ARGELANDER-INSTITUTE FOR ASTRONOMY – UNIVERSITY OF BONN

Constraining the **[CII] Luminosity Function** and the nature of **Dark Matter** with the LIM power spectrum

Based on: Marcuzzo et al., 2025 (arXiv:2504.06266) and Marcuzzo et al., in prep.

Elena Marcuzzo

in collaboration with:

Cristiano Porciani, Emilio Romano-Díaz, Prachi Khatri, Azadeh Moradinezhad, Matteo Viel

LIM25 – Line Intensity Mapping Conference

LAPTh – Annecy (France) , 5th June 2025

Projects overview

Luminosity Function

we focus on the astrophysical properties of galaxies, investigating the power of LIM in determining the shape of the [CII] LF

Statistics:
[CII] power spectrum monopole

Method:
Bayesian inference to constrain
the moments and parameters of the LF

Marcuzzo et al., 2025

Dark Matter

we study whether LIM is effective in distinguishing **ΛCDM** and **ΛWDM** cosmological scenarios

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Bayesian inference to constrain
the mass of the DM particles

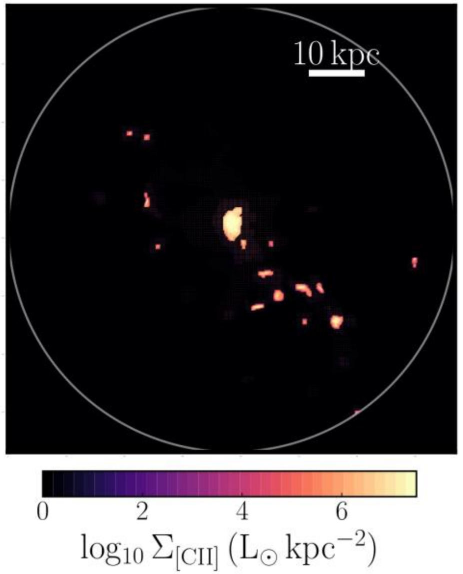
Marcuzzo et al., in prep.

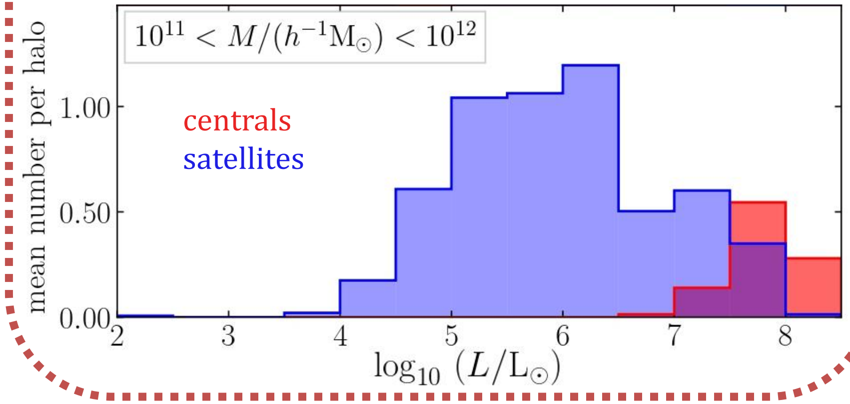
Modelling the [CII] power spectrum

Marcuzzo et al., 2025

HOD of [CII] emitters in MARIGOLD simulations
(in reference to Emilio's talk)

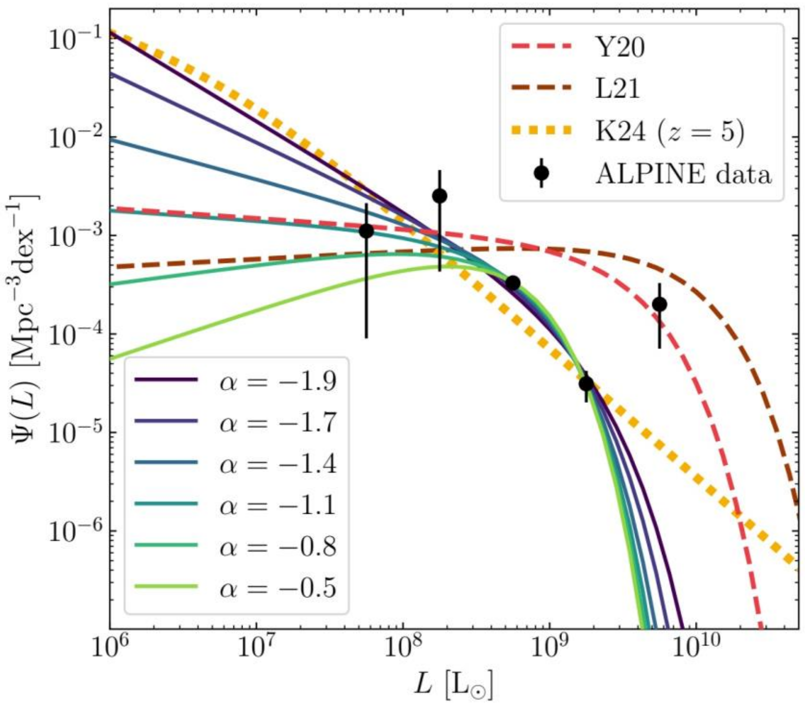
Khatri et al. (2024)



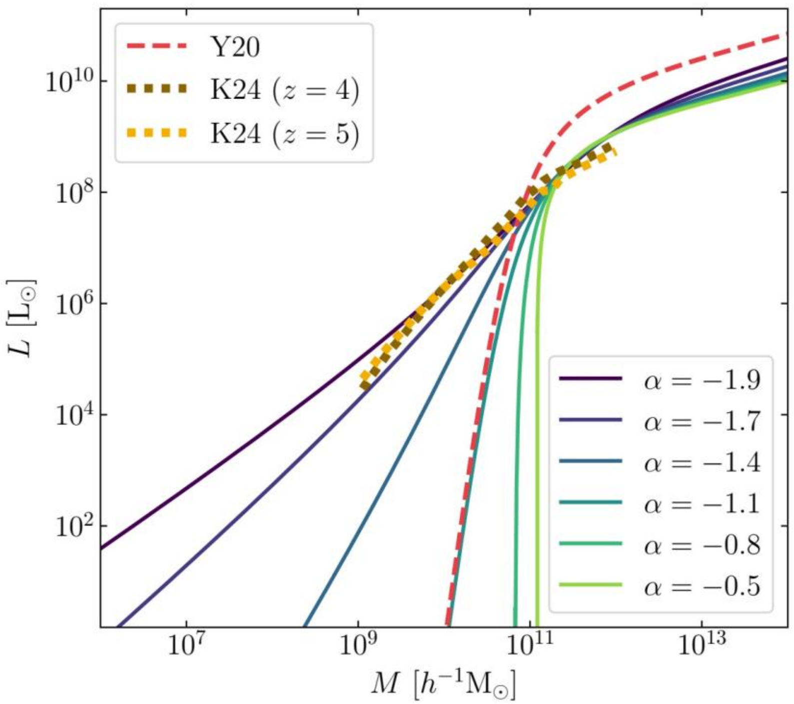


Halo abundance matching:
[CII] luminosity function + halo mass function

Several LF fits



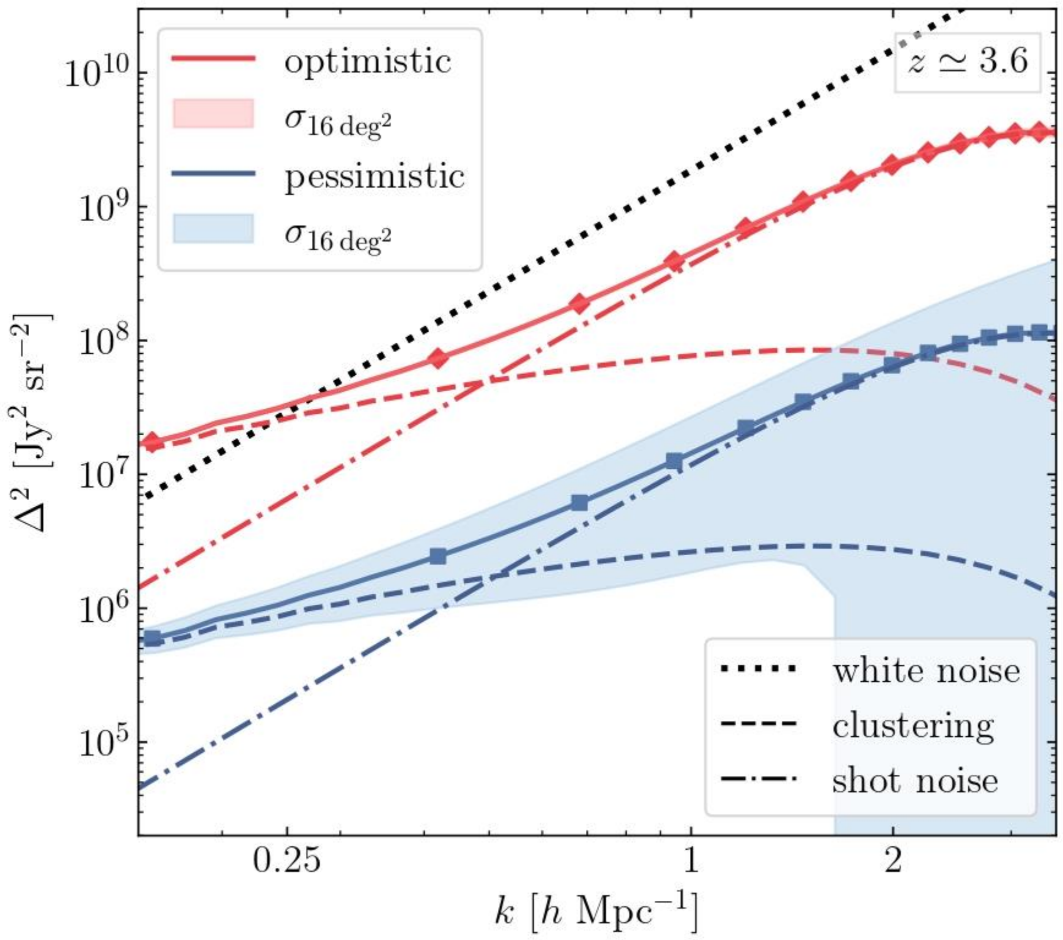
L_{CII}-M_h relation



Yan et al. (2020), Loiacono et al. (2021), Khatri et al. (2024)

Modelling the [CII] power spectrum

Marcuzzo et al., 2025



optimistic → high LF

pessimistic → low LF

$A_{surv} = 16\ \mathrm{deg}^2$
$R = 500$
$t_{surv} \simeq 32000$ h (to keep the same P_{WN})

📌 Error estimates and related results refer to a <u>next-generation</u> (FYST)DSS-like survey

CCAT-Prime Collaboration et al. (2023)

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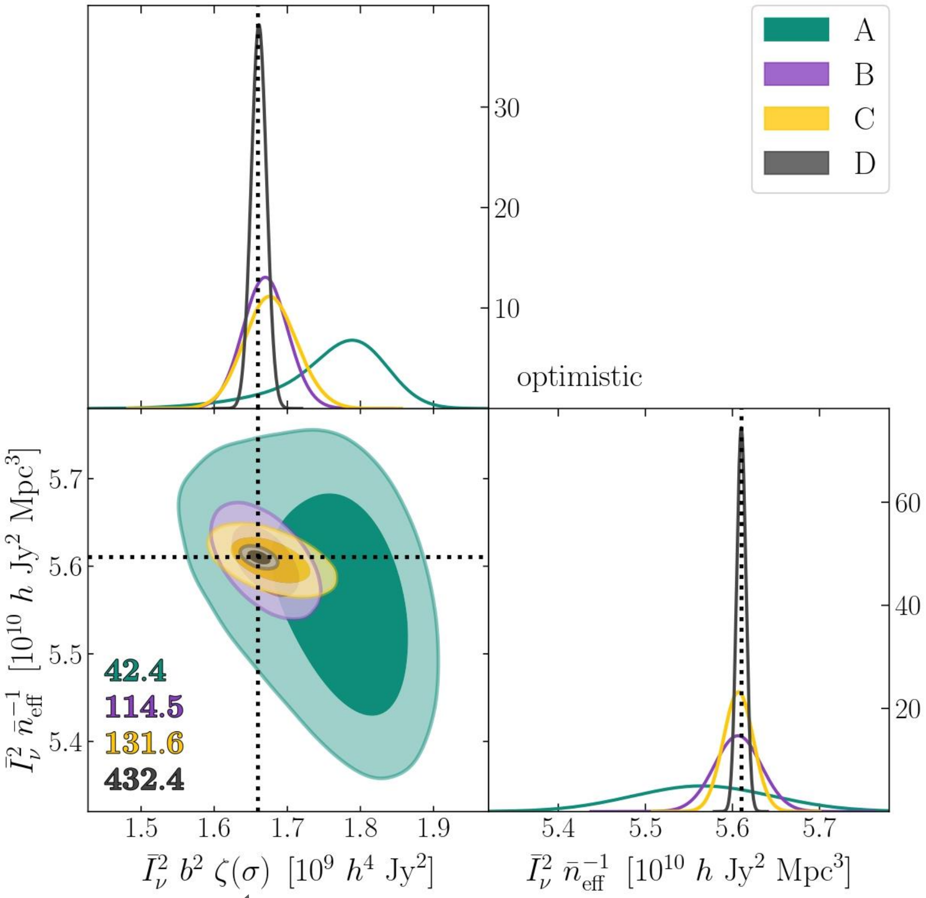
Marcuzzo et al., in prep.

PROJECT 1 – Constraining the [CII] luminosity function

A = next-generation DSS
B = 10x wider
C = √10x more sensitive
D = wider and more sensitive

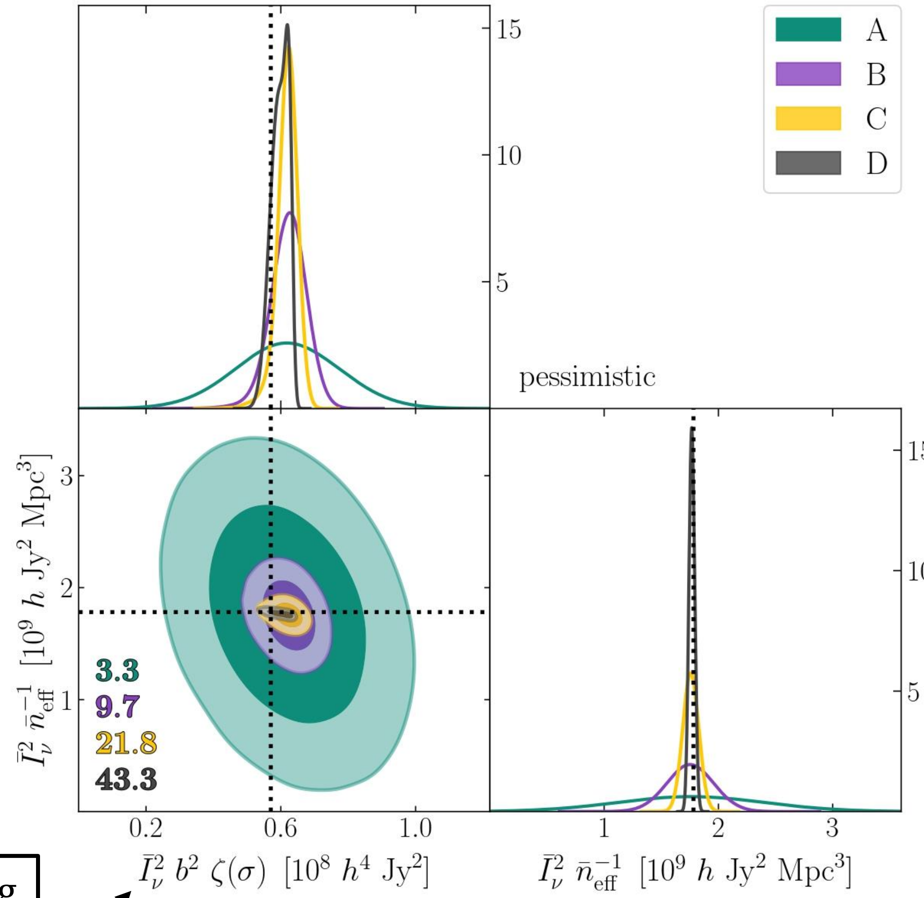
Marcuzzo et al., 2025

Constraints on clustering and shot noise components



Fingers of God

shot noise



clustering

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Marcuzzo et al., 2025

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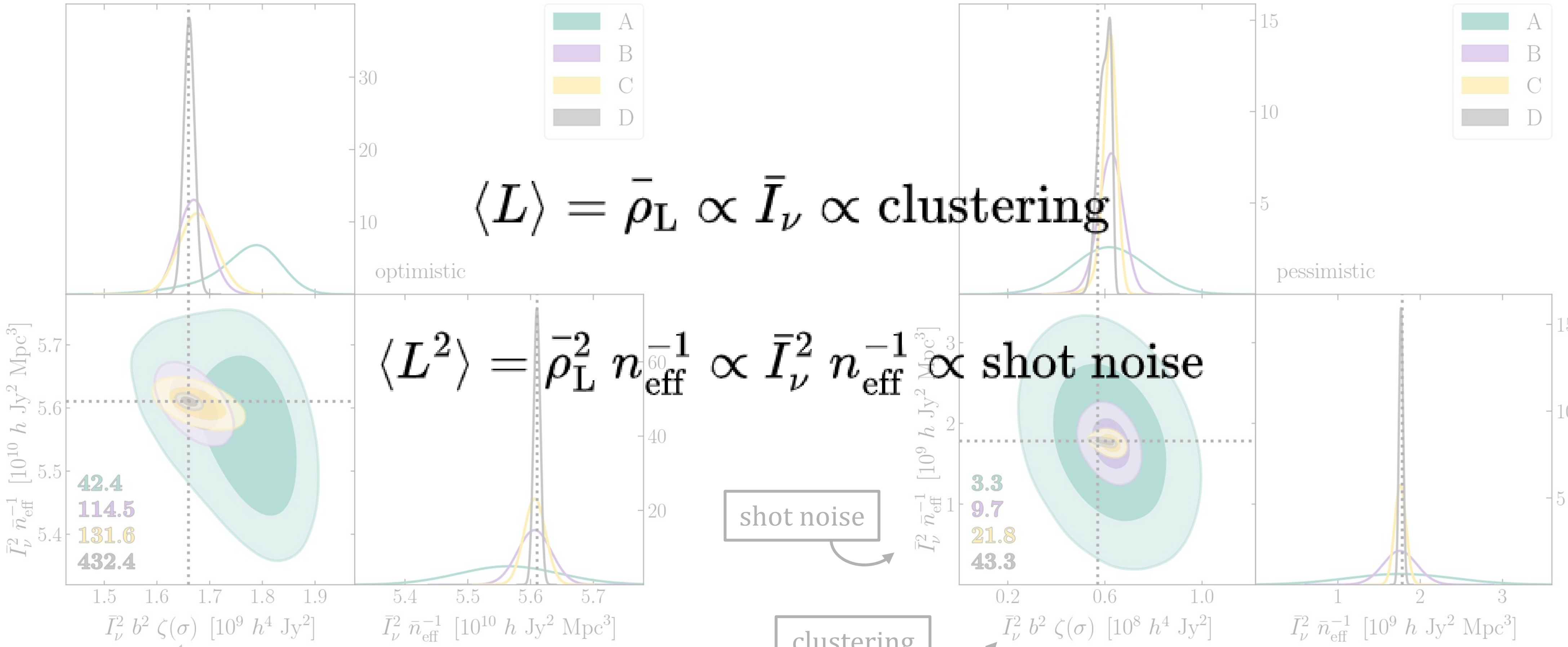
$$\langle L \rangle = \bar{\rho}_{\rm L} \propto \bar{I}_\nu \propto \text{clustering}$$

$$\langle L^2 \rangle = \bar{\rho}_{\rm L}^{2}\, n_{\rm eff}^{-1} \propto \bar{I}_\nu^{2}\, n_{\rm eff}^{-1} \propto \text{shot noise}$$



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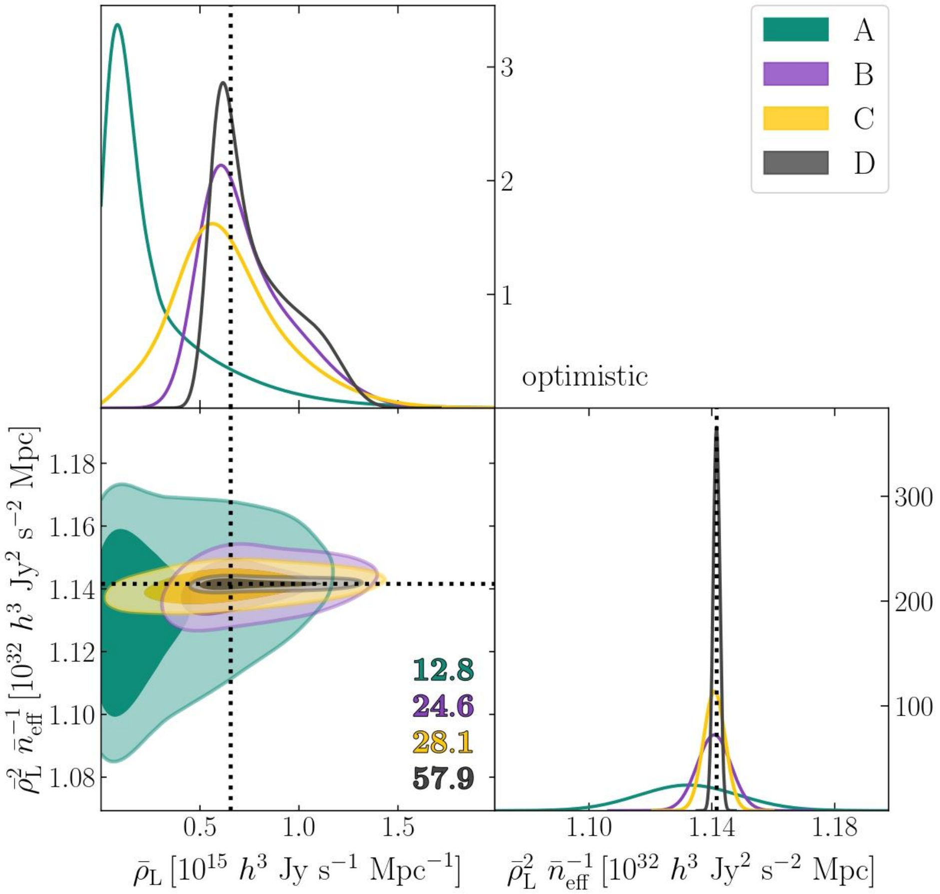
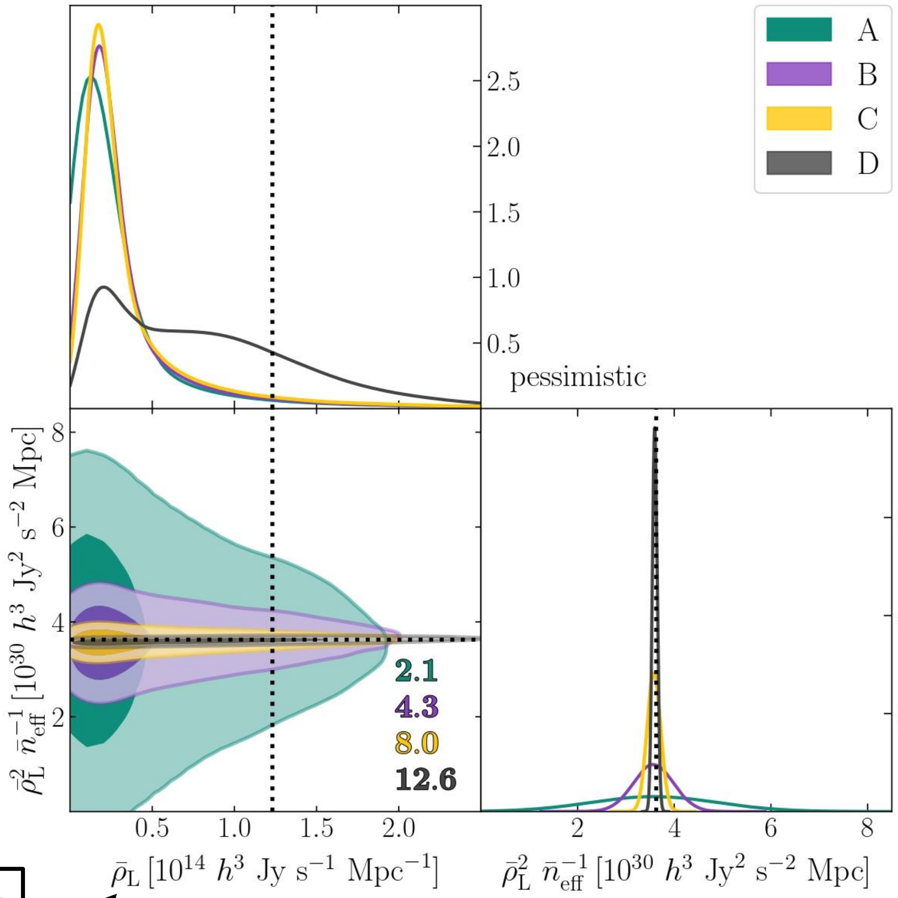


second moment



first moment

PROJECT 1 – Constraining the [CII] luminosity function

A = next-generation DSS
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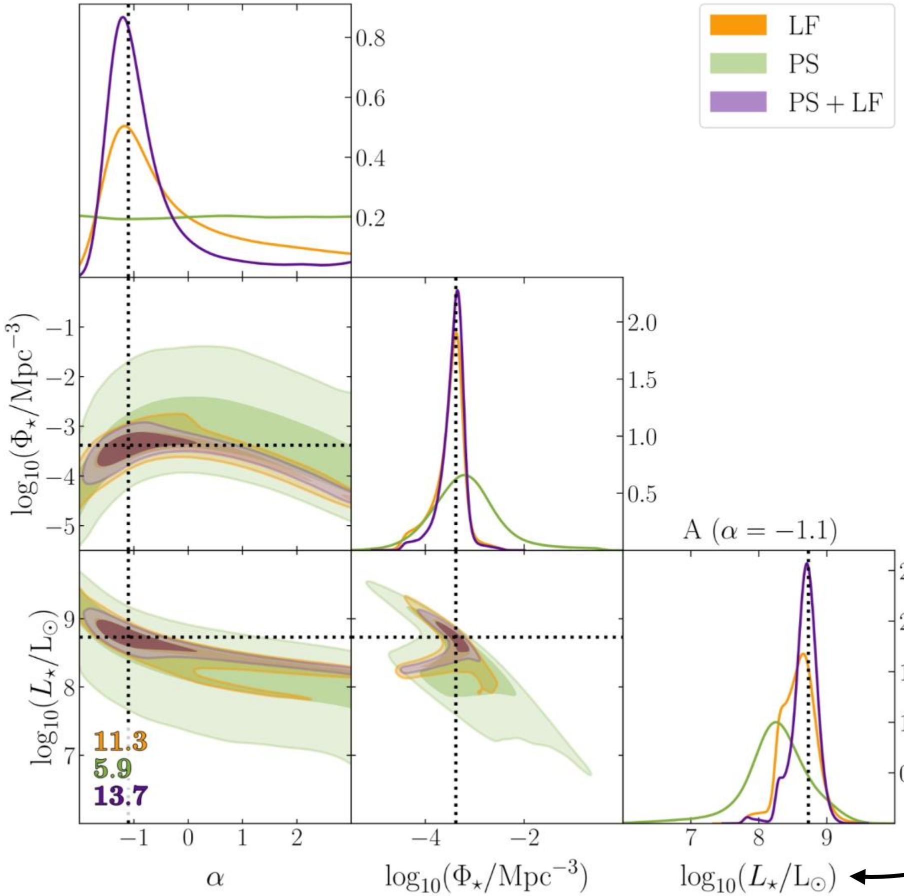
C = $\sqrt{10}$x more sensitive
D = wider and more sensitive

Marcuzzo et al., 2025

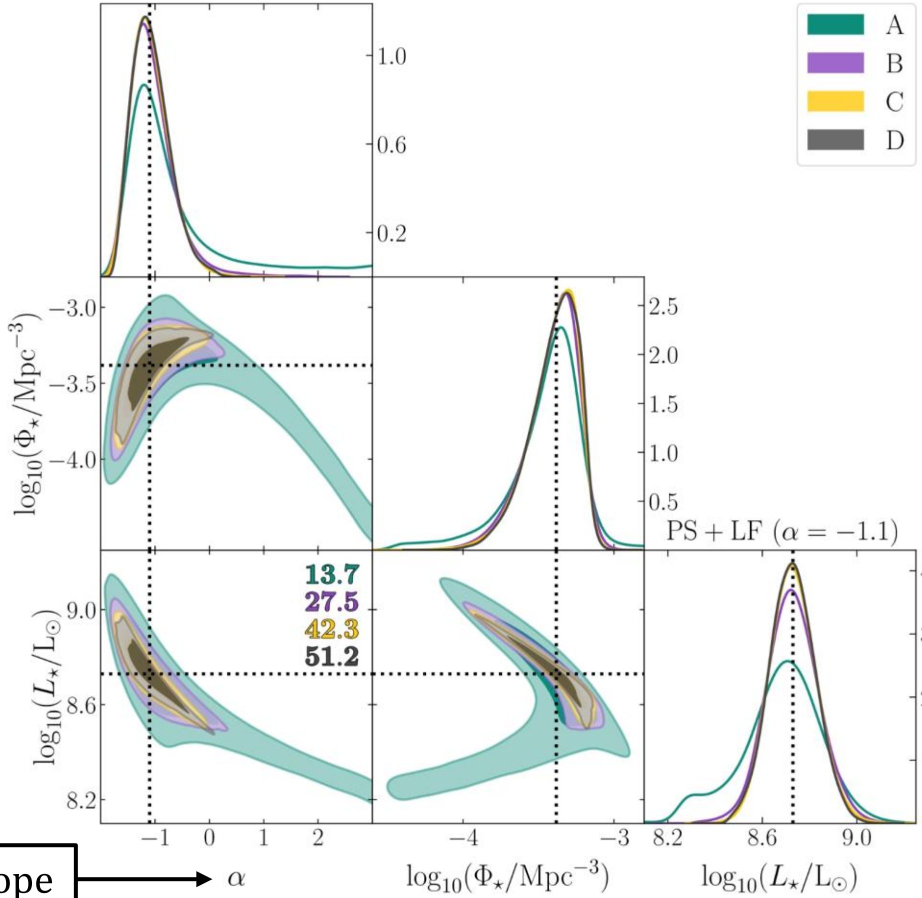
Constraints on the luminosity function parameters



normalisation

break

faint-end slope



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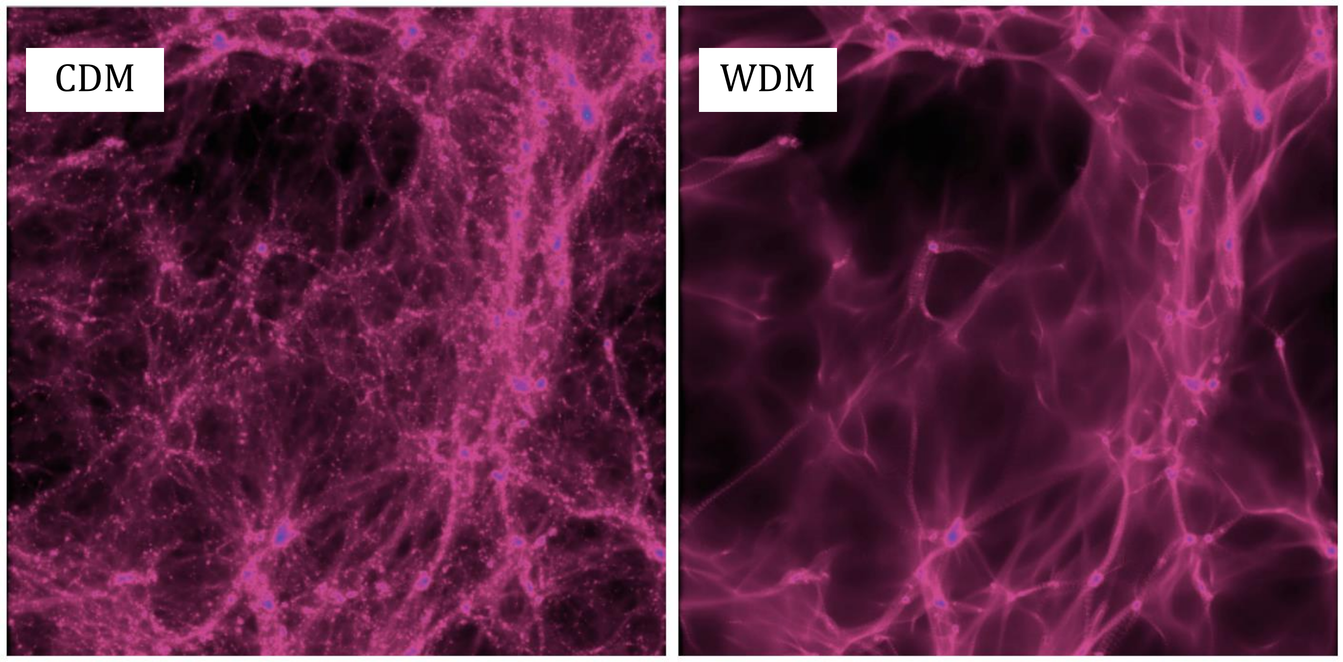
PROJECT 2 – Constraining the dark matter mass: CDM vs WDM

Marcuzzo et al., in prep.

The effect of warm dark matter

DM particles with non-negligible thermal velocities → small scale suppression → less (or absence of) small haloes

Bose et al., 2016



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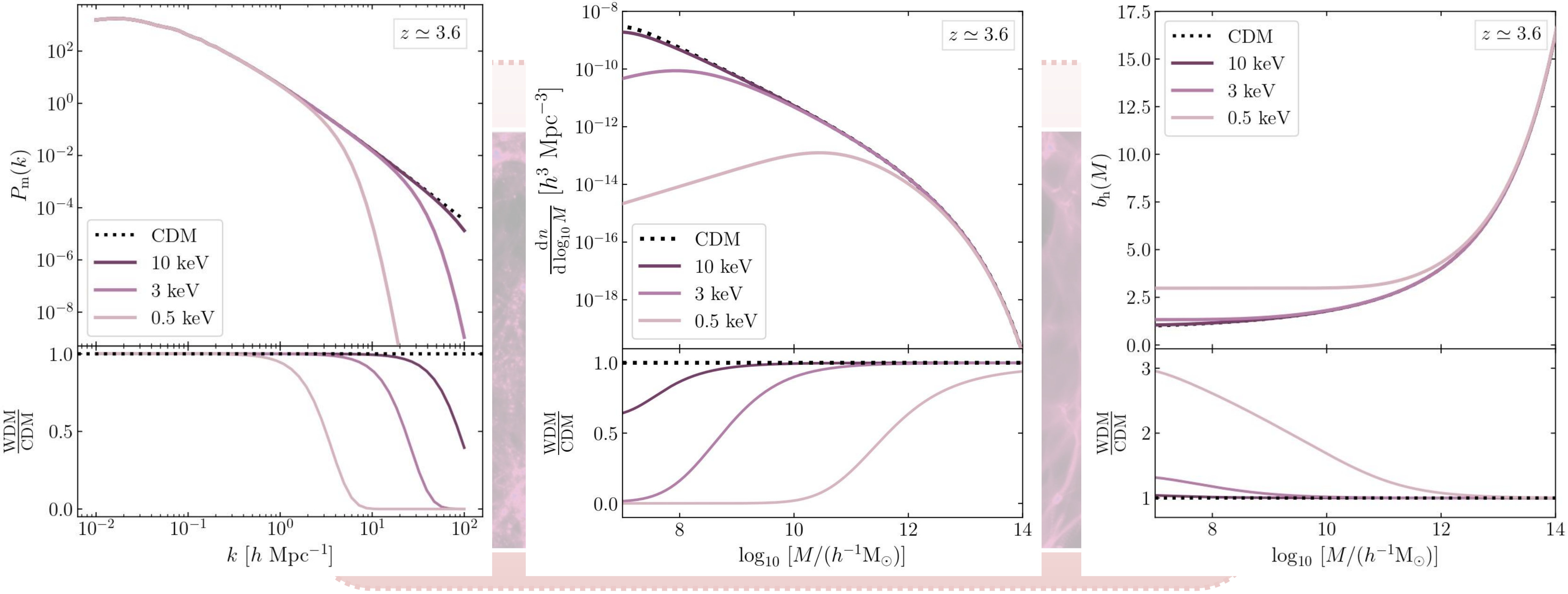


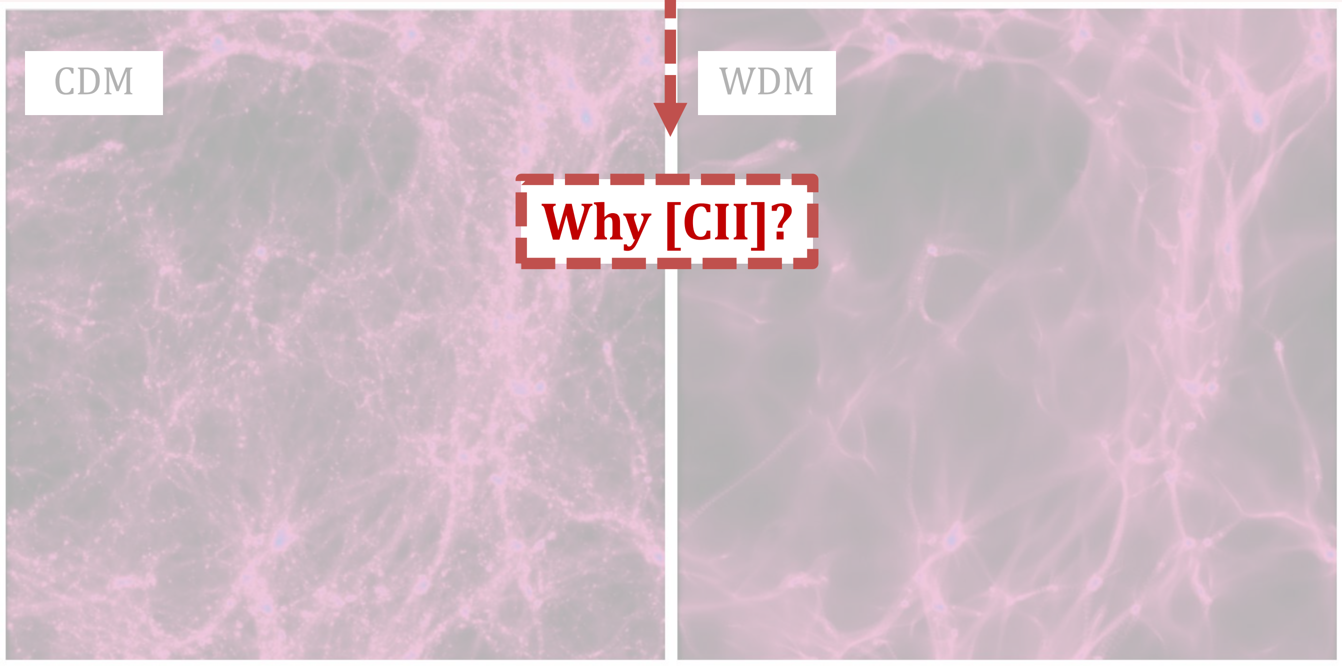
PROJECT 2 – Constraining the dark matter mass: CDM vs WDM

Marcuzzo et al., in prep.

The effect of warm dark matter

DM particles with greater thermal velocities → small scales suppression → less (or absence of) small haloes

Bose et al., 2016



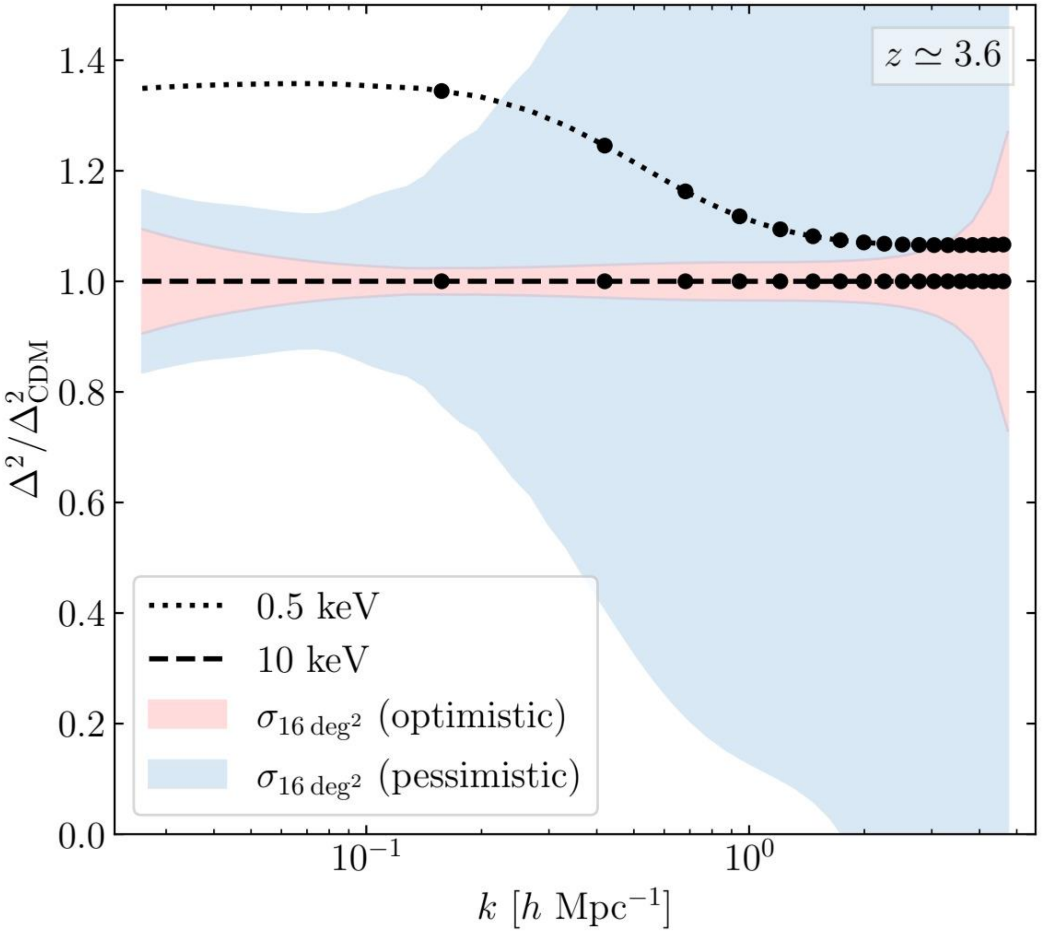
Why [CII]?

21cm studies: Stiwell et al. (2014), Carucci et al. (2015)

PROJECT 2 – Constraining the dark matter mass: CDM vs WDM

Marcuzzo et al., in prep.

[CII] power spectrum in WDM cosmologies



PROJECT 2 – Constraining the dark matter mass: CDM vs WDM

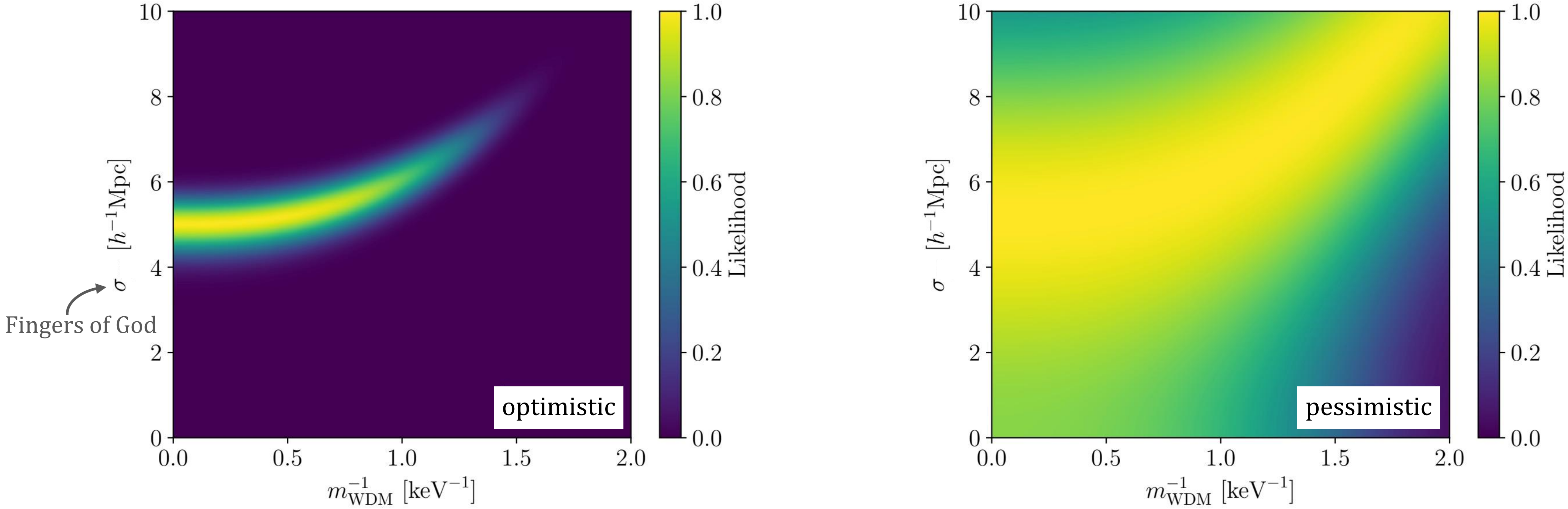
Marcuzzo et al., in prep.

true values

$\sigma = 5\ h^{-1}$Mpc
$m_{WDM} = \infty$ (i.e. CDM)

we fit CDM mock data with WDM model
taking the two free parameters in the ranges

$\sigma = [0\text{-}30]\ h^{-1}$Mpc
$m_{WDM} = [0.5\text{-}10]$ keV



We assume uniform priors for σ and marginalize over this parameter.

PROJECT 2 – Constraining the dark matter mass: CDM vs WDM

Marcuzzo et al., in prep.

Priors for m_{WDM}:

» $\pi \propto m_{\mathrm{WDM}}^{-\beta}\ ,\ \ \beta \in [0,1)$

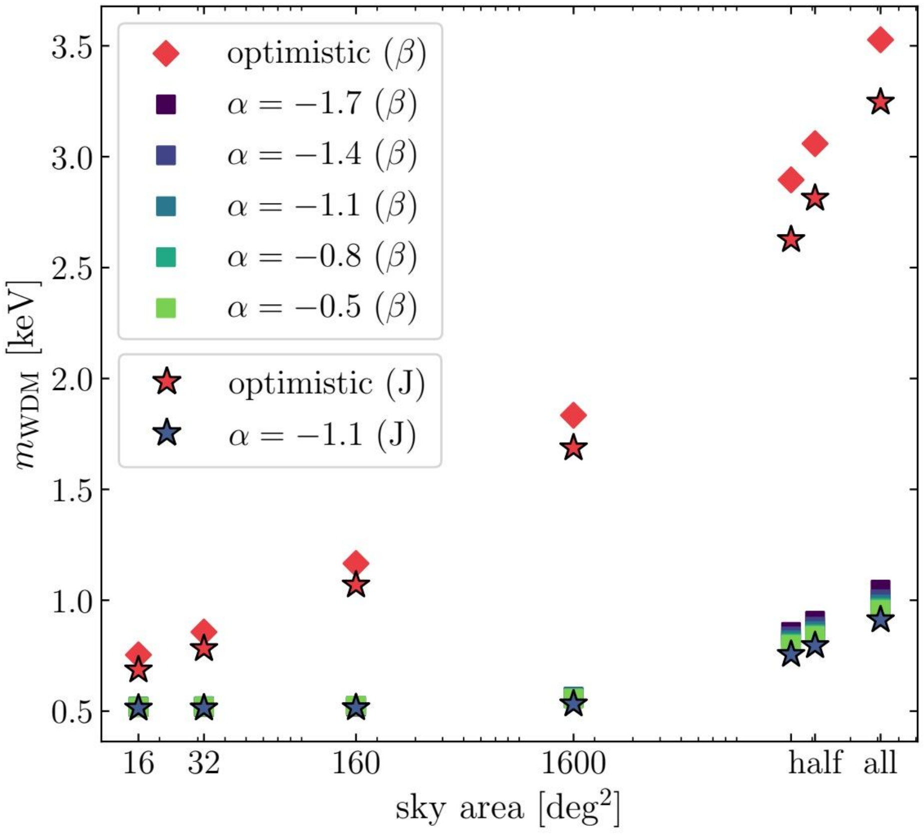
» Jeffreys (non-informative) prior

we get the

1D marginalised posteriors

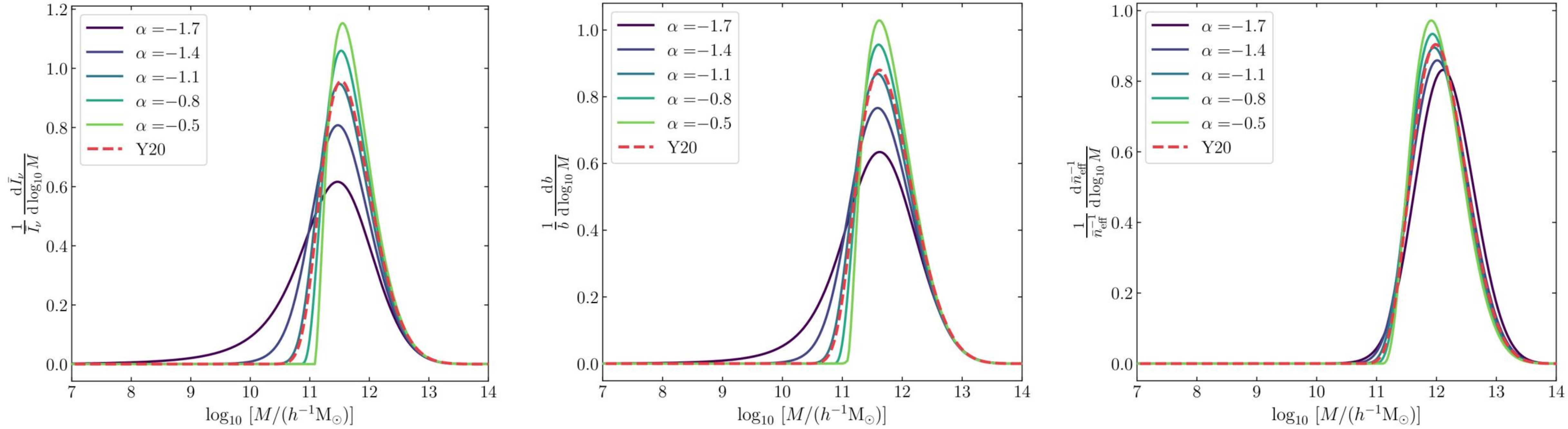
and compute the

95% credibility levels on m_{WDM}



Marcuzzo et al., in prep.

Main limitation of our analysis



Low-mass haloes/faint galaxies give a negligible contribution to the LIM power spectrum

Summary and conclusions

Assuming 'our' next-generation DSS survey, the LIM power spectrum of the [CII] emission line can be used to **constrain the shape of the luminosity function** and **probe dark matter models**:

- ✓ The **clustering** and **shot noise** components are constrained with a signal to noise ~3 and ~10 in the pessimistic and optimistic scenarios, respectively.

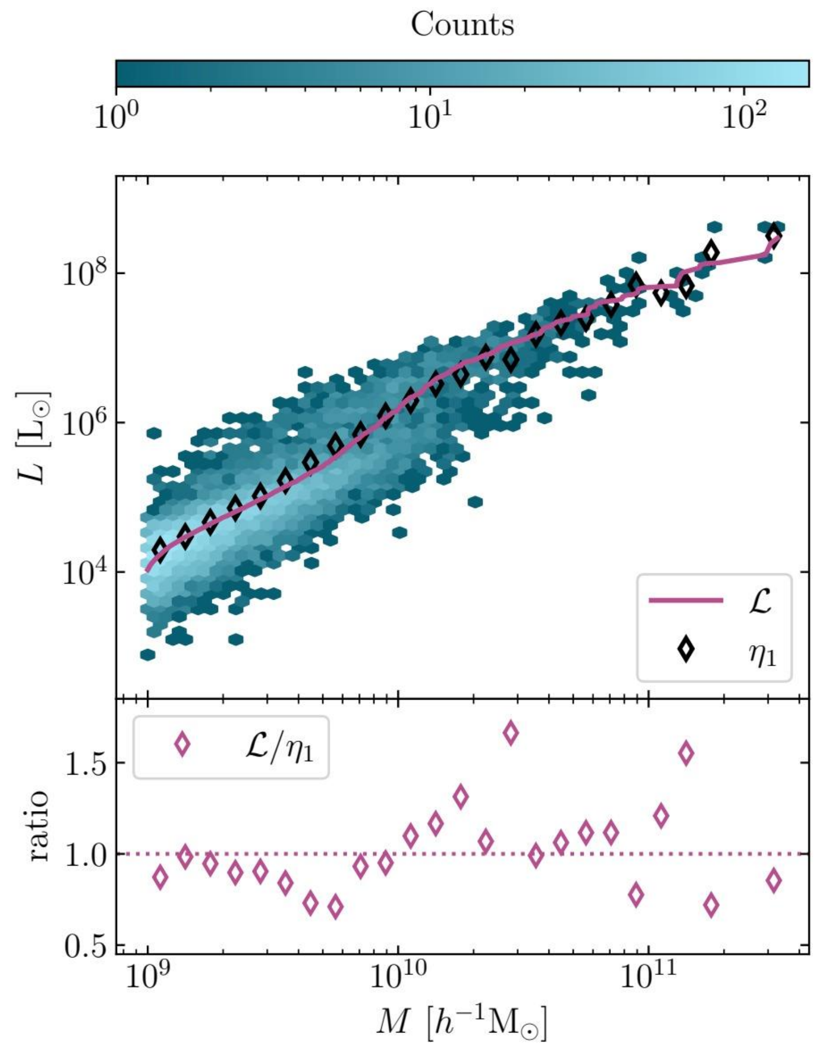
- ✓ By deriving constraints on LF moments we find that $\langle \mathbf{L^2} \rangle$ is constrained with a signal to noise ~0.5 (pessimistic) and ~14 (optimistic), but with increasing precision when having wider survey area and/or higher sensitivity.
  Viceversa, $\langle \mathbf{L} \rangle$ remains highly uncertain mainly due to degeneracy with RSDs → statistical uncertainty of ~50% even under the most optimistic LF and survey assumptions.

- ✓ The LF normalisation, $\mathbf{\Phi^*}$, and break, $\mathbf{L^*}$, are well constrained, while the faint-end slope, $\boldsymbol{\alpha}$, remains unconstrained unless area and/or sensitivity are significantly increased.

- ✓ CDM and WDM can be distinguished up to $\mathbf{m_{WDM}} \simeq 3$ keV, but only in the scenario with high LF and wide sky coverage.

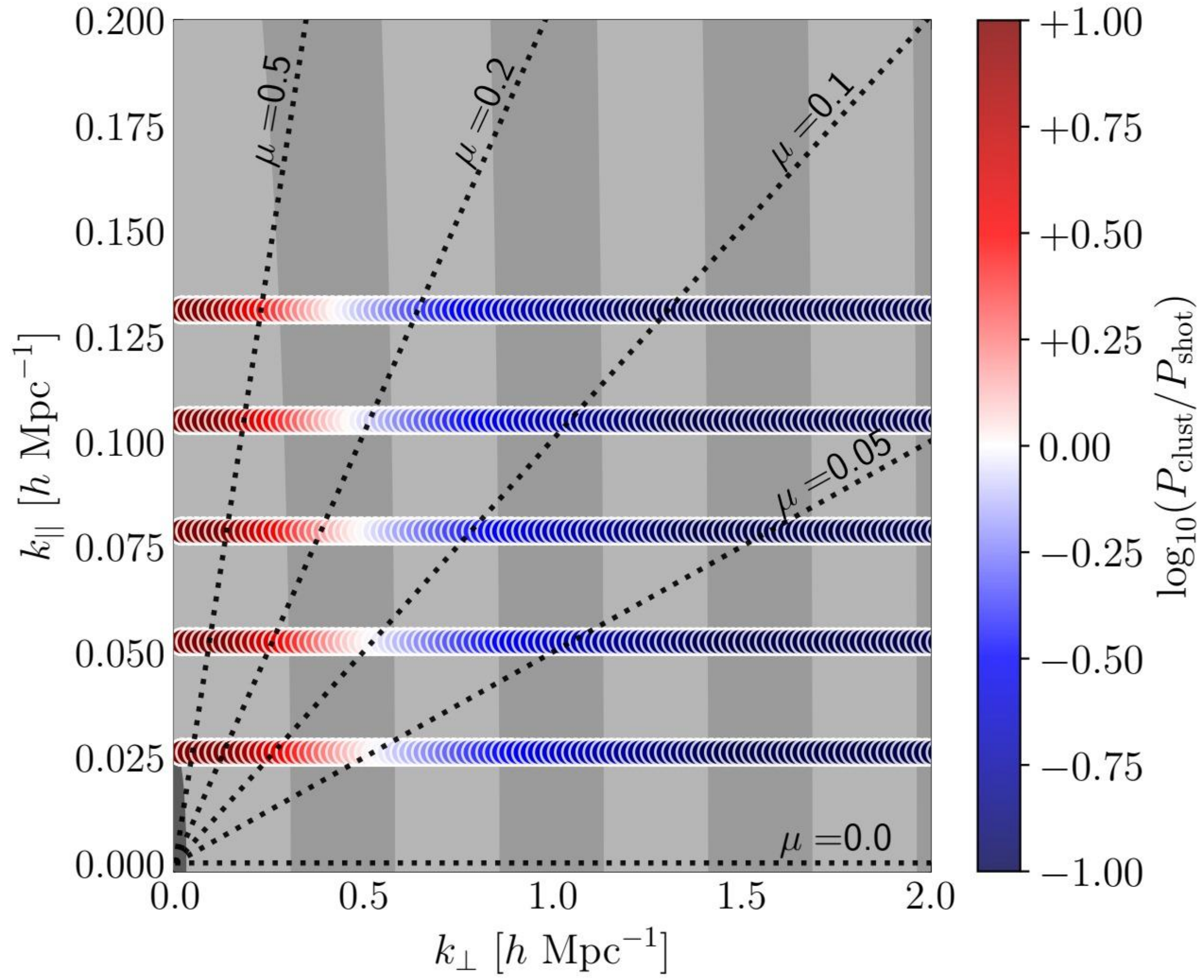
Many thanks for your attention!

BACKUP SLIDES

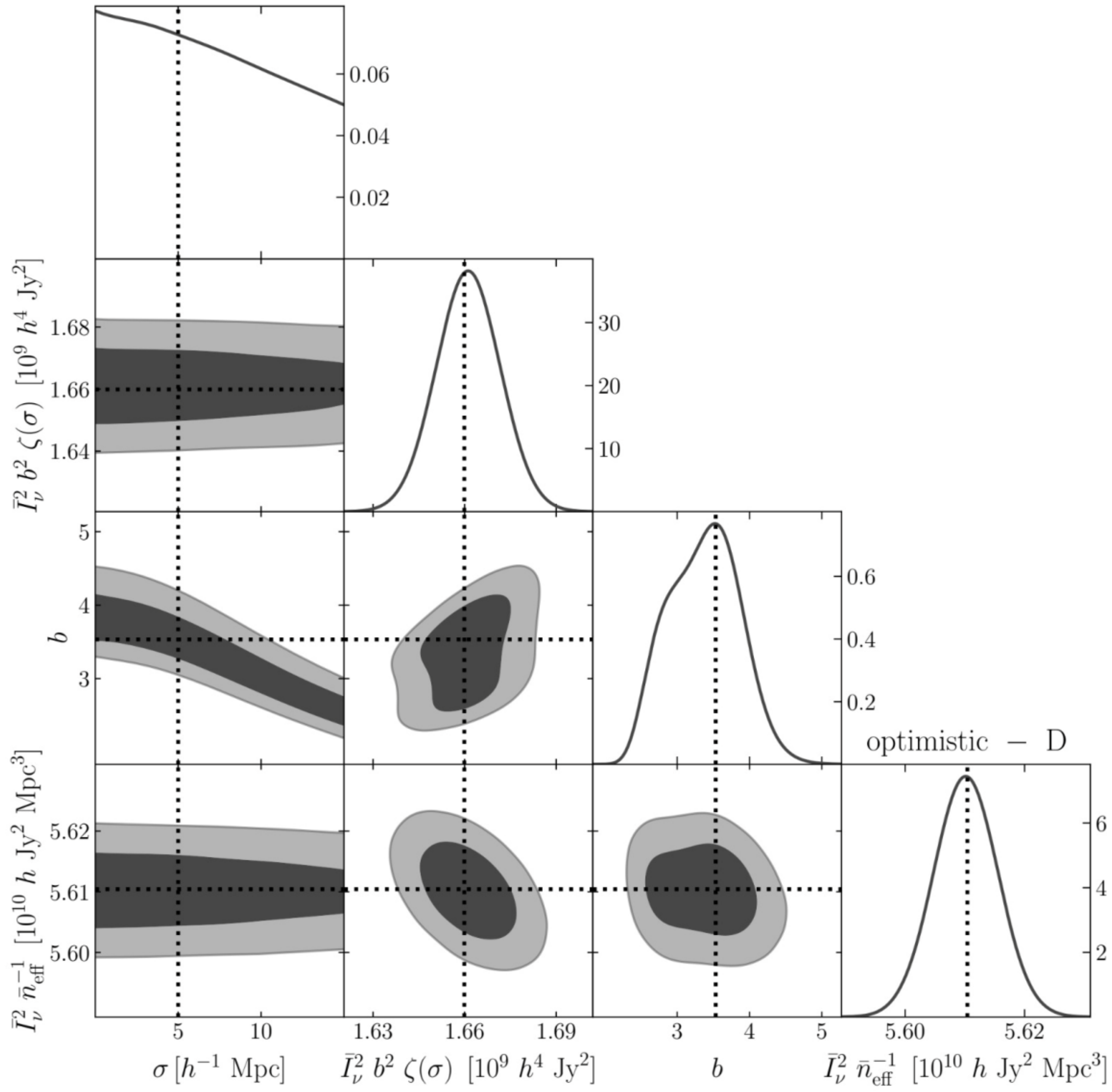


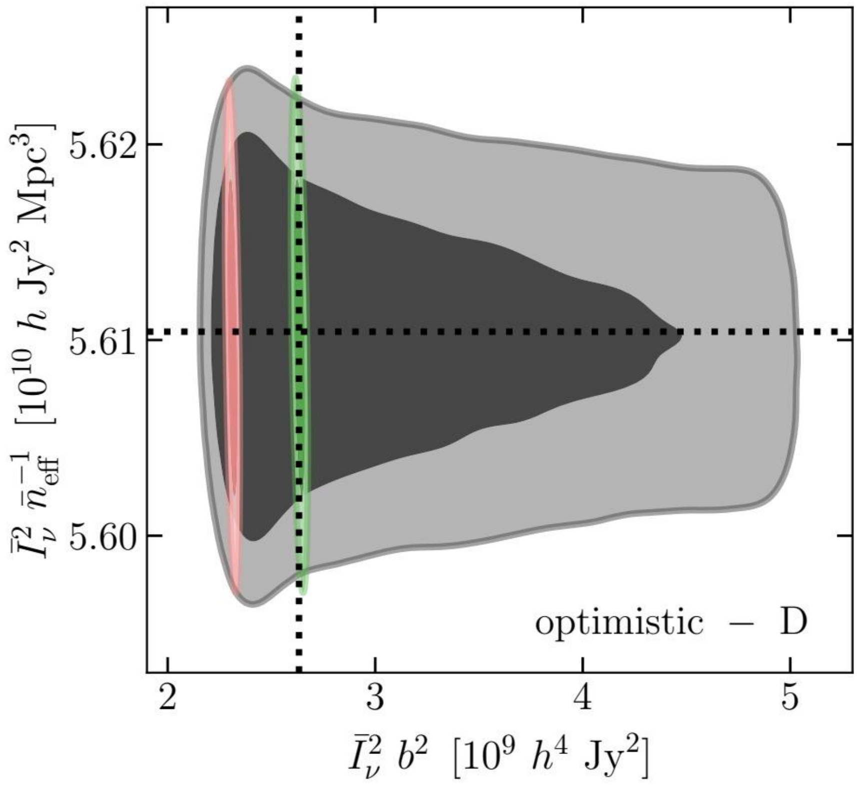
Counts
10^0
10^1
10^2
L [L$_\odot$]
10^4
10^6
10^8
$\mathcal{L}$
η_1
$\mathcal{L}/\eta_1$
ratio
0.5
1.0
1.5
10^9
10^{10}
10^{11}
M [h^{-1}M$_\odot$]
Counts
10^0
10^1
10^2
L^2 [L$^2_\odot$]
10^7
10^{10}
10^{13}
10^{16}
$\mathcal{L}^2$
η_2
$\mathcal{L}^2/\eta_2$
ratio
0.5
1.0
1.5
10^9
10^{10}
10^{11}
M [h^{-1}M$_\odot$]

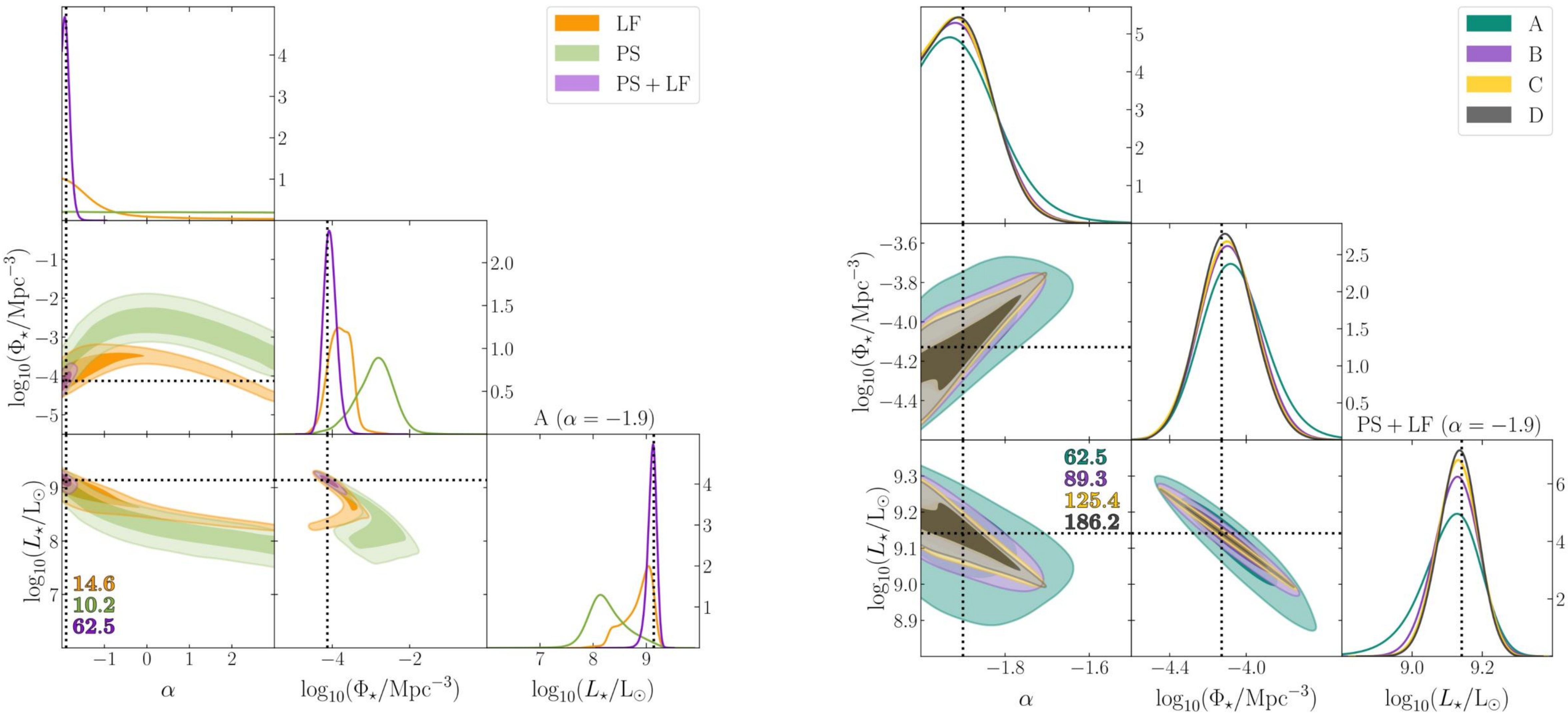
R=100



0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
$k_{||}$ [h Mpc^{-1}]
0.0
0.5
1.0
1.5
2.0
$k_{\perp}$ [h Mpc^{-1}]
μ =0.5
μ =0.2
μ =0.1
μ =0.05
μ =0.0
+1.00
+0.75
+0.50
+0.25
0.00
−0.25
−0.50
−0.75
−1.00
$\log_{10}(P_{\rm clust}/P_{\rm shot})$


0.06
0.04
0.02
1.68
1.66
1.64
$\bar{I}_\nu^2\ b^2\ \zeta(\sigma)\ [10^9\ h^4\ \mathrm{Jy}^2]$
30
20
10
5
4
3
b
0.6
0.4
0.2
optimistic − D
5.62
5.61
5.60
$\bar{I}_\nu^2\ \bar{n}_{\mathrm{eff}}^{-1}\ [10^{10}\ h\ \mathrm{Jy}^2\ \mathrm{Mpc}^3]$
6
4
2
5
10
$\sigma\,[h^{-1}\ \mathrm{Mpc}]$
1.63
1.66
1.69
$\bar{I}_\nu^2\ b^2\ \zeta(\sigma)\ [10^9\ h^4\ \mathrm{Jy}^2]$
3
4
5
b
5.60
5.62
$\bar{I}_\nu^2\ \bar{n}_{\mathrm{eff}}^{-1}\ [10^{10}\ h\ \mathrm{Jy}^2\ \mathrm{Mpc}^3]$

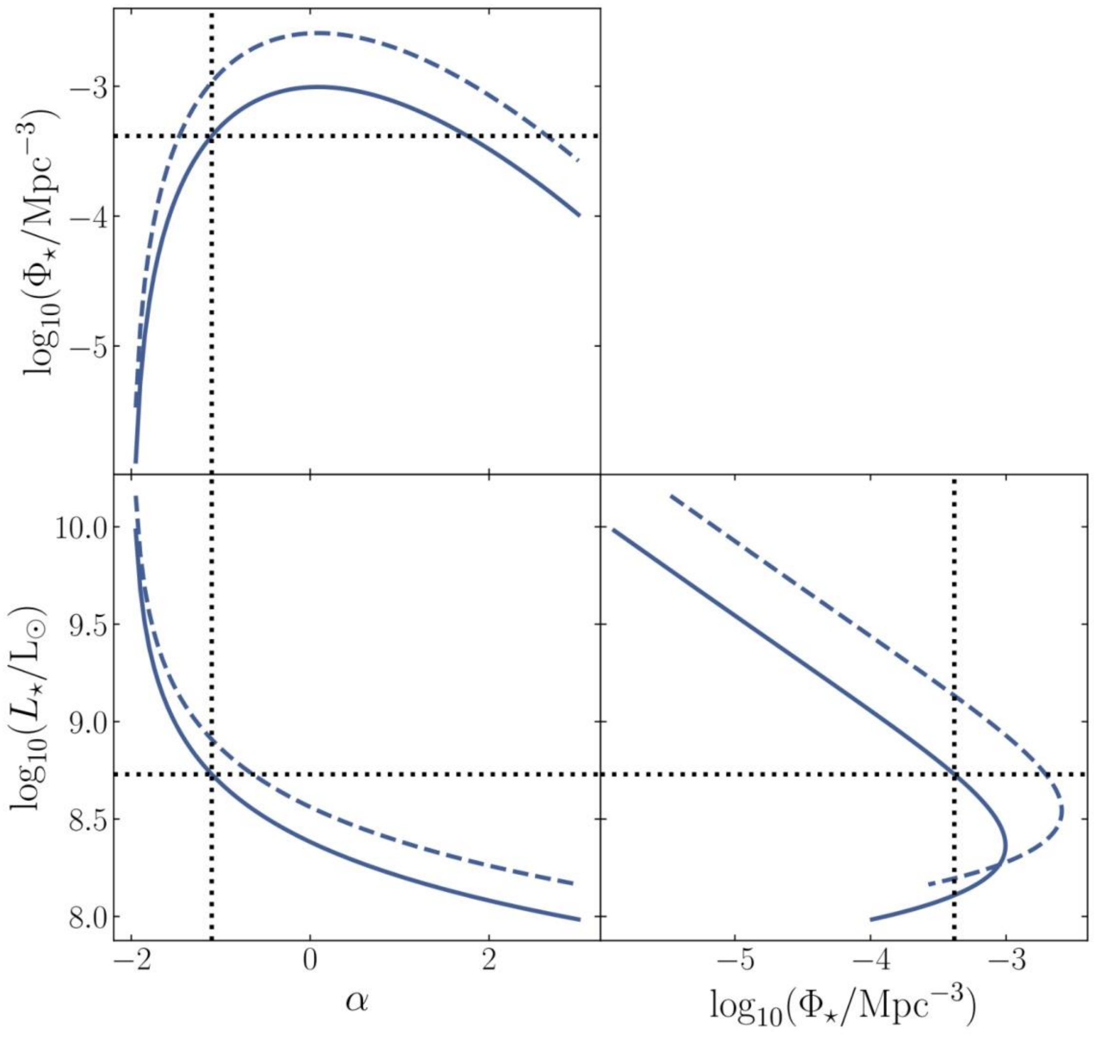

5.62
5.61
5.60
$\bar{I}_\nu^2\ \bar{n}_{\mathrm{eff}}^{-1}\ [10^{10}\ h\ \mathrm{Jy}^2\ \mathrm{Mpc}^3]$
optimistic − D
2
3
4
5
$\bar{I}_\nu^2\ b^2\ [10^9\ h^4\ \mathrm{Jy}^2]$

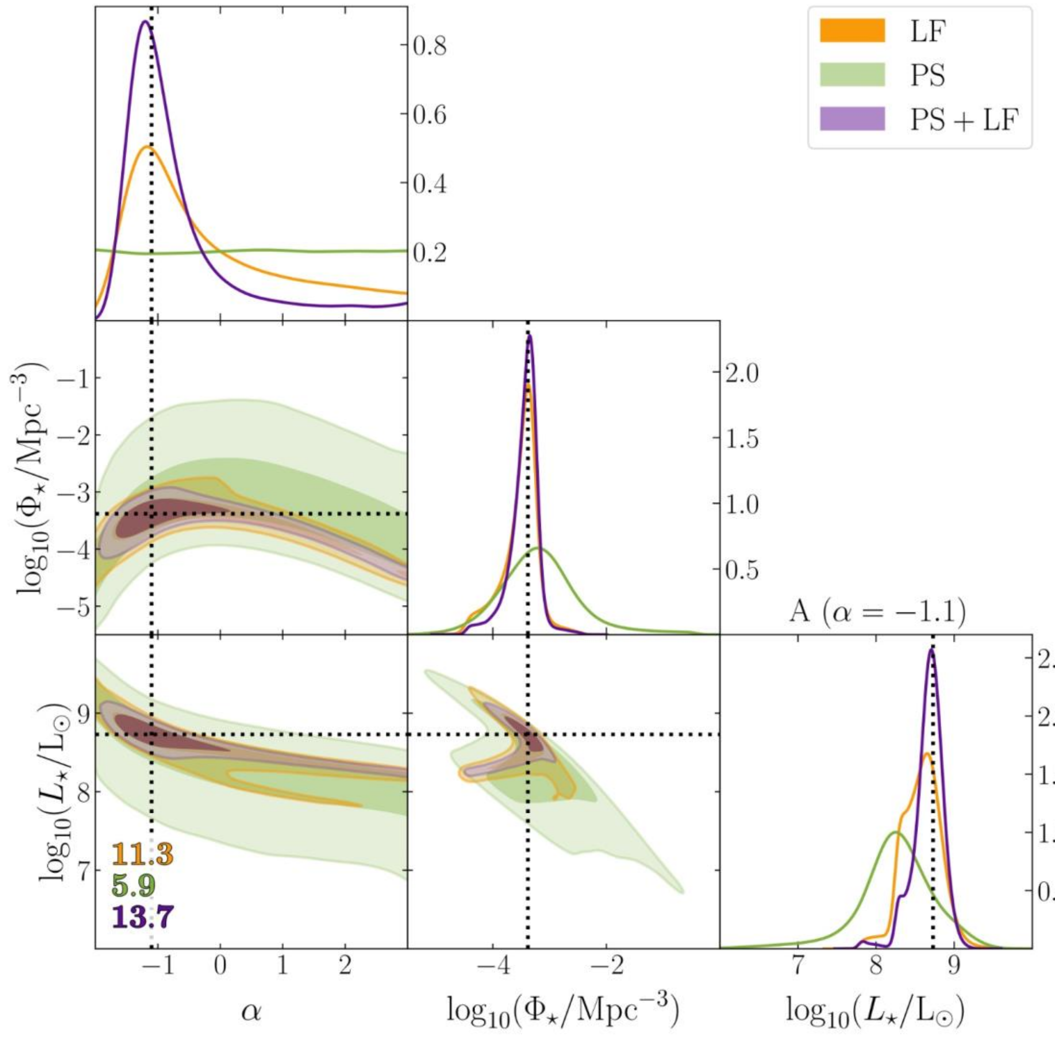


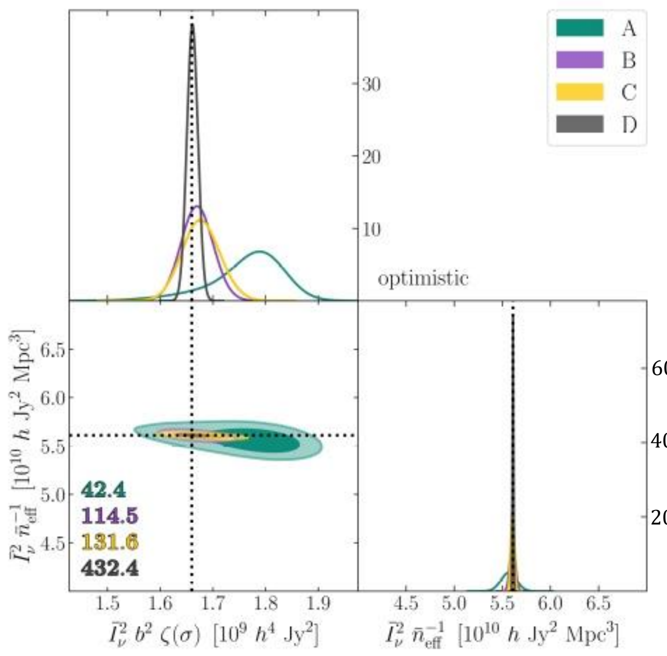
LF
PS
PS + LF
A ($\alpha = -1.9$)
14.6
10.2
62.5
α
$\log_{10}(\Phi_\star/\mathrm{Mpc}^{-3})$
$\log_{10}(L_\star/\mathrm{L}_\odot)$
A
B
C
D
PS + LF ($\alpha = -1.9$)
62.5
89.3
125.4
186.2

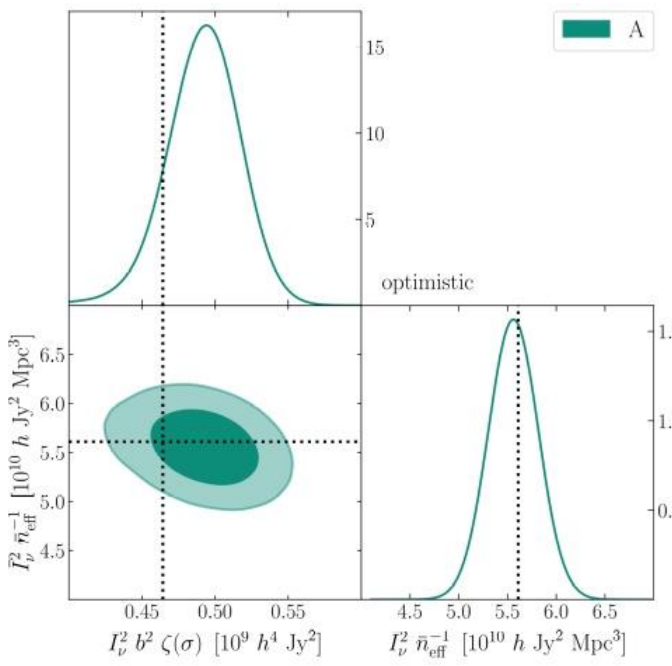
$$\bar{\rho}_L = \Gamma(\alpha + 2)\,\Phi_*\,L_*$$

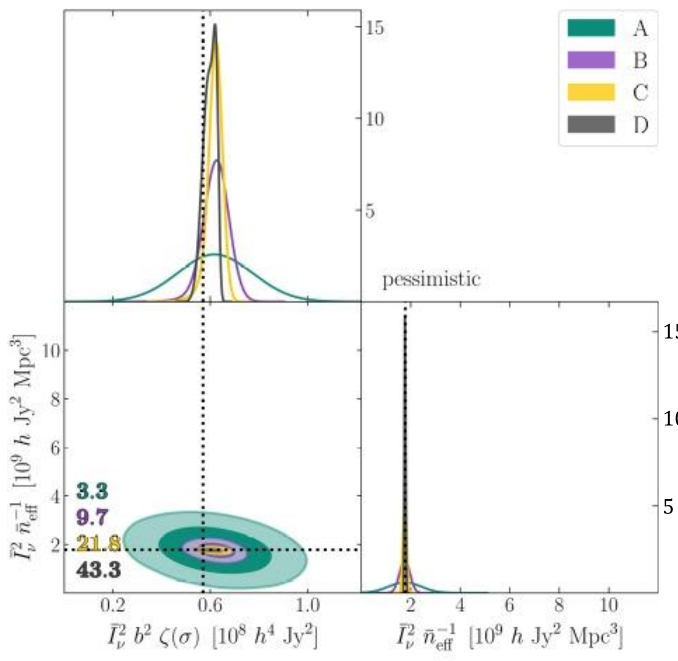
$$\bar{\rho}_L^2\,\bar{n}_{\rm eff}^{-1} = \Gamma(\alpha + 3)\,\Phi_*\,L_*^2$$

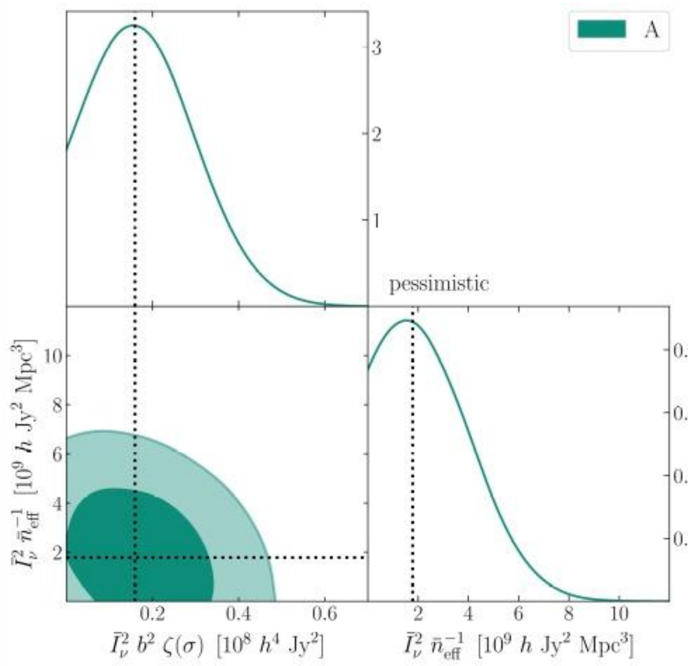


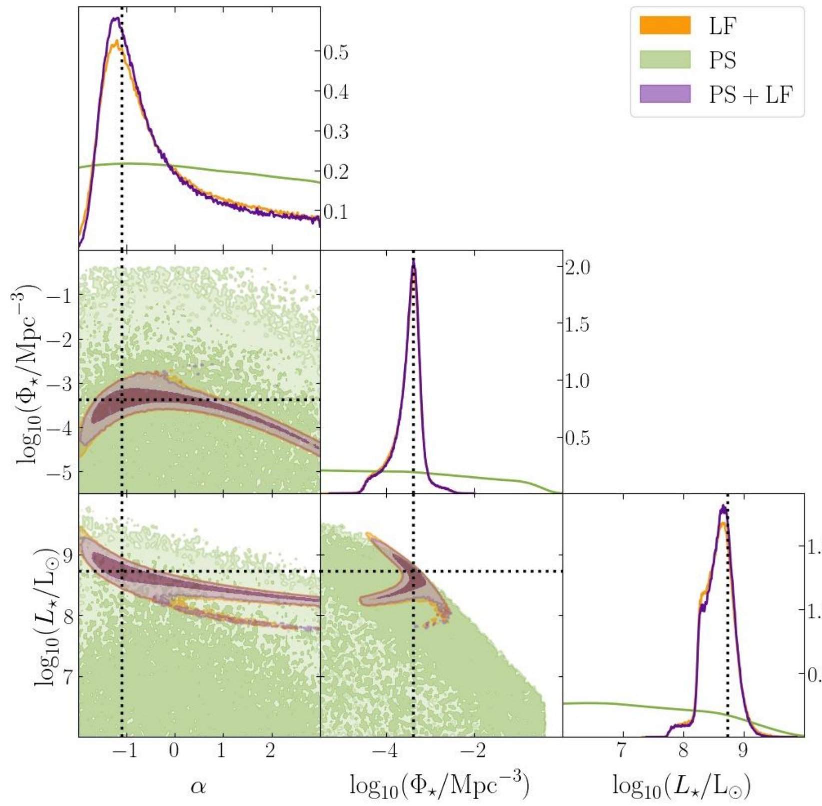



A
B
C
D
optimistic
42.4
114.5
131.6
432.4
$\bar{I}_\nu^2\, b^2\, \zeta(\sigma)$ $[10^9\ h^4\ \mathrm{Jy}^2]$
$\bar{I}_\nu^2\, \bar{n}_{\mathrm{eff}}^{-1}$ $[10^{10}\ h\ \mathrm{Jy}^2\ \mathrm{Mpc}^3]$


A
optimistic
$I_\nu^2\, b^2\, \zeta(\sigma)$ $[10^9\ h^4\ \mathrm{Jy}^2]$
$\bar{I}_\nu^2\, \bar{n}_{\mathrm{eff}}^{-1}$ $[10^{10}\ h\ \mathrm{Jy}^2\ \mathrm{Mpc}^3]$


A
B
C
D
pessimistic
3.3
9.7
21.8
43.3
$\bar{I}_\nu^2\, b^2\, \zeta(\sigma)$ $[10^8\ h^4\ \mathrm{Jy}^2]$
$\bar{I}_\nu^2\, \bar{n}_{\mathrm{eff}}^{-1}$ $[10^9\ h\ \mathrm{Jy}^2\ \mathrm{Mpc}^3]$


A
pessimistic
$\bar{I}_\nu^2\, b^2\, \zeta(\sigma)$ $[10^8\ h^4\ \mathrm{Jy}^2]$
$\bar{I}_\nu^2\, \bar{n}_{\mathrm{eff}}^{-1}$ $[10^9\ h\ \mathrm{Jy}^2\ \mathrm{Mpc}^3]$


LF
PS
PS + LF
α
$\log_{10}(\Phi_\star/\mathrm{Mpc}^{-3})$
$\log_{10}(L_\star/\mathrm{L}_\odot)$

Useful formulae

$$P(k,\mu,z) = P_{\rm clust}(k,\mu,z) + P_{\rm shot}(z) = \bar{I}^2_\nu(z)\,[b(z) + f(z)\,\mu^2]^2\,\mathcal{D}(k,\mu,z)\,P_{\rm m}(k,z) + \frac{\bar{I}^2_\nu(z)}{\bar{n}_{\rm eff}(z)}$$

$$\mathcal{D}(k,\mu) = \left[1 + \frac{(k\mu\sigma)^2}{2}\right]^{-2}$$

$$P_{\rm obs}(k,\mu,z) = P(k,\mu,z)\,W_\perp(k,\mu)\,W_{||}(k,\mu)$$

$$P_0(k,z) = \frac{\int_{k_{\rm f}^{||}/k}^{\min\left(1,k_{\rm N}^{||}/k\right)} P_{\rm obs}(k,\mu,z)\,{\rm d}\mu}{\int_{k_{\rm f}^{||}/k}^{\min\left(1,k_{\rm N}^{||}/k\right)} {\rm d}\mu}$$

$$\sigma_{P_0}(k) = \frac{P_0(k) + P_{\rm WN}}{\sqrt{N_{\rm m}(k)}}$$

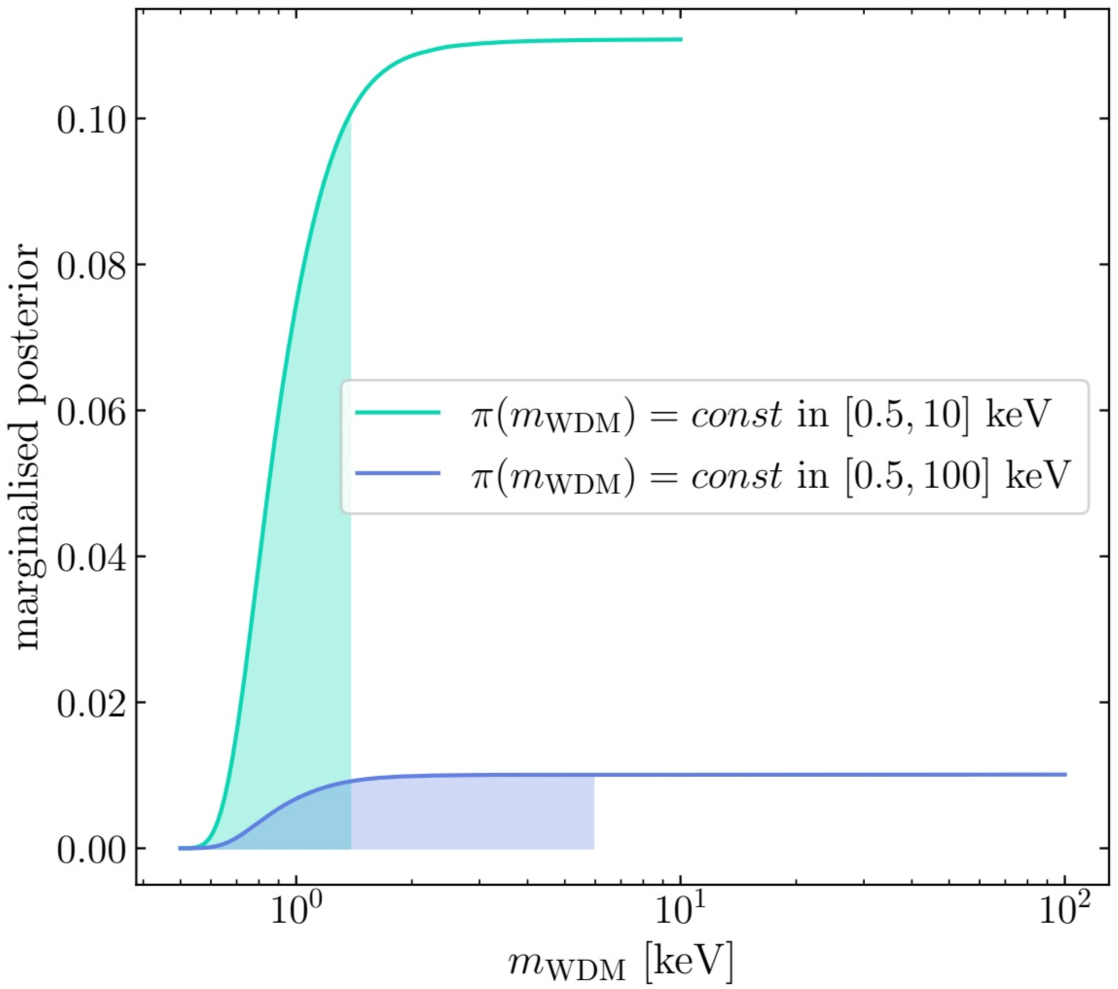
$$N_{\rm m}(k) = \frac{\min(k,k_{\rm N}^{||})\,k\,\Delta k\,V_{\rm surv}}{4\pi^2}$$

$$\left.\begin{aligned} b(z) &= \frac{1}{\bar{\rho}_L(z)}\int_0^\infty \eta_1(M,z)\,b_{\rm h}(M,z)\,\frac{{\rm d}\bar{n}_{\rm h}}{{\rm d}M}(M,z)\,{\rm d}M \\ \bar{n}^{-1}_{\rm eff}(z) &= \frac{1}{\bar{\rho}^2_L(z)}\int_0^\infty \eta_2(M,z)\,\frac{{\rm d}\bar{n}_{\rm h}}{{\rm d}M}(M,z)\,{\rm d}M \end{aligned}\right\}$$

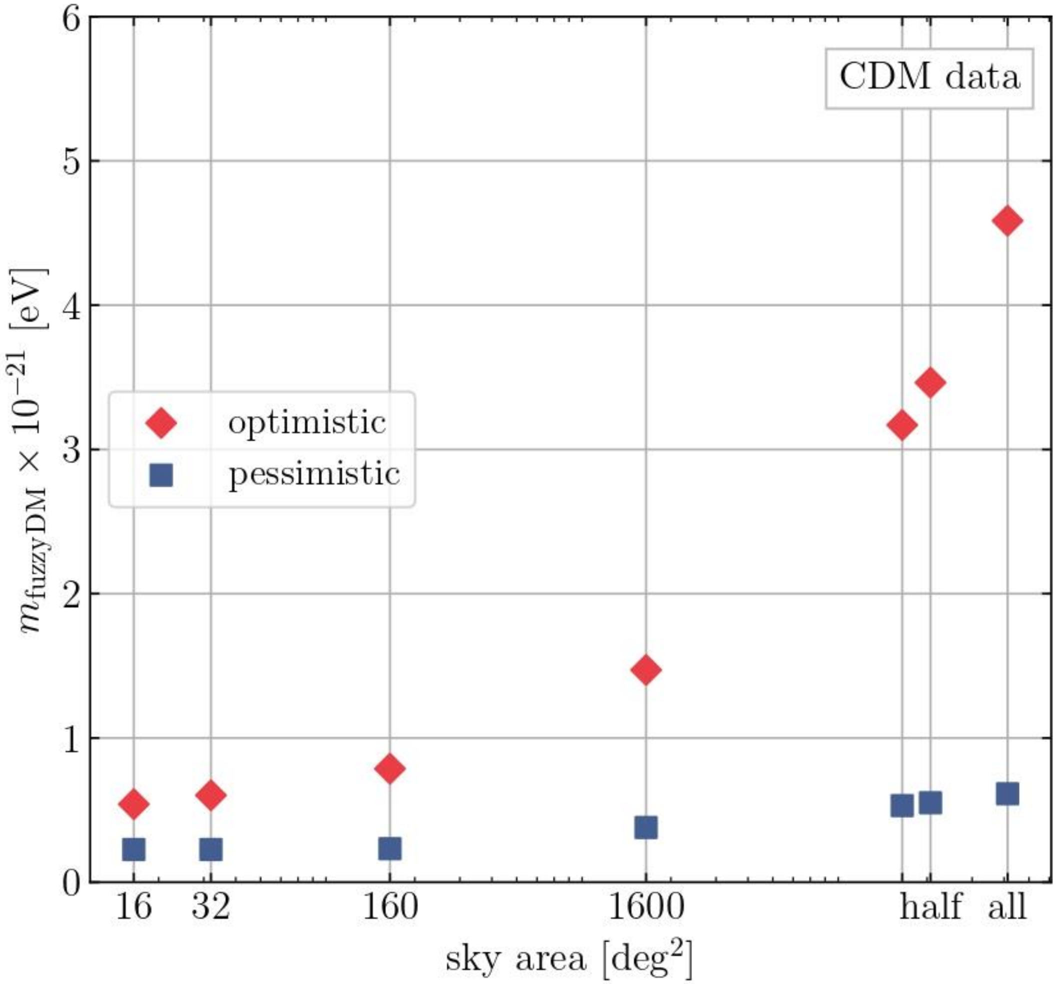
where

$$\bar{\rho}_L(z) = \int_0^\infty \eta_1(M,z)\,\frac{{\rm d}\bar{n}_{\rm h}}{{\rm d}M}(M,z)\,{\rm d}M$$

$$\eta_n(M,z) = \int_0^\infty L^n\,\phi(L|M,z)\,{\rm d}L$$



marginalised posterior
0.00
0.02
0.04
0.06
0.08
0.10
10^0
10^1
10^2
m_{WDM} [keV]
$\pi(m_{\mathrm{WDM}}) = const$ in $[0.5, 10]$ keV
$\pi(m_{\mathrm{WDM}}) = const$ in $[0.5, 100]$ keV


CDM data
optimistic
pessimistic
$m_{\text{fuzzyDM}} \times 10^{-21}$ [eV]
0
1
2
3
4
5
6
16
32
160
1600
half
all
sky area [deg^2]

$$\pi \propto m_{\rm WDM}^{-\beta} \ , \ \ \beta \in [0,1)$$

$$\pi \propto \sqrt{\det F_{ij}} \ , \ \ F_{ij} = \sum_k \frac{\partial P(k)}{\partial \theta_i} \frac{\partial P(k)}{\partial \theta_j} \frac{1}{\sigma^2_{P(k)}}$$

$$P_{\rm WDM}(k) = T^2(k)\, P_{\rm CDM}(k) \ ,$$

where (e.g. Viel et al. 2005)

$$T(k) = \left[1 + (\alpha k)^{2\nu}\right]^{-5/\nu} \ ,$$

with $\nu = 1.12$ and

$$\alpha = 0.049 \left(\frac{m_{\rm WDM}}{1\,\rm keV}\right)^{-1.11} \left(\frac{\Omega_{\rm WDM}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} h^{-1}\,{\rm Mpc} \ .$$

We also consider the possibility that DM is made of ultra light bosons with kpc-scale De Broglie wavelengths, commonly dubbed as “fuzzy DM” (FDM, Hu et al. 2000). In this case, we associate the mass of the FDM particles, $m_{\rm FDM}$, with the parameter α in Eq. (22) through the relation

$$k_{0.5} = 4.5 \left(\frac{m_{\rm FDM}\, c^2}{10^{-22}{\rm eV}}\right)^{4/9} \ {\rm Mpc}^{-1} \ . \tag{25}$$

where $T^2(k_{0.5}) = 0.5$.