CLASSICAL & QUANTUM

PROBES OF

AXION-LIKE PARTICLES

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COSMO '22, RIO DE JANEIRO, 23RD AUGUST, 2022

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Barcelona


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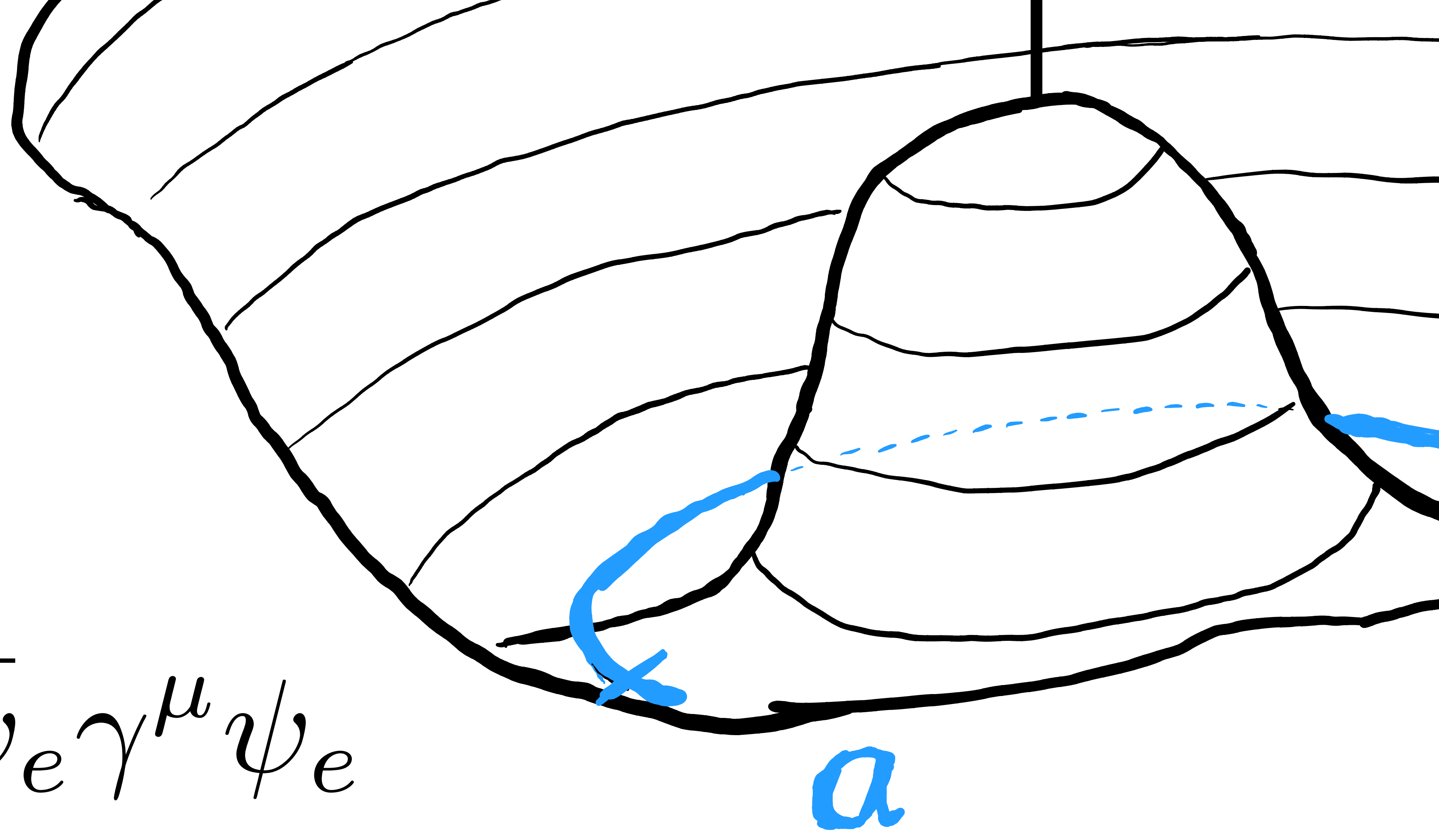
Axion-like particles

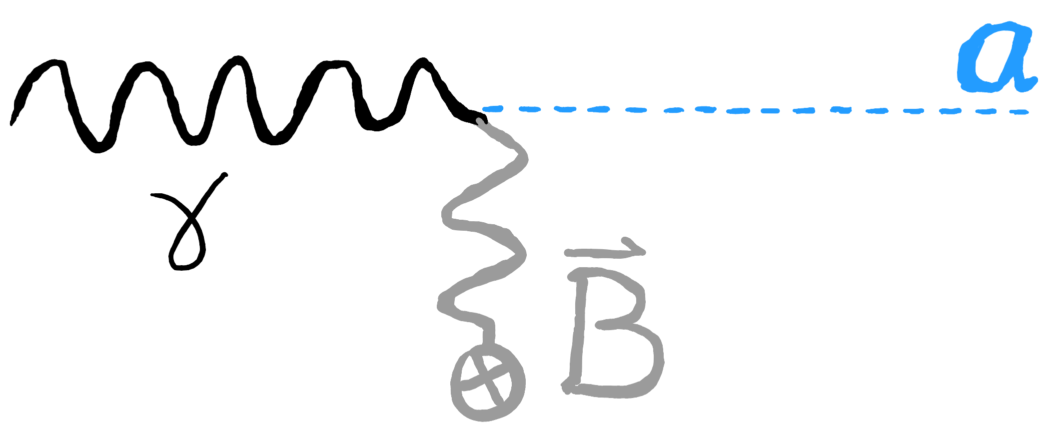
[cf. Francesc’s talk]



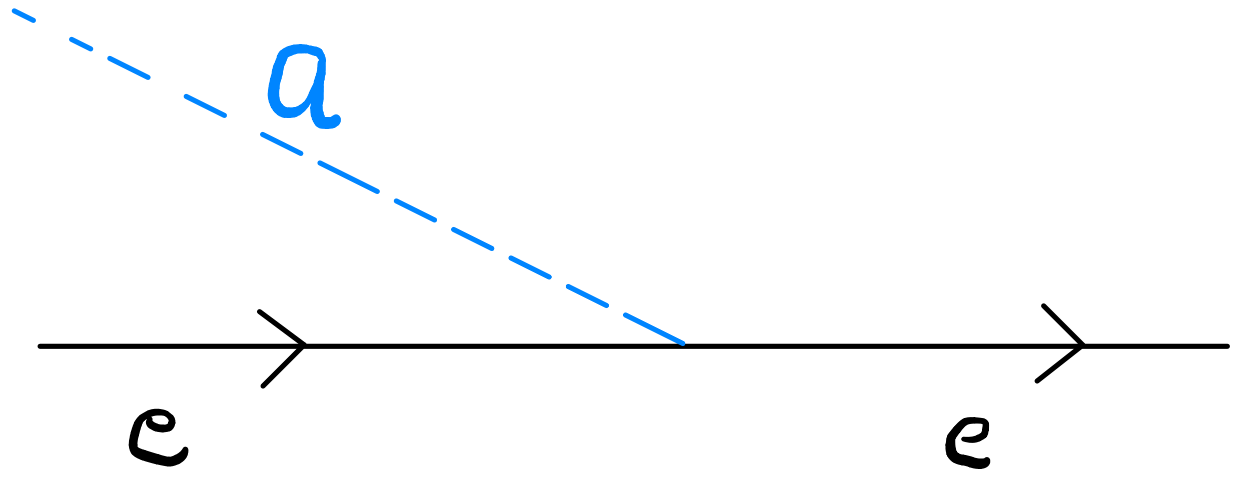
$$\mathcal{L} \supset \frac{1}{2} m_a^2\, a^2 + \frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \hat{g}_{ae}(\partial_\mu a)\bar{\psi}_e\gamma^\mu\psi_e$$

m_a — from negligible to large

$g_{a\gamma}$



$\hat{g}_{ae}$



How can we use astrophysics to probe this theory?

Classical ALP-photon mixing

in a magnetised plasma

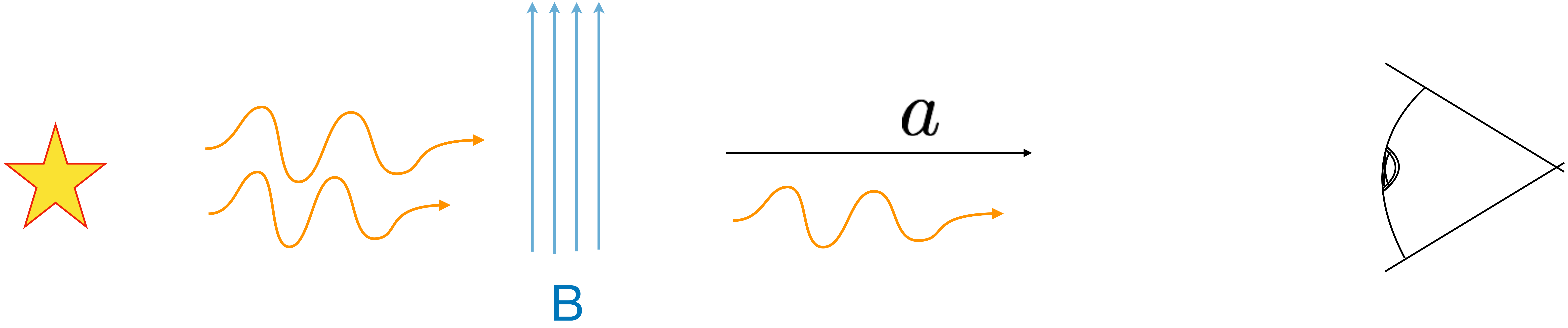
Schrödinger-like equation

for relativistic ALPs

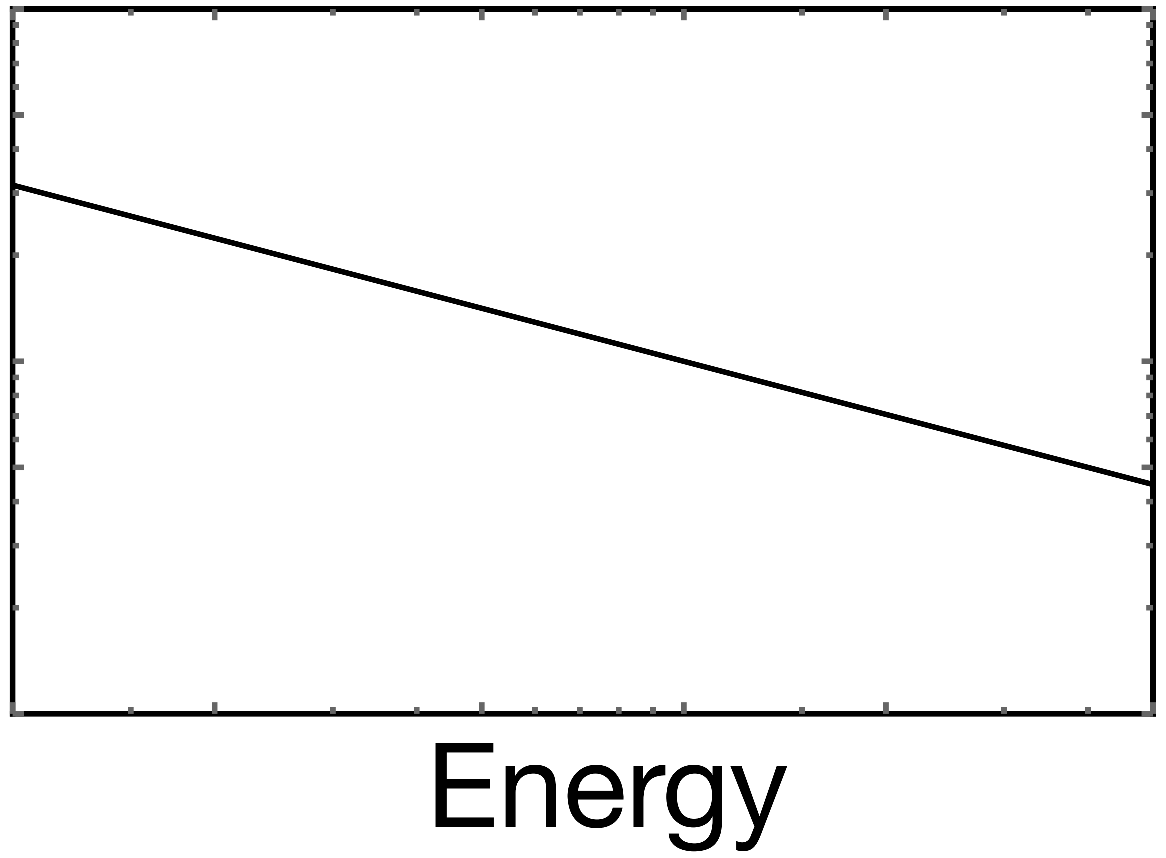
$$i\frac{d}{dz}\Psi(z) = (H_0 + H_I)\Psi(z)\,;$$

$$\Psi(z) = \begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix} \qquad H_0 = -\frac{1}{2\omega}\begin{pmatrix} \omega_{pl}(z)^2 & 0 & 0 \\ 0 & \omega_{pl}(z)^2 & 0 \\ 0 & 0 & m_a^2 \end{pmatrix} \qquad H_I = \frac{g_{a\gamma}}{2}\begin{pmatrix} 0 & 0 & B_x \\ 0 & 0 & B_y \\ B_x & B_y & 0 \end{pmatrix}\;;$$

The photon disappearance channel

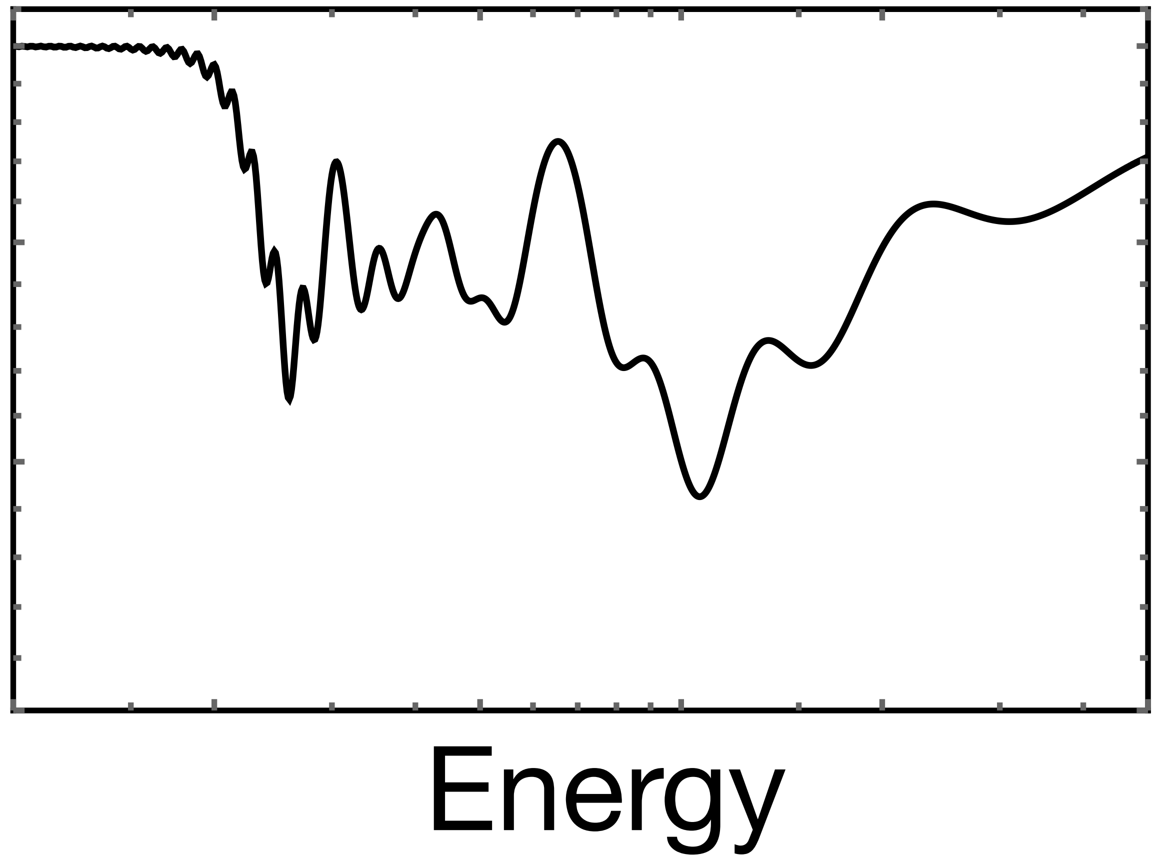


Initial photon spectrum



*

Survival probability



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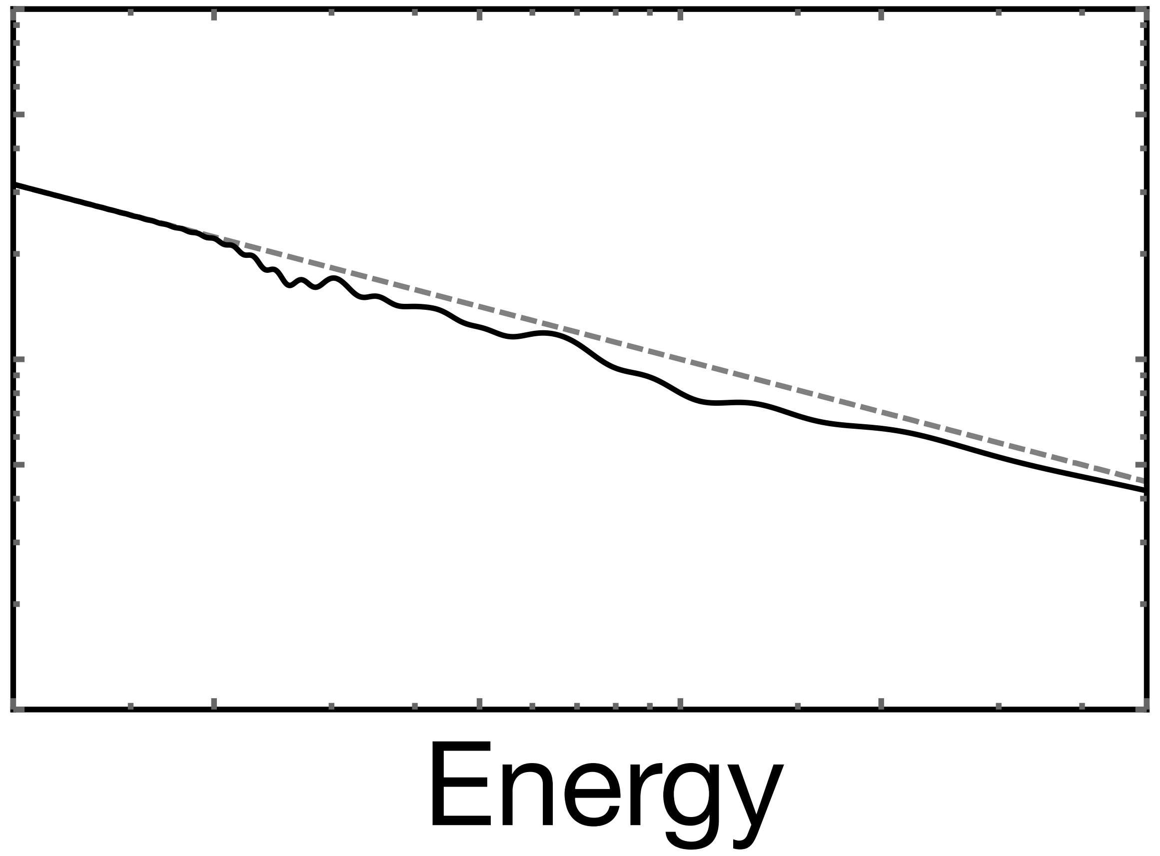
Final photon spectrum



[Sikivie],
[Raffelt, Stodolsky]

Galaxy clusters are ideal axion-photon converters

Largest gravitational bound objects (~100s kpc).

Magnetised (μG).

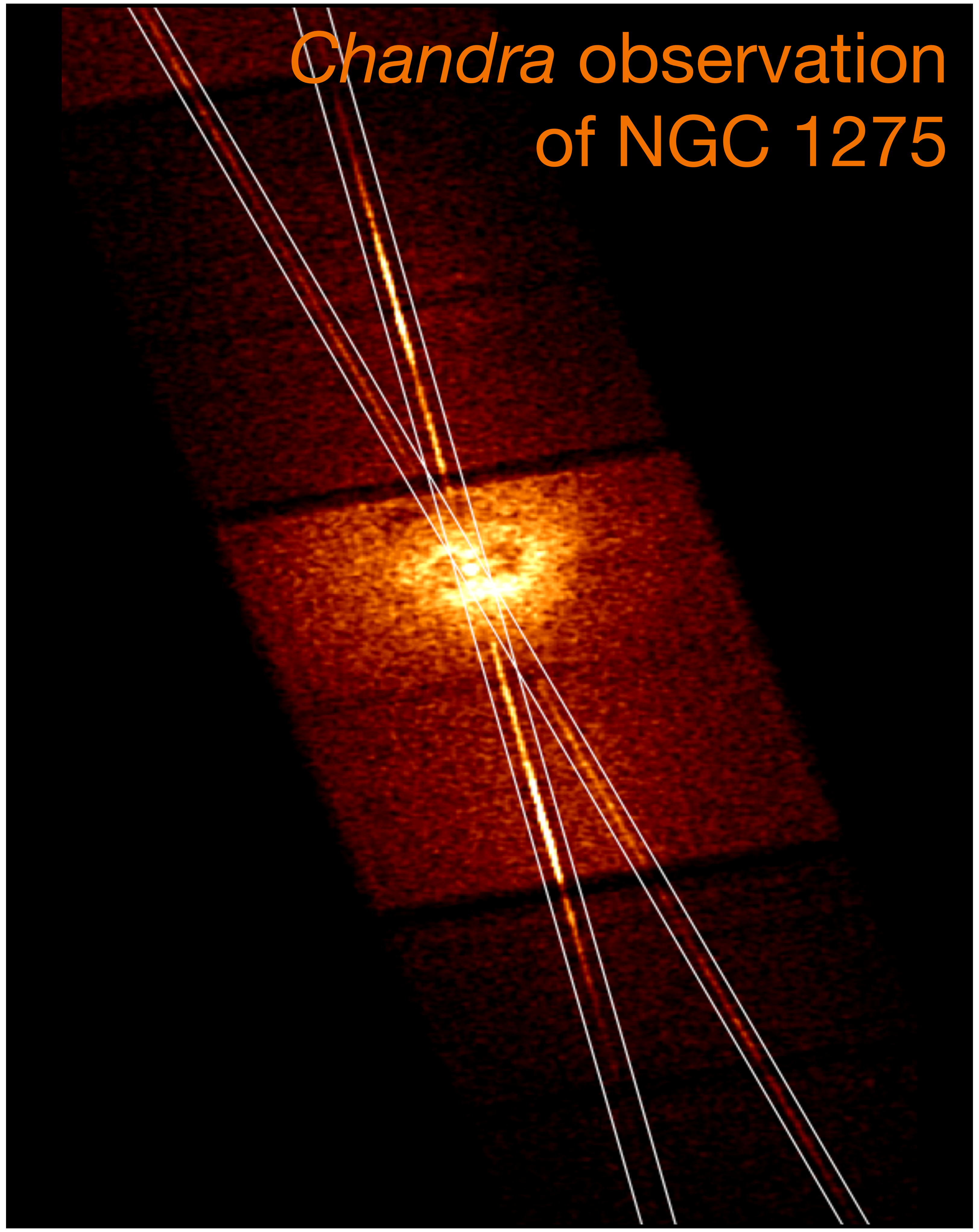
Long coherence lengths (~kpc).

Luminous sources (AGNs, quasars).

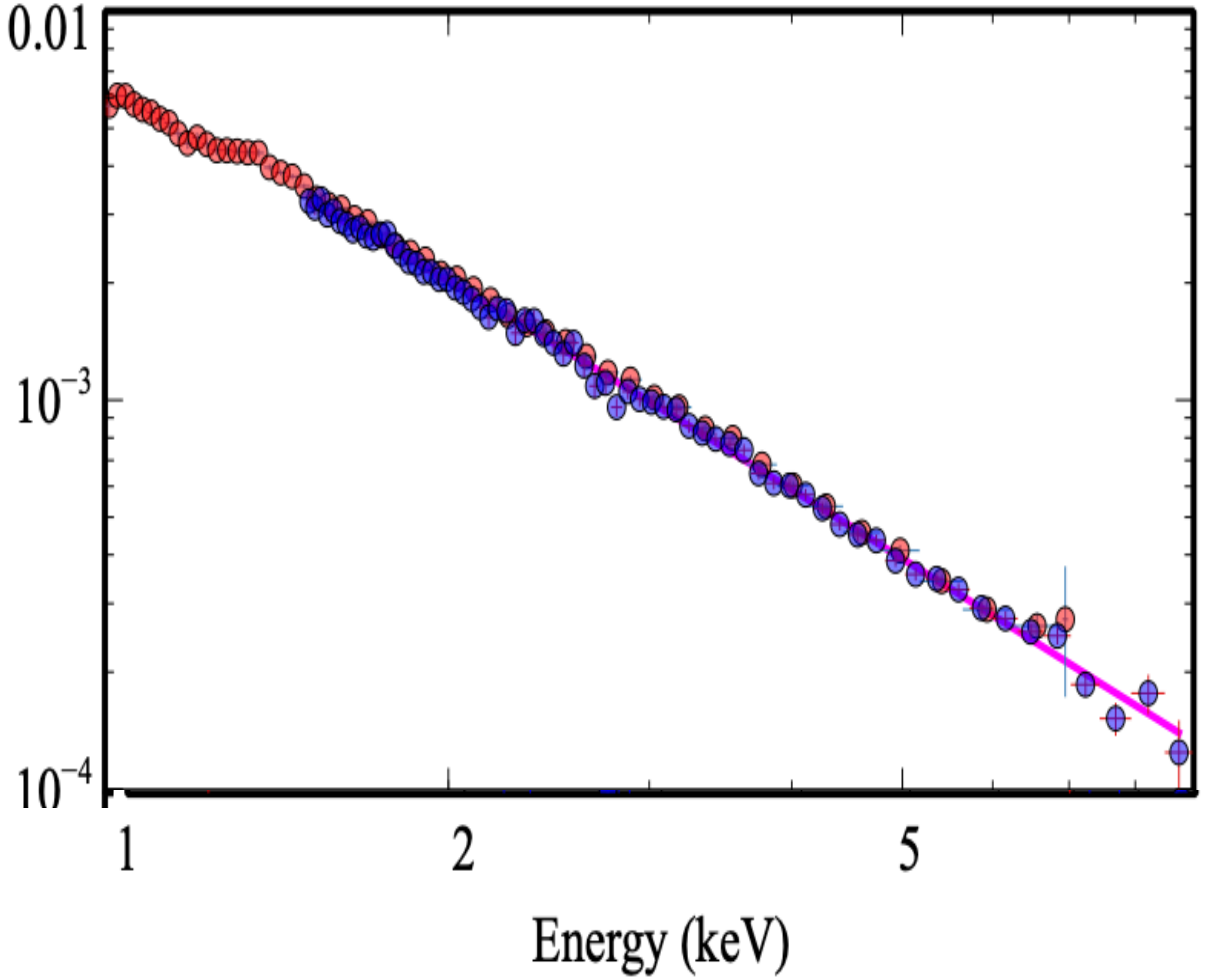
Unsuppressed *conversion ratios*:

$$P_{\gamma a} \sim \mathcal{O}\left(\frac{1}{2}\right) \times \left(\frac{g_{a\gamma}}{10^{-11}\,\mathrm{GeV}}\right)^2$$

Precision spectra

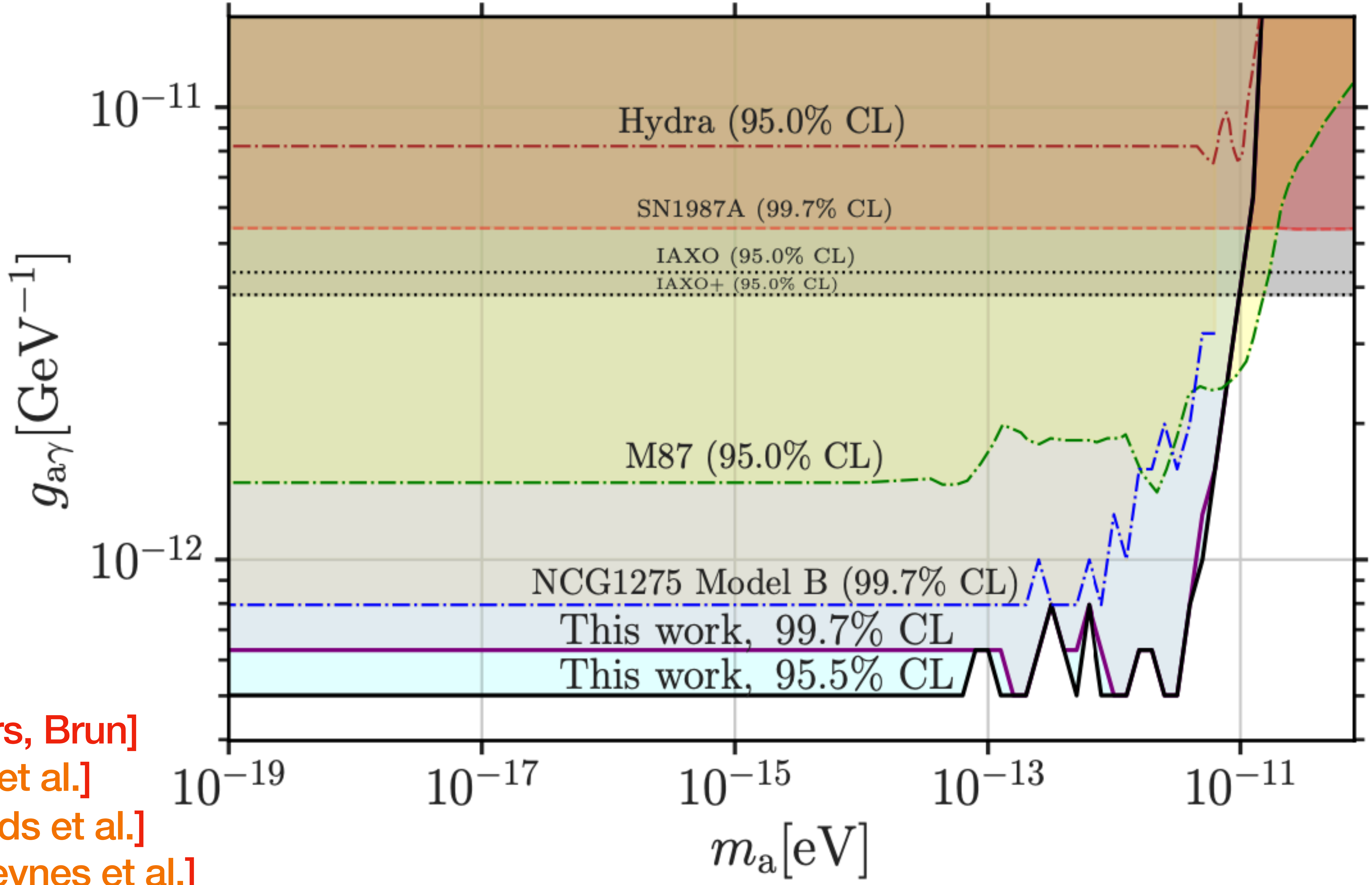


[Reynolds, *DM*, et al.]
[Sisk-Reynes et al.]



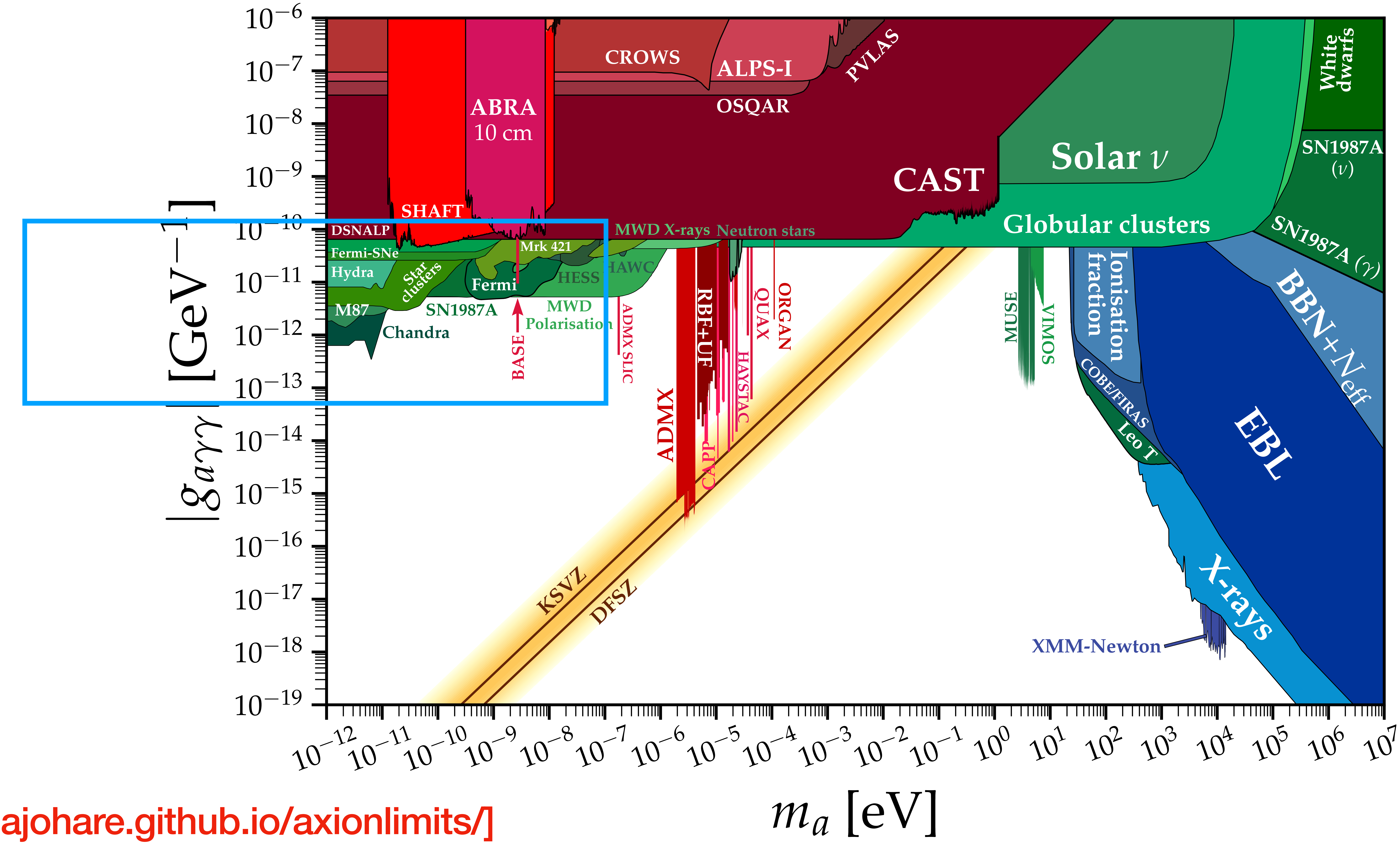
Amplitude of hypothetical
oscillations must be ≲2.5%.

Strongest limits by an order of magnitude



[Wouters, Brun]
[Marsh et al.]
[Reynolds et al.]
[Sisk Reynes et al.]

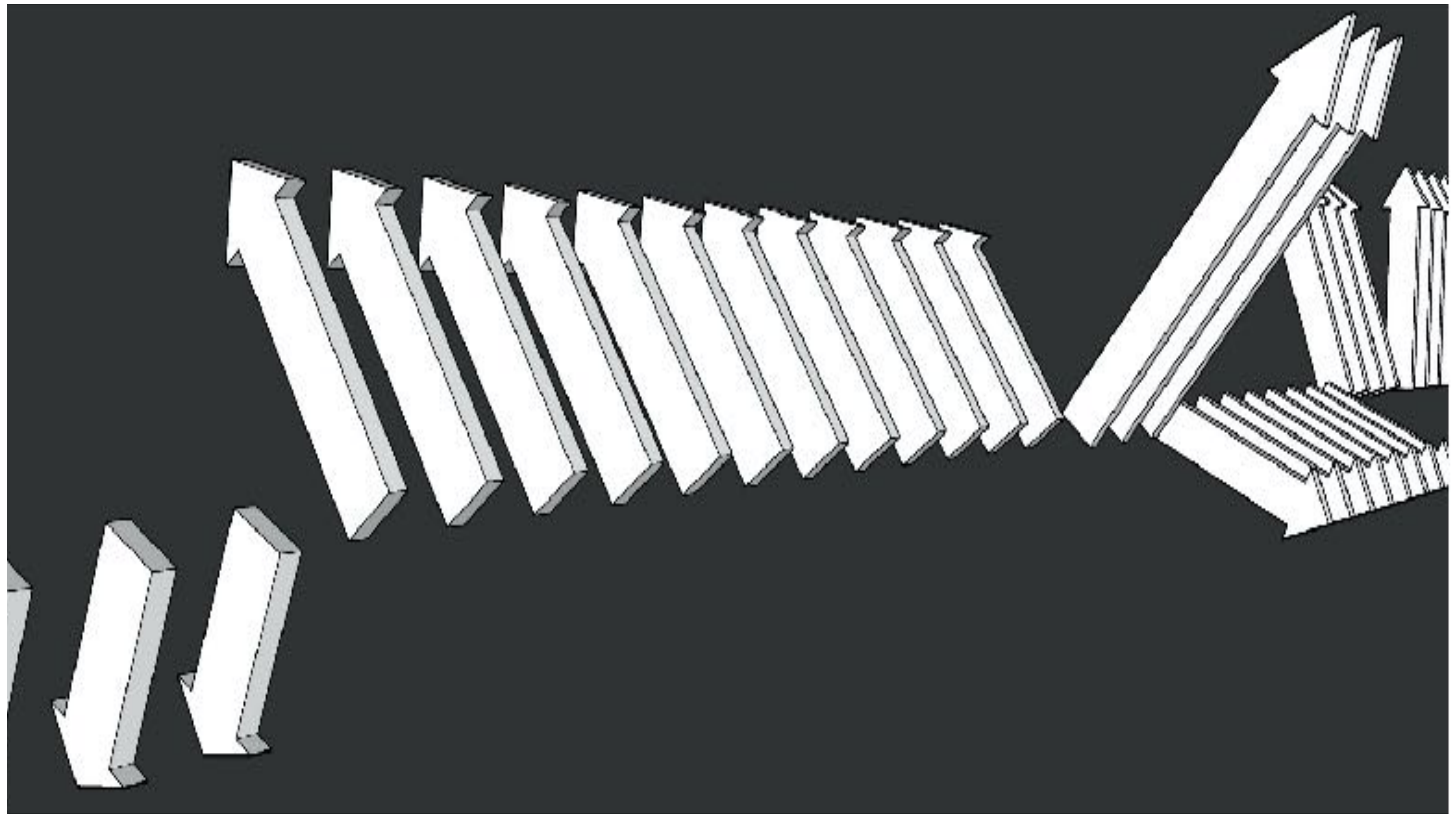
Context



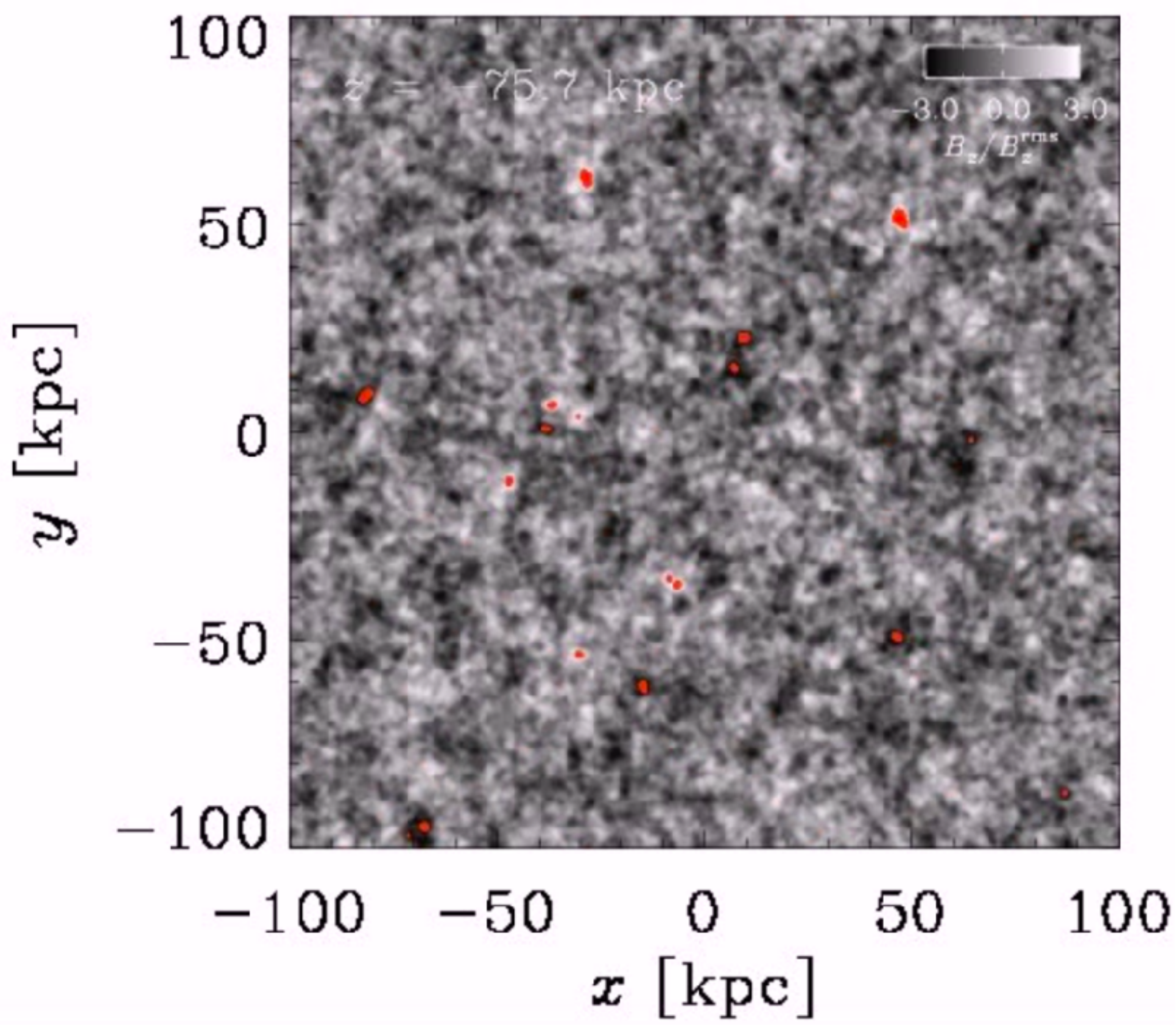
[Wouters, Brun],
[Conlon et al.],
[Berg et al.],
[*DM* et al.],
[Reynolds et al.],
[Chen, Conlon],
[Day, Krippendorf],
[Sisk Reynes et al.],
[Matthews et al.],
[Schallmoser et al.]

[cajohare.github.io/axionlimits/]

Magnetic field models

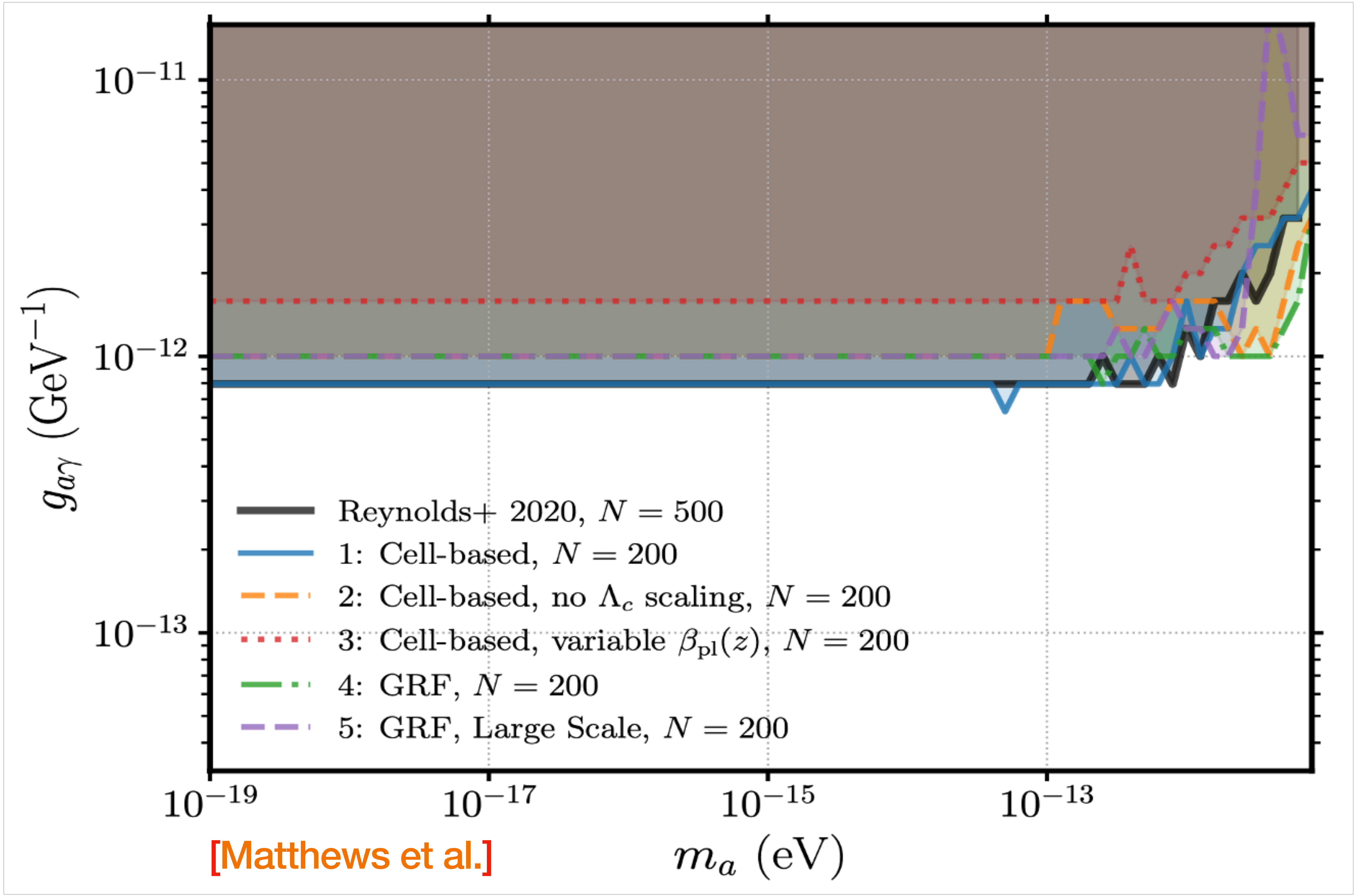


Status: standard practice



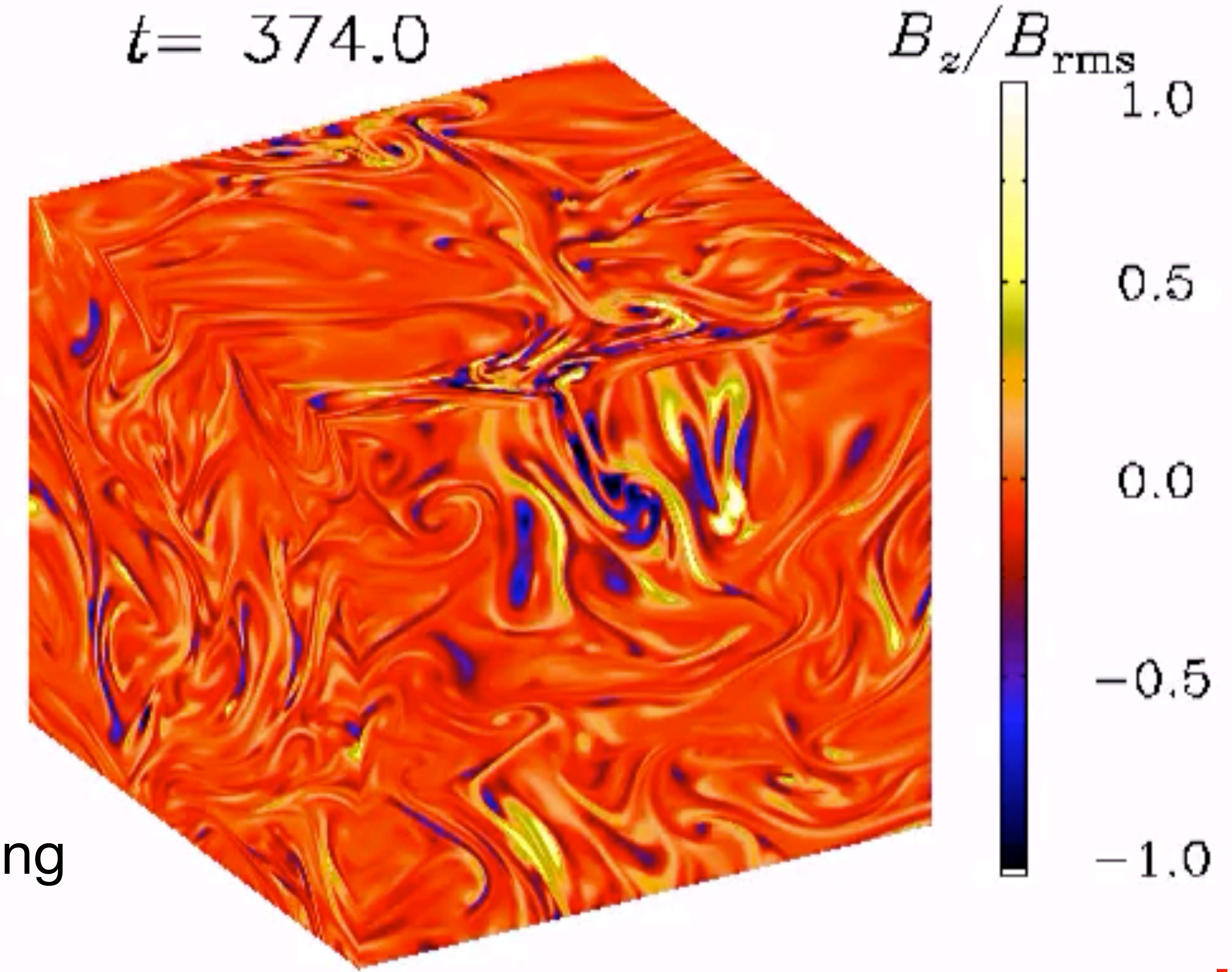
Status: “state-of-the-art”

How robust are these limits?



[Matthews et al.]

Dedicated MHD simulations: time-evolution



$L^3 = (200\ \mathrm{kpc})^3$
#lattice points = 512^3
periodic bc, external forcing
Dynamo-enhanced,
turbulent magnetic field

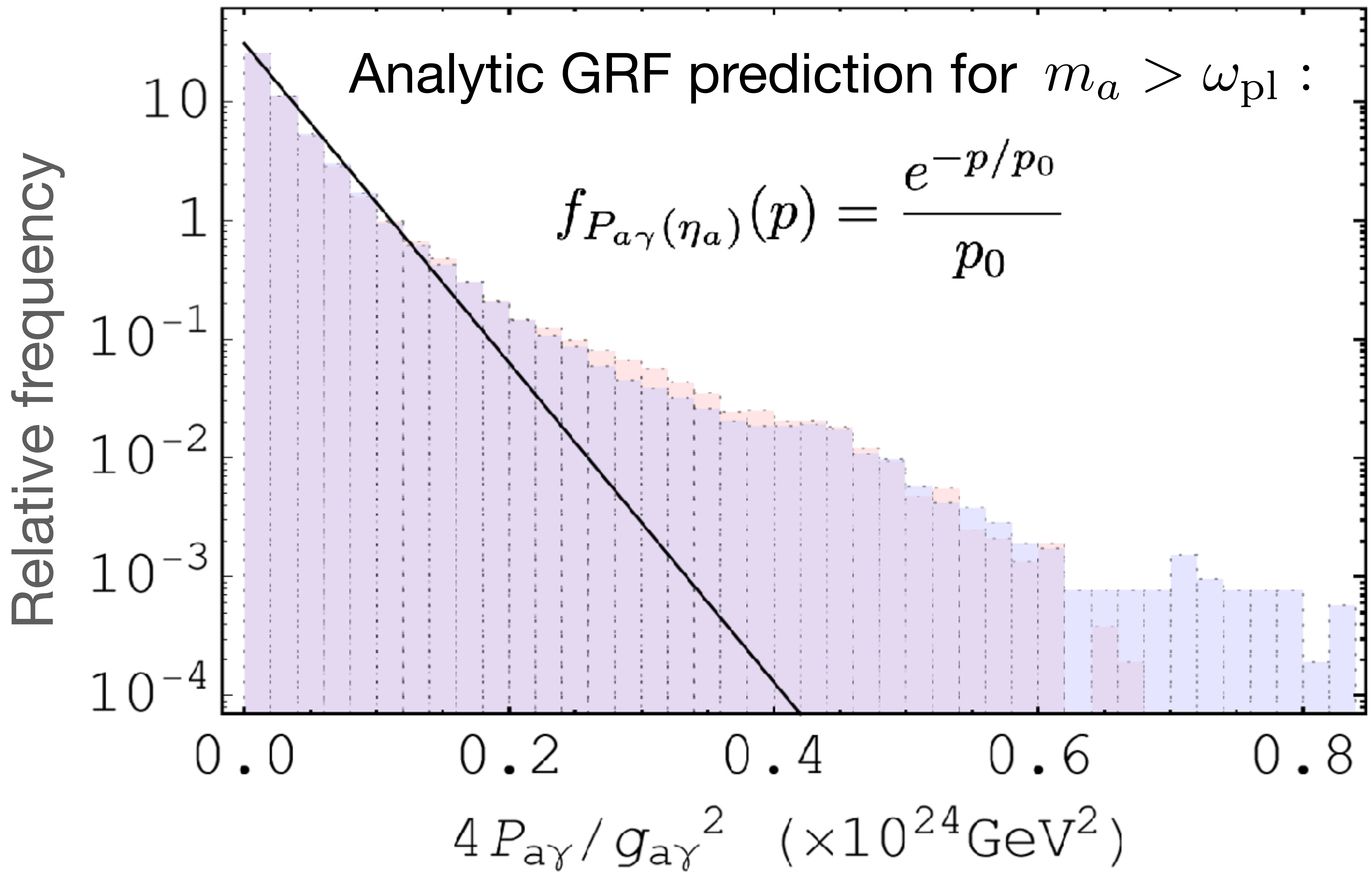
[Carenza et al.]

GRF v MHD

(same power spectrum)

Red: $|\mathbf{B}| > 3B_{\rm rms}$

Heavy-tailed MHD distributions



Analytic GRF prediction for $m_a > \omega_{\rm pl}$:

$$f_{P_{a\gamma}(\eta_a)}(p) = \frac{e^{-p/p_0}}{p_0}$$

Conversion ratio

$$p_0 = \frac{g_{a\gamma}^2}{4}\frac{L}{2\pi}P_{1\rm D}(\eta_a)$$

$$\eta_a = \frac{m_a^2}{2\omega}$$

Skewness & kurtosis:

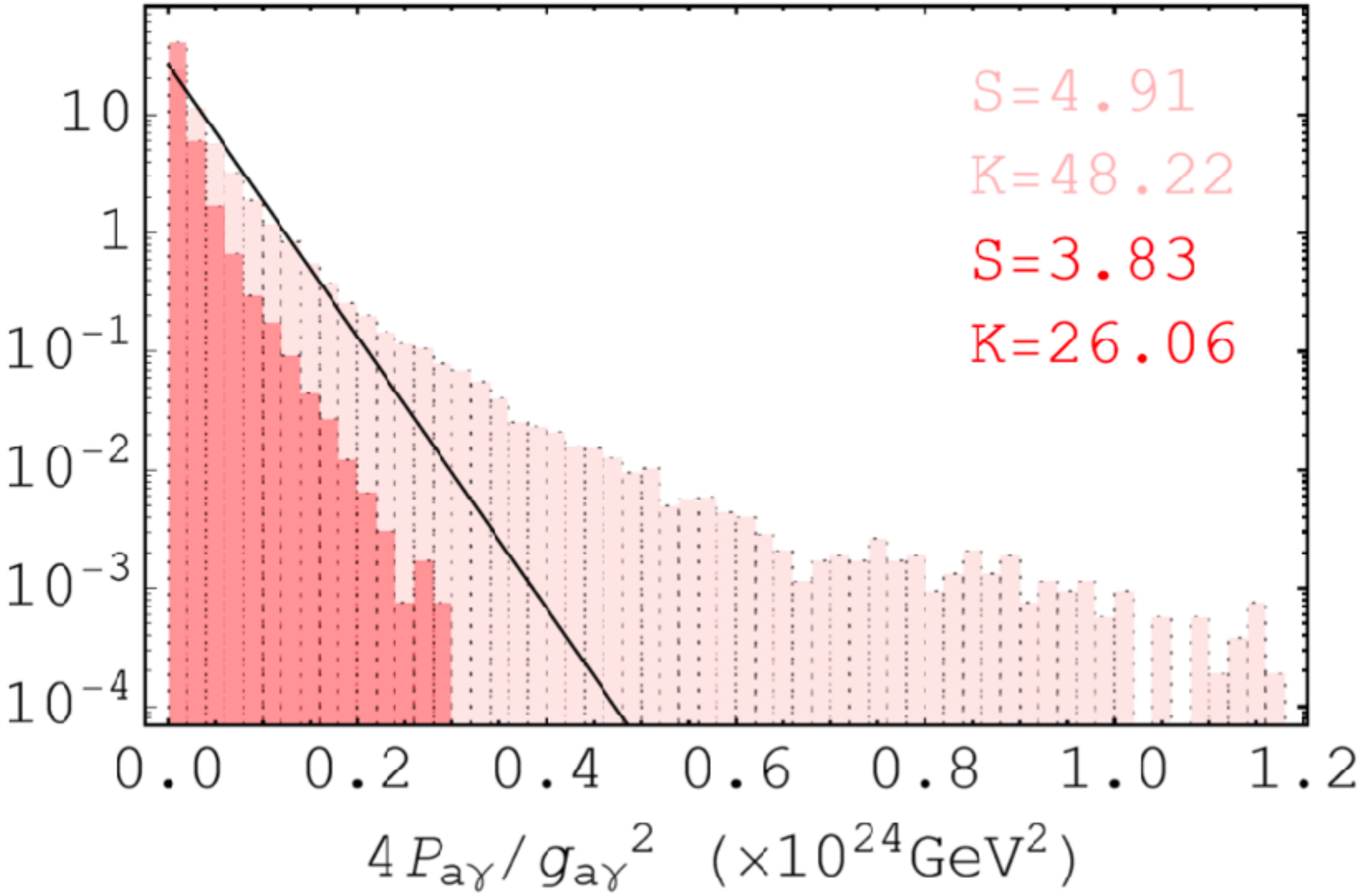
GRF:	MHD:
S = 2	S=3.88
K = 9	K=25.56
	S=4.60
	K=41.80

Result generalises for arbitrary ALP mass

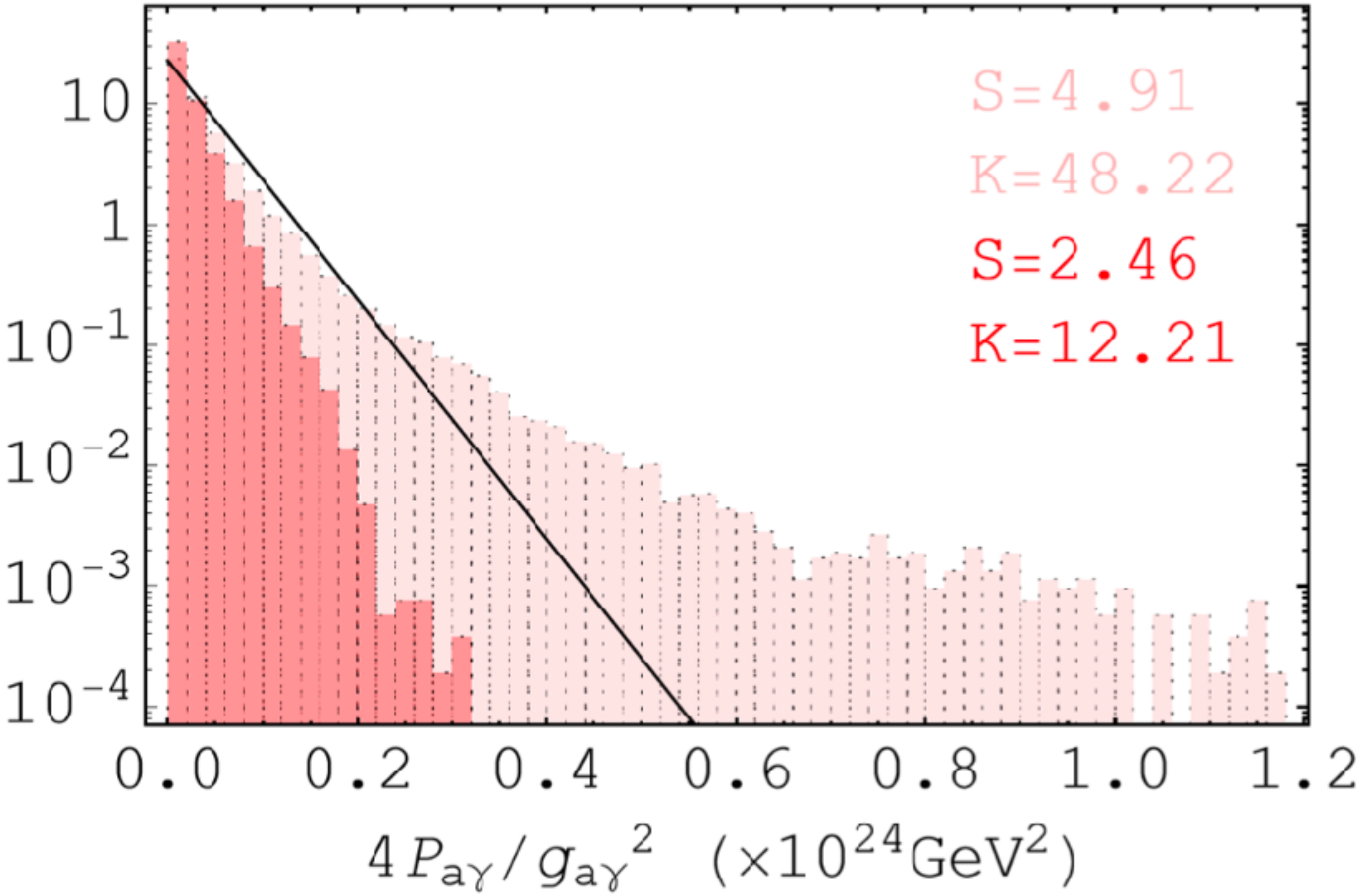
Non-Gaussianity

Two possible sources:

Mask large coherence lengths



Mask high peaks



Non-Gaussianity

Typical predictions essentially set by average:

$$\langle P_{\gamma a}(\eta_a)\rangle = \frac{g_{a\gamma}^2}{4}\langle|\tilde{B}_i(\eta_a)|^2\rangle = \frac{g_{a\gamma}^2}{4}\frac{L}{2\pi}P_{\mathrm{1D}}(\eta_a)$$

Same for MHD and GRF

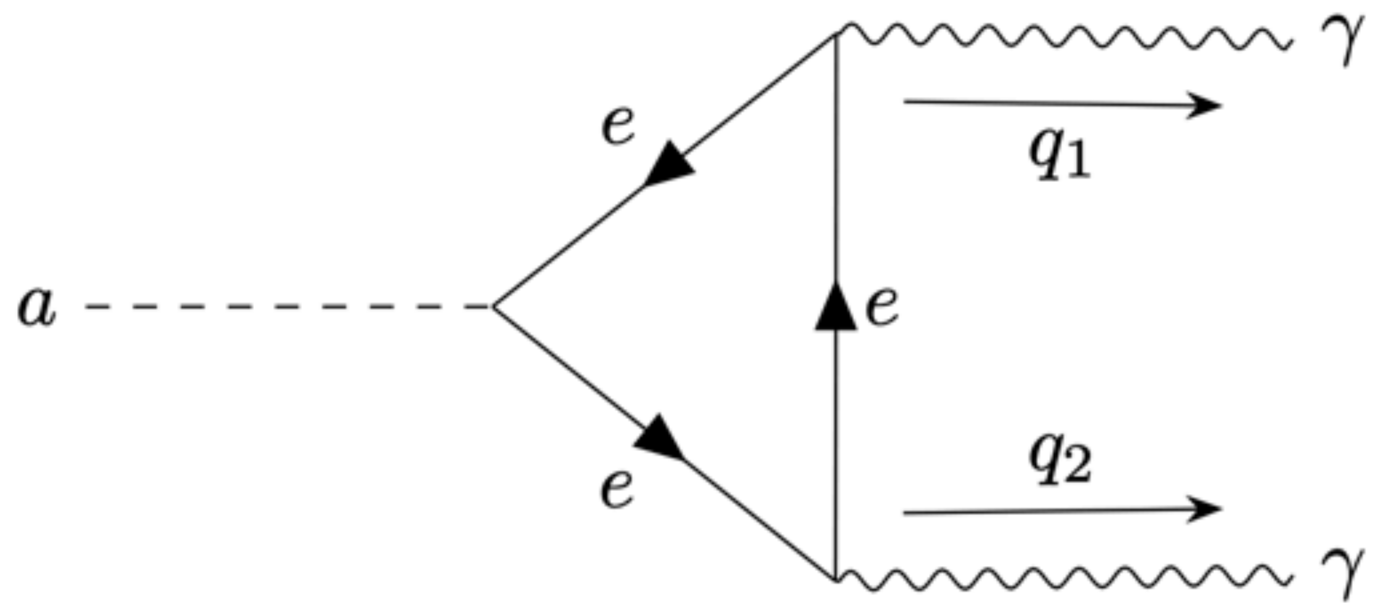
Heavy tails come from larger-than-Gaussian higher-order correlations, i.e.

$$\langle P_{\gamma a}(\eta_a)^2\rangle\,,\quad \langle P_{\gamma a}(\eta_a)^3\rangle\,,\quad \langle P_{\gamma a}(\eta_a)^4\rangle \quad \text{etc.}$$

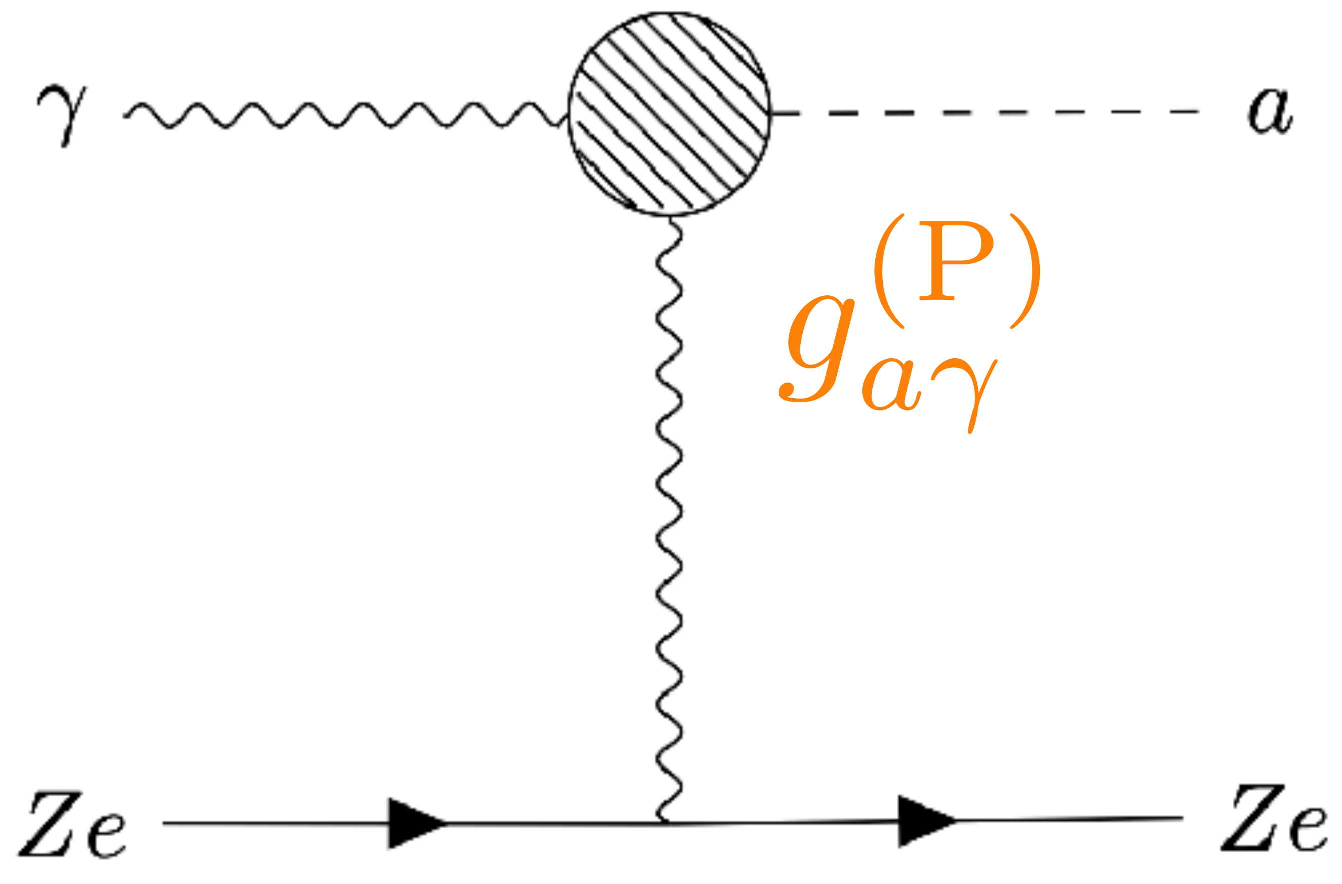
Larger conversion from MHD
— suggest existing limits conservative

Quantum ALP-processes

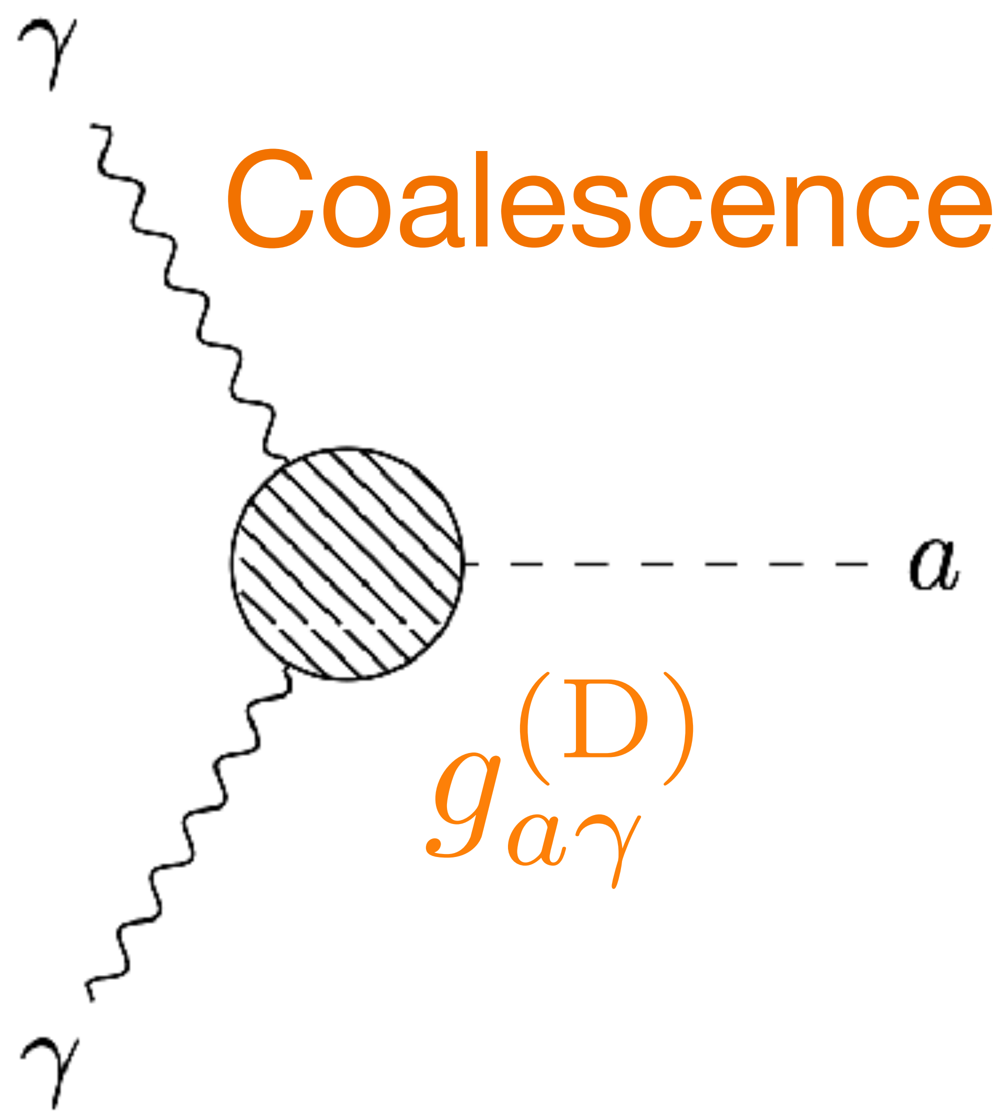
ALPs that don’t couple to photons at tree-level still acquire an effective coupling from loops:



Primakoff/inverse Primakoff

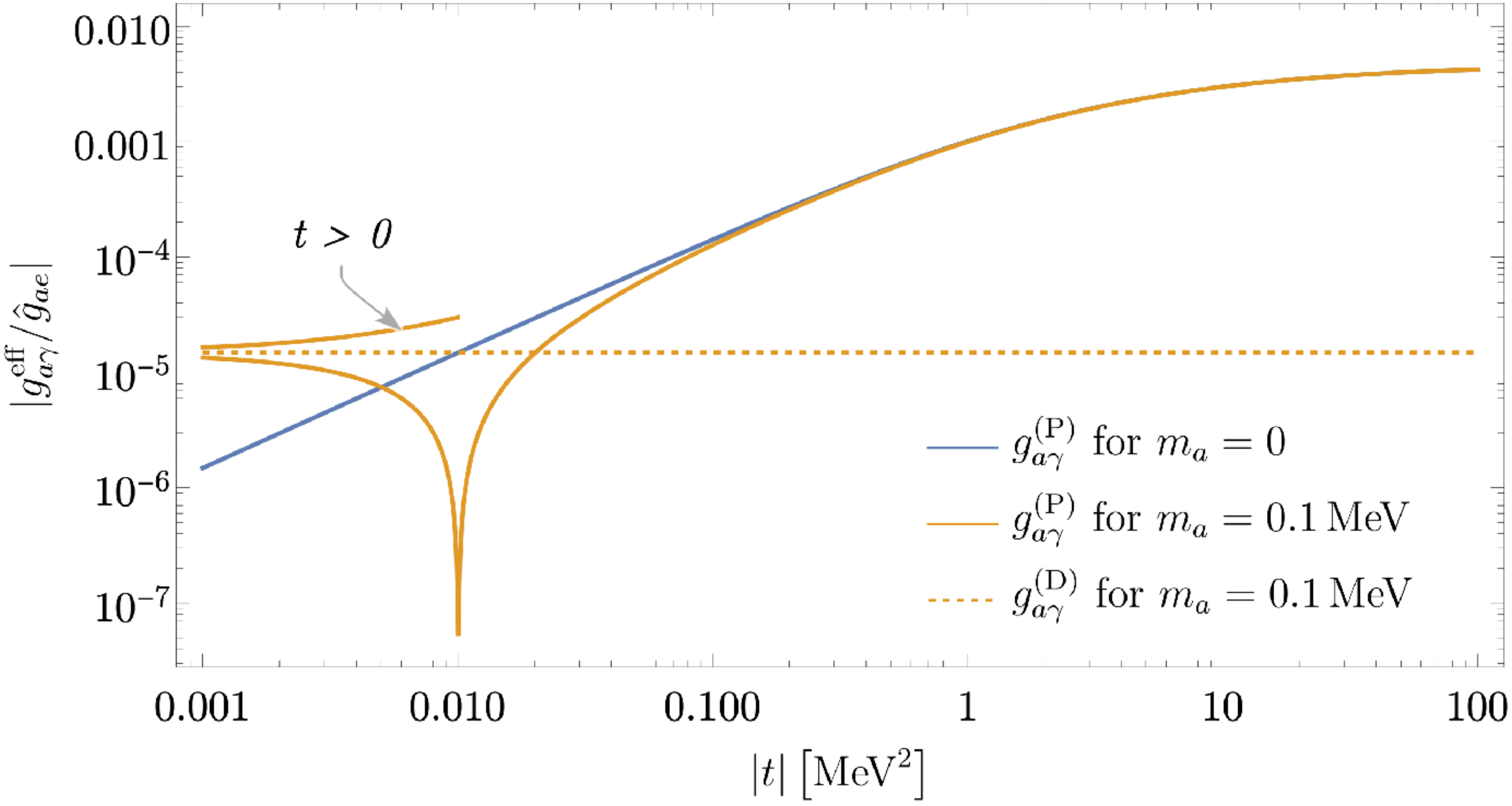


Coalescence/decay



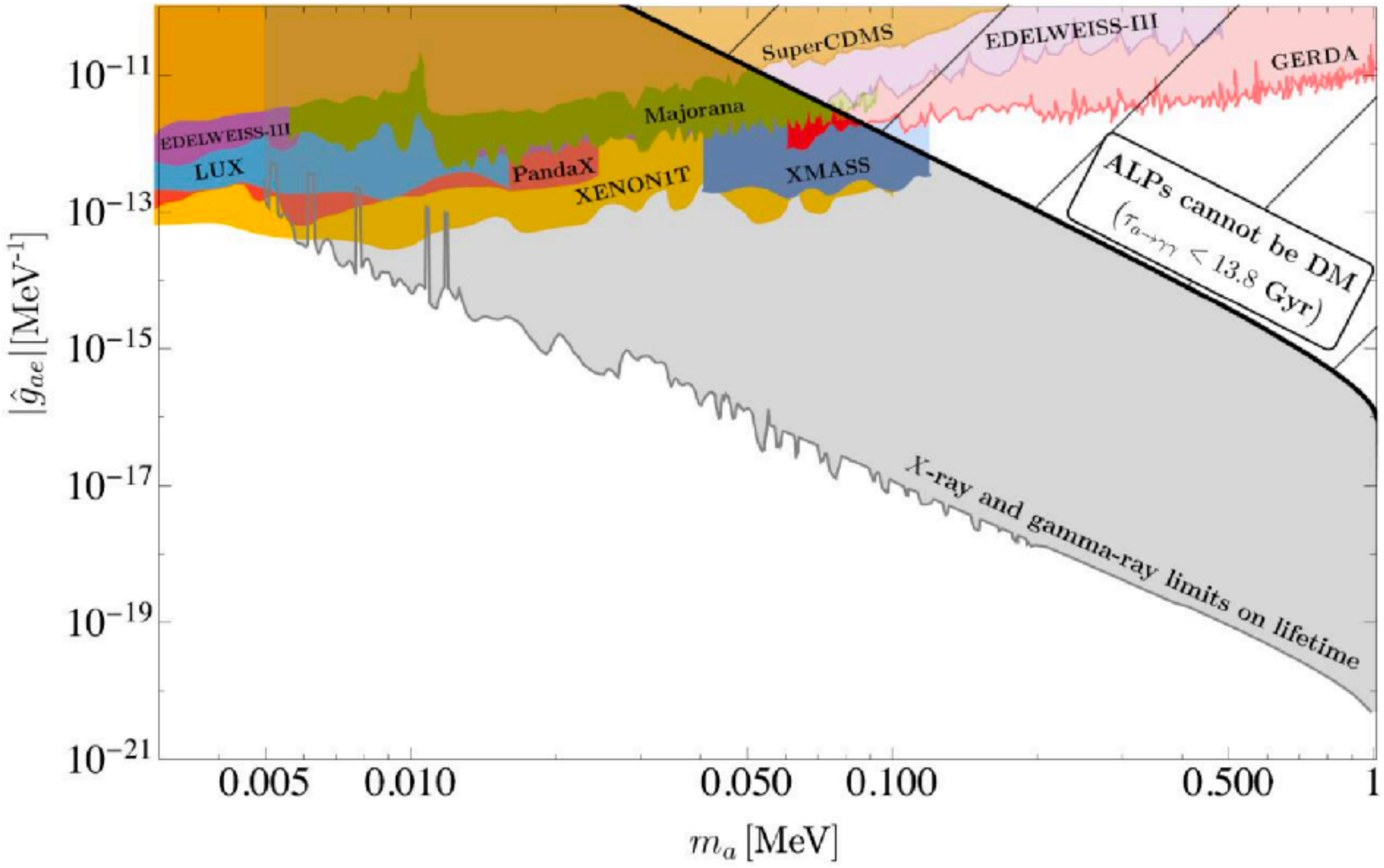
[Ferreira, Marsh, Müller]

Momentum-dependent coupling



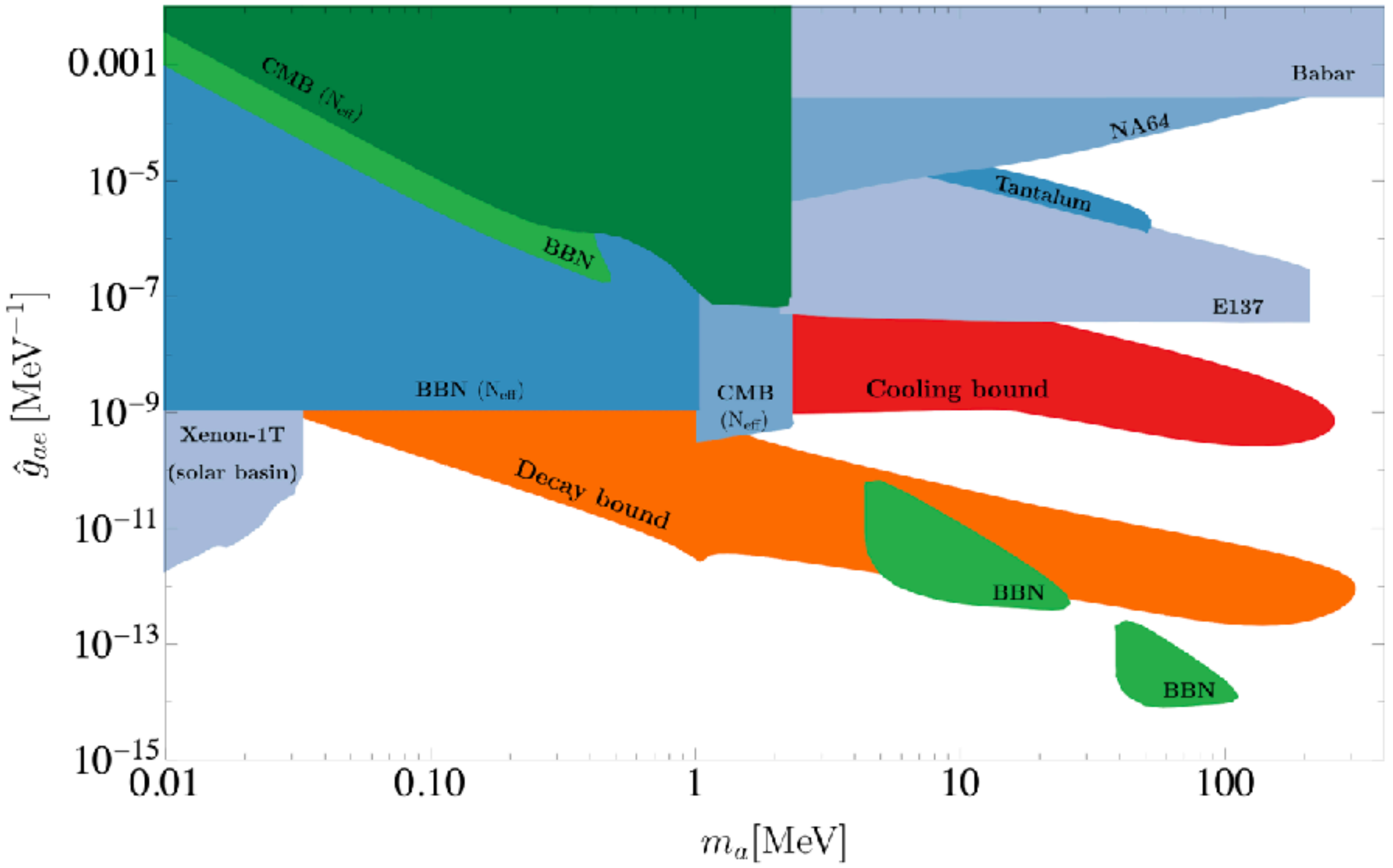
Two applications

ALP dark matter decay



[Ferreira, Marsh, Müller]
Phys.Rev.Lett. 128 (2022) 22

Decay and cooling bound from SN1987A



[Ferreira, Marsh, Müller]
arXiv:2205.07896

Conclusions

Astrophysical probes can be very sensitive to ALPs.

MHD models will be the next state-of-the-art for ALP-photon conversion.

MHD structure suggests new observables.

Quantum processes can dominate — and have drastic consequences.