS
H(z) Stern et al 09
H0 Riess et al 08

Forecasts (BAO & SN)

Dramatic improvement on these constraints expected with future BAO (notably EUCLID) and SN (SNAP) missions







Summary

- Vast quantity of high quality cosmo data fast approaching: CMB, BAOs, Gravitational waves, 21cm,...
- Fruitful interplay between HEP/cosmo theory and cosmological observation (cf compactification scales from inflation!)
- New physics at sub-eV scales (notably ALPs & MCPs) generic in fundamental theory
- Cosmological distance measurements are already placing bounds on microphysical (& astrophysical) parameters
- Dramatic improvement expected as new data arrives and astrophysics better understood