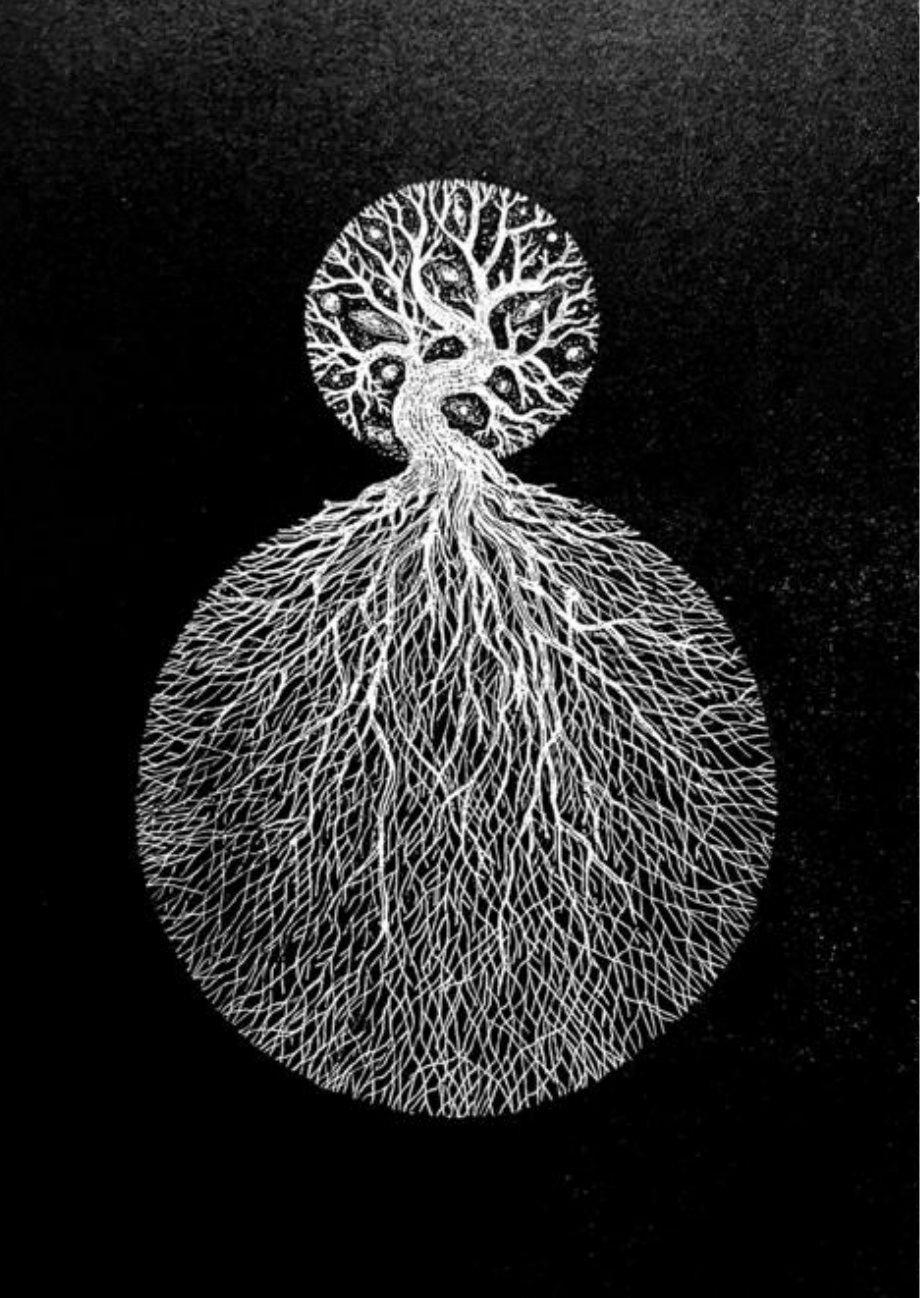

Synergies across the spectrum for cosmology and astroparticle physics

Stefano Camera

Department of Physics, Alma Felix University of Turin, Italy

Physics Torino Department of Excellence

INFN TORINO Istituto Nazionale di Fisica Nucleare Sezione di Torino

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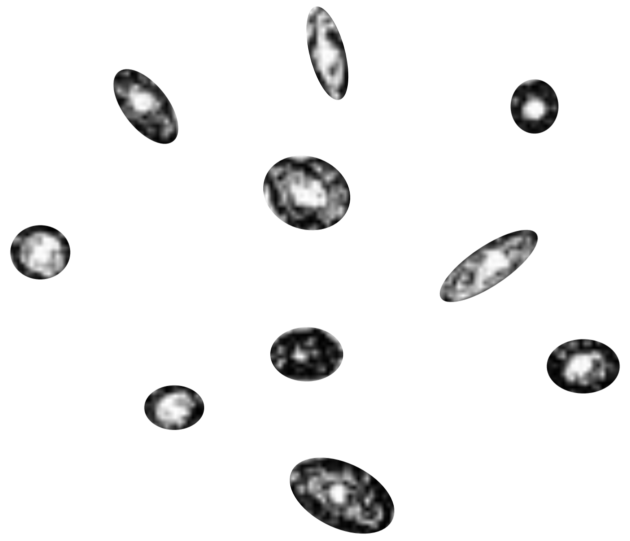
The concordance cosmological model



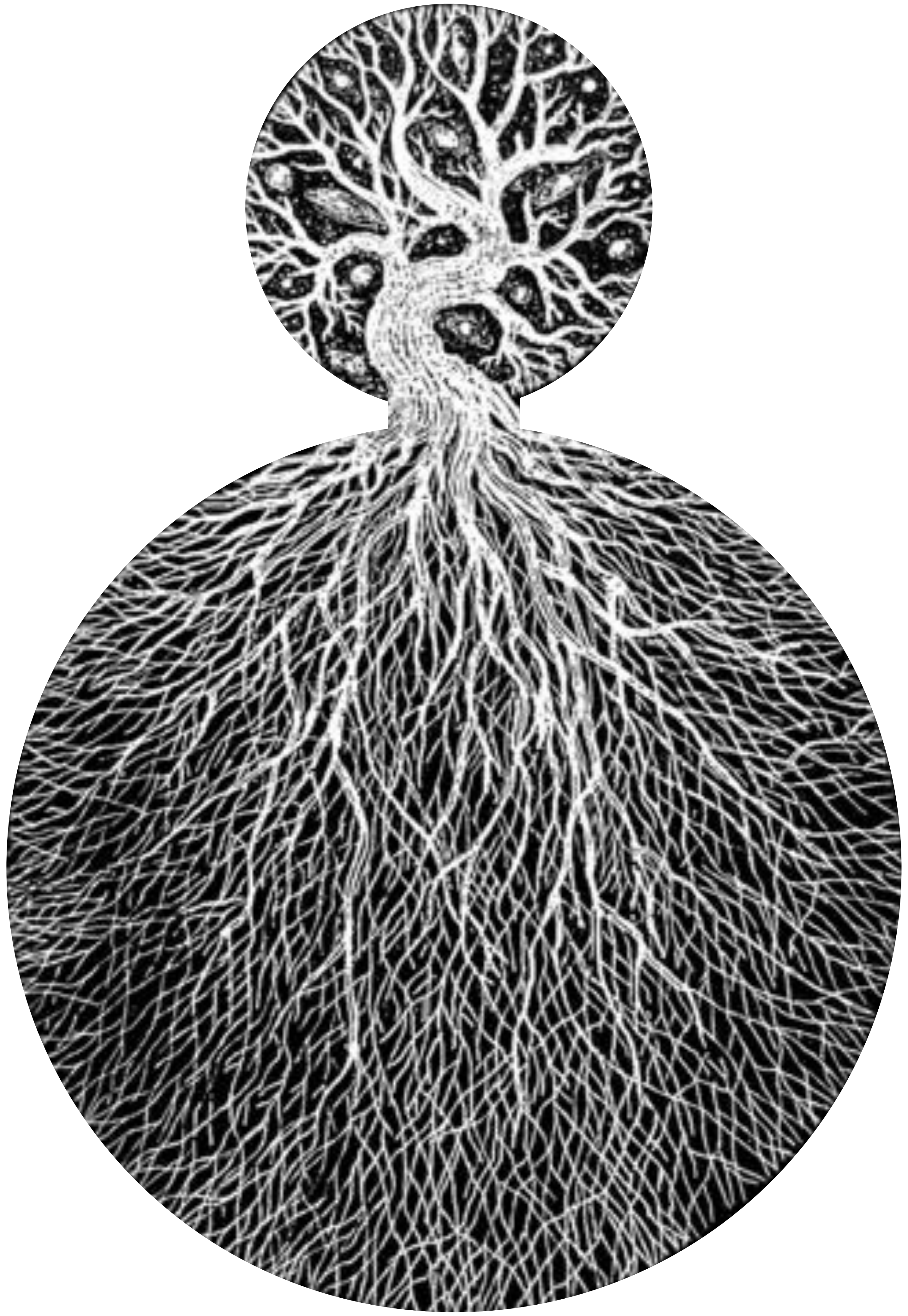
- Stars in galaxies: 7%

The concordance cosmological model

- Stars in galaxies: 7%
- Gas in galaxies and clusters: 93%

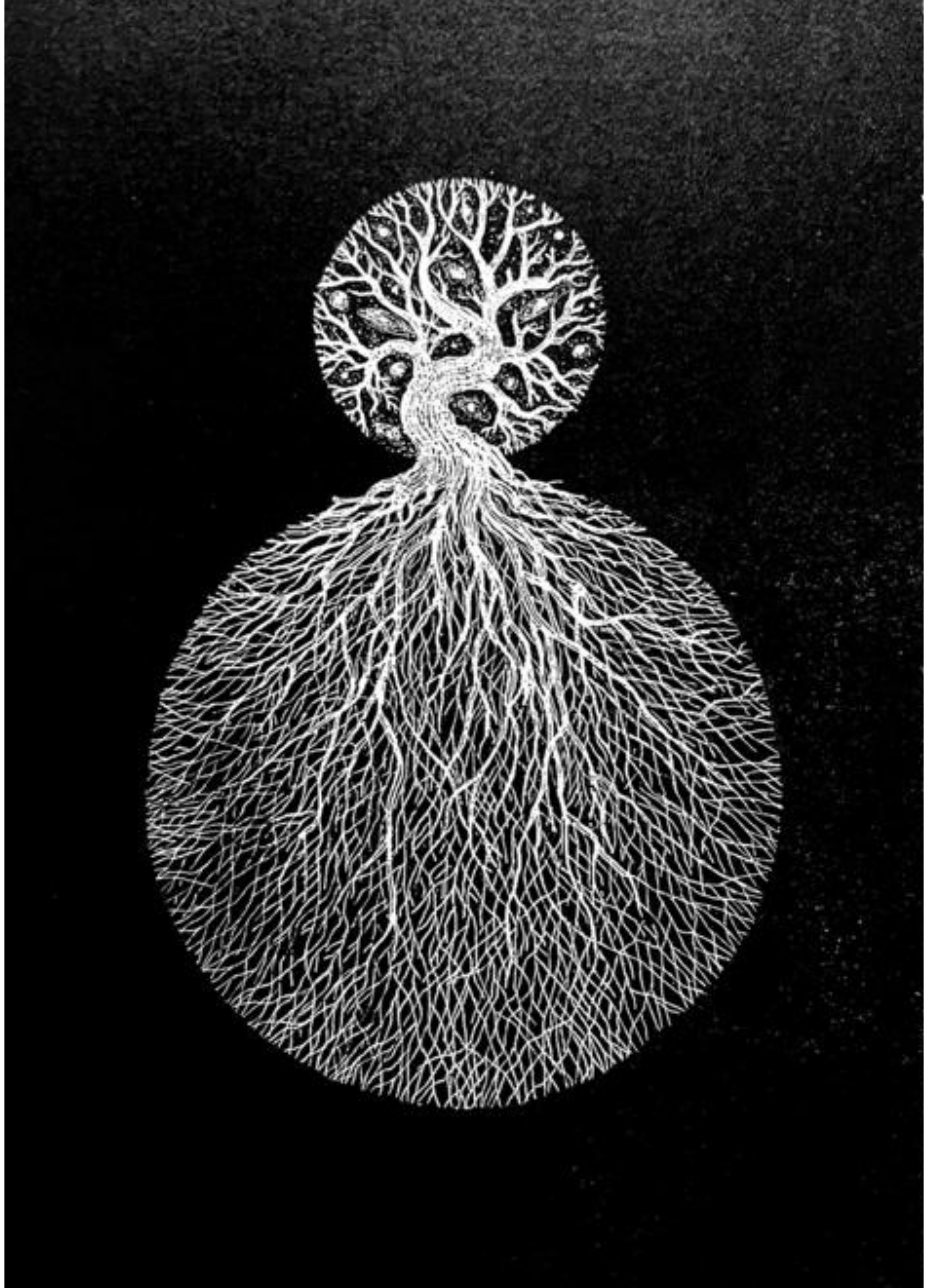
The concordance cosmological model

- Ordinary matter: 5%
- Dark matter: 25%



The concordance cosmological model

- Ordinary matter: 5%
- Dark matter: 25%
- Dark energy: 70%



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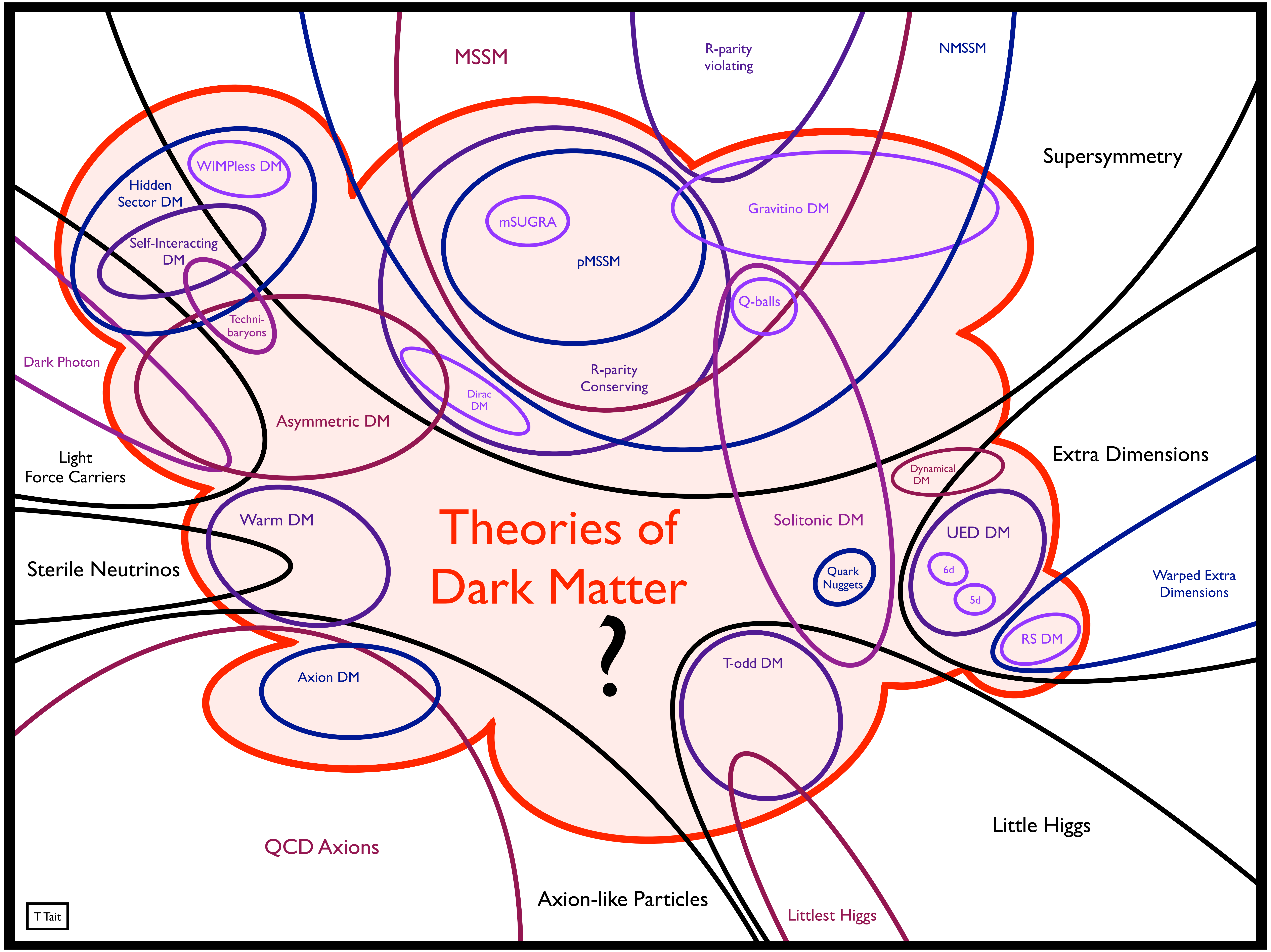
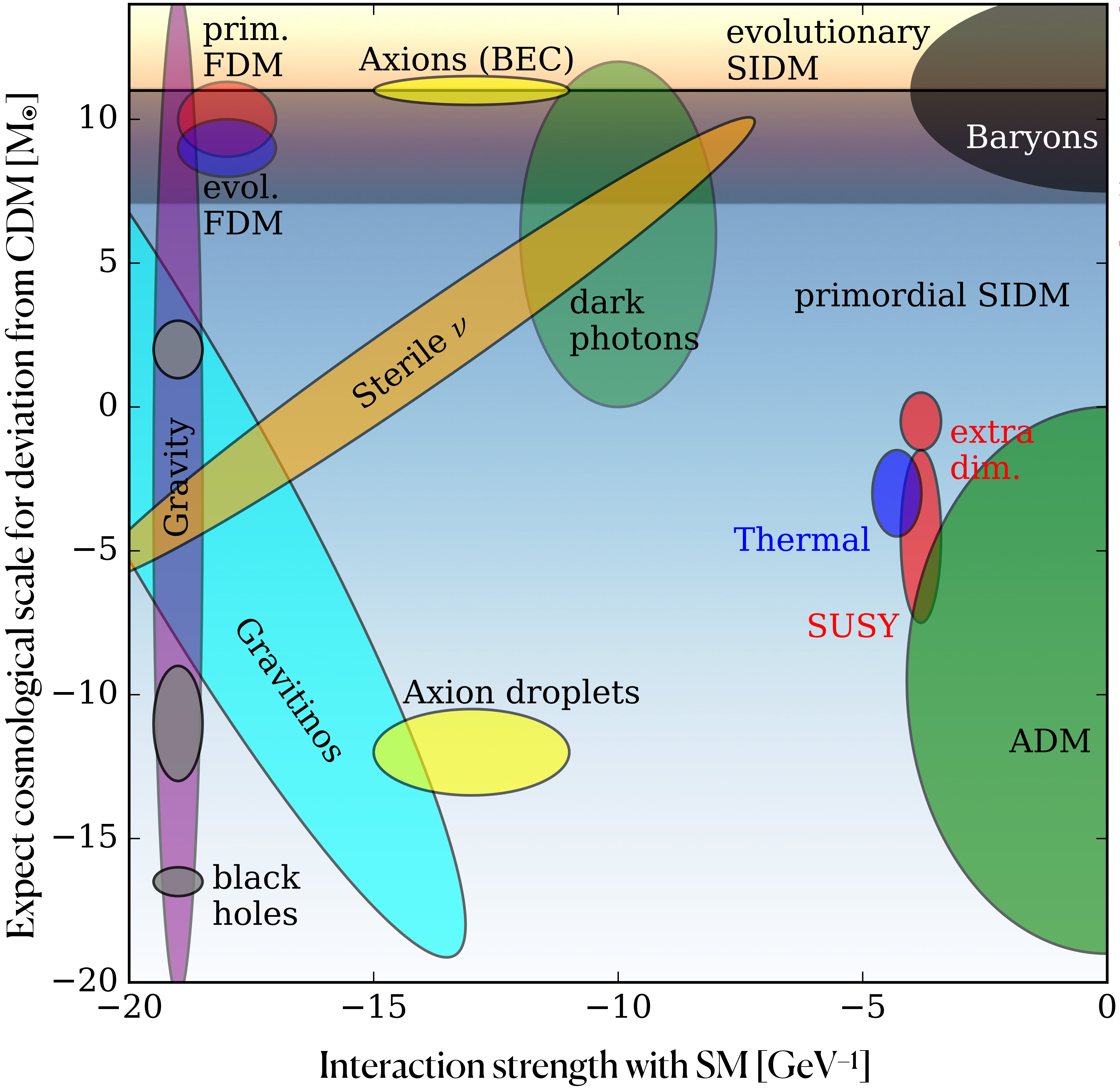
Dark matter (for particle physicists)



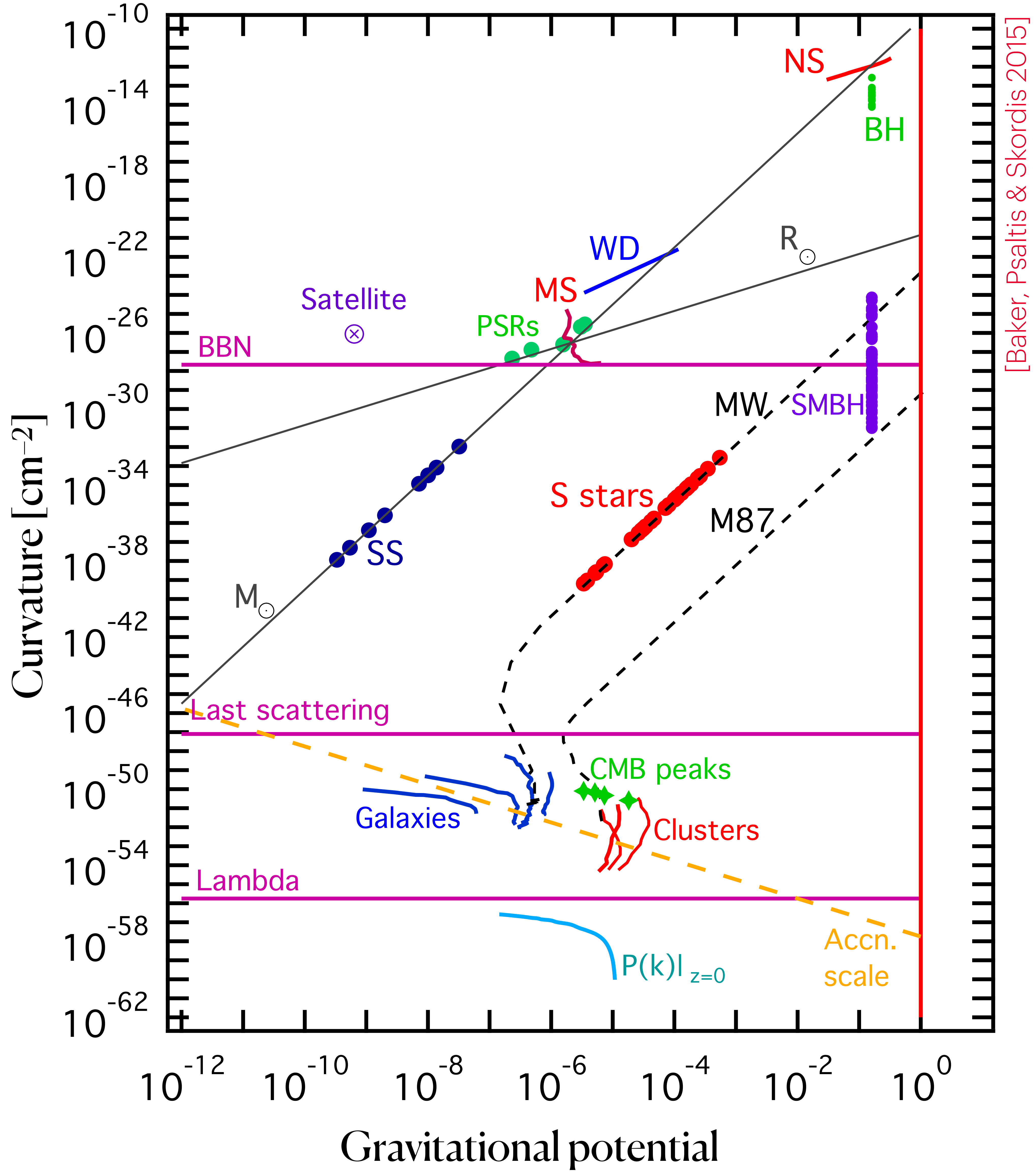
[Credits: T. Tait]

Dark matter (for cosmologists)



[Buckley & Peter 2017]

Dark energy (for astronomers)



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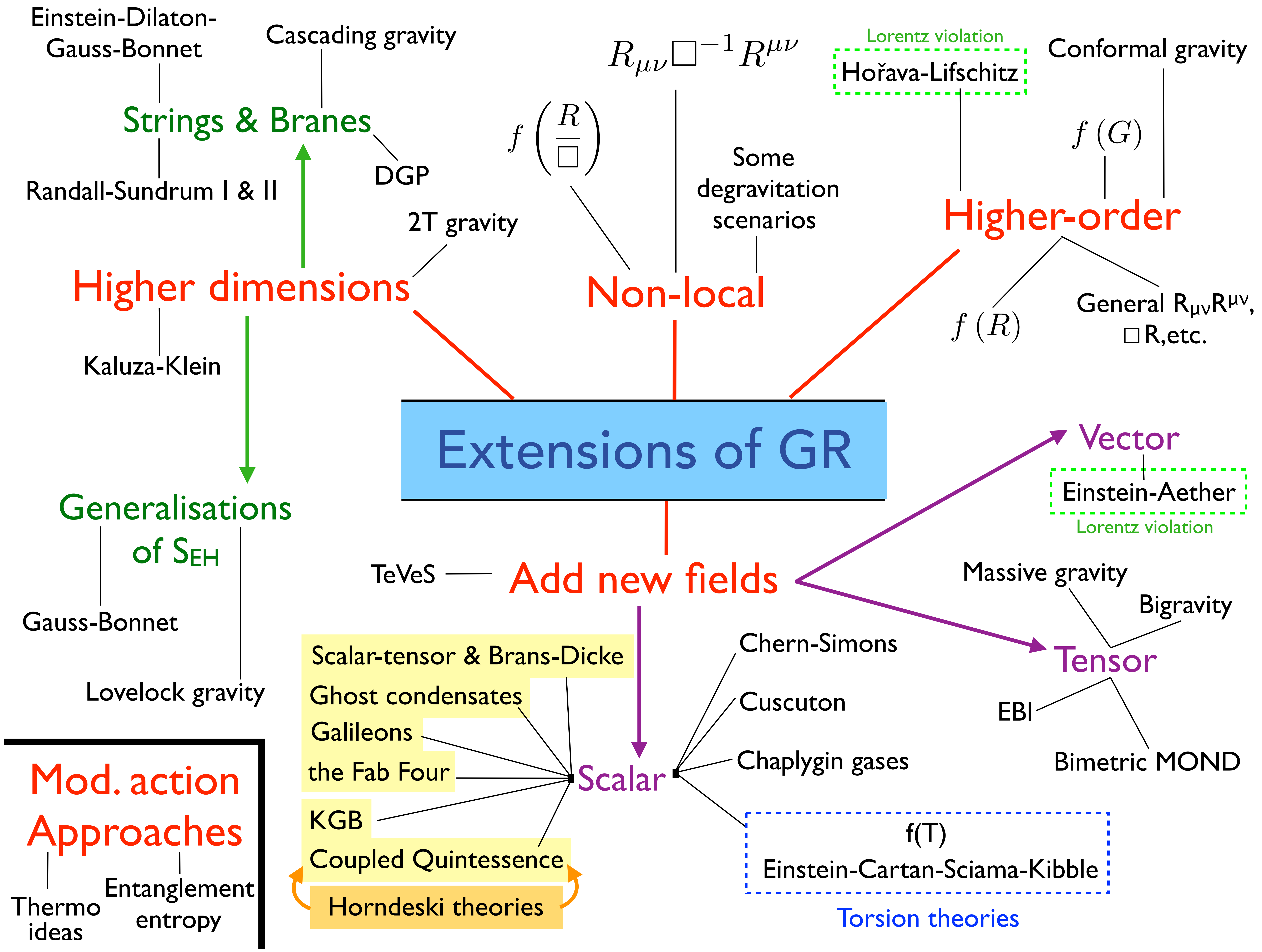
Dark energy (for relativists)



[Credits: T. Baker]

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Correlations 101

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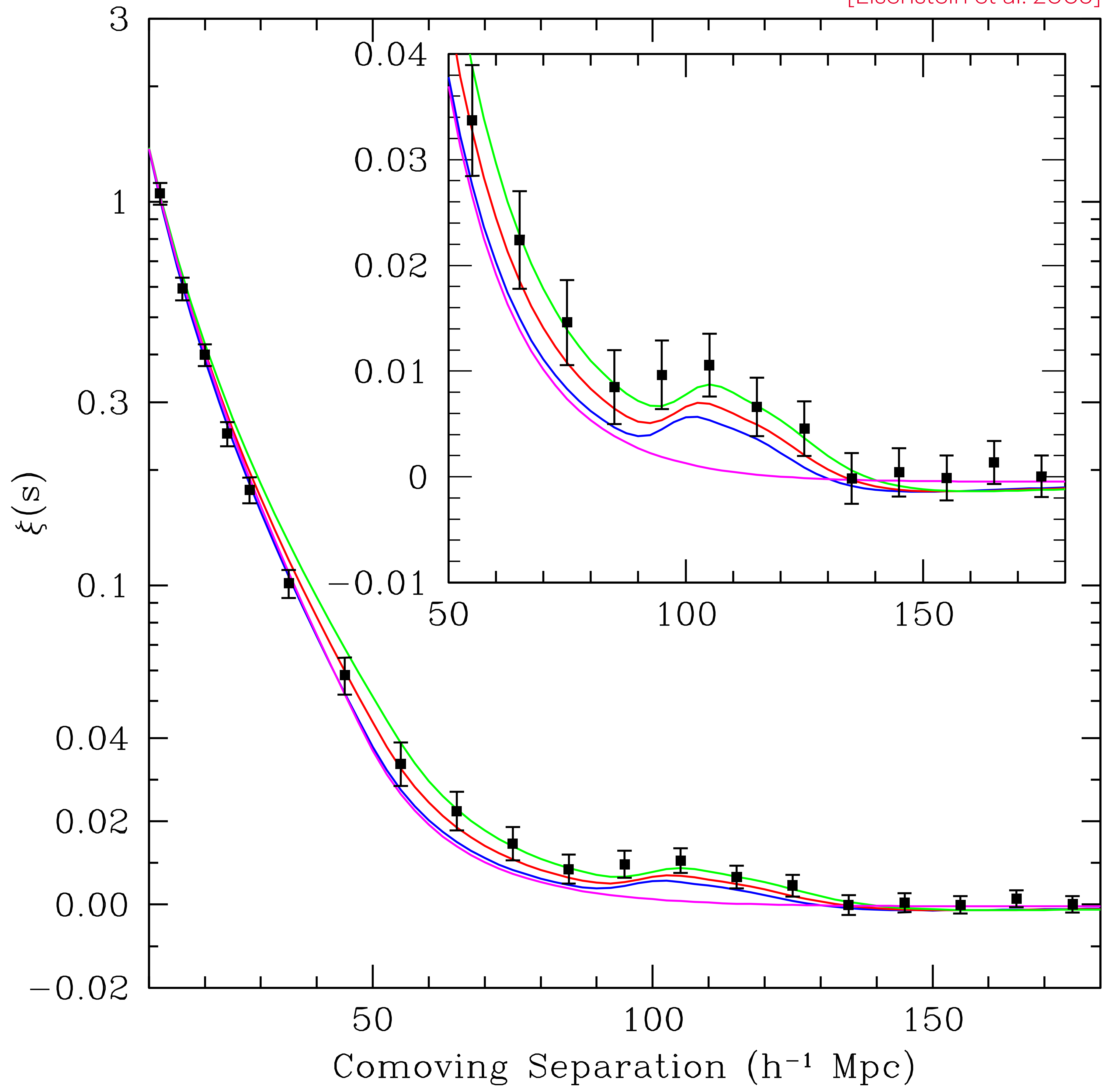
- Cosmological perturbation $f(t,\boldsymbol{x})$
  [temperature fluctuations, density perturbations, ...]
- Two-point correlation function $\langle f(z,\boldsymbol{x})\,f(z,\boldsymbol{y})\rangle = \xi_{ff}(z,|\boldsymbol{x}-\boldsymbol{y}|)$
- *Example no. 1:* Galaxy correlation function

$$f(t,\boldsymbol{x}) \to \Delta(z,\boldsymbol{x}) \equiv \frac{n_\mathrm{g}(z,\boldsymbol{x})-\bar{n}_\mathrm{g}(z)}{\bar{n}_\mathrm{g}(z)}$$

Correlations 101

[Eisenstein et al. 2005]



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Correlations 101

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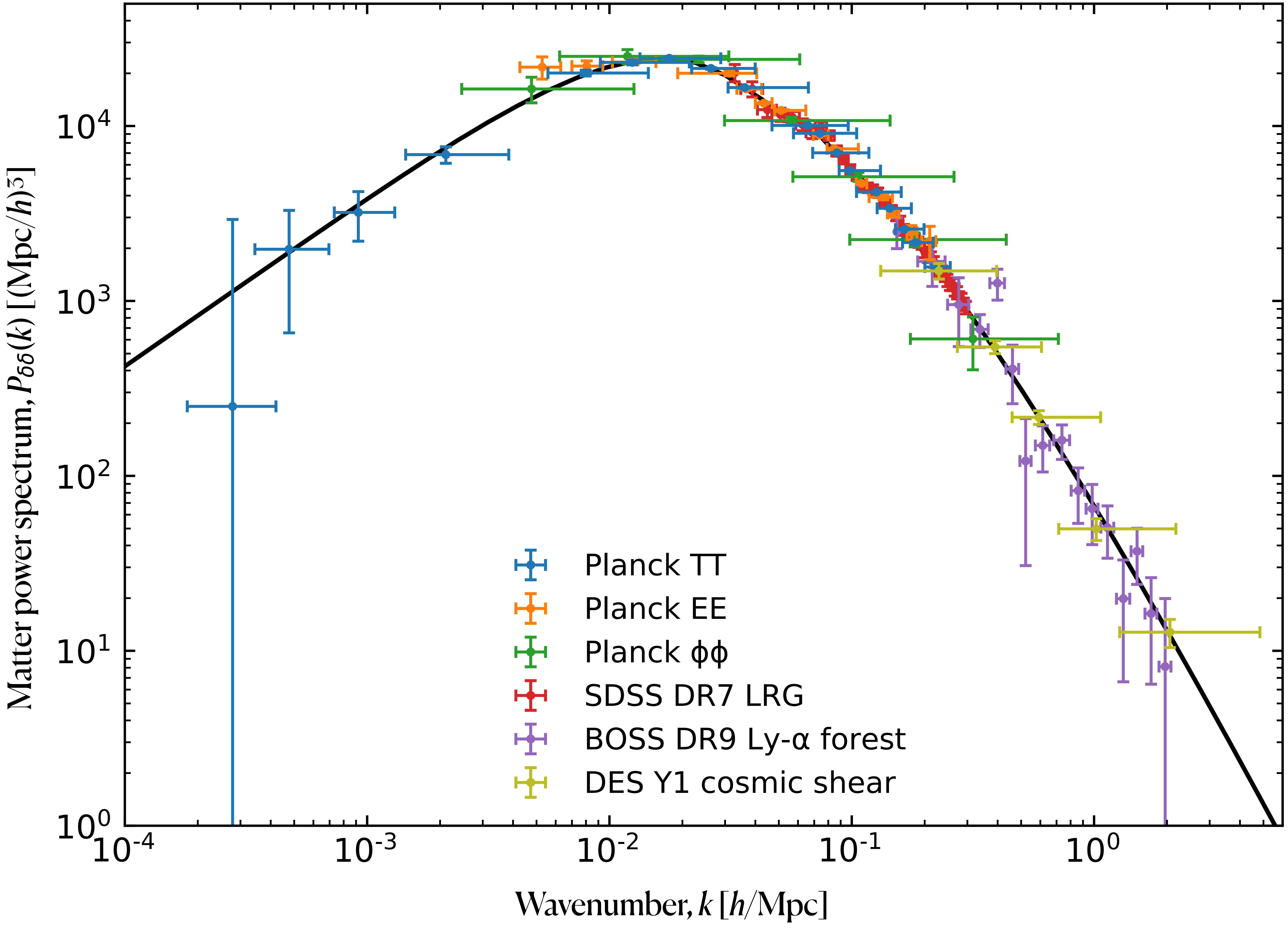
- Cosmological perturbation $f(t, \boldsymbol{x})$
  [temperature fluctuations, density perturbations, …]
- Two-point correlation function $\langle f(z, \boldsymbol{x})\, f(z, \boldsymbol{y})\rangle = \xi_{ff}(z, |\boldsymbol{x} - \boldsymbol{y}|)$
- Fourier-space power spectrum $\langle \hat{f}(z, \boldsymbol{k})\, \hat{f}(z, \boldsymbol{k}')\rangle = (2\,\pi)^3\, \delta_{(\mathrm{D})}(\boldsymbol{k} + \boldsymbol{k}')\, P_{ff}(z, k)$
- *Example no. 2:* Matter power spectrum

$$f(t, \boldsymbol{x}) \to \delta(z, \boldsymbol{x}) \equiv \frac{\rho(z, \boldsymbol{x}) - \bar{\rho}(z)}{\bar{\rho}(z)}$$

Correlations 101

[Planck Collaboration 2018]



Correlations 101

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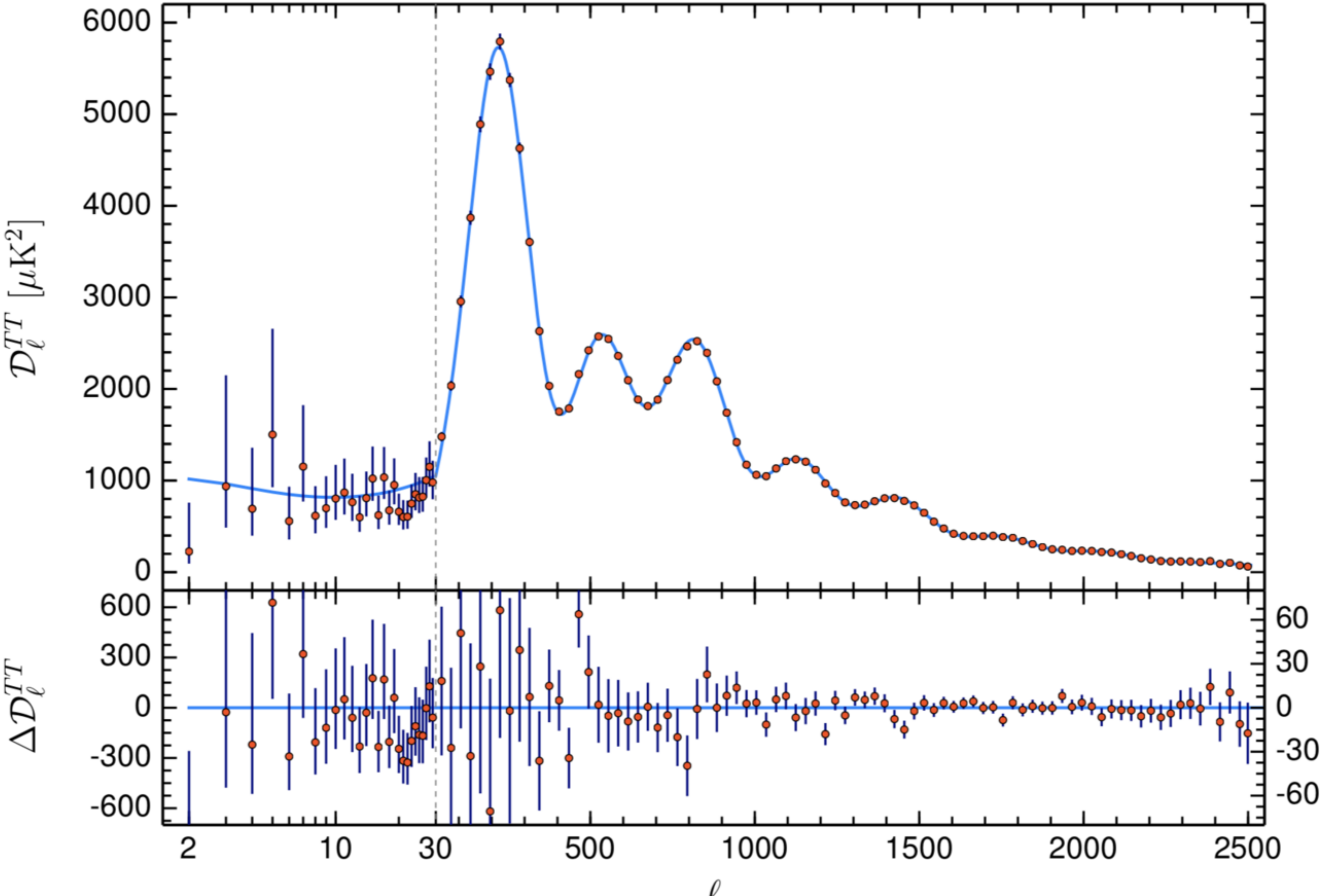
Stefano Camera

- Cosmological perturbation $f(t,\boldsymbol{x})$
  [temperature fluctuations, density perturbations, …]
- Two-point correlation function $\langle f(z,\boldsymbol{x})\,f(z,\boldsymbol{y})\rangle = \xi_{ff}(z,|\boldsymbol{x}-\boldsymbol{y}|)$
- Fourier-space power spectrum $\langle \hat{f}(z,\boldsymbol{k})\,\hat{f}(z,\boldsymbol{k}')\rangle = (2\,\pi)^3\,\delta_{(\mathrm{D})}(\boldsymbol{k}+\boldsymbol{k}')\,P_{ff}(z,k)$
- Harmonic-space power spectrum $\langle \tilde{f}_{\ell m}(z)\,\tilde{f}_{\ell' m'}(z')\rangle = \delta^{\ell\ell'}_{(\mathrm{K})}\,\delta^{mm'}_{(\mathrm{K})}\,C^{ff}_{\ell}(z,z')$
- *Example no. 3:* CMB temperature power spectrum

$$f(t,\boldsymbol{x}) \to \Theta(\hat{\boldsymbol{n}}) \equiv \frac{T(t_0,\hat{\boldsymbol{n}})-\bar{T}(t_0)}{\bar{T}(t_0)}$$

Correlations 101

[Planck Collaboration 2018]



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Correlations 101

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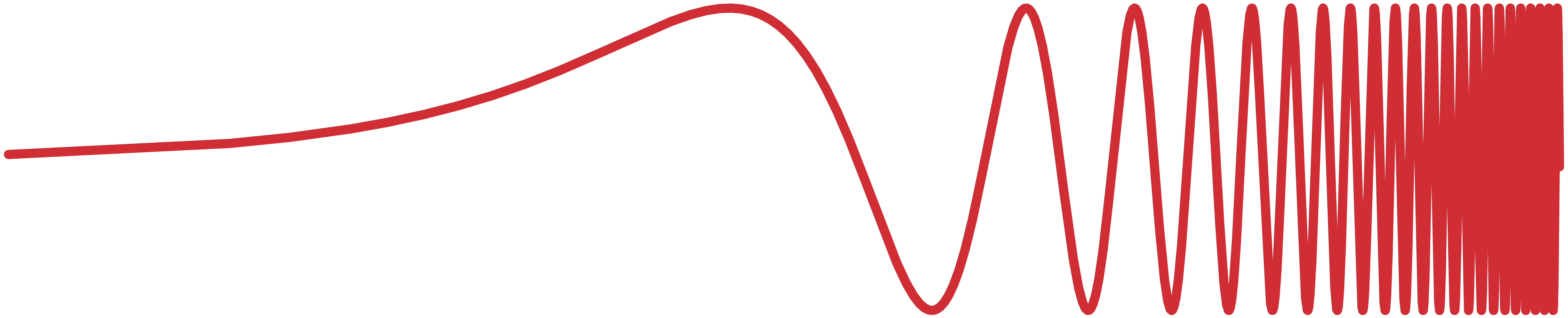
- Cosmological perturbation
  [temperature fluctuations, density perturbations, …]

$$f(t,\boldsymbol{x}) \qquad g(z,\boldsymbol{k})$$

- Two-point correlation function $\langle f(z,\boldsymbol{x})\,\cancel{f}\,g(z,\boldsymbol{y})\rangle = \xi_{f\cancel{f}g}(z,|\boldsymbol{x}-\boldsymbol{y}|)$
- Fourier-space power spectrum $\langle \hat{f}(z,\boldsymbol{k})\,\cancel{\hat{f}}\,g(z,\boldsymbol{k}')\rangle = (2\,\pi)^3\,\delta_{(\mathrm{D})}(\boldsymbol{k}+\boldsymbol{k}')\,P_{f\cancel{f}g}(z,k)$
- Harmonic-space power spectrum $\langle \tilde{f}_{\ell m}(z)\,\cancel{\tilde{f}}\,g_{\ell' m'}(z')\rangle = \delta^{\ell\ell'}_{(\mathrm{K})}\,\delta^{mm'}_{(\mathrm{K})}\,C_\ell^{f\cancel{f}g}(z,z')$

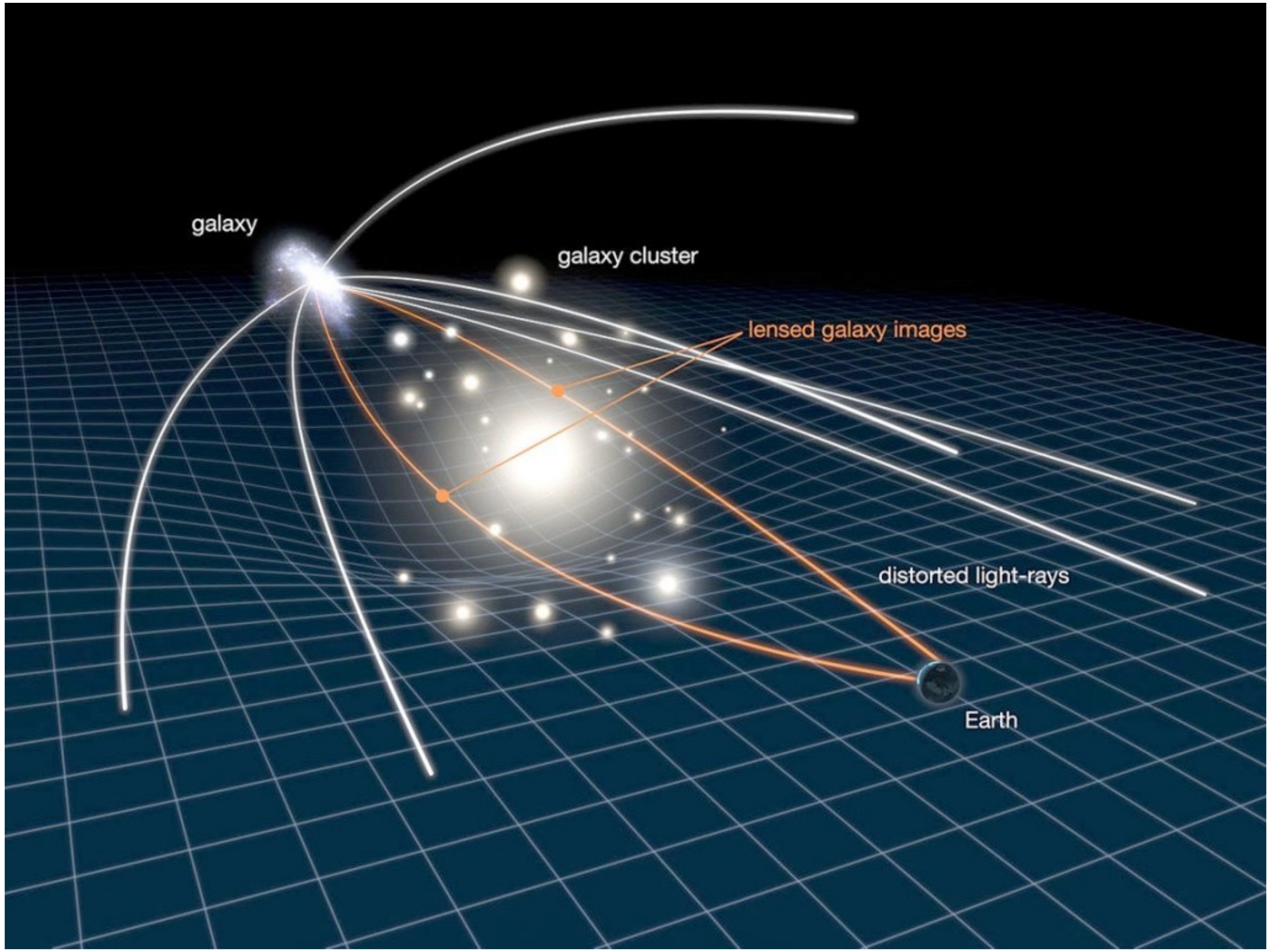
- *Measurements:* observational systematics, noise, cosmic variance

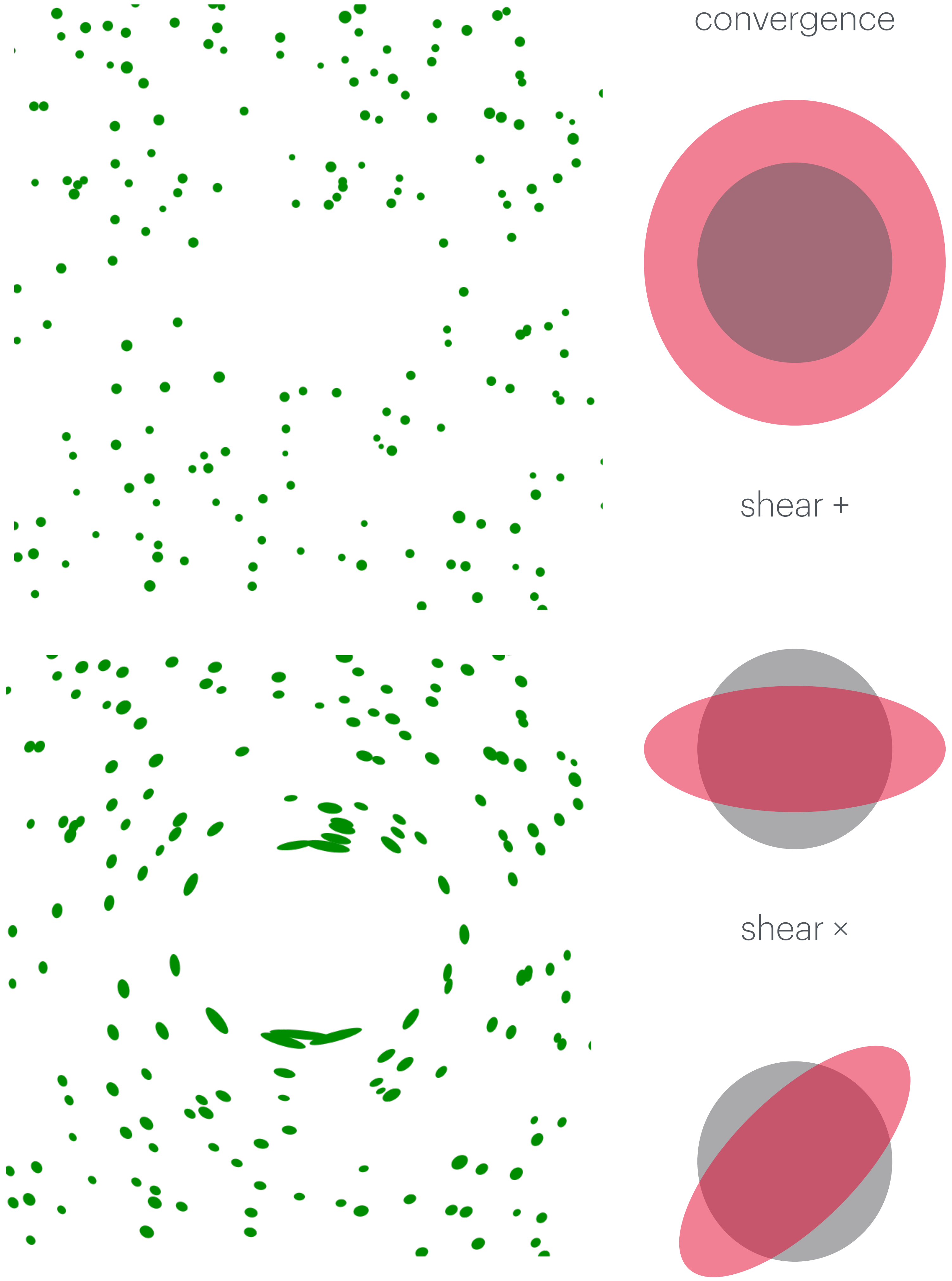
Data across the spectrum



- Radio: SKA Observatory and its precursors/pathfinders (LOFAR, MeerKAT, ASKAP)
- Optical/near-infrared: *Euclid* (but also DES, DESI, *Roman*, Rubin, ...)
- High and ultra-high energies: *Fermi*-LAT, CTA (and Auger, Telescope Array)

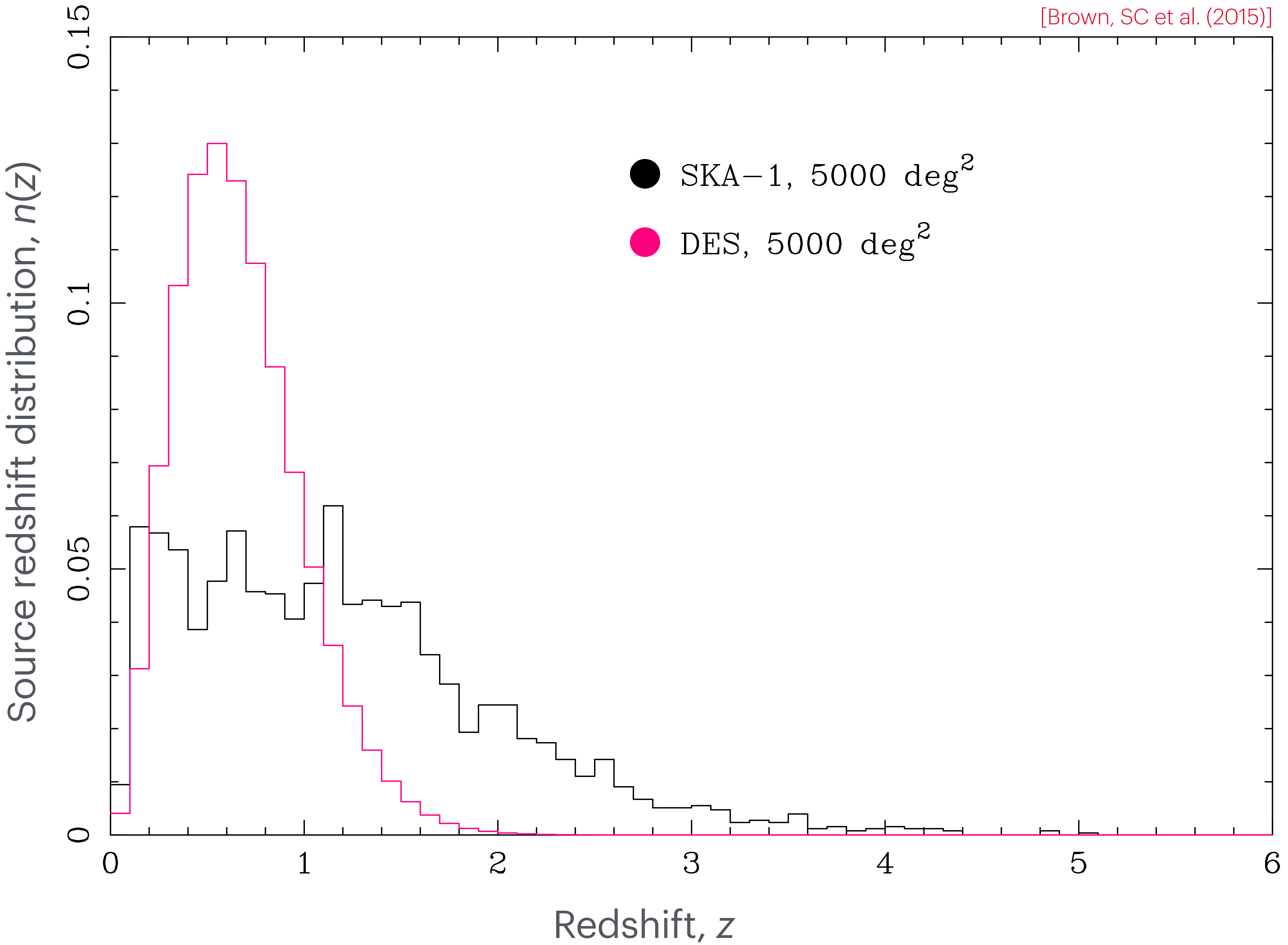
Synergies vs systematics





Radio-optical cosmic shear

[Brown, SC et al. (2015)]



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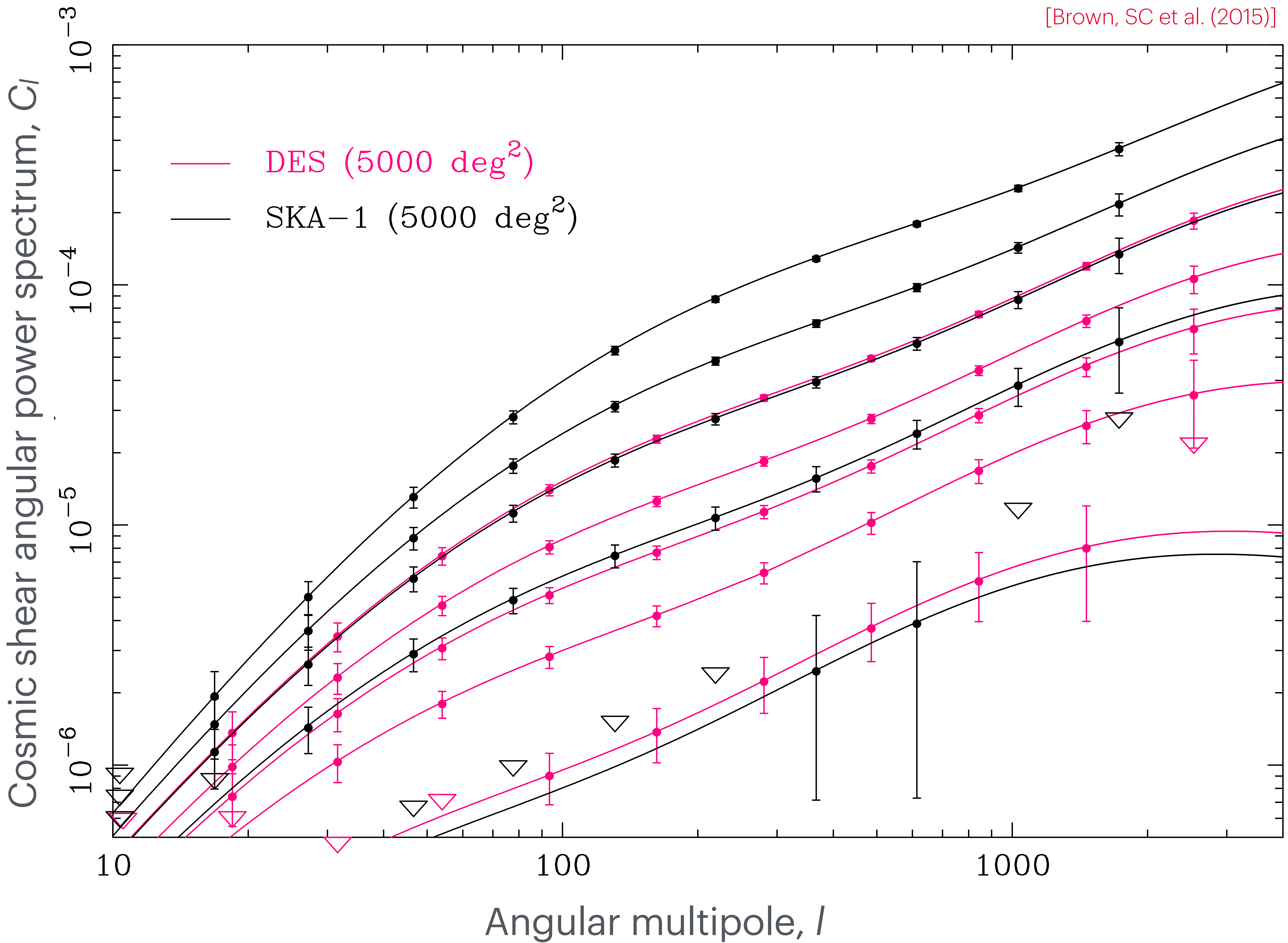
Radio-optical cosmic shear

[Brown, SC et al. (2015)]



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Radio-optical cosmic shear

$$\epsilon(z,\hat{\boldsymbol{n}}) = \gamma(z,\hat{\boldsymbol{n}}) + \epsilon^{\rm sys}(z,\hat{\boldsymbol{n}})$$

$$\langle\epsilon\,\epsilon\rangle = \langle\gamma\,\gamma\rangle + \cancel{2\,\langle\gamma\,\epsilon^{\rm sys}\rangle} + \langle\epsilon^{\rm sys}\,\epsilon^{\rm sys}\rangle$$

$$\langle\epsilon_{\rm (o)}\,\epsilon_{\rm (r)}\rangle = \langle\gamma\,\gamma\rangle + \cancel{\langle\gamma\,\epsilon^{\rm sys}_{\rm (r)}\rangle} + \cancel{\langle\gamma\,\epsilon^{\rm sys}_{\rm (r)}\rangle} + \cancel{\langle\epsilon^{\rm sys}_{\rm (o)}\,\epsilon^{\rm sys}_{\rm (r)}\rangle}$$

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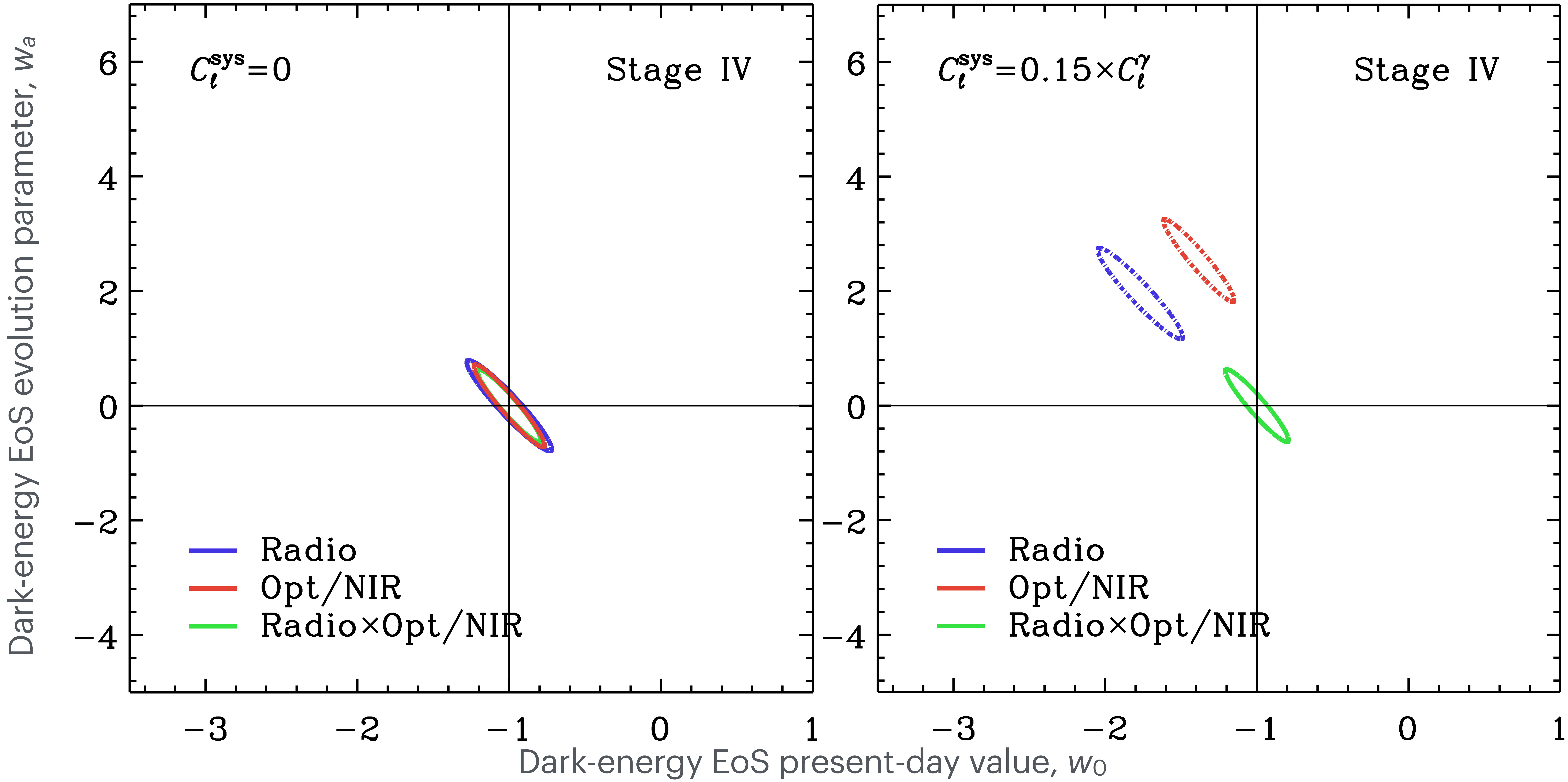
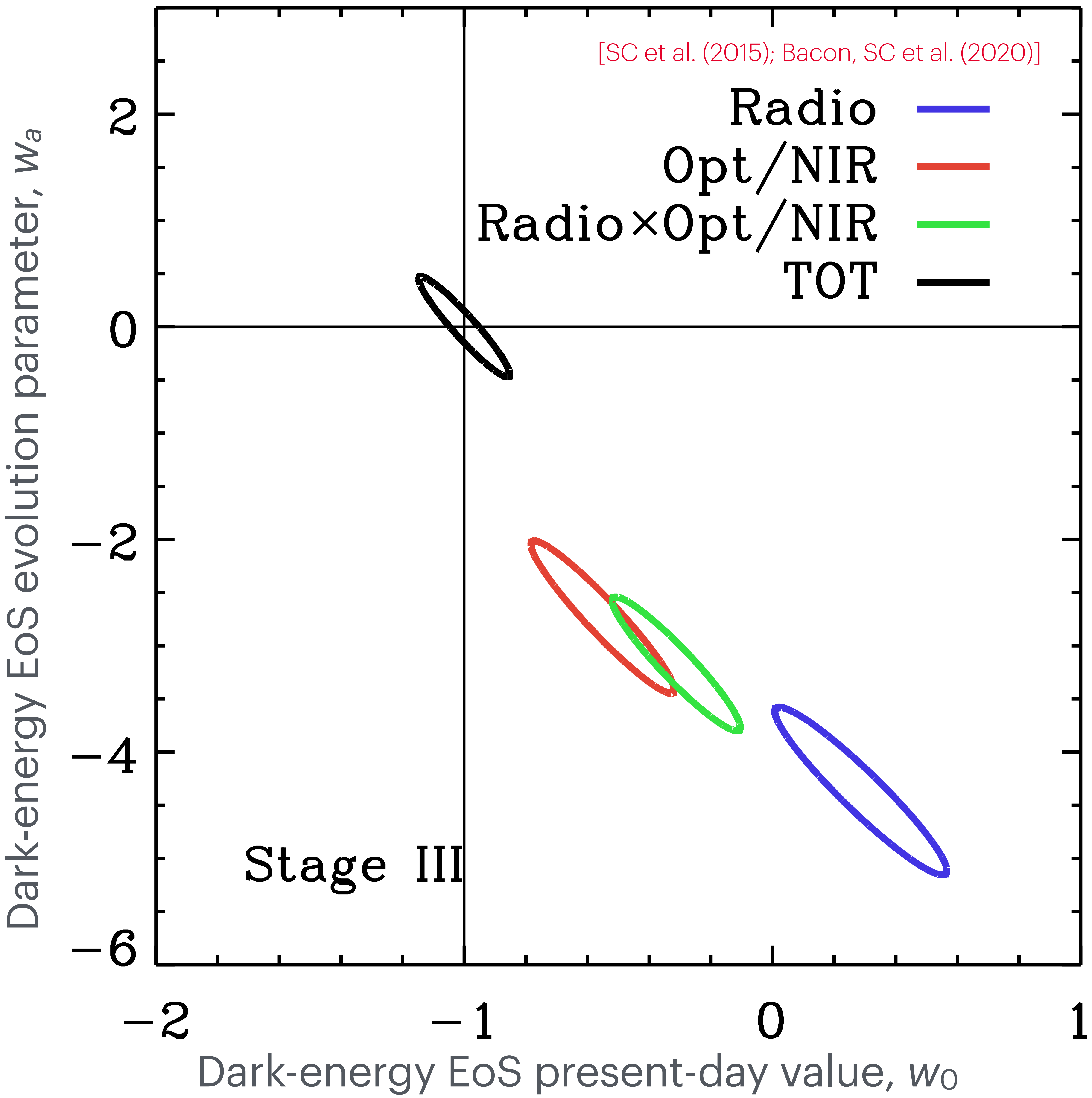
Radio-optical cosmic shear

[SC et al. (2015); Bacon, SC et al. (2020)]



Radio-optical cosmic shear



Radio-optical cosmic shear

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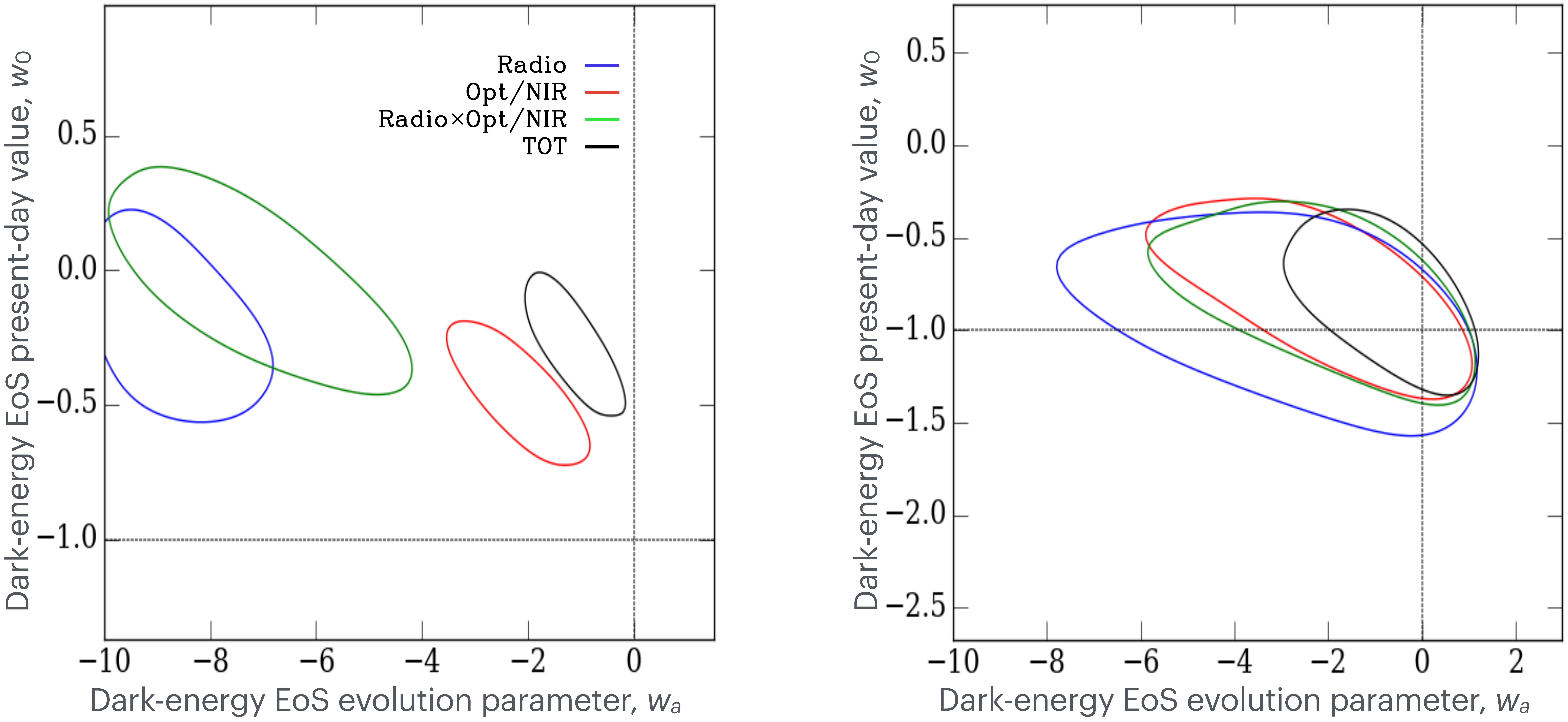
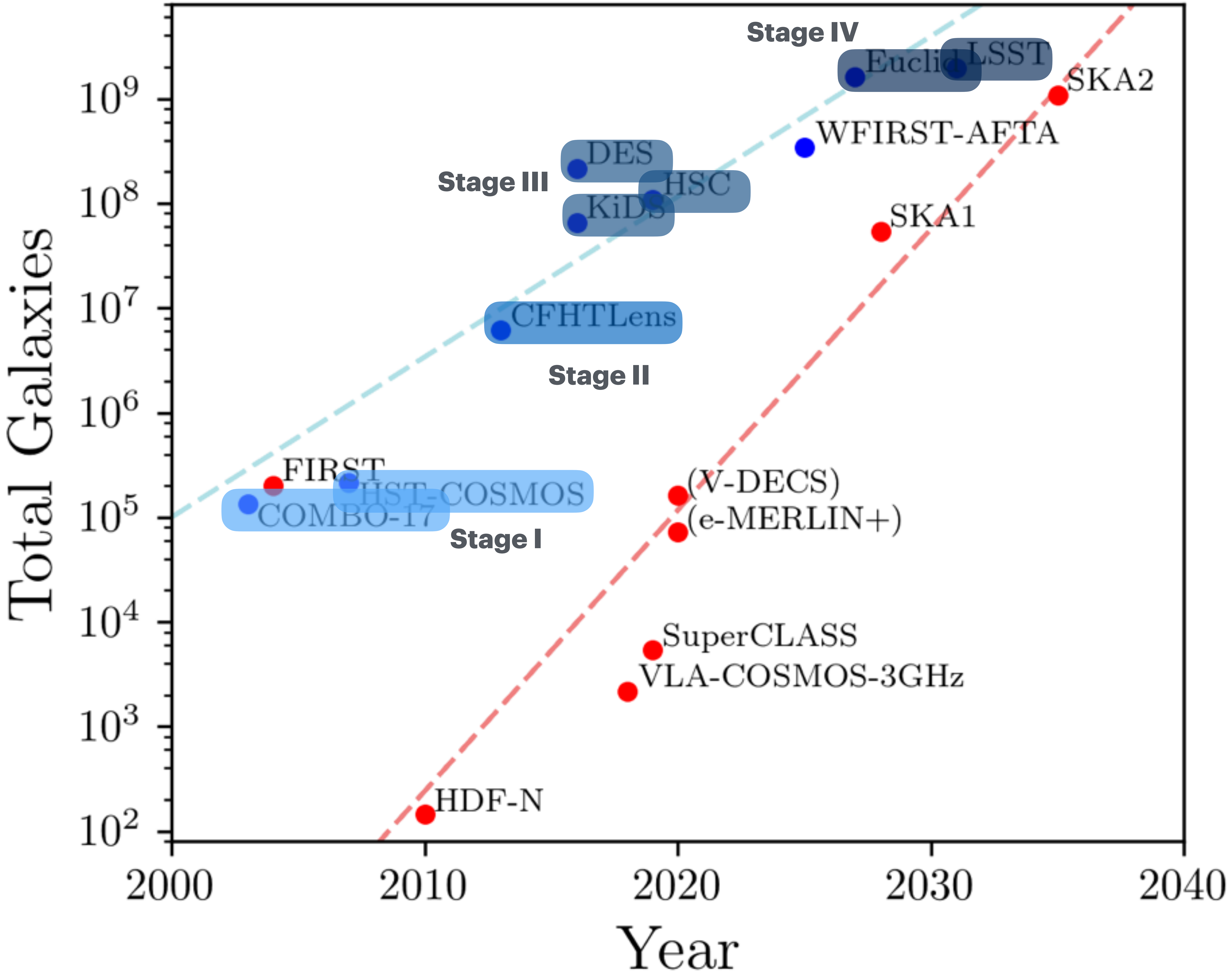
[Berardi & SC (in prep.), Ingrao & SC (in prep.)]



Radio-optical cosmic shear

[Credits: I. Harrison]



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Synergies vs noise

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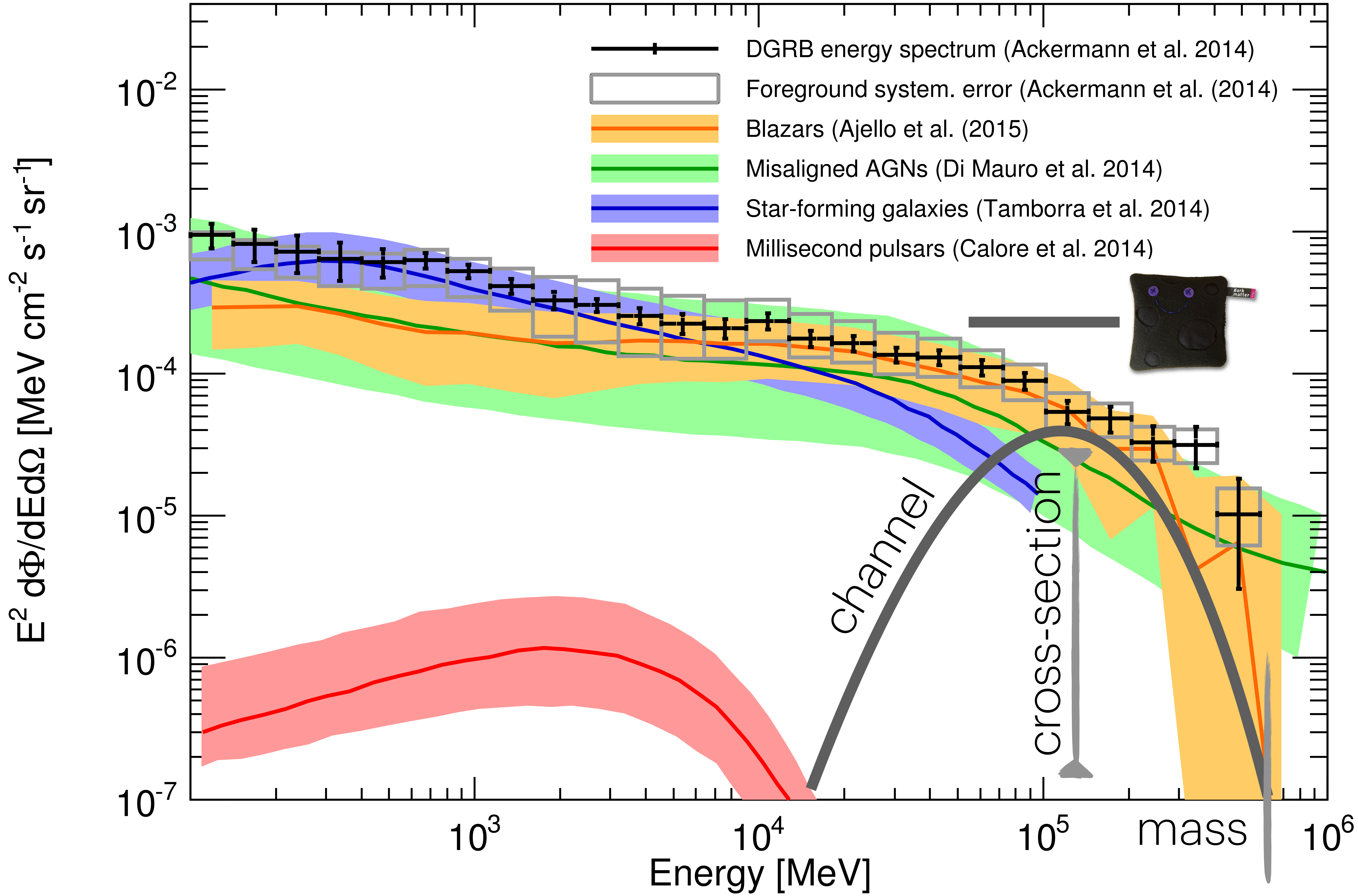
NASA's Fermi telescope reveals best-ever view of the gamma-ray sky

Fermi
Gamma-ray
Space Telescope

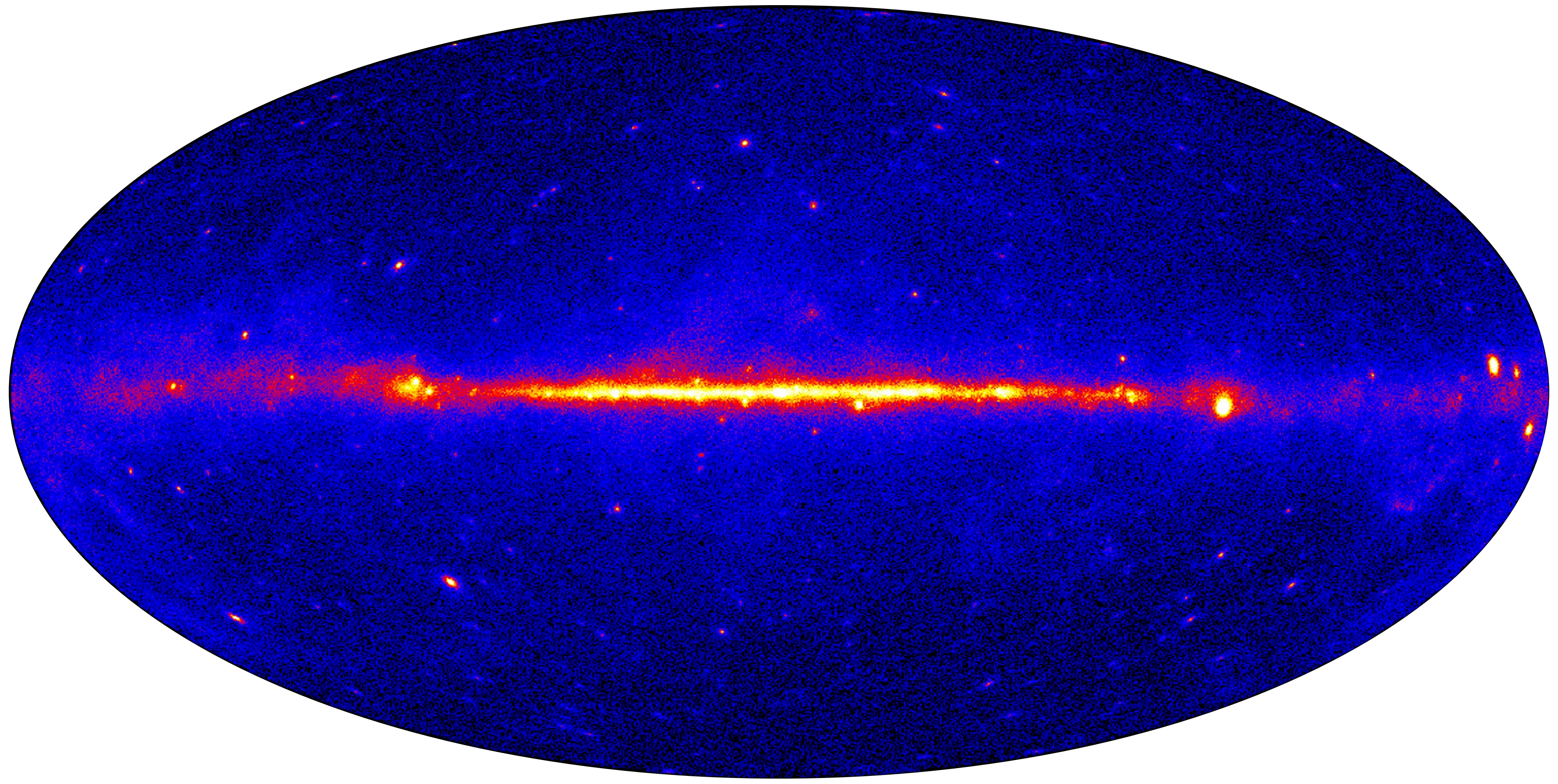
Credit: NASA/DOE/Fermi LAT Collaboration

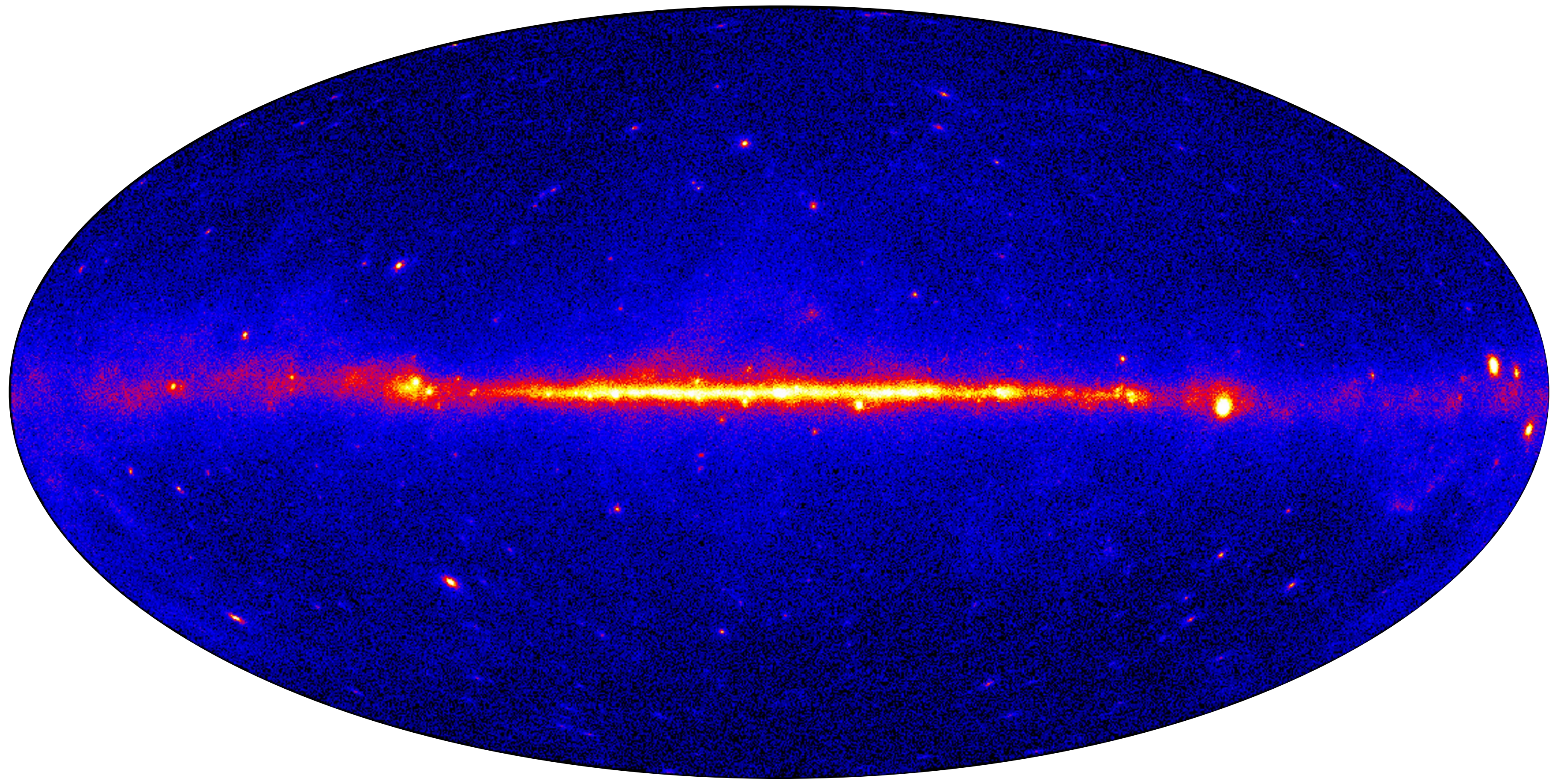
Dark matter indirect searches

[Fornasa & Sánchez-Conde (2015)]

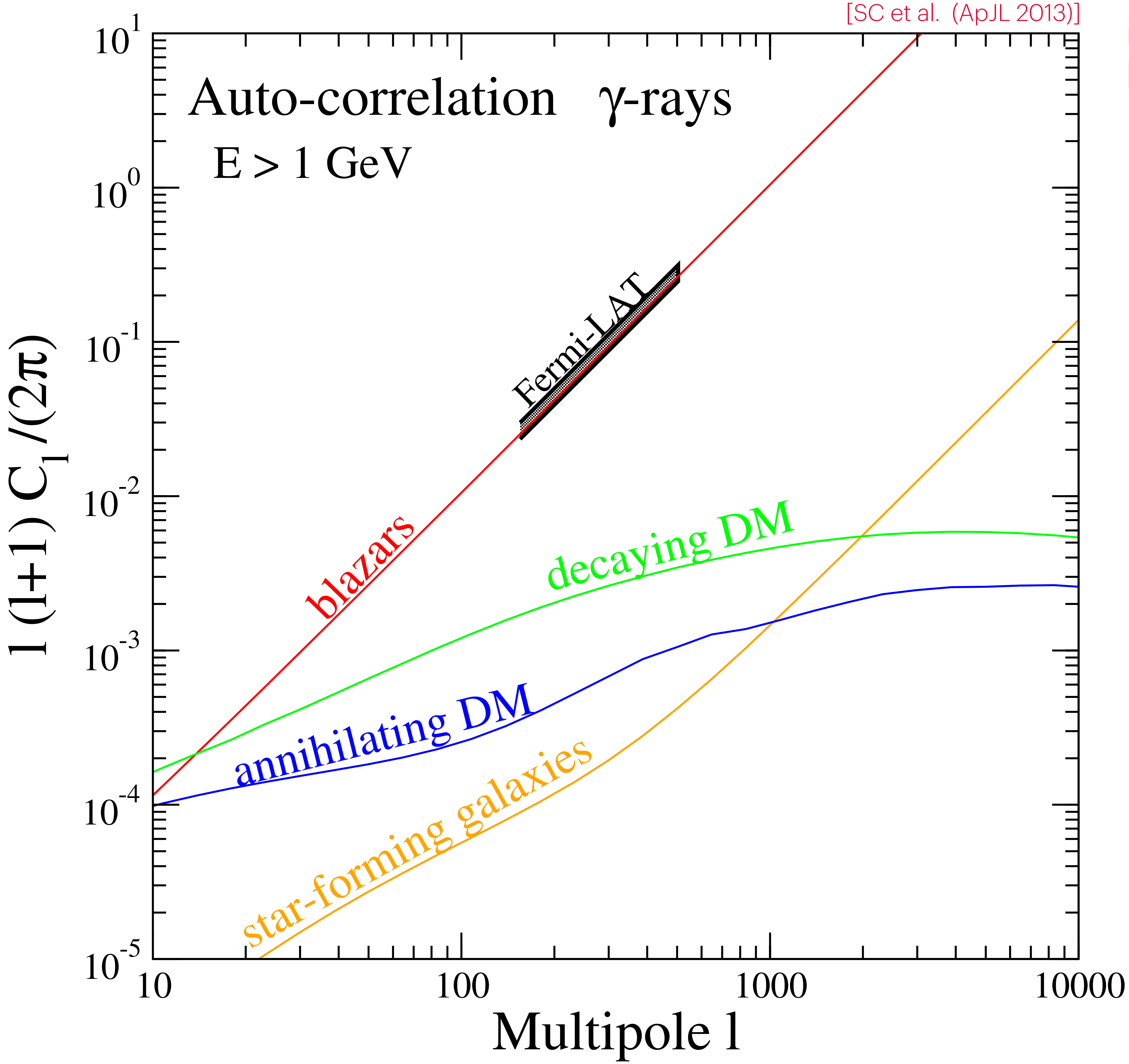


Dark matter indirect searches

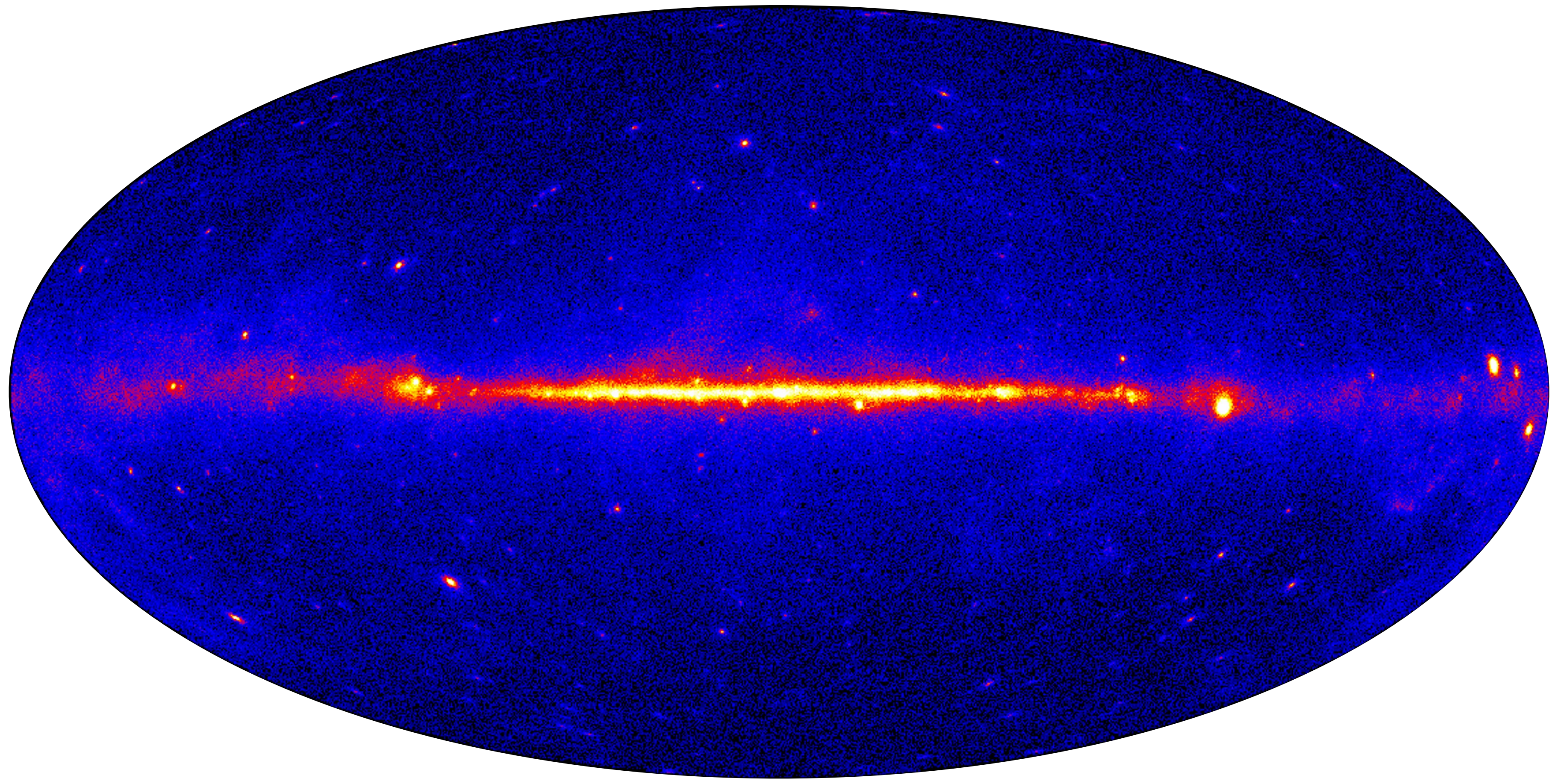




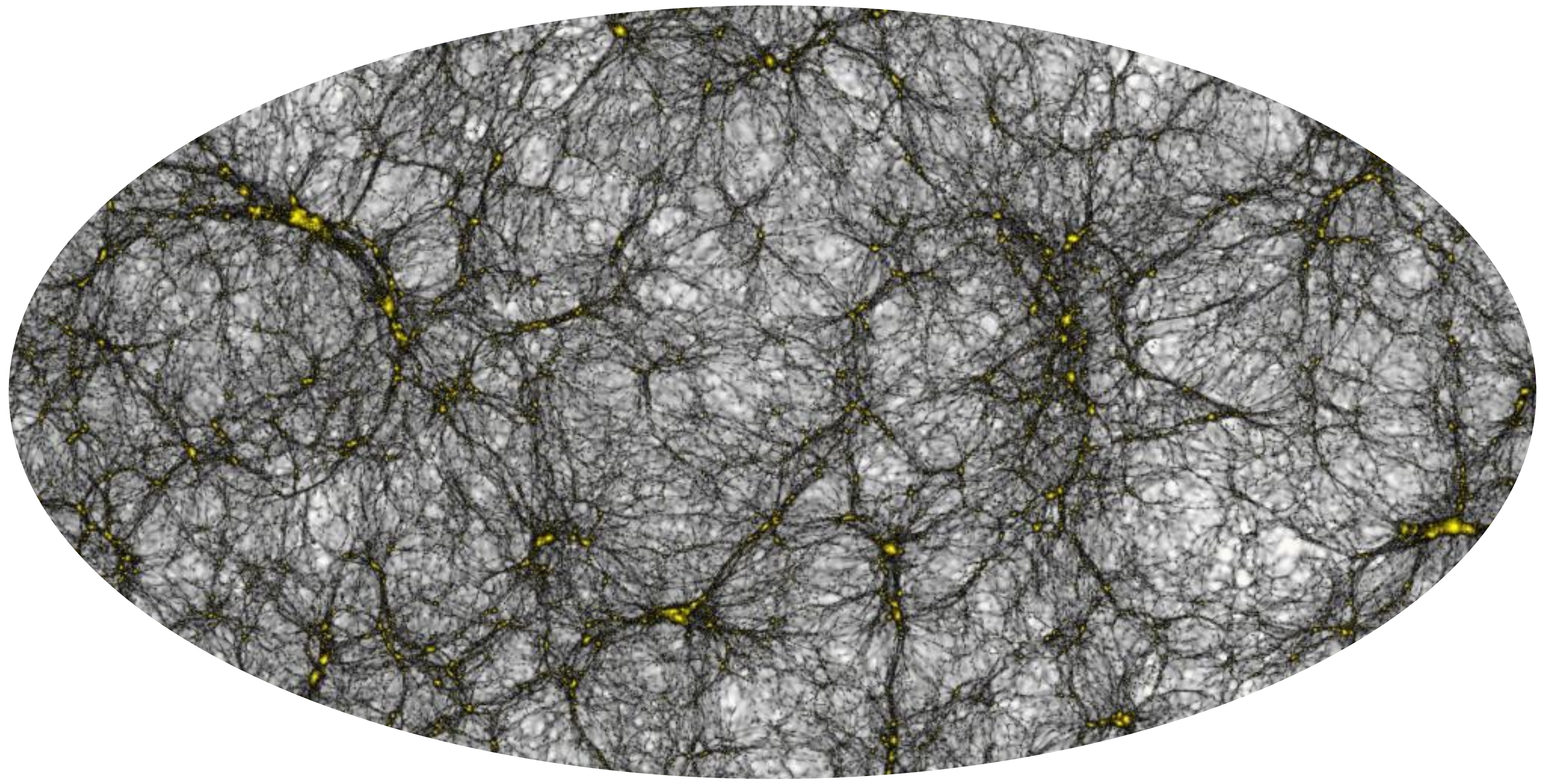
[SC et al. (ApJL 2013)]



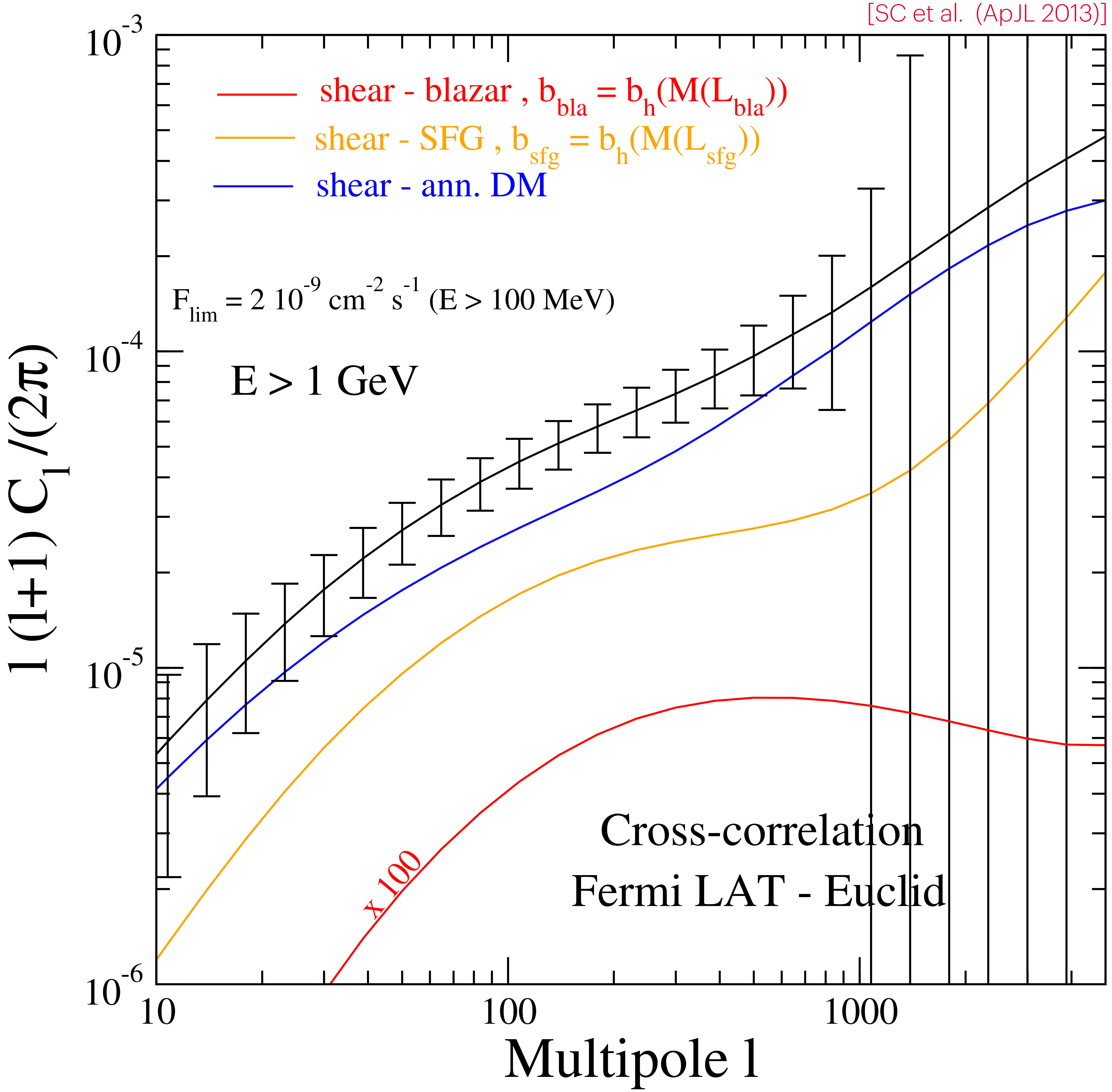
Dark matter indirect searches



×



[SC et al. (ApJL 2013)]



Dark matter indirect searches

- Bounds from non-detections:
  - Clustering of galaxies [SDSS LRGs] x UGRB [Fermi Pass7-reprocessed (76 mths)]
    [Shirasaki et al. 2015]
  - Cosmic shear [CFHTLenS+RCSLenS] x UGRB [Fermi P7r (76 mths), P8 (85 mths)]
    [Shirasaki et al. 2014, 2016]
  - Cosmic shear [Subaru HSC] x UGRB [P8 (85 mths)]
    [Shirasaki et al. 2018]
  - Cosmic shear [CFHTLenS+RCSLenS+KiDS] x UGRB [Fermi P8 (84 mths)]
    [Tröster, SC et al. 2017]

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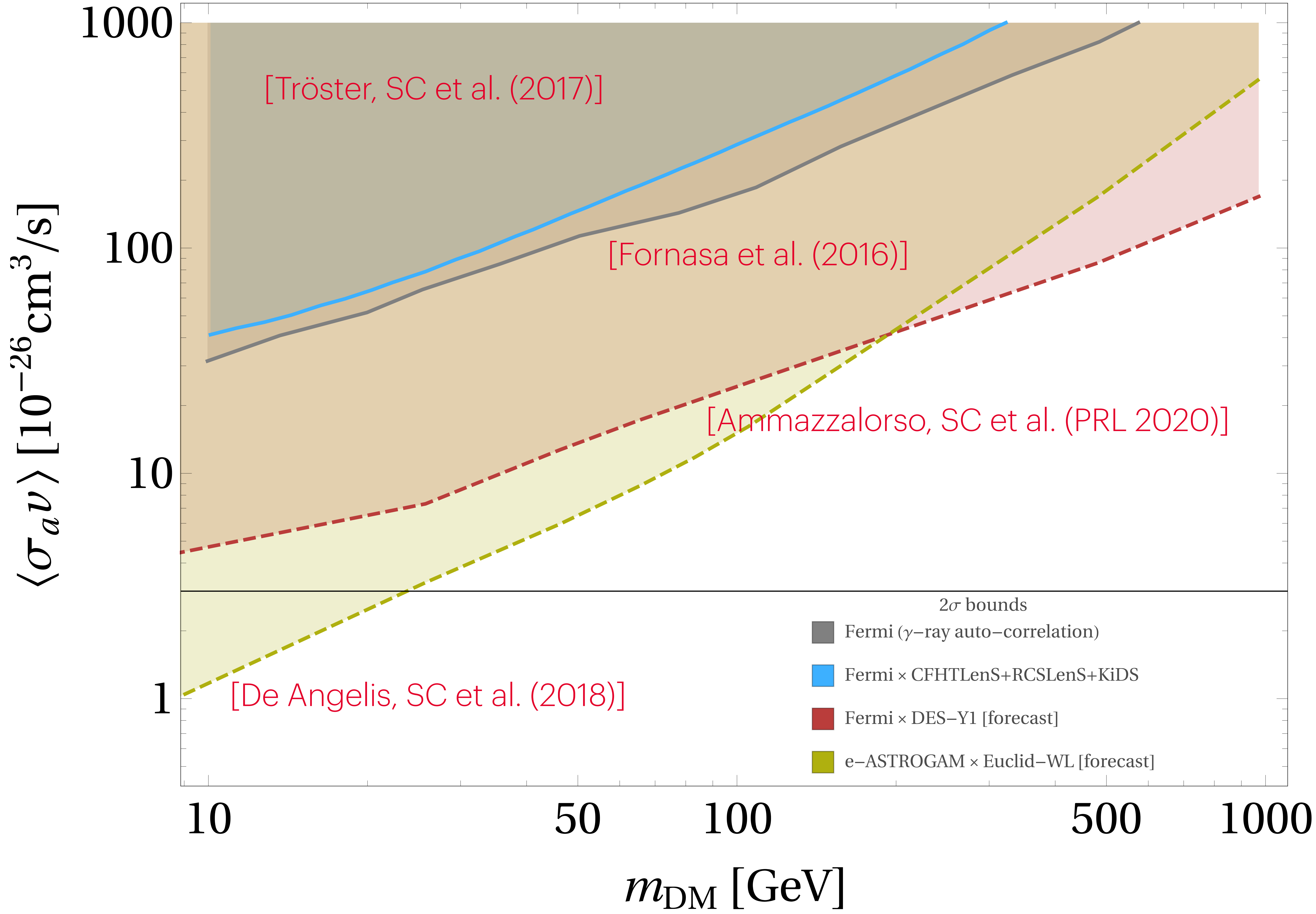
Dark matter indirect searches



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Dark matter indirect searches

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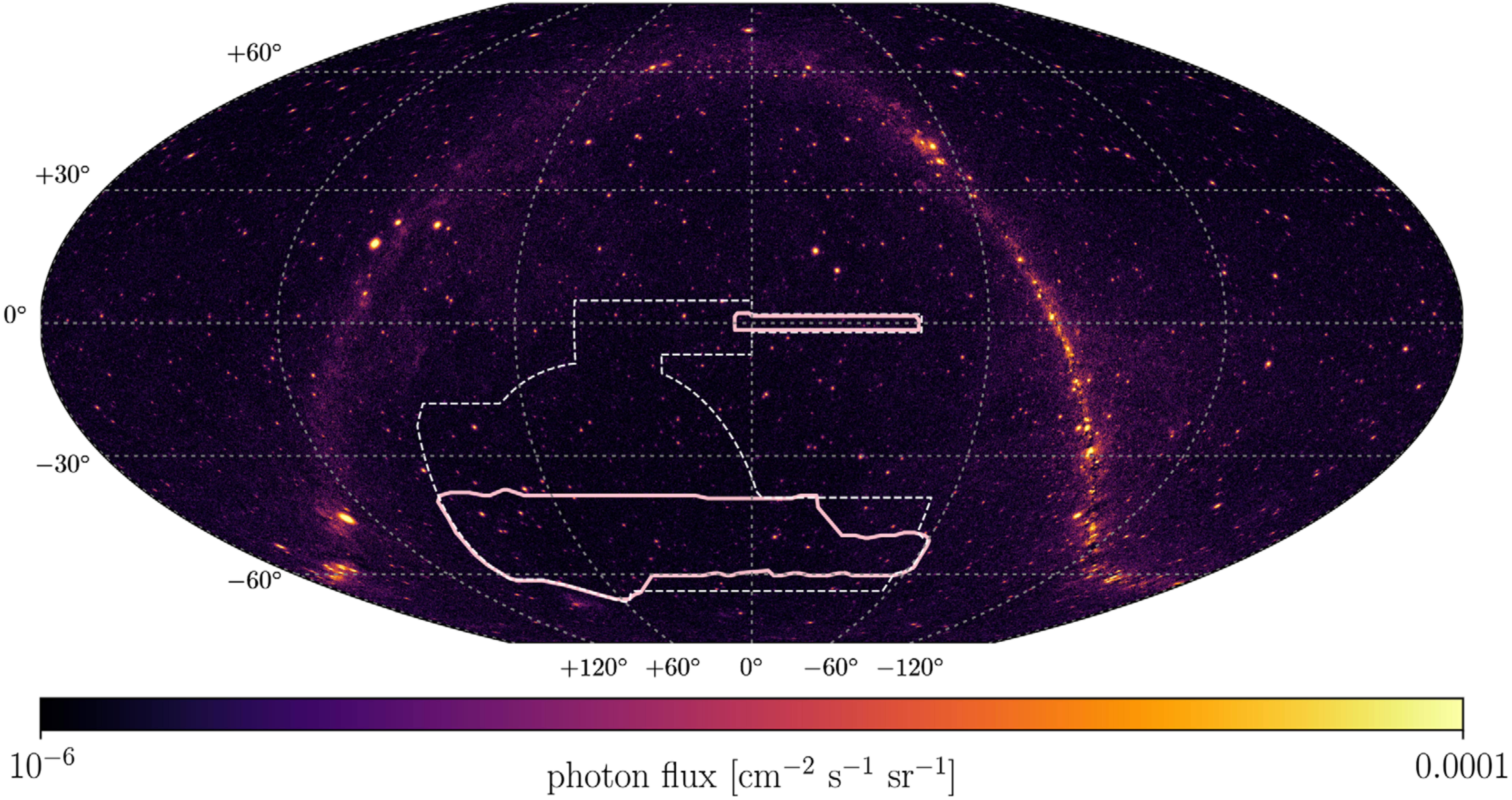
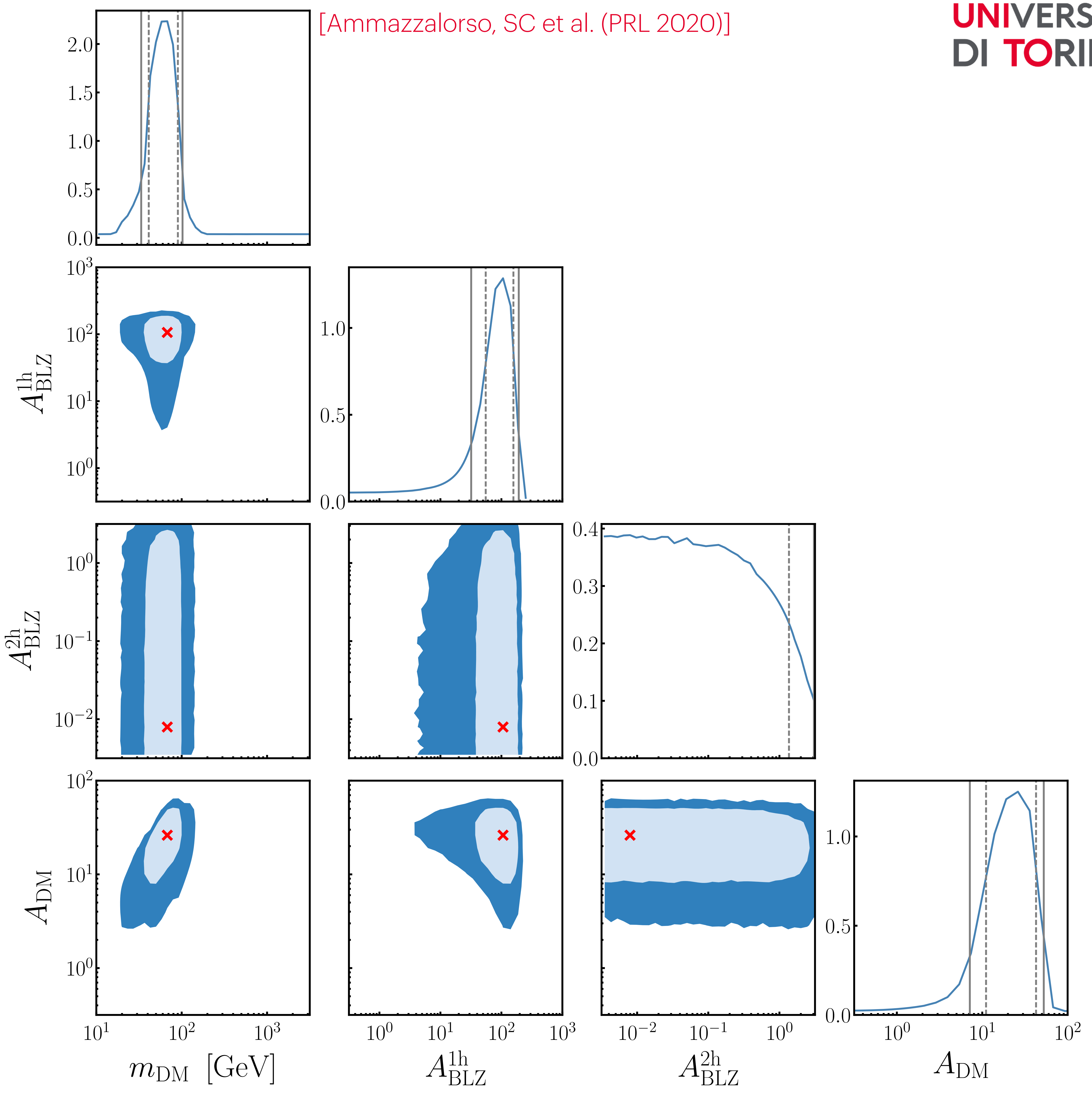
[Ammazzalorso, SC et al. (PRL 2020)]



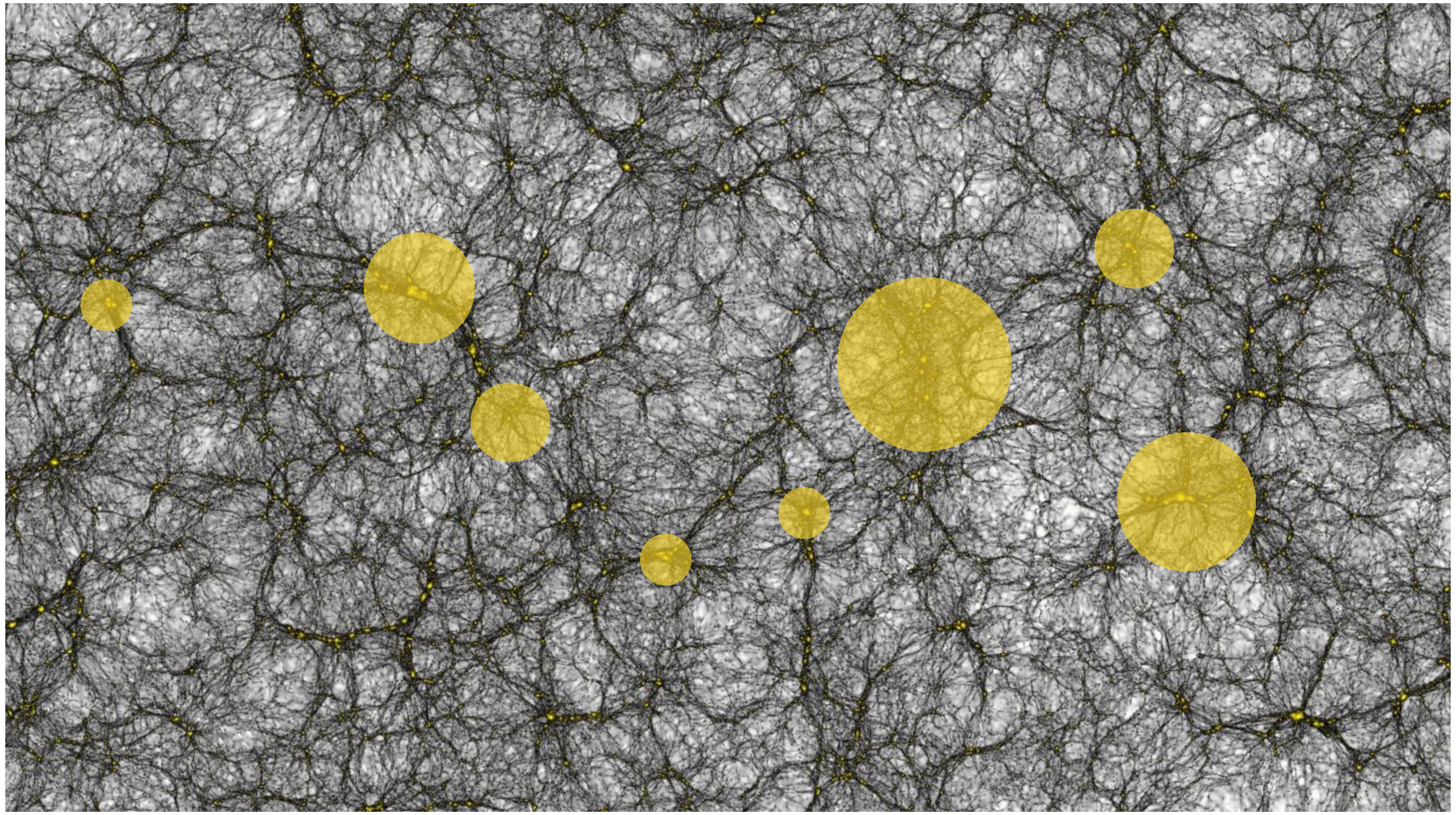
Dark matter indirect searches

- Bounds from detection (@5.3σ)
  - Cosmic shear [DES Y1]
  - UGRB [Fermi (108 mths)]

[Ammazzalorso, SC et al. (PRL 2020)]



Synergies vs cosmic variance



$$\Delta = \frac{n_\mathrm{g} - \bar{n}_\mathrm{g}}{\bar{n}_\mathrm{g}}$$

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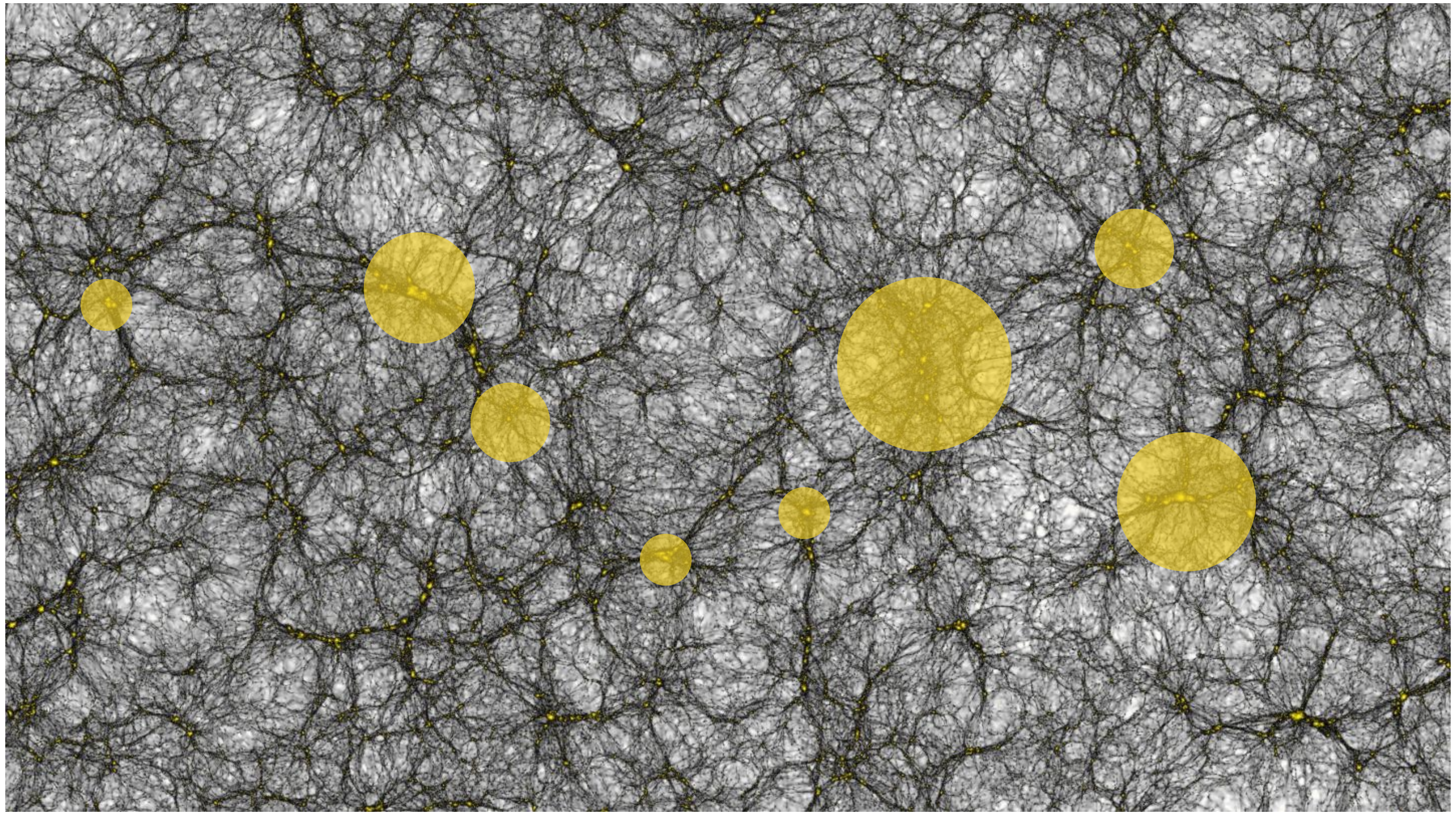
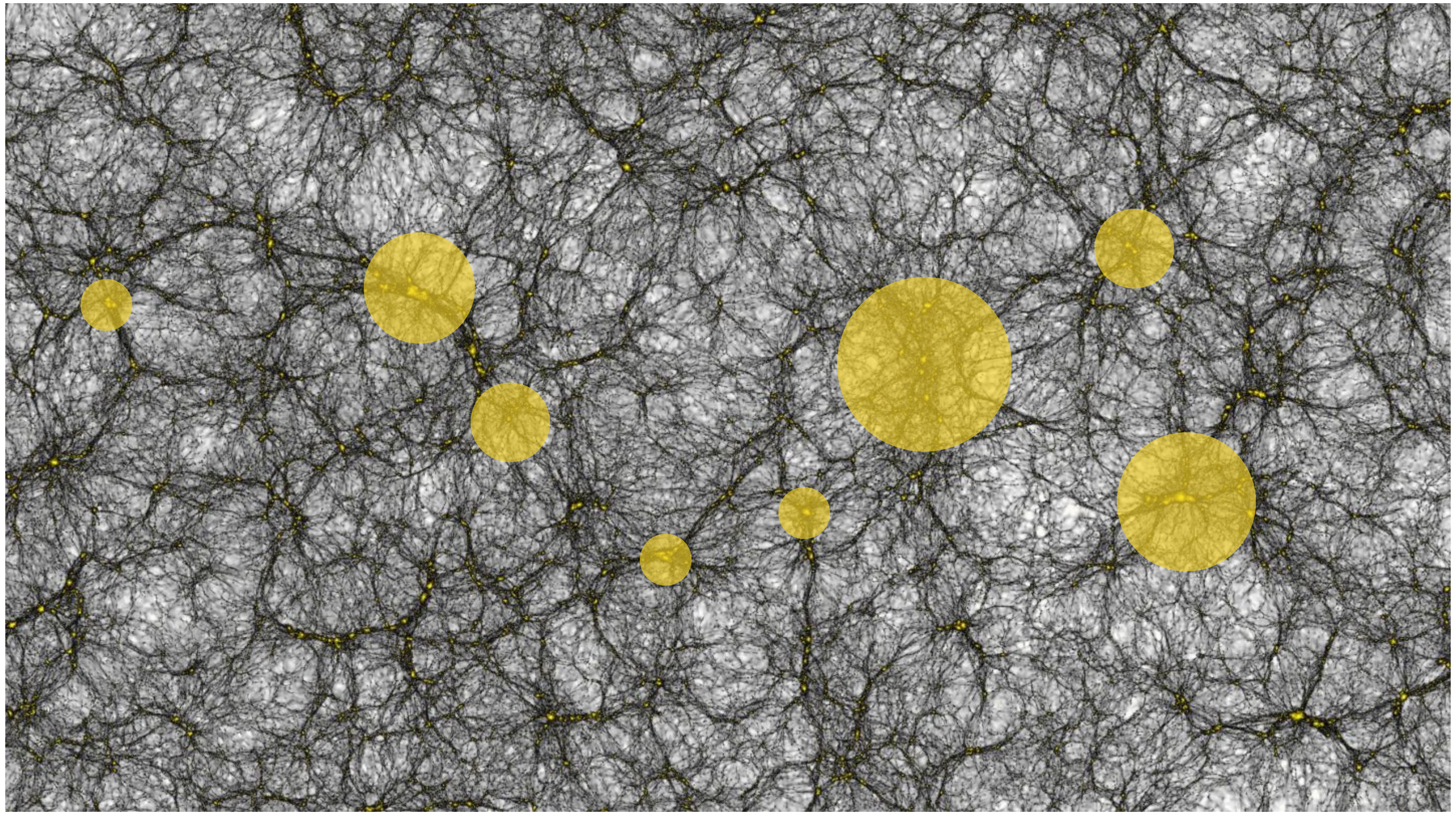
Synergies vs cosmic variance



$$\Delta = \Delta^{(\mathrm{den})} + \Delta^{(\mathrm{vel})} + \Delta^{(\mathrm{len})} + \Delta^{(\mathrm{rel})}$$

[Yoo (2009); Bonvin & Durrer (2010);
Challinor & Lewis (2010)]

Synergies vs cosmic variance



$$\Delta = \boxed{\Delta^{(\mathrm{den})}} + \underbrace{\Delta^{(\mathrm{vel})}}_{\equiv \boxed{\Delta^{(\mathrm{RSD})}}} + \Delta^{(\mathrm{len})} + \underbrace{\Delta^{(\mathrm{rel})}}_{\supset \boxed{\Delta^{(\mathrm{Dop})}}}$$

Doppler in galaxy power spectrum

Magnitude of Doppler

$$\Delta(\boldsymbol{k}) = \left(b + f\,\mu^2 + \mathrm{i}\,\frac{\alpha\, f}{r\, k}\,\mu \right) \delta(\boldsymbol{k})$$

Growth rate

(Linear) galaxy bias

Cosine of angle $\hat{\boldsymbol{k}} \cdot \hat{\boldsymbol{r}}$

(Radial comoving) distance to source

[MacDonald (2008); Abramo & Bertacca (2017)]

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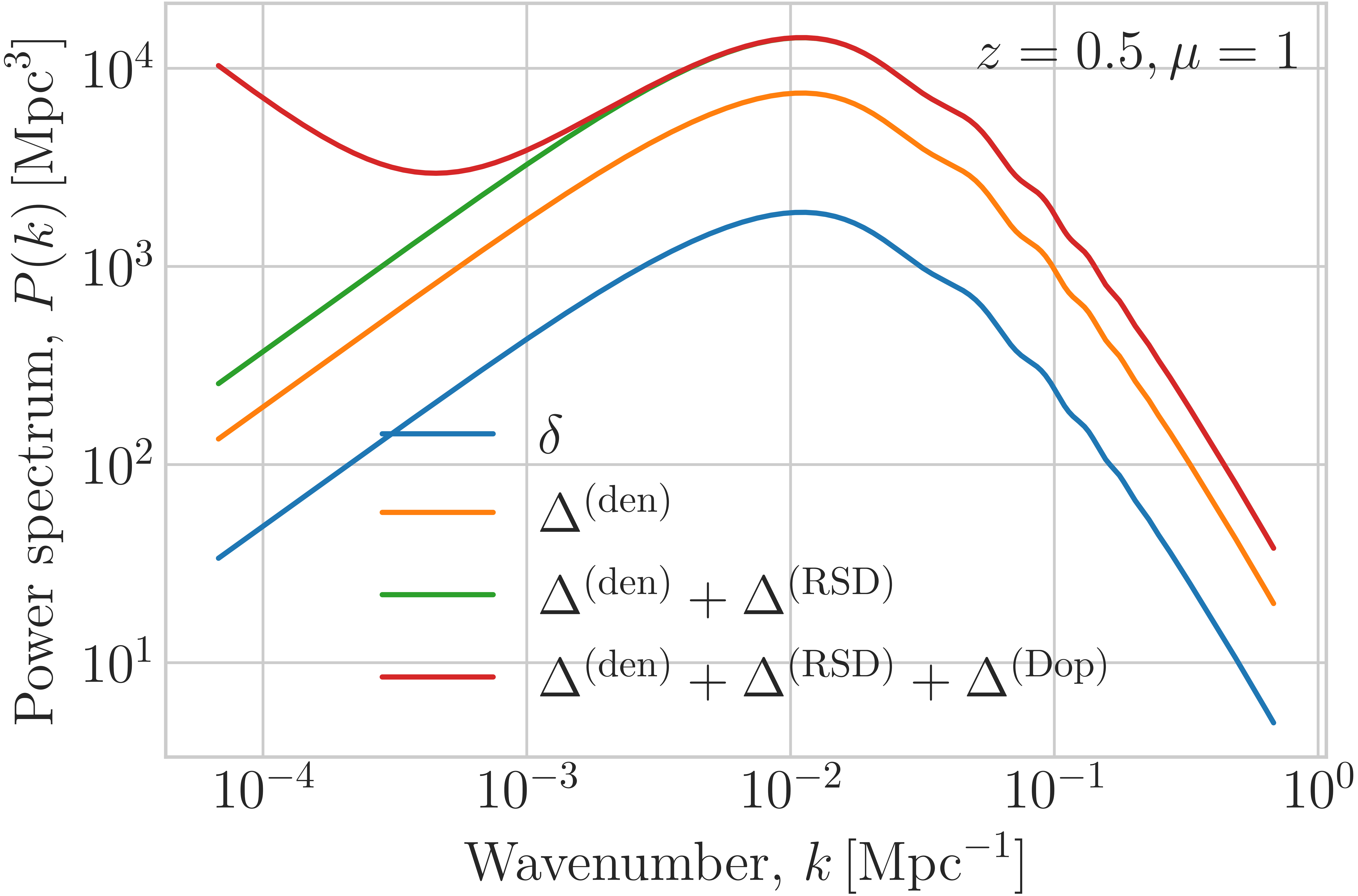
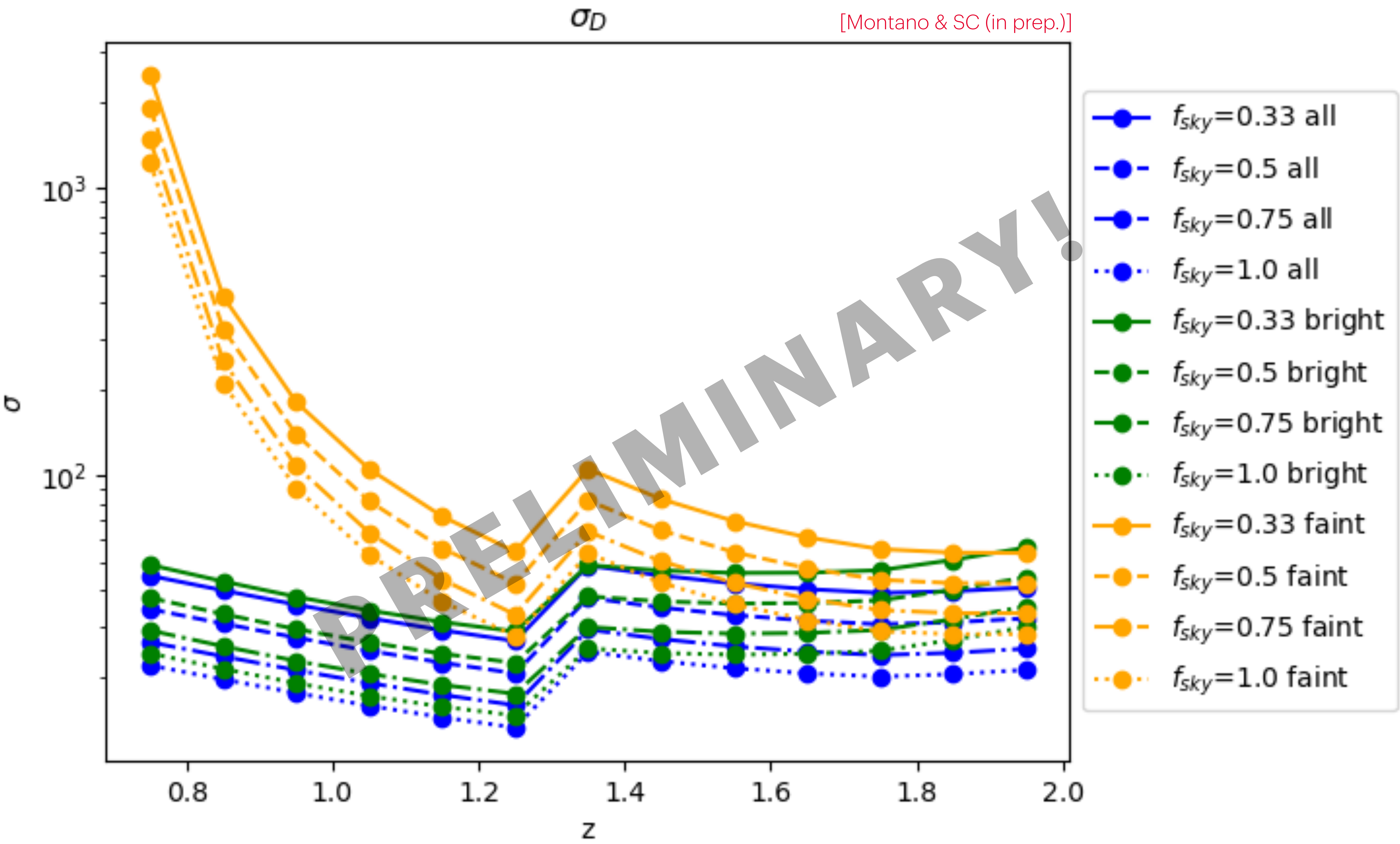
Doppler in galaxy power spectrum



Doppler in galaxy power spectrum



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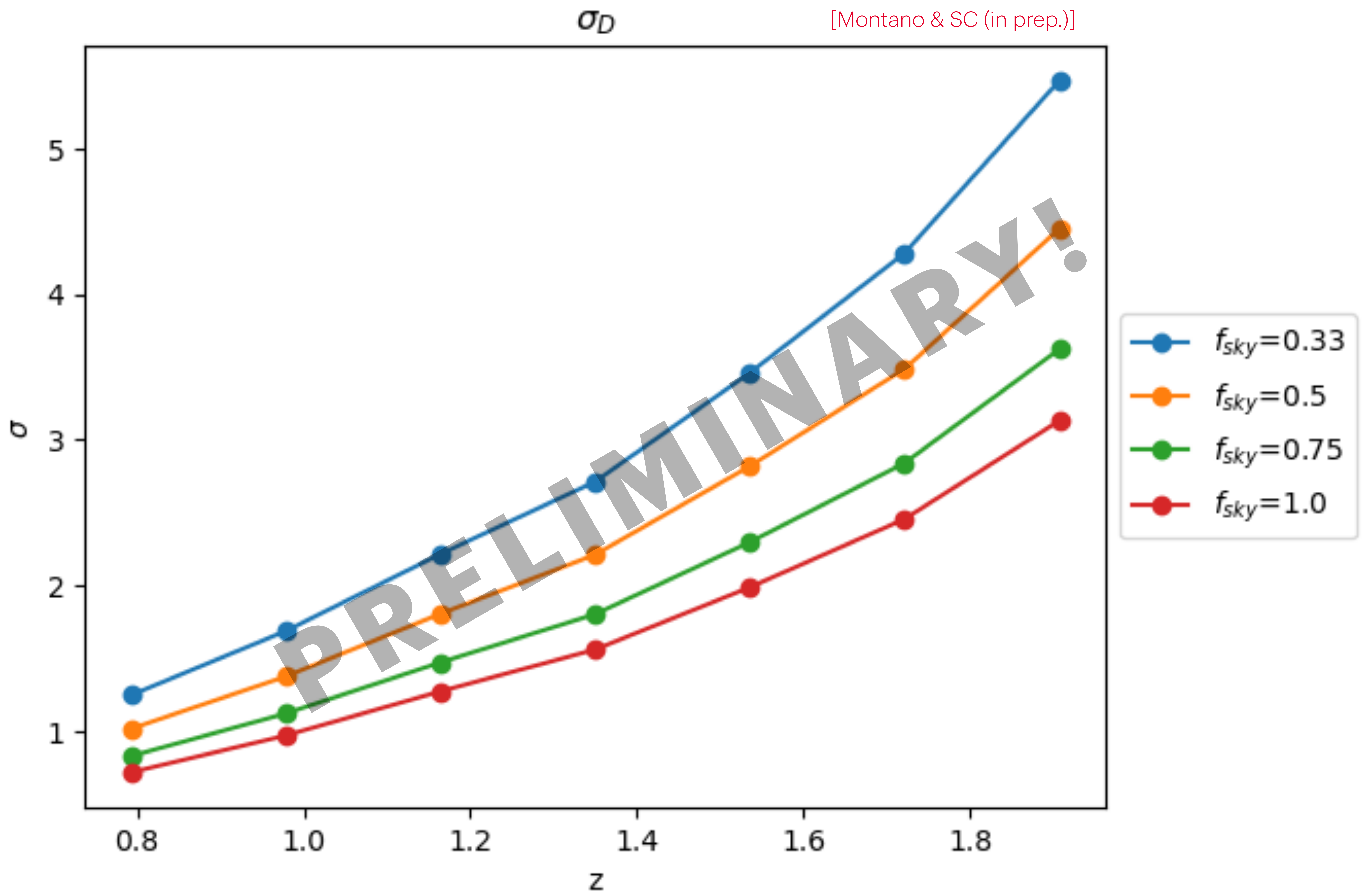
Doppler in galaxy power spectrum



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Conclusions

- Great time for cosmological synergies at various wavelengths
- Cross-correlations crucial for:
  - Cross-checking validity of cosmological results
  - Removing/alleviating contamination from systematic effects
    [e.g. radio-optical cosmic shear]
  - Accessing signal buried in noise or cosmic variance
    [e.g. particle dark matter, relativistic effects]