Fermilab

A new path for dark matter searches:
Cross-correlation between γ rays and gravitational tracers

Elena Pinetti (Fermilab)

TeVPA2022 – 10th August 2022

«Got plenty of nothing», arXiv:2205.03360

[Submitted on 6 May 2022]

Got plenty of nothing: cosmic voids as a probe of particle dark matter

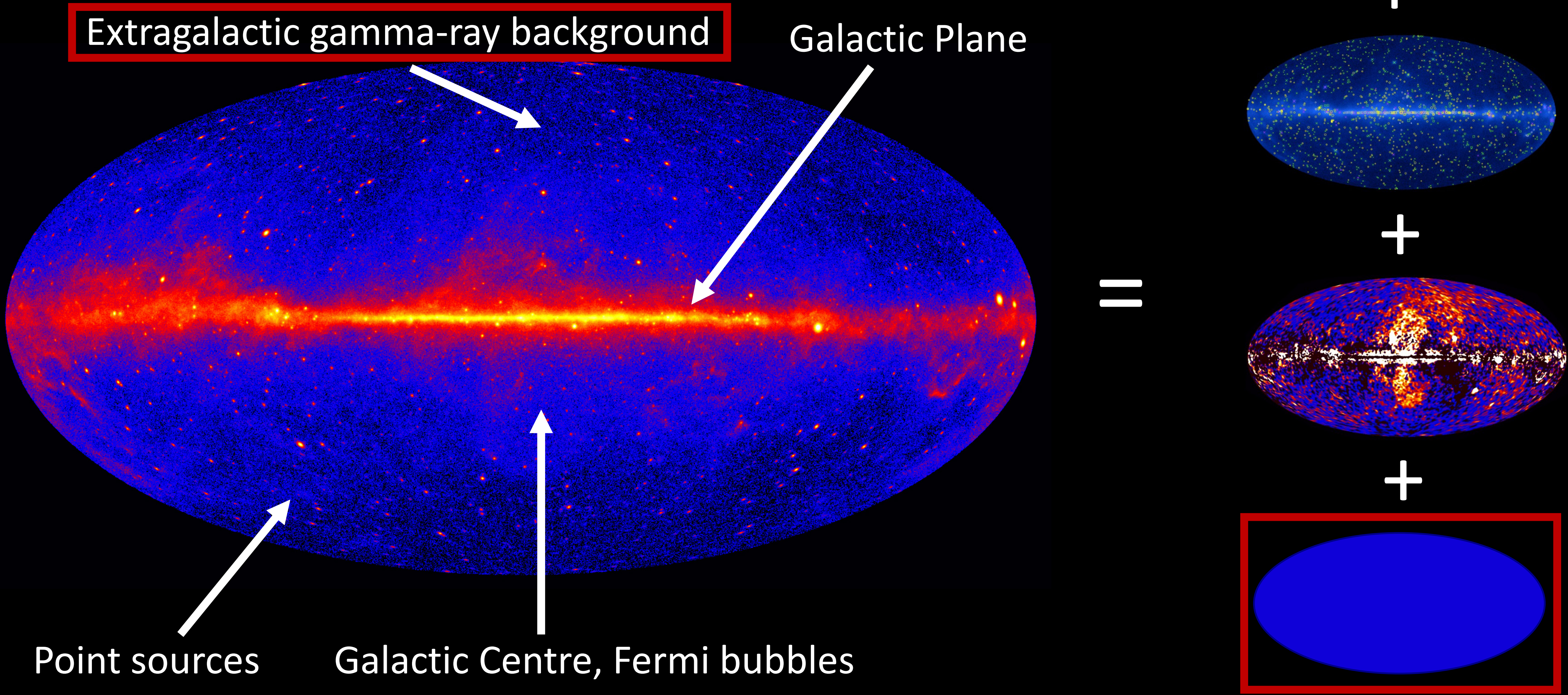
S. Arcari, E. Pinetti, N. Fornengo

The search for a particle dark matter signal in terms of radiation produced by dark matter annihilation or decay has to cope with the extreme faintness of the predicted signal and the presence of masking astrophysical backgrounds. It has been shown that using the correlated information between the dark matter distribution in the Universe with the fluctuations of the cosmic radiation fields has the potential to allow setting apart a pure dark matter signal from astrophysical emissions, since spatial fluctuations in the radiation field due to astrophysical sources and dark matter emission have different features. The cross-correlation technique has been proposed and adopted for dark matter studies by looking at dark matter halos (over-densities). In this paper we extend the technique by focusing on the information on dark matter distribution offered by cosmic voids, and by looking specifically at the gamma-ray dark matter emission: we show that, while being under-dense and therefore producing a reduced emission as compared to halos, nevertheless in voids the relative size of the cross-correlation signal due to decaying dark matter vs. astrophysical sources is significantly more favourable, producing signal-to-background ratios S/B (even significantly) larger than 1 for decay lifetimes up to 2×10^{30} s. This is at variance with the case of halos, where S/B is typically (even much) smaller than 1. We show that forthcoming galaxy surveys such as Euclid combined with future generation gamma-ray detectors with improved specifications have the ability to provide a hint of such a signal with a predicted significance up to 4.2σ for galaxies and 2.7σ for the cosmic shear. The bound on the dark matter lifetime attainable exploiting voids is predicted to improve on current bounds in a mass range for the WIMP of $20 \div 200$ GeV.

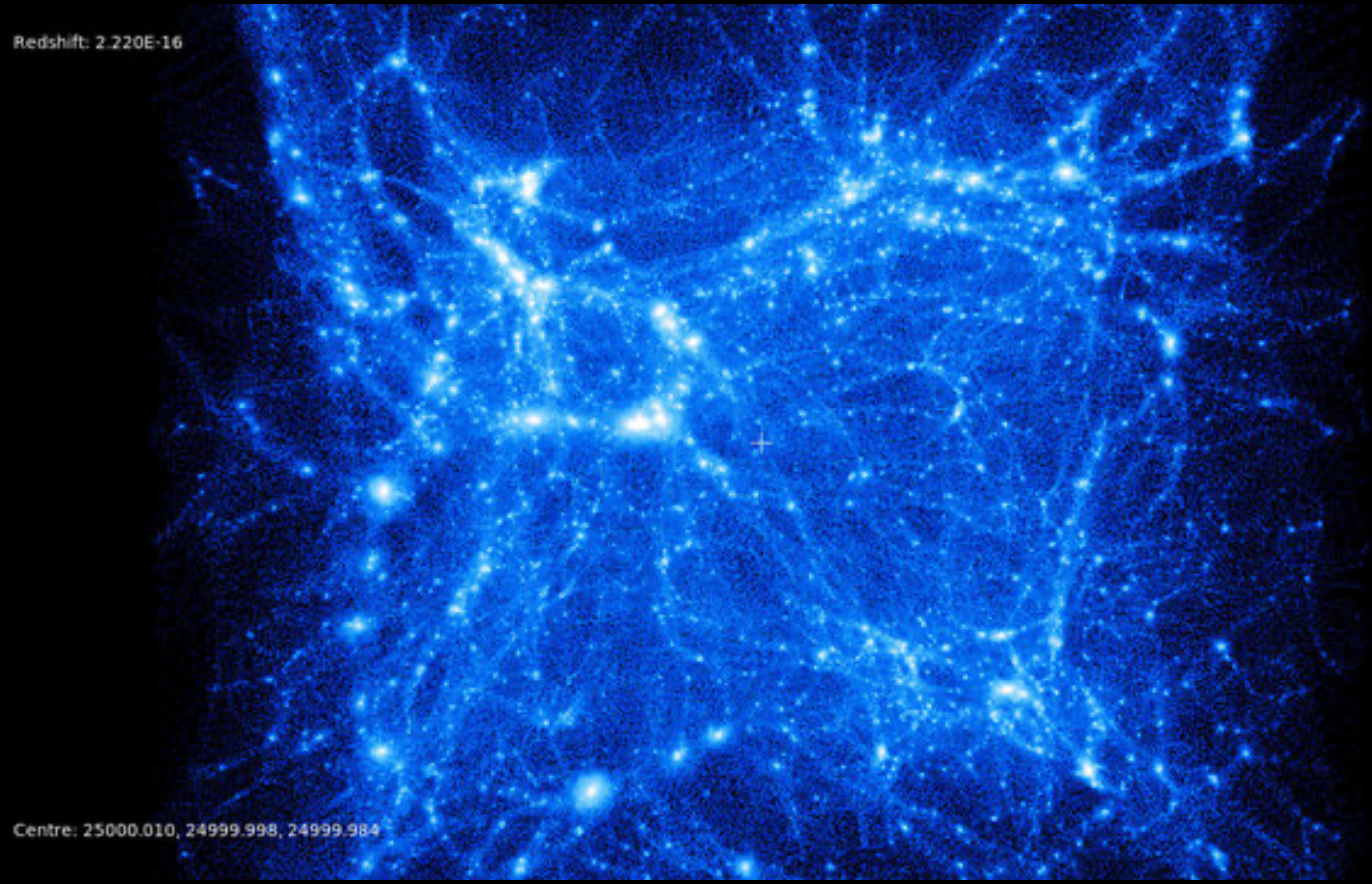
Submitted to JCAP

Thanks to my collaborators: Stefano Arcari (U. Ferrara), Nicolao Fornengo (U. Turin)

Gamma-ray sky



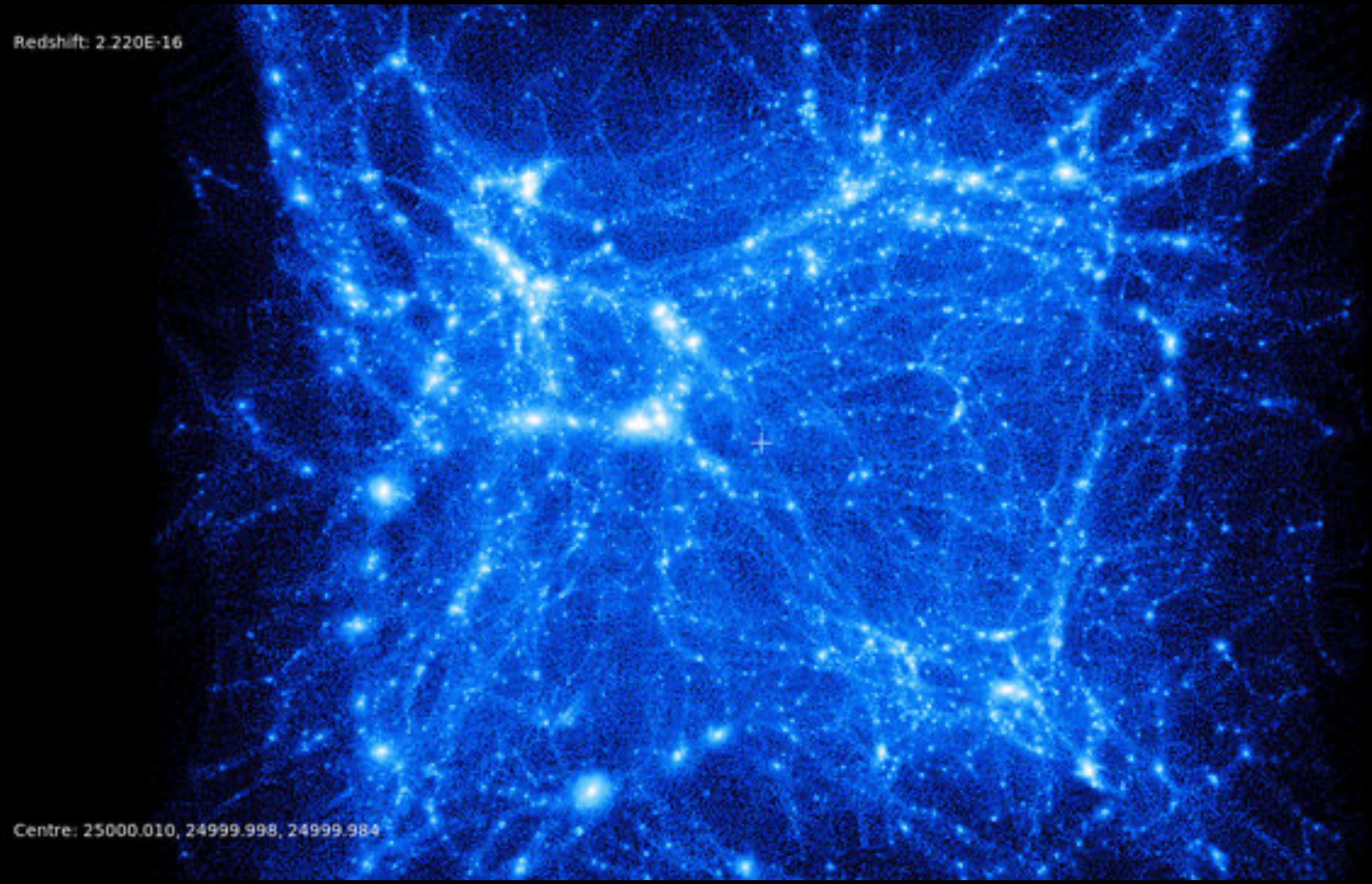
What N-body simulations tell us?



Chacon et al, Rev.Mex.Fis.E 17 (2020) 2

- Hierarchical
- Anisotropic

What N-body simulations tell us?



Chacon et al, Rev.Mex.Fis.E 17 (2020) 2

- Hierarchical
- Anisotropic

Anisotropic EM signal

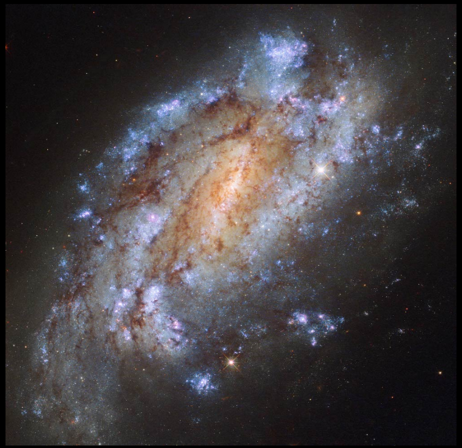
Unresolved Gamma-Ray Background

Astrophysical sources

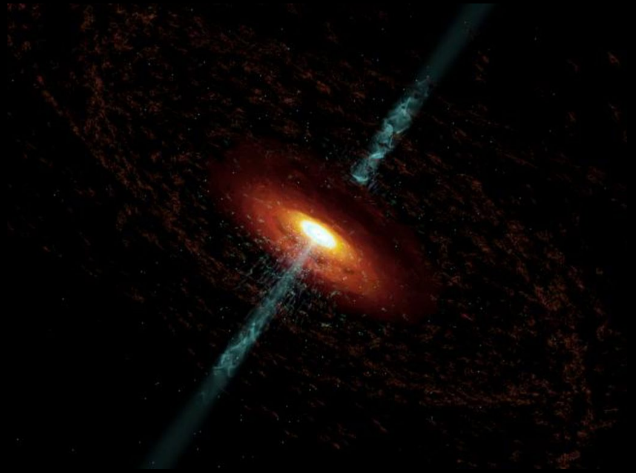
+

Dark Matter

Star-forming galaxies



Active Galactic Nuclei



Blazars:
- BL Lacs
- Flat-Spectrum Radio Quasars

Misaligned AGN

Cross-correlation technique

Gravitational tracers

Galaxy catalogues

Clusters catalogues

Neutral hydrogen

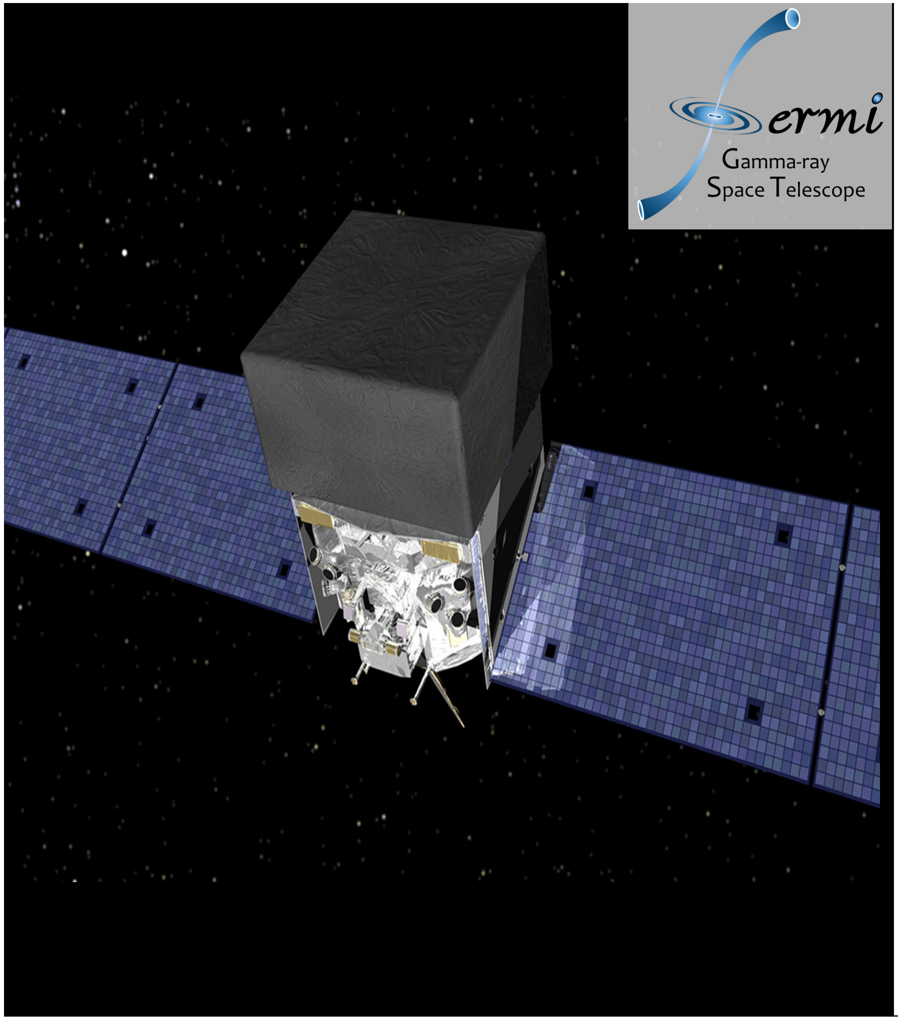
Weak lensing

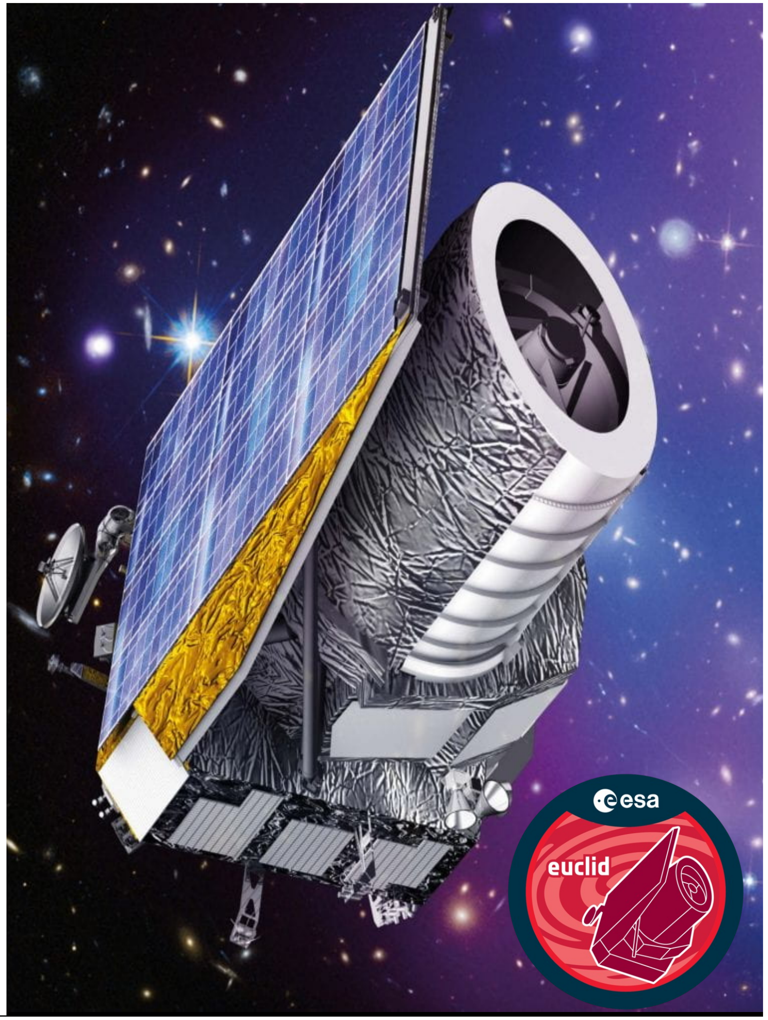
✖

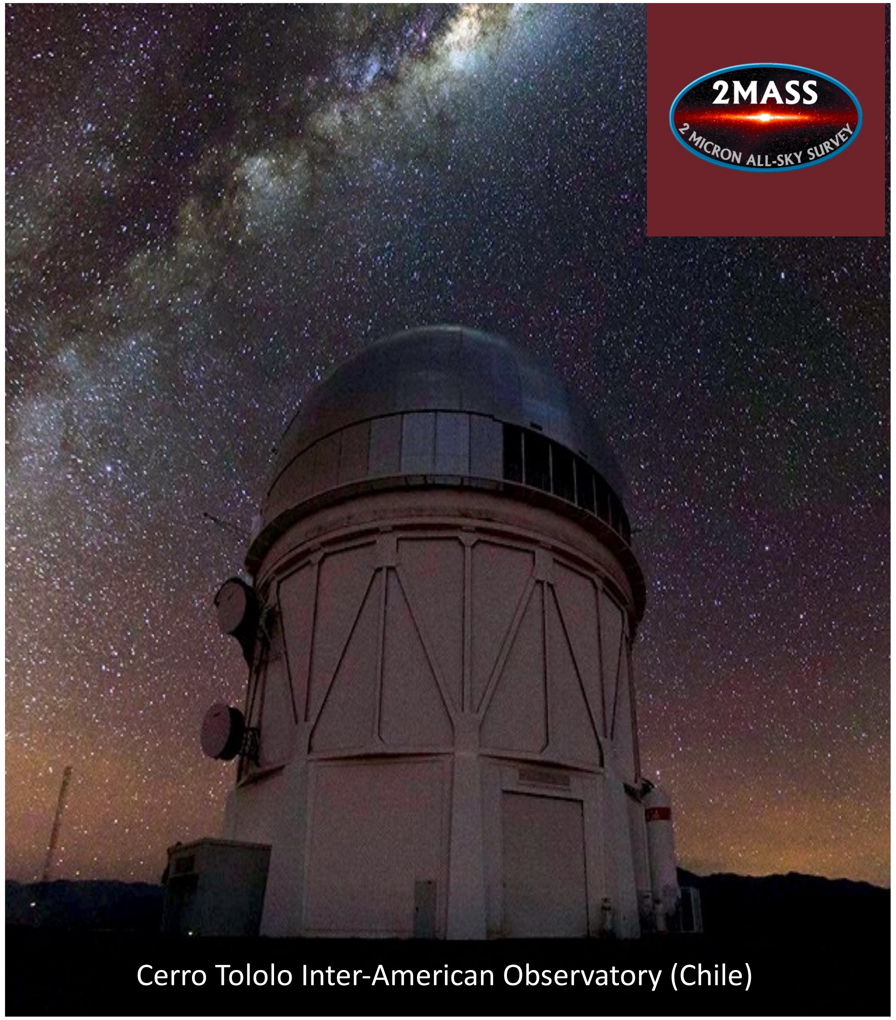
EM signals

- γ rays
- X rays
- IR emission
- Radio waves

Experiments







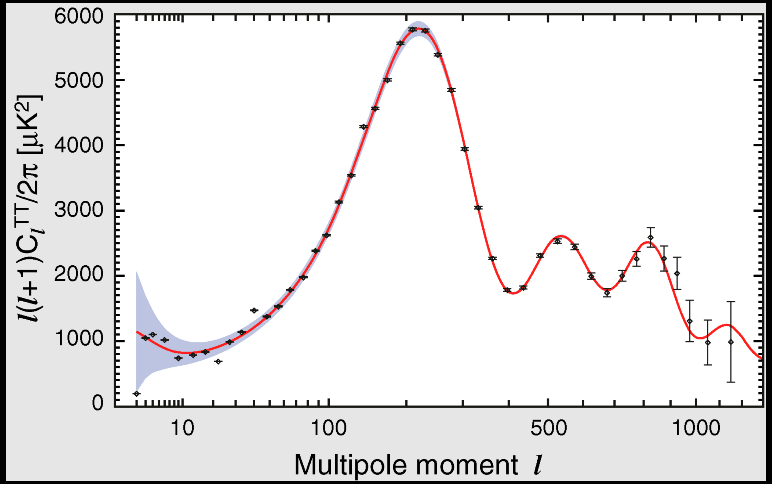
Fermi/Fermissimo

Euclid

2MASS

Angular power spectrum

The example of CMB:



$I_g(\hat{n})$ = intensity of the source field g

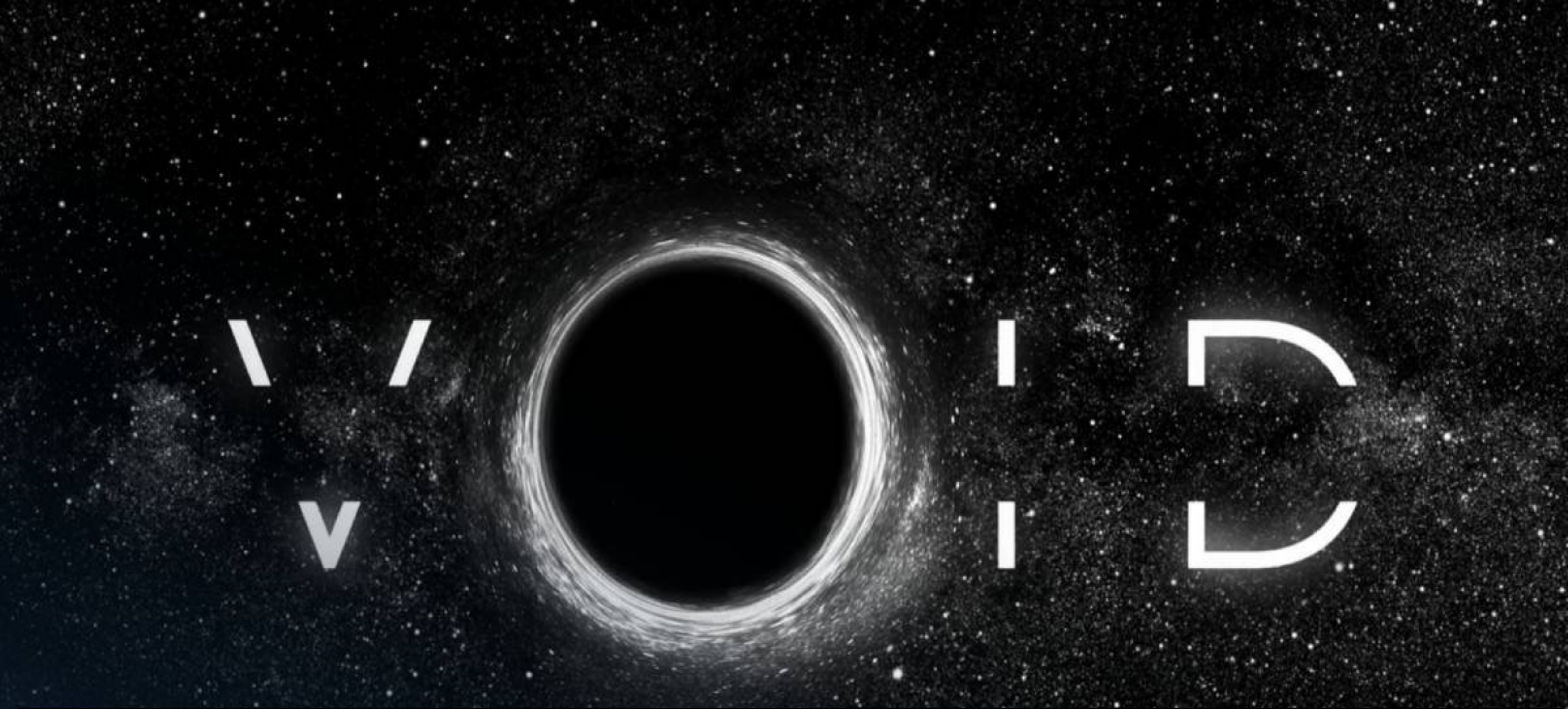
$$\delta I_g = I_g(\hat{n}) - \langle I_g \rangle = \langle I_g \rangle \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{n})$$

$$C_\ell^{ij} = \frac{1}{2\ell+1} \left\langle \sum_{m=-\ell}^{\ell} a_{\ell m}^{(i)} \, a_{\ell m}^{*(j)} \right\rangle$$

$$C_\ell^{ij} = \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) \, P_{ij}\left(k = \frac{\ell}{\chi}\right)$$

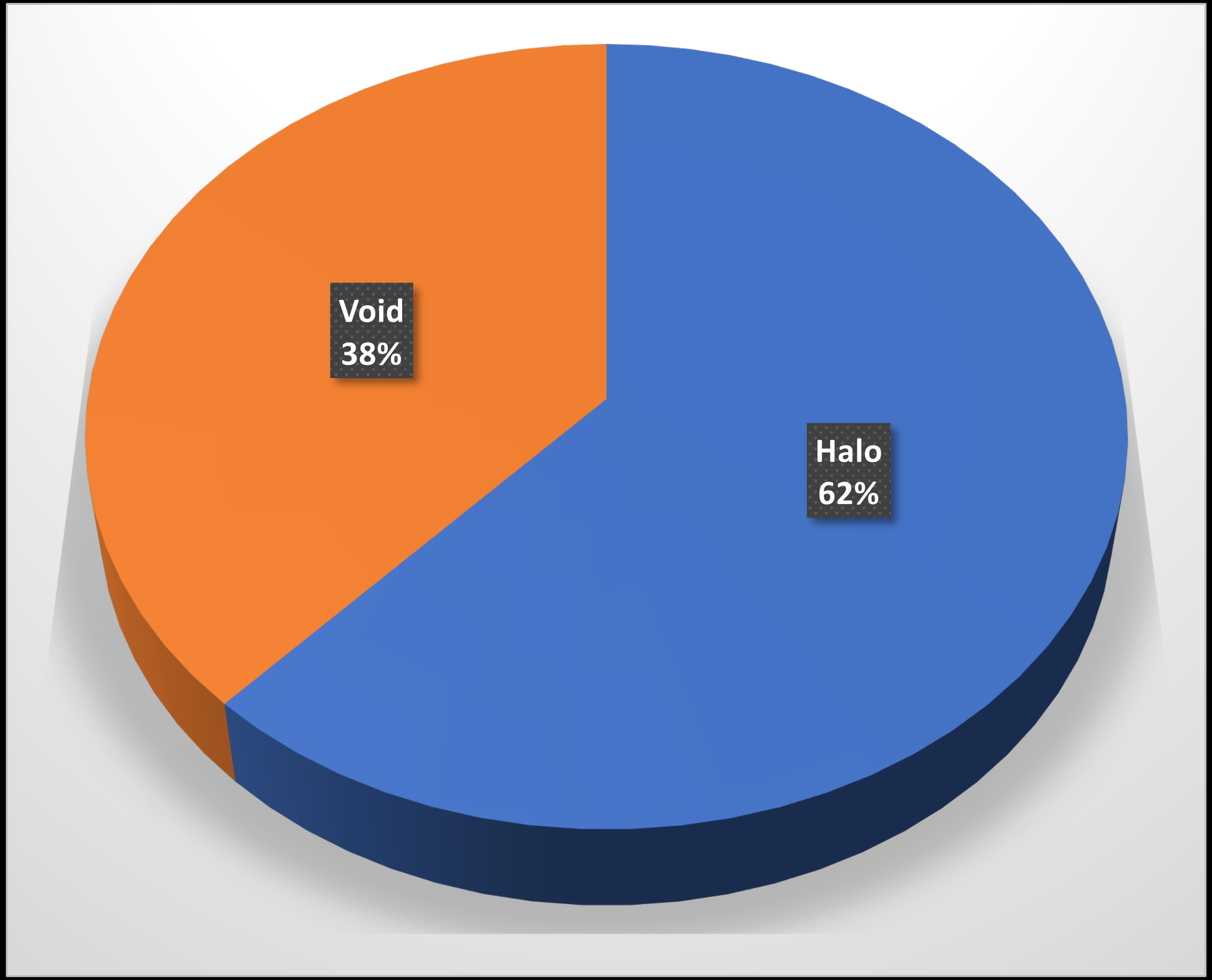
Window functions

Fourier Power Spectrum

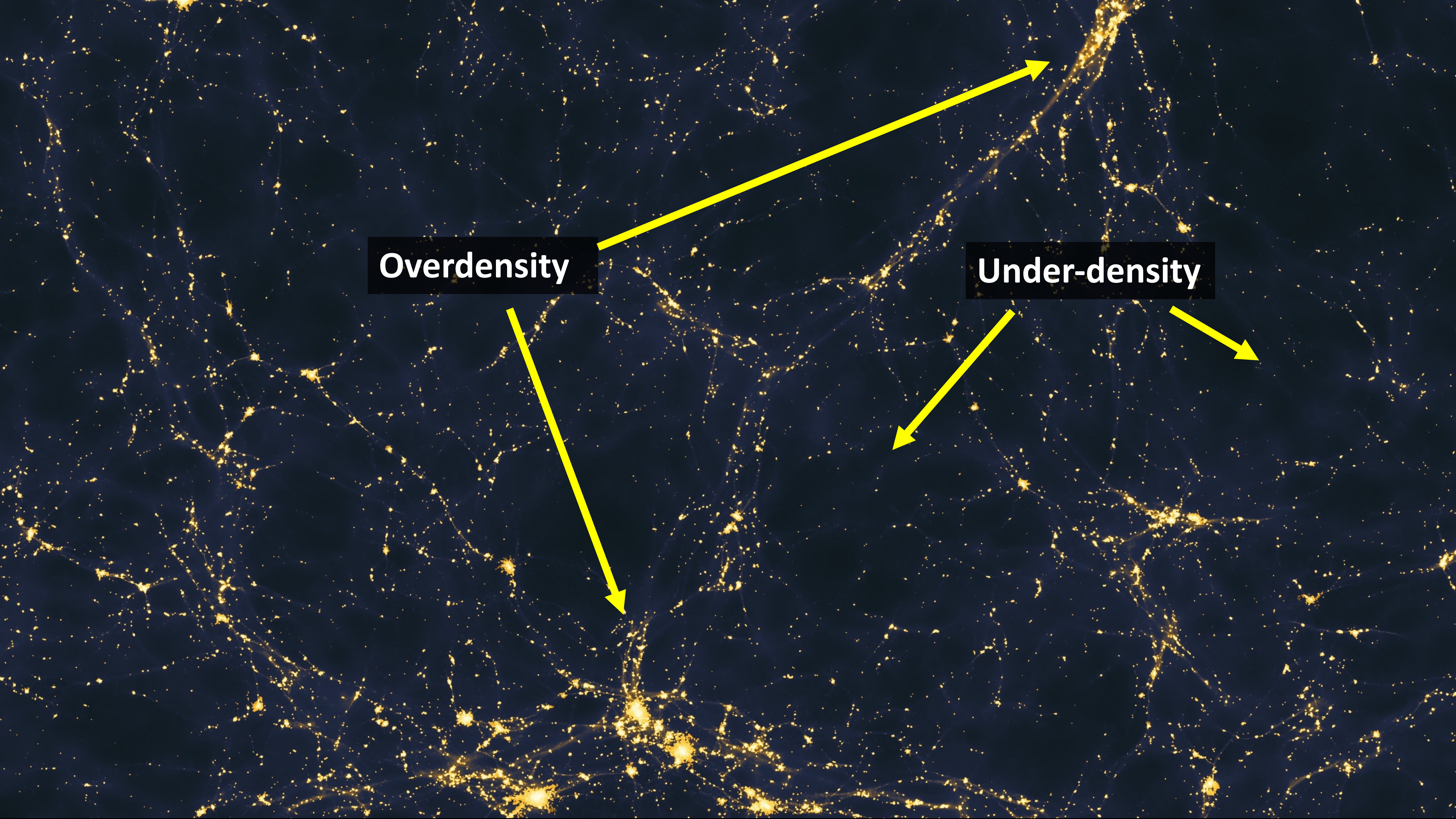


Cosmic voids

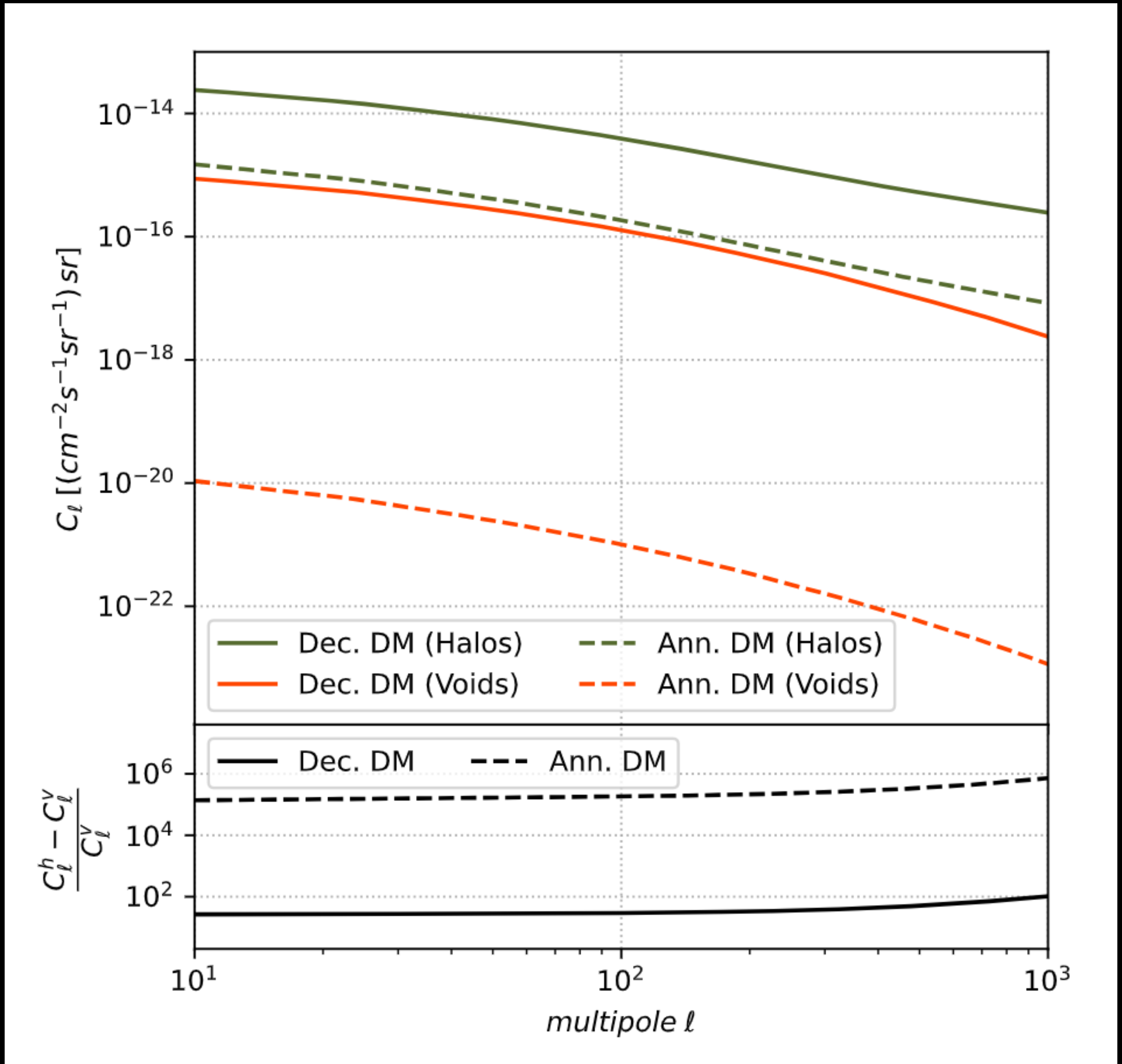
Cosmic voids



R. Voivodic et al, JCAP 10 (2020) 033, arXiv: 2003.06411


Overdensity
Under-density

Halos vs Voids



$m_\chi = 100$ GeV $\langle \sigma v \rangle = 3\times10^{-26}\ \mathrm{cm^3/s}$

Channel: $b\bar{b}$ $\tau = 3\times10^{27}\mathrm{s}$

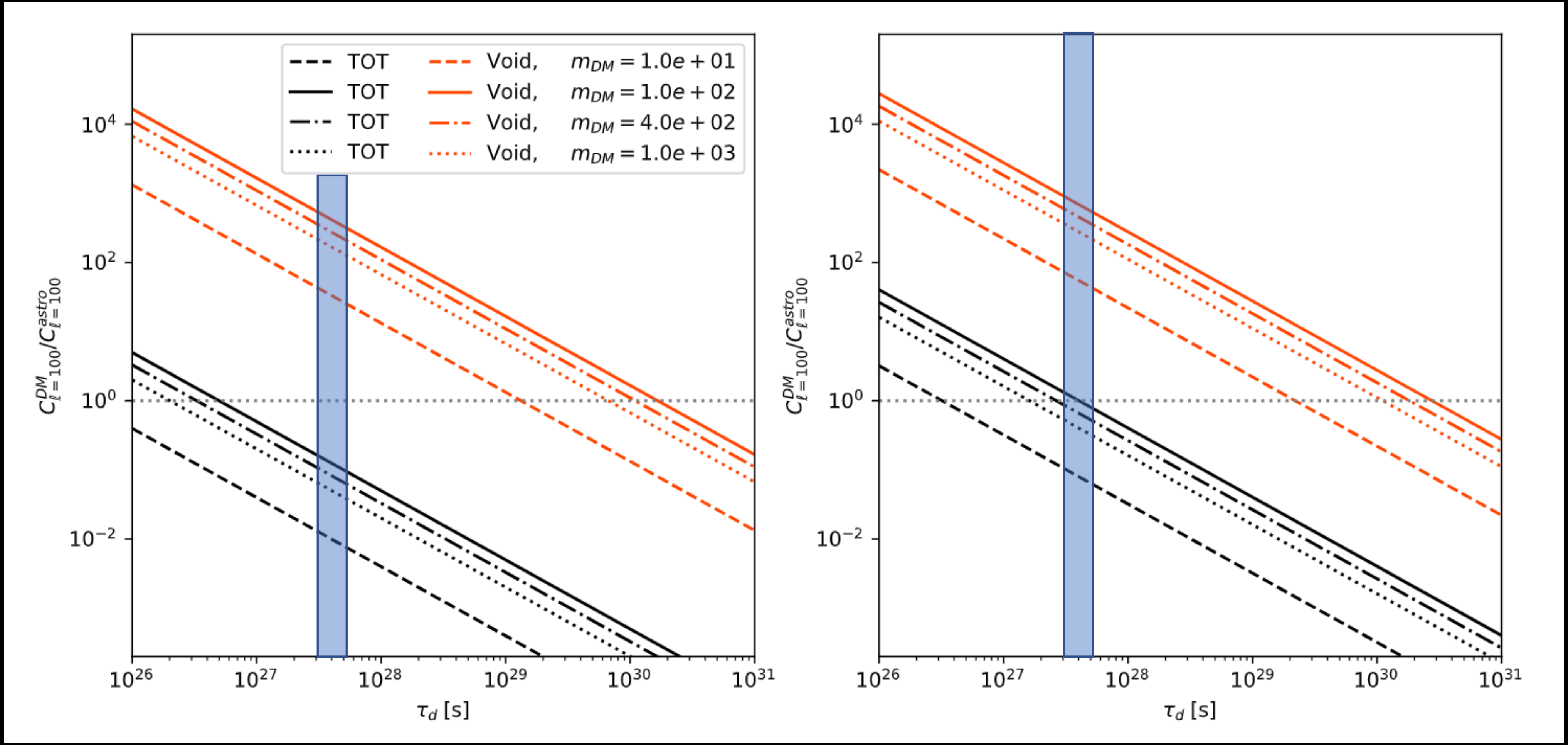
What do we learn?

1. Cosmic voids can be useful to search for decaying dark matter

Halos vs Voids

Weak lensing

Galaxies



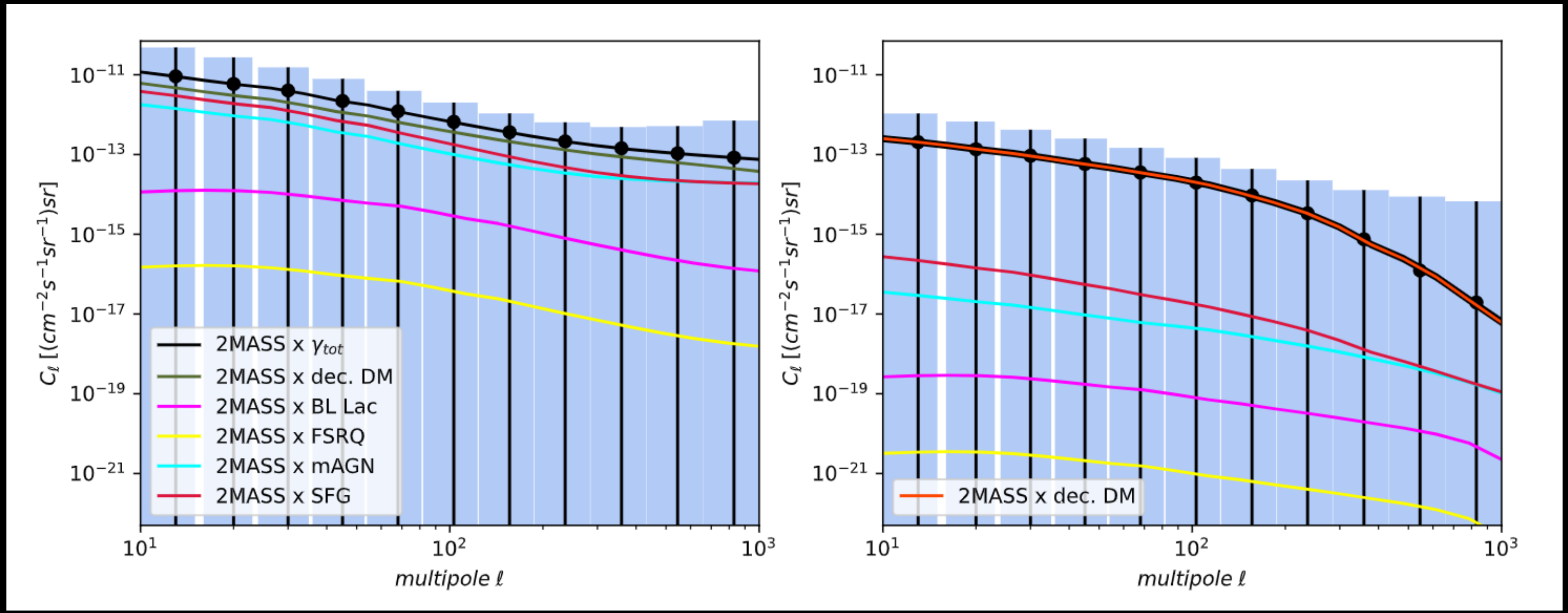
What do we learn?

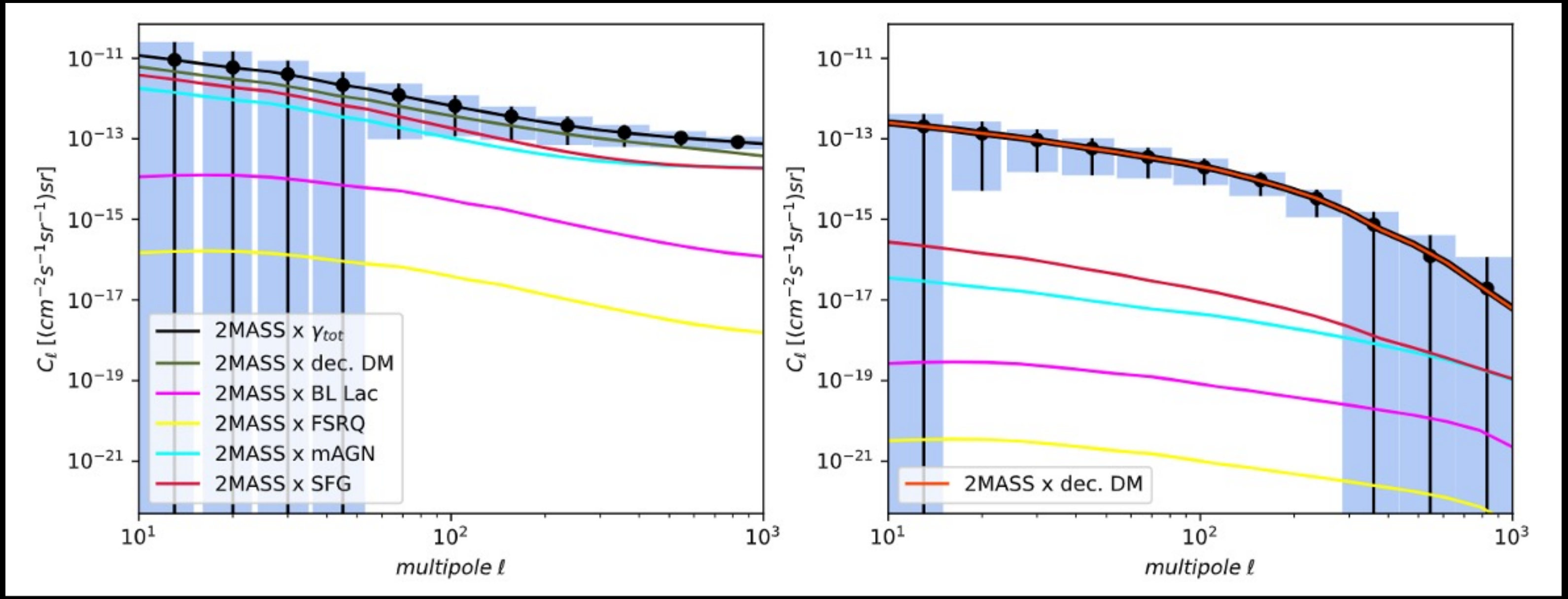
1. Cosmic voids can be useful to search for decaying dark matter

2. Background free environment

Angular Power Spectrum

Halos | Voids





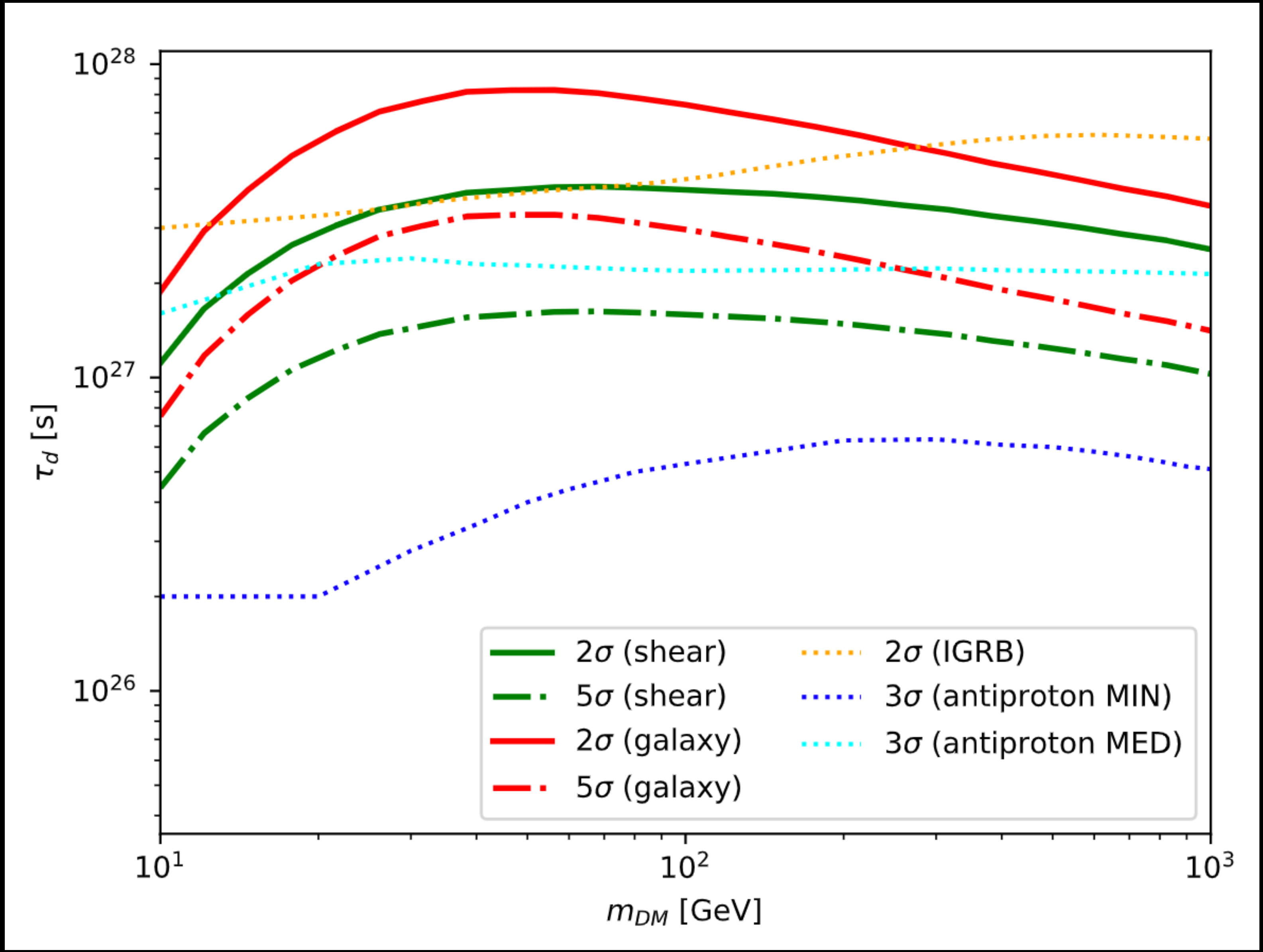
What do we learn?

1. Cosmic voids can be useful to search for decaying dark matter

2. Background free environment

3. Next-generation gamma-ray detector for a clean detection

Dark matter constraints



Blanco & Hooper, JCAP 03 (2019), 019 arXiv:1811.05988

N. Fornengo, L. Maccione and A. Vittino, JCAP 1404 (2014) 003, arXiv:1312.3579.

An eye toward the future

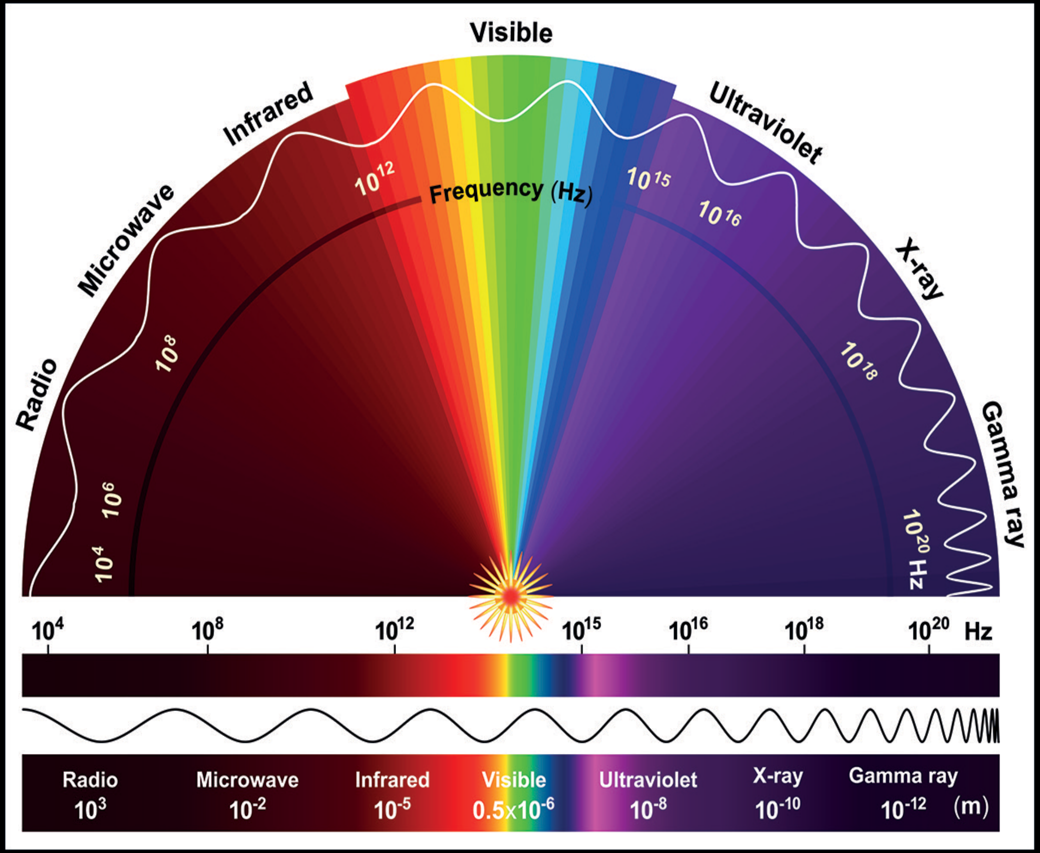
Neutral hydrogen

Most powerful radio telescope ever built: great redshift and angular resolution

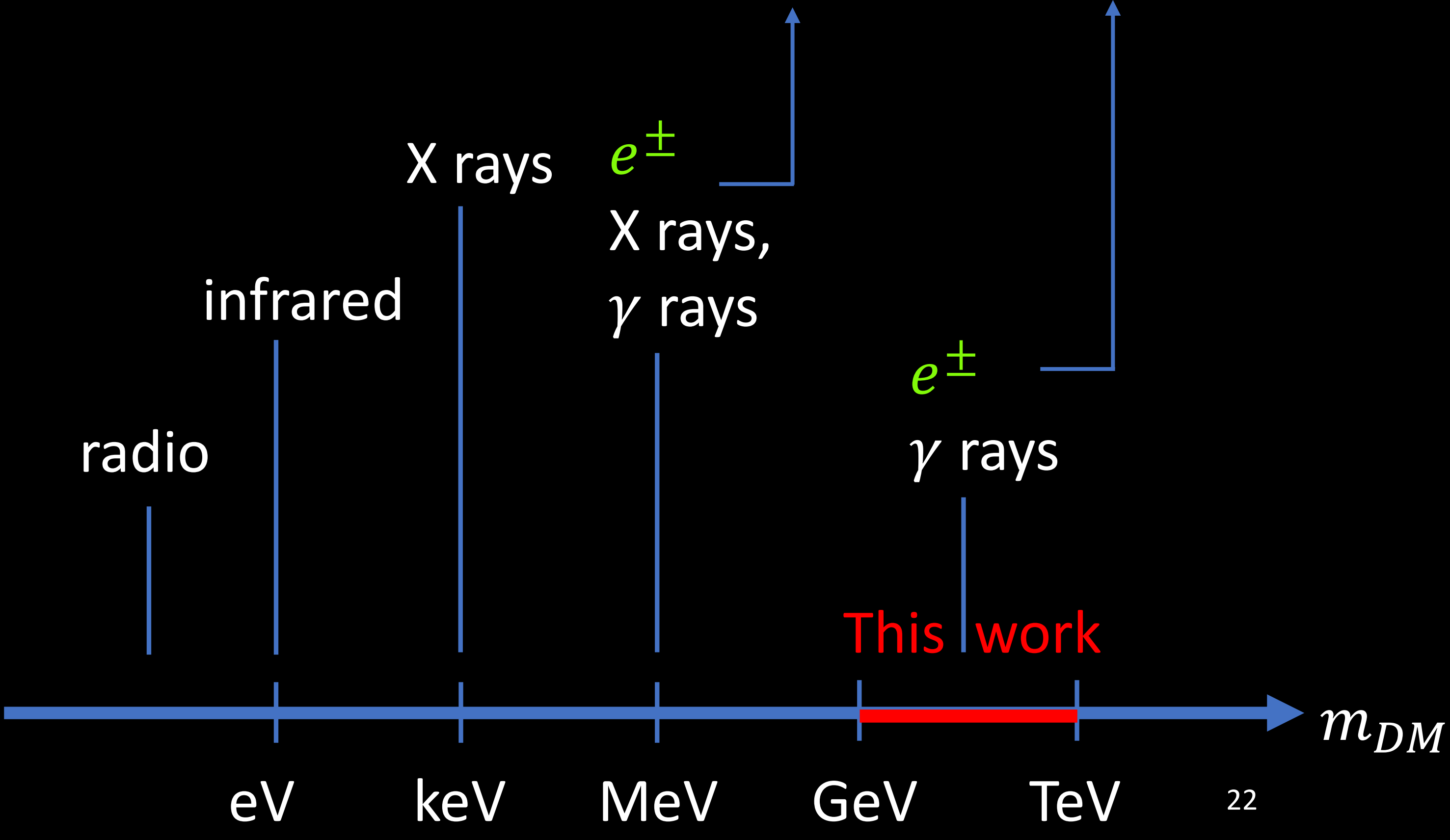
Galaxy surveys

21cm Intensity Mapping

Different signals/candidates



X rays, γ rays: IC on CMB and on the ISRF
radio: synchrotron on ambient magnetic fields

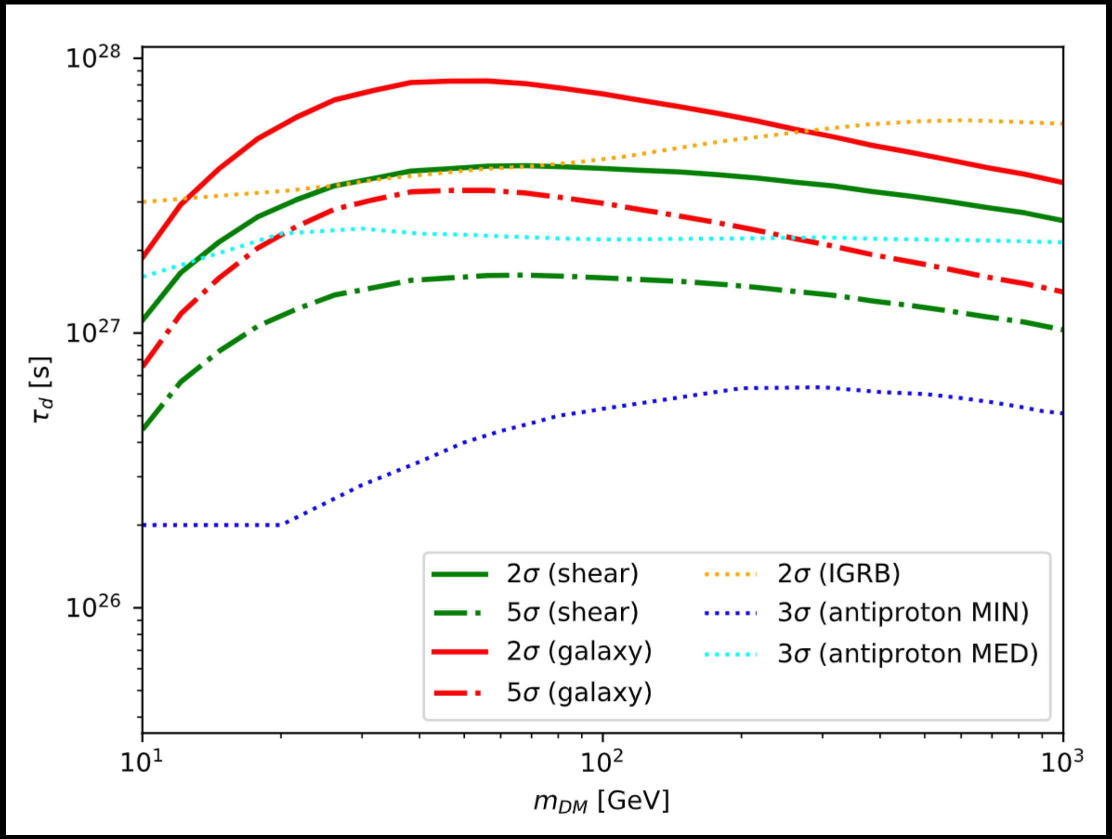


Conclusions

1. Cosmic voids are an interesting probe for dark matter searches

2. A decaying dark matter signal is expected to be up to 4 odg higher than the astrophysical background

3. Further study with different detectors and different signals are recommended



Conclusions

Thank you for your attention!

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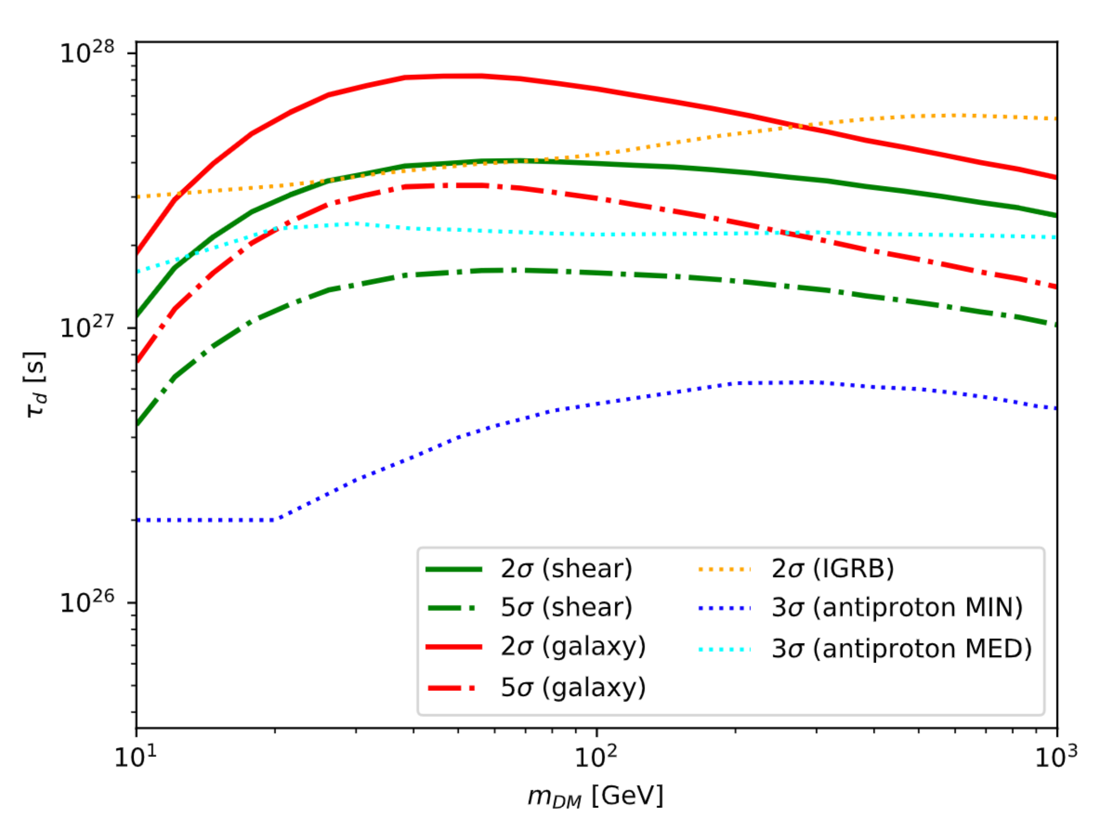
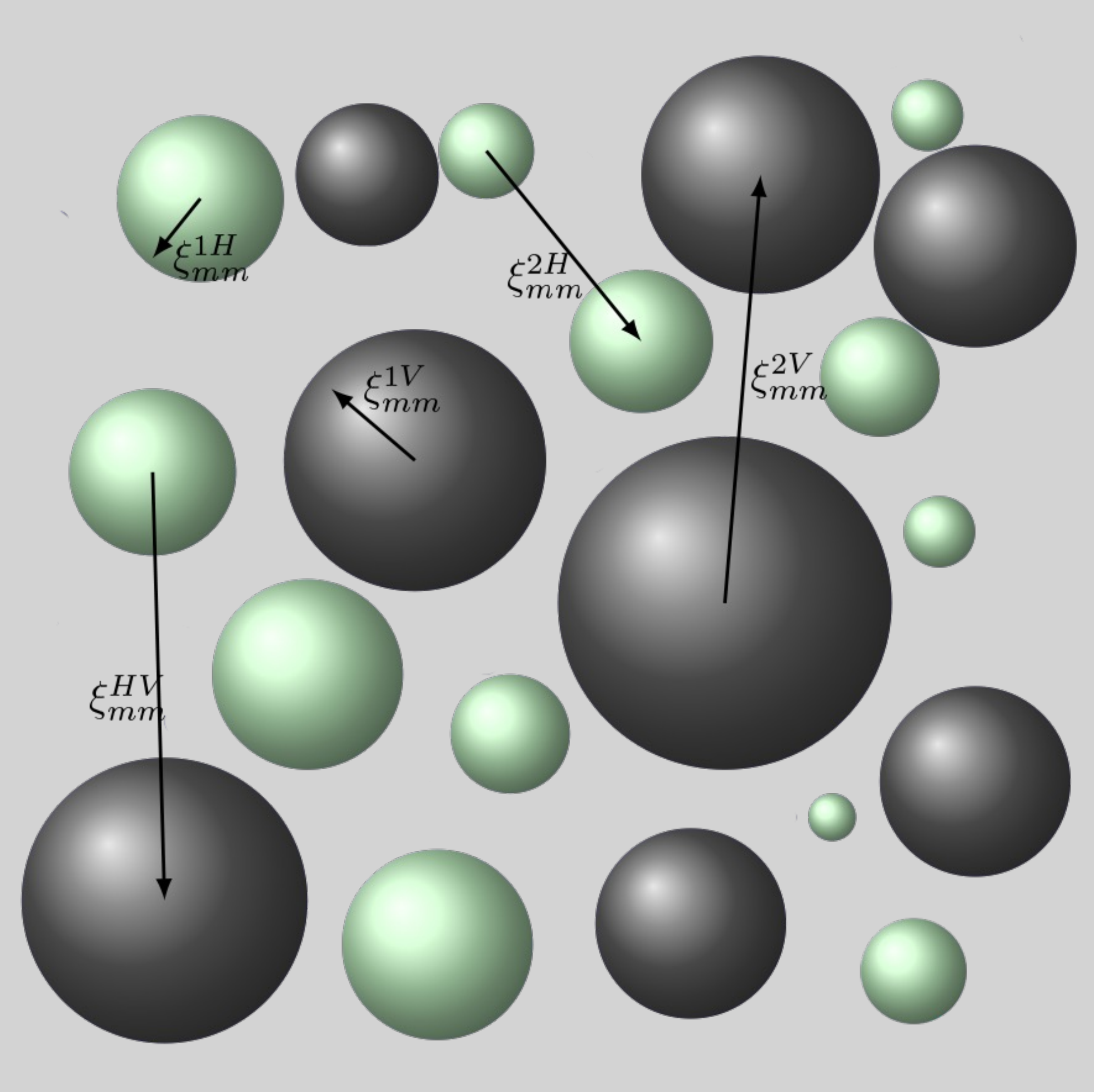


Back-up slides

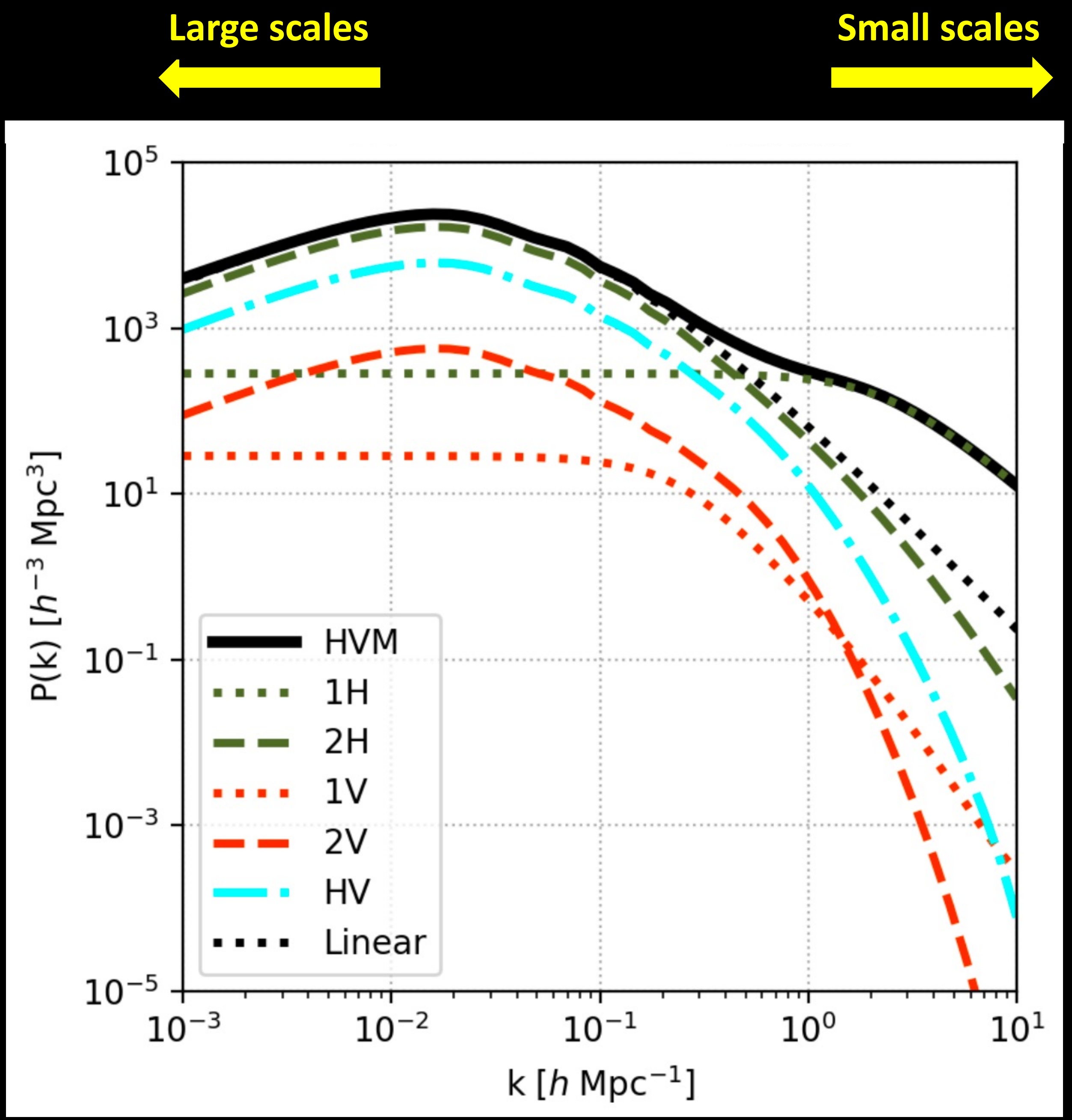
Fourier Power Spectrum

$$P_{ij} = P_{ij}^{1H} + P_{ij}^{2H} + P_{ij}^{1V} + P_{ij}^{2V} + P_{ij}^{HV}$$

R. Voivodic et al, JCAP 10 (2020) 033, arXiv: 2003.06411

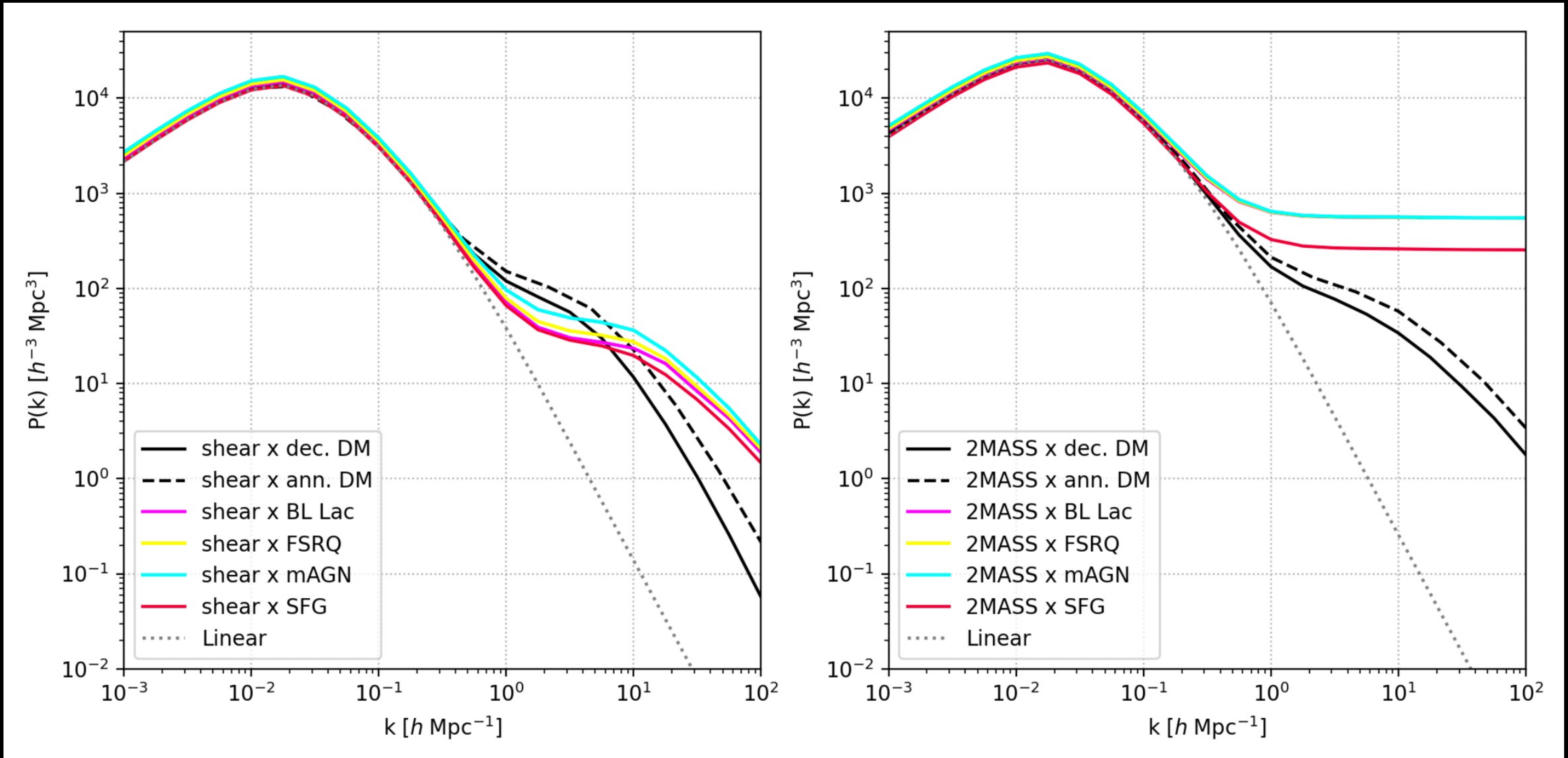


Fourier Power Spectrum

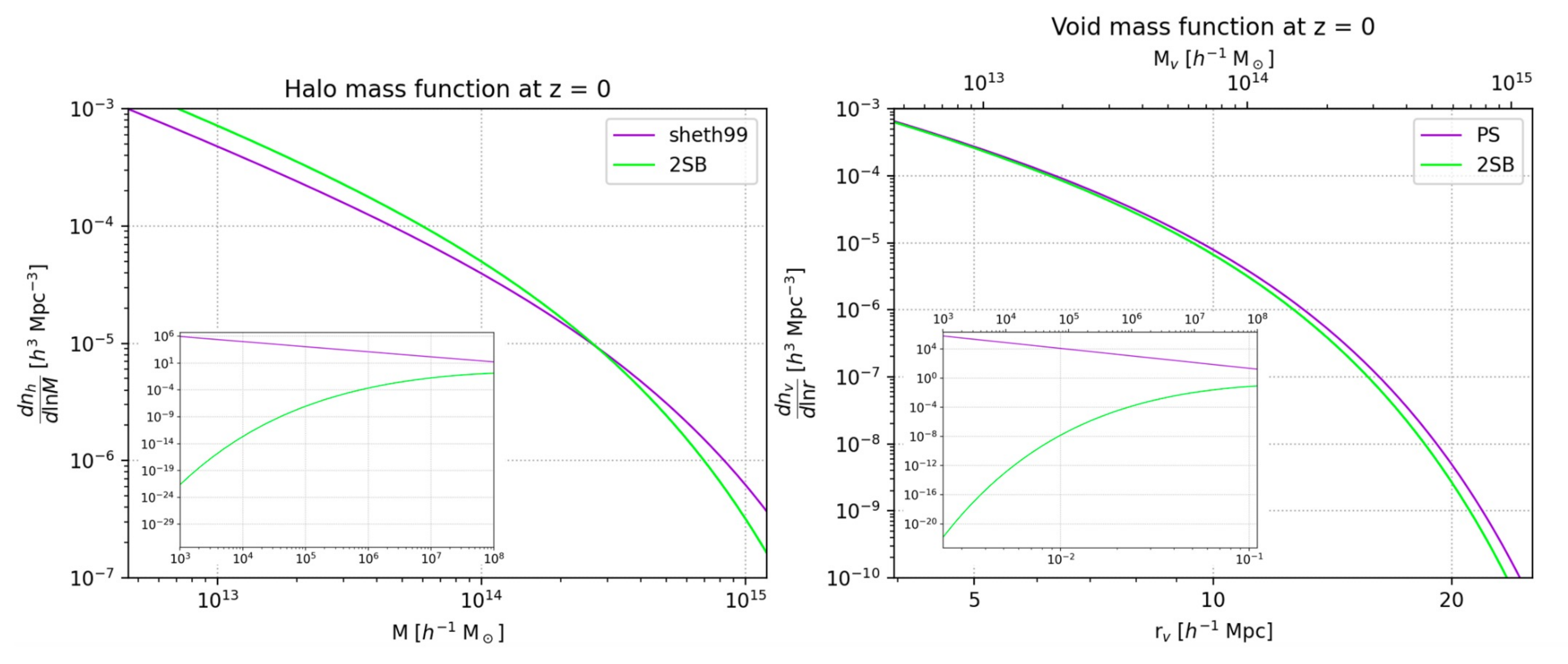


Fourier Power Spectrum

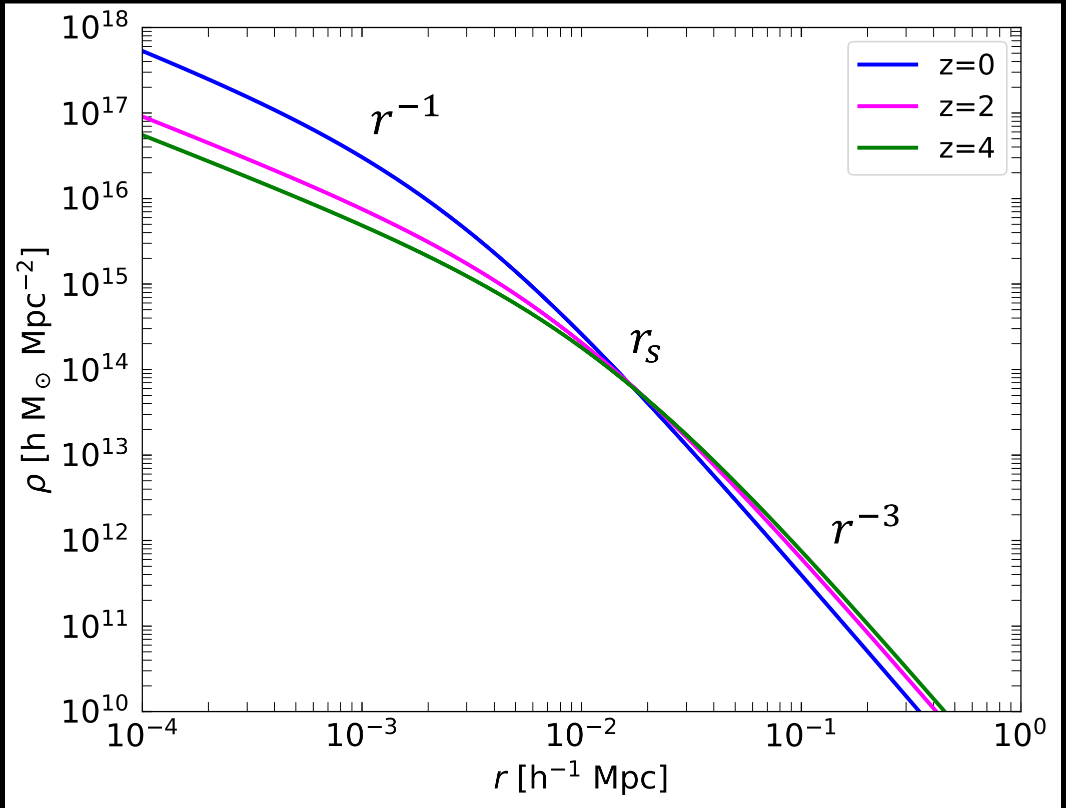
Large scales ← → **Small scales**

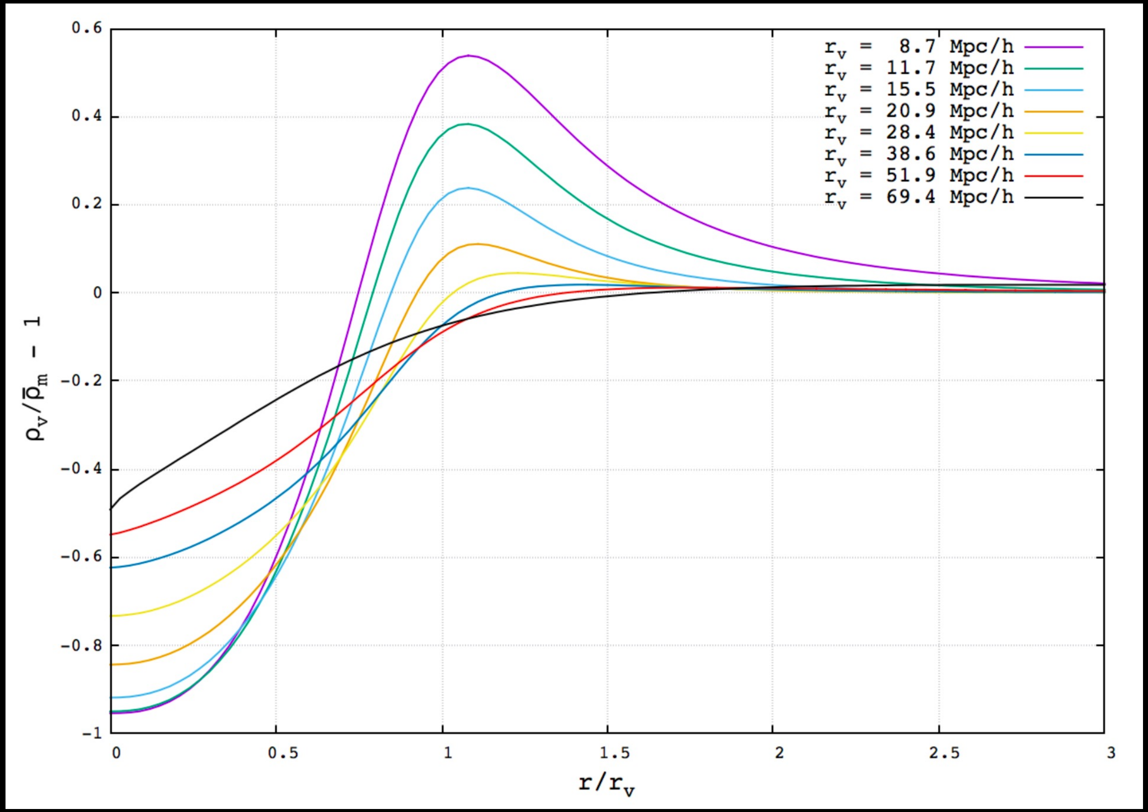


Mass function



Density profile





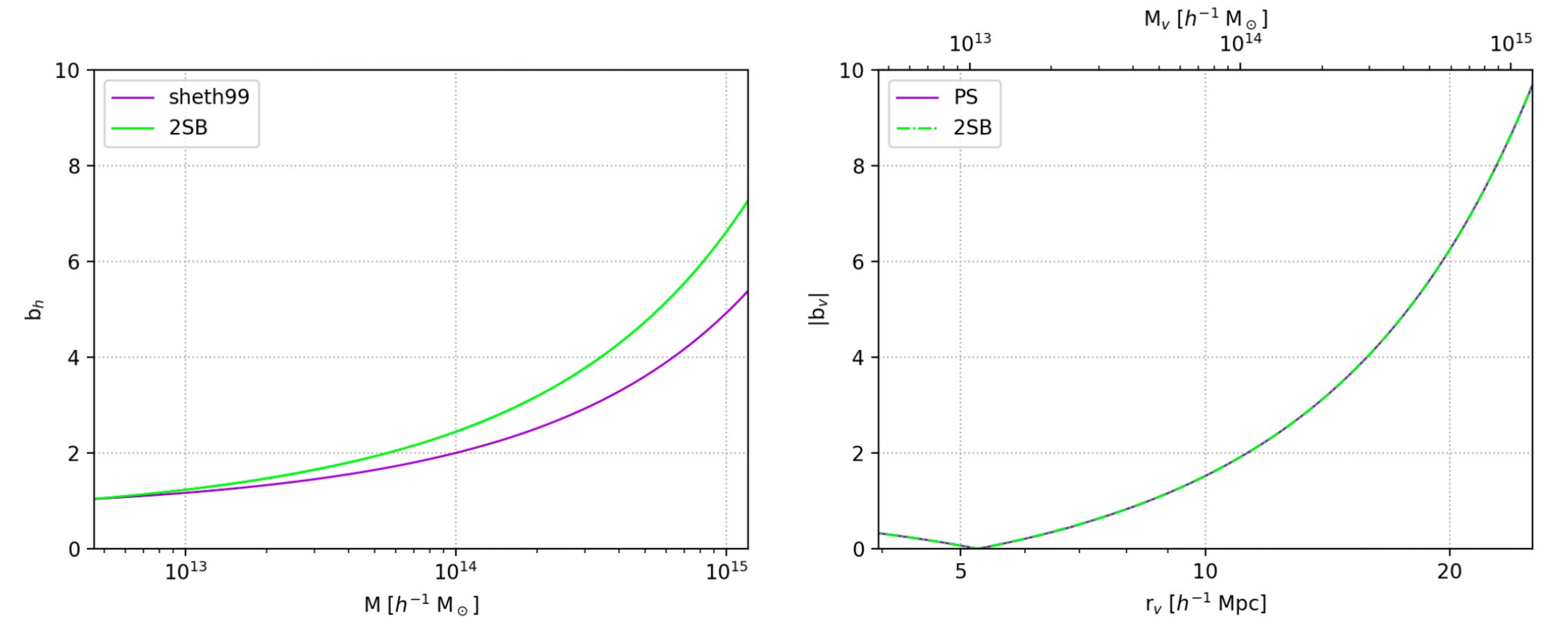
Halo: Navarro-Frenk-White

Void: Hamaus-Sutter-Wandelt

Bias

$$\delta_{h/v}(x) = b_{h/v}(M,z)\,\delta(x)$$

Halo/void density constrast — Bias — Matter density constrast

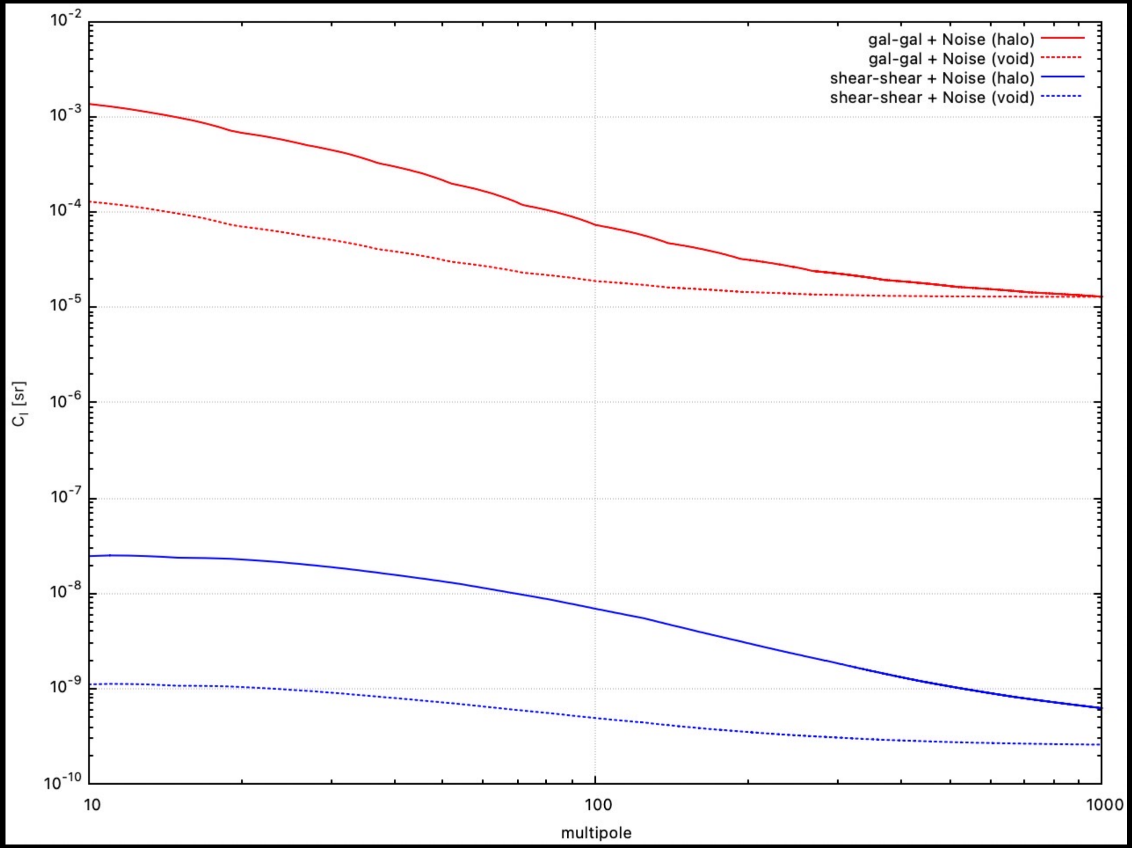


Halo bias

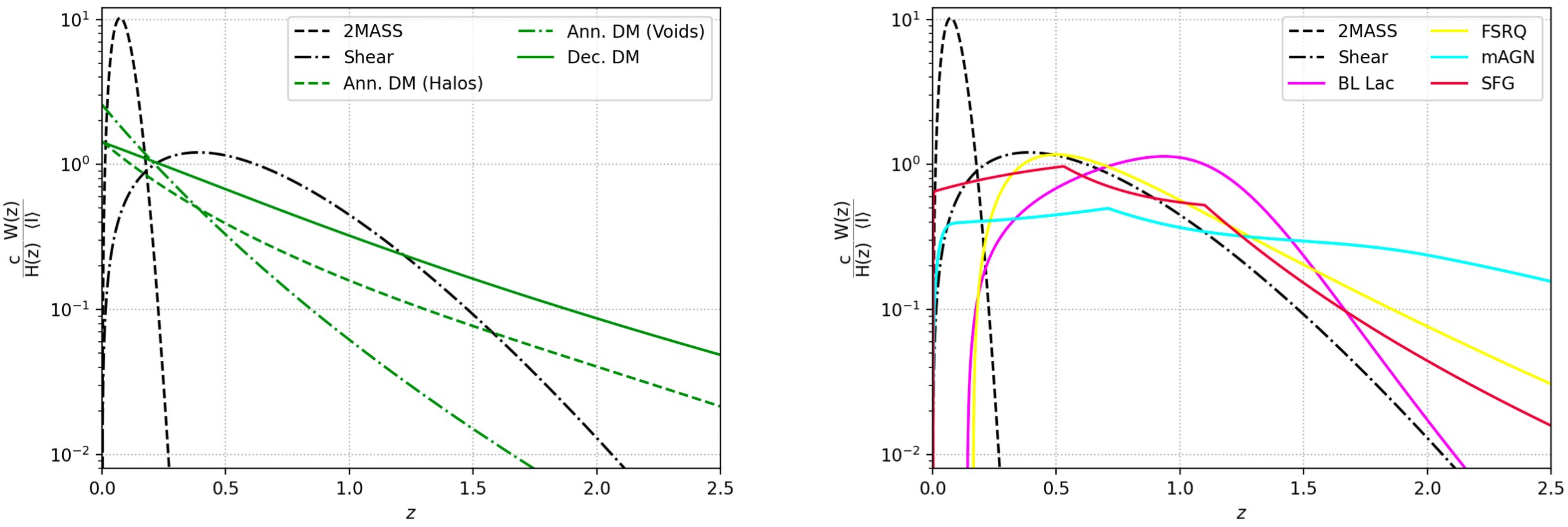
Void bias

Variance of the signal

$$\Delta C_\ell^{g\times\gamma} = \sqrt{\frac{1}{(2\ell+1)\,f_{sky}}\left[\left(C_\ell^{g\times\gamma}\right)^2 + \left(C_\ell^{\gamma\gamma} + \frac{N_\gamma}{B_{\ell,\gamma}^2}\right)\left(C_\ell^{g\times g} + \frac{N_g}{B_{\ell,g}^2}\right)\right]}$$

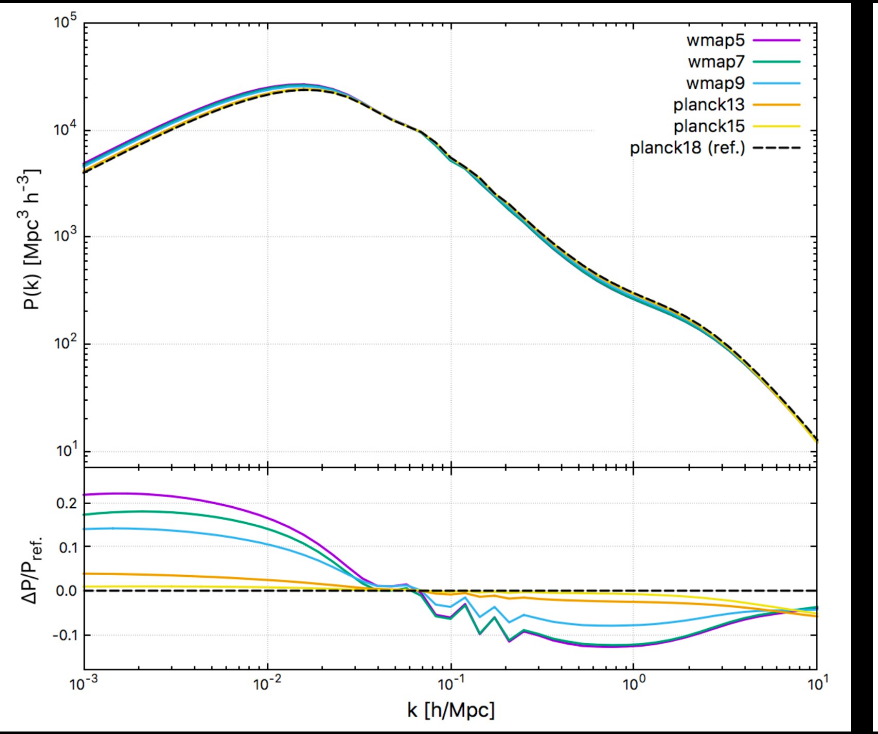


Window functions

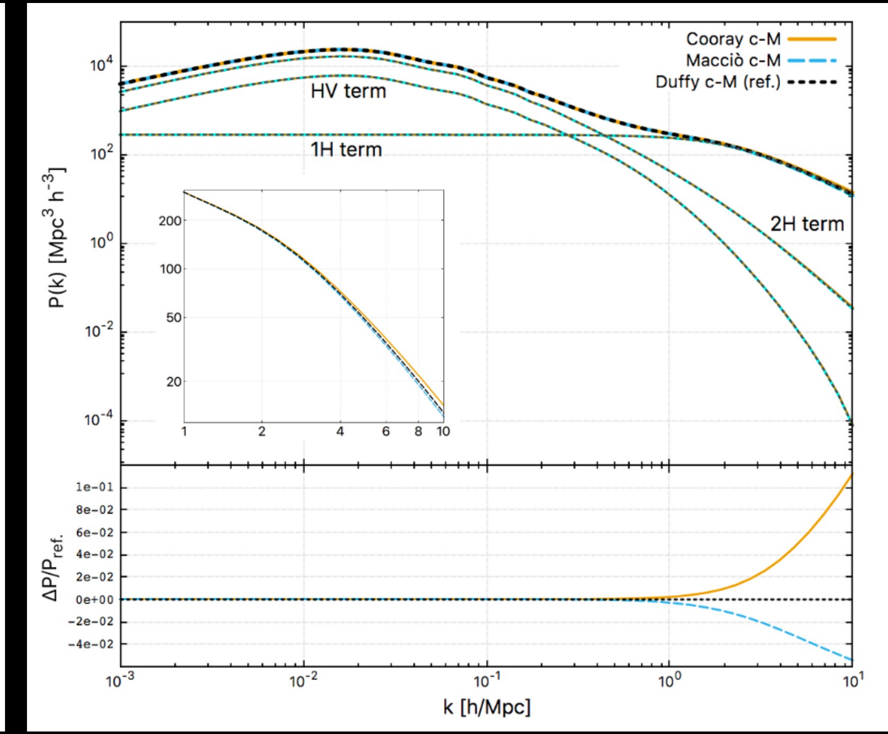


Model dependencies

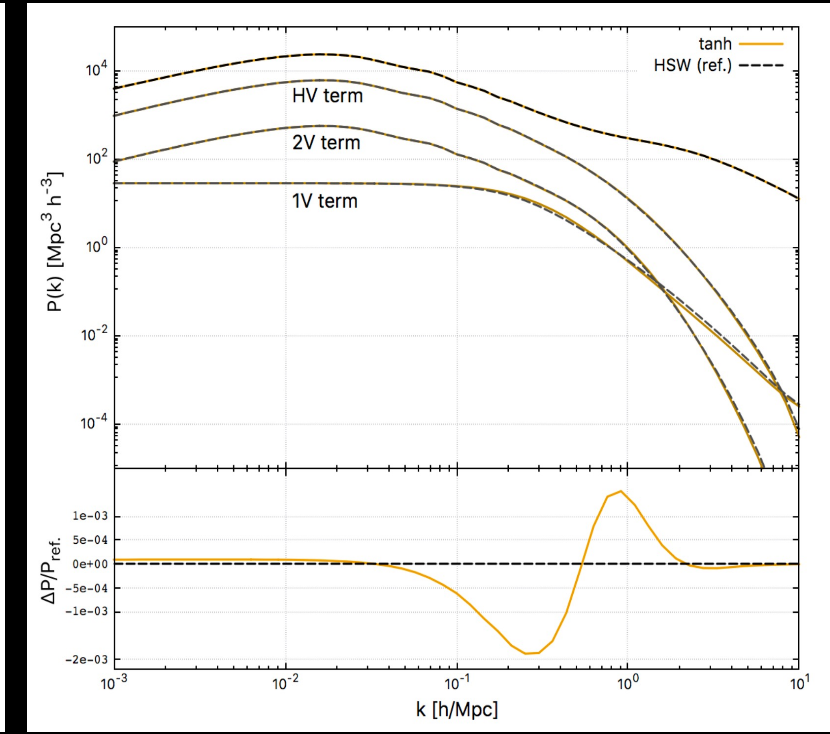
Cosmology



Concentration



Void profile



Statistical analysis

$$C_\ell = p\,\tilde{C}_\ell^{\rm DM} + A\,\tilde{C}_\ell^{\rm astro}$$

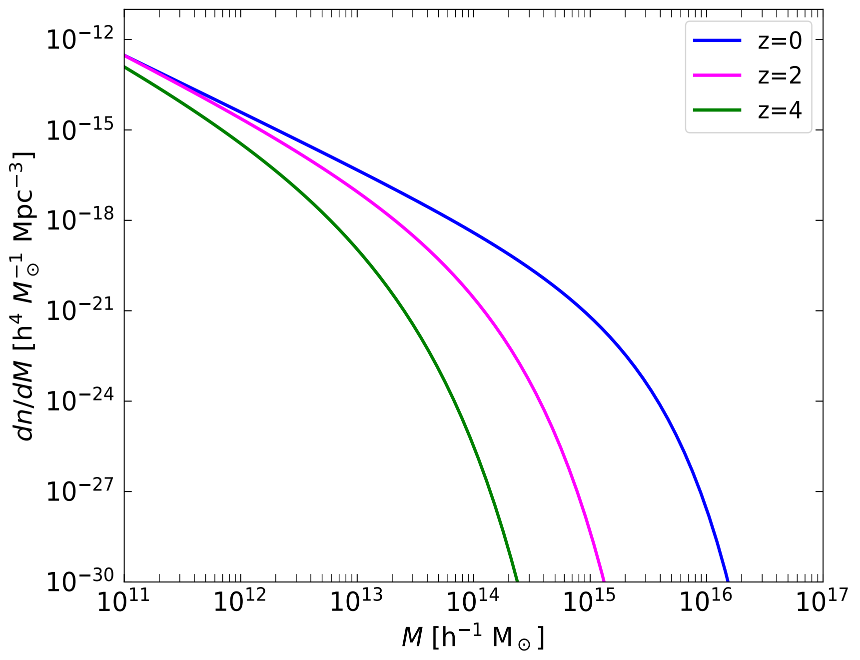
where $p = (3 \times 10^{27}\ {\rm s}/\tau_d)$ is the decay lifetime-normalization with respect to the fiducial cross-correlation for DM computed with $\tau_d = 3 \times 10^{27}$ s and A is a free normalization for the total astrophysical signal computed with our fiducial model (see Appendix A). With

$$F = \begin{pmatrix} \sum_{\ell,E} \frac{(\tilde{C}_\ell^{\rm DM})^2}{\sigma^2} & \sum_{\ell,E} \frac{\tilde{C}_\ell^{\rm DM}\tilde{C}_\ell^{\rm astro}}{\sigma^2} \\ \sum_{\ell,E} \frac{\tilde{C}_\ell^{\rm DM}\tilde{C}_\ell^{\rm astro}}{\sigma^2} & \sum_{\ell,E} \frac{(\tilde{C}_\ell^{\rm astro})^2}{\sigma^2} \end{pmatrix}$$

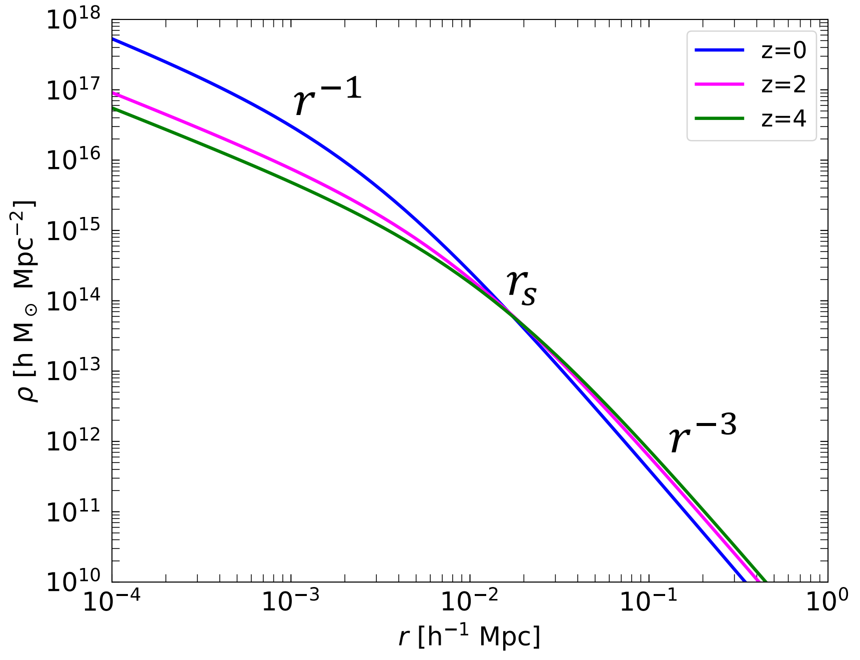
$$\sigma(\theta_a) = \sqrt{(F^{-1})_{aa}}$$

$$\theta_a^{\rm bound} = n \times \sigma(\theta_a)$$

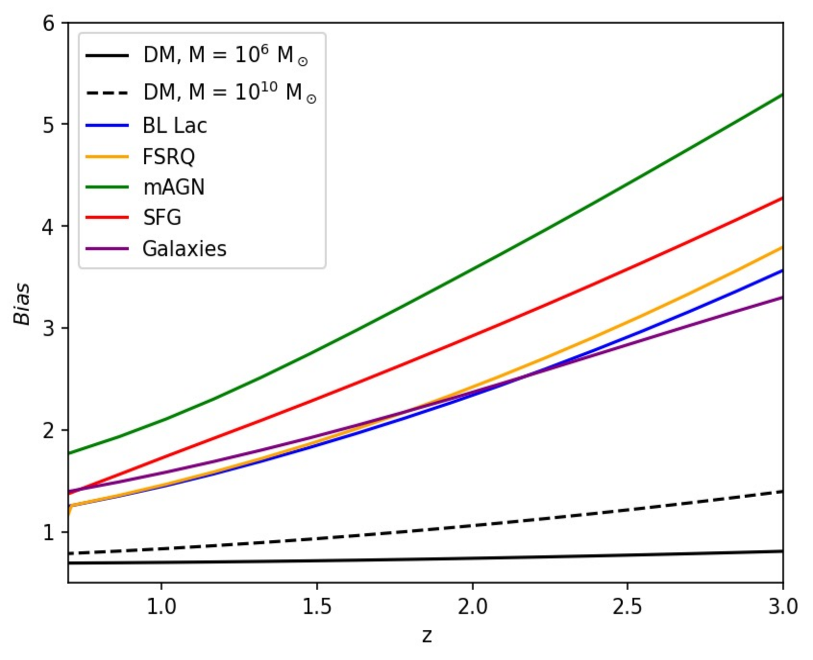
Halo model



Halo mass function: Sheth-Tormen

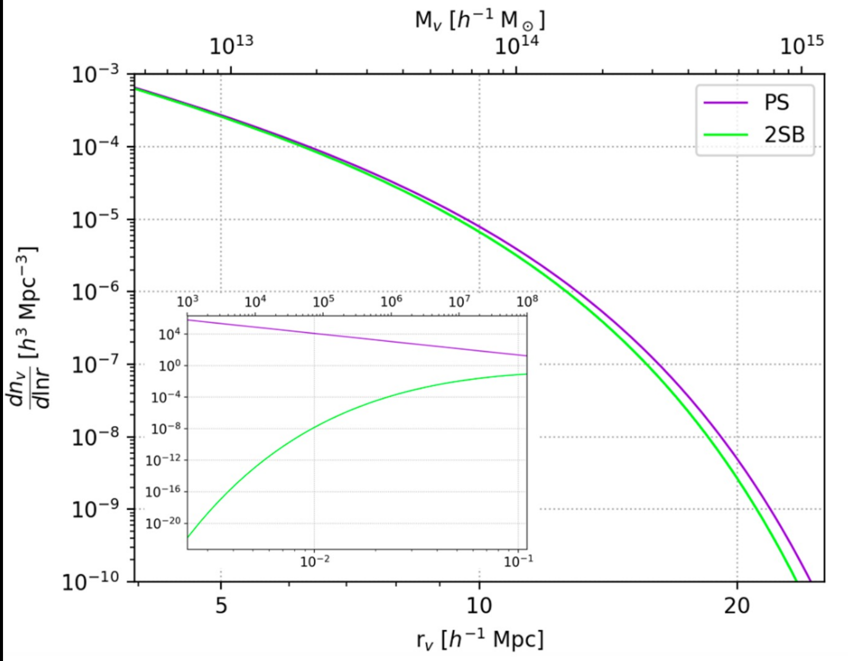


Density profile: NFW

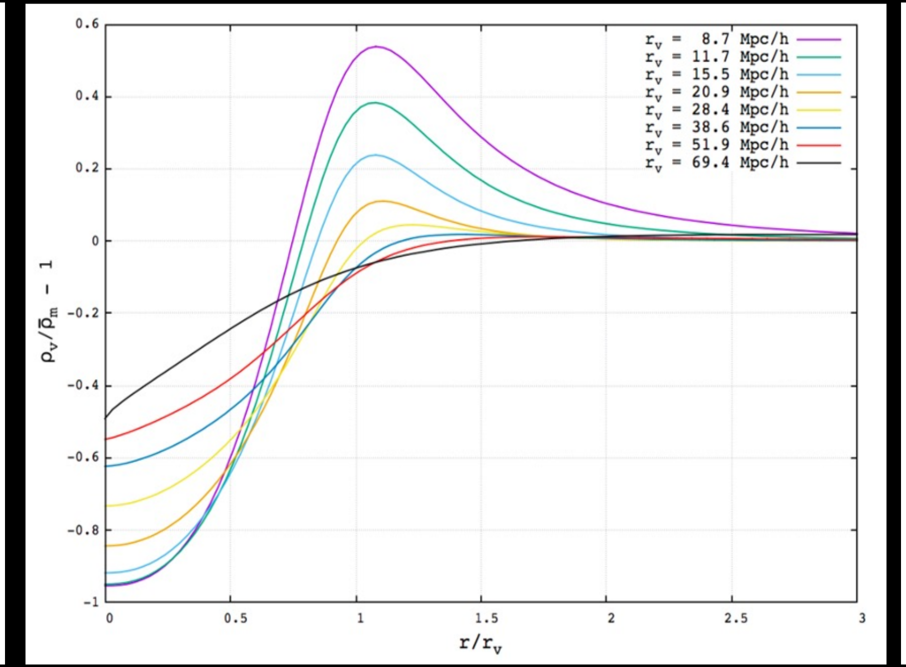


Bias

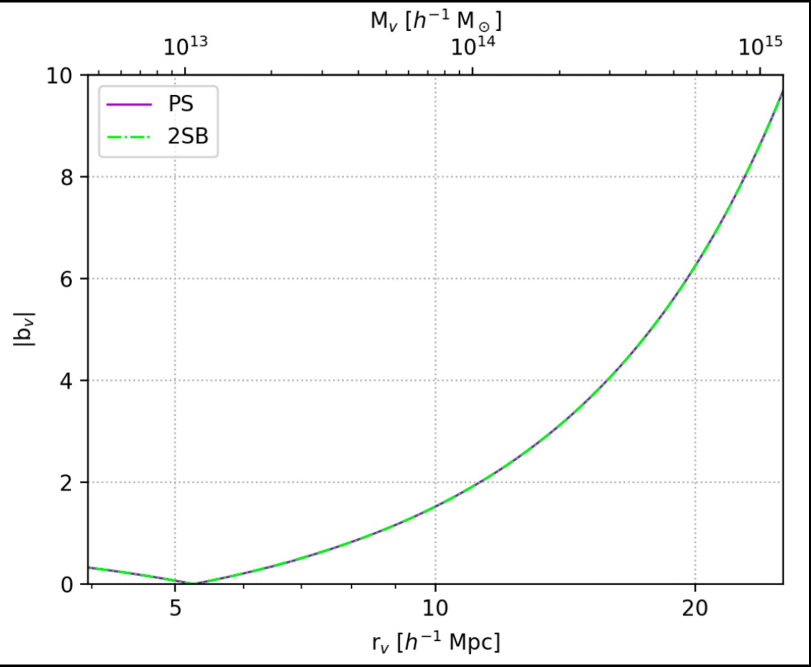
Halo-Void model



Void mass function



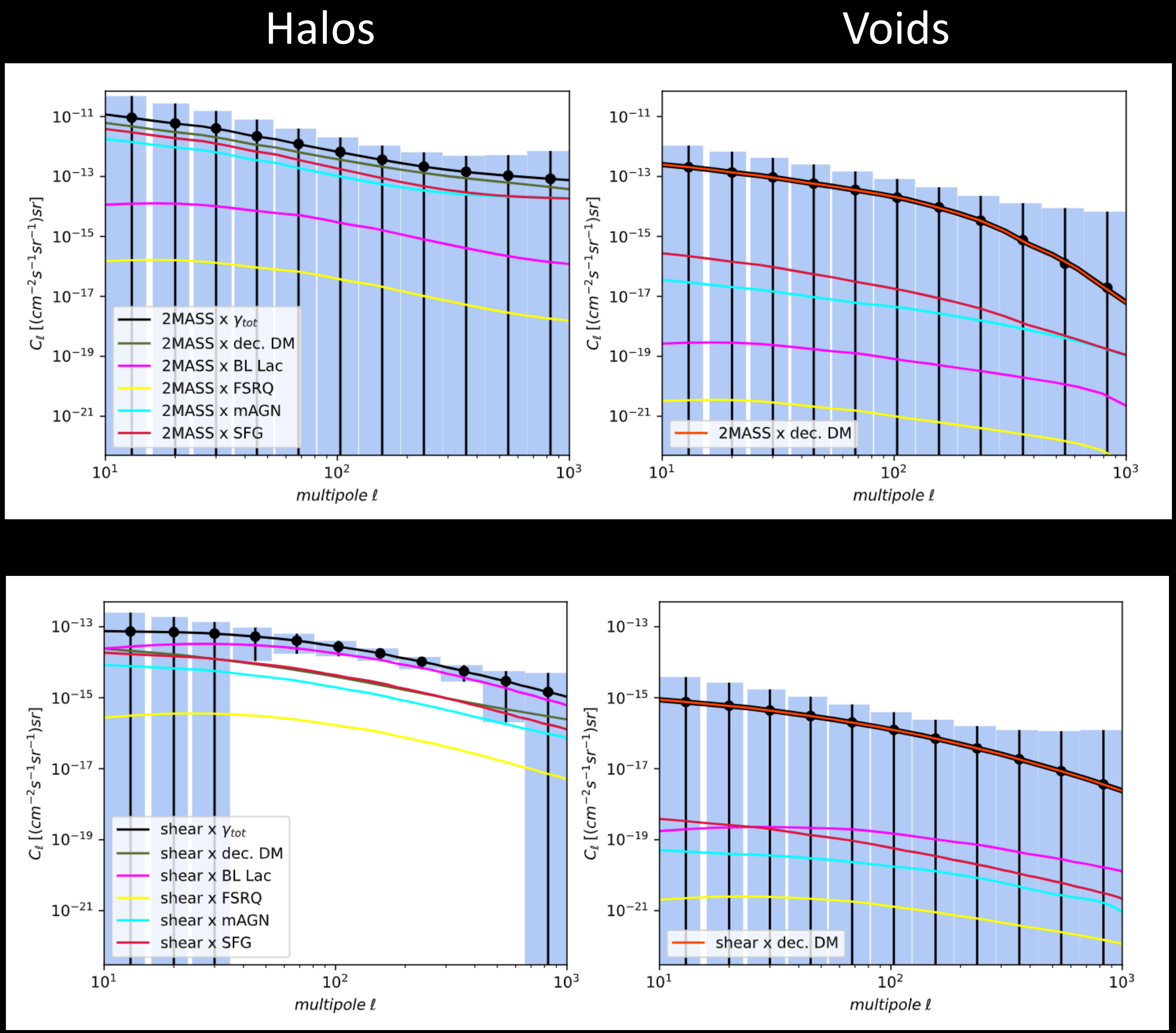
Void Density profile:
Hamaus-Sutter-Wandelt



Void bias

R. Voivodic et al, JCAP 10 (2020) 033, arXiv: 2003.06411

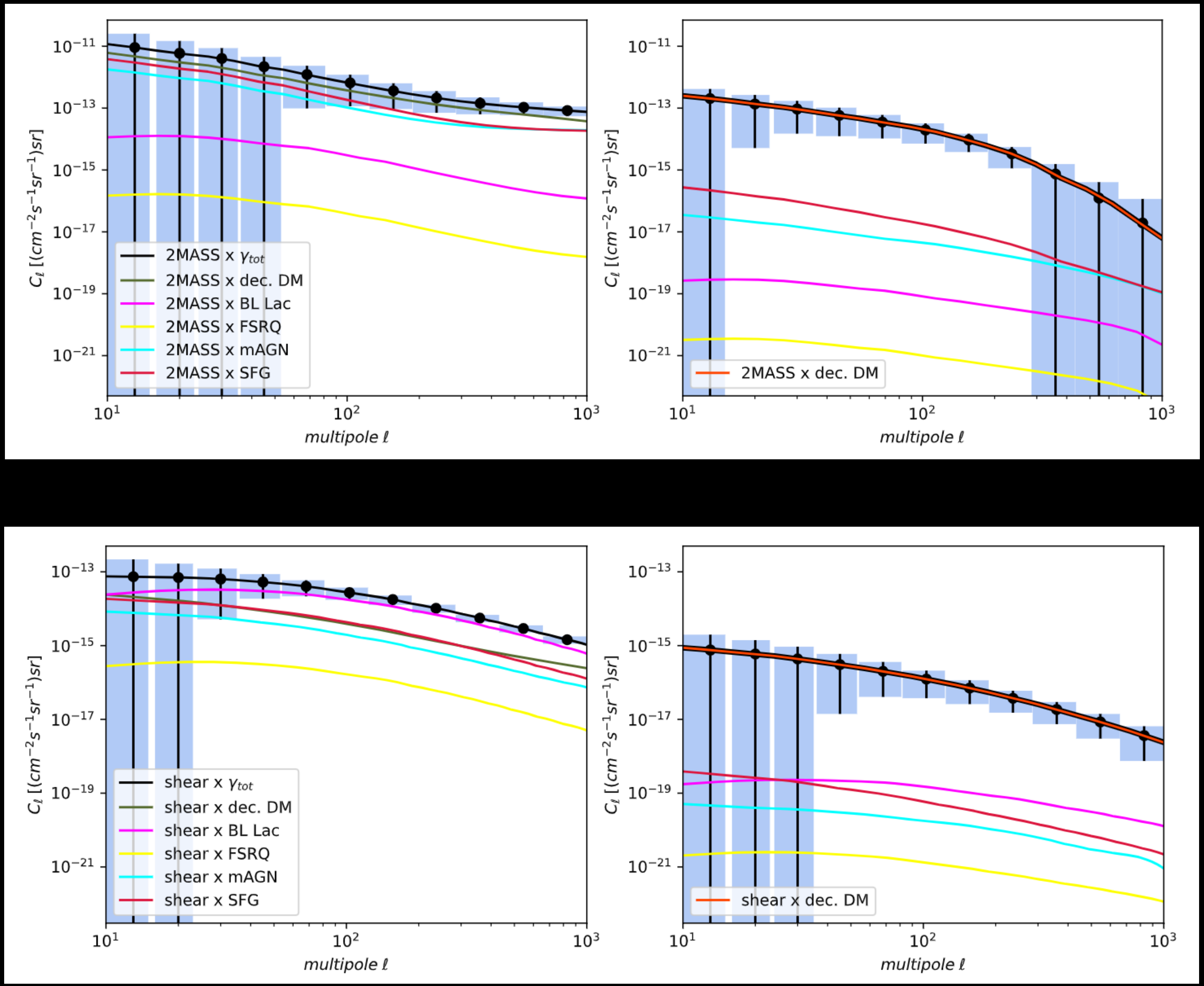
Angular Power Spectrum



Fermissimo

Halos

Voids



Gamma-ray flux from dark matter

Decaying dark matter:

$$\frac{d\phi}{dE_\gamma\, d\Omega}(E_\gamma, \theta) = \frac{1}{4\pi} \frac{1}{\tau\, m_{\mathrm{DM}}} \frac{dN}{dE_\gamma}(E_\gamma)\, D(\theta)$$

$$D(\theta) = \int_{l.o.s} \rho(s(r,\theta))ds$$

Particle properties

Energy spectrum

D-factor

Annihilating dark matter:

$$\frac{d\phi}{dE_\gamma\, d\Omega}(E_\gamma, \theta) = \frac{1}{4\pi} \frac{\langle \sigma_{ann} v \rangle}{2m_{DM}^2} \frac{dN}{dE_\gamma} J(\theta)$$

$$J(\theta) = \int_{l.o.s} \rho^2(s(r,\theta))ds$$

Halo-Void Model

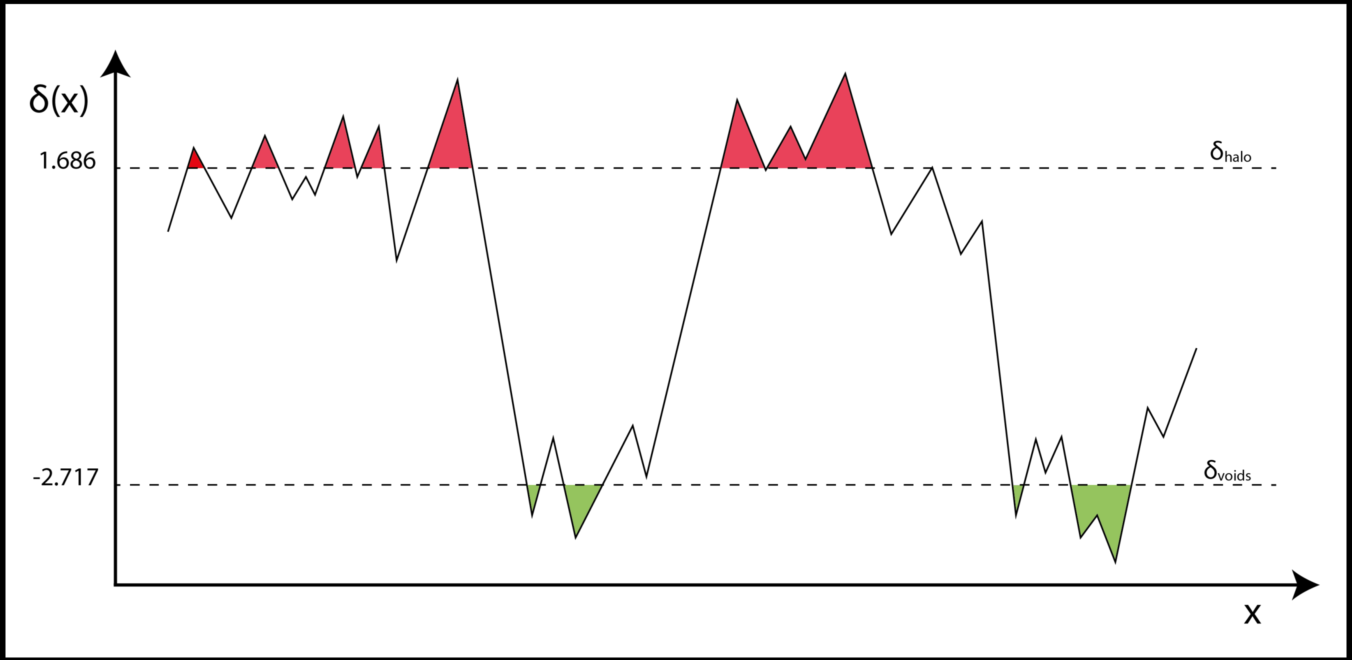
$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$$

Density contrast

$$\delta(\vec{x}, t) > \delta_{th,halo}$$

$$\delta(\vec{x}, t) < \delta_{th,void}$$

The region collapses and a halo/void forms

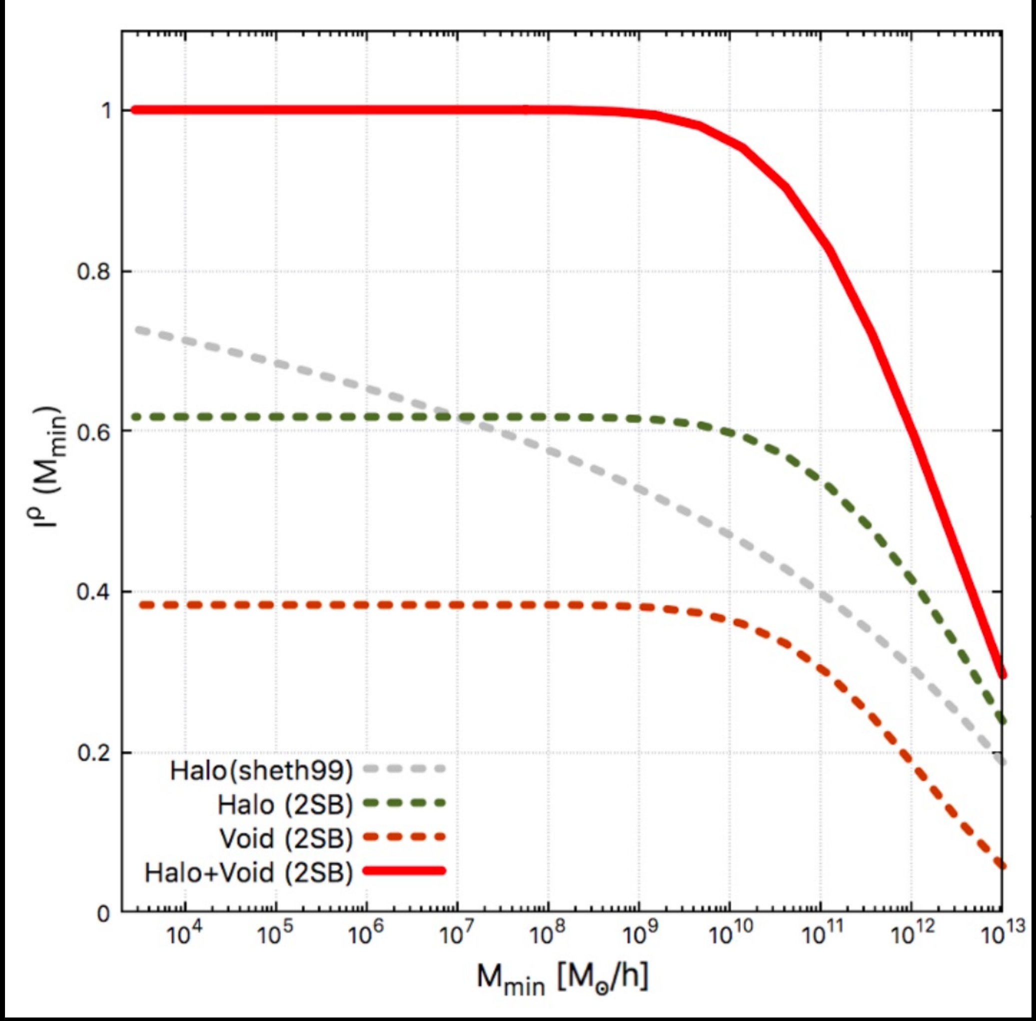


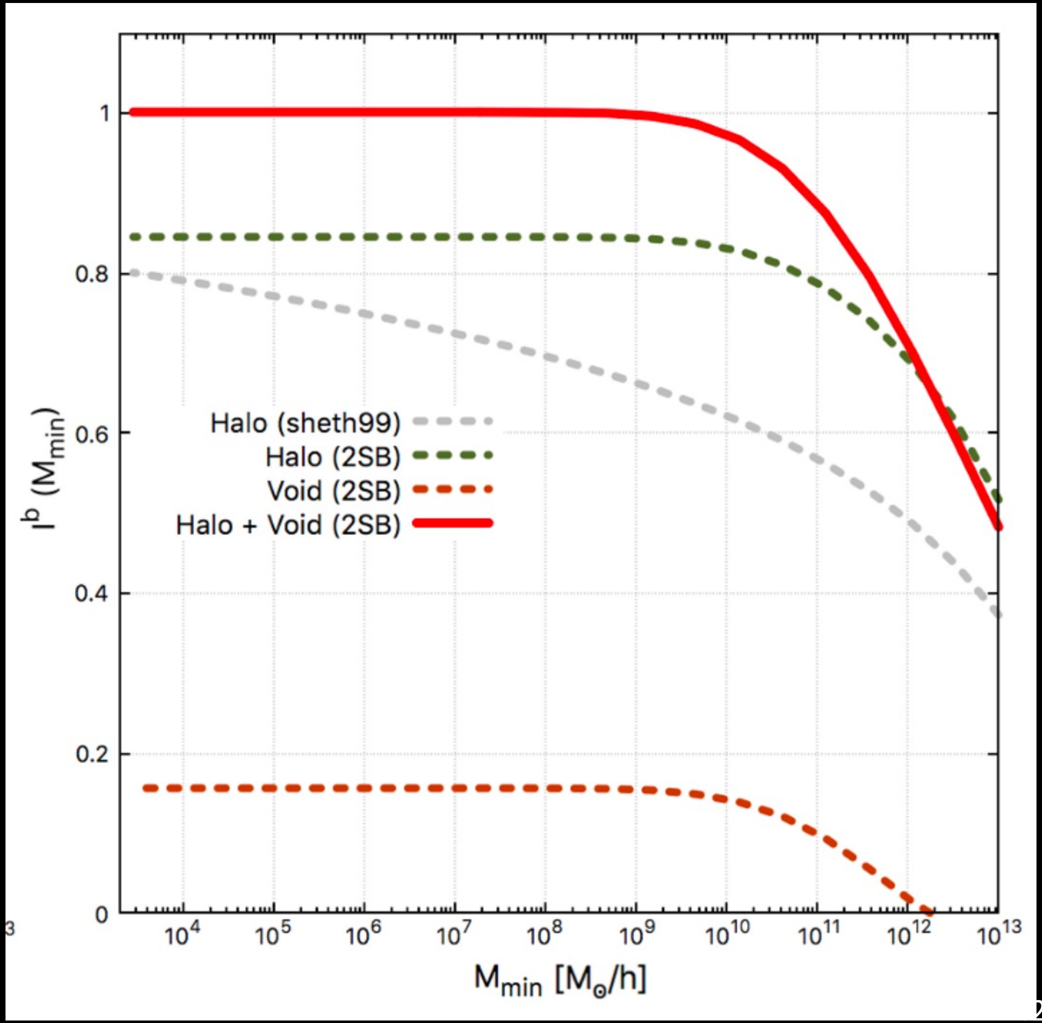
Halo/Void Bias

Convergence problem

$$I^{\rho} \stackrel{\text{def.}}{=} \frac{\overline{\rho}}{\overline{\rho}_m} = \int_{M_{min}}^{\infty} d\ln M \, \frac{M}{\overline{\rho}_m} \frac{dn}{d\ln M} = 1$$

$$I^{b} \stackrel{\text{def.}}{=} \overline{b} = \int_{M_{min}}^{\infty} d\ln M \, \frac{M}{\overline{\rho}_m} \frac{dn}{d\ln M} b(M) = 1$$





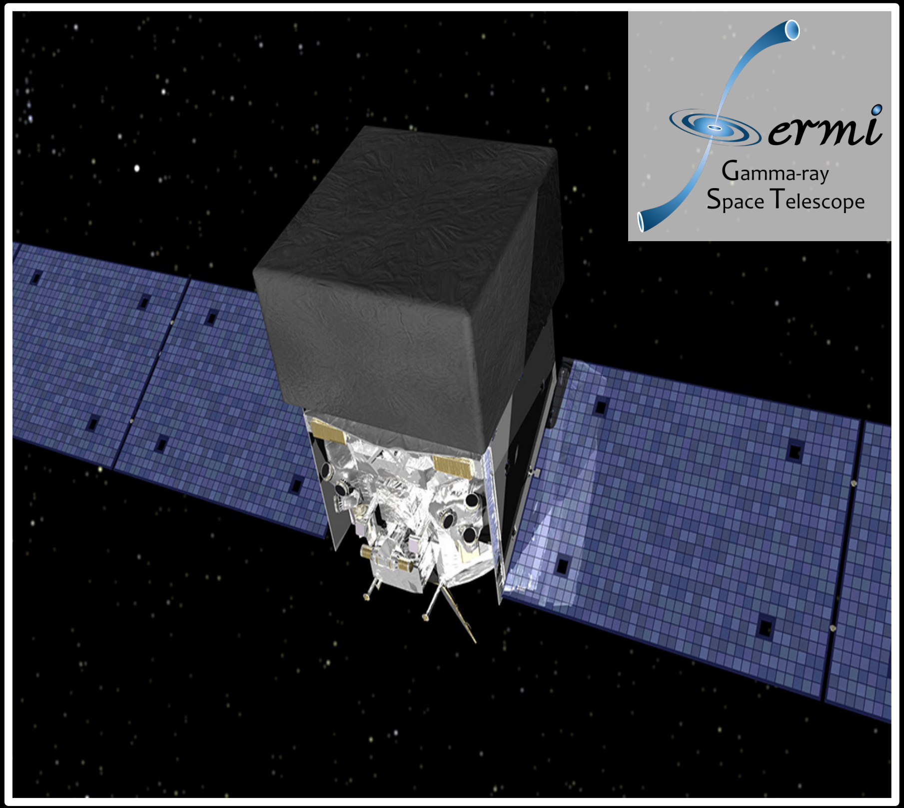
Fermi Gamma-Ray Space Telescope

The Fermi Gamma-Ray Space Telescope is the most sensitive gamma-ray space observatory on orbit

Main instrument on board: Large Area Telescope (LAT)

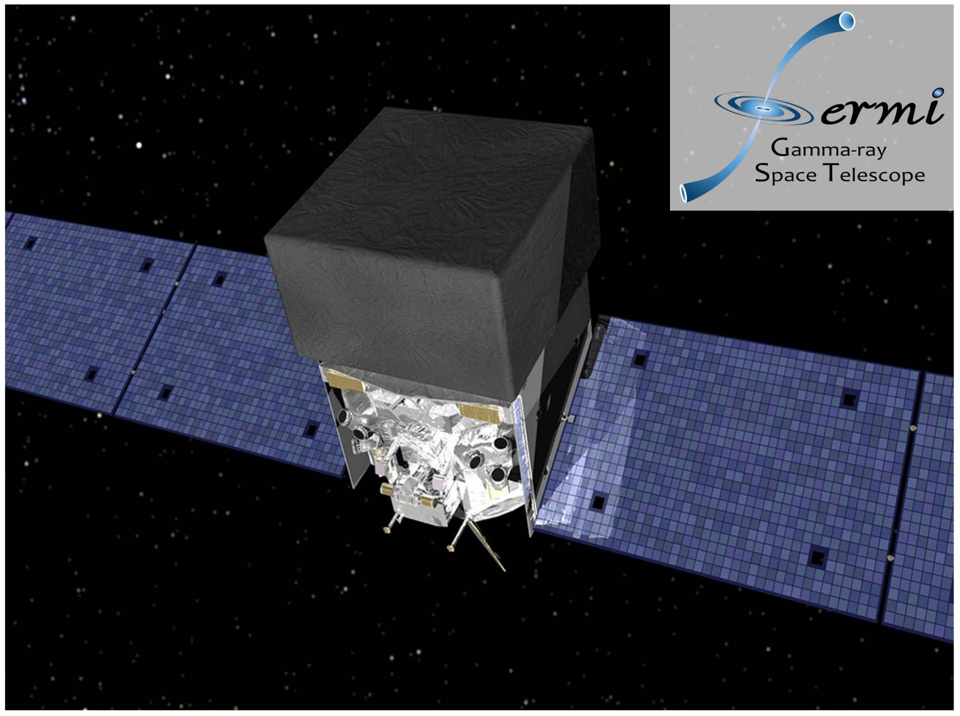
Mission objectives: study astrophysical and cosmological phenomena, such as high-energy sources (e.g. AGN, pulsars) and dark matter

Launch date: 2008



Fermi-LAT specifications

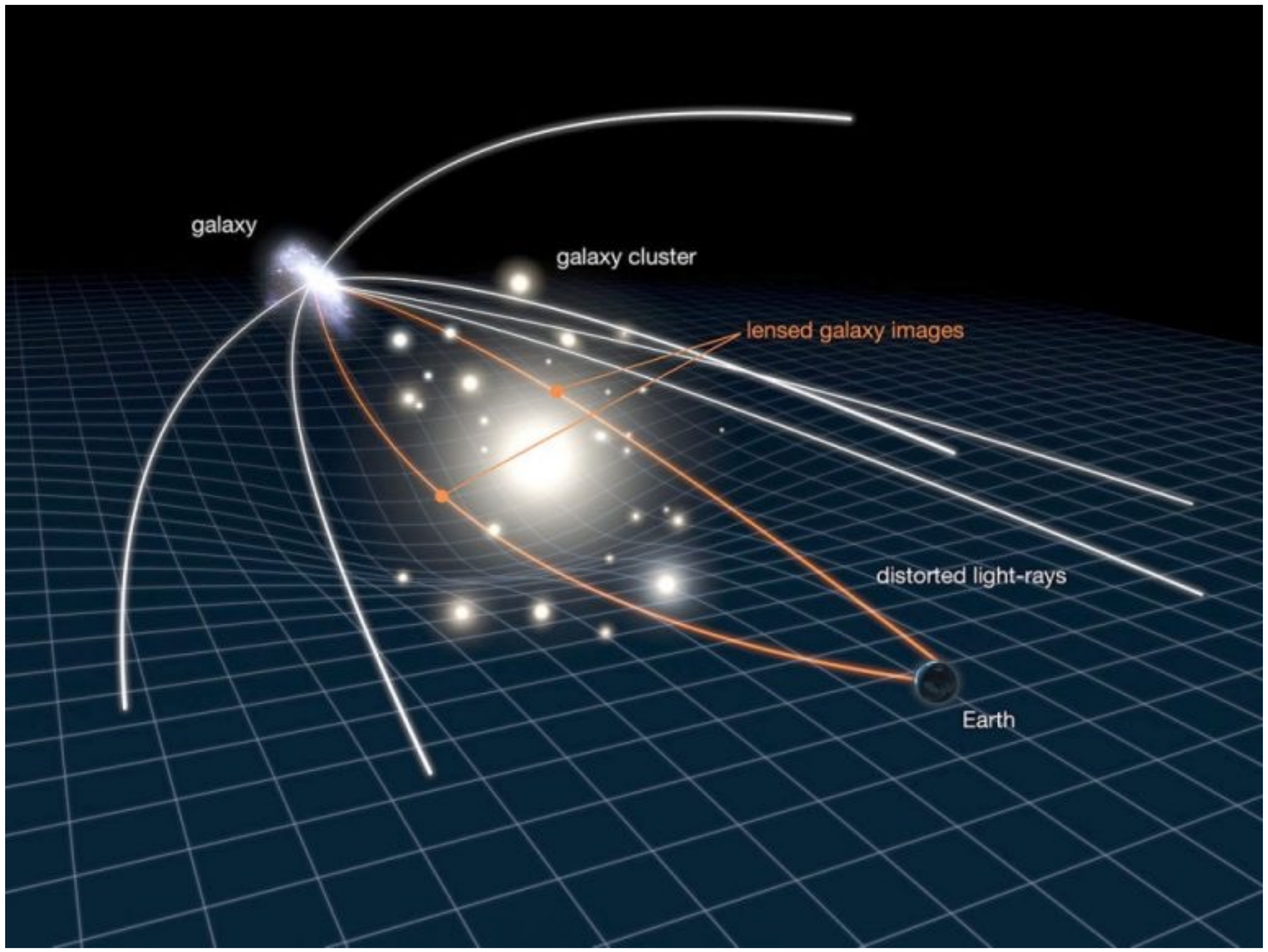
Bin	$E_{\min}$ (GeV)	$E_{\max}$ (GeV)	C_N ($\mathrm{cm}^{-4}\ \mathrm{s}^{-2}\ \mathrm{sr}^{-1}$)	f_{sky}	$\sigma_0^{\mathrm{Fermi}}$ (deg)	E_b (GeV)
1	0.5	1.0	1.056×10^{-17}	0.134	0.87	0.71
2	1.0	1.7	3.548×10^{-18}	0.184	0.50	1.30
3	1.7	2.8	1.375×10^{-18}	0.398	0.33	2.18
4	2.8	4.8	8.324×10^{-19}	0.482	0.22	3.67
5	4.8	8.3	3.904×10^{-19}	0.549	0.15	6.31
6	8.3	14.5	1.768×10^{-19}	0.574	0.11	11.0
7	14.5	22.9	6.899×10^{-20}	0.574	0.09	18.2
8	22.9	39.8	3.895×10^{-20}	0.574	0.07	30.2
9	39.8	69.2	1.576×10^{-20}	0.574	0.07	52.5
10	69.2	120.2	6.205×10^{-21}	0.574	0.06	91.2
11	120.2	331.1	3.287×10^{-21}	0.597	0.06	199.5
12	331.1	1000	5.094×10^{-22}	0.597	0.06	575.4



	Fermissimo
Exposure	$2 \cdot \exp_{\mathrm{Fermi}}$
Angular resolution	$0.2 \cdot \sigma_\mathrm{b}^{\mathrm{Fermi}}$

Ackermann et al, PRL 121, 241101 (2018), arXiv:1812.02079

Weak lensing



EUCLID

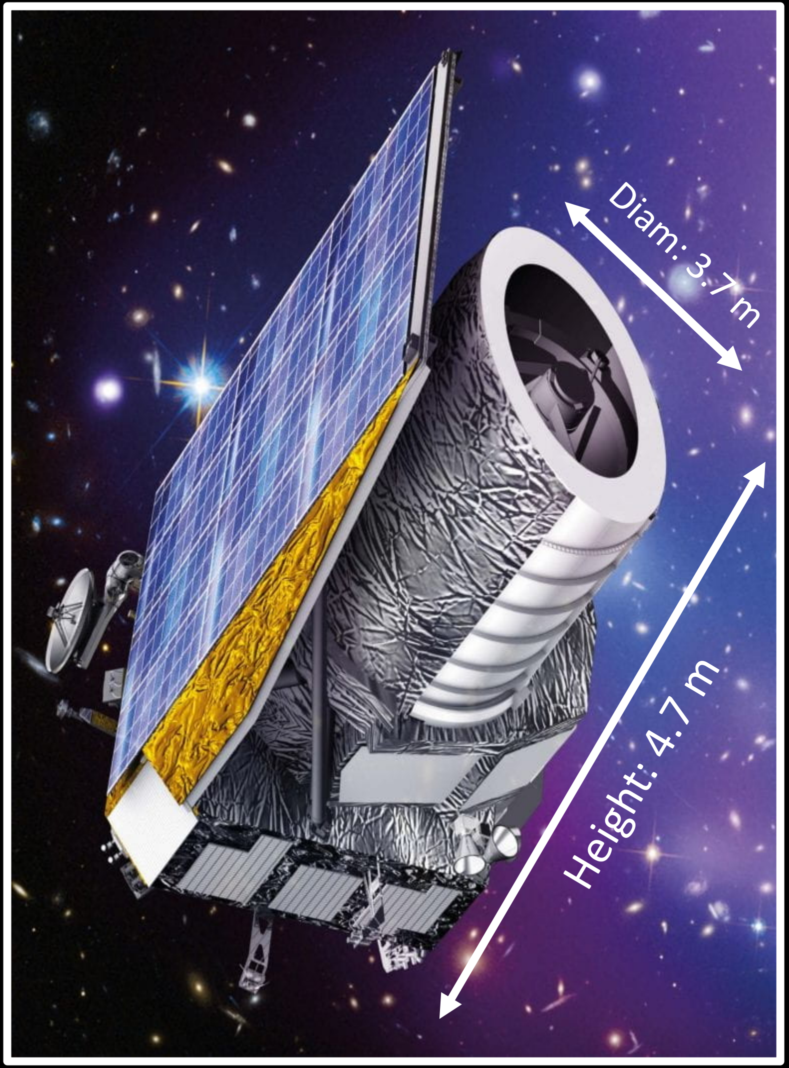
Euclid is a cosmology survey mission, optimised to determine the properties of dark energy and dark matter

Mission objective: 3D map of the Universe up to z=2

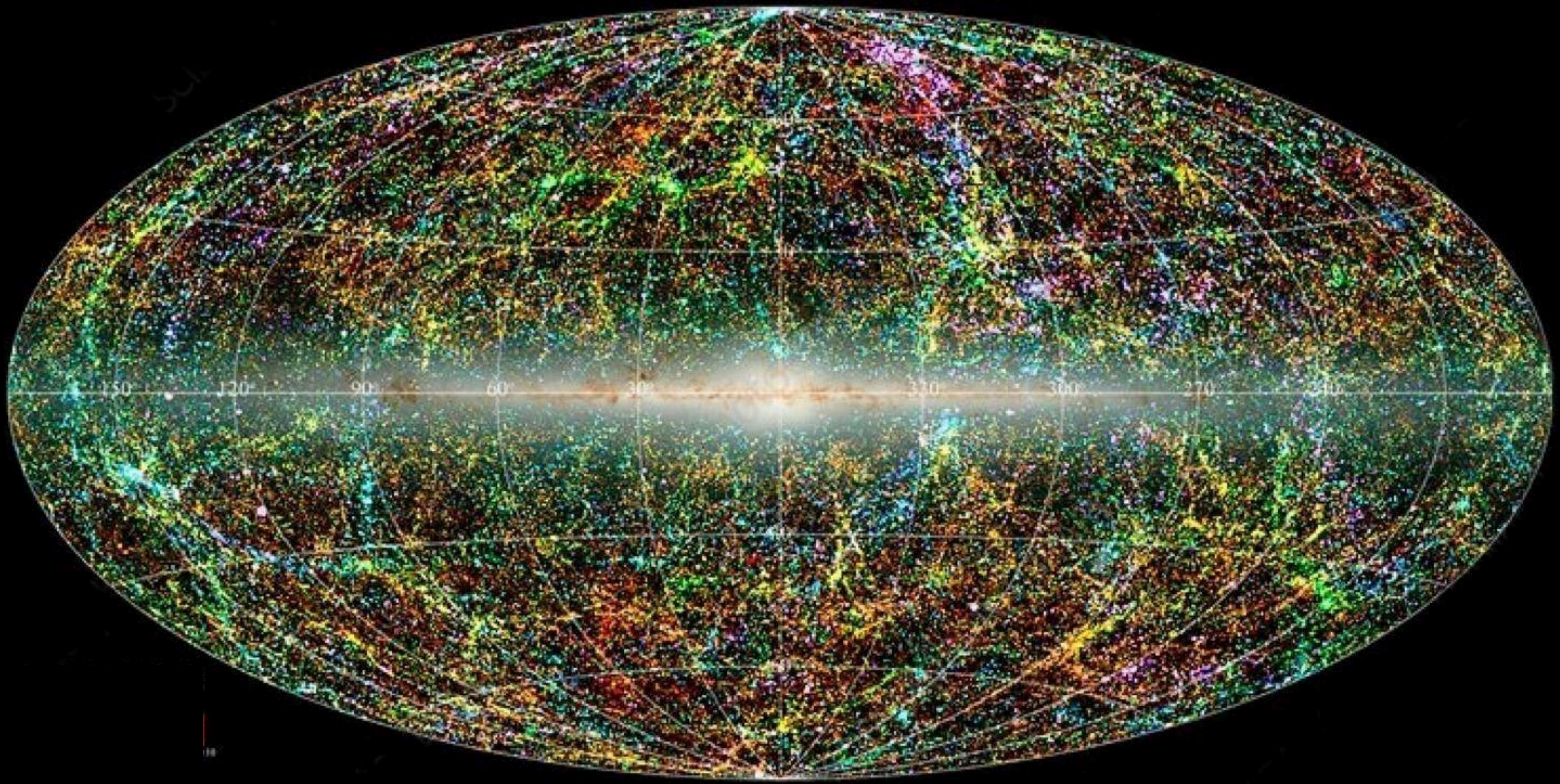
Wavelength: optical & near-infrared light

People: 2000+ scientists, from 100+ institutes

Launch date: 2023



Galaxy catalogues



Two Micron All Sky Survey (2MASS)

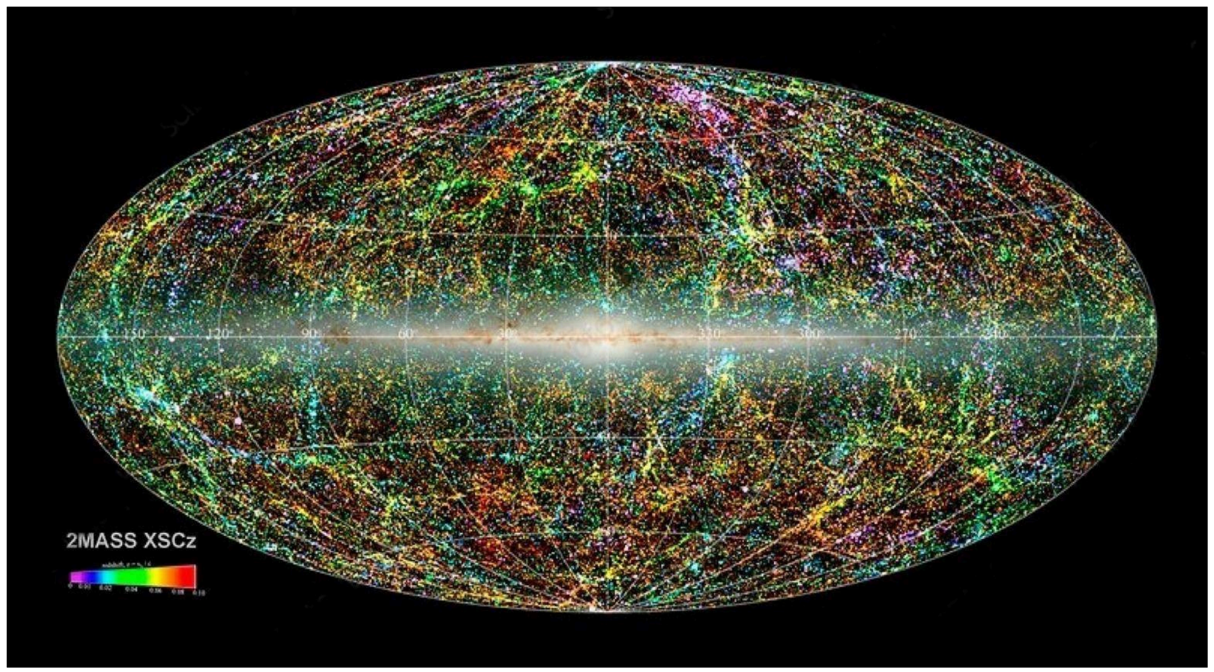
2MASS catalogue

Two Micron All-Sky Survey (2MASS) is an astronomical survey of the whole sky

Wavelength: infrared light

Astronomical catalog with 400+ million observed objects

Operational years: 1997-2001

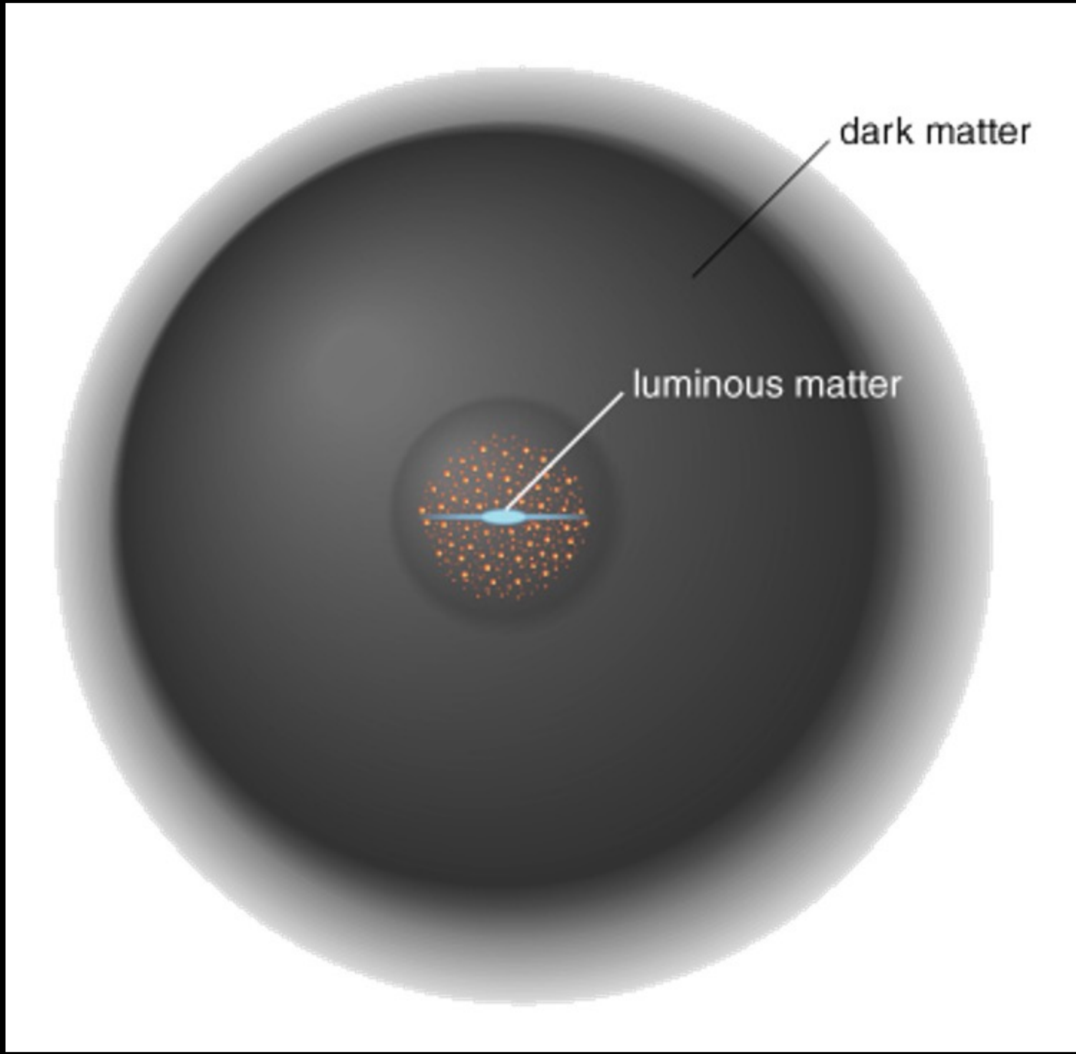


Gravitational tracers

Baryonic matter (galaxies, clusters of galaxies, neutral hydrogen) resides within dark matter halos

They trace the dark matter distribution

- Statistics (galaxies and clusters > weak lensing)
- Biased (galaxies, clusters, HI) vs unbiased (weak lensing)
- Redshift distribution



Variance of the signal

Noise of the detector

$$\Delta C_\ell^{g\times\gamma} = \sqrt{\frac{1}{(2\ell+1)\,f_{sky}}\left[\left(C_\ell^{g\times\gamma}\right)^2 + \left(C_\ell^{\gamma\gamma} + \frac{N_\gamma}{B_{\ell,\gamma}^2}\right)\left(C_\ell^{g\times g} + \frac{N_g}{B_{\ell,g}^2}\right)\right]}$$

Sky coverage

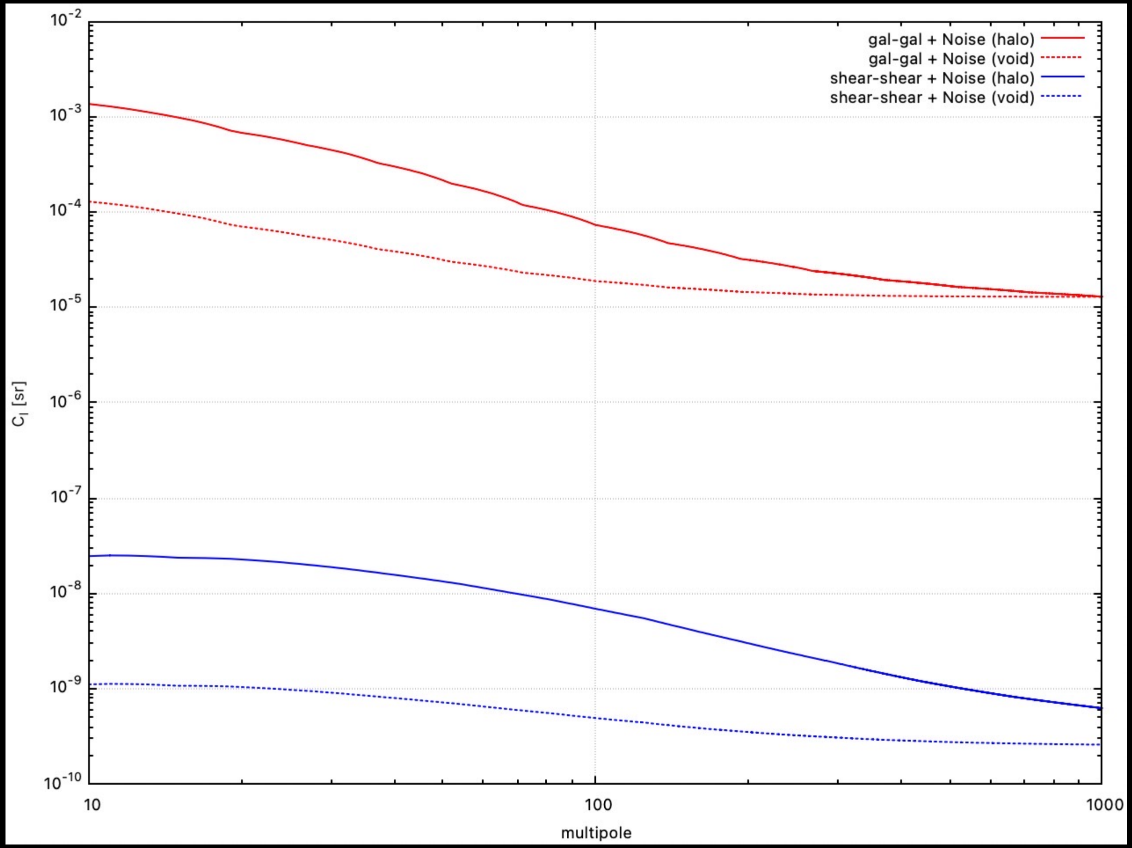
Cross-correlation signal

Auto-correlation signal

Beam window function

Variance of the signal

$$\Delta C_\ell^{g\times\gamma} = \sqrt{\frac{1}{(2\ell+1)\,f_{sky}}\left[\left(C_\ell^{g\times\gamma}\right)^2 + \left(C_\ell^{\gamma\gamma} + \frac{N_\gamma}{B_{\ell,\gamma}^2}\right)\left(C_\ell^{g\times g} + \frac{N_g}{B_{\ell,g}^2}\right)\right]}$$



Halo-Void Dust Model

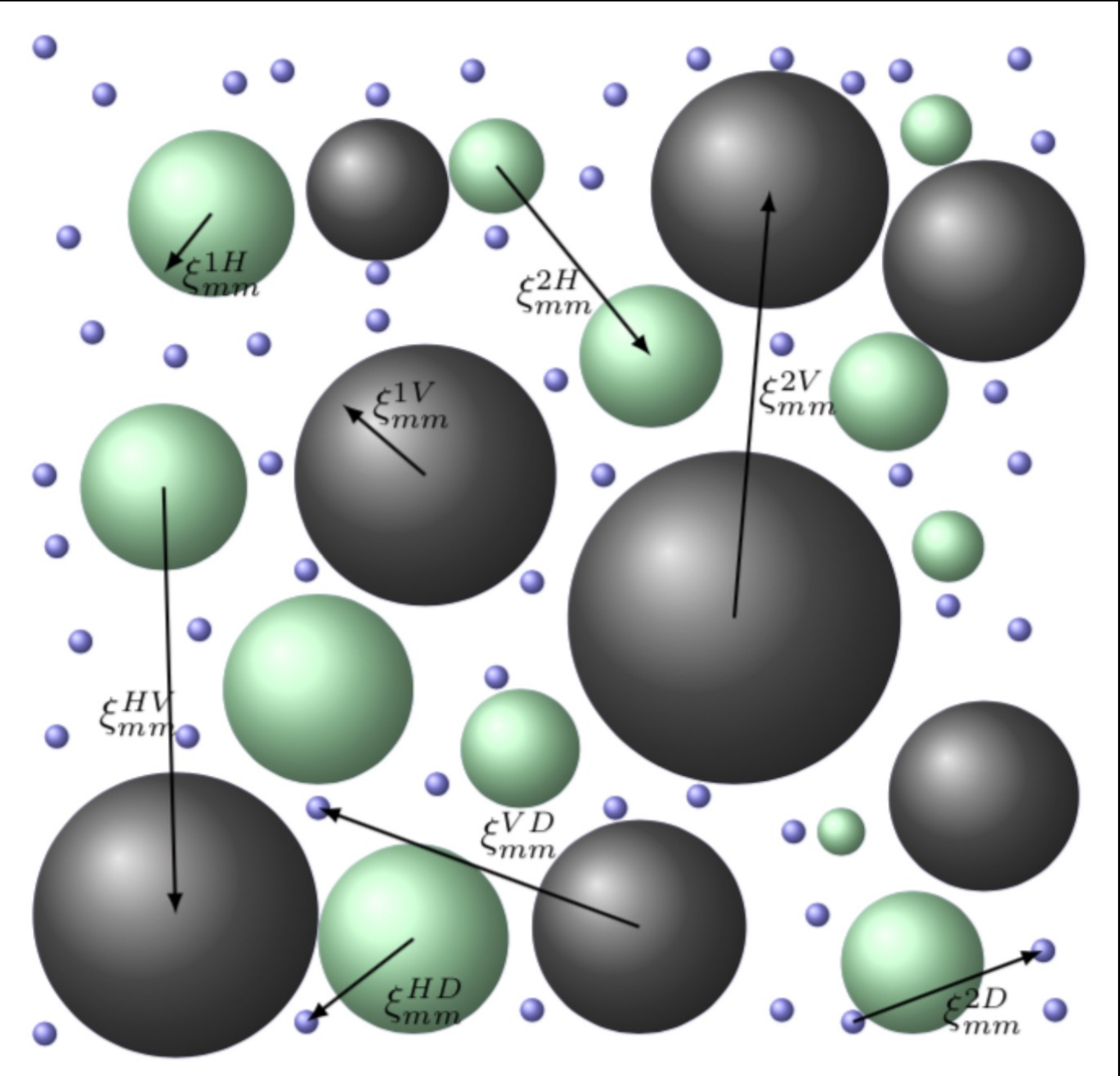
$$P^{1H}(k) = \frac{1}{\bar{\rho}_m^2} \int \mathrm{d}M \, \frac{\mathrm{d}n_h}{\mathrm{d}M} |\rho_h(k \,|\, M)|^2$$

$$P^{2H}(k) = \frac{1}{\bar{\rho}_m^2} \left[\int \mathrm{d}M \, \frac{\mathrm{d}n_h}{\mathrm{d}M} \rho_h(k \,|\, M) b_h(M) \right]^2 P^L(k)$$

$$P^{1V}(k) = \frac{1}{\bar{\rho}_m^2} \int \mathrm{d}M \, \frac{\mathrm{d}n_v}{\mathrm{d}M} |\rho_v(k \,|\, M)|^2$$

$$P^{2V}(k) = \frac{1}{\bar{\rho}_m^2} \left[\int \mathrm{d}M \, \frac{\mathrm{d}n_v}{\mathrm{d}M} \rho_v(k \,|\, M) b_v(M) \right]^2 P^L(k)$$

$$P^{HV}(k) = \frac{1}{\bar{\rho}_m^2} \int \mathrm{d}M_1 \, \frac{\mathrm{d}n_h}{\mathrm{d}M_1} \rho_h(k \,|\, M_1) b_h(M_1) \int \mathrm{d}M_2 \, \frac{\mathrm{d}n_v}{\mathrm{d}M_2} \rho_v(k \,|\, M_2) b_v(M_2) \, P^L(k)$$



R. Voivodic et al, JCAP 10 (2020) 033, arXiv: 2003.06411

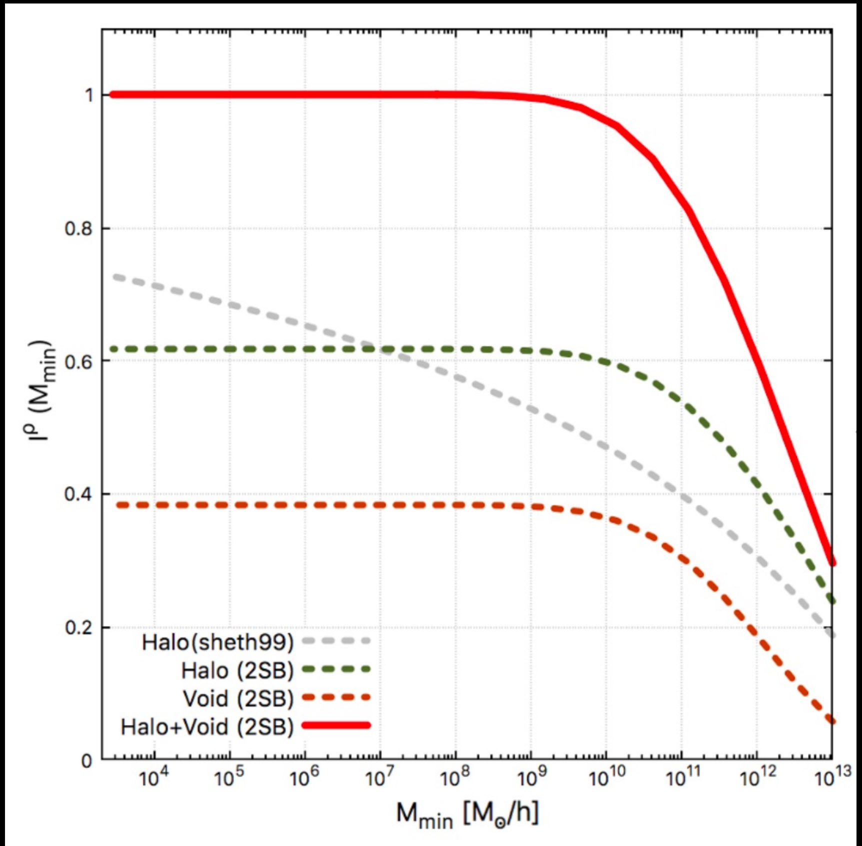
Beyon the Halo Model: convergence problem

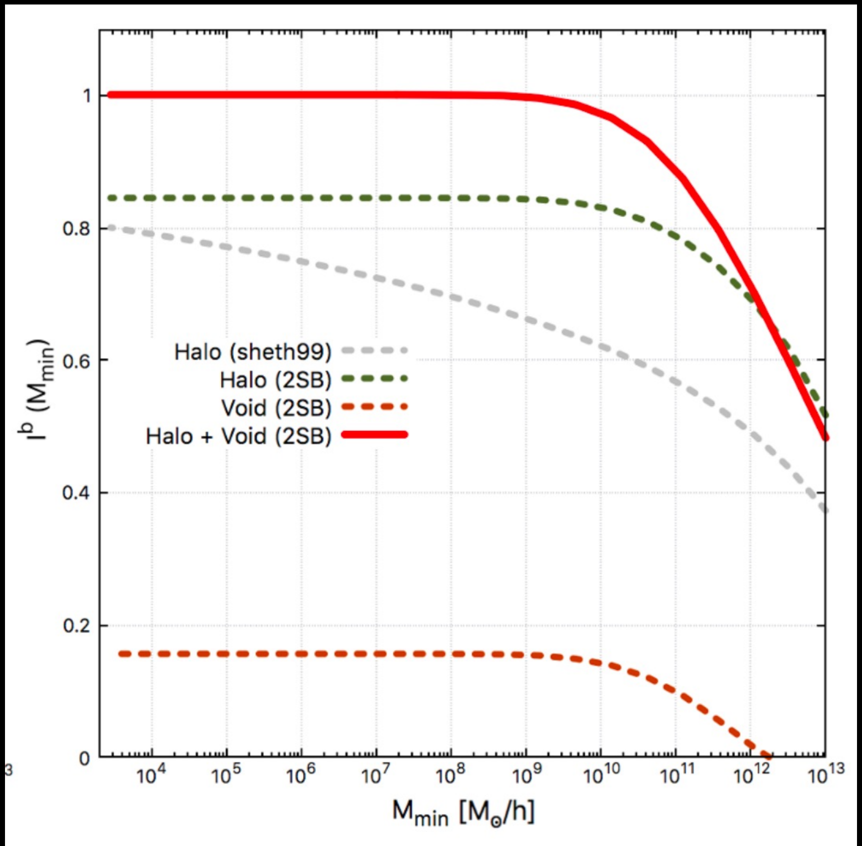
$$I^{\rho} \stackrel{\text{def.}}{=} \frac{\overline{\rho}}{\overline{\rho}_m} = \int_{M_{\min}}^{\infty} d\ln M \, \frac{M}{\overline{\rho}_m} \frac{dn}{d\ln M} = 1$$

$$I^{b} \stackrel{\text{def.}}{=} \overline{b} = \int_{M_{\min}}^{\infty} d\ln M \, \frac{M}{\overline{\rho}_m} \frac{dn}{d\ln M} b(M) = 1$$

0.7

0.8





Angular power spectra