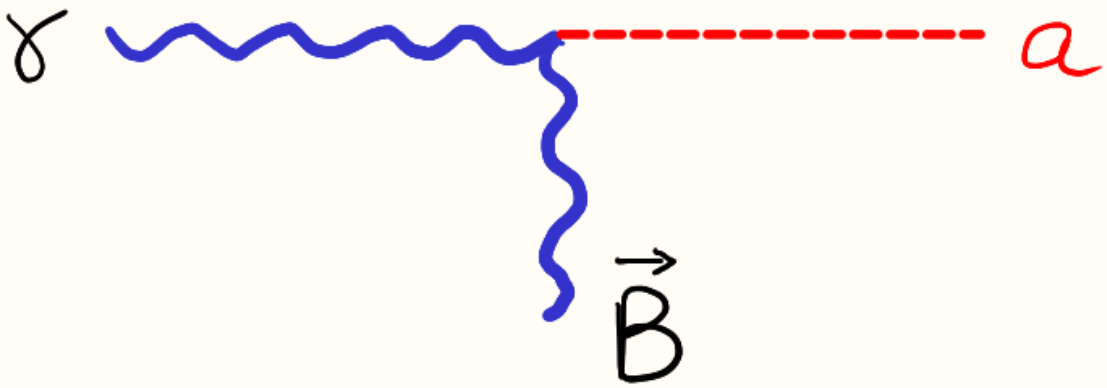
Constraints on Axions from Cosmic Distance Measurements

Manuel Buen-Abad, JiJi Fan, CS, 2011.05993

Basics of Axion-Photon Conversion



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

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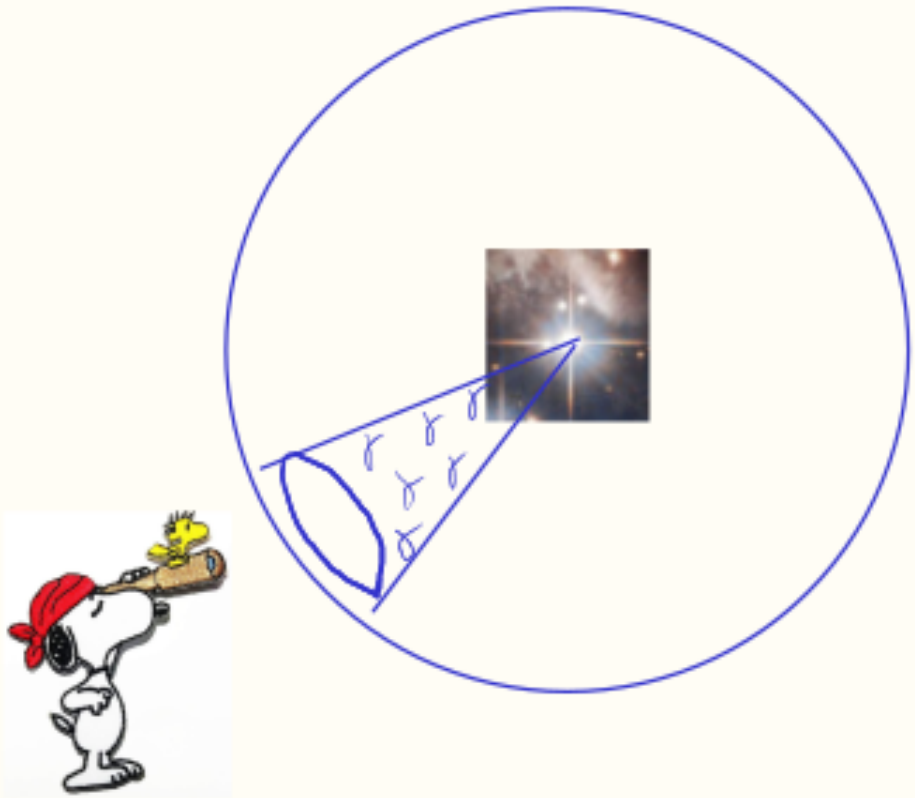

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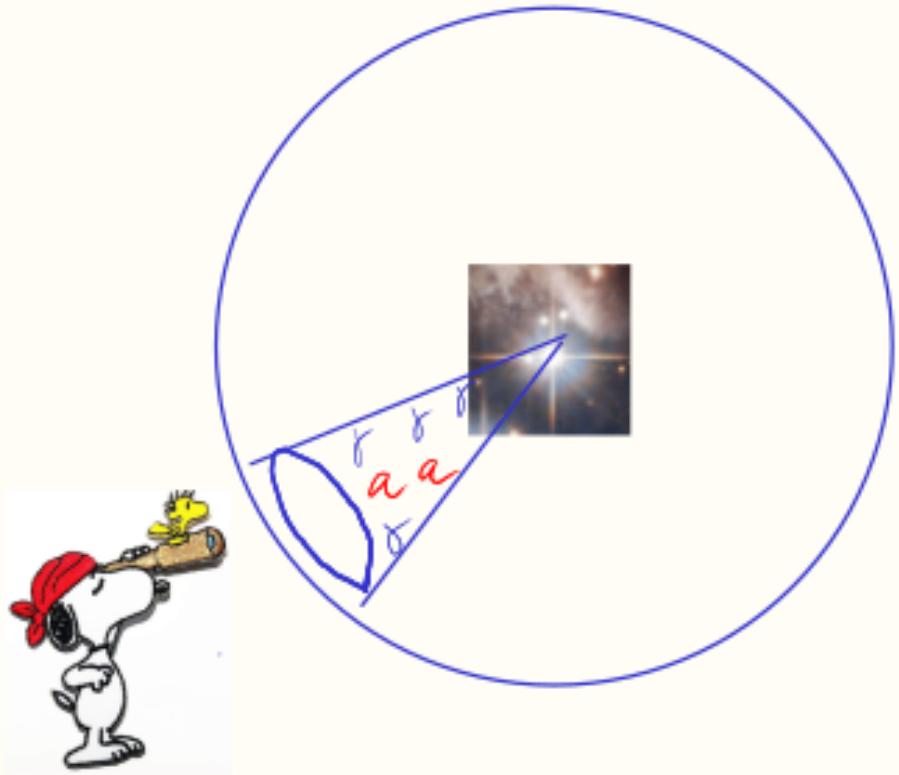

$$P \propto g_{a\gamma}^2 B^2 x^2$$

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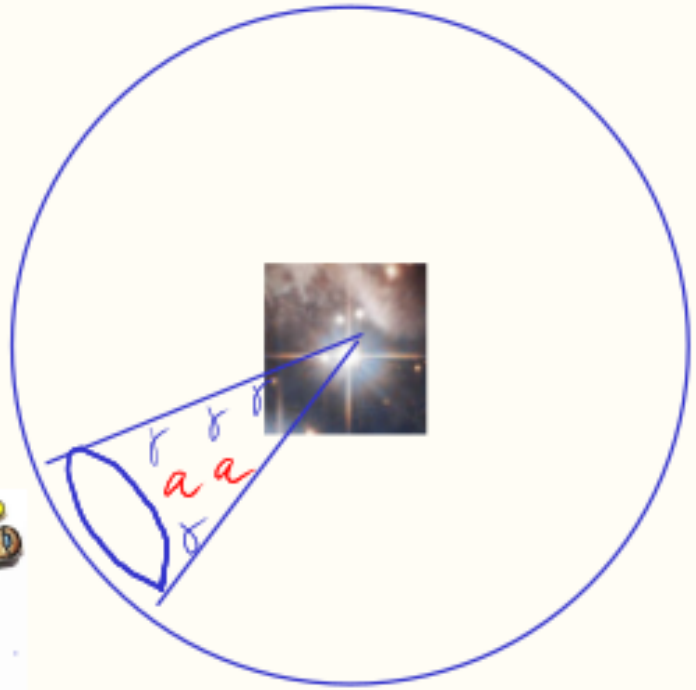

Main idea:

- Photon-axion oscillation directly affects the measured brightness.
- Modified brightness affects the inferred distance.

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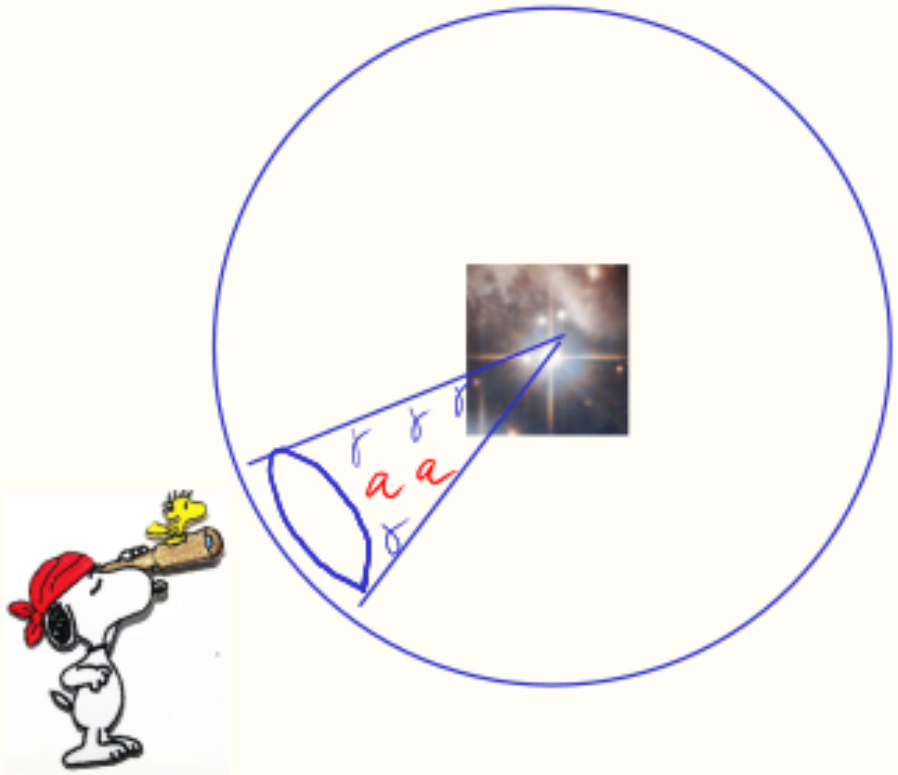

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More specifically, it affects

- D_L: standard candle

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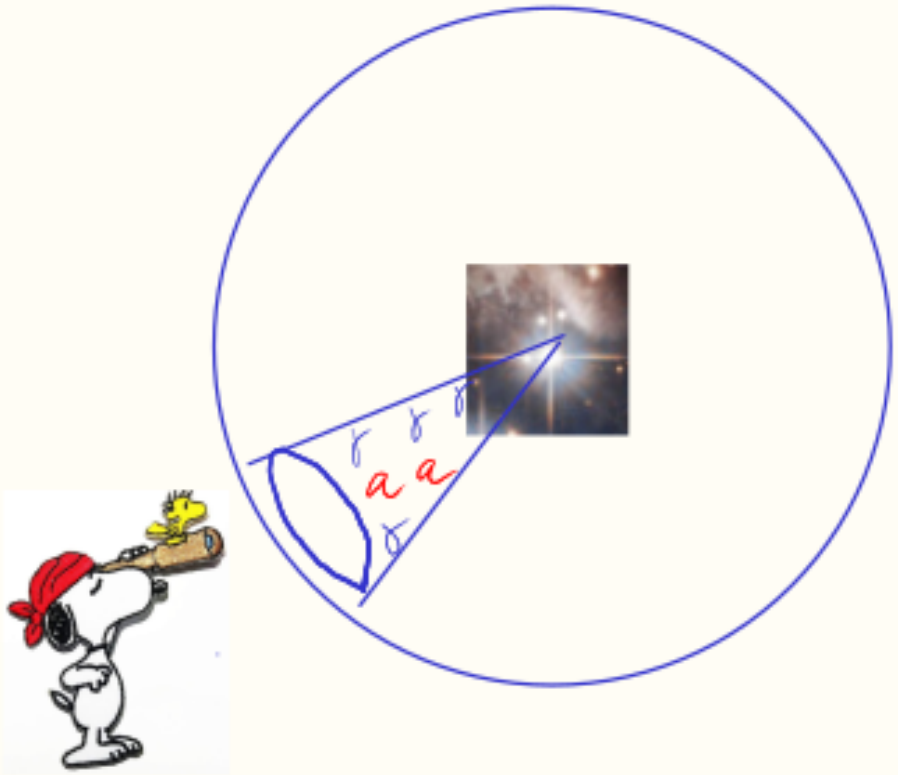

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- D_A: (non-standard) rulers that rely on brightness to anchor its physical size

Type Ia Supernova

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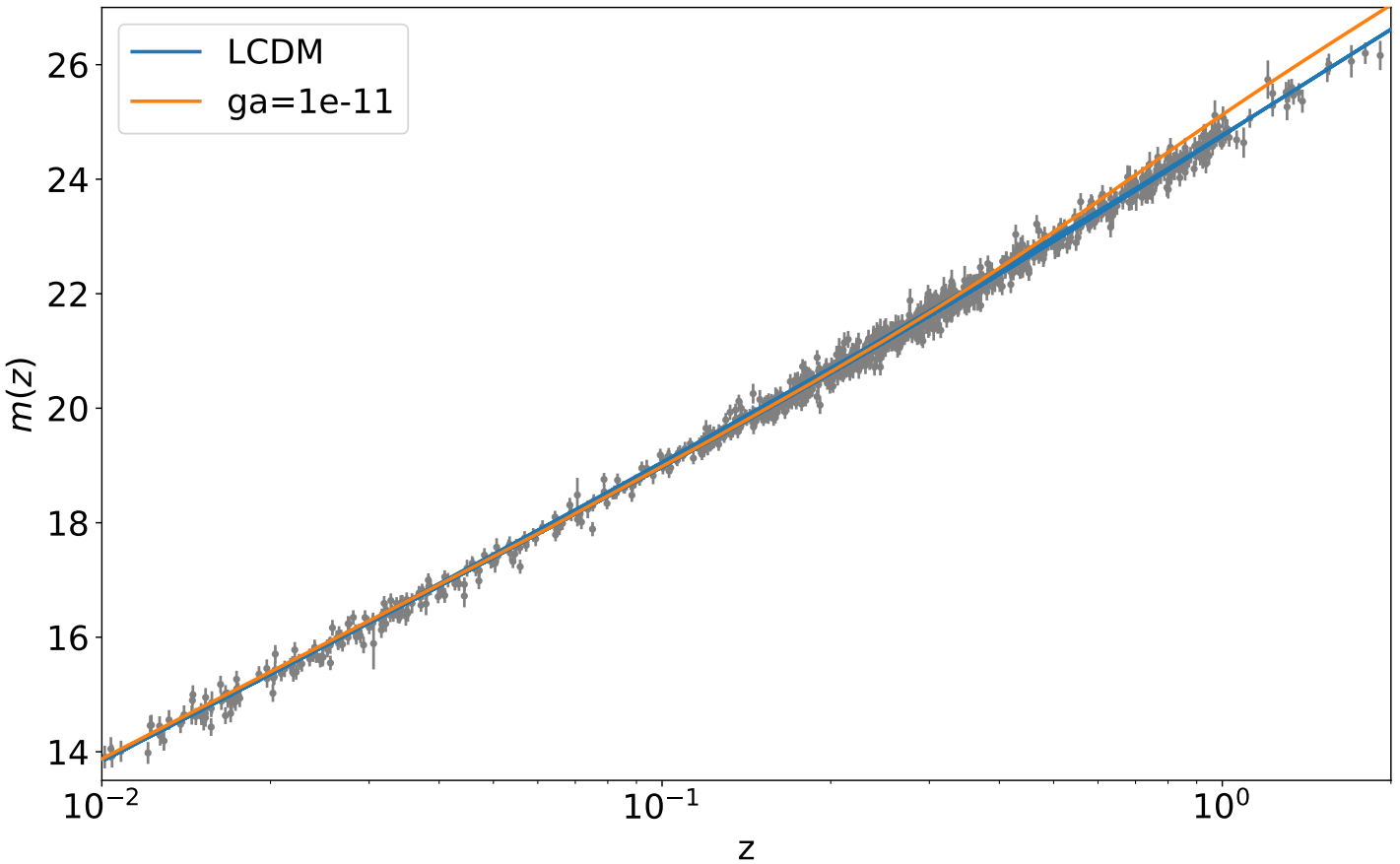
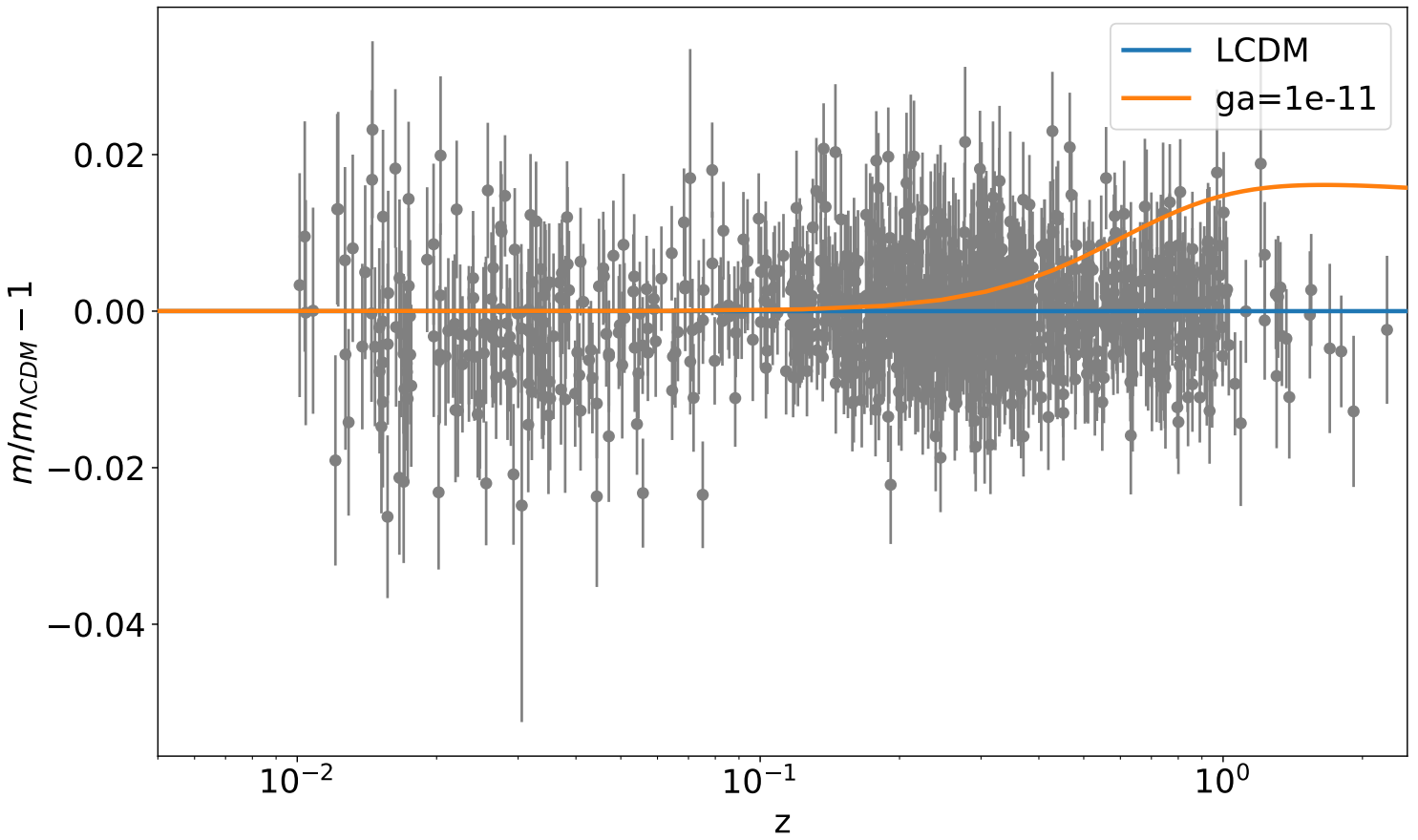
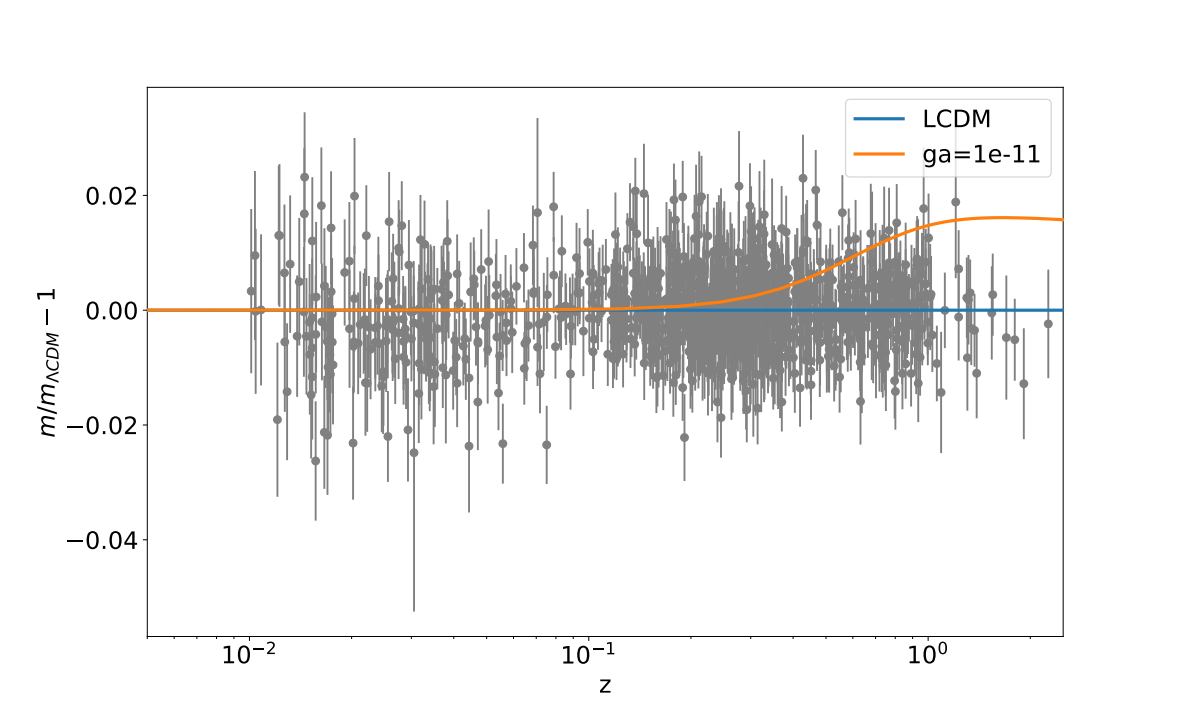
- In a ΛCDM universe, $D_L = D_L(z)$, this shows up as a change in $F(z)$ shape which is constrained by SN Ia data set


LCDM
ga=1e-11
m(z)
z
26
24
22
20
18
16
14
10^{-2}
10^{-1}
10^{0}


LCDM
ga=1e-11
0.02
0.00
−0.02
−0.04
$m/m_{\Lambda CDM} - 1$
10^{-2}
10^{-1}
10^{0}
z

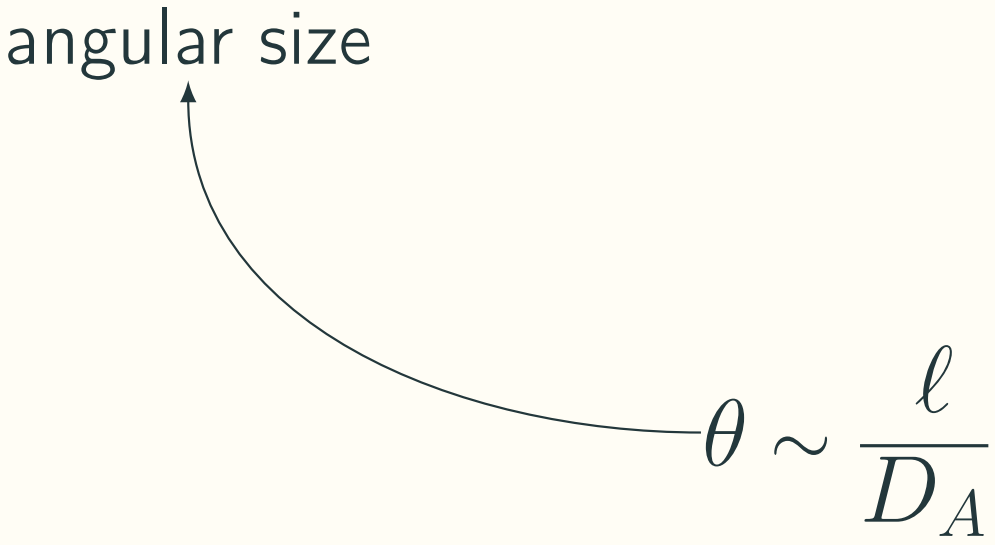


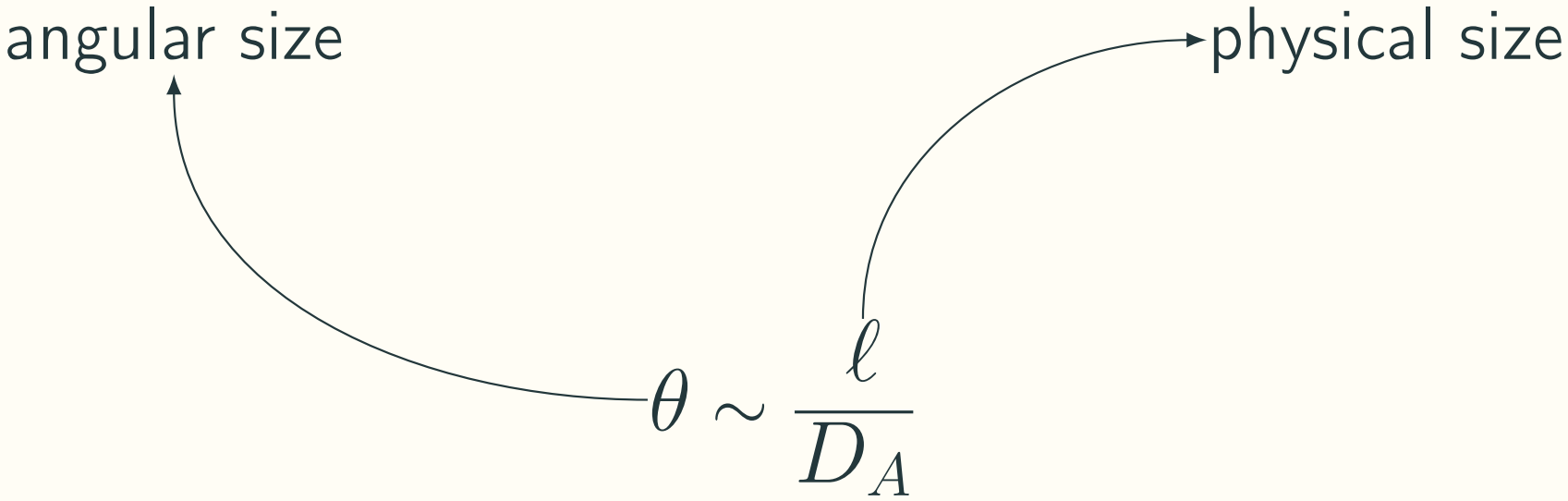
The likelihood:

$$-2\ln\mathcal{L}_{Pan} = \sum_{i,j=1}^{1048} \left(m_i^{Pan} - m^{th}(z_i;\theta,M)\right) C_{ij}^{Pan} \left(m_j^{Pan} - m^{th}(z_j;\theta,M)\right)$$

Galaxy Clusters

$$\theta \sim \frac{\ell}{D_A}$$


angular size
$\theta \sim \frac{\ell}{D_A}$


angular size
physical size
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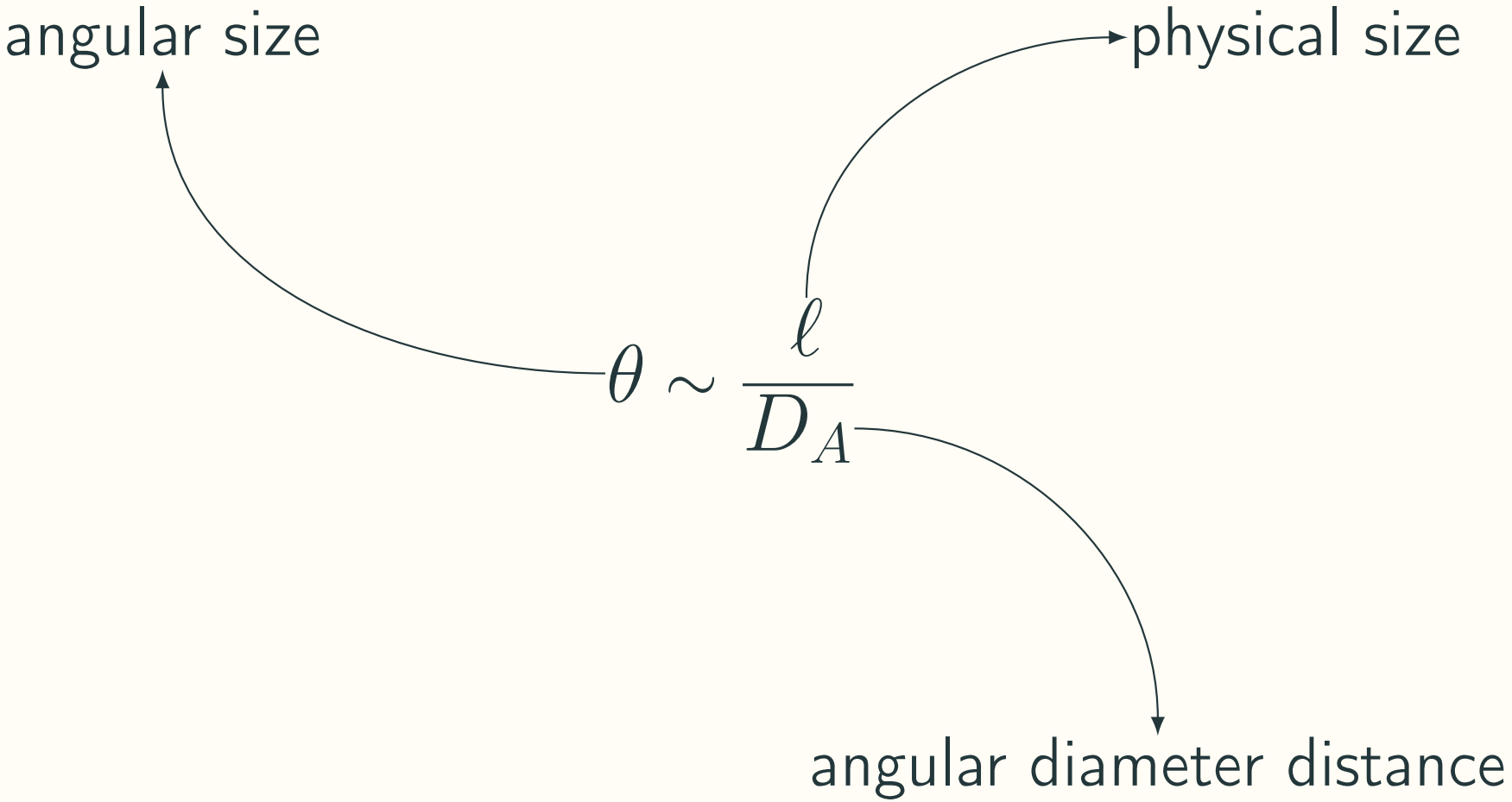
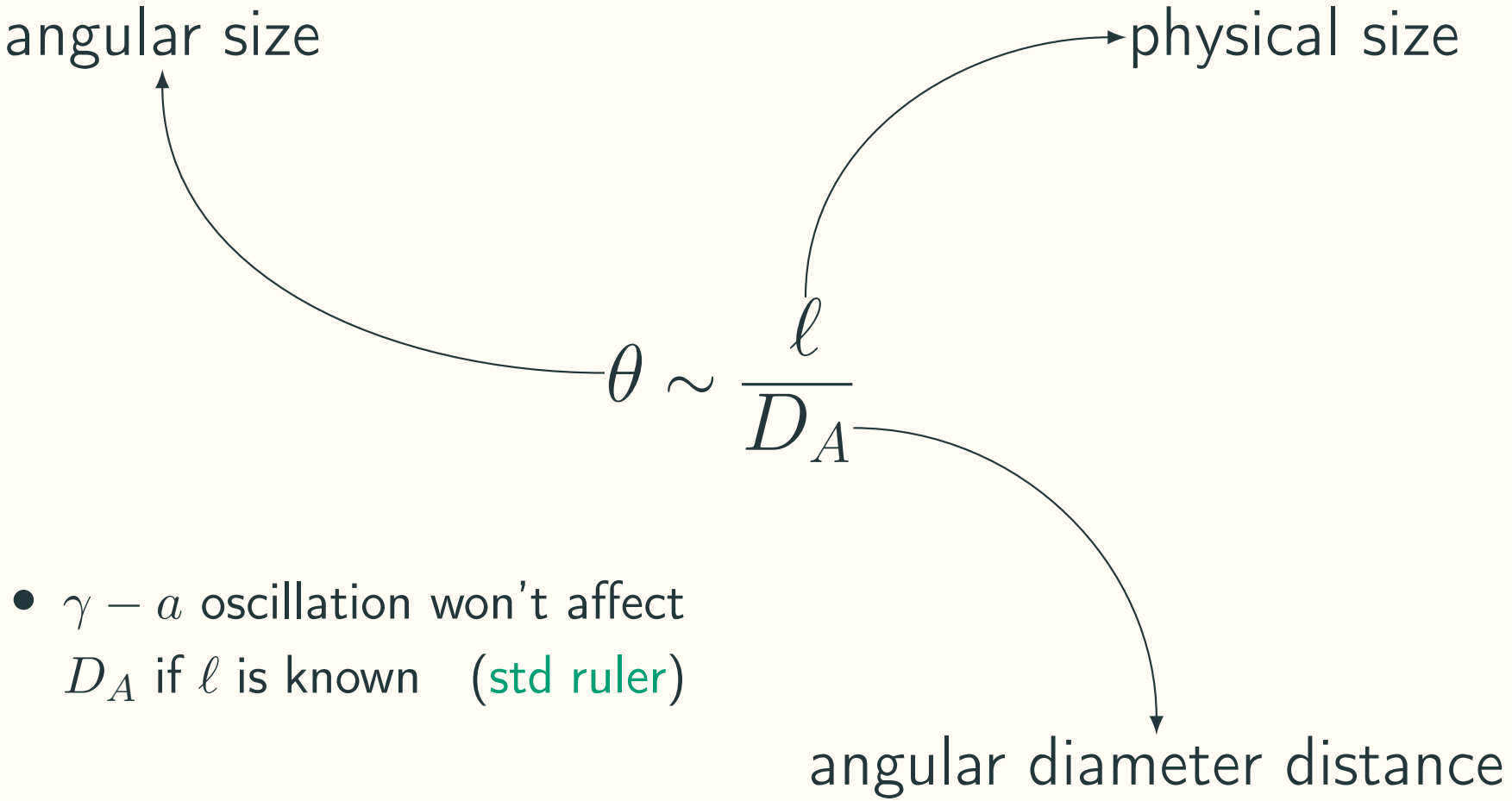
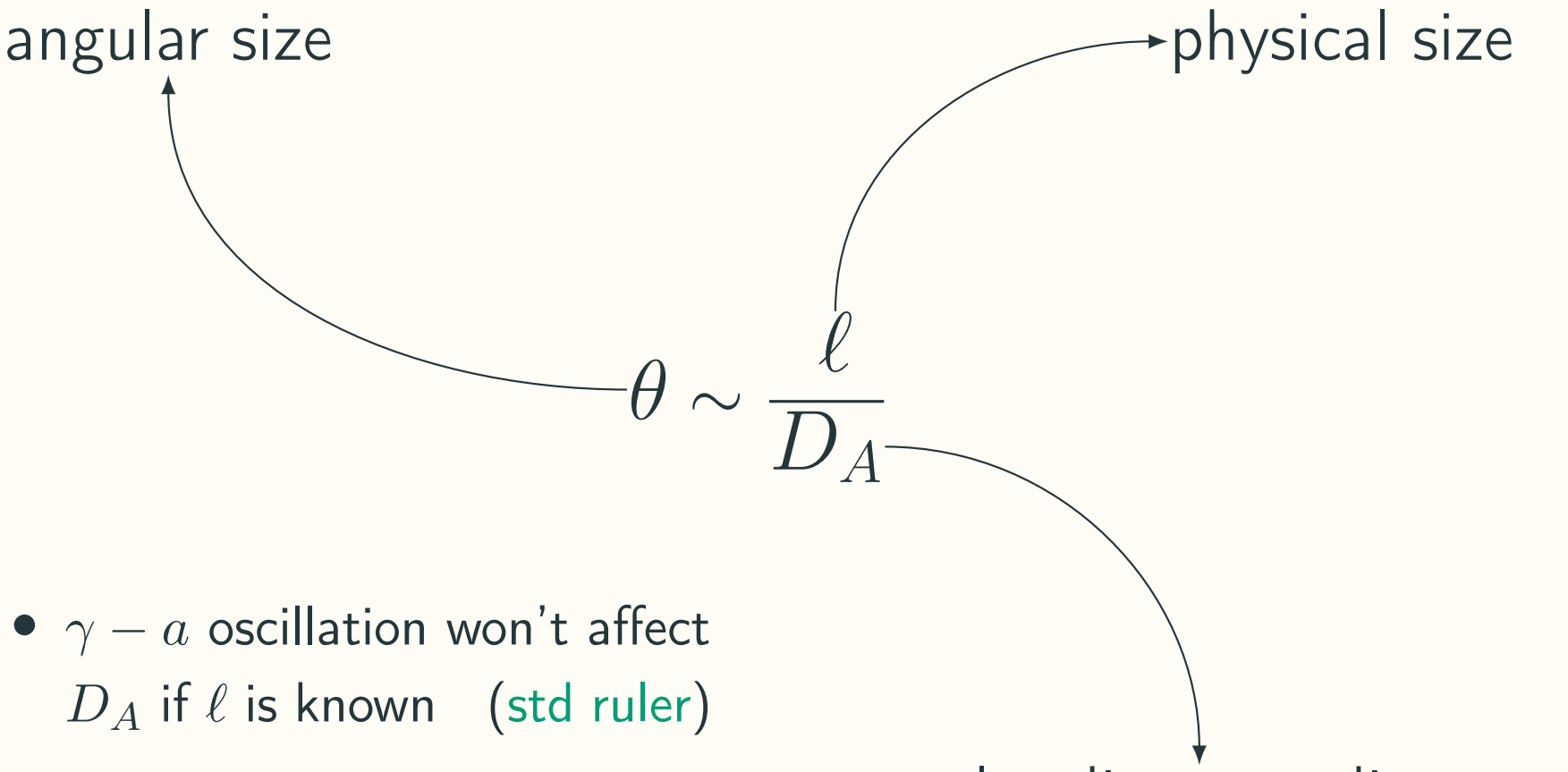

angular size
physical size
$\theta \sim \frac{\ell}{D_A}$
angular diameter distance



- $\gamma - a$ oscillation won't affect D_A if ℓ is known (std ruler)



- $\gamma - a$ oscillation won't affect D_A if ℓ is known (std ruler)
- Some objects have unknown size ℓ, which can only be inferred from their brightness measurement

Galaxy Clusters

Observable:

- X-ray surface brightness

$$S_X \propto \int n_e^2 \Lambda_{ee} d\ell = \int n_e^2 \Lambda_{ee} D_A d\theta$$

- Sunyaev-Zel'dovich Effect (SZE)

$$\Delta T_{CMB} \propto \int n_e T_e d\ell = \int n_e T_e D_A d\theta$$

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

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With axions, the observables are affected as

$$\Delta T_{CMB} \to \Delta T_{CMB} \times P_{\gamma\gamma}^{IGM}(\omega_{CMB})$$
$$S_X \to S_X \times P_{\gamma\gamma}^{IGM}(\omega_X)\left\langle P_{\gamma\gamma}^{ICM}(\omega_X)\right\rangle$$

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

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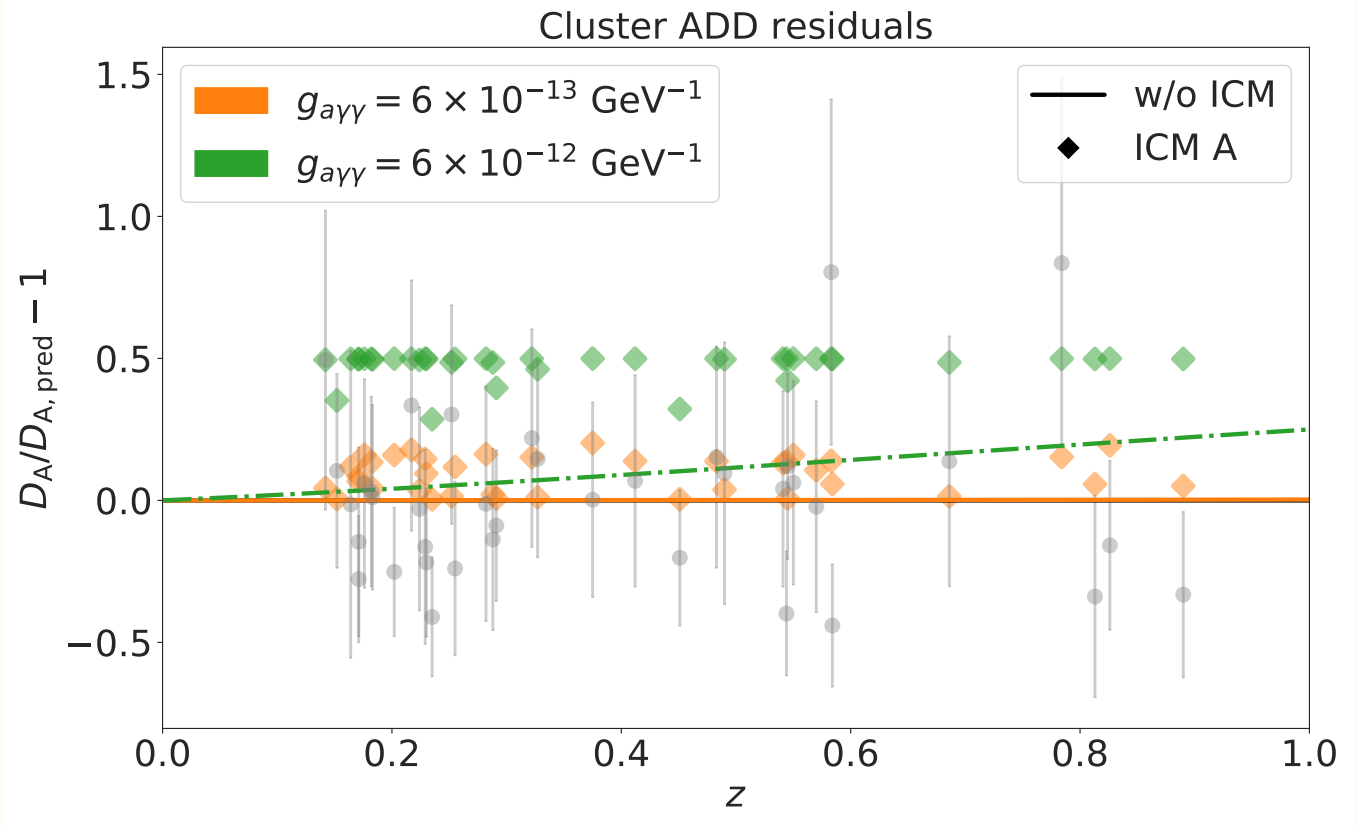
which leads to a modification of the angular diameter distance

$$D_A \to D_A \times \frac{P_{\gamma\gamma}^{IGM}(\omega_{CMB})^2}{P_{\gamma\gamma}^{IGM}(\omega_X)}\left\langle P_{\gamma\gamma}^{ICM}(\omega_X)\right\rangle$$



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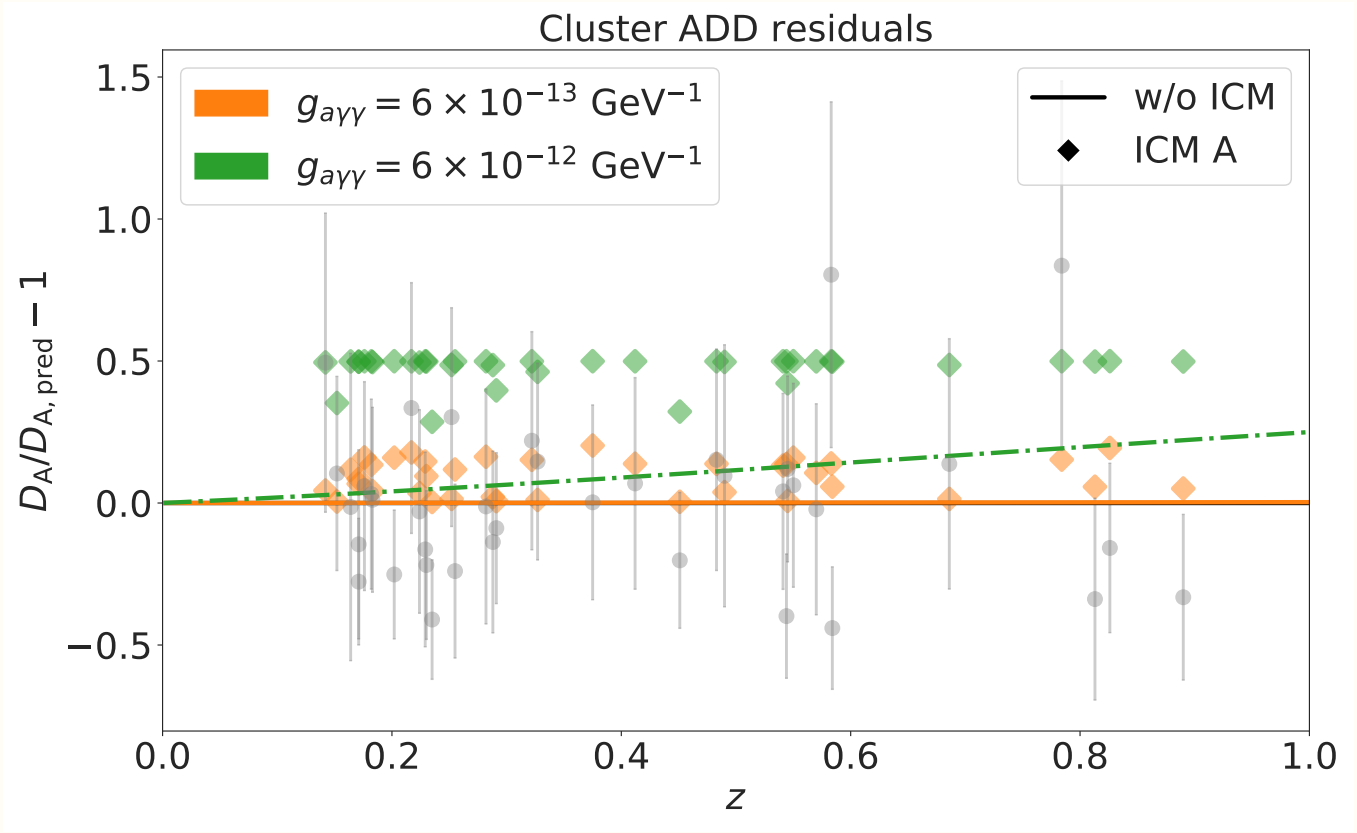
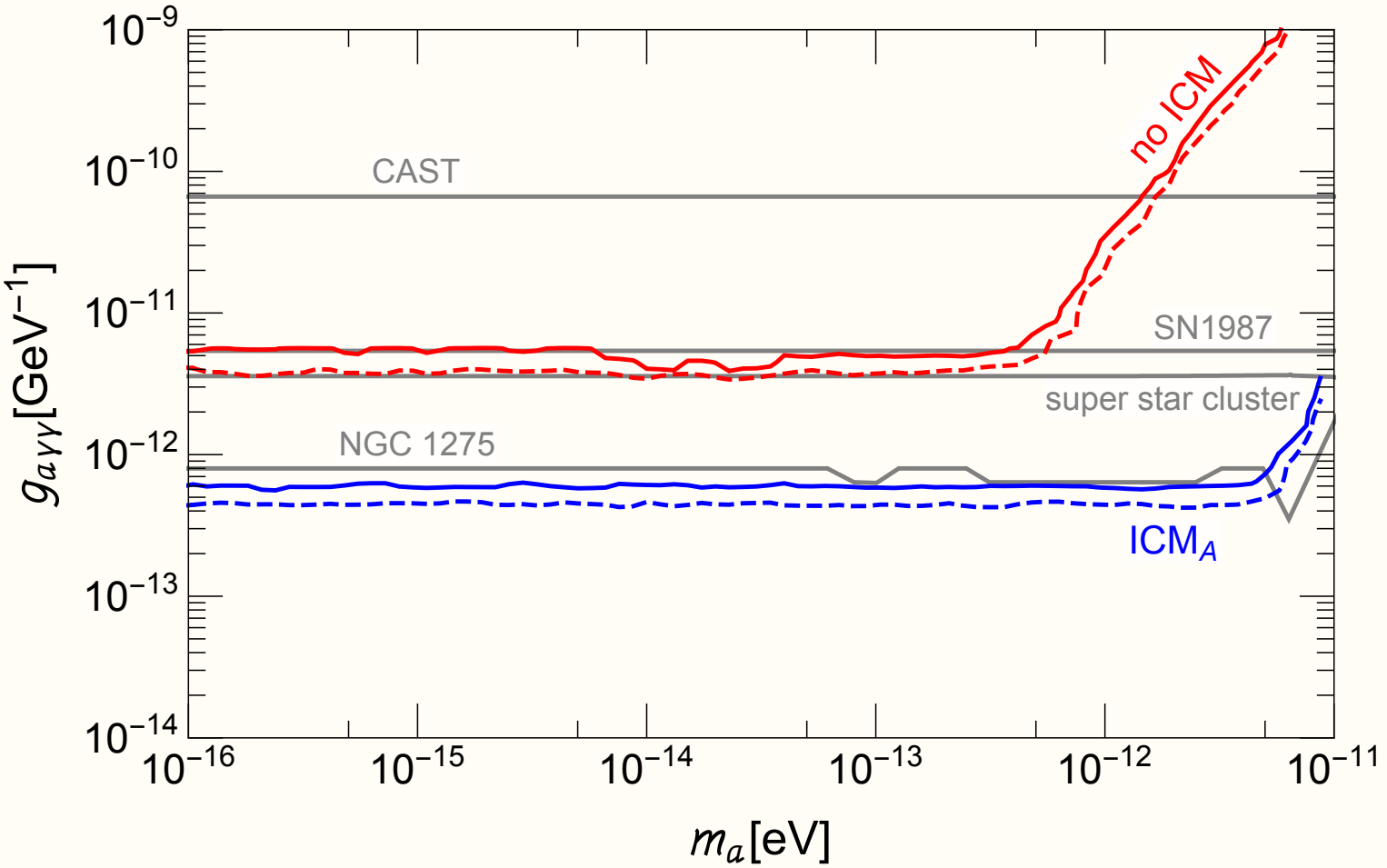


$$-2\ln\mathcal{L}_{cl} = \sum_{i=1}^{38}\left(\frac{D_{A,i}^{exp} - D_A^{th}(z_i;\theta)}{\sigma_i^{exp}}\right)^2$$

Results – New Way to Constrain $a\gamma$ Coupling



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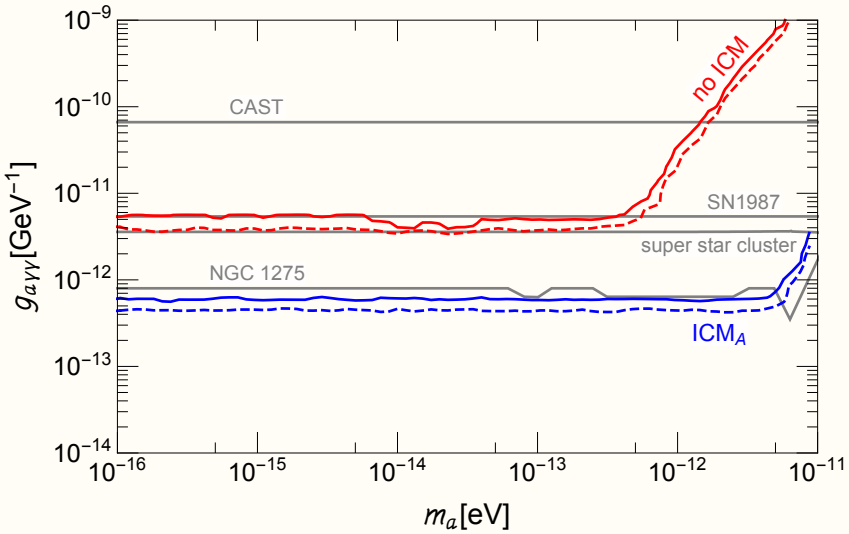


- IGM
- ICM

  - - with BAO (Planck r_s prior)
  - with BAO (SH0ES M_0 prior)

  $B_{IGM} = 1$ nG
  $B_{ICM} = 25\ \mu\mathrm{G}(n_e(r)/n_e(0))^{0.7}$
  $s_{IGM} = 1$ Mpc
  $s_{ICM} \in (3.5\ \mathrm{kpc}, 10\ \mathrm{kpc})$

$P(z)_{\gamma\to a}$:

- IGM $\to D_L(z) \to$ SNIa data;
- ICM $\to D_A(z) \to$ clusters;
- Constraints on $m_a \lesssim 10^{-12}$ eV
- Independent of H_0 tension
- Different systematics from other bounds (*i.e.* CMB spectrum)
  - IGM: $g_{a\gamma\gamma} \propto B_{IGM}^{-1} s_{IGM}^{-1/2}$
  - ICM: quantified w/ B_{ICM} models
- Improvements:
  - $F(z)$ SNe
  - S_X and ΔT_{CMB} in galaxy clusters
  - B_{IGM}, B_{ICM}

Back up slides

Photon-axion oscillation

In a homogeneous environment:

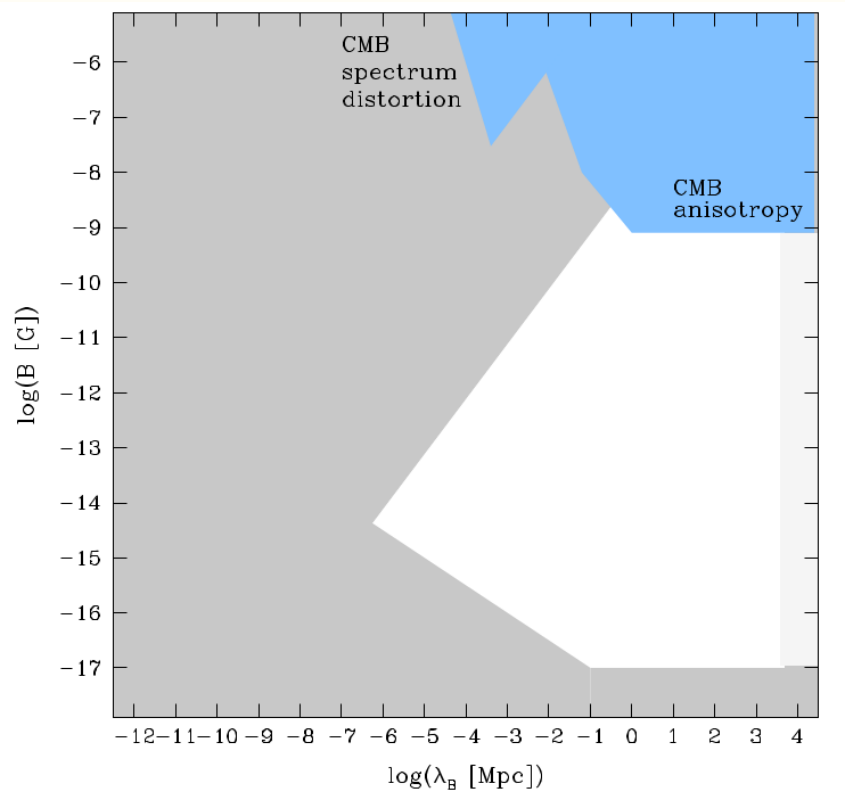
$$P_{\gamma\to a} = \frac{(2\Delta)^2}{k^2}\sin^2\left(\frac{kx}{2}\right)$$
$$= \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + (m_a^2 - m_\gamma^2)^2/(4\omega^2)}\sin^2\left(\left(\frac{1}{2}\sqrt{g_{a\gamma}^2 B^2 + \frac{(m_a^2 - m_\gamma^2)^2}{4\omega^2}}\right)x\right),$$

where m_γ is the photon plasma frequency, $m_\gamma^2 = \frac{4\pi\alpha n_e}{m_e}$.

Three scales: Δ, k, x.

	$kx < 1$	$kx > 1$
$\Delta \sim k$	$\frac{1}{4}g_{a\gamma}^2 B^2 x^2$	$\sim \frac{1}{2}$
$\Delta \ll k$	$\frac{1}{4}g_{a\gamma}^2 B^2 x^2$	$\frac{2g_{a\gamma}^2 B^2}{(m_a^2 - m_\gamma^2)/\omega^2}$

IGM – magnetic field strength



IGM magnetic field:

- CMB anisotropies, lack of Faraday rotation of of quasars, $B_{IGM} \lesssim \mathrm{nG}$.

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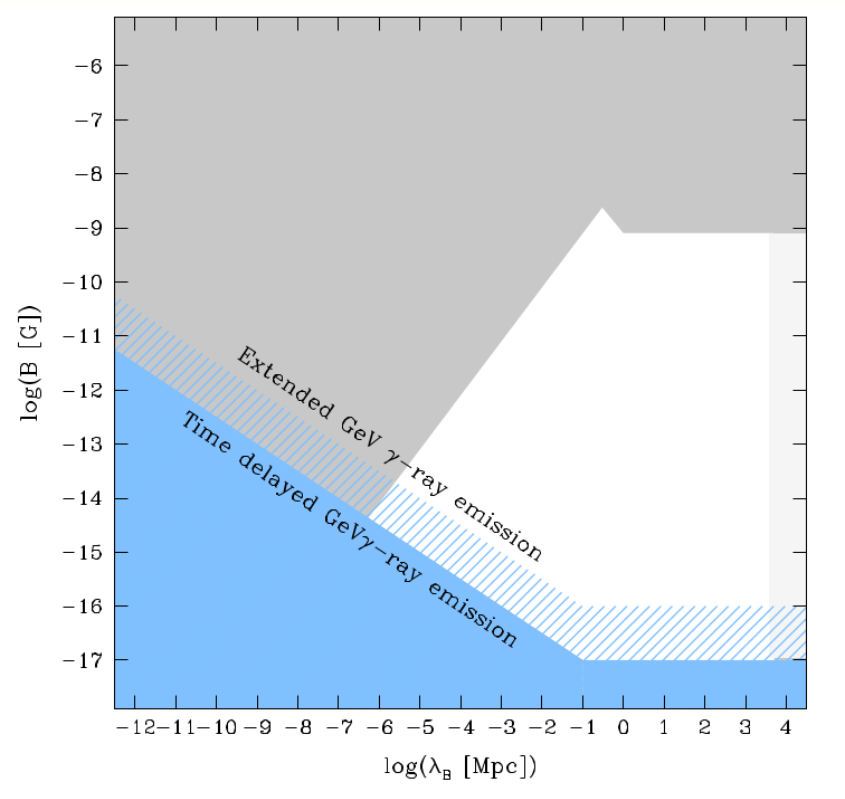

IGM magnetic field:

- CMB anisotropies, lack of Faraday rotation of of quasars, $B_{IGM} \lesssim \mathrm{nG}$.
- Non-observation of cascade emission of TeV γ-ray, $B_{IGM} \gtrsim 10^{-16}$ G.

IGM – magnetic field strength

Note that in the oscillation formula,

$$P_0 = \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + (m_a^2 - m_\gamma^2)^2/(4\omega^2)} \sin^2\left(\left(\frac{1}{2}\sqrt{g_{a\gamma}^2 B^2 + \frac{(m_a^2 - m_\gamma^2)^2}{4\omega^2}}\right) z\right),$$

$(g_{a\gamma} B)$ shows up hand-in-hand.

- So what we bound in IGM is actually on $(g_{a\gamma} B)$.
- In this work, we take common benchmark $B_{IGM} \sim \mathrm{nG}$.
- Future detection of $B_{IGM} < \mathrm{nG}$ will rescale the bounds on $g_{a\gamma}$ as B_{IGM}/nG.

c.f. Durrer and Neronov 2013, Vachaspati 2010

IGM – electron density

$$P_0 = \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + (m_a^2 - m_\gamma^2)^2/(4\omega^2)} \sin^2\left(\left(\frac{1}{2}\sqrt{g_{a\gamma}^2 B^2 + \frac{(m_a^2 - m_\gamma^2)^2}{4\omega^2}}\right) z\right),$$

At low redshift, $z < 0.5$,

$$\text{baryons} \begin{cases} \text{Lyman-}\alpha \text{ forest, } 28 \pm 11\%, \gtrsim 90\% \text{ volume} \\ \text{warm-hot intergalactic matter, } \lesssim 10\% \text{ volume} \end{cases}$$

- $\bar{n}_{e,Ly\alpha} \approx 6.5 \times 10^{-8}\ \text{cm}^{-3}$

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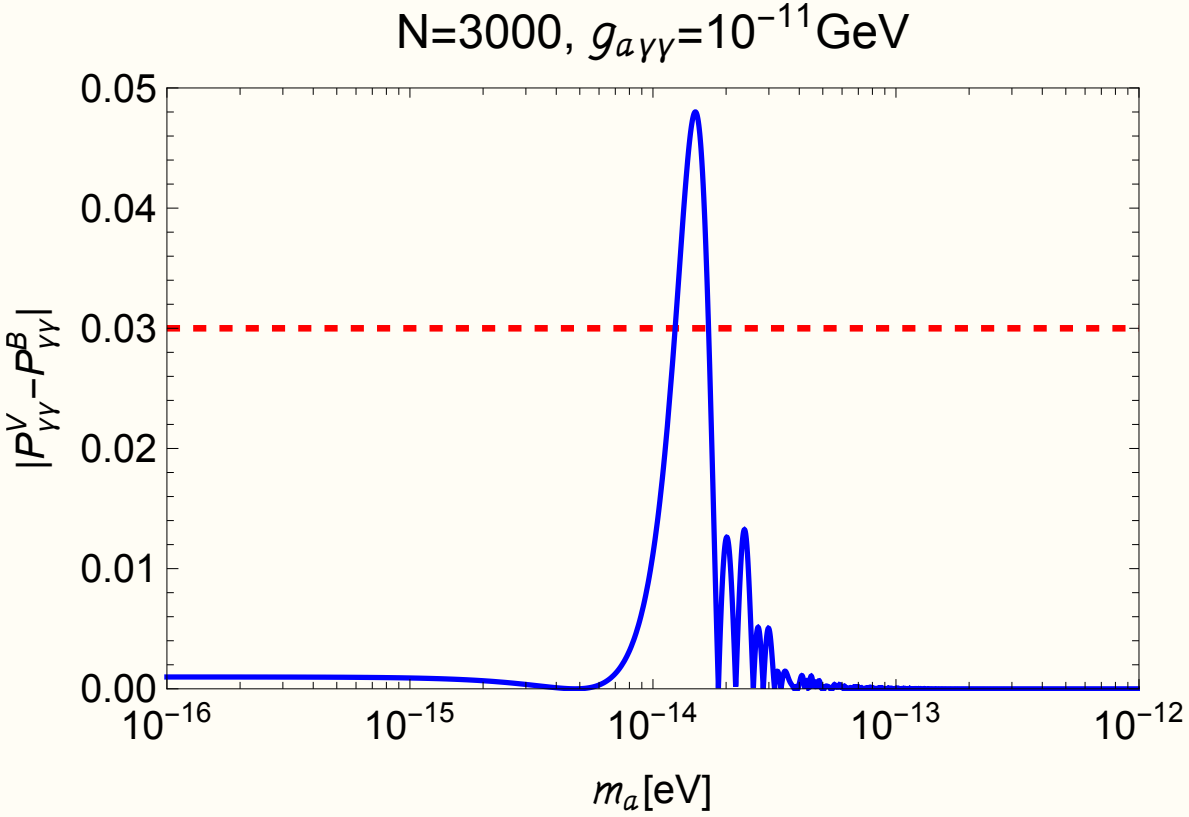
Simulation shows at $z < 1$ *(c.f. Martizzi 2018)*

$$\text{Lyman-}\alpha \begin{cases} \text{underdense patches, a.k.a. cosmic voids} & \sim 30 - 50\% \text{ vol.} \\ \text{2D structures, a.k.a. sheets} & \sim 30 - 50\% \text{ vol.} \end{cases}$$

- $n_e \approx 1.6 \times 10^{-8}\ \mathrm{cm}^{-3}$ (cosmic voids)
- $n_e \approx 3.0 \times 10^{-8}\ \mathrm{cm}^{-3}$ (sheets)


N=3000, $g_{a\gamma\gamma}$=10^{-11}GeV
0.05
0.04
0.03
0.02
0.01
0.00
$|P^V_{\gamma\gamma}-P^B_{\gamma\gamma}|$
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
m_a[eV]

ICM – Electron density

The ICM electron density can be modeled using the double-β profile

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

- "Regular" clusters (Coma-like): single beta $f = 1$
- "Cool-core" clusters (Perseus-like): double-β to account for the core

ICM – Electron density

Bonamente et al. 2006

Cluster	$\mathcal{N}$ (10^{-25} g cm^{-3})	r_s (arcsec)	n_{e0} (cm^{-3})	r_{c1} (arcsec)	β	f	r_{c2} (arcsec)	D_A Gpc
CL 0016+1609	$0.10^{+0.14}_{-0.06}$	225^{+233}_{-96}	$1.40^{+0.18}_{-0.15}\times10^{-2}$	$10.3^{+4.4}_{-2.5}$	$0.761^{+0.031}_{-0.036}$	$0.48^{+0.05}_{-0.05}$	$47.8^{+3.8}_{-3.7}$	$1.38^{+0.22}_{-0.22}$
Abell 0068	$3.29^{+7.60}_{-2.51}$	70^{+62}_{-27}	$8.89^{+1.68}_{-1.18}\times10^{-3}$	–	$0.693^{+0.026}_{-0.028}$	–	$47.8^{+2.8}_{-3.0}$	$0.63^{+0.16}_{-0.19}$
Abell 0267	$2.02^{+3.04}_{-1.24}$	75^{+50}_{-31}	$1.17^{+0.11}_{-0.10}\times10^{-2}$	–	$0.698^{+0.031}_{-0.030}$	–	$40.9^{+2.8}_{-2.8}$	$0.60^{+0.11}_{-0.09}$
Abell 0370	$1.63^{+1.80}_{-0.87}$	51^{+21}_{-13}	$5.33^{+0.58}_{-0.40}\times10^{-3}$	–	$0.740^{+0.035}_{-0.028}$	–	$55.6^{+3.1}_{-2.6}$	$1.08^{+0.19}_{-0.20}$
MS 0451.6-0305	$0.27^{+0.58}_{-0.16}$	110^{+75}_{-44}	$1.26^{+0.12}_{-0.09}\times10^{-2}$	–	$0.777^{+0.019}_{-0.019}$	–	$34.5^{+1.1}_{-1.1}$	$1.42^{+0.26}_{-0.23}$
MACS J0647.7+7015	$12.01^{+16.67}_{-8.41}$	36^{+22}_{-13}	$2.19^{+0.34}_{-0.25}\times10^{-2}$	–	$0.653^{+0.019}_{-0.017}$	–	$19.9^{+1.2}_{-1.2}$	$0.77^{+0.21}_{-0.18}$
Abell 0586	$1.78^{+1.97}_{-1.05}$	102^{+40}_{-26}	$1.83^{+0.25}_{-0.21}\times10^{-2}$	–	$0.627^{+0.017}_{-0.013}$	–	$32.0^{+1.7}_{-1.4}$	$0.52^{+0.15}_{-0.12}$
MACS J0744.8+3927	$0.27^{+0.84}_{-0.22}$	94^{+102}_{-51}	$1.14^{+0.22}_{-0.15}\times10^{-1}$	$3.4^{+0.6}_{-0.7}$	$0.635^{+0.049}_{-0.039}$	$0.93^{+0.01}_{-0.01}$	$25.8^{+4.7}_{-4.7}$	$1.68^{+0.48}_{-0.38}$
Abell 0611	$1.73^{+1.87}_{-0.90}$	64^{+15}_{-12}	$5.27^{+0.97}_{-1.00}\times10^{-2}$	$2.8^{+0.4}_{-0.3}$	$0.600^{+0.014}_{-0.008}$	$0.66^{+0.08}_{-0.07}$	$22.5^{+1.6}_{-1.2}$	$0.78^{+0.18}_{-0.18}$
Abell 0665	$0.18^{+0.14}_{-0.09}$	340^{+150}_{-86}	$9.13^{+1.34}_{-1.06}\times10^{-3}$	$3.2^{+0.8}_{-0.5}$	$0.730^{+0.015}_{-0.016}$	$0.11^{+0.10}_{-0.08}$	$64.4^{+1.7}_{-1.8}$	$0.66^{+0.09}_{-0.10}$
Abell 0697	$0.76^{+1.63}_{-0.59}$	93^{+66}_{-32}	$9.82^{+1.55}_{-1.28}\times10^{-3}$	–	$0.584^{+0.014}_{-0.016}$	–	$41.6^{+1.6}_{-1.9}$	$0.88^{+0.30}_{-0.23}$
Abell 0773	$1.22^{+1.98}_{-0.88}$	54^{+40}_{-19}	$8.04^{+0.68}_{-0.64}\times10^{-3}$	–	$0.564^{+0.020}_{-0.022}$	–	$40.2^{+2.2}_{-2.3}$	$0.98^{+0.17}_{-0.14}$
ZW 3146	$0.66^{+0.08}_{-0.05}$	121^{+4}_{-6}	$1.70^{+0.02}_{-0.03}\times10^{-1}$	$4.4^{+0.1}_{-0.1}$	$0.668^{+0.005}_{-0.004}$	$0.881^{+0.004}_{-0.003}$	$25.5^{+0.7}_{-0.4}$	$0.83^{+0.02}_{-0.02}$
MS 1054-0321	$0.04^{+0.08}_{-0.02}$	666^{+571}_{-359}	$6.15^{+0.71}_{-0.56}\times10^{-3}$	–	$1.791^{+0.148}_{-0.209}$	–	$83.7^{+4.9}_{-7.3}$	$1.33^{+0.28}_{-0.26}$
MS 1137.5+6625	$1.73^{+7.31}_{-1.40}$	16^{+18}_{-9}	$1.26^{+0.16}_{-0.11}\times10^{-2}$	–	$0.667^{+0.044}_{-0.043}$	–	$14.2^{+1.5}_{-1.3}$	$2.85^{+0.52}_{-0.63}$
MACS J1149.5+2223	$0.74^{+3.06}_{-0.50}$	110^{+46}_{-29}	$8.53^{+1.04}_{-0.89}\times10^{-3}$	–	$0.673^{+0.020}_{-0.022}$	–	$42.8^{+2.1}_{-2.4}$	$0.80^{+0.19}_{-0.16}$
Abell 1413	$0.47^{+0.58}_{-0.27}$	121^{+51}_{-47}	$3.66^{+0.65}_{-0.42}\times10^{-2}$	$6.5^{+1.5}_{-1.3}$	$0.531^{+0.018}_{-0.014}$	$0.76^{+0.02}_{-0.02}$	$39.3^{+4.5}_{-3.7}$	$0.78^{+0.18}_{-0.13}$
CL J1226.9+3332	$4.09^{+9.41}_{-3.58}$	46^{+58}_{-19}	$3.01^{+0.47}_{-0.44}\times10^{-2}$	–	$0.715^{+0.038}_{-0.038}$	–	$15.8^{+1.3}_{-1.4}$	$1.08^{+0.42}_{-0.28}$
MACS J1311.0-0310	$7.59^{+17.81}_{-7.09}$	19^{+47}_{-9}	$3.93^{+0.72}_{-0.55}\times10^{-2}$	–	$0.613^{+0.022}_{-0.020}$	–	$9.3^{+0.7}_{-0.7}$	$1.38^{+0.47}_{-0.37}$
Abell 1689	$2.68^{+1.20}_{-1.16}$	75^{+19}_{-10}	$4.054^{+0.36}_{-0.26}\times10^{-2}$	$21.7^{+0.9}_{-1.0}$	$0.873^{+0.039}_{-0.041}$	$0.87^{+0.01}_{-0.01}$	$104.9^{+5.1}_{-5.5}$	$0.65^{+0.09}_{-0.09}$
RX J1347.5-1145	$4.57^{+1.06}_{-0.86}$	47^{+5}_{-5}	$2.81^{+0.16}_{-0.12}\times10^{-1}$	$3.9^{+0.2}_{-0.1}$	$0.631^{+0.009}_{-0.008}$	$0.942^{+0.004}_{-0.004}$	$22.9^{+1.8}_{-1.4}$	$0.96^{+0.06}_{-0.08}$
MS 1358.4+6245	$0.58^{+0.21}_{-0.19}$	90^{+26}_{-18}	$9.62^{+0.79}_{-0.78}\times10^{-2}$	$3.3^{+0.2}_{-0.2}$	$0.675^{+0.017}_{-0.016}$	$0.934^{+0.003}_{-0.003}$	$37.2^{+1.7}_{-1.9}$	$1.13^{+0.09}_{-0.10}$
Abell 1835	$0.28^{+0.10}_{-0.03}$	150^{+11}_{-11}	$1.10^{+0.05}_{-0.02}\times10^{-1}$	$9.3^{+0.2}_{-0.2}$	$0.798^{+0.013}_{-0.017}$	$0.940^{+0.001}_{-0.001}$	$63.7^{+1.5}_{-1.6}$	$1.07^{+0.02}_{-0.08}$
MACS J1423.8+2504	$1.83^{+0.02}_{-0.07}$	33^{+1}_{-1}	$1.60^{+0.02}_{-0.08}\times10^{-1}$	$4.2^{+0.1}_{-0.1}$	$0.721^{+0.012}_{-0.008}$	$0.975^{+0.001}_{-0.001}$	$36.7^{+0.9}_{-0.7}$	$1.49^{+0.06}_{-0.03}$
Abell 1914	$5.79^{+2.60}_{-1.85}$	81^{+14}_{-11}	$1.72^{+0.13}_{-0.08}\times10^{-2}$	$6.6^{+0.6}_{-0.8}$	$0.899^{+0.007}_{-0.012}$	$0.008^{+0.018}_{-0.008}$	$68.3^{+0.7}_{-1.0}$	$0.44^{+0.04}_{-0.05}$
Abell 1995	$0.07^{+0.06}_{-0.04}$	359^{+205}_{-117}	$9.35^{+0.74}_{-0.56}\times10^{-3}$	$31.2^{+3.0}_{-3.5}$	$1.298^{+0.062}_{-0.096}$	$0.462^{+0.033}_{-0.033}$	$83.5^{+3.7}_{-7.1}$	$1.19^{+0.15}_{-0.14}$
Abell 2111	$0.47^{+2.74}_{-0.38}$	172^{+354}_{-107}	$5.99^{+1.05}_{-0.79}\times10^{-3}$	–	$0.600^{+0.026}_{-0.025}$	–	$50.4^{+3.8}_{-3.5}$	$0.64^{+0.20}_{-0.17}$
Abell 2163	$0.26^{+0.12}_{-0.09}$	390^{+87}_{-52}	$1.09^{+0.07}_{-0.04}\times10^{-2}$	$4.0^{+1.3}_{-0.7}$	$0.560^{+0.004}_{-0.005}$	$0.022^{+0.037}_{-0.022}$	$66.8^{+0.9}_{-0.8}$	$0.52^{+0.04}_{-0.05}$
Abell 2204	$0.92^{+0.30}_{-0.15}$	120^{+13}_{-18}	$2.01^{+0.12}_{-0.09}\times10^{-1}$	$7.5^{+0.3}_{-0.3}$	$0.710^{+0.031}_{-0.025}$	$0.960^{+0.003}_{-0.004}$	$67.4^{+2.0}_{-1.8}$	$0.61^{+0.06}_{-0.07}$
Abell 2218	$1.02^{+0.70}_{-0.60}$	110^{+35}_{-22}	$7.02^{+0.66}_{-0.66}\times10^{-3}$	–	$0.739^{+0.014}_{-0.017}$	–	$68.3^{+1.7}_{-2.1}$	$0.66^{+0.14}_{-0.11}$
RX J1716.4+6708	$0.34^{+3.38}_{-0.30}$	146^{+545}_{-106}	$1.94^{+0.61}_{-0.40}\times10^{-2}$	–	$0.589^{+0.042}_{-0.035}$	–	$12.3^{+2.0}_{-1.7}$	$1.04^{+0.51}_{-0.43}$
Abell 2259	$0.65^{+1.15}_{-0.54}$	141^{+155}_{-56}	$9.29^{+2.97}_{-1.71}\times10^{-3}$	–	$0.560^{+0.025}_{-0.024}$	–	$41.0^{+3.9}_{-2.8}$	$0.58^{+0.29}_{-0.25}$
Abell 2261	$1.36^{+0.85}_{-0.85}$	68^{+25}_{-15}	$4.16^{+0.54}_{-0.63}\times10^{-2}$	$10.0^{+1.9}_{-1.7}$	$0.628^{+0.025}_{-0.022}$	$0.77^{+0.04}_{-0.05}$	$37.8^{+6.5}_{-5.2}$	$0.73^{+0.20}_{-0.13}$
MS 2053.7-0449	$0.26^{+1.41}_{-0.22}$	40^{+64}_{-22}	$9.22^{+1.08}_{-0.92}\times10^{-3}$	–	$0.522^{+0.048}_{-0.042}$	–	$10.8^{+1.9}_{-1.7}$	$2.48^{+0.41}_{-0.44}$

ICM – Magnetic field

We follow previous studies and assume a B_{ICM} profile

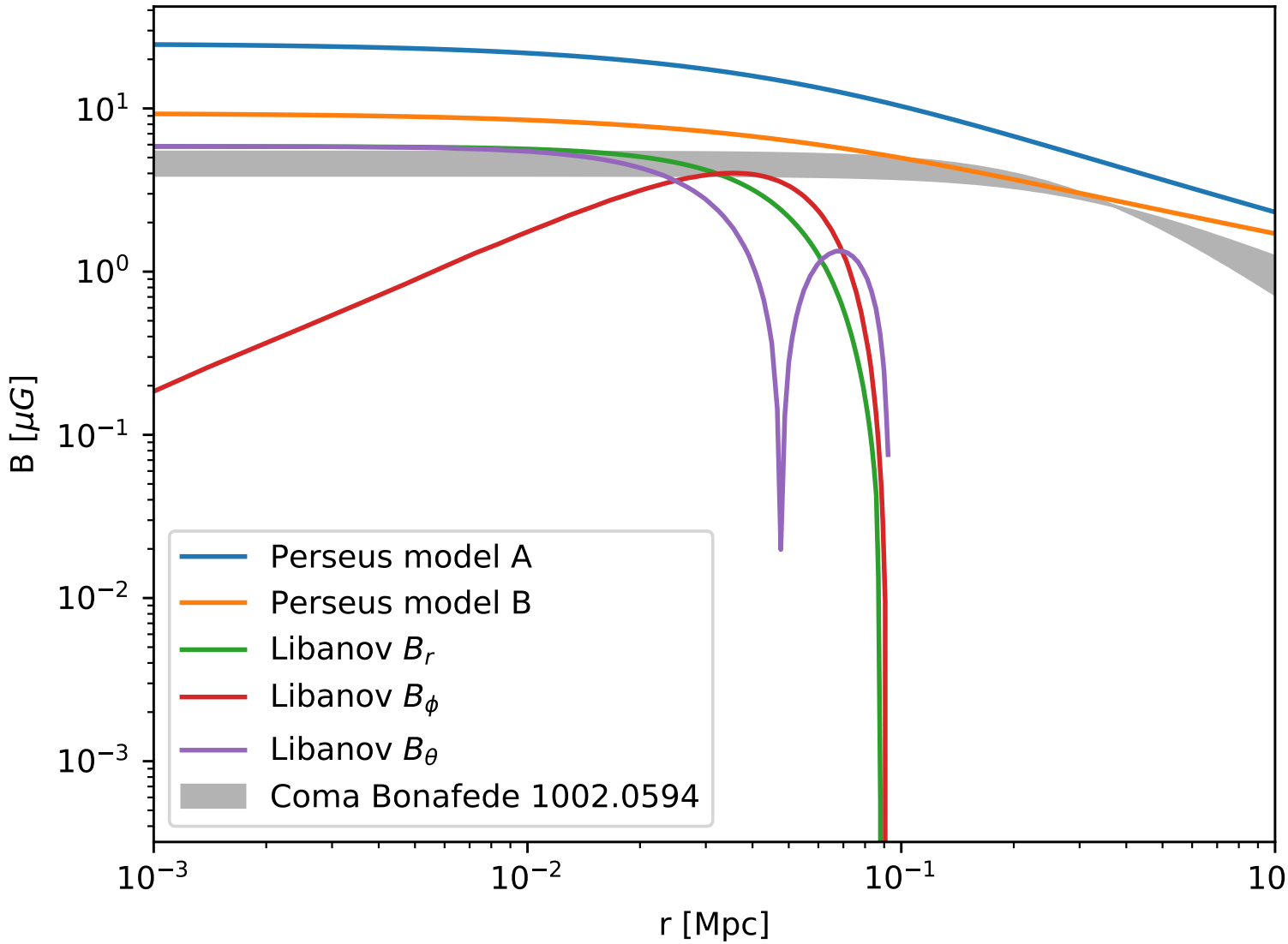
$$B_{ICM} = B_{ref} \left(\frac{n_e(r)}{n_e(r_{ref})} \right)^{\eta}$$

with two profiles similar to Perseus, and one similar to Coma

Model	r_{ref}	B_{ref}	η
A	0 kpc	25 μG	0.7
B	25 kpc	7.5 μG	0.5
C	0 kpc	4.7 μG	0.5

Bonafede et al. 2010, Feretti et al. 2012, Reynolds et al. 2019, Angus et al. 2014

ICM – Magnetic field



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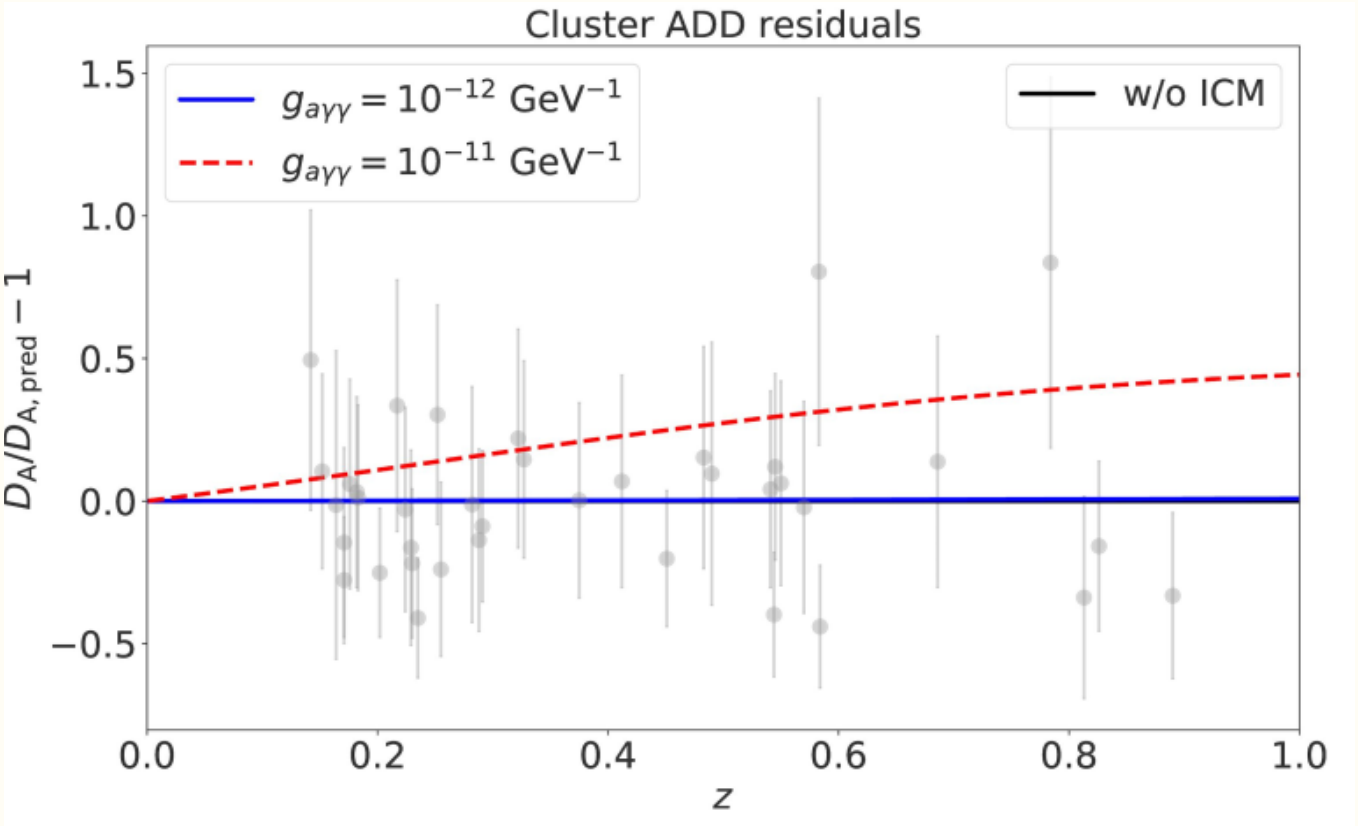
C	0 kpc	4.7 μG	0.5
no ICM	n/a	0 μG	n/a

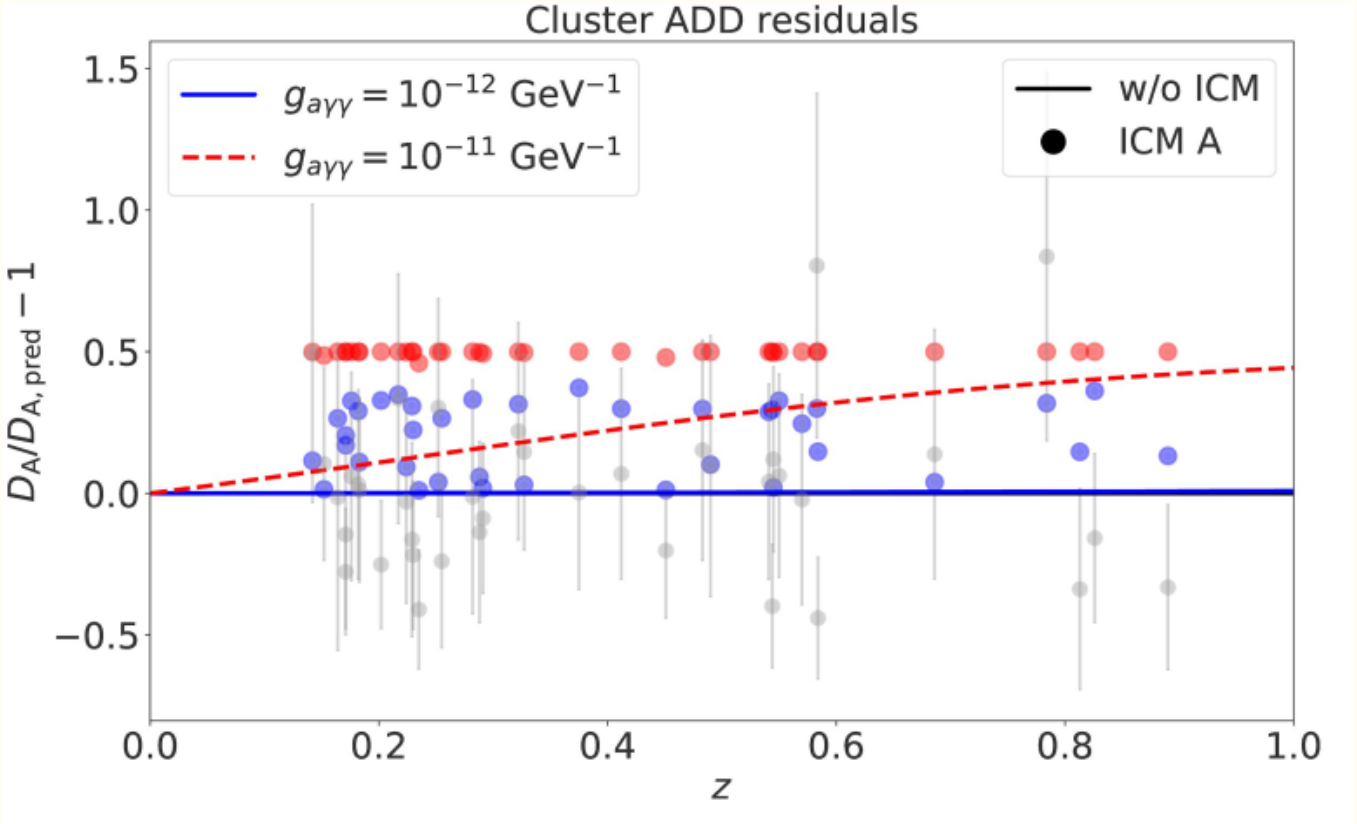
Bonafede et al. 2010, Feretti et al. 2012, Reynolds et al. 2019, Angus et al. 2014, Libanov and Troitsky 2020



$$\Delta T_{CMB} \to \Delta T_{CMB} \times P_{\gamma\gamma}^{IGM}(\omega_{CMB})$$

$$S_X \to S_X \times P_{\gamma\gamma}^{IGM}(\omega_X)$$

$$D_A \to D_A \times \frac{P_{\gamma\gamma}^{IGM}(\omega_{CMB})^2}{P_{\gamma\gamma}^{IGM}(\omega_X)}$$



$$\Delta T_{CMB} \to \Delta T_{CMB} \times P_{\gamma\gamma}^{IGM}(\omega_{CMB})$$

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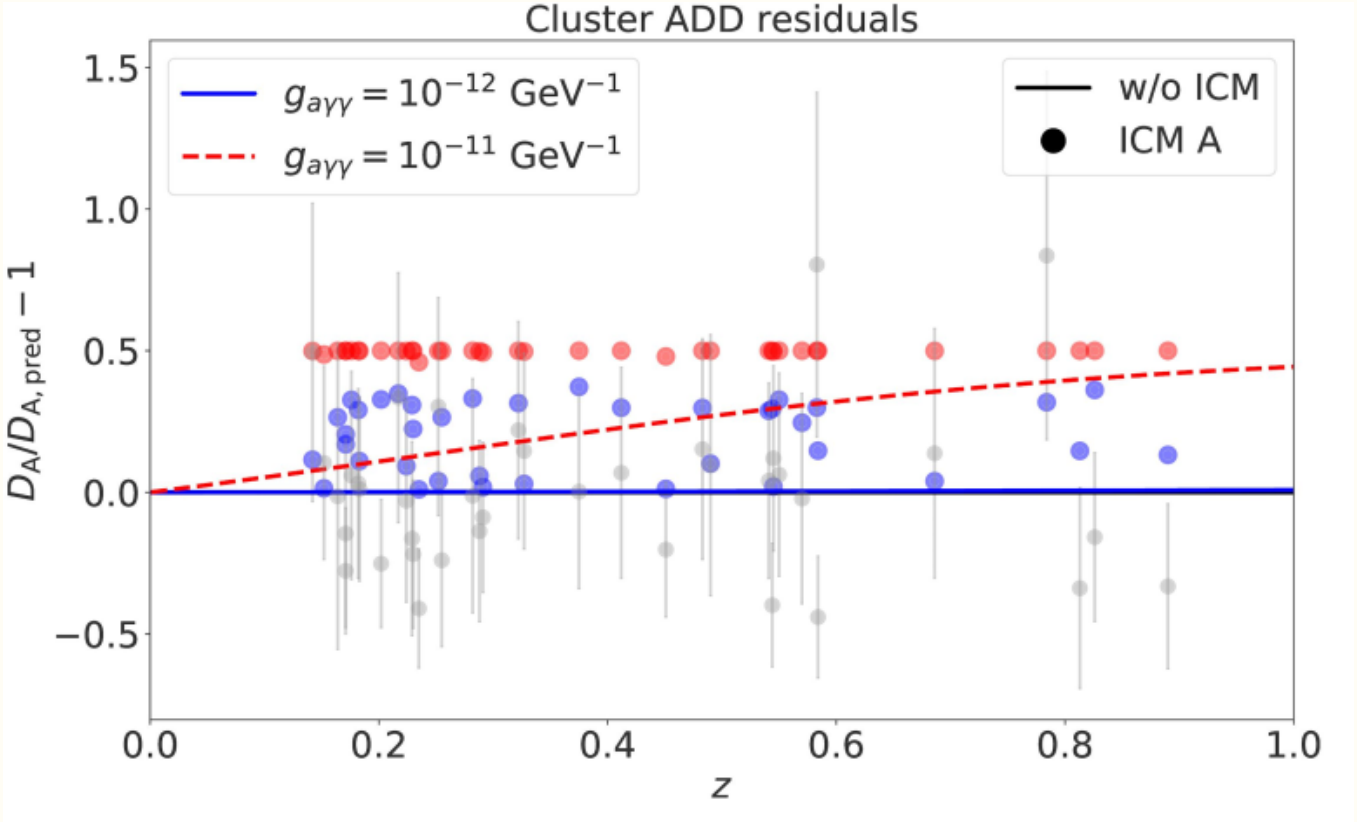


$$-2\ln\mathcal{L}_{cl} = \sum_{i=1}^{38}\left(\frac{D_{A,i}^{exp} - D_A^{th}(z_i;\theta)}{\sigma_i^{exp}}\right)^2$$

Other data sets

- SH0ES:

$$-2\ln\mathcal{L}_{SH0ES} = \sum_{i=1}^{19}\left(\frac{m_{10,i}^{SH0ES} - m_{10}}{\sigma_i^{SH0ES}}\right)^2$$

- TDCOSMO:

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

- BAO: (BOSS DR12 CMASS and LOWZ; 6dFGS, MGS)

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

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

- Planck

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

Late vs Early

- The theory parameters:

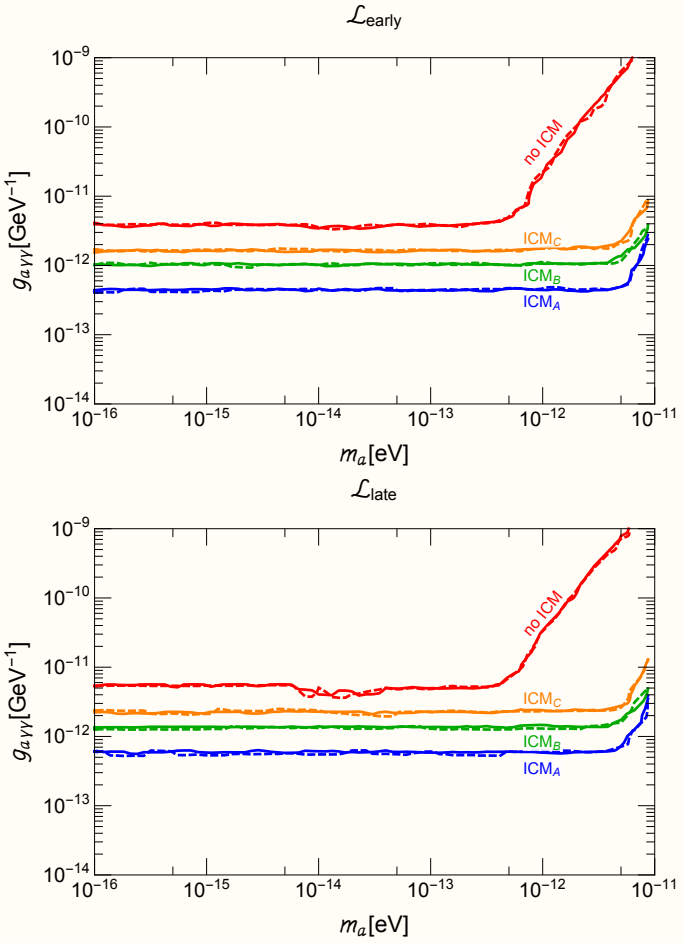
$$\theta = \big(\underbrace{H_0, \Omega_\Lambda}_{\Lambda CDM}; \ \underbrace{m_a, g_{a\gamma}}_{\text{axion}}; \ \underbrace{m_{10}, r_s^{drag}}_{\text{nuisance}} \big)$$

- The likelihoods:

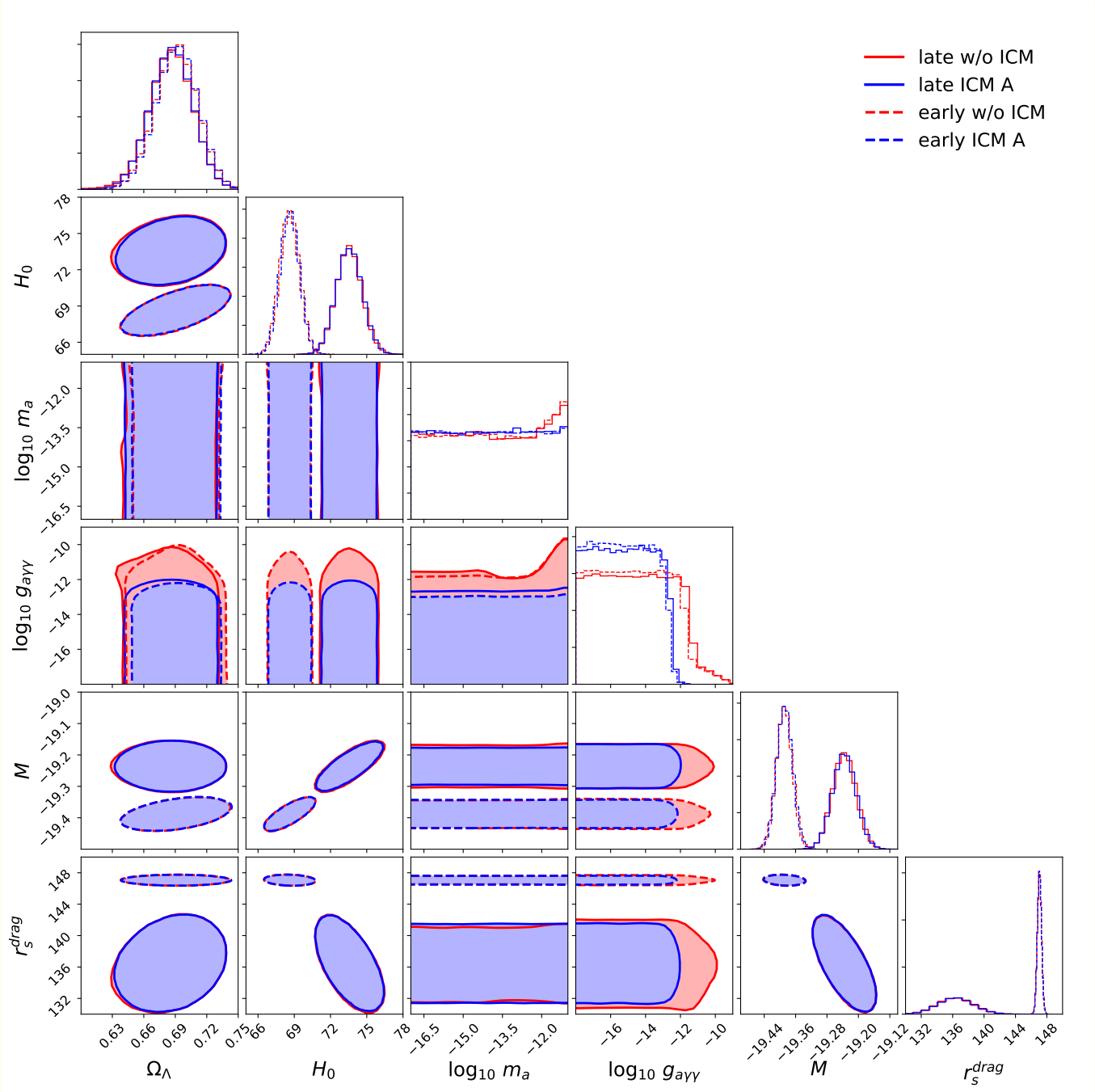
$$\mathcal{L}_{\text{early}} \equiv \mathcal{L}_{\text{Pan}} \cdot \mathcal{L}_{\text{cluster}} \cdot \mathcal{L}_{\text{BAO}} \cdot \mathcal{L}_{\text{Pl}}$$
$$\mathcal{L}_{\text{late}} = \mathcal{L}_{\text{Pan}} \cdot \mathcal{L}_{\text{cluster}} \cdot \mathcal{L}_{\text{BAO}} \cdot \mathcal{L}_{\text{SH0ES}} \cdot \mathcal{L}_{\text{TD}}$$

- Production runs:

$$\left\{ \begin{matrix} \text{early} \\ \text{late} \end{matrix} \right\} \otimes \left\{ \begin{matrix} n_e^{IGM} = 1.6 \times 10^{-8} \ \text{cm}^{-3} \\ n_e^{IGM} = 3.0 \times 10^{-8} \ \text{cm}^{-3} \end{matrix} \right\} \otimes \left\{ \begin{matrix} \text{ICM A} \\ \text{ICM B} \\ \text{ICM C} \\ \text{no ICM} \end{matrix} \right\}$$



- Little difference between $n_e^{IGM} = 1.6 \times 10^{-8}$ and $3.0 \times 10^{-8}\ \mathrm{cm}^{-3}$
  - linear to nonlinear regime triggered by m_a
- Small difference between early and late
  - What matters most is the shape of H(z)
- "ICM A" is most optimistic, "no ICM" most conservative.
  - Only in 'no ICM' runs the constraint is on $g_{a\gamma}B$


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

Code: Modular Design

Interface:

- `cosmo_axions_run.py`
- `cosmo_axions_analysis.py`

Code: Modular Design

Interface:

- `cosmo_axions_run.py` `$python cosmo_axions_run.py -L likelihoods/ -o path/to/output/ -i inputs/the_param_file.param -N chain_length -w number_of_walkers`
- `cosmo_axions_analysis.py` `$python cosmo_axions_analysis.py -i path/to/your/chain/`

Code: Modular Design

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- `cosmo_axions_run.py`
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Internal:

- `data.py`
- `chi2.py`
- `cosmo.py`
- `ag_probs.py`
- `icm.py`
- `igm.py`

Code: Modular Design

Interface:

- `cosmo_axions_run.py`
- `cosmo_axions_analysis.py`

Internal:

- `data.py` data loading and initialization
- `chi2.py` defines log(lkl) of each data set
- `cosmo.py` cosmological functions, $H(z)$, $D_A(z)$, $\tau(z)$, etc.
- `ag_probs.py` axion-photon related functions, $m_\gamma(n_e)$, $P(z)$, etc.
- `icm.py` ICM related functions, $n_e^{ICM}(r)$, $P_{ICM}(r)$, etc.
- `igm.py` IGM related functions, $P_{IGM}(r)$, etc.

likelihoods/

- BAO
- cluster
- Pantheon
- SH0ES

likelihoods/

- BAO BAO_*.txt
- cluster add.txt, bonamente_add.txt
- Pantheon lcparam*.txt, sys_*.txt
- SH0ES lstAnchor.csv

Input card

inputs/

- likelihoods to use:

```
...
use_TDCOSMO = True
use_SHOES = True
use_early = False
use_Pantheon = True
use_BOSSDR12 = True
use_BAOlowz = True
use_clusters = True
...
```

- range to scan:

```
# var = [initial, low, up, step]
OmL = [0.6847, 0.6, 0.75, 0.015]
h0 = [ 0.73, 0.6, 0.8, 0.02]
logma = [ -14, -17, -11, 0.25]
logga = [ -11, -18., -8., 0.1]
M0 = [ -19.3, -21, -18, 0.1]
rs = [147.78, 120., 160., 1.]
```

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Pull requests, forks, and issue tickets are all welcomed!