PROBING
AXION-LIKE PARTICLES
WITH
X-RAY ASTRONOMY

M.C. DAVID MARSH
STOCKHOLM UNIVERSITY

MITP VIRTUAL WORKSHOP "SHOOT FOR THE STARS, AIM FOR THE AXIONS" 7/11, 2022

Main collaborators

Stockholm


Pierluca Carenza


Ramkishor Sharma


Axel Brandenburg


Eike Müller

Cambridge


James Matthews


Julia Sisk-Reynes


Christopher Reynolds


Helen Russell

Motivation

The Standard Model (SM) of particle physics is incomplete.

Axions are among our best guesses for what can lie beyond the SM.

Astrophysics can be extremely sensitive to axions:
we already reach into well-motivated territory where axions may live.

It’s conceivable that we will see mounting evidence for ALPs from astrophysics:
may provide clear experimental target.

Outline

1. What I didn't know that I didn't know about axion-photon conversion

2. Where we are, and where we are going, with X-ray constraints on ALPs

Classical ALP-photon mixing
in a magnetised plasma

Classical field theory:

$$(\Box + m_a^2)a = -g_{a\gamma}\dot{\mathbf{A}} \cdot \mathbf{B}_0 \ ,$$

$$(\Box + \omega_{pl}^2)\mathbf{A} = g_{a\gamma}\dot{a}\,\mathbf{B}_0 \ ;$$

Schrödinger-like equation
for relativistic ALPs

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

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

[Raffelt, Stodolsky]

Perturbative formalism

Small amplitude oscillations motivate perturbative solutions.

In QM: $\mathcal{A}_{i\to f} = \frac{-i}{\hbar}\int_{-\infty}^{\infty} dt\,(H_I)_{if}\, e^{-i\omega_{if}t} = \frac{-i}{\hbar}\mathcal{F}\left[(H_I)_{if}\right]$

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

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

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

$$\eta_a = \frac{1}{12.8\,\text{kpc}}\left(\frac{m_a}{10^{-12}\,\text{eV}}\right)^2\left(\frac{\text{keV}}{\omega}\right)$$

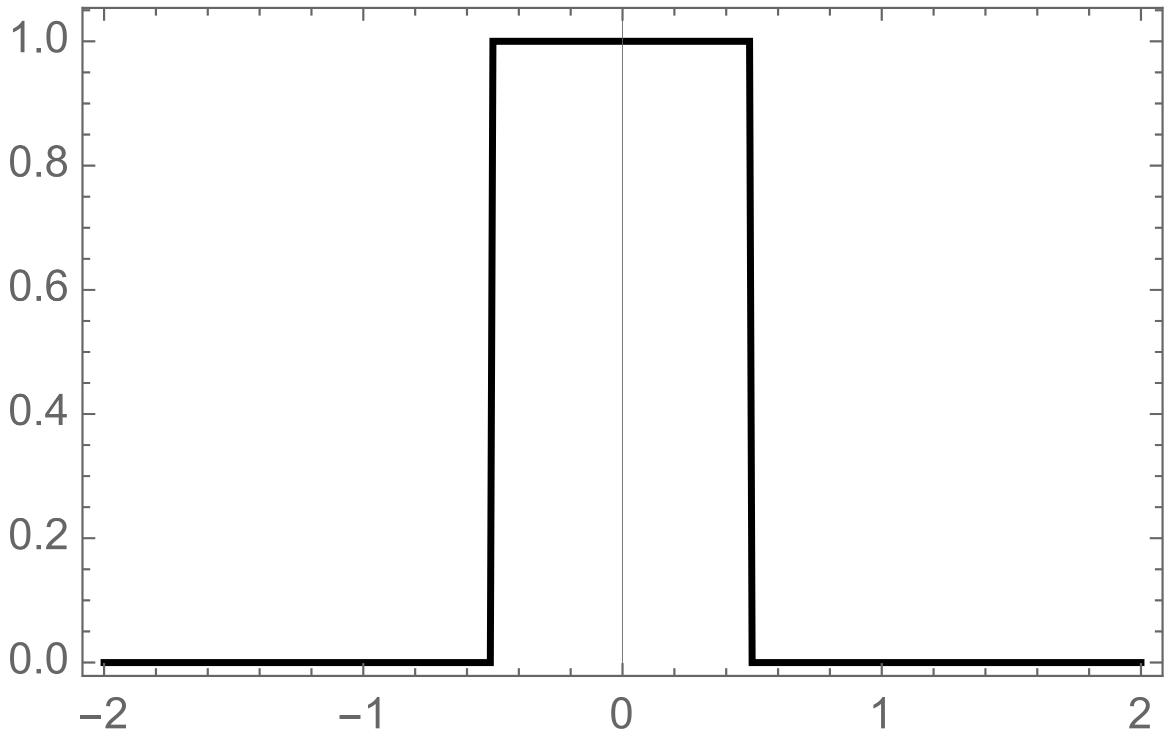
$$\tilde{B}_i(\eta_a) = \int_{-L/2}^{L/2} dz\, B_i(z\hat{z})e^{-iz\eta_a}$$

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

Simplest example

Magnetic field

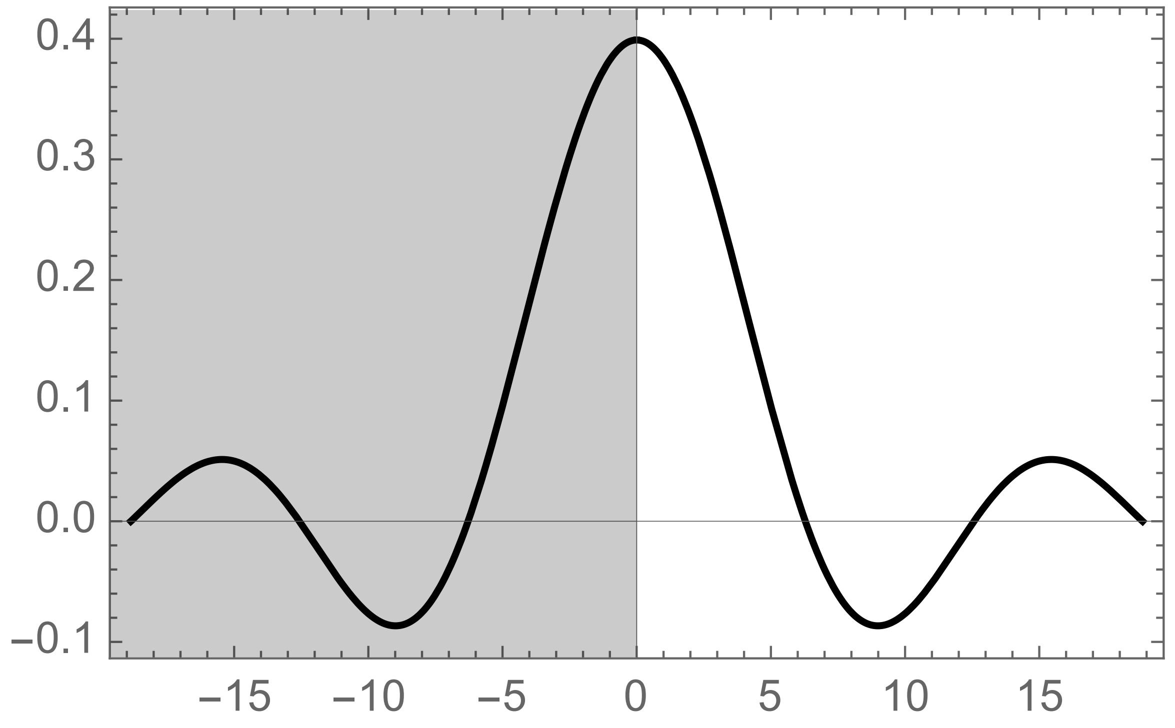
B/B_0



z/R

$\xrightarrow{\mathcal{F}}$

Amplitude



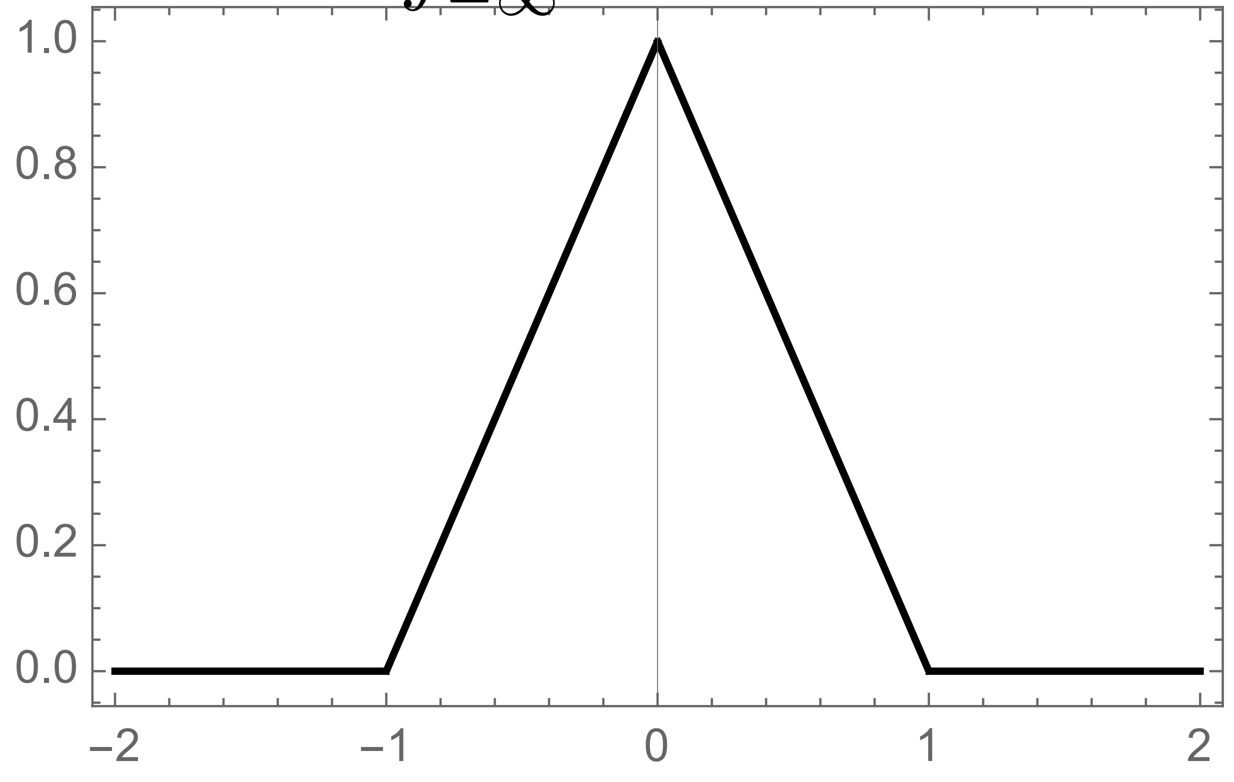
$\eta = m_a^2/(2\omega)$

$\downarrow c_B$

$\downarrow |\mathcal{A}|^2$

Autocorrelation

$$c_B(L) = \int_{-\infty}^{\infty} dz\, B(z) B(z+L)$$

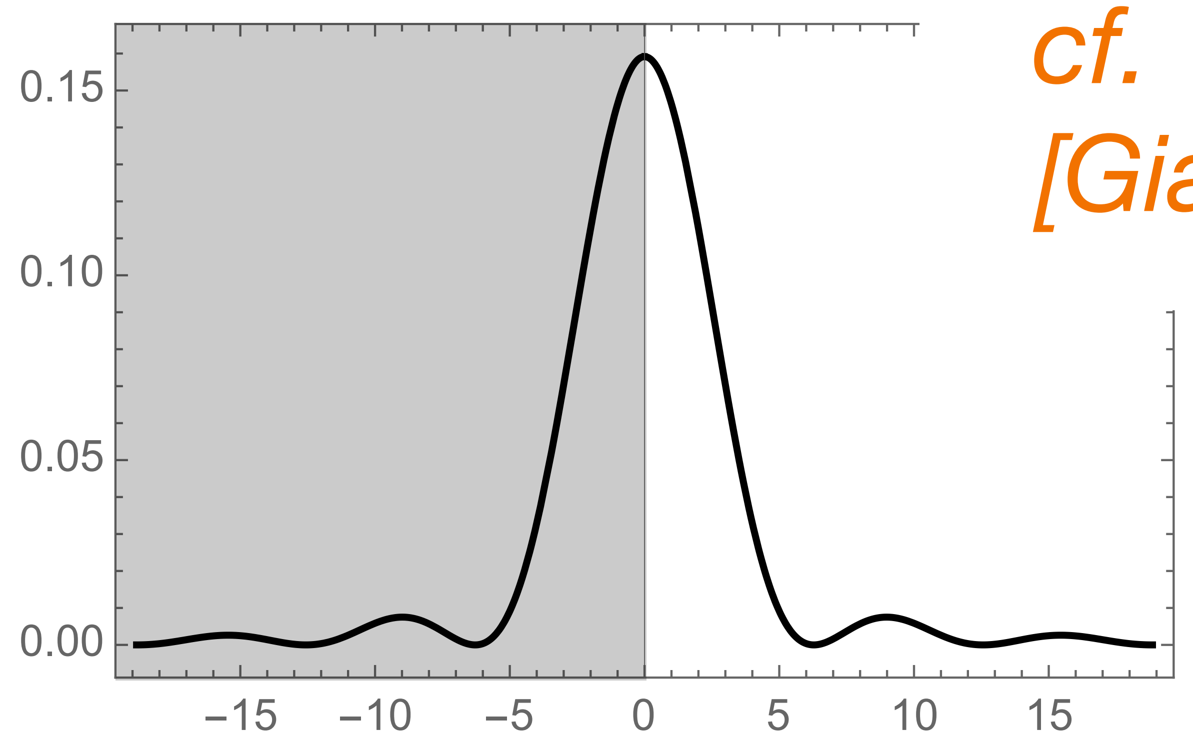


L/R

$\xrightarrow{\mathcal{F}}$

Probability

$P_{\gamma_x \to a}$



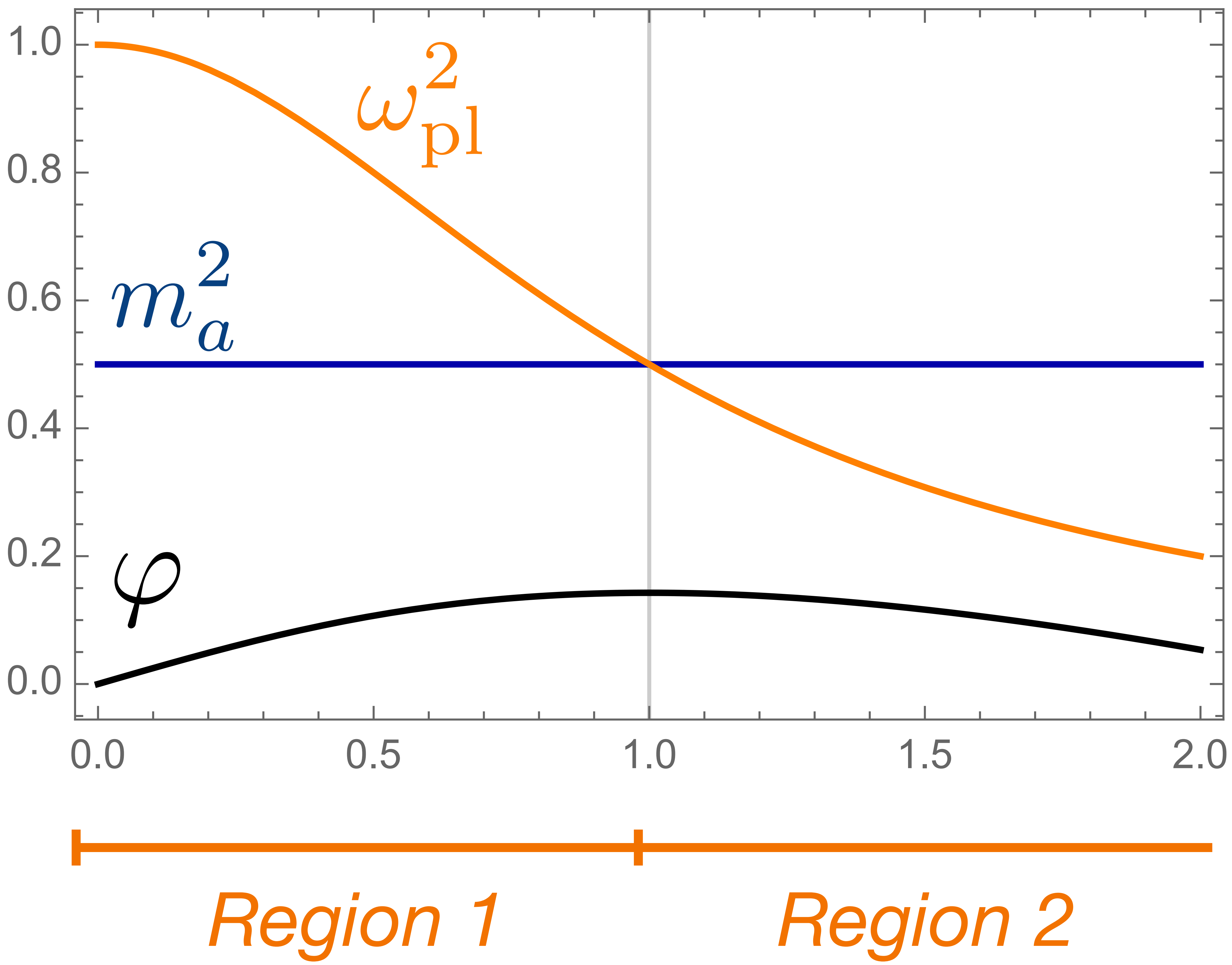
$\eta = m_a^2/(2\omega)$

cf. 'coherence' [Gianotti's talk]

[*DM* et al.]

The general case for $m_a/\omega_{\rm pl}(z)$

$$\mathcal{A}_{\gamma_i\to a} \sim \int dz\, B_i(z)\, e^{i\frac{1}{\omega}\varphi(z)} \qquad \varphi(z) = \frac{1}{2}\int^z dz'\left[\omega_{\rm pl}^2(z') - m_a^2\right]$$



Coordinate change $z \to \varphi$
is well-defined between resonance points

$$\mathcal{A}_{\gamma_i\to a} \sim \mathcal{F}\left[\frac{B_i(\varphi)}{\omega_{\rm pl}^2(\varphi) - m_a^2}\right]_{\rm Reg.\,1} + \mathcal{F}\left[\frac{B_i(\varphi)}{\omega_{\rm pl}^2(\varphi) - m_a^2}\right]_{\rm Reg.\,2}$$

Captures both resonant and non-resonant contribution.

[*DM* et al.]

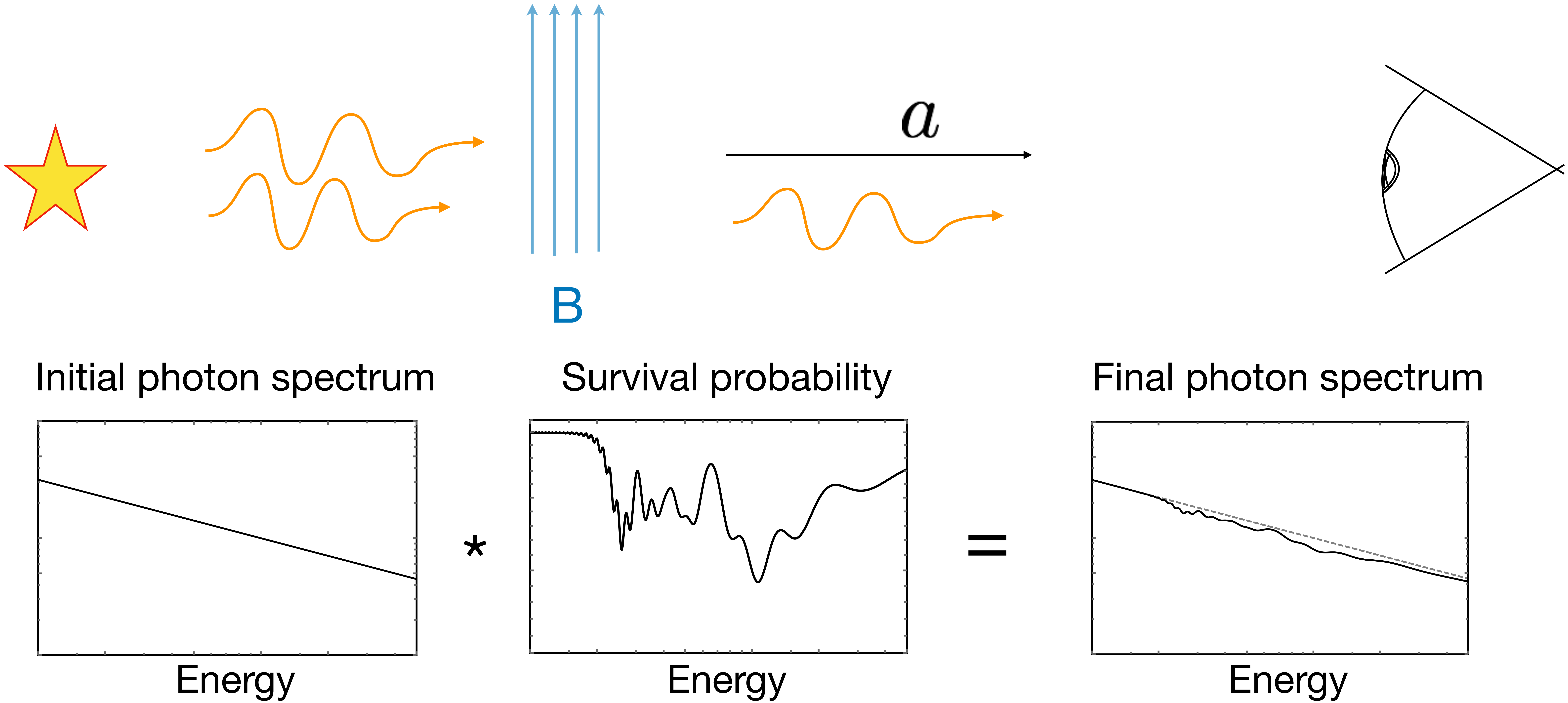
Useful?

Yes!

Conceptually: what really matters for axion-photon conversion

Computationally: the first F in FFT stands for fast

The photon disappearance channel



[Sikivie],
[Raffelt, Stodolsky]

Galaxy clusters are ideal axion-photon converters

Luminous sources (AGNs, quasars).

Largest gravitational bound objects (~Mpc).

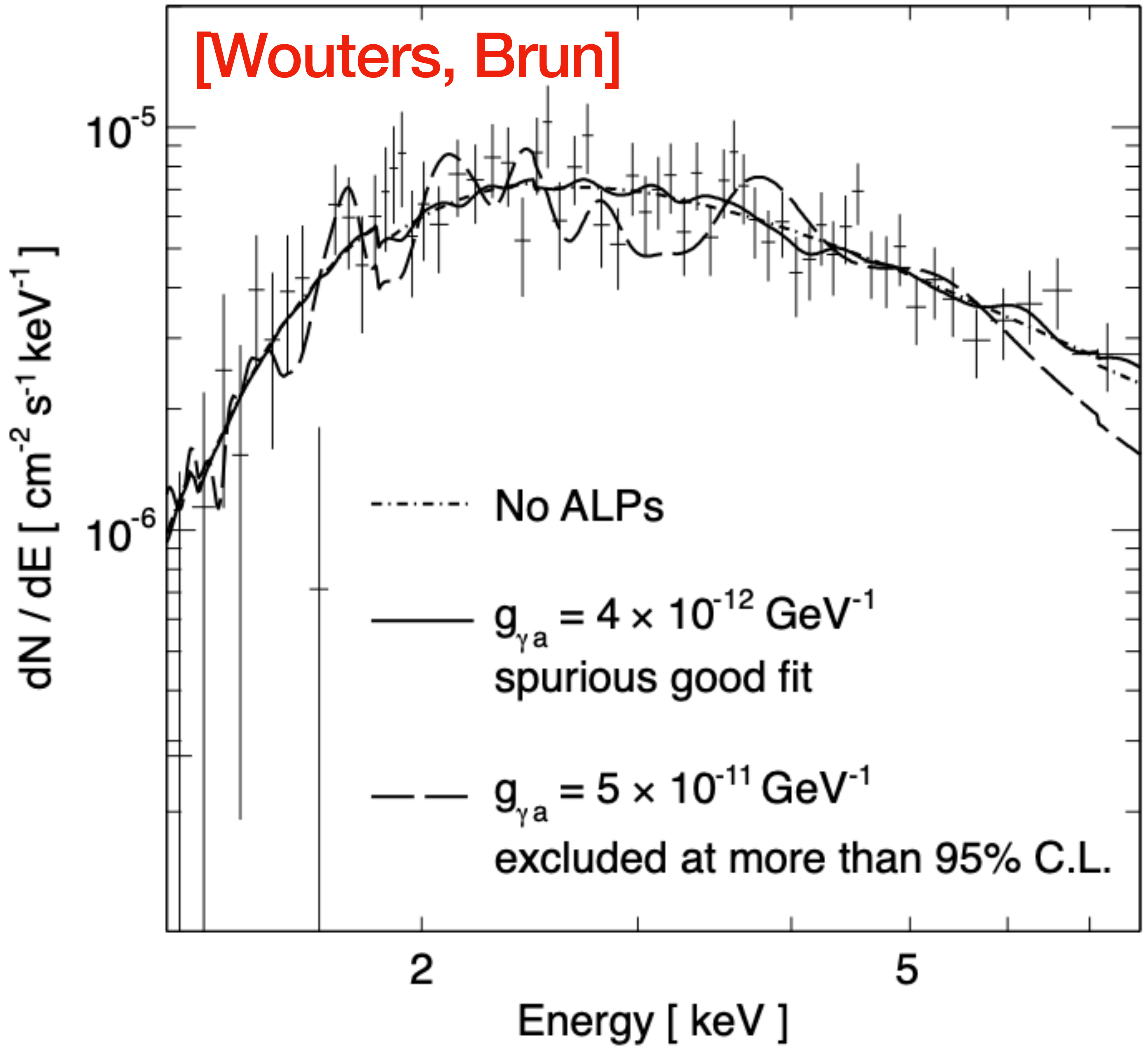
Magnetised (μG).

Long coherence lengths (~kpc).

Unsuppressed *conversion ratios*:

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

X-ray searches for ALPs



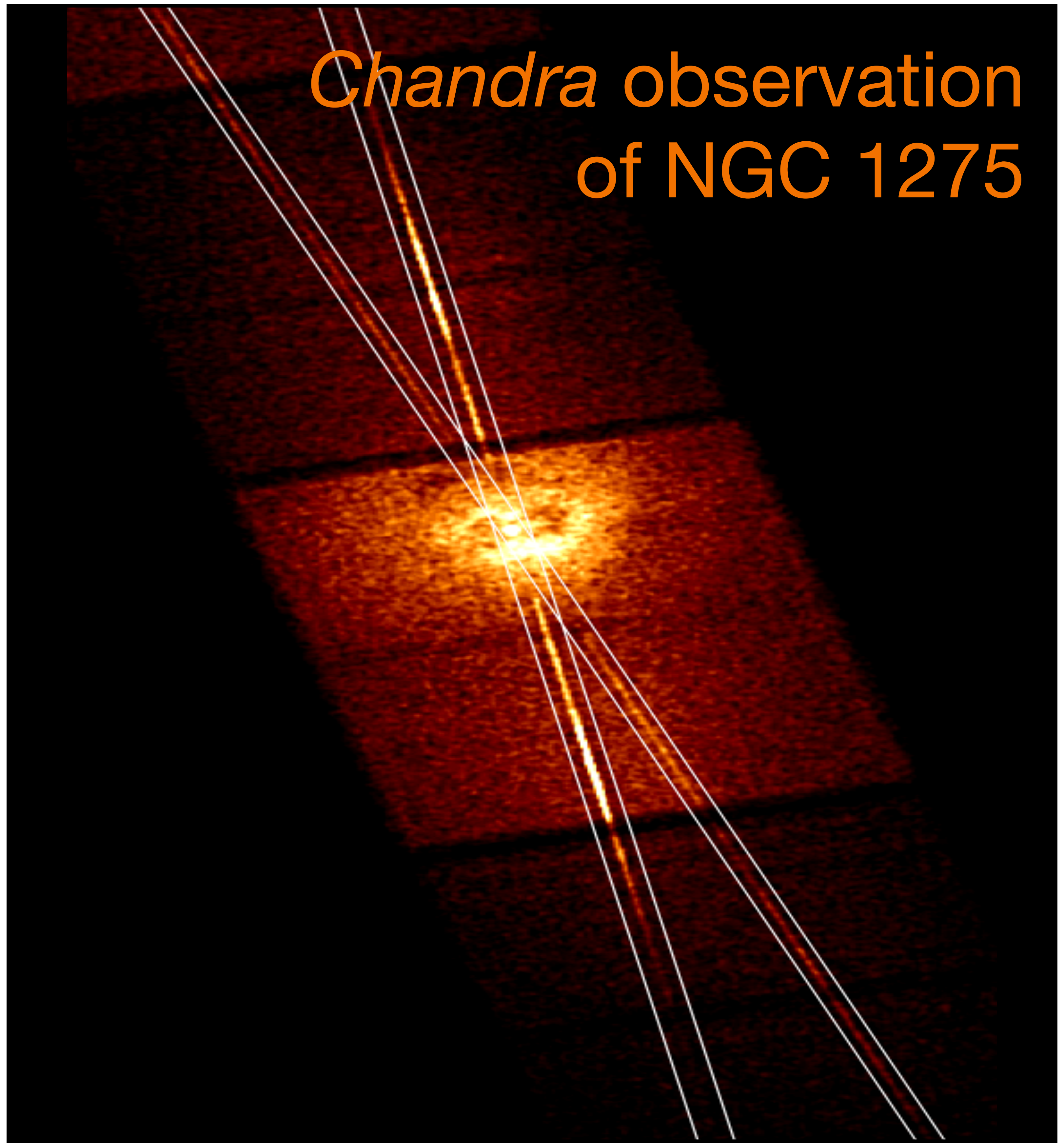
Improvements over past decade:

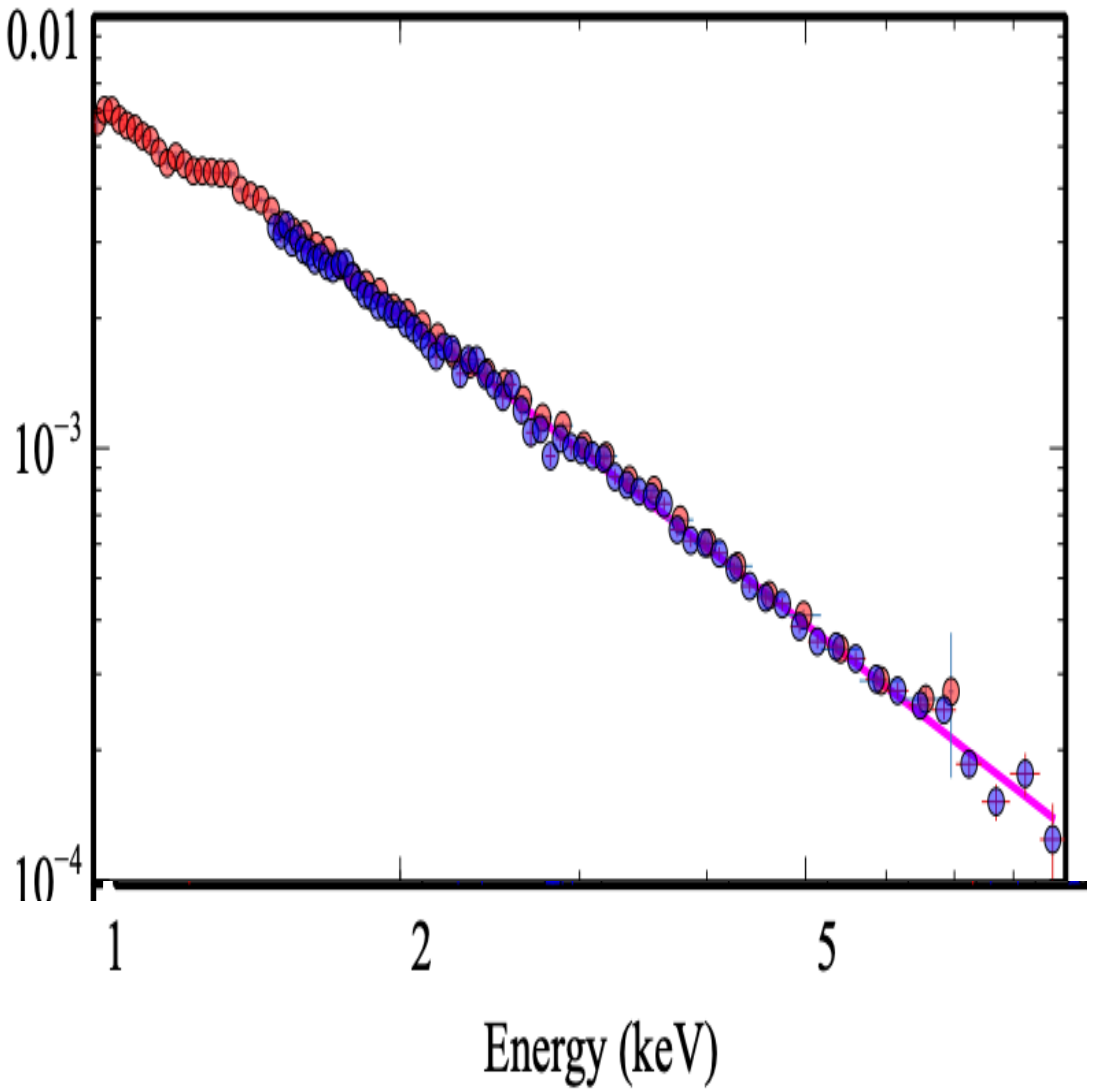
1. Better data
2. More sources (analysed by several groups)
3. Better stat. methods
4. Better magnetic field models
5. ML techniques explored

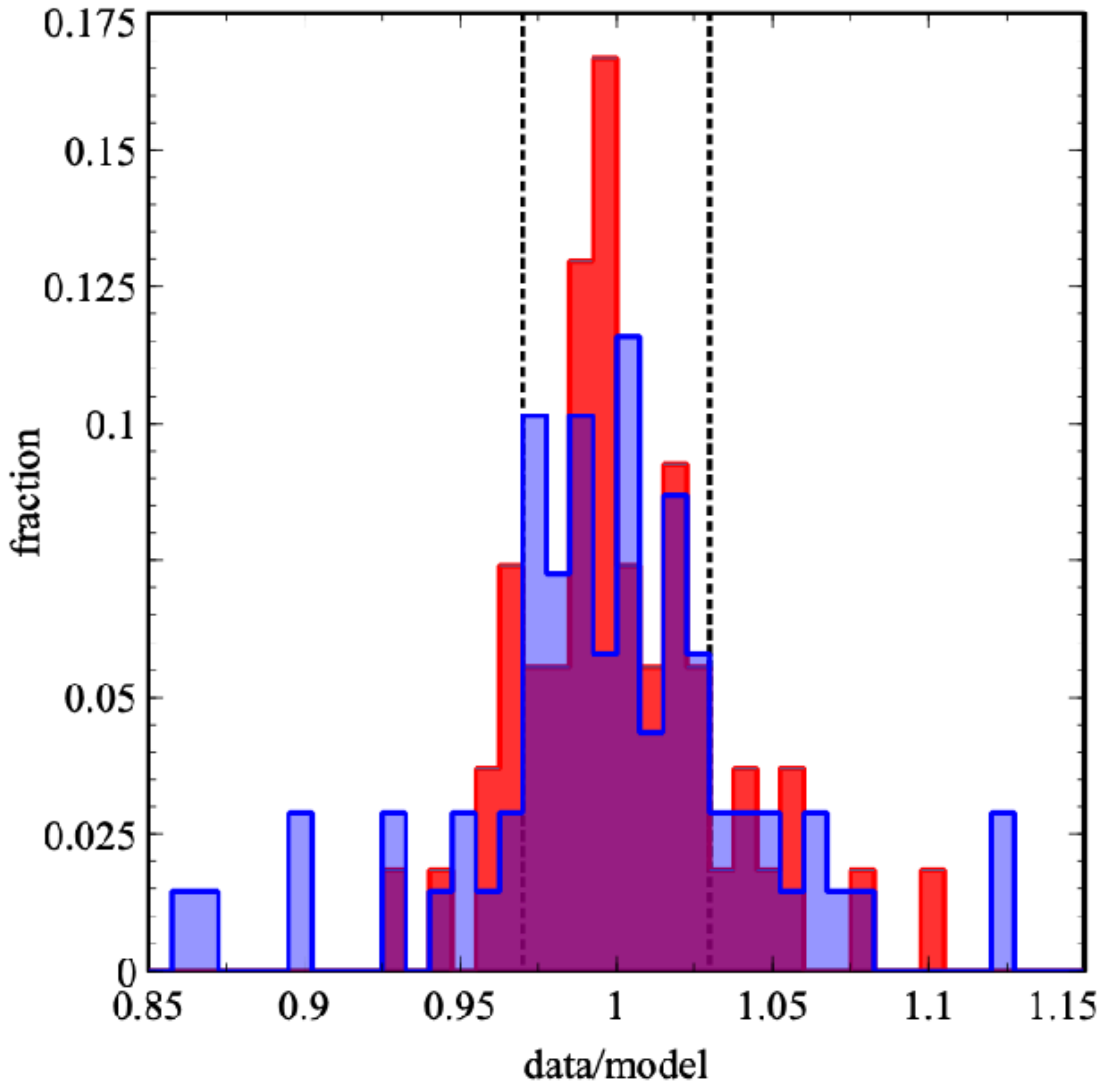
[Wouters, Brun], [Conlon et al.], [Berg et al.], [*DM* et al.], [Reynolds et al.], [Chen, Conlon], [Day, Krippendorf], [Sisk Reynes et al.], [Matthews et al.], [Schallmoser et al.]

Precision spectra

Diffraction grating spectroscopy using *Chandra*



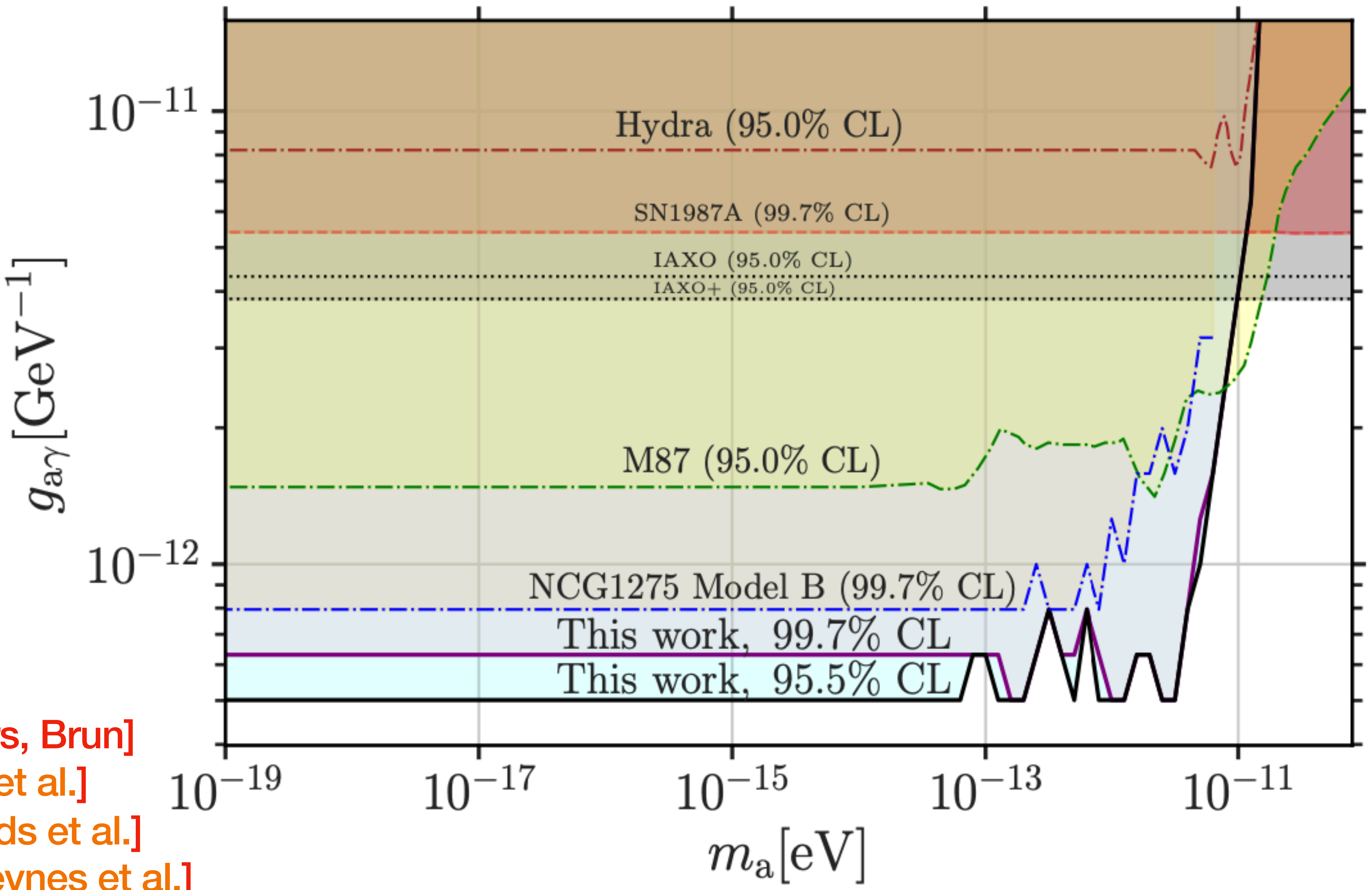




[Reynolds, *DM*, et al.]
[Sisk-Reynes et al.]

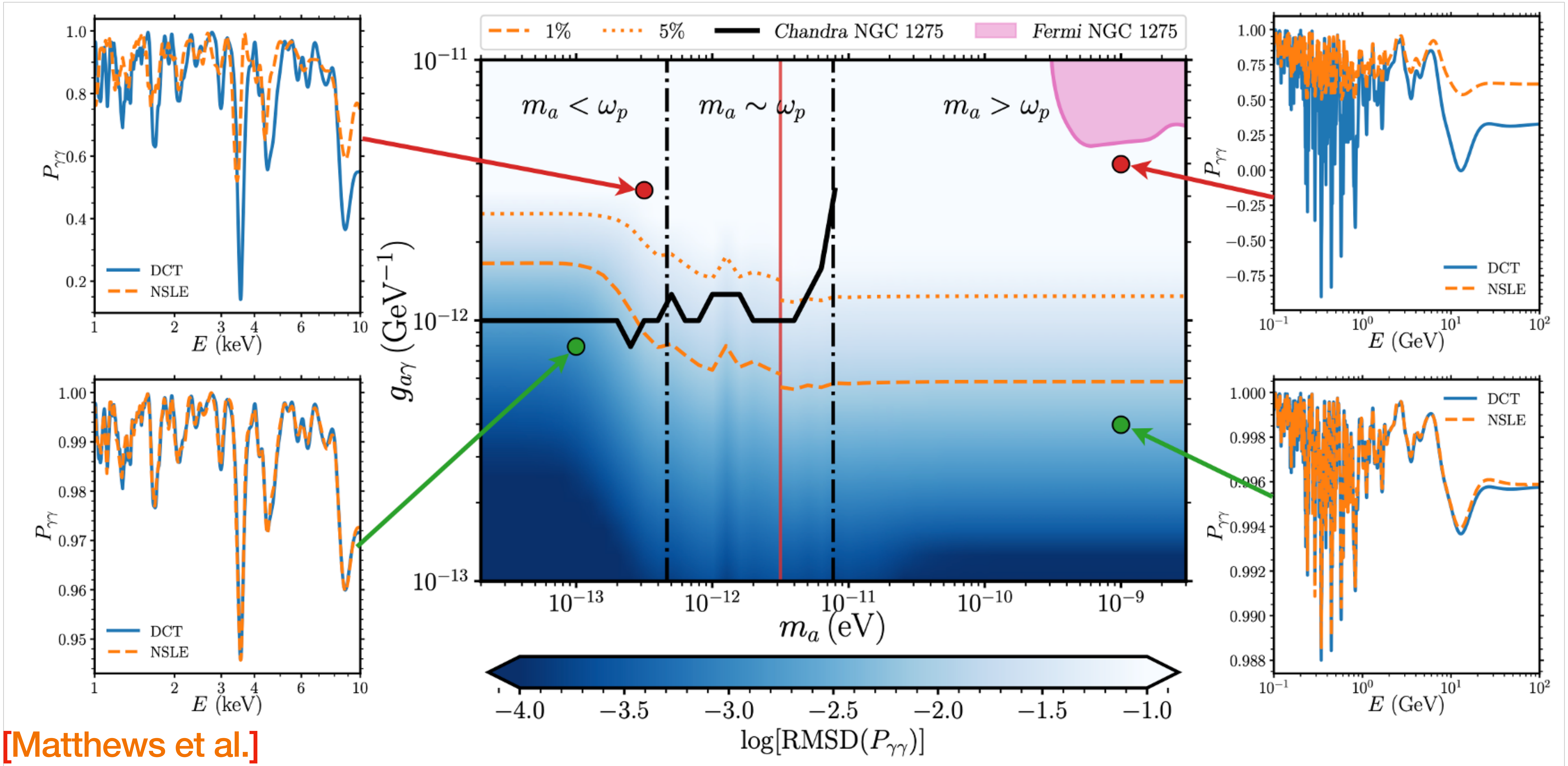
Amplitude of hypothetical oscillations must be ≲5% (cf. quasar H-1821: ≲2.5%).

Strongest limits by an order of magnitude



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

Perturbative formalism: applicability

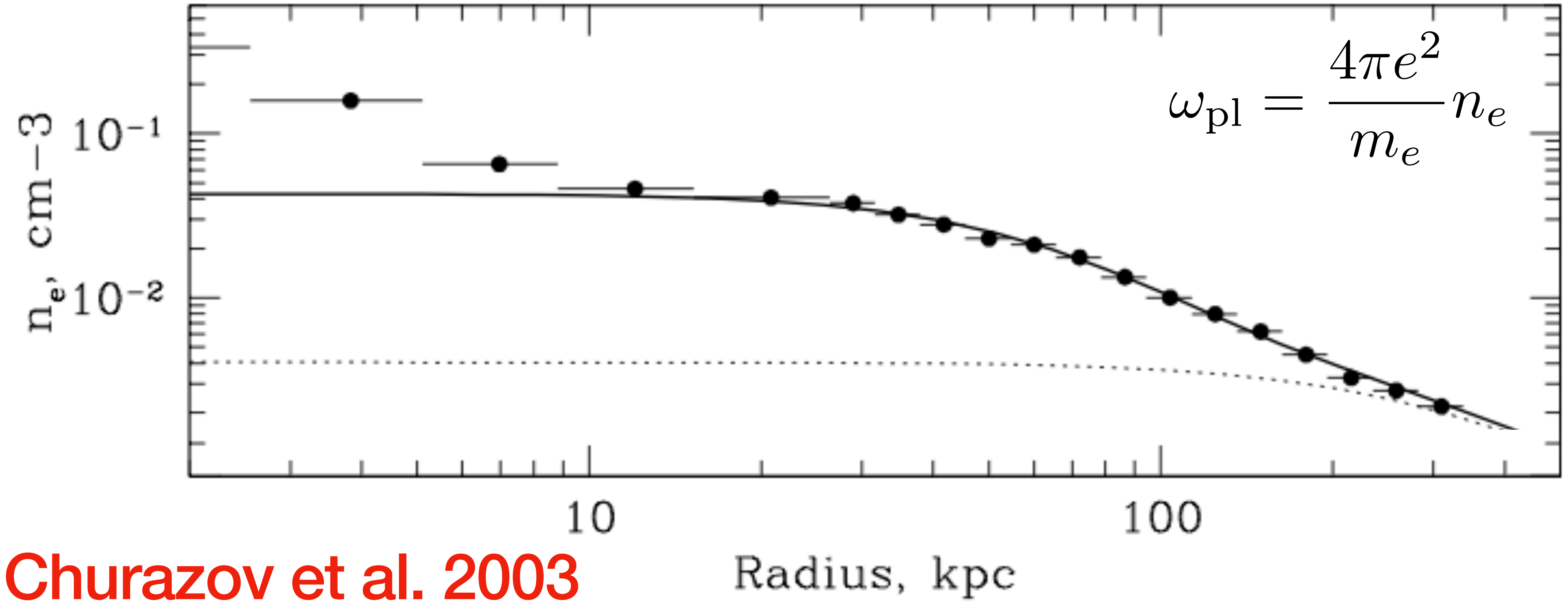


[Matthews et al.]

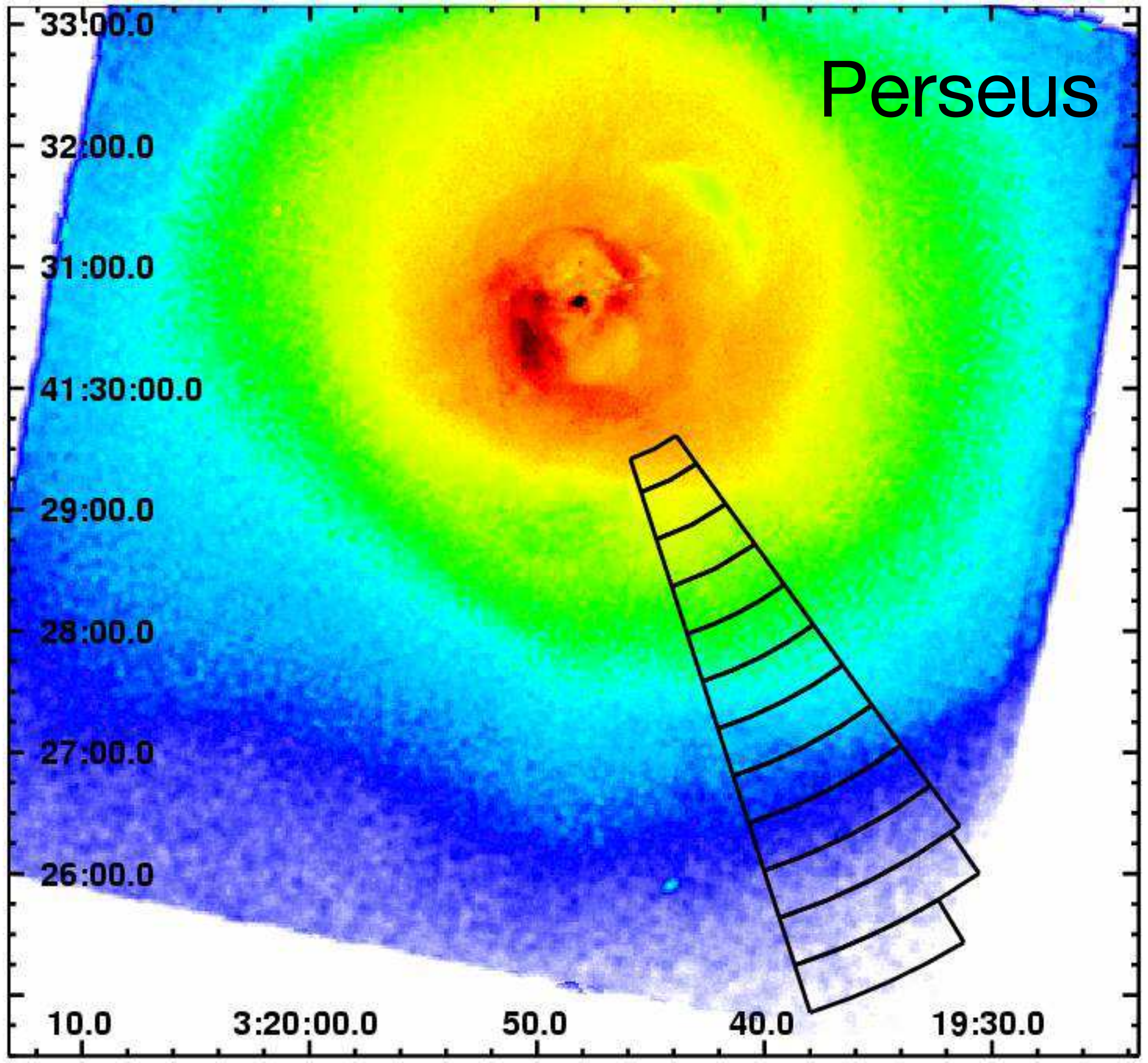
Plasma density of the intracluster medium (ICM)

The ICM is turbulent: Kolmogorov-like spectrum of fluctuations, moderate-to-high Reynolds number

Status: ALP searches so far only used smooth analytic model from de-projection.



Churazov et al. 2003



Sanders et al. 2005

Cluster magnetic fields

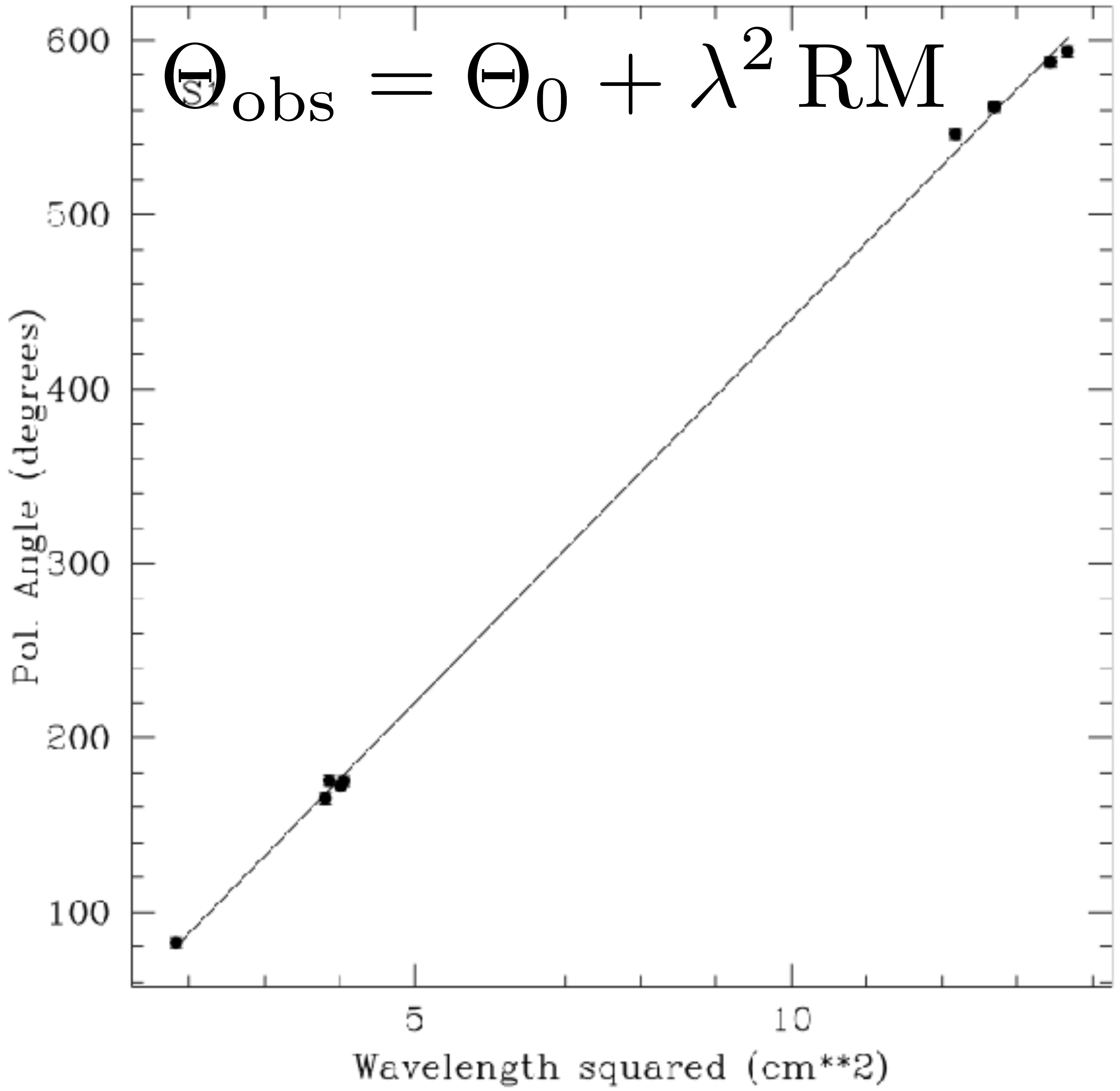
Coherence lengths: kpc

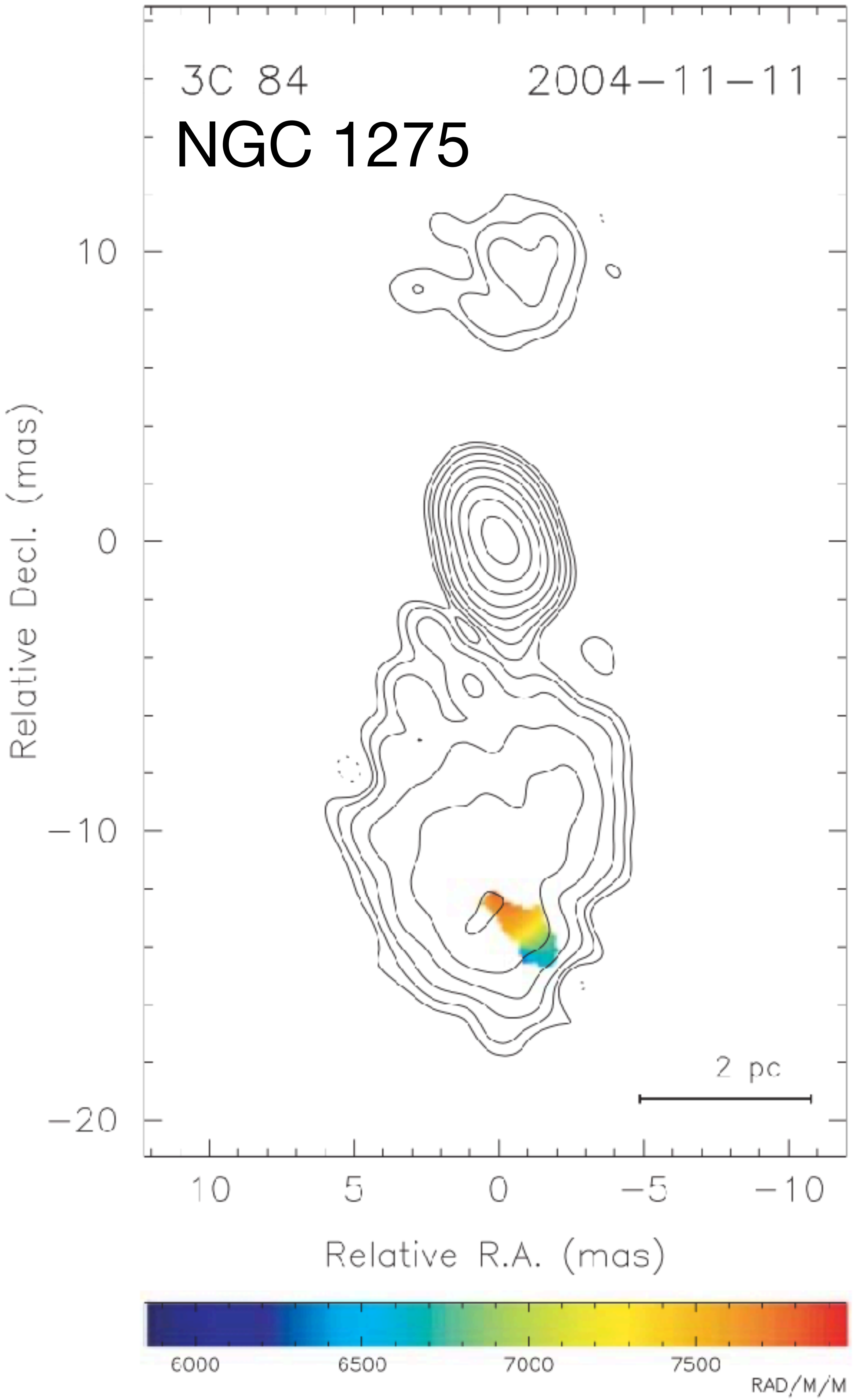
Field strengths: 1-25 μG at centre

Full magnetic field not knowable — must marginalise over.
Construct models consistent with Faraday RMs.

Rotation measures

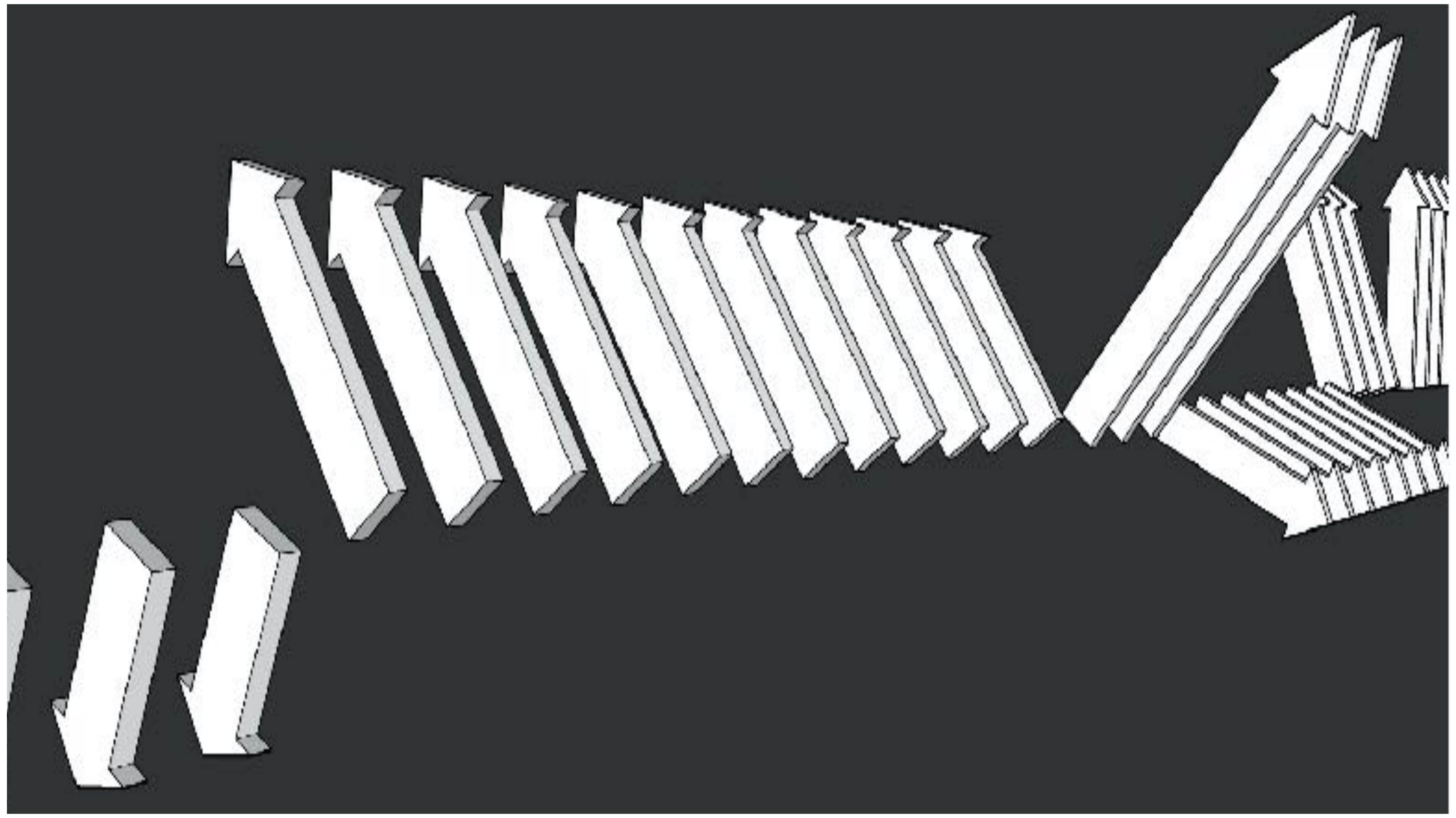
$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2} \int_{\mathrm{l.o.s.}} n_e B_{||} \, d\ell$$





Taylor et al. 2006

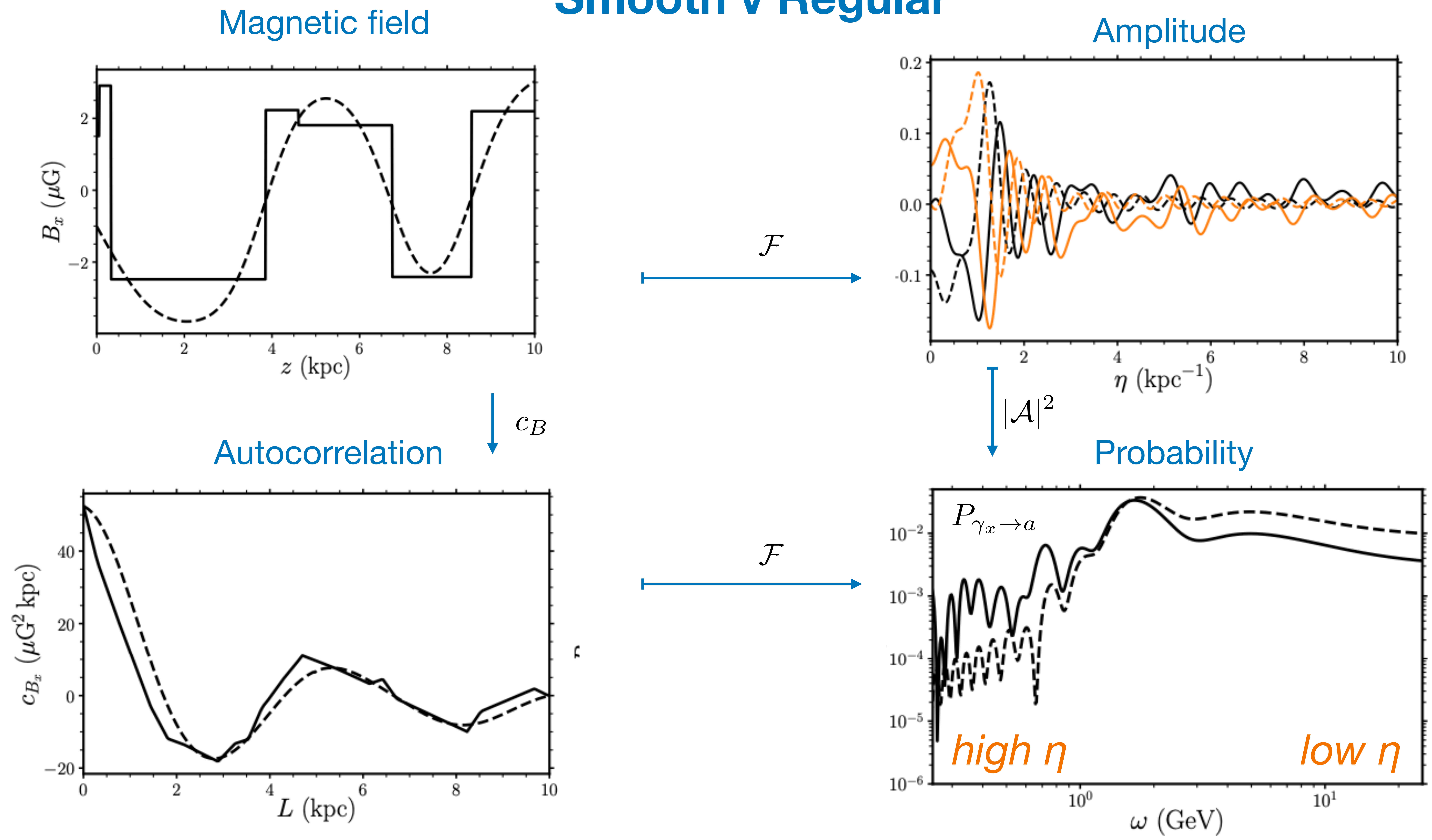
Modelling the magnetic field



One dimensional cell models

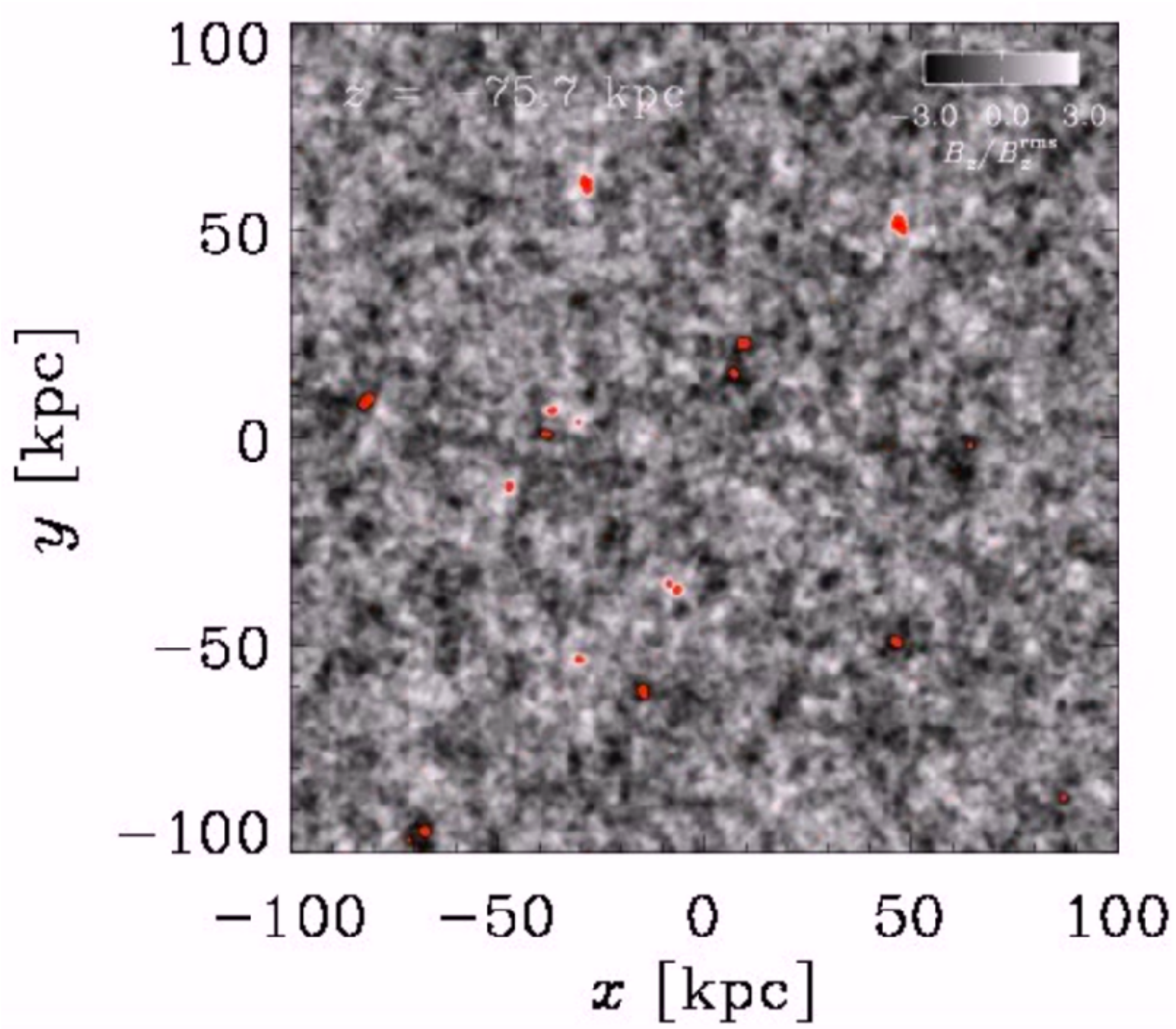
Status: standard practice for ALP searches (& Faraday RM studies)

Smooth v Regular

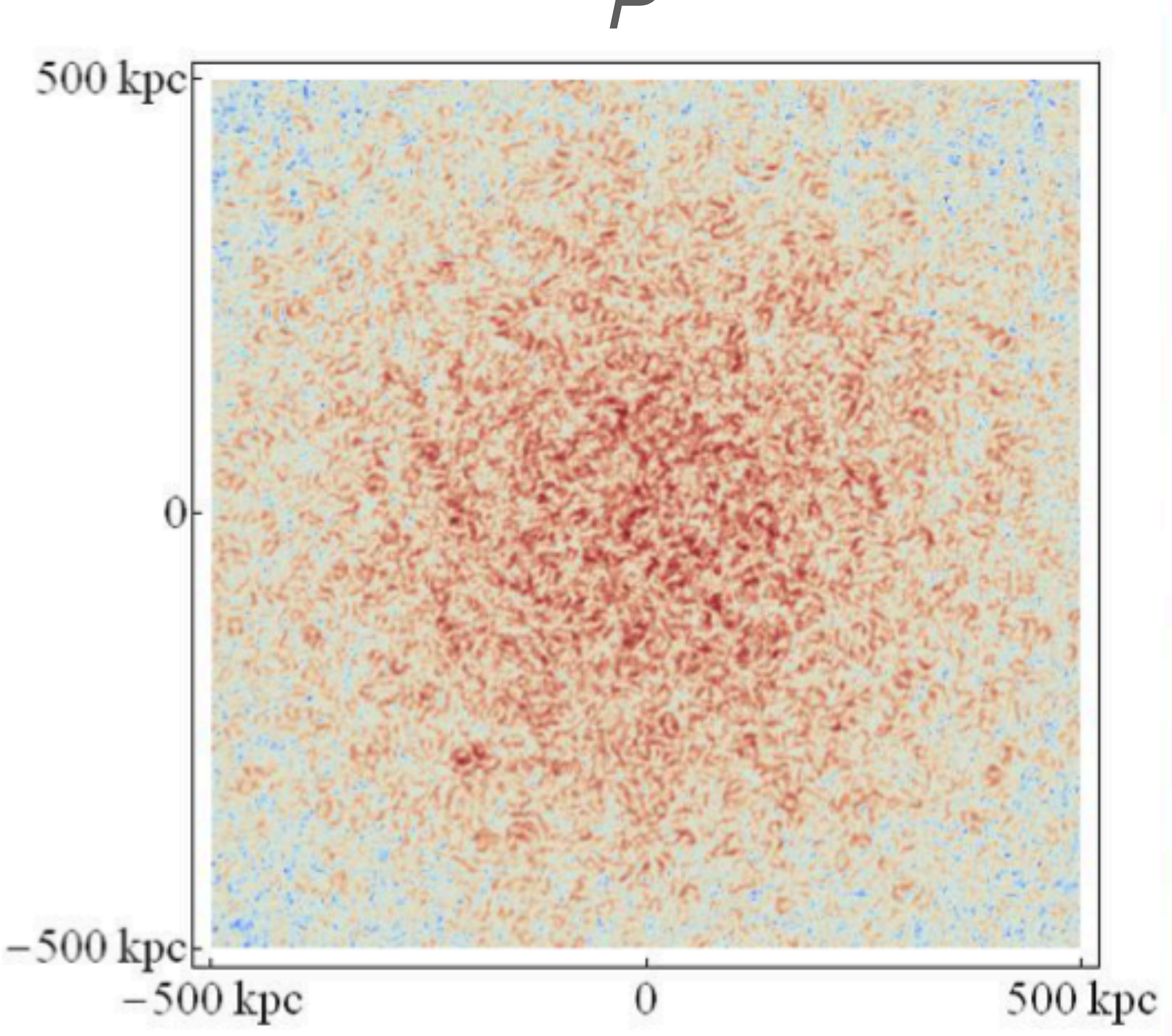


Gaussian random fields

B



P

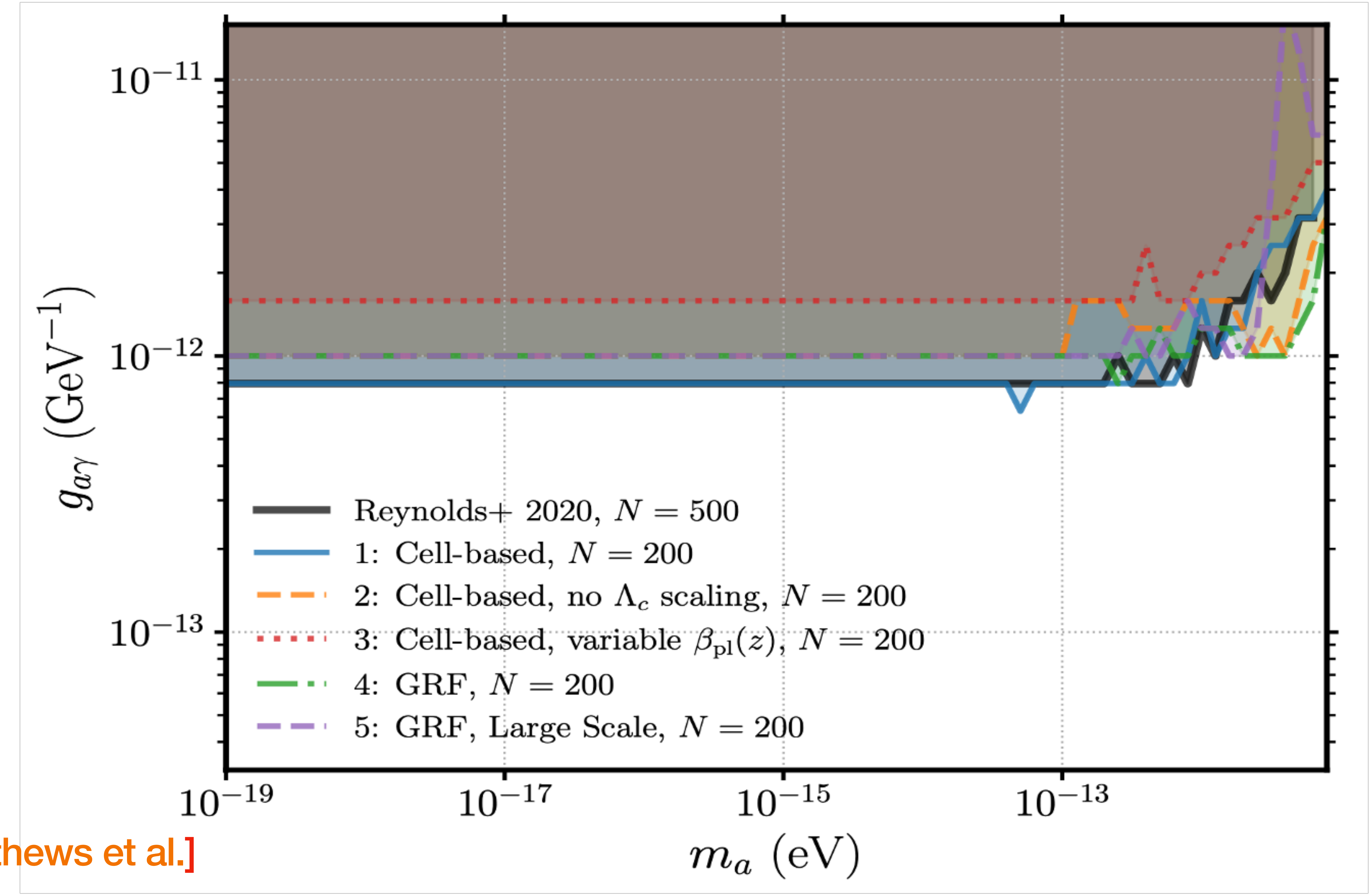


[Carenza et al.]

Status: "state-of-the-art"

[Angus et al.]

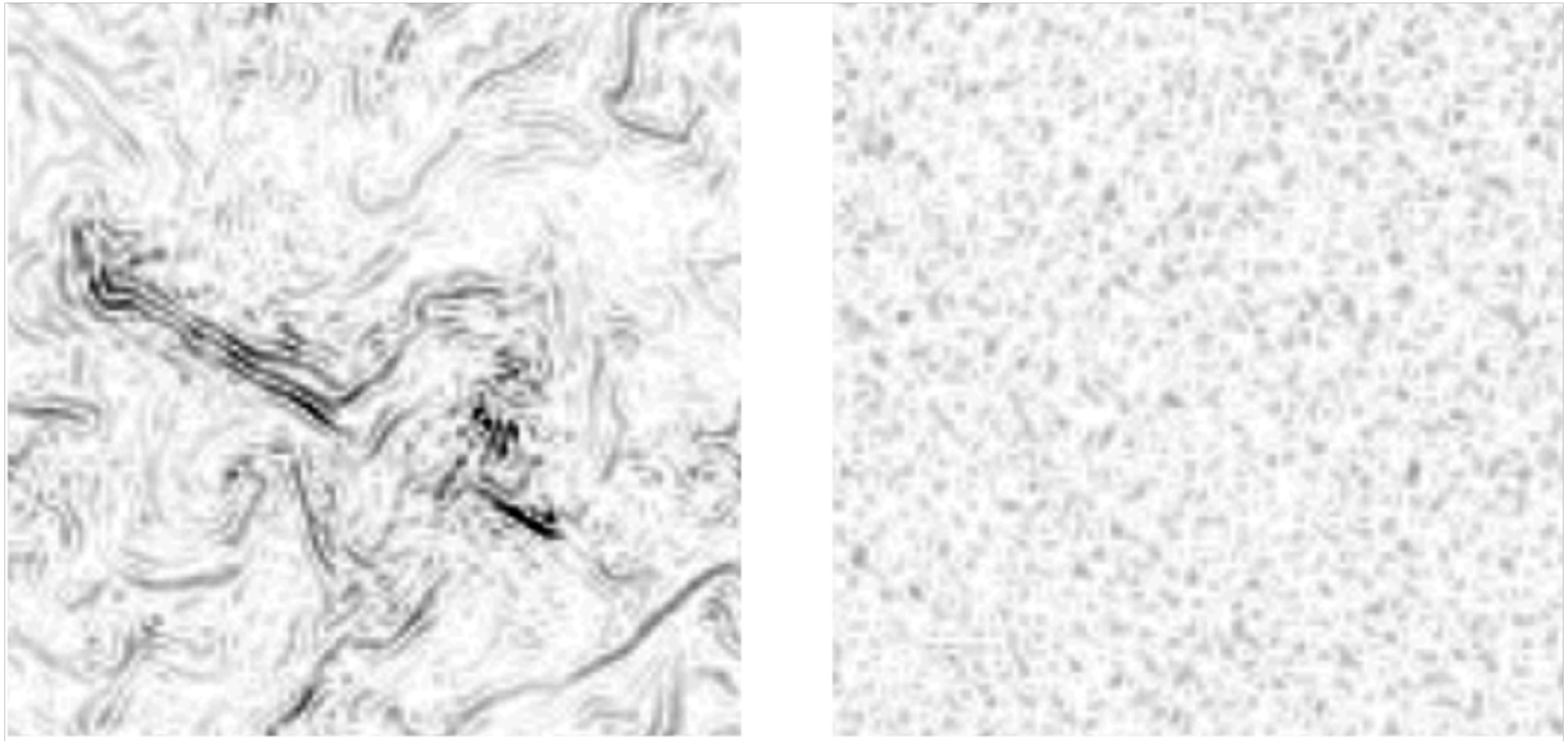
GRF v cell-models



[Matthews et al.]

Structure and phases

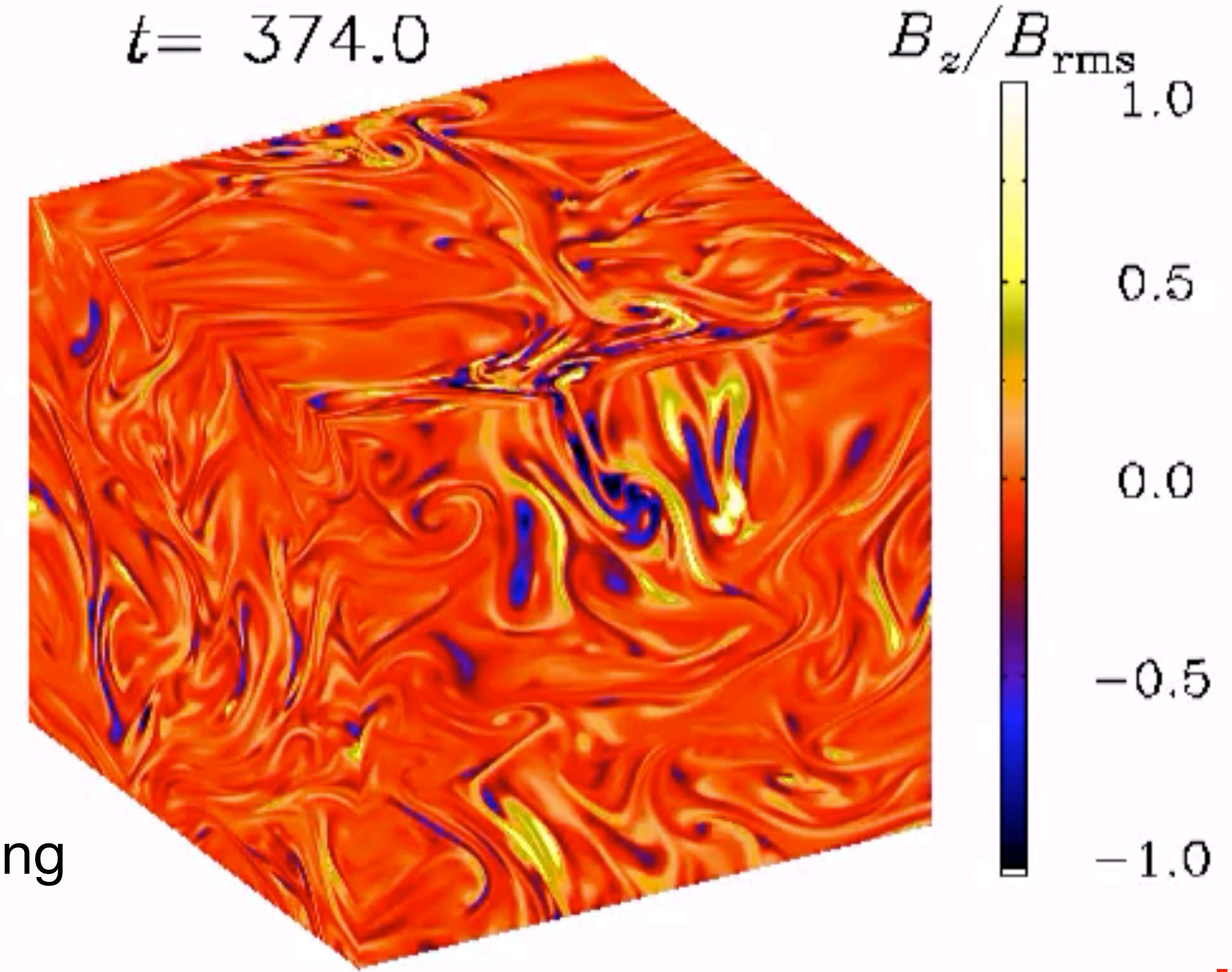
$$P_{\gamma a}(\eta_a) = \frac{g_{a\gamma}^2}{4}|\tilde{B}_i(\eta_a)|^2$$



[Maron, Goldreich]

Is ALP-photon conversion independent of MHD structure?

Dedicated MHD simulations: time-evolution



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

[Carenza et al.]

GRF v MHD

(same power spectrum)

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

Statistics at fixed energy

Want: statistical properties from ensemble of trajectories

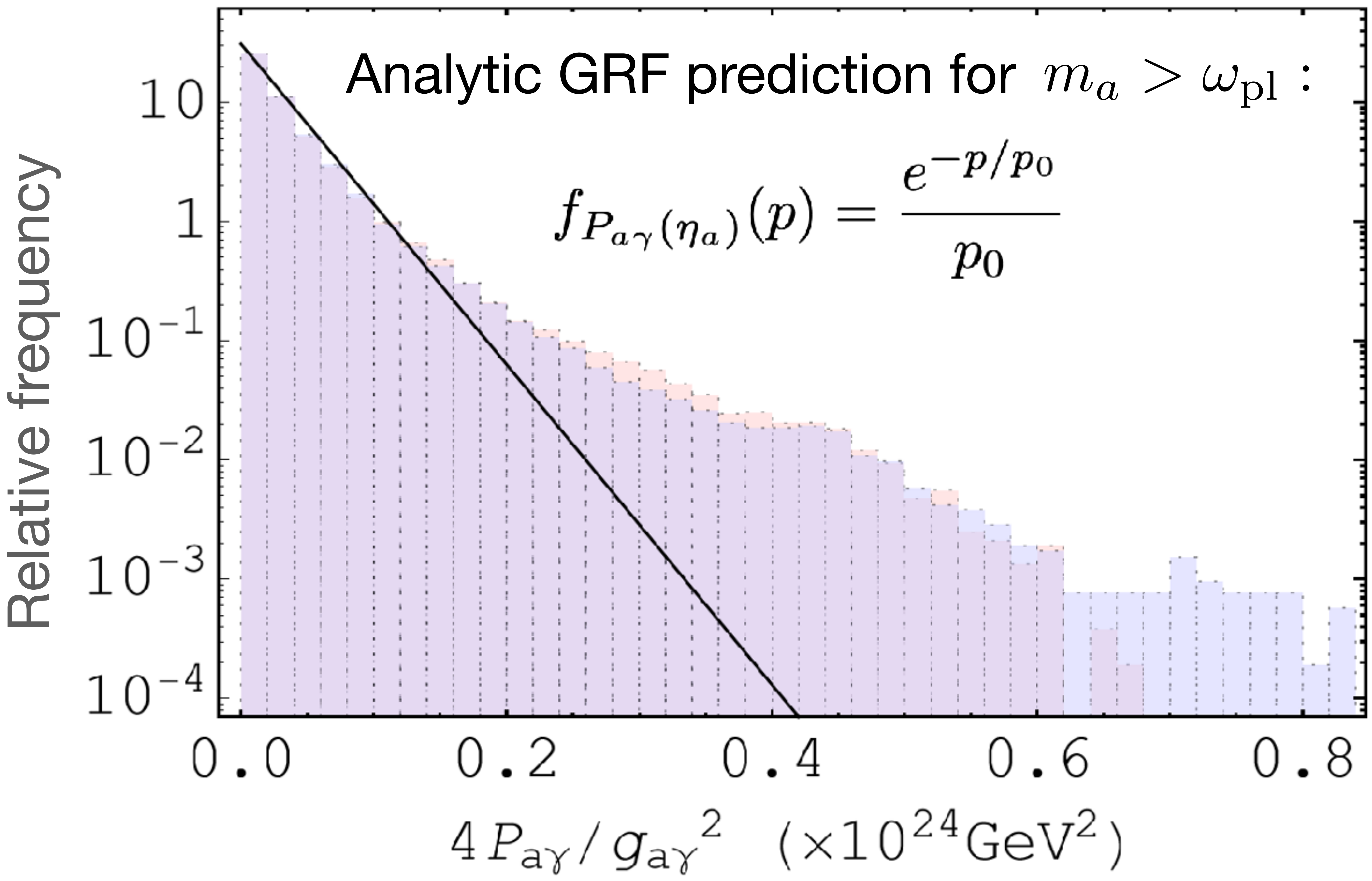
Analytic probability distribution for GRF using ergodic theorem:

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

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

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

Heavy-tailed MHD distributions



Conversion ratio

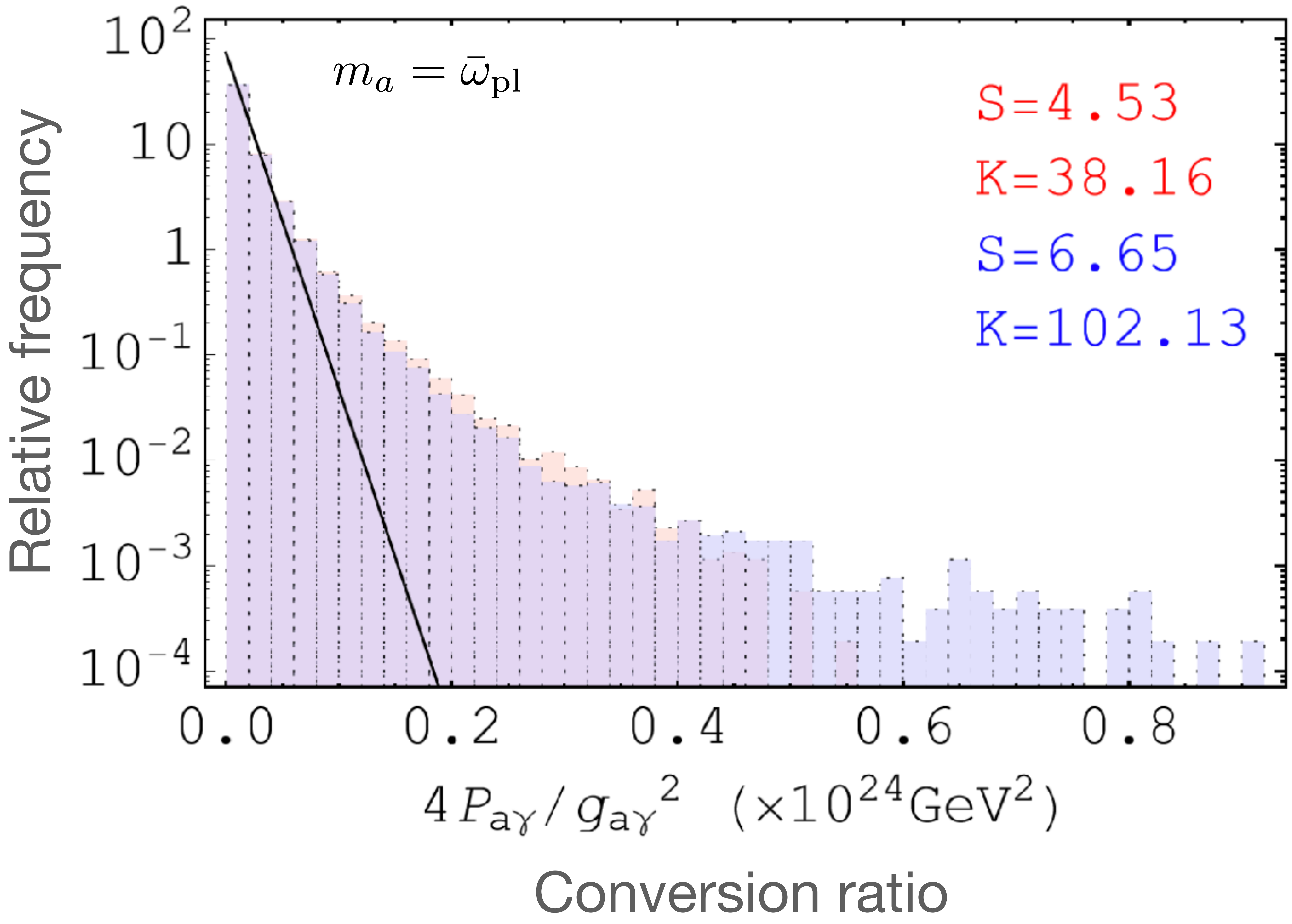
$$p_0 = \frac{g_{a\gamma}^2}{4}\frac{L}{2\pi}P_{\rm 1D}(\eta_a)$$

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

Skewness & kurtosis:

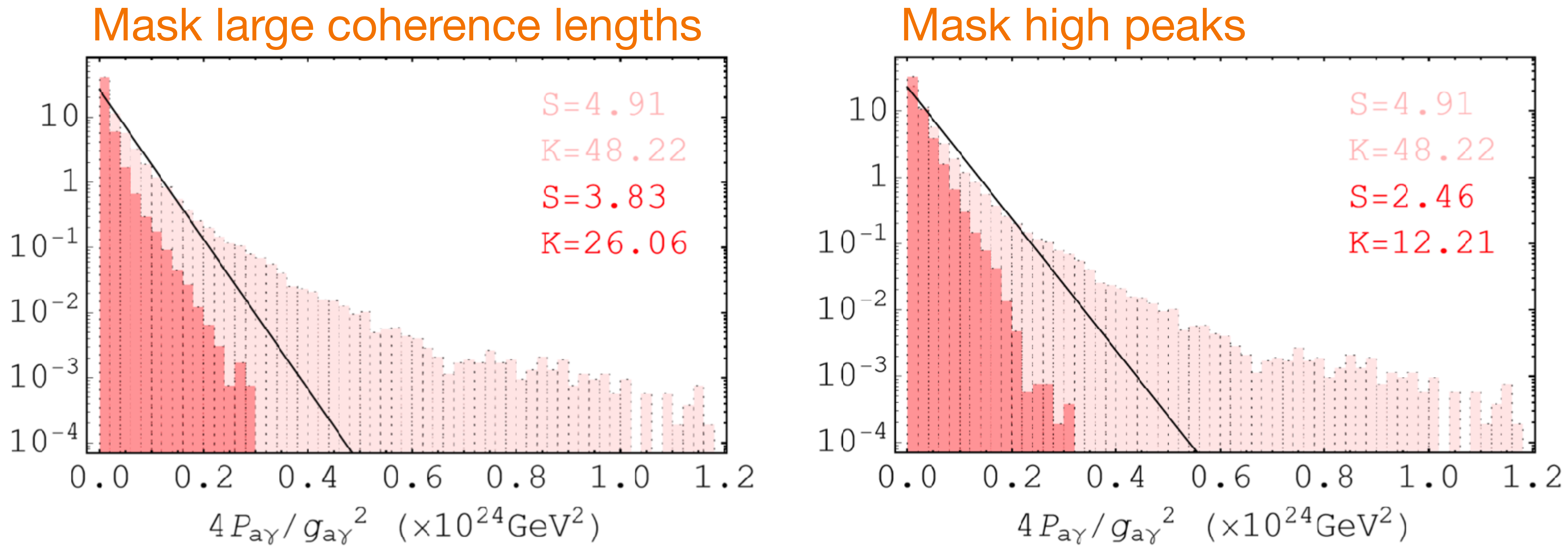
GRF:	MHD:
S = 2	S=3.88
K = 9	K=25.56
	S=4.60
	K=41.80

Holds for arbitrary masses, polarisations



Non-Gaussianity

Two possible sources:



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.

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

Larger conversion from MHD
— suggest existing limits conservative

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.

Observational prospects good: next-generation missions will be more sensitive; make new ways to constrain ALPs possible.