Hunting ALPs in Galaxy Clusters

work in progress with Joe Conlon and Francesca Day

Markus Rummel, University of Oxford

Bad Honnef, 24/02/2016


ENTERING
BORING
GREAT SUCCESS!
VERY NICE

Outline

- Axion-like particles
- Galaxy Clusters
- ALP induced spectral distortions

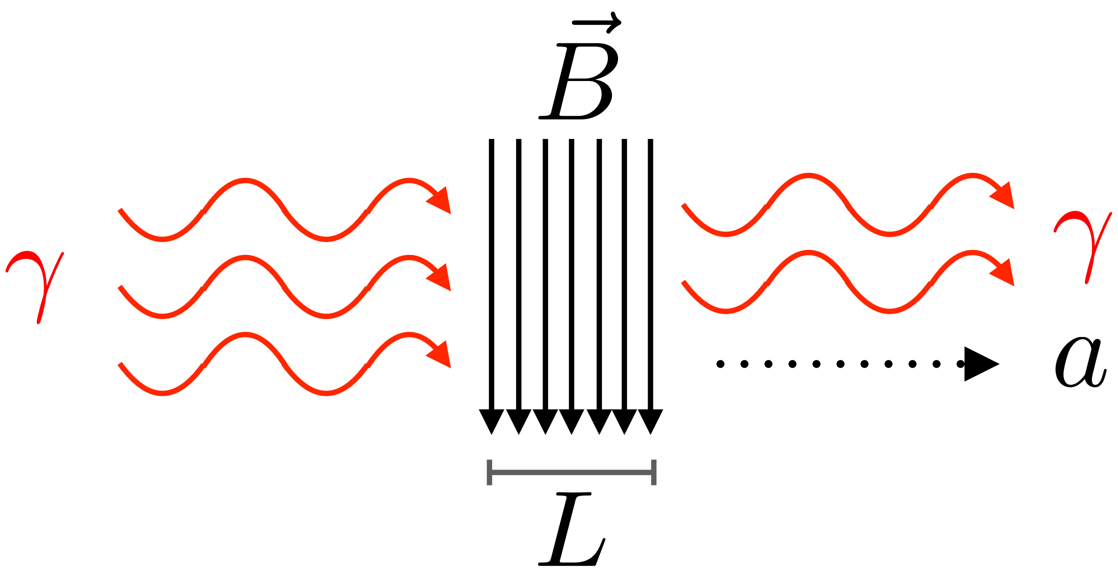
Axion-Like Particles

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{a}{4M}F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}m_a^2 a^2$$

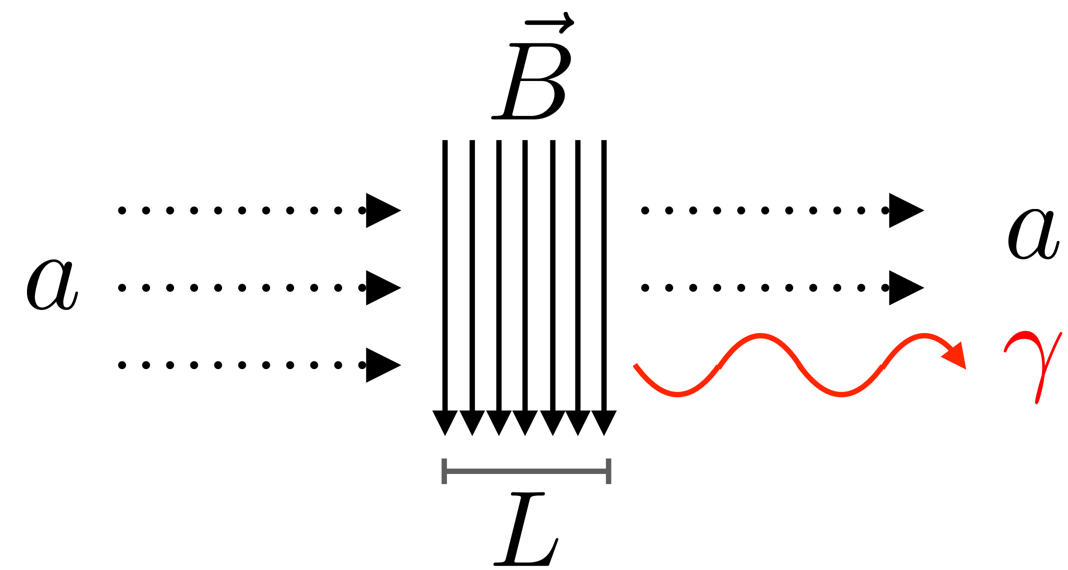
- Generically arise in string compactifications
- For general ALPs $M = g_{a\gamma\gamma}^{-1}$ and m_a are unspecified and unrelated (unlike for the QCD axion)
- $M \gtrsim 2 \times 10^{11}\ \mathrm{GeV}$ Supernovae Bound
- Coupling to electromagnetism:

$$\frac{1}{M}\, a\, \boldsymbol{E} \cdot \boldsymbol{B}$$

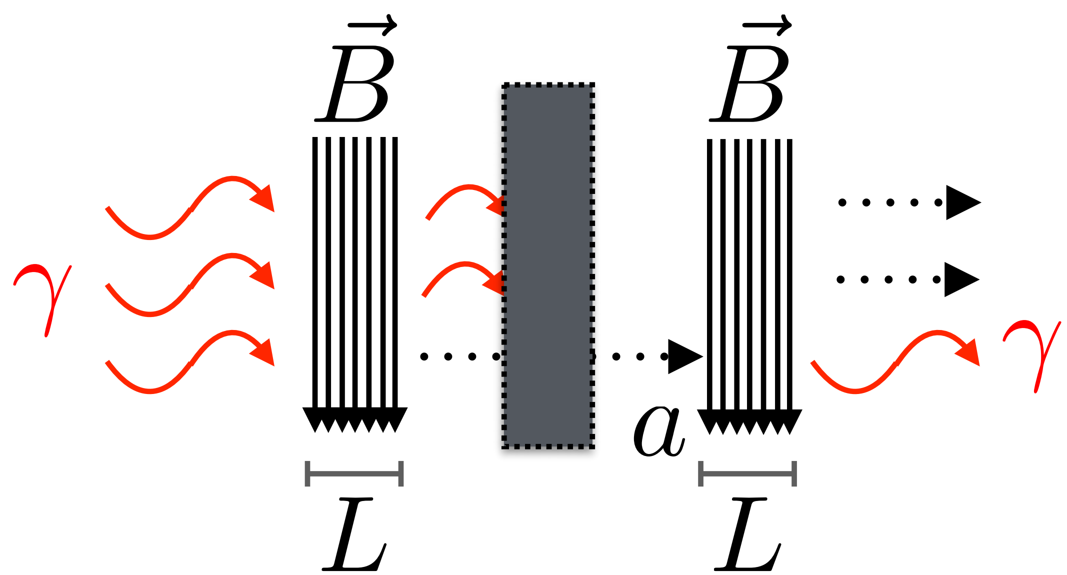
How could we see ALPs?



e.g. spectral distortions



e.g. CAST, IAXO



e.g. ALPS II

ALP photon conversion

General scaling of conversion probability in coherent magnetic fields:

$$P(a \to \gamma) \sim \frac{B^2 L^2}{4M^2}$$

Needs

- BIG magnetic fields B^2 and/or
- LONG coherence length L^2
- Suppressed by weak couplings M^{-2}

ALP photon conversion

General conversion formula in transverse magnetic field $B_\perp$ of domain size L :

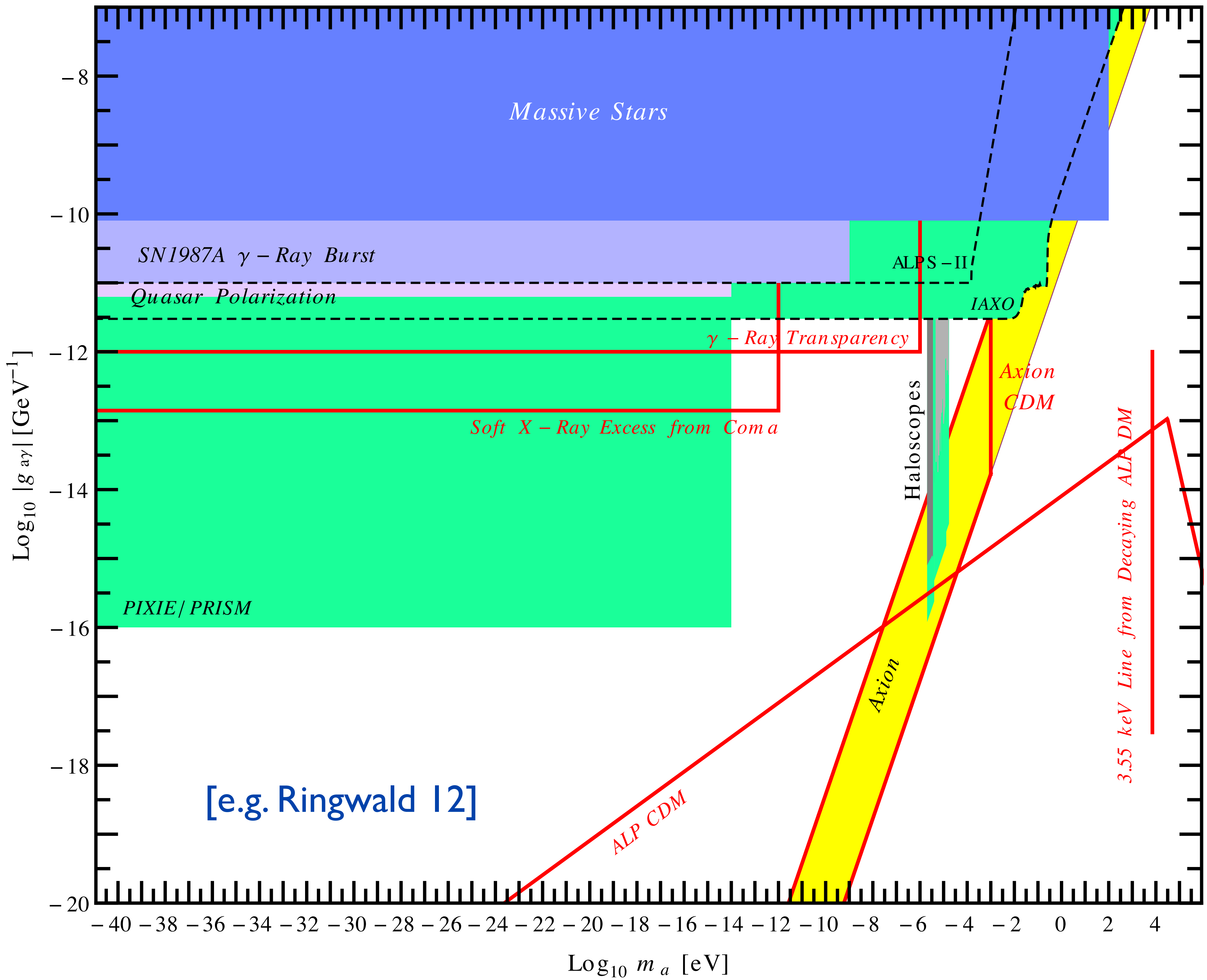
$$P(a \to \gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$$

with

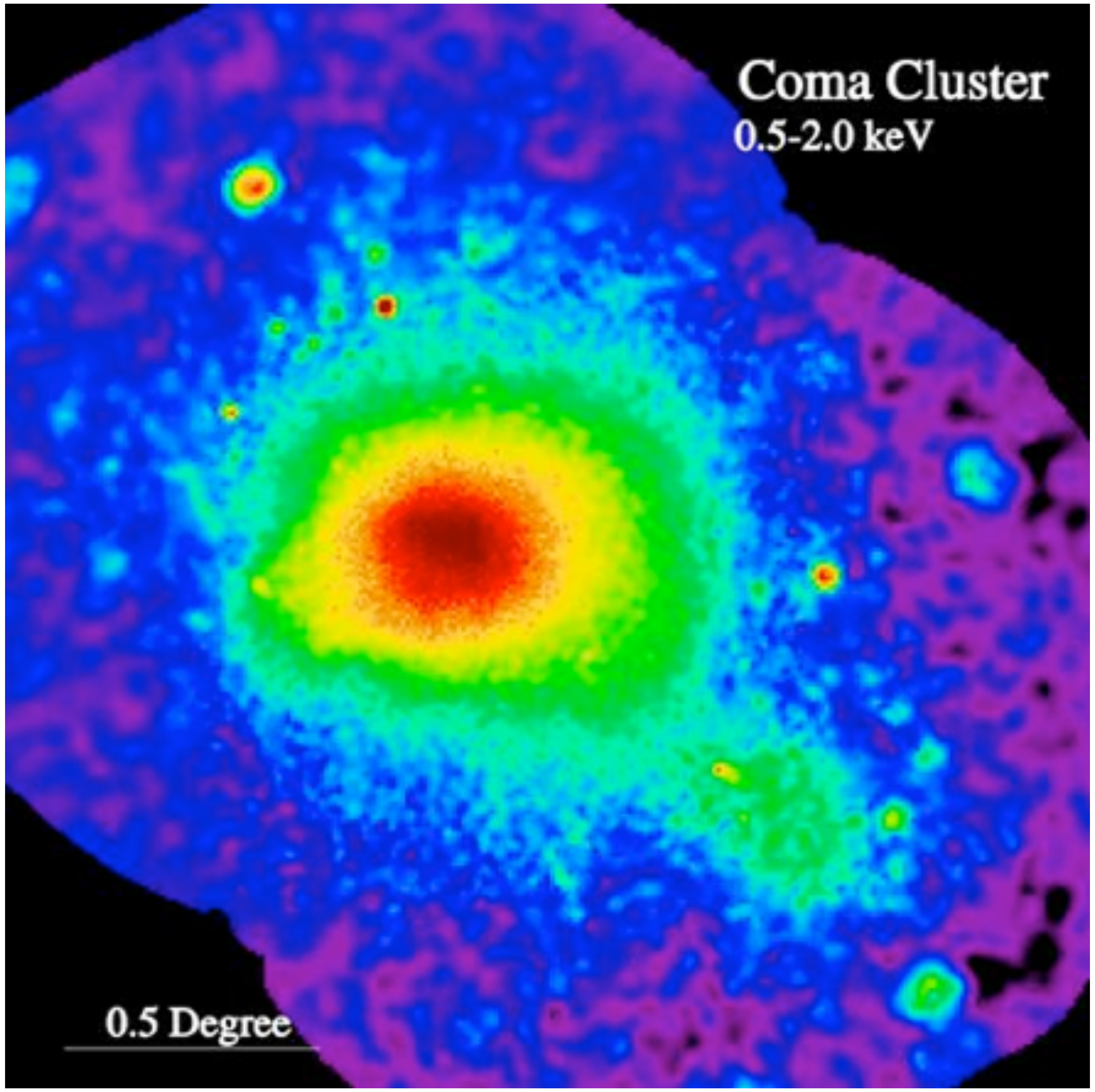
$$\theta \approx 2.8 \cdot 10^{-5} \times \left(\frac{10^{-3}\text{cm}^{-3}}{n_e}\right)\left(\frac{B_\perp}{1\ \mu\text{G}}\right)\left(\frac{E_a}{200\ \text{eV}}\right)\left(\frac{10^{14}\ \text{GeV}}{M}\right),$$

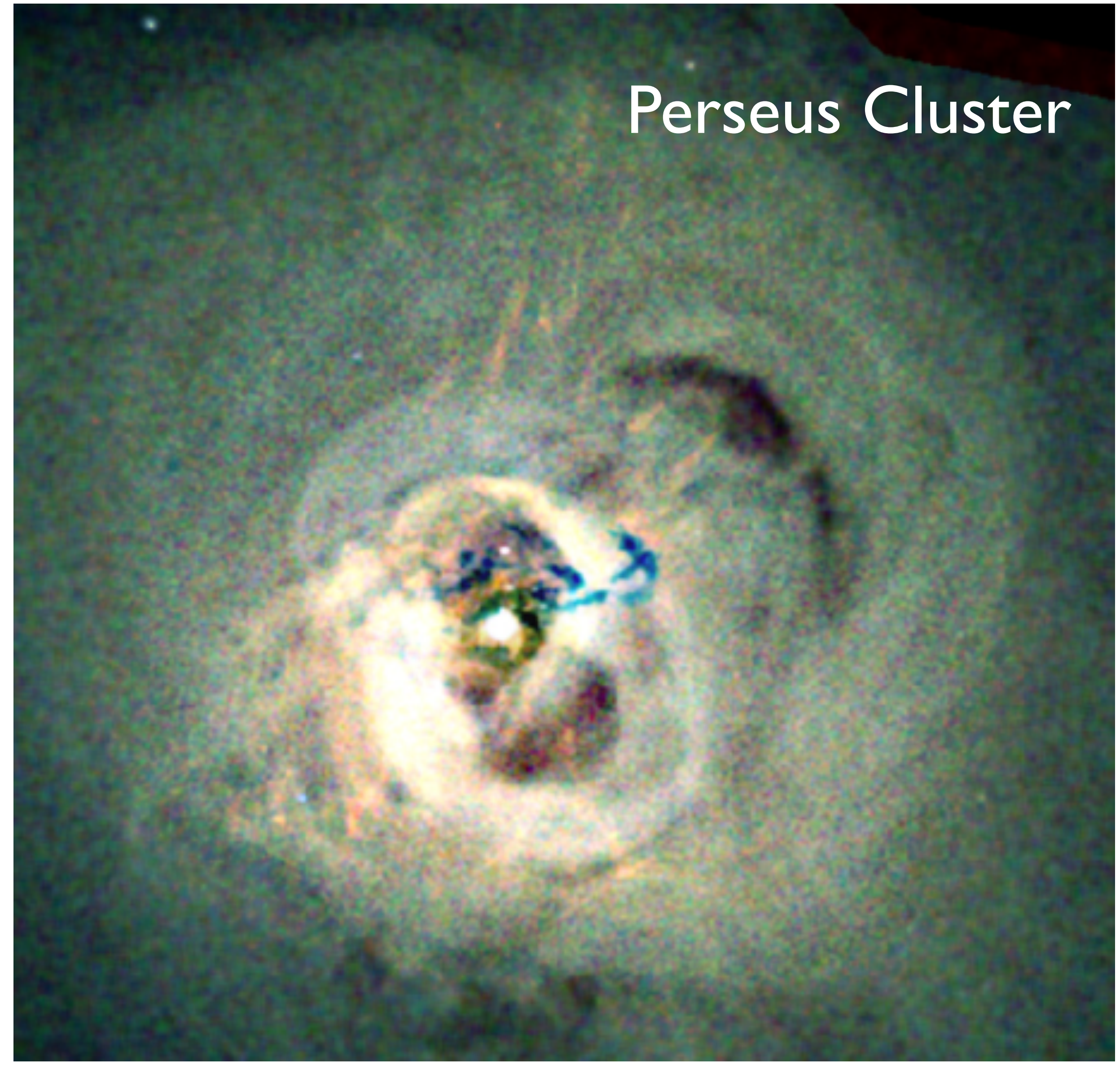
$$\Delta = 0.27 \times \left(\frac{n_e}{10^{-3}\text{cm}^{-3}}\right)\left(\frac{200\ \text{eV}}{E_a}\right)\left(\frac{L}{1\ \text{kpc}}\right).$$

ALP Parameter Space



Galaxy Clusters

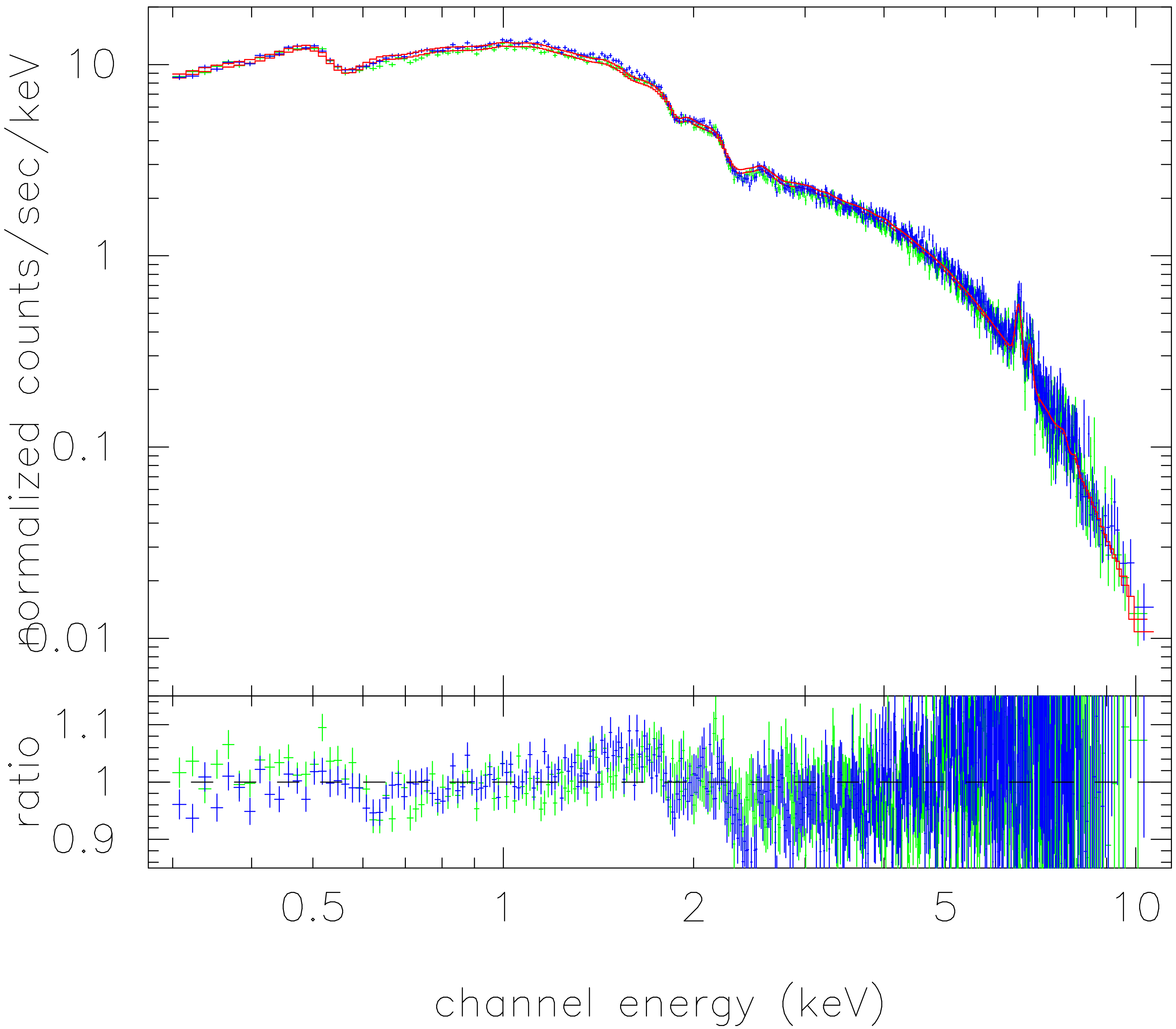




$z = 0.023$

$z = 0.018$

Thermal Spectra of Galaxy Cluster



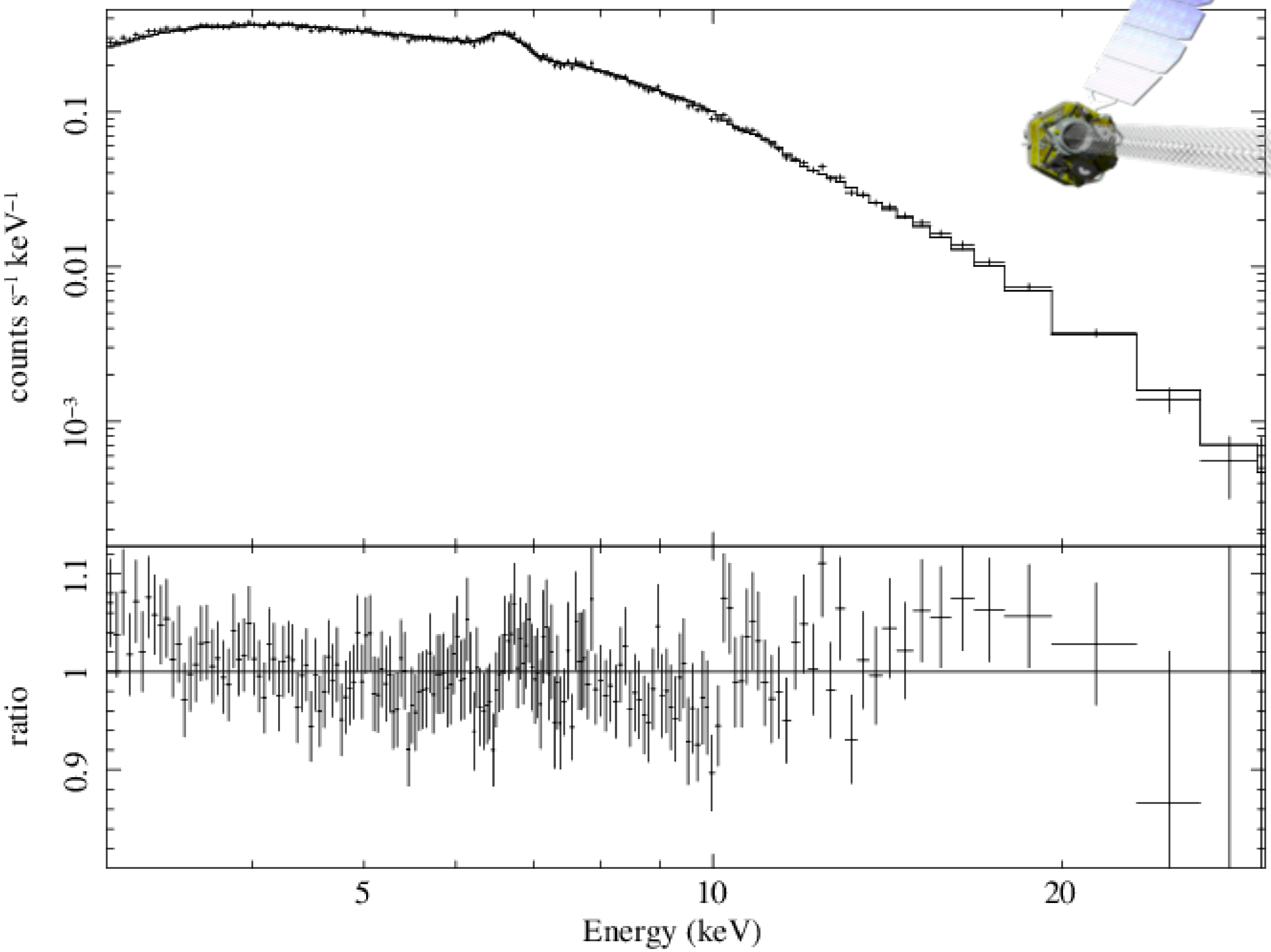
XMM-Newton, Coma cluster, central 300 kpc

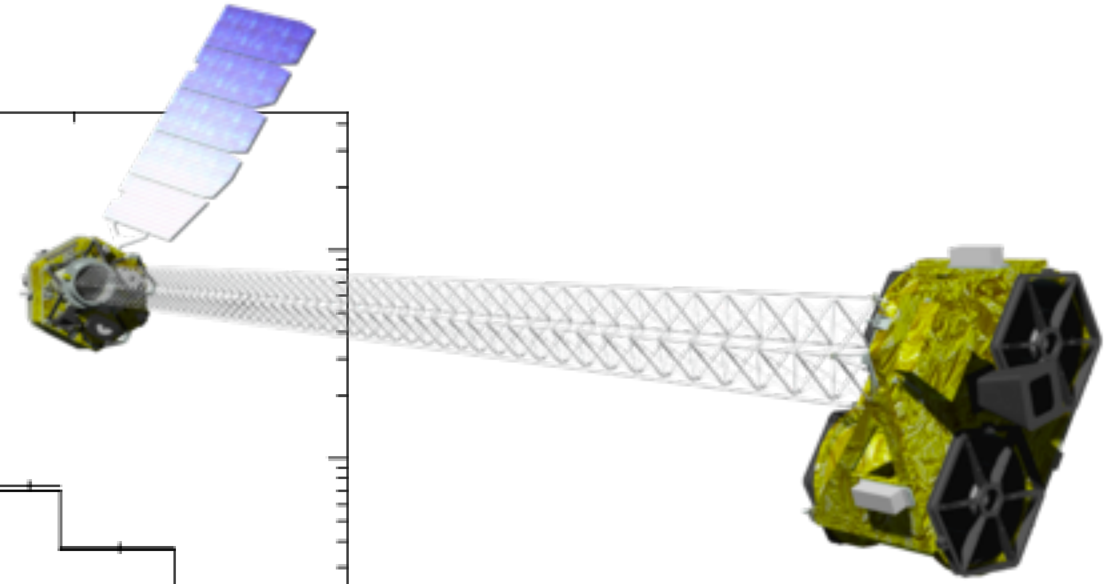
$$I(\nu) = A n_e^2 \frac{g(\nu, T)\exp\left(-\frac{h\nu}{kT}\right)}{\sqrt{kT}}$$

$$+ \text{ atomic lines}$$

Well known to ~ 1% accuracy

Thermal Spectra of Galaxy Cluster





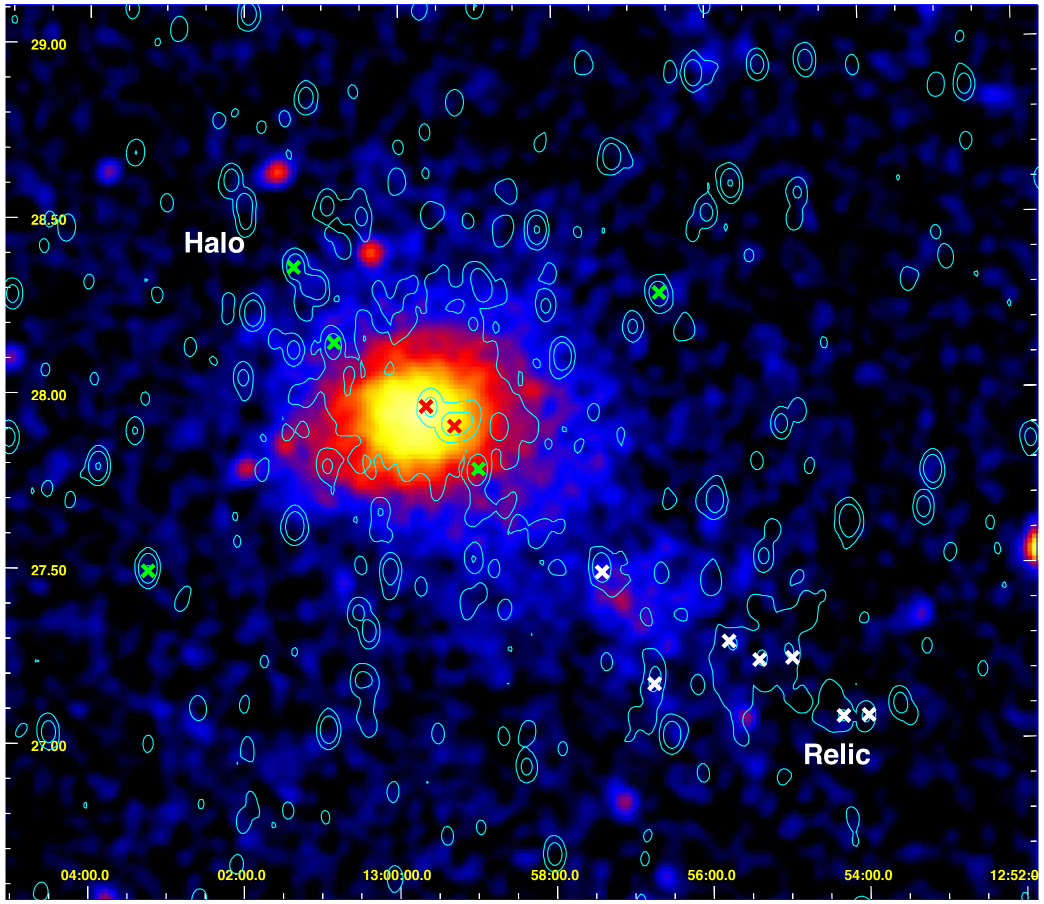
NuSTAR,
Coma cluster,
central 100 kpc

Magnetic Fields in Galaxy Clusters

- Electron density via X-ray brightness profile

$$n_e(r) = n_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta}$$

- Magnetic field via Faraday rotation $RM = \frac{e^3}{2\pi m_e^2} \int_{l.o.s} n_e(l) B_{\|}(l) \mathrm{d}l$



[Bonafede,Vazza,Bruggen,Murgia, Govoni,Feretti,Giovannini,Ogrean'13]

$$\Rightarrow B(r) = C \cdot B_0 \left(\frac{n_e(r)}{n_0}\right)^{\eta}$$ (via simulation vs RM)

$$\Rightarrow \text{turbulent } B \sim \mathcal{O}(\mu\text{G}) \text{ with } L \sim \mathcal{O}(10\text{kpc})$$

Why Clusters are good for seeing ALPs

- Astrophysical parameters at X-ray energies:

$$P_{a\to\gamma} \equiv 2P_{\gamma\to a} = 2.0{\cdot}10^{-5}\times\left(\frac{B_\perp}{3\ \mu\mathrm{G}}\frac{L}{10\ \mathrm{kpc}}\frac{10^{13}\ \mathrm{GeV}}{M}\right)^2$$

- Terrestrial parameters at X-ray energies

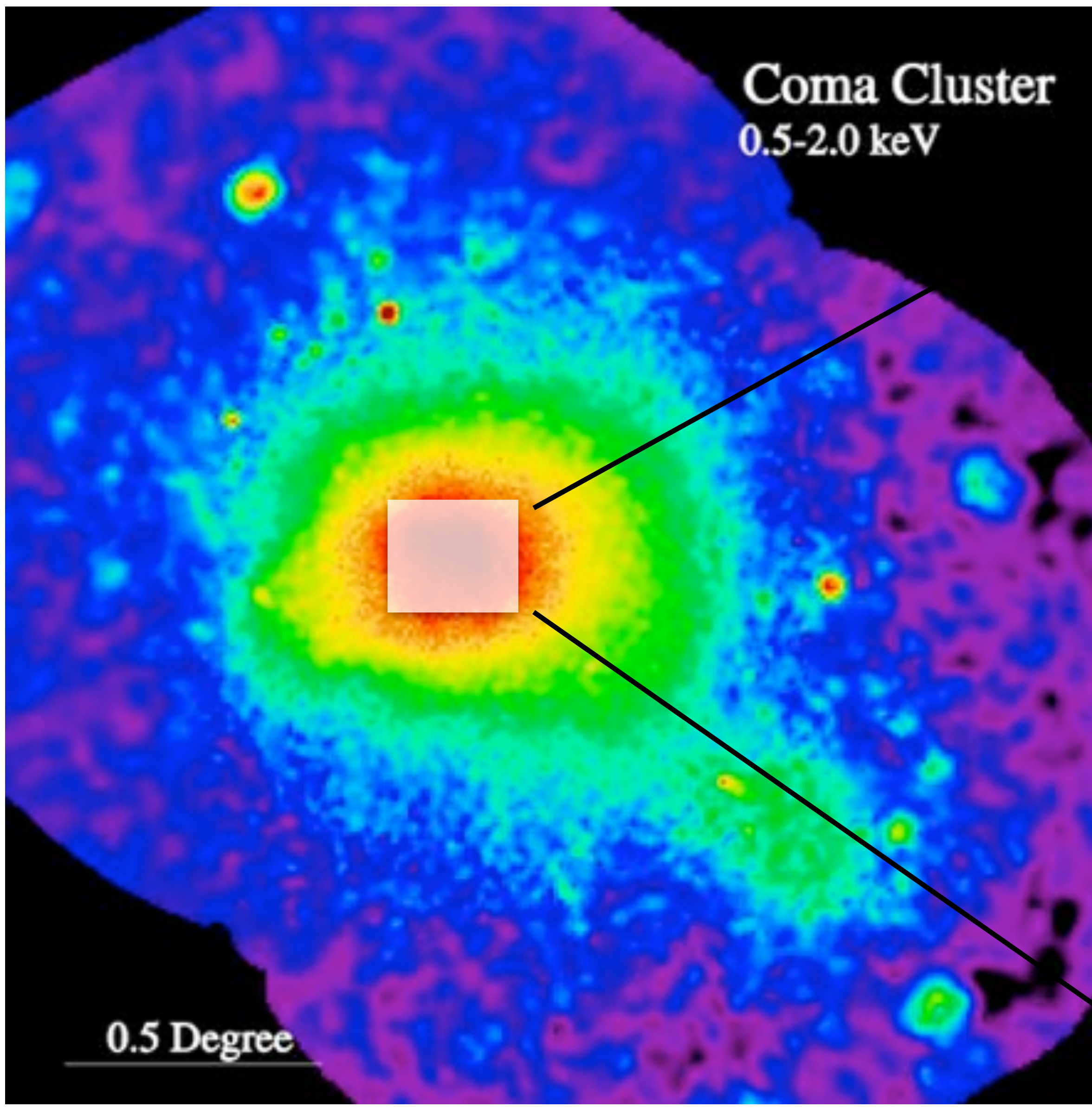
$$P_{a\to\gamma} \equiv 2P_{\gamma\to a} \simeq 2.0{\cdot}10^{-23}\times\left(\frac{B_\perp}{10\mathrm{T}}\frac{L}{10\mathrm{m}}\frac{10^{13}\ \mathrm{GeV}}{M}\right)^2$$

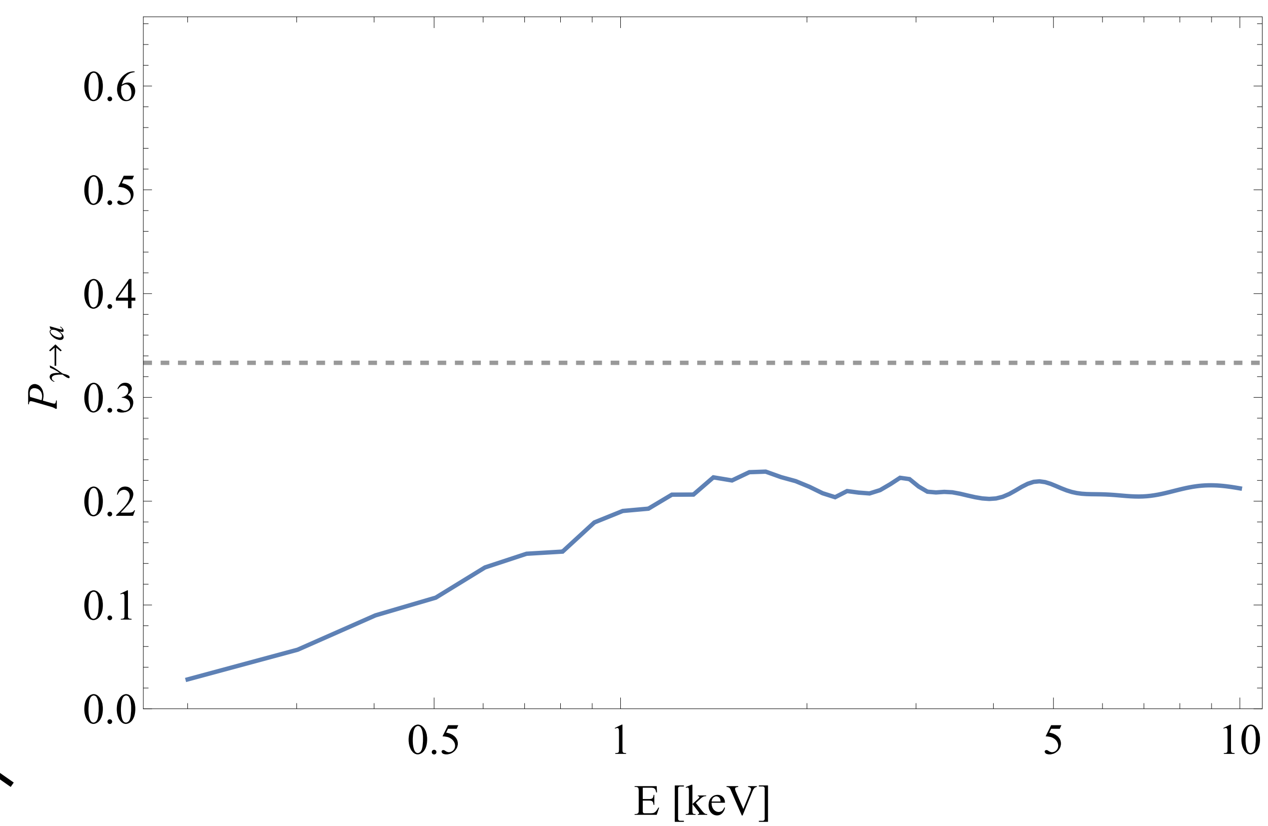
$\Rightarrow$ Much longer coherence length beats stronger magnetic field

Distortion large field of view

$$100 \times 100 \text{ kpc}$$

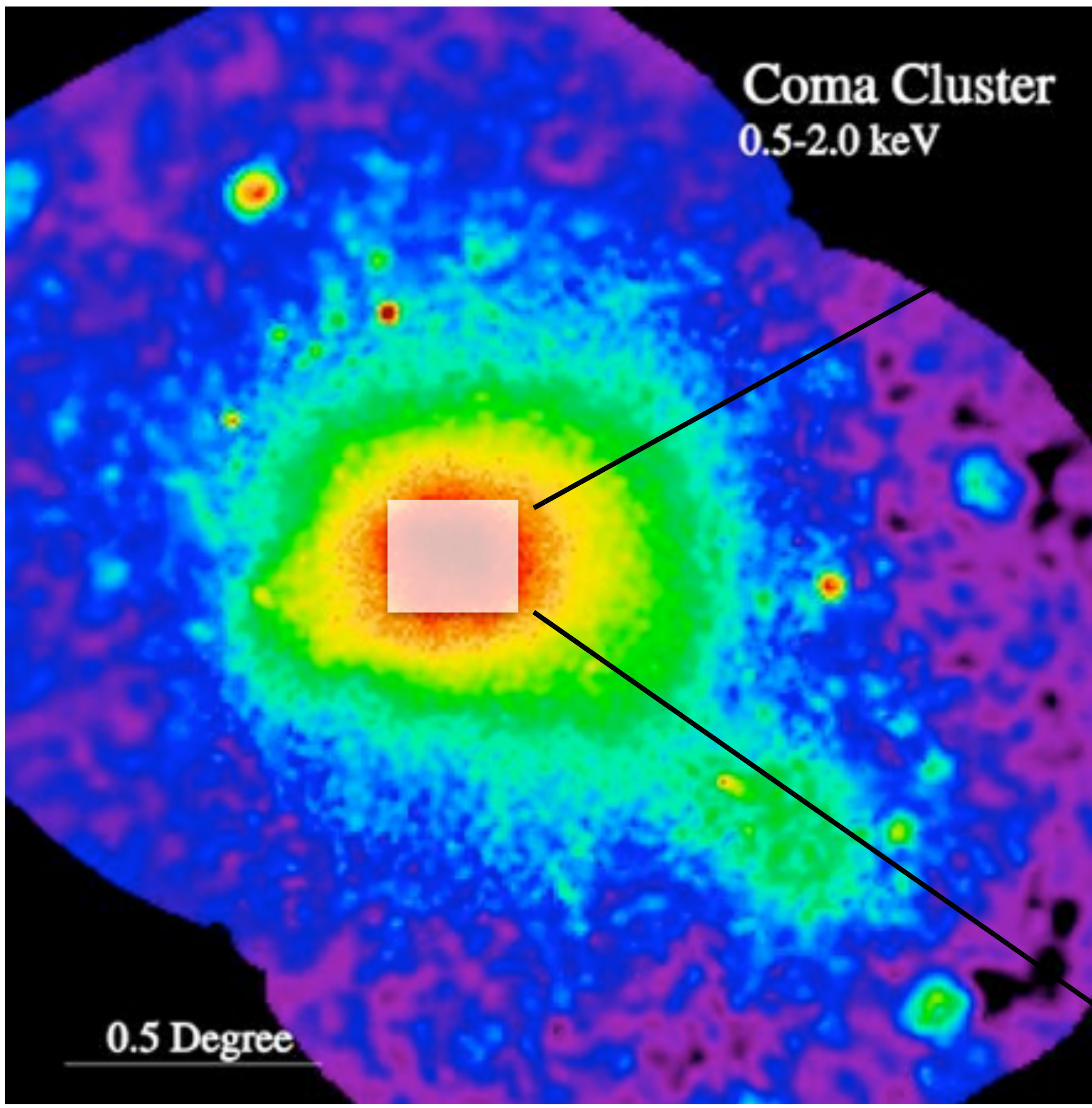
$$f_{\text{distorted}}(\omega) = (1 - \langle P_{\gamma\to a}\rangle(\omega))\, f_{\text{intrinsic}}(\omega)$$





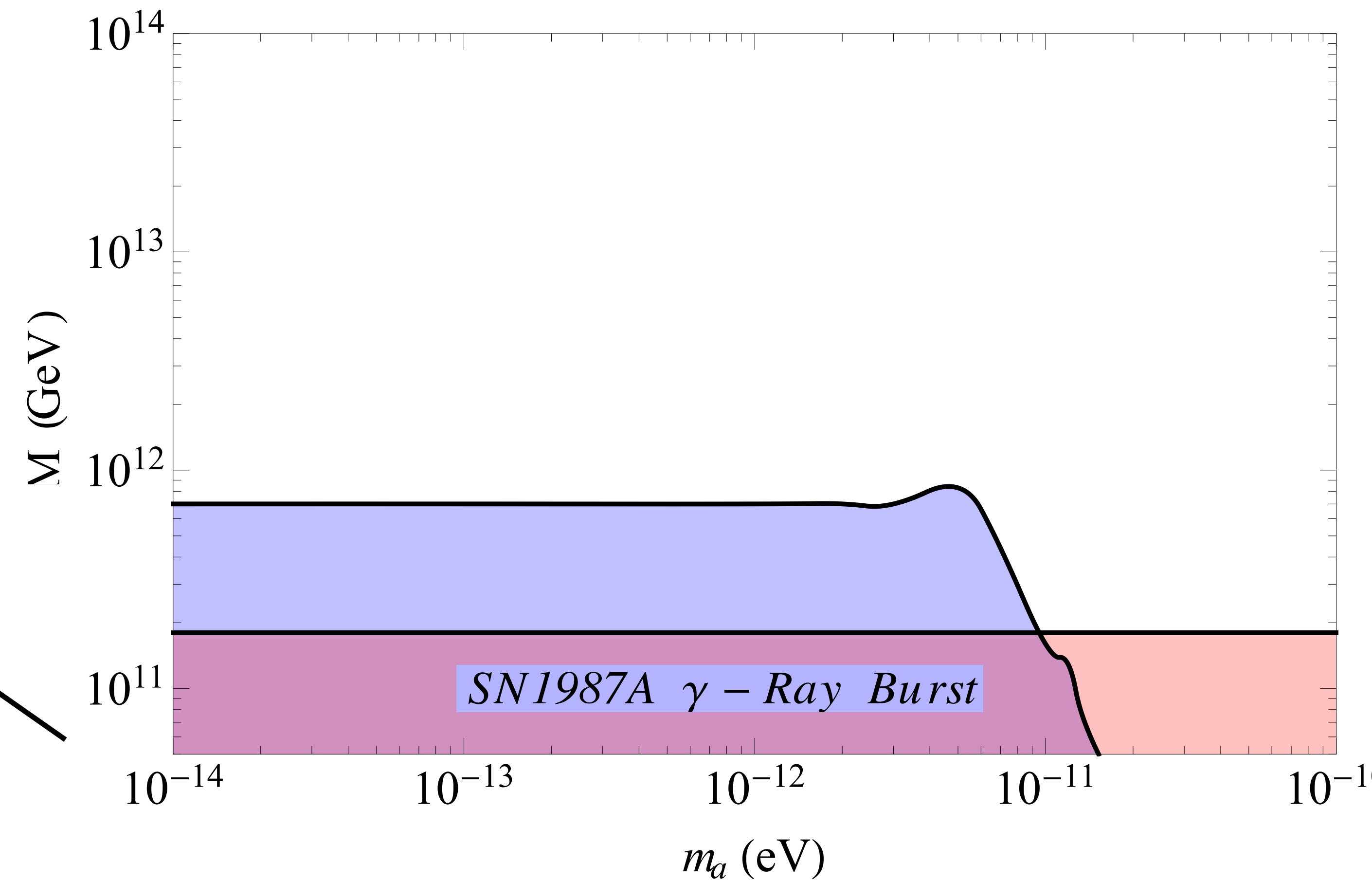
Distortion large field of view

$$100 \times 100 \text{ kpc}$$



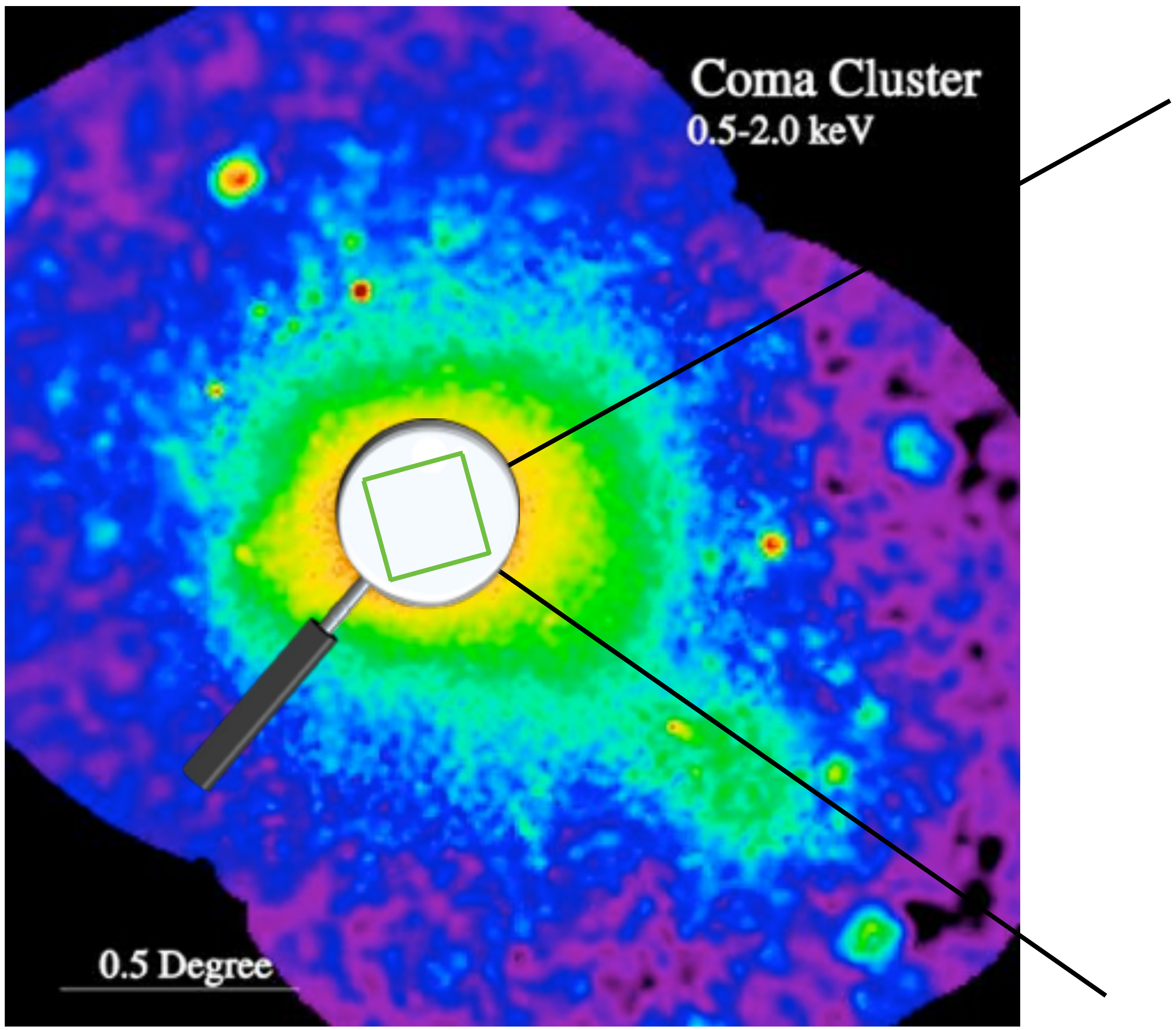
Can be used to bound M:

[Conlon, Marsh, Powell 15]



Distortion small field of view

$$10 \times 10\ \text{kpc}$$



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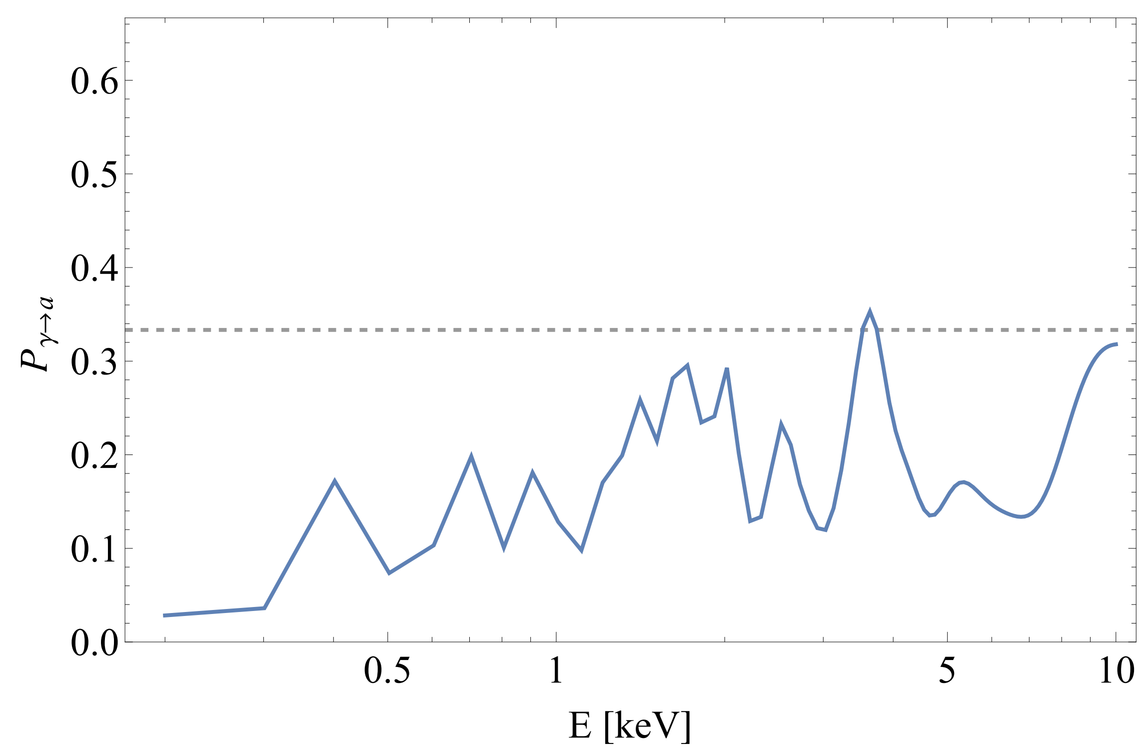
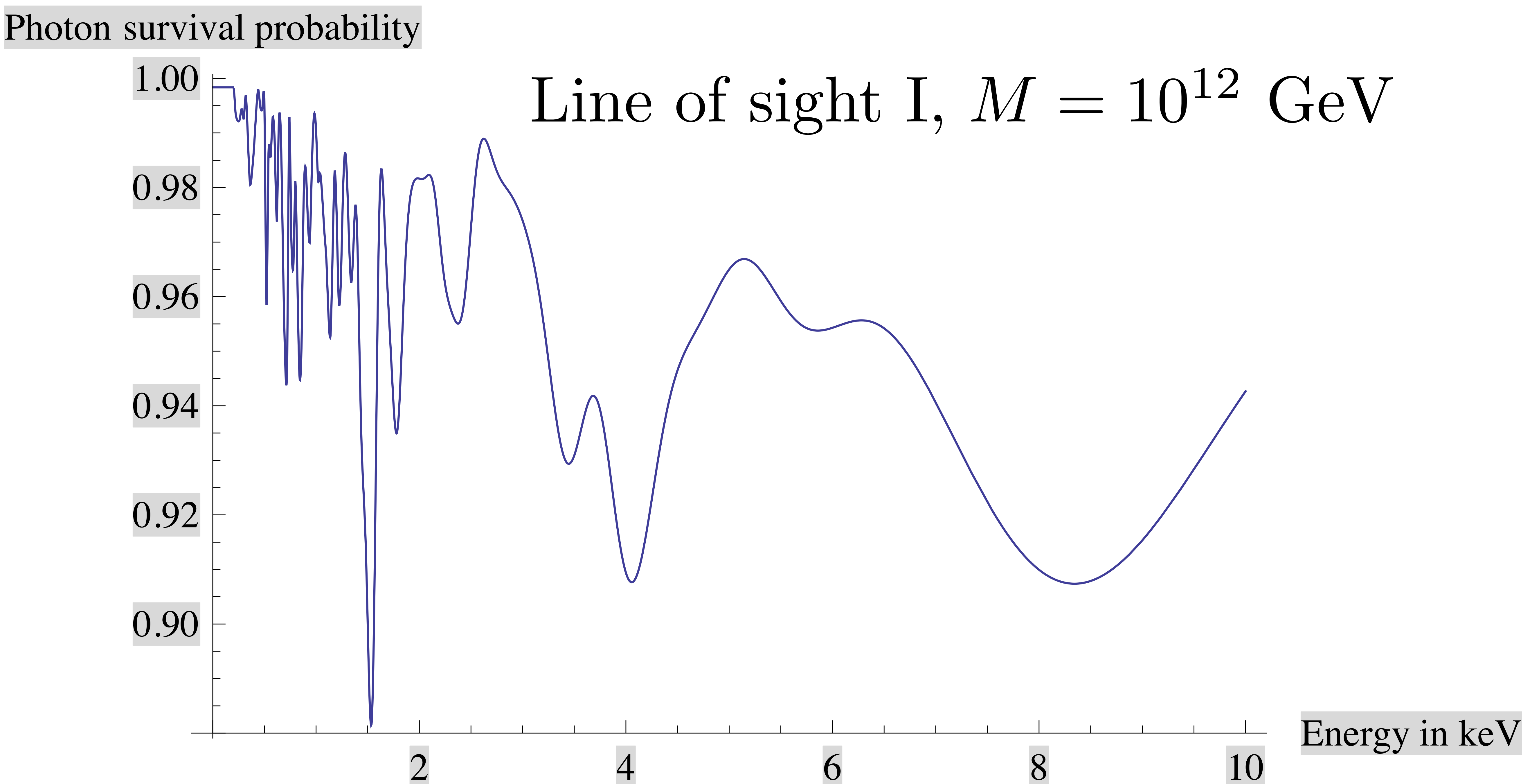


Distortion small field of view



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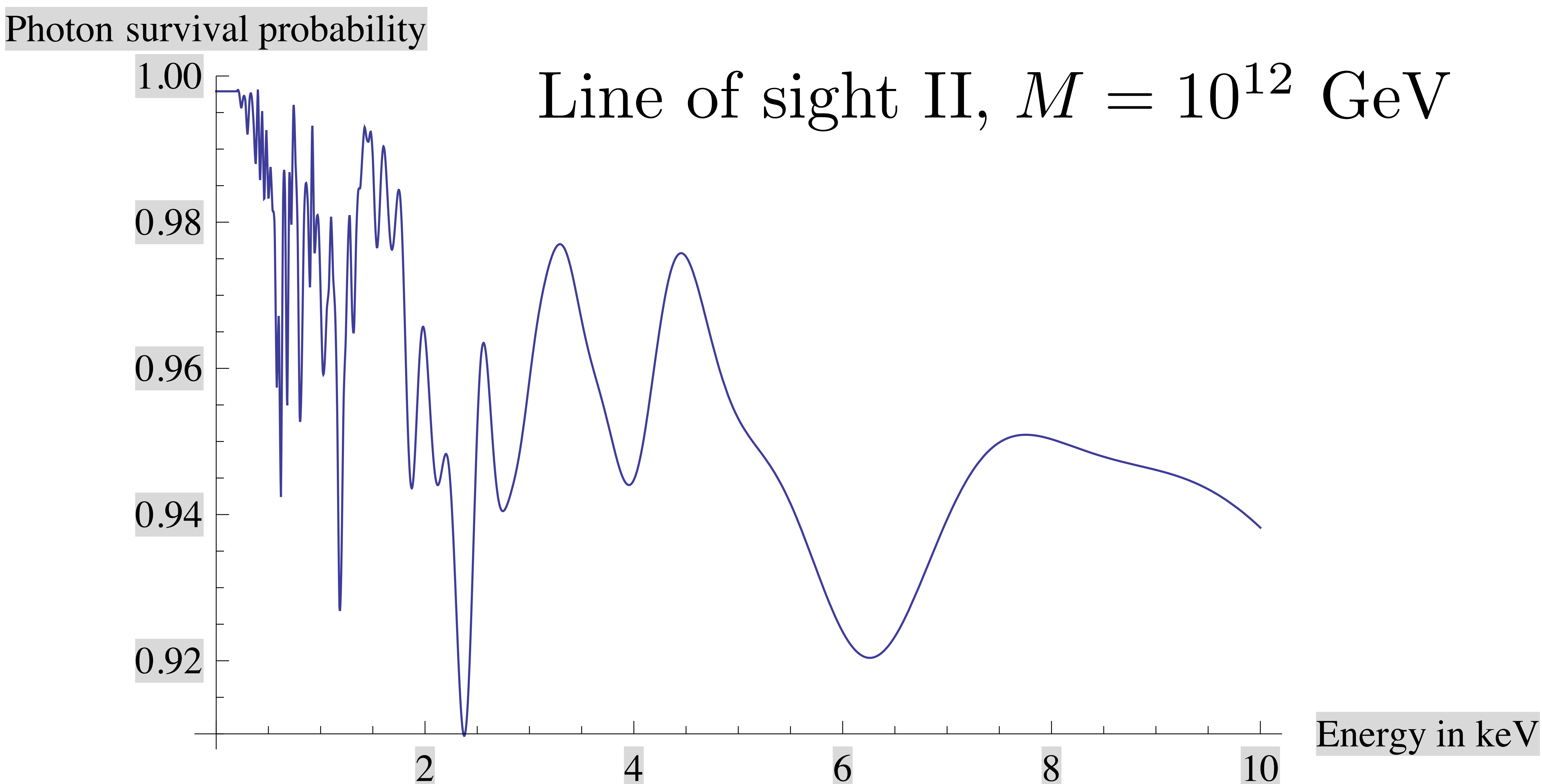
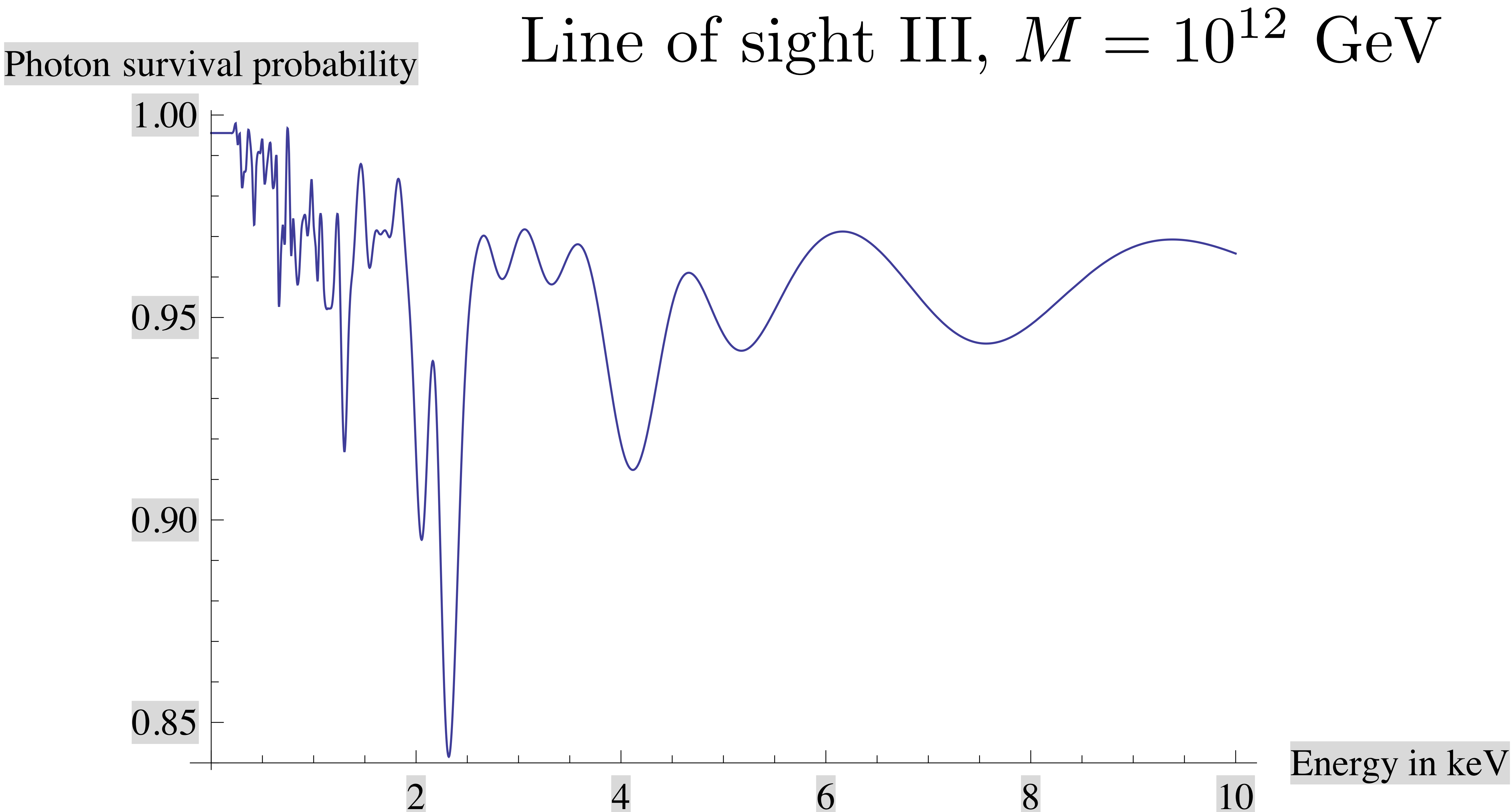
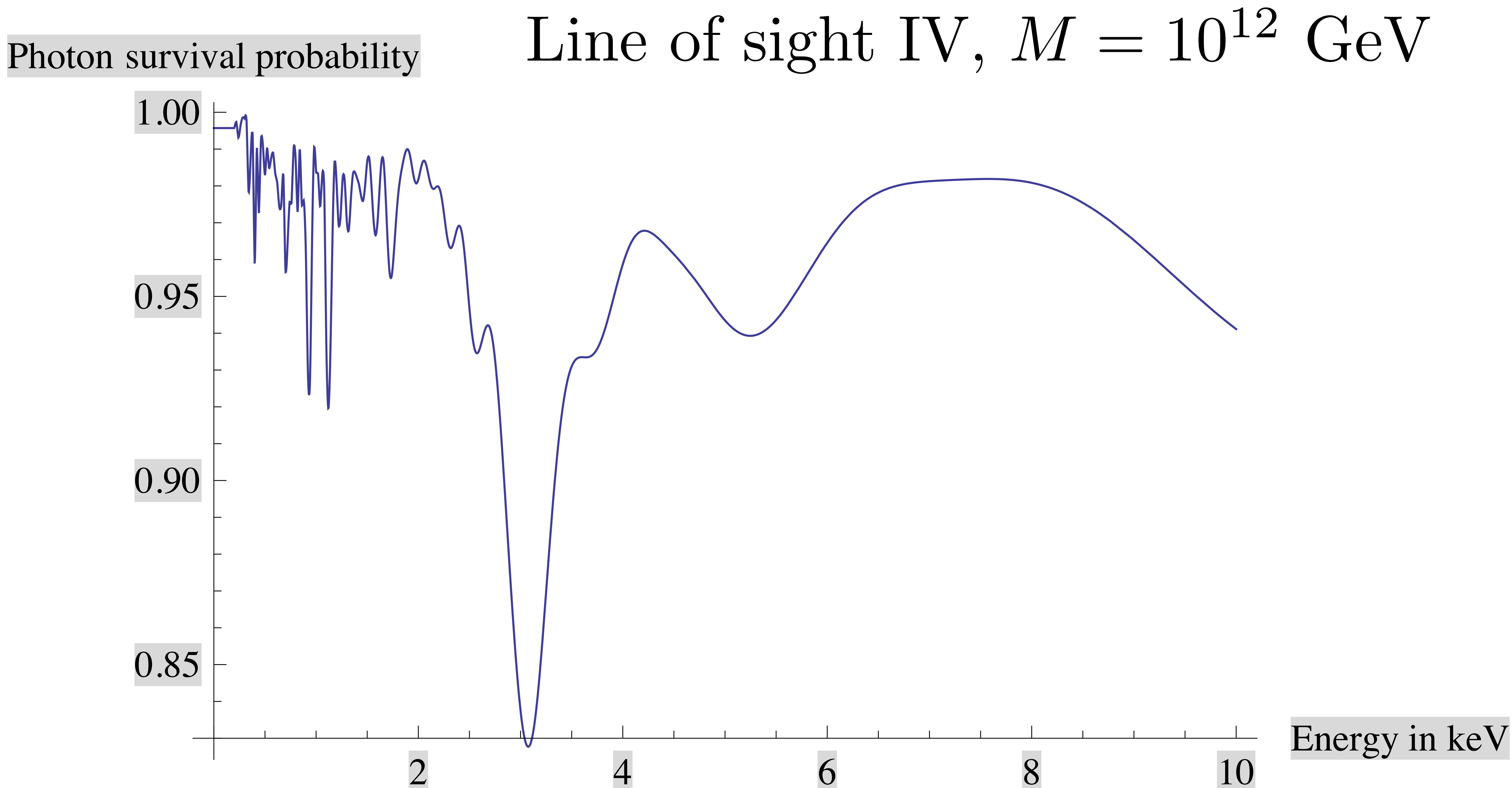


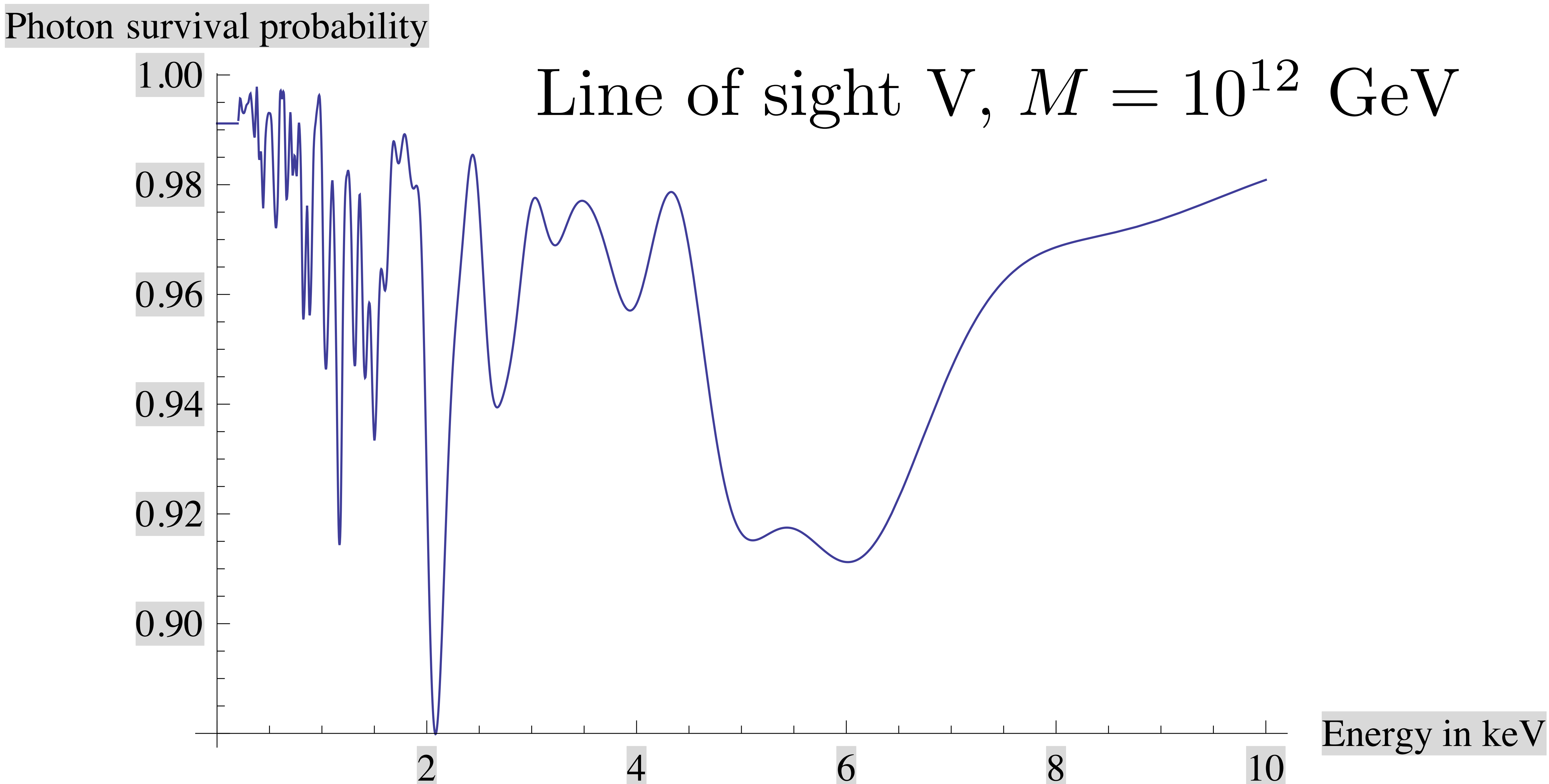
Distortion small field of view



Distortion small field of view



Distortion small field of view



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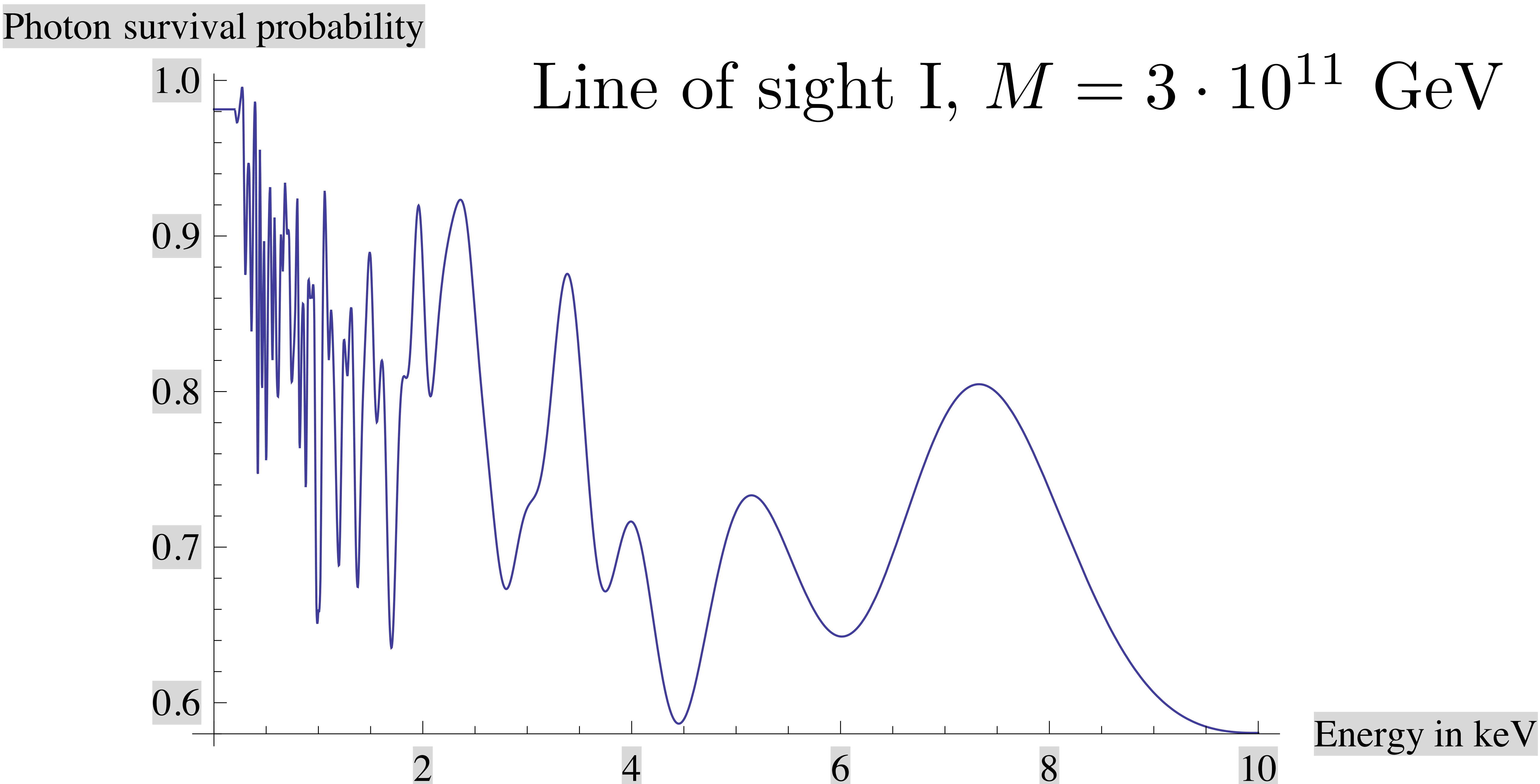
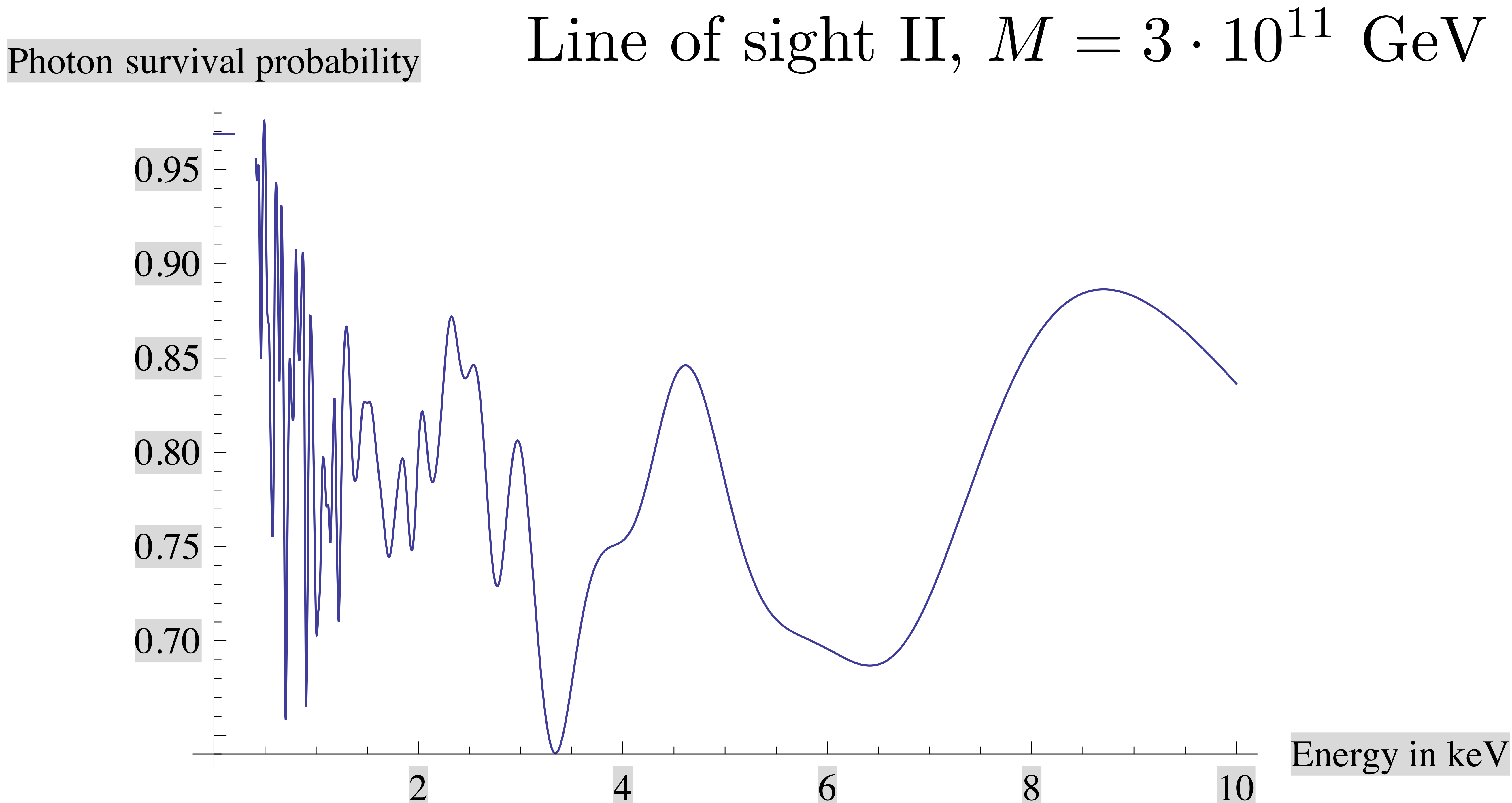
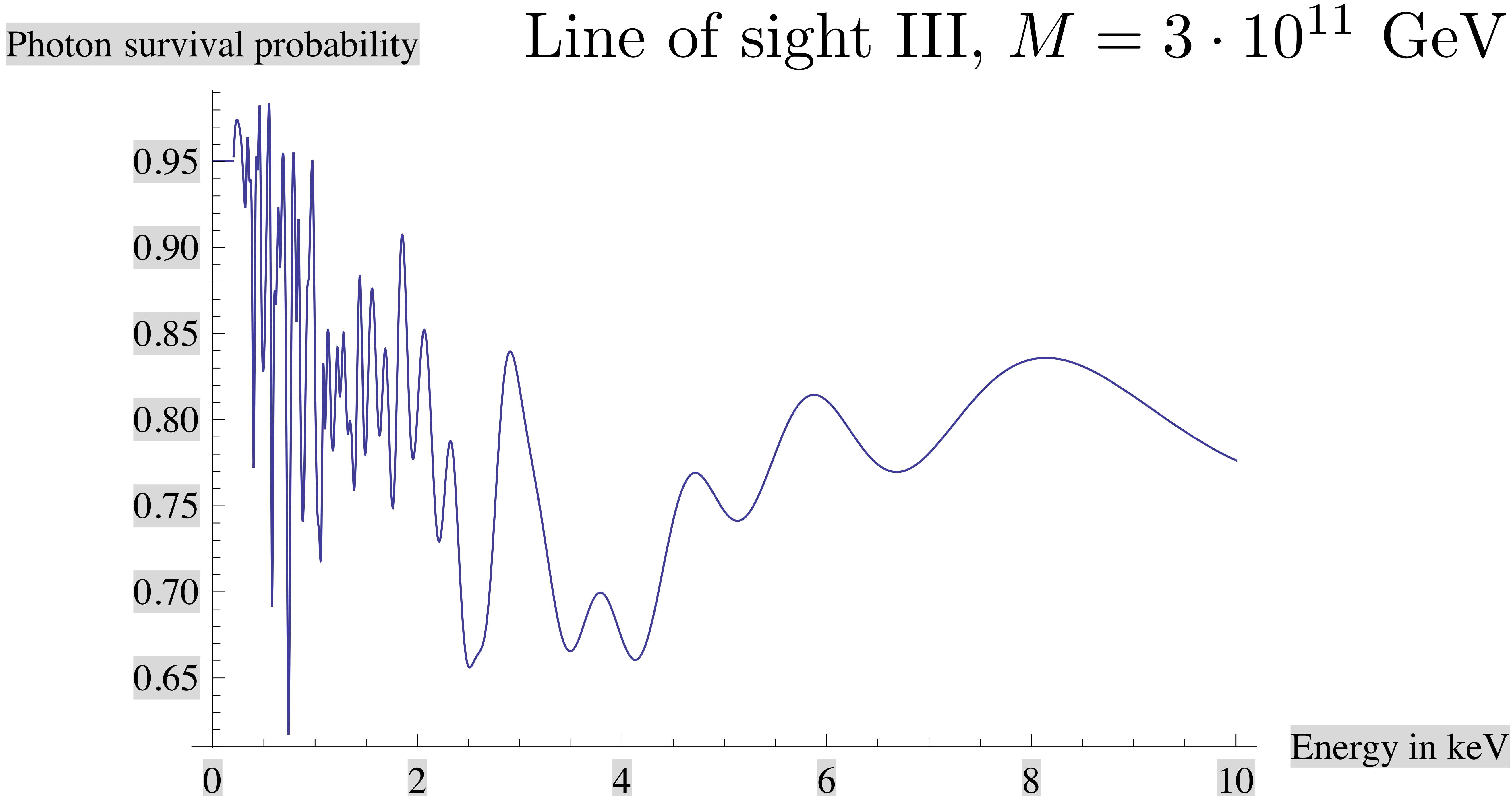


Distortion small field of view



Distortion small field of view



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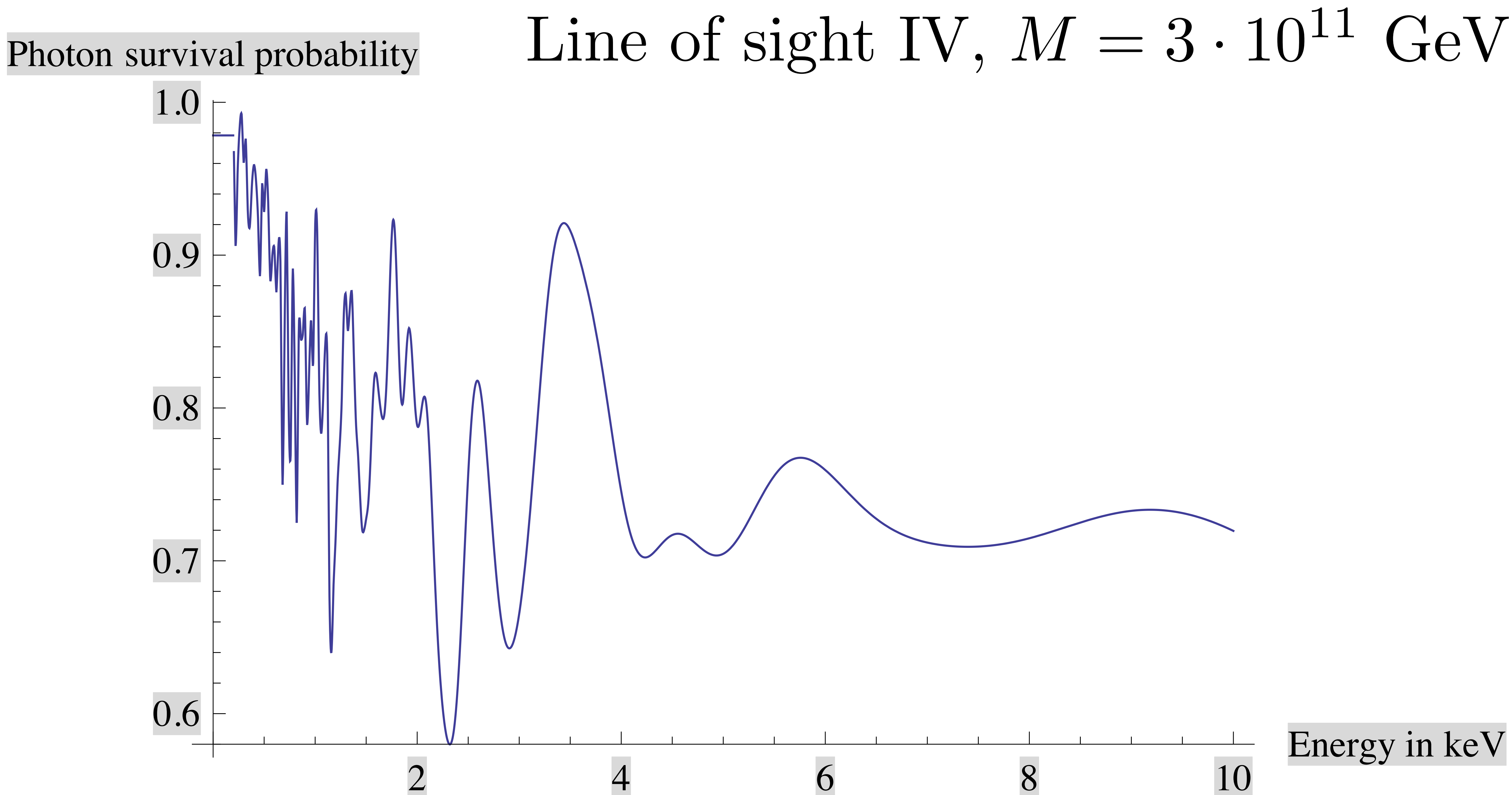

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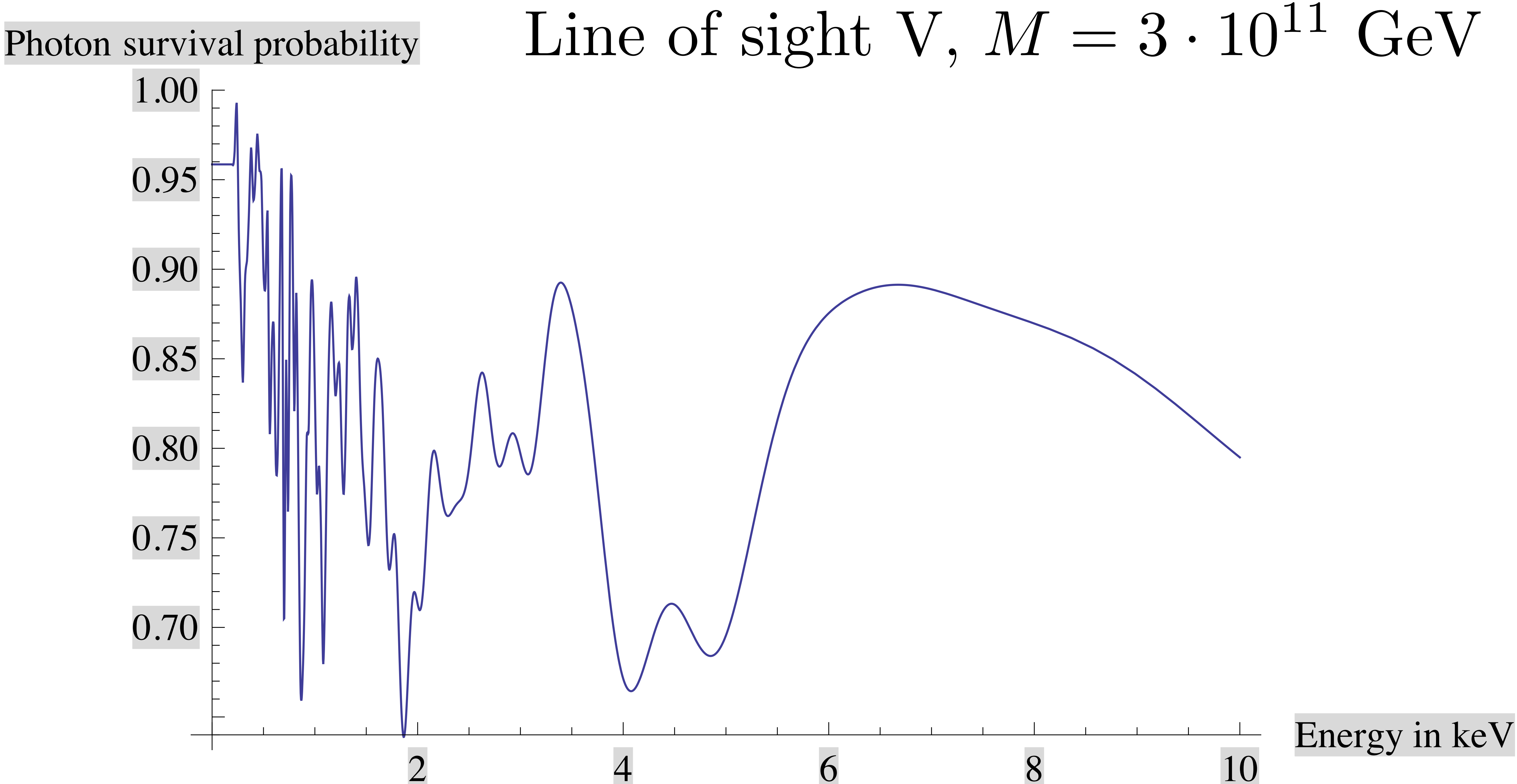
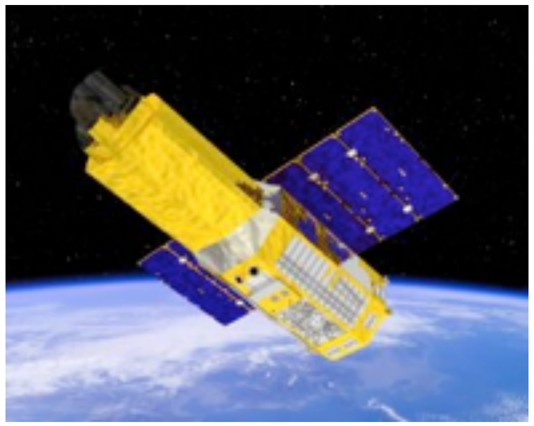


ALP induced spectral distortions on small scales

- Irregularities/ oscillations in 1/E are very distinctive from known astrophysical features (e.g. atomic lines)
- Nobody has searched for them in galaxy clusters
- We should look for them!
- Worst case, we can improve the bounds on ALP to photon coupling for light ALPs $m_a < 10^{-12}$ eV

Which telescope?

Suzaku



$\Delta E = 100$ eV,
$\Delta\phi = 60''$

XMM-Newton

$\Delta E = 100$ eV,
$\Delta\phi = 5''$

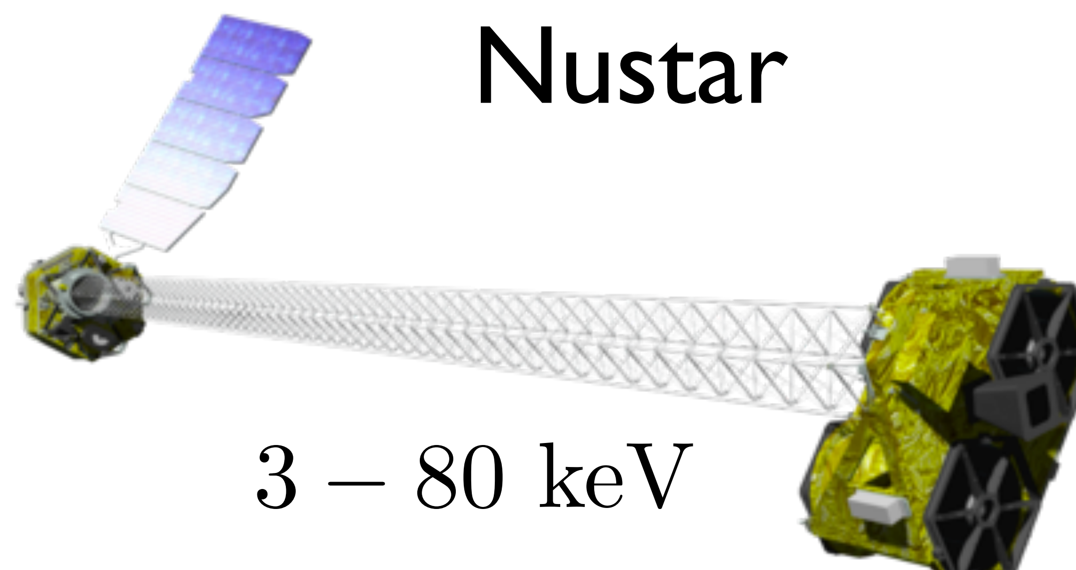
Chandra

$\Delta E = 100$ eV,
$\boxed{\Delta\phi = 0.5''}$

Hitomi/Astro-H

$\boxed{\Delta E = 5 \text{ eV}}$, $\Delta\phi = 60''$

Nustar



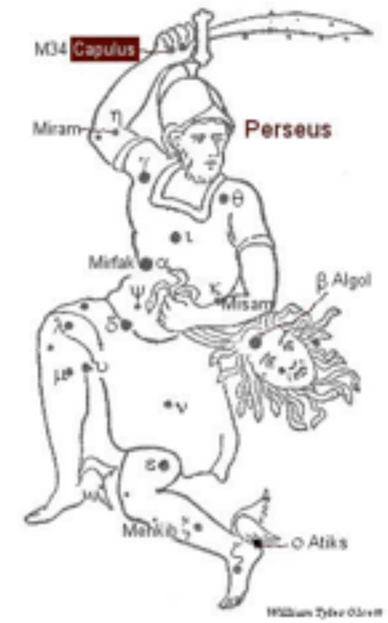
$3 - 80$ keV

$\Delta E = 500$ eV, $\Delta\phi = 10''$

Which clusters?

Nearby clusters: High count rate + angular resolution

Coma,
500 ks
$z = 0.023$



Perseus,
600 ks
$z = 0.018$

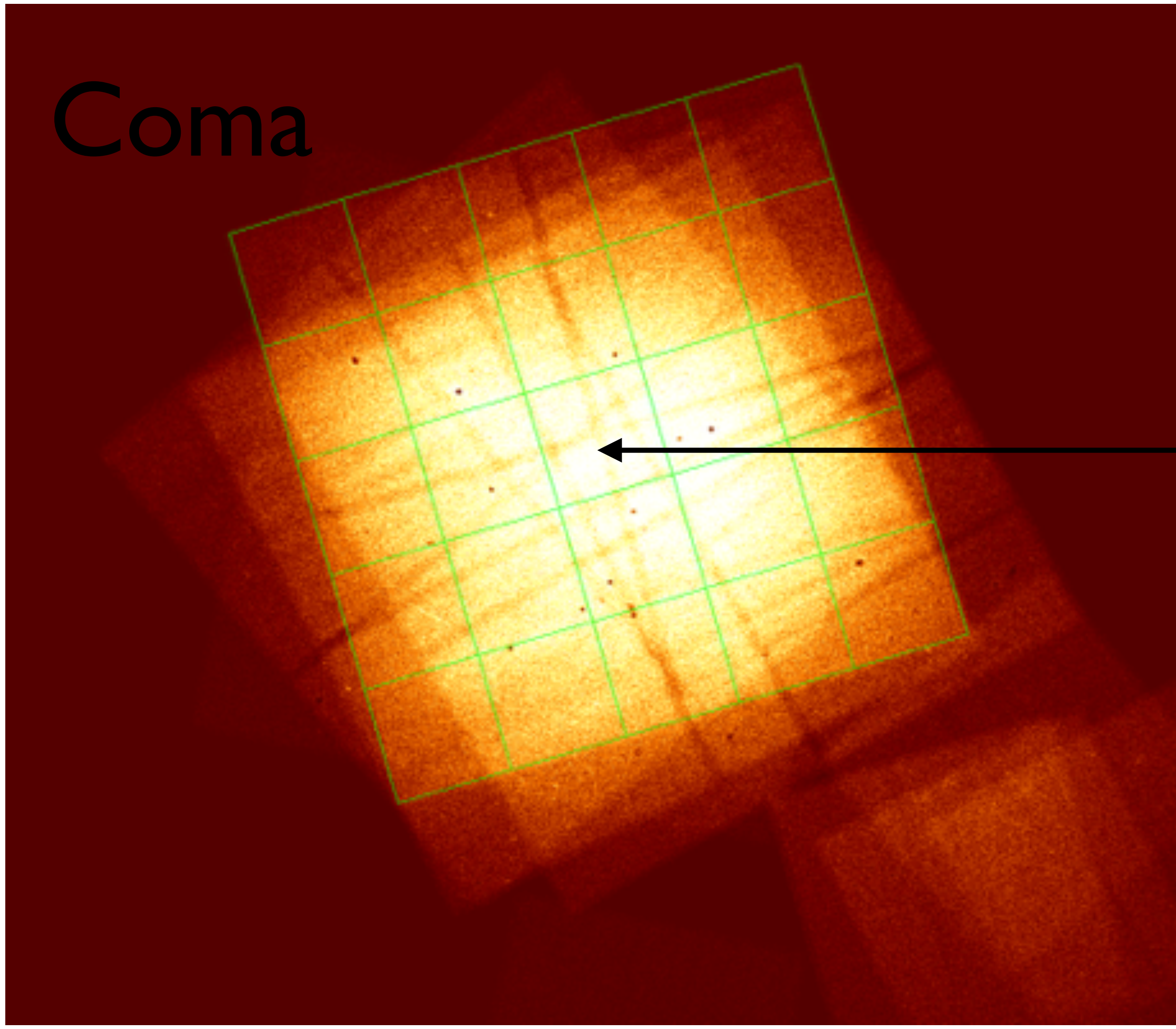
Centaurus,
700 ks
$z = 0.009$

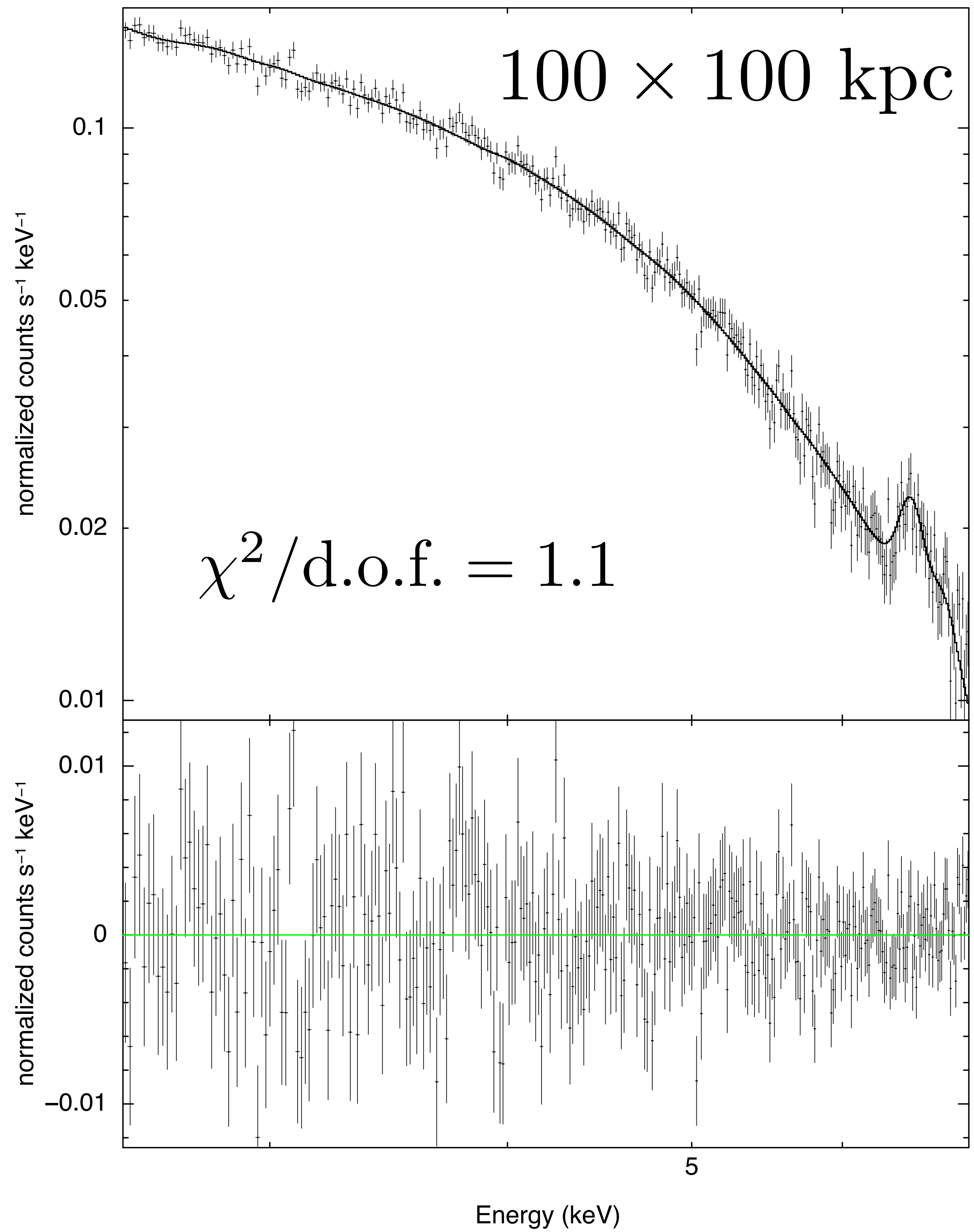
Ophiuchus,
300 ks
$z = 0.028$

Strategy

- Prepare observations for analysis (remove flares, remove point sources, substract background, stack observations)
- Fit temperature and atomic lines in large regions (e.g. 100x100 kpc)
- Fit normalization only in small regions (e.g. 10x10 kpc) and look for deviations from the thermal spectrum

The thermal spectrum

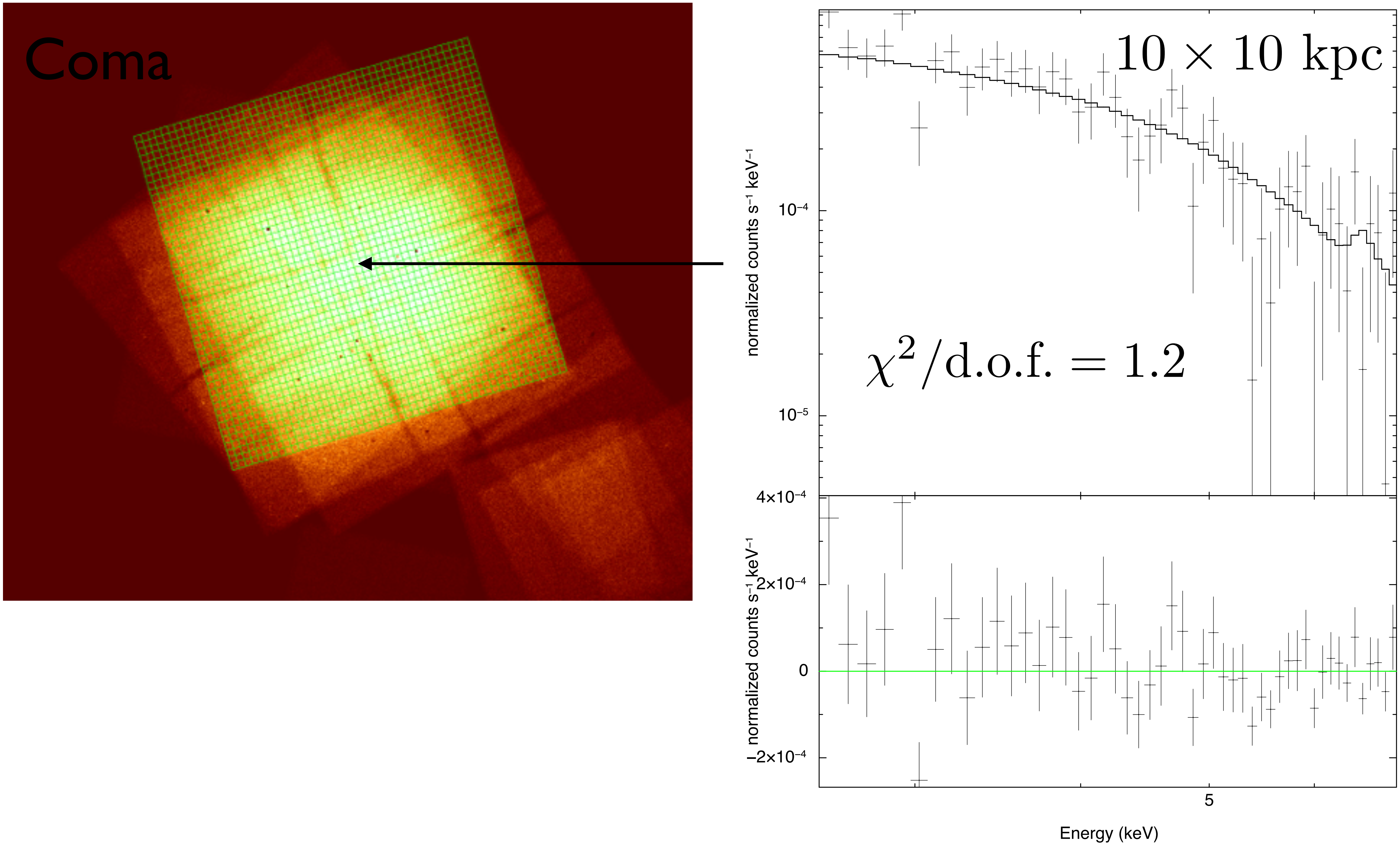




$T = 8.23 \pm 0.16$ keV

$\mathrm{Abundance} = 0.23 \pm 0.014\odot$

Small scale deviations?



Conclusions

- ALPs generically arise in string compactifications
- Their properties can be probed via ALP-photon conversion
- Galaxy clusters provide excellent environment to look for ALPs
- ALP induced small scale spectral distortions - stay tuned for results!

Future Data

Chandra:

Appr Exp	Exposure	Target Name	PI Name	RA	Dec	Status	Data Mode	Exp Mode	Avg Cnt Rate	Evt Cnt	Start Date
10.0	10.08	Coma Cluster	Calibration	12 59 48.00	+27 58 00.00	archived			90.86	916084	2014-11-21 01:12:03
10.0	10.09	Coma Cluster	Calibration	12 59 48.00	+27 58 00.00	archived			80.28	810345	2015-05-24 17:56:10
50.0		Coma cluster	Zhuravleva	12 58 35.90	+28 04 29.30	scheduled	VFAINT	TE			2016-03-05 12:03:57
180.0		Coma cluster	Zhuravleva	12 58 35.90	+28 04 29.30	unobserved	VFAINT	TE			2017-02-10 00:00:00
180.0		Coma cluster	Zhuravleva	12 58 35.90	+28 04 29.30	unobserved	VFAINT	TE			2016-03-12 00:00:00
180.0		Coma cluster	Zhuravleva	12 58 35.90	+28 04 29.30	unobserved	VFAINT	TE			2016-11-02 00:00:00
180.0		Coma cluster	Zhuravleva	12 58 35.90	+28 04 29.30	unobserved	VFAINT	TE			2016-11-02 00:00:00
180.0		Coma cluster	Zhuravleva	12 58 35.90	+28 04 29.30	unobserved	VFAINT	TE			2016-03-14 00:00:00
50.0		Coma cluster	Zhuravleva	12 58 35.90	+28 04 29.30	unobserved	VFAINT	TE			2016-03-07 00:00:00

$= 1000 \text{ ks} \Rightarrow 1500 \text{ ks total!}$

Hitomi/Astro-H:

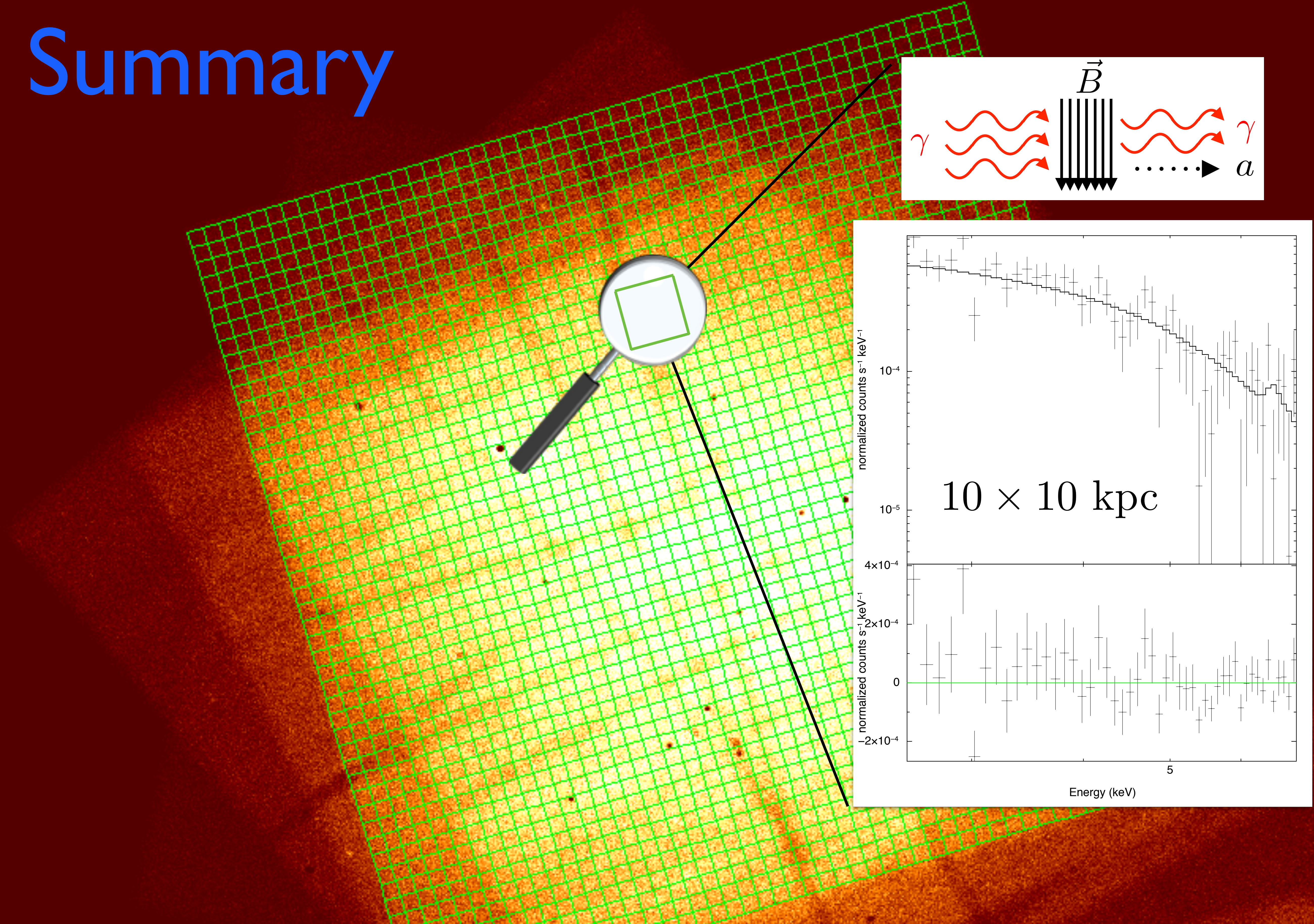
launched last week!

Japanese H-IIA rocket launches ASTRO-H mission

February 17, 2016 by William Graham

Japan launched the ASTRO-H x-ray astronomy satellite via its H-IIA rocket Wednesday, with a launch from the country's Tanegashima launch site occurring at 17:45 local time (08:45 UTC). ASTRO-H, which is was previously known as the New X-ray Telescope (NeXT), is a high-energy astronomy mission led by the Japan Aerospace Exploration Agency (JAXA).

Summary



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