Pheno 2021

Constraints on Axions from Cosmic Distance Measurements

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w/ JiJi Fan & Chen Sun

arXiv:2011.05993

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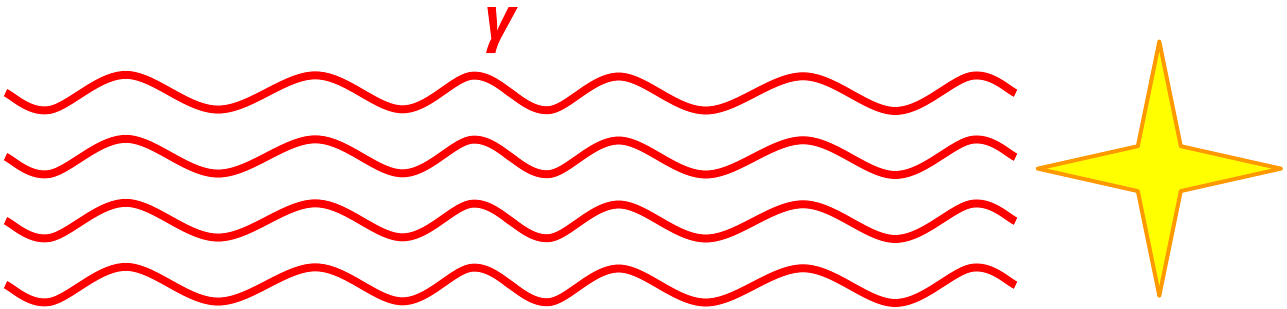
Axion-photon conversion



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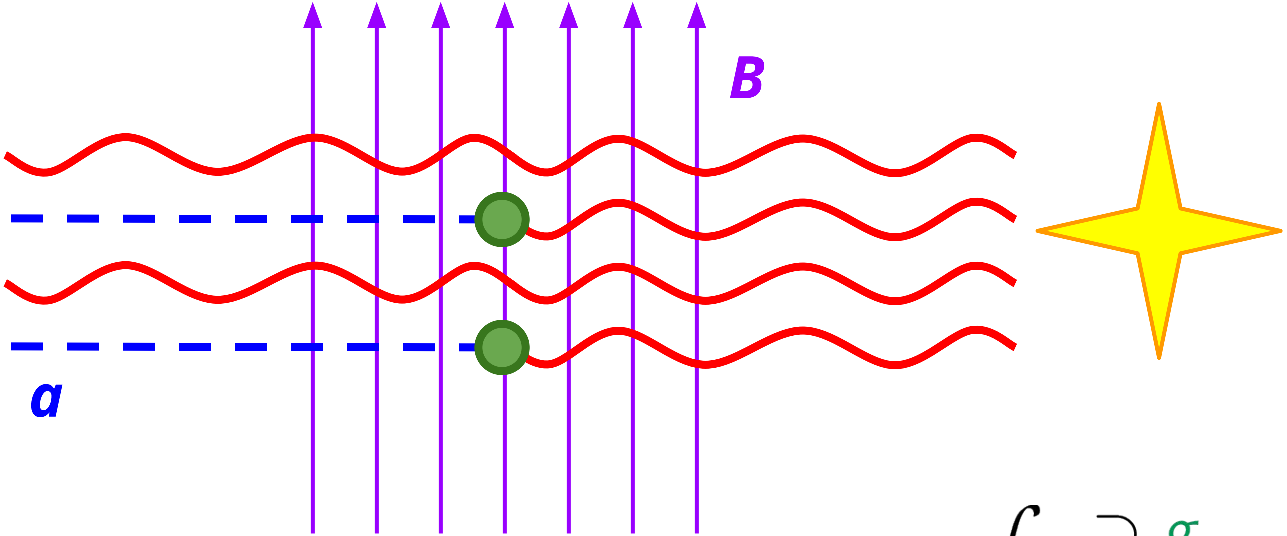
Axion-photon conversion = dimming

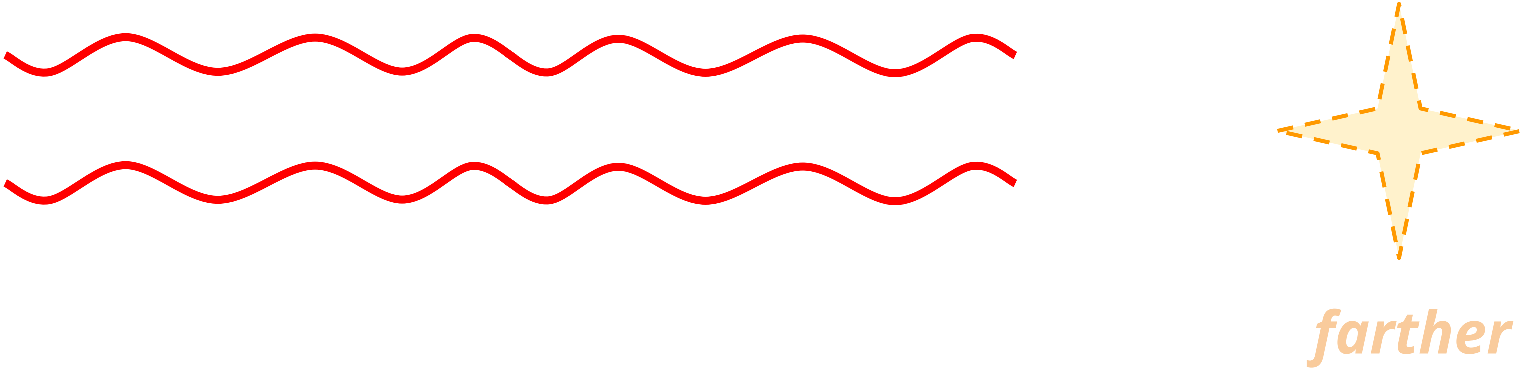


$$\mathcal{L}_a \supset g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

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

arXiv:2011.05993

Axion-photon conversion = dimming



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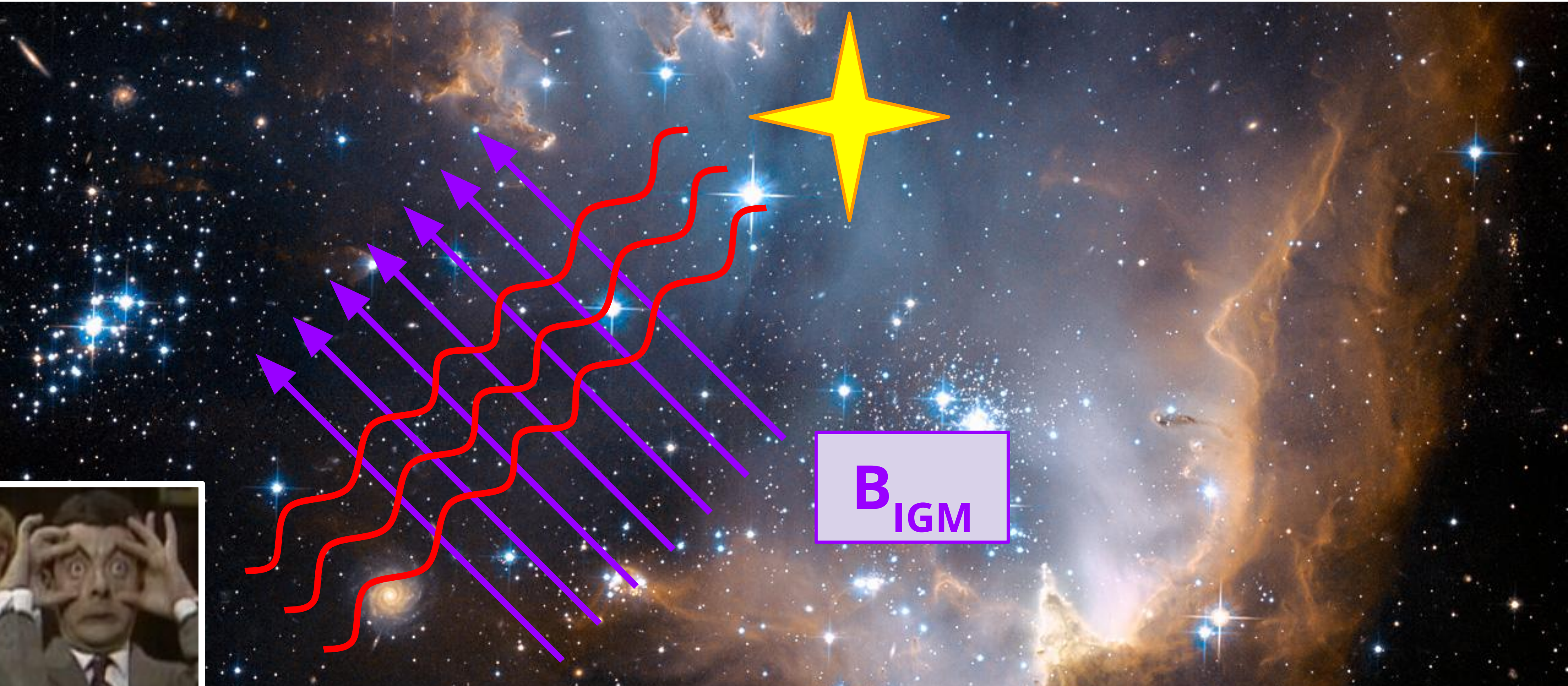
Cosmic Distance

Hubble Telescope

Cosmic Distance

Hubble Telescope



A word on IGM magnetic fields

- **IGM**: Intergalactic Medium (space between large structures)
- $\boldsymbol{B}_{\mathbf{IGM}}$: *theorized* [Durrer & Neronov 2013]
    - Early: inflation, phase transitions
    - Late: outflows of galaxies
- Benchmarks [Han 2017]
    - $\boldsymbol{B}_{\mathbf{IGM}}$ **~ 1 nG**
    - $\boldsymbol{s}_{\mathbf{IGM}}$ **~ 1 Mpc**

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Luminosity Distance (LD)

- In ΛCDM:

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

flux

luminosity

LD: cosmo dependent

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Luminosity Distance (LD)

- In ΛCDM: $$F = \frac{L}{4\pi {D_L}^2}$$

- With axions: $$F = P_{\gamma\gamma}^{\mathrm{IGM}} \frac{L}{4\pi D_L^2}$$

$$P_{a\gamma} \sim (g_{a\gamma\gamma} B)^2 \, x^2$$
$$P_{\gamma\gamma} = 1 - P_{a\gamma}$$

arXiv:2011.05993

[Csaki, Kaloper, & Terning '01]

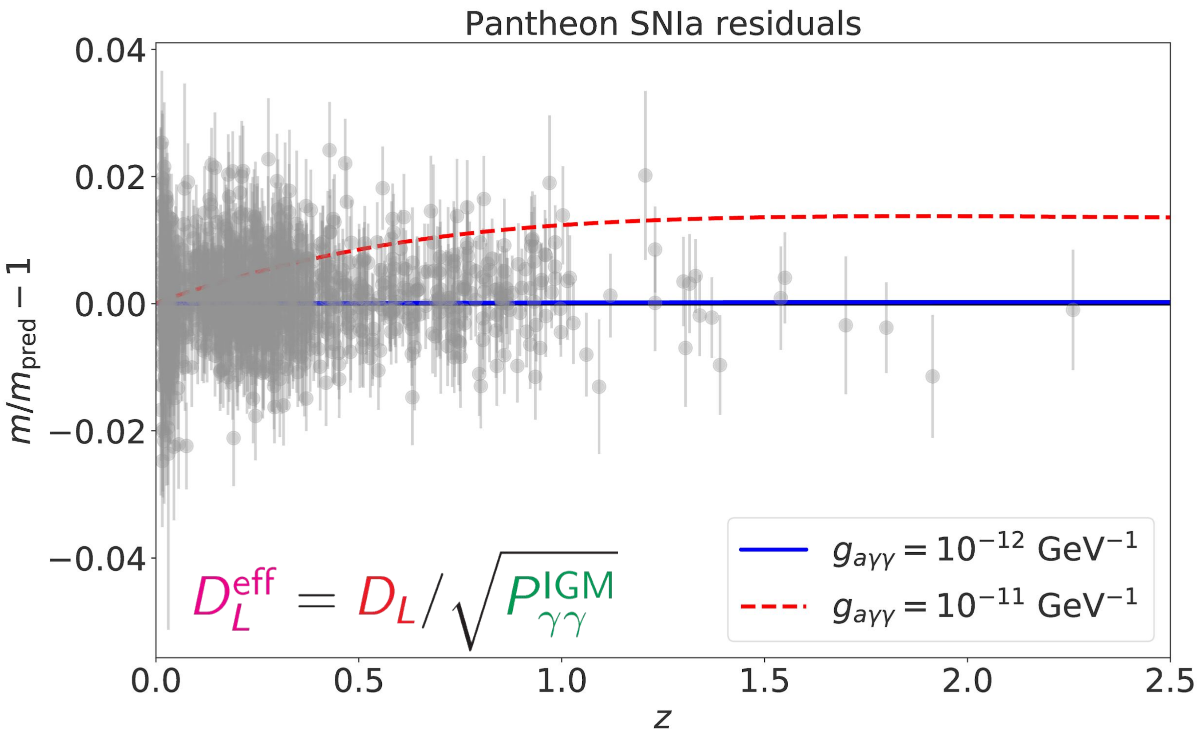
Luminosity Distance (LD)

- In ΛCDM: $$F = \frac{L}{4\pi {D_L}^2}$$
- With axions: $$F = P_{\gamma\gamma}^{\rm IGM} \frac{L}{4\pi D_L^2}$$ $$P_{a\gamma} \sim (g_{a\gamma\gamma} B)^2 x^2$$ $$P_{\gamma\gamma} = 1 - P_{a\gamma}$$
- Effective LD: $$D_L^{\rm eff} = D_L / \sqrt{P_{\gamma\gamma}^{\rm IGM}}$$

[Csaki, Kaloper, & Terning ‘01]

arXiv:2011.05993

LD: SNe Ia (Pantheon)



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[Scolnic *et al.* '17]

Angular Diameter Distance (ADD): clusters

- In ΛCDM: $$D_A \propto \frac{I_{SZ}^2}{I_X}$$

arXiv:2011.05993

[Gunn '78; Silk & White '78; Birkinshaw '79; Cavaliere *et. al* '79; Bonamente *et al.* '04]

Angular Diameter Distance (ADD): clusters

- In ΛCDM: $D_A \propto \frac{I_{SZ}^2}{T_X}$

CMB (Sunyaev-Zeldovich)

X-rays

arXiv:2011.05993

[Gunn '78; Silk & White '78; Birkinshaw '79; Cavaliere *et. al* '79; Bonamente *et al.* '04]

ADD: clusters

- In ΛCDM: $$D_A \propto \frac{I_{SZ}^2}{I_X}$$
- With axions: $$D_A^{\mathrm{eff}} \propto \frac{\left(P_{\gamma\gamma,SZ}^{\mathrm{IGM}}\right)^2 I_{SZ}^2}{P_{\gamma\gamma,X}^{\mathrm{IGM}} I_X}$$

arXiv:2011.05993

[Gunn ‘78; Silk & White ‘78; Birkinshaw ‘79; Cavaliere *et. al* ‘79; Bonamente *et al.* ‘04]

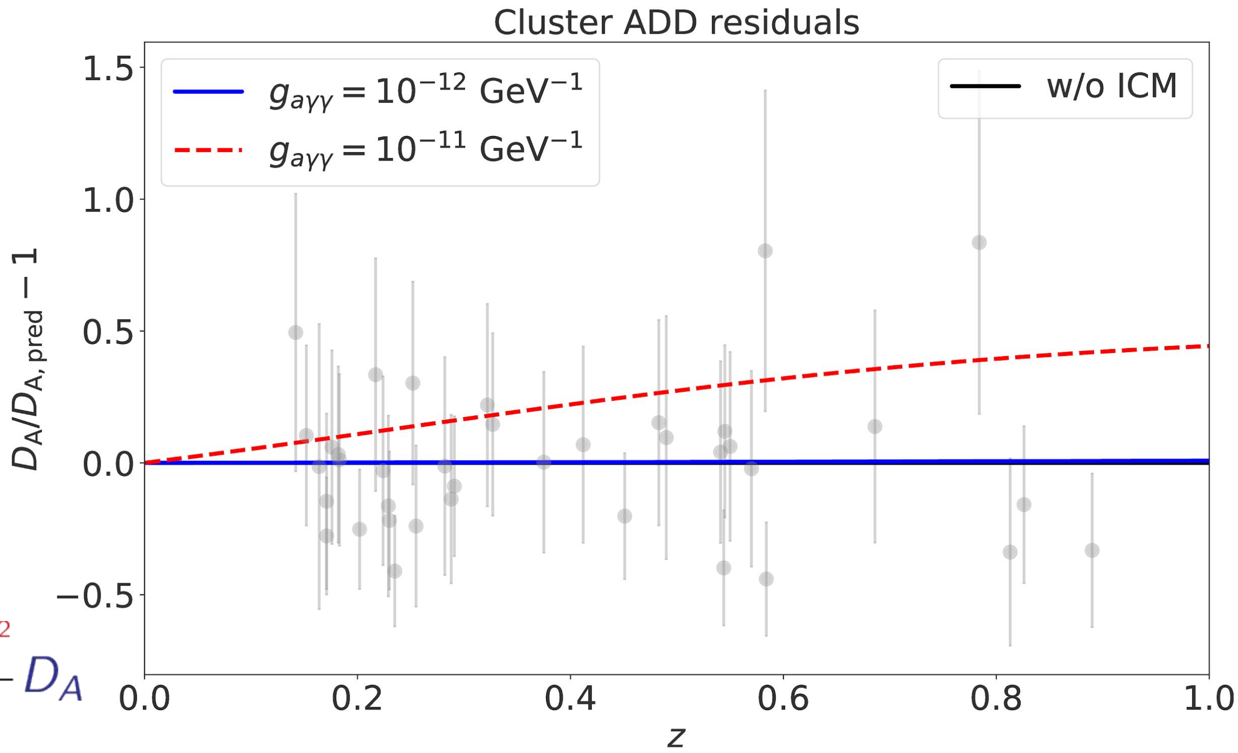
ADD: clusters

- In ΛCDM: $$D_A \propto \frac{I_{SZ}^2}{I_X}$$
- With axions: $$D_A^{\mathrm{eff}} \propto \frac{\left(P_{\gamma\gamma,SZ}^{\mathrm{IGM}}\right)^2 I_{SZ}^2}{P_{\gamma\gamma,X}^{\mathrm{IGM}}\, I_X}$$
- Effective ADD: $$D_A^{\mathrm{eff}} = \frac{\left(P_{\gamma\gamma,SZ}^{\mathrm{IGM}}\right)^2}{P_{\gamma\gamma,X}^{\mathrm{IGM}}} D_A$$

arXiv:2011.05993

[Gunn '78; Silk & White '78; Birkinshaw '79; Cavaliere *et. al* '79; Bonamente *et al.* '04]

ADD: clusters



$$D_A^{\mathrm{eff}} = \frac{\left(P^{\mathrm{IGM}}_{\gamma\gamma,SZ}\right)^2}{P^{\mathrm{IGM}}_{\gamma\gamma,X}} D_A$$

arXiv:2011.05993

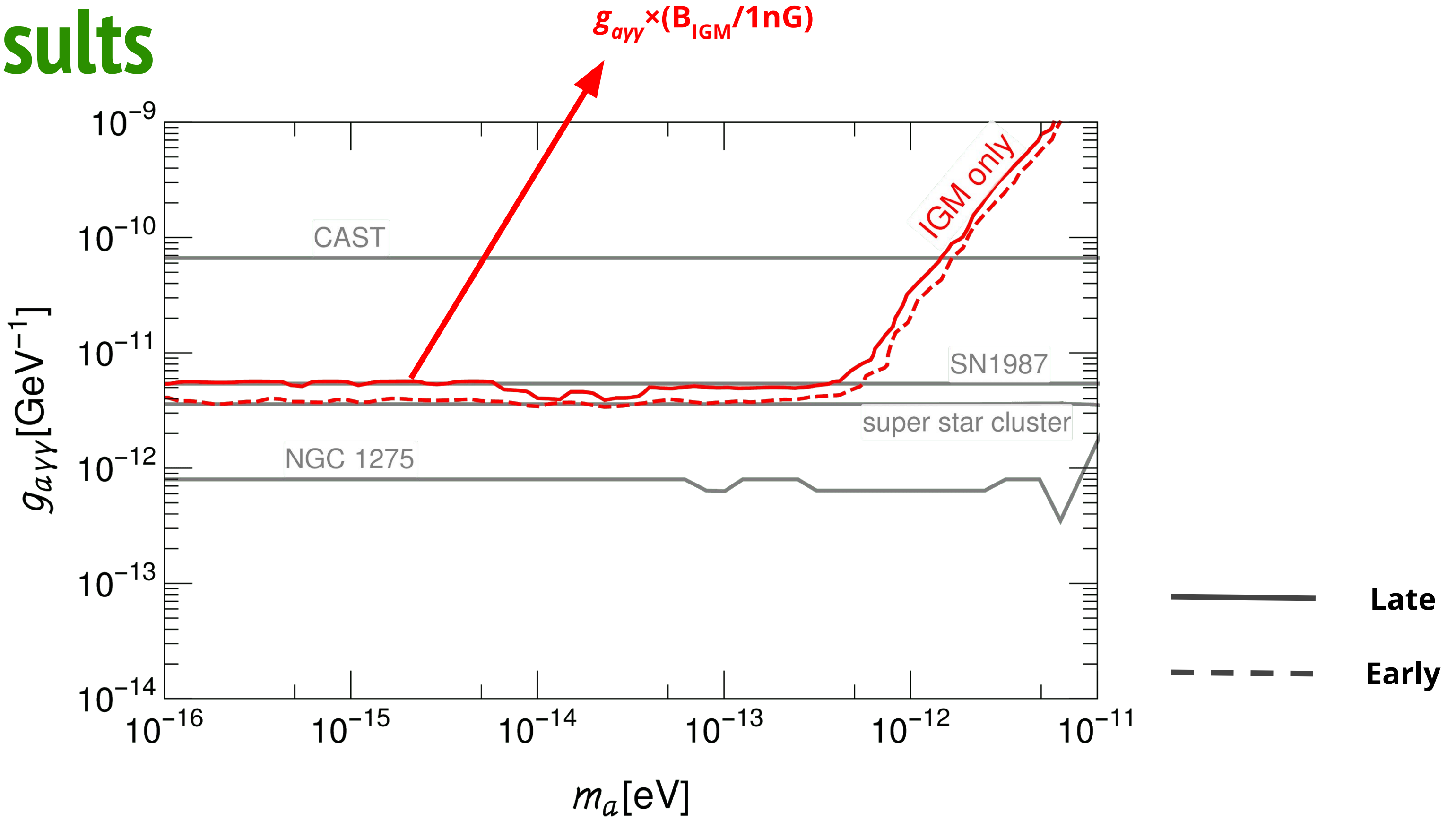
[Bonamente *et al.* ‘04]

Methodology

- Cosmic distances in **ΛCDM+axions** model
  - Parameters: $\{H_0, \Omega_\Lambda, L_{SN}, r_s^{drag}, \boldsymbol{g_{a\gamma\gamma}}, \boldsymbol{m_a}\}$
  - Scan parameter space with `emcee` [Foreman-Mackey *et al.* '13]
- MCMC runs
  - Datasets: SNe Ia + clusters + BAO + *early*/*late* (SH0ES+TDCOSMO **or** Planck '18)
  - IGM properties
  - With or without magnetic ICM effects

arXiv:2011.05993 (https://github.com/ManuelBuenAbad/cosmo_axions)

Results



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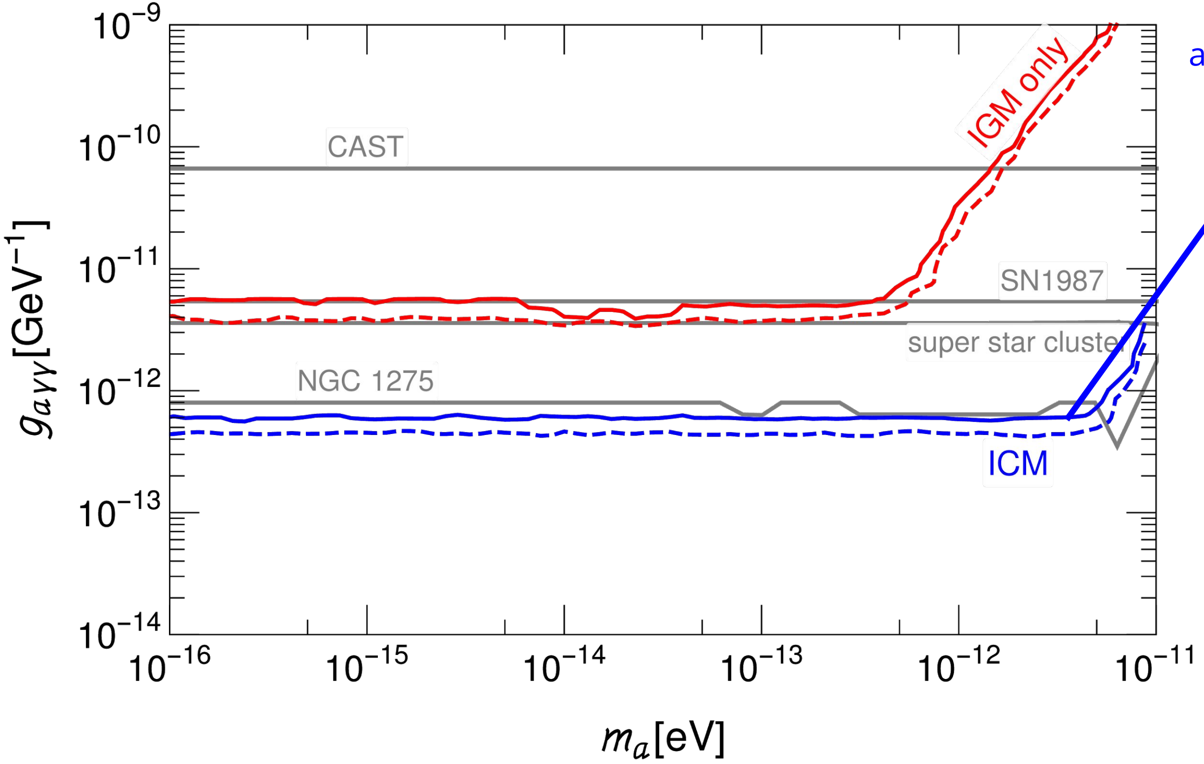
Results



axion-photon conversion ***inside*** clusters

[Reynolds *et al.* ‘19; Bonafede *et al.* ‘10; cf. Libanov & Troitsky ‘19]

Late

Early

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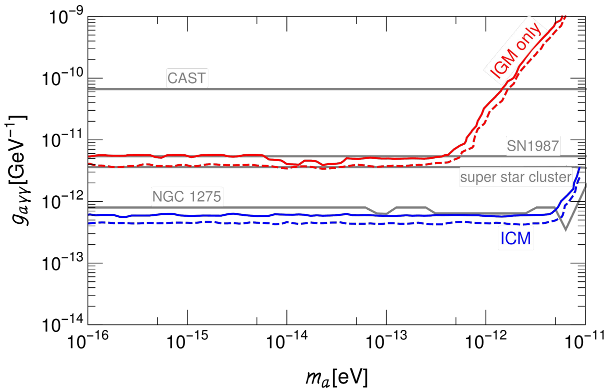
(https://github.com/ManuelBuenAbad/cosmo_axions)

Conclusions



- IGM: Strong bounds on $\boldsymbol{g_{a\gamma\gamma}}$ for $\boldsymbol{m_a}<10^{-12}$ eV
  - Common benchmark (B_{IGM} = 1 nG)
- Independent of Hubble crisis!
  - Measurements of *shape* of $H(z)/H_0$, **not** of scale H_0
- Magnetic ICM effects ⇒ **stronger bounds** (*independent* of IGM!)
  - Subject to uncertainties [Reynolds *et al.* '19; Bonafede *et al.* '10; cf. Libanov & Troitsky '19]
- Improvement:
  - Better measurements of shape of $H(z)/H_0$
  - Determine IGM/ICM magnetic properties!

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(https://github.com/ManuelBuenAbad/cosmo_axions)

Backup Slides

A “bright” puzzle

- Light sources: *dimming* = *farther* ⇒ ***brightening = closer***
    - $D \propto 1/H_0$: smaller D ⇒ **larger H_0**
    - H_0 deduced from SNe would be larger: **address Hubble tension!**
- To brighten instead of dim
    - Initial flux of *axions* ⟶ convert en-route ⟶ reach observer as *photons*
        - Produced in/around SNe
        - Hard to satisfy production conditions *and* sizeable en-route conversion!
- Try for yourself!

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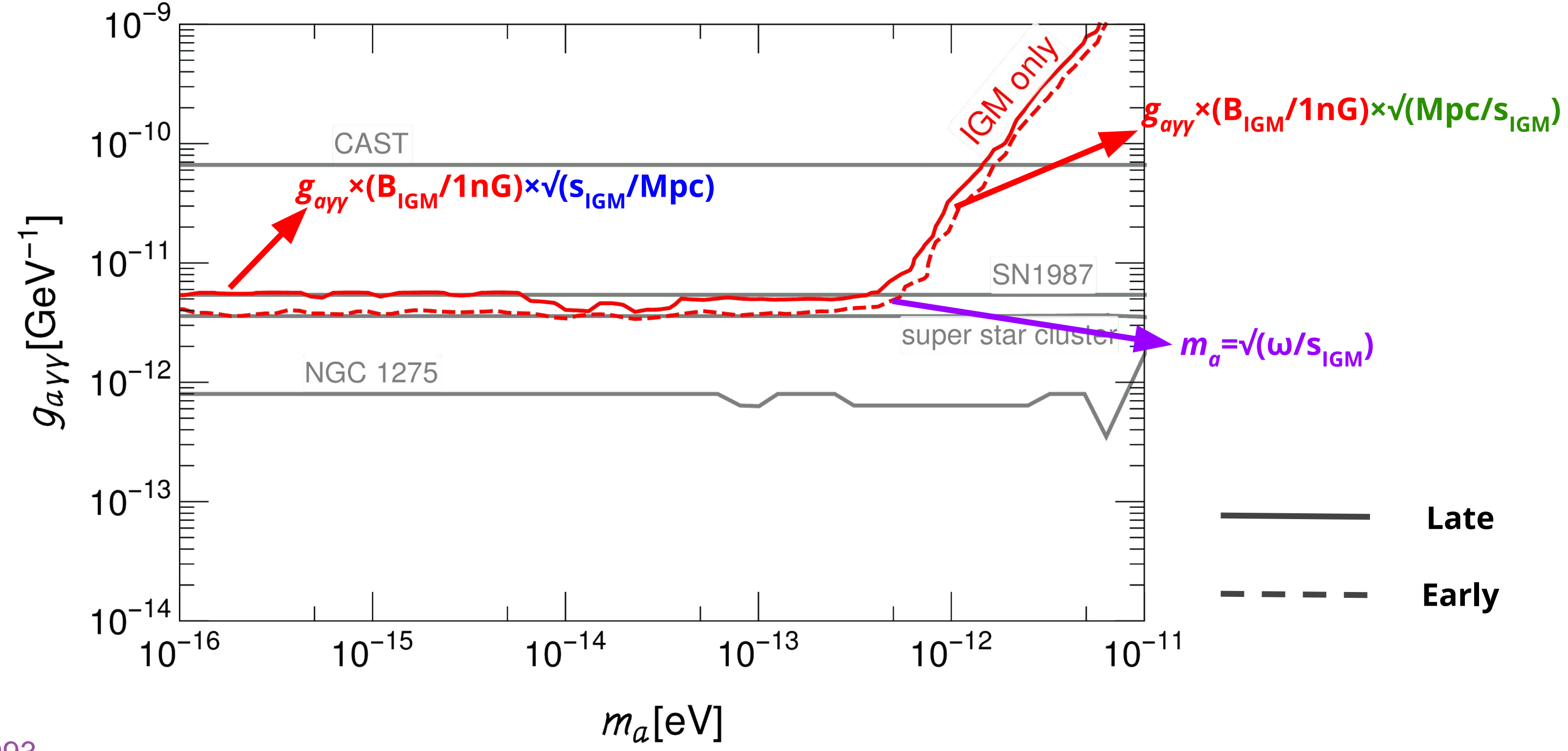
IGM magnetic field strength and domain size



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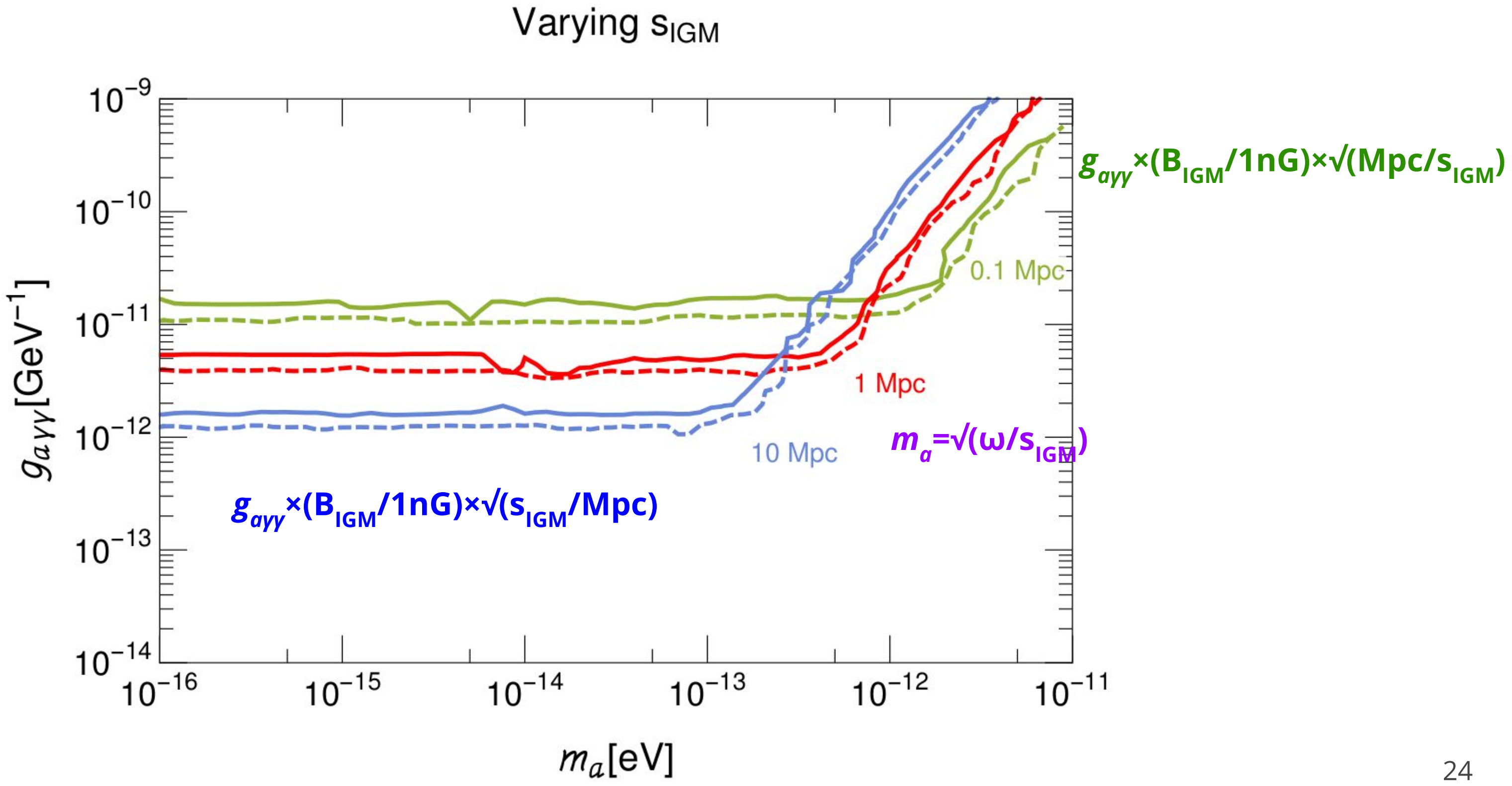
IGM magnetic field strength and domain size



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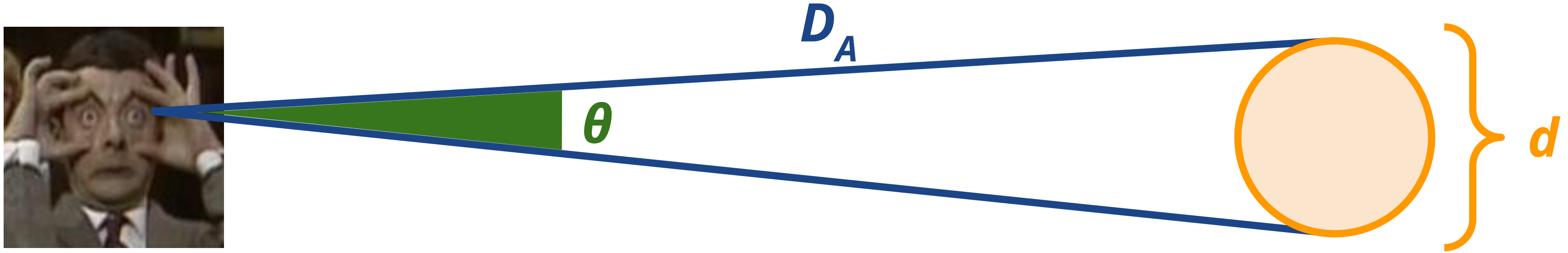
Angular Diameter Distance (ADD)



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

arXiv:2011.05993

ADD: clusters

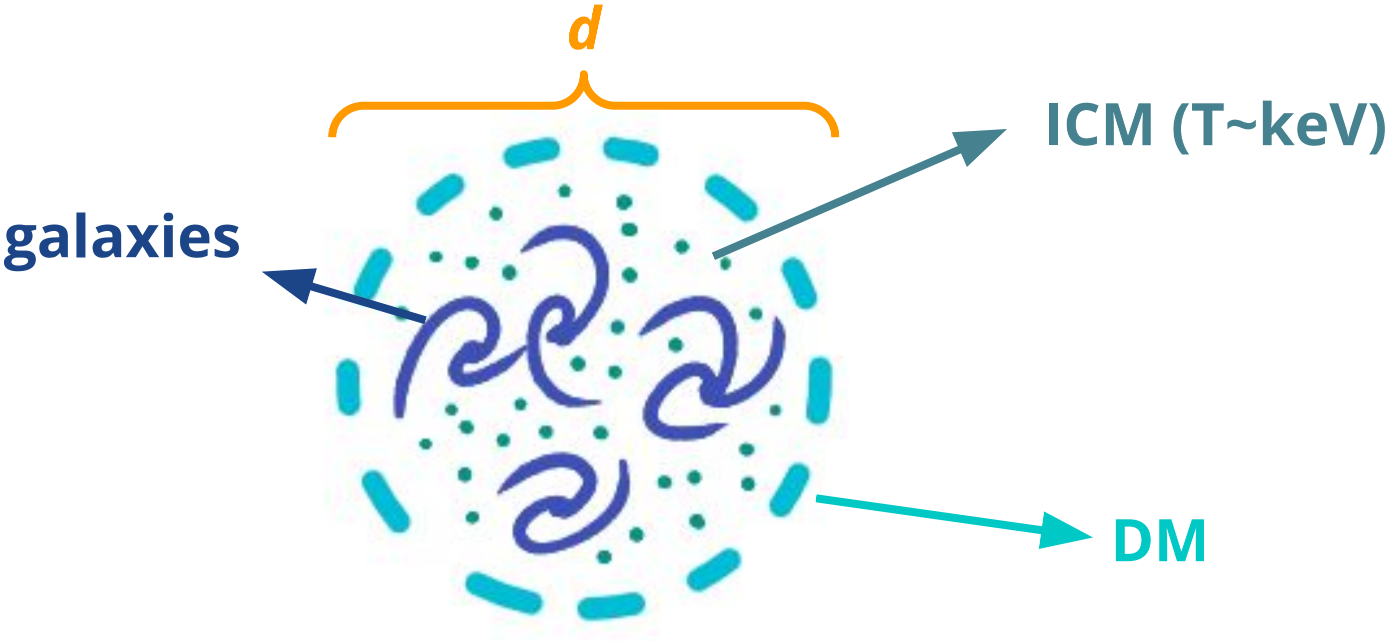
- Normally, ADD would be unaffected by axions: no dependence upon photon brightness
  - E.g. Baryon Acoustic Oscillations (BAO) in galaxy surveys

- However, clusters' ***d*** can be determined from **light**!

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

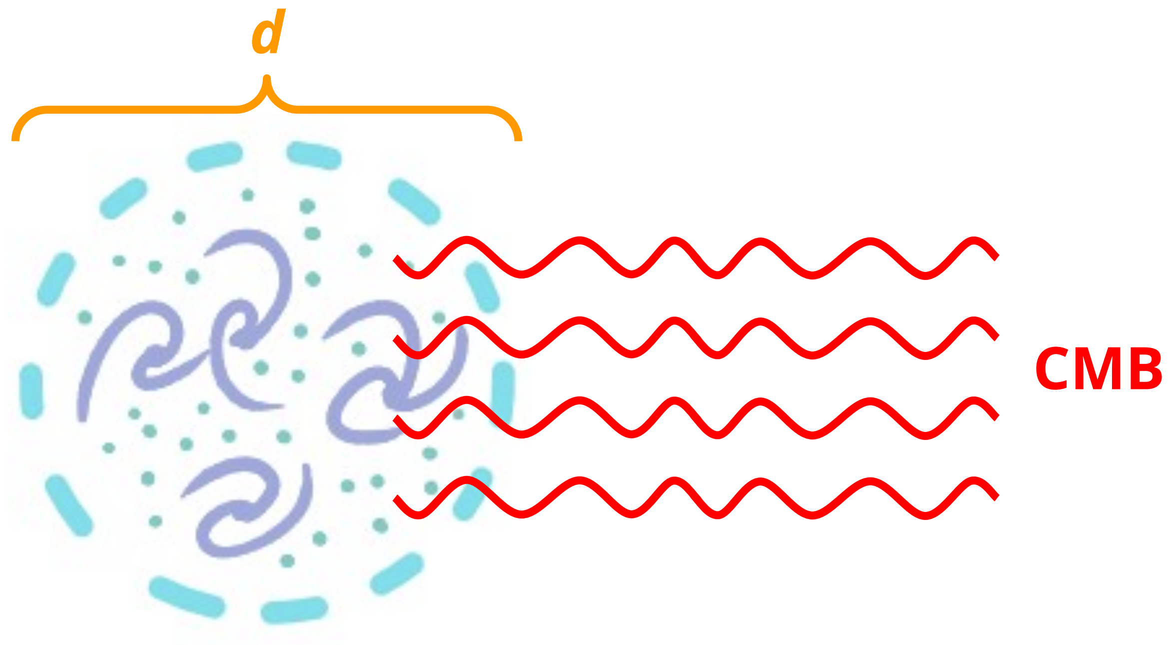
arXiv:2011.05993

ADD: clusters



arXiv:2011.05993

ADD: clusters - Sunyaev-Zeldovich effect



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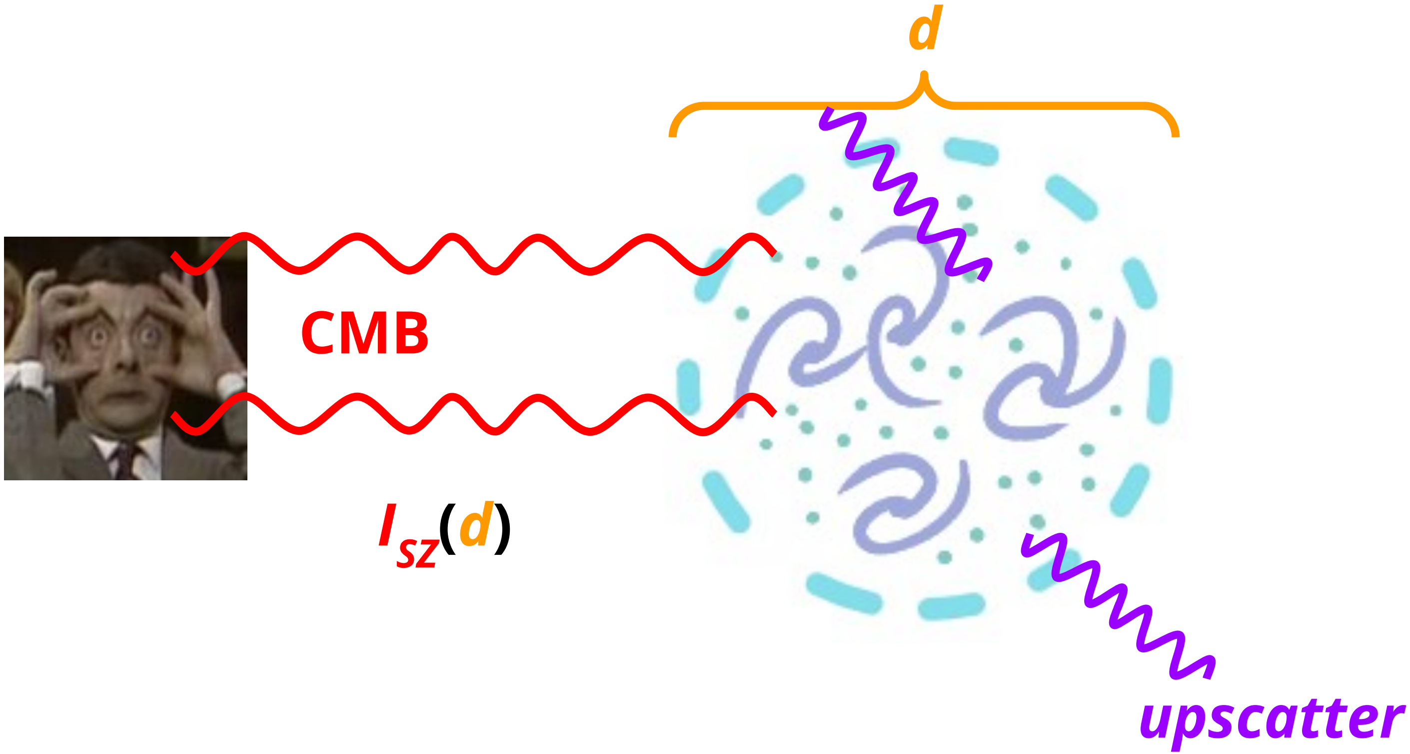
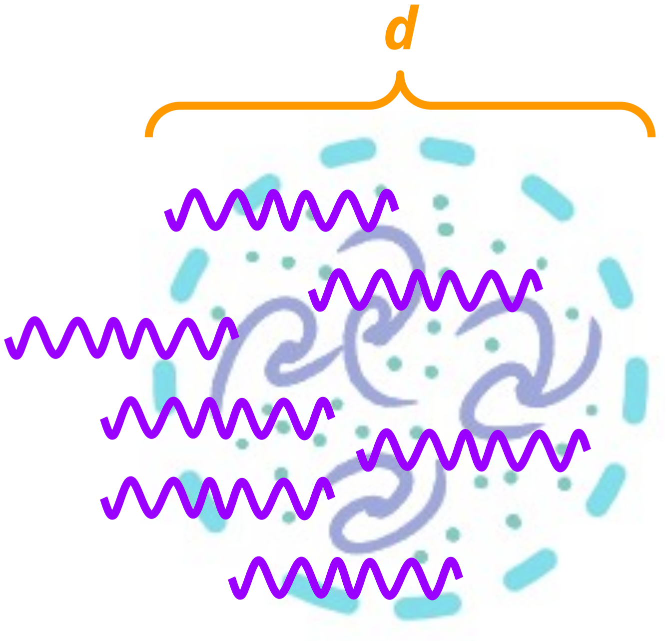
ADD: clusters - Sunyaev-Zeldovich effect



arXiv:2011.05993

ADD: clusters - X-rays



$I_X(d)$

X-rays from ICM

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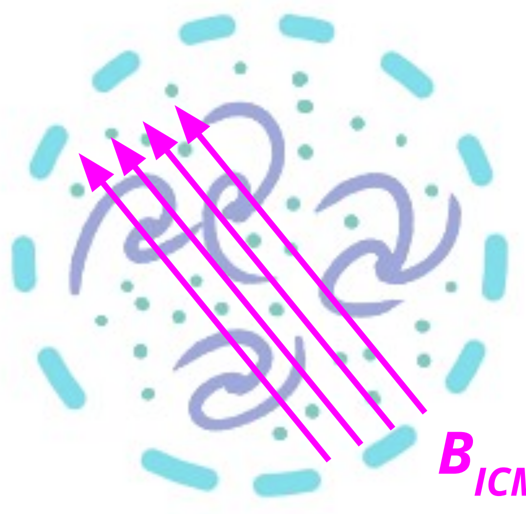
Clusters: Magnetic ICM Effects



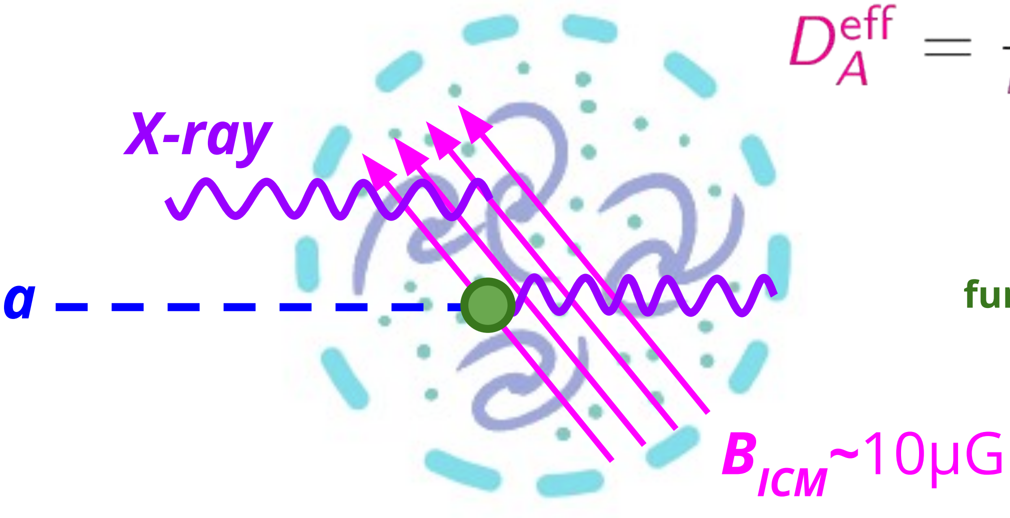
B_{ICM}~10μG

arXiv:2011.05993

[Reynolds *et al.* ‘19; Bonafede *et al.* ‘10; cf. Libanov & Troitsky ‘19]

Clusters: Magnetic ICM Effects

$$D_A \propto \frac{I_{SZ}^2}{I_X}$$



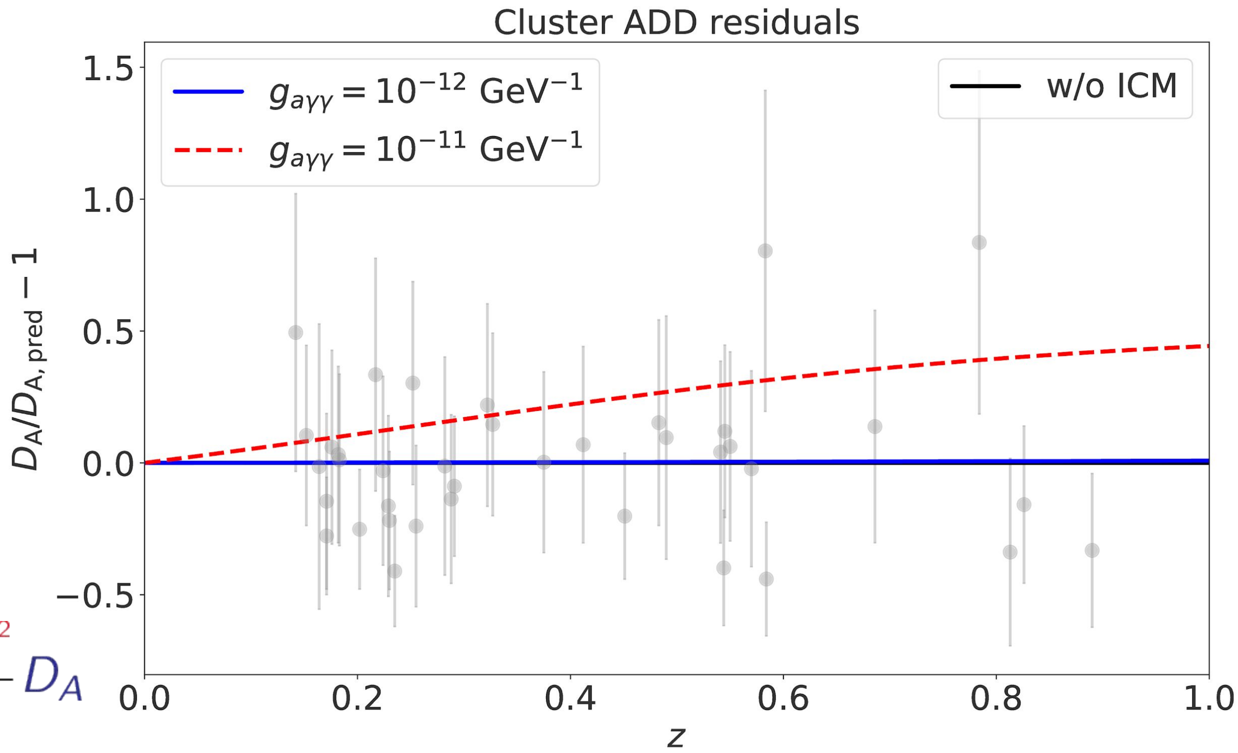
$$D_A^{\rm eff} = \frac{\left(P^{\rm IGM}_{\gamma\gamma,SZ}\right)^2}{P^{\rm IGM}_{\gamma\gamma,X}\,P^{\rm ICM}_{\gamma\gamma,X}} D_A$$

further ICM suppression

arXiv:2011.05993

[Reynolds *et al.* ‘19; Bonafede *et al.* ‘10; cf. Libanov & Troitsky ‘19]

ADD: clusters

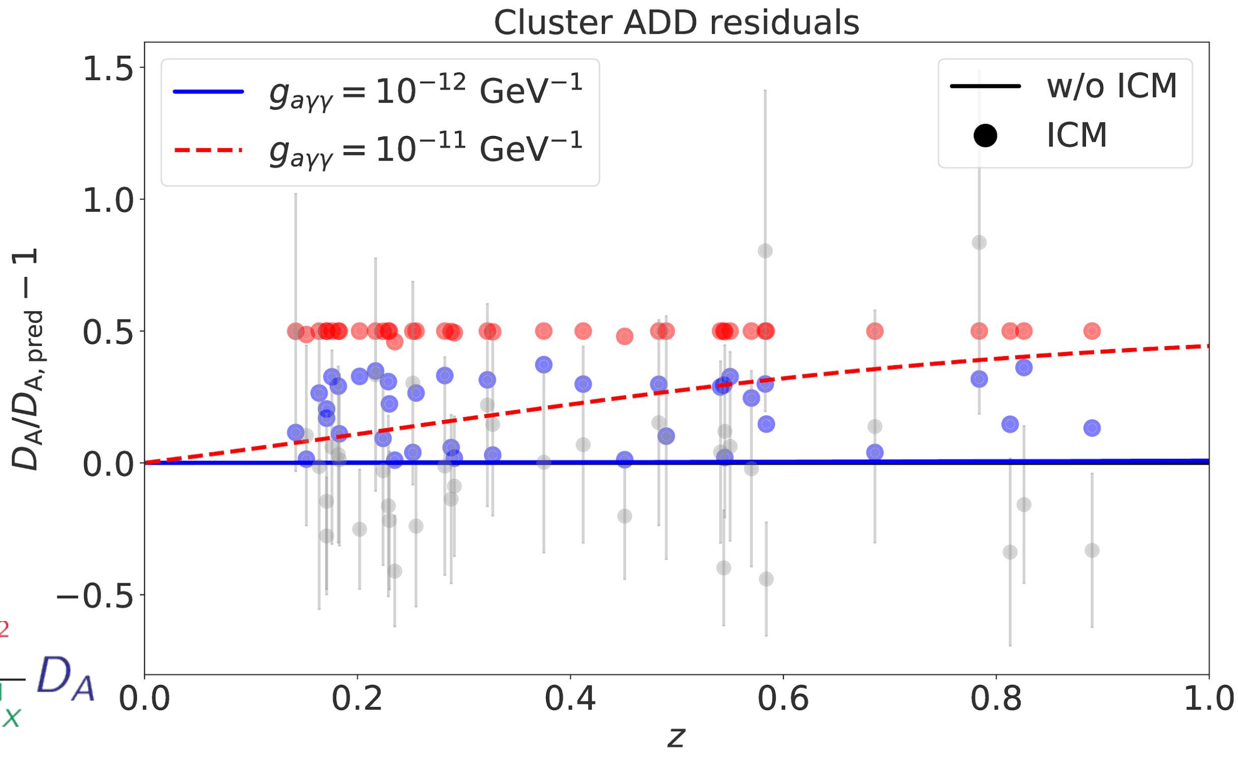


$$D_A^{\mathrm{eff}} = \frac{\left(P^{\mathrm{IGM}}_{\gamma\gamma,SZ}\right)^2}{P^{\mathrm{IGM}}_{\gamma\gamma,X}} D_A$$

arXiv:2011.05993

[Bonamente *et al.* '04]

ADD: clusters



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

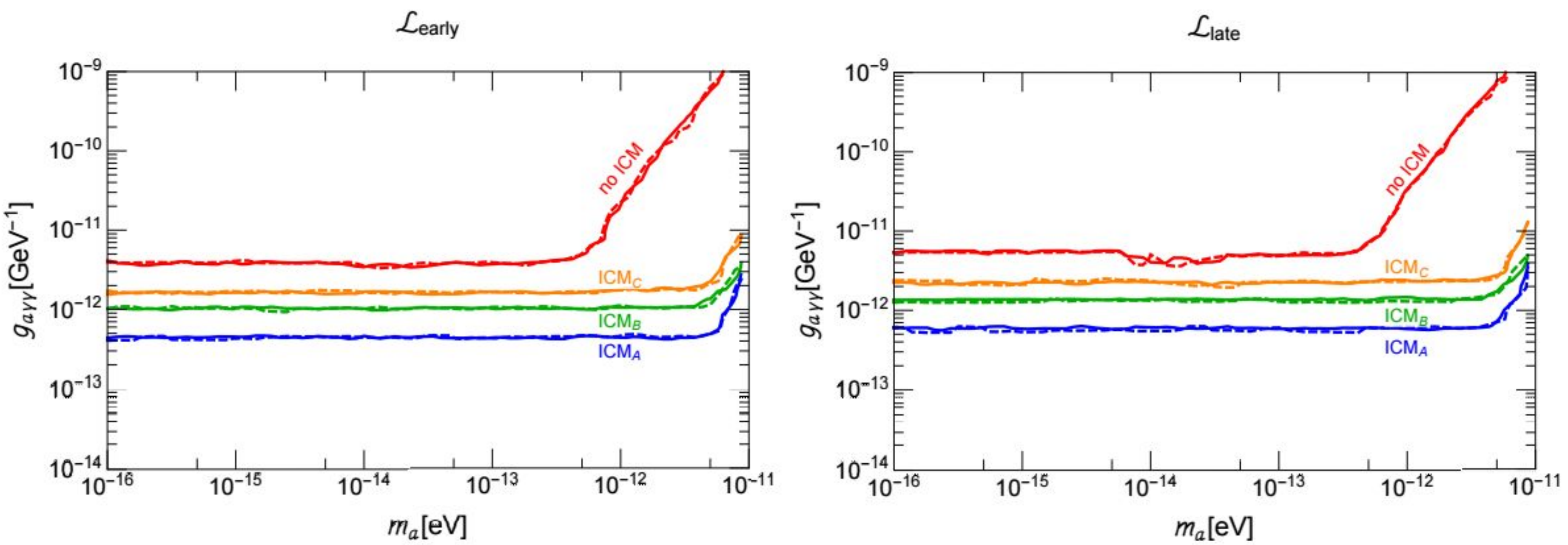
arXiv:2011.05993

[Bonamente *et al.* '04]

Results

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

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



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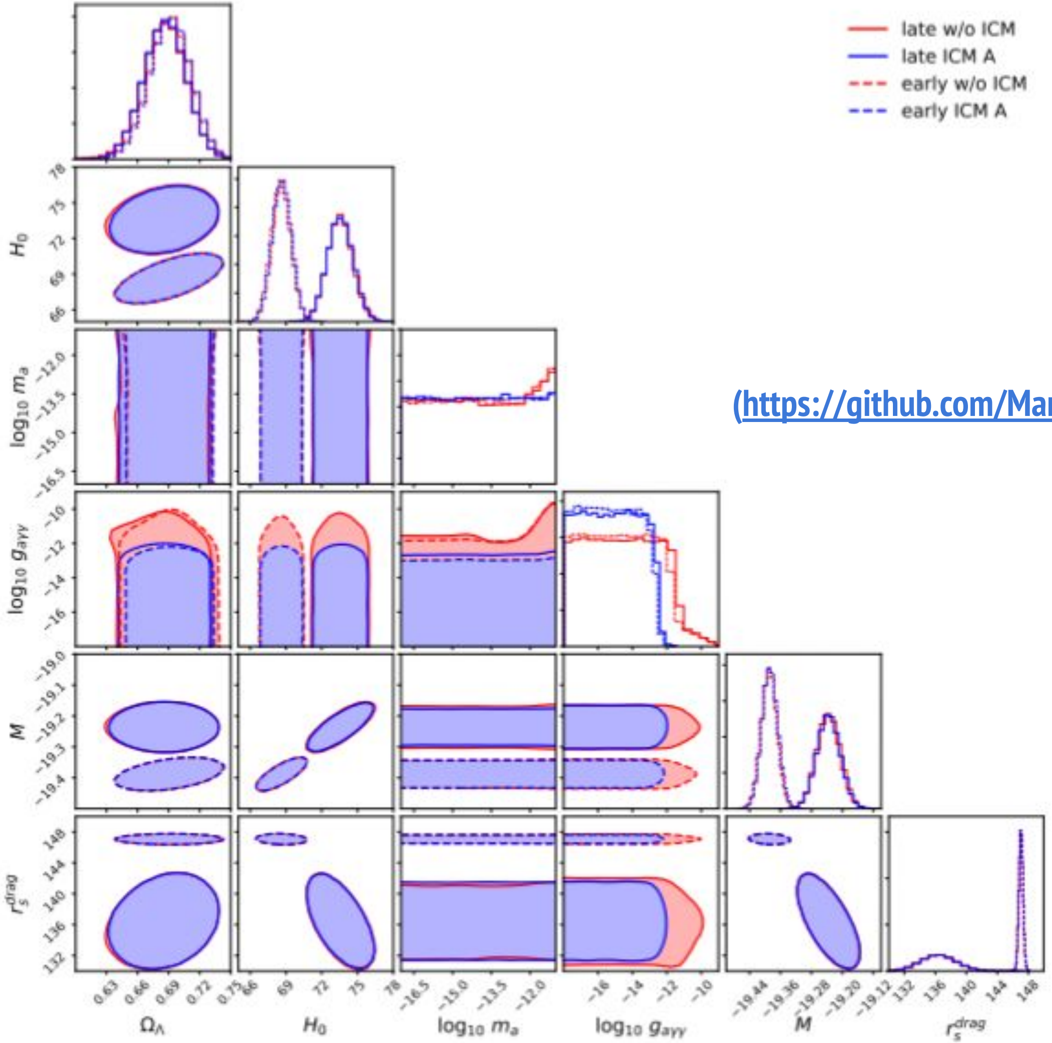
(https://github.com/ManuelBuenAbad/cosmo_axions)

MCMC



(https://github.com/ManuelBuenAbad/cosmo_axions)

arXiv:2011.05993

a↔️γ: single domain

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

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

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

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

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a↔γ: multiple domains

$$P_{a\gamma}(y) = (1 - A)\left(1 - \prod_{i=1}^{N}\left(1 - \frac{3}{2}P_{0,i}\right)\right)$$

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

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

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

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γ↔γ: IGM survival probability

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

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

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

arXiv:2011.05993

γ↔γ: ICM survival probability

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

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

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

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

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

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γ↔️γ: ICM survival probability

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

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

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Luminosity Distance

$$D_L(z) = (1+z)\int_0^z \mathrm{d}z' \, \frac{1}{H(z')}$$

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

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

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

arXiv:2011.05993

Angular Diameter Distance

$$D_A(z) = \frac{1}{1+z} \int_0^z \mathrm{d}z' \, \frac{1}{H(z')}$$

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

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

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

$$\frac{I_a^{\mathrm{clusters}}}{I_\gamma^{\mathrm{clusters}}} = \frac{1-\langle P_{\gamma\gamma}^{\mathrm{ICM}}\rangle}{\langle P_{\gamma\gamma}^{\mathrm{ICM}}\rangle} \qquad A_{\mathrm{X}} = \frac{2}{3}\left(1 + \frac{I_a^{\mathrm{clusters}}}{I_\gamma^{\mathrm{clusters}}}\right)$$

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