Dark energy and fundamental physics with the Euclid satellite

Stefano Camera

UNIVERSITÀ DI TORINO

Physics Torino Department of Excellence

INFN TORINO Istituto Nazionale di Fisica Nucleare Sezione di Torino

INAF Osservatorio Astrofisico di Torino

UNIVERSITY of the WESTERN CAPE

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Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Concordance cosmology

- *Most* of the matter in the Universe appears to be of *exotic* origin (*dark matter*)

Concordance cosmology

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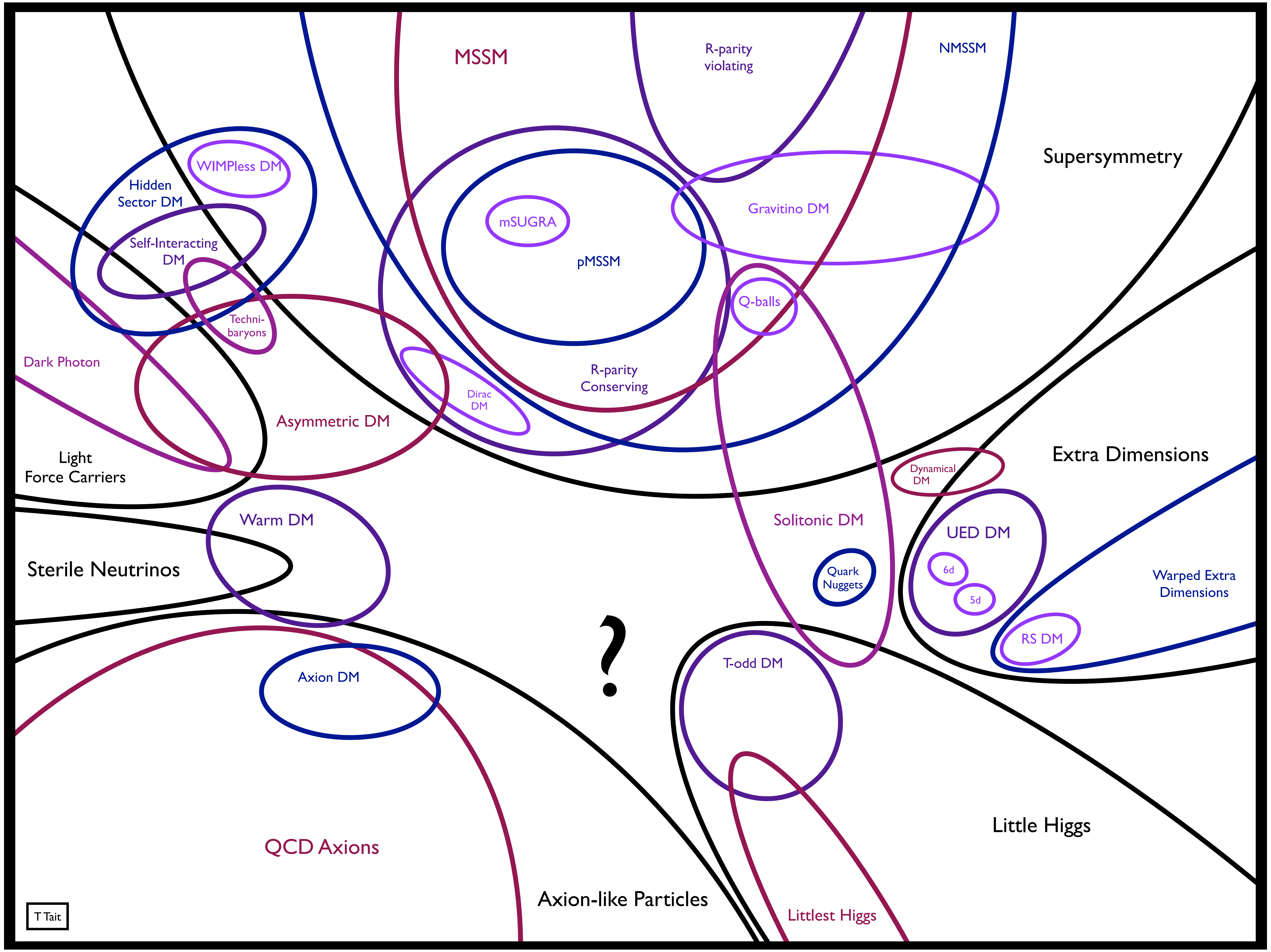
  - Another mysterious scalar field or simply a seemingly fine-tuned Λ?
  - Or, even, a symptom of an incorrect *gravity theory* on cosmological scales?

Dark matter



[Credits: T. Tait]

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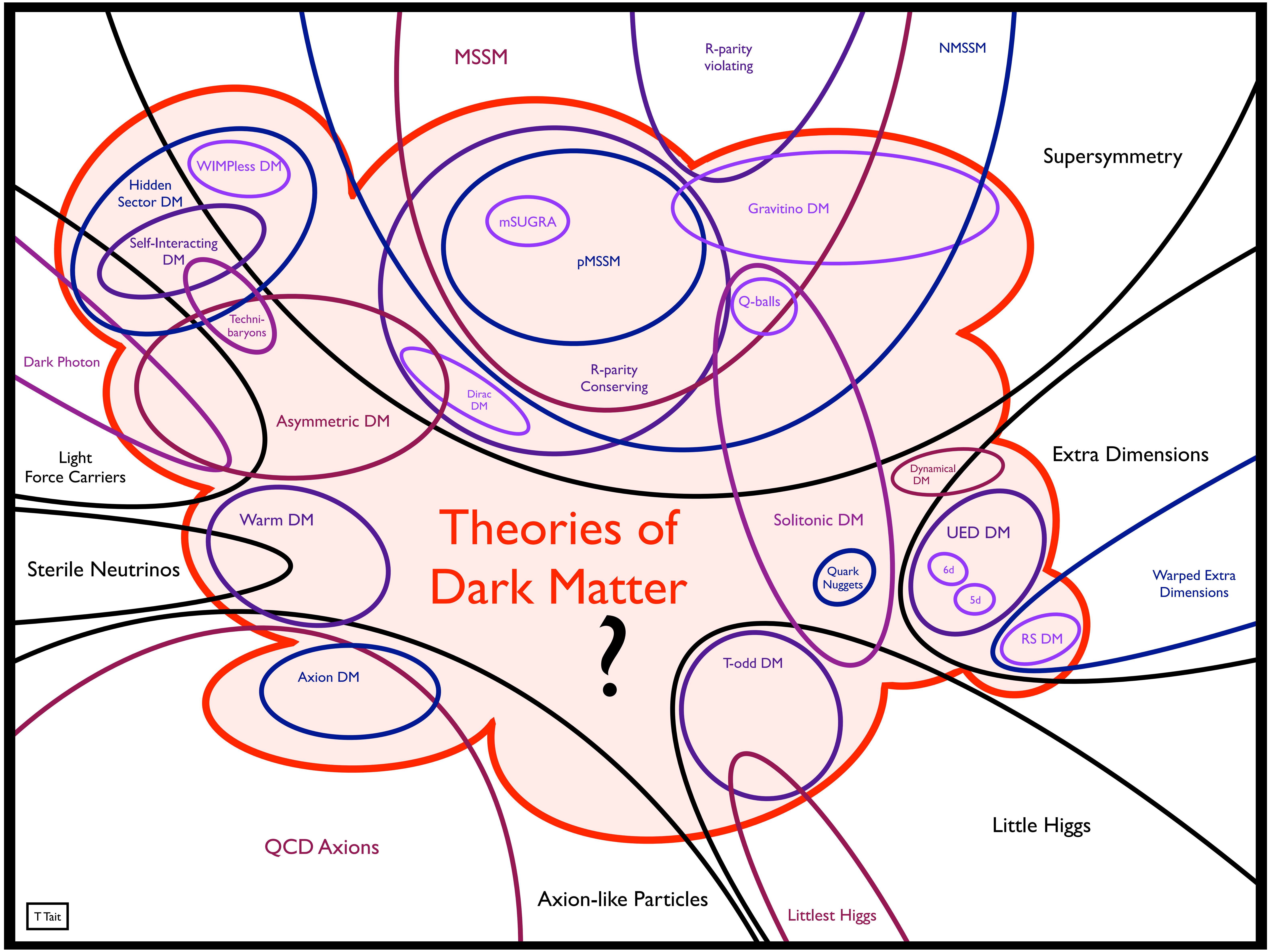
Dark matter



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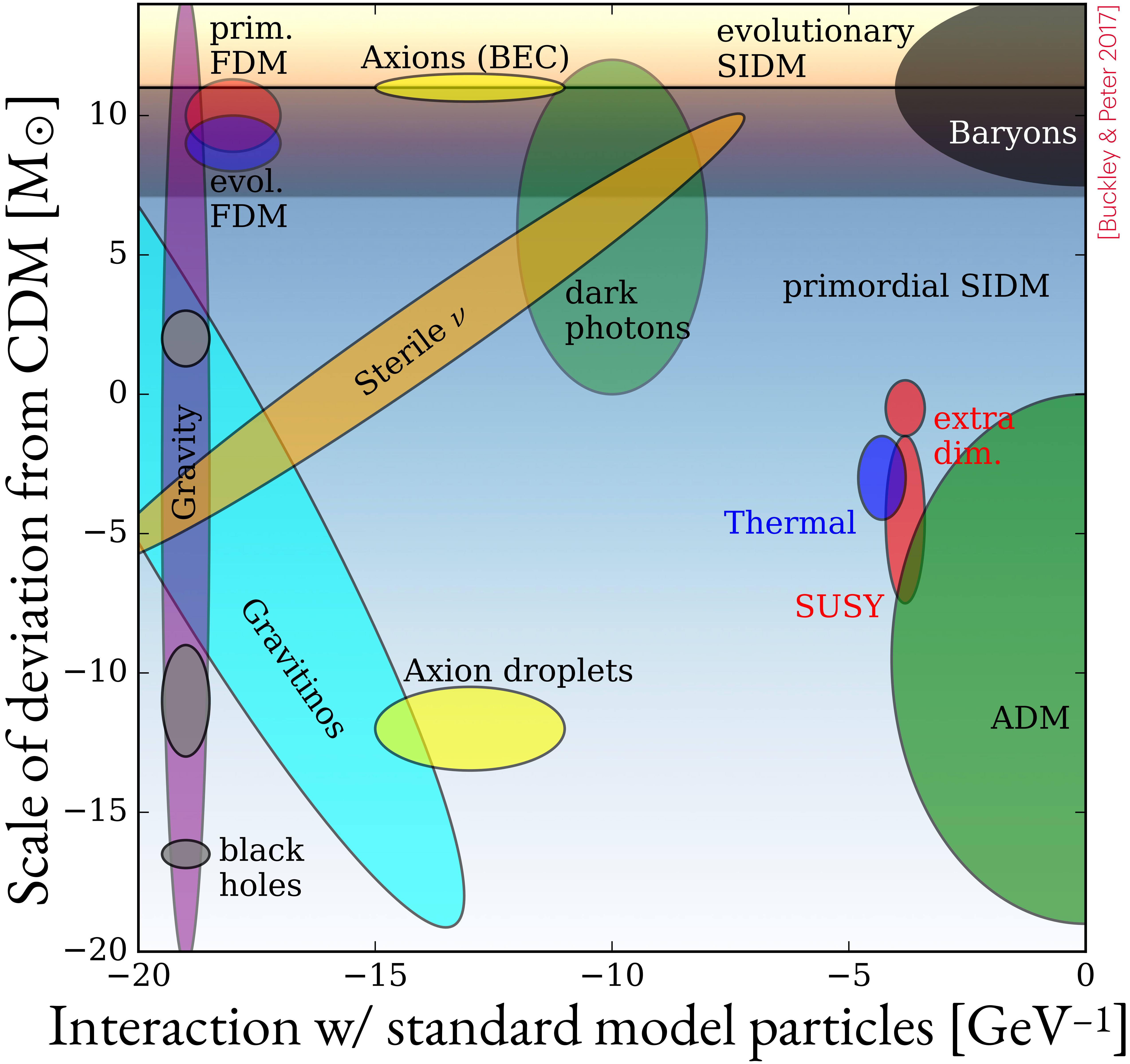

[Buckley & Peter 2017]

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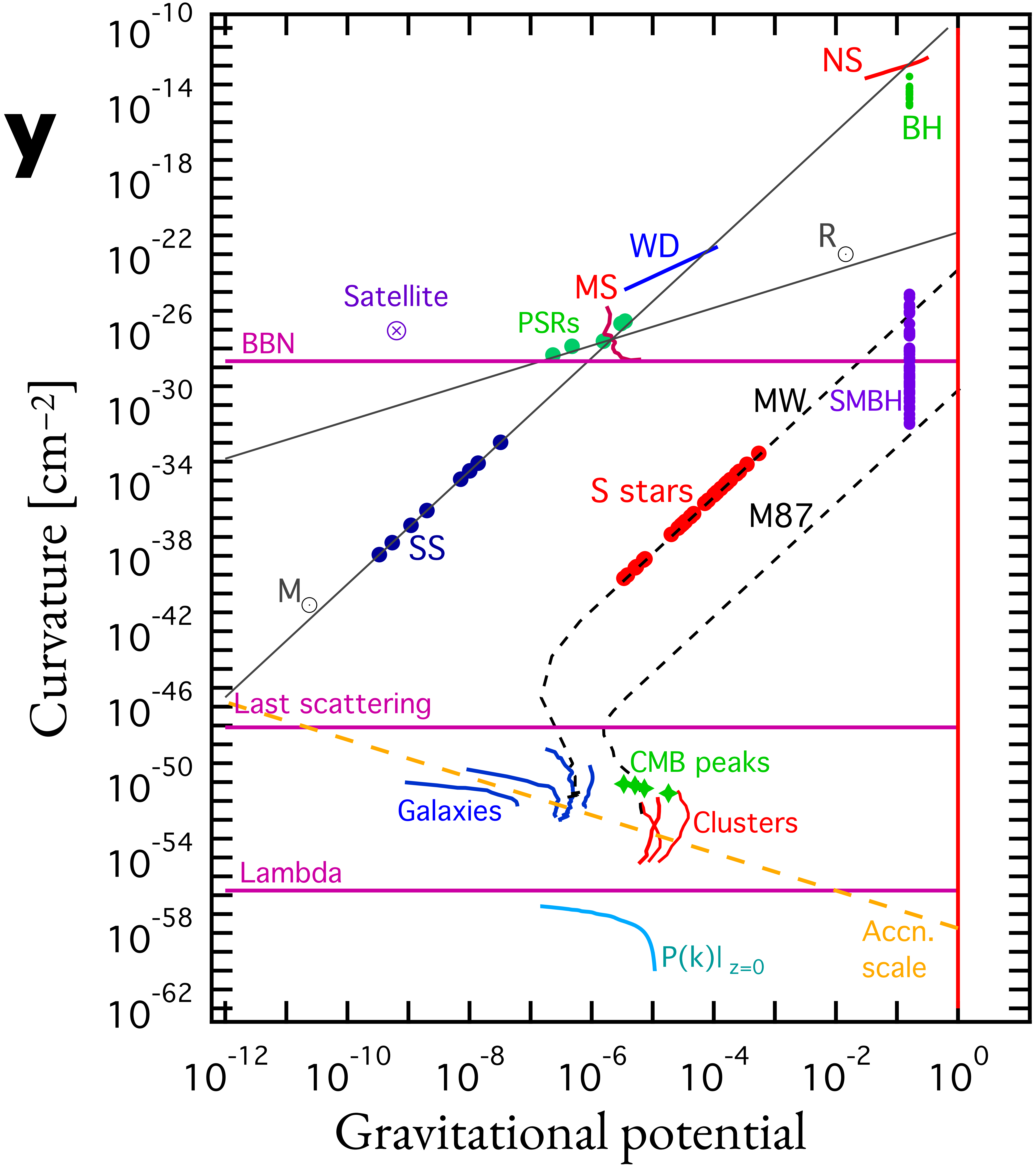
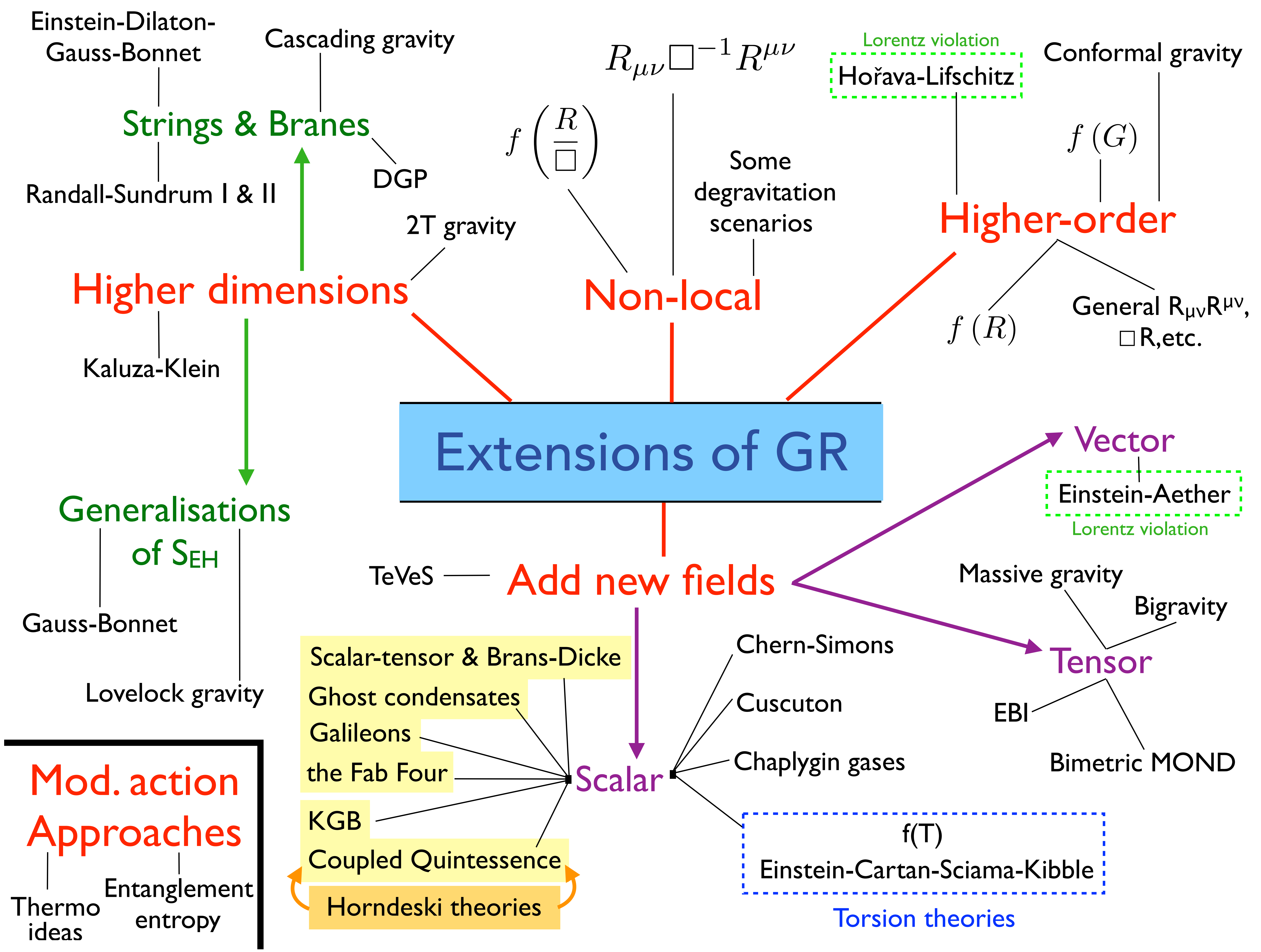
Λ/Dark energy



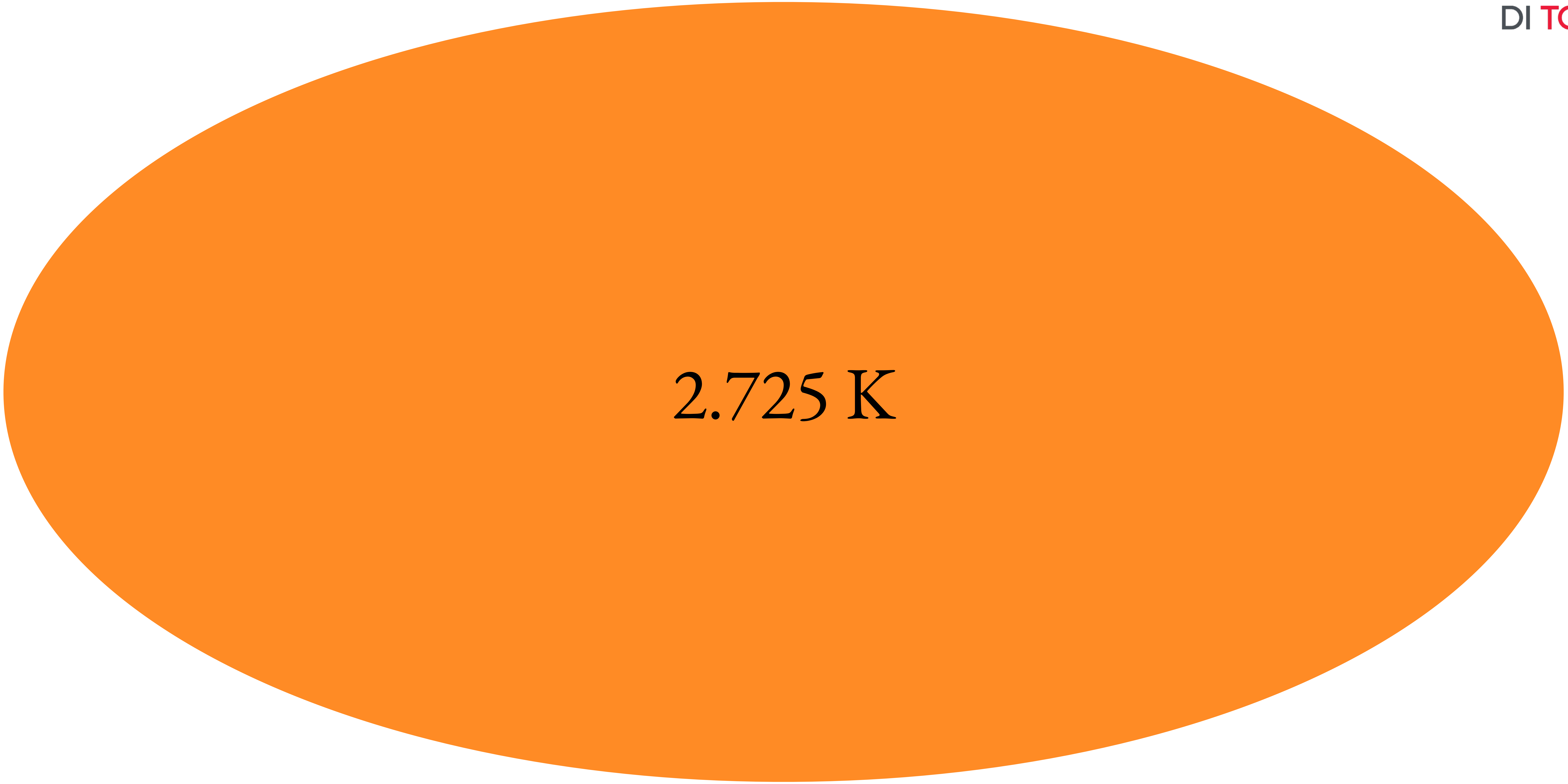
[Baker, Psaltis & Skordis 2015]

Λ/Dark energy



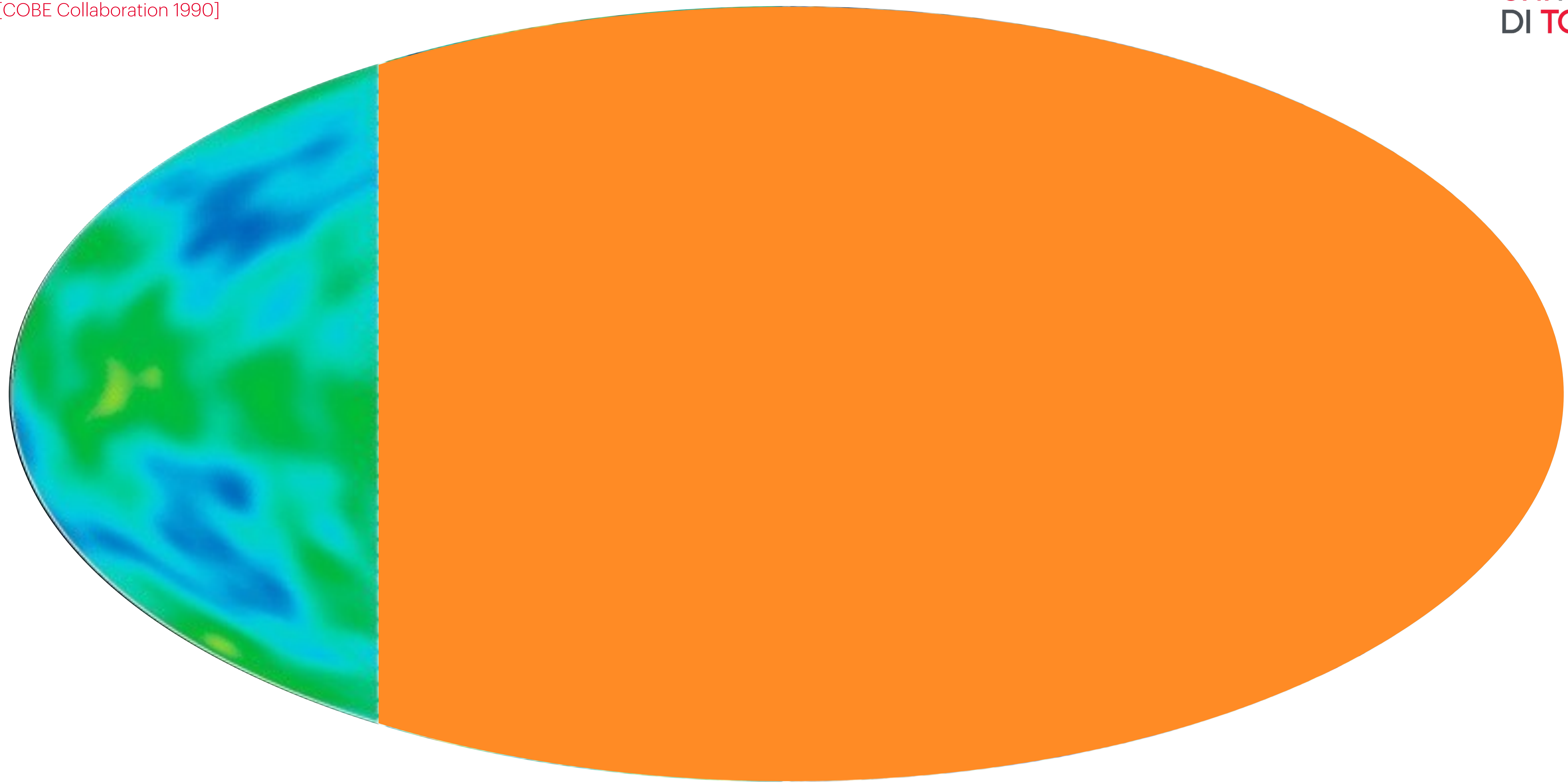
[Credits: T. Baker]

Cosmic microwave background



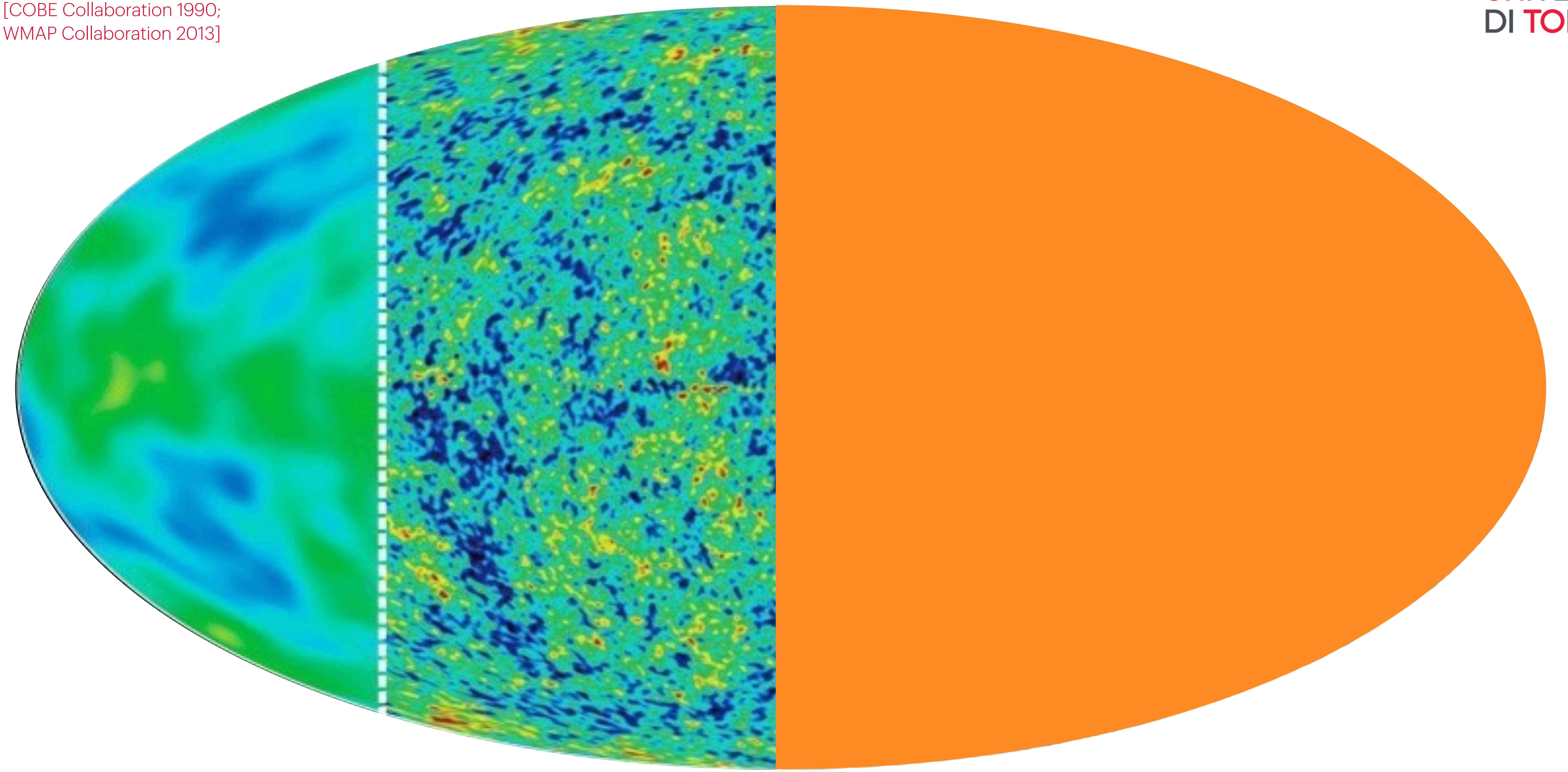
Cosmic microwave background

[COBE Collaboration 1990]



Cosmic microwave background

[COBE Collaboration 1990;
WMAP Collaboration 2013]



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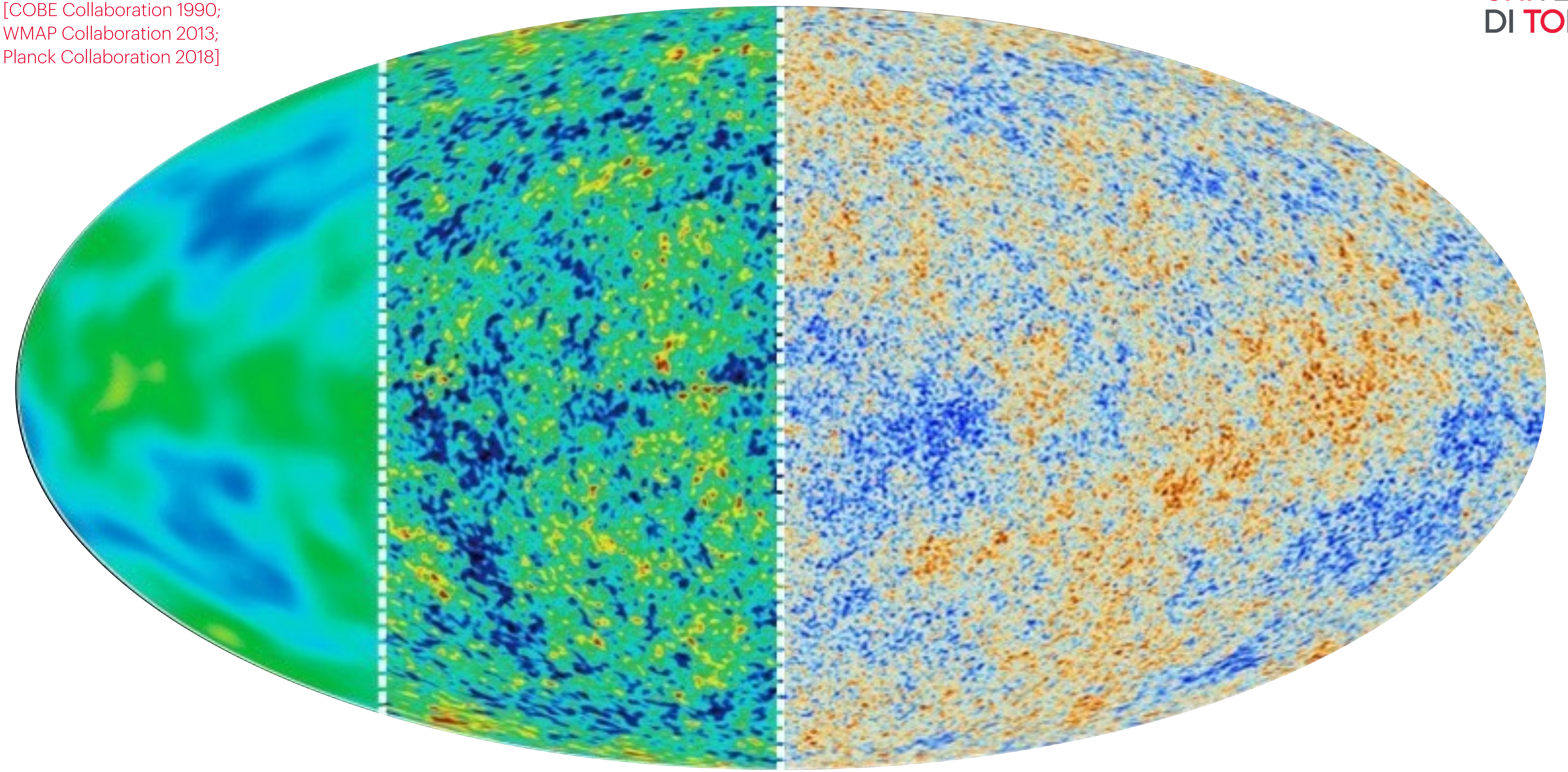

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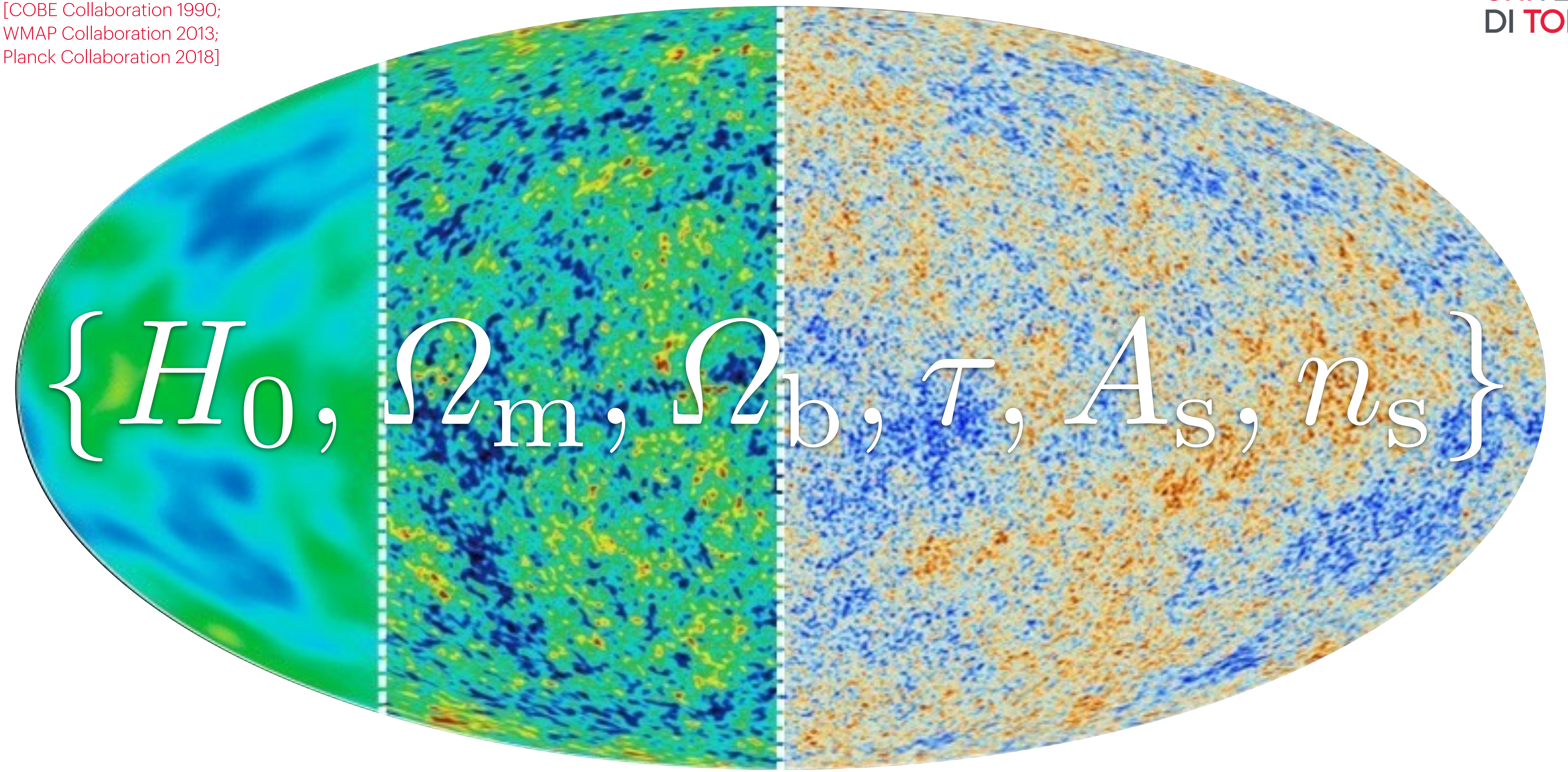
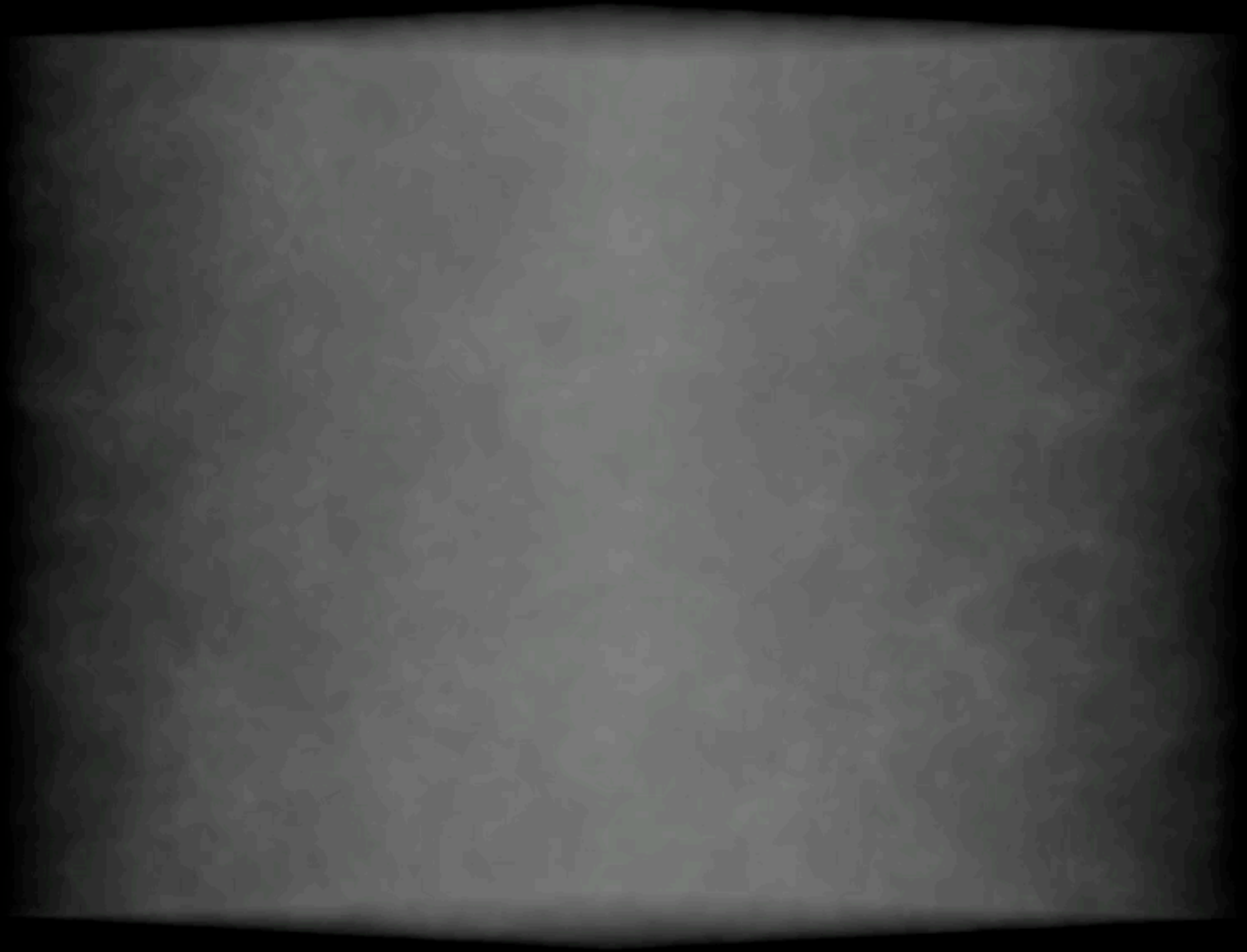


$$\{H_0, \Omega_{\rm m}, \Omega_{\rm b}, \tau, A_{\rm s}, n_{\rm s}\}$$

The cosmic large-scale structure

$z = 20.00$



[Credits: F. Villaescusa-Navarro]

The cosmic large-scale structure

$z = 15.03$

[Credits: F. Villaescusa-Navarro]

The cosmic large-scale structure

$z = 10.03$

[Credits: F. Villaescusa-Navarro]

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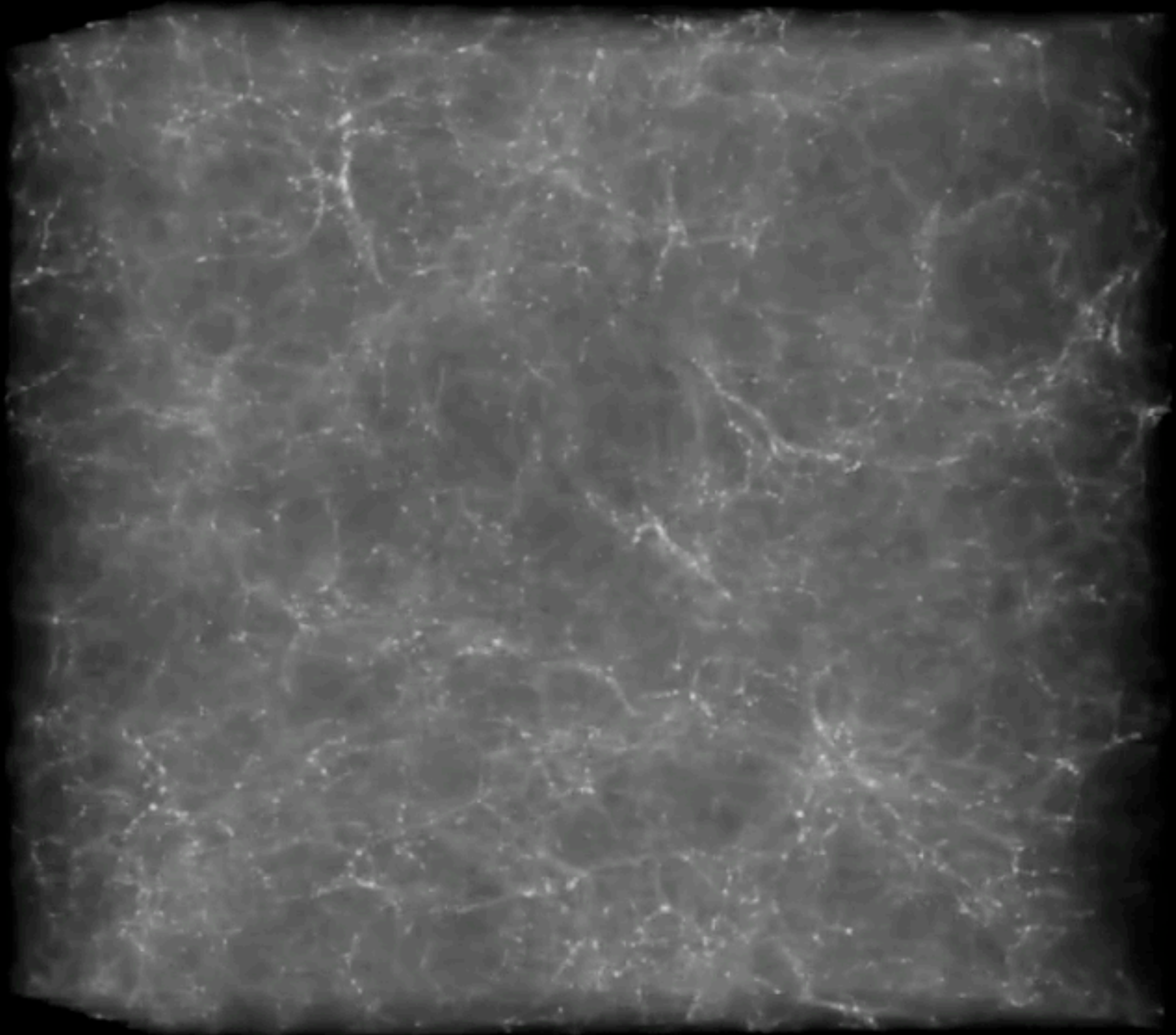
The cosmic large-scale structure

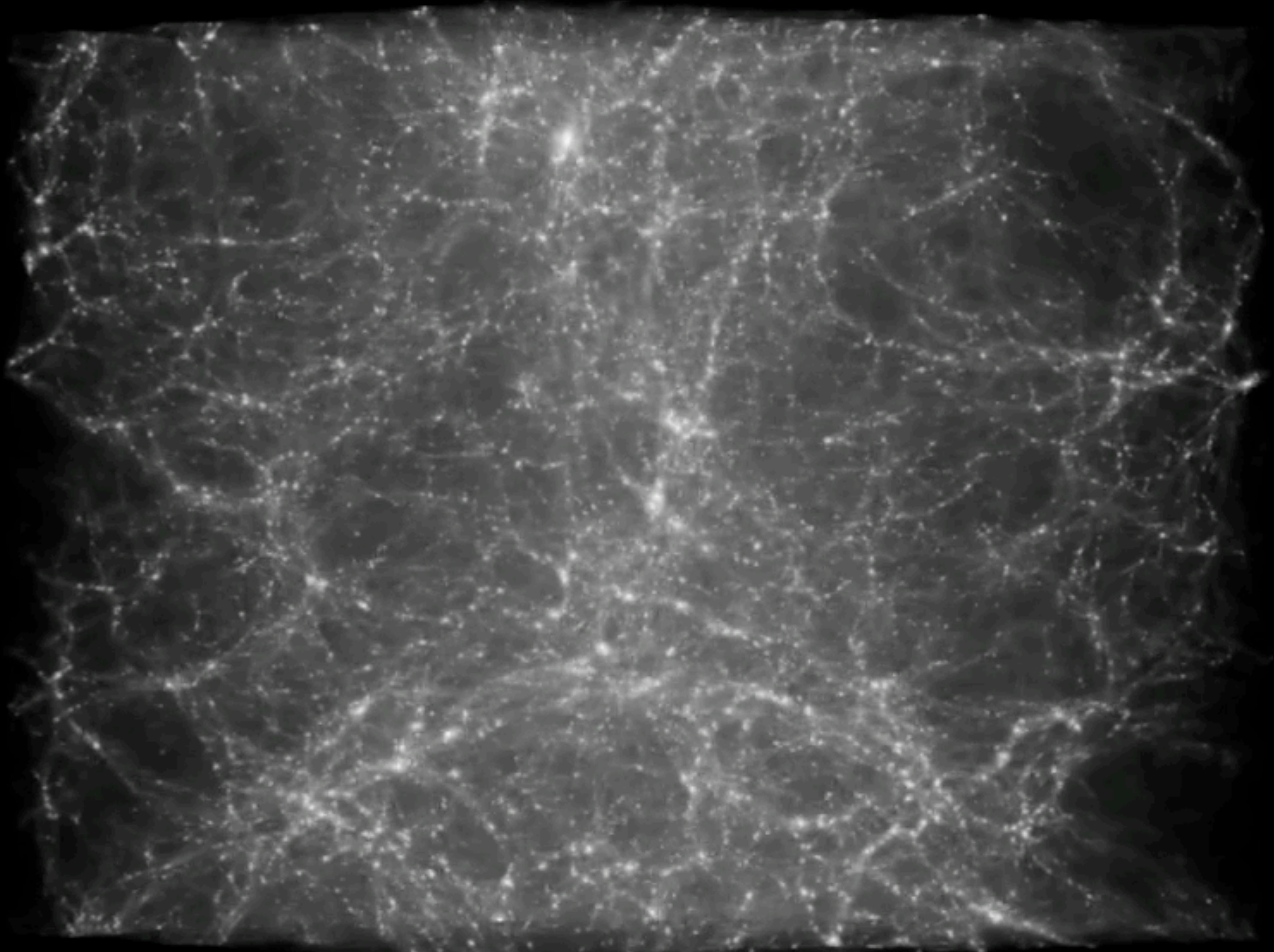
$z = 5.00$



[Credits: F. Villaescusa-Navarro]

The cosmic large-scale structure

$z = 2.51$



[Credits: F. Villaescusa-Navarro]

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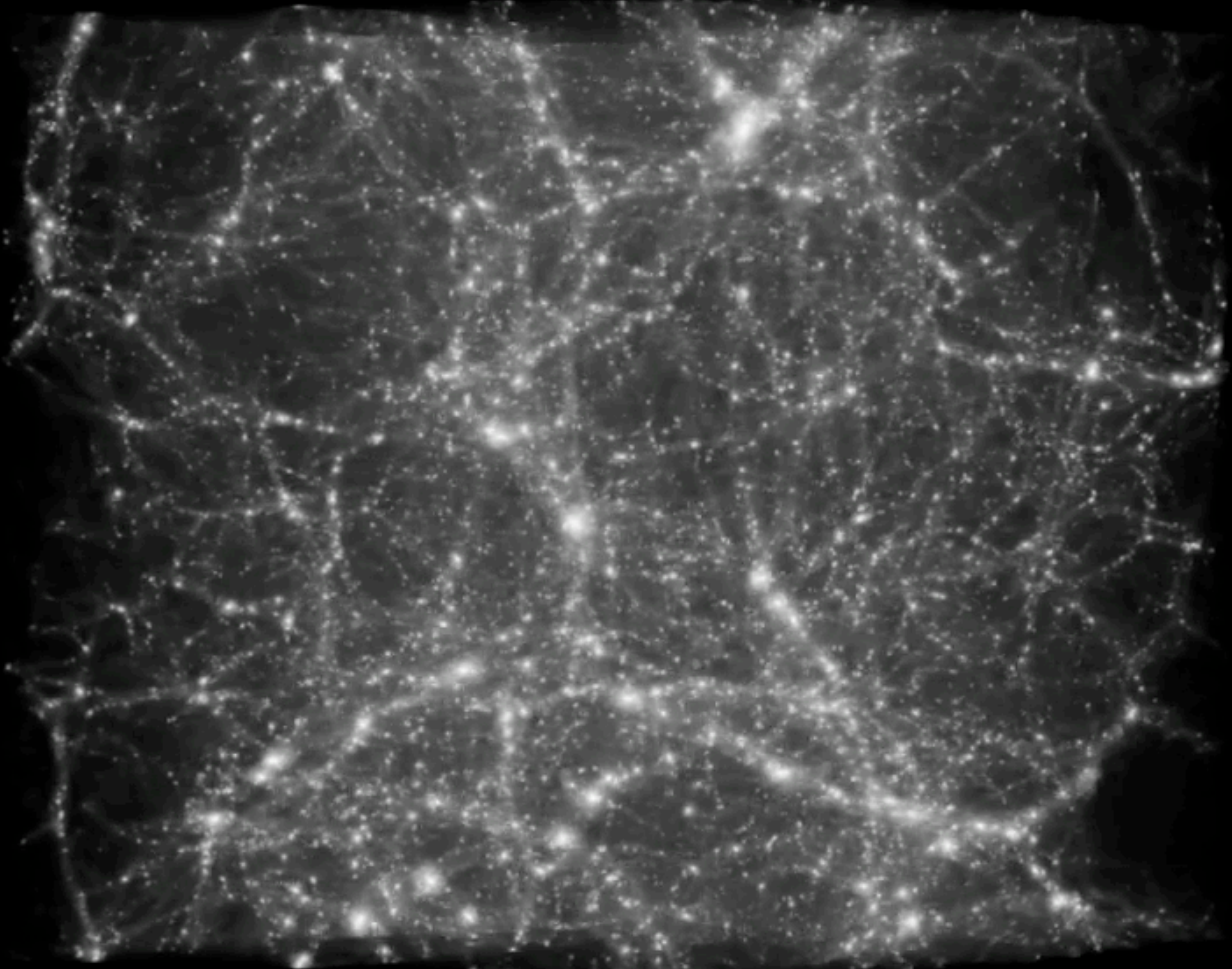
The cosmic large-scale structure

$z = 1.00$



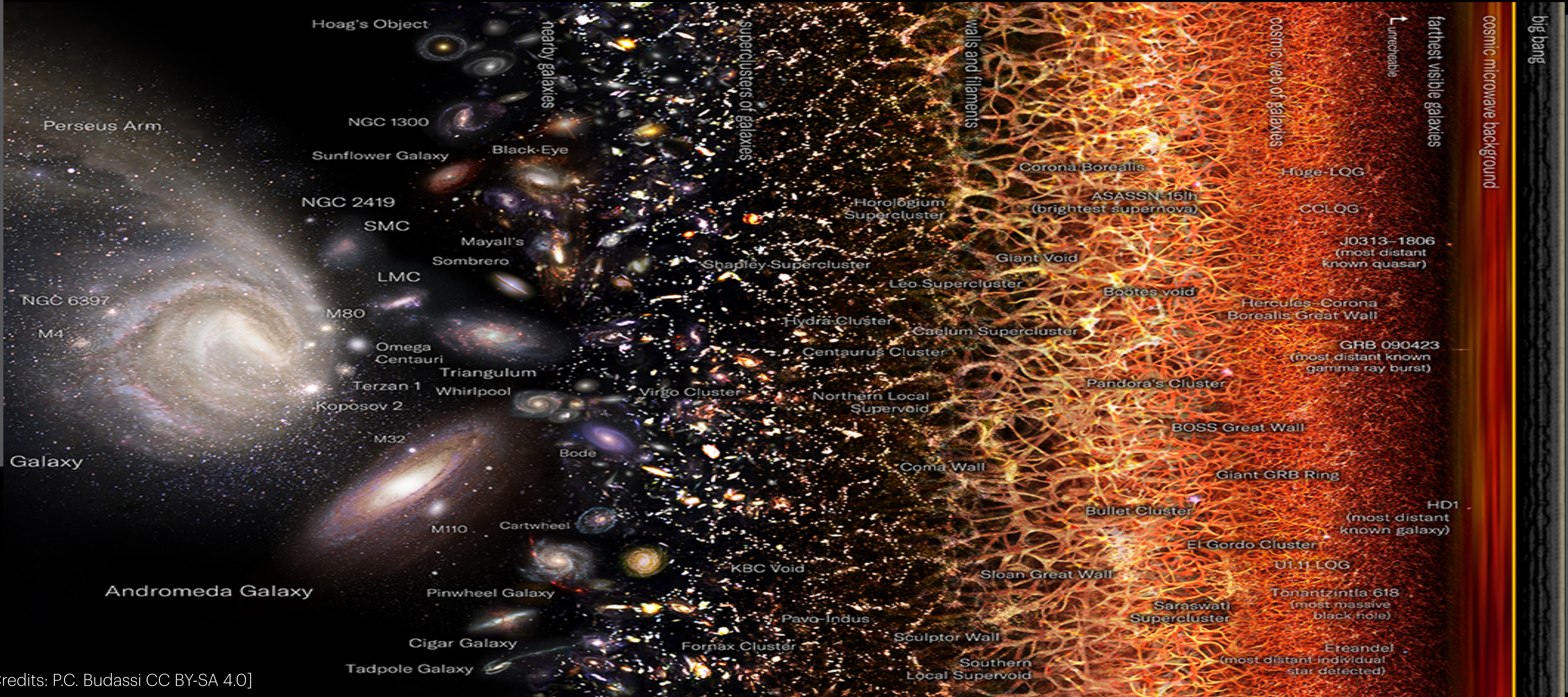
[Credits: F. Villaescusa-Navarro]

The cosmic large-scale structure

$z = 0.00$

[Credits: F. Villaescusa-Navarro]

The cosmic large-scale structure



[Credits: P.C. Budassi CC BY-SA 4.0]

The cosmic large-scale structure

Correlators

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

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

Correlators

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- Two-point correlation function $\langle f(t, \boldsymbol{x})\, f(t, \boldsymbol{y})\rangle = \xi_{ff}(t, \boldsymbol{x} - \boldsymbol{y})$

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- Two-point correlation function $\langle f(t,\boldsymbol{x})\, f(t,\boldsymbol{y})\rangle = \xi_{f\,f}(t,\boldsymbol{x}-\boldsymbol{y})$

- Fourier-space power spectrum $\langle \hat{f}(t,\boldsymbol{k})\, \hat{f}(t,\boldsymbol{k}')\rangle = (2\,\pi)^3\,\delta(\boldsymbol{k}+\boldsymbol{k}')\,P_{f\,f}(t,\boldsymbol{k})$

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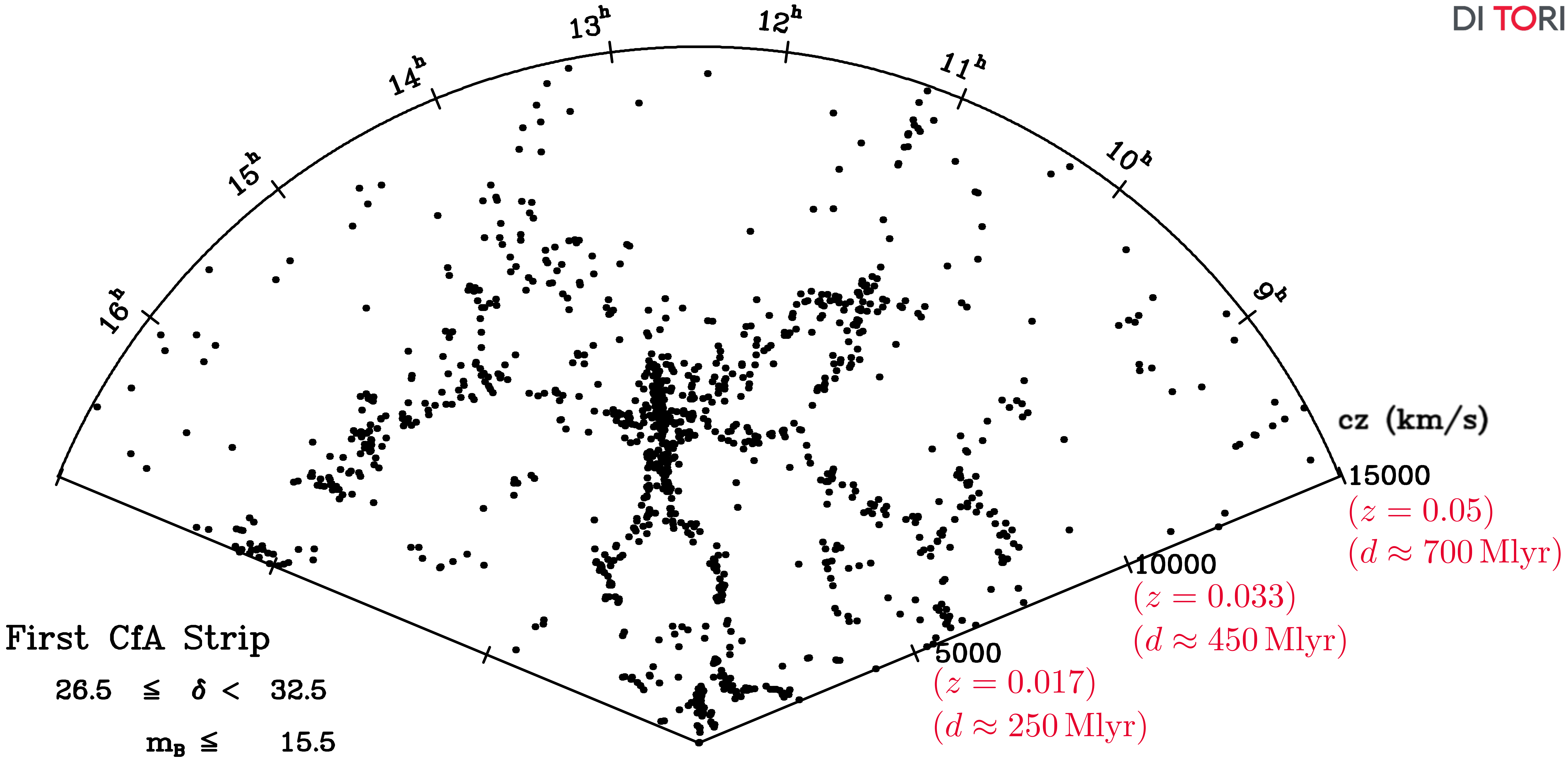
- Harmonic-space power spectrum $\langle \tilde{f}_{lm}(z)\, \tilde{f}_{l'm'}(z')\rangle = \delta_{ll'}\, \delta_{mm'}\, C_l^{ff}(z, z')$

Galaxy clustering



[Geller & Huchra 1989]

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Galaxy clustering

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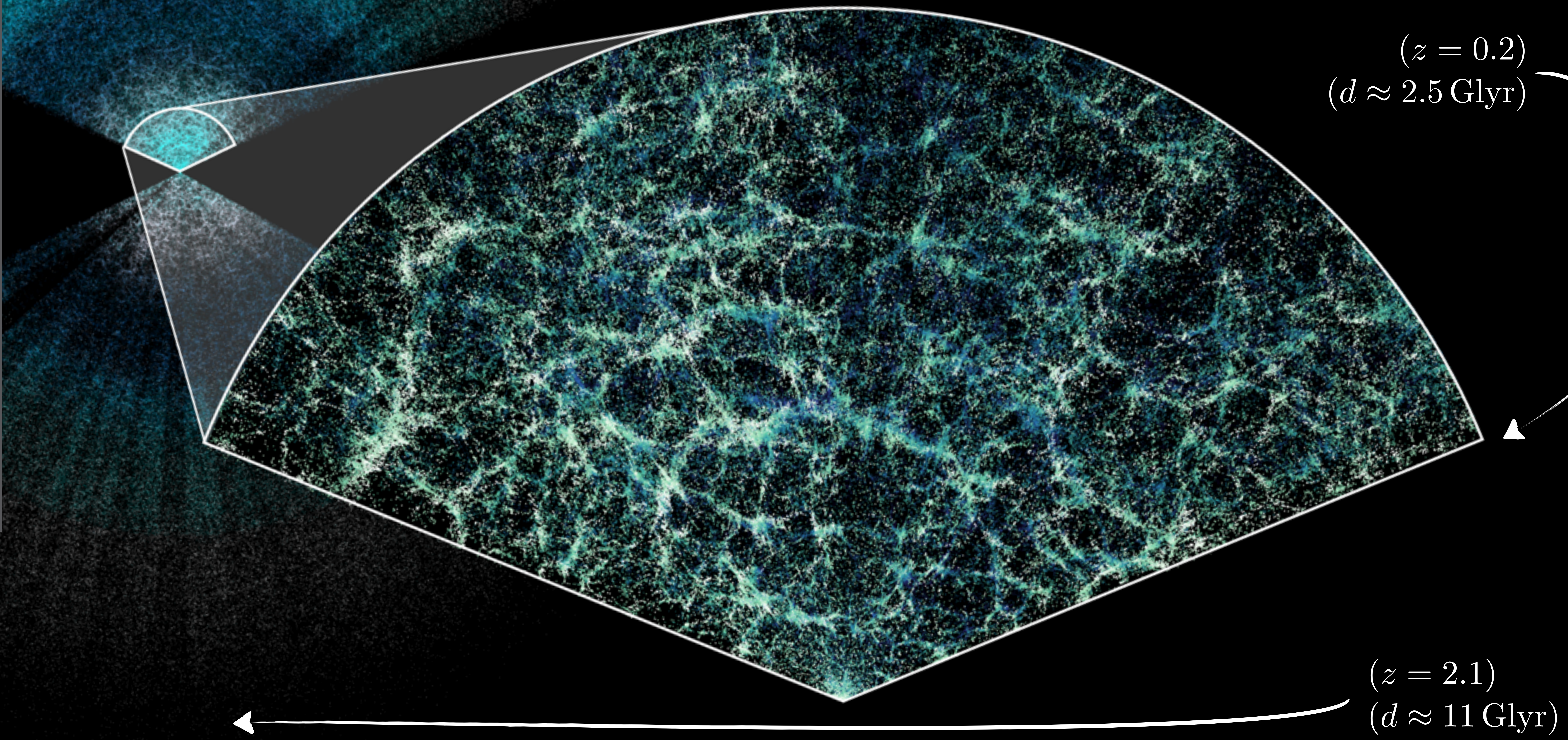

[Credits: C. Lamman/DESI Collaboration 2024]

Galaxy clustering

$$w_\Lambda := p_\Lambda/\rho_\Lambda = -1$$

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Galaxy clustering

$$w_{\mathrm{DE}} \equiv w_{\mathrm{DE}}(a)$$

Galaxy clustering

$$w_{\mathrm{DE}} \equiv w_{\mathrm{DE}}(a) = w_0 + w_a\,(1 - a)$$

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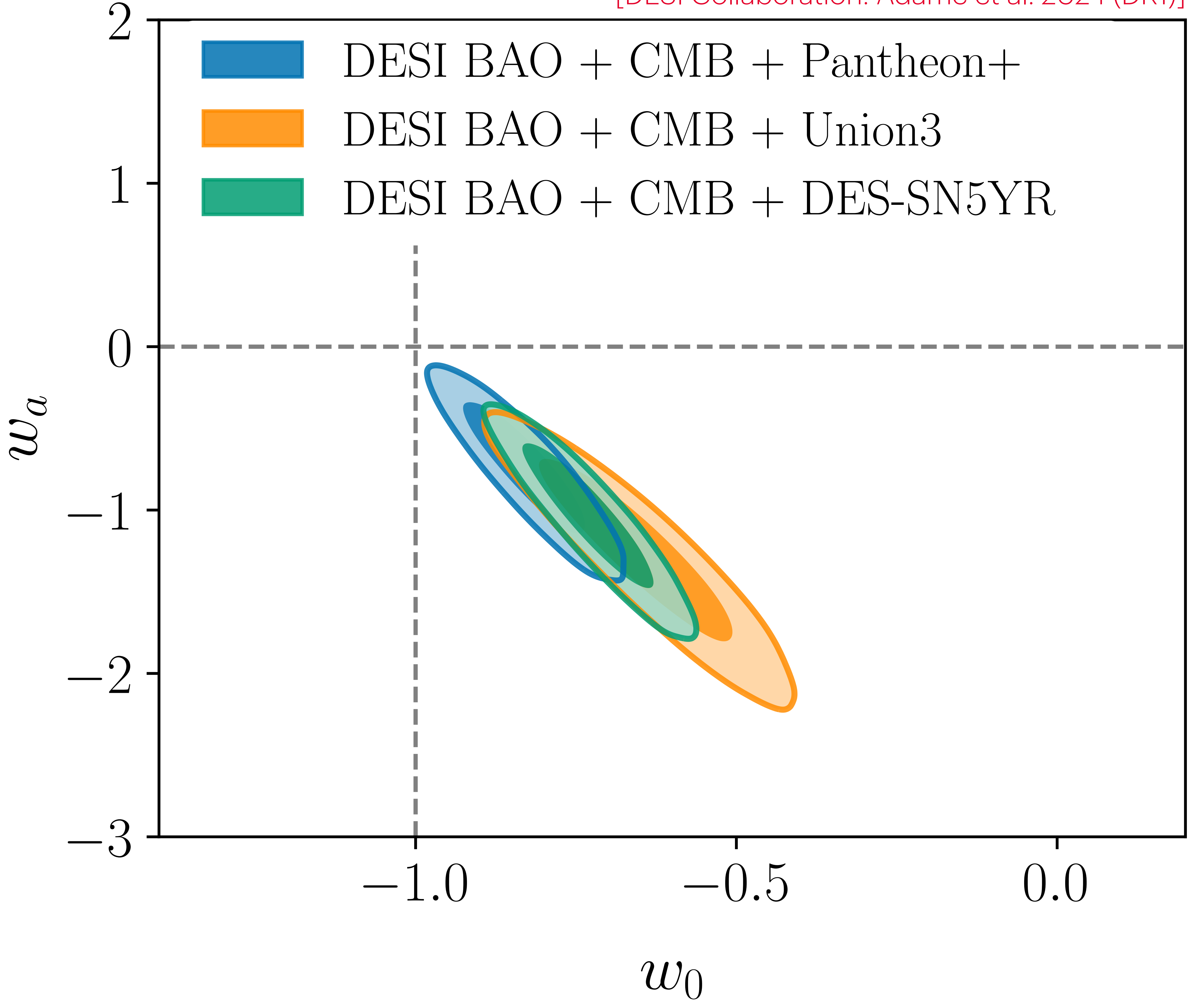
[DESI Collaboration: Adame et al. 2024 (DR1)]



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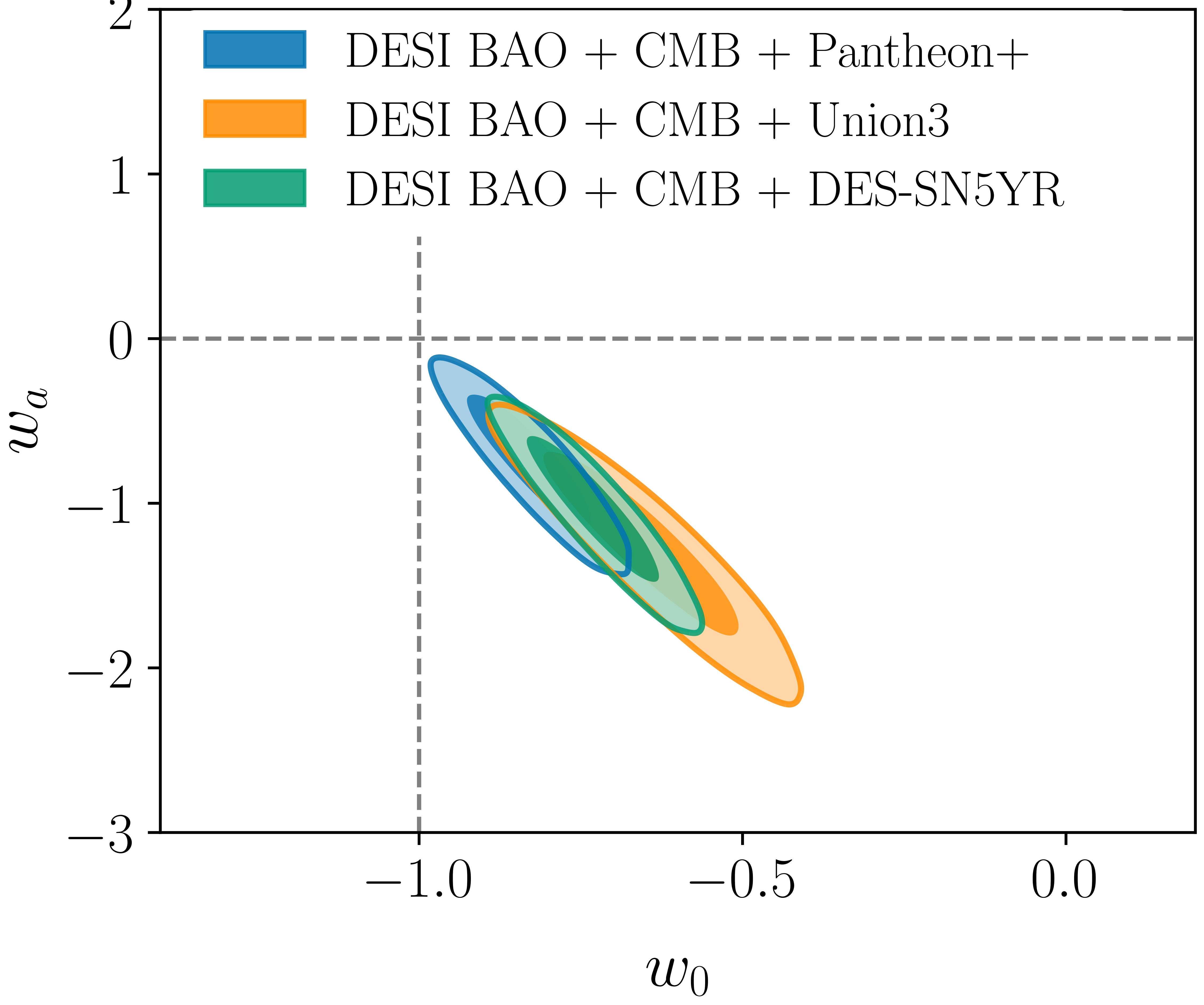
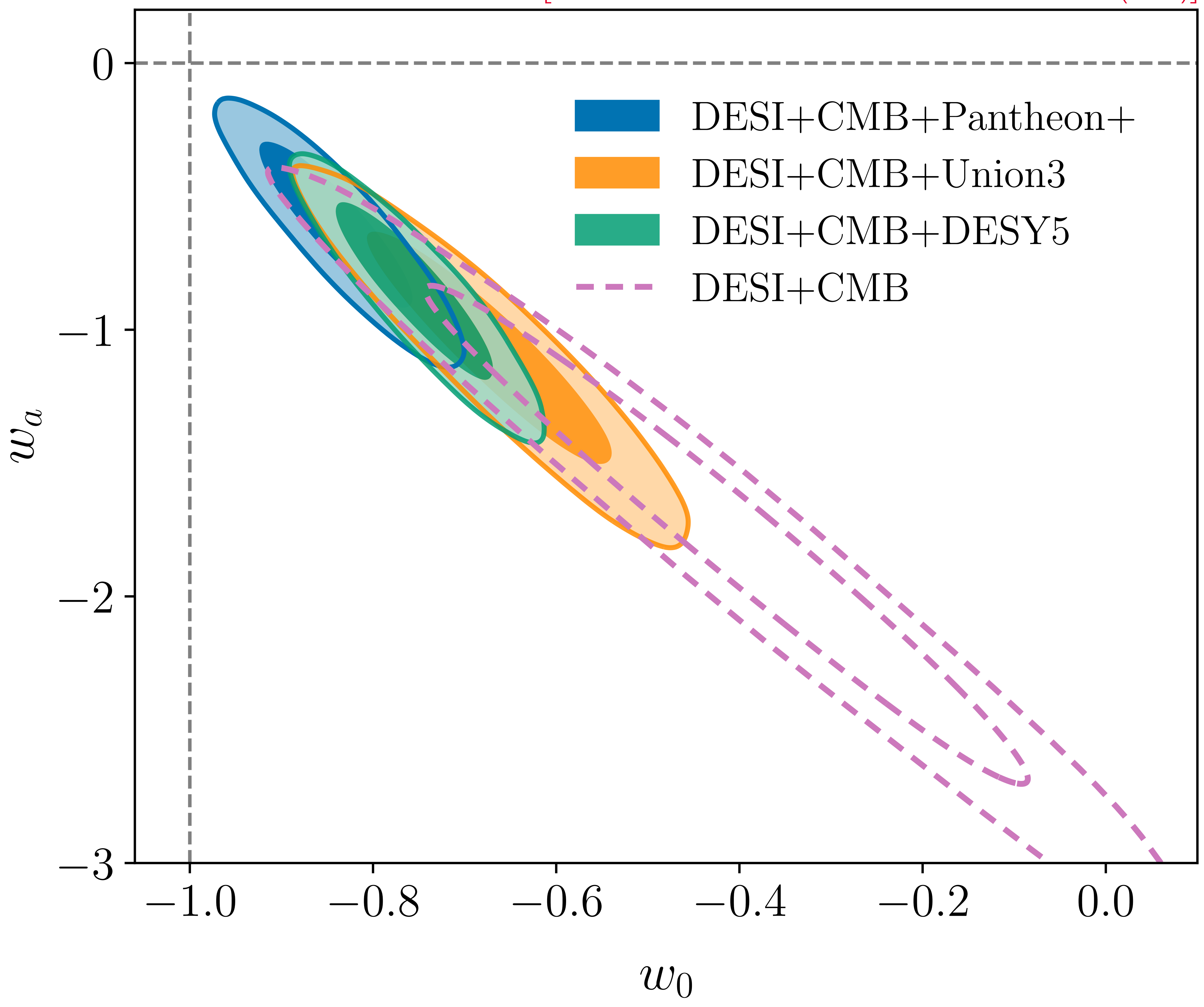


[DESI Collaboration: Abdul-Karim et al. 2025 (DR2)]



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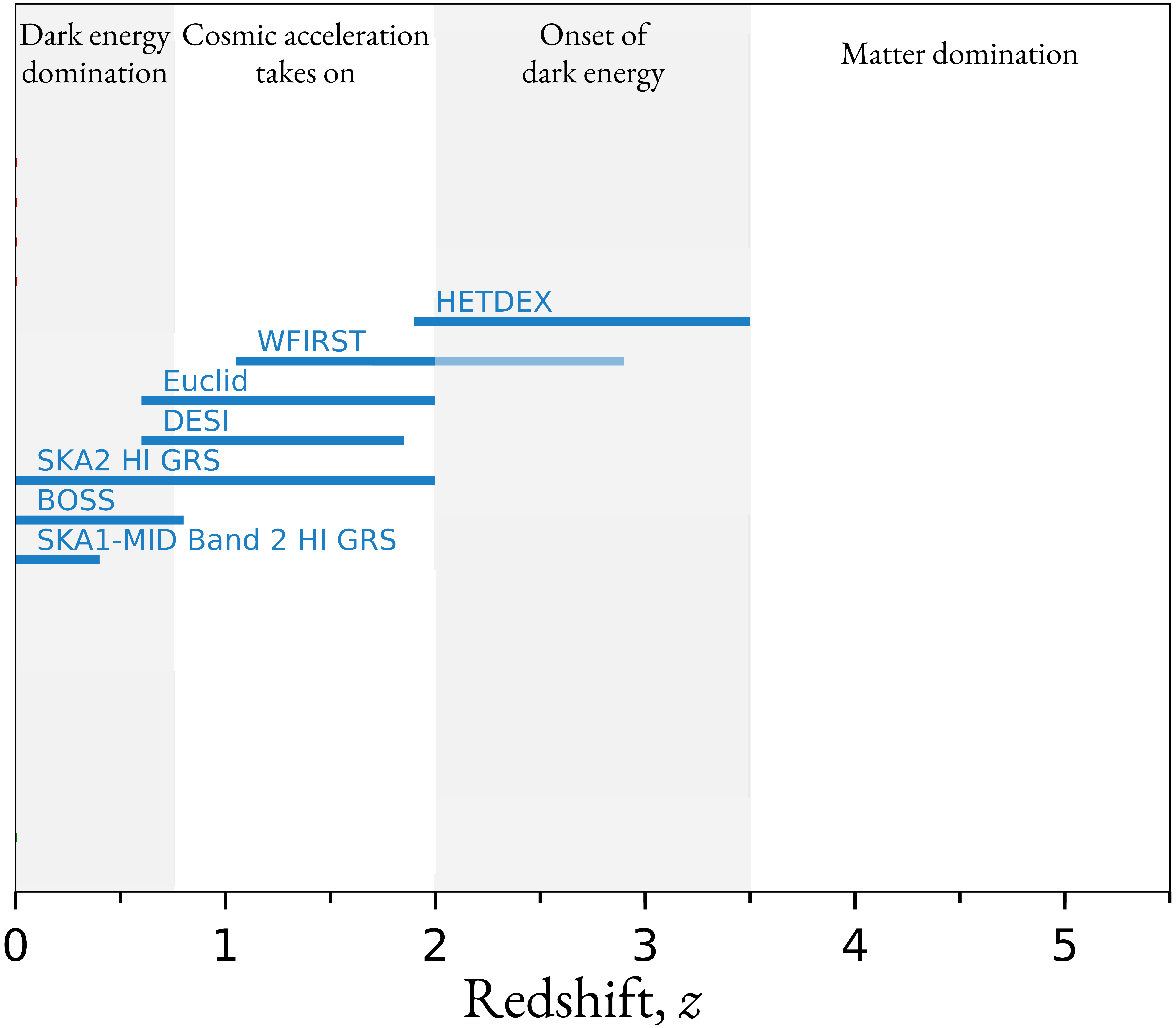
Galaxy clustering

[Bull et al. ⊃ SC 2020]



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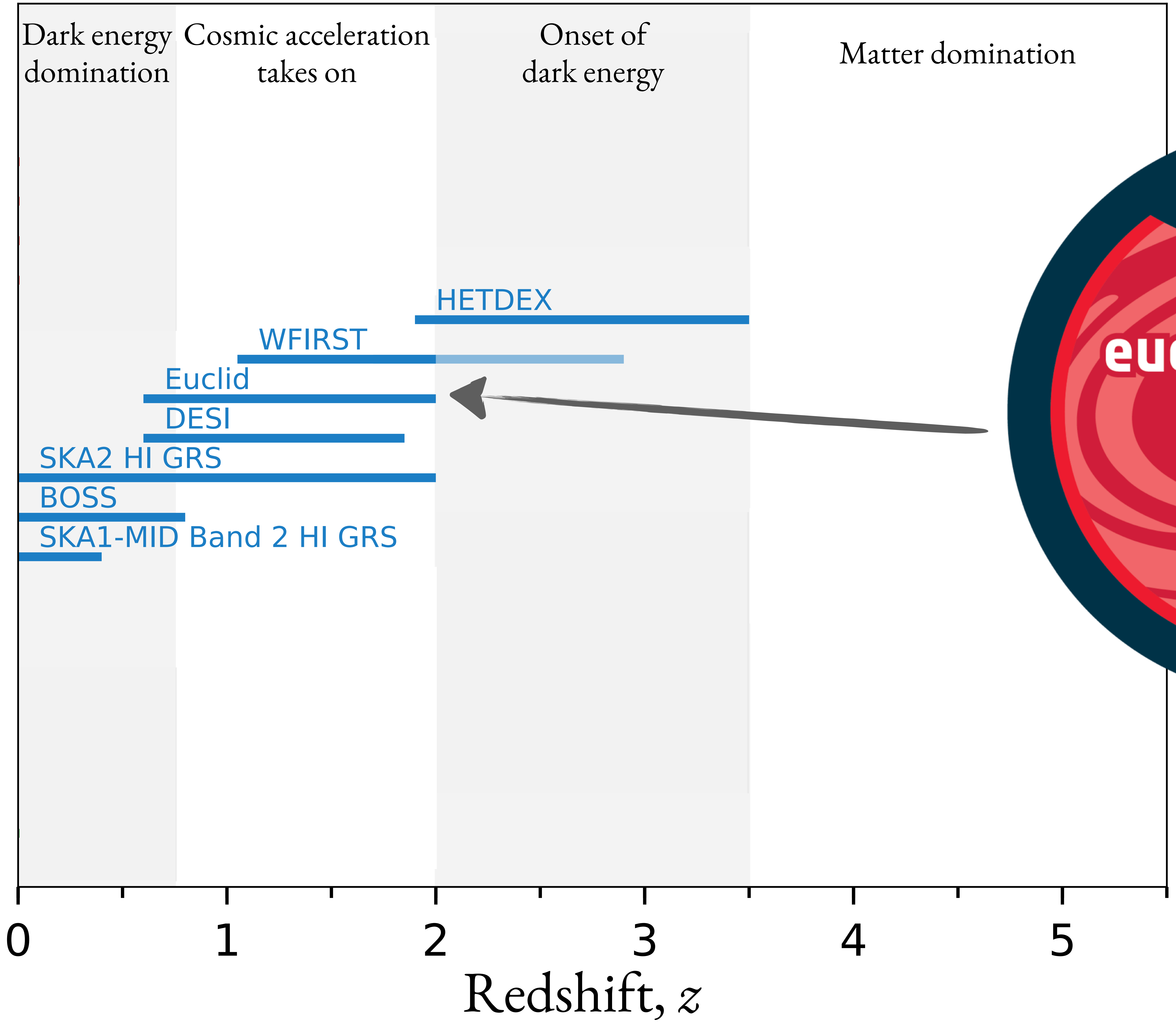

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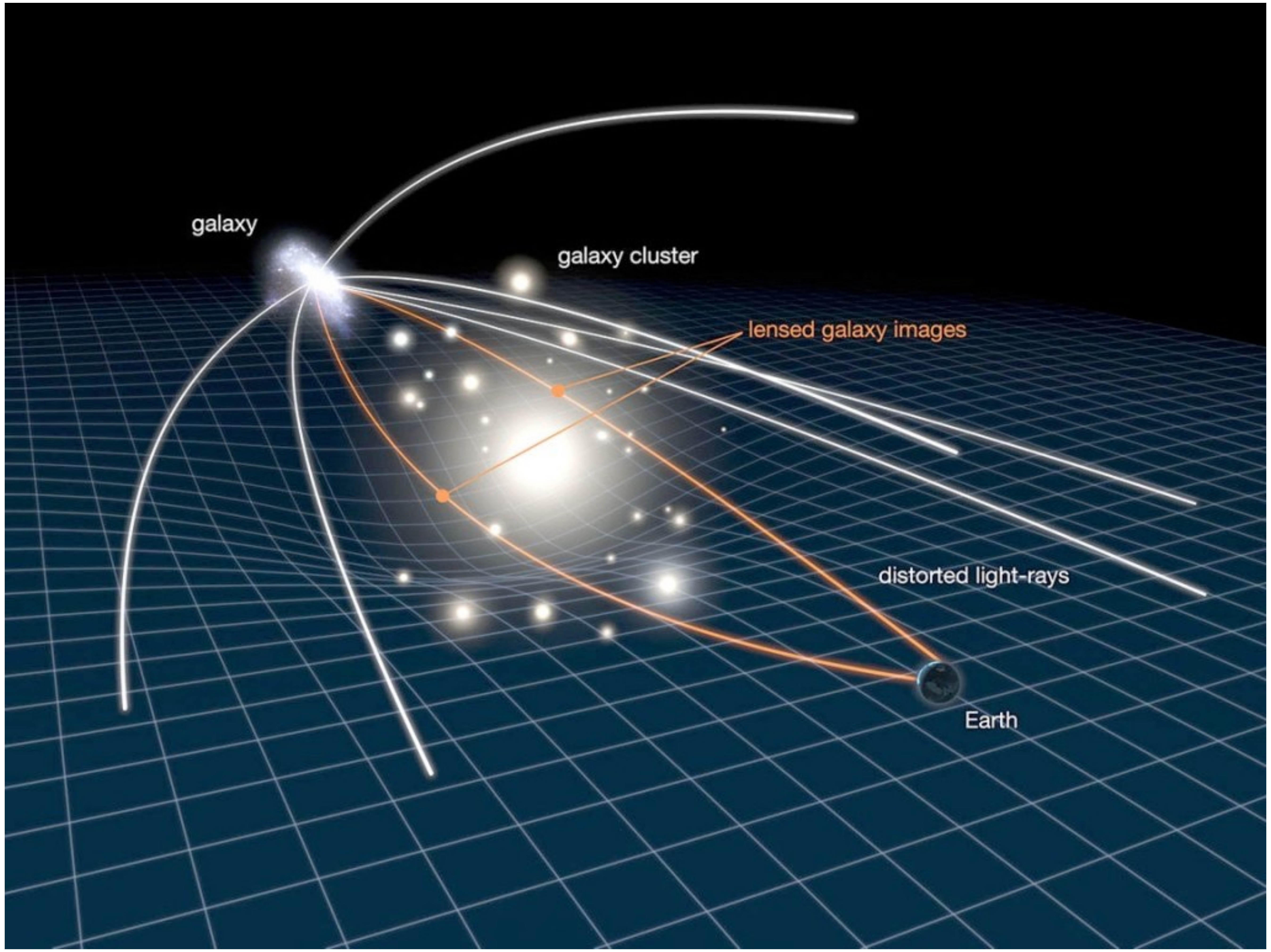
Weak lensing



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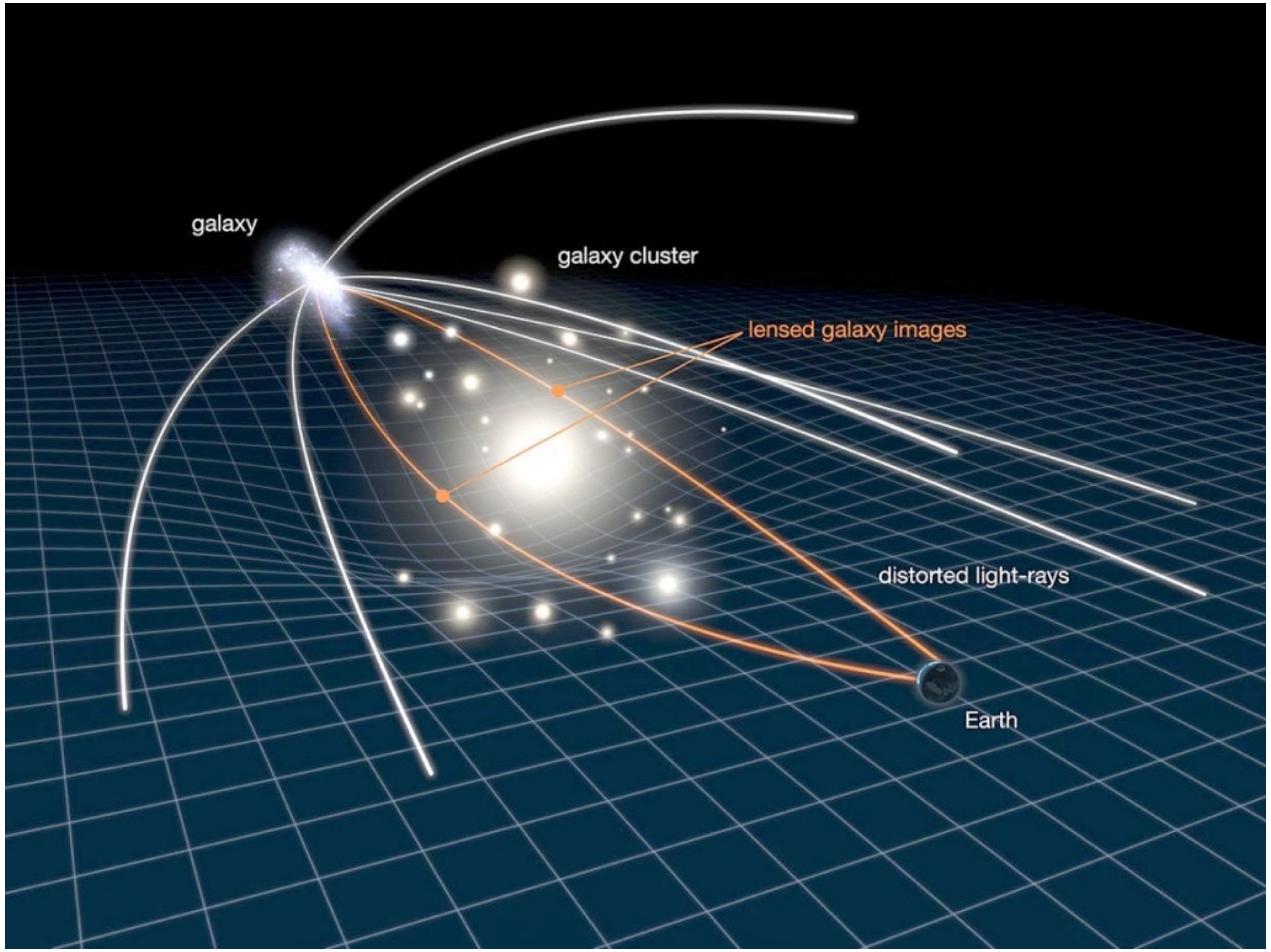

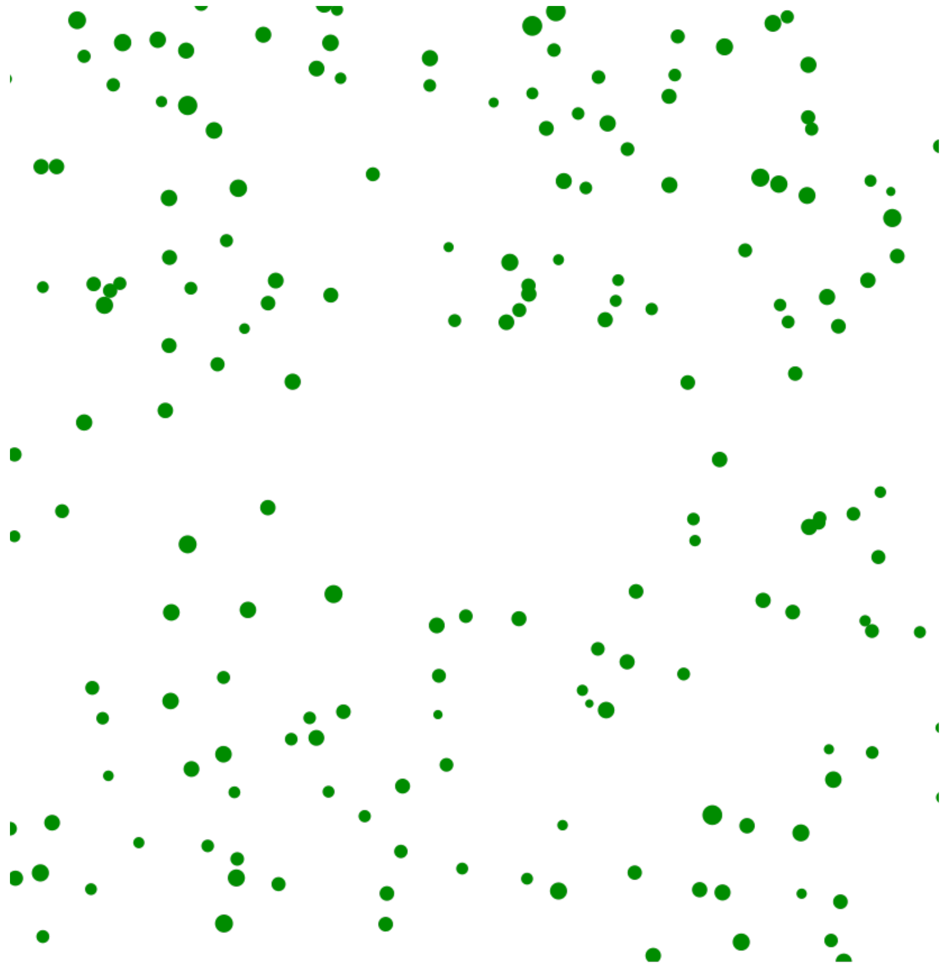

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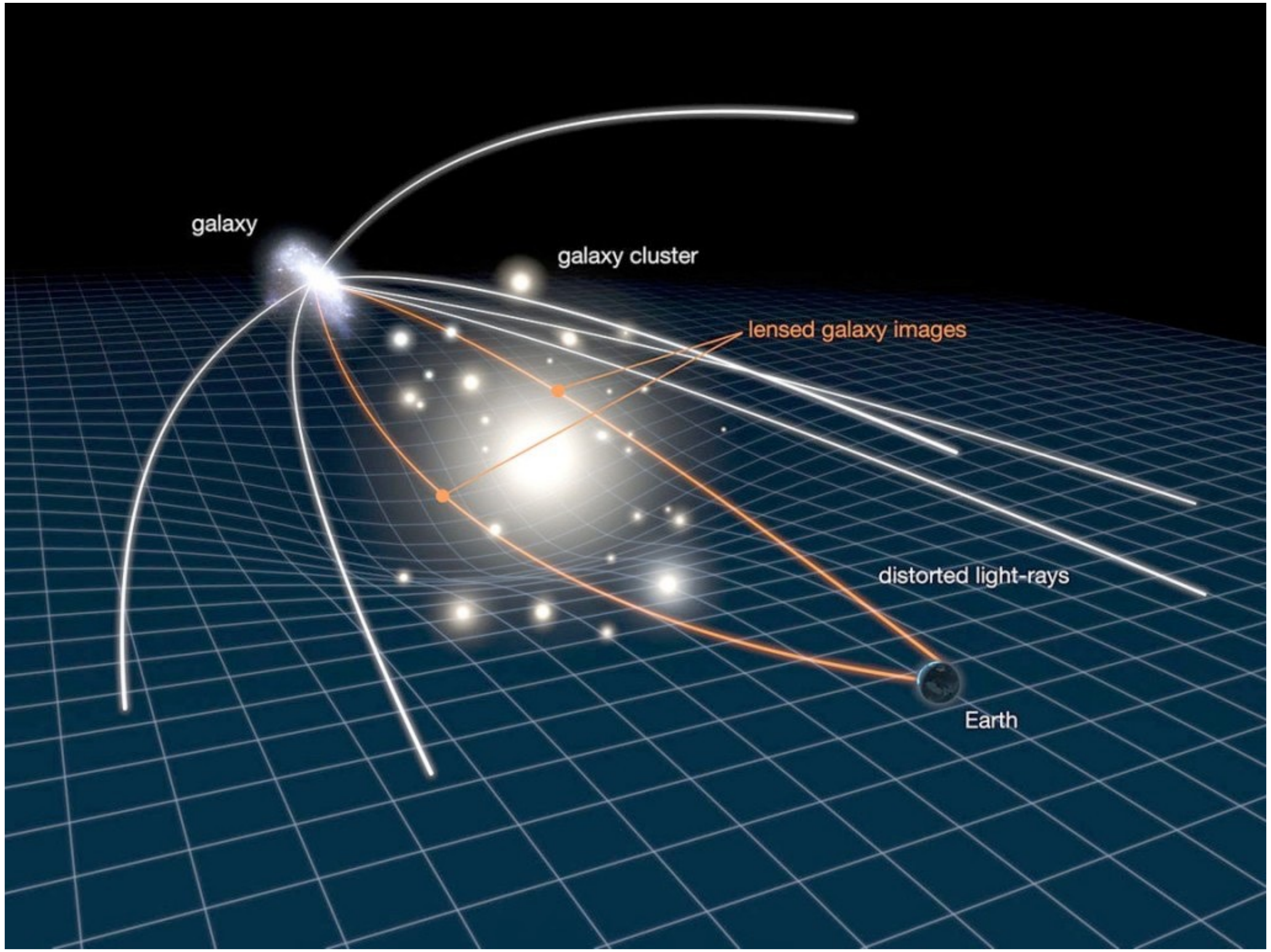

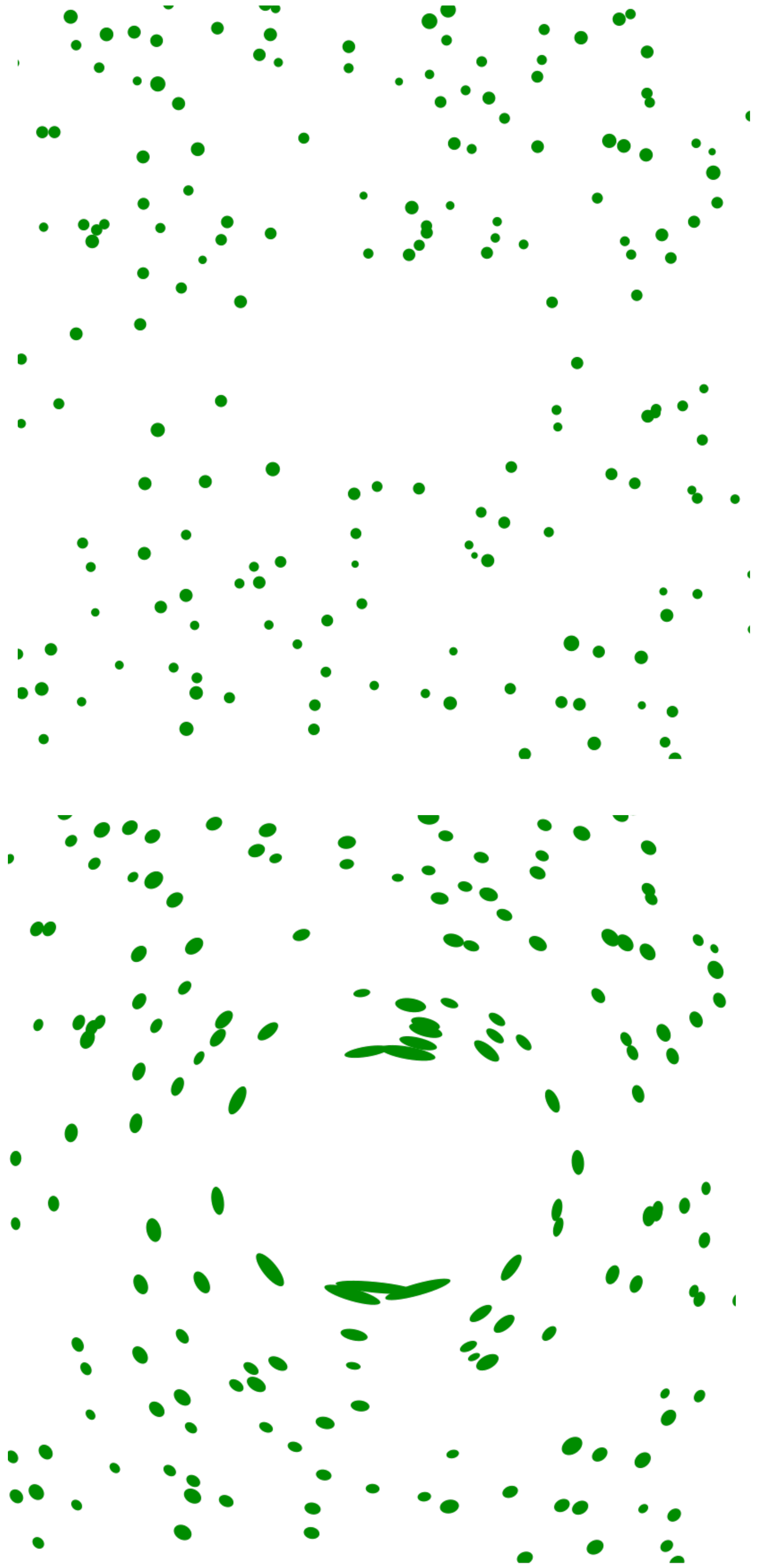

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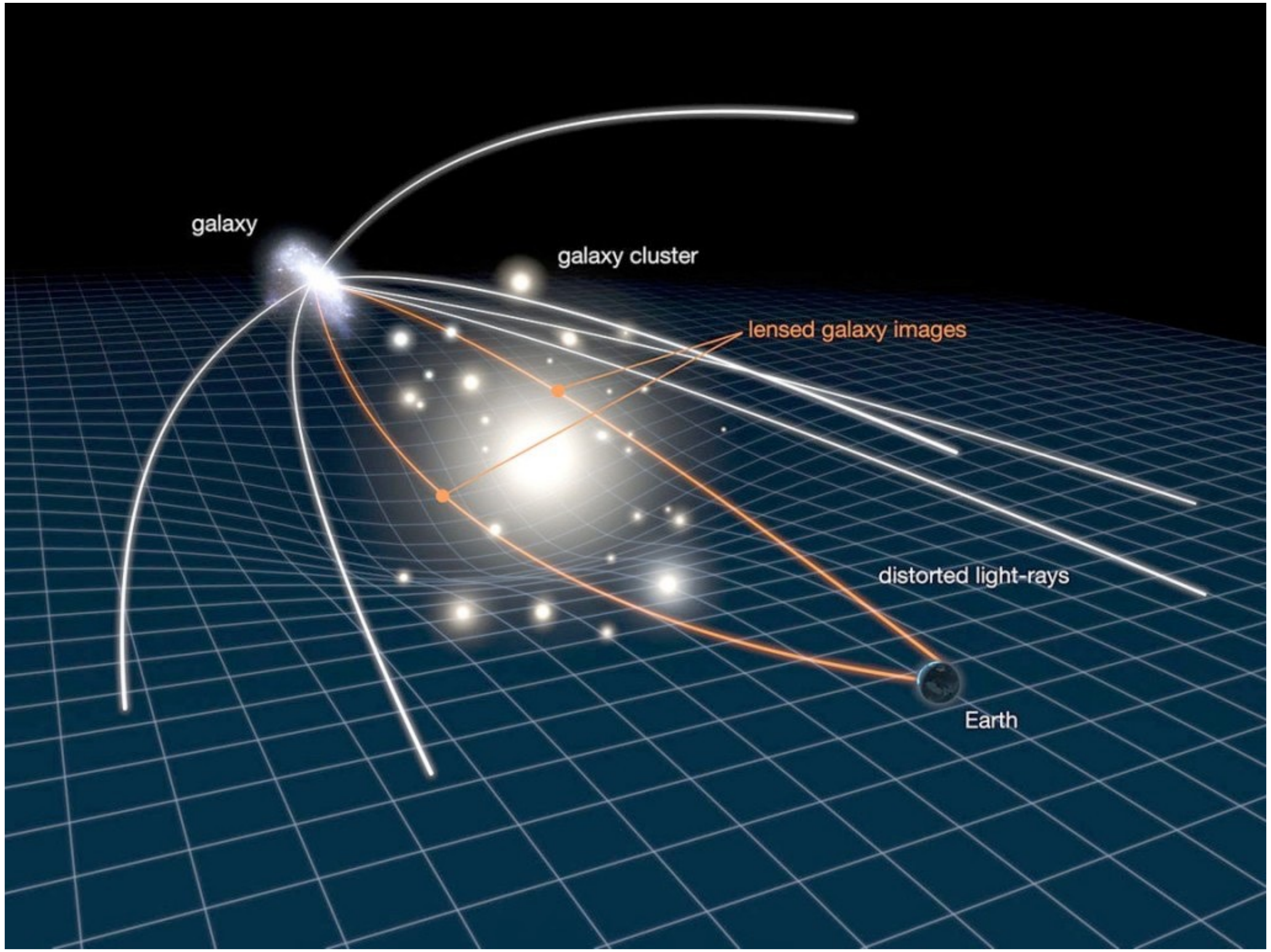
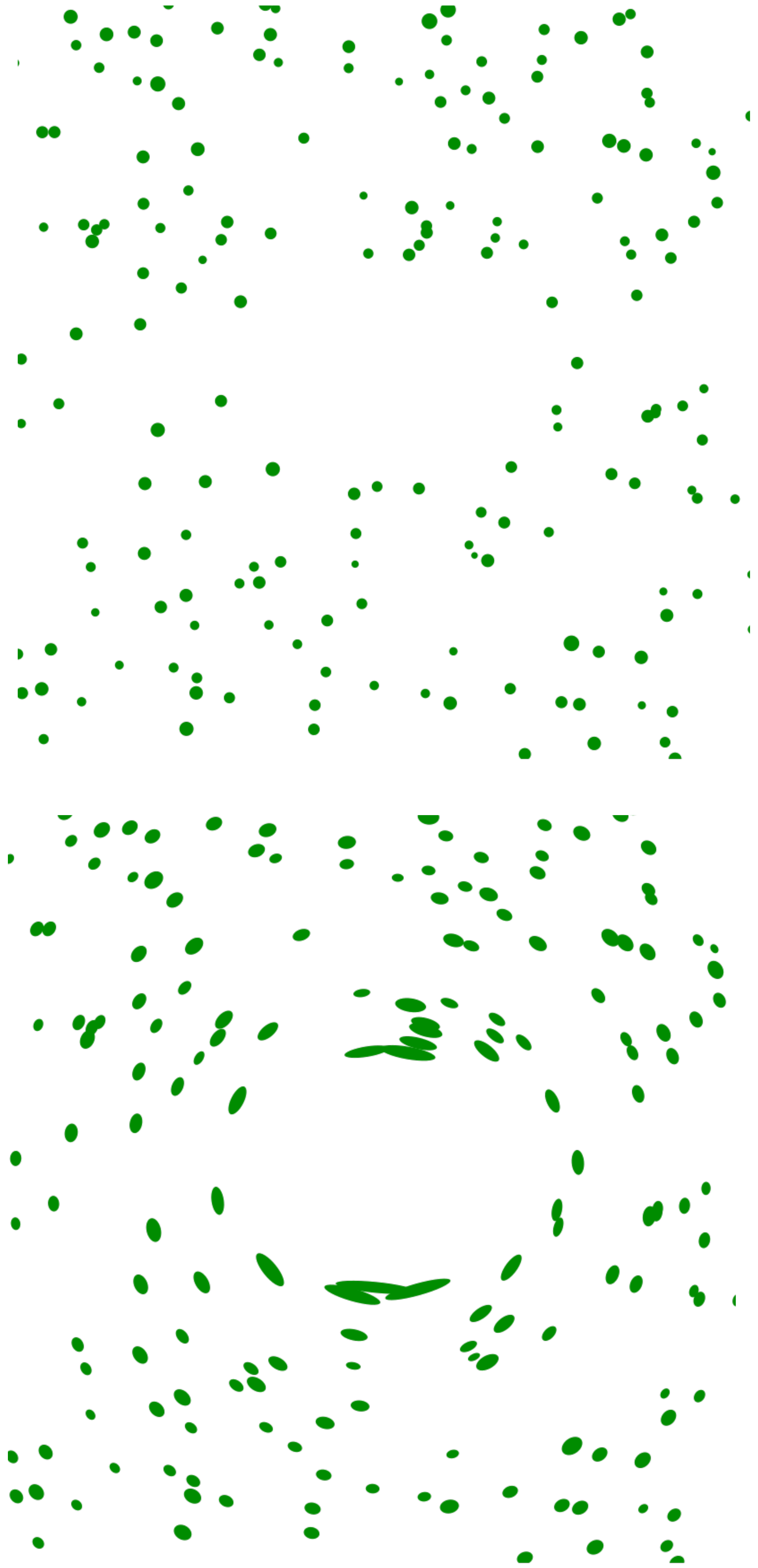
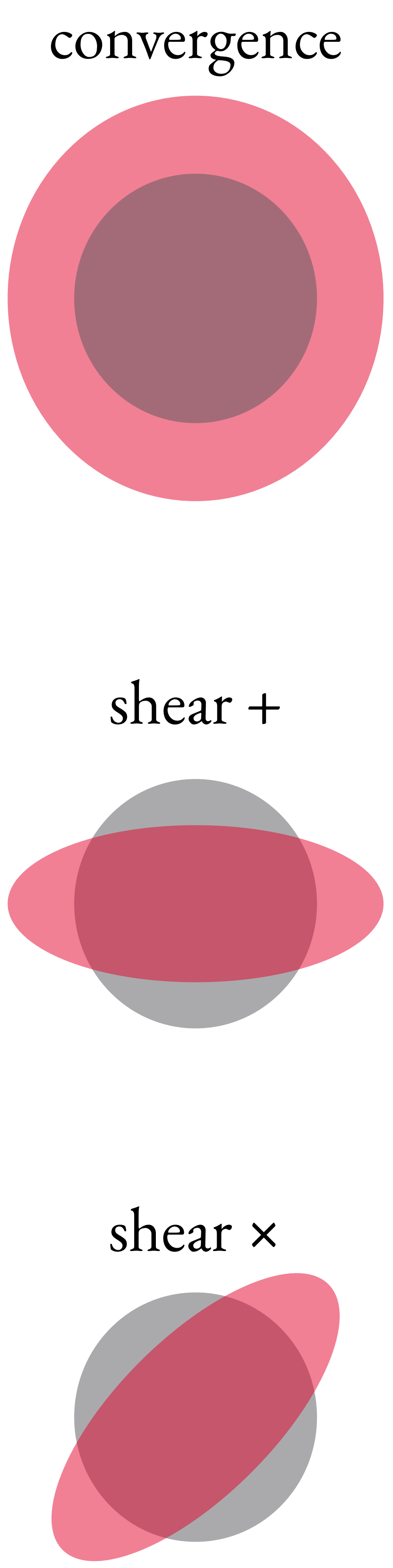


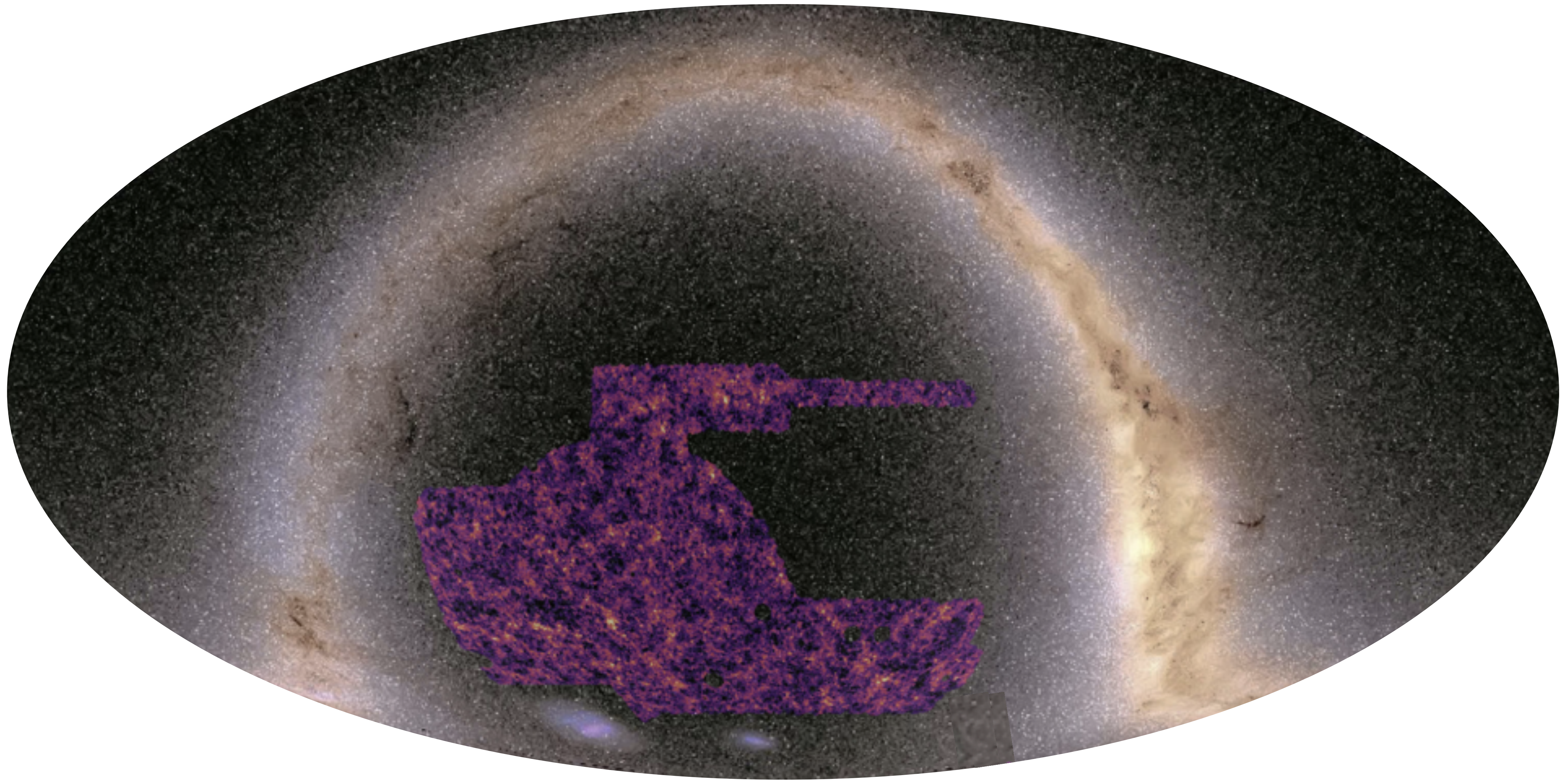


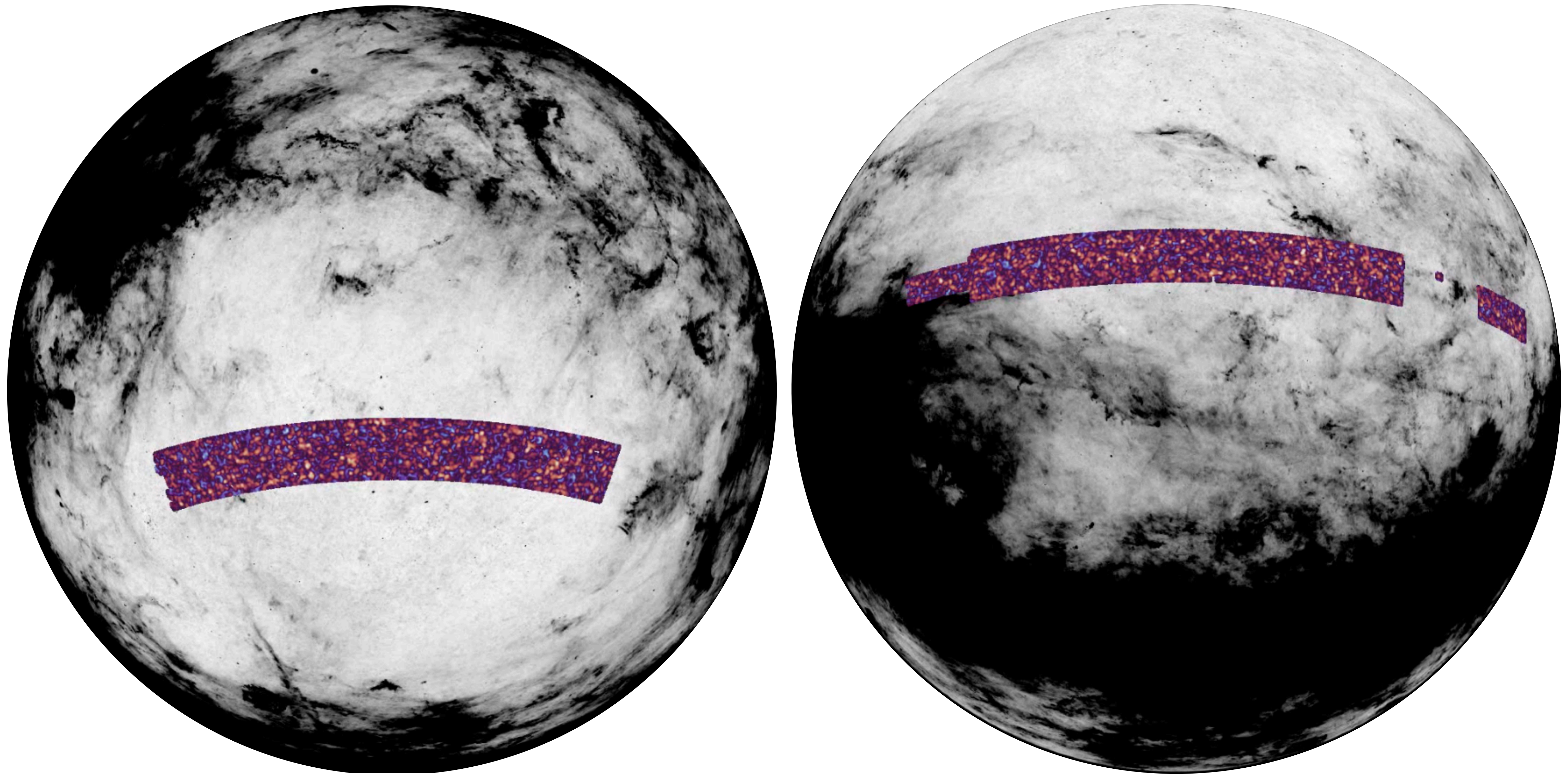


Weak lensing

DARK ENERGY SURVEY

[Credits: N. Jeffrey/DES Collaboration 2021]



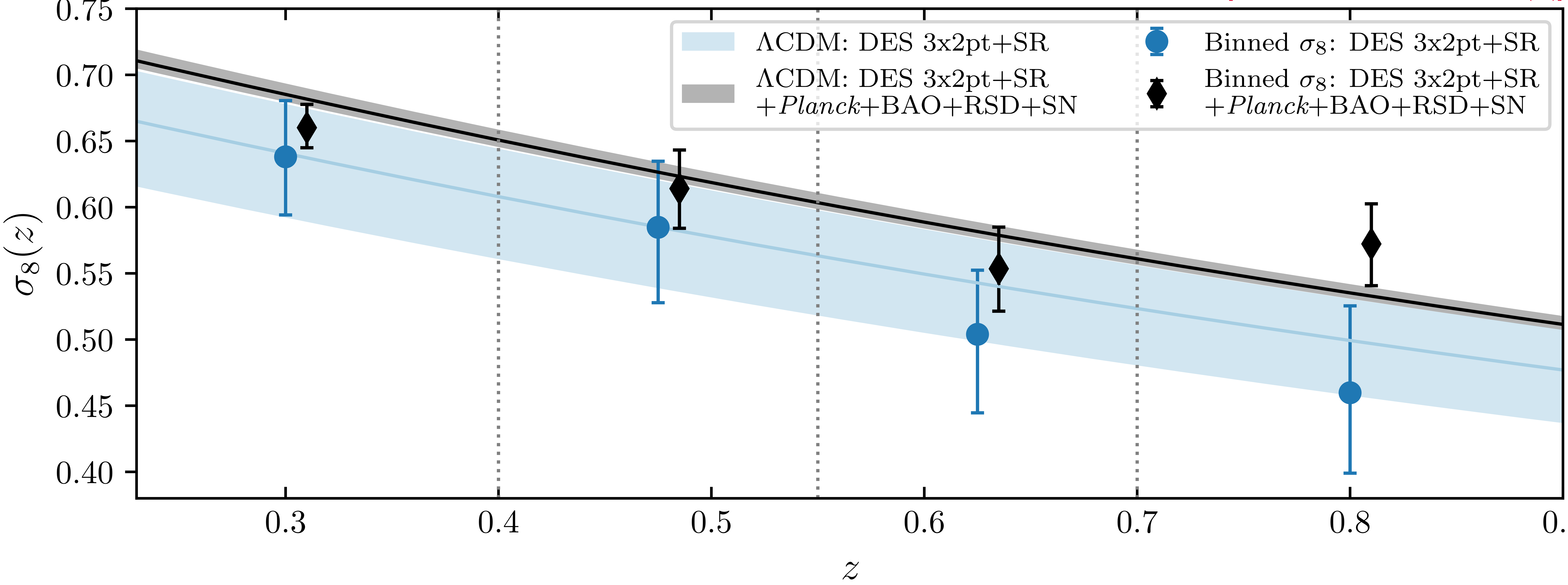


KiDS
The Kilo-Degree Survey

[Credits: A. Wright/KiDS Collaboration 2025]

Weak lensing

[DES Collaboration: Abbott et al. 2023 (Y3)]



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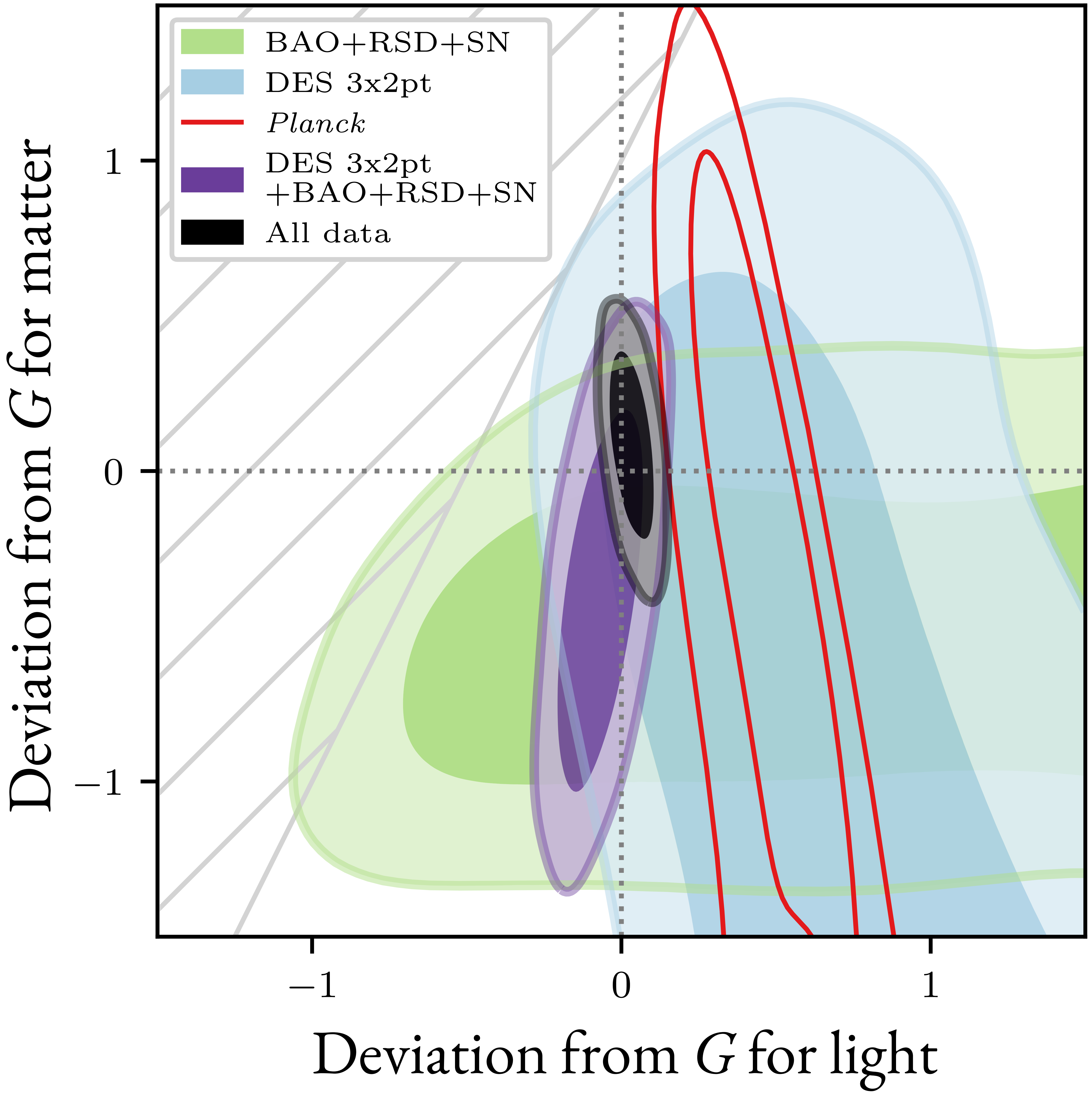
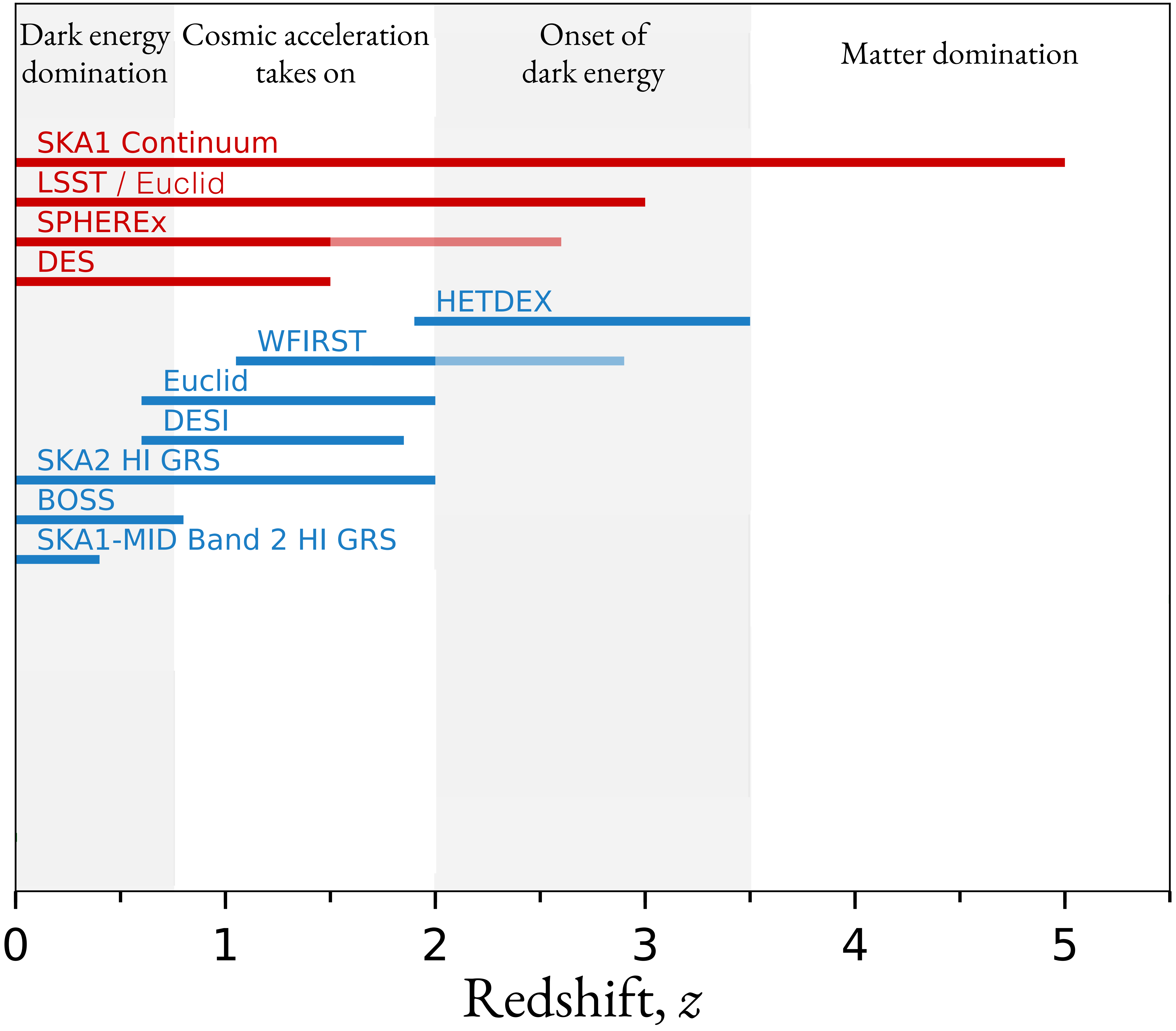
[DES Collaboration: Abbott et al. 2023 (Y3)]



Weak lensing

[Bull et al. ⊃ SC 2020]



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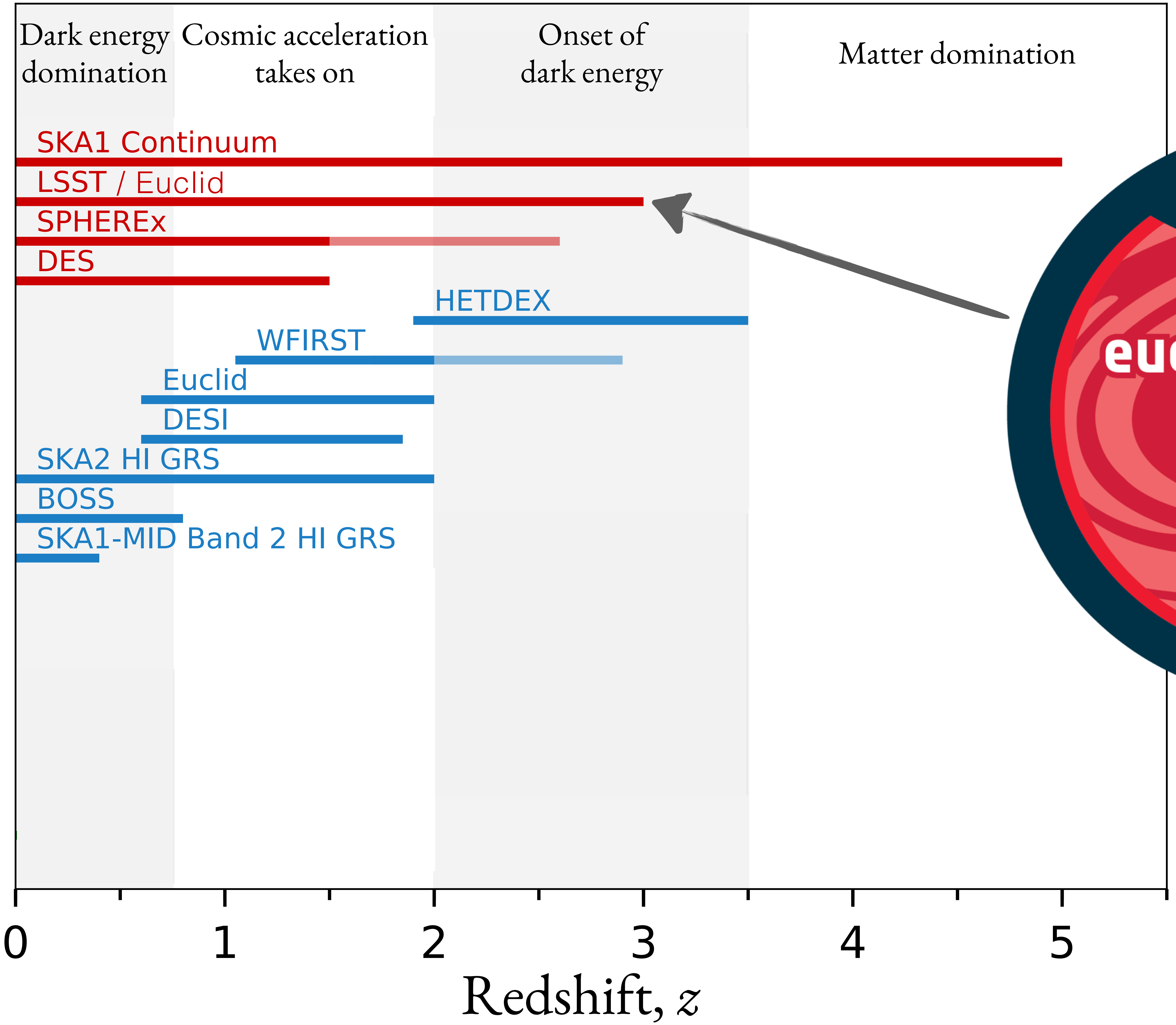

Clustering-lensing complementarity

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Clustering-lensing complementarity

$$\frac{\mathrm{g}(\eta, \boldsymbol{x})}{a^2(\eta)} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ & 1 & 0 & 0 \\ & & 1 & 0 \\ & & & 1 \end{pmatrix}$$

Clustering-lensing complementarity

$$\frac{\mathrm{g}(\eta,\boldsymbol{x})}{a^2(\eta)} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ & 1 & 0 & 0 \\ & & 1 & 0 \\ & & & 1 \end{pmatrix} + 2\begin{pmatrix} -\Psi(\eta,\boldsymbol{x}) & 0 & 0 & 0 \\ & \Phi(\eta,\boldsymbol{x}) & 0 & 0 \\ & & \Phi(\eta,\boldsymbol{x}) & 0 \\ & & & \Phi(\eta,\boldsymbol{x}) \end{pmatrix}$$

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$$\nabla^2\Psi(\boldsymbol{x}) = 4\,\pi\,G\,\rho(\boldsymbol{x})$$

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Clustering-lensing complementarity

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$$a^2\,\nabla^2\,\Psi(\boldsymbol{x}) = 4\,\pi\,G\,\bar{\rho}\,\Delta(\boldsymbol{x})/b$$

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Clustering-lensing complementarity

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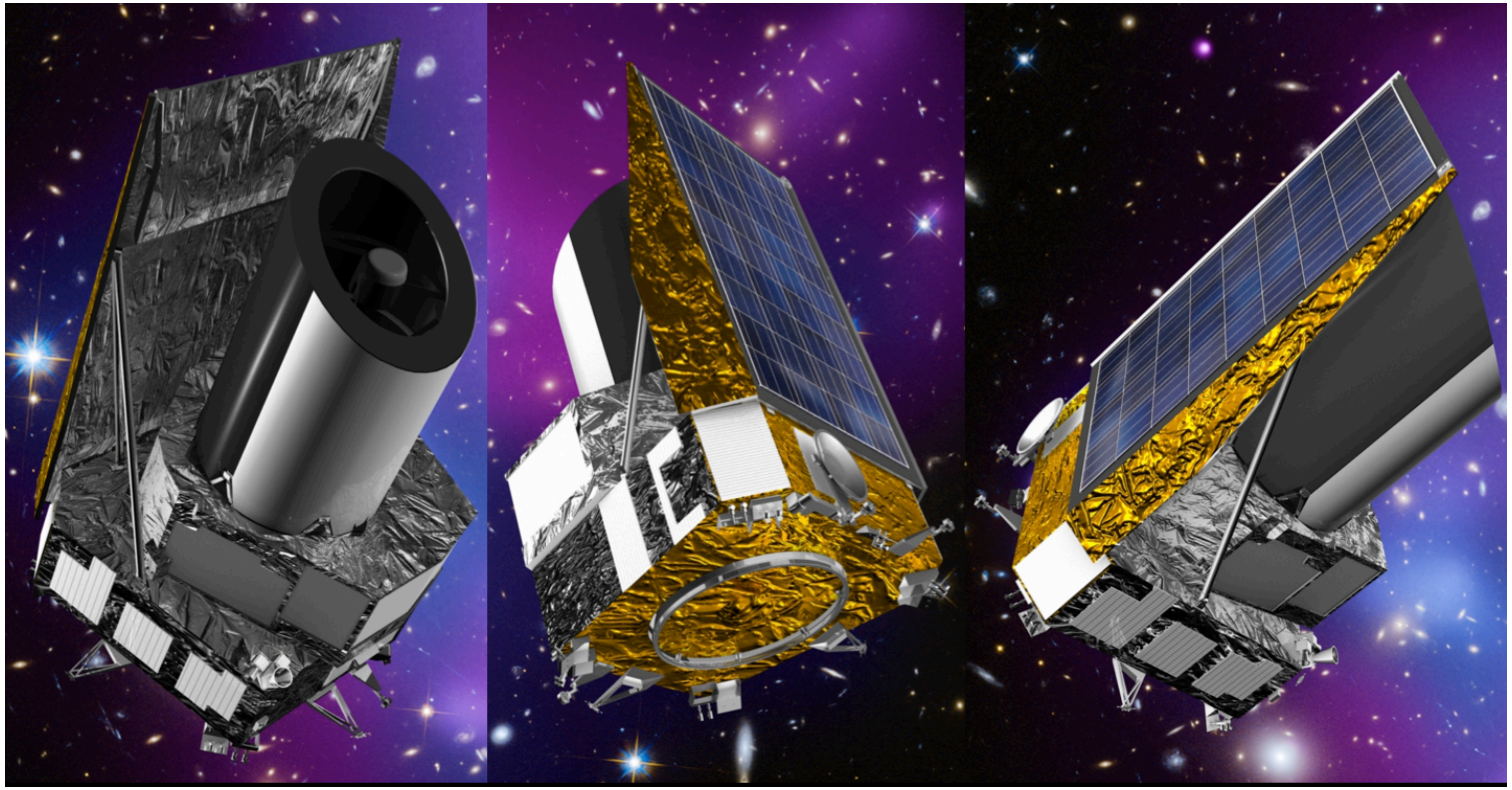
$$\hat{\boldsymbol{\alpha}}(\boldsymbol{x}) = \int_0^{x_\parallel} \mathrm{d}r\,\frac{x_\parallel - r}{x_\parallel}\,r\,\boldsymbol{\nabla}_\perp\left[\Psi(r,\boldsymbol{x}_\perp) + \Phi(r,\boldsymbol{x}_\perp)\right]$$

The Euclid Satellite



European Space Agency

The Euclid Satellite

Turin, November 2019

Euclid specs

[Euclid 'Red Book', 2011]

SURVEYS		
	Area (deg2)	Description
Wide Survey	15,000 (required) 20,000 (goal)	Step and stare with 4 dither pointings per step.
Deep Survey	40	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey

PAYLOAD					
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	$3\ 10^{-16}$ erg cm-2 s-1 3.5σ unresolved line flux
Detector Technology	36 arrays 4k×4k CCD	16 arrays 2k×2k NIR sensitive HgCdTe detectors			
Pixel Size Spectral resolution	0.1 arcsec	0.3 arcsec			0.3 arcsec R=250

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Euclid specs

[Euclid 'Red Book', 2011]

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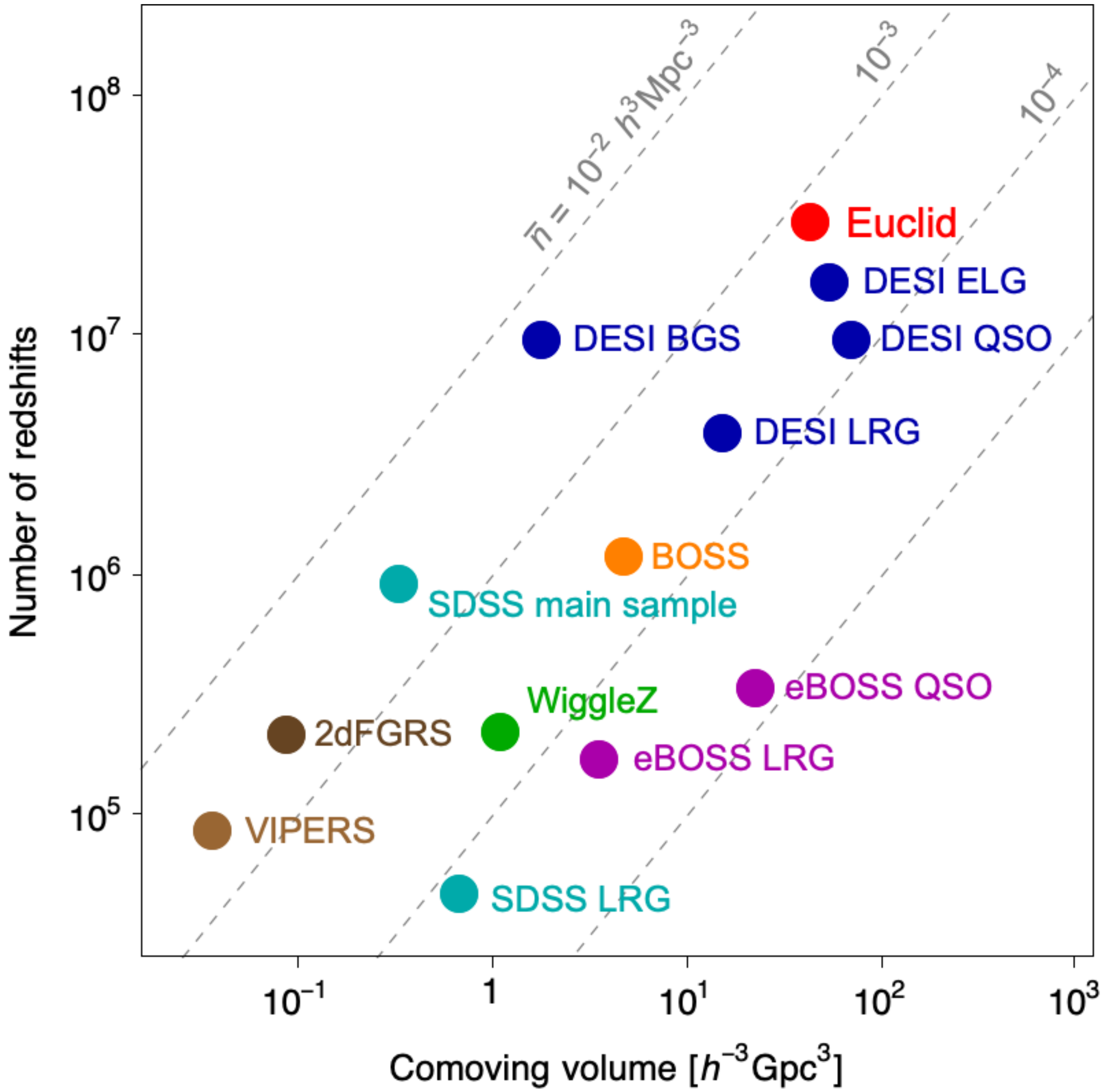
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	$3\ 10^{-16}$ erg cm-2 s-1 3.5σ unresolved line flux
Detector Technology	36 arrays 4k×4k CCD	16 arrays 2k×2k NIR sensitive HgCdTe detectors			
Pixel Size Spectral resolution	0.1 arcsec	0.3 arcsec			0.3 arcsec R=250

Euclid specs

[Euclid Collaboration: Mellier et al. ⊃ SC 2024]



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Euclid specs

[Euclid 'Red Book', 2011]

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SURVEYS		
	Area (deg2)	Description
Wide Survey	15,000 (required) 20,000 (goal)	Step and stare with 4 dither pointings per step.
Deep Survey	40	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey

PAYLOAD					
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
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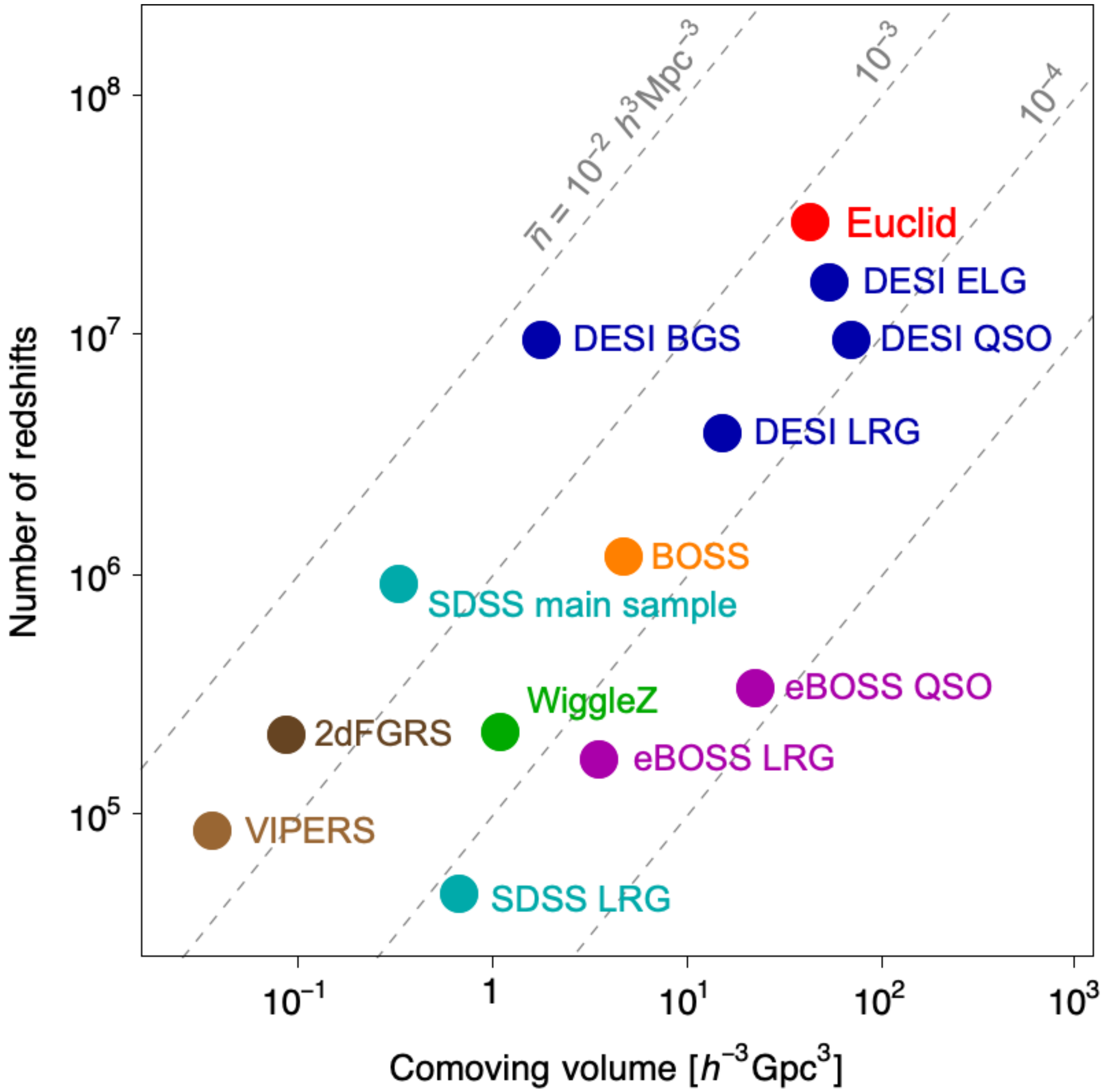
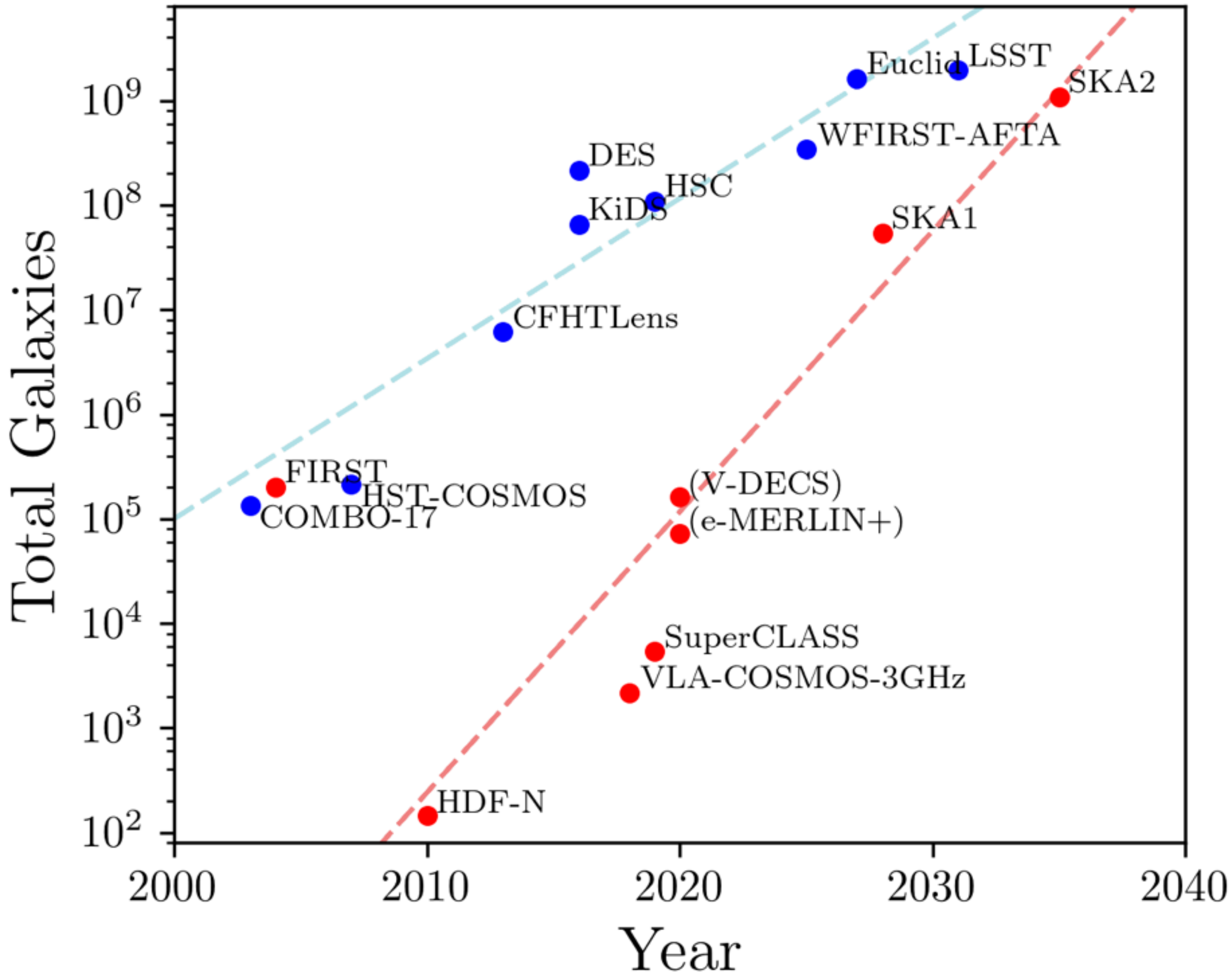


[Credits: I. Harrison]



Euclid science

- *Euclid*'s main scientific objectives:
  - Reach a precision on *dark energy* parameters $(w_0, w_a) < (2\%, 10\%)$
  - Measure the *growth* index γ better than 2%
  - Bound the sum of *neutrino masses* below 0.03 eV
  - Constrain *primordial non-Gaussianity* amplitude $f_{\rm NL}$ with precision ~2

Euclid science

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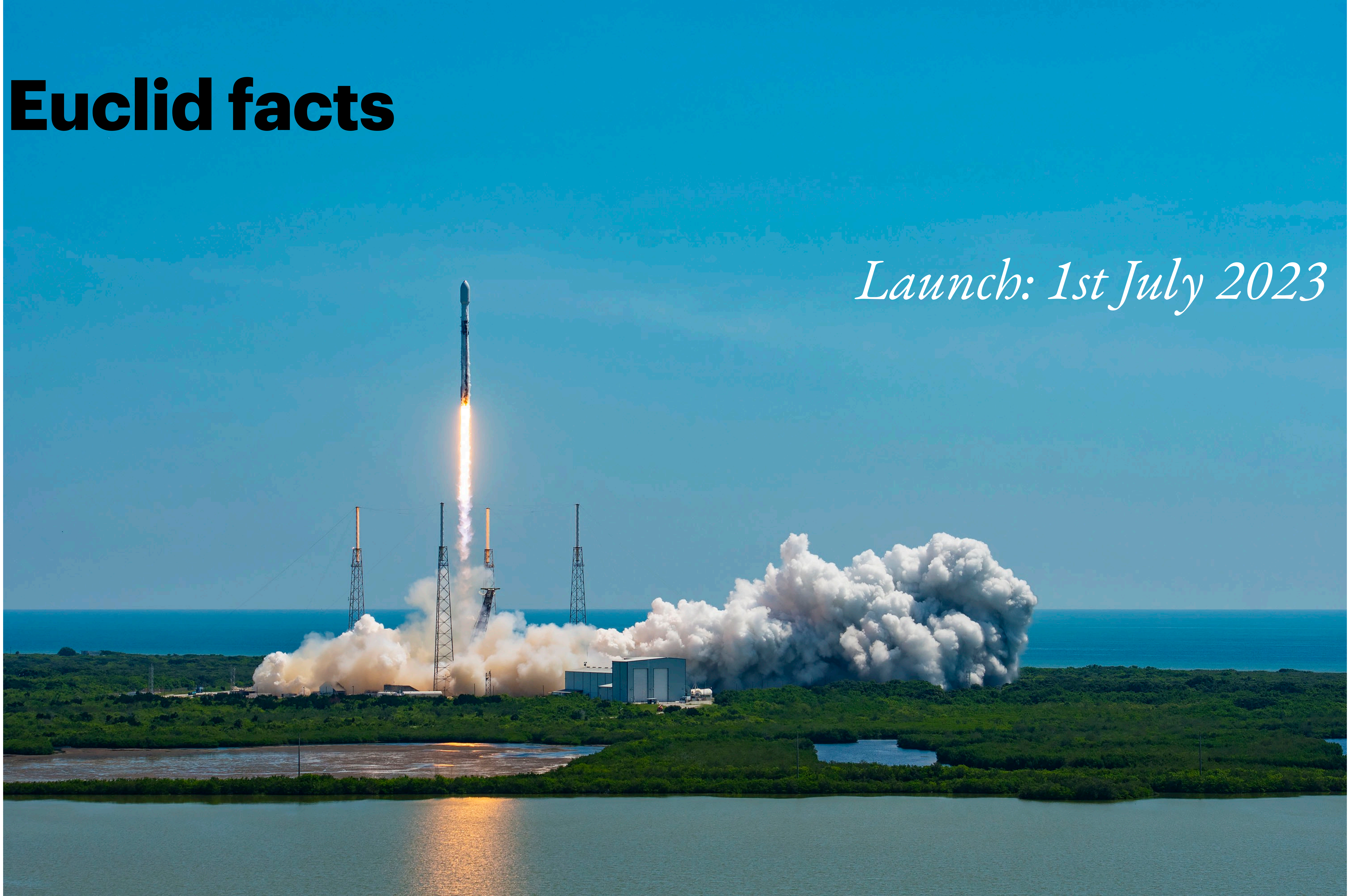
- *Euclid*'s main probes:
  - Spectroscopic *galaxy clustering* survey
  - Photometric *weak lensing* survey
- *Euclid*'s ancillary probes:
  - Clustering of the *photometric galaxy* sample (in fact, 3×2pt is a main probe)
  - *Galaxy clusters* (number counts and clustering)
  - Cross-correlation with *cosmic microwave background*
  - Hubble rate measurements with *strong lensing*

Euclid facts



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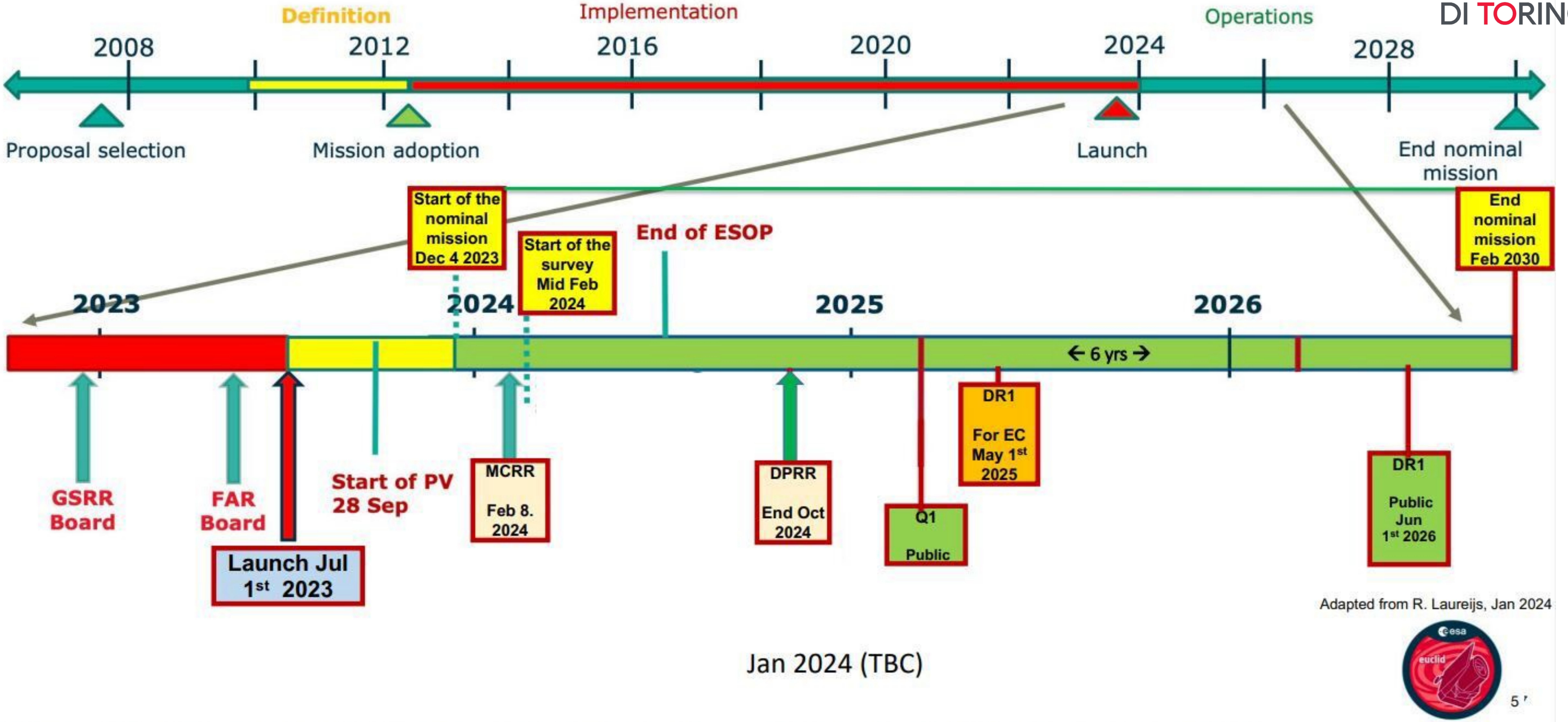
Euclid facts



Adapted from R. Laureijs, Jan 2024

[Courtesy of G. Guzzo]

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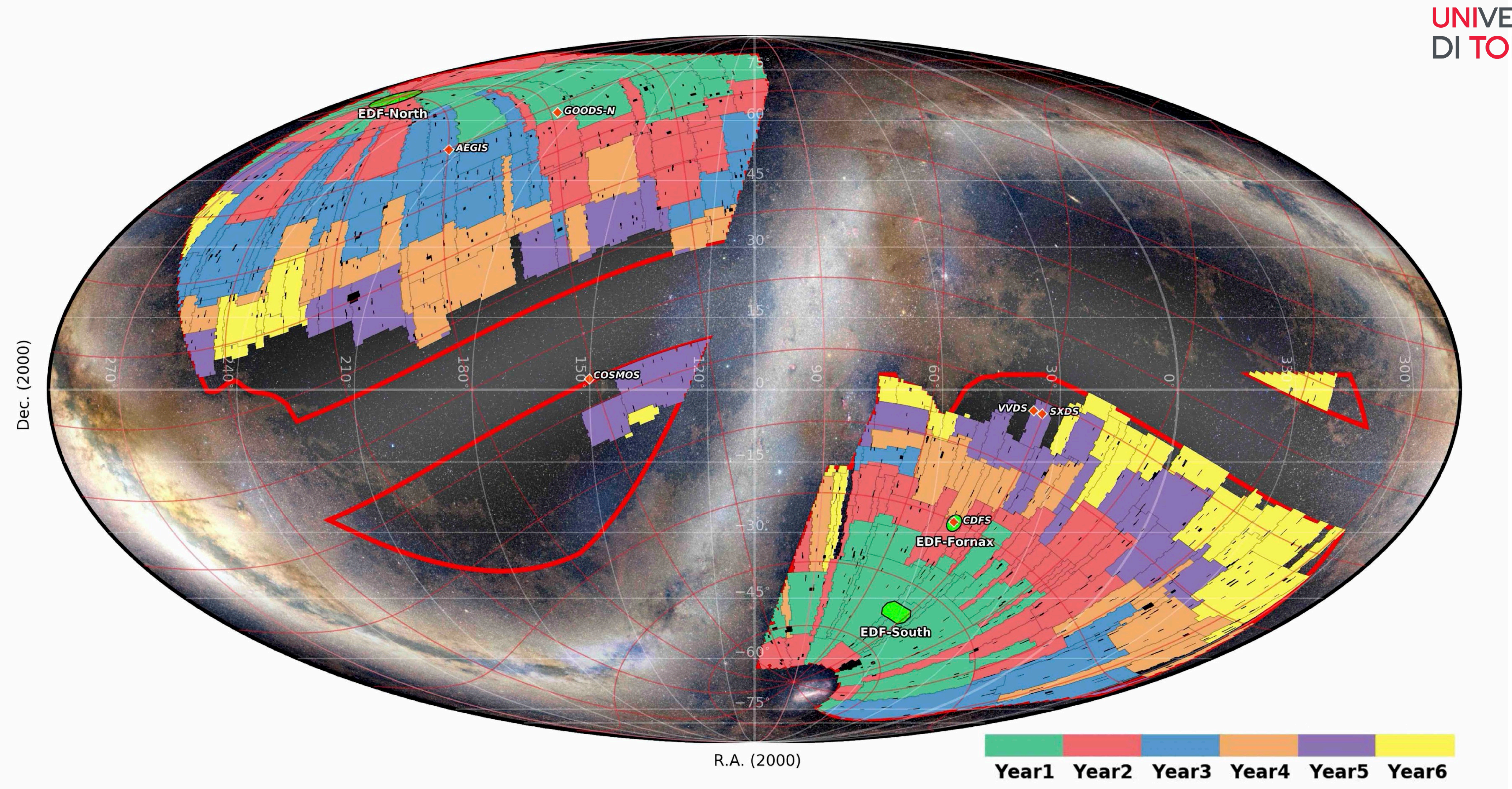
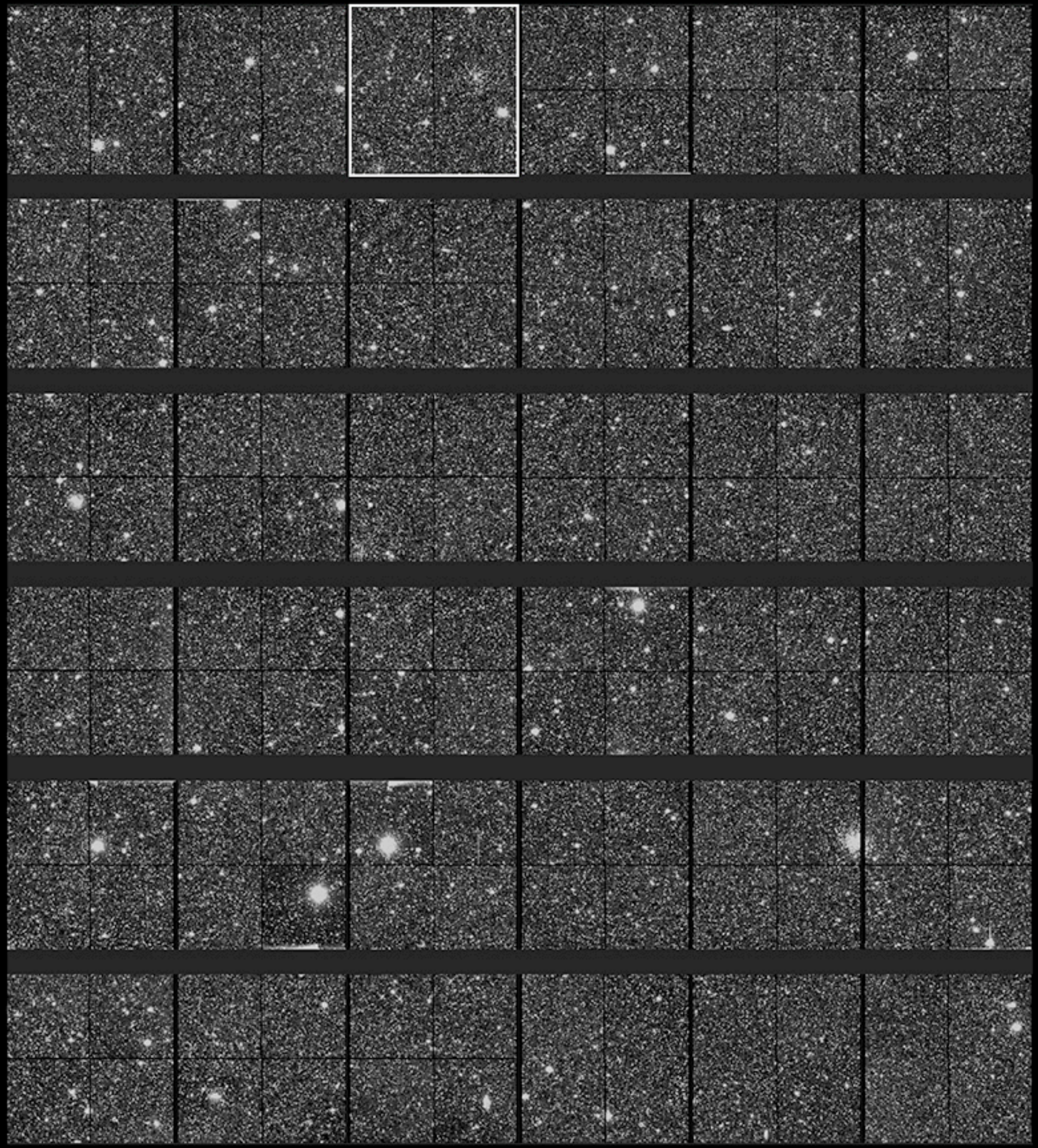
Euclid facts

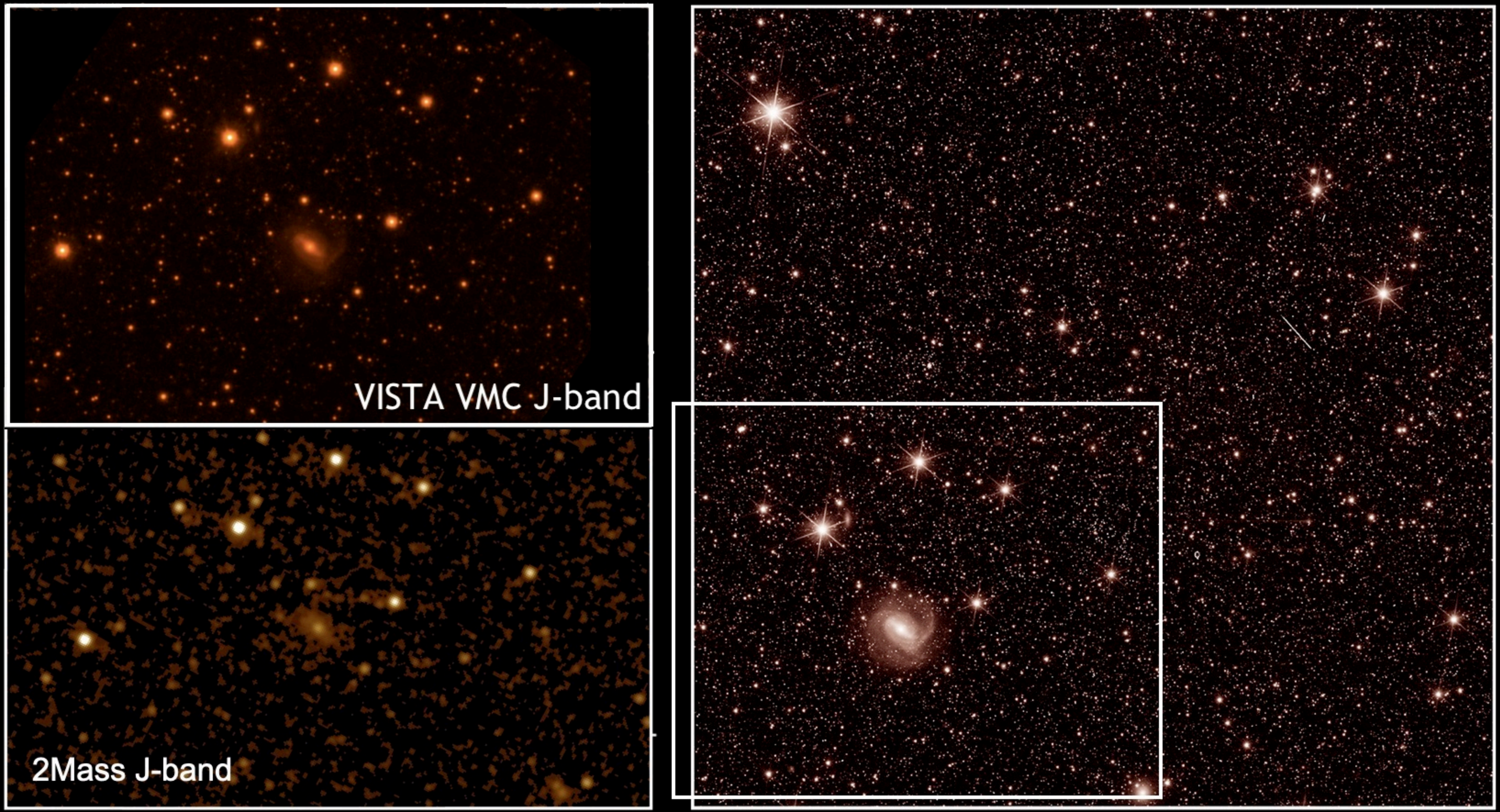


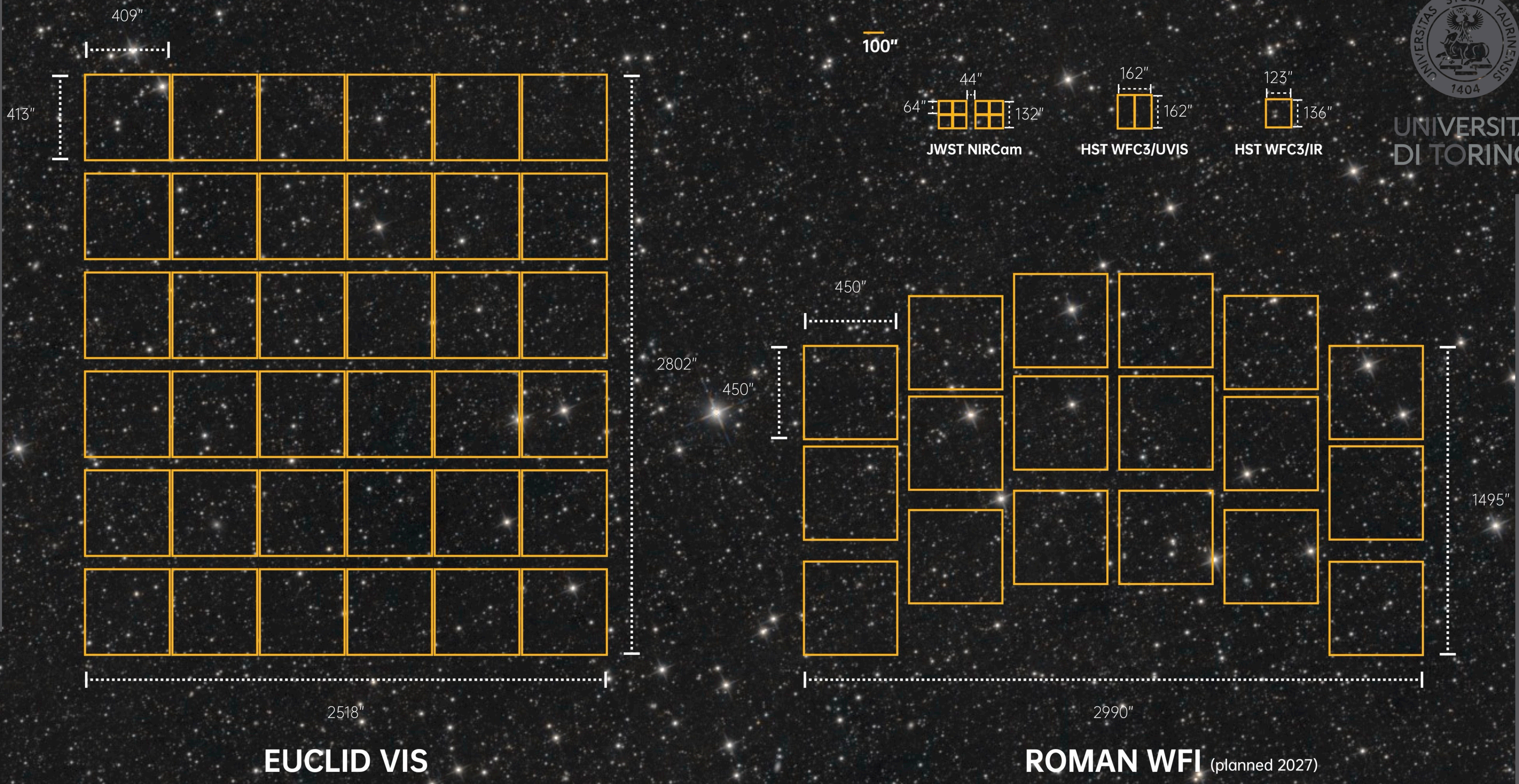
Euclid facts

EARLY COMMISSIONING TEST IMAGE, VIS INSTRUMENT



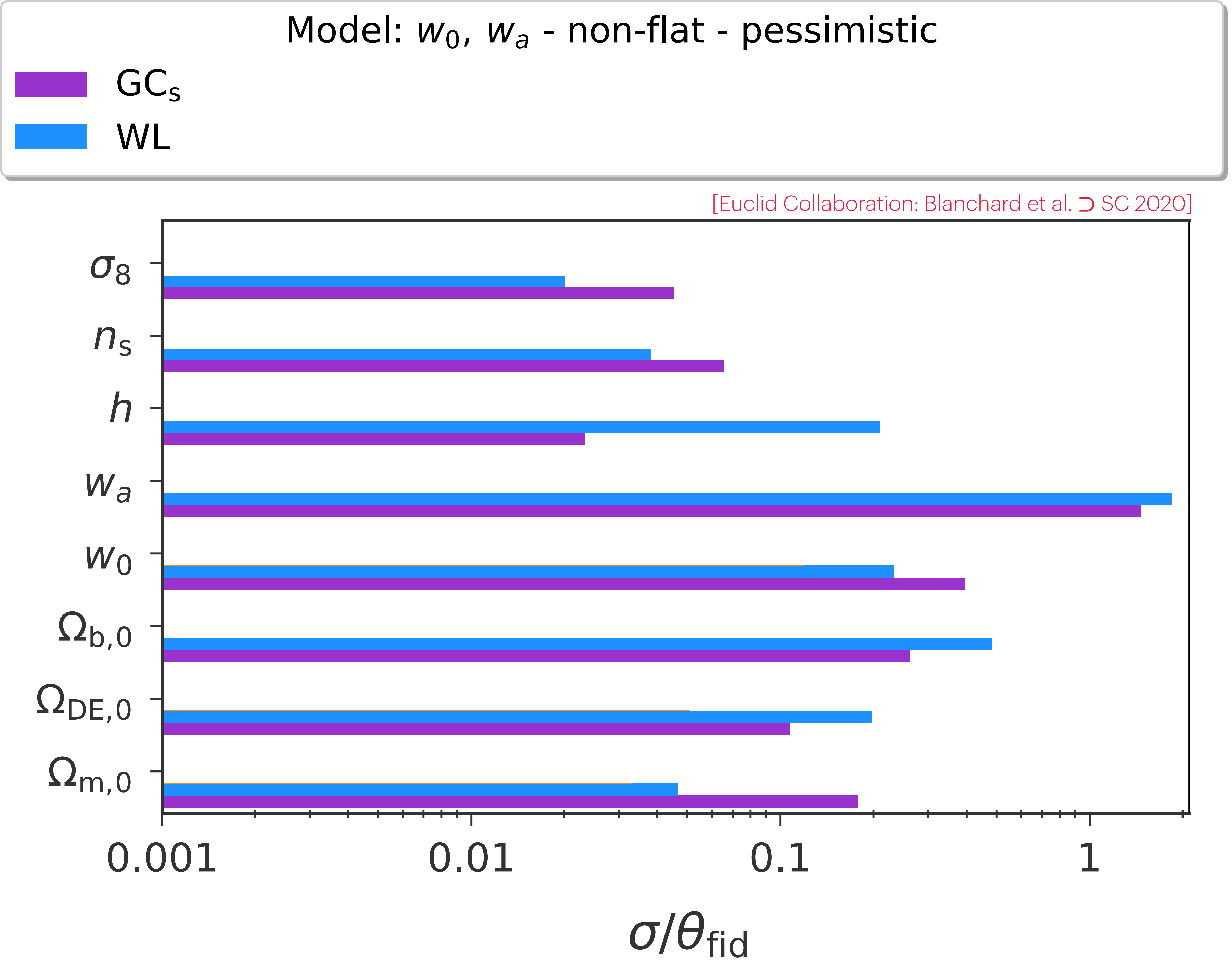
Euclid facts





[Credits: Yuzheng Kang]

Euclid forecasts



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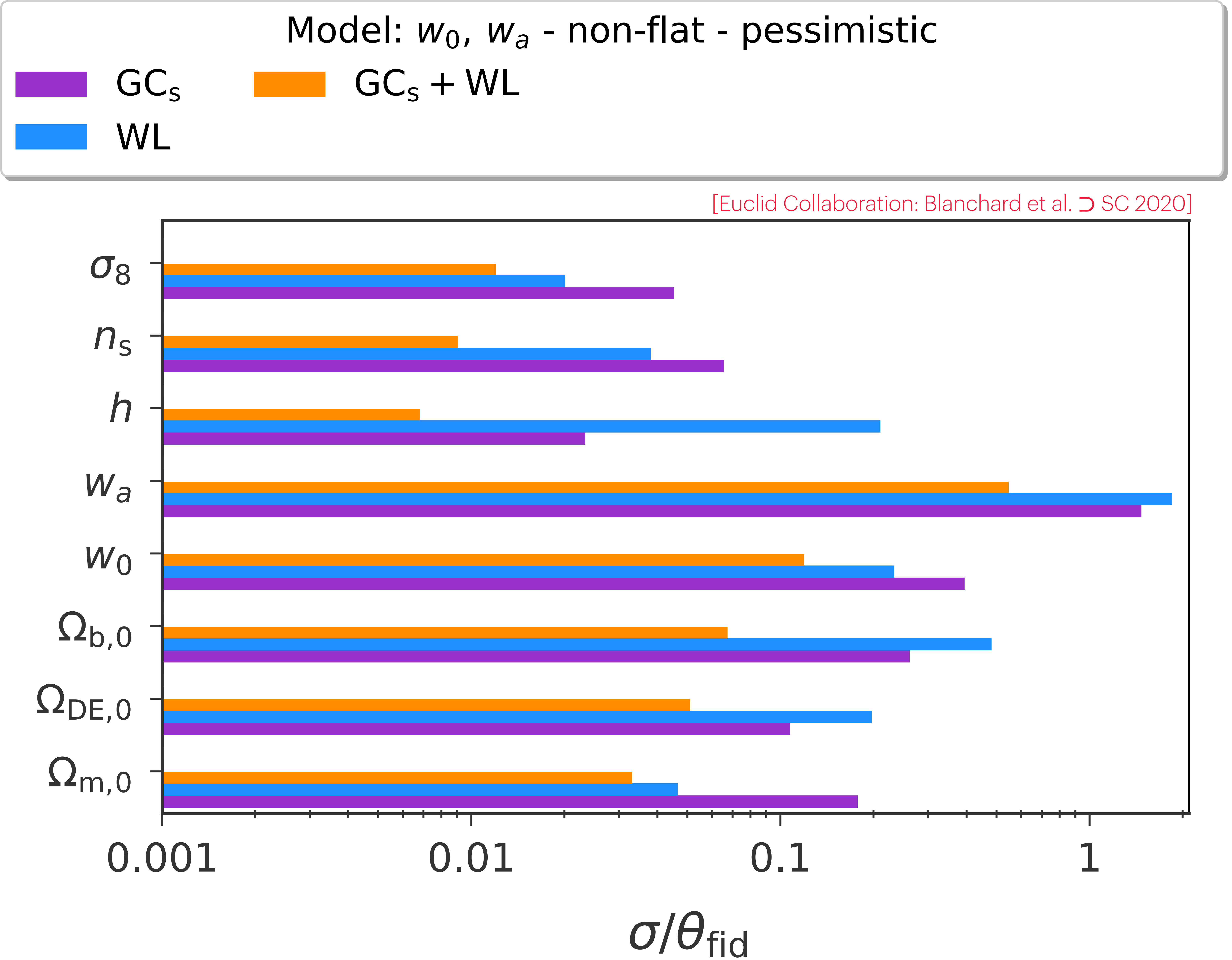
Euclid forecasts



[Euclid Collaboration: Blanchard et al. ⊃ SC 2020]

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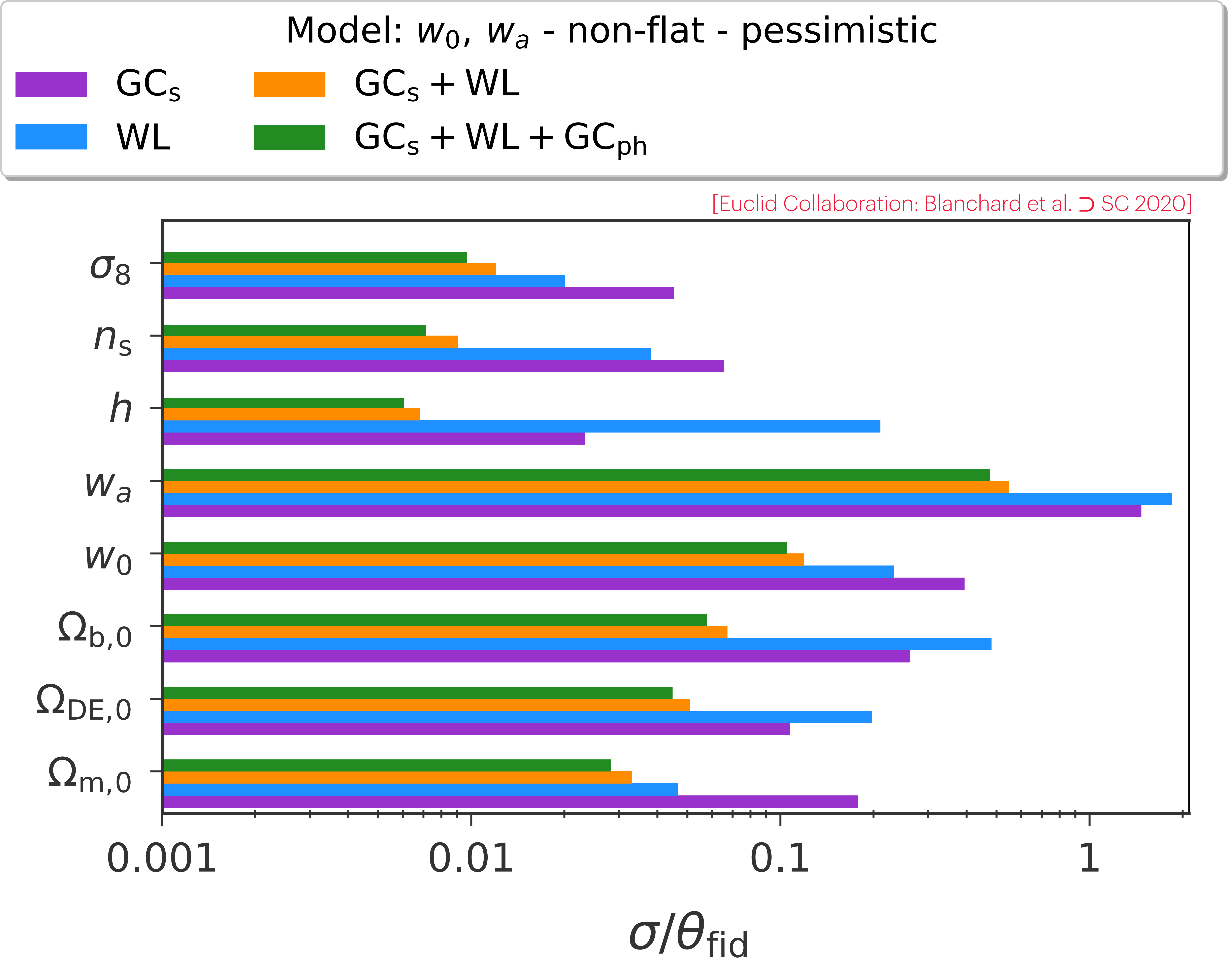
Euclid forecasts



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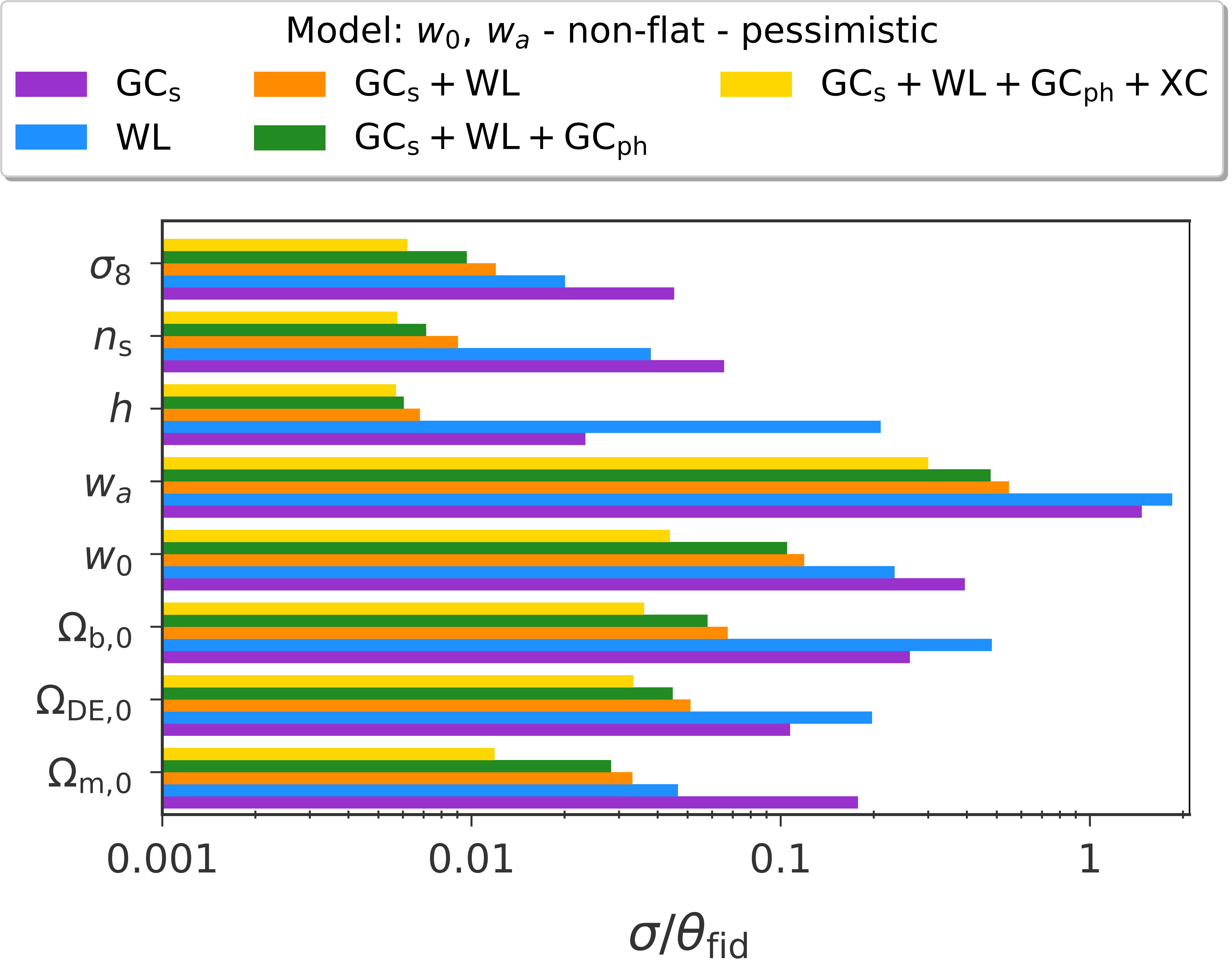
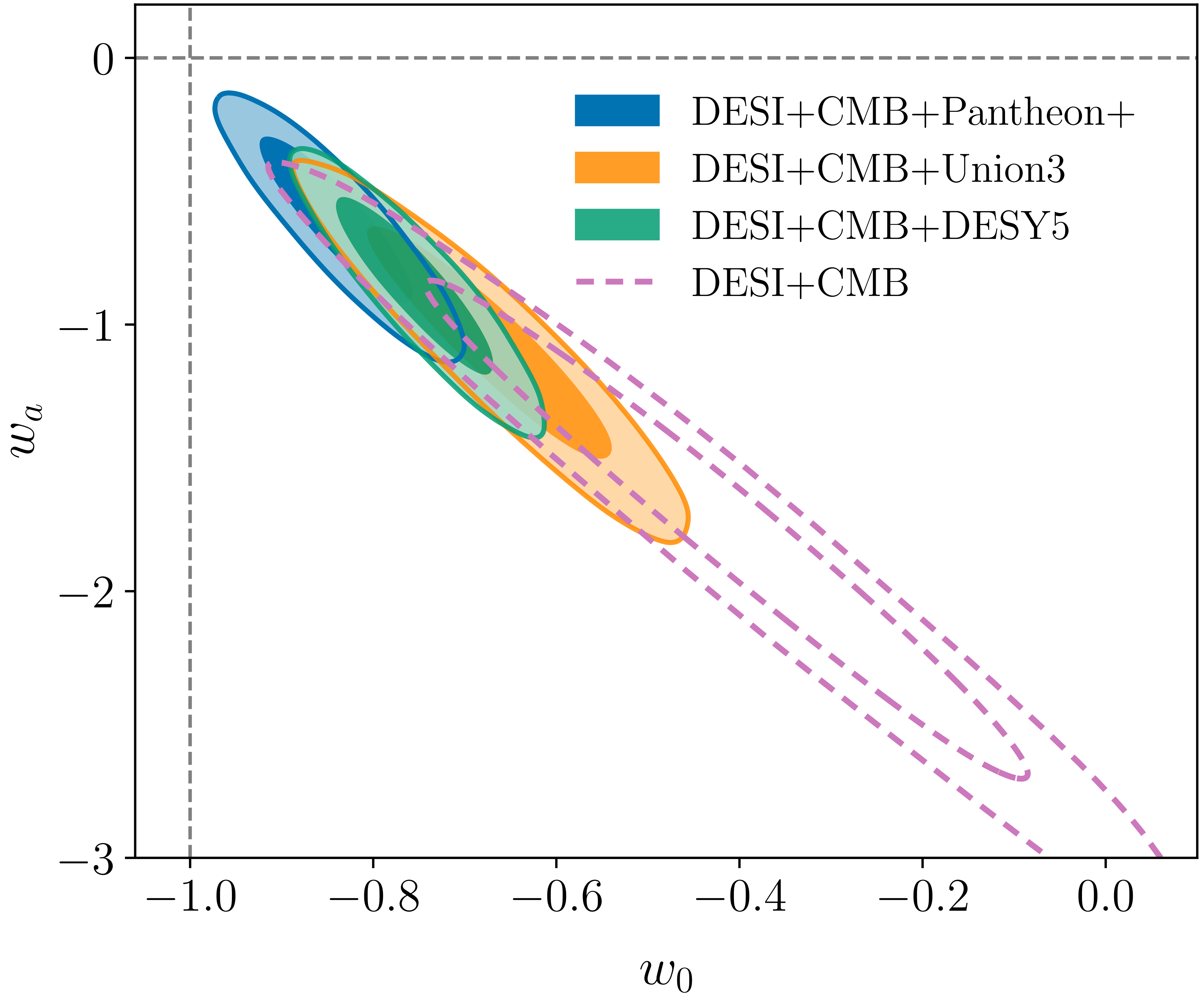
Euclid forecasts



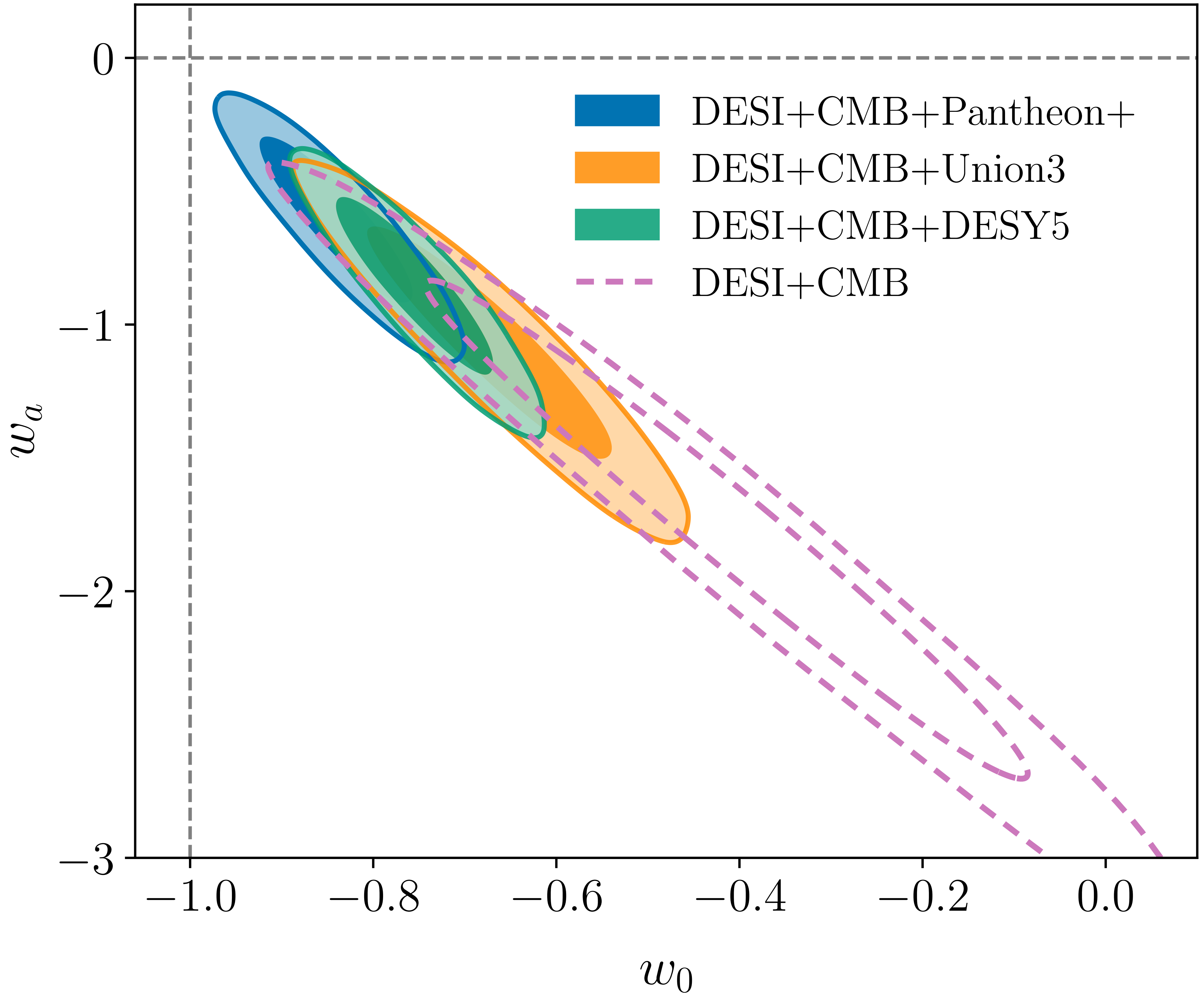
Euclid forecasts

[DESI Collaboration: Abdul-Karim et al. 2025 (DR2)]

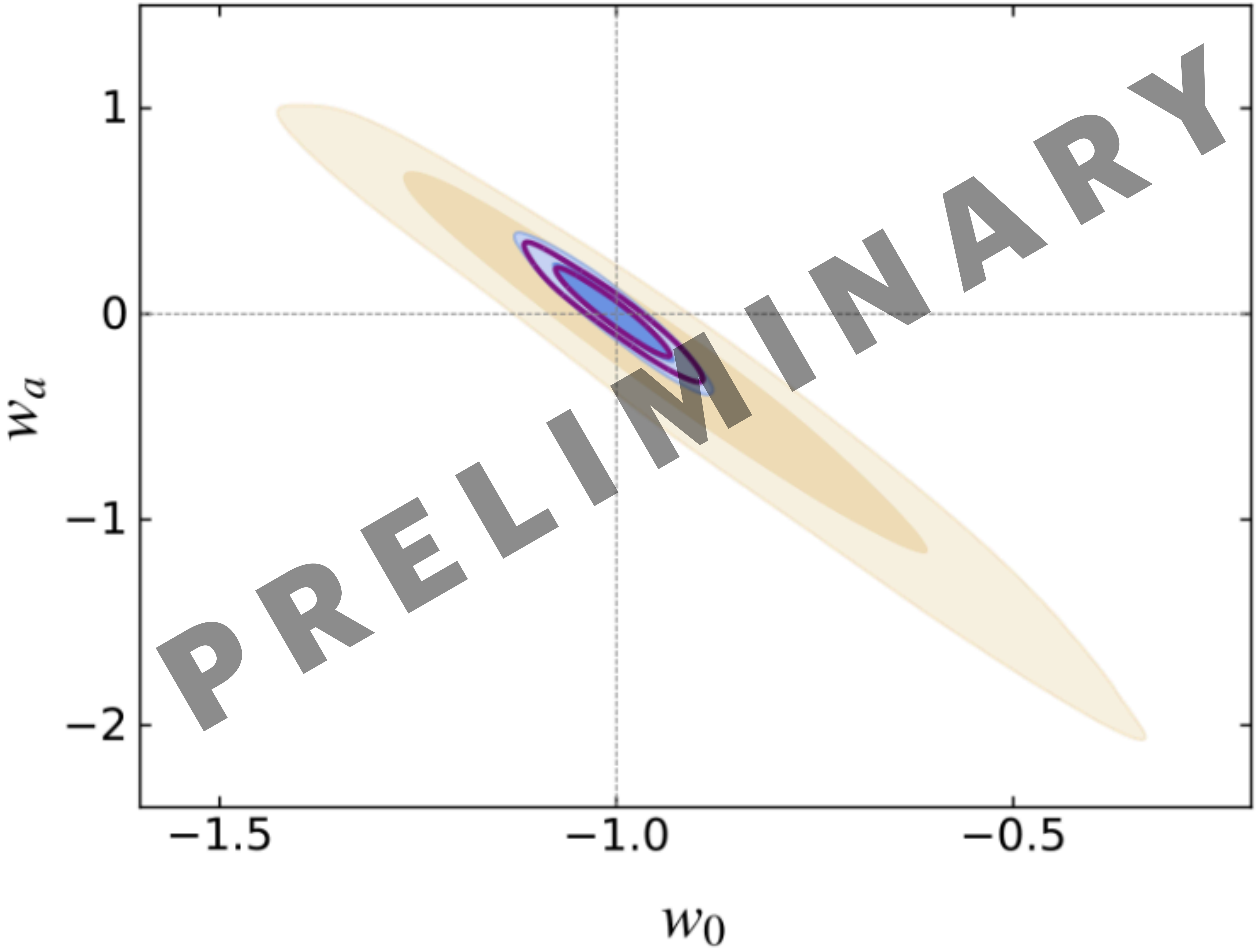


Euclid forecasts

[DESI Collaboration: Abdul-Karim et al. 2025 (DR2)]



[Euclid Collaboration: Cañas-Herrera ⊃ SC et al. (under review)]



Multi-wavelength synergies

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- Cosmological perturbation $f(t, \boldsymbol{x})$
  [temperature fluctuations, density perturbations, ...]
- Two-point correlation function $\langle f(t, \boldsymbol{x})\, f(t, \boldsymbol{y}) \rangle = \xi_{ff}(t, \boldsymbol{x} - \boldsymbol{y})$
- Fourier-space power spectrum $\langle \hat{f}(t, \boldsymbol{k})\, \hat{f}(t, \boldsymbol{k}') \rangle = (2\,\pi)^3\, \delta(\boldsymbol{k} + \boldsymbol{k}')\, P_{ff}(t, \boldsymbol{k})$
- Harmonic-space power spectrum $\langle \tilde{f}_{lm}(z)\, \tilde{f}_{l'm'}(z') \rangle = \delta_{ll'}\, \delta_{mm'}\, C_l^{ff}(z, z')$

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Multi-wavelength synergies

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

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

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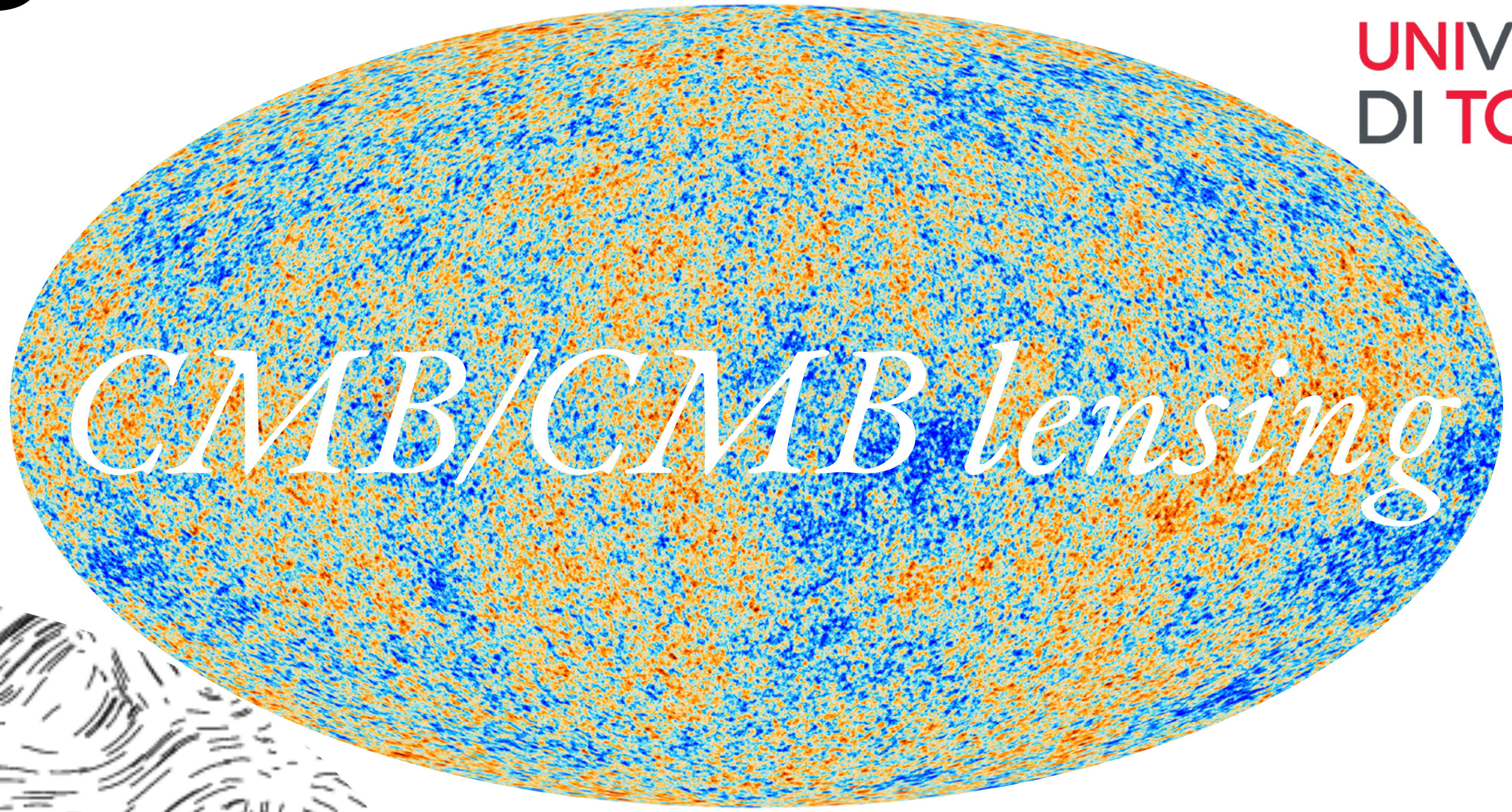
Measurements: observational systematics, noise, cosmic variance

Multi-wavelength synergies

Multi-wavelength synergies



Multi-wavelength synergies

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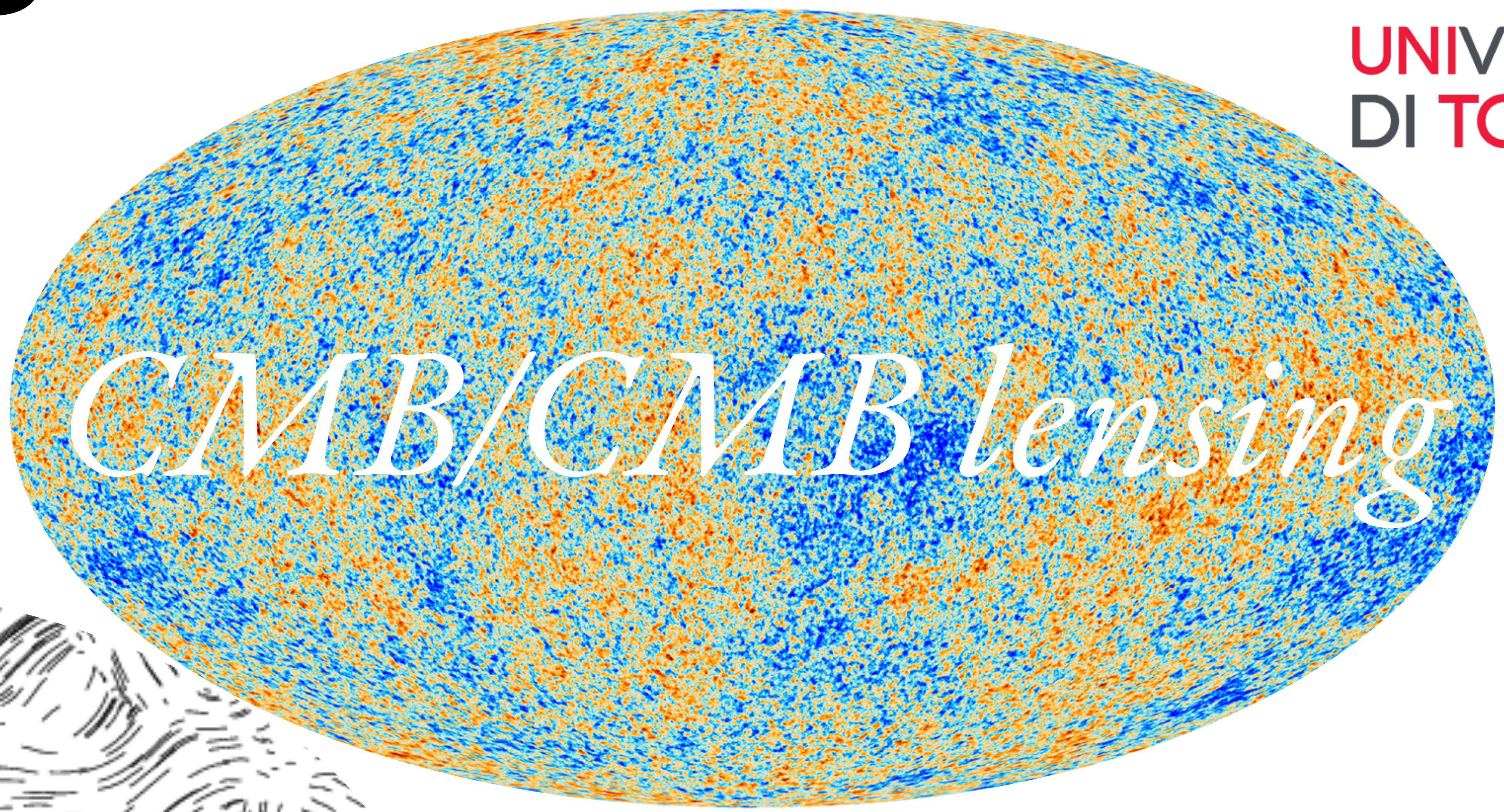
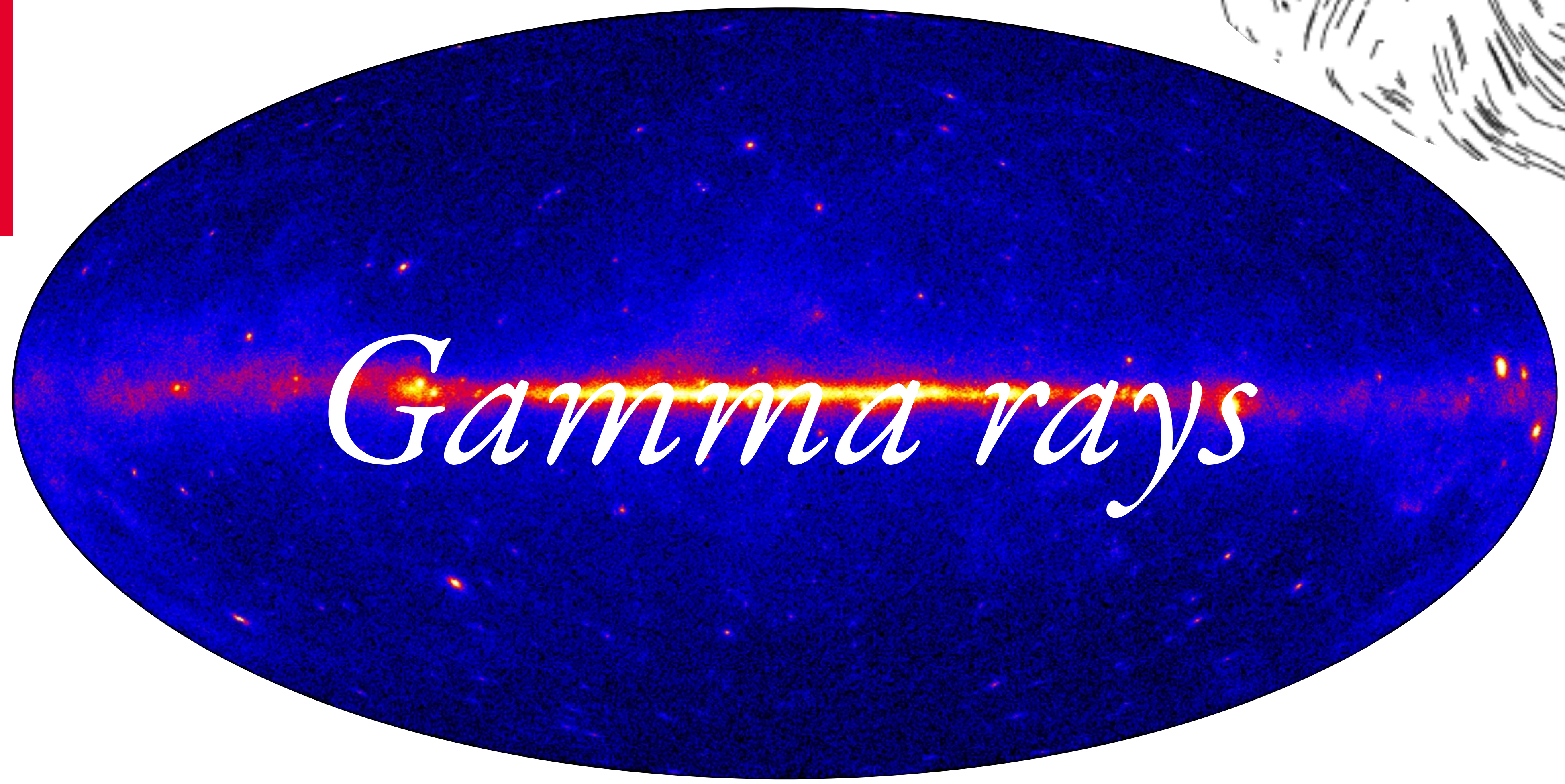
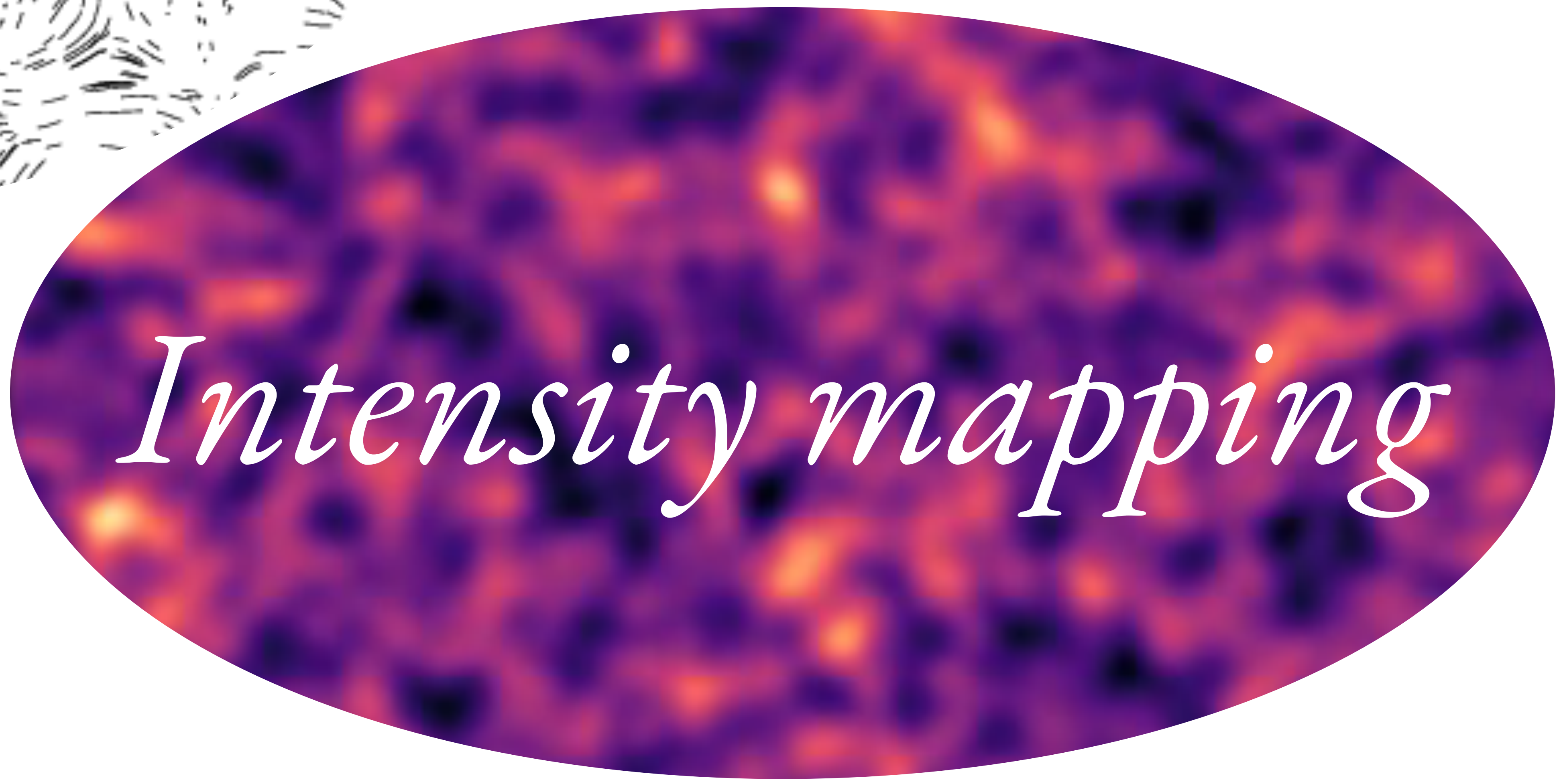
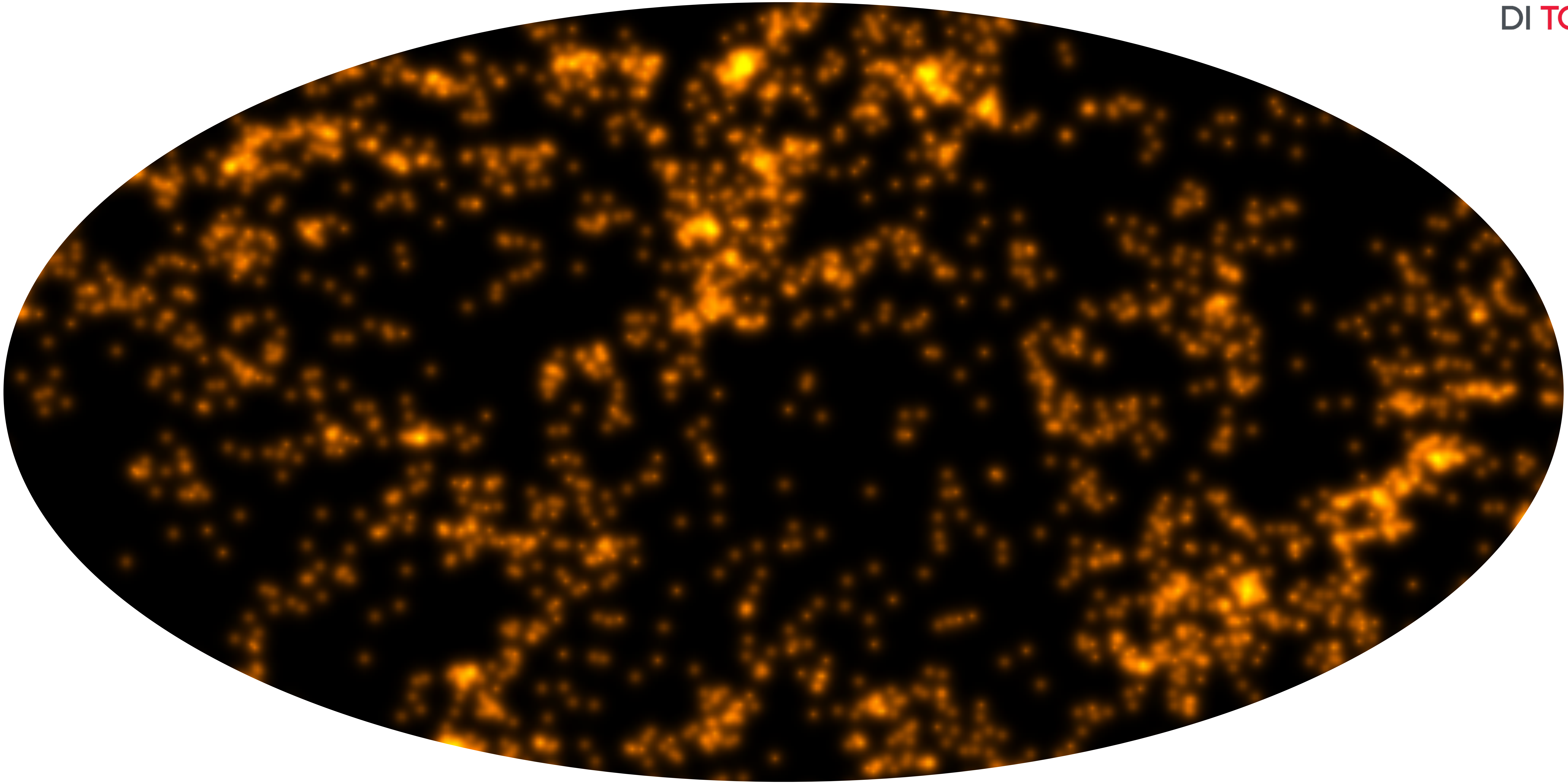






Intensity mapping



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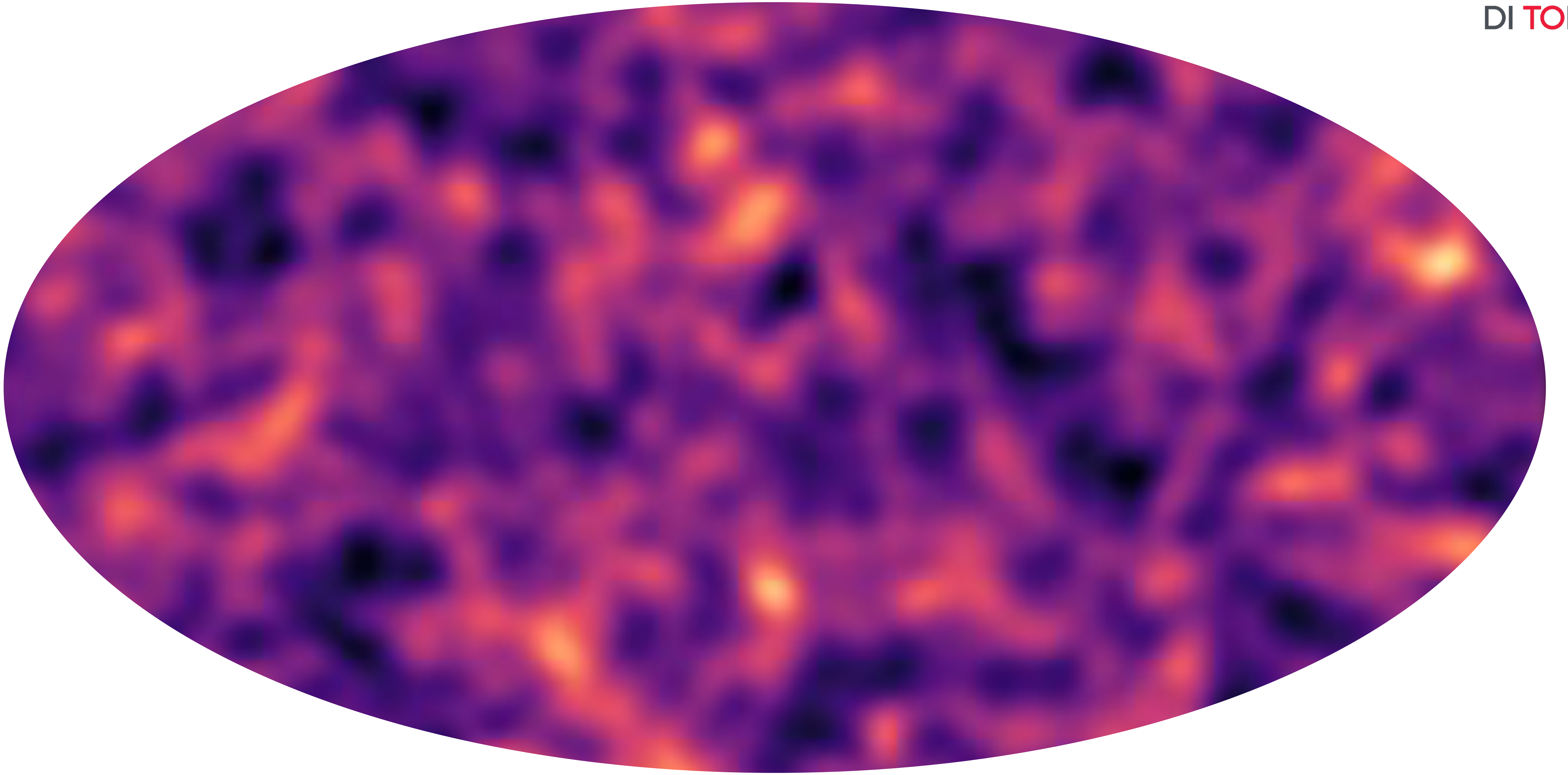

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Intensity mapping

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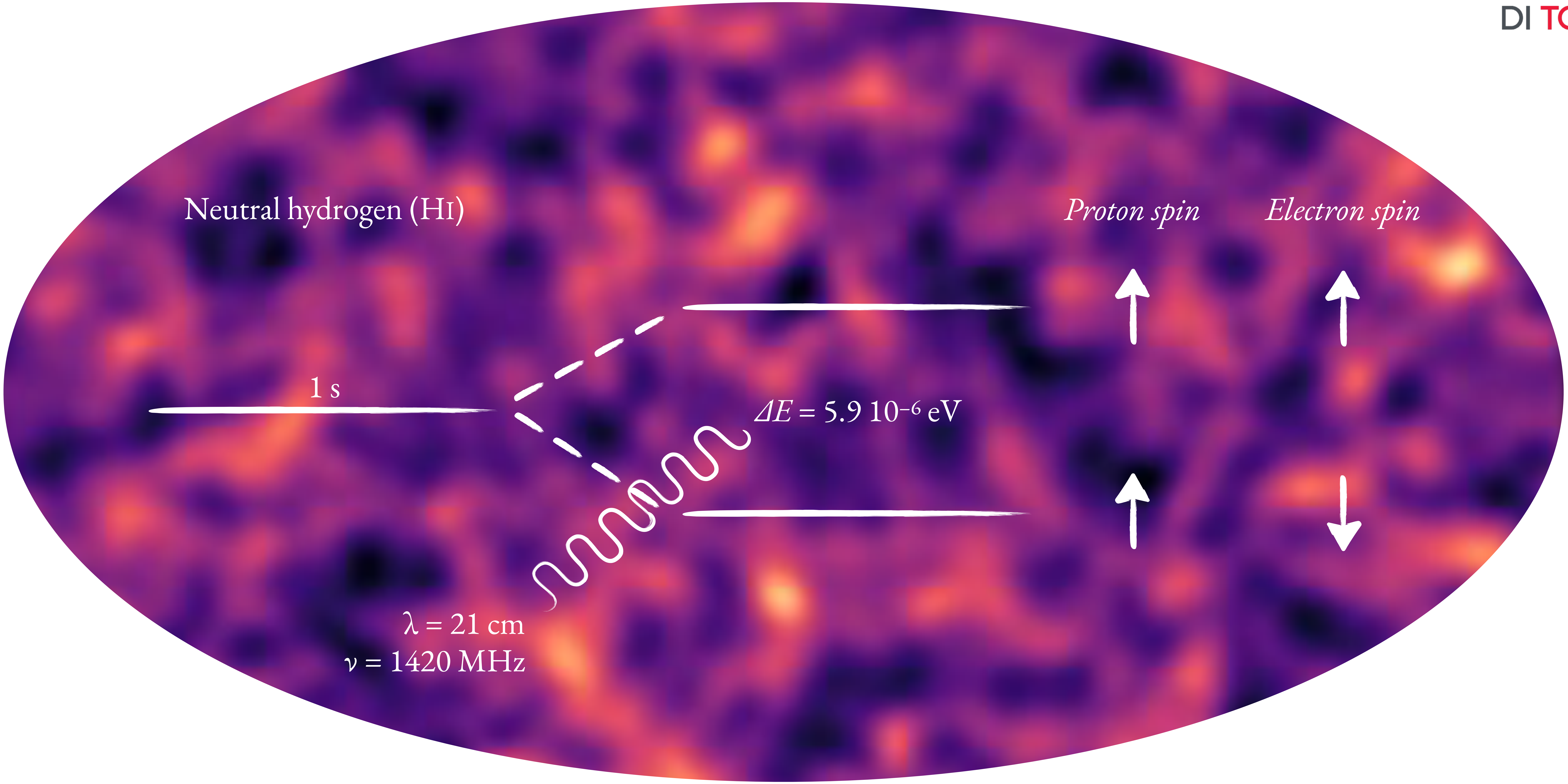

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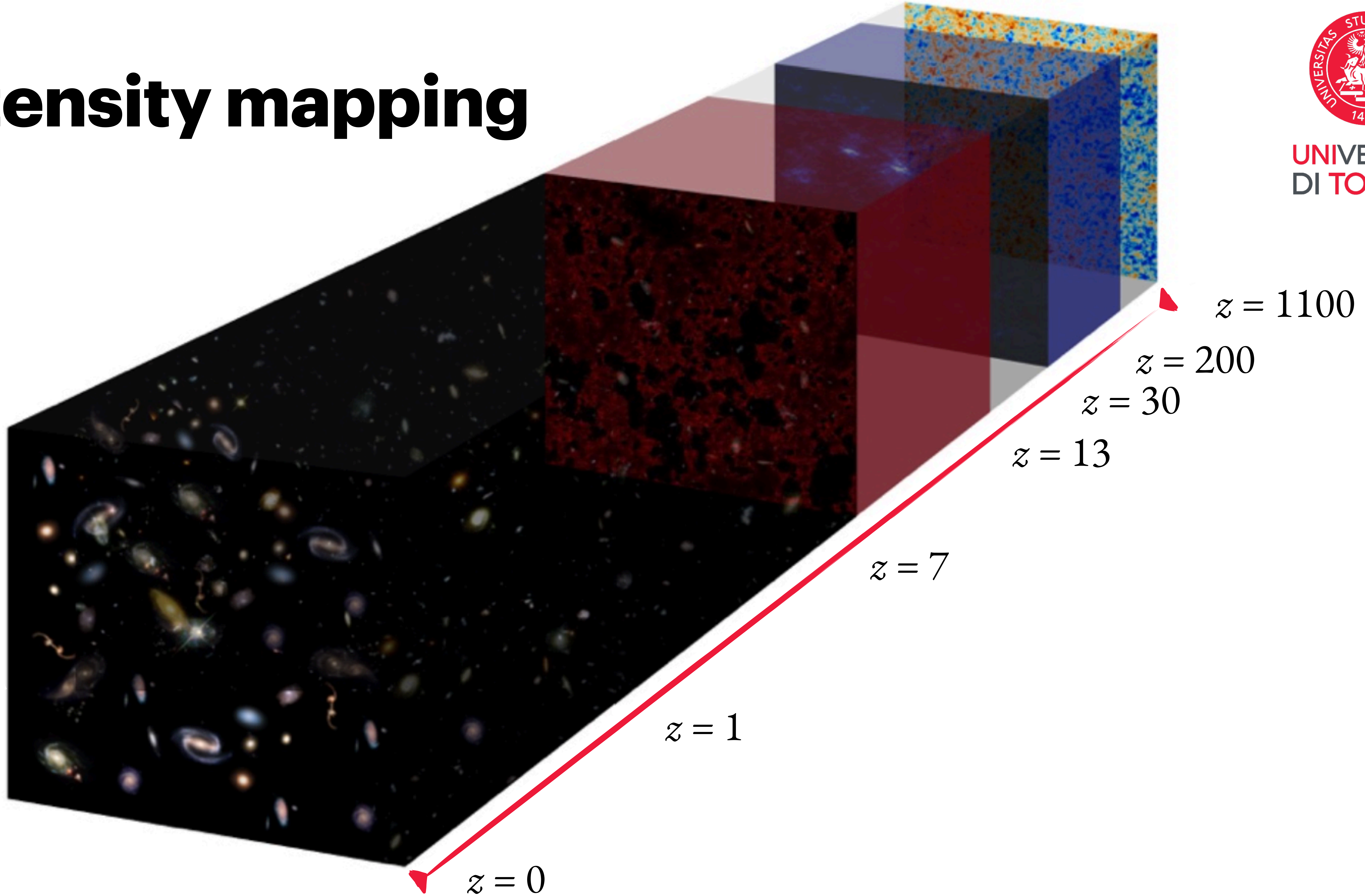

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Intensity mapping

- Comparing the clustering of different tracers of the underlying cosmic LSS

[Seljak 2009; Seljak & McDonald 2009]

- Exploit that on large scales the bias is deterministic despite the LSS being stochastic

Intensity mapping

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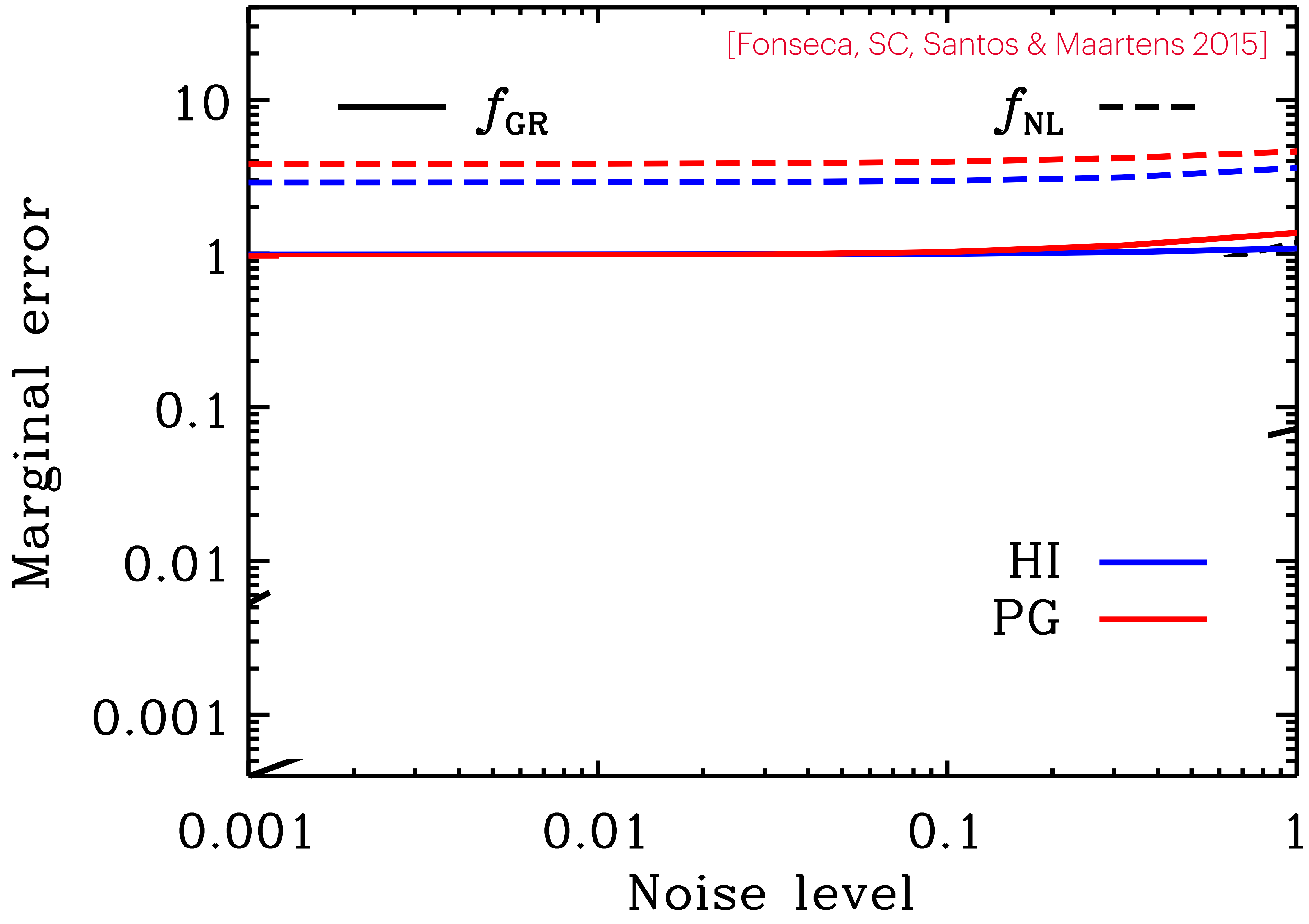

Intensity mapping

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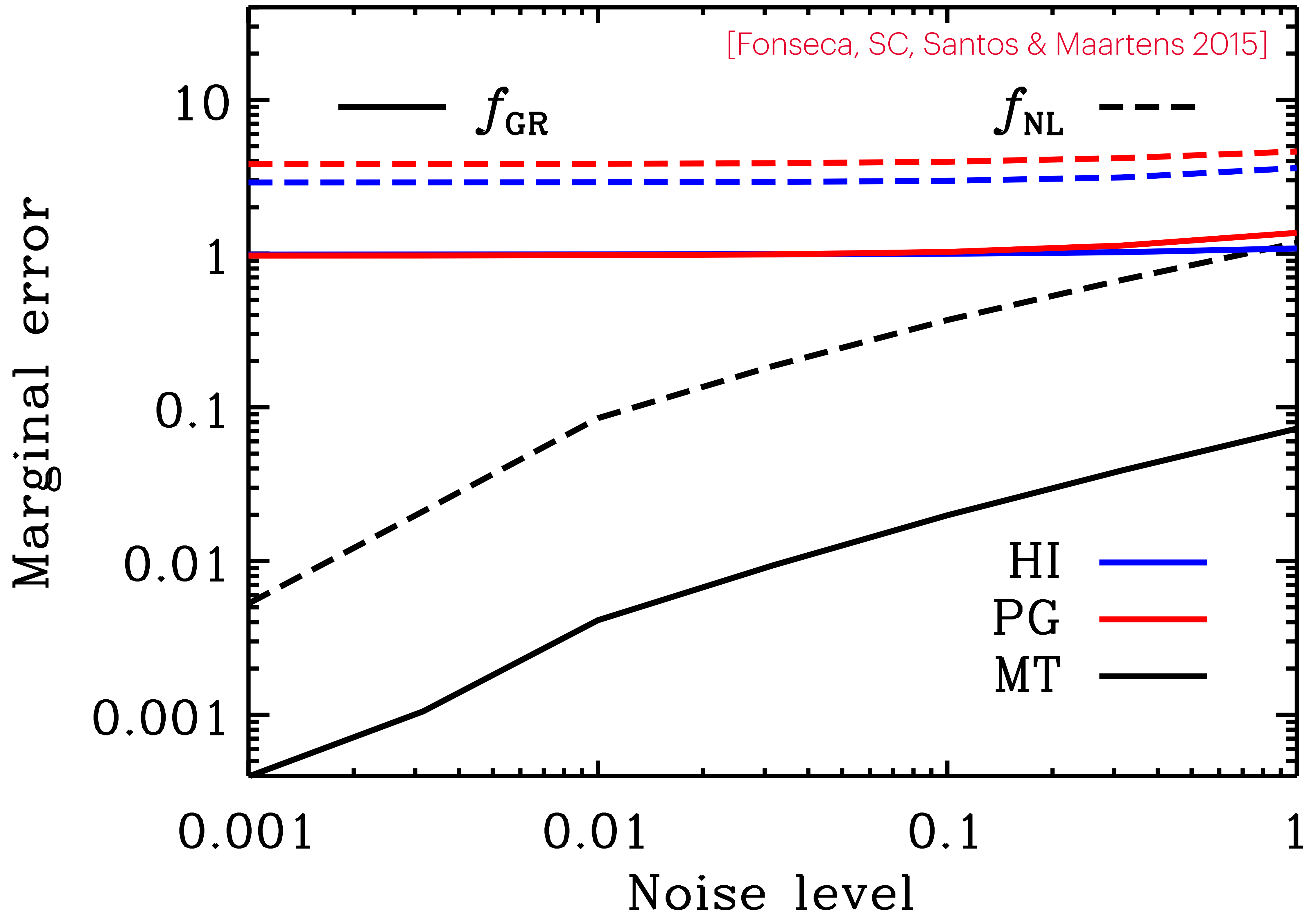
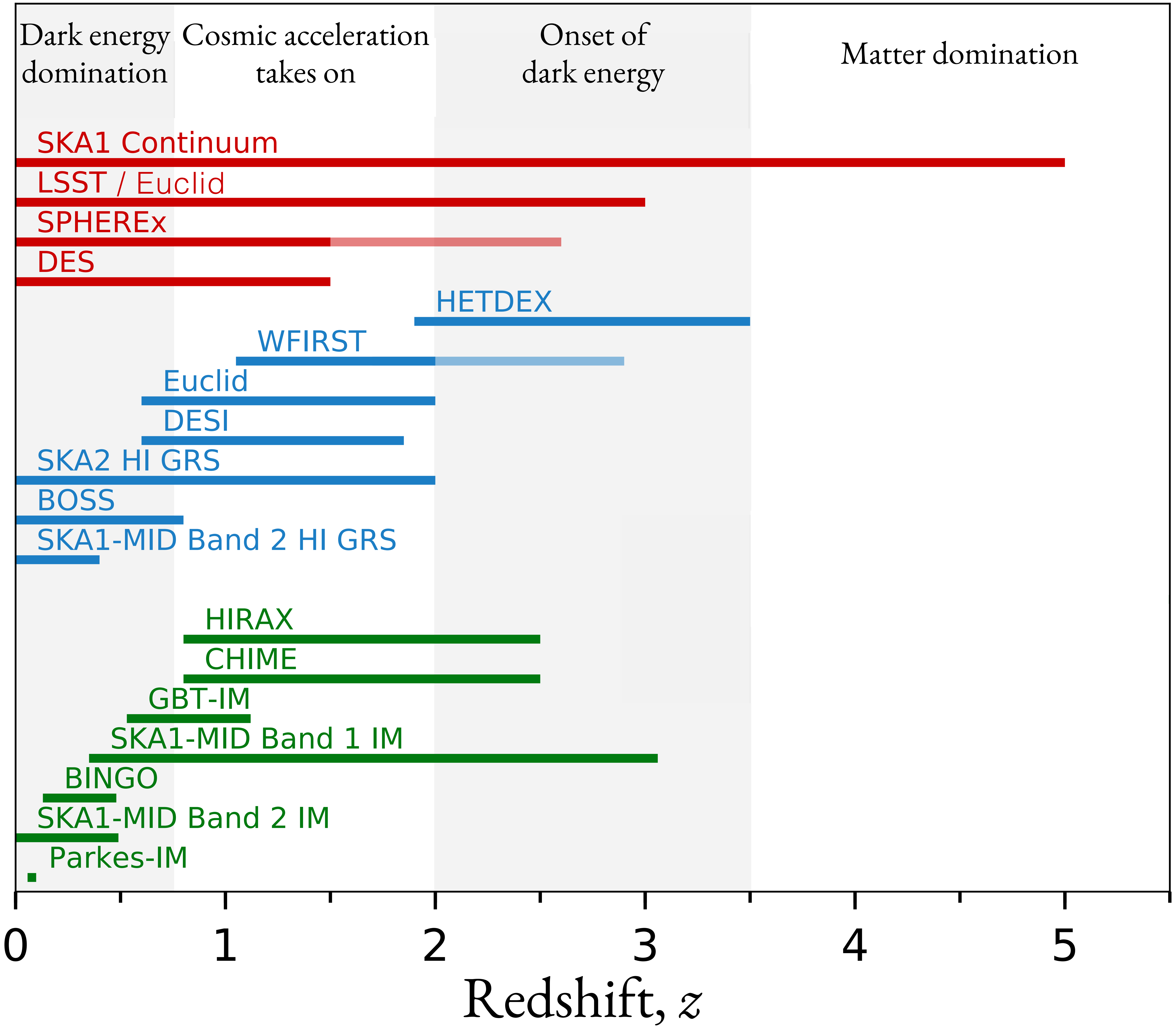


Intensity mapping

[Bull et al. ⊃ SC 2020]



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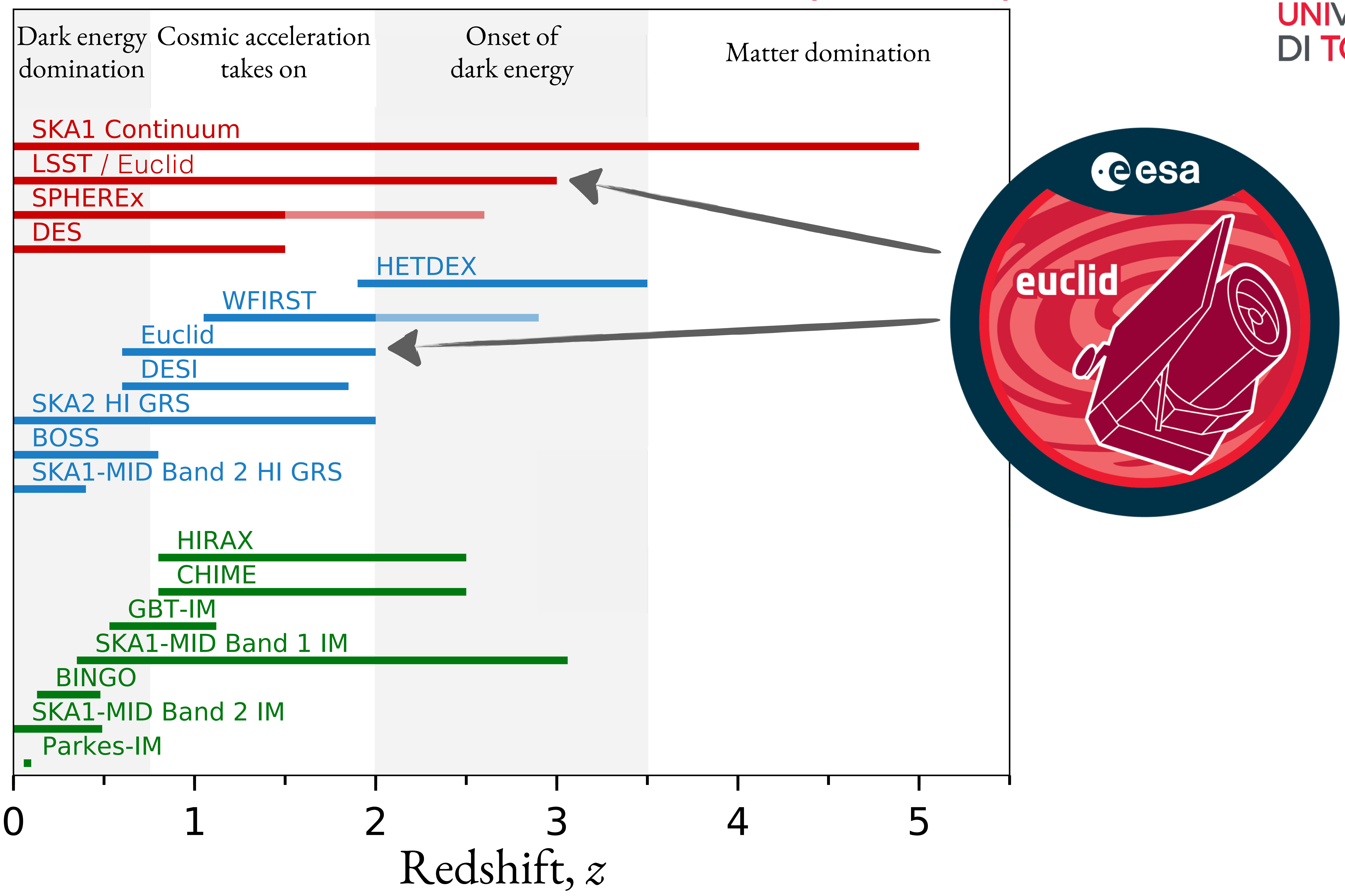

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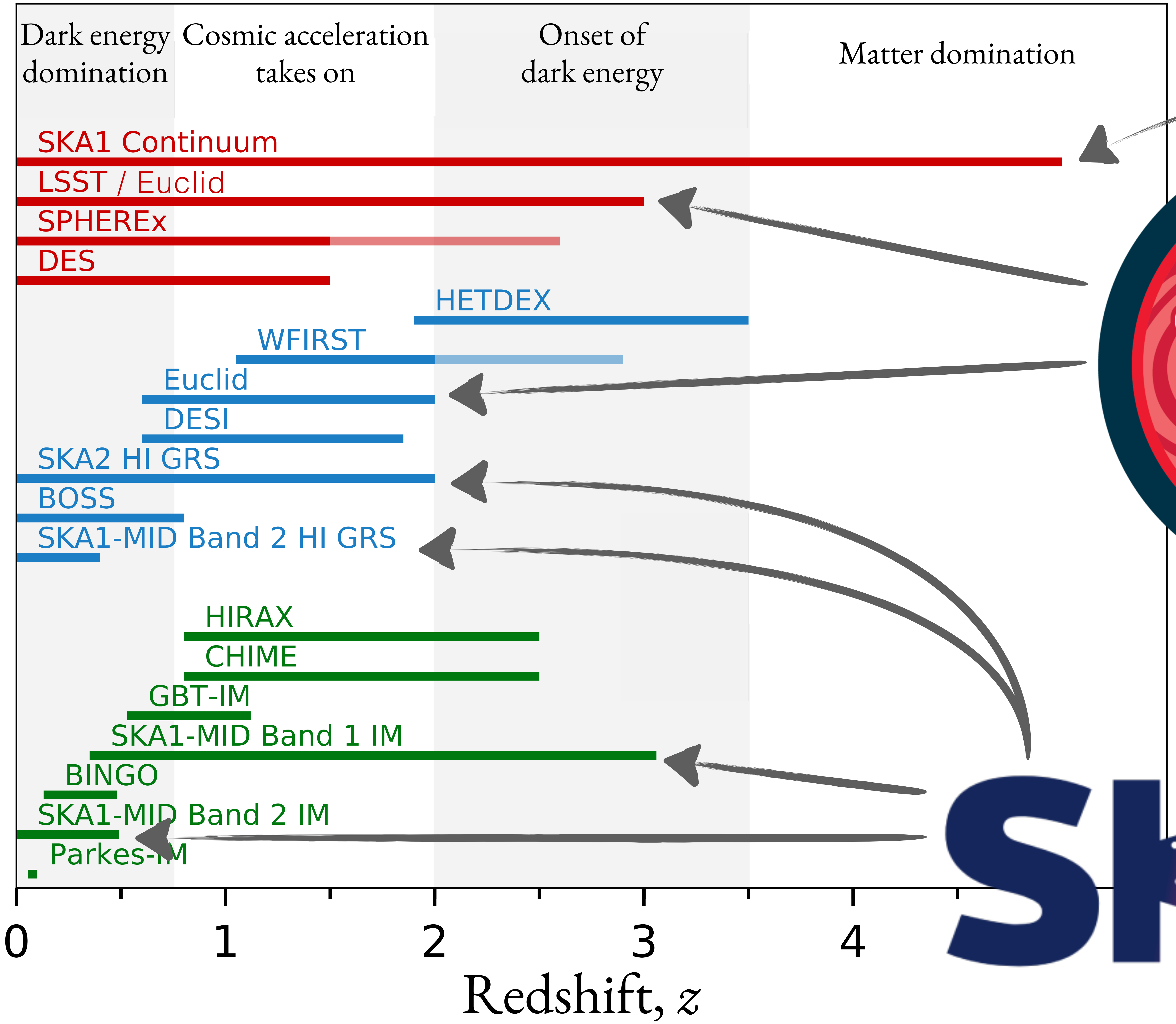
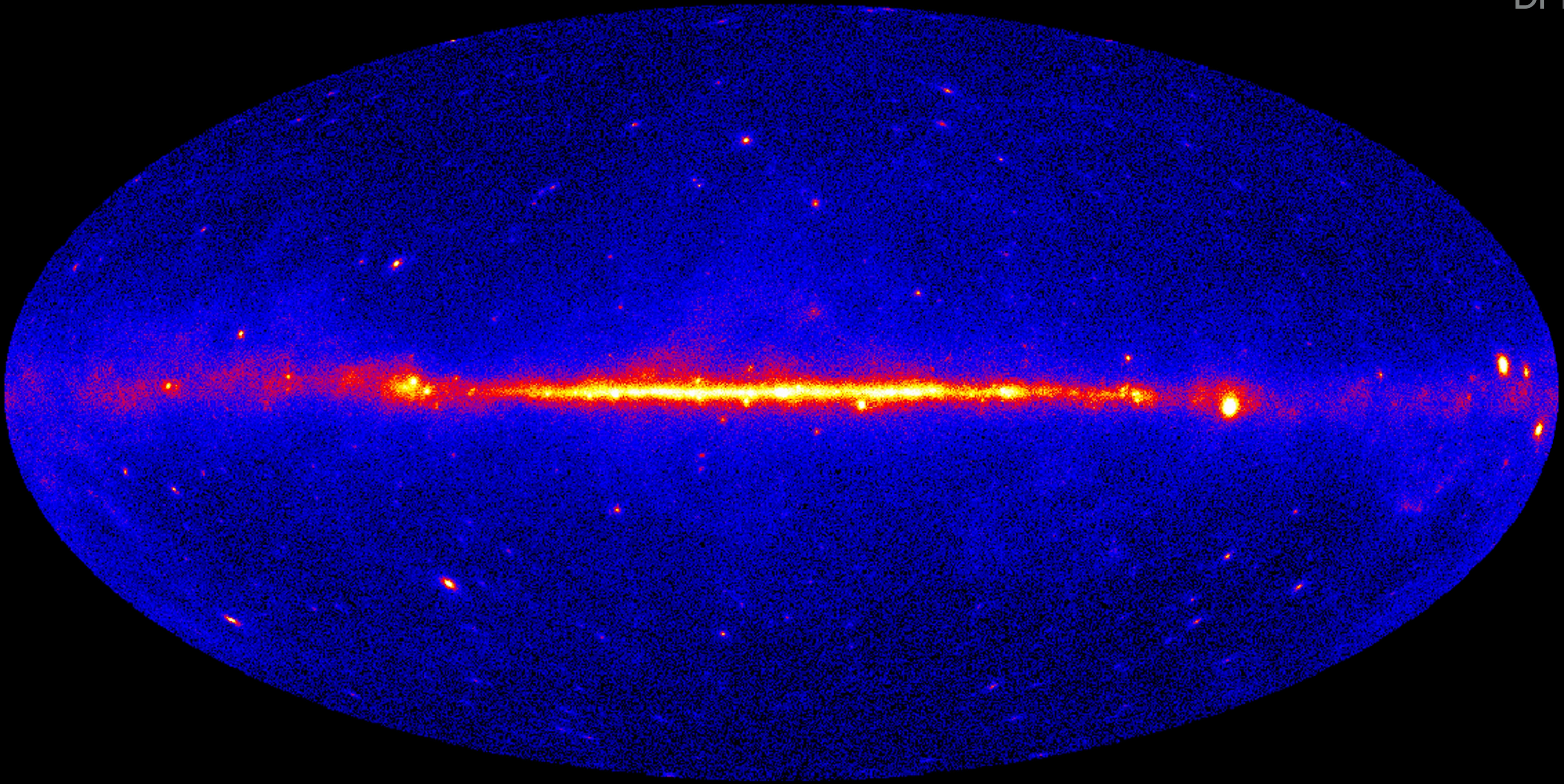


Clustering/lensing & γ rays



[Credits: NASA/DOE/Fermi-LAT Collaboration]

Clustering/lensing & γ rays

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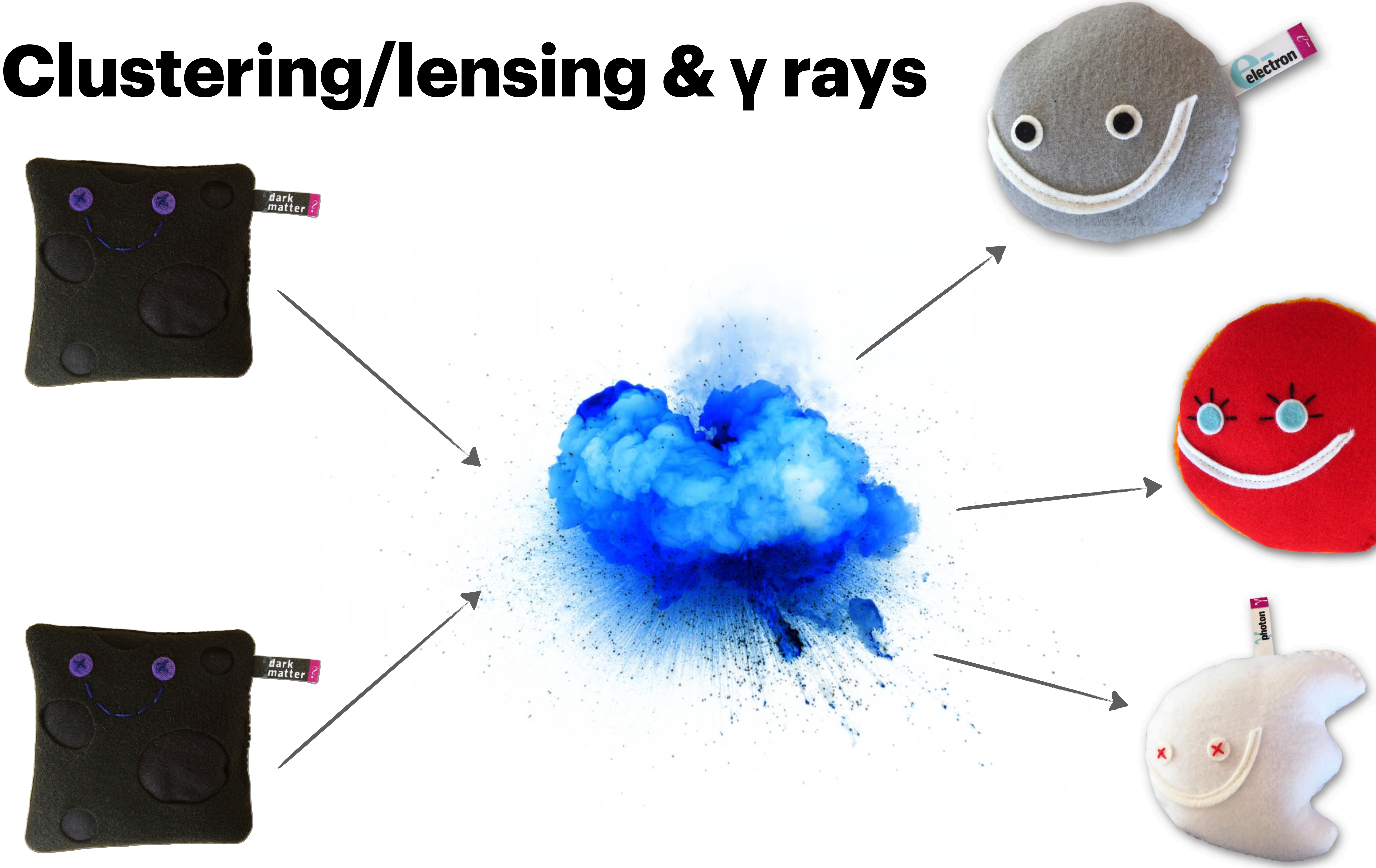

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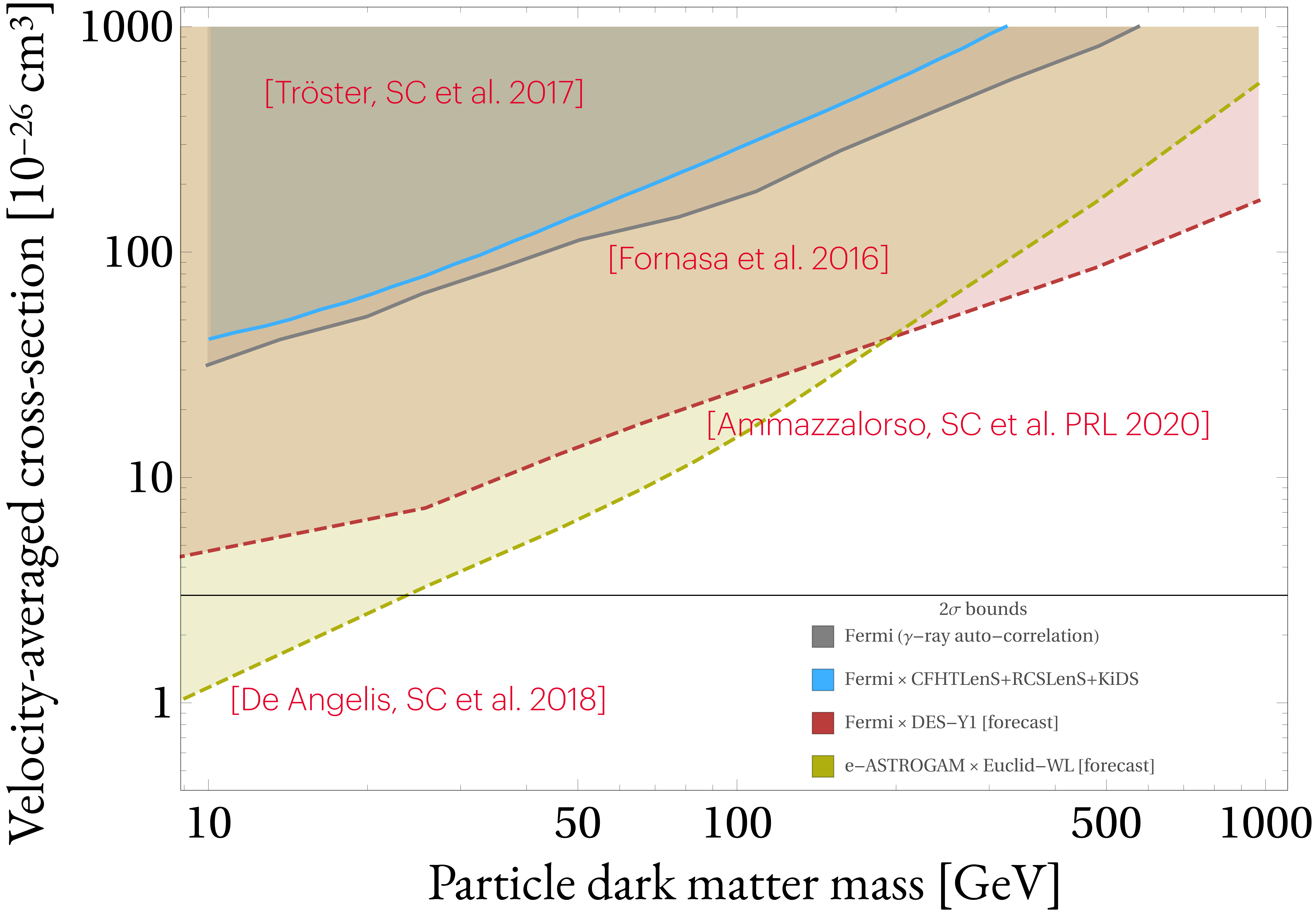

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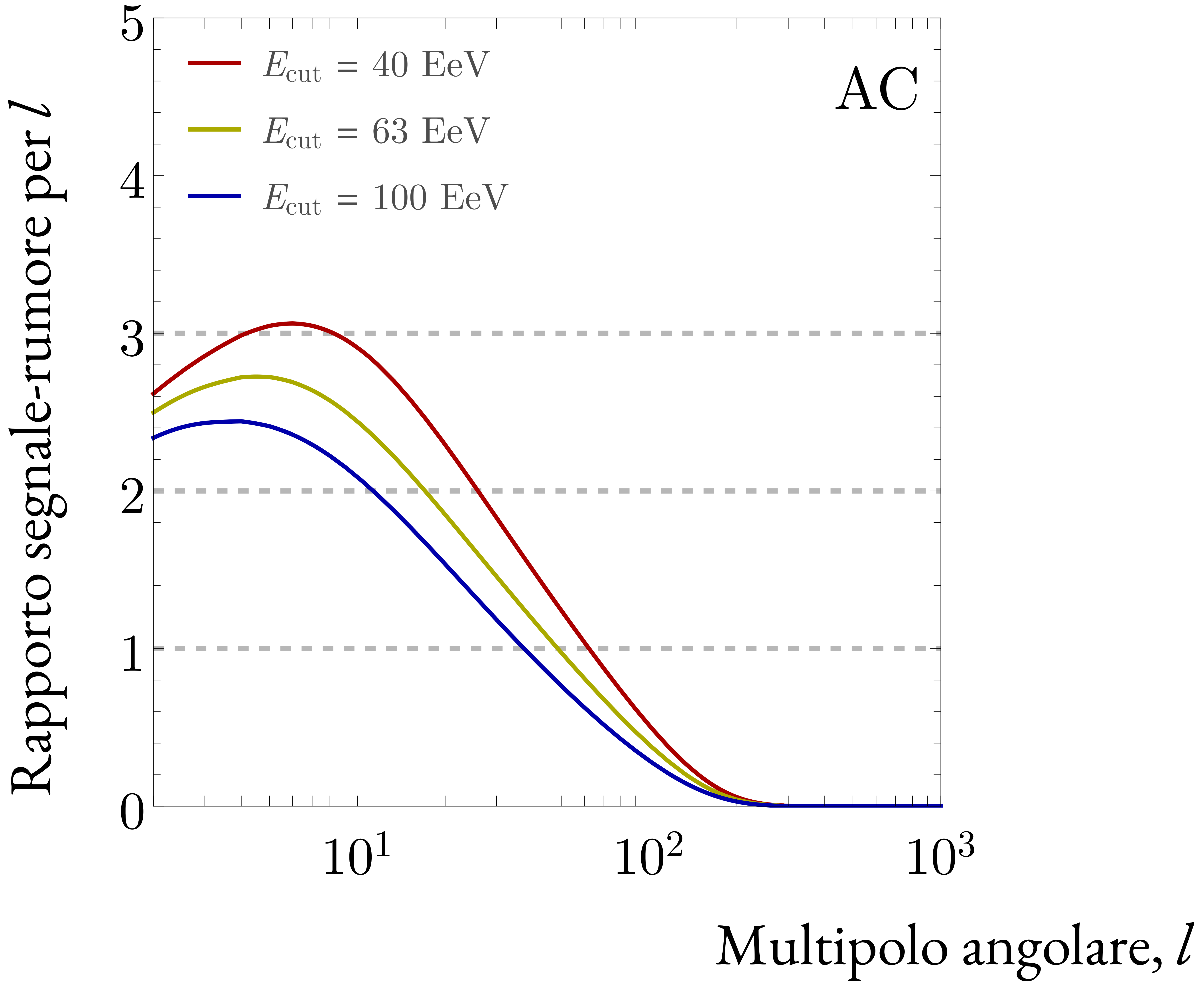
Clustering & UHECRs

[Urban, SC & Alonso 2020, 2022]



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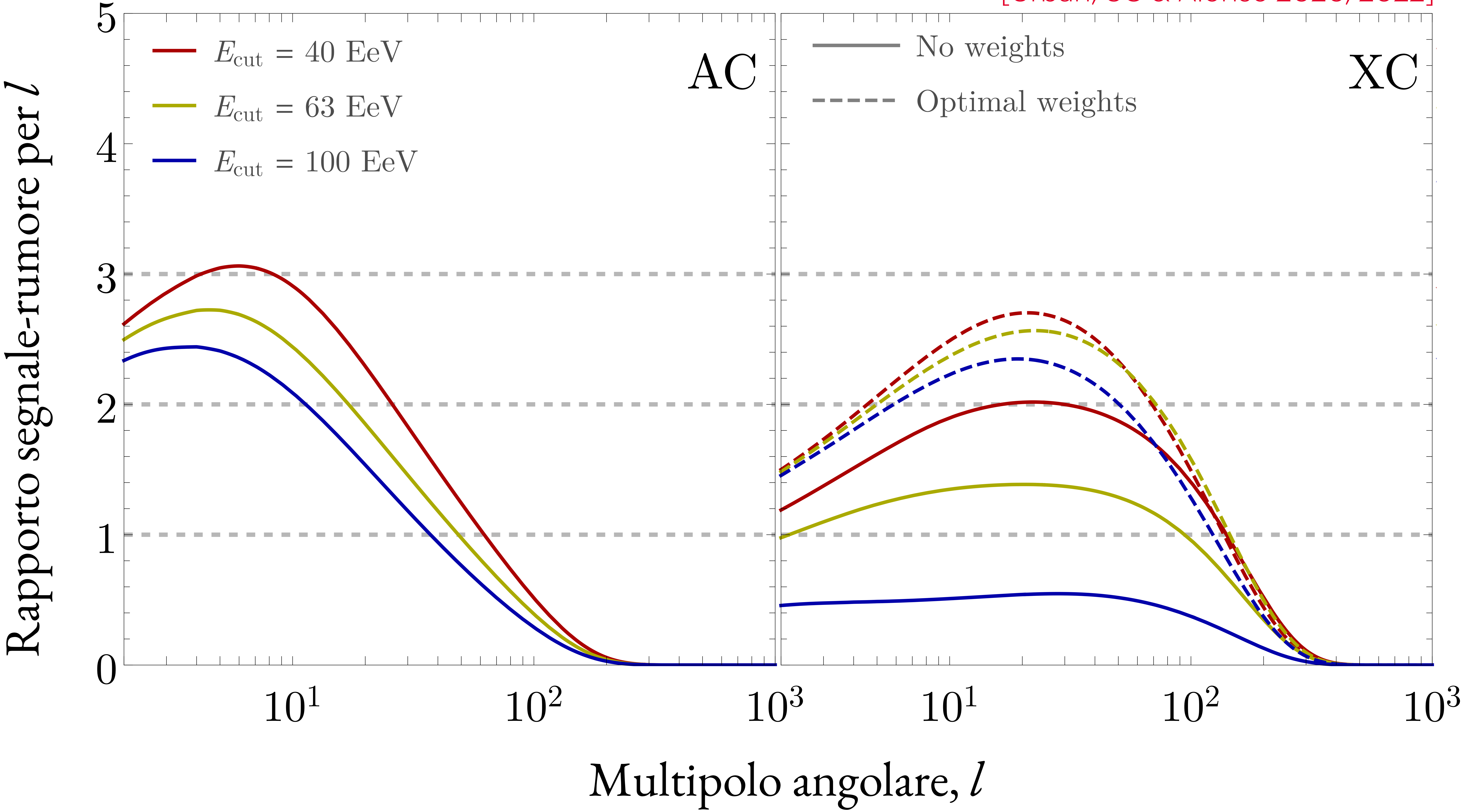
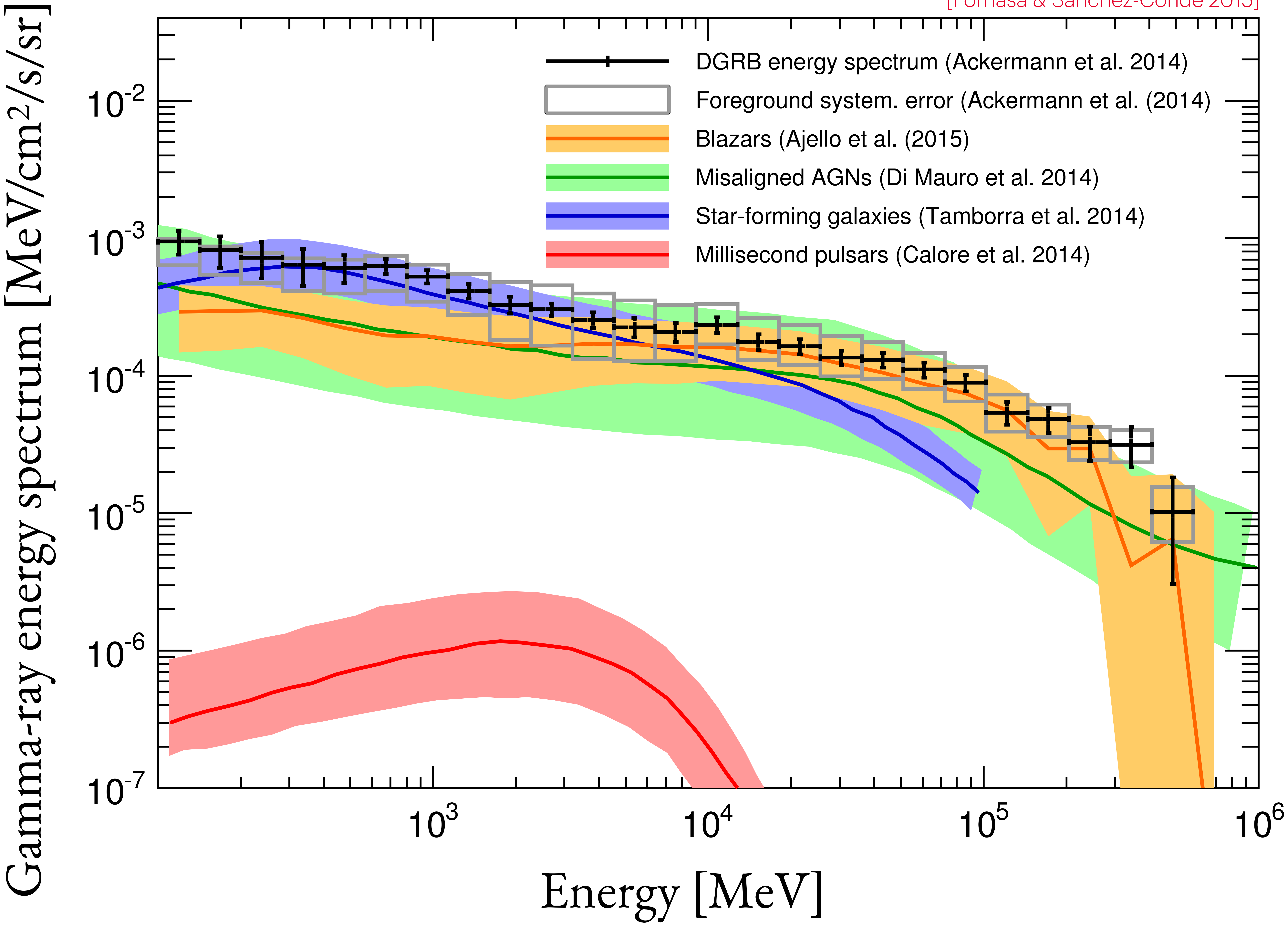


Back-up slides

Dark matter indirect searches

[Fornasa & Sánchez-Conde 2015]



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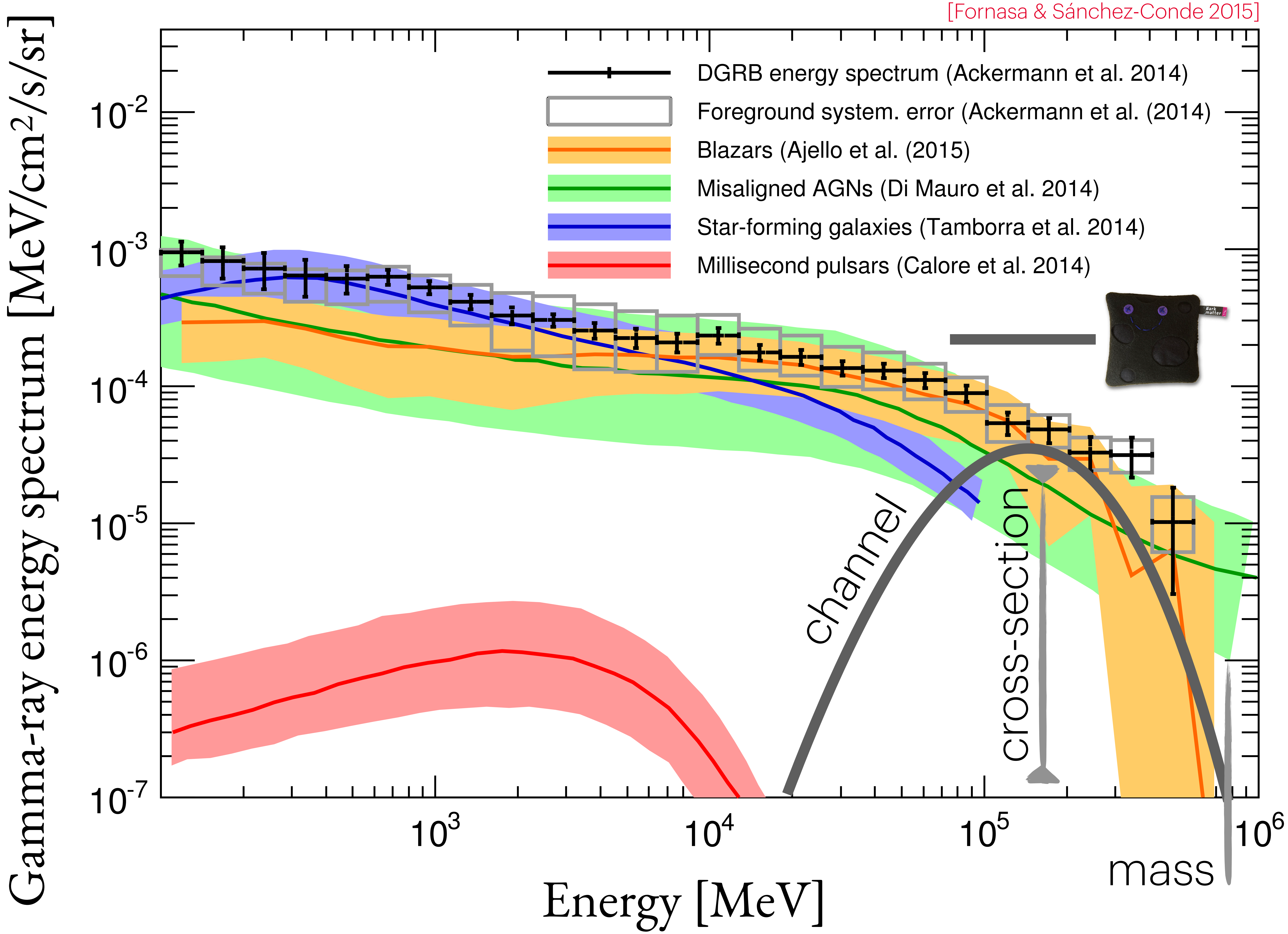
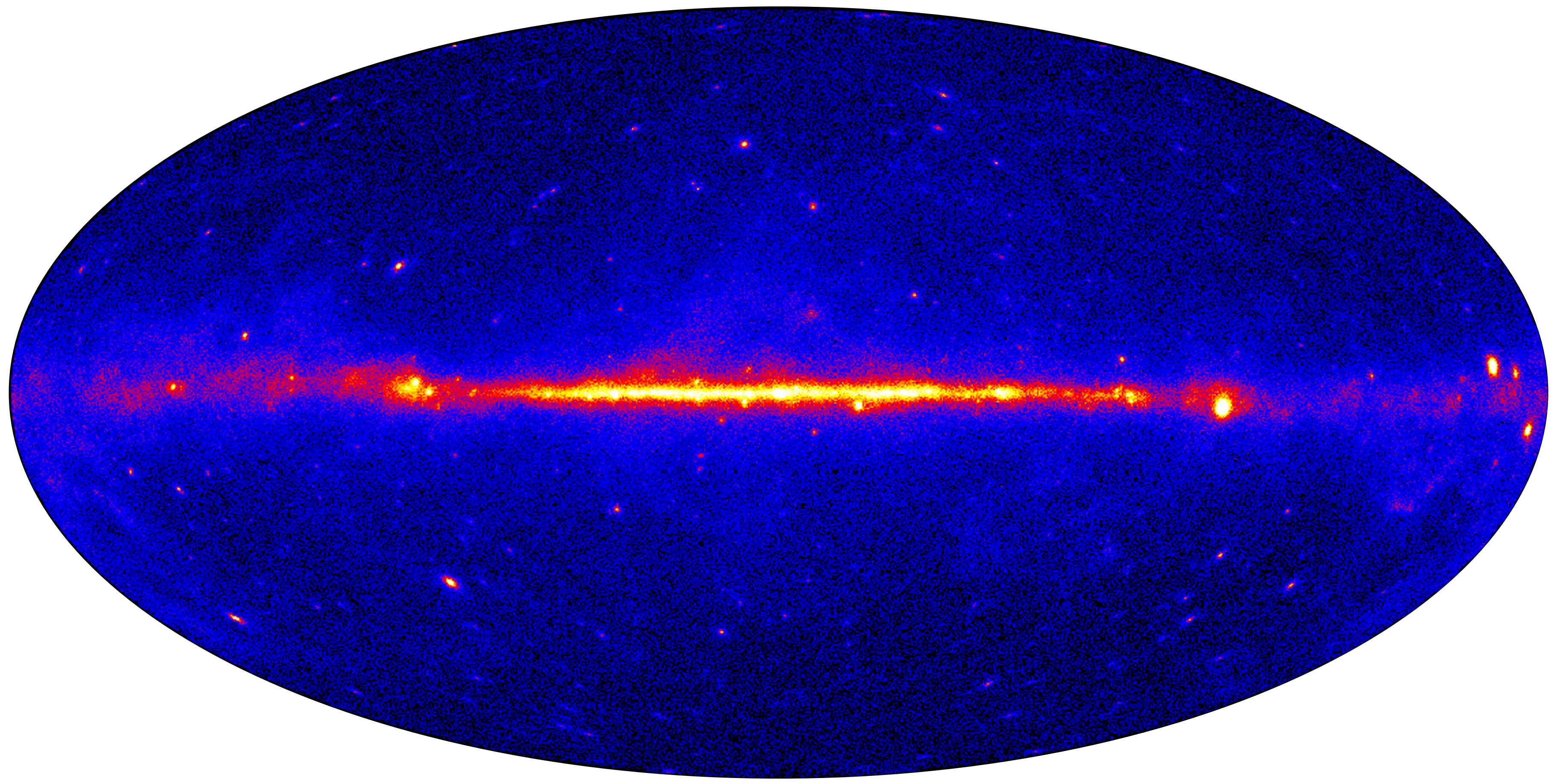
Dark matter indirect searches



Dark matter indirect searches



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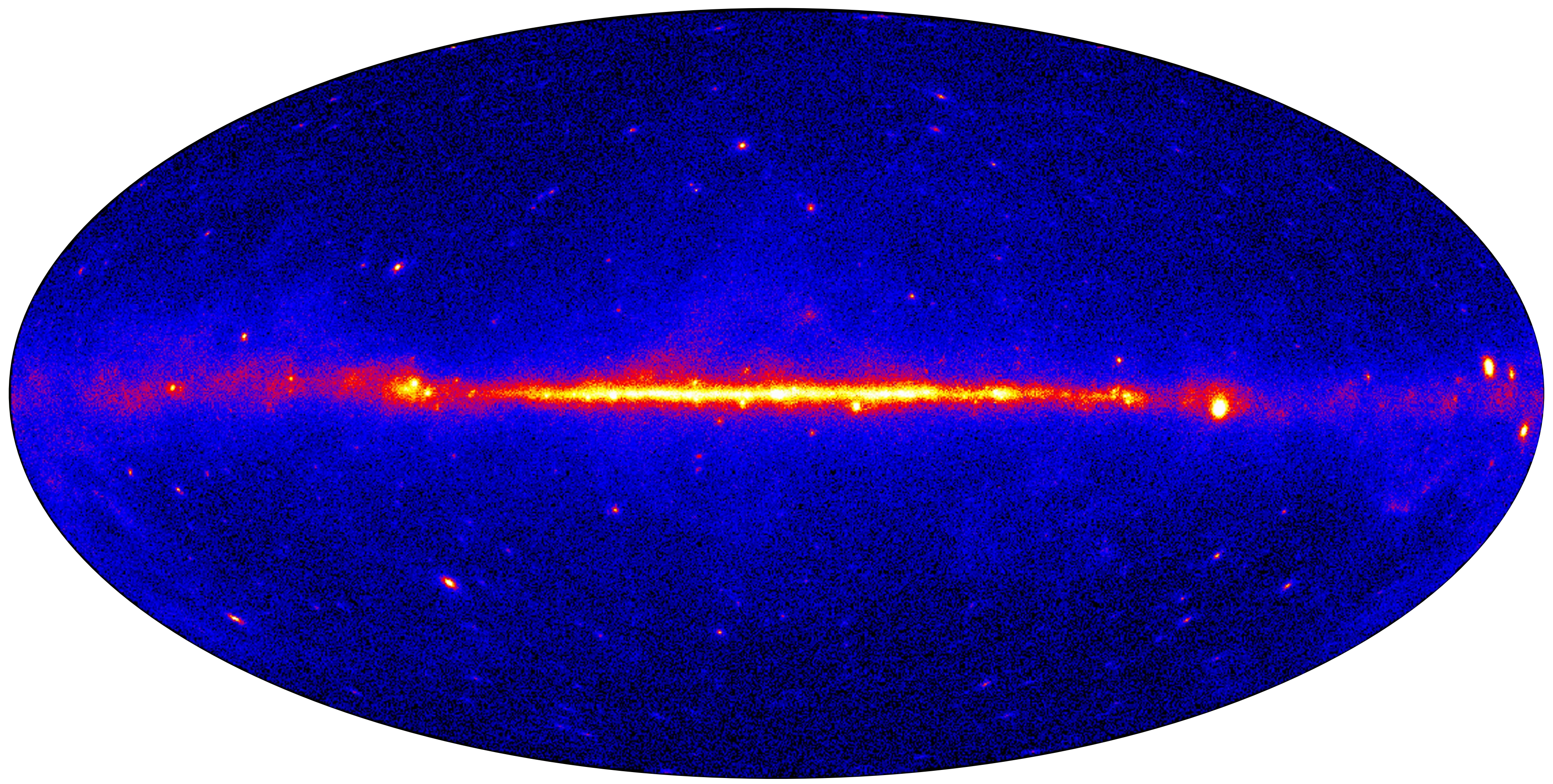
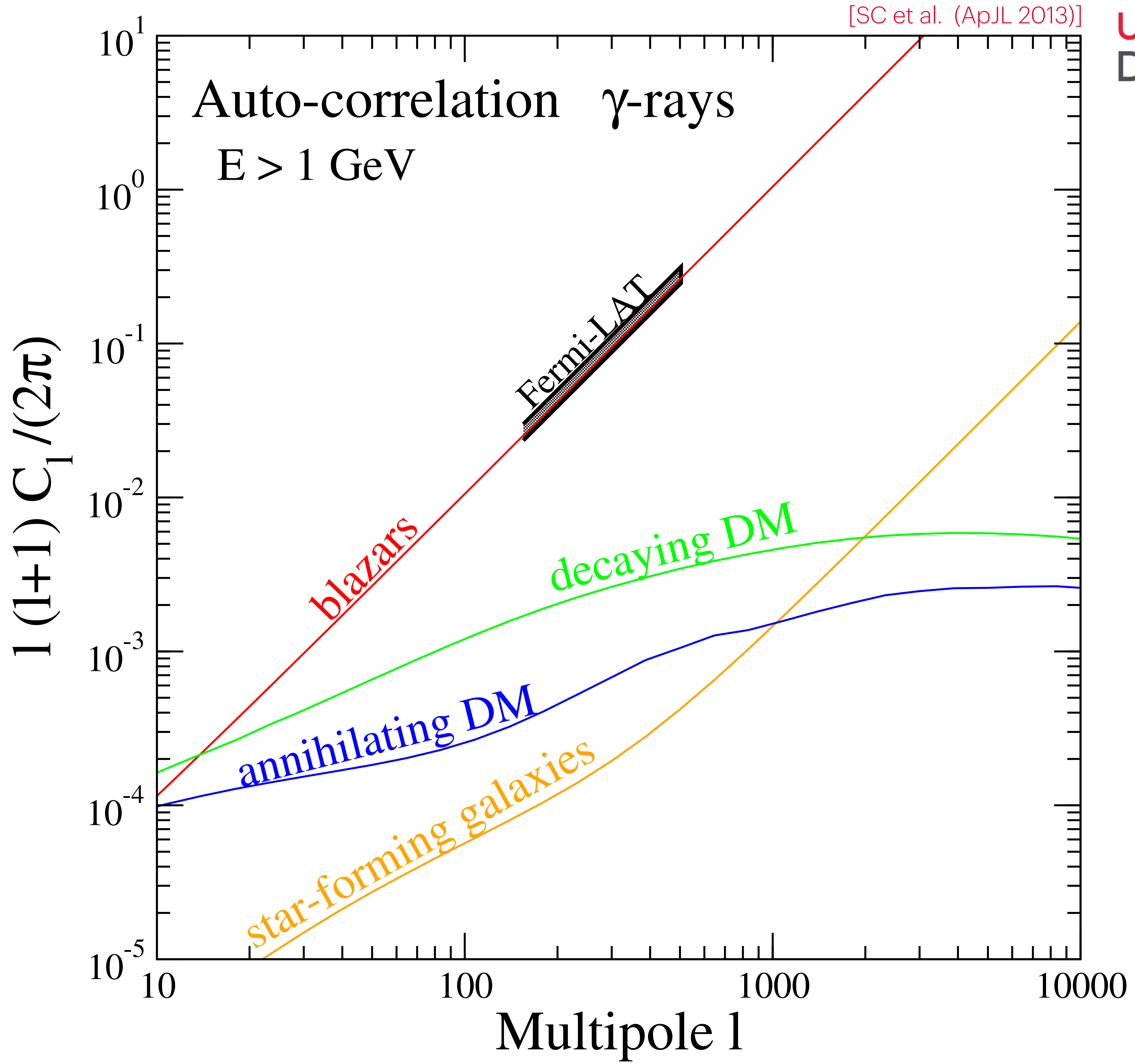
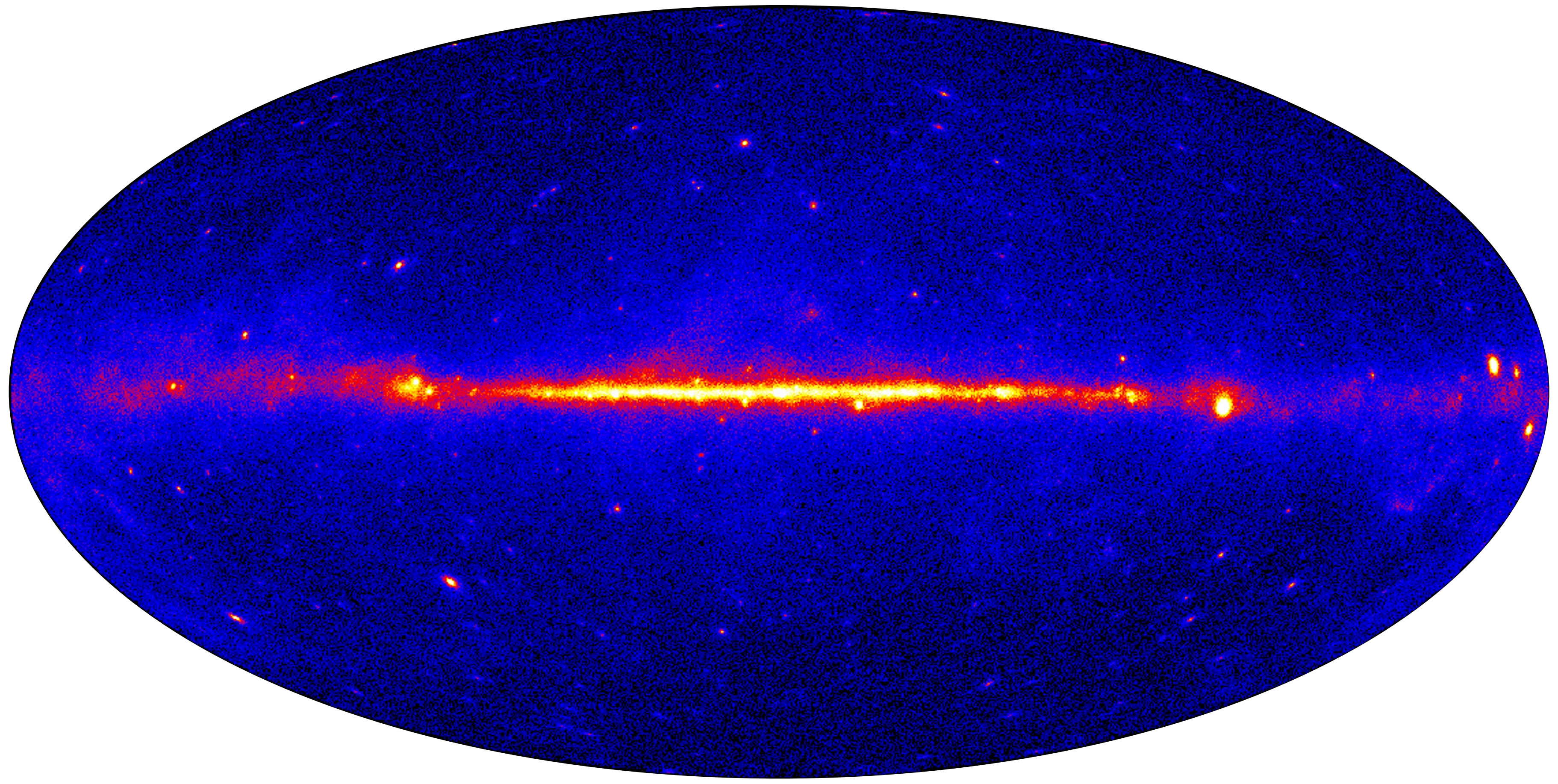




Dark matter indirect searches



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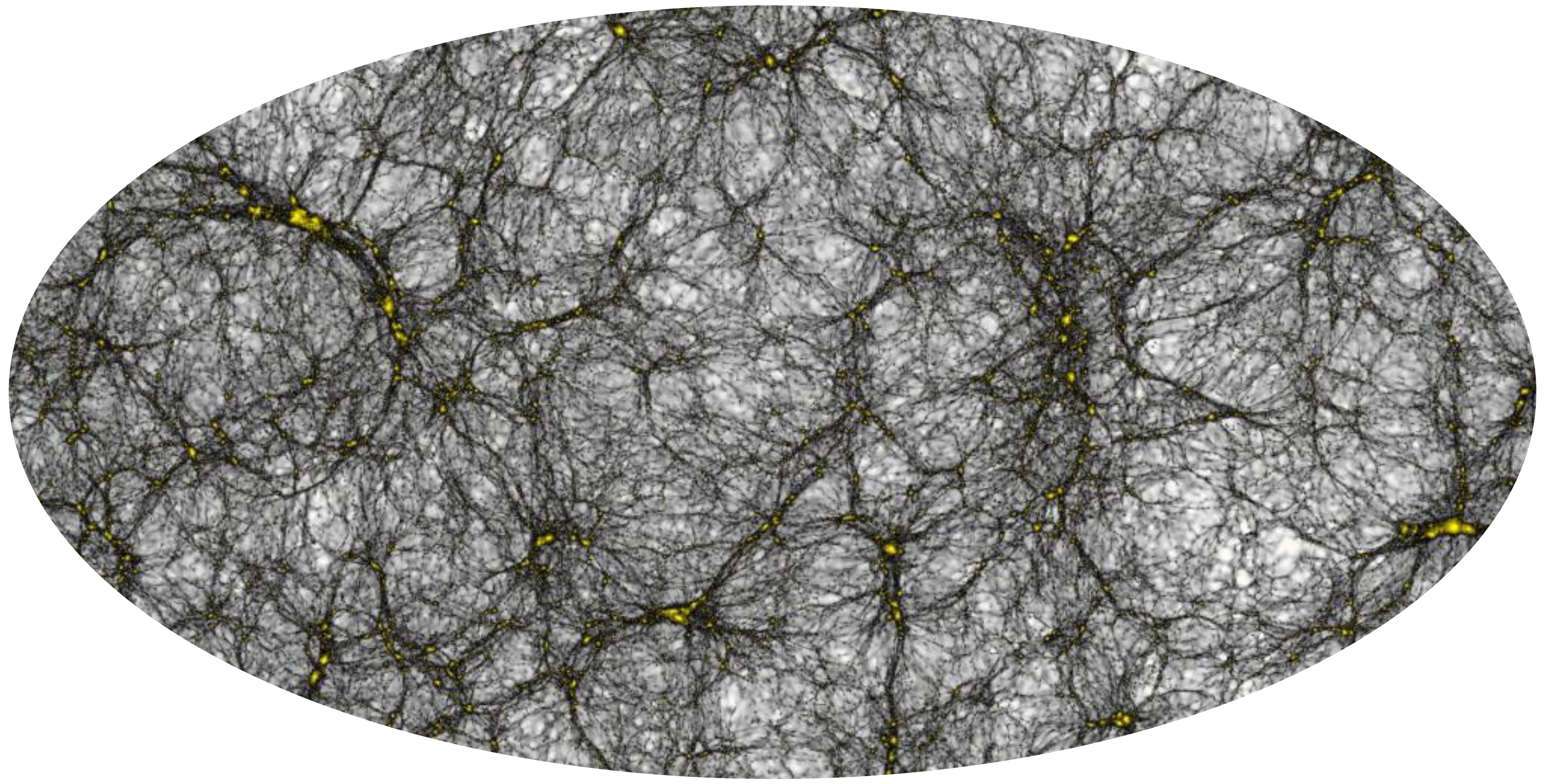
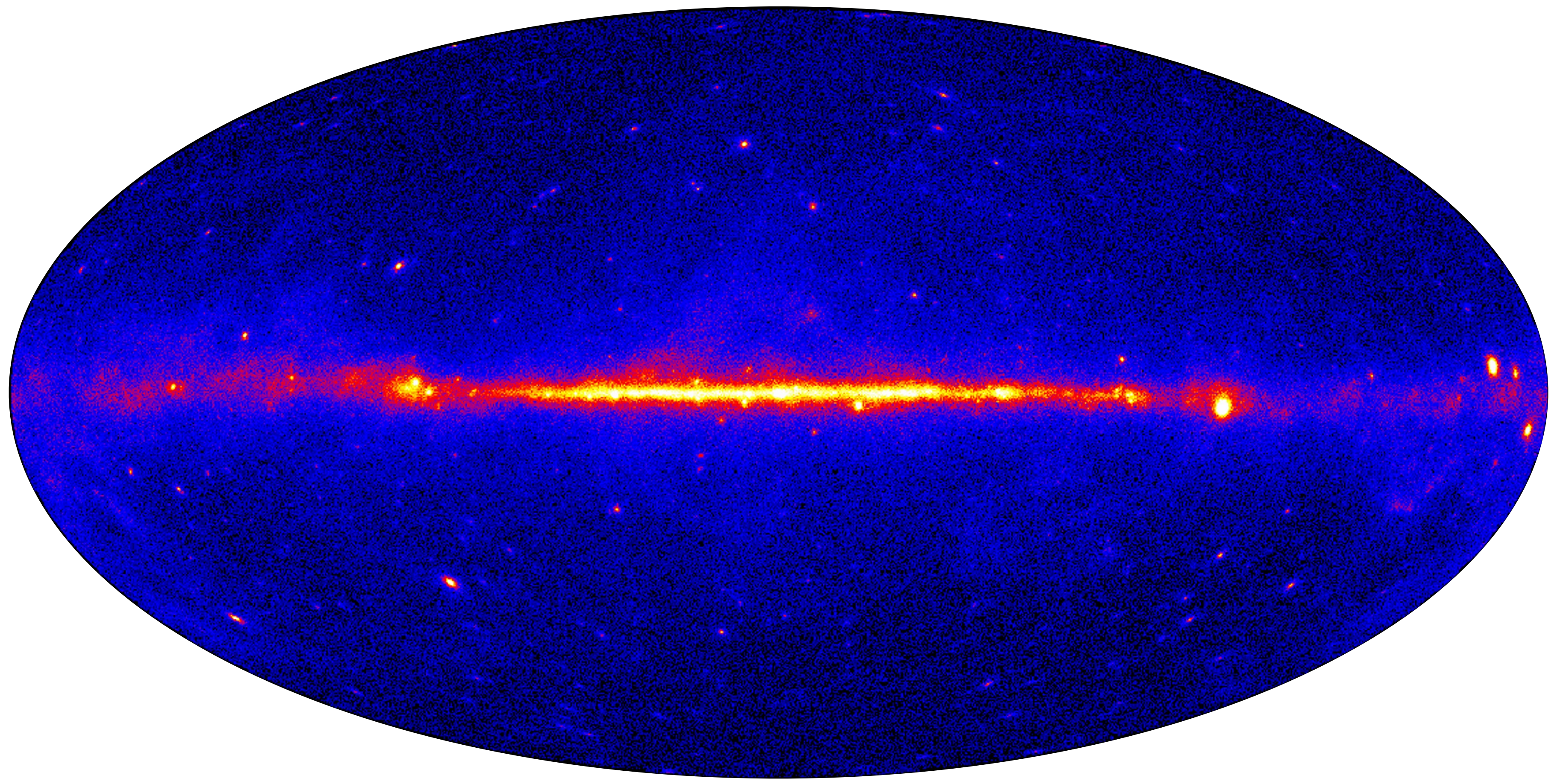


Dark matter indirect searches



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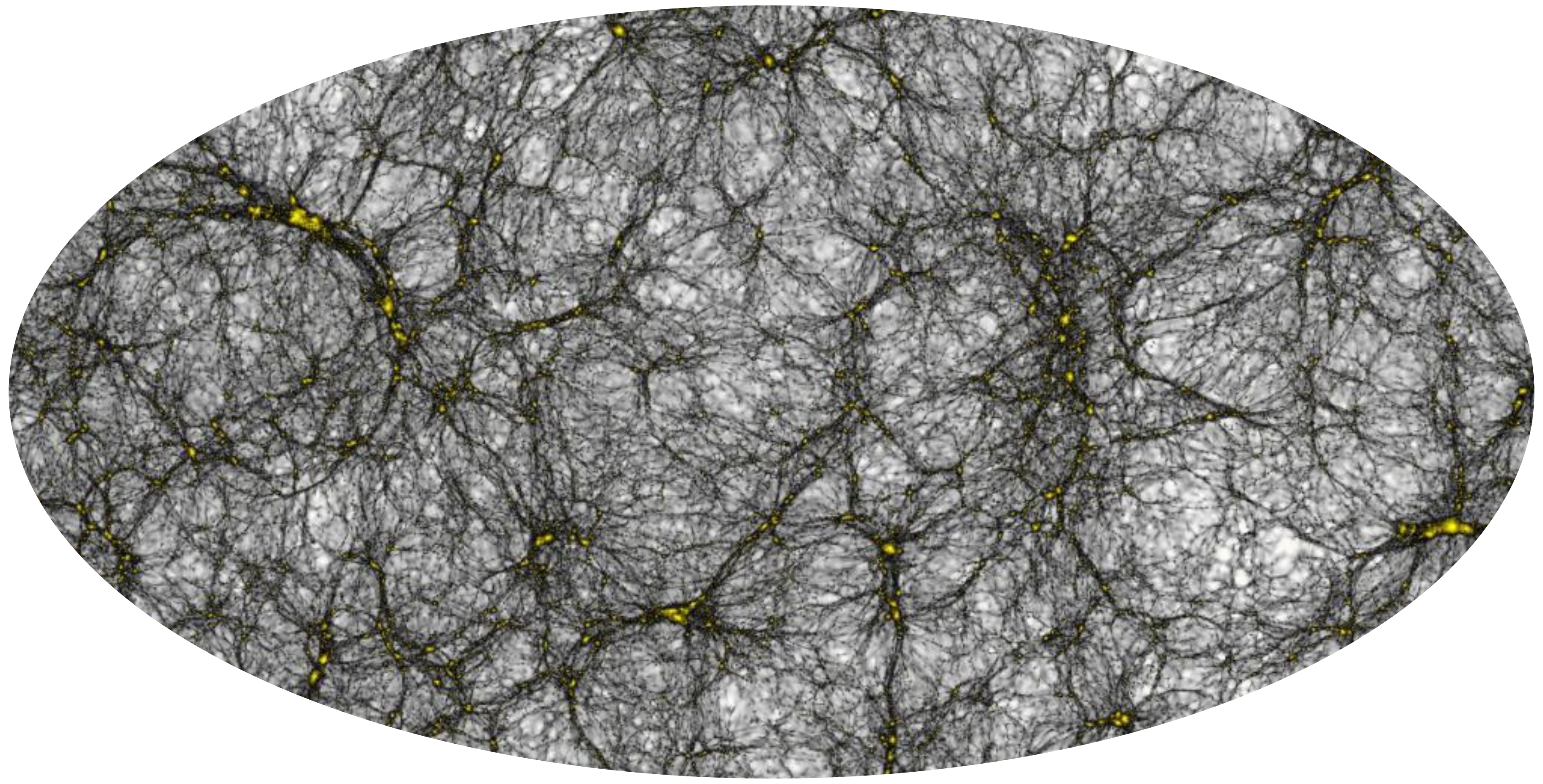
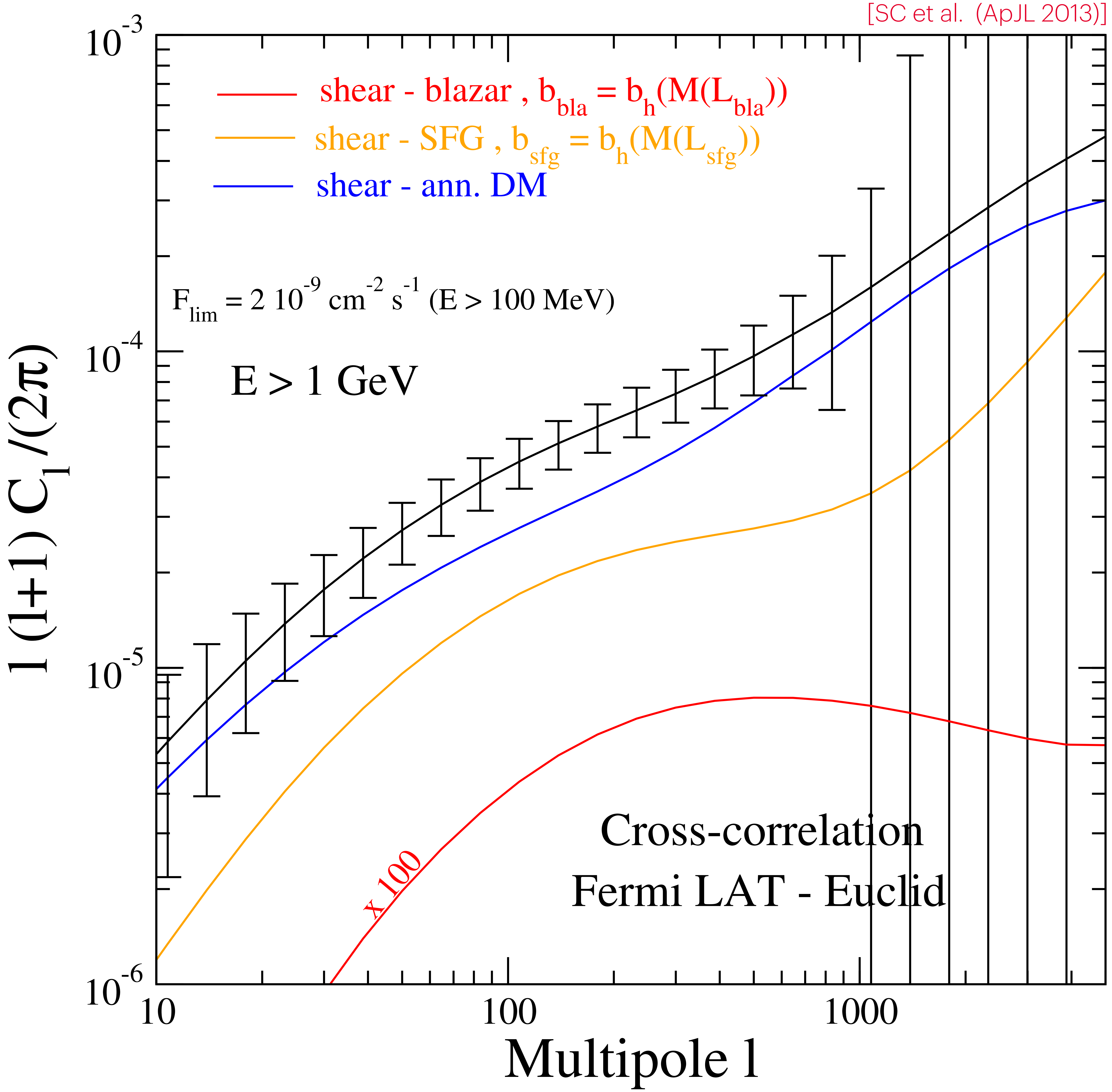


[SC et al. (ApJL 2013)]



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Dark matter indirect searches

- *Bounds* from non-detections:

  - Clustering of galaxies [SDSS LRGs] × UGRB [Fermi (76 mth)]
    [Shirasaki et al. 2015]
  - Cosmic shear [CFHTLenS+RCSLenS] × UGRB [Fermi (76 mth, 85 mth)]
    [Shirasaki et al. 2014, 2016]
  - Cosmic shear [Subaru HSC] × UGRB [P8 (85 mth)]
    [Shirasaki et al. 2018]
  - Cosmic shear [CFHTLenS+RCSLenS+KiDS] × UGRB [Fermi P8 (84 mth)]
    [Tröster, SC et al. 2017]

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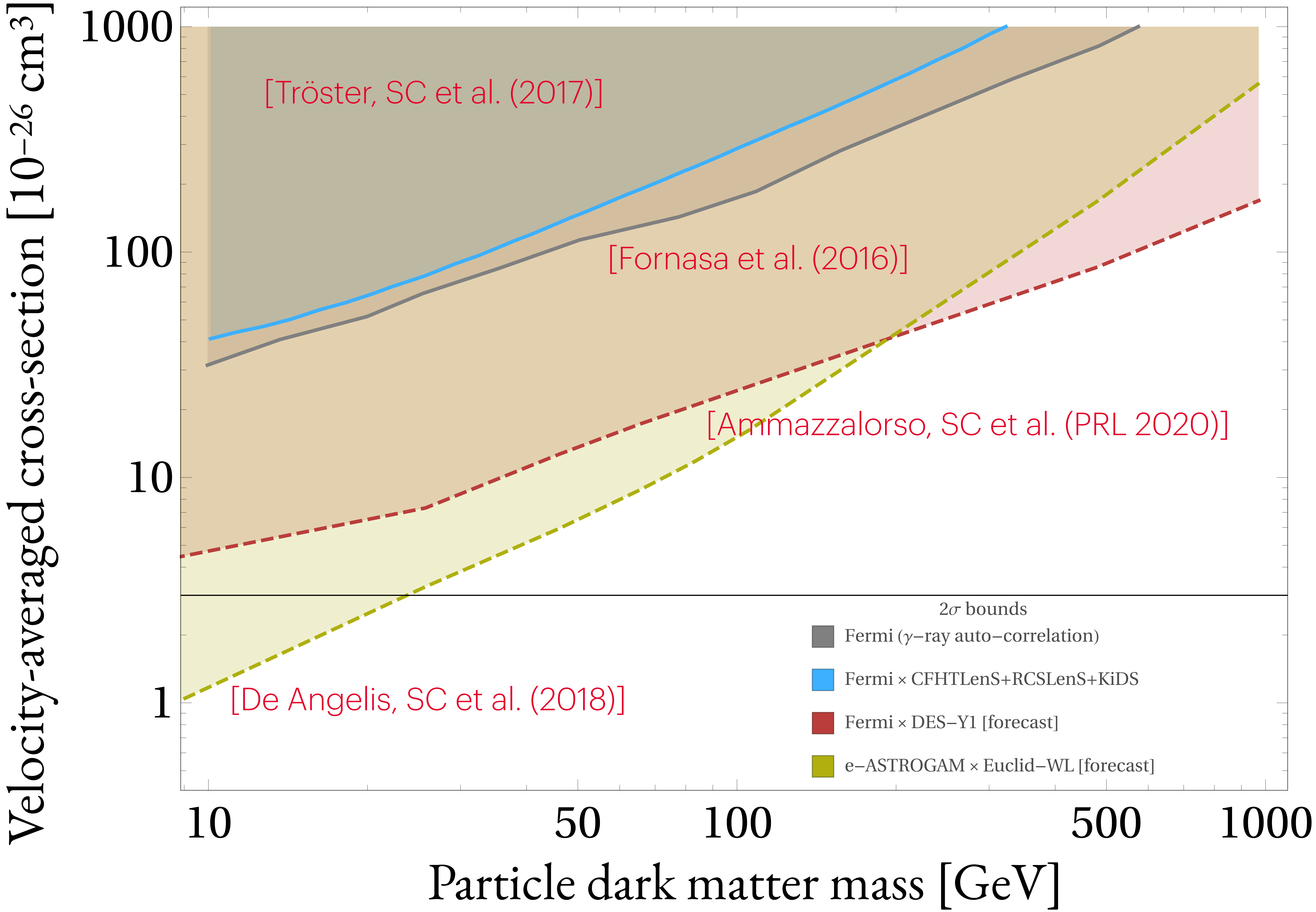
Dark matter indirect searches



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Dark matter indirect searches

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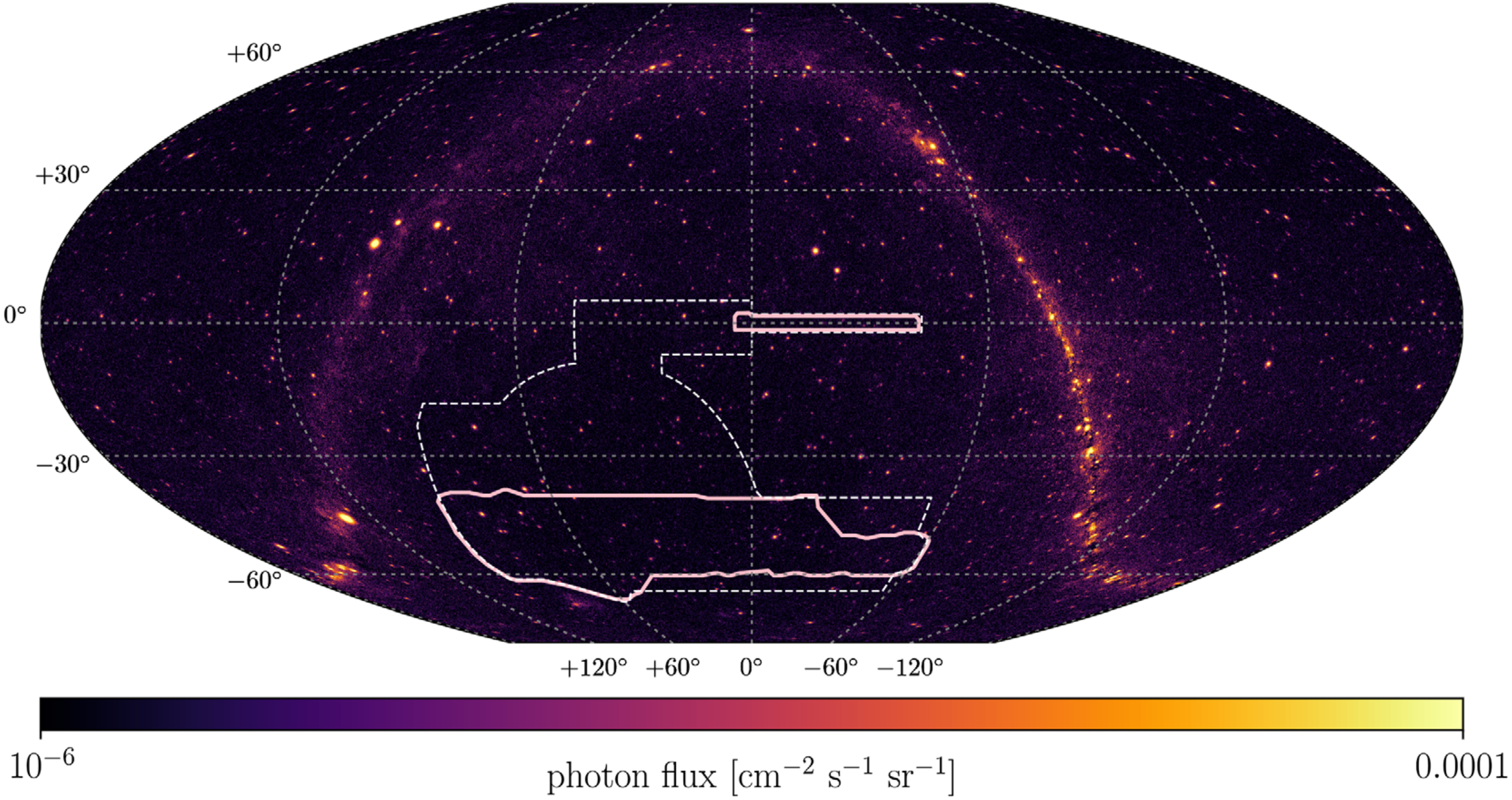
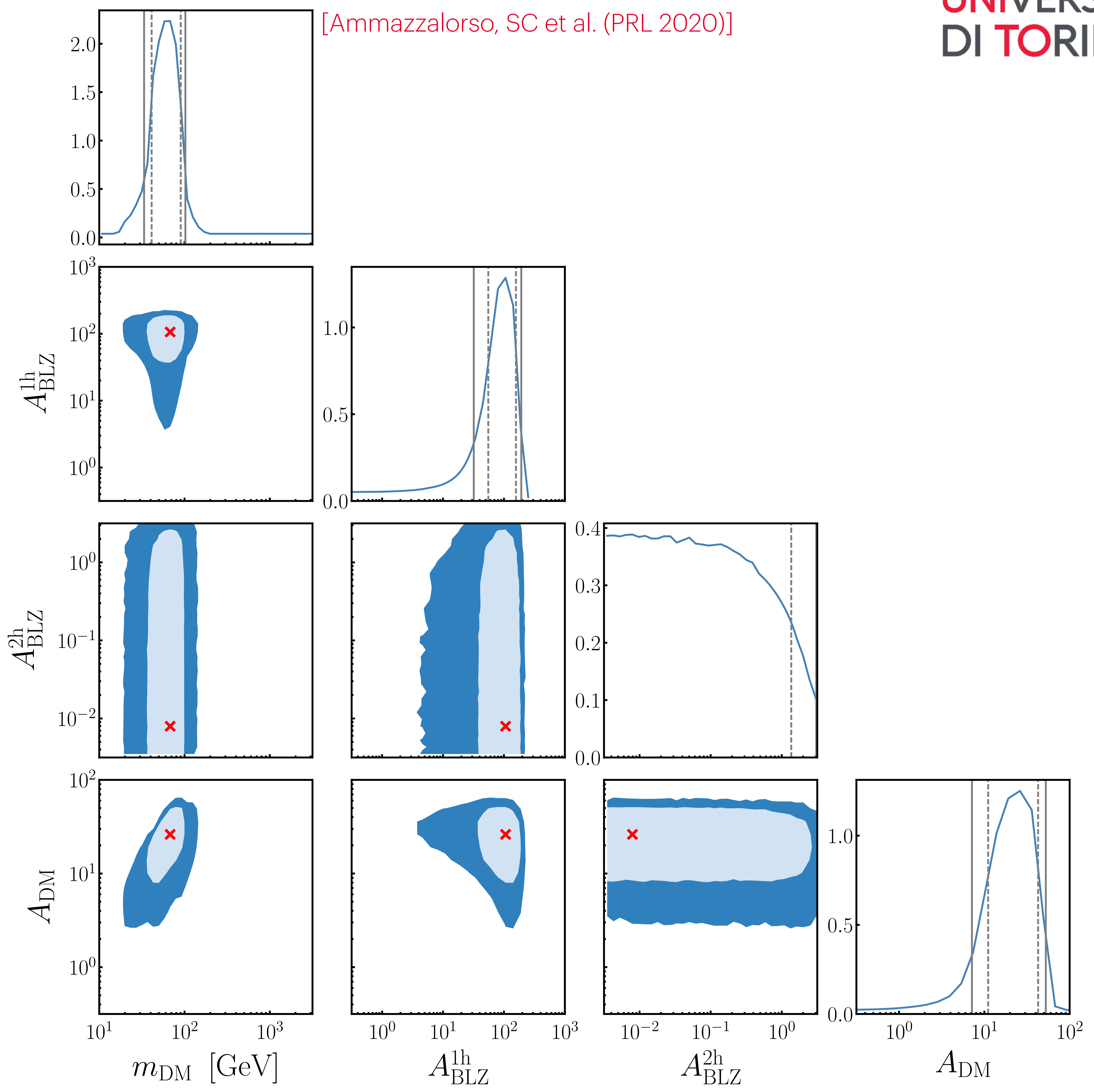
[Ammazzalorso, SC et al. (PRL 2020)]



Dark matter indirect searches

- Bounds from detection (@5.3σ)
  - Cosmic shear [DES Y1]
  - UGRB [Fermi (9 yr)]



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

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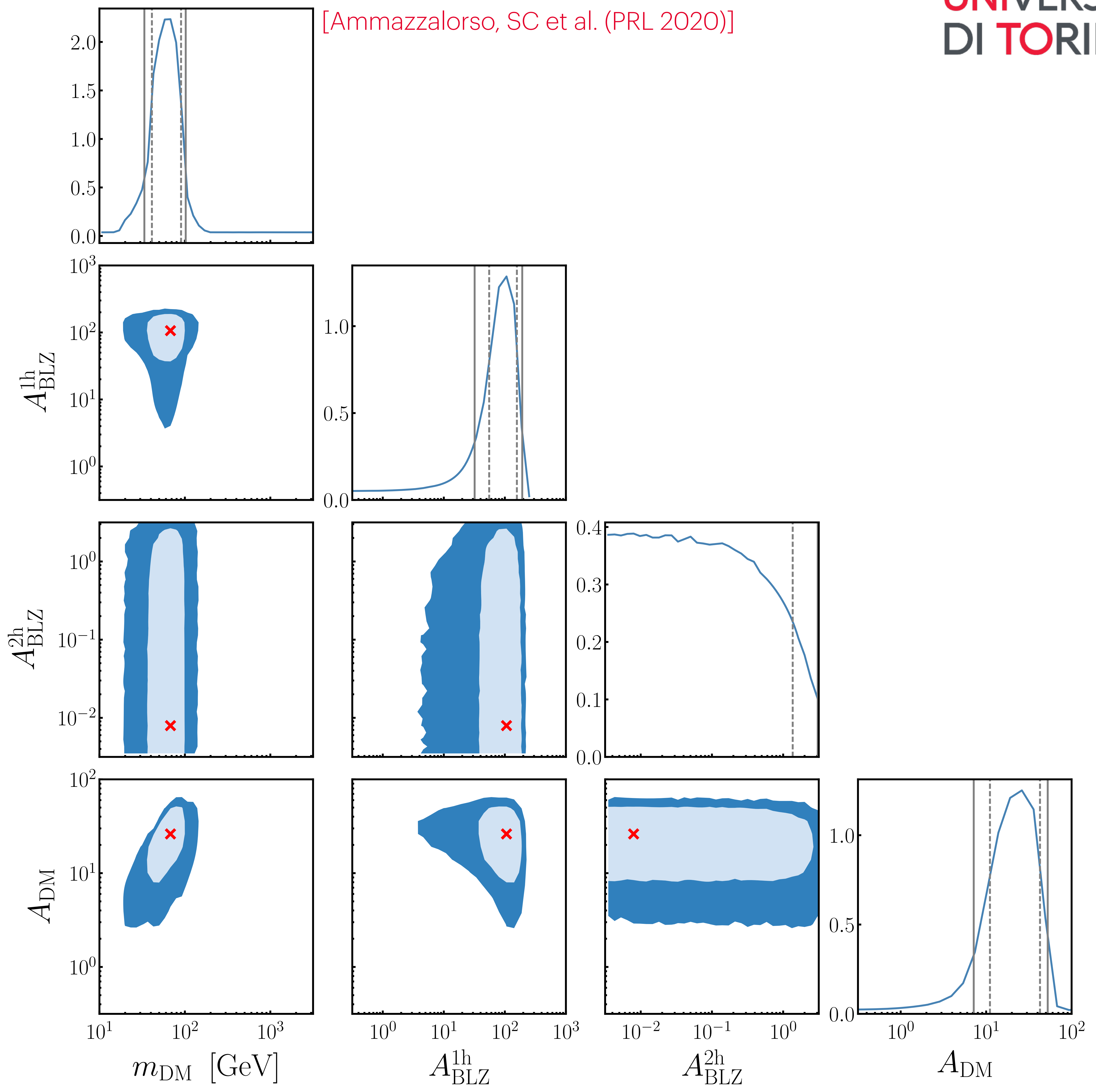
Dark matter indirect searches

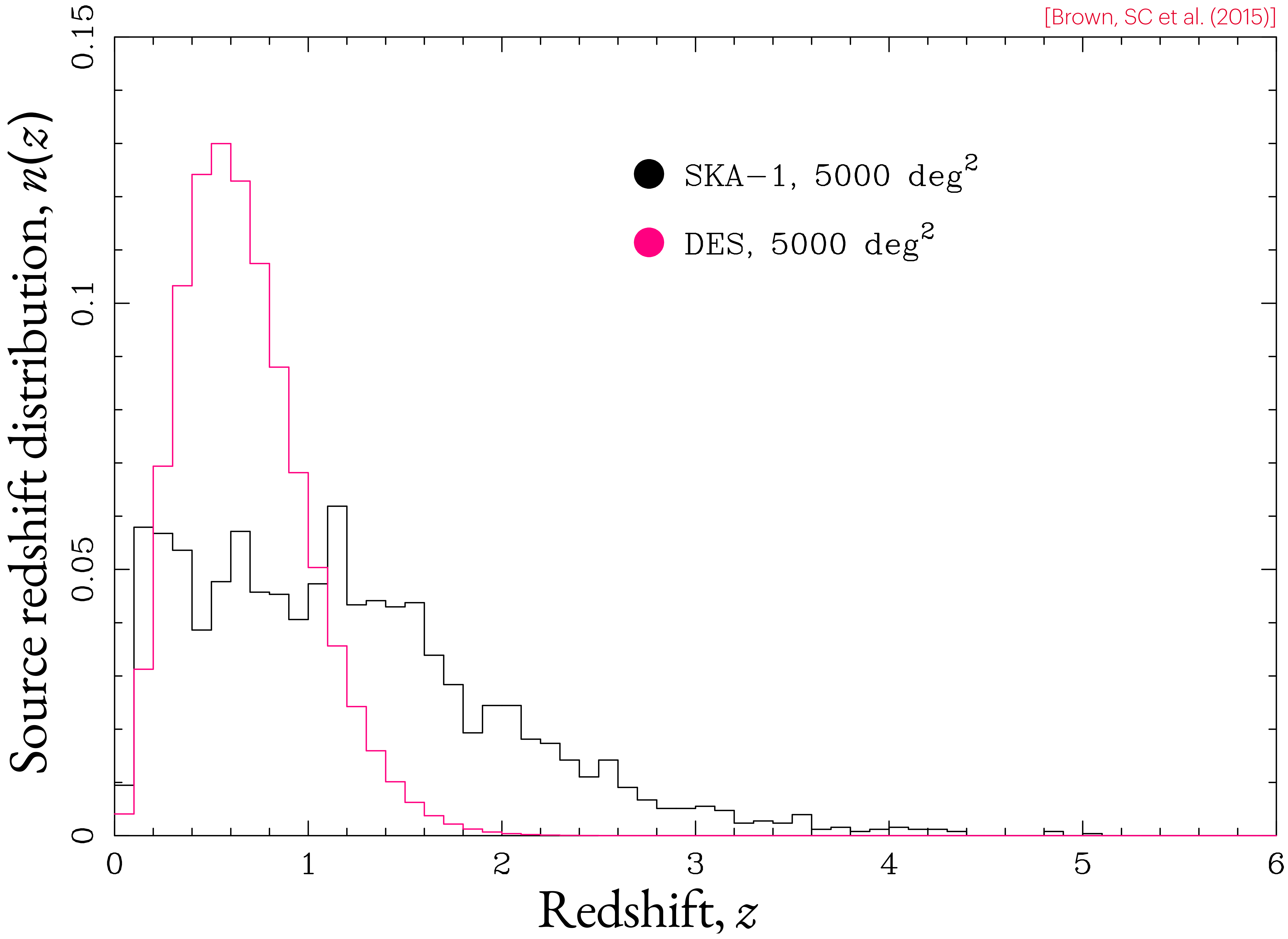
- Bounds from detection (@5.3σ)
  - Cosmic shear [DES Y1]
  - UGRB [Fermi (9 yr)]
- Bounds from detection (@??σ)
  [Thakore et al. ⊃ SC (internal review)]
  - Cosmic shear [DES Y3]
  - UGRB [Fermi (12 yr)]

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



Radio-optical cosmic shear

[Brown, SC et al. (2015)]



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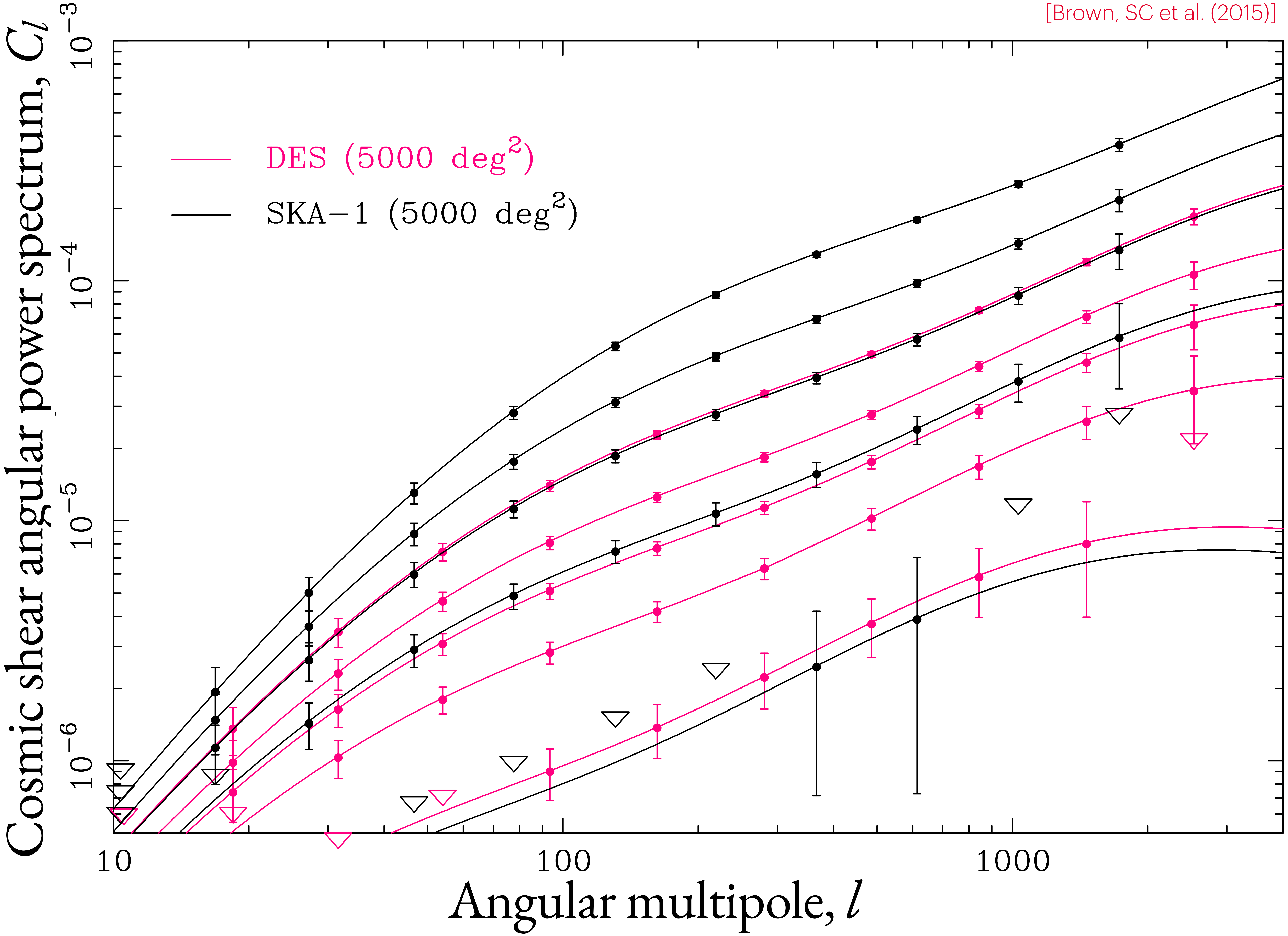
[Brown, SC et al. (2015)]



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Radio-optical cosmic shear

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

Radio-optical cosmic shear

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

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

Radio-optical cosmic shear

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

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

Radio-optical cosmic shear

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

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

Radio-optical cosmic shear

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Radio-optical cosmic shear

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

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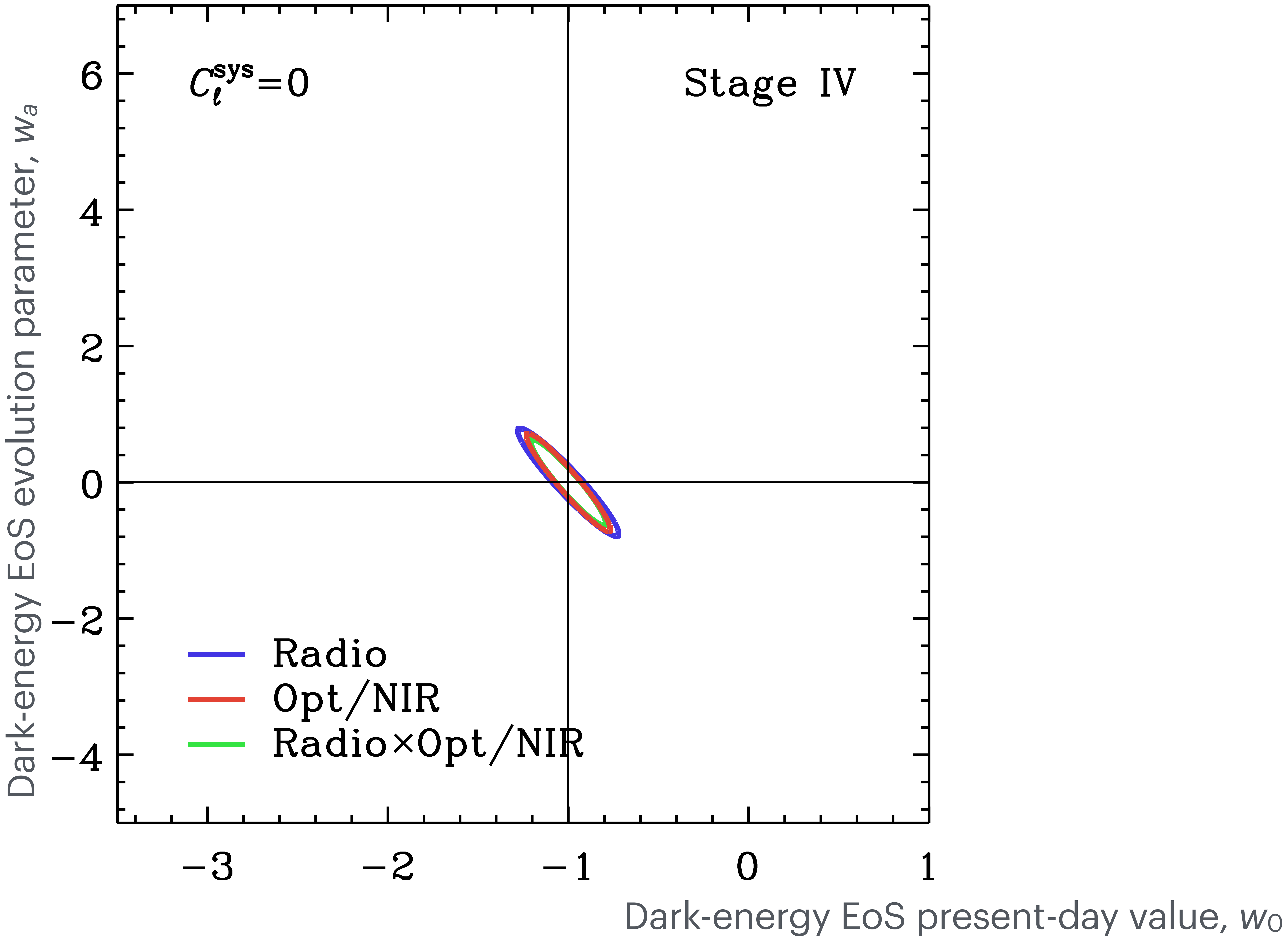

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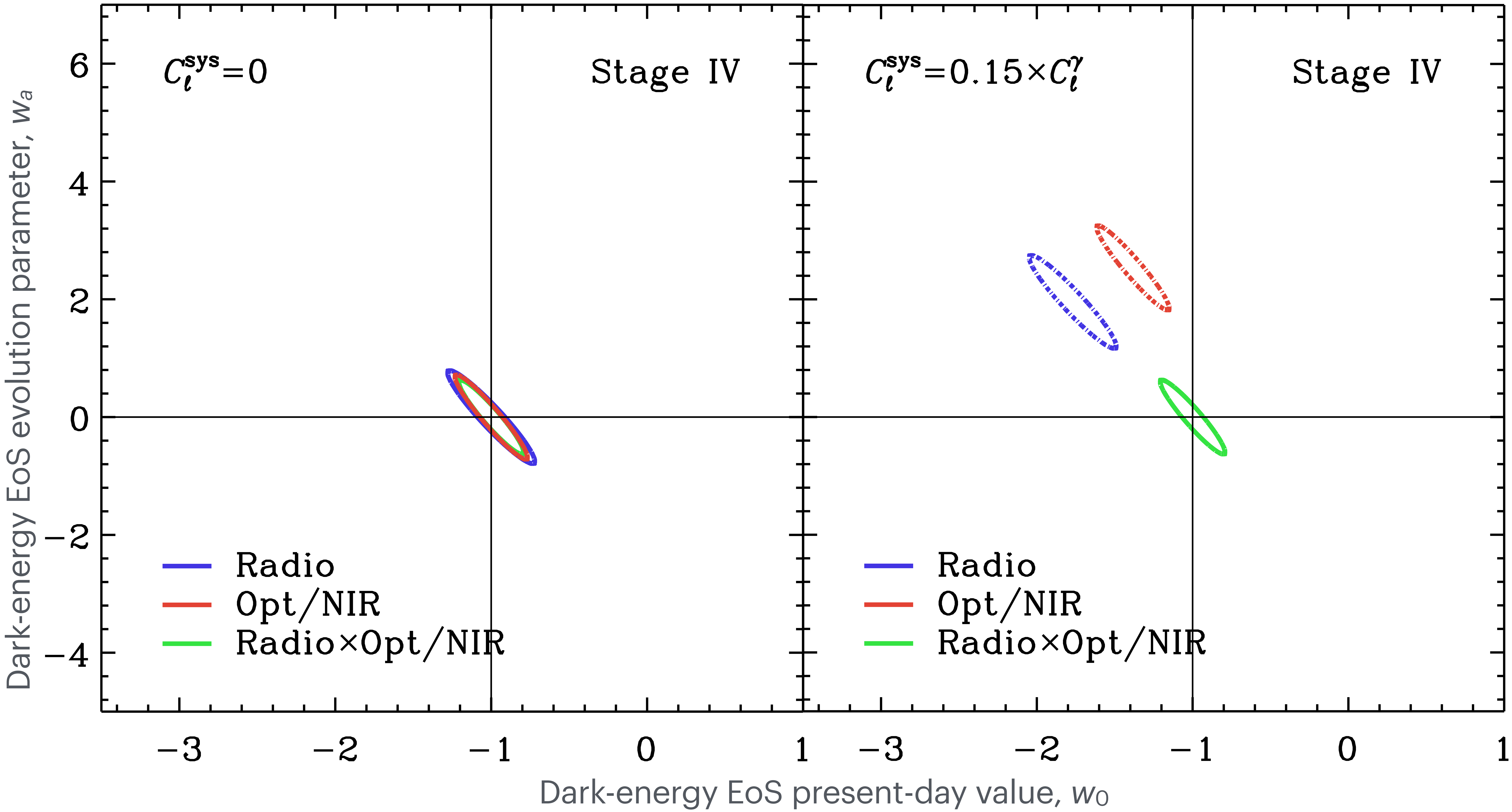

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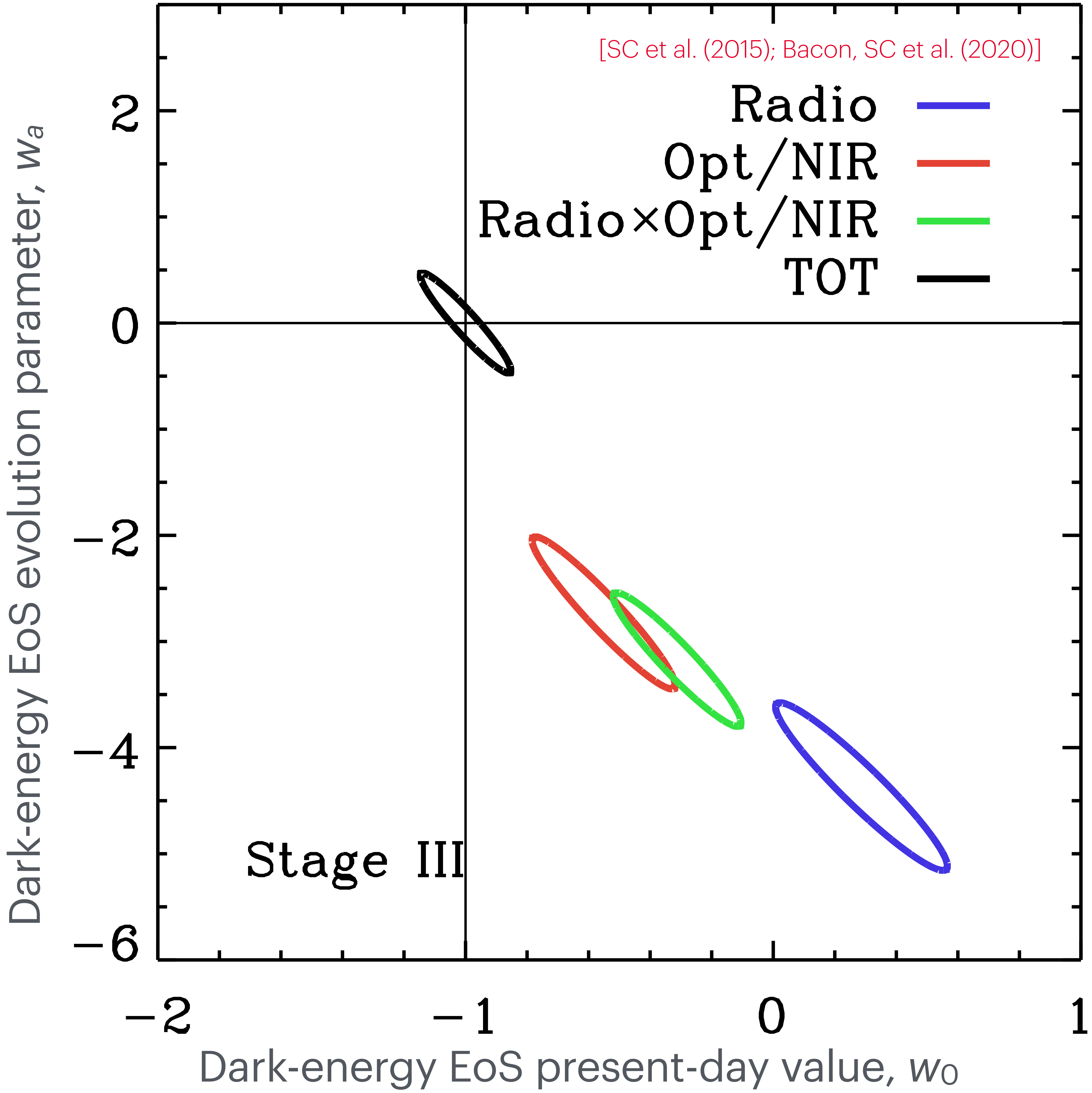
Radio-optical cosmic shear



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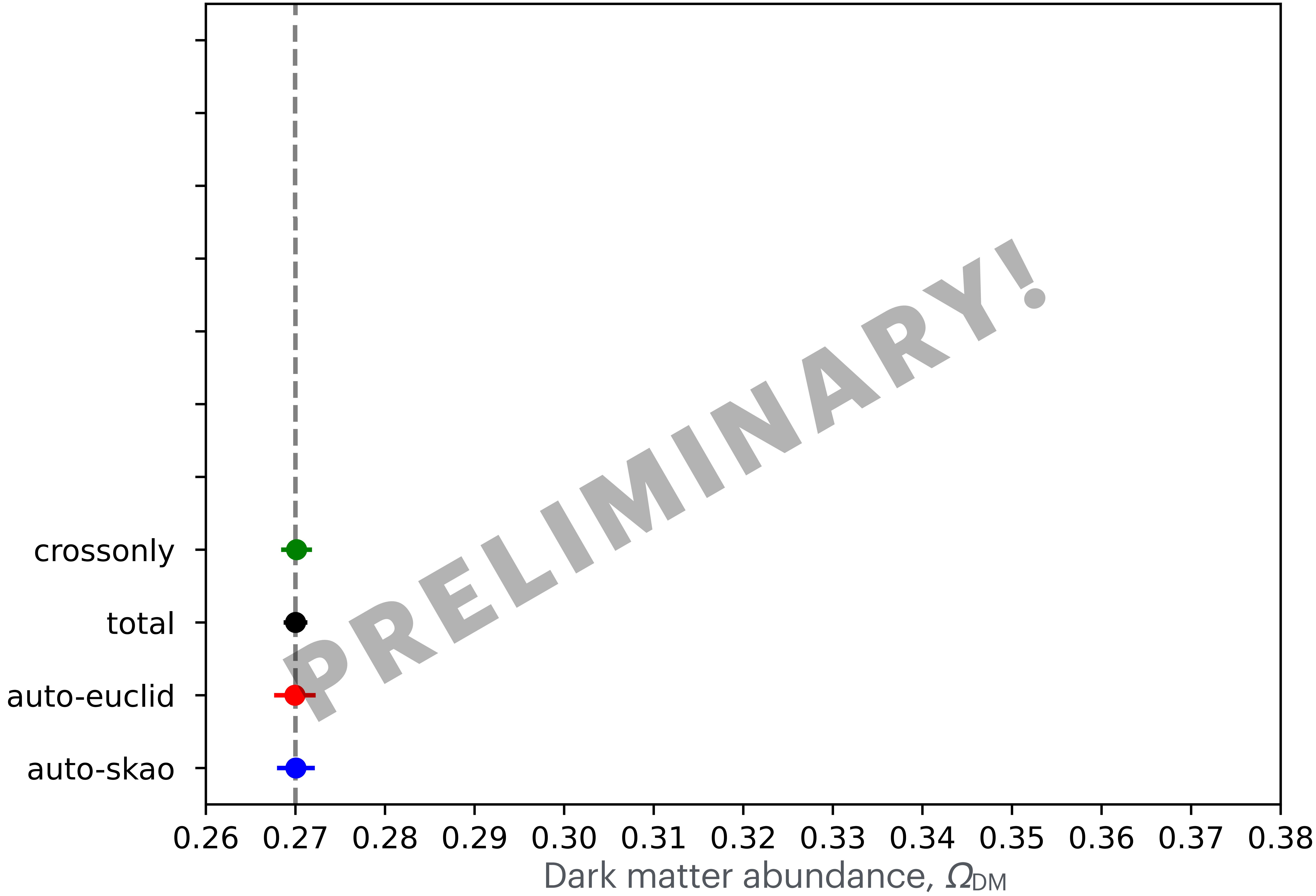
Radio-optical cosmic shear

[Ingrao, SC et al. (in prep.)]



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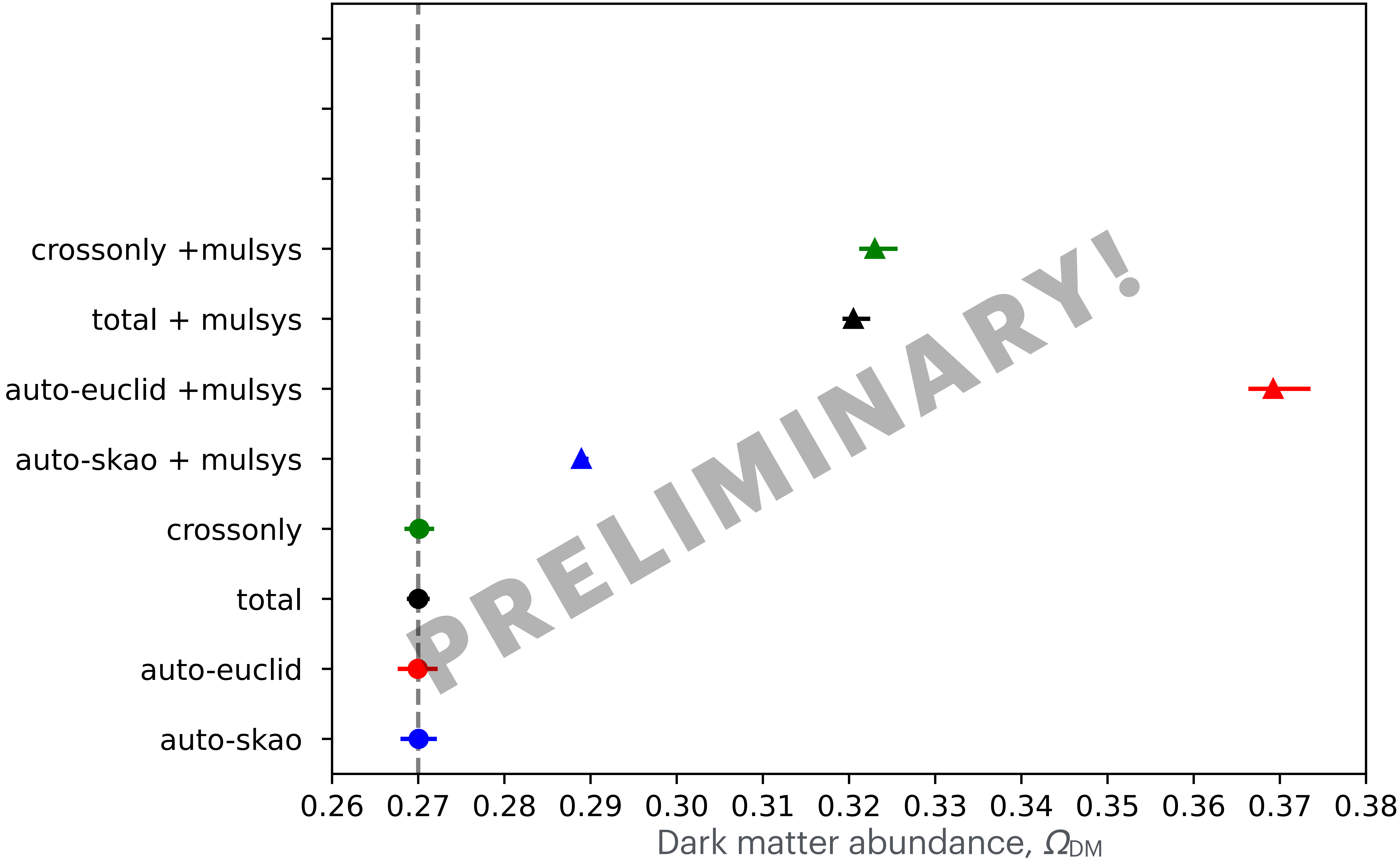

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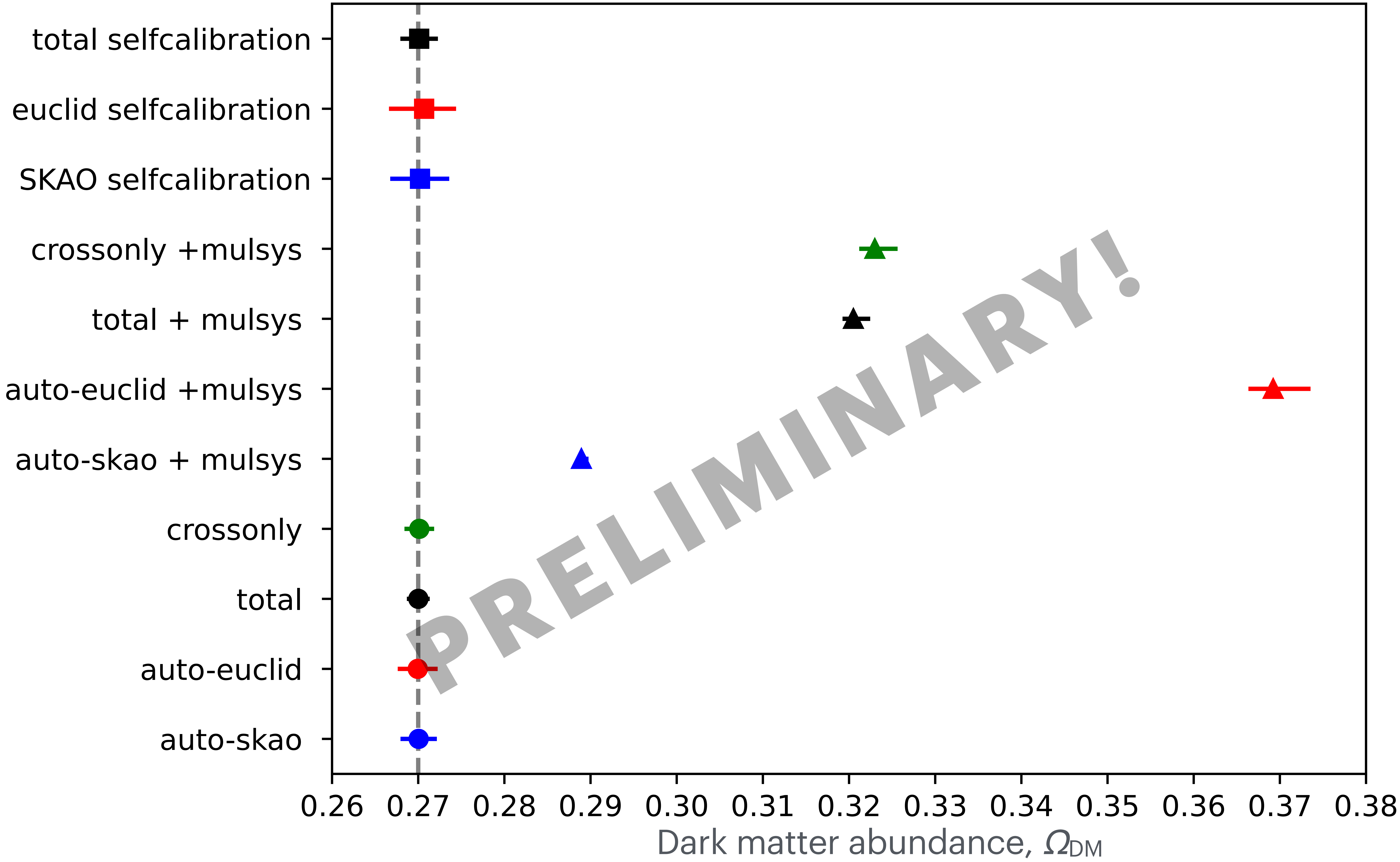

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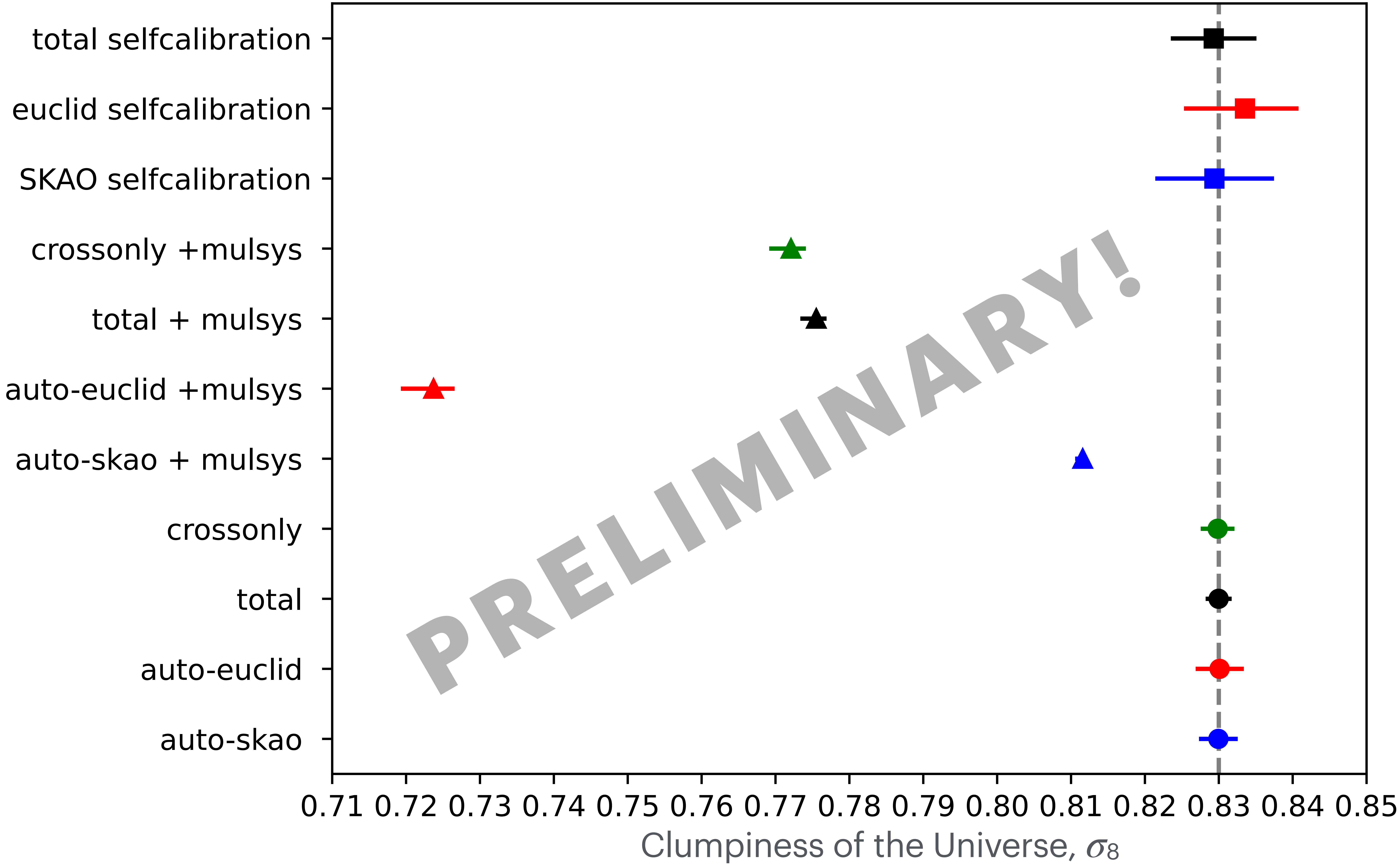

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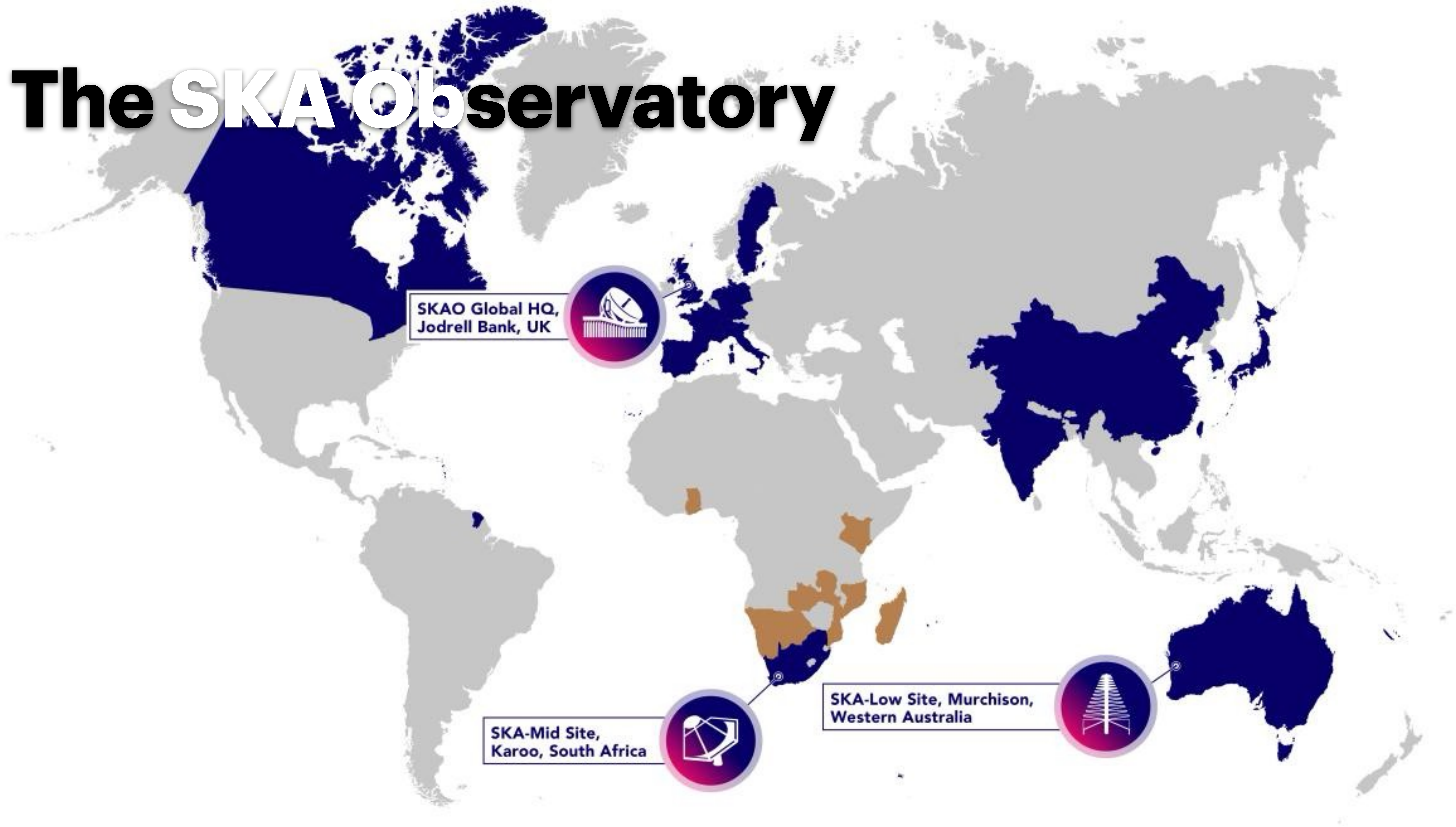
The SKA Observatory



SKAO Partnership - includes SKAO Member States* and SKAO Observers (as of June 2022)

African Partner Countries

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The SKA Observatory

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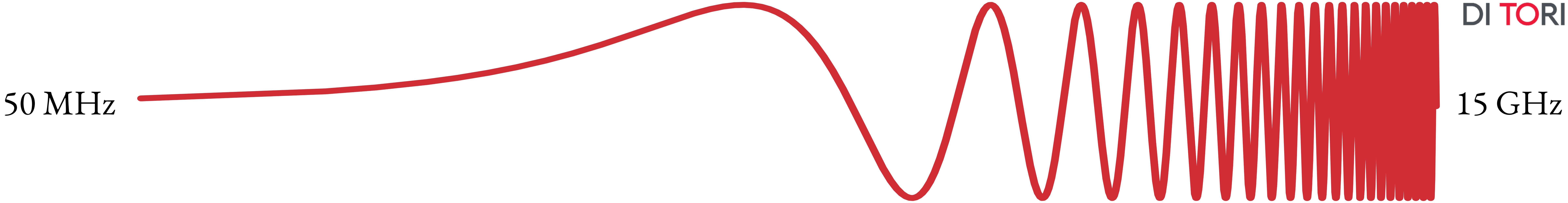
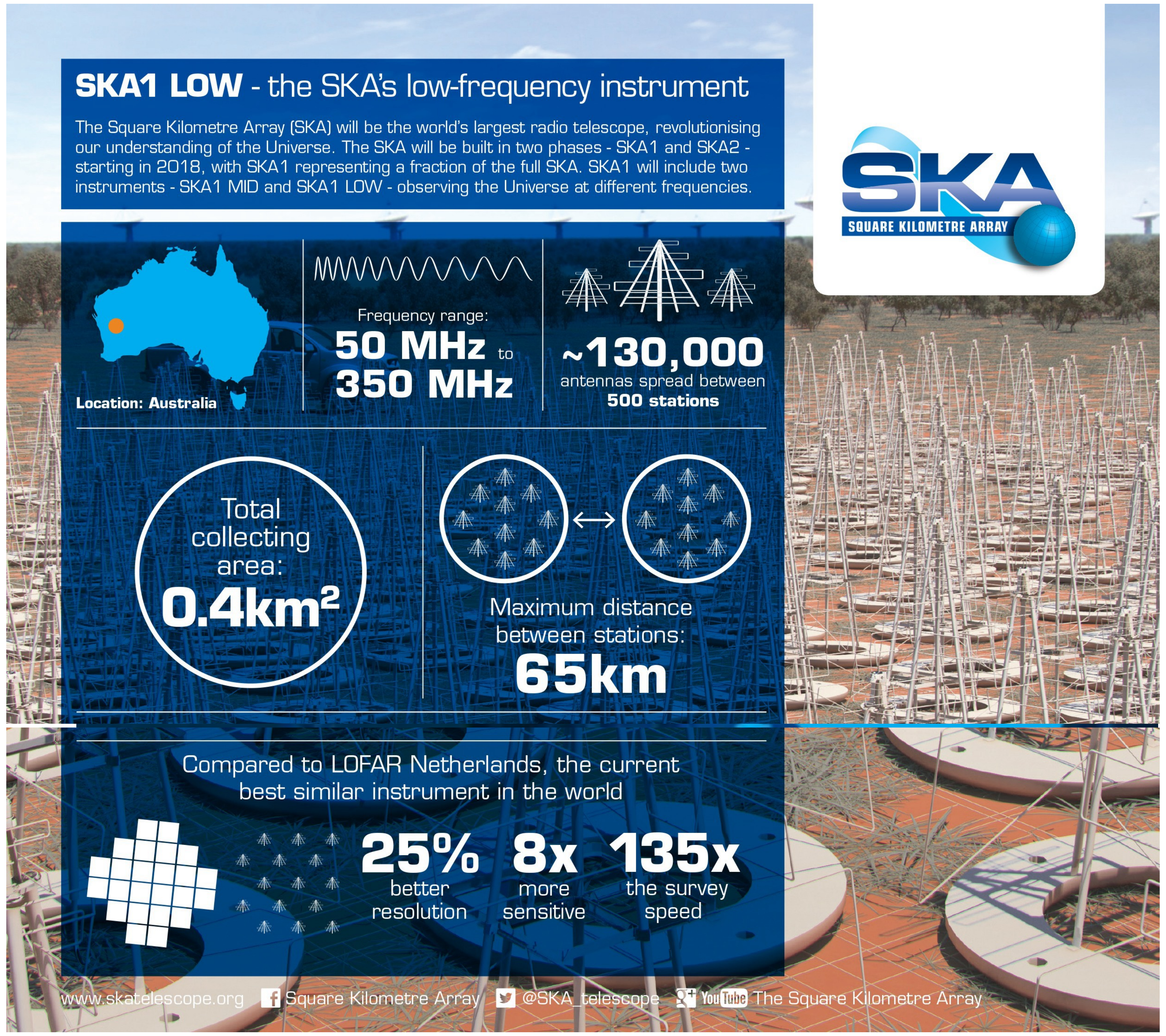
- The SKA Observatory (formerly known as 'Square Kilometre Array') will be the largest radio-telescope on Earth and will be built in two locations

The SKA Observatory

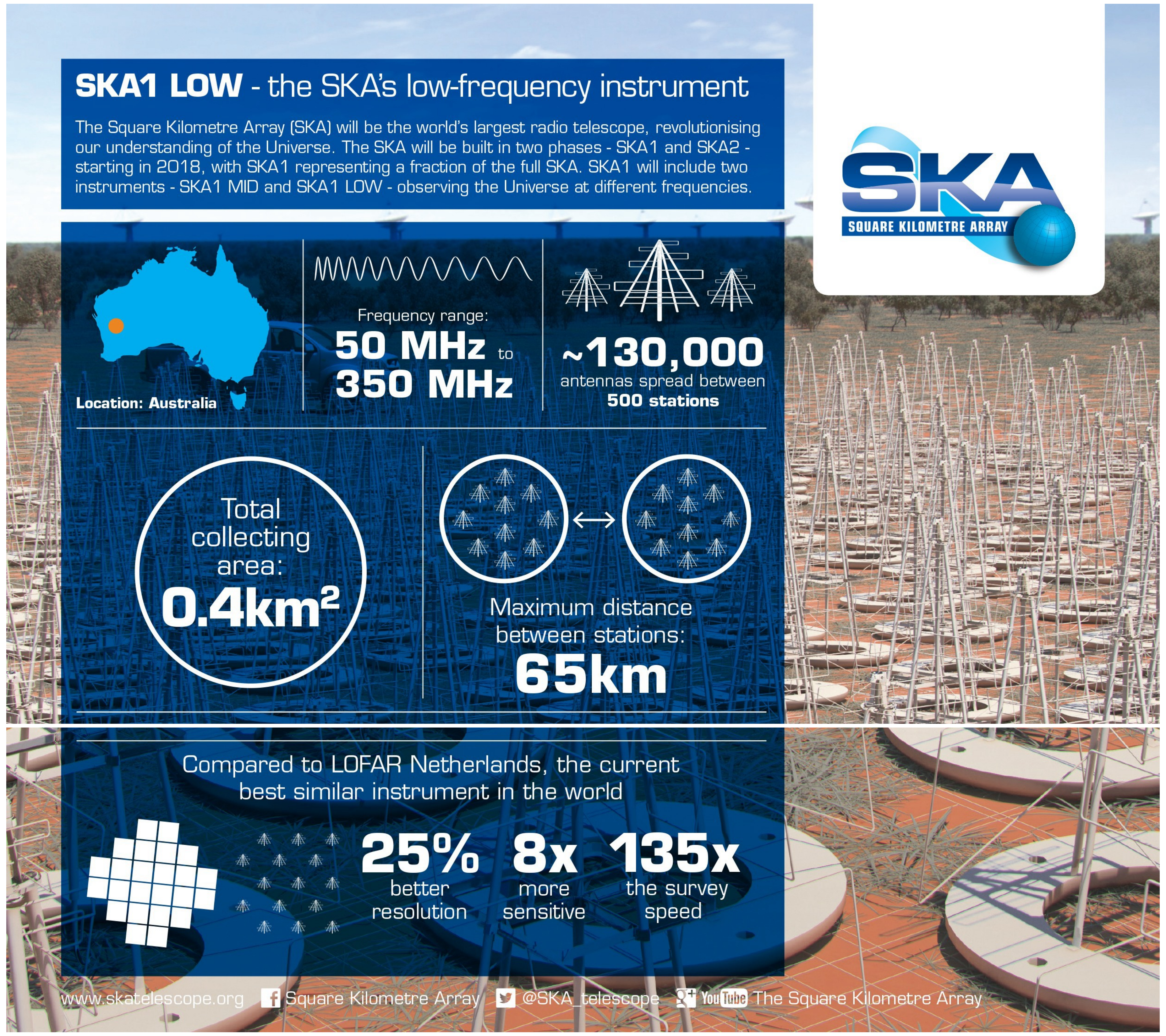


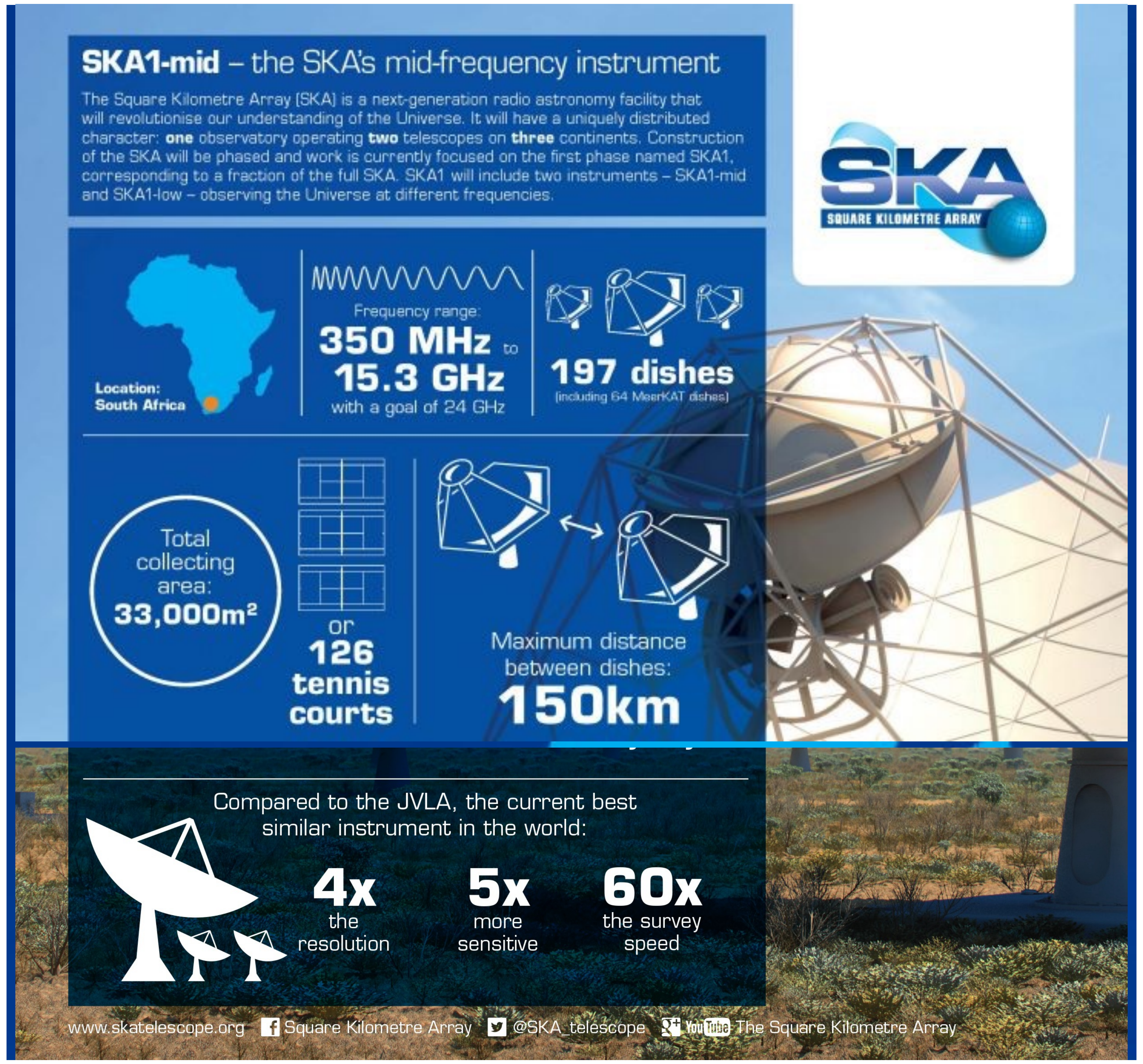


The SKA Observatory

50 MHz

15 GHz





Towards the SKAO

[Courtesy of A. Bonaldi]

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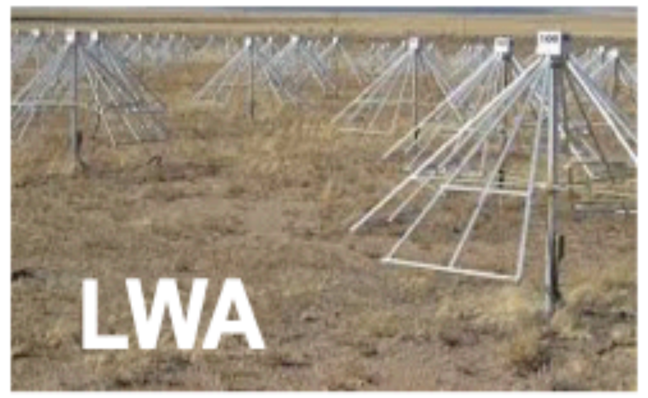
Precursors

Located at future SKA sites (South Africa and Australia)

Pathfinders

Engaged in SKA related technology and science studies



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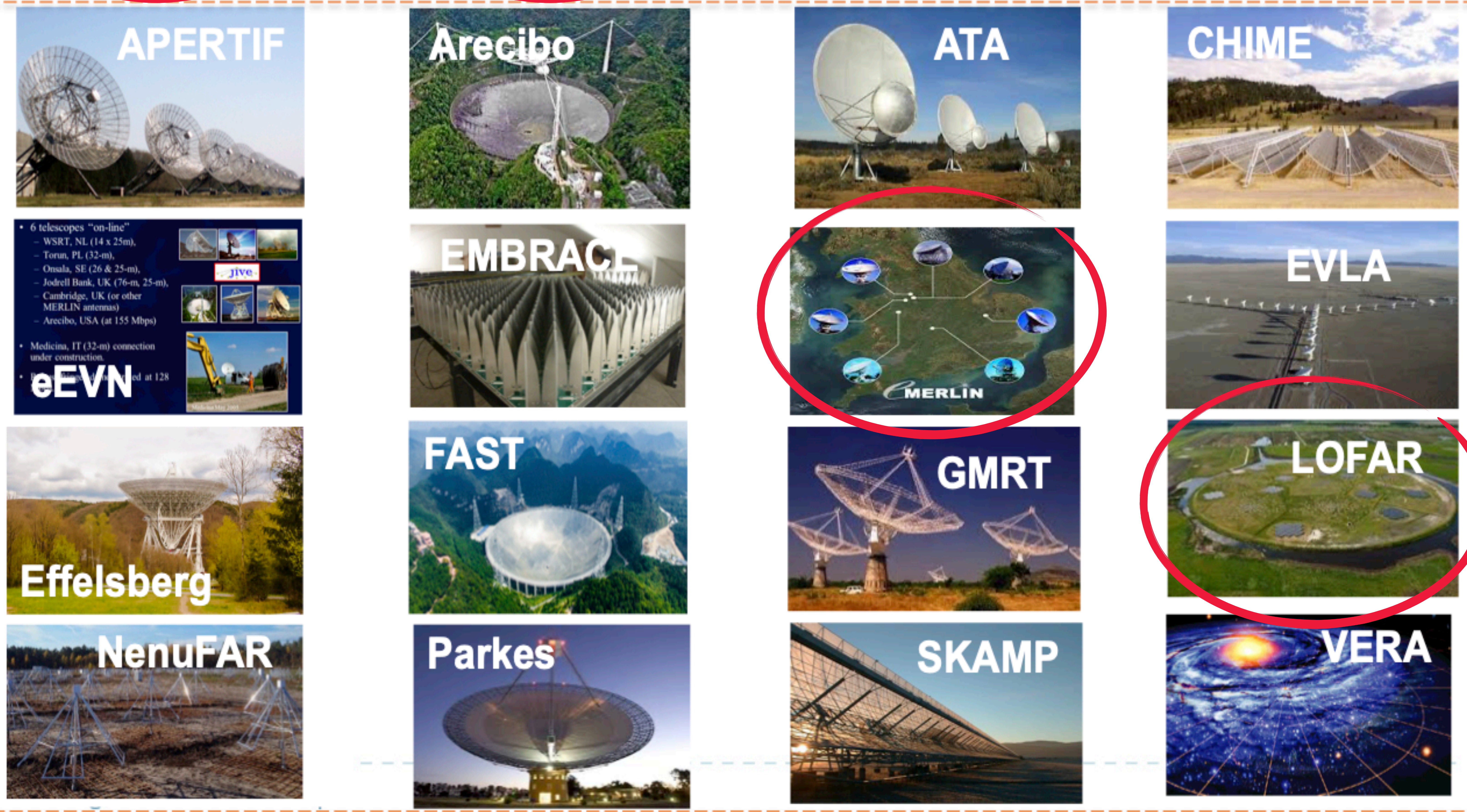

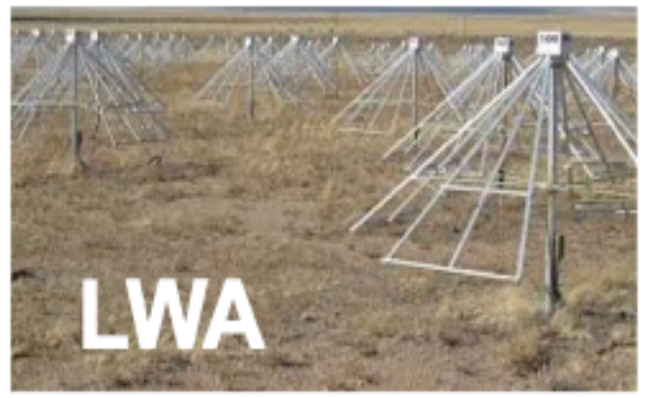

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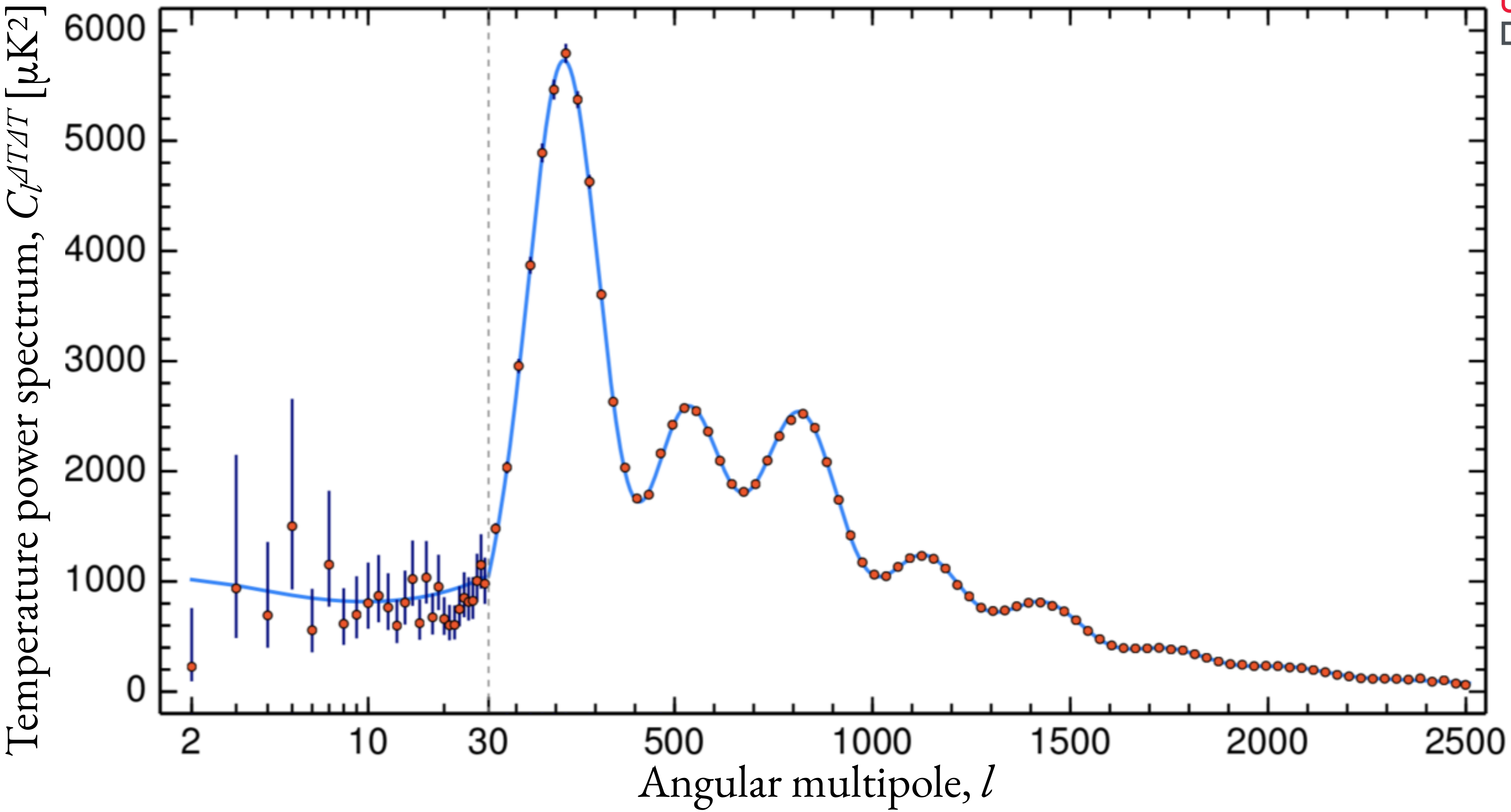
Correlators

- Cosmological perturbation $f(t, \boldsymbol{x})$
  [temperature fluctuations, density perturbations, …]
- Two-point correlation function $\langle f(t, \boldsymbol{x})\, f(t, \boldsymbol{y})\rangle = \xi_{ff}(t, \boldsymbol{x} - \boldsymbol{y})$
- Fourier-space power spectrum $\langle \hat{f}(t, \boldsymbol{k})\, \hat{f}(t, \boldsymbol{k}')\rangle = (2\,\pi)^3\, \delta(\boldsymbol{k} + \boldsymbol{k}')\, P_{ff}(t, \boldsymbol{k})$
- Harmonic-space power spectrum $\langle \tilde{f}_{lm}(z)\, \tilde{f}_{l'm'}(z')\rangle = \delta_{ll'}\, \delta_{mm'}\, C_l^{ff}(z, z')$
- *Example:* harmonic-space power spectrum of cosmic microwave background

$$f(t, \boldsymbol{x}) \to \mathit{\Delta} T(\hat{\boldsymbol{n}}) = T(t_0, \hat{\boldsymbol{n}}) - \bar{T}(t_0)$$

Correlators

[Planck Collaboration 2018]



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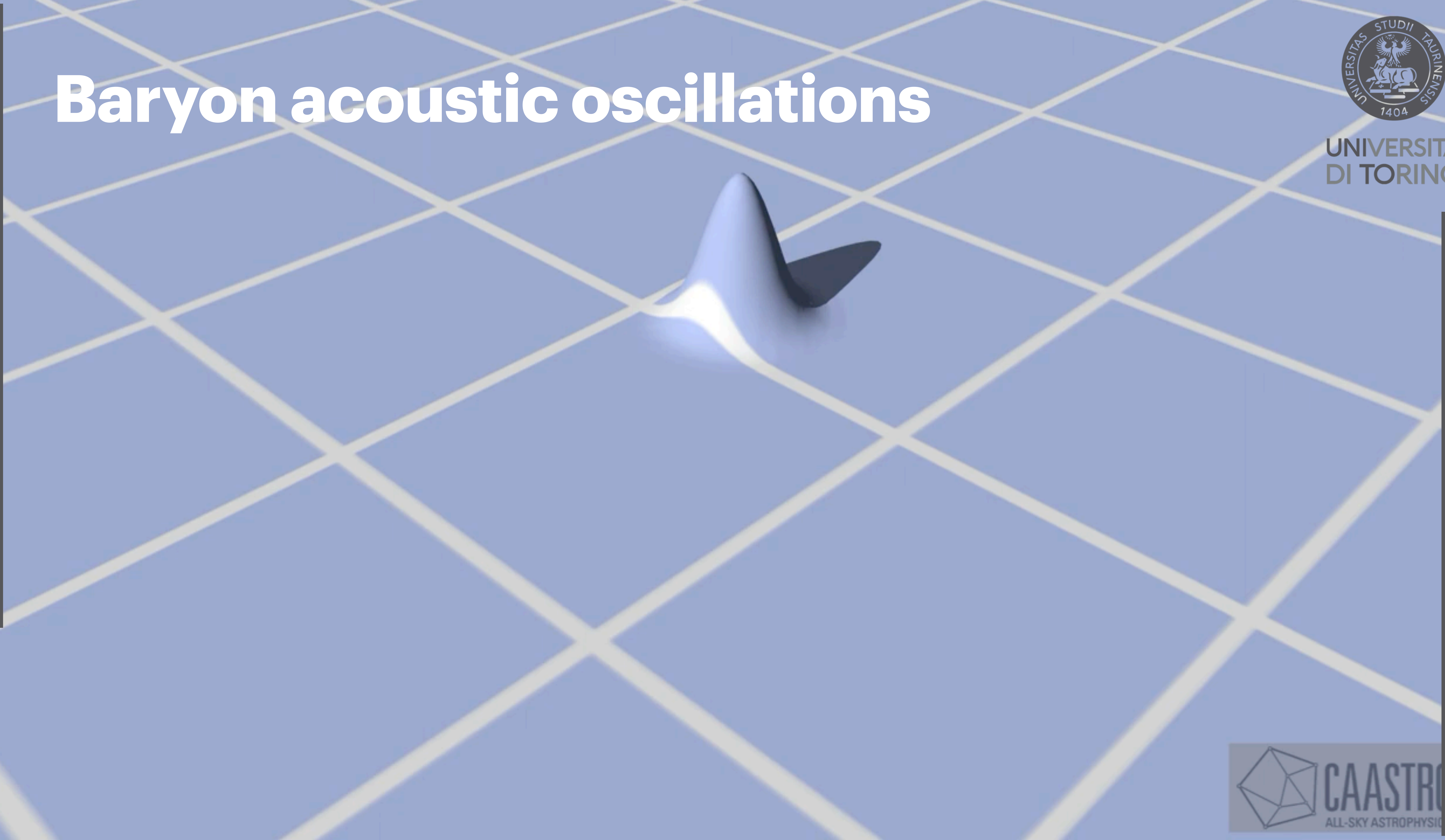
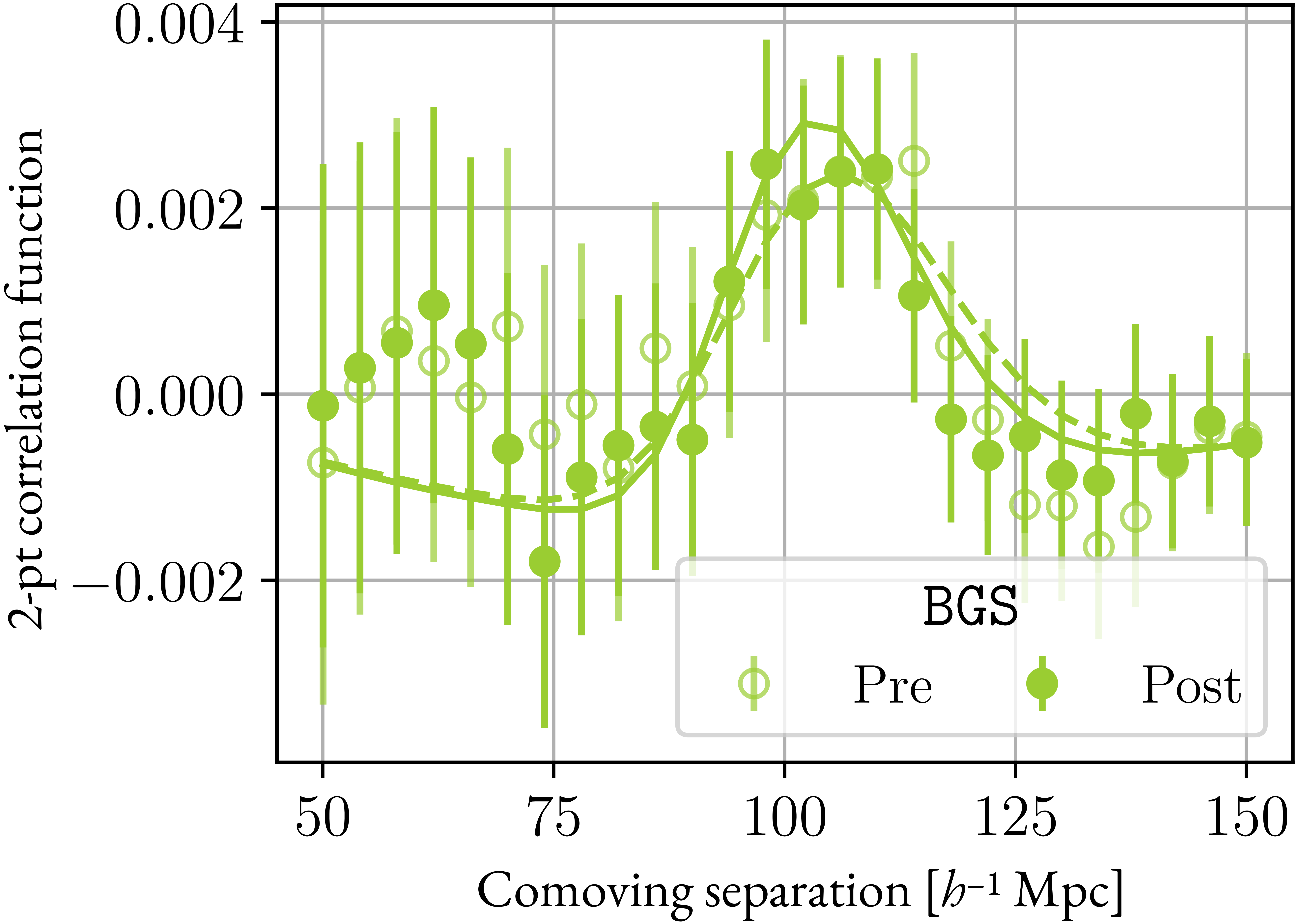
Baryon acoustic oscillations



Baryon acoustic oscillations

[DESI Collaboration 2024]



Baryon acoustic oscillations

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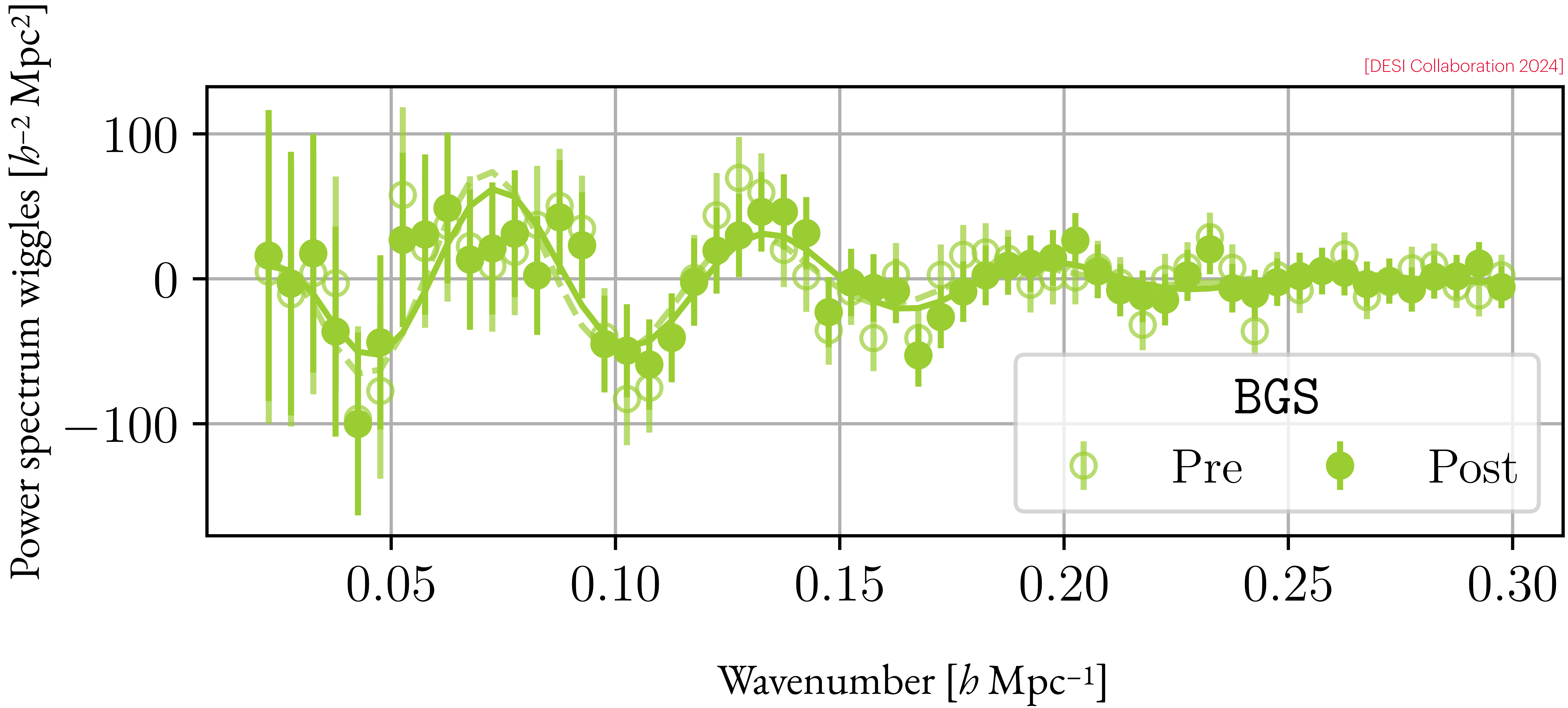
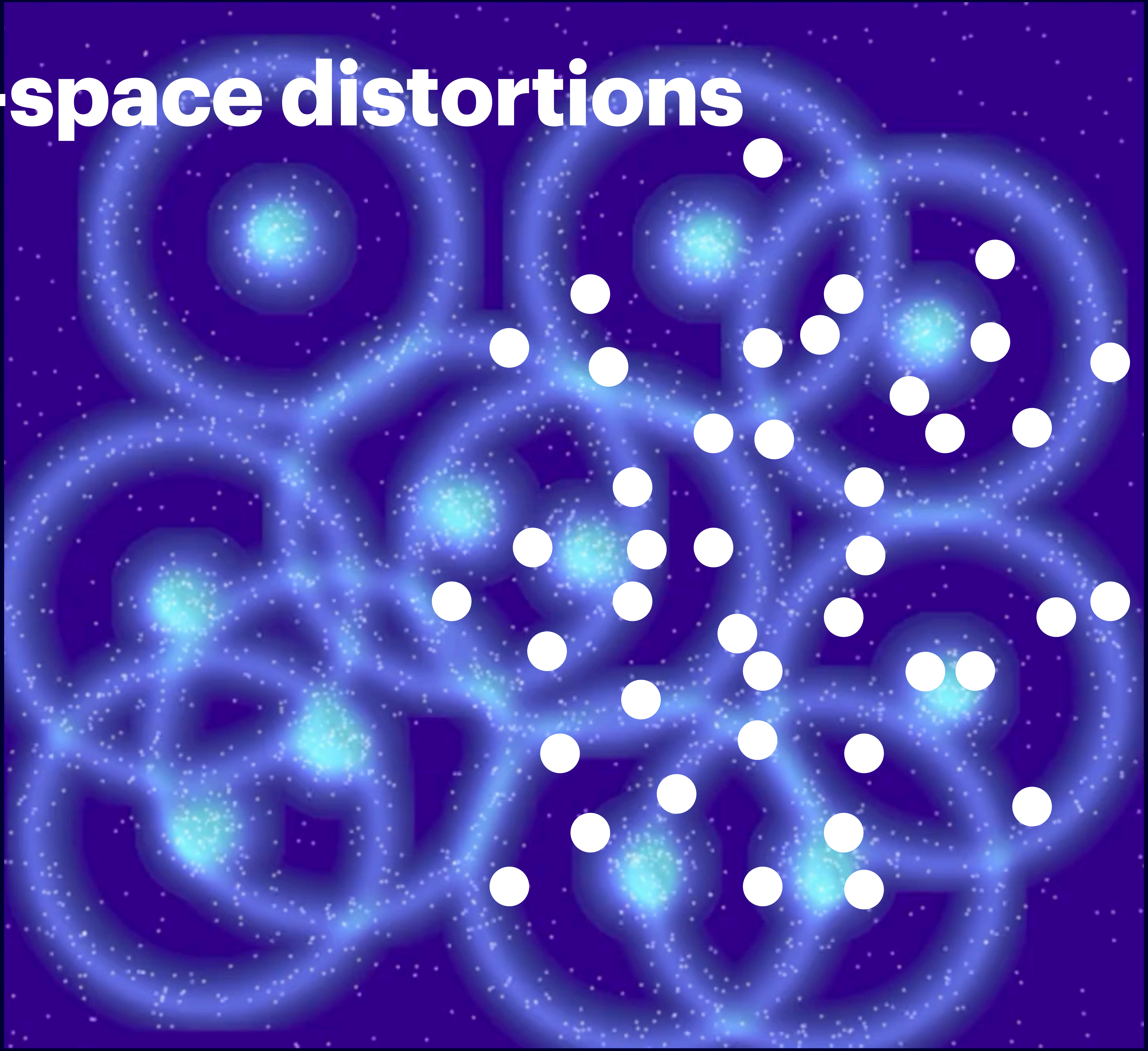
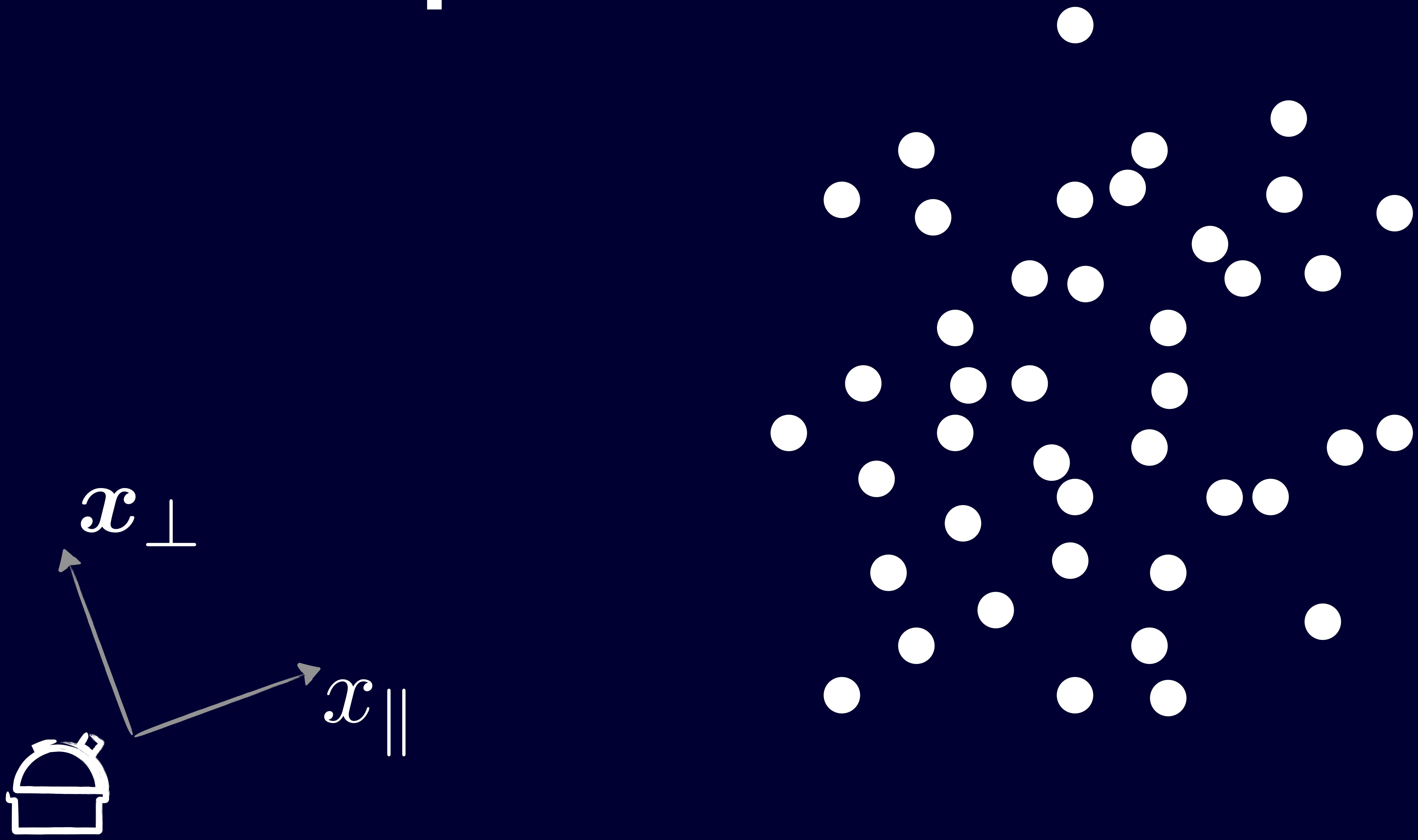
[DESI Collaboration 2024]



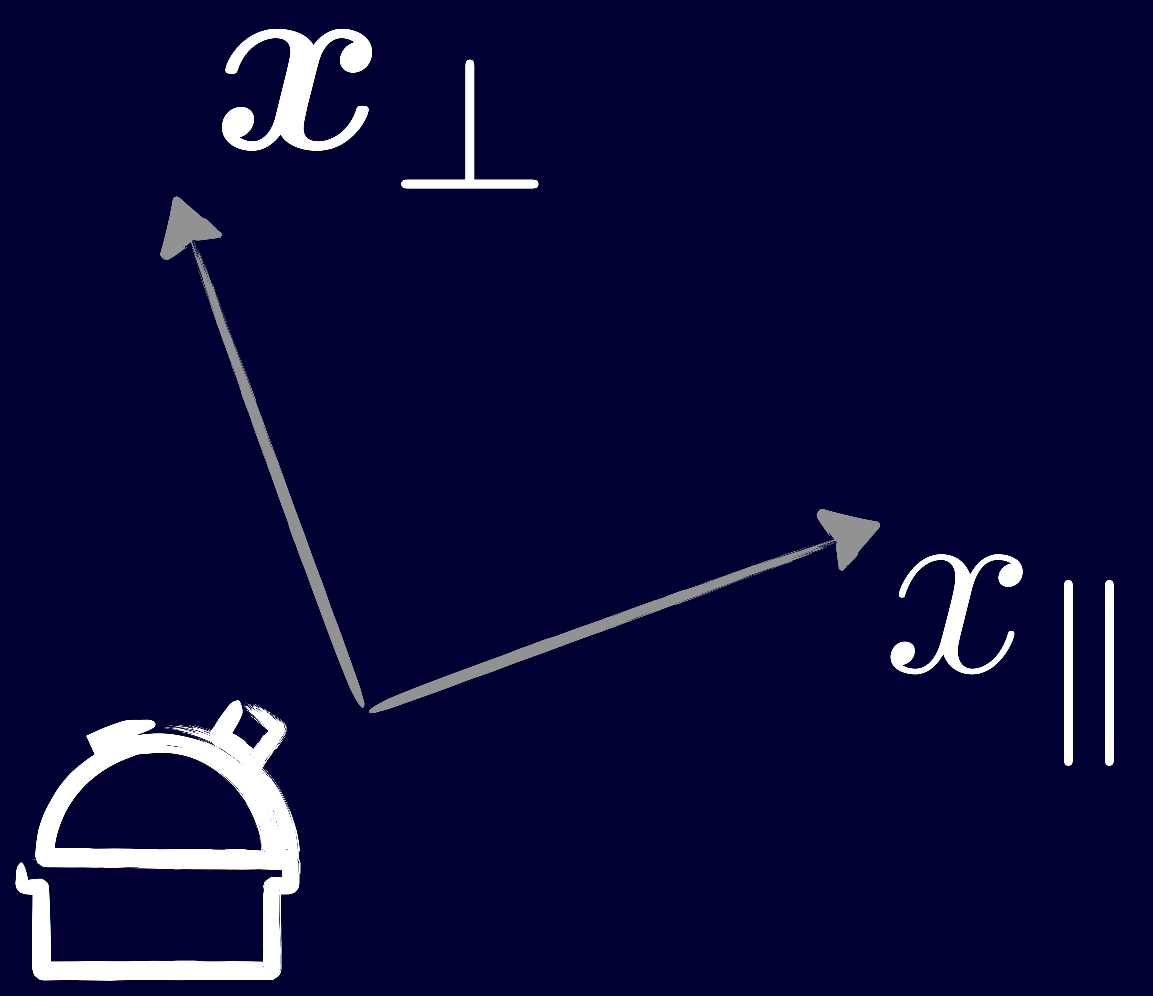
Redshift-space distortions

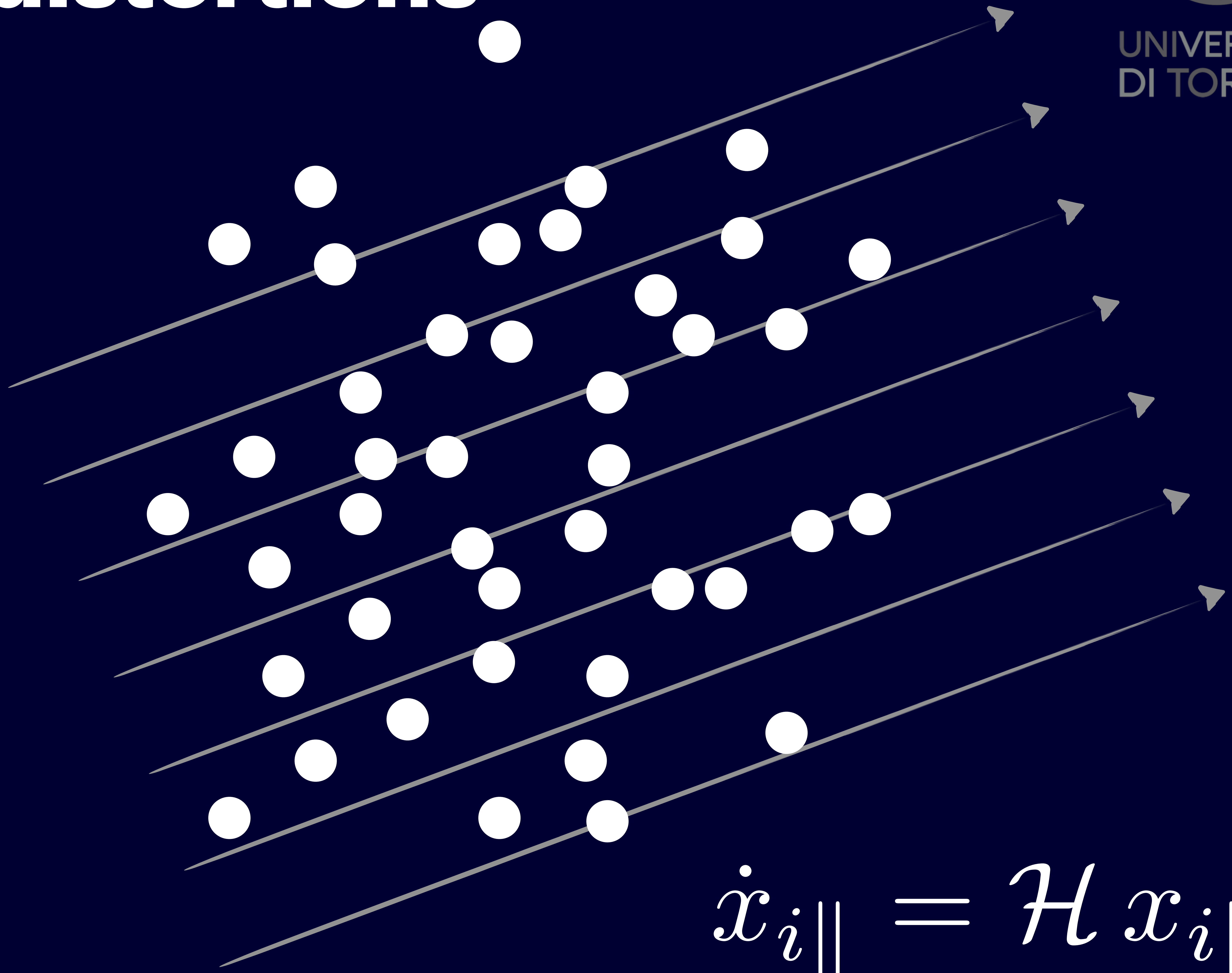


Redshift-space distortions



Redshift-space distortions





$$\dot{x}_{i\parallel} = \mathcal{H}\, x_{i\parallel}$$

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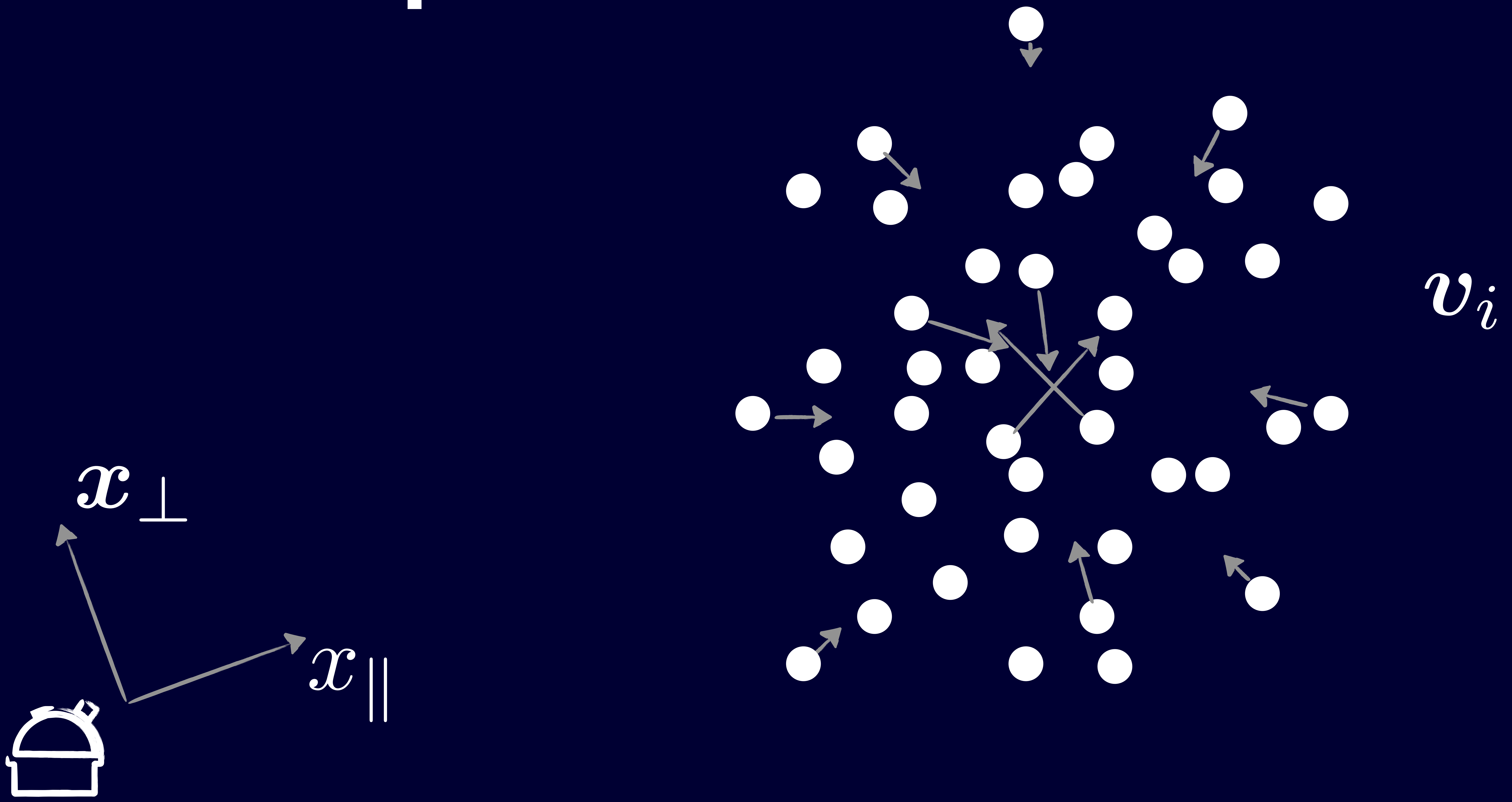
Redshift-space distortions



Redshift-space distortions

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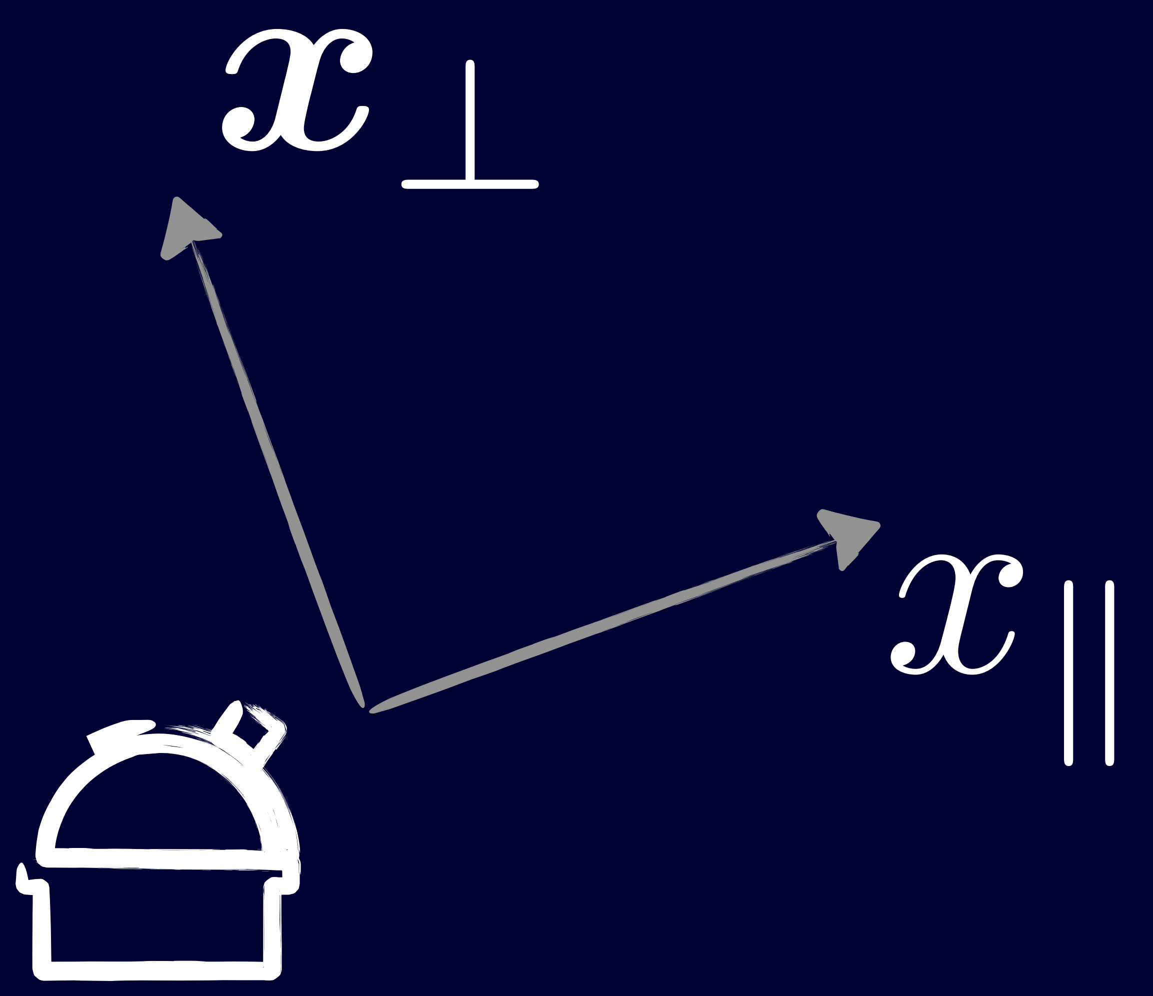
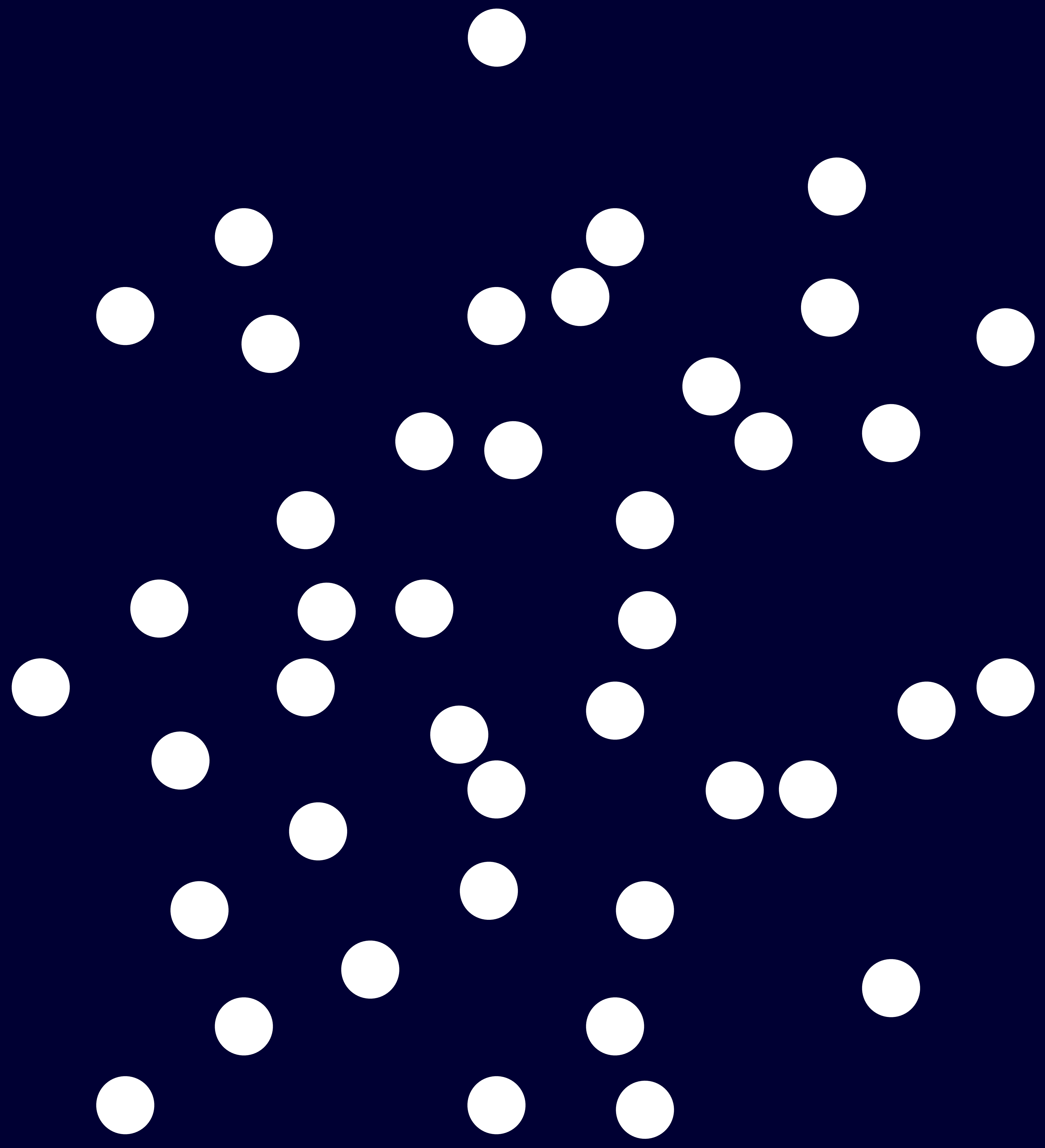
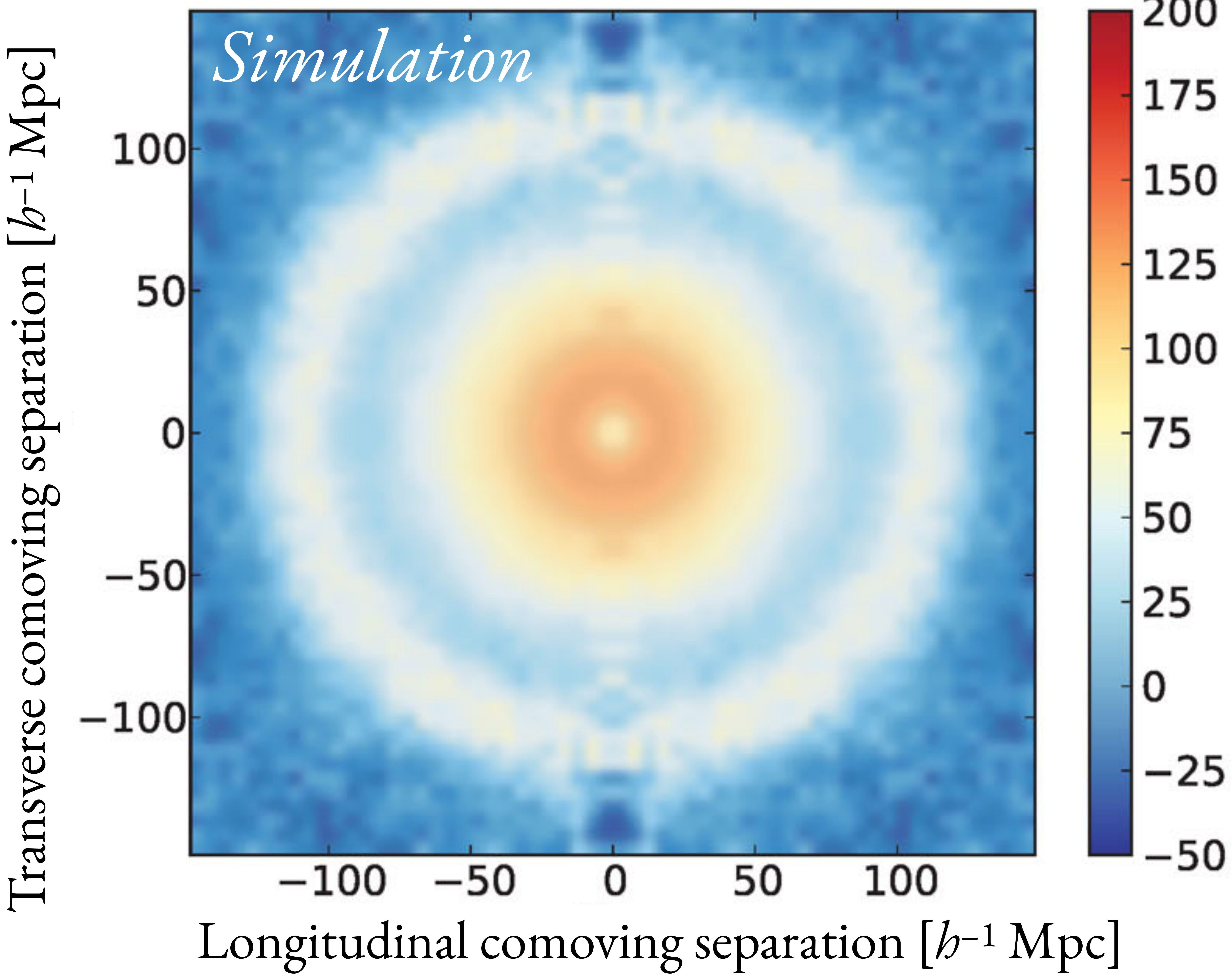
$$\boldsymbol{x}_i = \left(x_{i\parallel} - \frac{\partial_\parallel v_{i\parallel}}{\mathcal{H}}, \boldsymbol{x}_\perp\right)$$



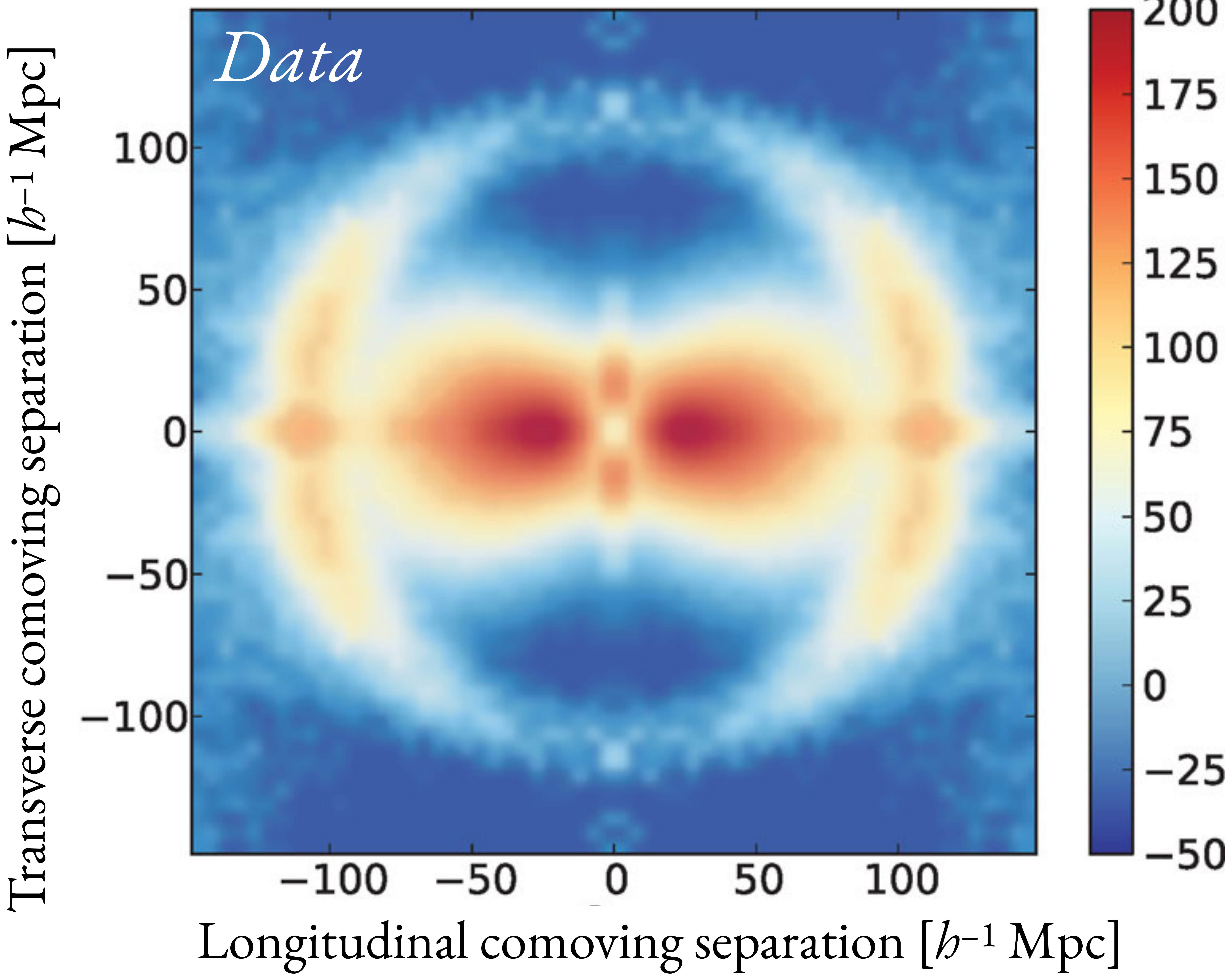


Redshift-space distortions



[Padmanabhan et al. 2012]

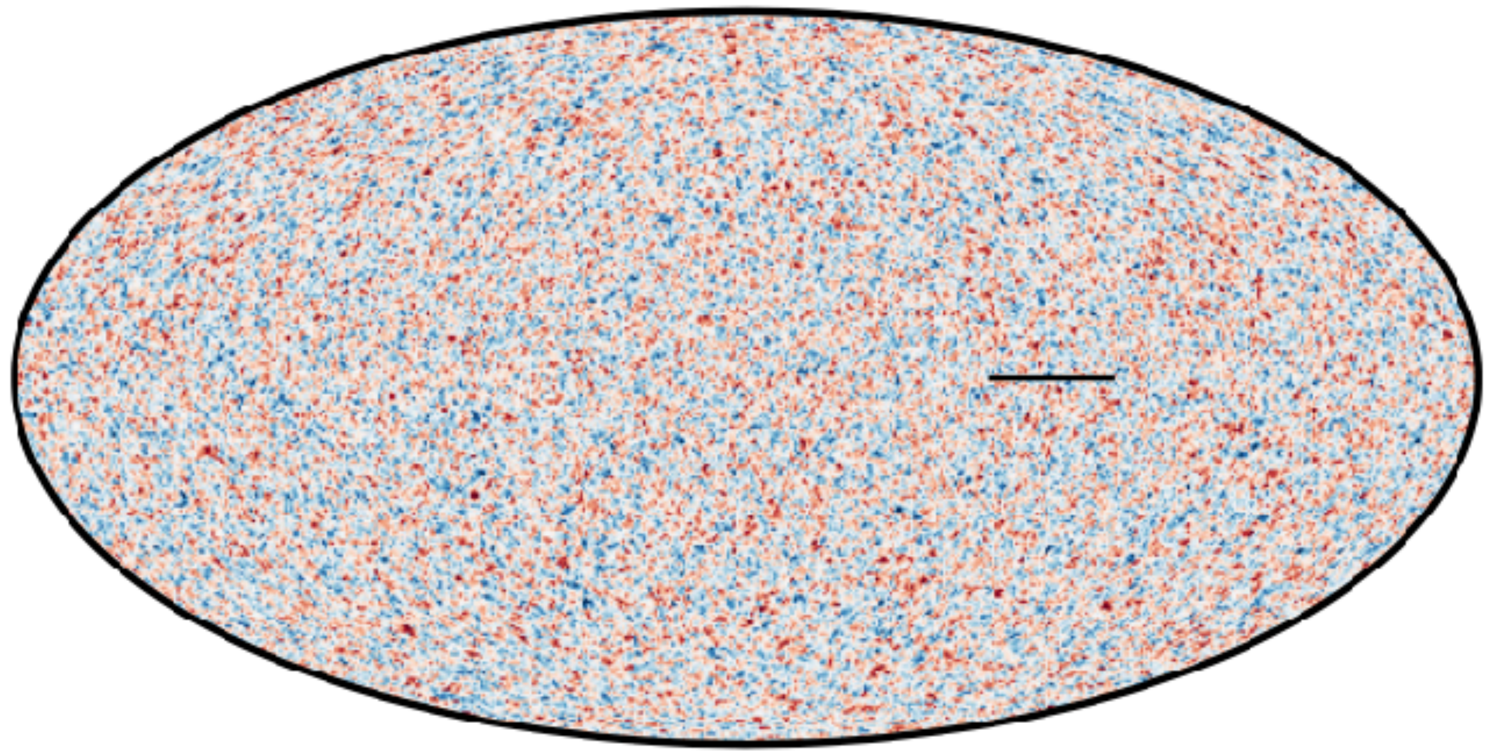
Redshift-space distortions



[Padmanabhan et al. 2012]

Intensity mapping challenges

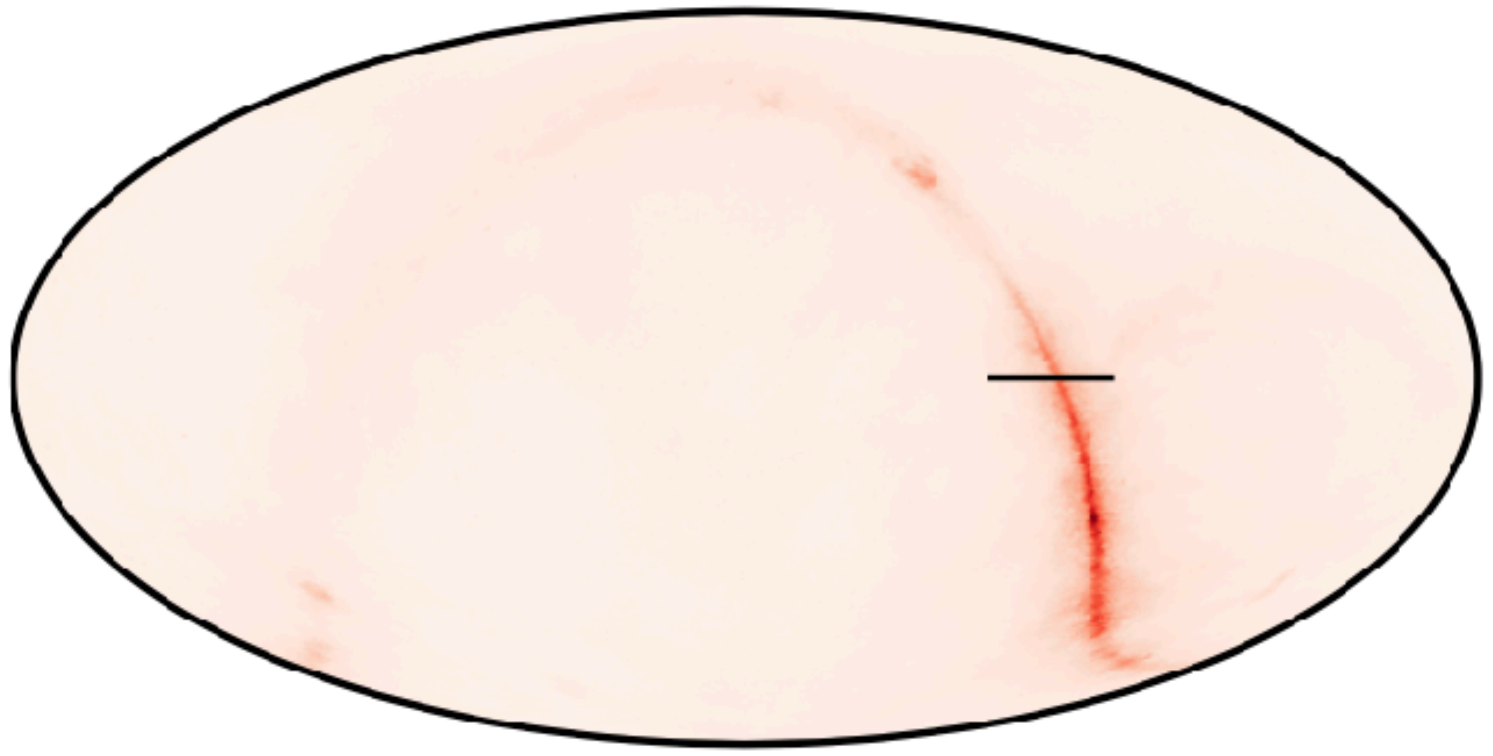
21cm Signal



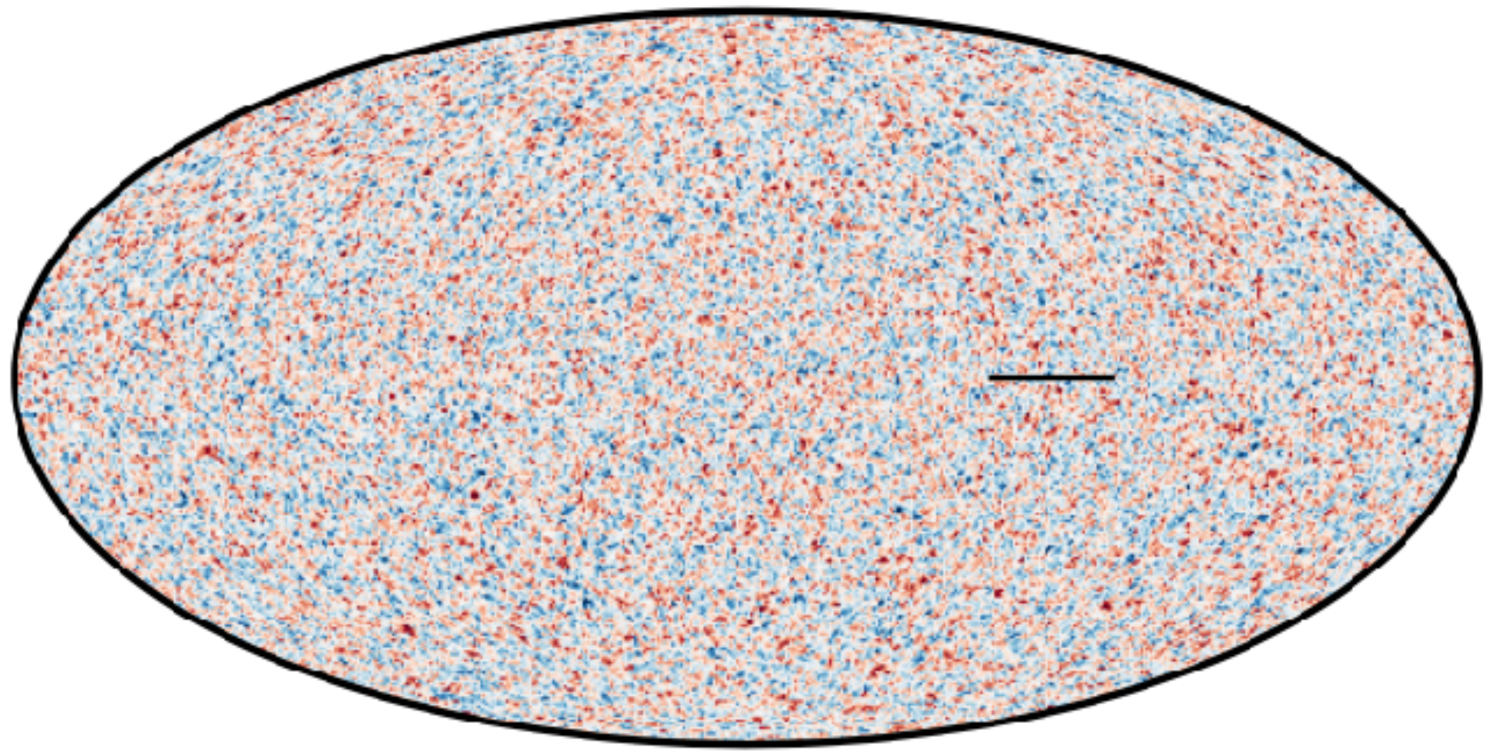
[Credits: R. Shaw]

Intensity mapping challenges

Unpolarised Foreground

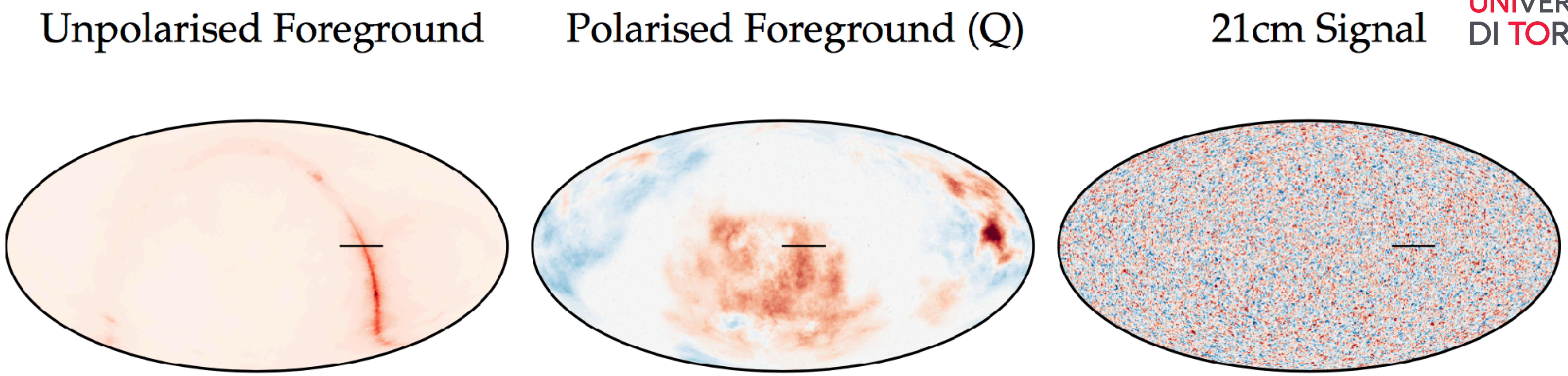


21cm Signal



[Credits: R. Shaw]

Intensity mapping challenges



[Credits: R. Shaw]

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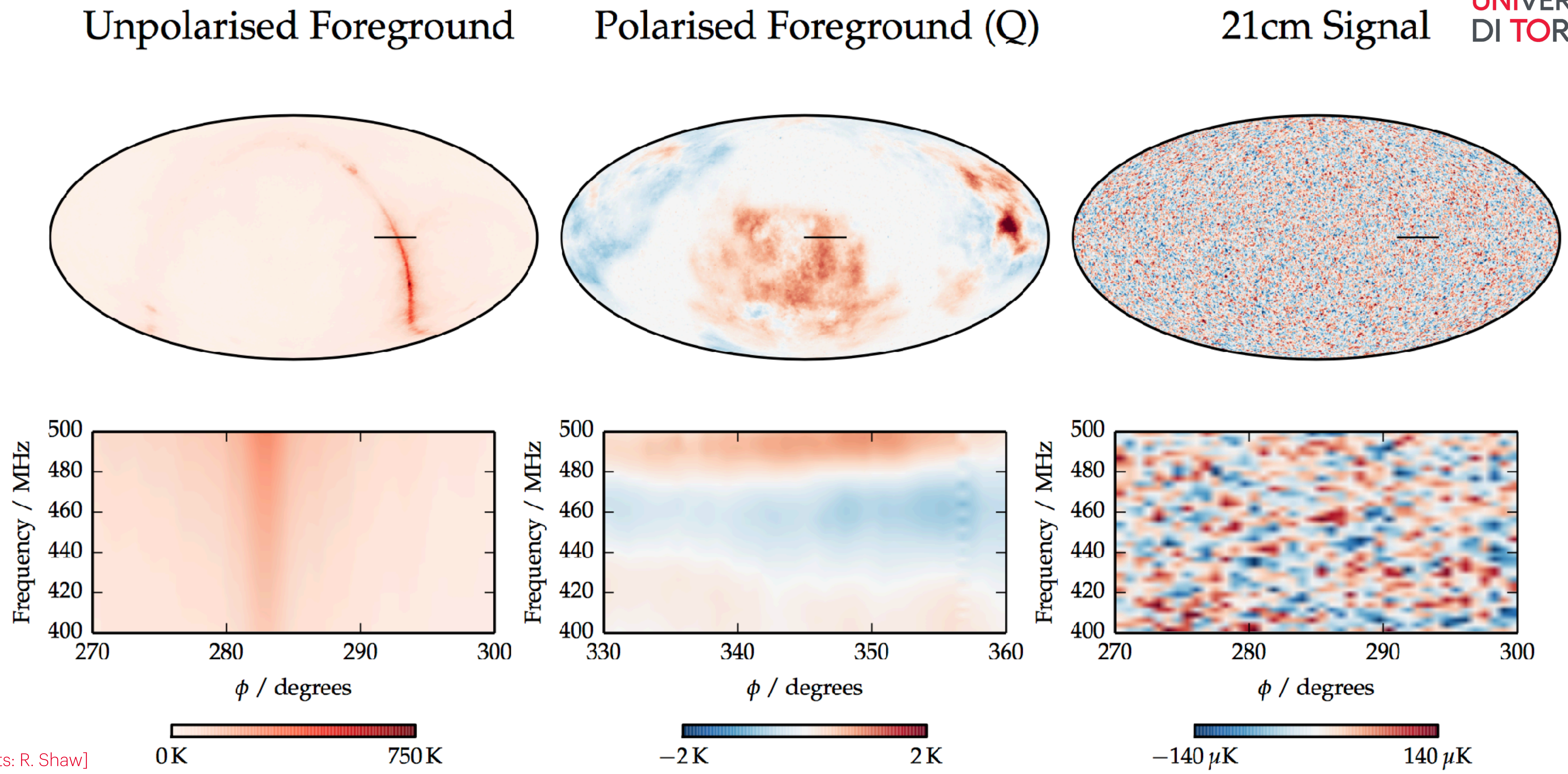

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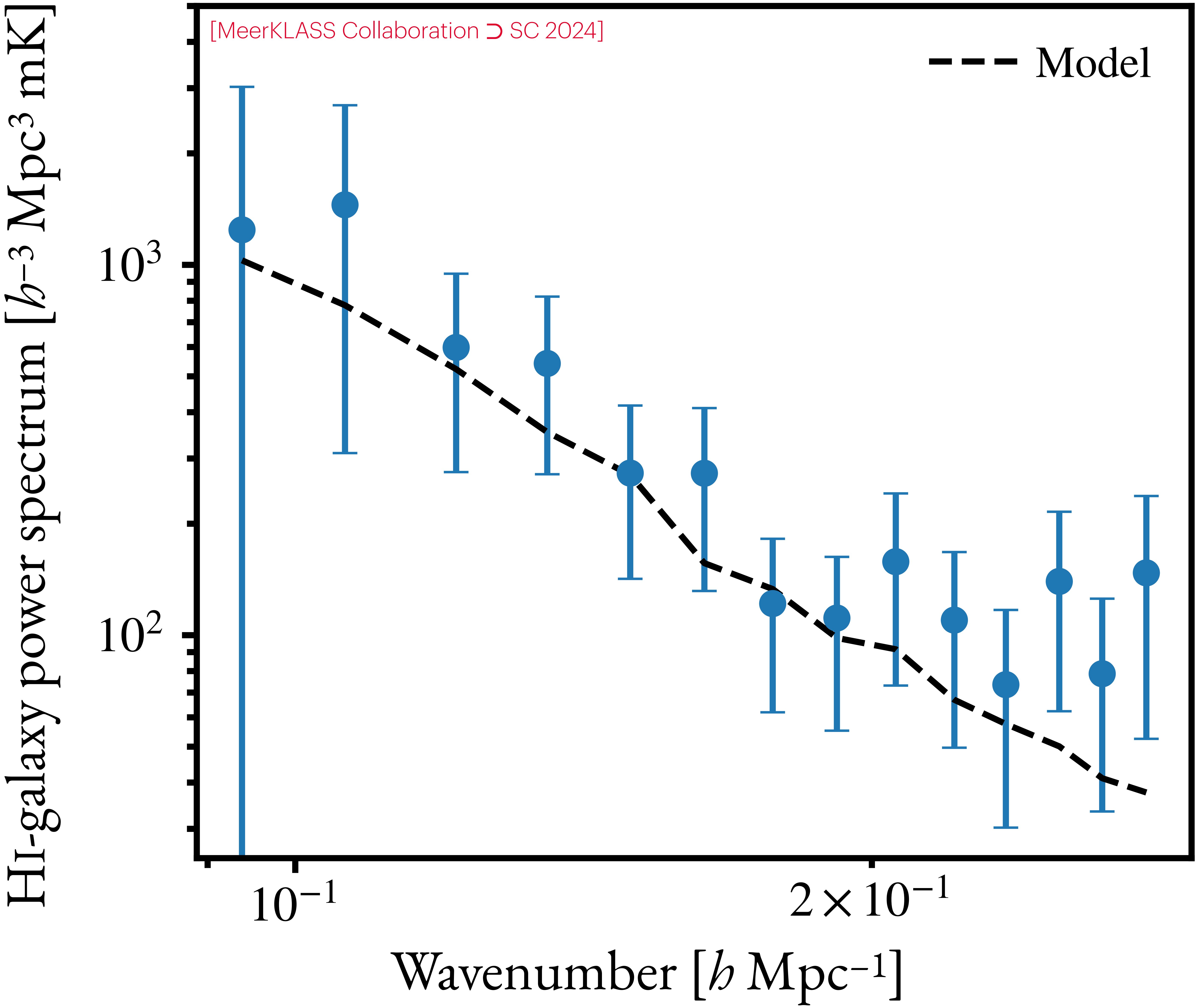

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