The **heavy tails** of axion-photon conversion

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Mostly based on arXiv:2208.04333

Collaborators


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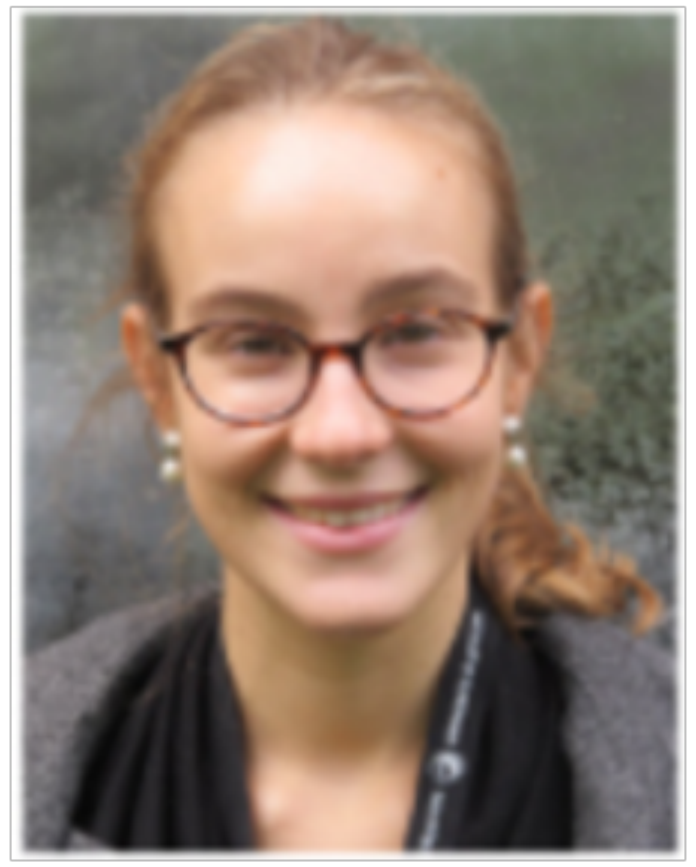
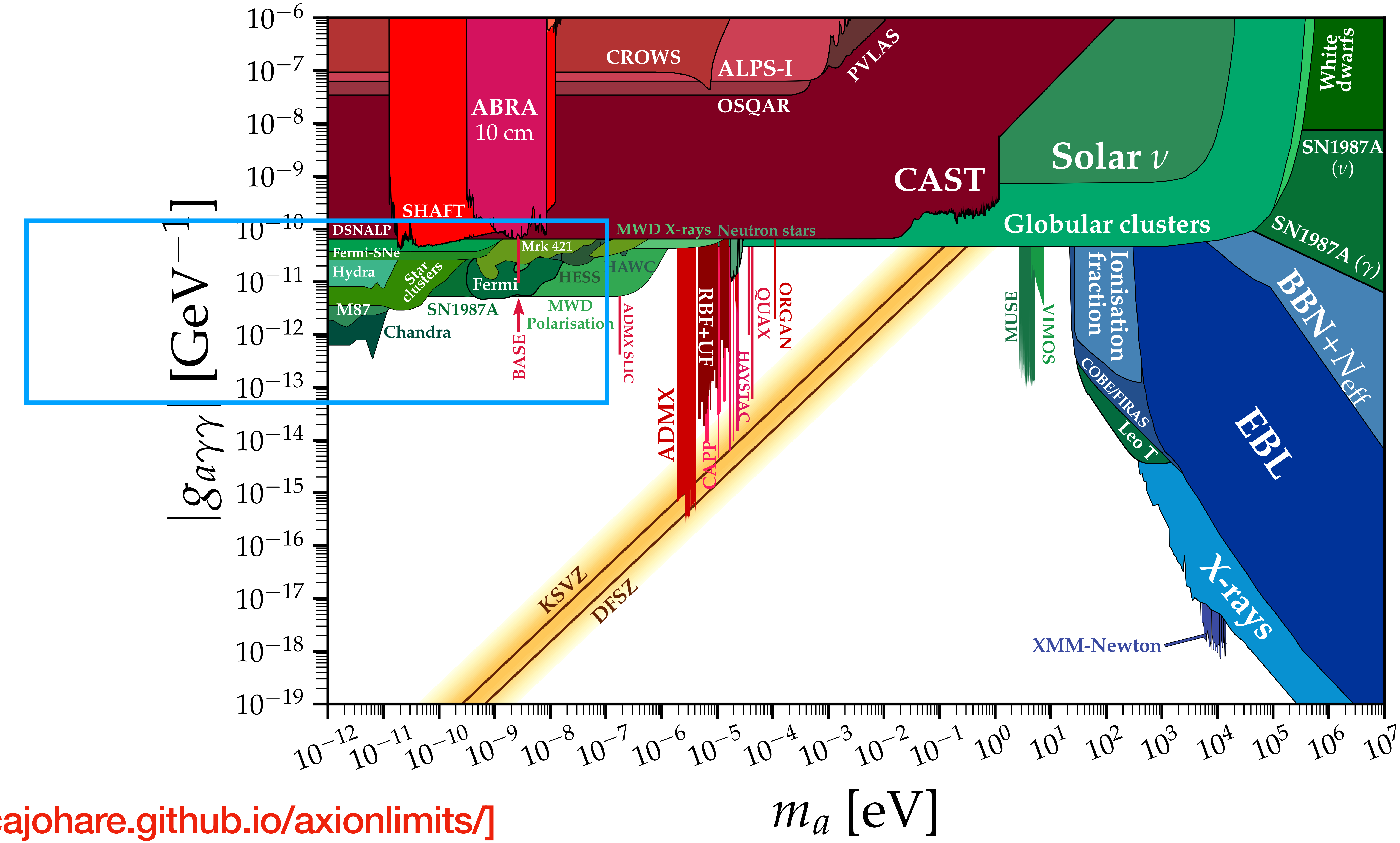

Julia Sisk-Reynes


Christopher Reynolds


Helen Russell

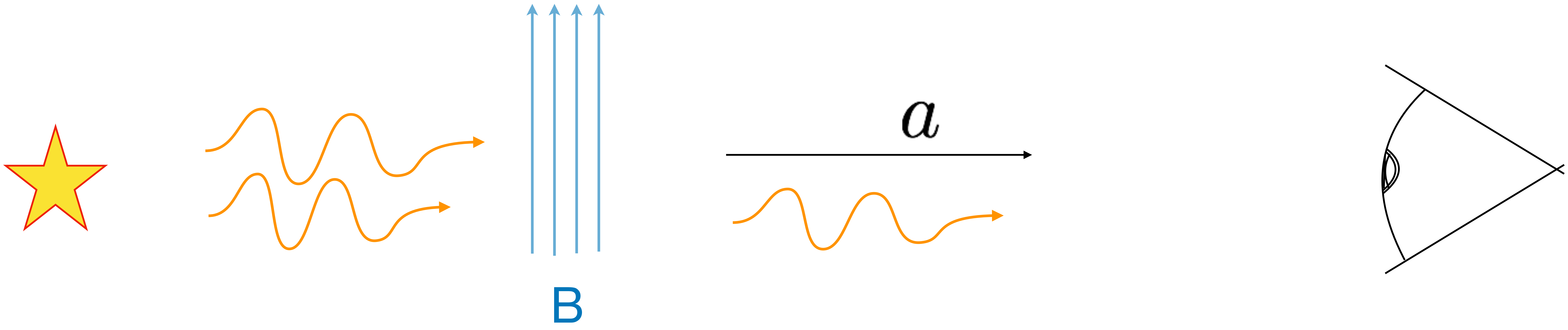
Context

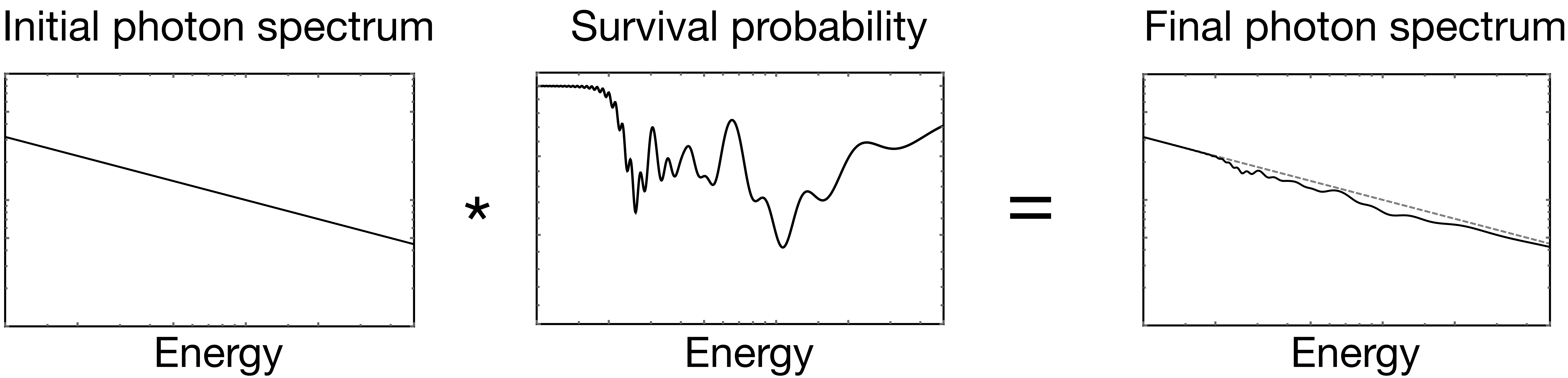


[cajohare.github.io/axionlimits/]

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

The photon disappearance channel





[Sikivie],
[Raffelt, Stodolsky]

Galaxy clusters as axion-photon converters

Largest gravitational bound objects (~100s kpc).

Magnetised (μG).

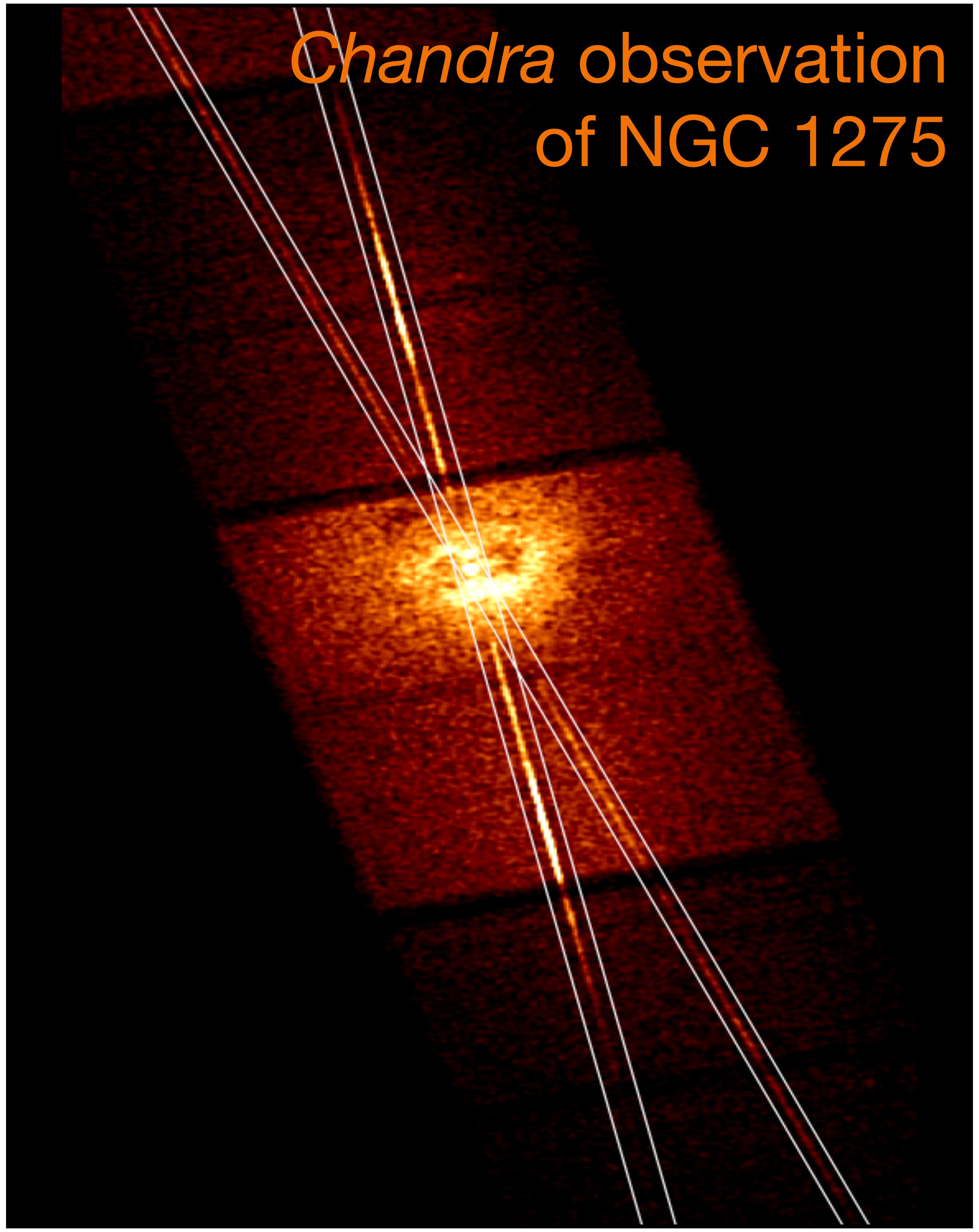
Long coherence lengths (~kpc).

Luminous sources (AGNs, quasars).

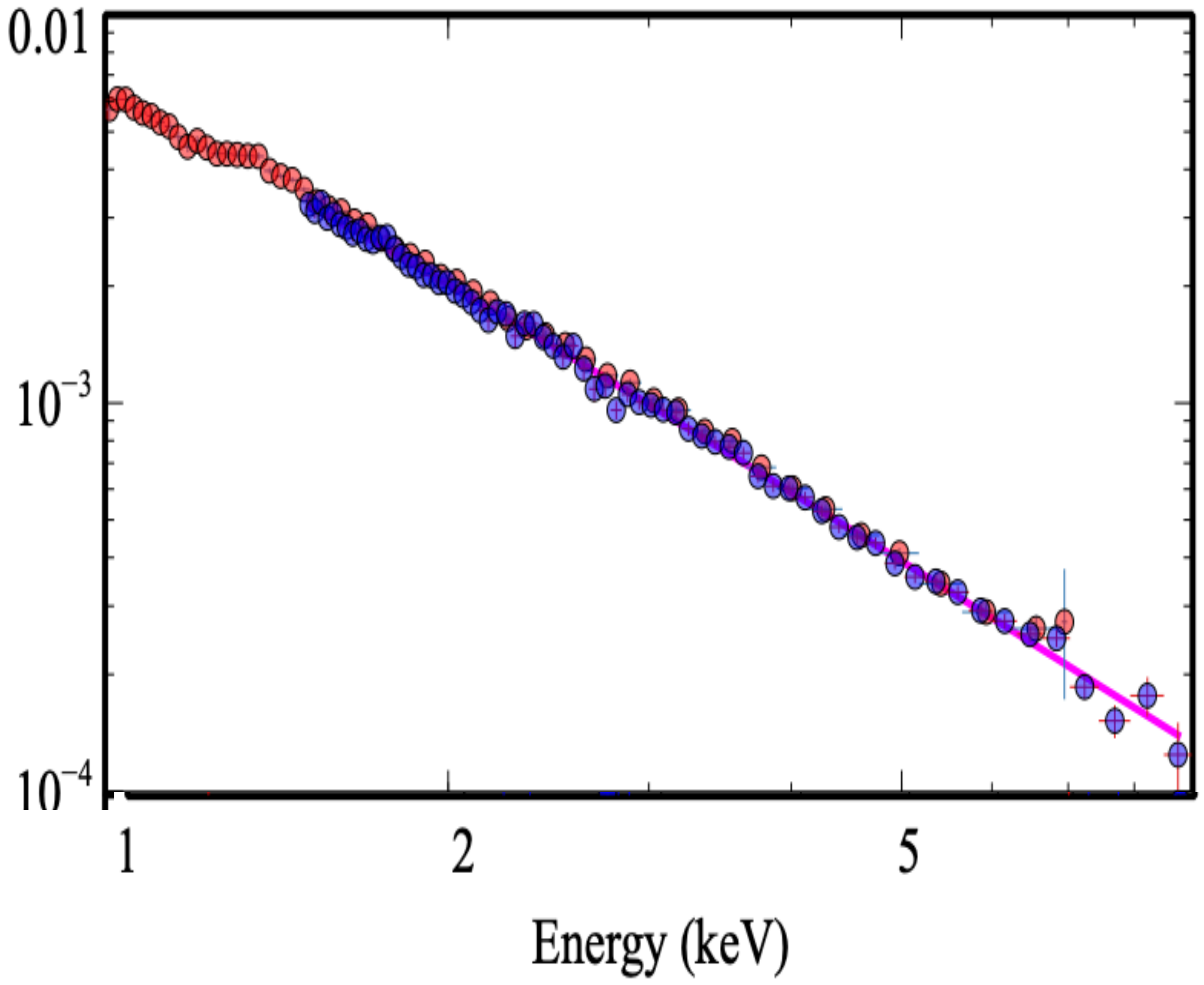
Unsuppressed *conversion ratios*:

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

Precision spectra

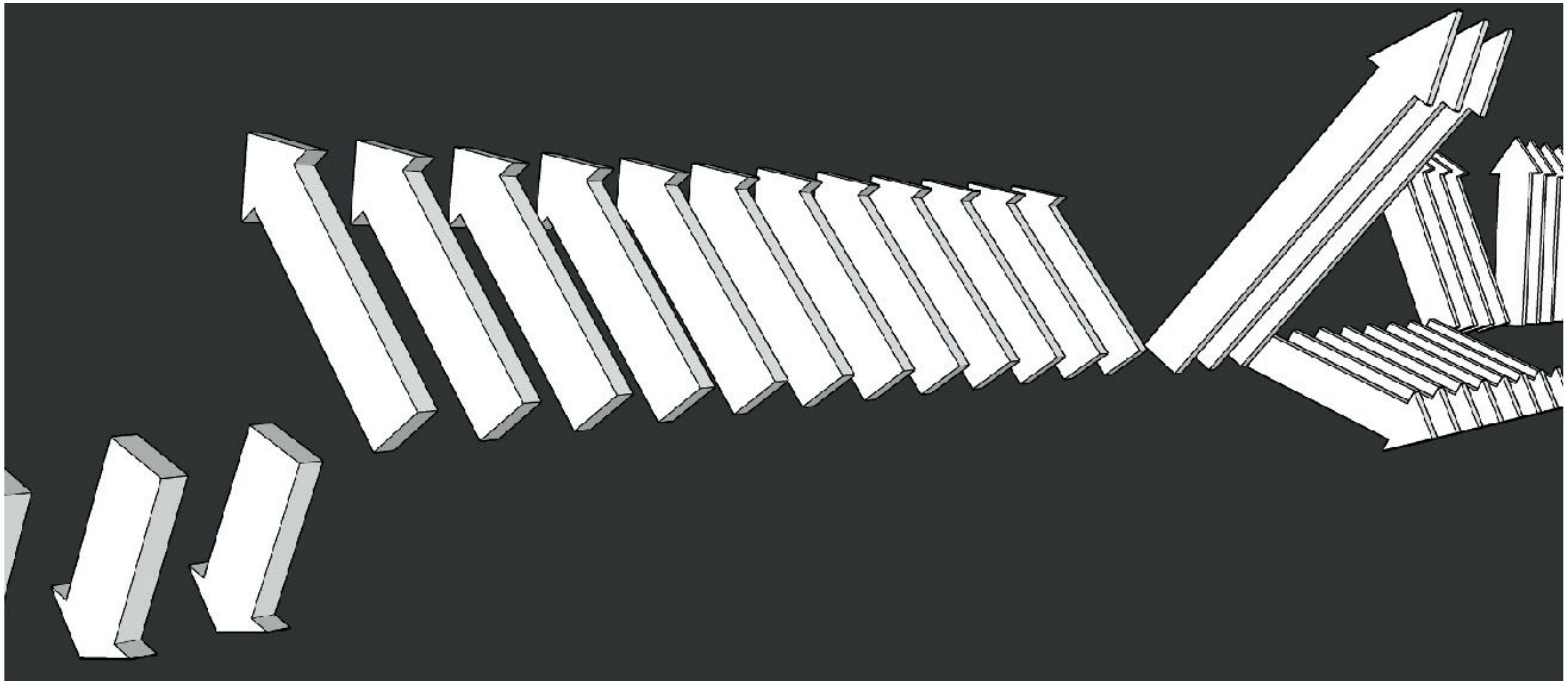


[Reynolds, *DM*, et al.]
[Sisk-Reynes et al.]



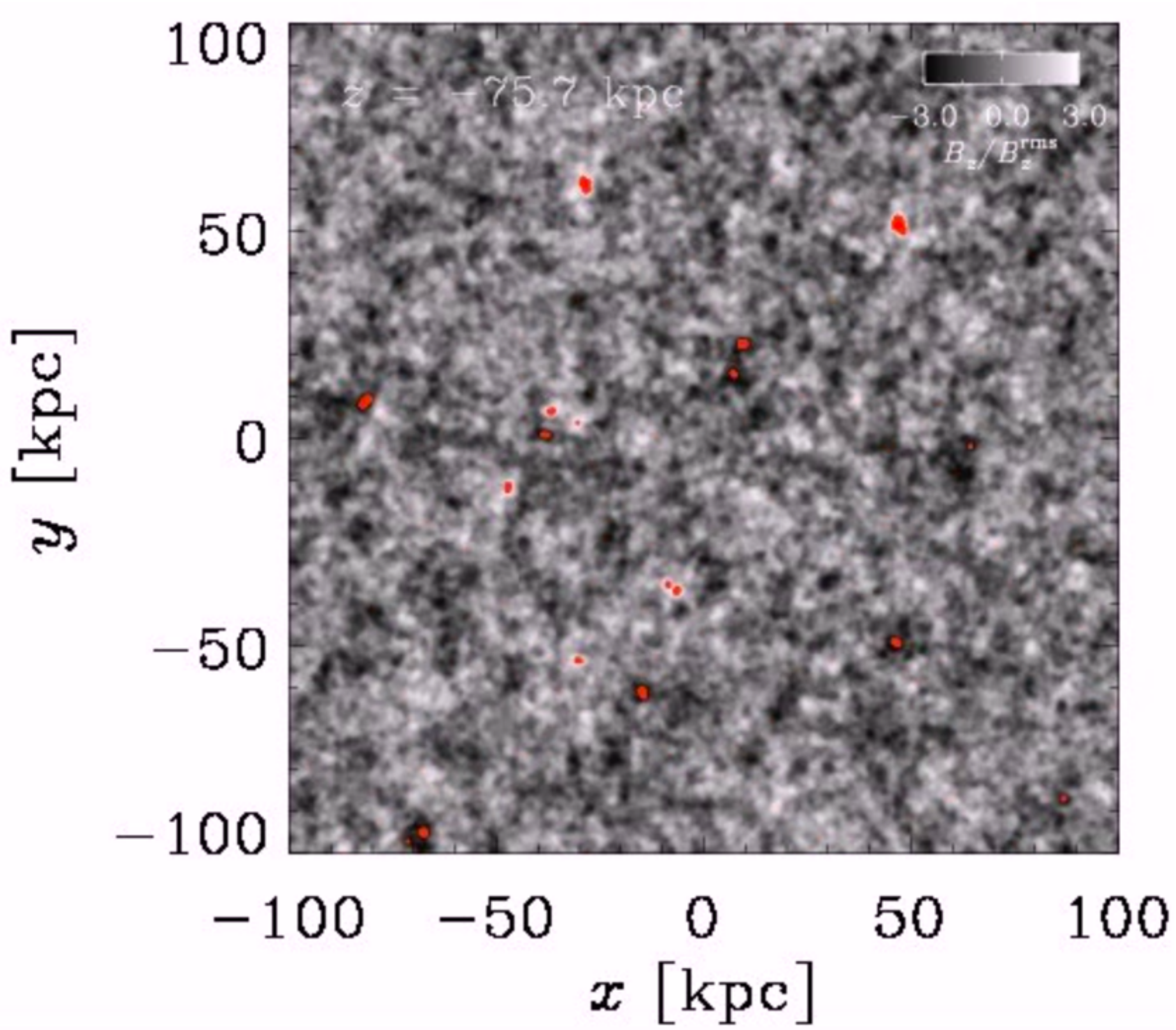
Amplitude of hypothetical oscillations must be ≲2.5%.

Magnetic field models v1: “cell models”



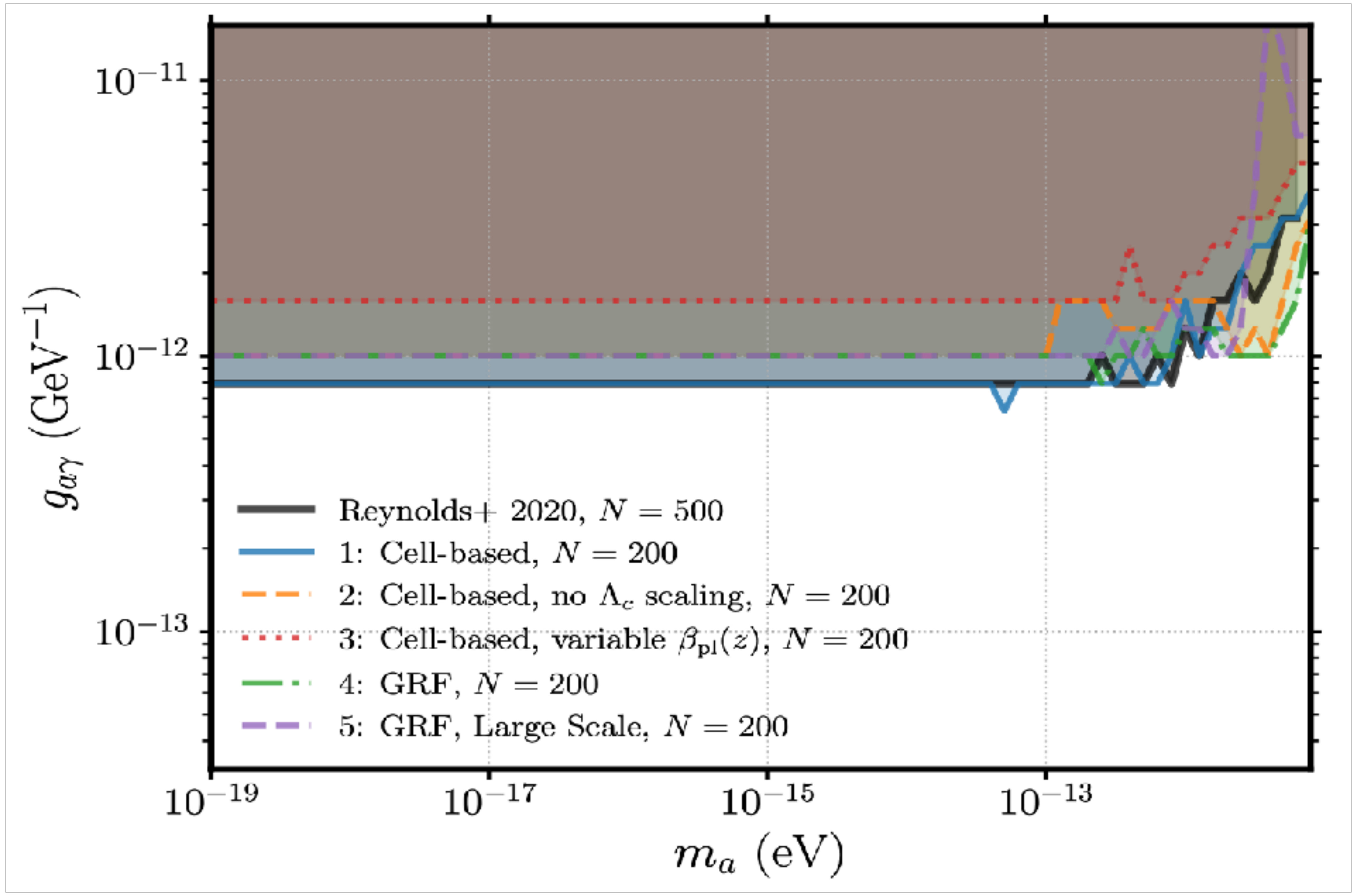
Status: standard practice

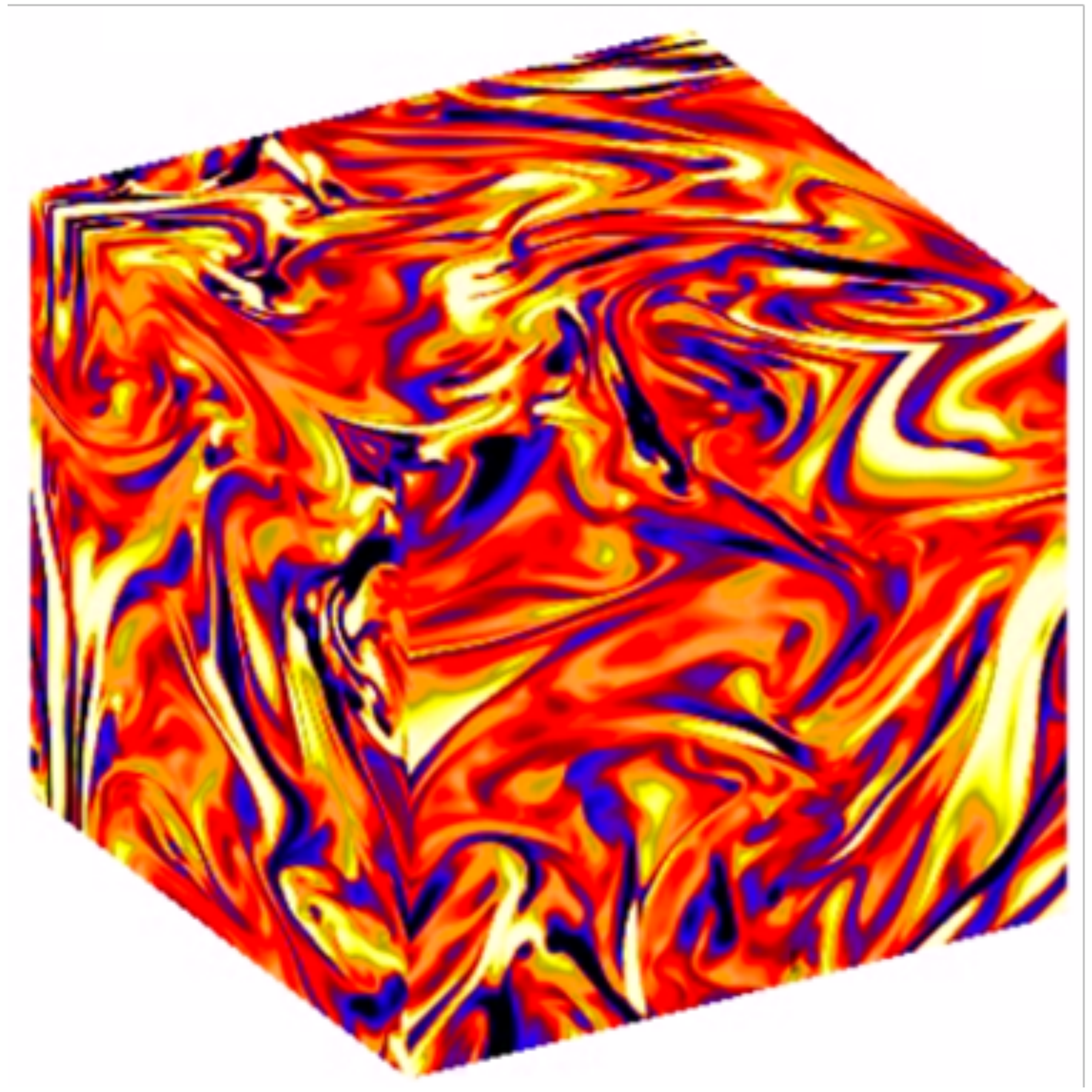
Magnetic field models v2: Gaussian random fields



Status: “state-of-the-art”

How robust are these limits?





[Matthews et al.]

Perturbative formalism

Small amplitude oscillations motivate perturbative solutions.

Simplest case: $m_a > \omega_{\rm pl}$

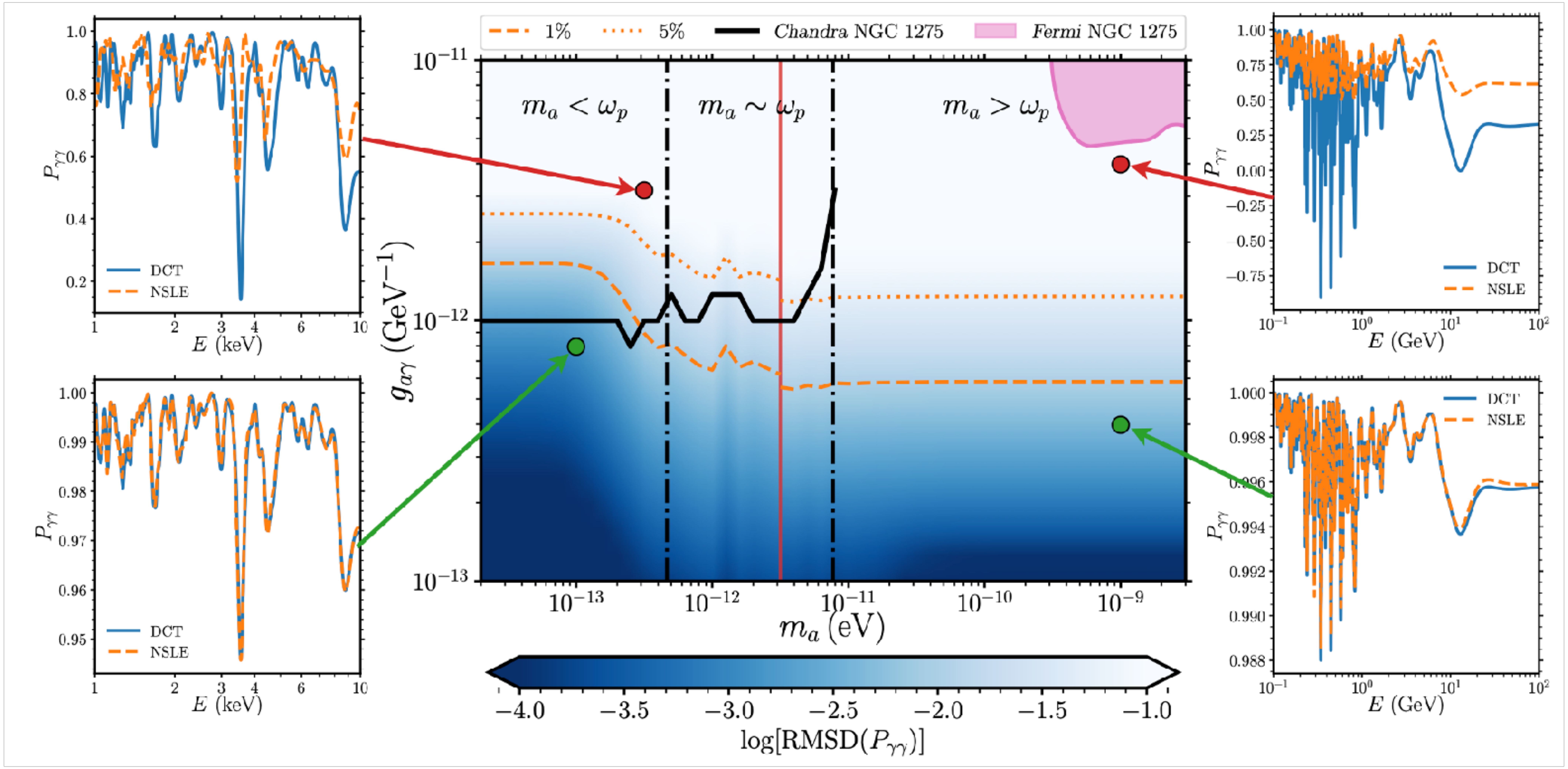
$$P_{\gamma a}(\eta_a) = \frac{g_{a\gamma}^2}{4} |\tilde{B}_i(\eta_a)|^2$$

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

$$\tilde{B}_i(\eta_a) = \int_{-L/2}^{L/2} dz\, B_i(z\hat{z}) e^{-iz\eta_a}$$

[Raffelt, Stodolsky]
[*DM* et al.]

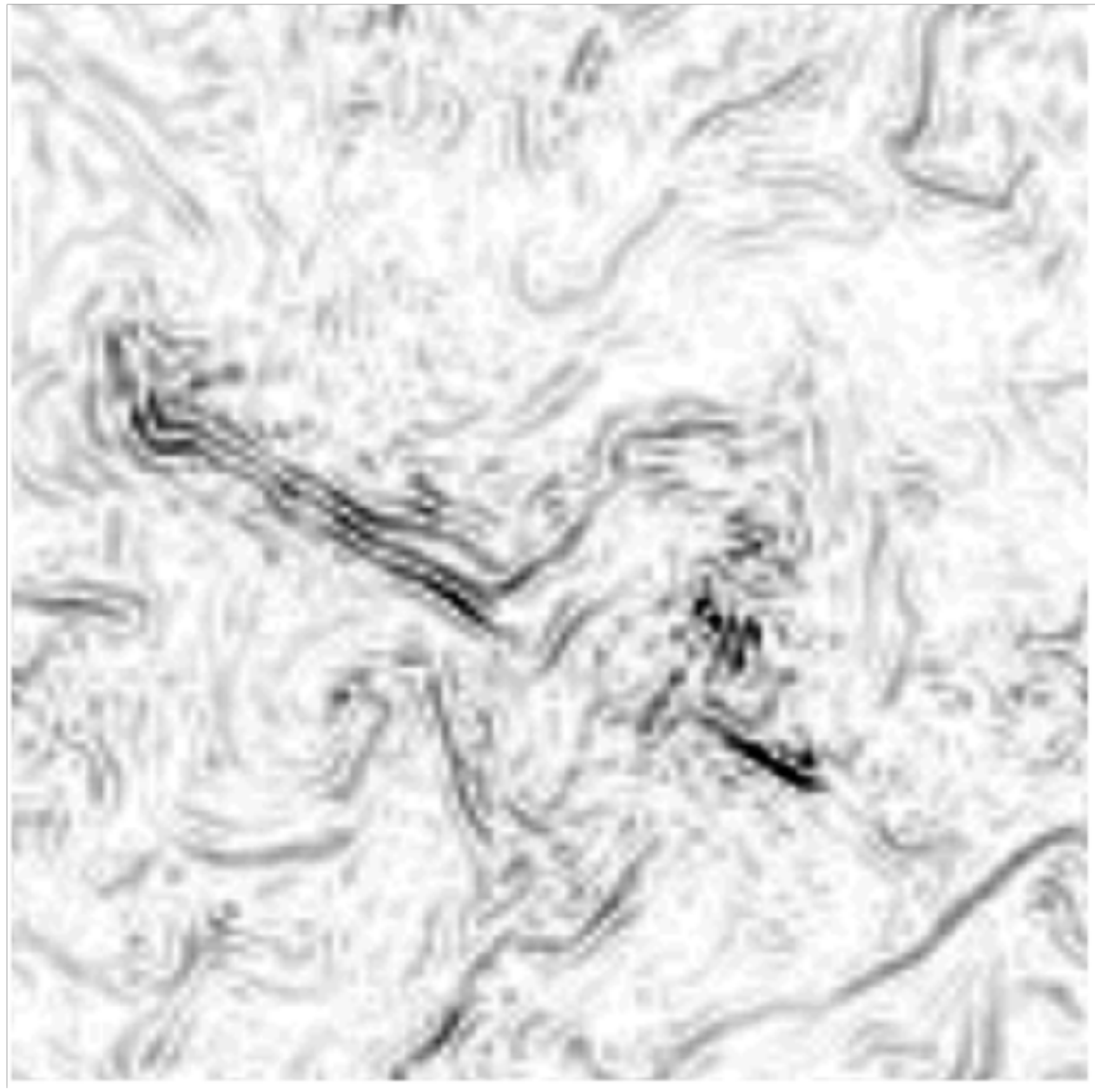
Perturbative formalism: applicability

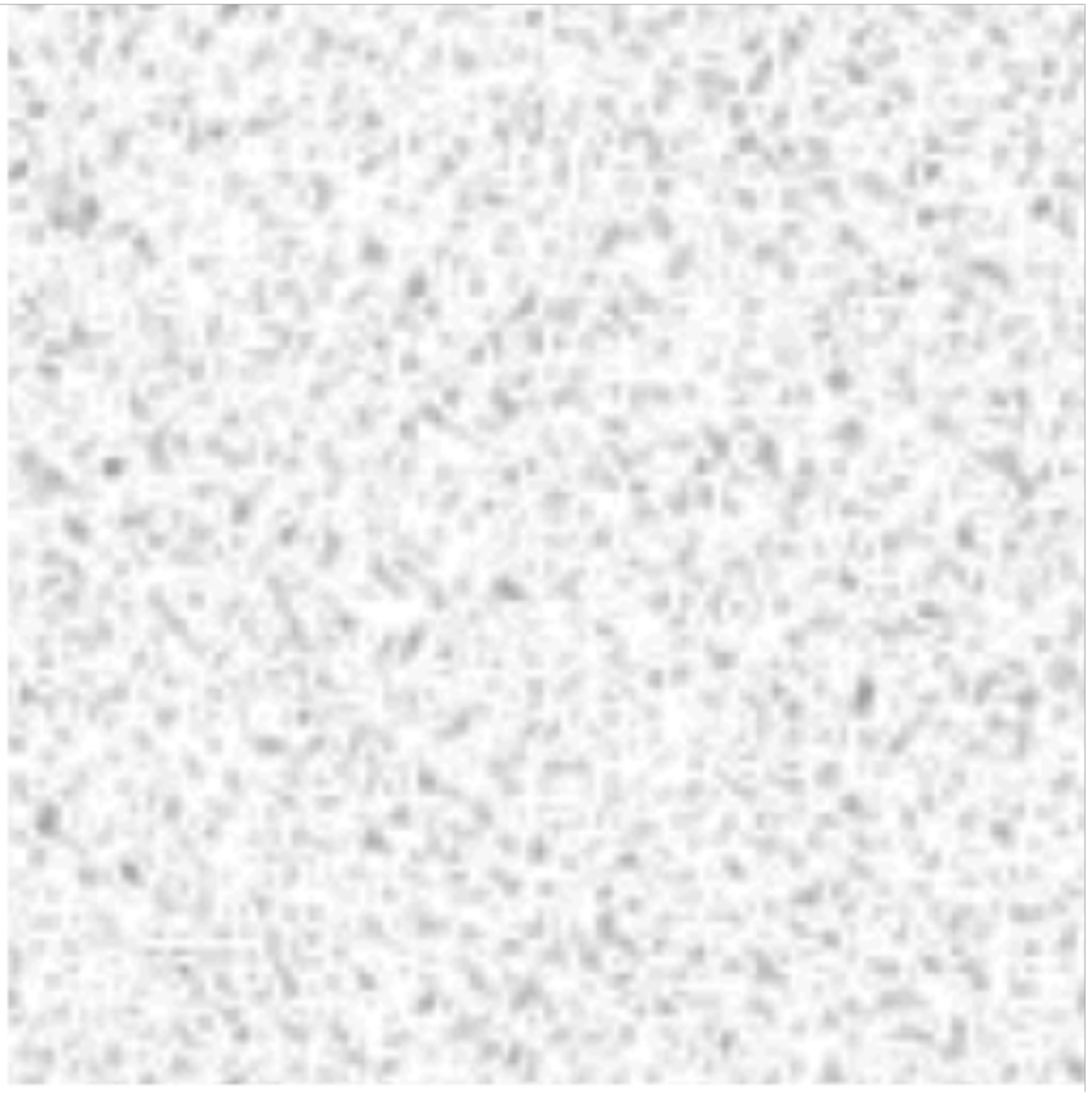


[Matthews et al.]

Structure and phases

$$P_{\gamma a}(\eta_a) = \frac{g_{a\gamma}^2}{4} |\tilde{B}_i(\eta_a)|^2$$

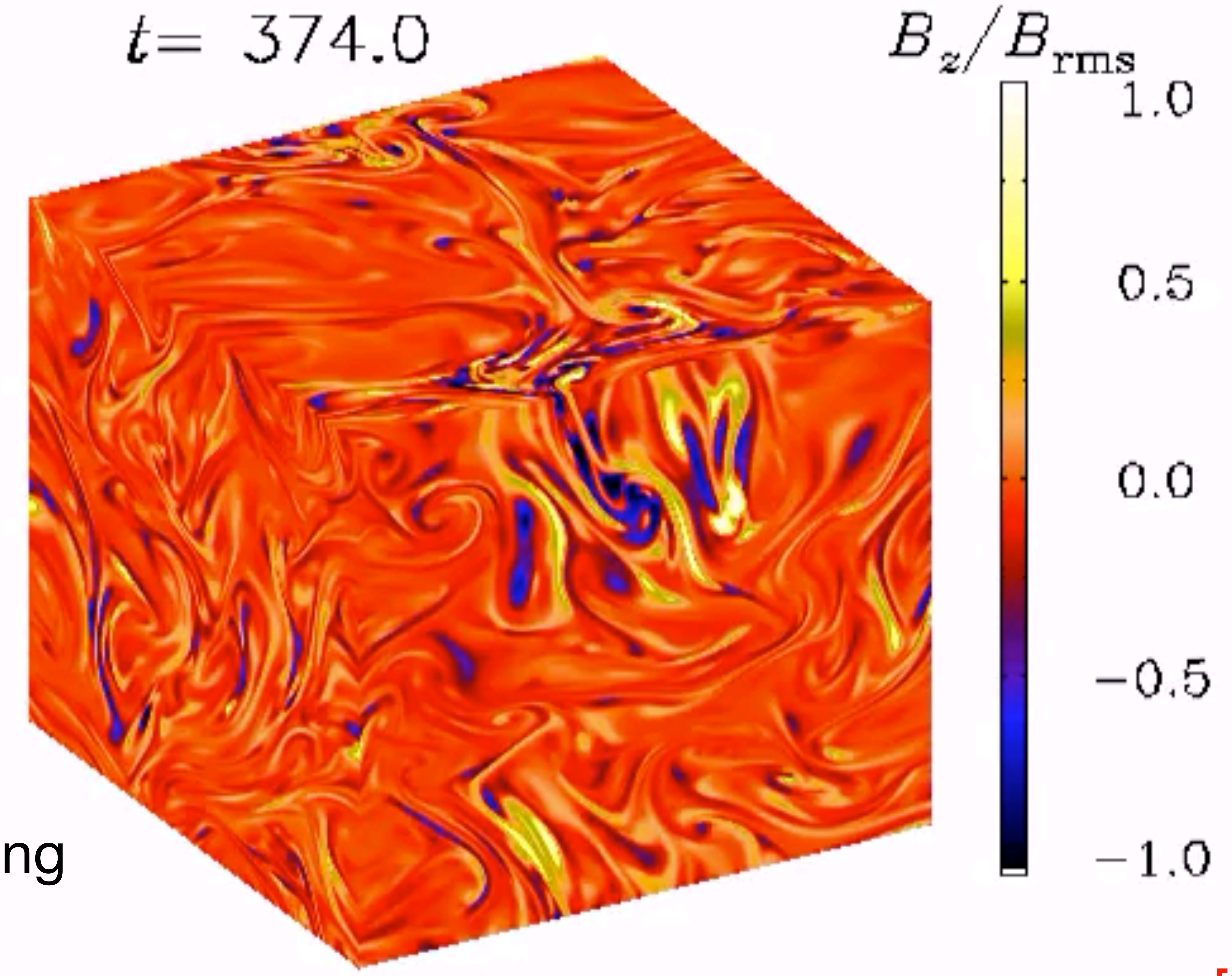




[Maron, Goldreich]

Is ALP-photon conversion independent of MHD structure?

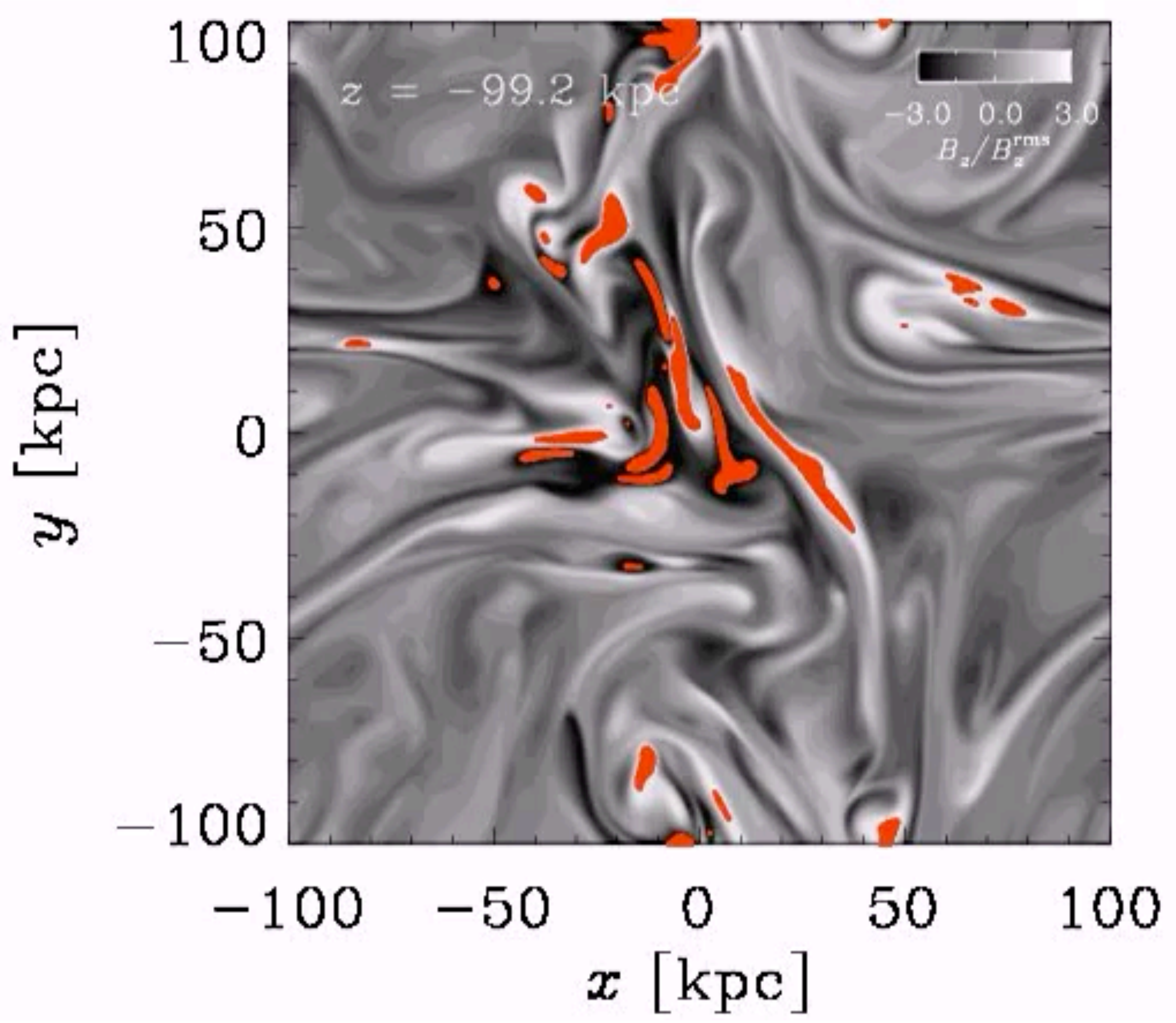
Dedicated MHD simulations: time-evolution



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

[Carenza et al.]

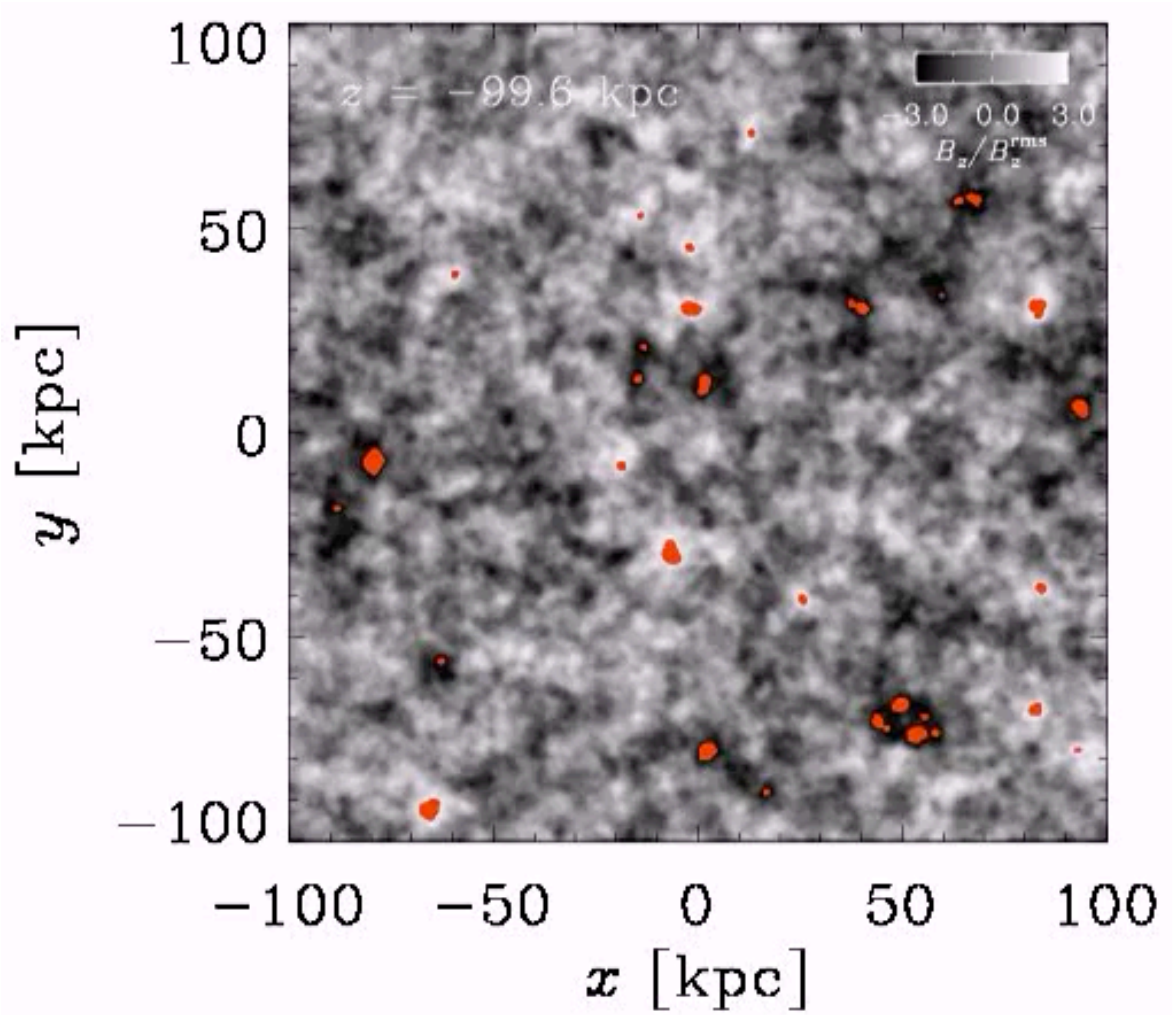
MHD magnetic field: cross-sections



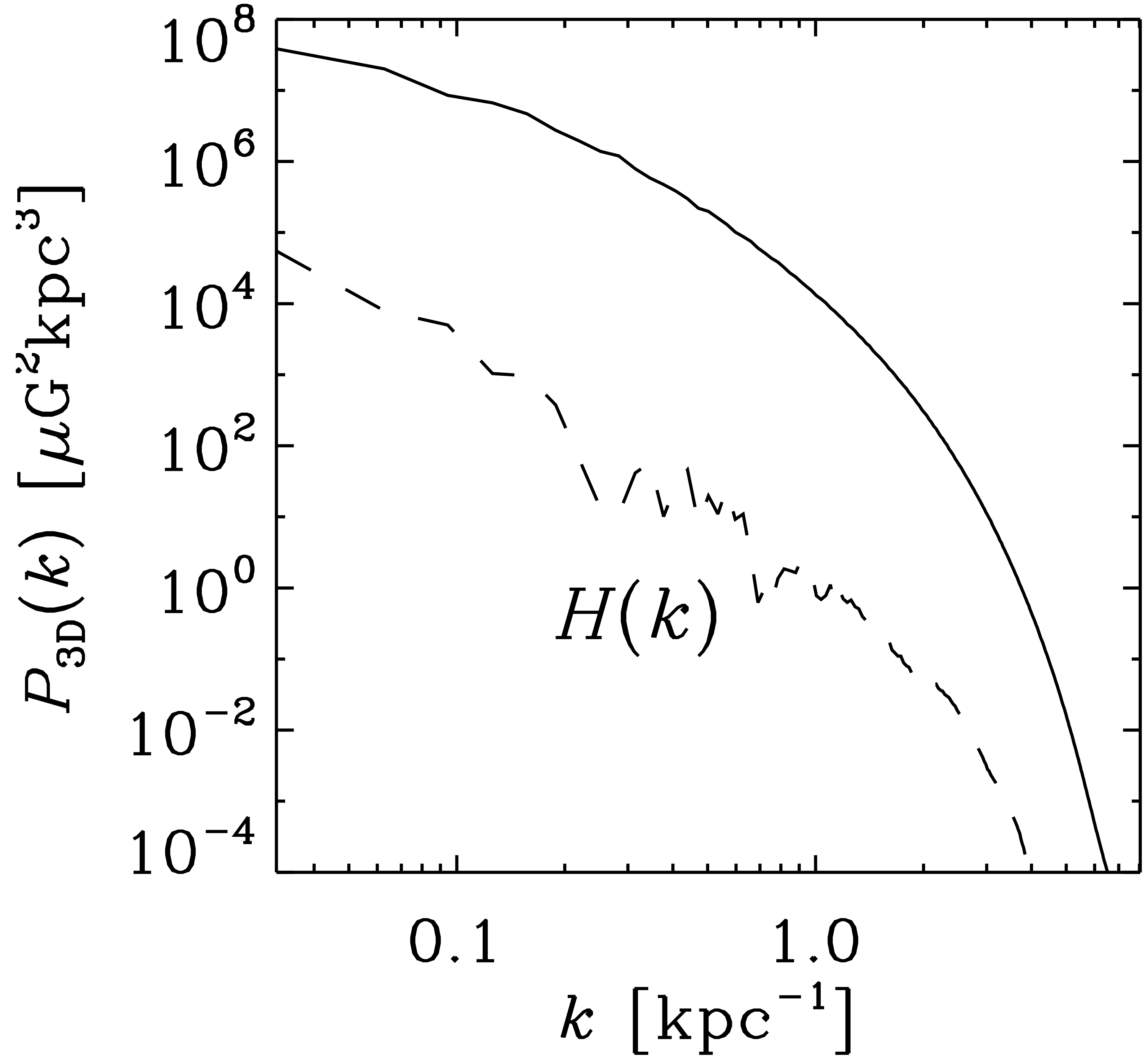
Red: $|\mathbf{B}| > 3B_{\rm rms}$

Want: statistical properties from ensemble of trajectories

GRF magnetic field: cross-sections



$$P_{3D}^{(GRF)} \equiv P_{3D}^{(MHD)}$$



Analytic GRF predictions

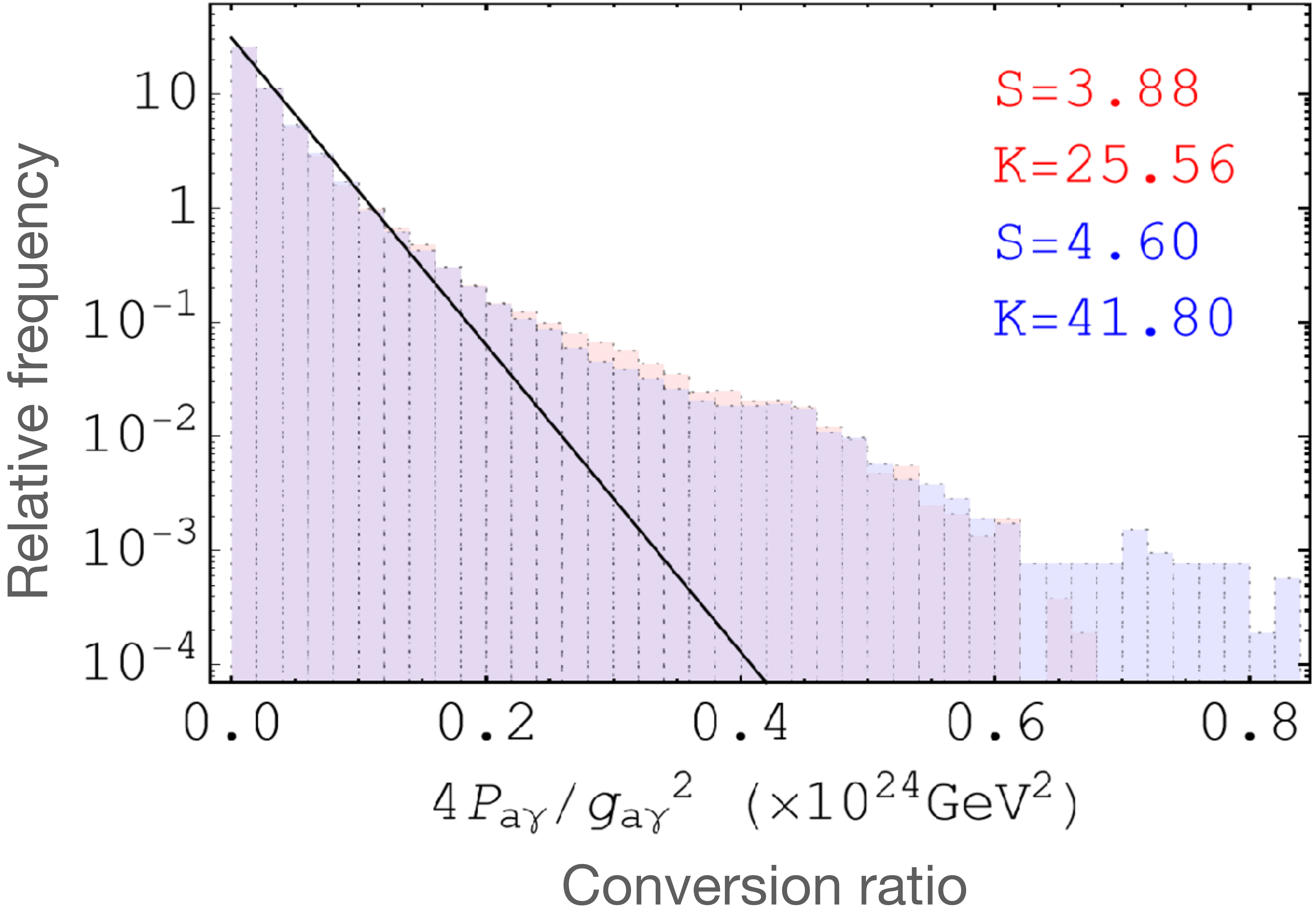
$$\langle \widehat{B}_a(\mathbf{k})\widehat{B}_b^*(\mathbf{k}')\rangle = \delta^3(\mathbf{k}-\mathbf{k}')\left[\frac{P_{3\mathrm{D}}(k)}{2}\left(\delta_{ab}-\frac{k_a k_b}{k^2}\right) - i\epsilon_{abc}\frac{k_c}{k}H(k)\right] ,$$

$$P_{1\mathrm{D}}(\eta_a) = \int \frac{dk_\perp k_\perp}{2(2\pi)^3} P_{3\mathrm{D}}\left(\sqrt{\eta_a^2+k_\perp^2}\right)\left(1-\frac{1}{2}\frac{k_\perp^2}{\eta_a^2+k_\perp^2}\right)$$

Probability distribution of conversion ratios:

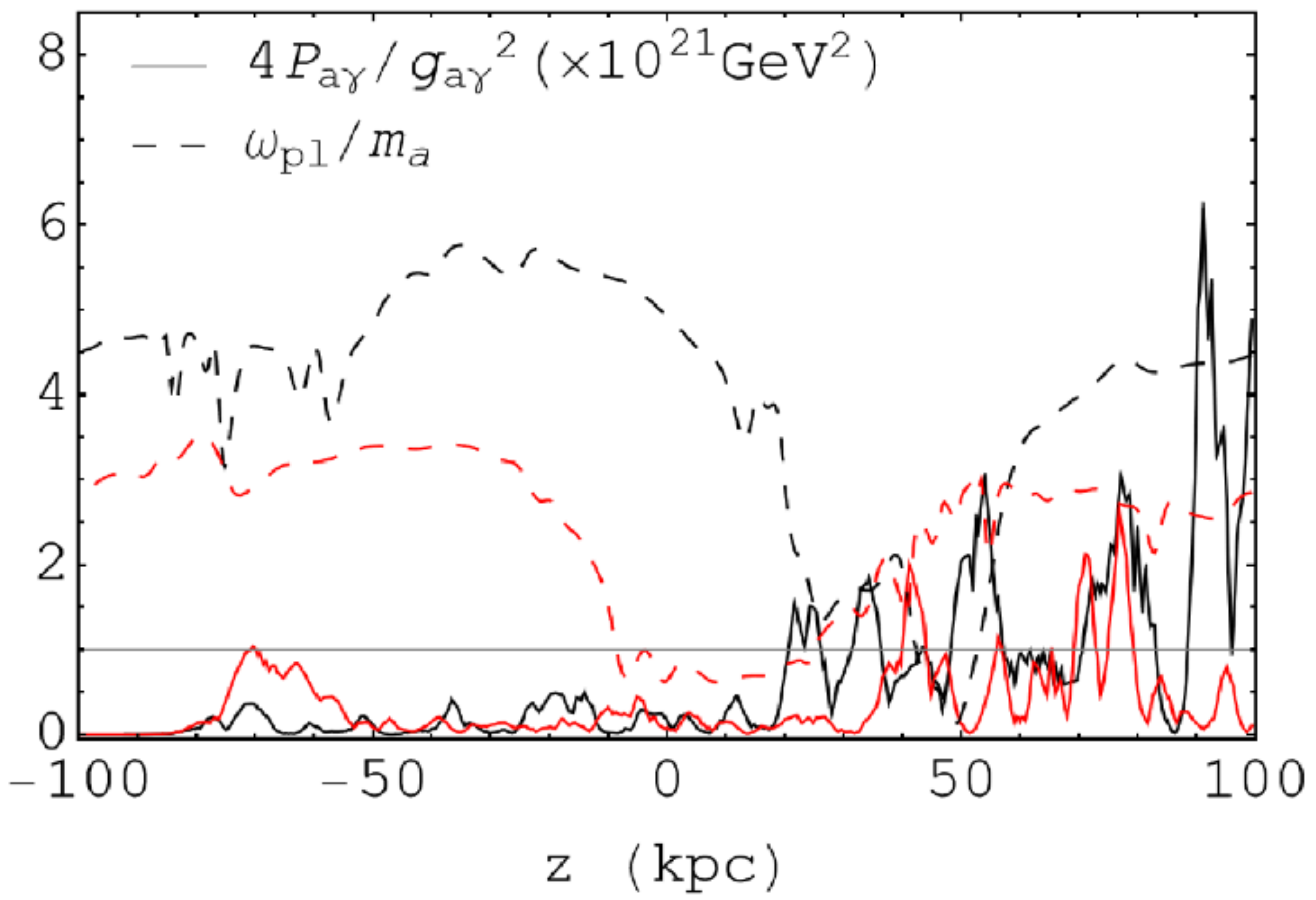
$$f_{P_{a\gamma}(\eta_a)}(p) = \frac{e^{-p/p_0}}{p_0} \qquad p_0 = \frac{g_{a\gamma}^2}{4}\frac{L}{2\pi}P_{1\mathrm{D}}(\eta_a)$$

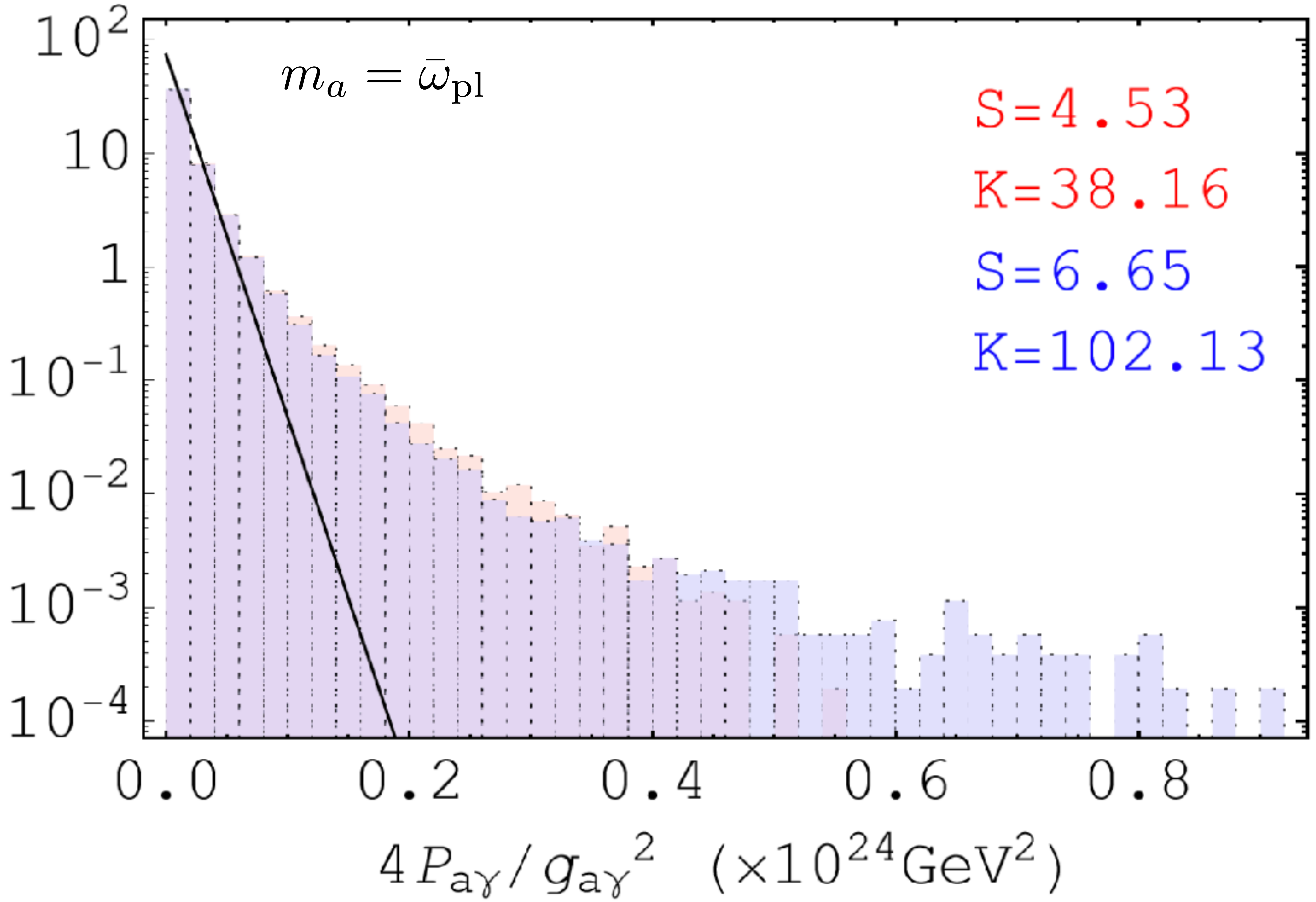
Heavy-tailed MHD distributions



GRF:
S = 2,
K = 9.

Holds for arbitrary masses, polarisations





Non-Gaussianity

Structure does not directly affect conversion ratios, but non-Gaussianity does.

Expectation value of conversion ratio depends only on power spectrum of B:

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

Same for MHD and GRF

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

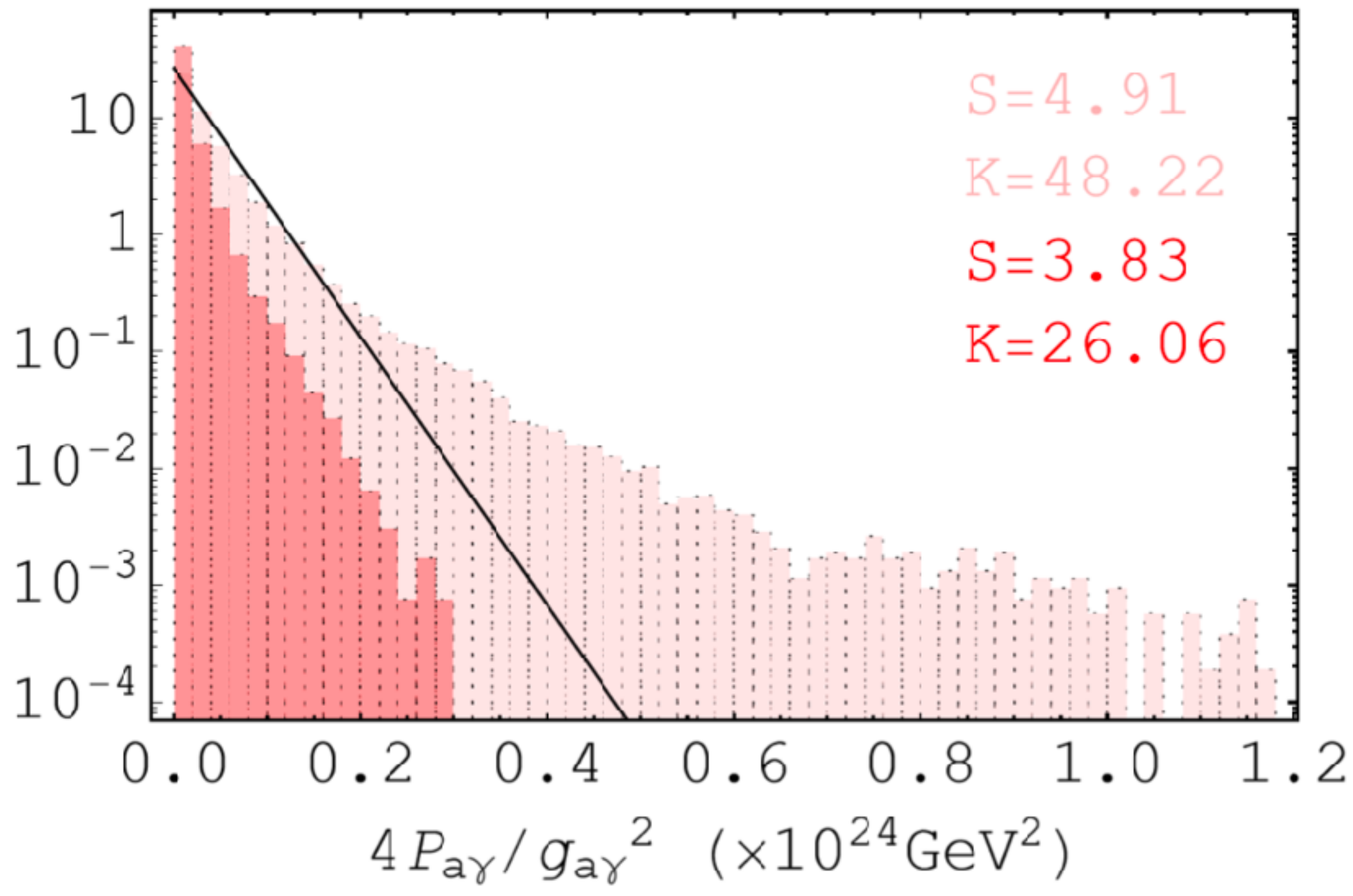
$$\langle P_{\gamma a}(\eta_a)^2\rangle\,,\quad \langle P_{\gamma a}(\eta_a)^3\rangle\,,\quad \langle P_{\gamma a}(\eta_a)^4\rangle \quad \text{etc.}$$

Different for MHD and GRF

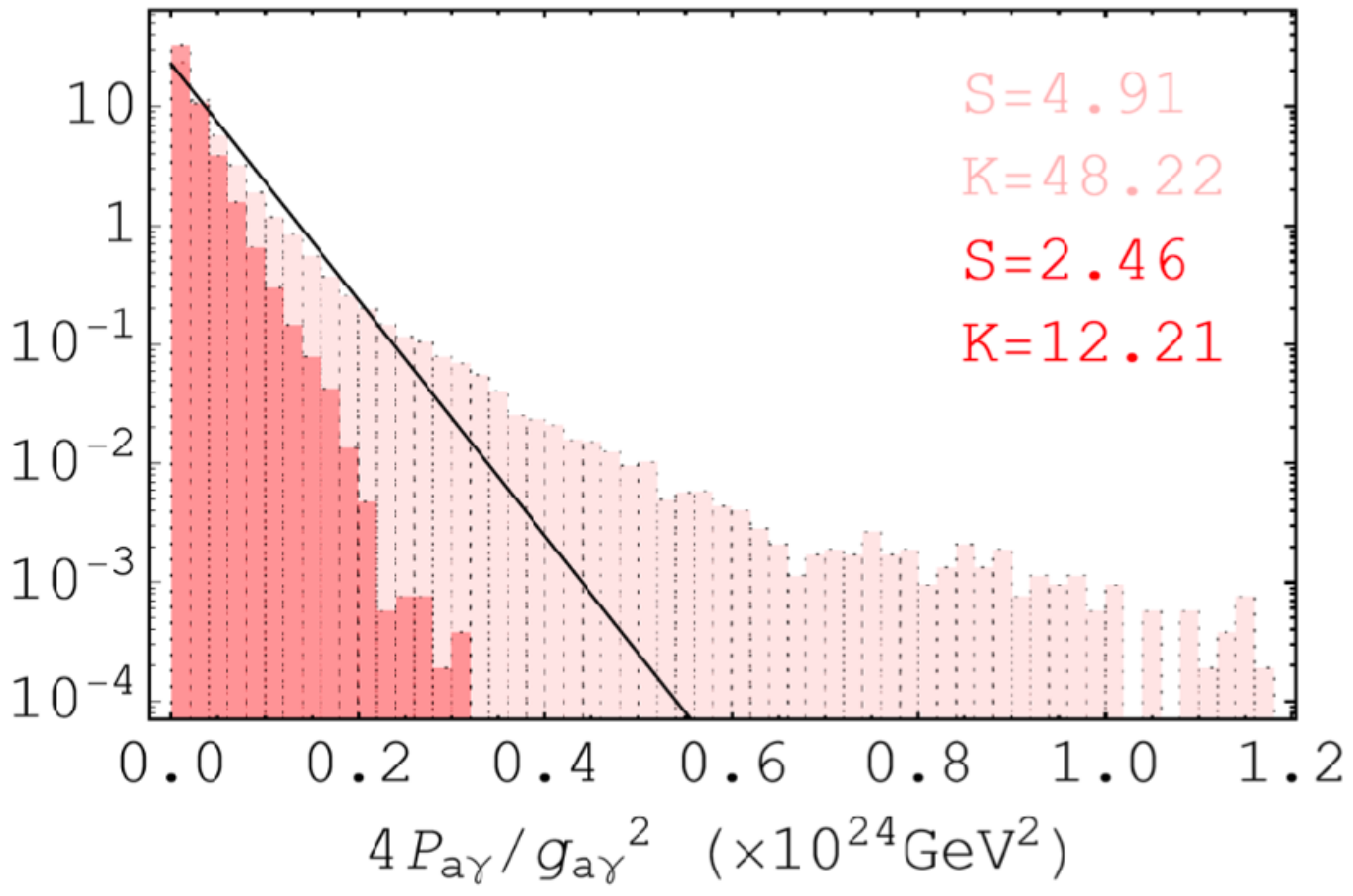
Non-Gaussianity

Two possible sources:

Mask large coherence lengths



Mask high peaks



Conclusions

MHD and GRF predictions agree for typical fluctuations.

MHD predicts heavy tails: larger probability of large conversion ratios.

Suggests existing limits conservative.

Future directions

Use full cluster MHD simulations with existing data.

Getting ready for the next-generation of X-ray satellites, e.g. *Athena*.