Ultra-high energy cosmic rays in harmonic space

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Rationale

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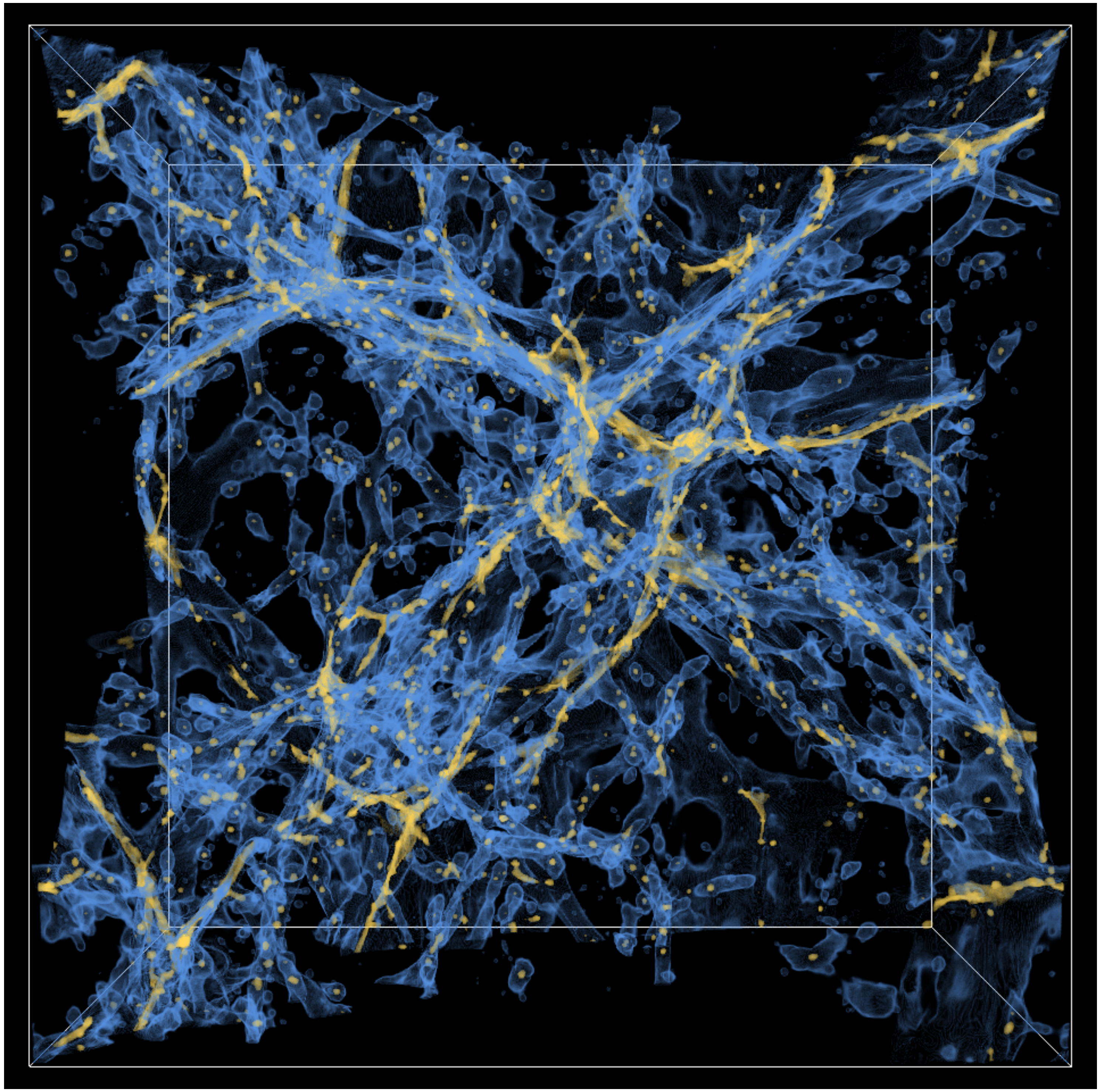
[Lukic et al.; Image: Casey Stark]



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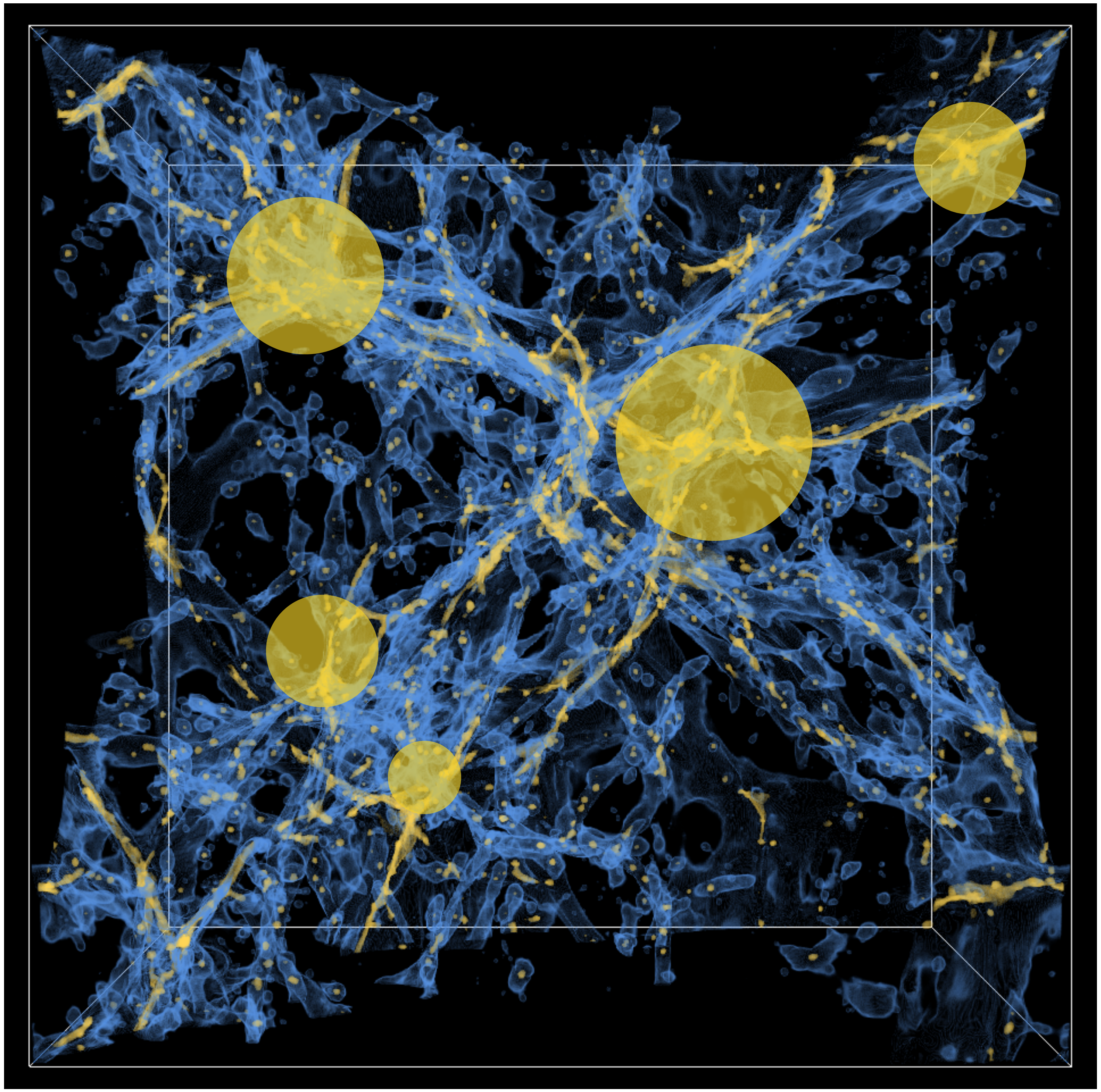

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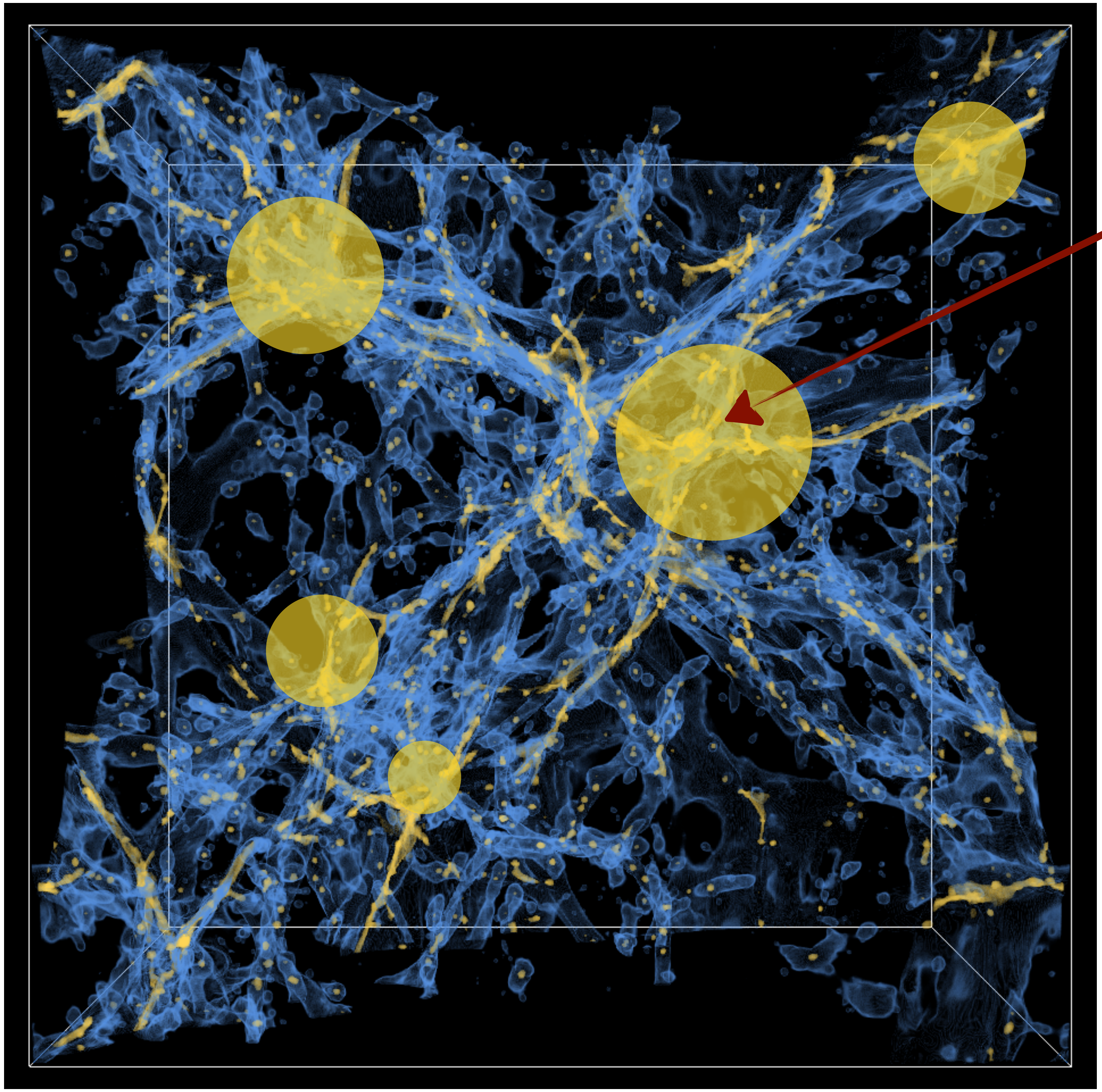

Galaxies,
galaxy clusters,
gravitational lensing

Rationale

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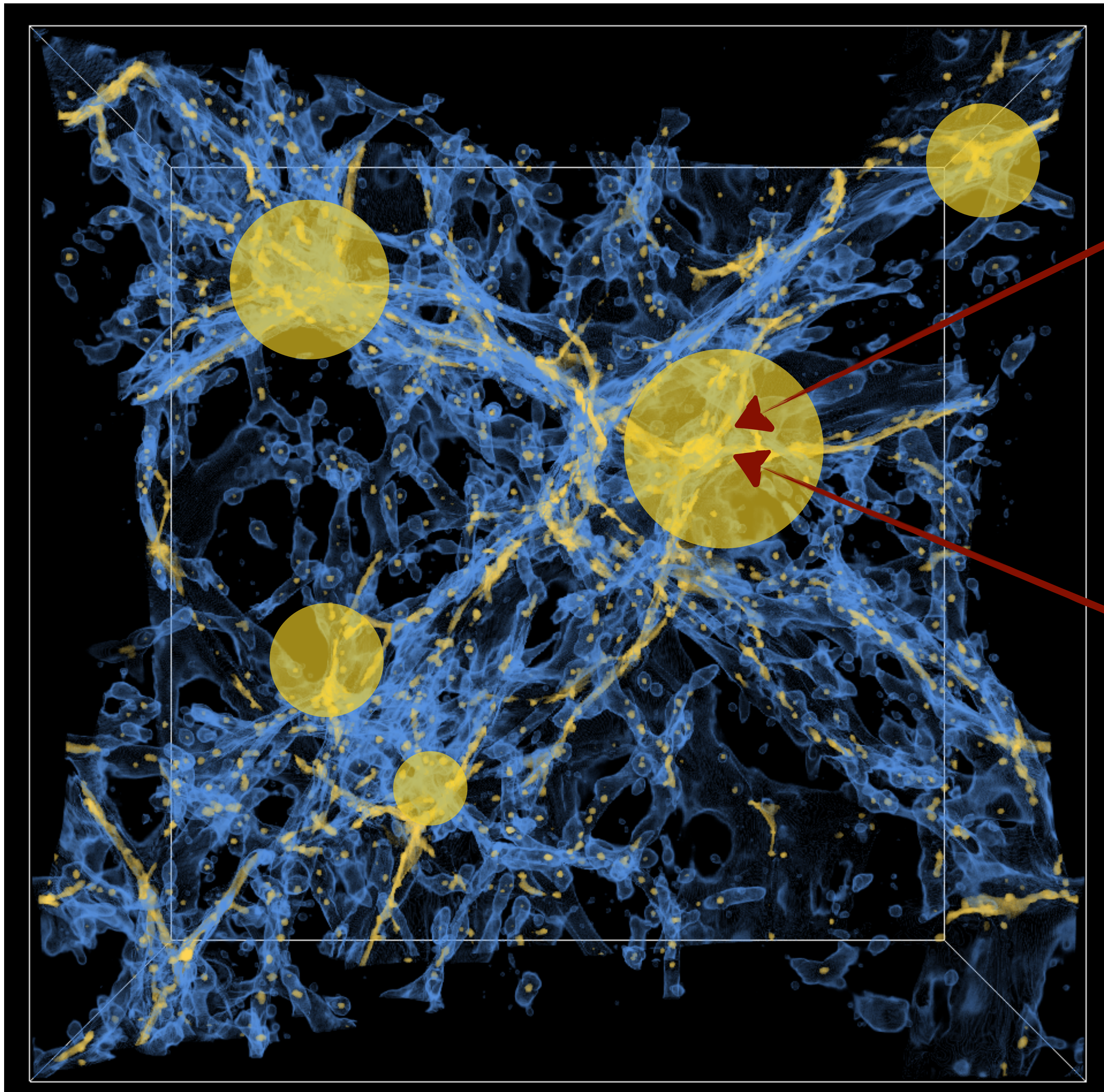

Galaxies,
galaxy clusters,
gravitational lensing

Cosmic rays from
astrophysical sources
hosted within the
dark matter halo

Correlations 1.01

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- Cosmological perturbations
  [temperature anisotropies, density fluctuations…]

$$f(t, \boldsymbol{x})$$

Correlations 1.01

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- Cosmological perturbations $f(t, \boldsymbol{x})$
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- Correlation function $\xi^f(t, |\boldsymbol{x} - \boldsymbol{y}|) = \langle f(t, \boldsymbol{x}) f(t, \boldsymbol{y}) \rangle$

Correlations 1.01

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- Fourier-space power spectrum

$$\langle \hat{f}_{\boldsymbol{k}}(t) \hat{f}^{\star}_{\boldsymbol{k}'}(t) \rangle = (2\pi)^3 \delta_{\rm D}(\boldsymbol{k} - \boldsymbol{k}') P^f(k, t)$$

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- Harmonic-space power spectrum
  $$\langle \tilde{f}_{\ell m}(z) \tilde{f}^\star_{\ell' m'}(z') \rangle = \delta^{\rm K}_{\ell\ell'} \delta^{\rm K}_{mm'} C^f_\ell(z, z')$$

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- *E.g.*: CMB temperature anisotropies $f(t,\boldsymbol{x})\to T(t_0,\hat{\boldsymbol{n}})$

Correlations 1.01

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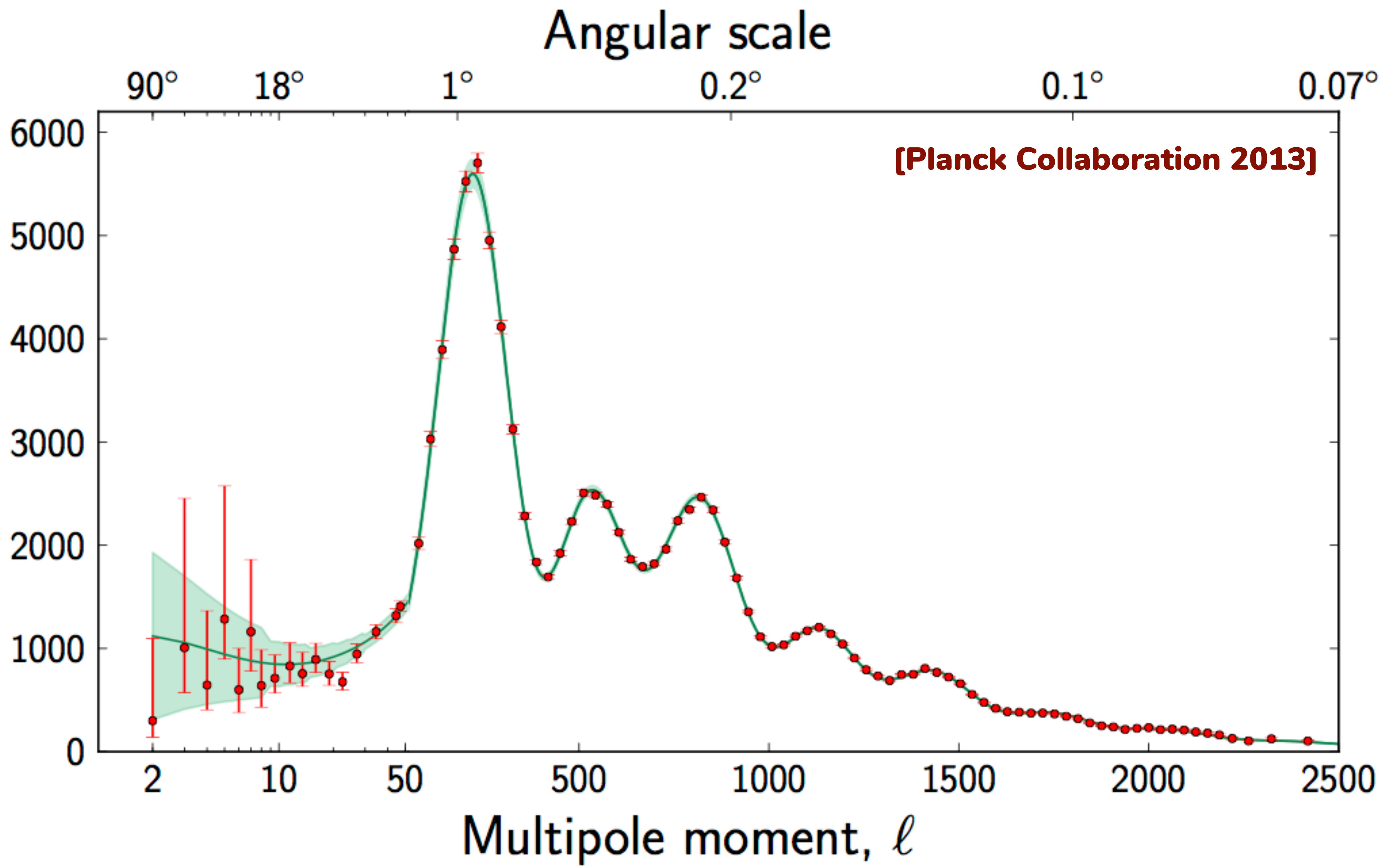

Cross-correlations

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- Cosmological perturbations $f(t,\boldsymbol{x}),\ g(t,\boldsymbol{x})$
  [temperature anisotropies, density fluctuations…]
- Correlation function $\xi^{fg}(t,|\boldsymbol{x}-\boldsymbol{y}|)=\langle f(t,\boldsymbol{x})g(t,\boldsymbol{y})\rangle$
- Fourier-space power spectrum
  $$\langle \hat{f}_{\boldsymbol{k}}(t)\hat{g}^\star_{\boldsymbol{k}'}(t)\rangle=(2\pi)^3\delta_{\rm D}(\boldsymbol{k}-\boldsymbol{k}')P^{fg}(k,t)$$
- Harmonic-space power spectrum
  $$\langle \tilde{f}_{\ell m}(z)\tilde{g}^\star_{\ell' m'}(z')\rangle=\delta^{\rm K}_{\ell\ell'}\delta^{\rm K}_{mm'}C^{fg}_\ell(z,z')$$
- *E.g.*: CMB-galaxy cross-correlation (measurement of **ISW**)

UHECR anisotropies

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- Fluctuations in detected UHECRs in a given direction on the sky and above a certain energy cut

$$\Delta_{\rm CR}(\hat{\boldsymbol{r}}, E_{\rm cut}) = \frac{{\rm Flux}(\hat{\boldsymbol{r}}, E_{\rm cut})}{{\rm MeanFlux}(E_{\rm cut})} - 1$$

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Cosmic expansion

Attenuation

UHECR anisotropies

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Perturbations in the 3D number density of UHECR sources

UHECR anisotropies

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- Fluctuations in observed galaxy positions in a given direction on the sky and in a volume centred in a certain mean redshift

$$\Delta_{\rm g}(\hat{\boldsymbol{r}}, z) = \frac{{\rm NumberDensity}(\hat{\boldsymbol{r}}, z)}{{\rm MeanNumberDensity(z)}} - 1$$

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Radial selection function

UHECR anisotropies

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3D galaxy density field

Harmonic-space power spectrum

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- Assuming that all UHECRs originate from observed galaxies

$$C_\ell = \int \mathrm{d}r \, \frac{\phi_a(r)\,\phi_b(r)}{r^2} P_{ab}\left[z(r), k = \frac{\ell + 1/2}{r}\right]$$

$$a, b = \{\mathrm{CR}, \mathrm{g}\}$$

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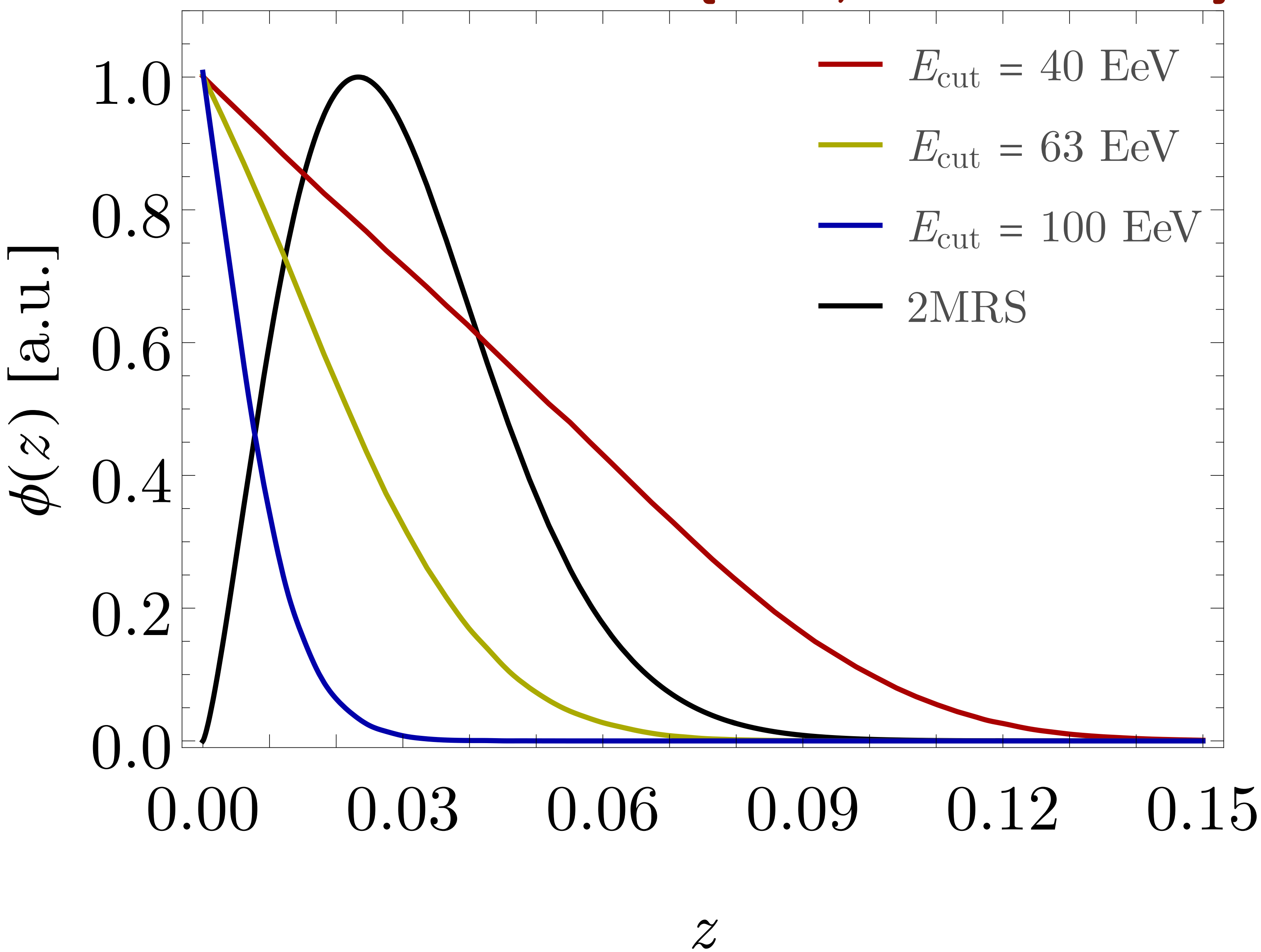
Fourier-space power spectrum of the two fields (**CR** and/or **g**)

How does it look like?

- UHECR and 2MRS (2MASS spectro-z survey) galaxy kernels

[Urban, SC & Alonso 2020]



How does it look like?

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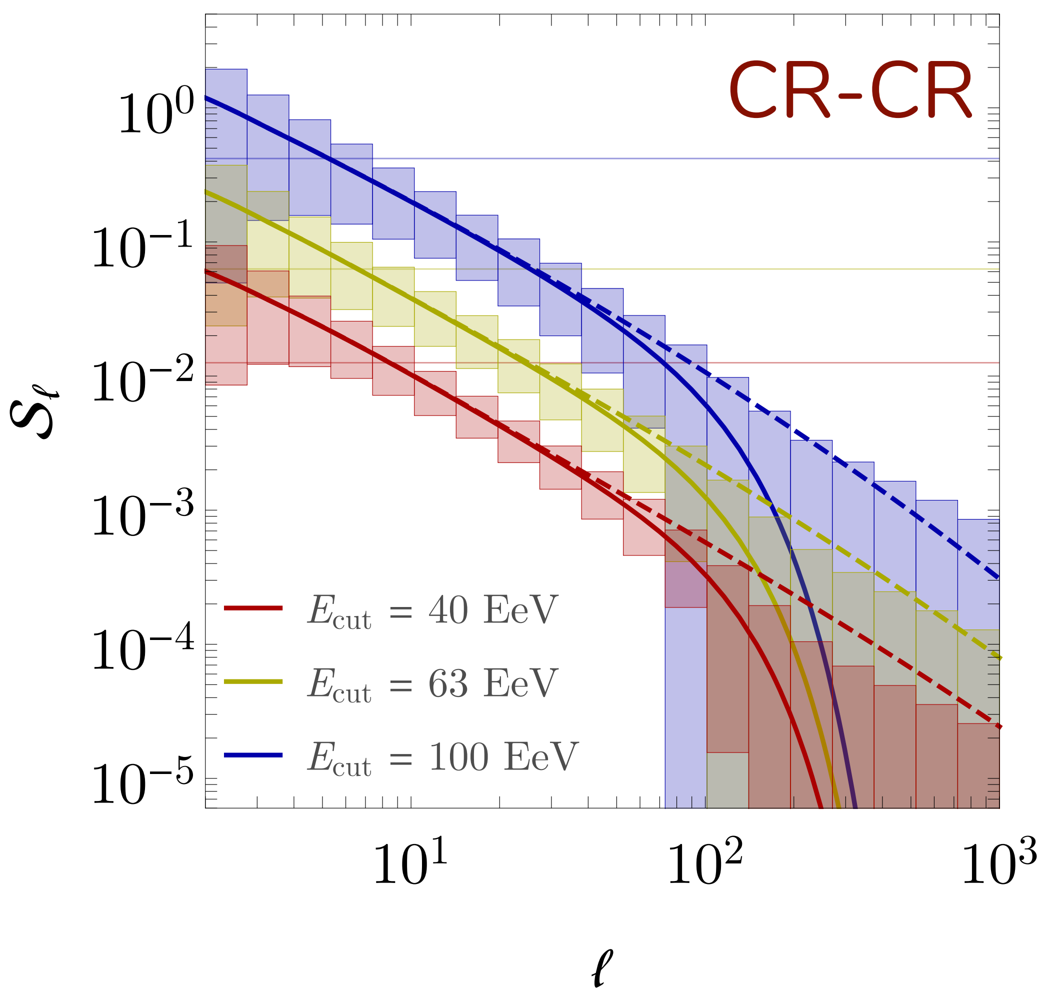
- Auto-correlation of UHECRs

[Urban, SC & Alonso 2020]



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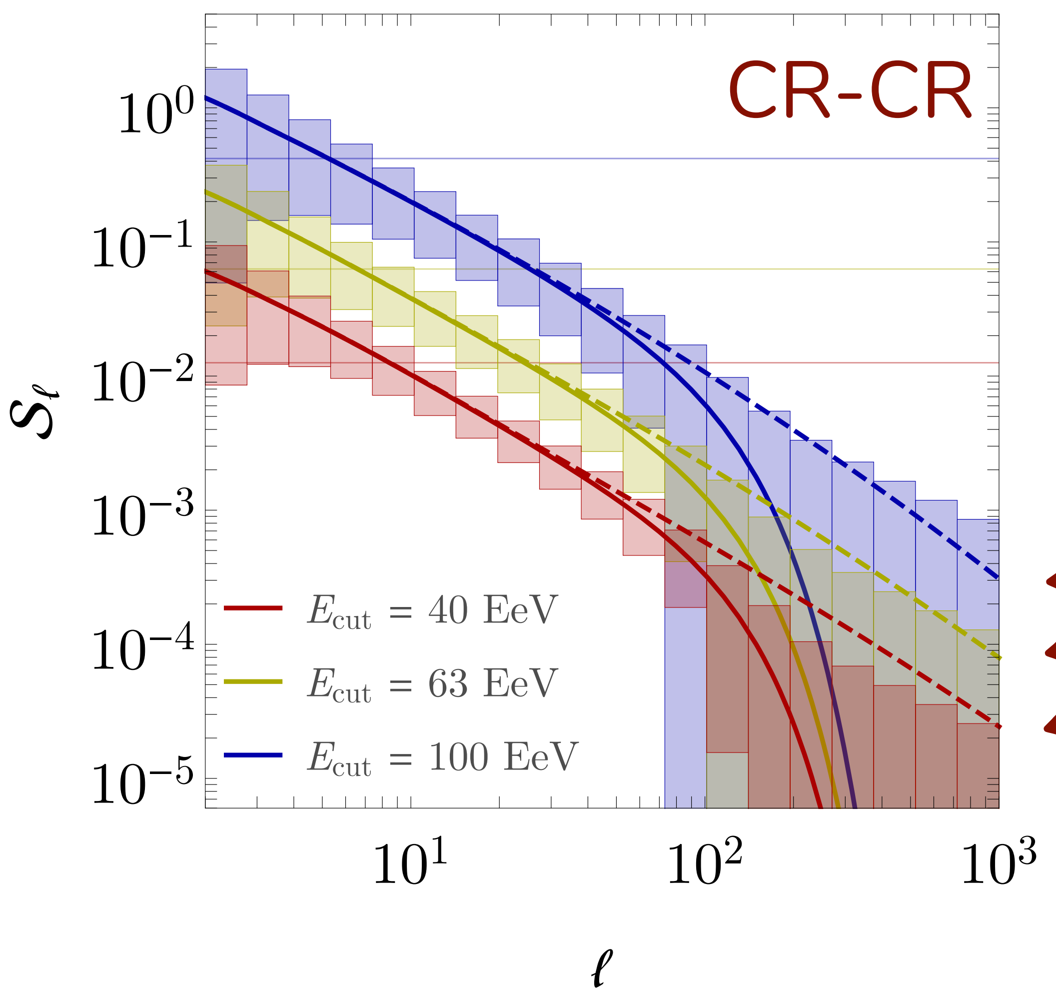

Not including a 1° beam smearing accounting for (x)GMF

How does it look like?

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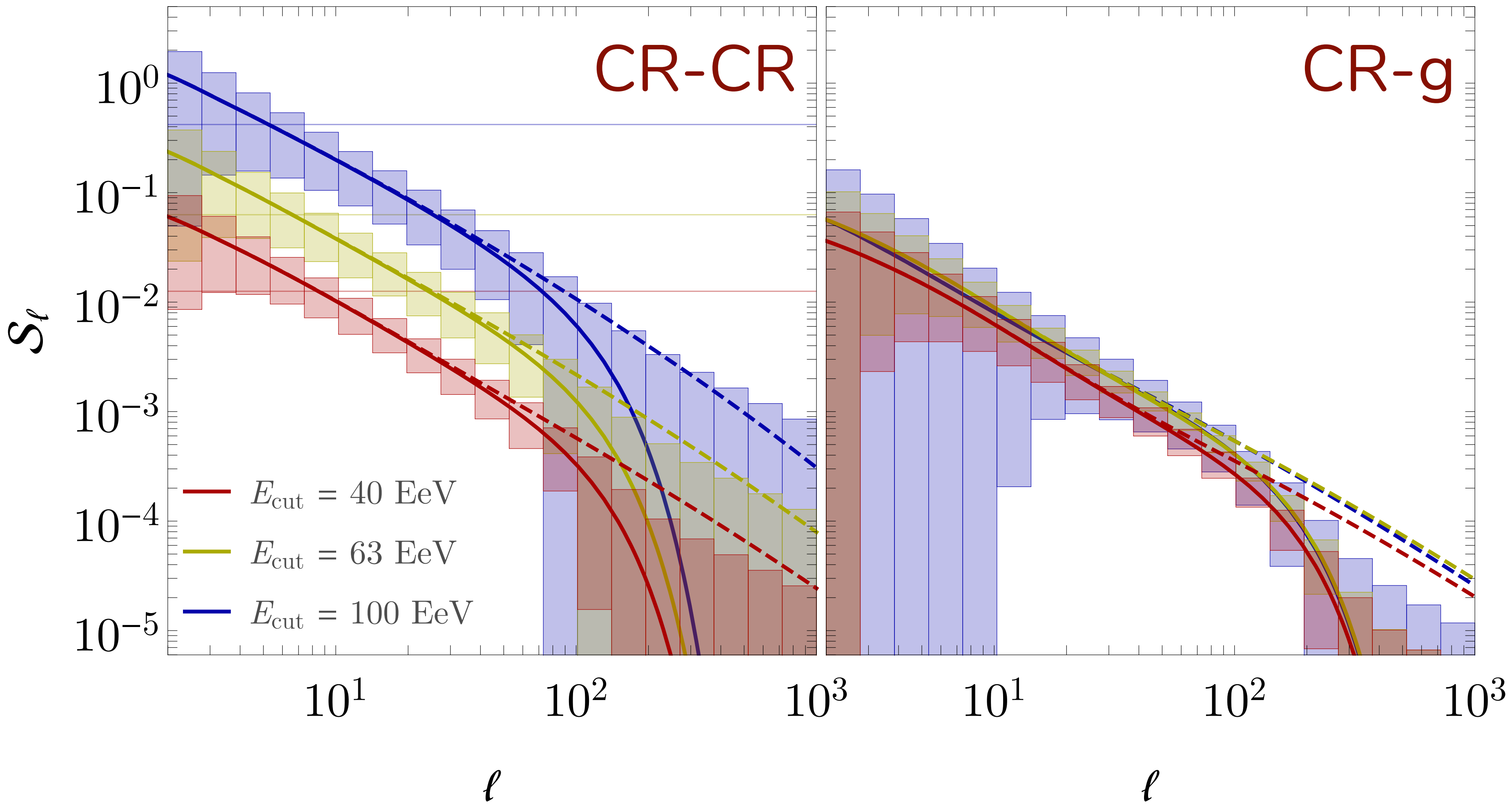
- Cross-correlation between UHECRs and 2MRS galaxies

[Urban, SC & Alonso 2020]



How does it look like?

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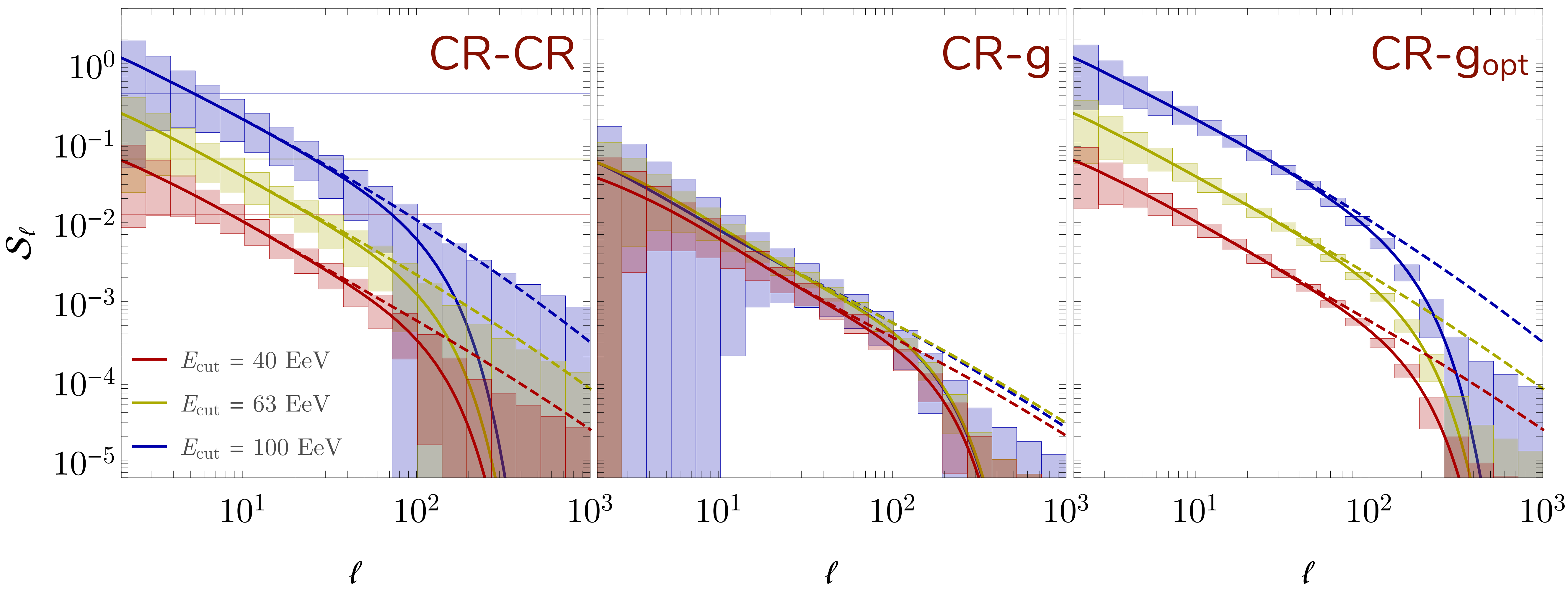
- Cross-correlation between UHECRs and 2MRS optimally-weighted galaxies

[Urban, SC & Alonso 2020]



Signal-to-noise ratio

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- Per-multipole signal-to-noise ratio

$$\mathrm{SNR}^2 = \sum_{\ell=\ell_\mathrm{min}}^{\ell_\mathrm{max}} \left(\mathrm{SNR}_\ell\right)^2$$

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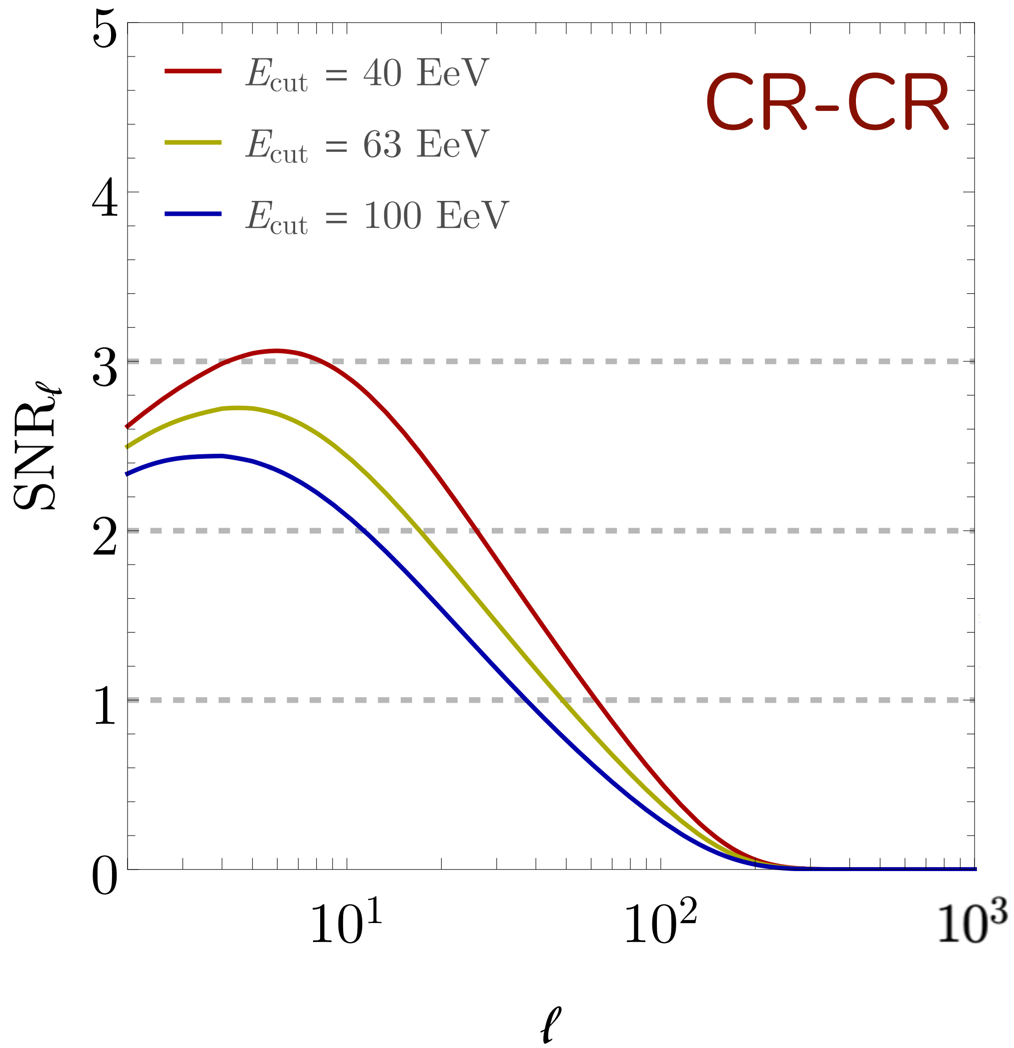

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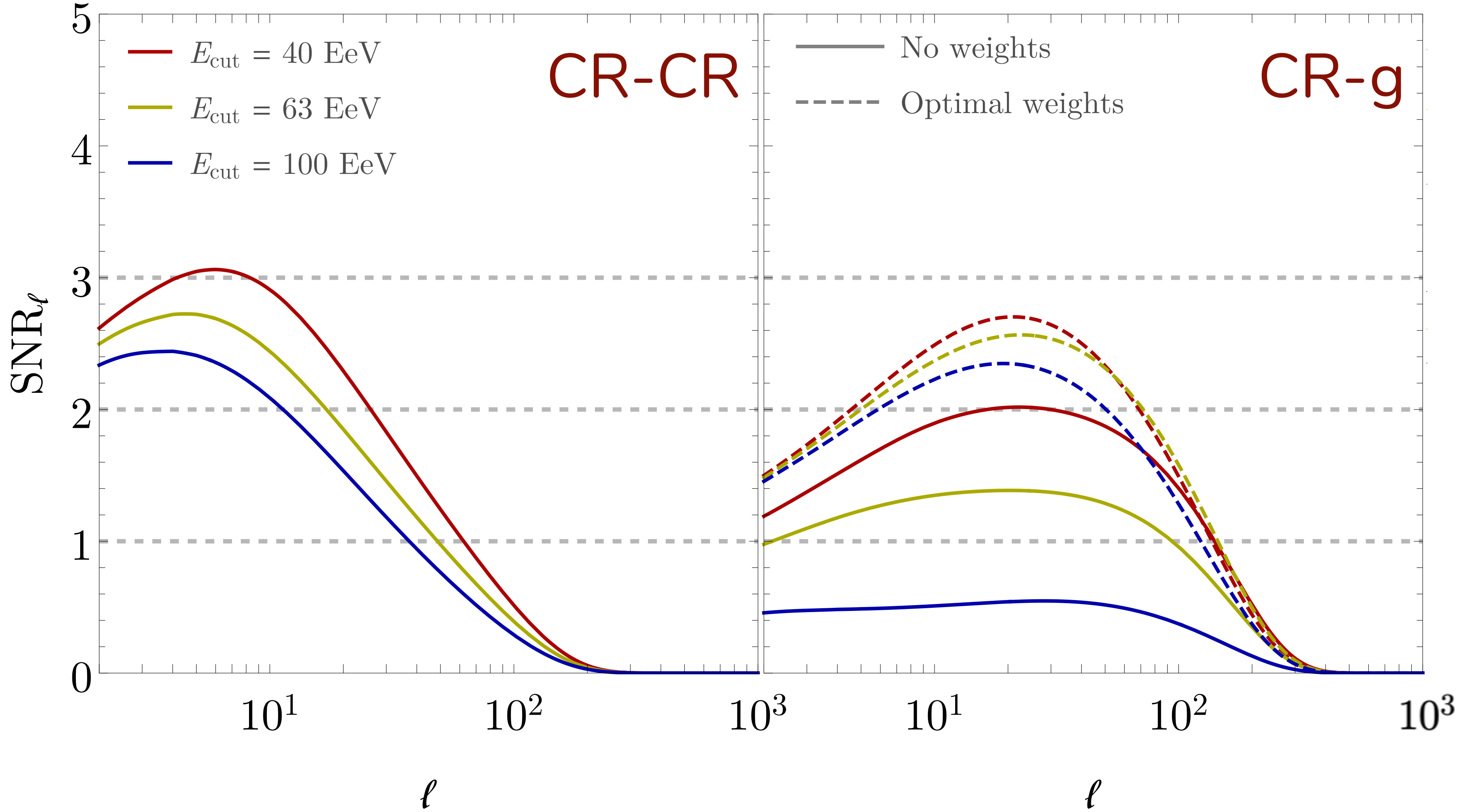

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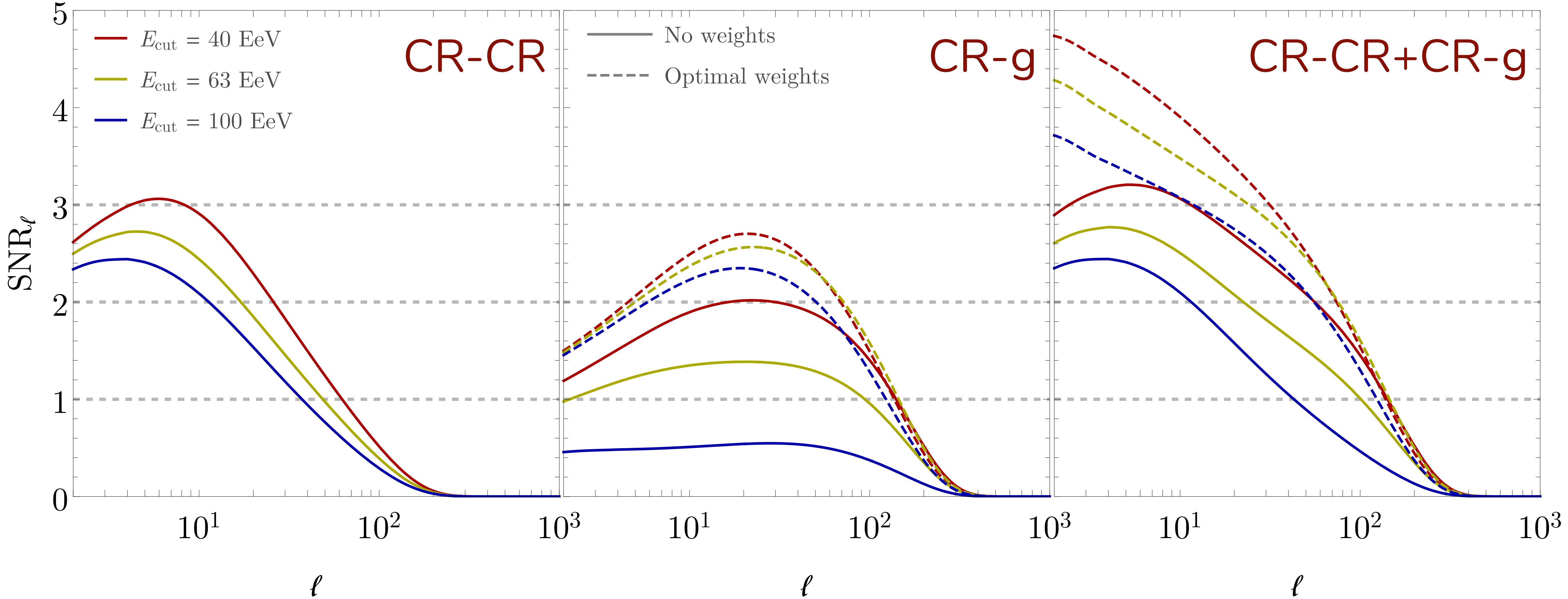

Conclusions

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- A new observable for UHECR physics:
  - The harmonic-space cross-correlation power spectrum between the arrival directions of UHECRs and the distribution of the cosmic large-scale structure as mapped by galaxies
- Easier to detect than UHECR alone (galaxies boost the signal)
- More sensitive to anisotropies on small angular scales
- Less prone to systematic effects and to the GMF smearing