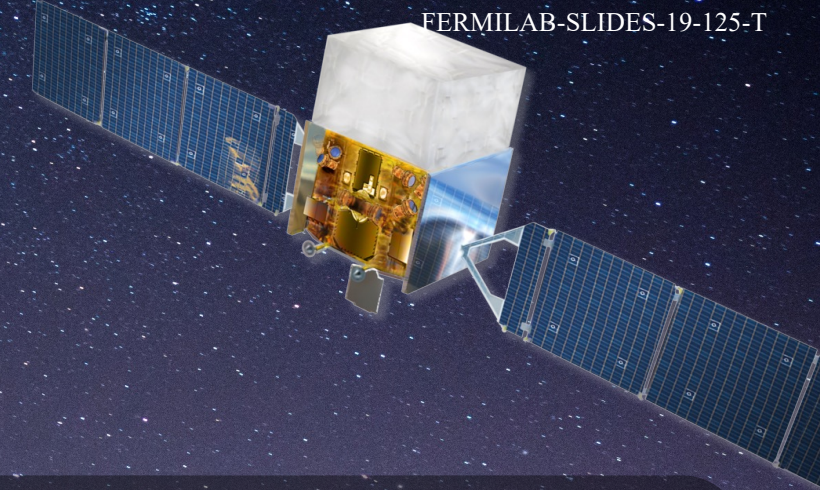




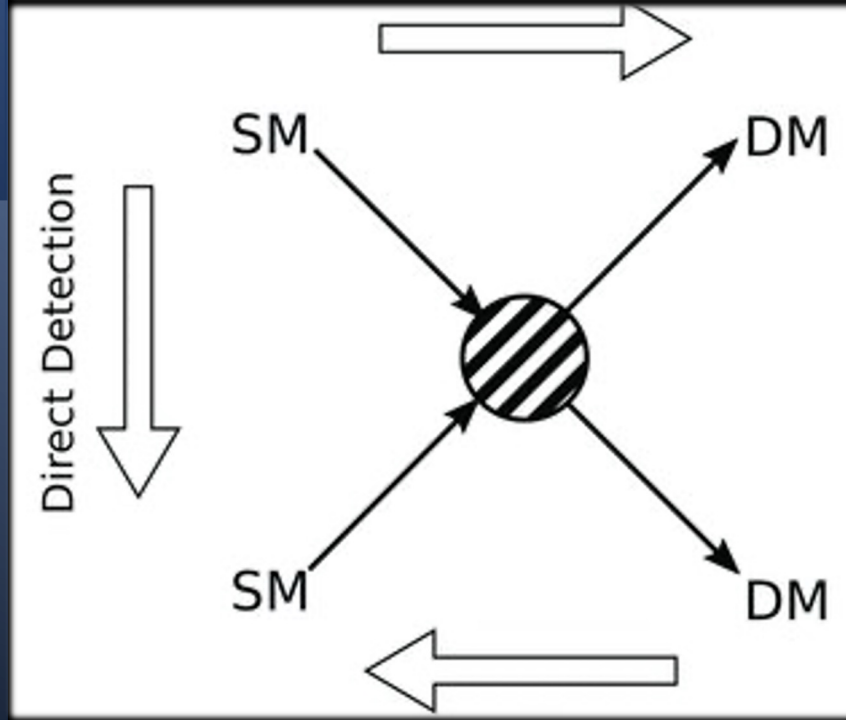
A new path for dark matter searches: Cross-correlation between γ rays and neutral hydrogen



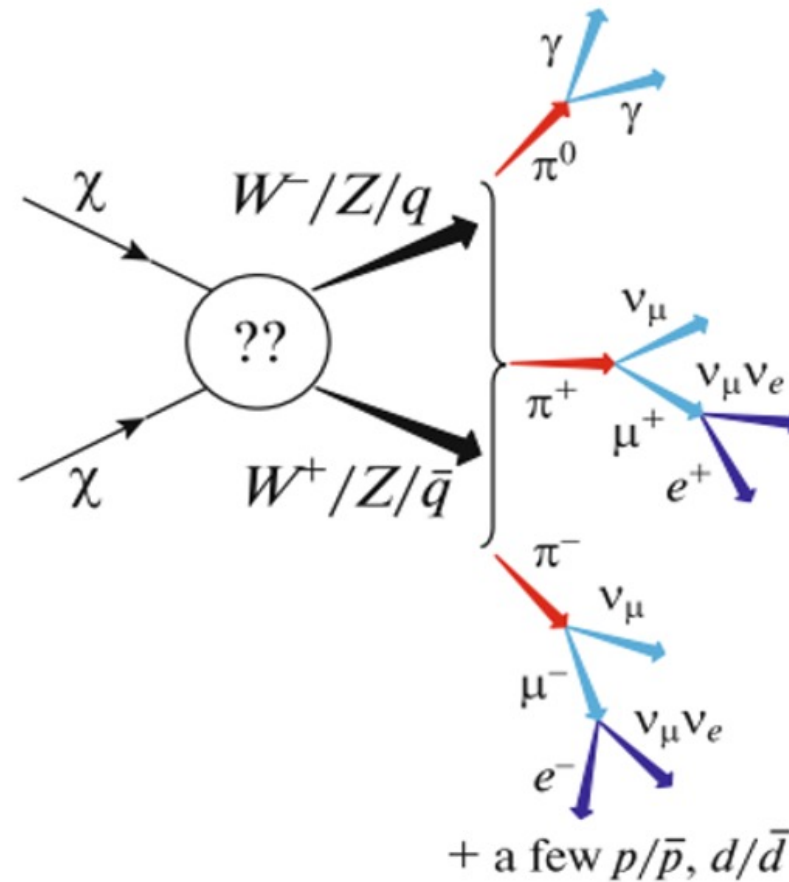
Elena Pinetti
Brookhaven National Laboratory, 14th April 2022

Dark matter in the
Universe

Detection strategies



Indirect searches



Photons

Neutrinos

Charged
cosmic rays

Identikit of dark matter particles

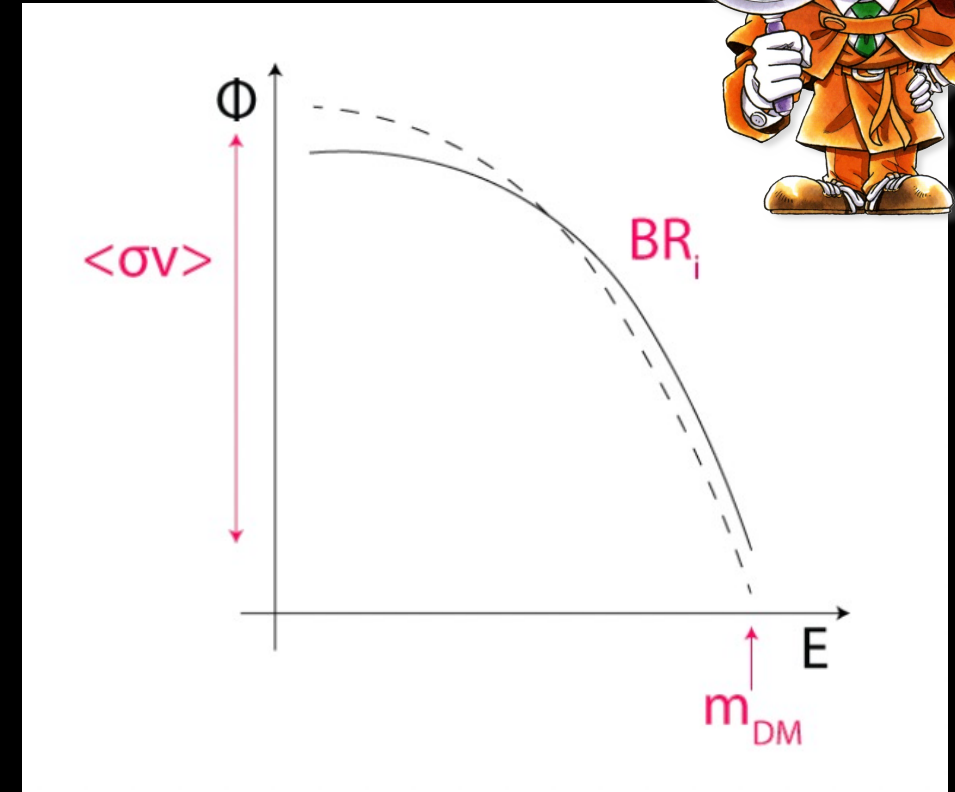


The relevant properties of a DM particle that we can derive from the indirect detection of an astrophysical signal are:

- Annihilation cross-section
- Mass
- Branching ratio in the different final states

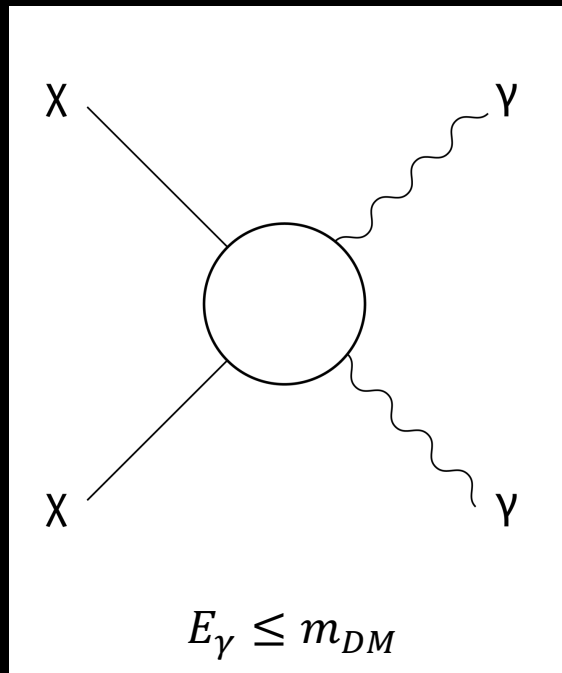
Signal amplitude: $m_{DM}, \langle \sigma v \rangle$

Spectral features: $m_{DM}, \text{branching ratio}$

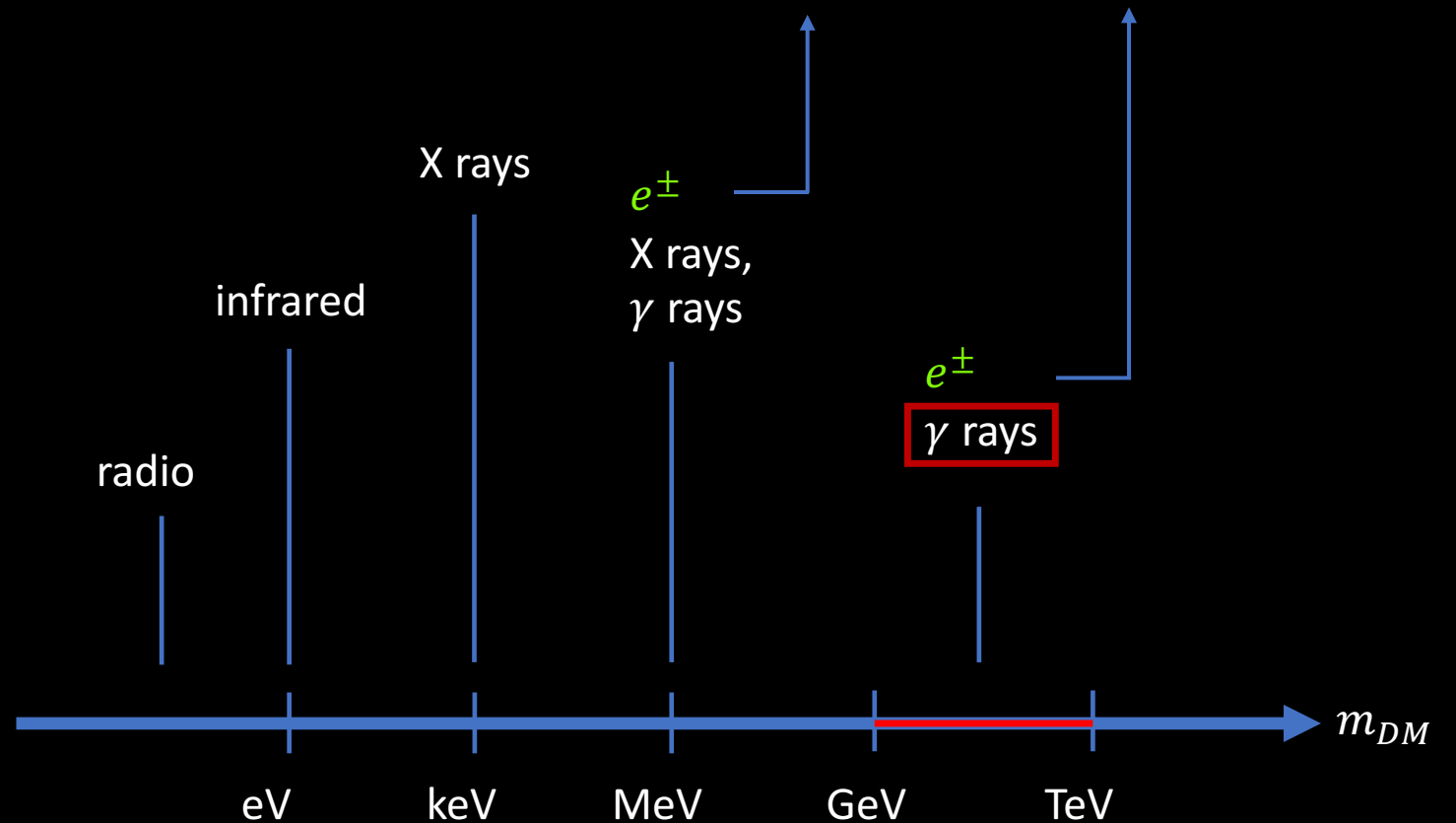


$$\chi\chi \rightarrow b\bar{b} \rightarrow (\dots) \rightarrow \gamma\gamma$$

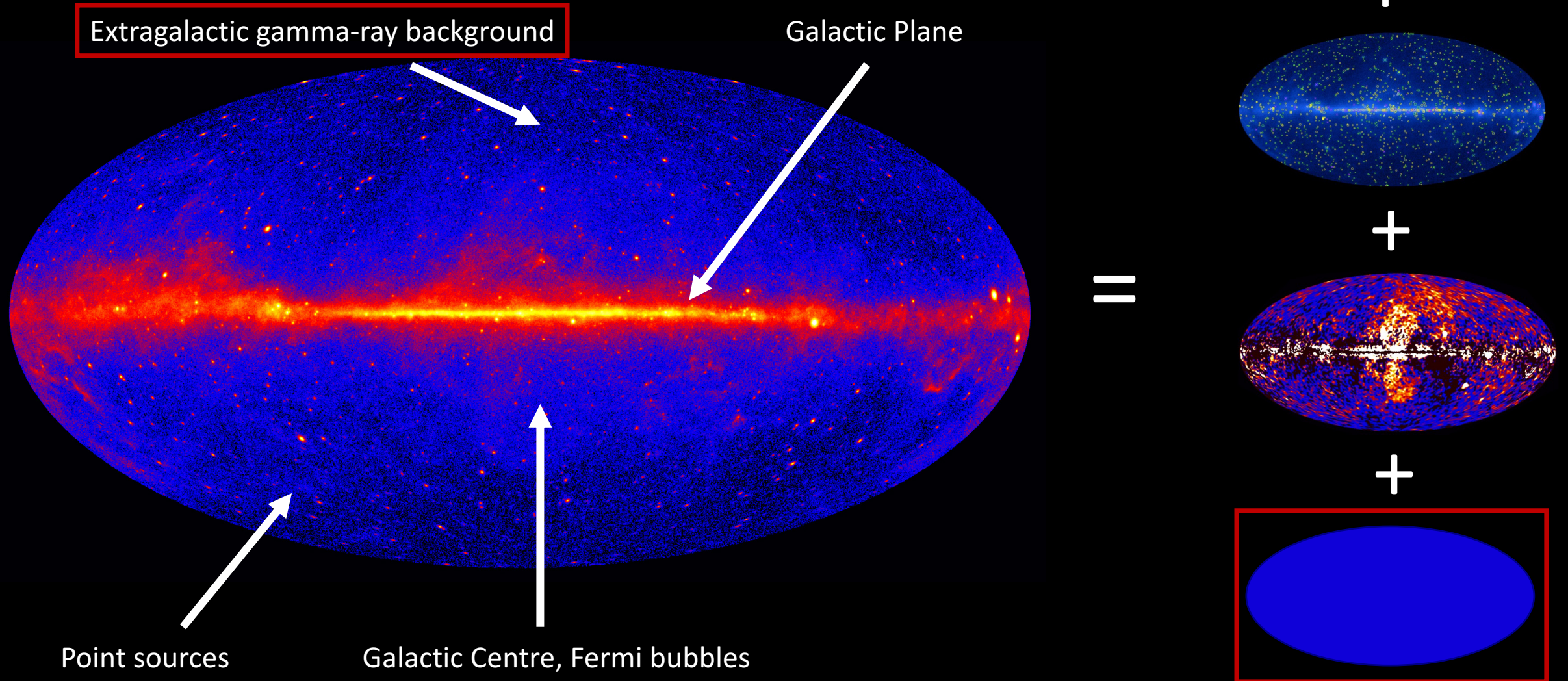
Multi-wavelength searches



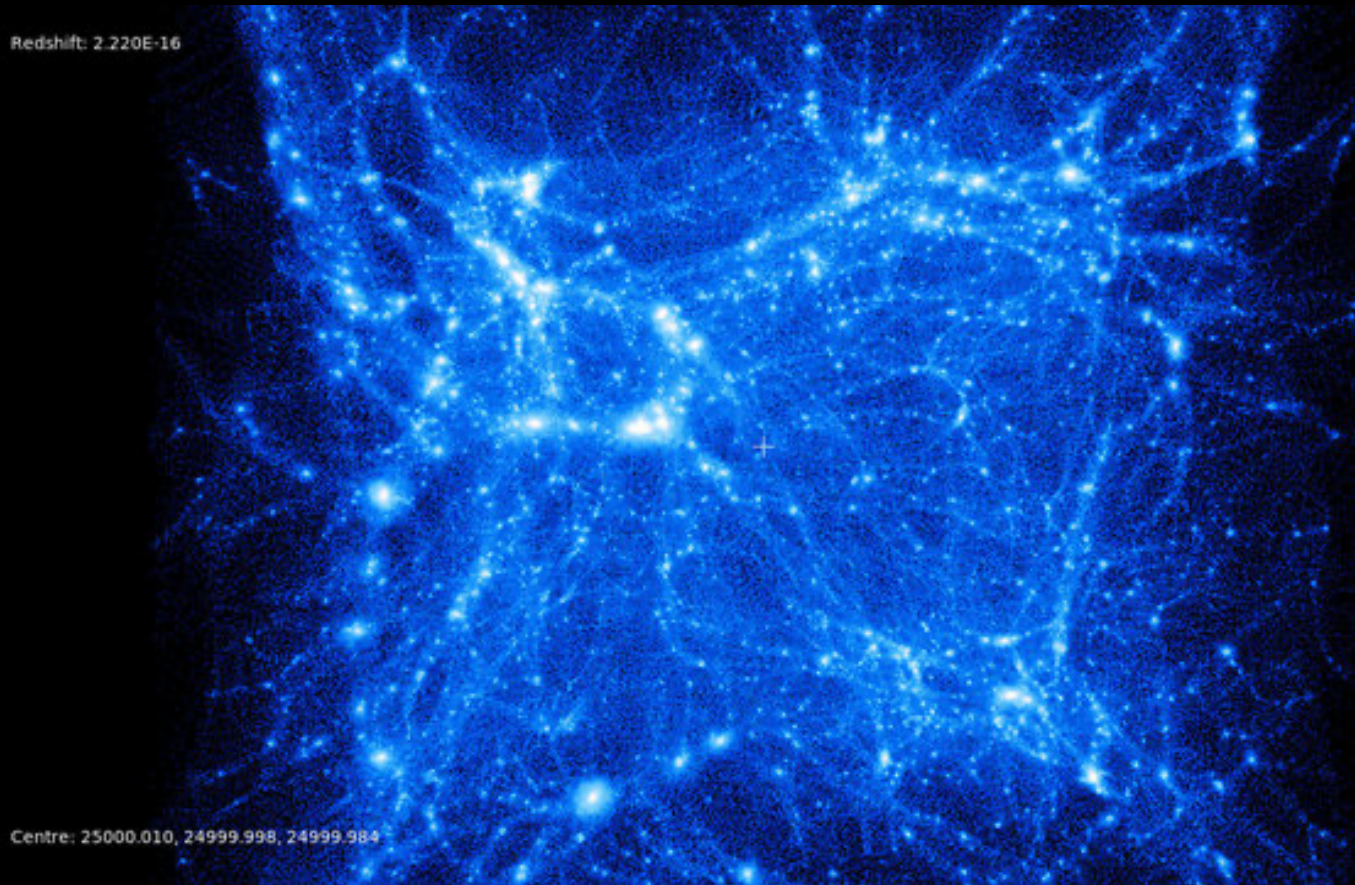
X rays, γ rays: IC on CMB and on the ISRF
radio: synchrotron on ambient magnetic fields



Gamma-ray sky



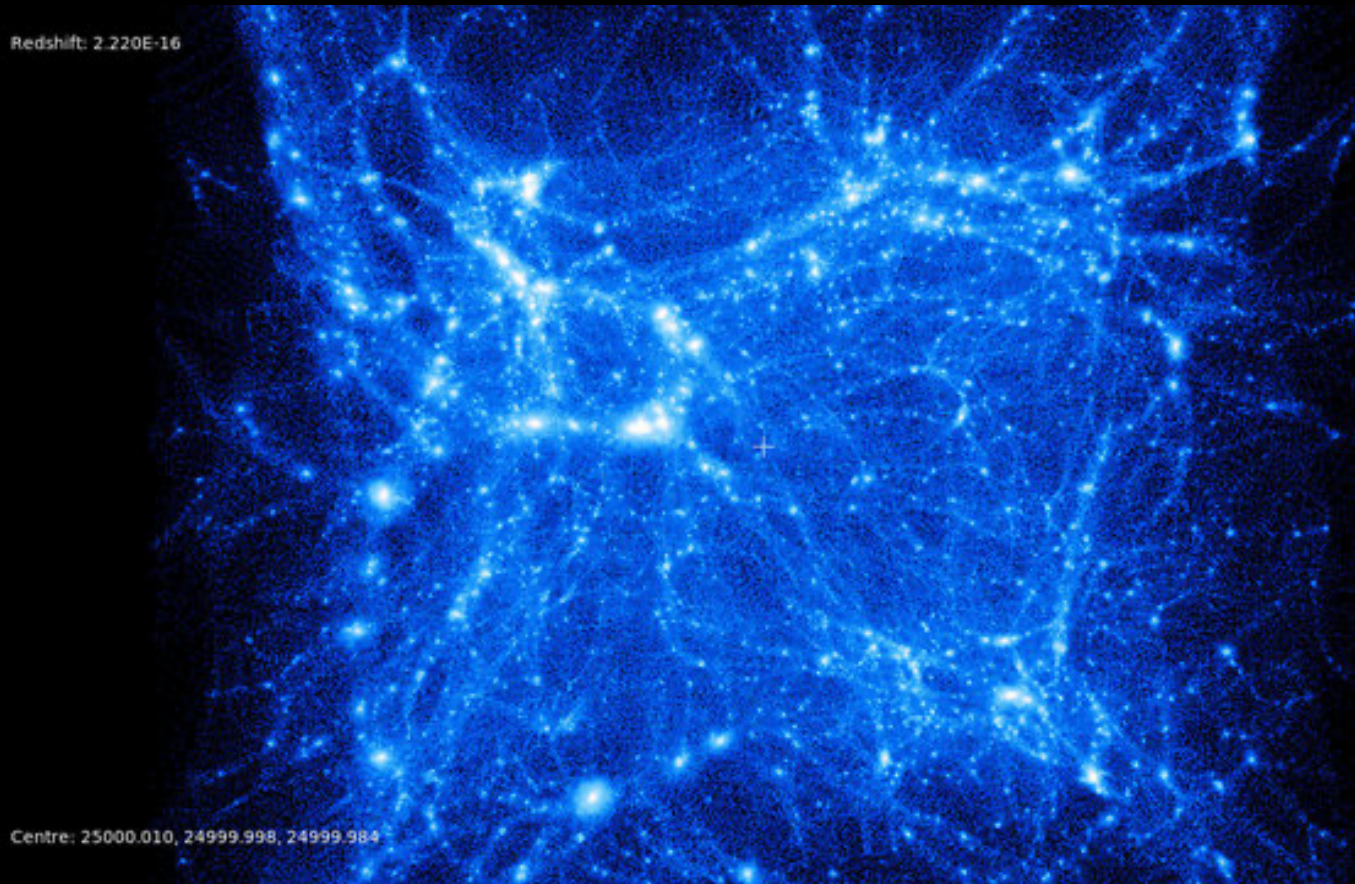
What N-body simulations tell us?



➤ Hierarchical

➤ Anisotropic

What N-body simulations tell us?



➤ Hierarchical

➤ Anisotropic



Anisotropic EM signal

Gamma-ray flux from dark matter

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

Particle
properties

Energy
spectrum

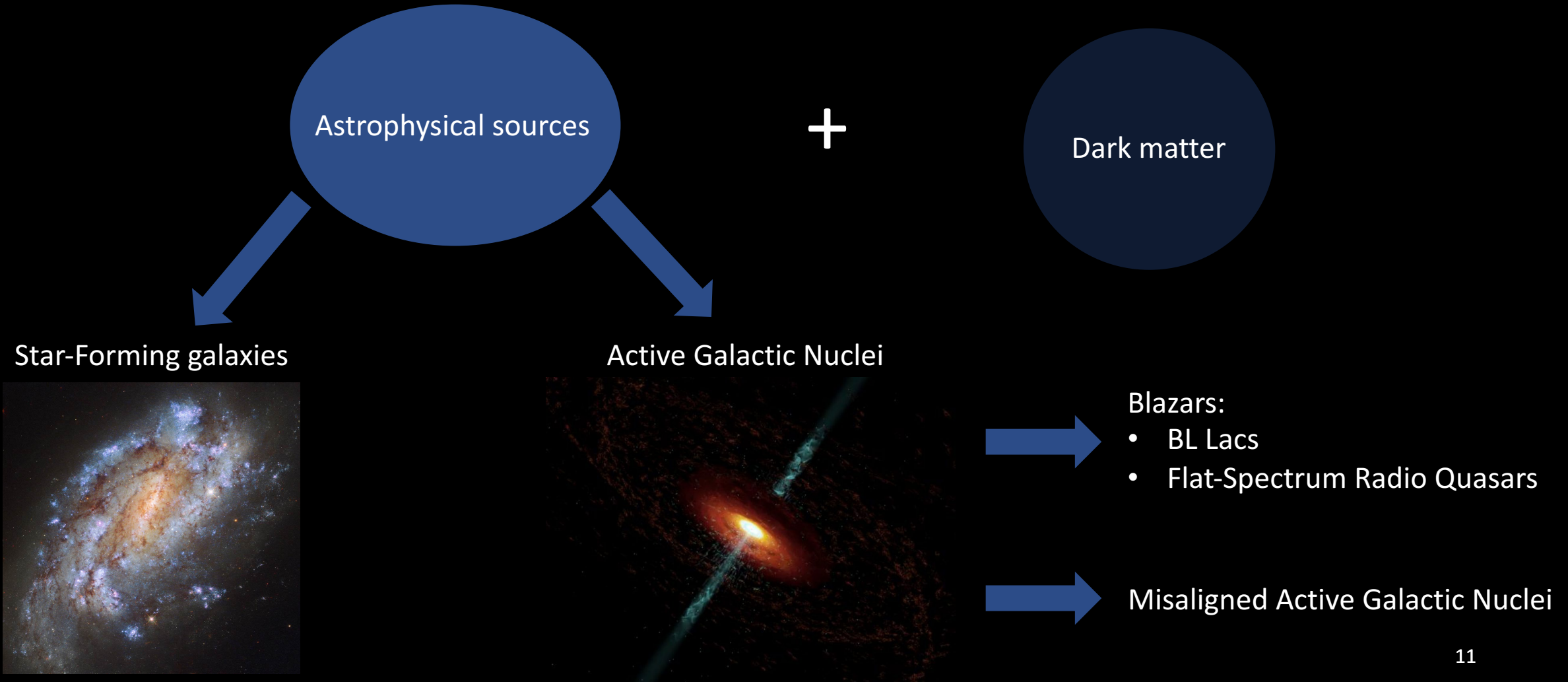
J-factor

DM density

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

Line of sight

Unresolved Gamma-Ray Background



Cross- correlation signal

EM signals

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

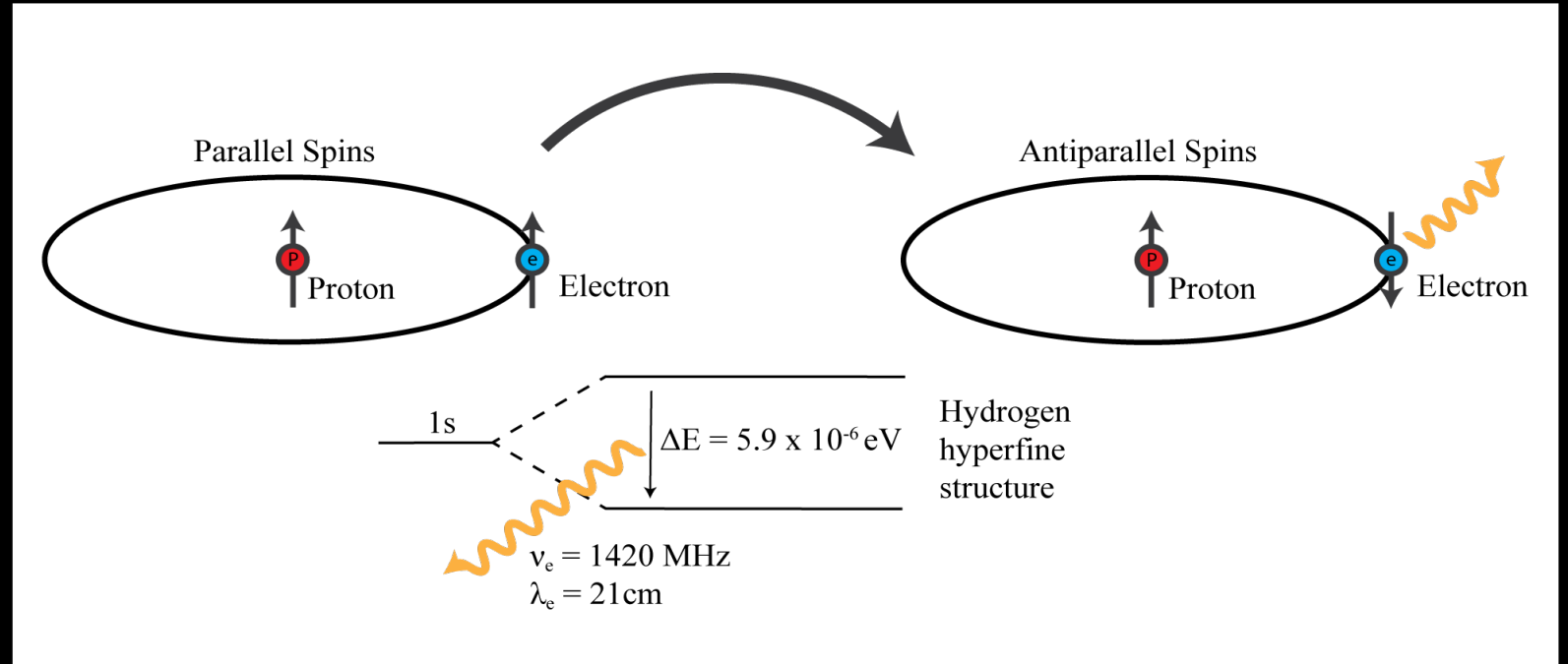
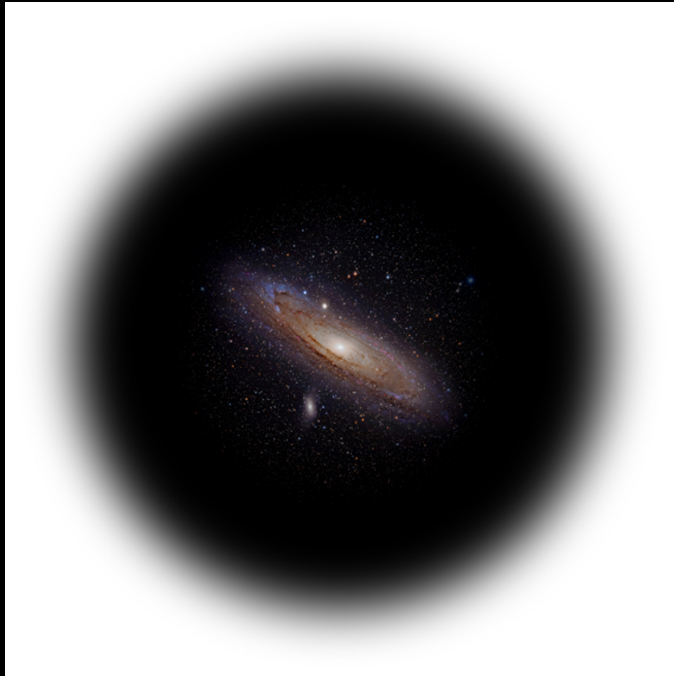


Gravitational tracers

Galaxy catalogues
Clusters catalogues
Weak lensing cosmic shear

HI **NEW!**

21cm line



$$\frac{\nu_o}{\nu_e} = (1 + z)^{-1}$$

Intensity mapping

Measuring the integrated emission
of a spectral line



No need to resolve the individual galaxies.

We can map the large-scale structure
in the Universe by measuring the
21cm line brightness temperature T_b :

$$I = \frac{2\nu^2 k_B T_b}{c^2}$$



Angular Power Spectrum

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

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

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



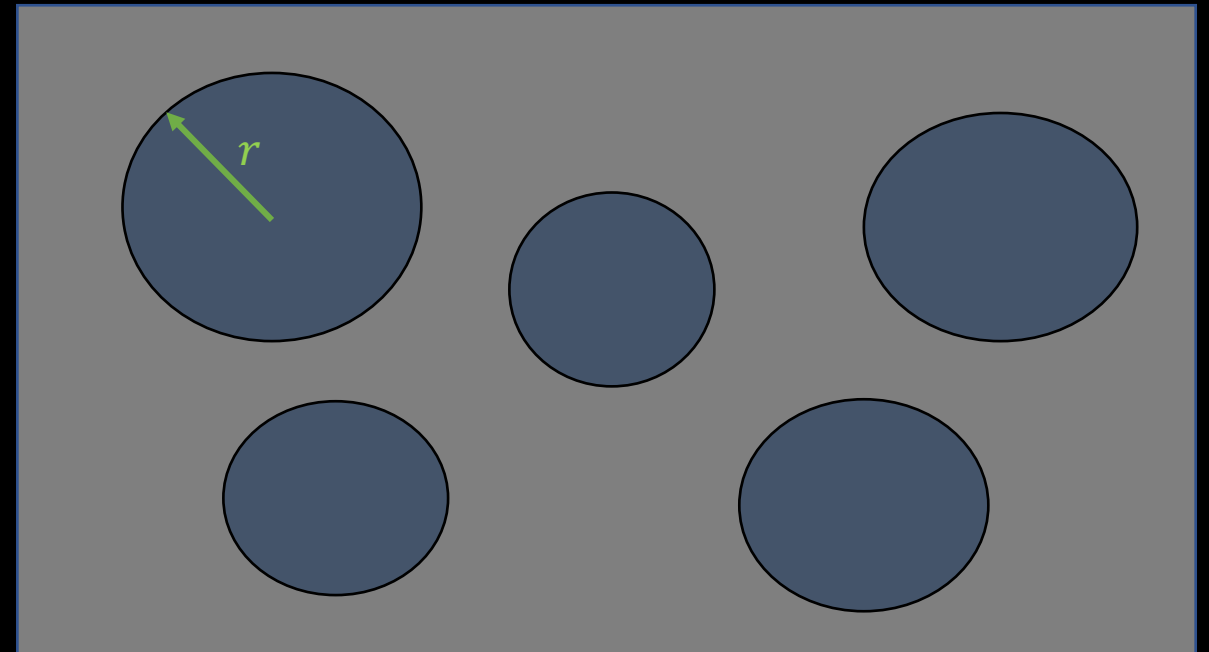
$$C_{\ell}^{ij} = \int \frac{d\chi}{\chi^2} w_i(\chi) w_j(\chi) P_{ij} \left(k = \frac{\ell}{\chi} \right)$$

Window functions

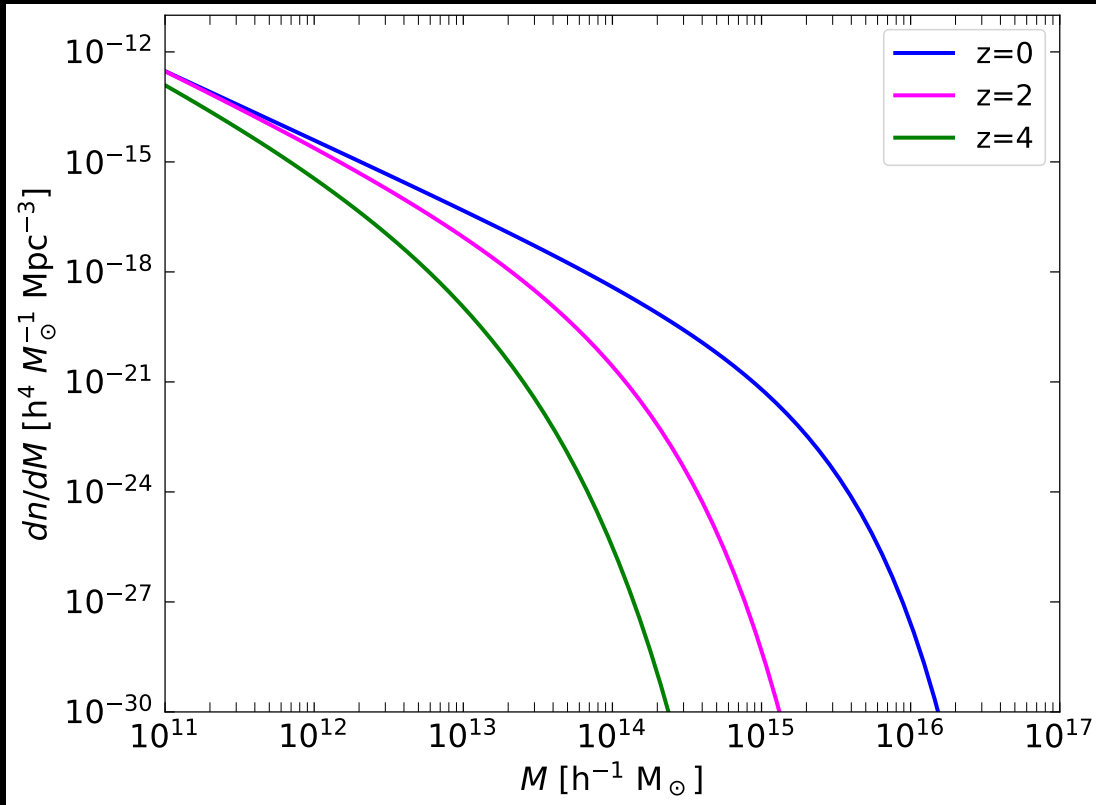
Fourier Power Spectrum

Halo model

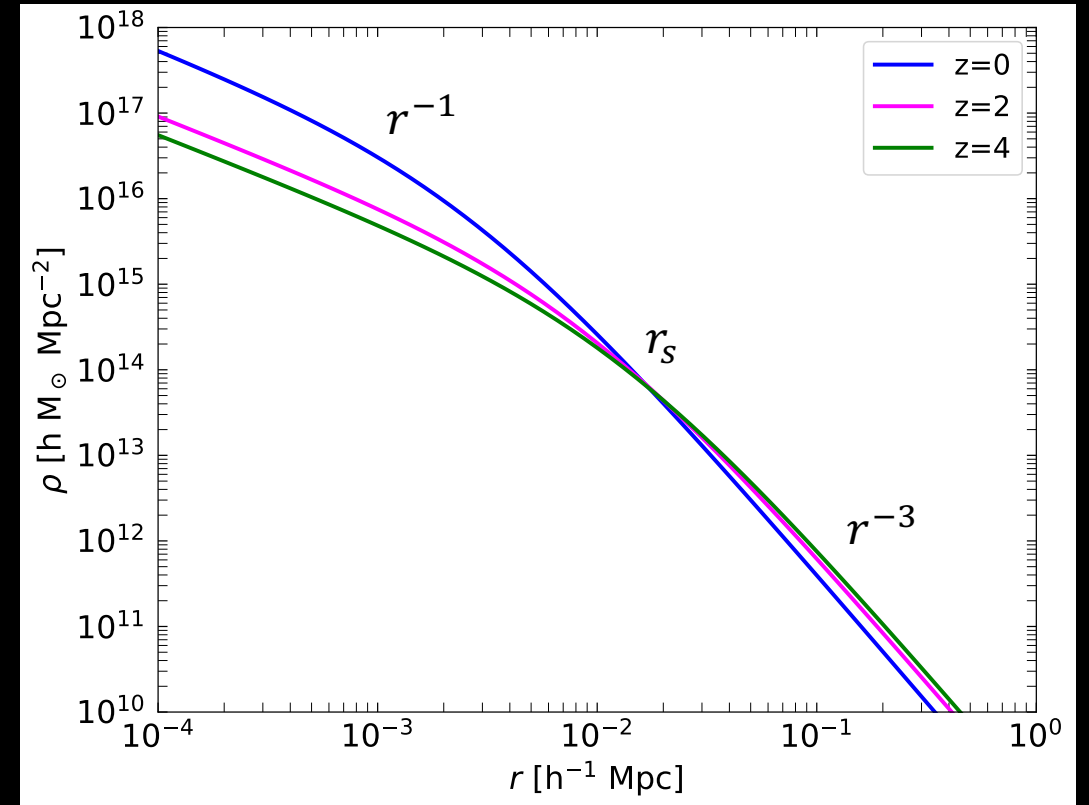
- The entire mass of the Universe is contained within distinct units, called halos.
- 2 levels:
 - Mass distribution within one single halo
 - Spatial distribution of the halos themselves



Halo model



Halo mass function: Sheth-Tormen



Density profile: NFW

Spherical collapse

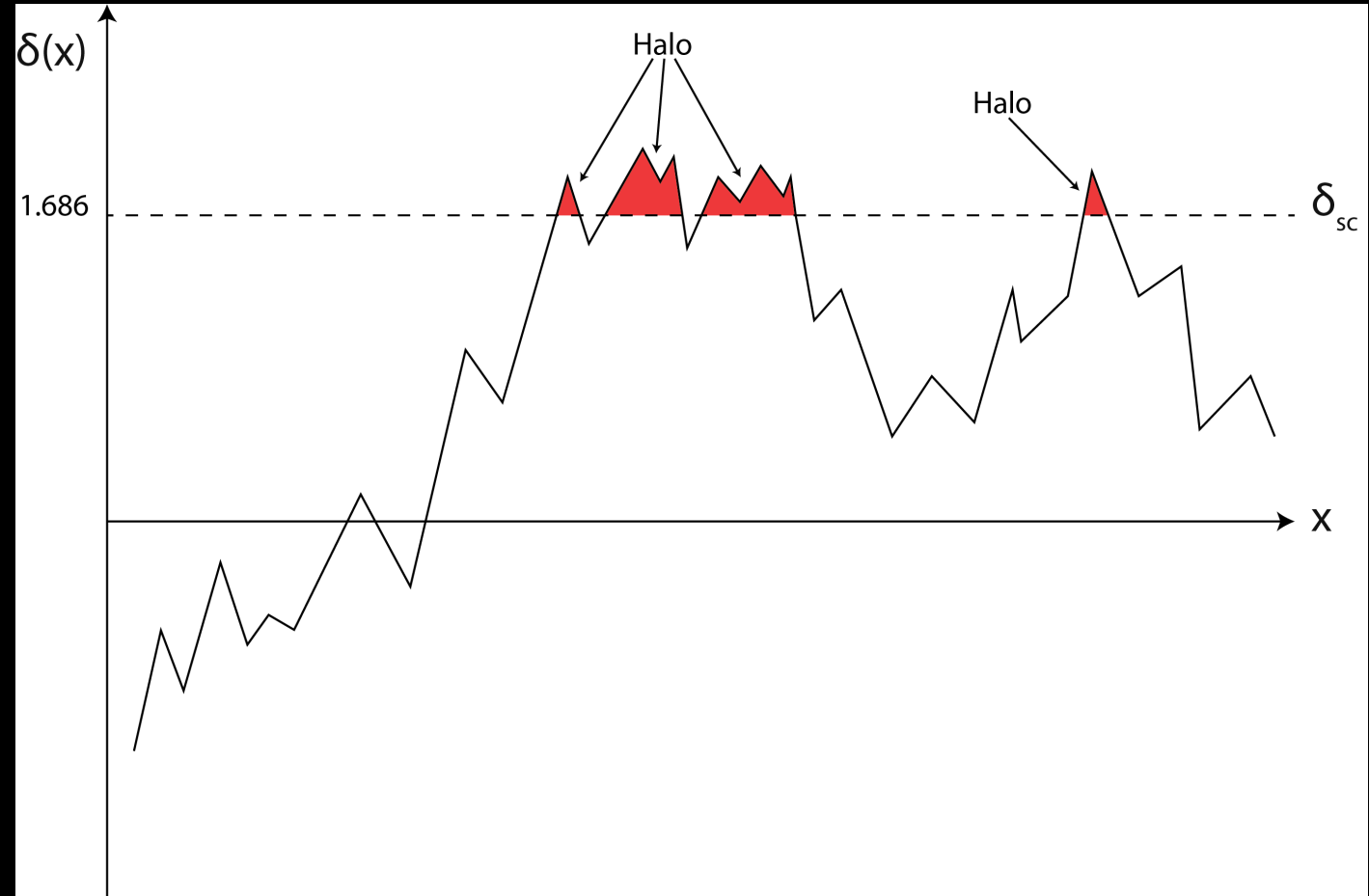
$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$$

Density contrast

$$\delta(\vec{x}, t) > \delta_{sc} = 1.686$$



The region collapses and a halo forms



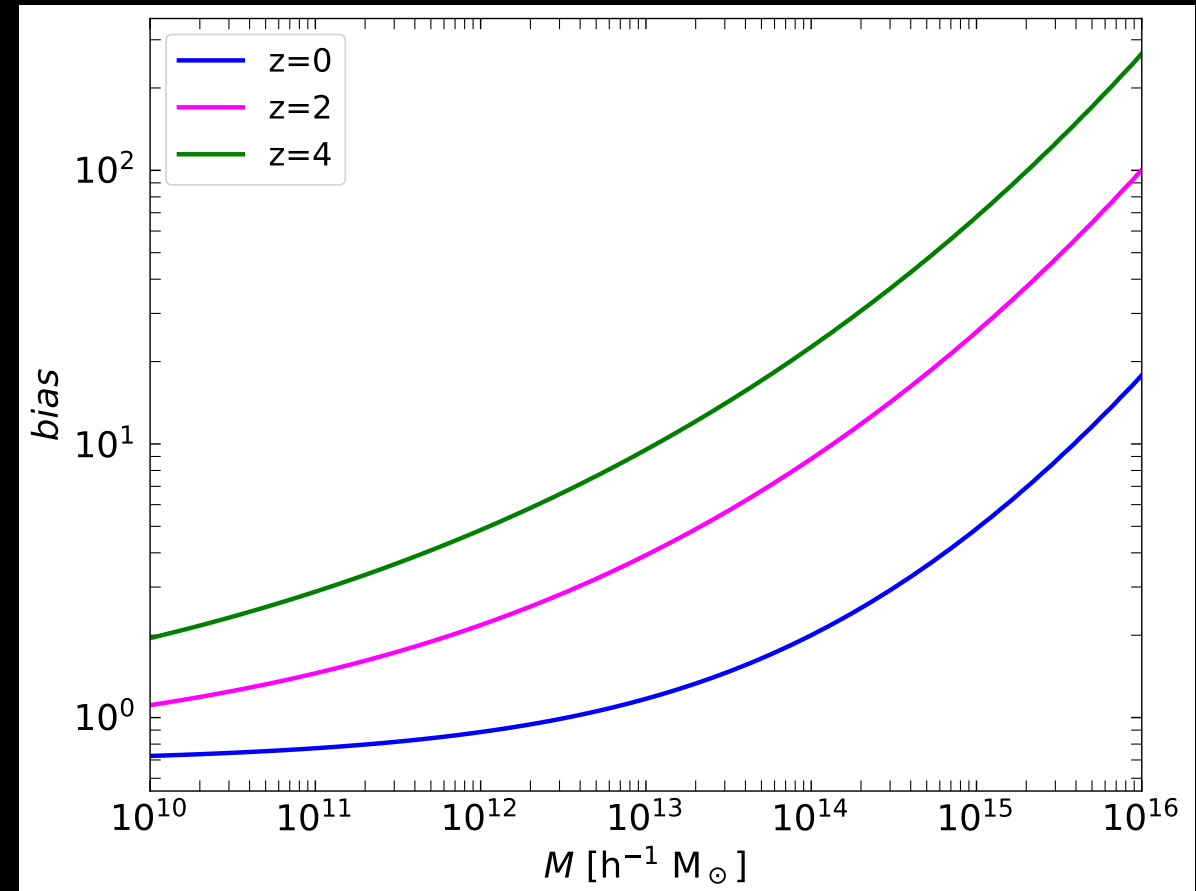
Halo bias

$$\delta_h(x) = b(M, z) \delta(x)$$

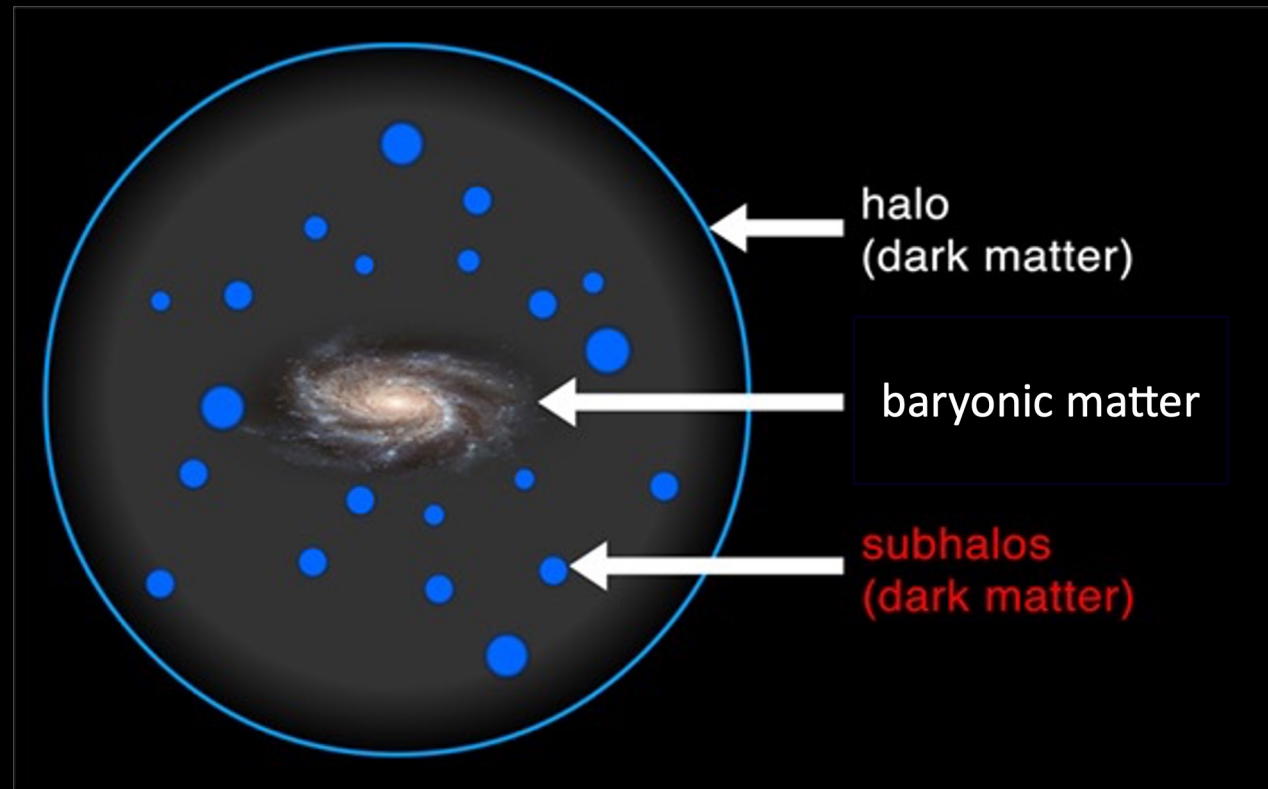
Halo density
contrast

Bias

Matter density
contrast



Subhaloes



Boost factor

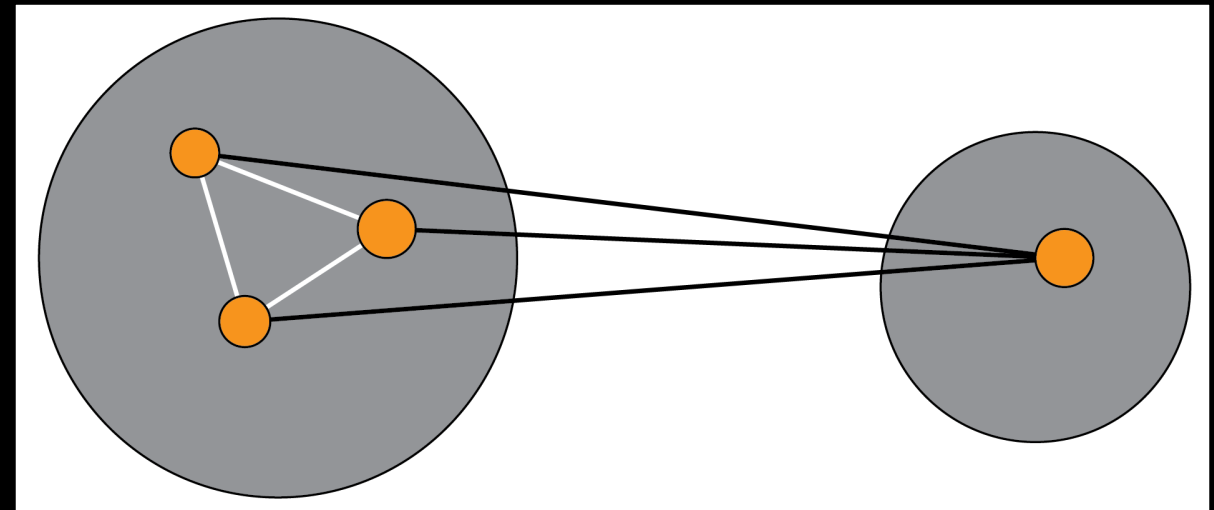
B_{sub} : Moliné et al. Volume 466,
Issue 4, p. 4974–4990 (2017)

Fourier power spectrum

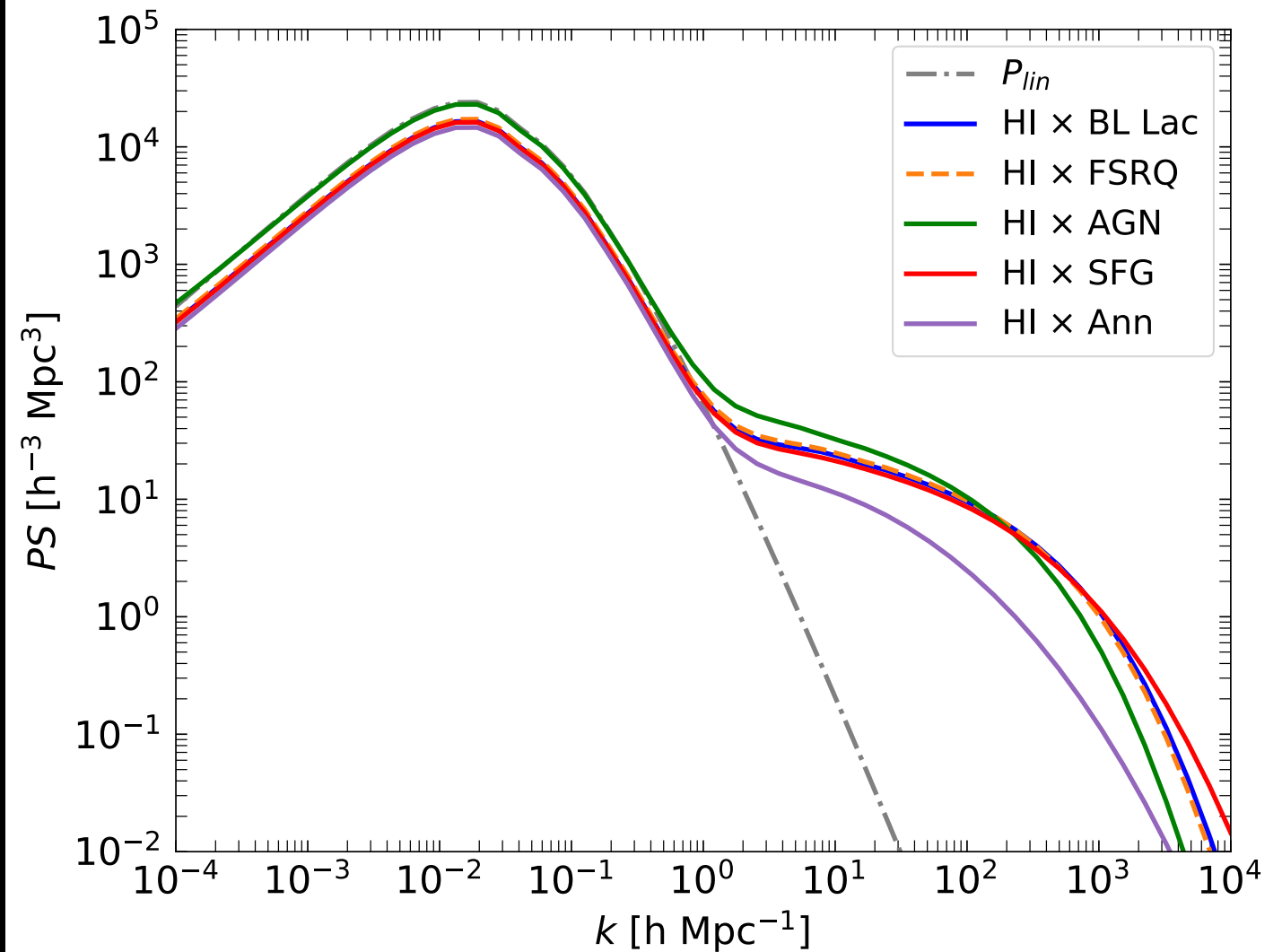
$$P_{ij} = P_{ij}^{1h} + P_{ij}^{2h}$$

$$P_{ij}^{1h} = \int_{M_{min}}^{M_{max}} dM \frac{dn}{dM} \tilde{f}_i^* \tilde{f}_j$$

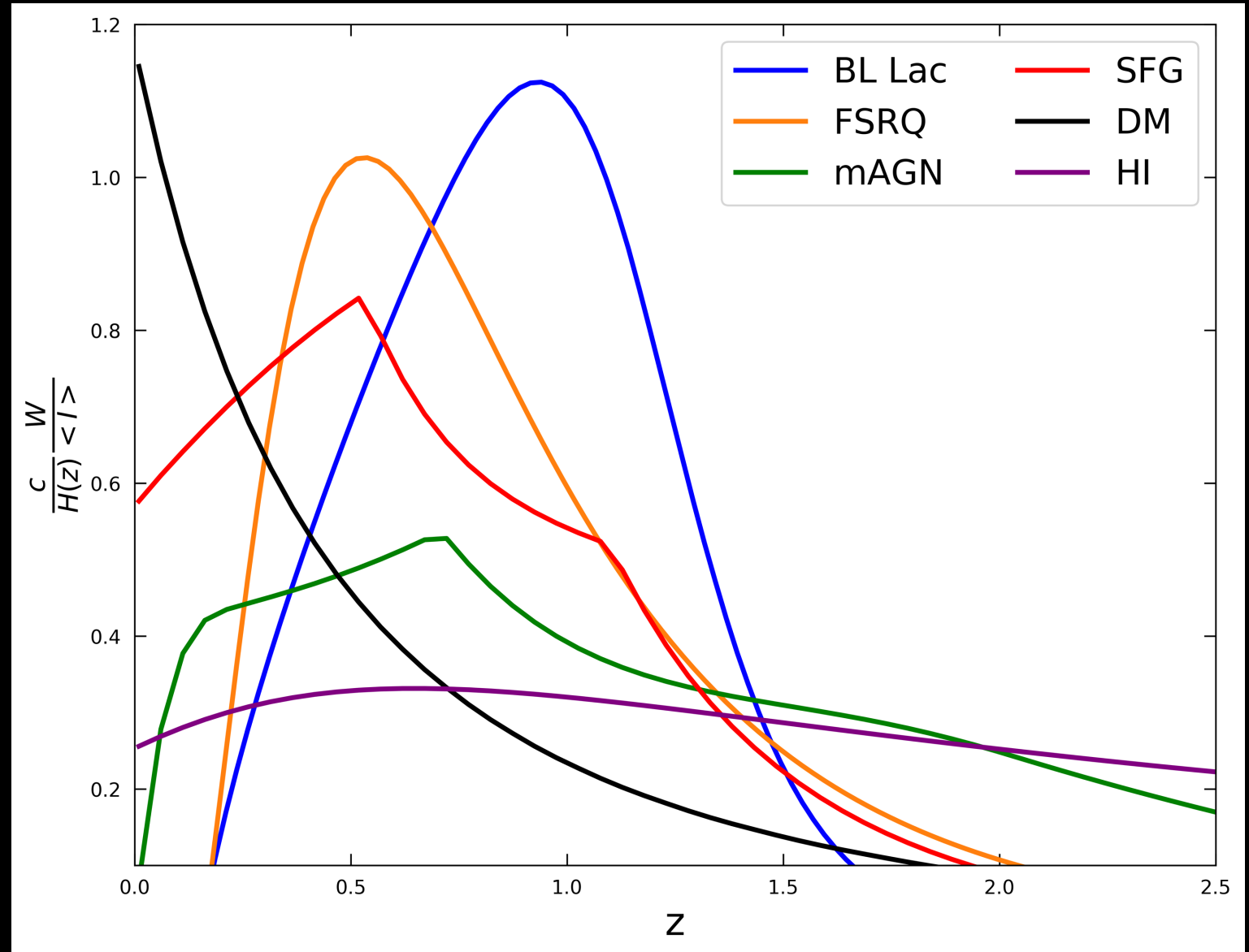
$$P_{ij}^{2h} = \left[\int_{M_{min}}^{M_{max}} dM_1 \frac{dn}{dM_1} b_i \tilde{f}_i^* \right] \left[\int_{M_{min}}^{M_{max}} dM_2 \frac{dn}{dM_2} b_j \tilde{f}_j \right] P_{lin}$$



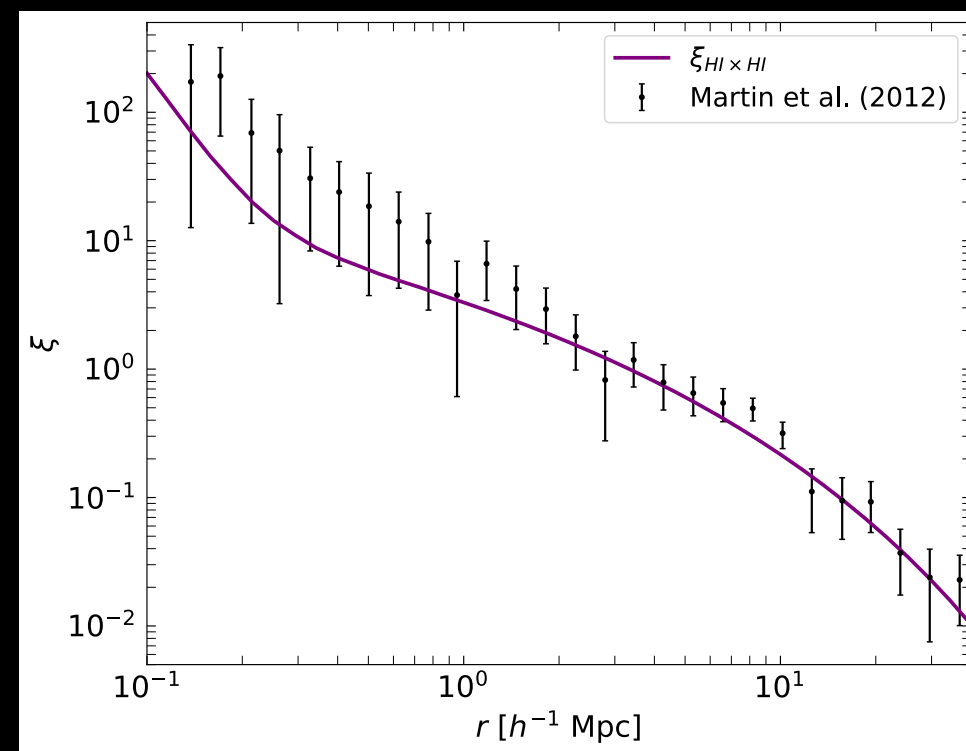
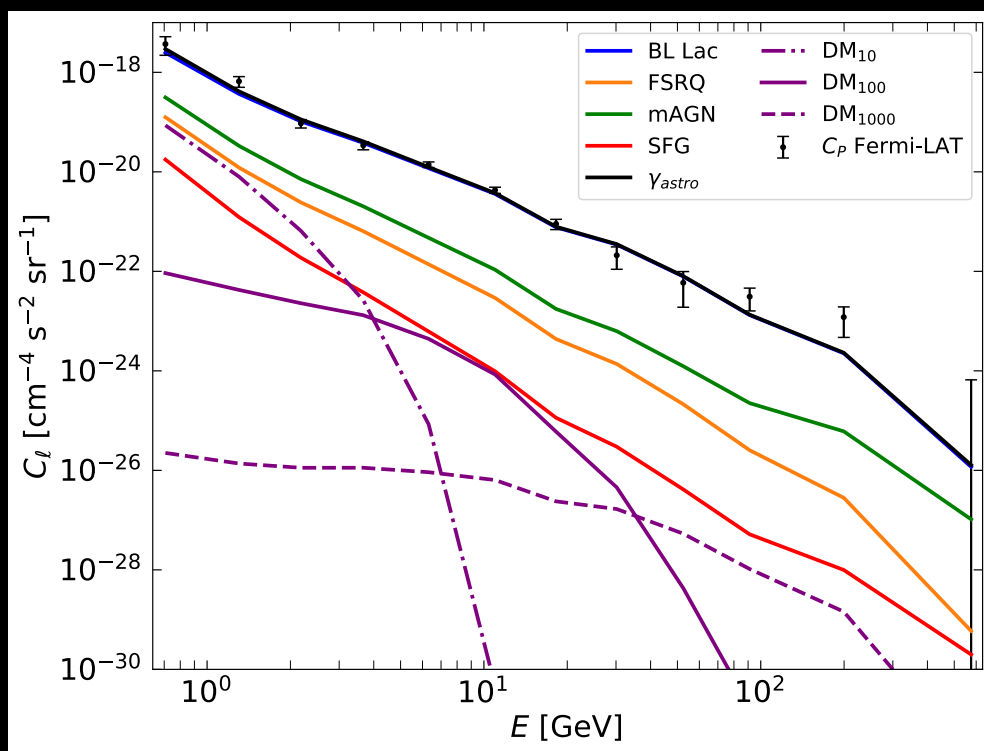
Fourier Power Spectrum



Window functions



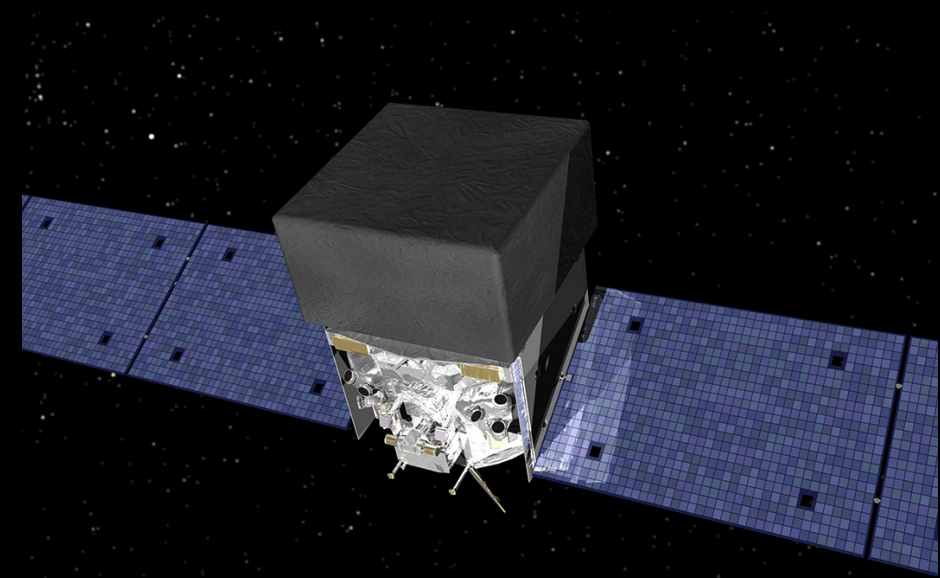
Validation



Experiments

Fermi-LAT specifications

Bin	$E_{\min}$ (GeV)	$E_{\max}$ (GeV)	C_N ($\text{cm}^{-4} \text{ s}^{-2} \text{ sr}^{-1}$)	f_{sky}	σ_0^{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	$2 \cdot \text{exp}_{\text{Fermi}}$
Angular resolution	Conservative: $0.5 \cdot \sigma_b^{\text{Fermi}}$ Optimistic: $0.2 \cdot \sigma_b^{\text{Fermi}}$

Intensity mapping specifications

	MeerKAT	SKA1
s [deg ²]	4000	25000
f_{sky}	0.097	0.61
t [hr]	4000	10000
N_d	64	133 + 64
D_{dish} [m]	13.5	14.5
D_{interf} [km]	1	3
$n(u)$	0.0005	0.005
N_{pol}	2	2
N_b	1	1
$[z_{\text{min}}, z_{\text{max}}]$	L-band: [0.0, 0.58] UHF-band: [0.4, 1.45]	Band 1: [0.35, 3.0] Band 2: [0.0, 0.5]
Configuration	Single-dish Interferometer	Single-dish Interferometer

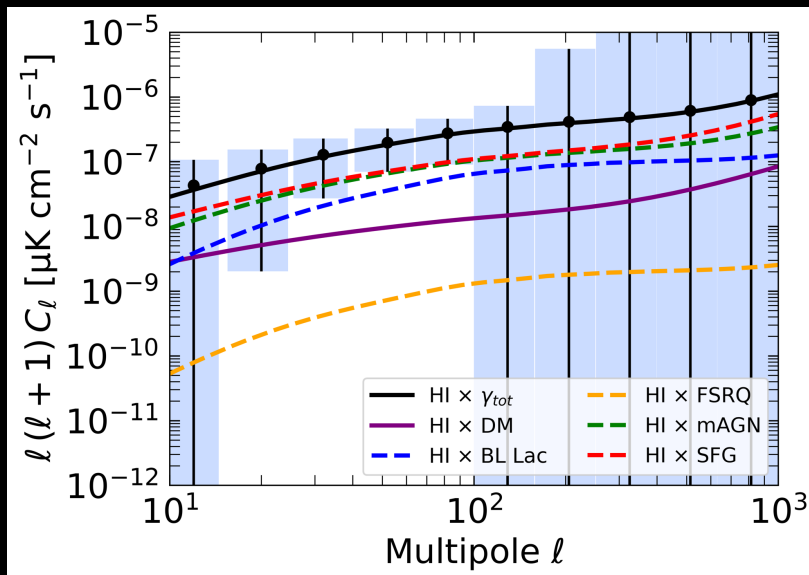


	s [deg ²]	f_{sky}	t [hr]	N_d	D_{interf} [km]	N_b
SKA2	30000	0.72	10000	20000	10	36

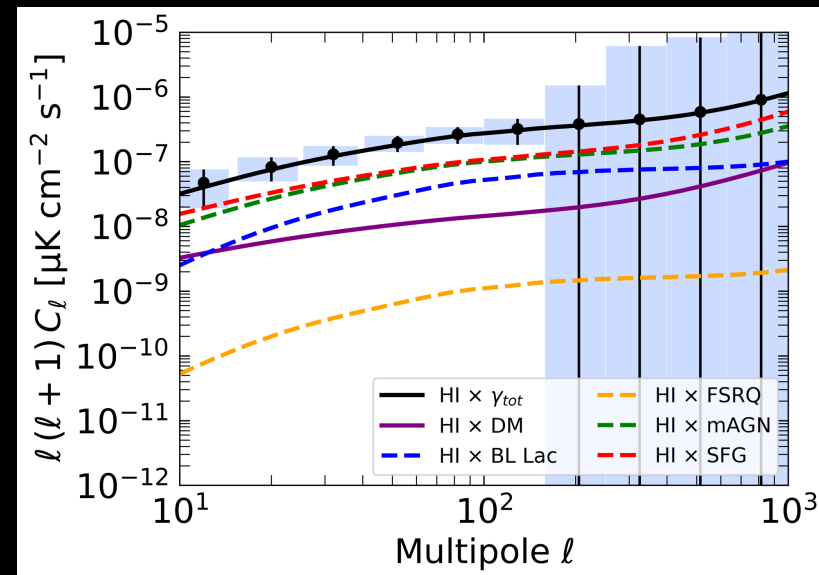
Results

Evolution of the error bars

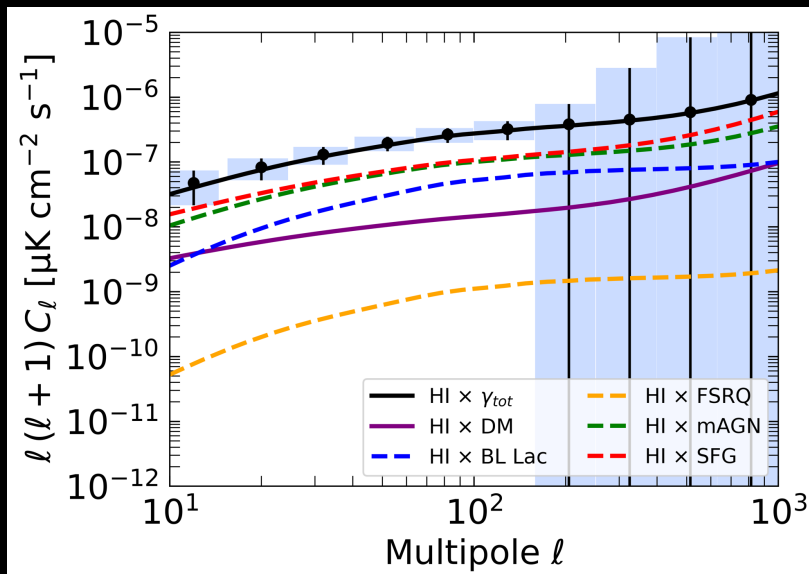
MeerKAT x Fermi



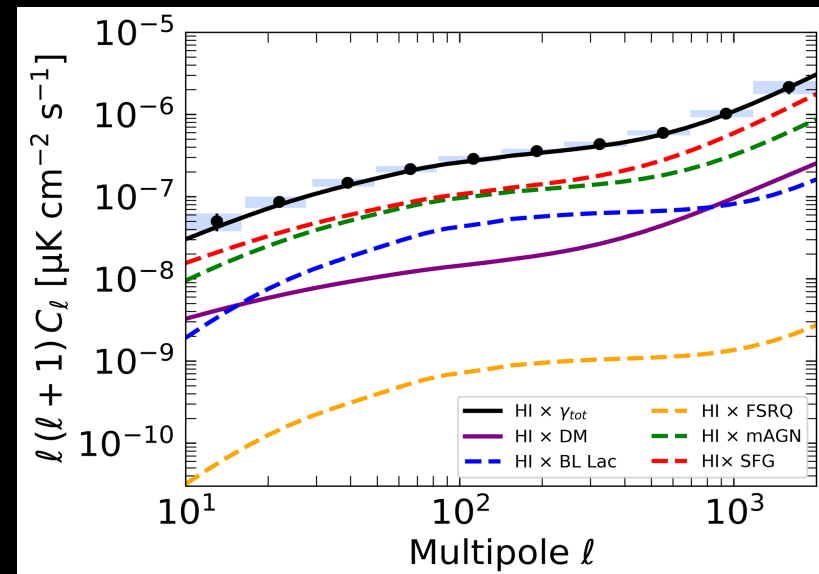
SKA1 x Fermi



SKA2 x Fermi



SKA2 x Fermissimo



Signal-to-noise ratio

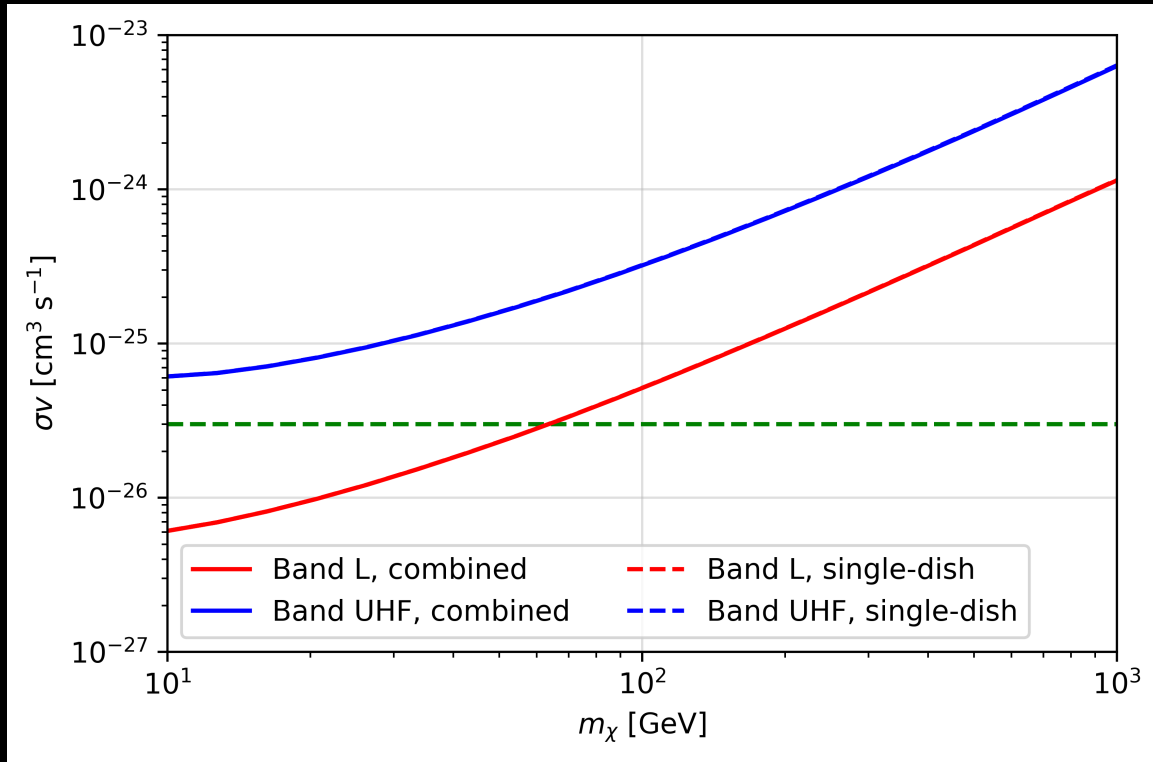
$$SNR^2 = \sum_{i=l,E} \left(\frac{C_i^{HI} \times S}{\Delta C_i^{HI} \times S} \right)^2$$

$$SNR = n \sigma$$

		Single-dish	Dish+Interferometer
MEERKAT	L-band	3.6	3.6
	UHF-band	3.7	3.7
SKA1	Band 1	4.5	4.6
	Band 2	5.7	5.7
SKA2	Band 1	7.1	8.2
	Band 2	6.7	7.0

Dark matter constraints

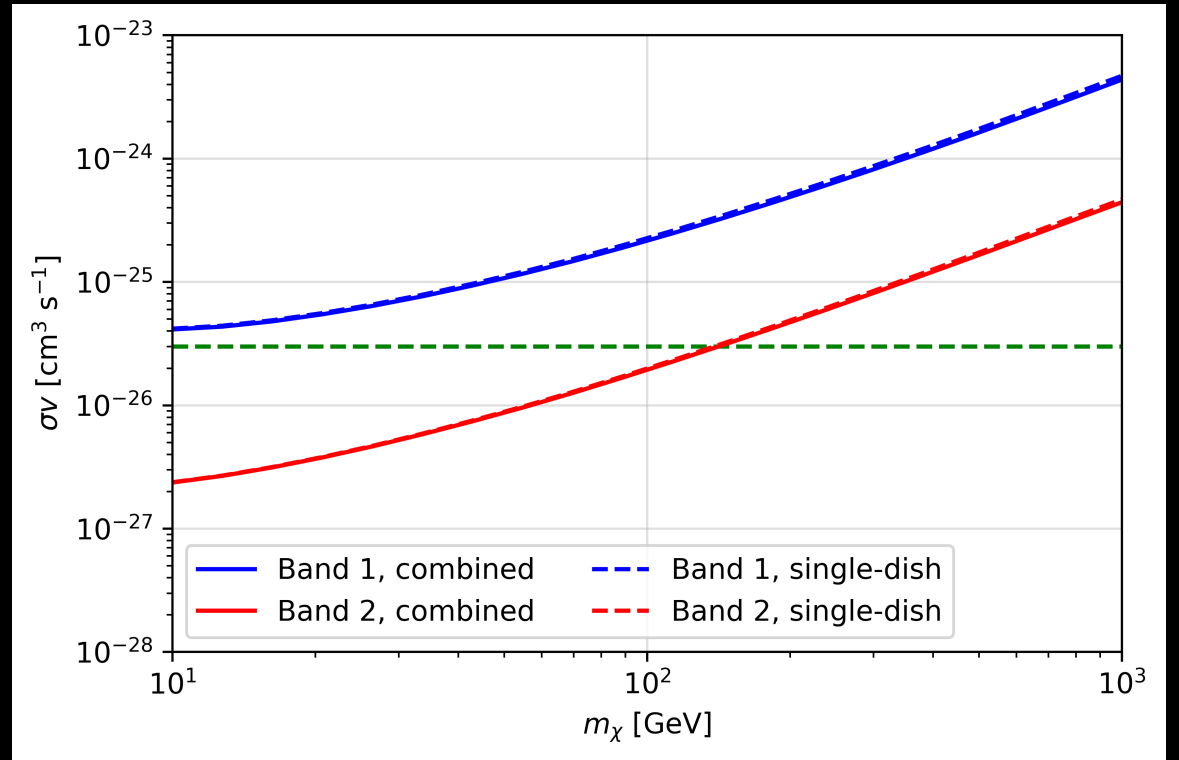
MeerKAT



L-band: $0 < z < 0.58$

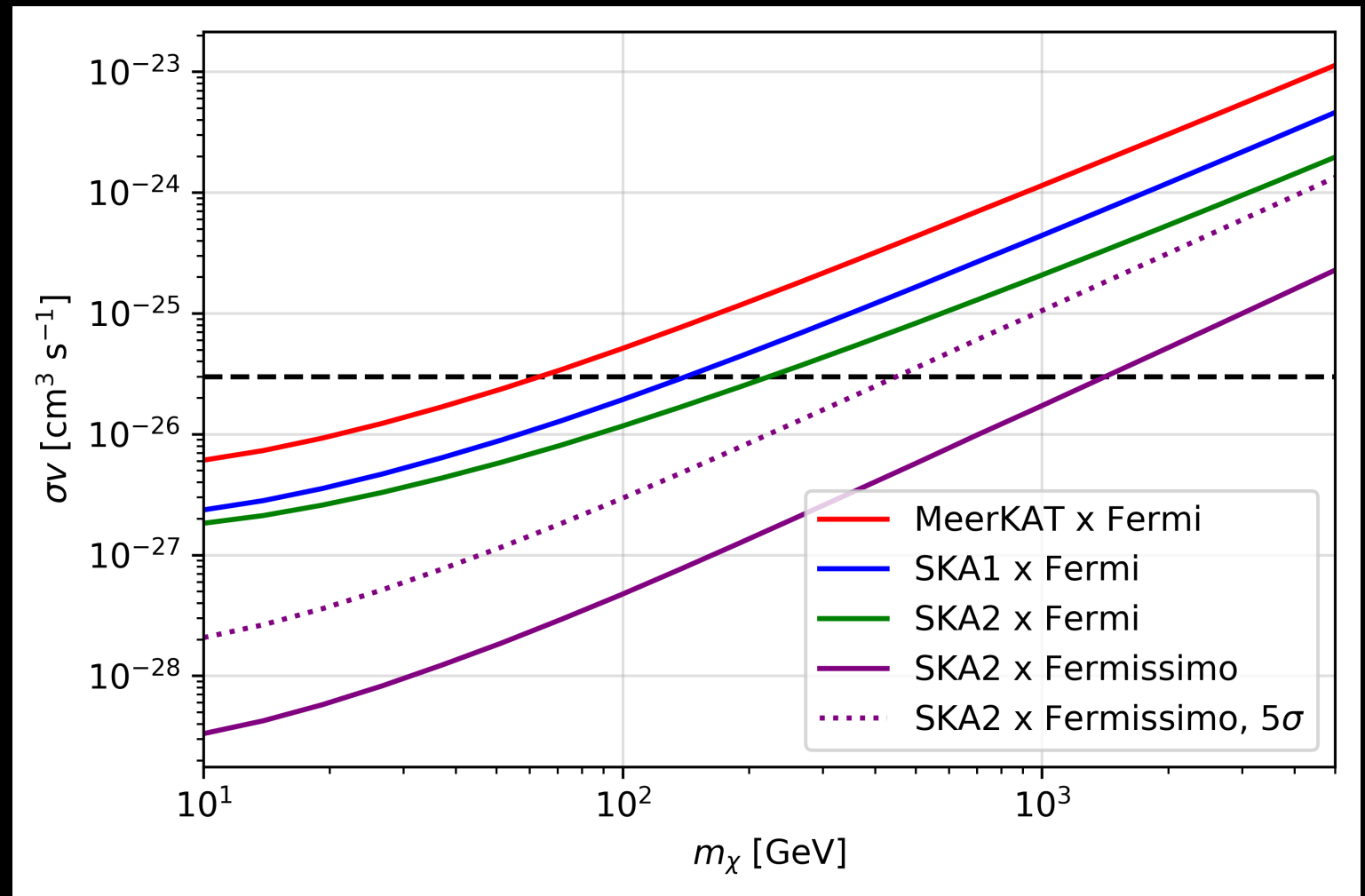
UHF-band: $0.4 < z < 1.45$

SKA1

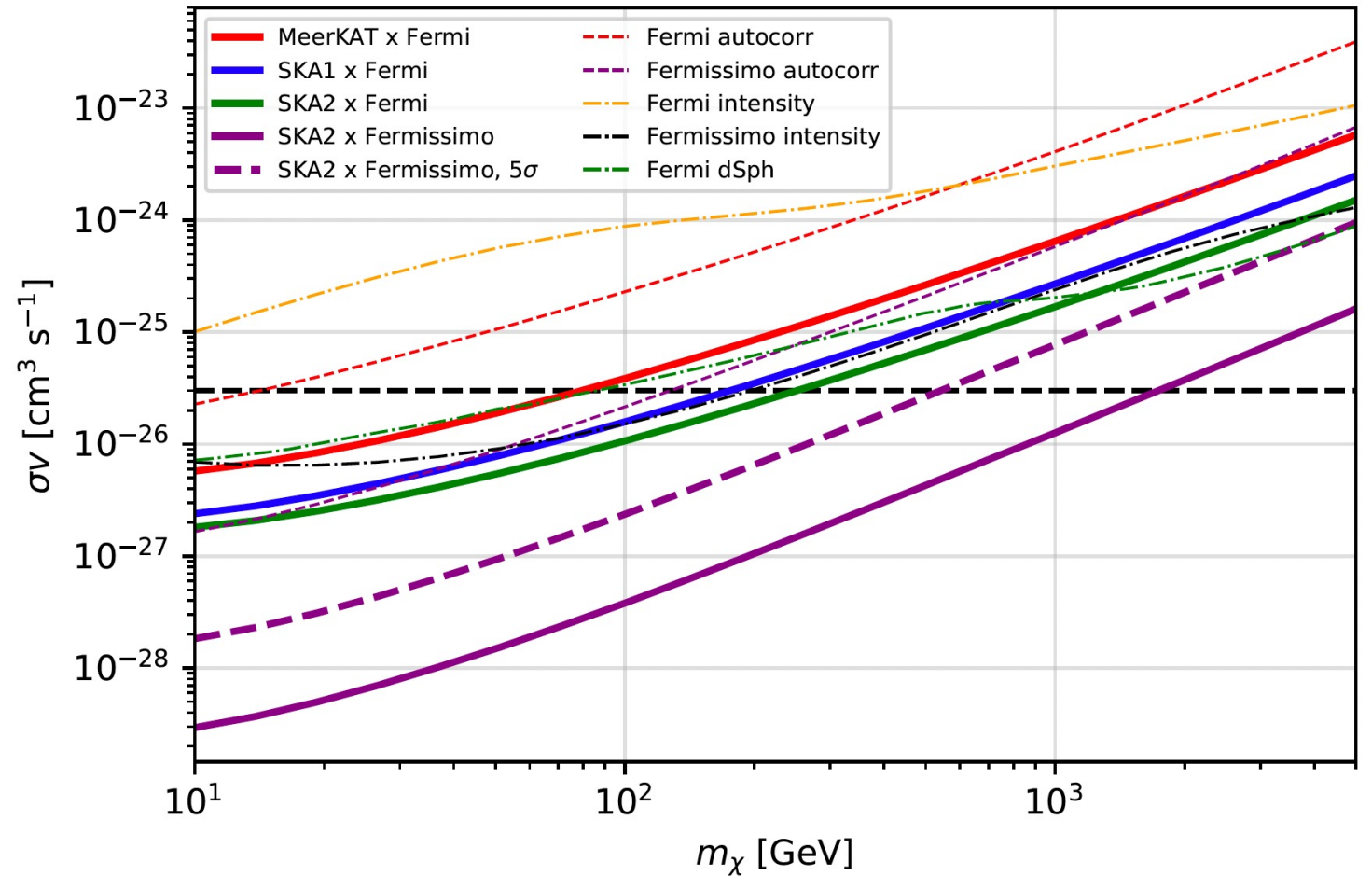


Band 1: $0.35 < z < 3$ Band 2: $0 < z < 0.5$

Dark matter constraints



Dark matter constraints



Fermi intensity: Ackermann et al, Phys. Rev. Lett. 121 (2018) (24) 241101

Fermi autocorr: Akermann et al, Astrophys. J. 799 (2015) (1) 86

Fermi dSph: Albert et al, Astrophys. J. 834, 110 (2017)

Take-home message

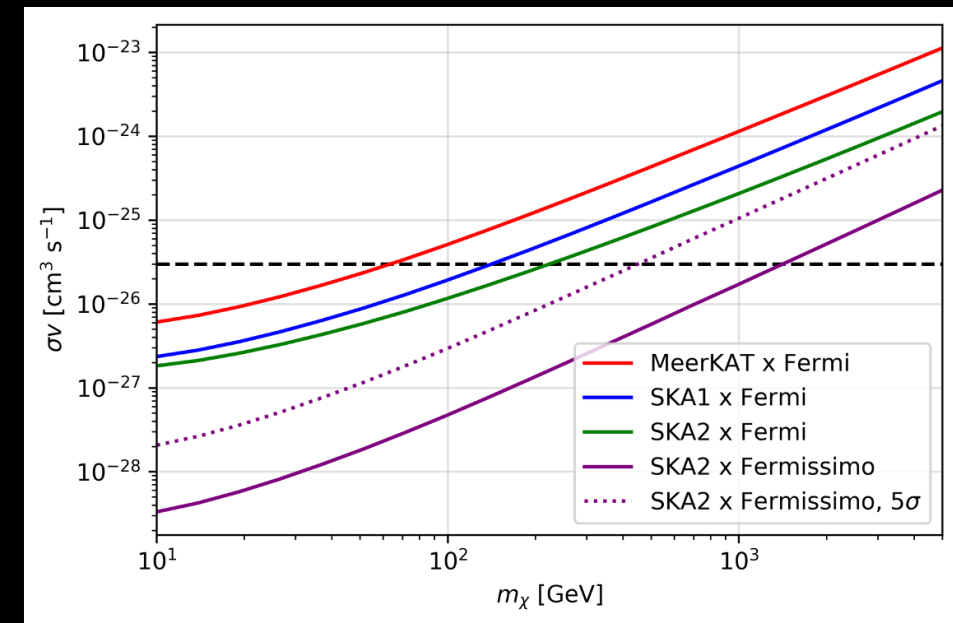
1 The cross-correlation $\text{HI} \times \gamma$ rays is a very promising channel

2 MeerKAT: $\text{SNR} = 3.7\sigma$
SKA1: $\text{SNR} > 5\sigma$

3 Competitive bounds for DM with SKA1 and SKA2+Fermissimo:

SKA1+Fermi	2σ bound	$0.65 \times \langle \sigma v \rangle_{\text{th}}$
SKA2+Fermissimo	2σ bound	$0.02 \times \langle \sigma v \rangle_{\text{th}}$
	5σ detection	$0.10 \times \langle \sigma v \rangle_{\text{th}}$

$$m_\chi = 100 \text{ GeV}$$



Pinetti et al, JCAP 07 (2020) 044,
[arXiv:1911.04989](https://arxiv.org/abs/1911.04989)

Take-home message

*Thank you for
your attention!*

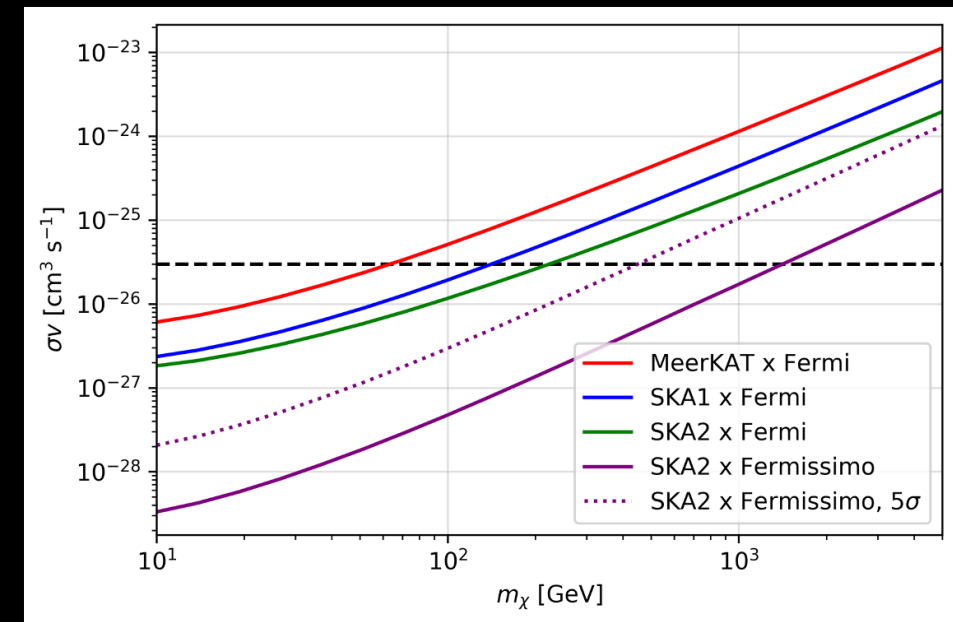
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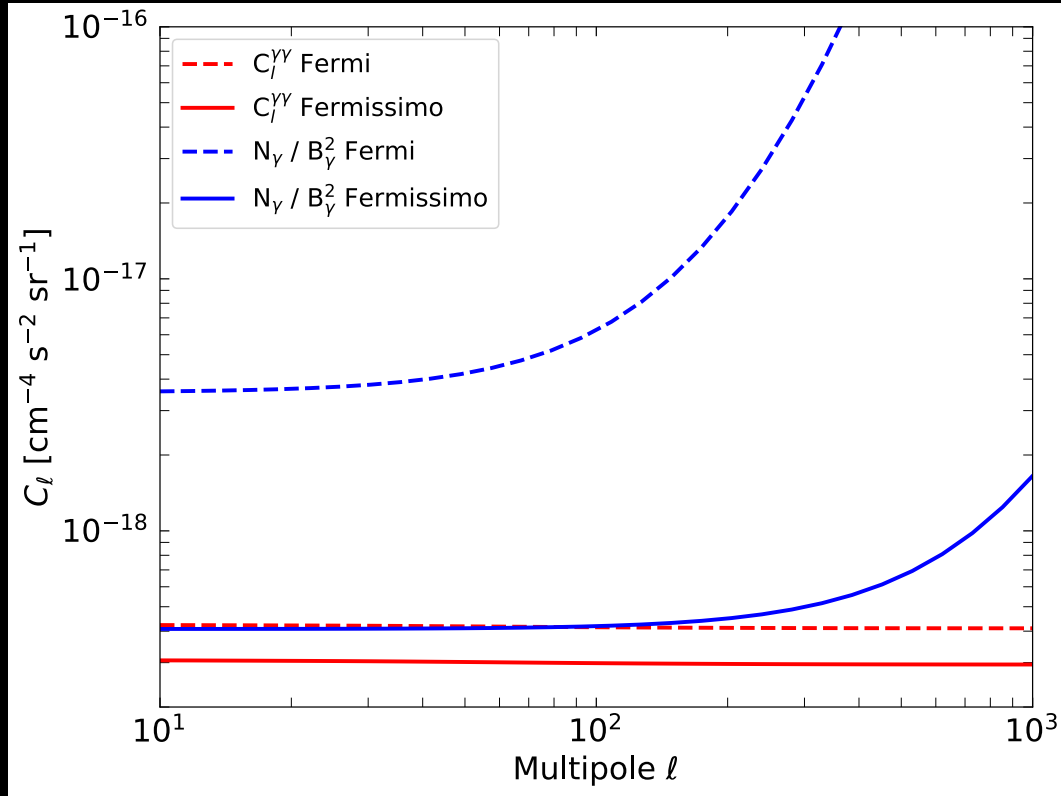


Pinetti et al, JCAP 07 (2020) 044,
[arXiv:1911.04989](https://arxiv.org/abs/1911.04989)

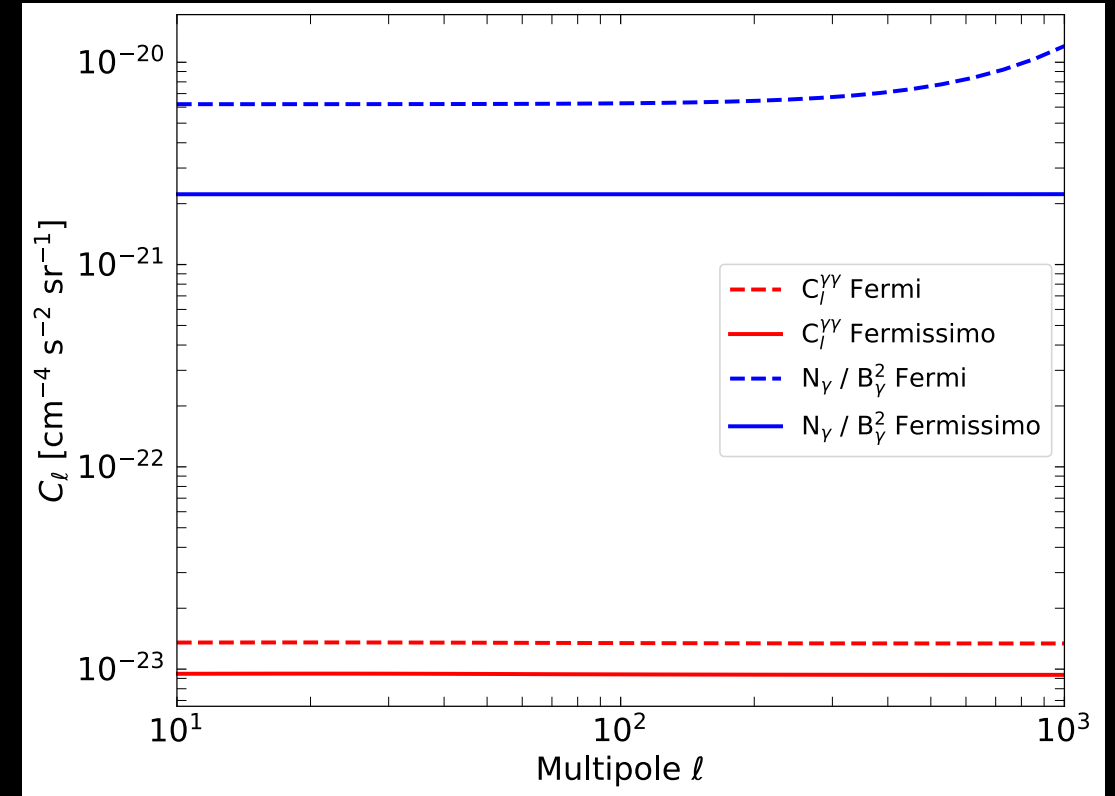
Back-up slides

Variance of the signal: γ rays

$$(\Delta C_\ell^{ij})^2 = \frac{1}{(2\ell + 1) f_{sky}} \left[(C_\ell^{ij})^2 + \left(C_\ell^{ii} + \frac{C_N^i}{B_{\ell,i}^2} \right) \left(C_\ell^{jj} + \frac{C_N^j}{B_{\ell,j}^2} \right) \right]$$



1.0-1.7 GeV



69.2-120.2 GeV

Intensity mapping specifications

	S (deg ²)	t (10 ³ hr)	N_{dish}	D_{dish} (m)	D_{interf} (km)	N_{b}	f_{sky}	$[z_{\text{min}}, z_{\text{max}}]$	
MEERKAT	4,000	4	64	13.5	1	1	0.097	[0.4, 1.45] [0.0, 0.58]	UHF-band L-band
SKA1	25,000	10	133+64	14.5	3	1	0.61	[0.35, 3] [0.0, 0.5]	Band 1 Band 2

$$C_{N,dish} = \frac{T_{\text{sys}}^2 S}{N_d t \Delta\nu N_b N_{\text{pol}}}$$

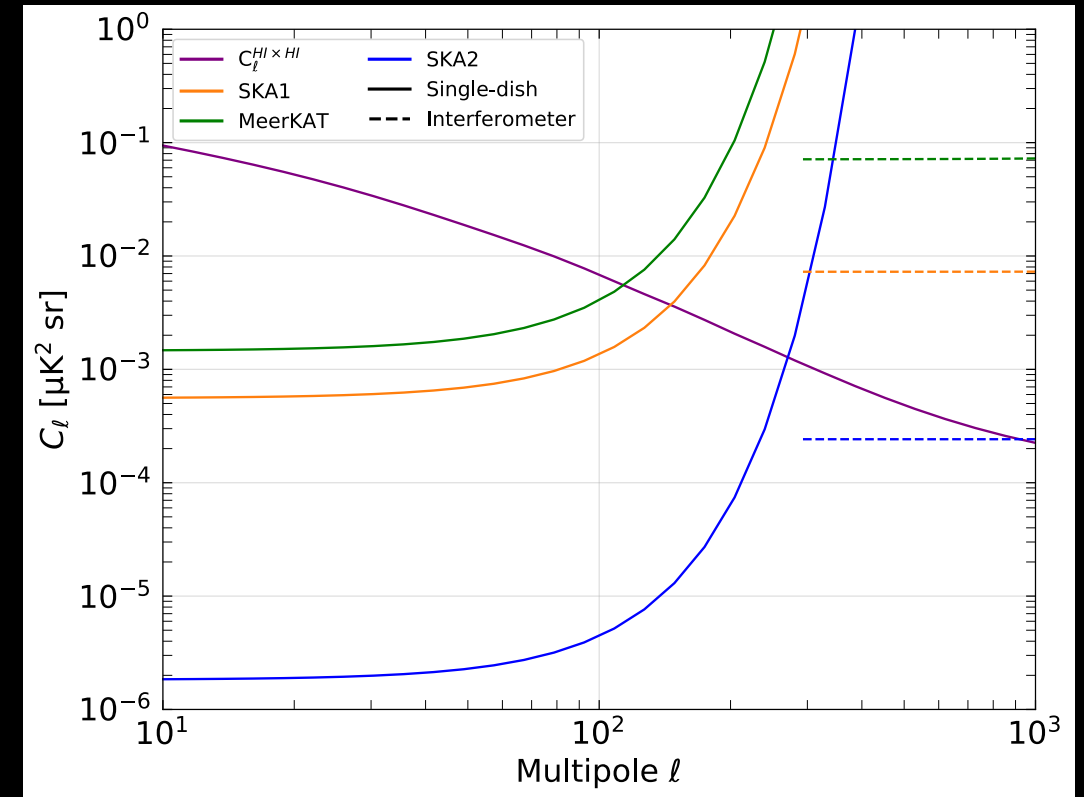
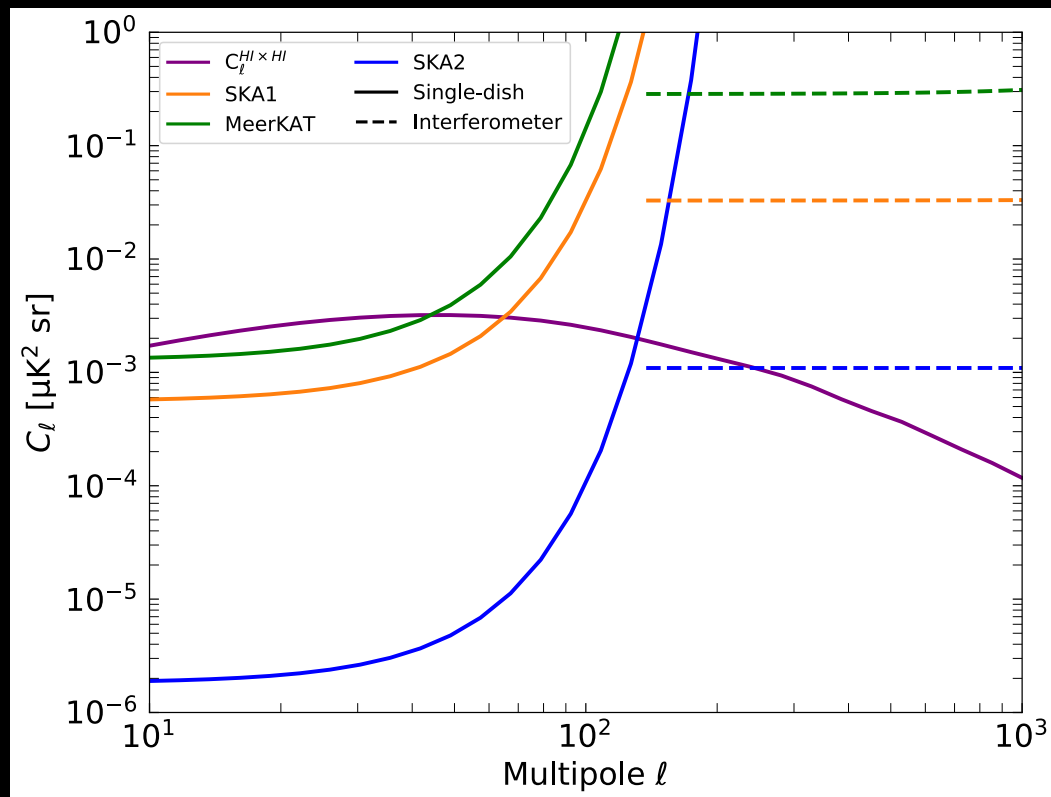
Camera et al, Phys. Rev.
Lett. 111 (2013)

$$C_{N,interf} = \frac{T_{\text{sys}}^2 S \text{ FoV}}{n(u) t \Delta\nu N_b N_{\text{pol}}}$$

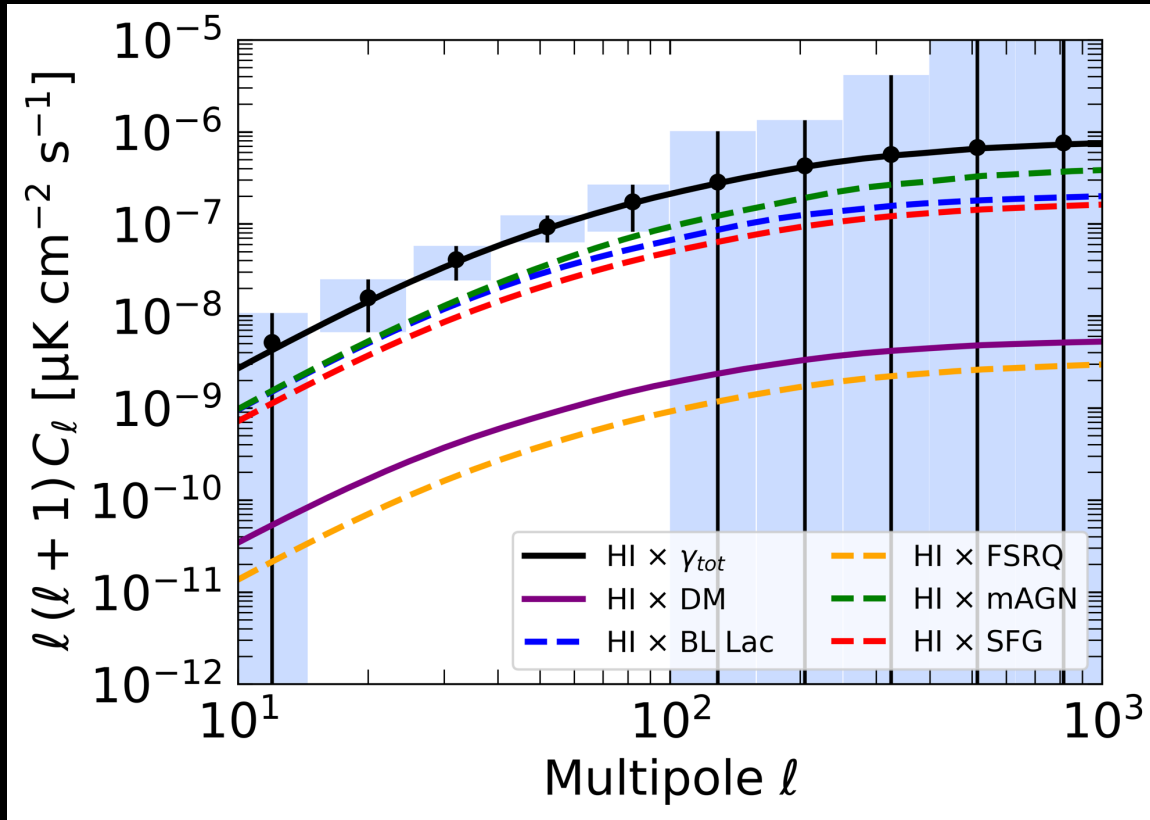
Bull et al, Astroph. J.
803 (2015)

Variance of the signal: 21cm

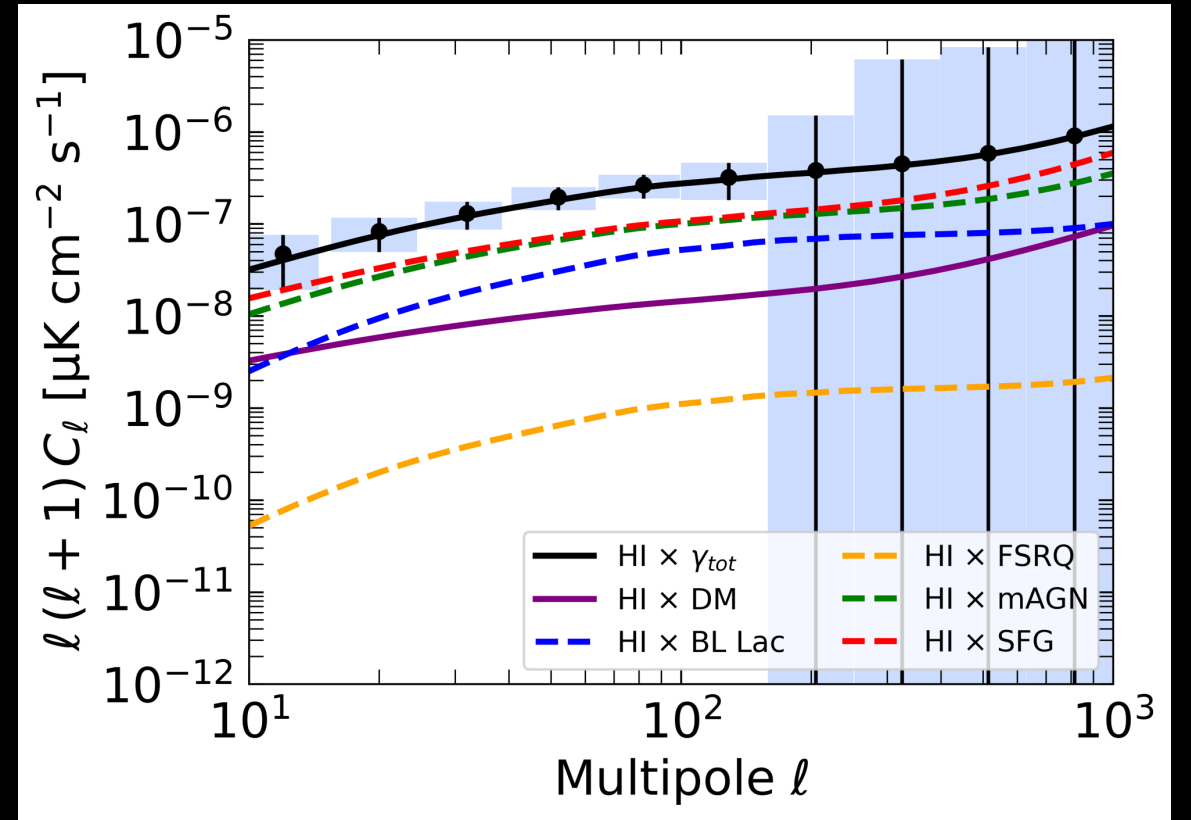
$$(\Delta C_\ell^{ij})^2 = \frac{1}{(2l+1) f_{sky}} \left[(C_\ell^{ij})^2 + \left(C_\ell^{ii} + \frac{C_N^i}{B_{\ell,i}^2} \right) \left(C_\ell^{jj} + \frac{C_N^j}{B_{\ell,j}^2} \right) \right]$$



Fermi x SKA1



Band 1: $0.35 < z < 3.0$

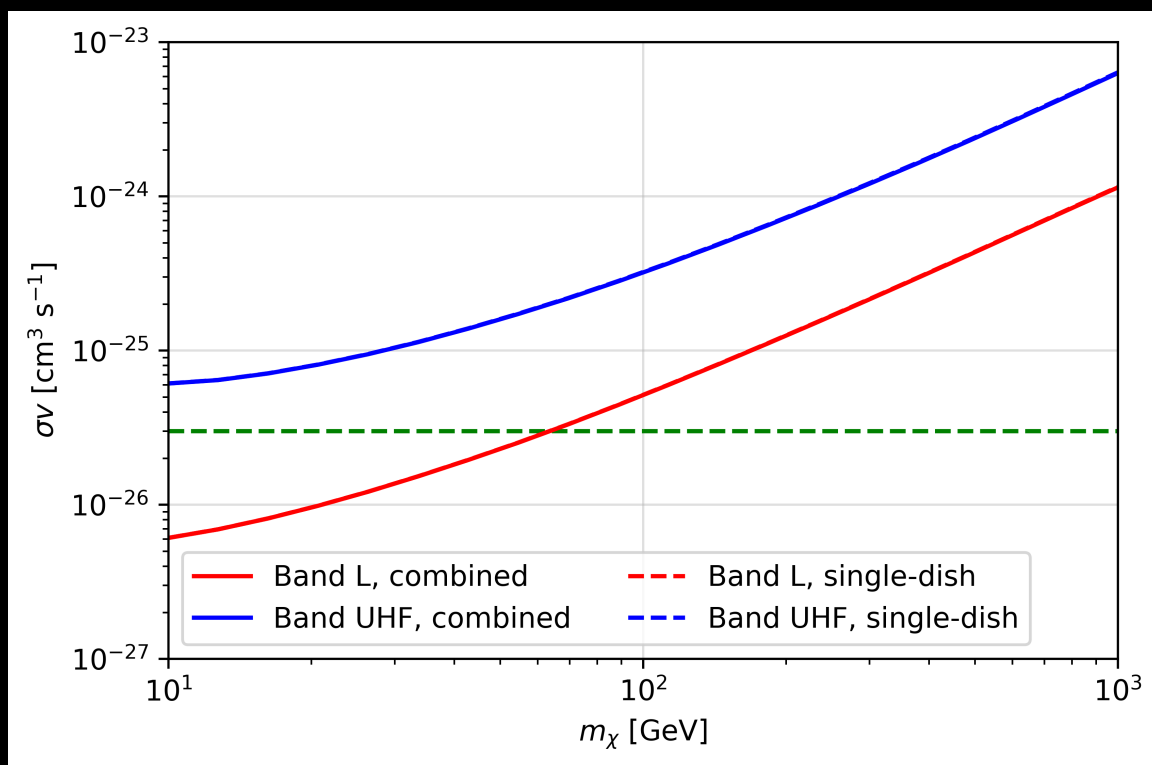


Band 2: $0 < z < 0.5$

Dark matter constraints

$$\Delta\chi^2 = \chi_{DM+S}^2 - \chi_S^2 = 4 \quad 95\% \text{ CL}$$

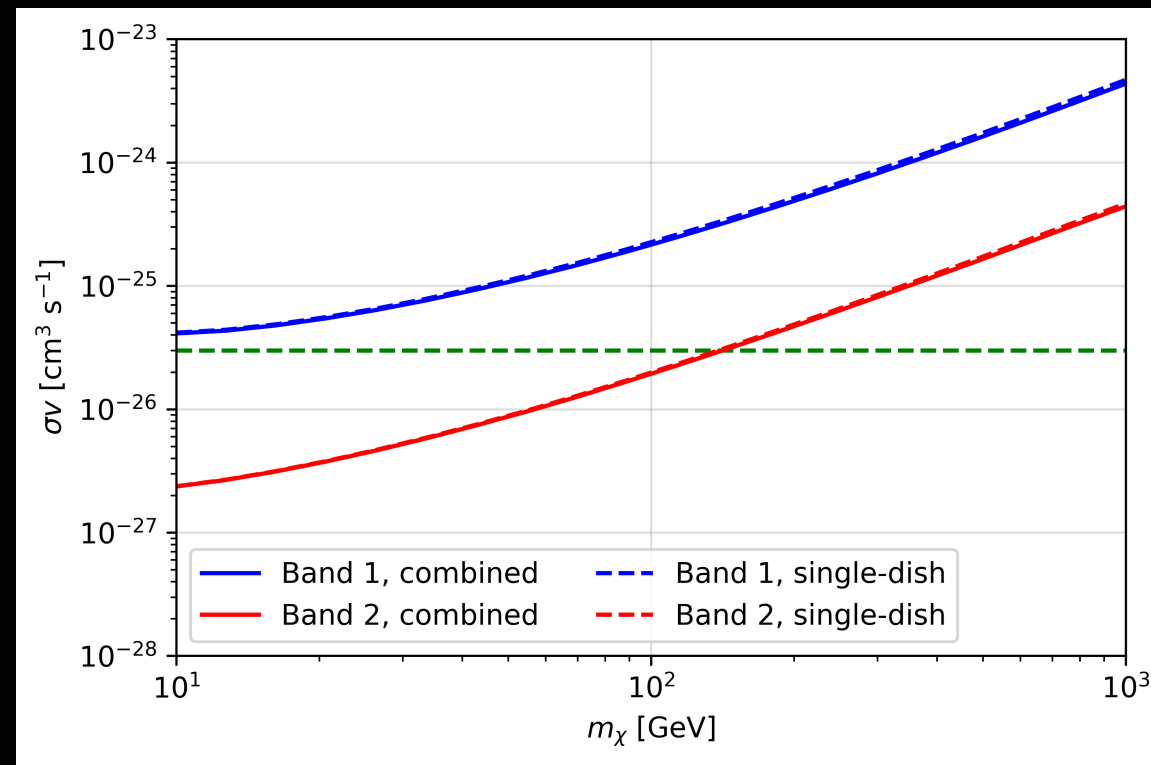
MeerKAT



L-band: $0 < z < 0.58$

UHF-band: $0.4 < z < 1.45$

SKA1



Band 1: $0.35 < z < 3$

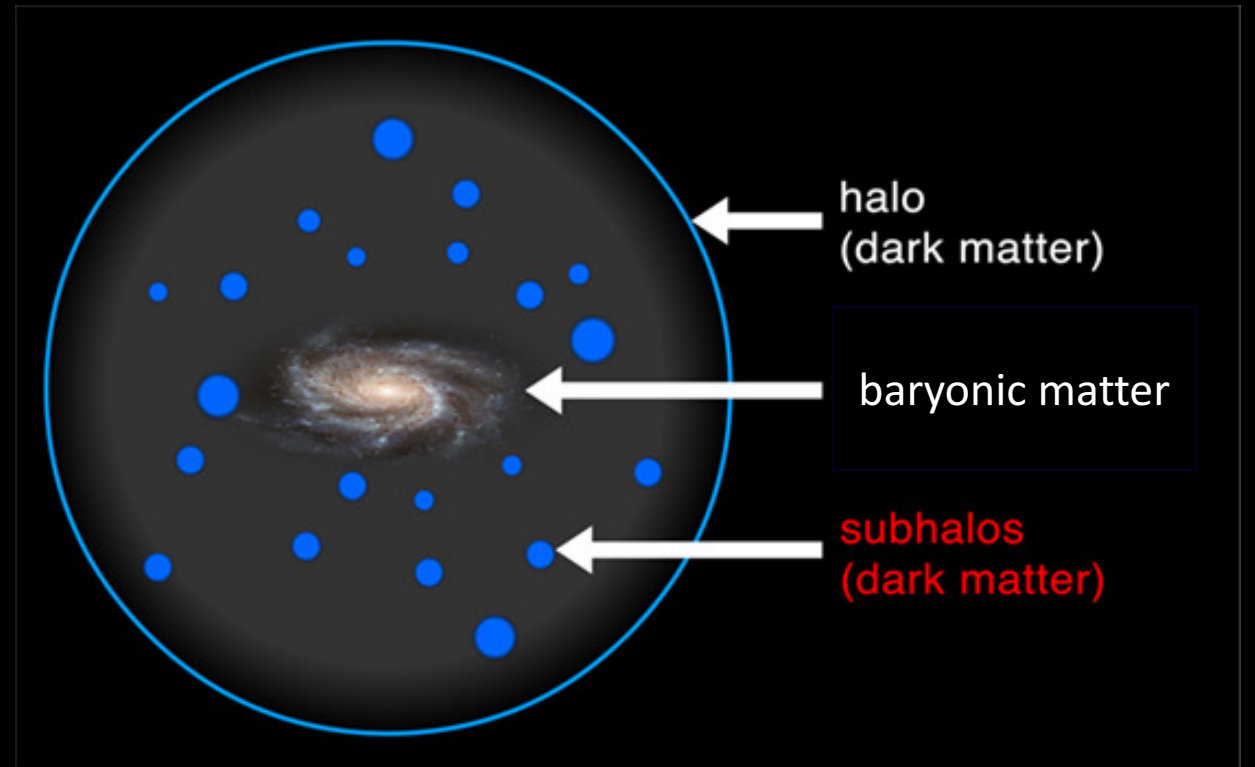
Band 2: $0 < z < 0.5$

Boost factor

$$\log B(M, z = 0) = \sum_{i=0}^5 d_i \left(\log \frac{M}{M_{\odot}} \right)^i$$

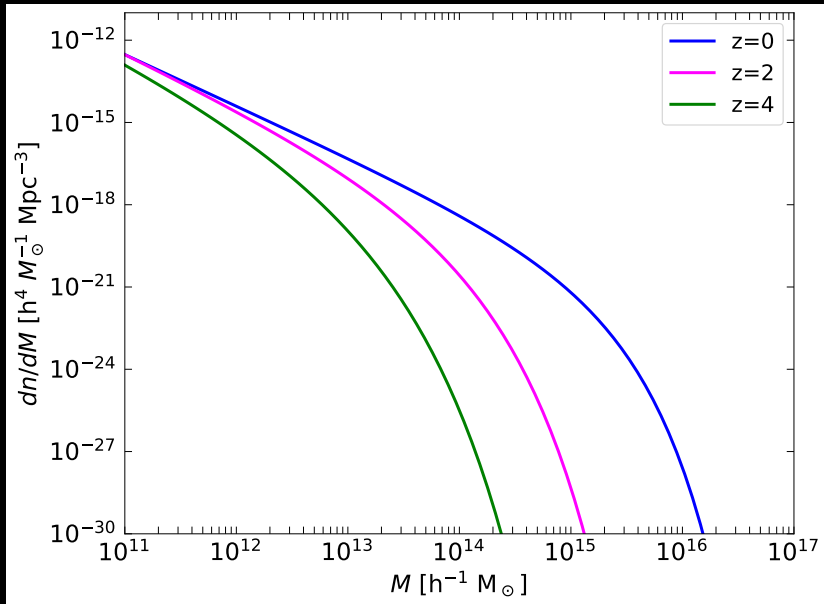
$$B(M, z) = \frac{B(M, z = 0)}{1 + z}$$

B_{sub} : Moliné et al. Volume 466, Issue 4, p. 4974–4990 (2017)

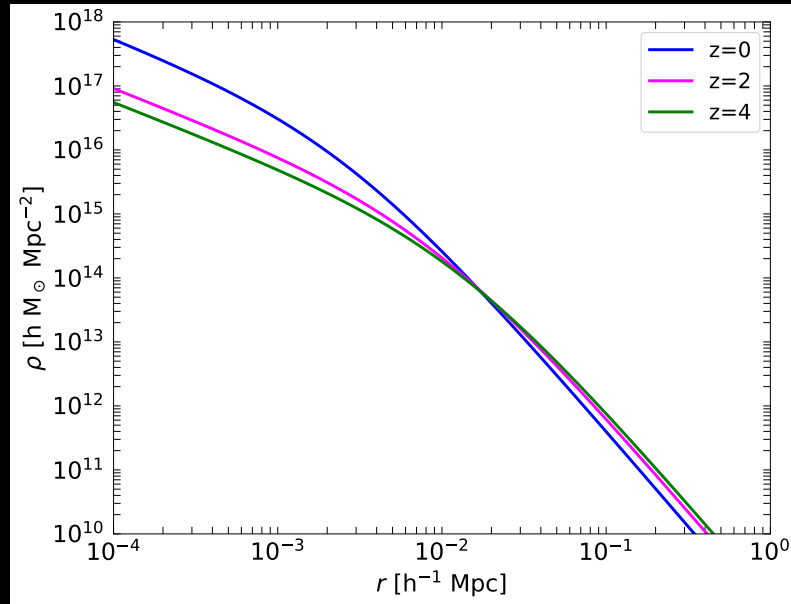


Halo model

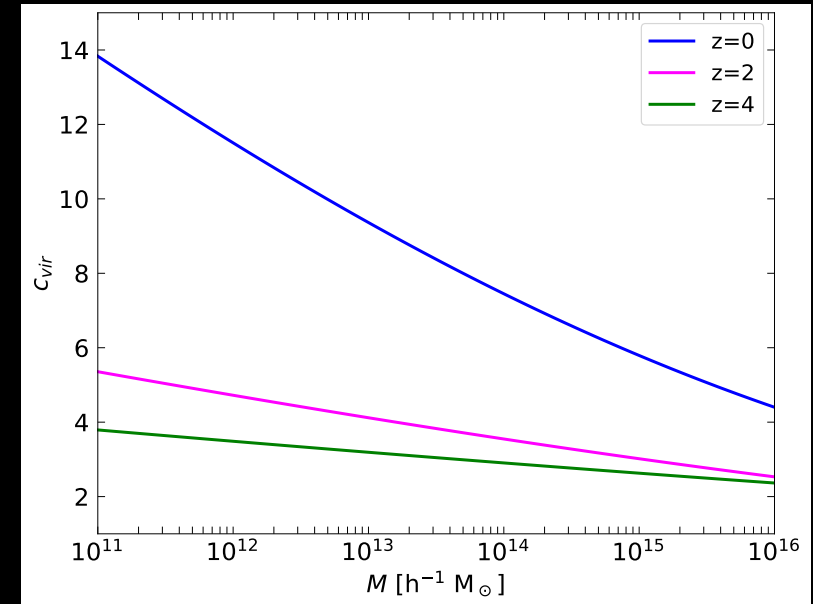
Halo mass function: Sheth-Tormen



Density profile: NFW



Halo concentration: Correa



Journal of Cosmology and Astroparticle Physics

Synergies across the spectrum for particle dark matter indirect detection: how HI intensity mapping meets gamma rays

Elena Pinetti^{1,2,3}, Stefano Camera^{1,2,4}, Nicolao Fornengo^{1,2} and Marco Regis^{1,2}

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[Journal of Cosmology and Astroparticle Physics](#), [Volume 2020](#), [July 2020](#)

Citation Elena Pinetti et al JCAP07(2020)044

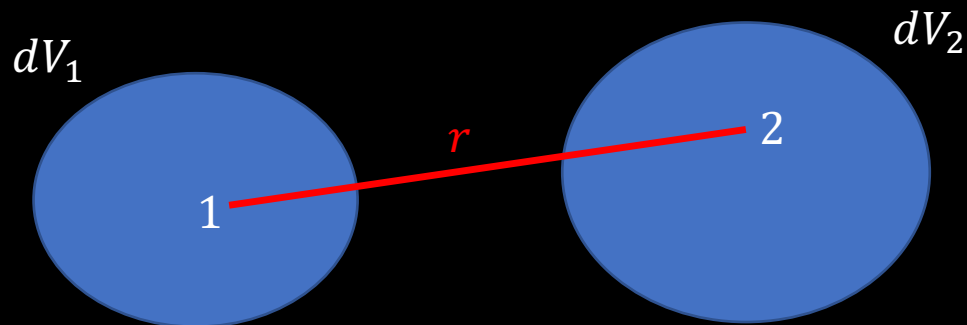
Fourier power spectrum

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

Density contrast

$$\xi(r) = \langle \delta(x) \delta(x+r) \rangle$$

$$dP_{12} = \bar{n}^2 dV_1 dV_2 [1 + \xi(r)]$$



$$P(k) = \int d^3r \xi(r) e^{ikr}$$

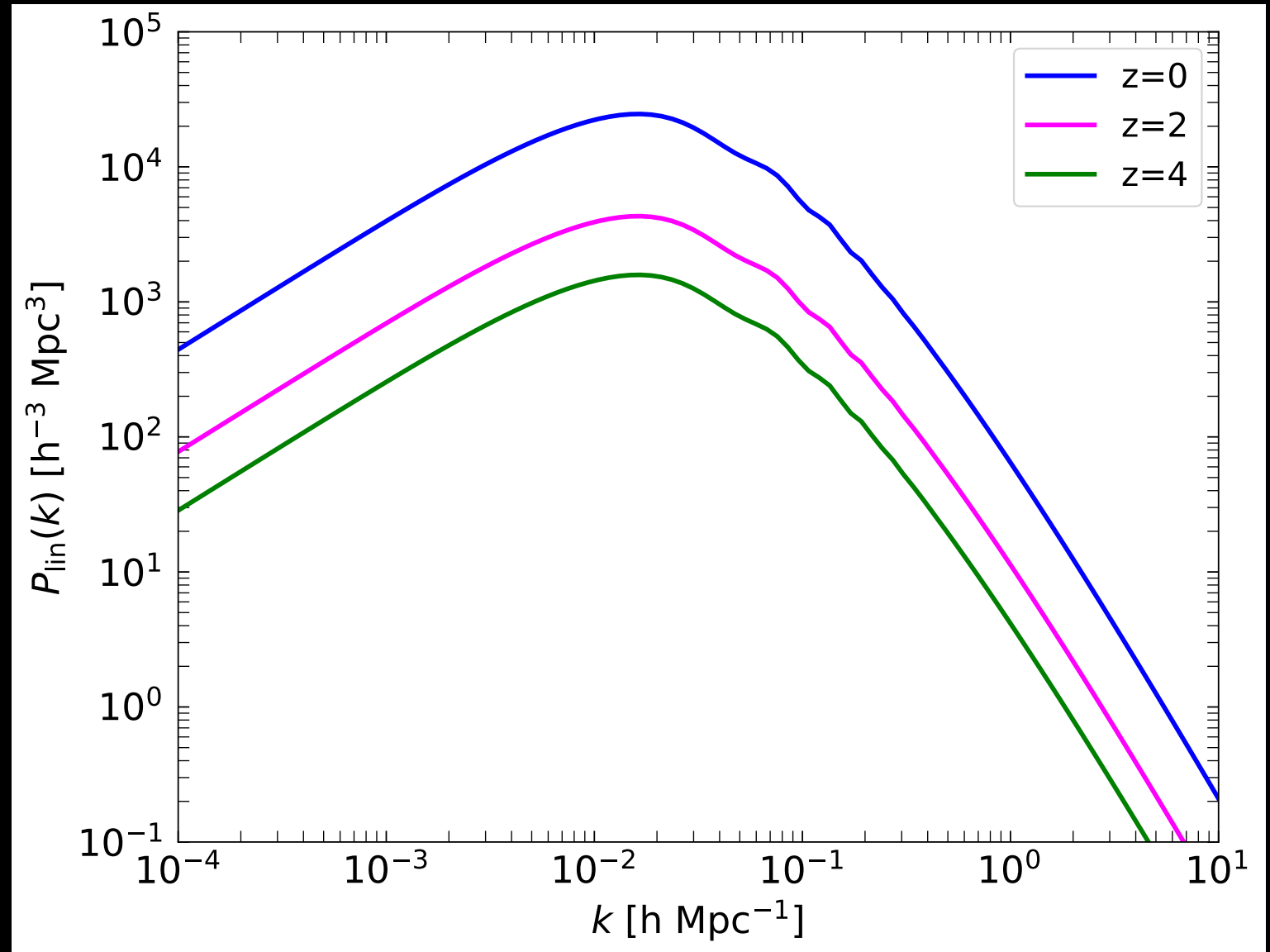
$$\frac{\Delta\rho}{\bar{\rho}} \ll 1$$

Linear regime

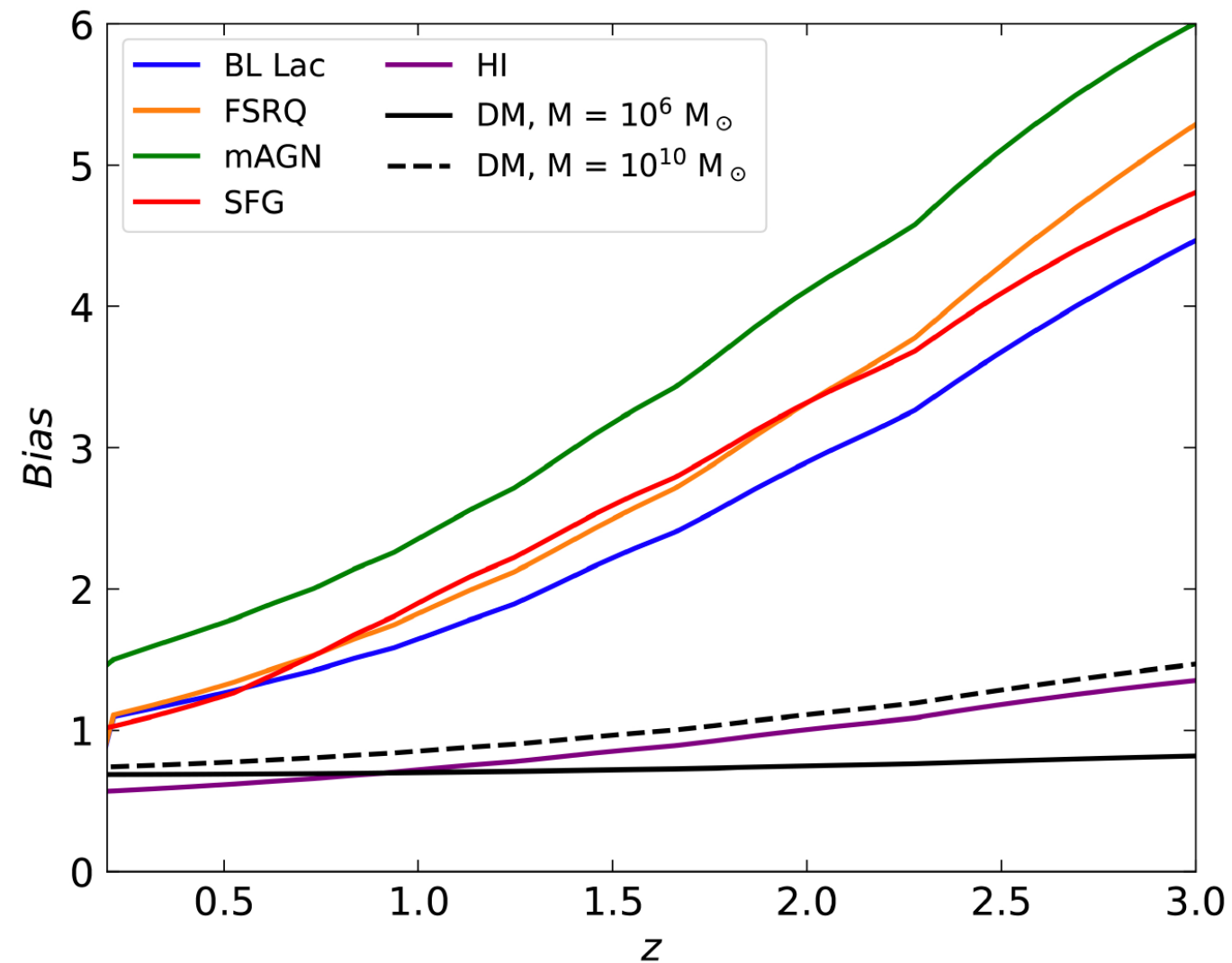
$$\frac{\Delta\rho}{\bar{\rho}} \sim 1$$

Non-linear regime

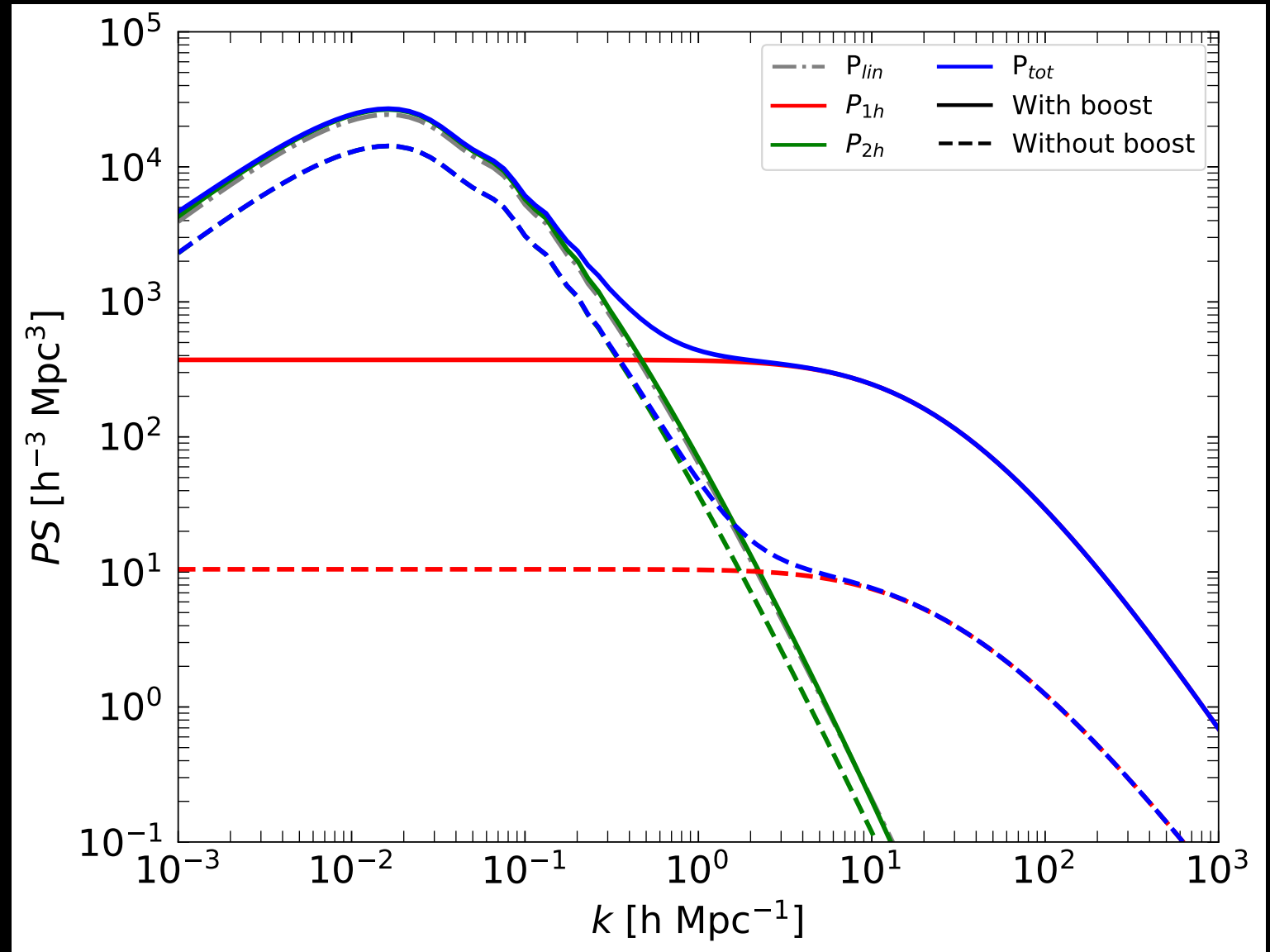
Linear power spectrum



Bias



Annihilating dark matter



Halo model vs N-body simulations

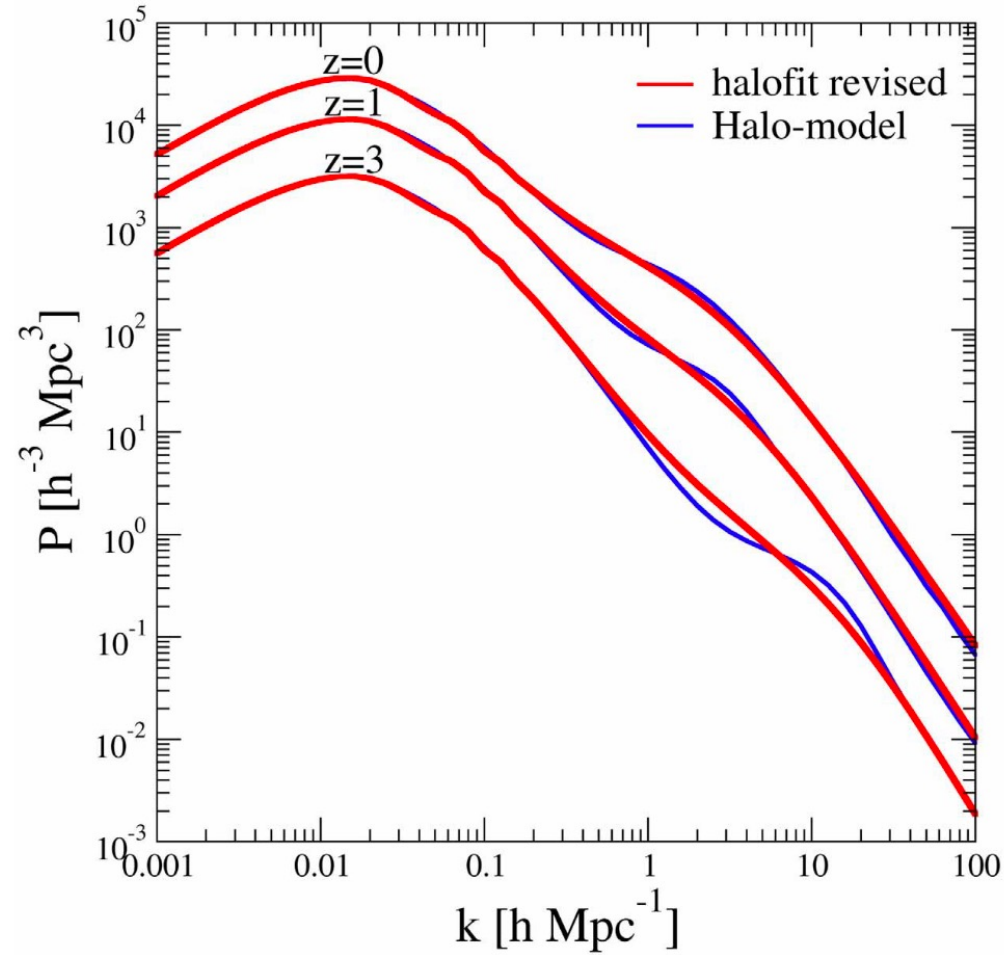


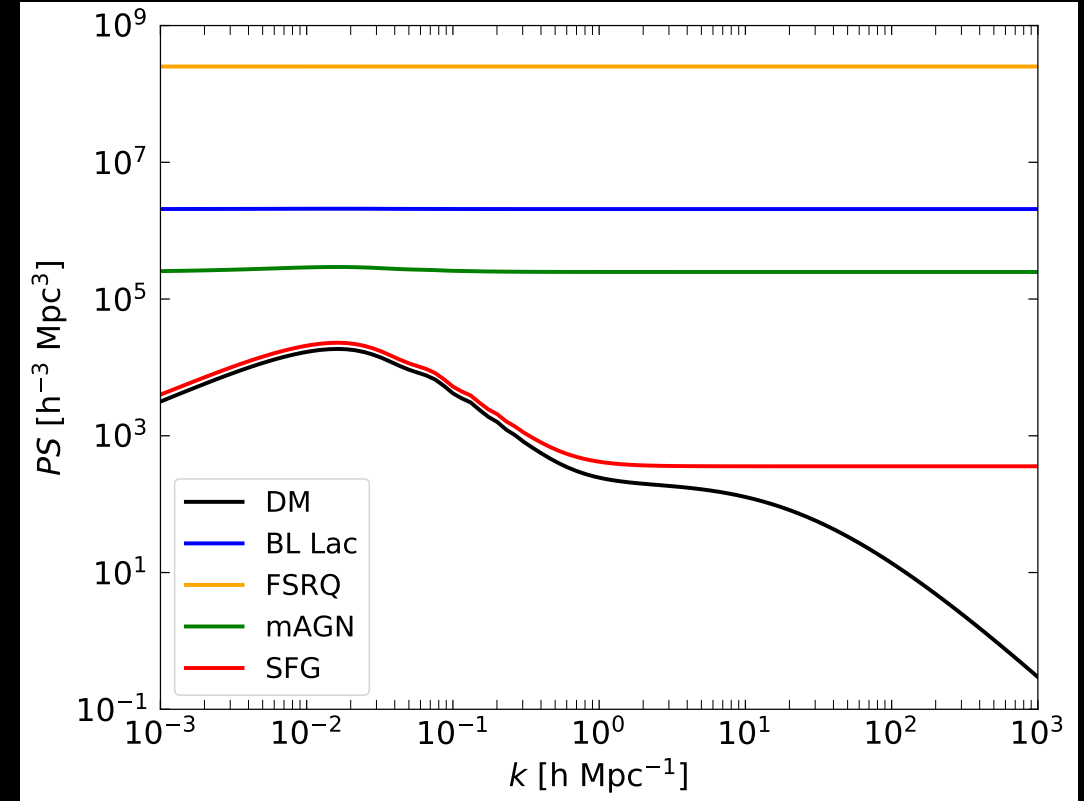
FIGURE 1 | 3D power spectra. Comparison between the non-linear 3D matter-PS obtained with the halo-model considered in this paper and the revised halofit results from high-resolution N -body simulations presented in Ref. [27], at different redshifts.

Astrophysical sources

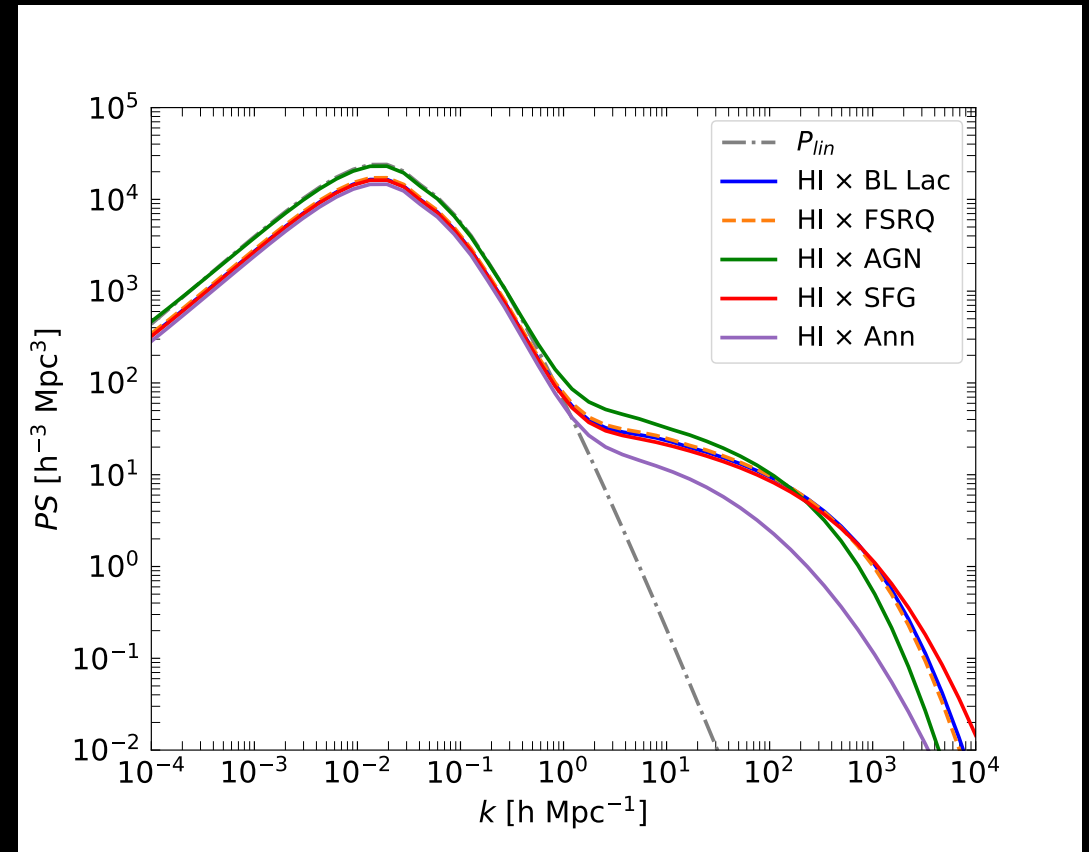
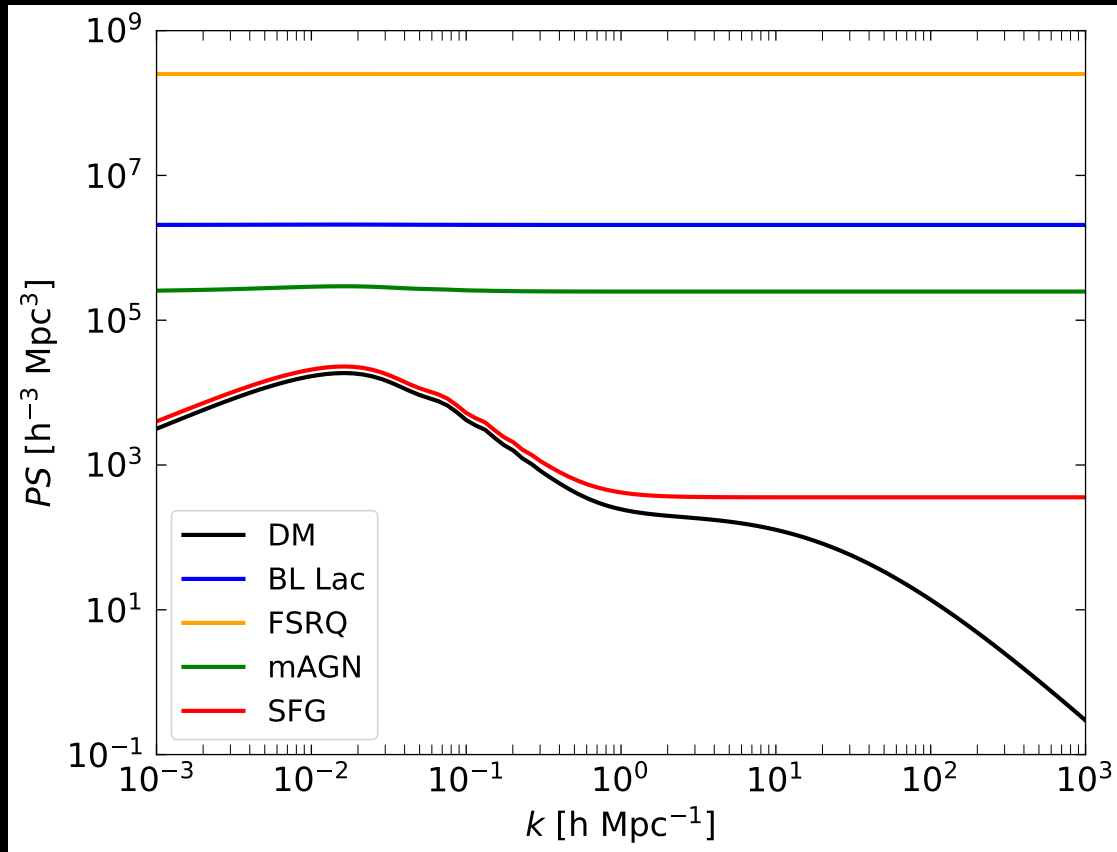
$$P_{SS}^{1h}(k, z) = \int_{L_{min}}^{L_{max}} dL \phi(L, z) \left(\frac{L}{\langle g_s \rangle} \right)^2$$

$$P_{SS}^{2h}(k, z) = \left[\int_{L_{min}}^{L_{max}} dL \phi(L, z) b(M(L), z) \frac{L}{\langle g_s \rangle} \right]^2 P_{lin}(k, z)$$

Type	Γ	L_{min} [erg/s]	L_{max} [erg/s]	GLF
BL Lac	2.11	7×10^{43}	10^{52}	Ajello et al (2014)
FSRQ	2.44	10^{44}	10^{52}	Ajello et al (2012)
mAGN	2.37	10^{40}	10^{50}	Di Mauro et al (2014)
SFG	2.7	10^{37}	10^{42}	Gruppioni et al (2013)



Astrophysical sources



Window functions

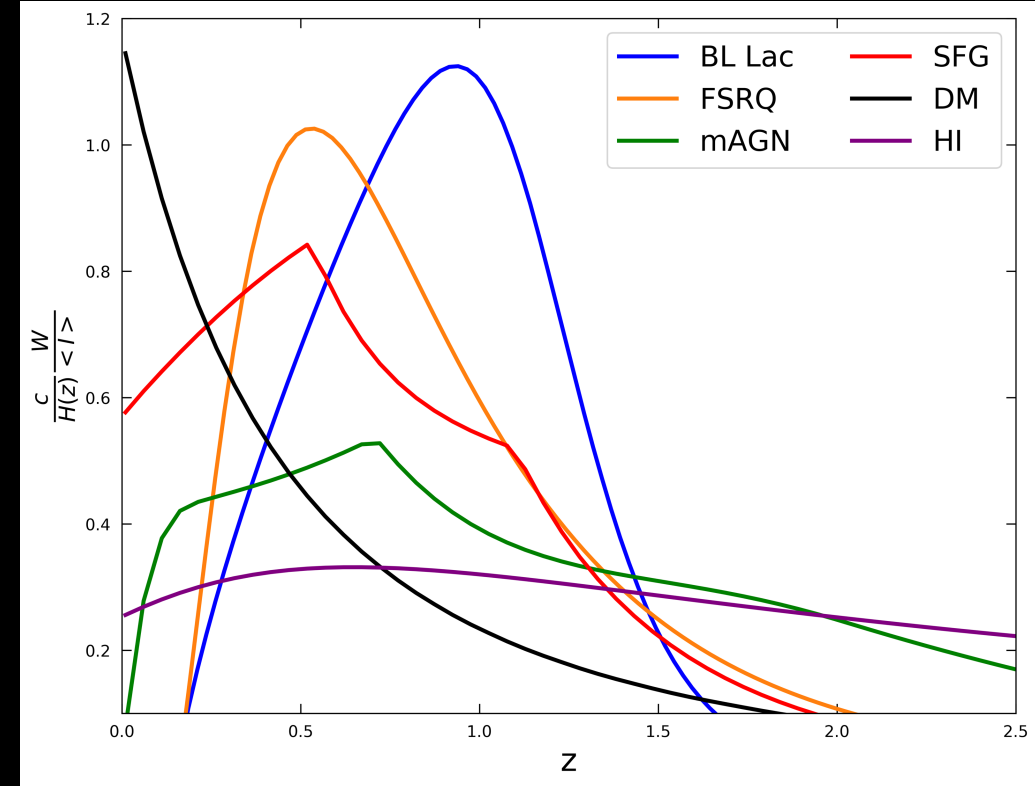
$$W_{HI}(z) = W_0 T_{obs}(z)$$

W_{HI} : Battye et al. 2012

$$T_{obs}(z) = 44 \mu K (1+z)^2 \frac{H_0}{H(z)}$$

$$W_s^\gamma(E, z) = \left(\frac{d_L}{1+z} \right)^2 \int_{L_{min}}^{L_{max}} dL \frac{d\mathcal{N}}{dE} \phi e^{-\tau}$$

$$W_\gamma(E, z) = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2} \Delta^2 \left(\frac{\Omega_{DM} \rho_c}{m_{DM}} \right)^2 (1+z)^3 \frac{dN}{dE} [E(1+z)] e^{-\tau}$$



dN/dE : Cembranos et al. 2010

τ : Finke et al. 2009

Blazars

$$\phi(L, z, \Gamma) = \phi(L, \Gamma) \times e(z, L).$$

Luminosity-dependent density evolution

$$\phi(L) = \frac{A}{\ln(10)L} \left[\left(\frac{L}{L_\star} \right)^{\gamma_1} + \left(\frac{L}{L_\star} \right)^{\gamma_2} \right]^{-1} \exp \left[-\frac{(\Gamma - \mu(L))^2}{2\sigma^2} \right]$$

$$e(z, L) = \left[\left(\frac{1+z}{1+z_c(L)} \right)^{-p_1} + \left(\frac{1+z}{1+z_c(L)} \right)^{-p_2} \right]^{-1}.$$

$$\mu(L) = \mu^\star + \beta \left[\log \frac{L}{\text{erg s}^{-1}} - 46 \right].$$

	A [Mpc ³ erg s ⁻¹ s]	$L_\star$ [erg s ⁻¹]	γ_1	γ_2	p_1	p_2	$z_\star$	β
BL Lacs	$9.20 \cdot 10^{-11}$	$2.43 \cdot 10^{48}$	1.12	3.71	4.50	-12.88	1.67	$4.46 \cdot 10^{-2}$
FSRQ	$3.06 \cdot 10^{-9}$	$0.84 \cdot 10^{48}$	0.21	1.58	7.35	-6.51	1.47	0.21

Blazar

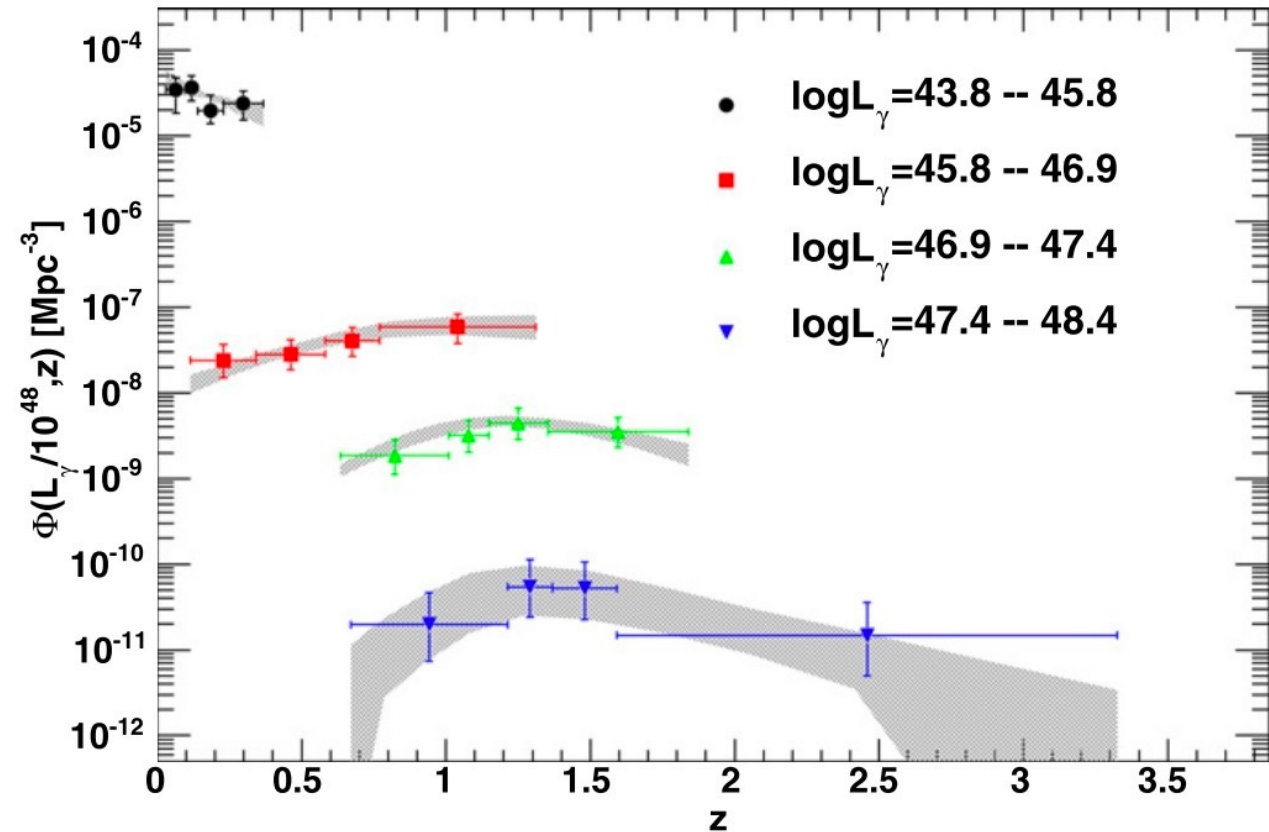


Figure 4. Growth and evolution of BL Lac objects, separated by luminosity class. The gray bands represent 68% confidence regions around the best-fitting LDDE LF model (for each Monte Carlo sample). Both data points and band errors include uncertainties for the source redshifts as well as statistical uncertainty. All but the least luminous class have a redshift peak near $z \approx 1.5$; the lowest luminosity BL Lac objects increase toward $z = 0$.

Intensity mapping foreground

Galactic

- Synchrotron emission
- Free-free emission

Extragalactic

- Bright radio galaxies
- AGN
- Star-forming galaxies

Atmospherical noise

Radio interference

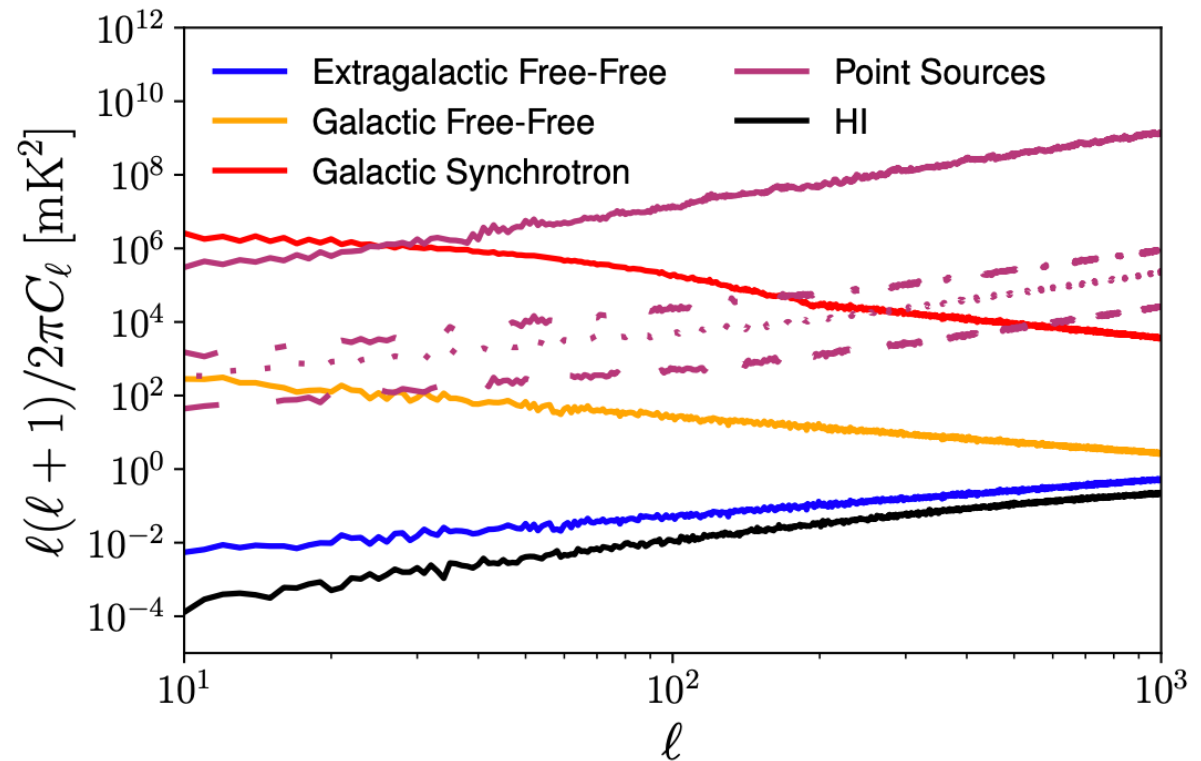
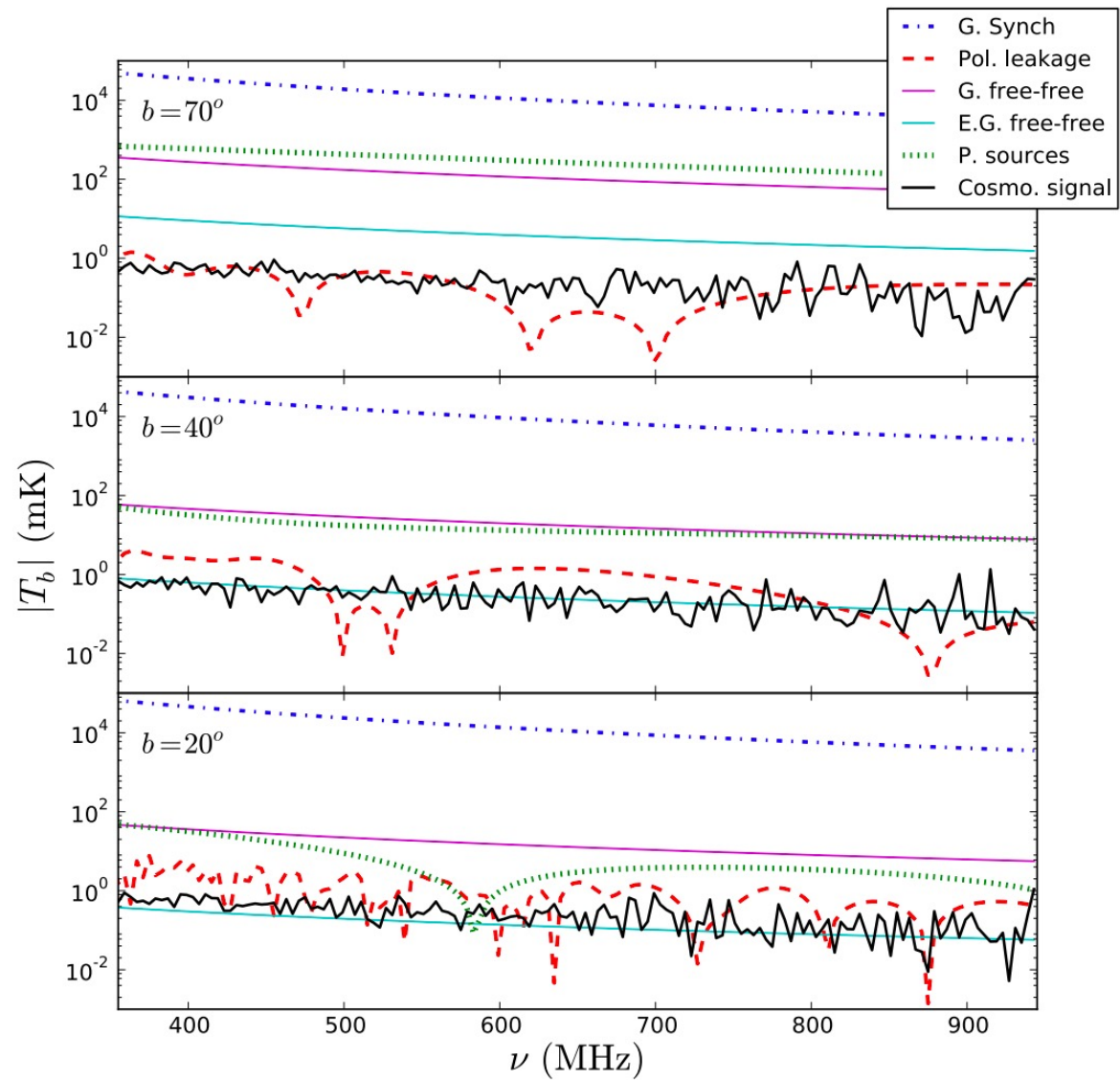


Figure 4. Angular power spectrum of the HI signal and the the foregrounds at 950 MHz. The point source C_ℓ are shown for different flux cuts: full catalogue (solid line), 10 Jy cut (dashed-dotted line), 1 Jy cut (dotted line) and 100 mJy cut (dashed line). [D. Matshawule et al, MNRAS \(2021\) Vol. 506, Issue 4, pp 5075-5092](#)

Intensity mapping foreground



Other window functions

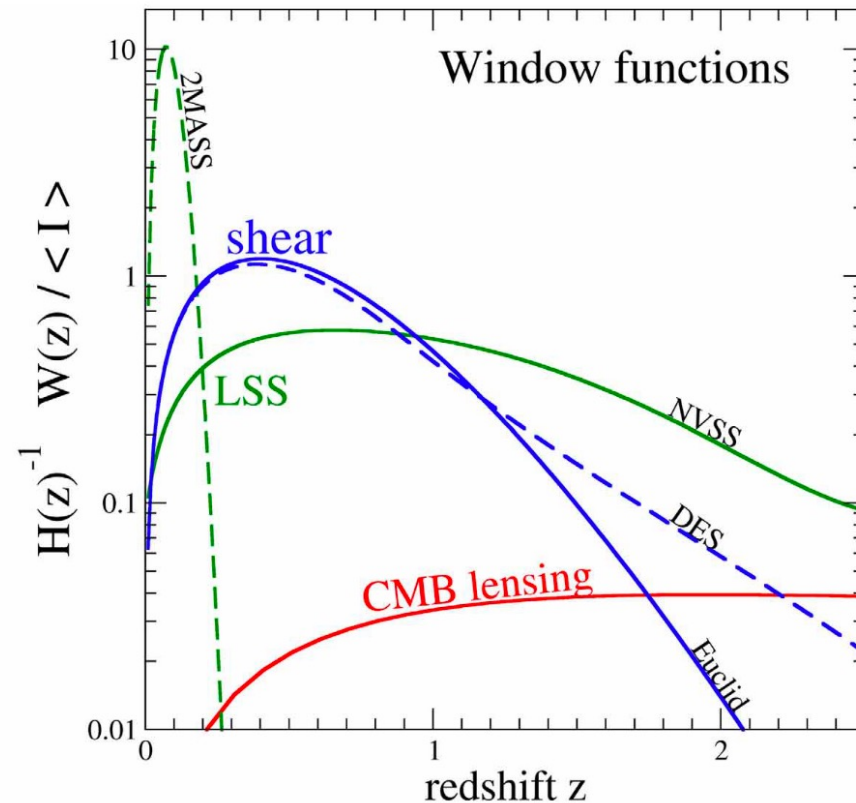
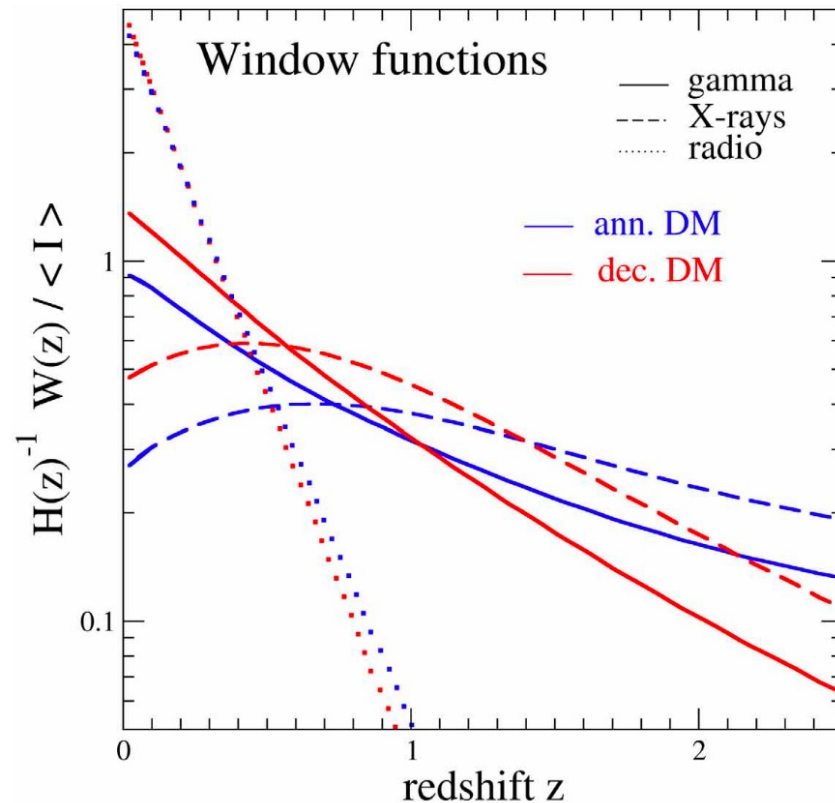
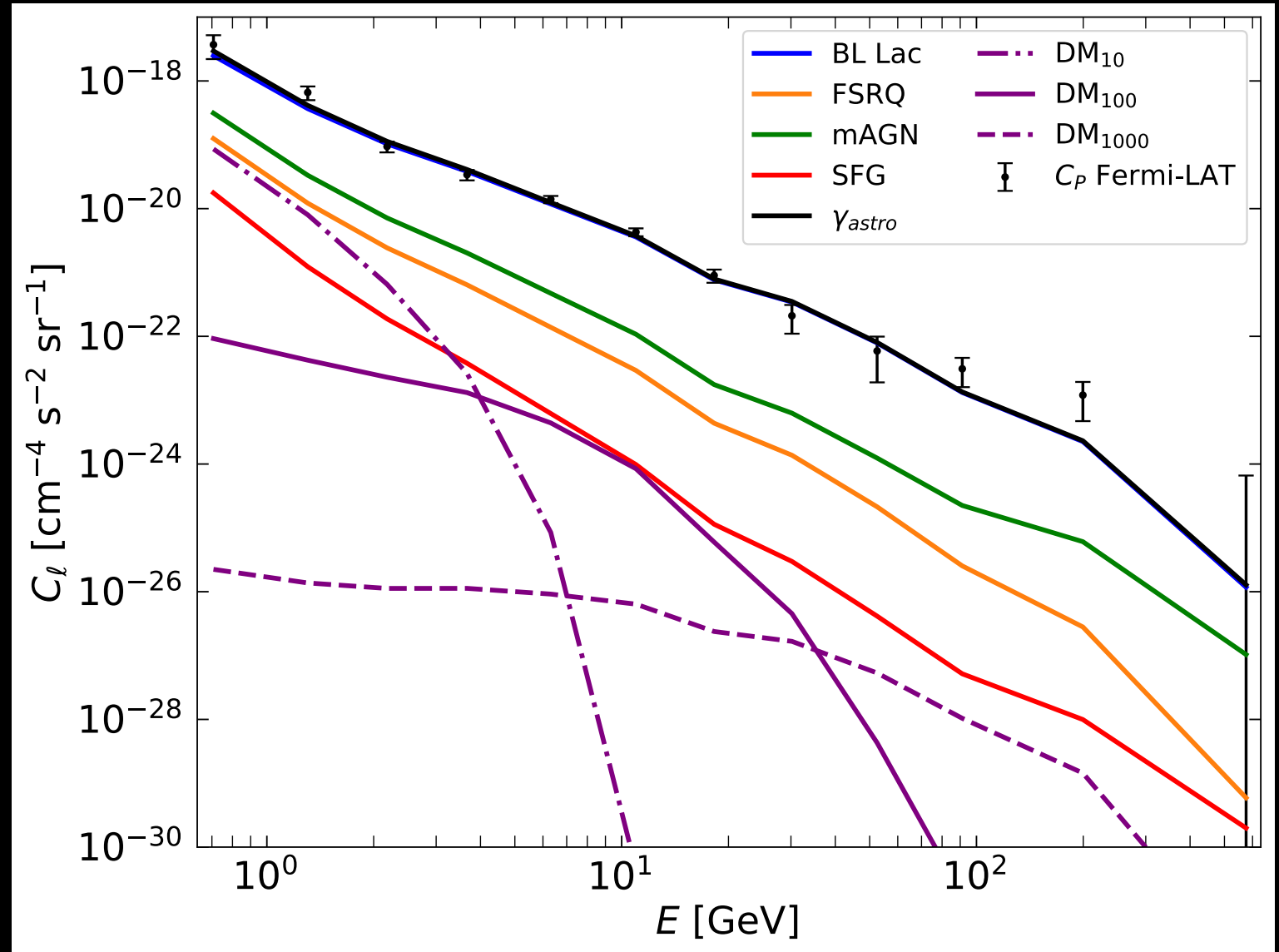


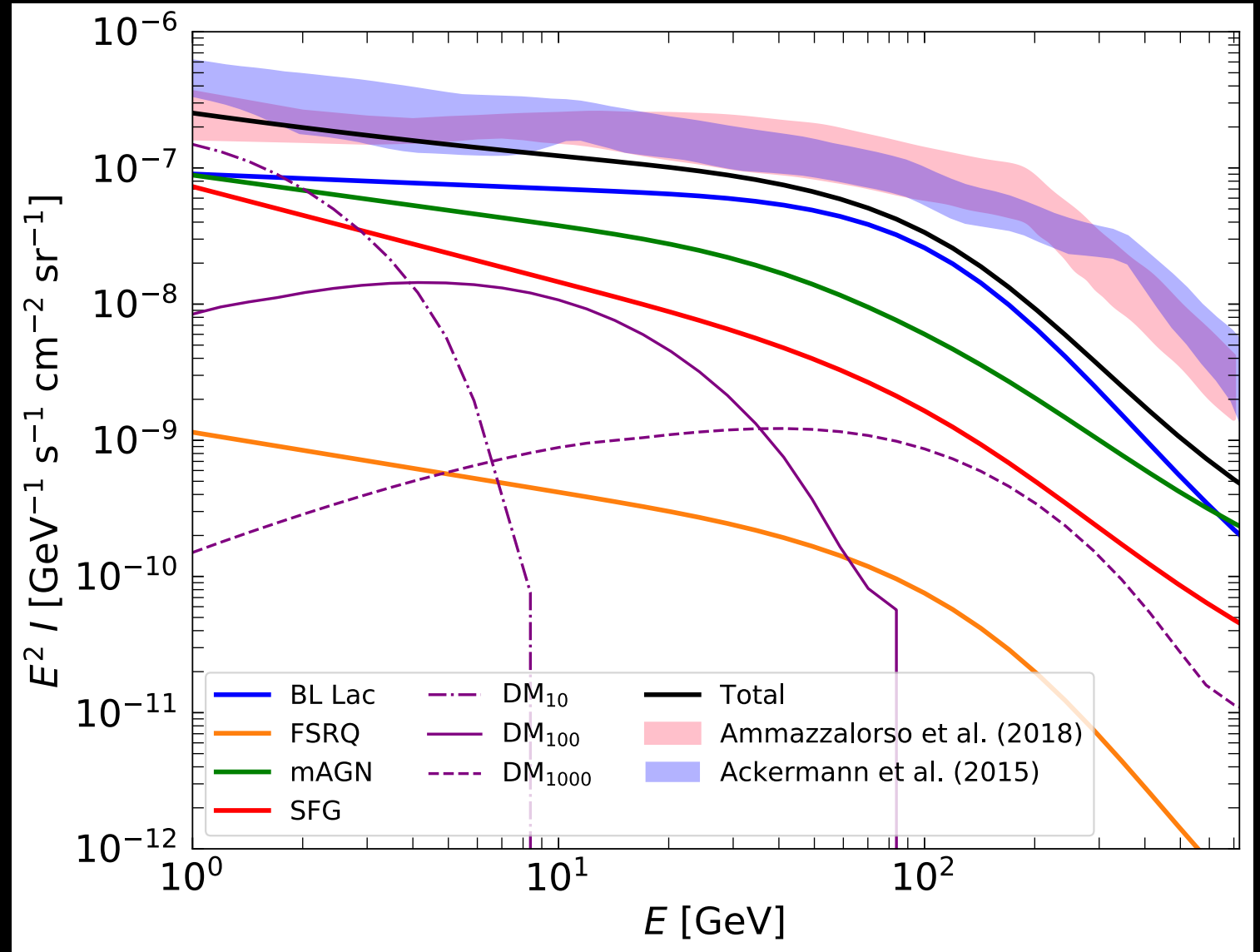
FIGURE 3 | Window functions. **Left:** Window functions as a function of the redshift for radio, X-ray, and gamma-ray emissions from annihilating/decaying DM. The window functions refer to reference frequencies/energies: $\nu = 1$ GHz for radio, $E = 10$ keV for X-rays, $E = 1$ GeV for gamma-rays. They have

been normalized to the total average intensity $\langle I \rangle$ such that the integral of the curves is equal to 1 for all cases. **Right:** Window functions vs. redshift for cosmic shear, CMB lensing, and two populations of galaxies (detected in the 2MASS and NVSS surveys) tracing LSS.

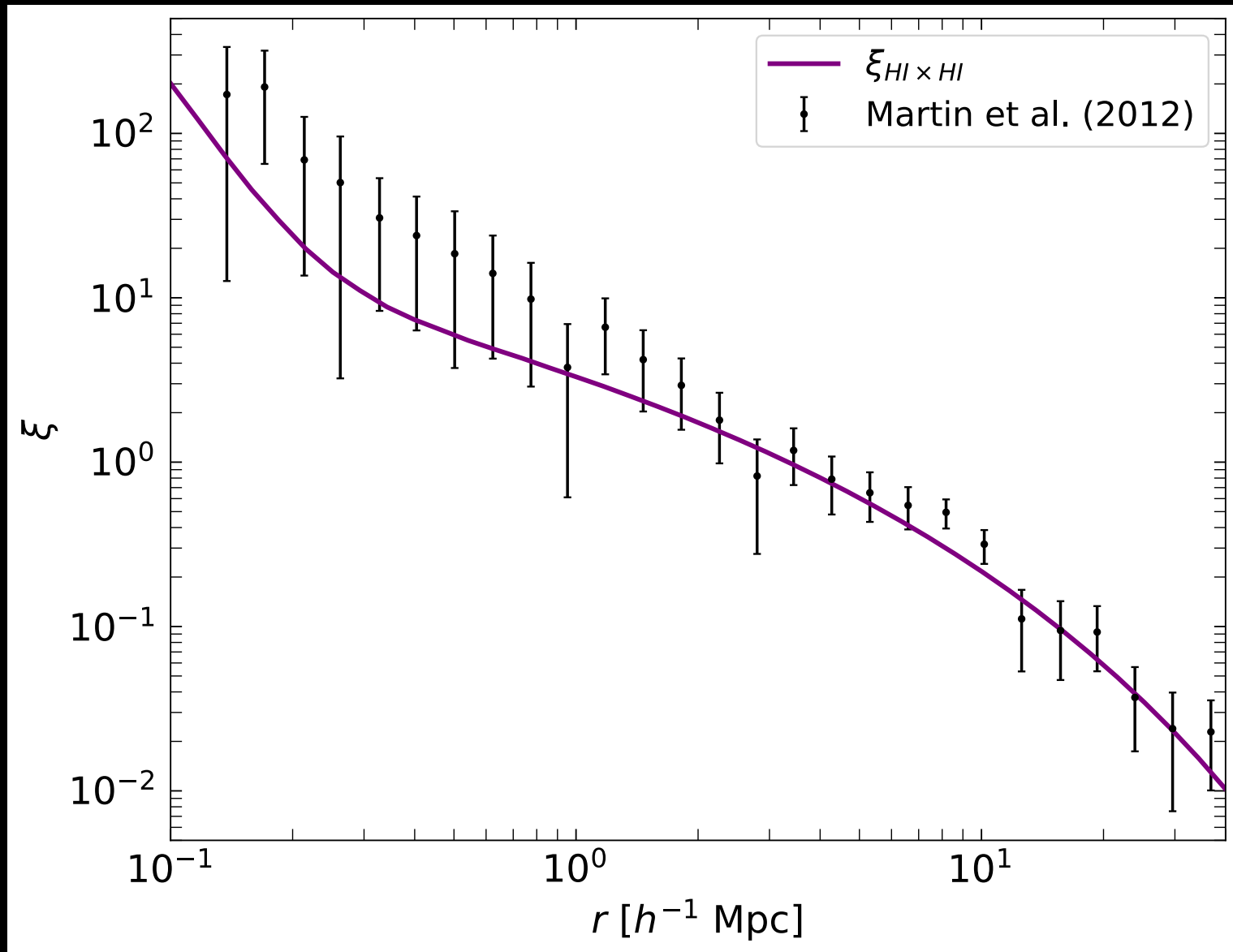
Gamma rays



Gamma rays



Neutral hydrogen



Phased Array Feeds

Phased Array Feed

Innovation in Radio
Astronomy

Design

Single instrument made up of
36 individual baseball-size
antennas

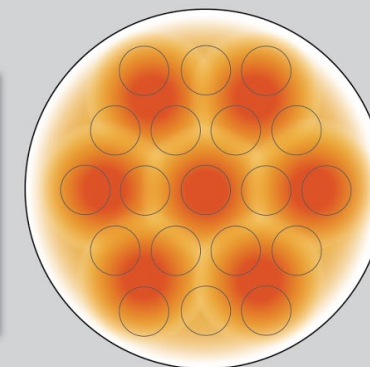
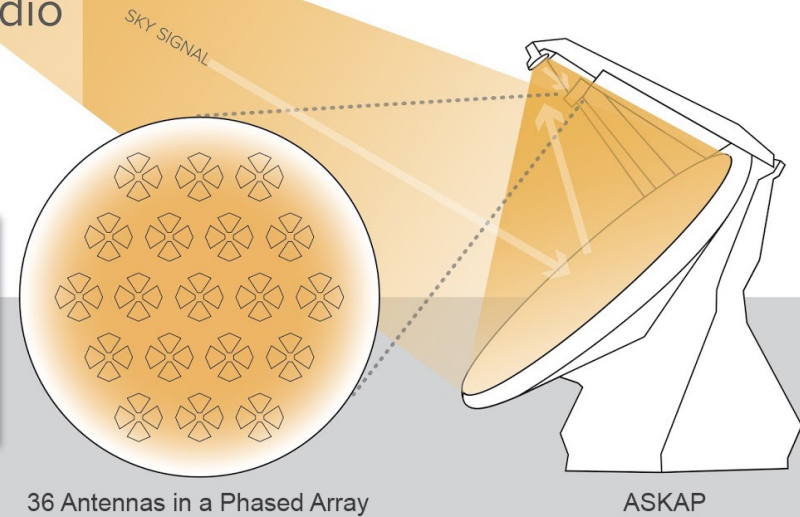
Phased array feed (PAF) design
allows for increased survey
speed and efficiency

HOW?

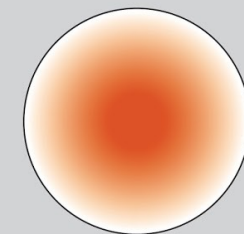
Beamforming

Unlike single feed, PAF uses
computer power to create
36 separate beams

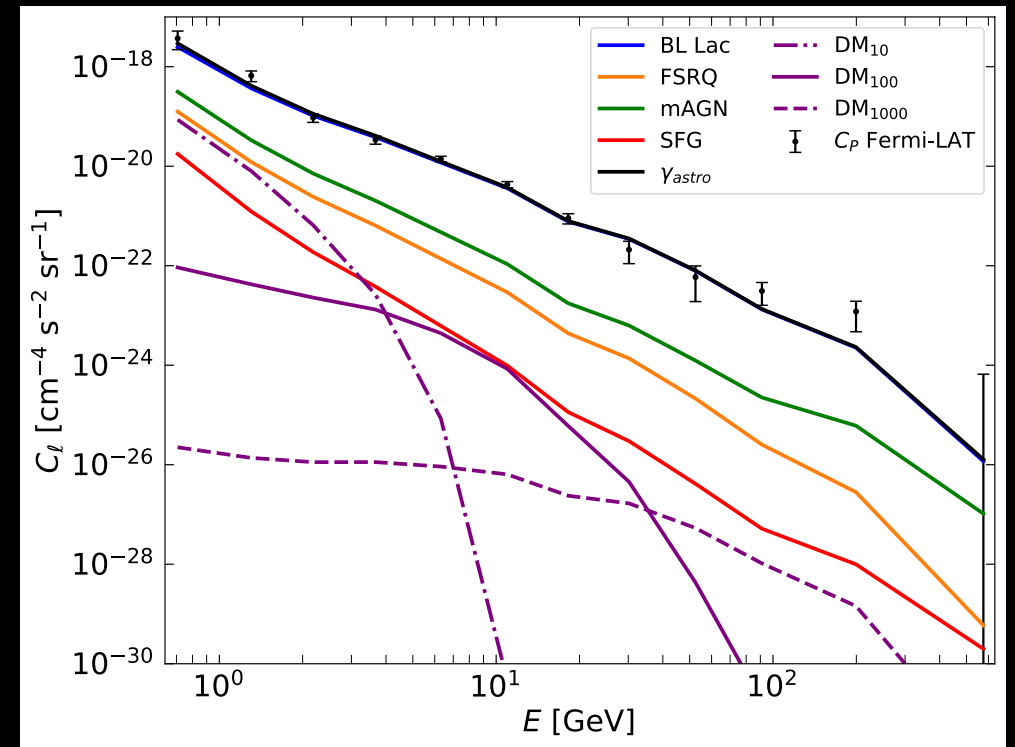
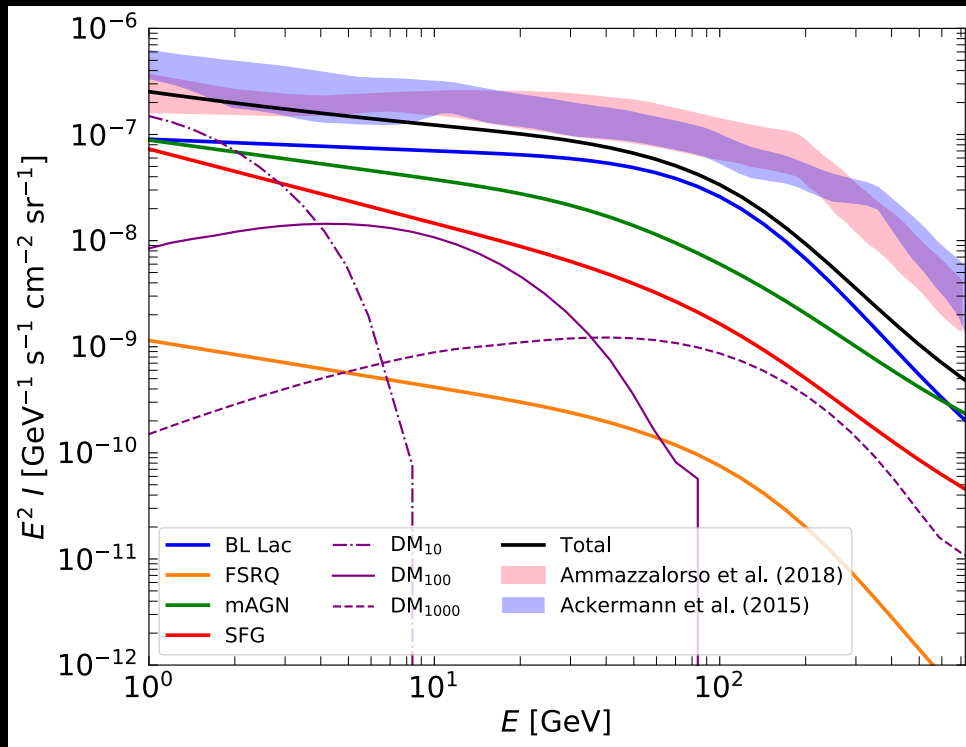
Since these beams can overlap,
the PAF system is better at
surveys and scanning wide
areas



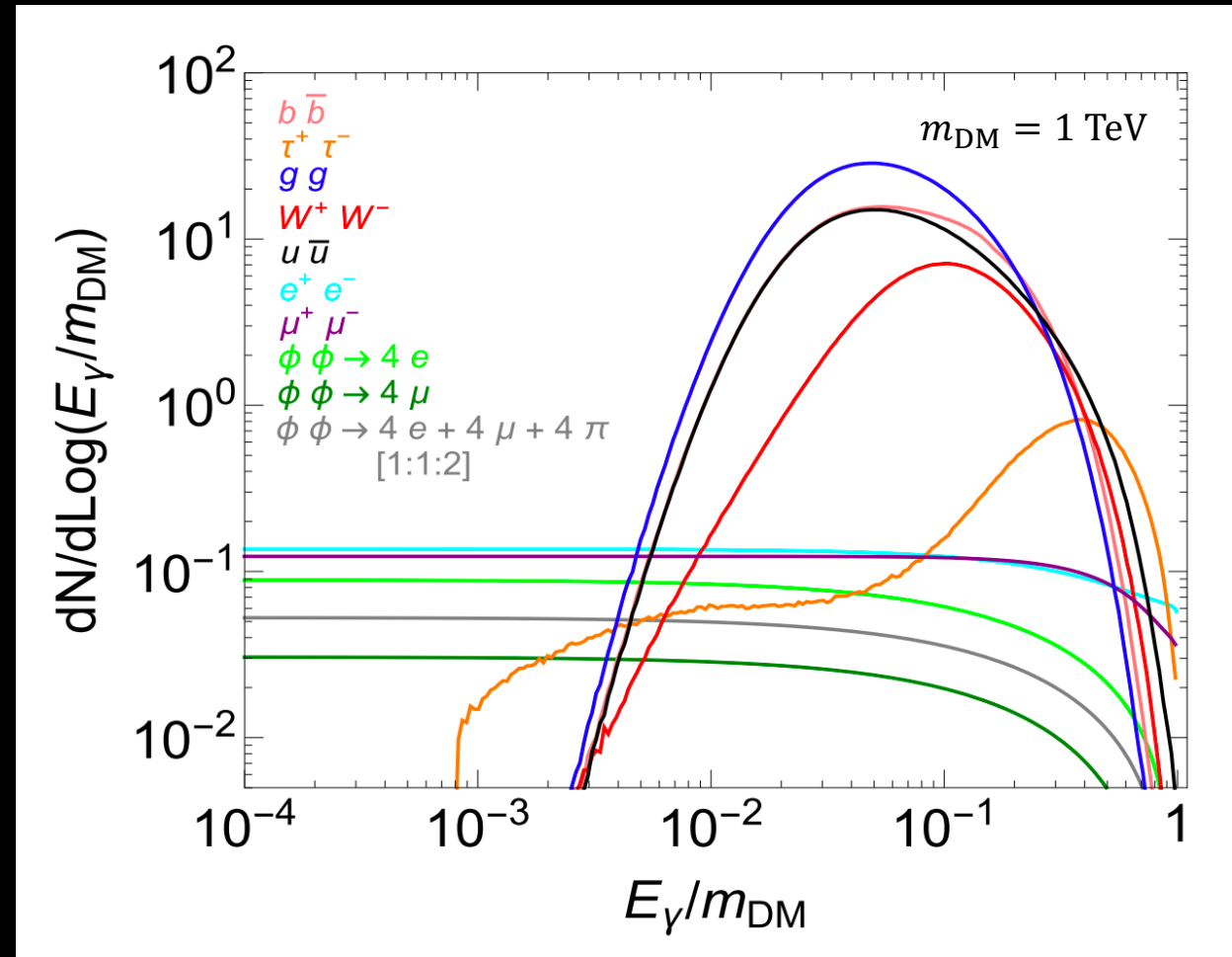
VS



Gamma-ray modelling



Energy spectrum



with $\rho \propto 1/r^{1.3}$ for $r \rightarrow 0$) profile. **Right:** Prompt γ -ray spectra produced in the annihilation of 1 TeV dark matter to e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$, W^+W^- , $u\bar{u}$, gg (g = a gluon), and $\phi\phi$, where ϕ decays either only to e^+e^- (with $m_\phi = 0.1$ GeV), or only to $\mu^+\mu^-$ (with $m_\phi = 0.9$ GeV), or to e^+e^- , $\mu^+\mu^-$, and $\pi^+\pi^-$ in the ratio 1 : 1 : 2 (with $m_\phi = 0.9$ GeV).

Error estimation

$$\Delta C_l = \sqrt{\frac{2}{(2l+1) f_{sky}}} \left(C_l + \frac{C_N}{B_l^2} \right) \quad \text{Auto-correlation}$$

$$\Delta C_l^{ij} = \sqrt{\frac{1}{(2l+1) f_{sky}}} \left[(C_l^{ij})^2 + \left(C_l^{ii} + \frac{N_i}{B_{l,i}^2} \right) \left(C_l^{jj} + \frac{N_j}{B_{l,j}^2} \right) \right] \quad \text{Cross-correlation}$$

$$T_{sys} = \left[30 + 60 \left(\frac{300 \text{ MHz}}{\nu} \right)^{2.35} \right] K$$

$$\sigma_b = \sigma_0 (1 + 0.25 \sigma_0 l)^{-1}$$

$$B_l^{HI} = \exp \left[-\frac{l^2}{2} \left(\frac{1.22}{\sqrt{8 \ln 2}} \frac{\lambda_o}{D} \right) \right]$$

$$\sigma_0^{Fermi} = \sigma_* (0.5 \text{ GeV}) \cdot \left(\frac{E}{0.5 \text{ GeV}} \right)^{-0.95} + 0.05 \text{ deg}$$

$$B_l^{DM} = \exp \left[-\frac{l^2 \sigma_b^2}{2} \right]$$

$$\sigma_0^{Fermissimo} = N \cdot \sigma_* (0.5 \text{ GeV}) \cdot \left(\frac{E}{0.5 \text{ GeV}} \right)^{-0.95}$$