Constraints on axions from cosmic distance measurements

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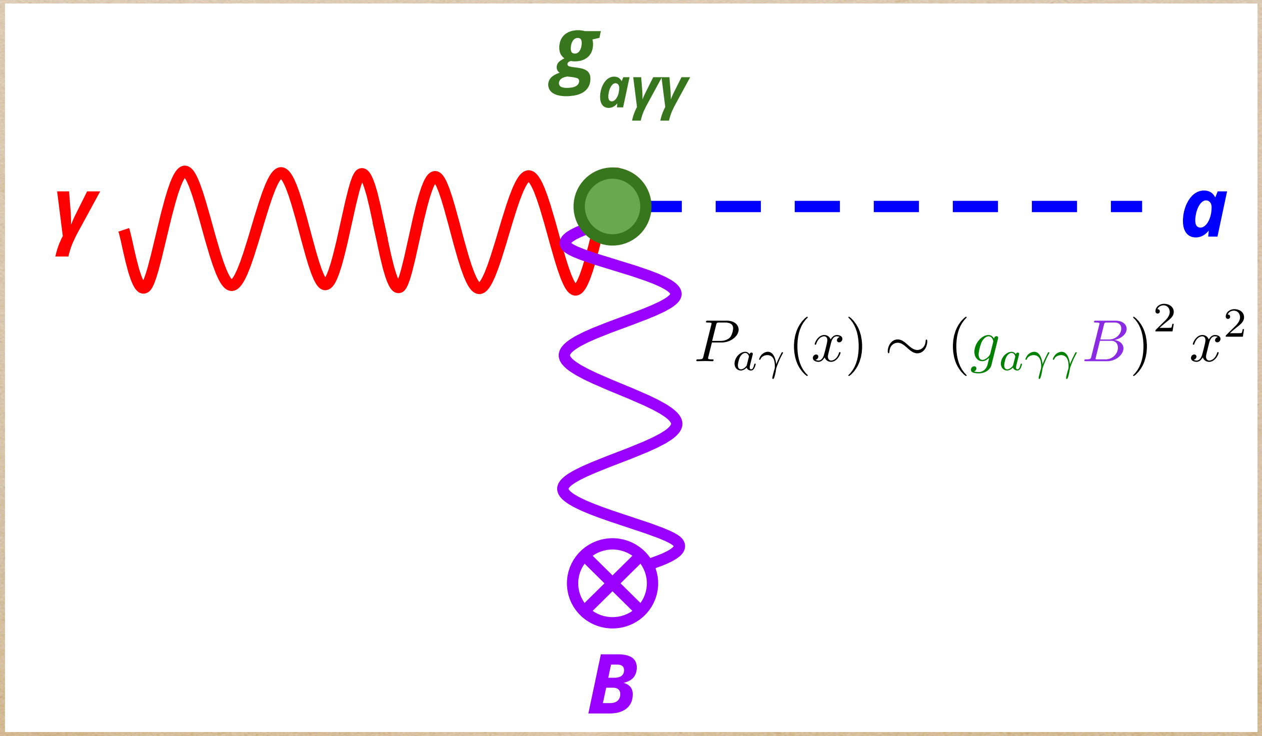
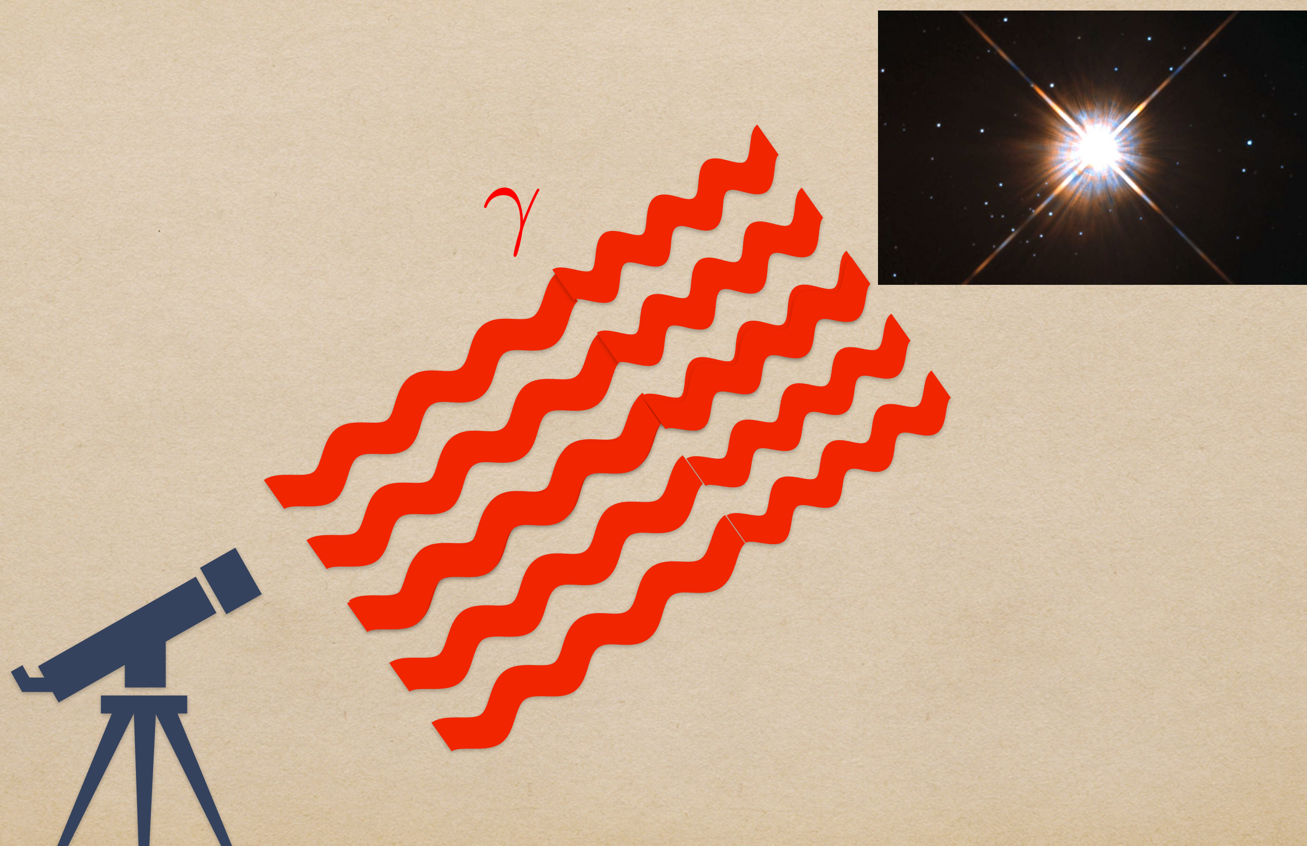
A Rainbow of Dark Sectors, Aspen winter conference, Mar 21 - Apr 1, 2021

Photon-axion oscillation

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

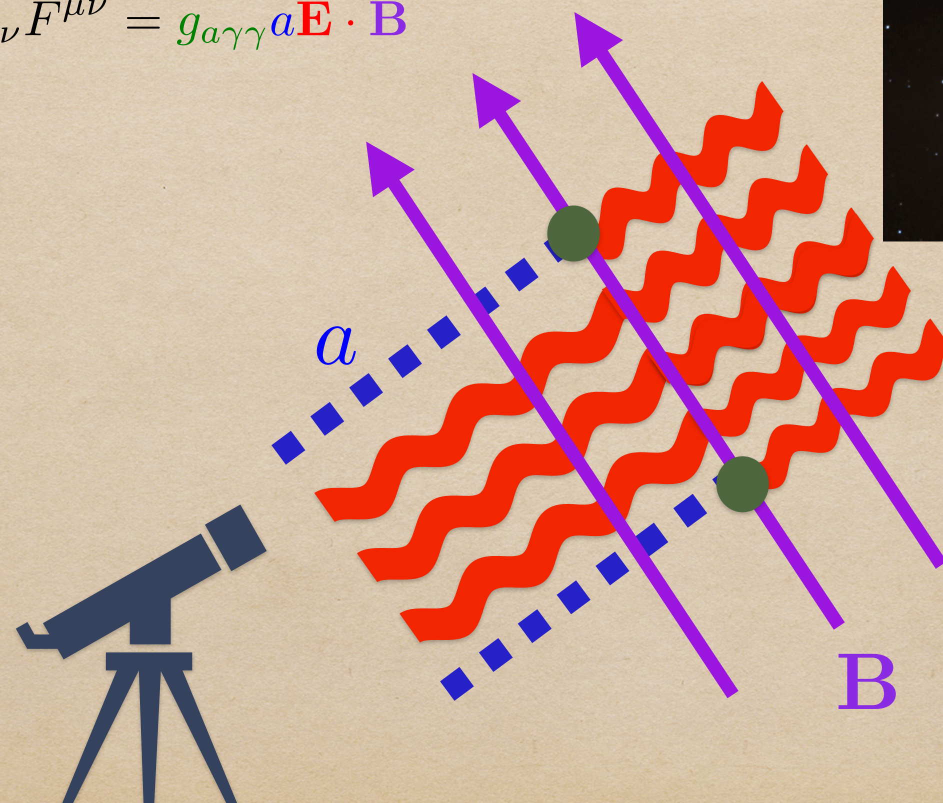


Dimming of bright sources



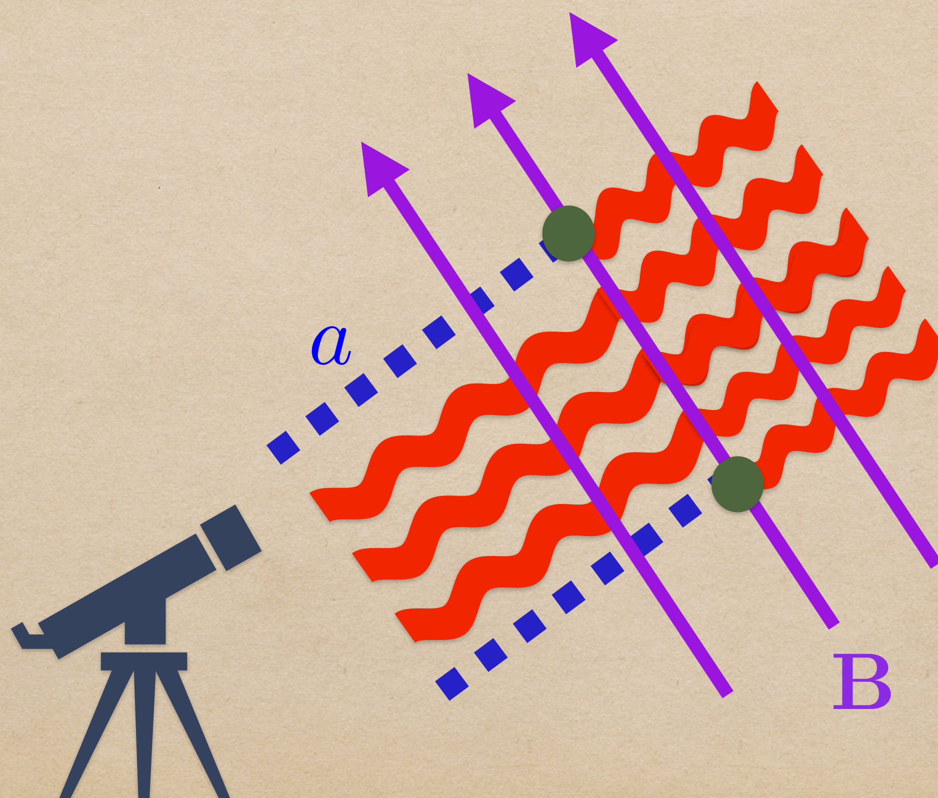
Dimming of bright sources

$$-\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}a\mathbf{E}\cdot\mathbf{B}$$



$$P_{a\gamma}(x) \sim (g_{a\gamma\gamma}B)^2\,x^2$$

Dimming of bright sources



Further

Cosmic Distance Measurements

A lot of progress in measuring cosmic distances over the years!

Luminosity distances (LD): relies on the *apparent* *brightness* of a source with known brightness (*standard candles*).

Source: type Ia Supernovae (SNIa).

Angular diameter distances (ADD): relies on the *apparent* *size* of a source with known size (*standard ruler*).

Source: galaxy clusters.

Luminosity Distances (LD)

ΛCDM

$$F(z) = \frac{L}{4\pi D_L{}^2(z)}$$

Luminosity

Flux

Luminosity distance:
depend on cosmology

Luminosity Distances (LD)

With γ-a conversion

$$F(z) = P_{\gamma\gamma}^{IGM}(z)\frac{L}{4\pi D_L{}^2(z)}$$

IGM: inter-galactic medium

$$P_{a\gamma} \sim \left(g_{a\gamma\gamma} B\right)^2 x^2$$

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

Effective LD

$$D_L^{\text{eff}} = D_L / \sqrt{P_{\gamma\gamma}^{IGM}}$$

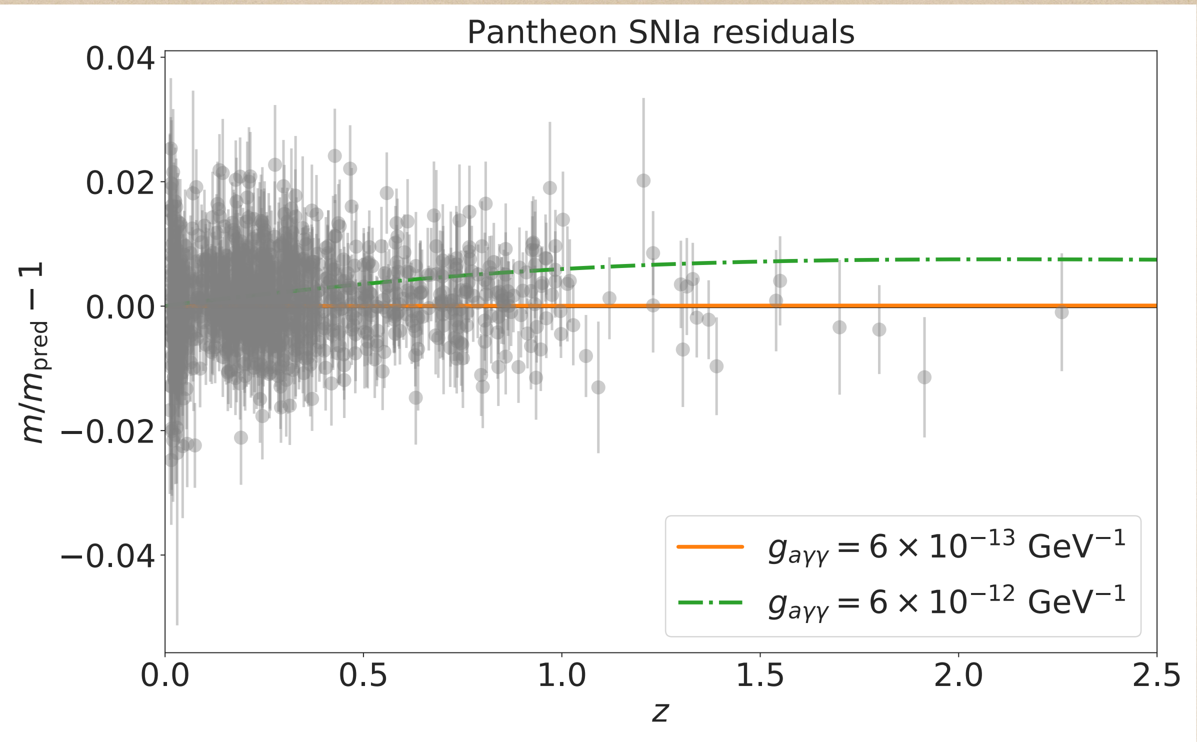
$$\left(P_{\gamma\gamma} < 1, \quad D_L^{\text{eff}} > D_L\right)$$

Csaki, Kaloper, and Terning, 2002

LD to type Ia SN (SNIa)

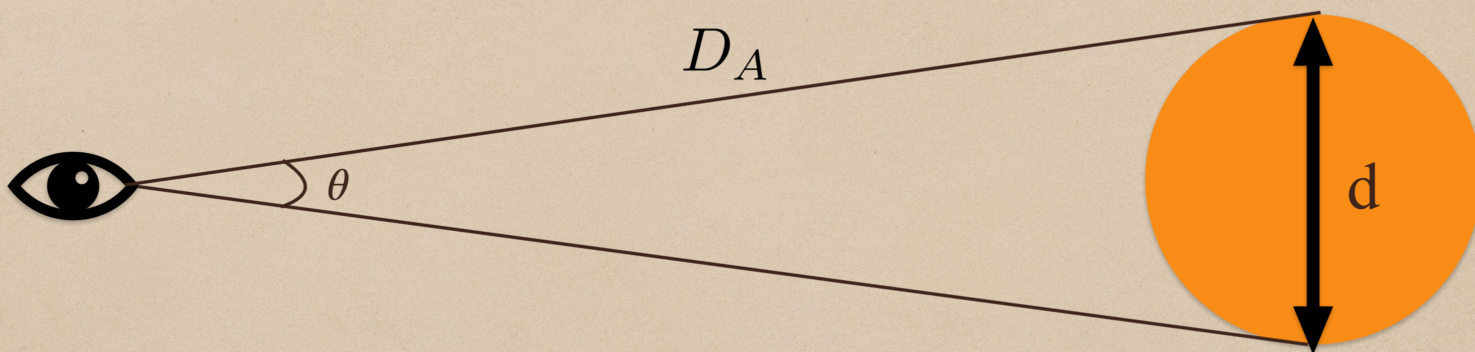
Pantheon data:
Scolnic et.al 2018

residue of
apparent
magnitude



redshift

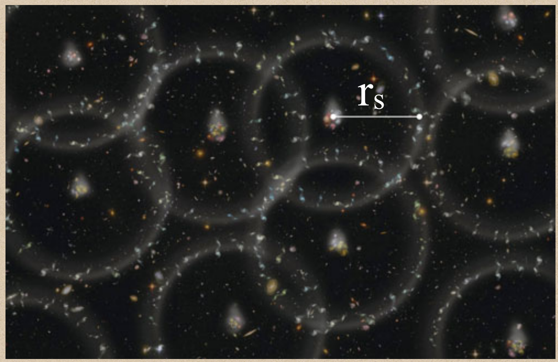
Angular Diameter Distances (ADD)



$$D_A = \frac{d}{\theta}$$

- ADDs are usually not affected by γ-a conversions since they are ***not*** inferred from brightness.

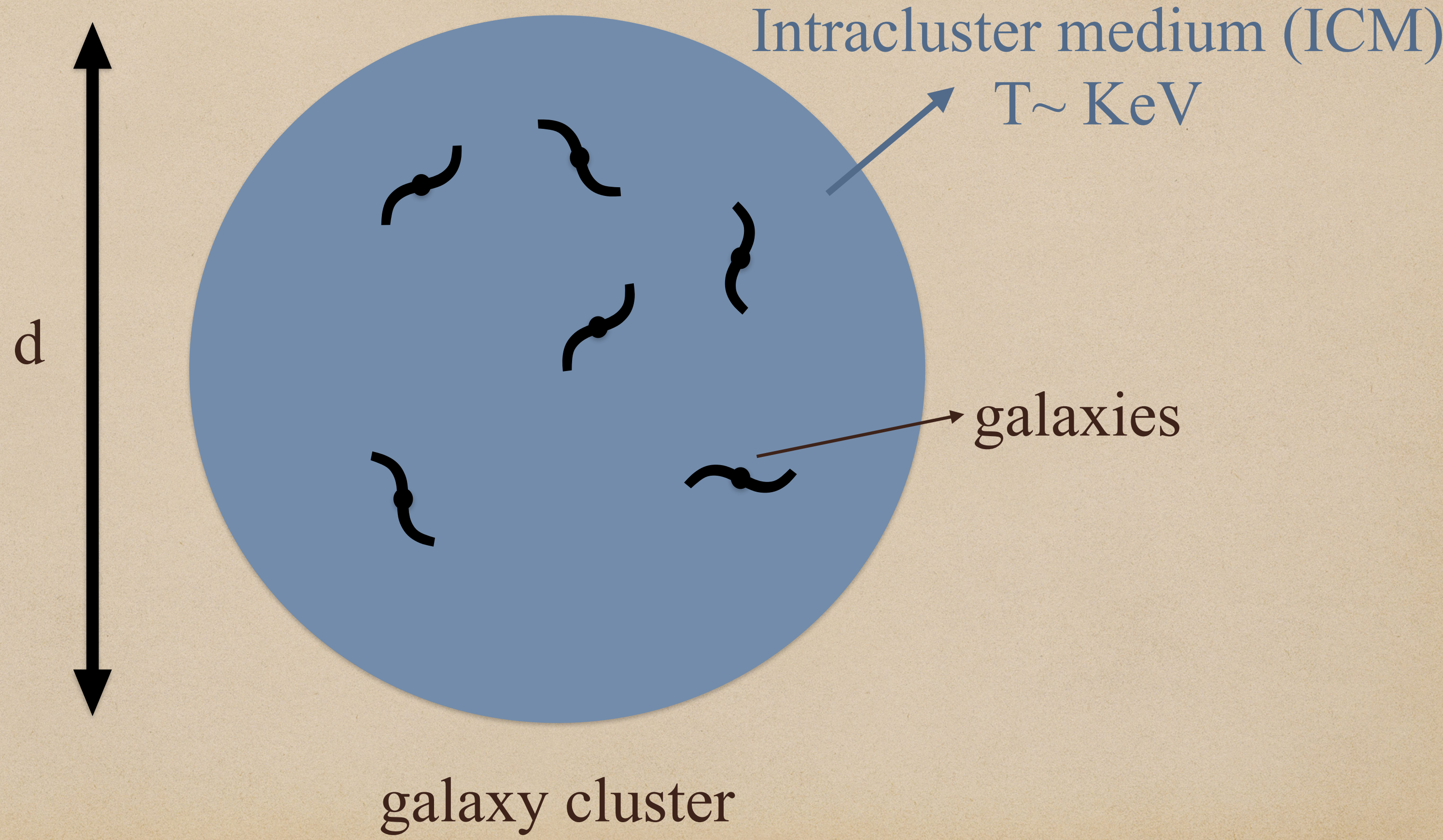
E.g.: baryonic acoustic oscillation (BAO);



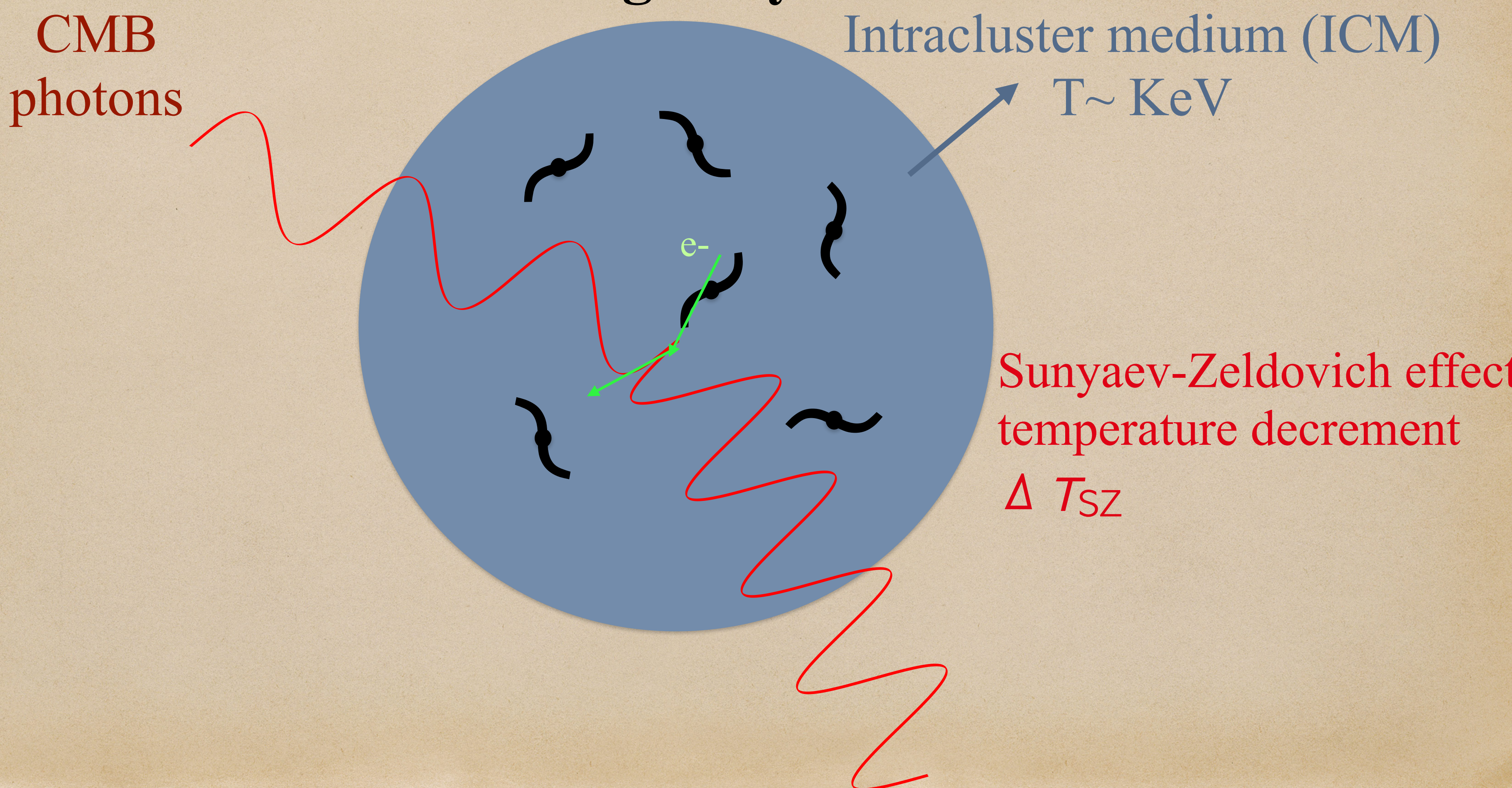
http://www.astro.ucla.edu/~wright/BAO-cosmology.html

- Yet they could be affected if the diameter, d, is determined from light! That happens when measuring ADD's to ***galaxy clusters***.

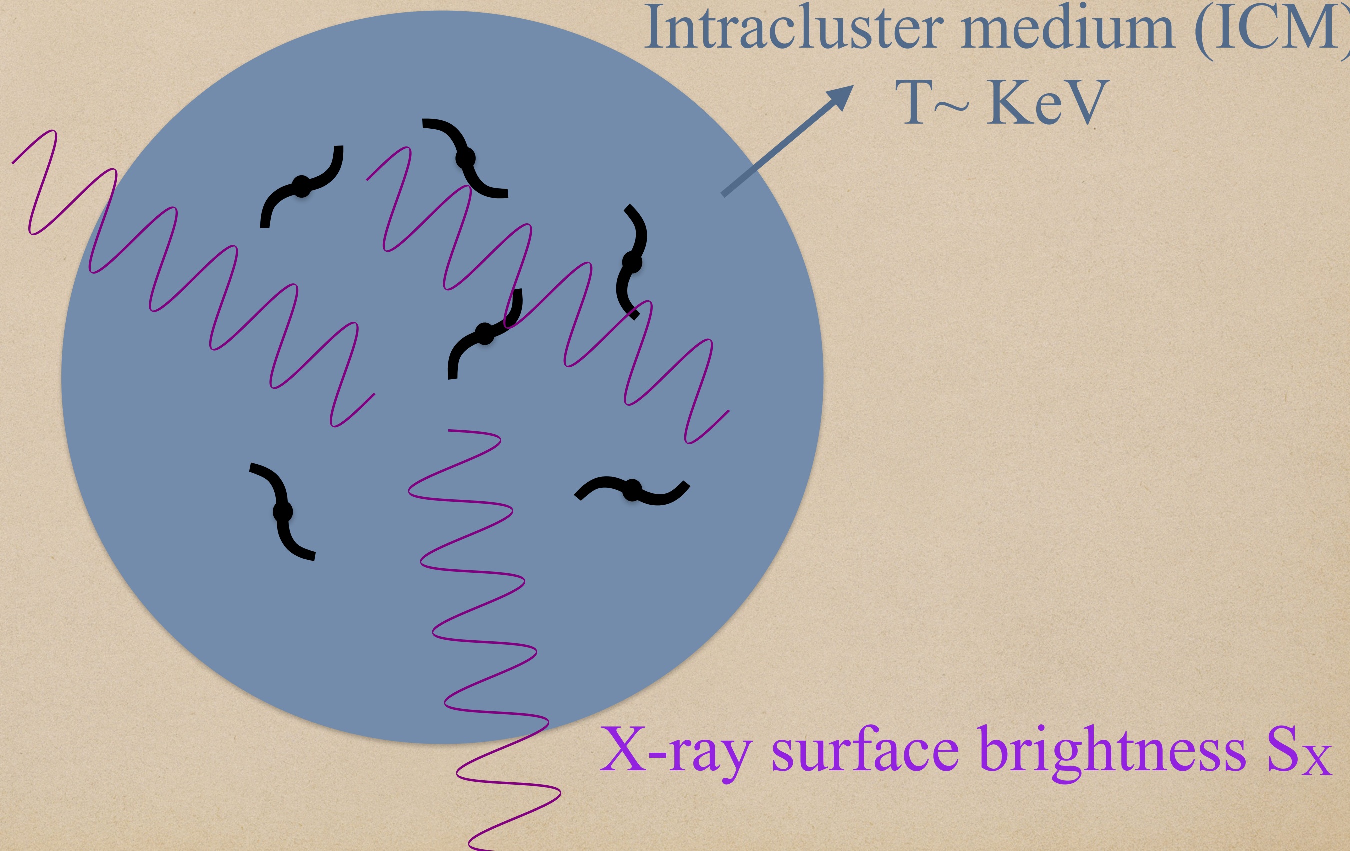
ADD to galaxy clusters



ADD to galaxy clusters



ADD to galaxy clusters



ADD to galaxy clusters

ΛCDM

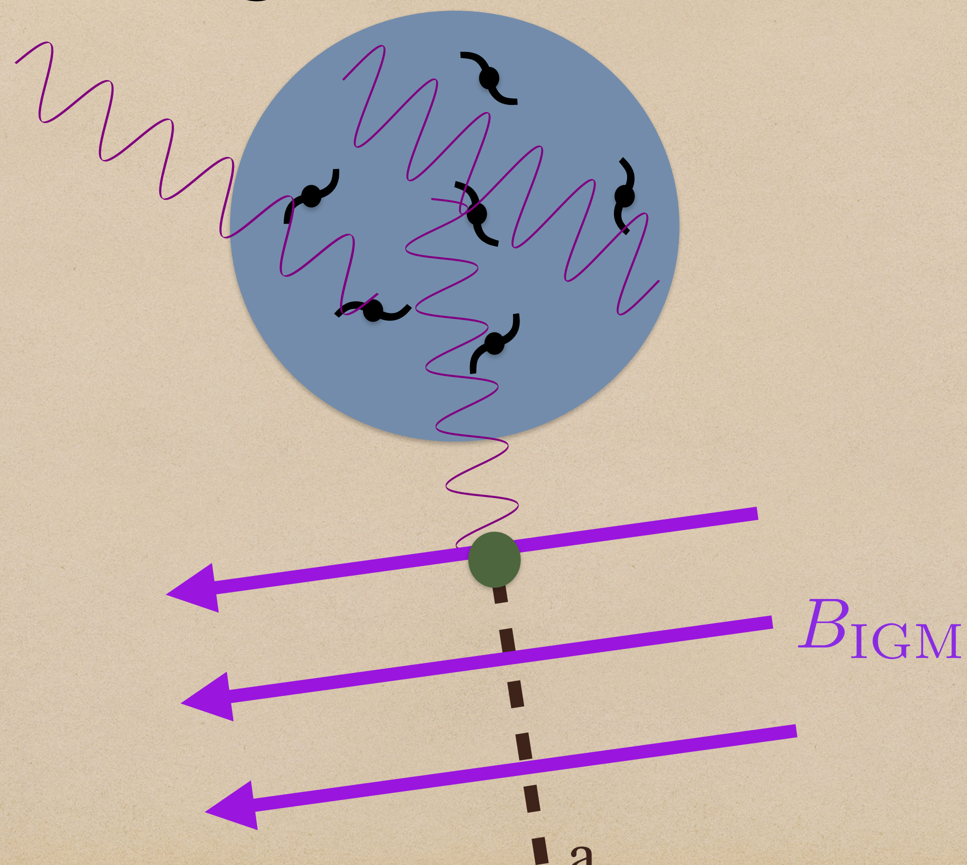
$$\Delta T_{\rm SZ} \propto D_A$$

$$S_X \propto D_A$$

$$D_A \propto \frac{\Delta T_{\rm SZ}^2}{S_X}$$

Bonamente et.al 2006

Magnetic IGM Effects



Magnetic ICM Effects

With γ-a conversion

$$D_A \propto \frac{\Delta T_{\rm SZ}^2}{S_X}$$

$$D_A^{\rm eff} = D_A \frac{\left(P_{\gamma\gamma,\rm SZ}^{\rm IGM}\right)^2}{P_{\gamma\gamma,X}^{\rm IGM} P_{\gamma\gamma,X}^{\rm ICM}}$$

survival probability taking into account of magnetic ICM effect (numerically the most important factor)

Datasets

- **Pantheon** (LD): apparent magnitudes of 1048 SNIa;
- **Clusters** (ADD): ADD measurements of 38 galaxy clusters;
- **BAO** (ADD): 6 measurements of $H_0 \times r_s^{drag}$;
- Distance "anchor" *(Hubble crisis;* review: Aylor et.al 2019*)*

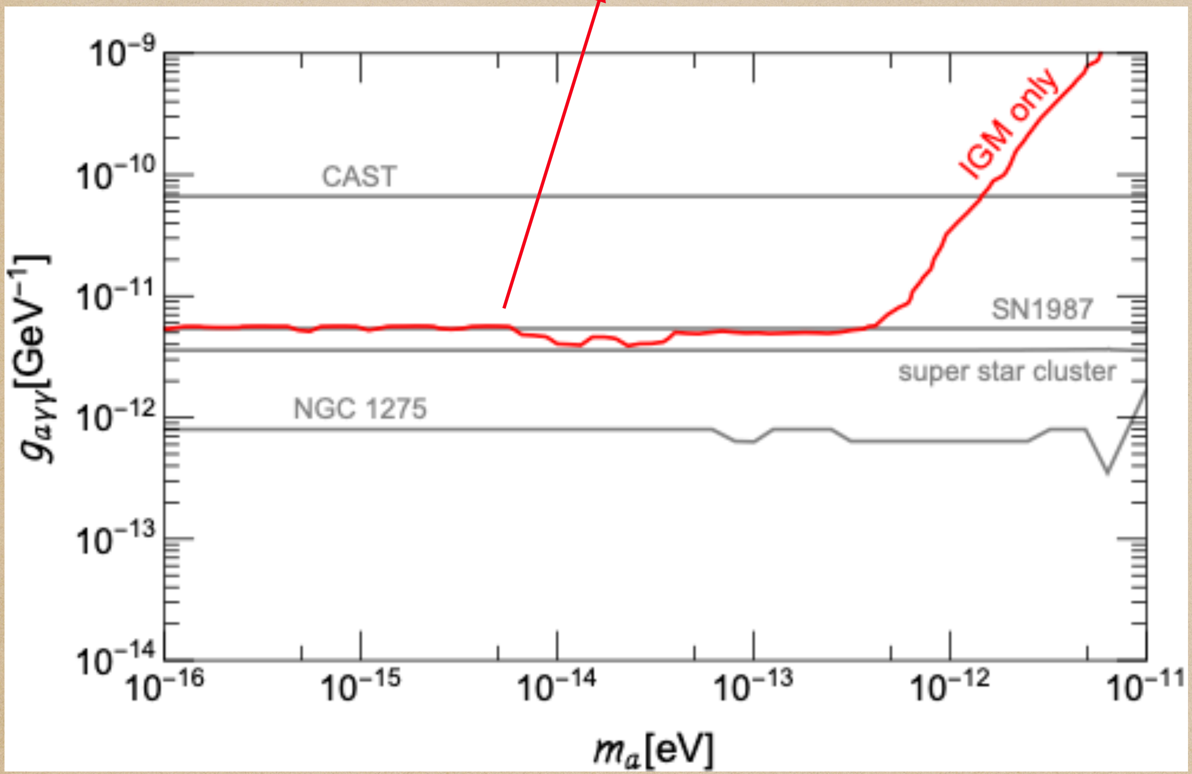
  \- *Late:* **SH0ES** (SNIa absolute brightness) + **TDCOSMO** (H_0)

  \- *Early*: **Planck 2018** (H_0, r_s^{drag})

Code available: *github.com/ManuelBuenAbad/cosmo_axions*

Results

$g_{a\gamma\gamma} \times (B_{\rm IGM}/1{\rm nG})$



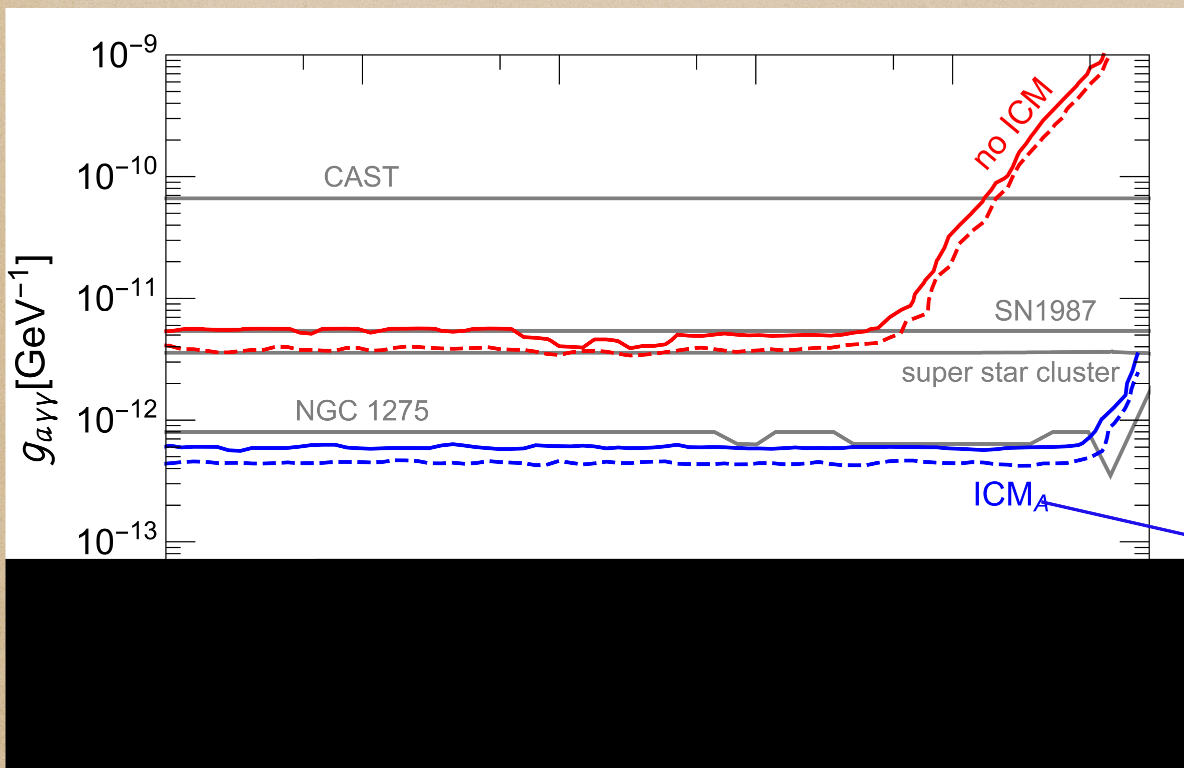
SH0ES+TDCOSMO

Results

SH0ES+TDCOSMO

Planck 2018

Results



SH0ES+TDCOSM

Planck 2018

X-ray photon - axion conversion in ICM;

independent of B_{IGM}

Takeaway

- IGM: strong bounds on axion-photon coupling for $m_a < 10^{-12}$ eV (assuming common benchmark $B_{IGM} = 1$nG)
- ICM: stronger bound (independent of IGM)
- Independent of Hubble crisis!
  - — Constraints from $H(z)/H_0$, not H_0!
- Improvements:
  - — Better measurements of shape $H(z)/H_0$
  - — Determine IGM/ICM properties more precisely

Thank you!

Backup

Axion-like particles

Axion: periodic pseudo-scalar. Important benchmark of feebly-coupled particles in BSM.

Classic example: QCD axion. Peccei, Quinn, Weinberg, Wilczek, Kim, Shifman, Vainshtein, Zakharov, Dine, Fischler, Srednicki, Zhitnitsky

Cold DM candidate Abott, Sikivie; Dine, Fischler; Preskill, Wise, Wilczek.

In this talk, focus on axion-like particles (not QCD axions and not necessarily dark matter) with a coupling

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

Plasma photon mass $m_\gamma^2 \equiv \frac{4\pi\alpha n_e}{m_e}$

$$\begin{pmatrix} m_\gamma^2 & i\omega g_{a\gamma\gamma} B \\ i\omega g_{a\gamma\gamma} B & m_a^2 \end{pmatrix}$$

In a single magnetic domain $P_0 = \frac{(2\Delta_{a\gamma})^2}{k^2} \sin^2\left(\frac{kx}{2}\right)$

photon-axion conversion prob.

$$k \equiv \sqrt{(2\Delta_{a\gamma})^2 + (\Delta_a - \Delta_\gamma)^2} \ ,$$

$$\Delta_{a\gamma} \equiv \frac{g_{a\gamma\gamma} B}{2} \ , \quad \Delta_a \equiv \frac{m_a^2}{2\omega} \ , \quad \Delta_\gamma \equiv \frac{m_\gamma^2}{2\omega} \ ,$$

In a single magnetic domain $P_0 = \frac{(2\Delta_{a\gamma})^2}{k^2} \sin^2\left(\frac{kx}{2}\right)$

When k x <<1, $P_0 \sim (g_{a\gamma\gamma}B)^2 x^2$

Over many domains, $P_{a\gamma}(y) = (1-A)\left(1 - \prod_{i=1}^{N}\left(1 - \frac{3}{2}P_{0,i}\right)\right)$ Grossman, Roy, Zupan 2002

$$A \equiv \tfrac{2}{3}\left(1 + \tfrac{I_a^0}{I_\gamma^0}\right)$$

$$\xrightarrow{N \gg 1} \quad P_{a\gamma}(y) = (1-A)\left(1 - \exp\left[\frac{1}{s}\int_0^y \mathrm{d}y' \; \ln\left(1 - \frac{3}{2}P_0(y')\right)\right]\right)$$

Photon-axion Conversion

In a single magnetic domain $$P_0 = \frac{(2\Delta_{a\gamma})^2}{k^2}\sin^2\left(\frac{kx}{2}\right)$$

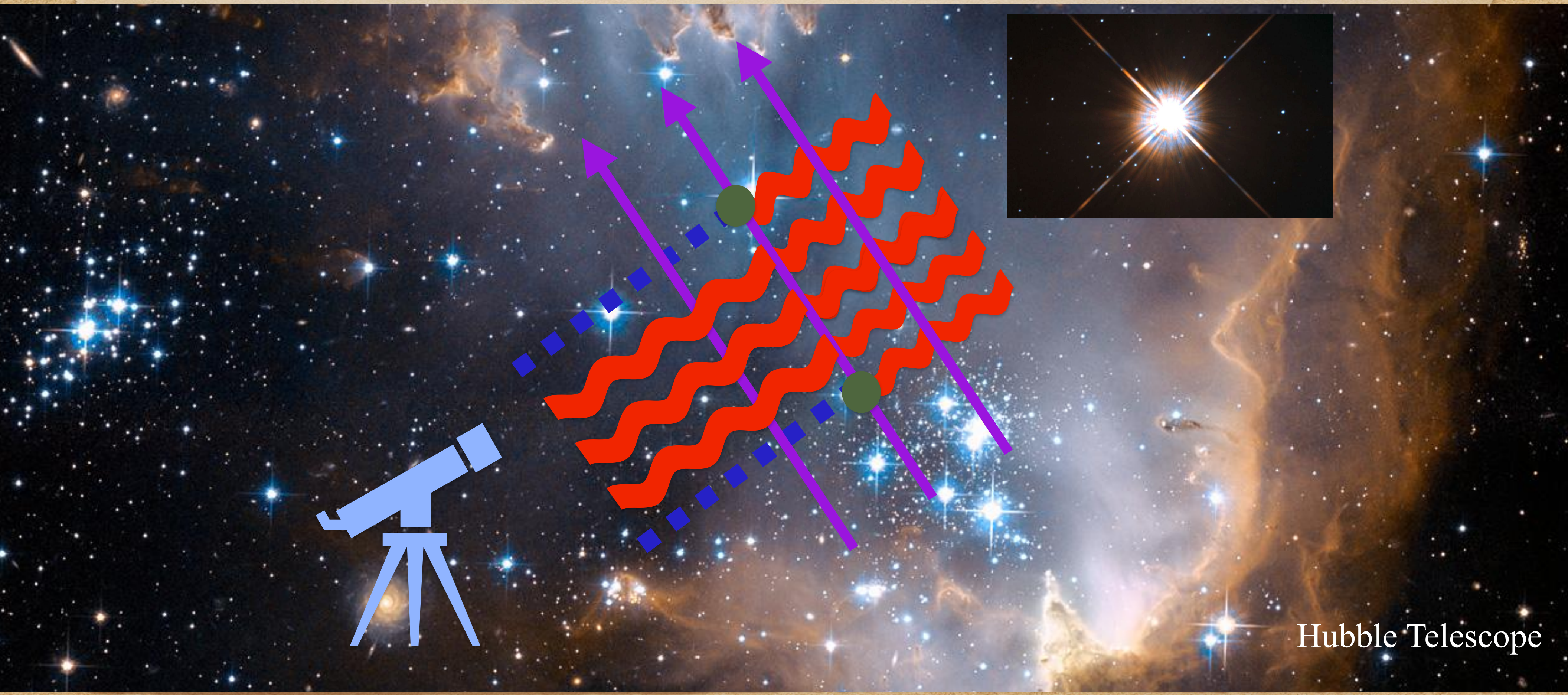
$$k \equiv \sqrt{(2\Delta_{a\gamma})^2 + (\Delta_a - \Delta_\gamma)^2}\ ,$$

$$\Delta_{a\gamma} \equiv \frac{g_{a\gamma\gamma}B}{2}\ , \quad \Delta_a \equiv \frac{m_a^2}{2\omega}\ , \quad \Delta_\gamma \equiv \frac{m_\gamma^2}{2\omega}\ ,\ m_\gamma^2 \equiv \frac{4\pi\alpha n_e}{m_e}$$

In IGM, $$P_{\gamma\gamma}^{\rm IGM}(z;\boldsymbol{\theta}) = A + (1-A)\exp\left[\frac{1}{s}\int_0^z {\rm d}z'\ \frac{\ln\left(1-\frac{3}{2}P_0(z';m_a,g_{a\gamma\gamma})\right)}{H(z';\Omega_\Lambda,H_0)}\right]\ ,$$

$$H(z';\Omega_\Lambda,H_0) = H_0\sqrt{\Omega_\Lambda + (1-\Omega_\Lambda)(1+z')^3} \qquad A \equiv \frac{2}{3}\left(1+\frac{I_a^0}{I_\gamma^0}\right)$$

Cosmic Distance



Luminosity Distances (LD)

ΛCDM

$$F(z) = \frac{L}{4\pi D_L{}^2(z)}$$

L → Luminosity

F → Flux

D_L → Luminosity distance: depend on cosmology

With γ-a conversion

$$F(z) = P^{IGM}_{\gamma\gamma}(z)\frac{L}{4\pi D_L{}^2(z)}$$

$P^{IGM}_{\gamma\gamma}$ → Photon survival probability

$$P_{a\gamma} \sim (g_{a\gamma\gamma}B)^2\, x^2$$

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

Intergalactic Magnetic Field

- Intergalactic medium (IGM): space between large scale structures.
- Magnetic field in IGM: “seed” for the observed magnetic field in astronomical sources, from stars to galaxy clusters. No direct observation though.
- Benchmark values: $B_{\mathrm{IGM}} \sim 1\,\mathrm{nG}$

$$L_{\mathrm{IGM}} \sim 1\,\mathrm{Mpc}$$

Review: Durrer and Neronov 2013; Han 2017

In ICM,

$$\langle P_{\gamma\gamma}^{\rm ICM}(m_a, g_{a\gamma\gamma})\rangle \equiv \frac{\int_{r_{\rm ini}}^{R_{\rm vir}} {\rm d}r\ n_{e,{\rm ICM}}^2(r) P_{\gamma\gamma}(r; m_a, g_{a\gamma\gamma})}{\int_{r_{\rm ini}}^{R_{\rm vir}} {\rm d}r\ n_{e,{\rm ICM}}^2(r)}\ ,$$

$$P_{\gamma\gamma}(r; m_a, g_{a\gamma\gamma}) = A + (1-A)\prod_{i=1}^{N(r)}\left(1 - \frac{3}{2}P_0(r_i)\right)\ ,$$

$$N(r) = (R_{\rm vir} - r)/L_{\rm ICM}$$

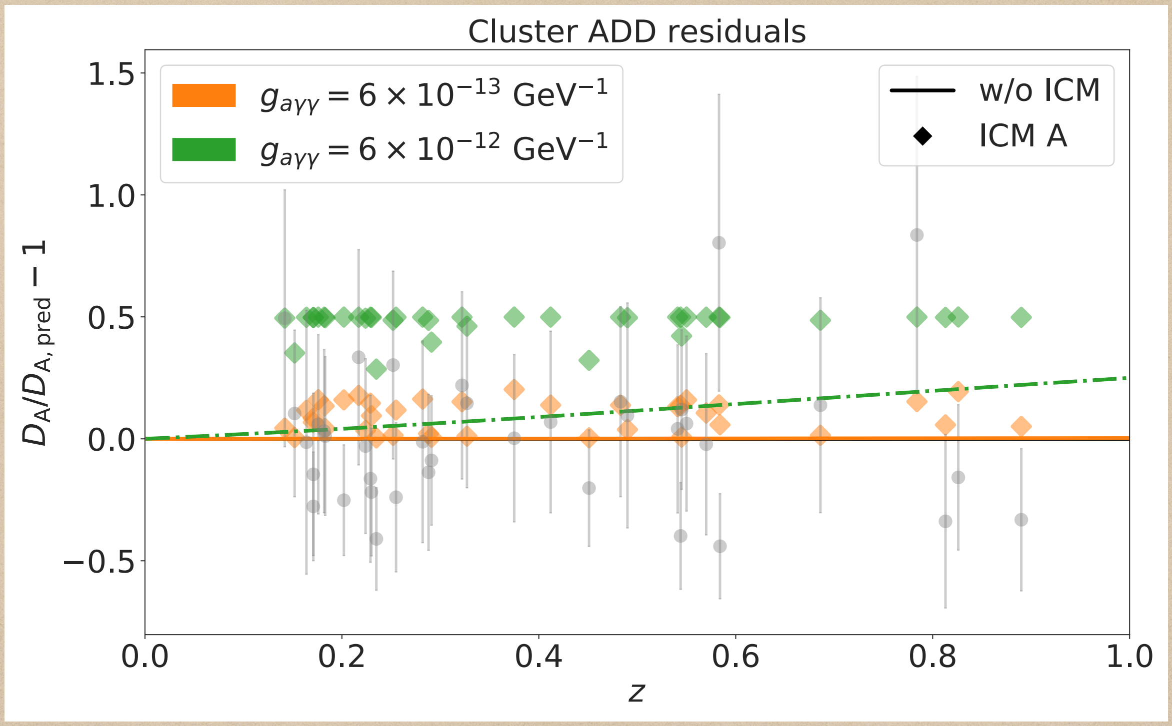
ICM modeling

$$n_{e,\mathrm{ICM}}(r) = n_{e,0}\left(f\left(1+\frac{r^2}{r_{c1}^2}\right)^{-\frac{3\beta}{2}} + (1-f)\left(1+\frac{r^2}{r_{c2}^2}\right)^{-\frac{3\beta}{2}}\right)$$

$$B_{\mathrm{ICM}}(r) = B_{\mathrm{ref}}\left(\frac{n_e(r)}{n_e(r_{\mathrm{ref}})}\right)^{\eta}$$

$$\text{Model A}: \quad r_{\mathrm{ref}} = 0\ \mathrm{kpc}, \quad B_{\mathrm{ref}} = 25\ \mu\mathrm{G}, \quad \eta = 0.7\ ,$$
$$\text{Model B}: \quad r_{\mathrm{ref}} = 25\ \mathrm{kpc}, \quad B_{\mathrm{ref}} = 7.5\ \mu\mathrm{G}, \quad \eta = 0.5\ ,$$
$$\text{Model C}: \quad r_{\mathrm{ref}} = 0\ \mathrm{kpc}, \quad B_{\mathrm{ref}} = 4.7\ \mu\mathrm{G}, \quad \eta = 0.5\ .$$

ADD residue



redshift

ADD data: Bonamente et.al 2006

Method

1. Cosmic distances in ΛCDM + γ-a conversion model

— Parameters $\boldsymbol{\Theta} = \{H_0, \Omega_\Lambda, M, r_s^{\mathrm{drag}}, m_a, g_{a\gamma\gamma}\}$

— Model γ-a conversion and include them in observables

Code available: *github.com/ManuelBuenAbad/cosmo_axions*

Method

2. Scan parameter space with MCMC (emcee Foreman-Mackey et.al 2013) with different combinations

— Early (Planck 18) vs. late (SH0ES and TDCOSMO)

$$\mathcal{L}_{\rm early} \equiv \mathcal{L}_{\rm Pan} \cdot \mathcal{L}_{\rm cl} \cdot \mathcal{L}_{\rm BAO} \cdot \mathcal{L}_{\rm Pl} \ ,$$

$$\mathcal{L}_{\rm late} \equiv \mathcal{L}_{\rm Pan} \cdot \mathcal{L}_{\rm cl} \cdot \mathcal{L}_{\rm BAO} \cdot \mathcal{L}_{\rm SH0ES} \cdot \mathcal{L}_{\rm TD}$$

— With vs. without magnetic ICM effects

— Vary IGM/ICM properties (electron densities, magnetic field)

Code available: *github.com/ManuelBuenAbad/cosmo_axions*

Likelihood

Pantheon

$$-2\ln\mathcal{L}_{\rm Pan} = \sum_{i,j=1}^{1048} \Delta_i C_{ij}^{\rm Pan} \Delta_j \ ,$$

$$\Delta_i \equiv m_i^{\rm Pan} - m^{\rm eff}(z_i; \boldsymbol{\theta}, M) \ ,$$

$$m^{\rm eff}(z; \boldsymbol{\theta}, M) = M + 25 + 5\log_{10}\left(D_L^{\rm eff}(z; \boldsymbol{\theta})/{\rm Mpc}\right) \ ,$$

$$D_L^{\rm eff}(z; \boldsymbol{\theta}) = D_L(z; \Omega_\Lambda, H_0)/\sqrt{P_{\gamma\gamma}(z; \boldsymbol{\theta})} \ ,$$

Cluster ADD

$$-2\ln\mathcal{L}_{\rm cl} = \sum_{i=1}^{38} \left(\frac{D_{A,i}^{\rm cl} - D_A^{\rm eff}(z_i; \boldsymbol{\theta})}{\sigma_i^{\rm cl}}\right)^2 \ ,$$

$$D_A^{\rm eff}(z; \boldsymbol{\theta}) = D_A(z; \Omega_\Lambda, H_0)\ \frac{P_{\gamma\gamma}^{\rm IGM}(z; \boldsymbol{\theta}, \omega_{\rm CMB})^2}{P_{\gamma\gamma}^{\rm IGM}(z; \boldsymbol{\theta}, \omega_{\rm X}, A_{\rm X})\langle P_{\gamma\gamma}^{\rm ICM}(m_a, g_{a\gamma\gamma})\rangle} \ ,$$

BAO $$-2\ln\mathcal{L}_{\rm BAO} = \sum_{i,j}\Delta_i C_{ij}^{\rm BAO}\Delta_j \ ,$$

$$\Delta_i \equiv Q_i^{\rm BAO} - Q^{\Lambda{\rm CDM}}(z_i;\Omega_\Lambda, H_0, r_s^{\rm drag}) \ ,$$

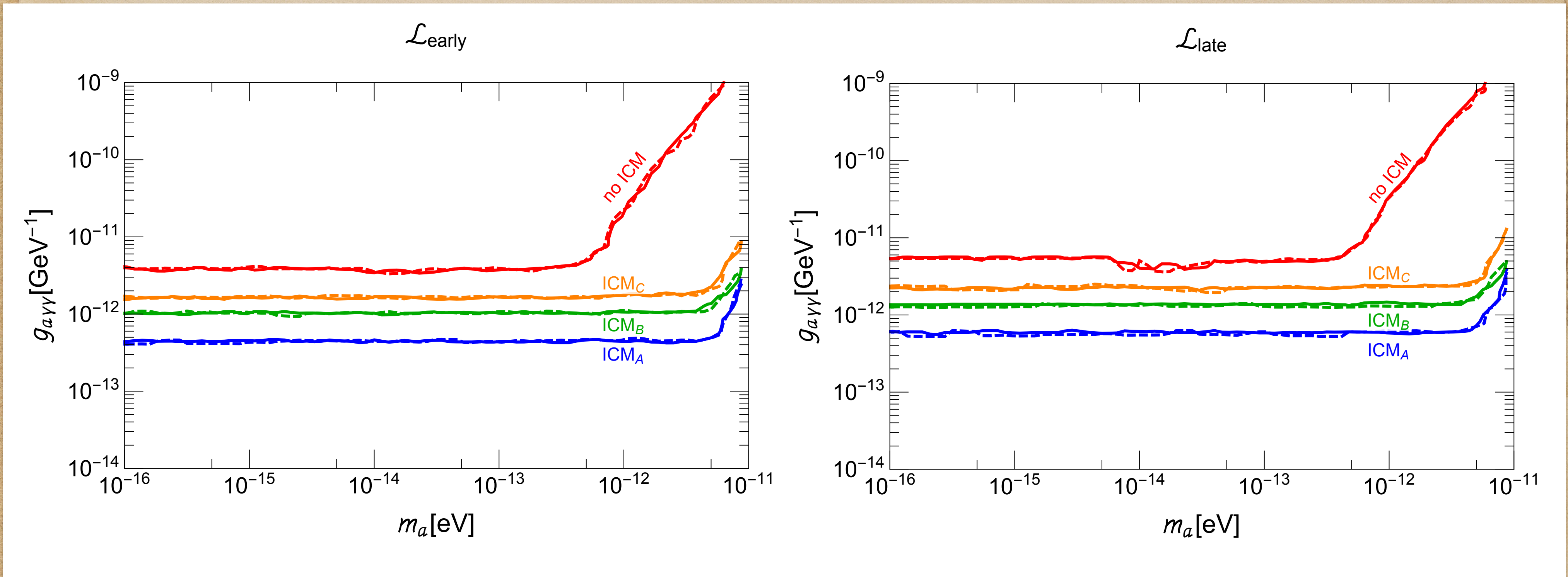
6dFGS, SDSS, BOSS

SH0ES $$-2\ln\mathcal{L}_{\rm SH0ES} = \sum_{i=1}^{19}\left(\frac{M_i^{\rm SH0ES} - M}{\sigma_i^{\rm SH0ES}}\right)^2$$ $H_0 = 74.5^{+5.6}_{-6.1}\ {\rm km\ \ sec^{-1}\,Mpc^{-1}}$

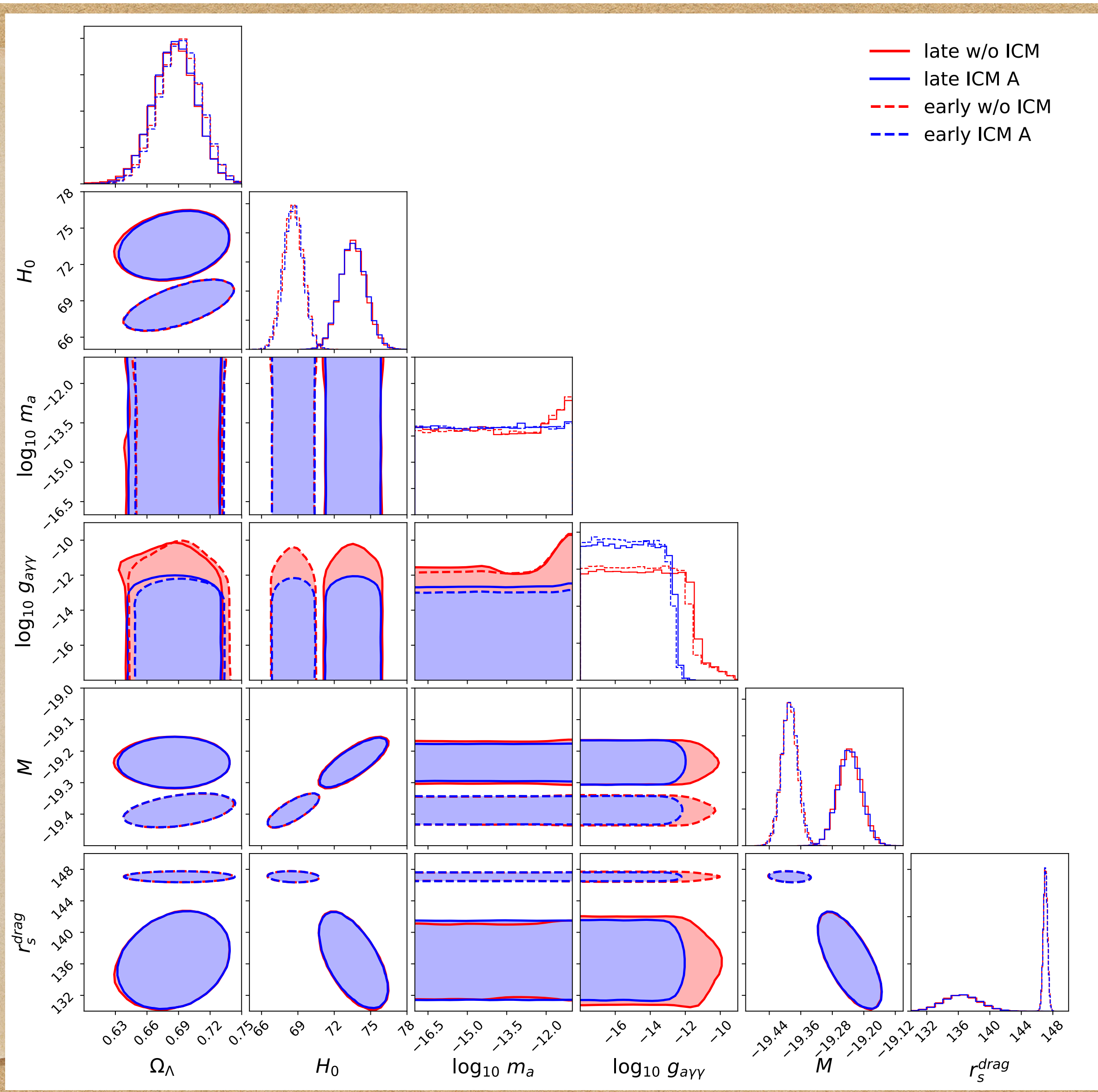
TDCOSMO $$-2\ln\mathcal{L}_{\rm TD} = \left(\frac{H_0^{\rm TD} - H_0}{\sigma^{\rm TD}}\right)^2$$

Planck $$-2\ln\mathcal{L}_{\rm Pl} = \left(\frac{r_s^{\rm drag,Pl} - r_s^{\rm drag}}{\sigma^{\rm Pl}}\right)^2$$

Additional results



NGC 1275 bound is also subject to similar uncertainties of ICM magnetic field.



late w/o ICM
late ICM A
early w/o ICM
early ICM A
Ω_Λ
H_0
$\log_{10} m_a$
$\log_{10} g_{a\gamma\gamma}$
M
r_s^{drag}

A Fun Puzzle

Light sources: dimming $\Longrightarrow$ further; *brightening* $\Longrightarrow$ *closer*.

$D \propto 1/H_0$: smaller D, larger H_0.

H_0 deduced from SNIa would be larger (compared to the true value). ***Alleviate Hubble tension*** between SH0ES+Pantheon (Riess et.al's measurement) and CMB!

A Fun Puzzle

abundant axion production at SNIa ($I_a/I_\gamma \sim 0.8$)

+

More axions convert to photons than the other way round when propagating in IGM

↓

SNIa further away is ***brightened***

A Fun Puzzle

abundant axion production at SNIa ($I_a/I_\gamma \sim 0.8$)

+

More axions convert to photons than the other way round when propagating in IGM

↓

SN further away is ***brightened***

Yet the two requirements point towards very different mass ranges of axions. Any way to make it work?