Distinguishing MG from GR using higher-order WL statistics

Austin Peel

*modified gravity *general relativity *weak lensing

Distinguishing MG from GR using higher-order WL statistics

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Collaborators

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Reference

A. Peel et al., submitted to A&A (2018) [arXiv:1805.05146]

Motivation

Dark energy is still a (big) problem.

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If a **non-standard gravity** universe is masquerading as ΛCDM, can we find out using **weak lensing** ?

Outline

1. Modifying gravity
2. Simulations
3. Aperture mass statistics
4. Model discrimination
5. Summary

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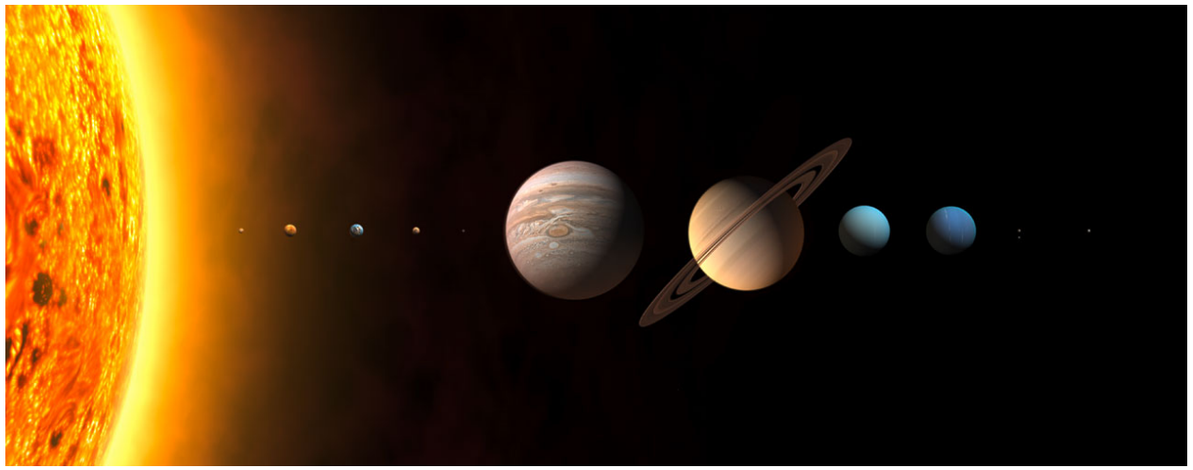
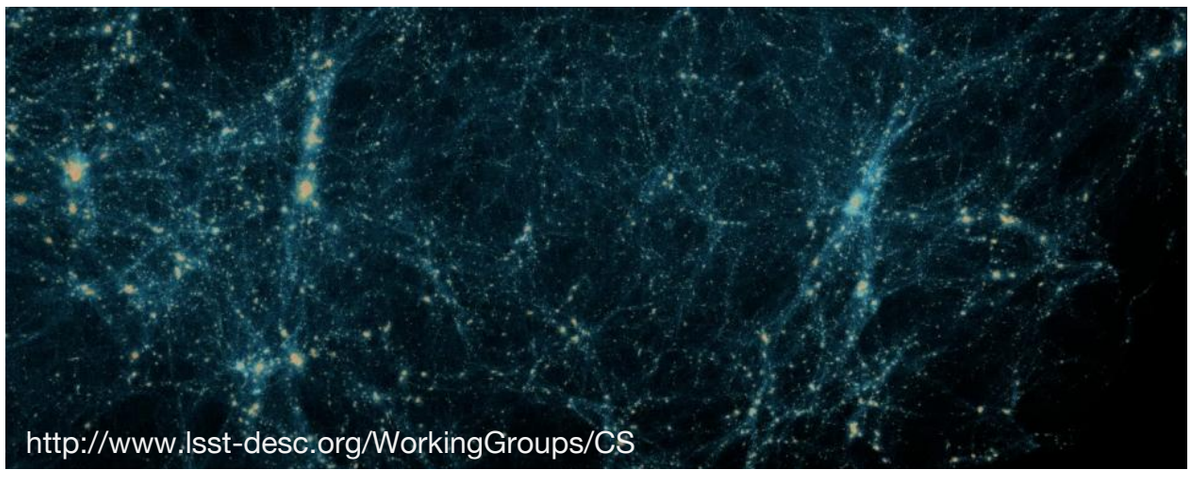
(✔) GR works very well here



many orders of magnitude



(?) we aren't sure about here

A good MG model should…

Change the fundamental gravitational interaction only on **large scales** (screening mechanism)

Result in a cosmology **close to ΛCDM** in the high-redshift regime (CMB constraints)

Provide late-time cosmic **acceleration**

Standard gravity (Einstein, 1915)

Ricci scalar

$$S = \frac{1}{16\pi G}\int \mathrm{d}^4x\,\sqrt{-g}\,R + S_m$$

One way to modify gravity

$$S = \frac{1}{16\pi G}\int \mathrm{d}^4x\,\sqrt{-g}\,[R + f(R)] + S_m$$

Standard gravity (Einstein, 1915)

Ricci scalar

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One way to modify gravity

$$S = \frac{1}{16\pi G}\int \mathrm{d}^4x\,\sqrt{-g}\,[R + f(R)] + S_m$$

Hu-Sawicki model (2007)

$$f(R) \equiv -m^2\frac{c_1(R/m^2)^n}{c_2(R/m^2)^n + 1} \qquad (n > 0)$$

Choose c_1/c_2 to give a desired background evolution.

⇒ 2 parameters : $f_{R0} \equiv \frac{\mathrm{d}f}{\mathrm{d}R}(z=0)$ $\qquad n = 1$

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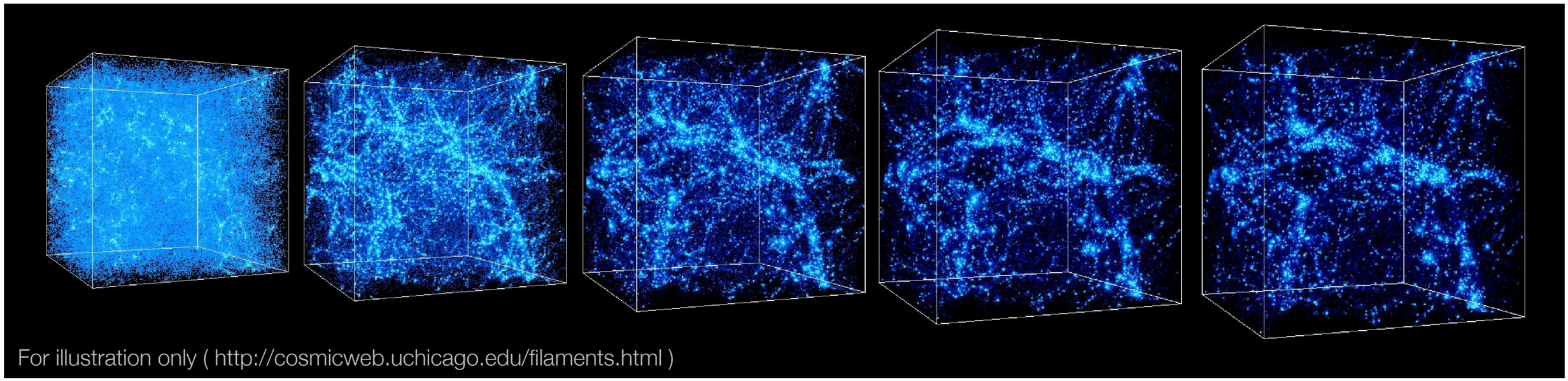
DUSTGRAIN-*pathfinder* simulations C. Giocoli et al. 2018 [arXiv:1806.04681]

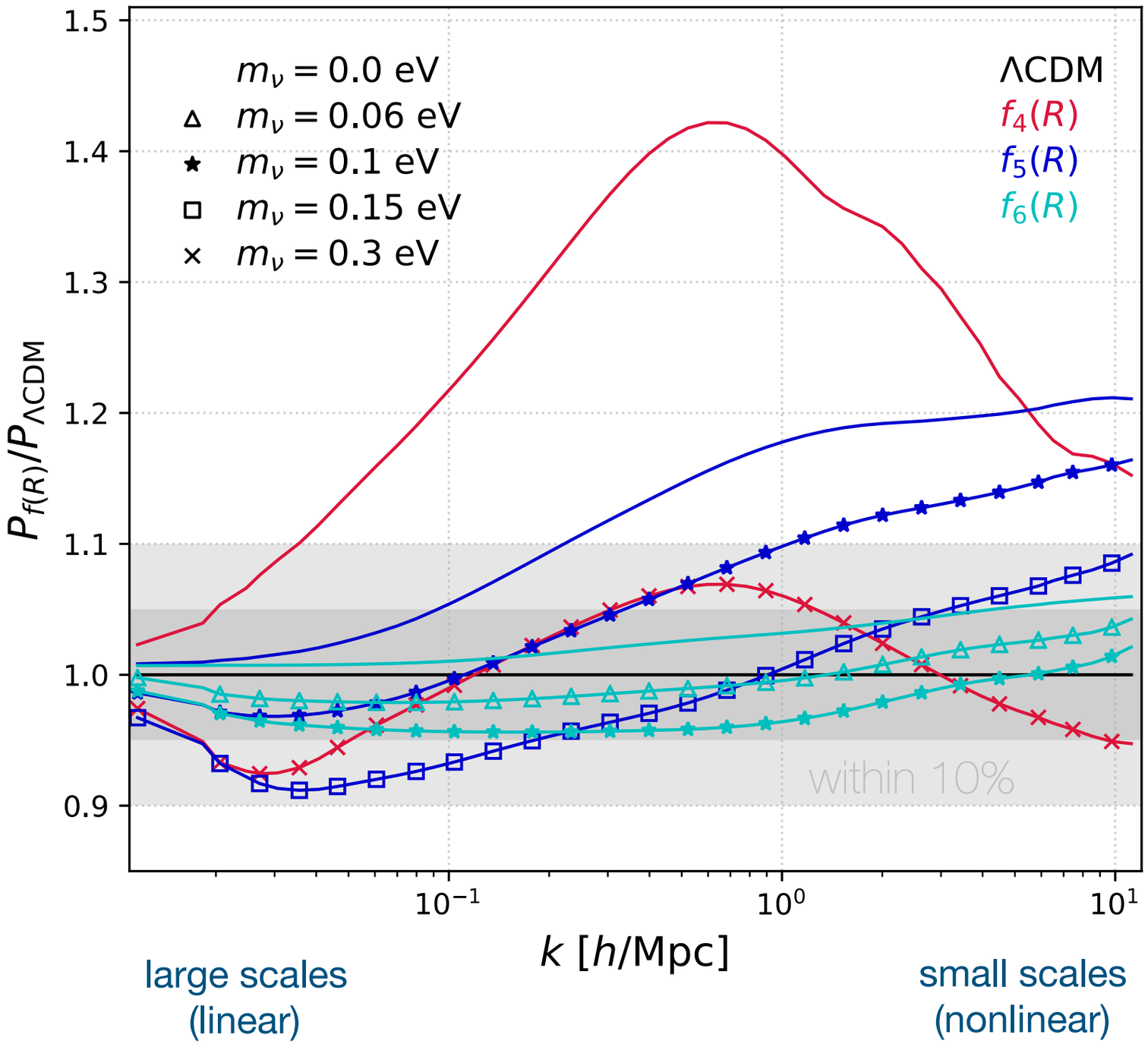
Sample joint parameter space of $f(R)$ gravity and massive neutrino cosmologies

Performed with MG-Gadget code that implements the extra fifth-force and screening



For illustration only (http://cosmicweb.uchicago.edu/filaments.html)

Simulation Name	Gravity type	f_{R0}	m_ν [eV]	$\Omega_{\rm CDM}$	Ω_ν	$m^p_{\rm CDM}$ [$\rm M_\odot$/h]	m^p_ν [$\rm M_\odot$/h]
ΛCDM	GR	–	0	0.31345	0	8.1×10^{10}	0
fR4	$f(R)$	-1×10^{-4}	0	0.31345	0	8.1×10^{10}	0
fR5	$f(R)$	-1×10^{-5}	0	0.31345	0	8.1×10^{10}	0
fR6	$f(R)$	-1×10^{-6}	0	0.31345	0	8.1×10^{10}	0
fR4-0.3eV	$f(R)$	-1×10^{-4}	0.3	0.30630	0.00715	7.92×10^{10}	1.85×10^{9}
fR5-0.15eV	$f(R)$	-1×10^{-5}	0.15	0.30987	0.00358	8.01×10^{10}	9.25×10^{8}
fR5-0.1eV	$f(R)$	-1×10^{-5}	0.1	0.31107	0.00238	8.04×10^{10}	6.16×10^{8}
fR6-0.1eV	$f(R)$	-1×10^{-6}	0.1	0.31107	0.00238	8.04×10^{10}	6.16×10^{8}
fR6-0.06eV	$f(R)$	-1×10^{-6}	0.06	0.31202	0.00143	8.07×10^{10}	3.7×10^{8}



large scales (linear)

small scales (nonlinear)

matter power spectra (relative to LCDM)

$f_4(R)$ farther from LCDM

$f_5(R)$ intermediate

$f_6(R)$ closer to LCDM

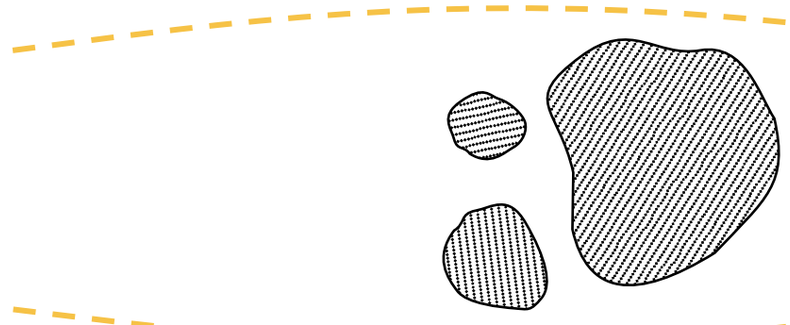
neutrinos suppress the growth of structure

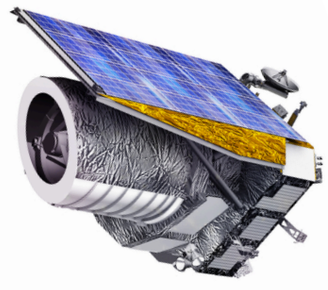
Weak gravitational lensing

galaxies here

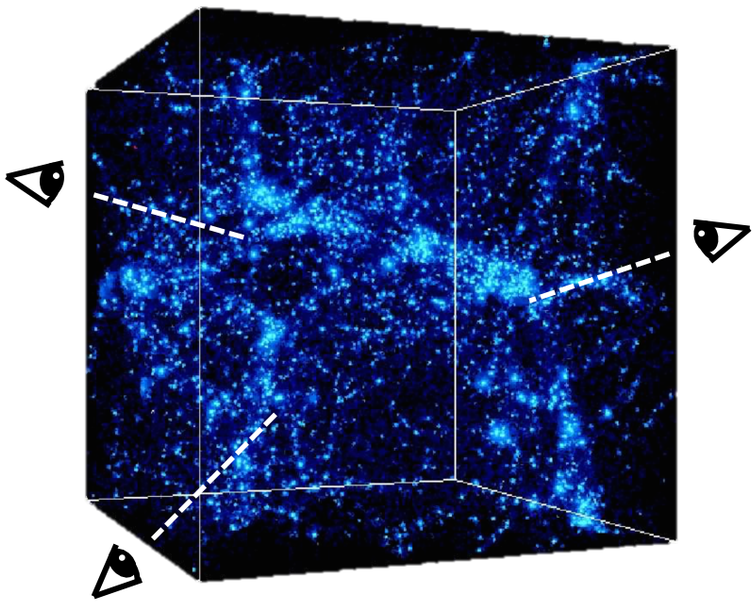
…tell us about…

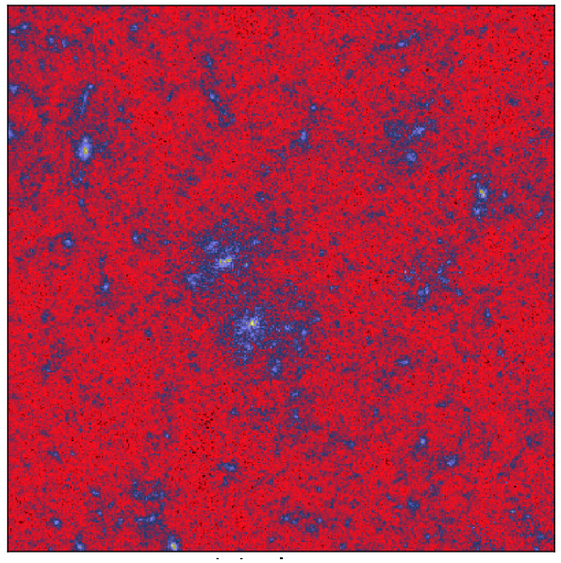
structures here





redshift z





$\times\ 256$ per redshift, per model

WL convergence map $\kappa(\boldsymbol{\theta})$

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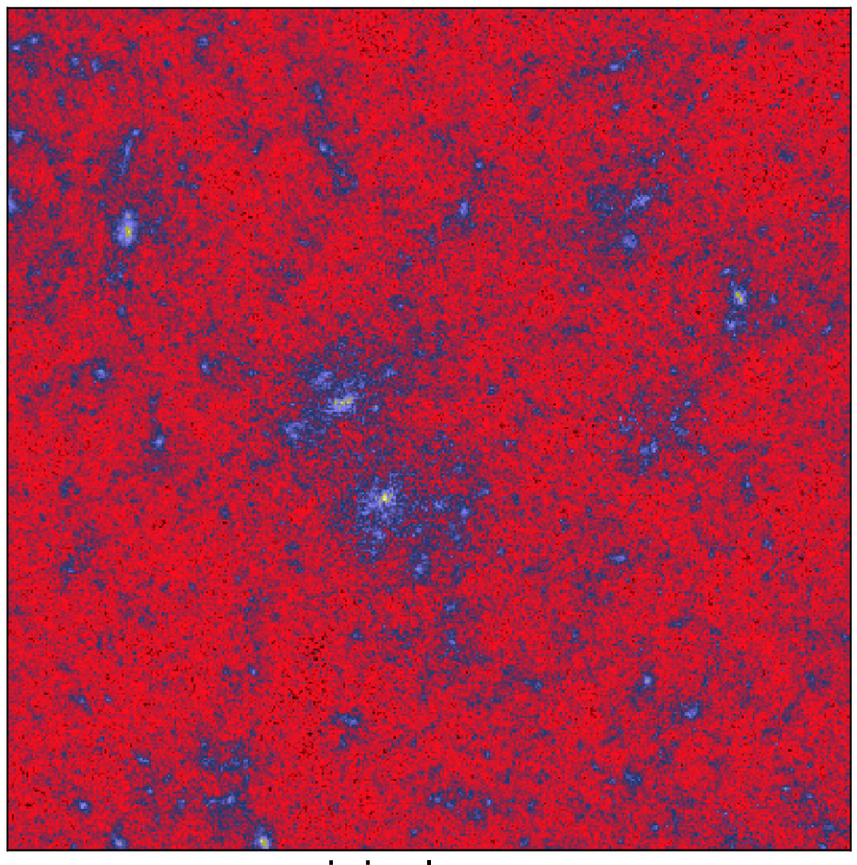
aperture mass :

$$M_{\rm ap}(\boldsymbol{\theta};\vartheta) = \int \mathrm{d}^2\theta'\, U_\vartheta(|\boldsymbol{\theta}' - \boldsymbol{\theta}|)\,\kappa(\boldsymbol{\theta}')$$

isotropic filter function

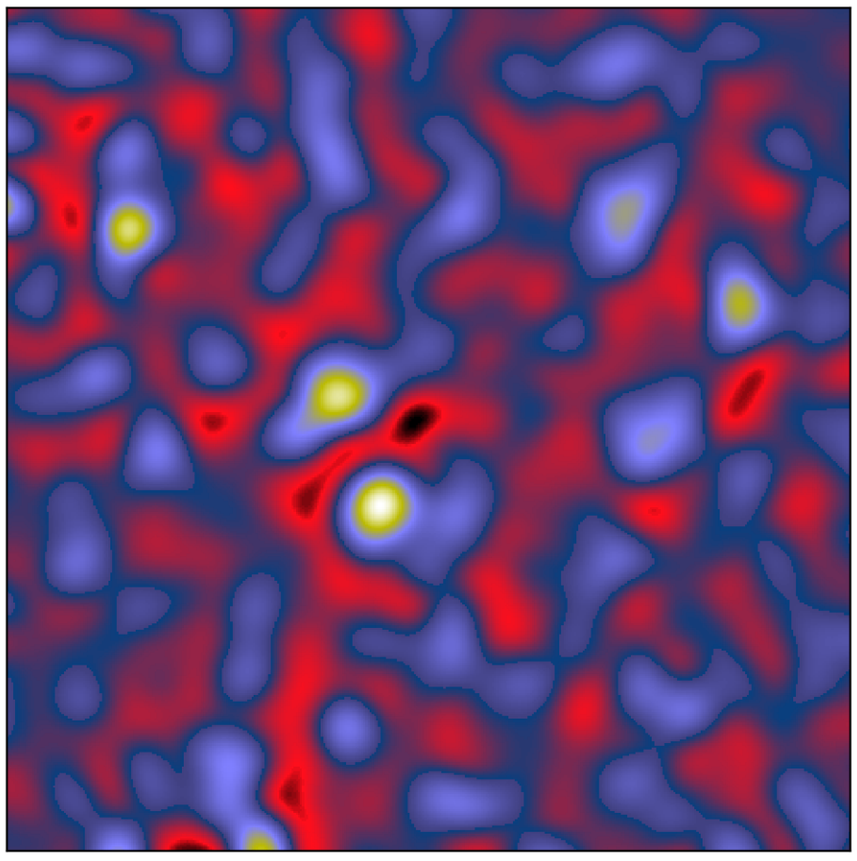
mass map

implemented as a **wavelet** transform (starlet)



original κ map

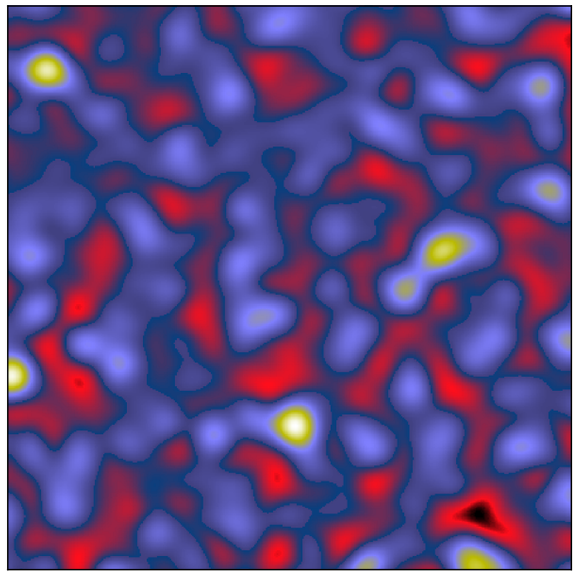
$=\sum$



aperture size $\vartheta_5 = 4.69$ arcmin

aperture mass map

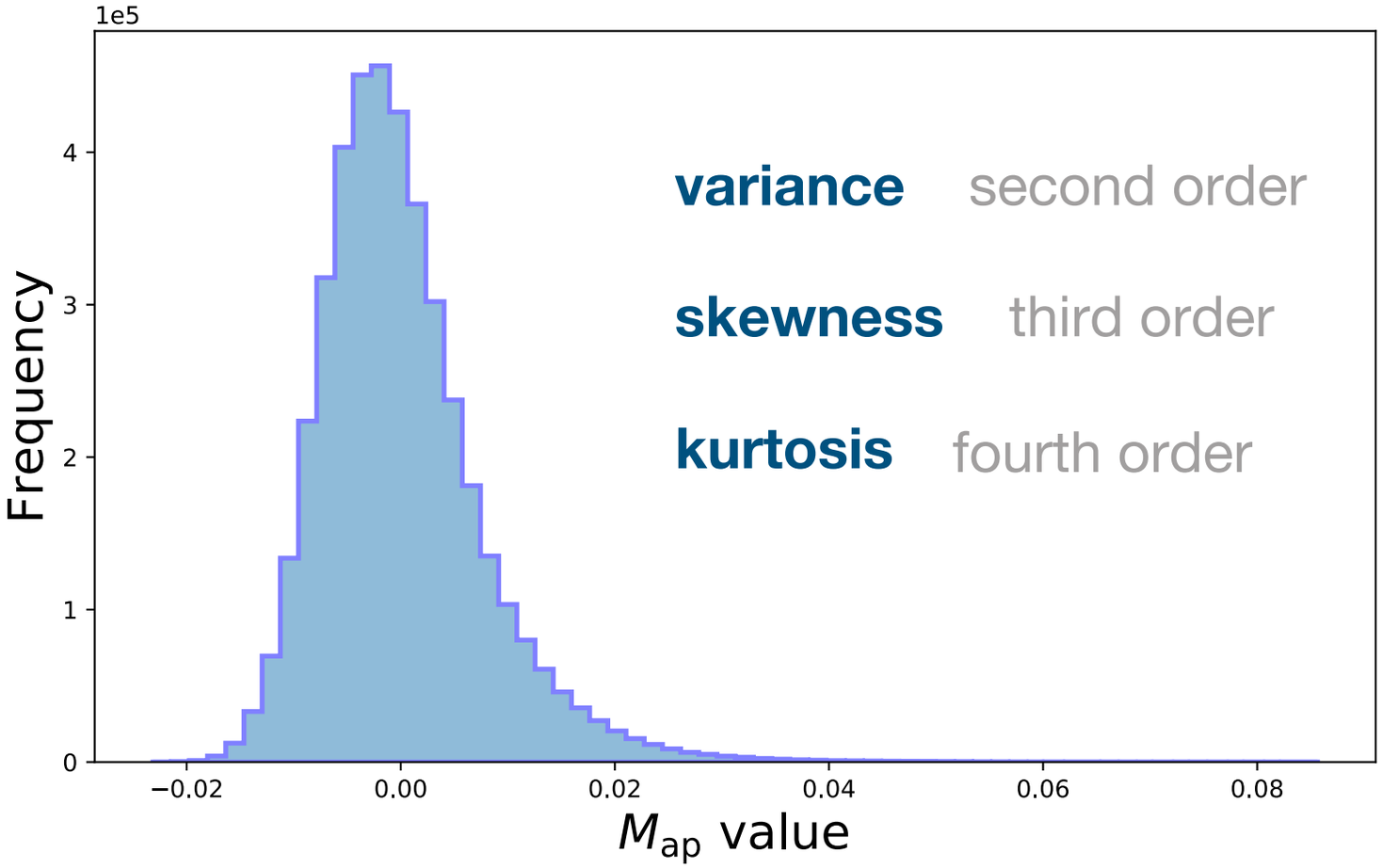
$$M_{\rm ap}(\text{model}, \vartheta_j, z_s) =$$



$$5 \times 5 \ \text{deg}^2$$

400×400 shown, but

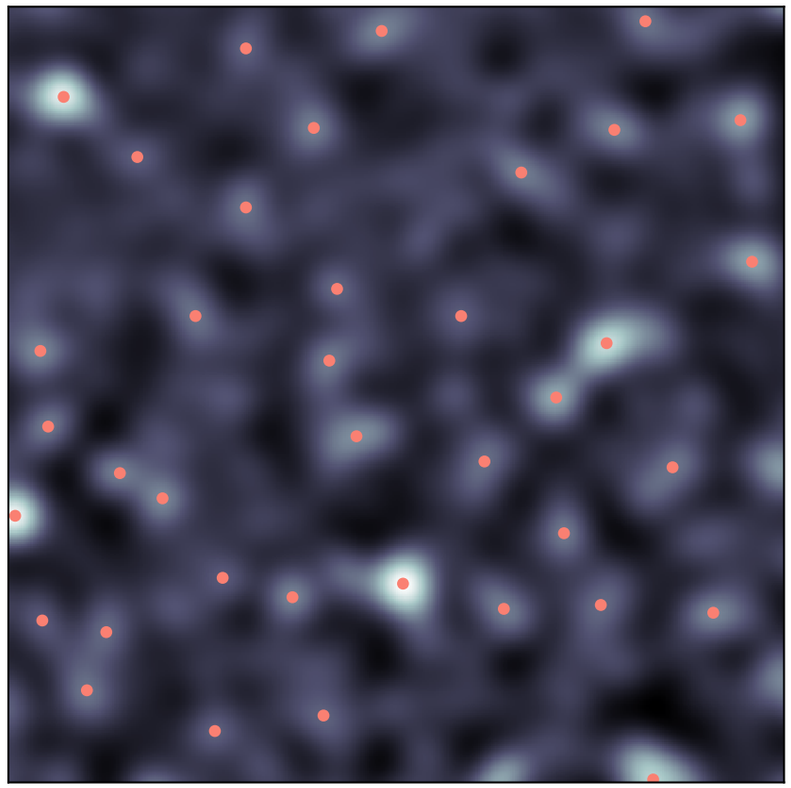
2048×2048 in practice



variance second order

skewness third order

kurtosis fourth order



peak count

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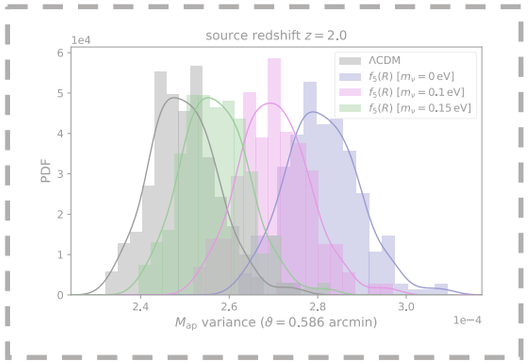
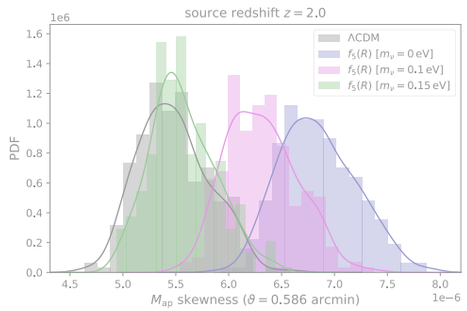
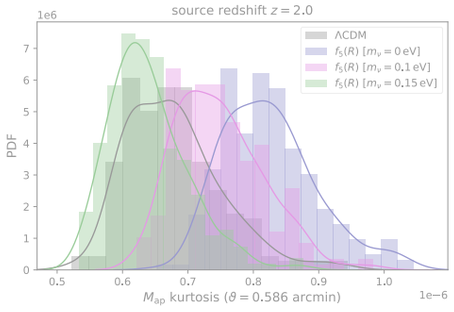
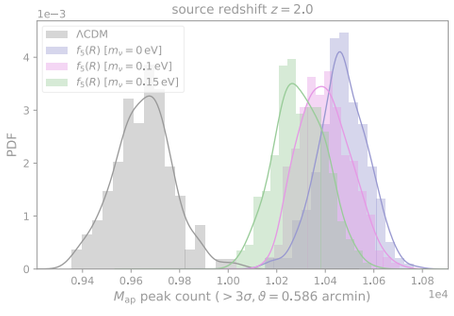
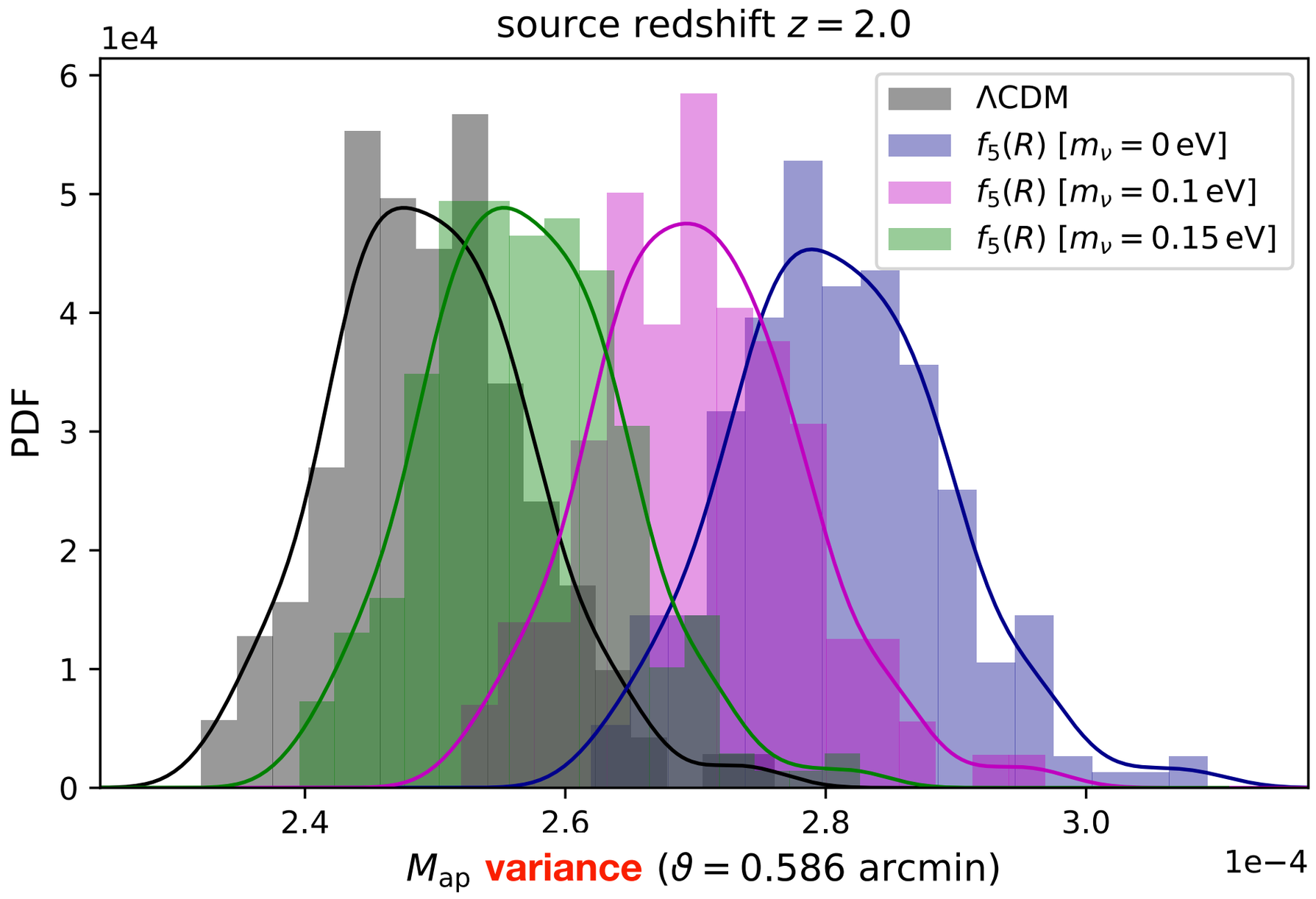


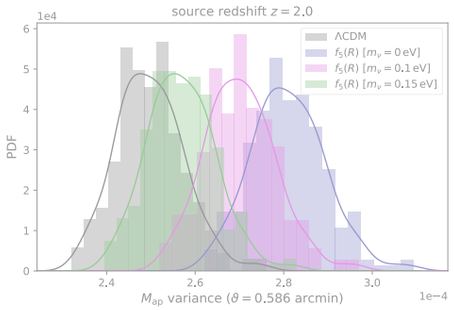


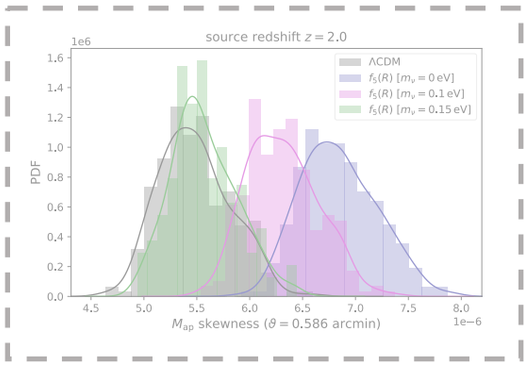


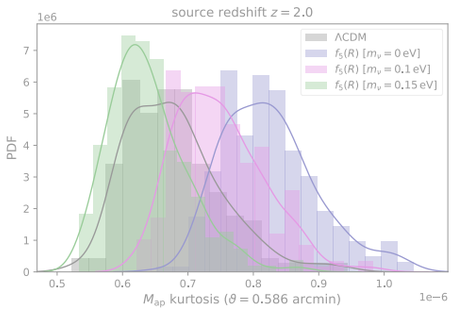


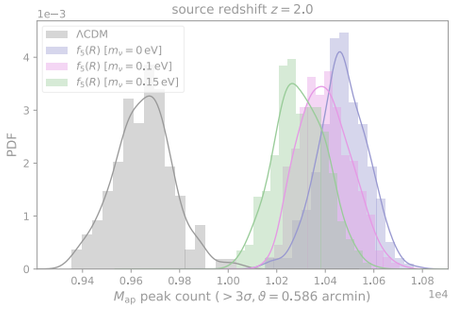
Distributions of observables



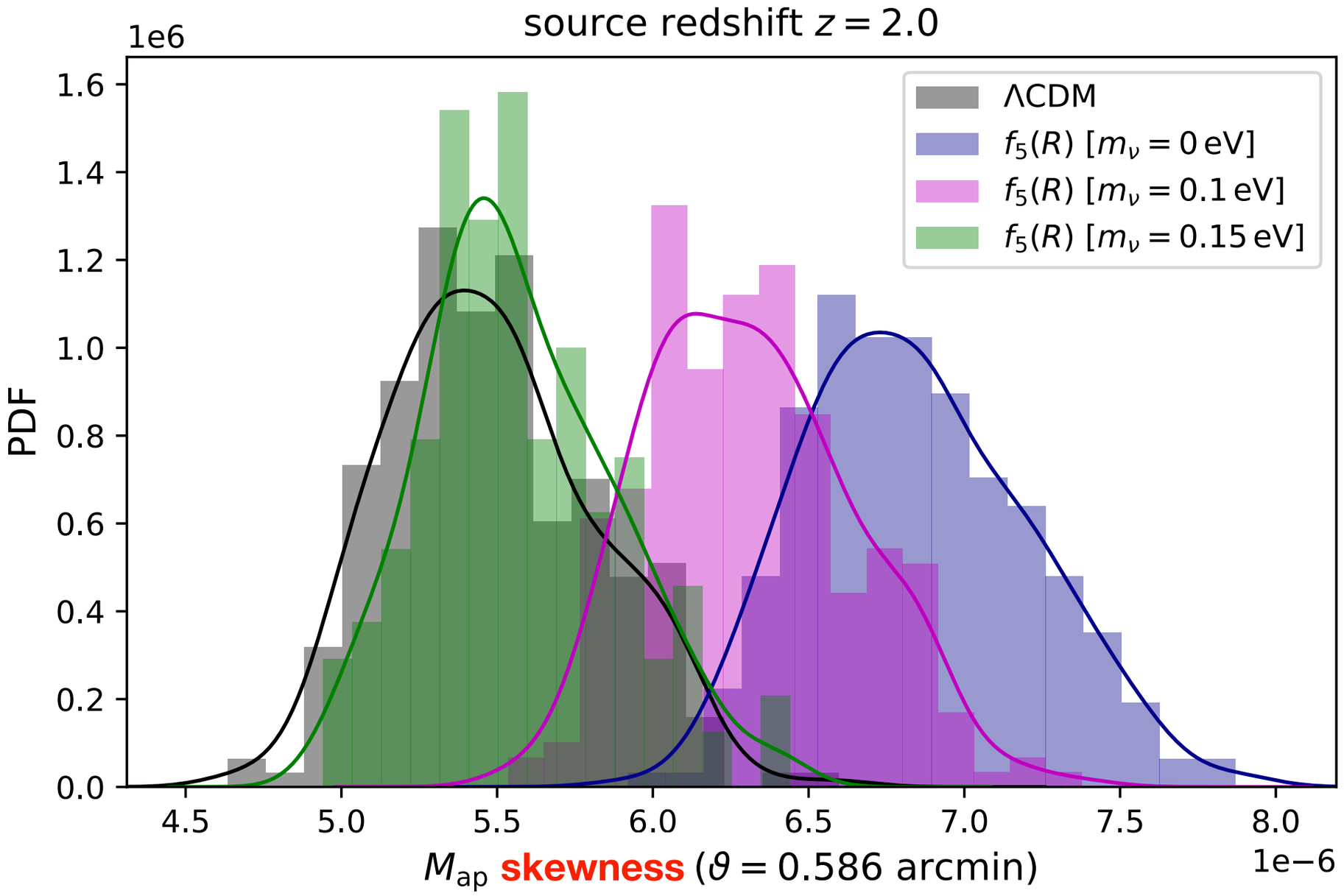


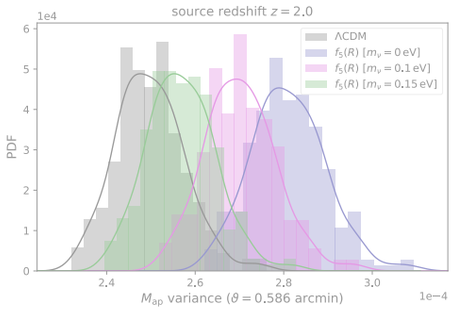


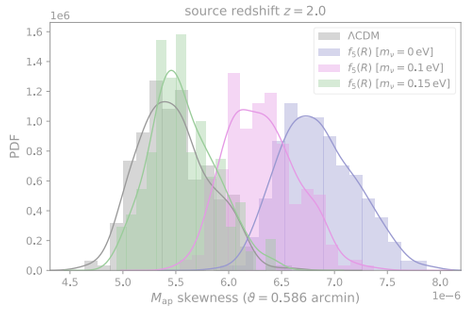


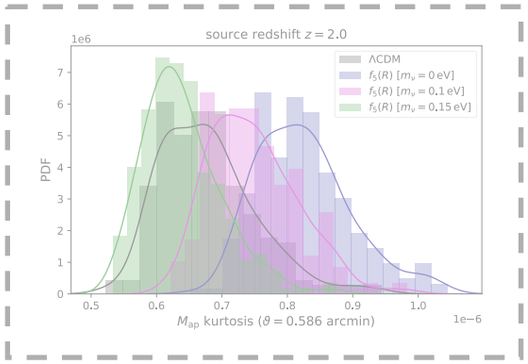


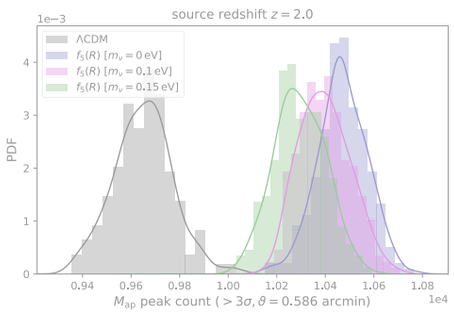
Distributions of observables



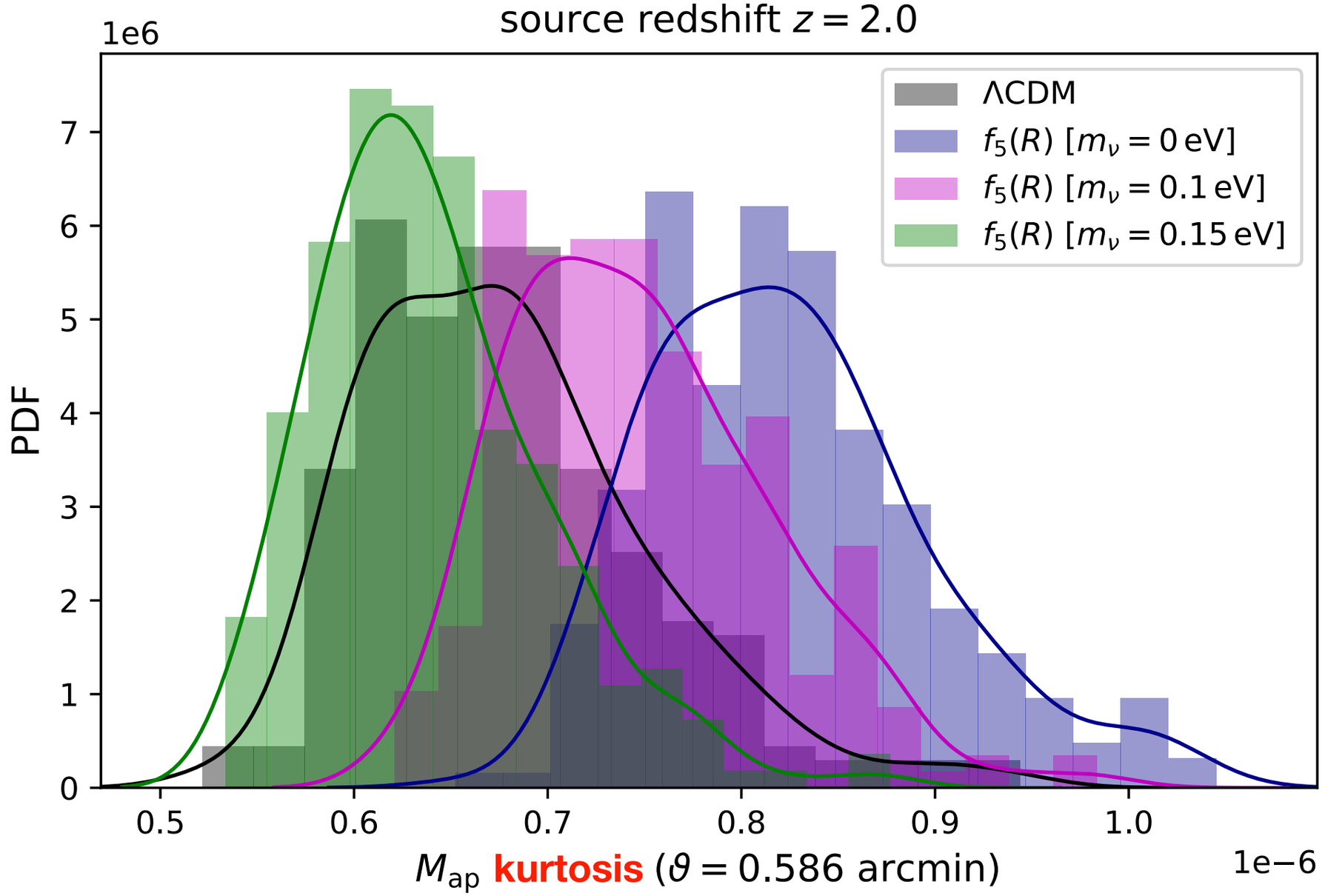


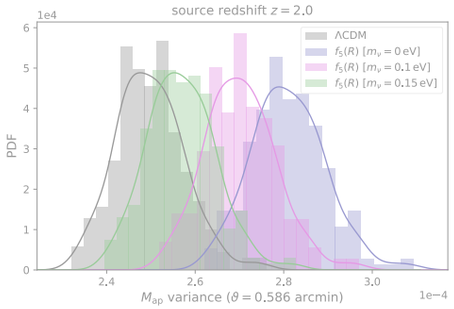


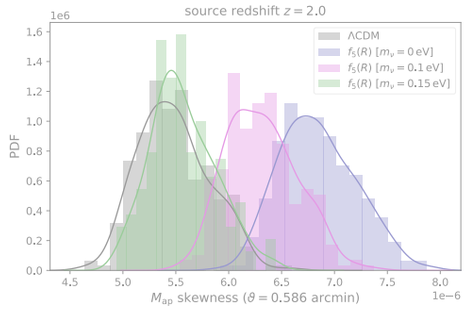


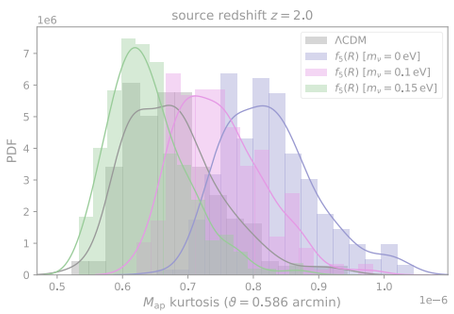


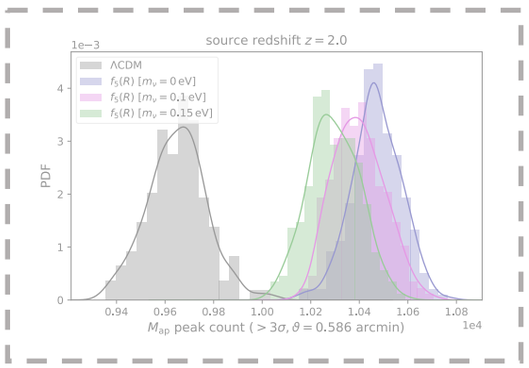
Distributions of observables



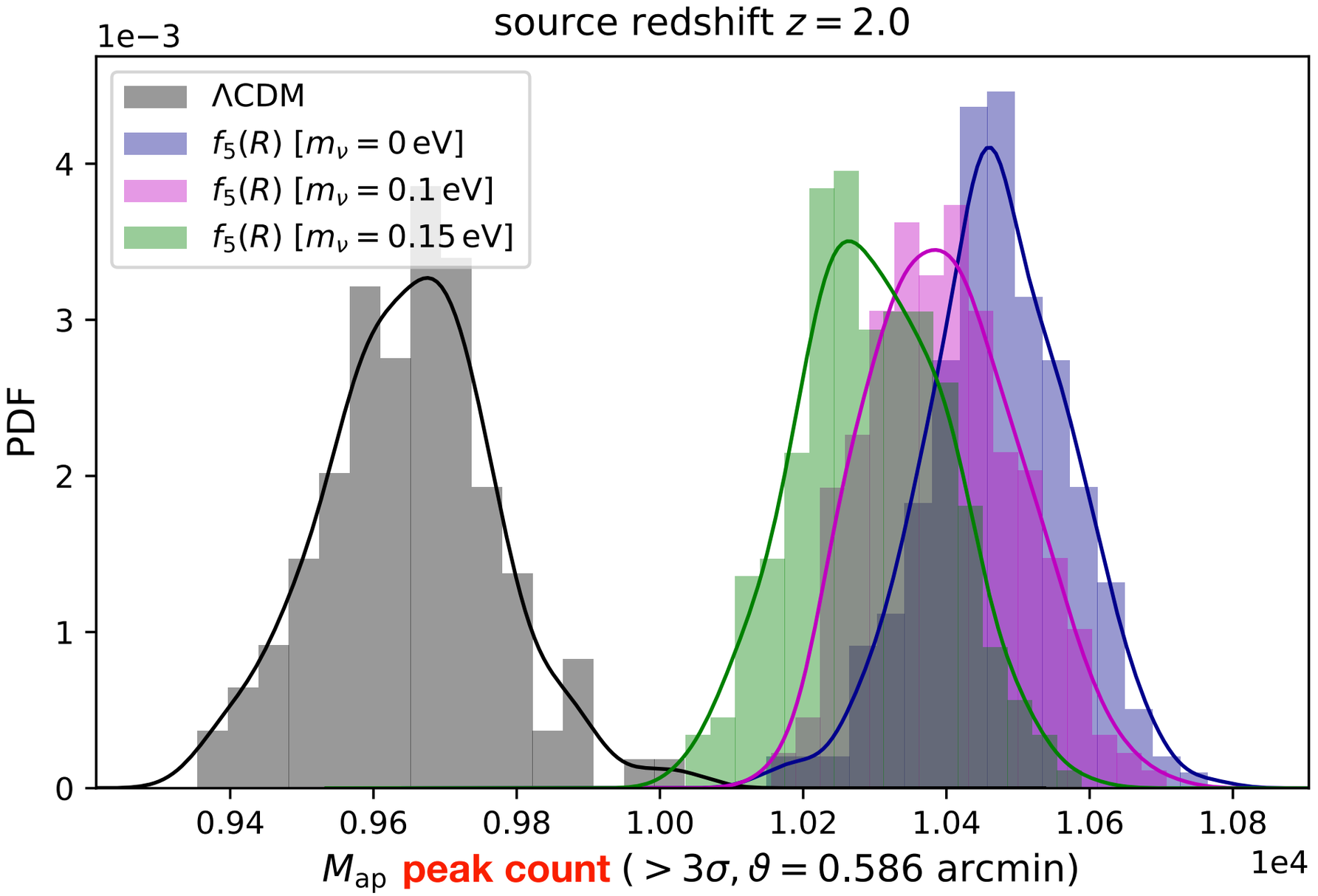


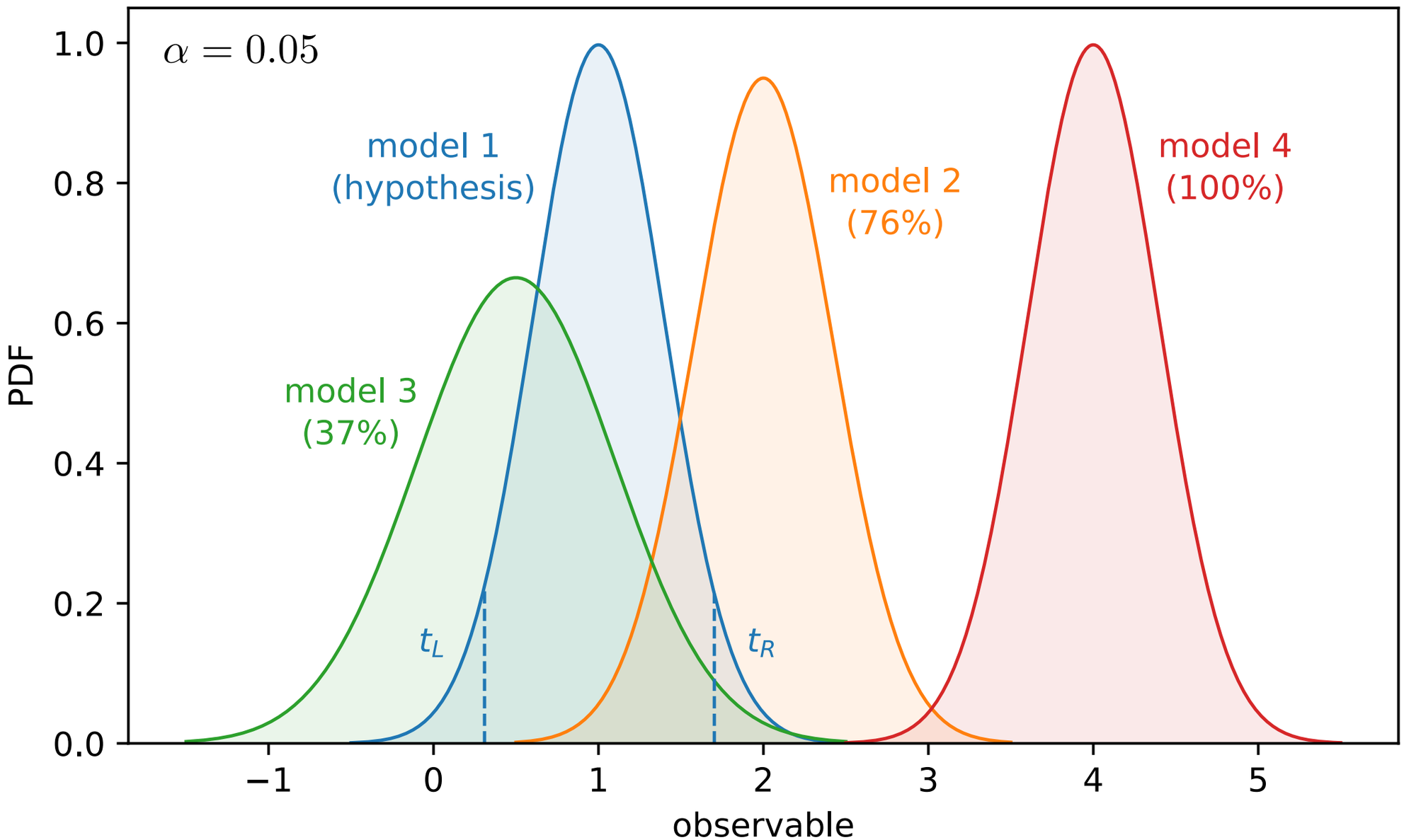




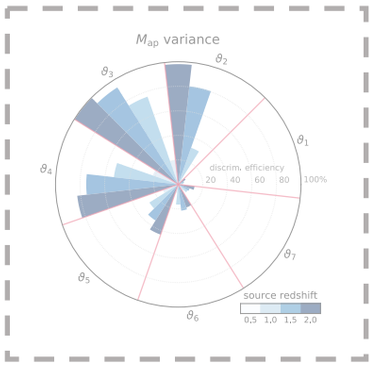


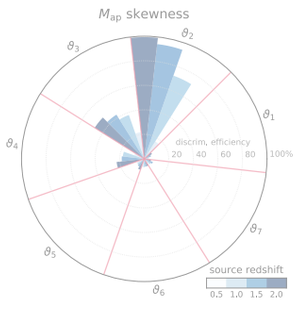
Distributions of observables

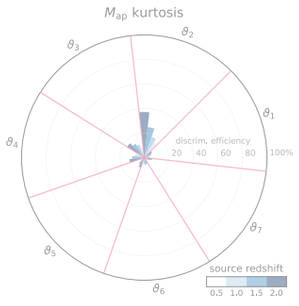


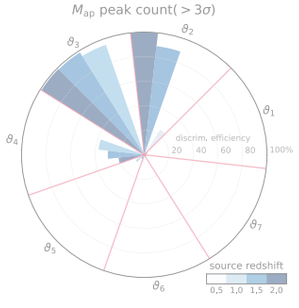


Discrimination efficiency : *toy example*

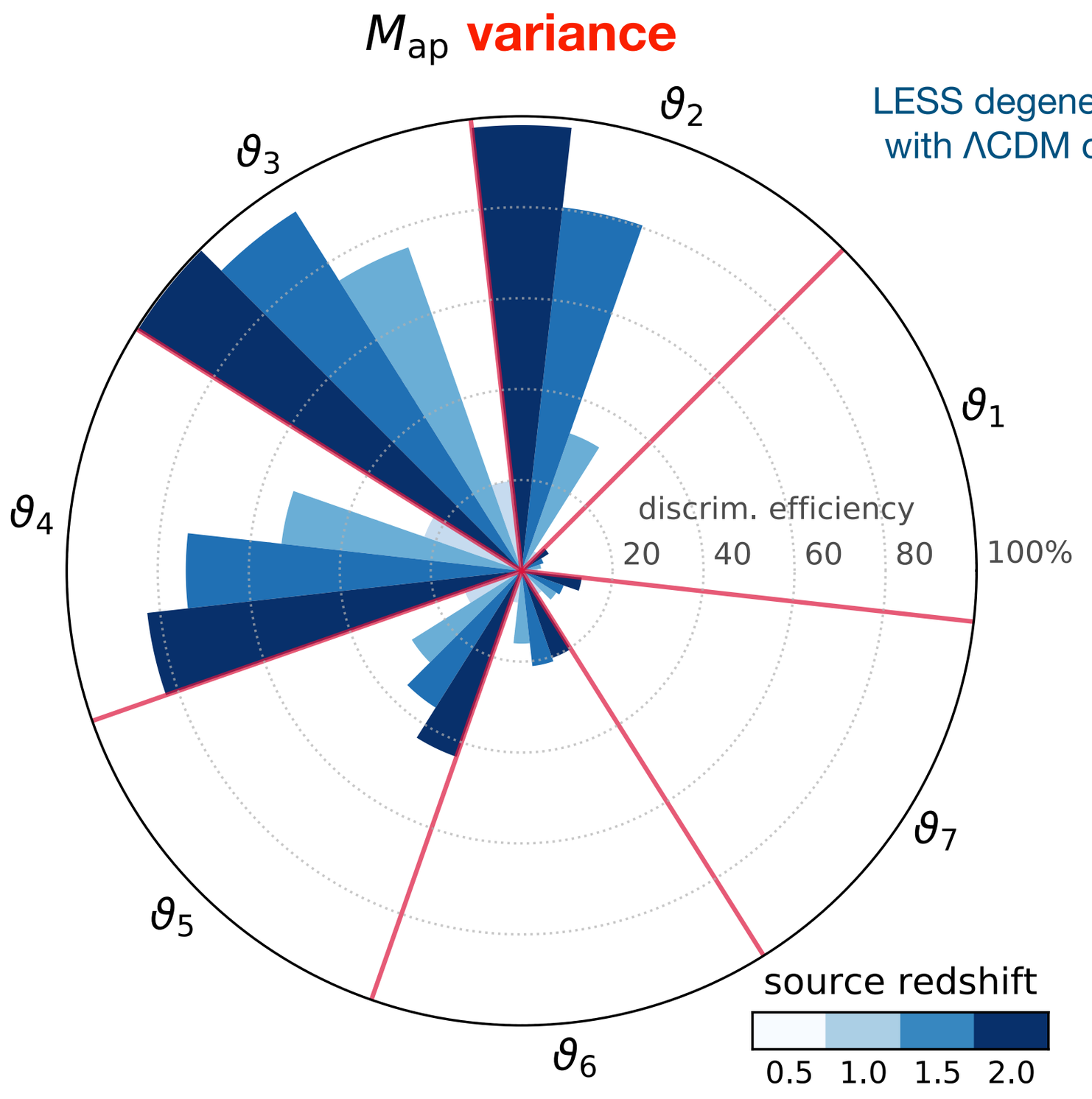

M_{ap} variance
ϑ_1
ϑ_2
ϑ_3
ϑ_4
ϑ_5
ϑ_6
ϑ_7
discrim. efficiency
20 40 60 80 100%
source redshift
0.5 1.0 1.5 2.0

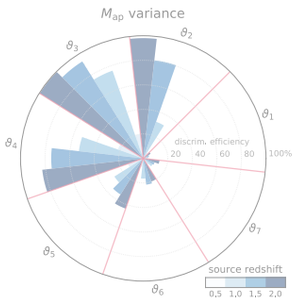

M_{ap} skewness
ϑ_1
ϑ_2
ϑ_3
ϑ_4
ϑ_5
ϑ_6
ϑ_7
discrim. efficiency
20 40 60 80 100%
source redshift
0.5 1.0 1.5 2.0

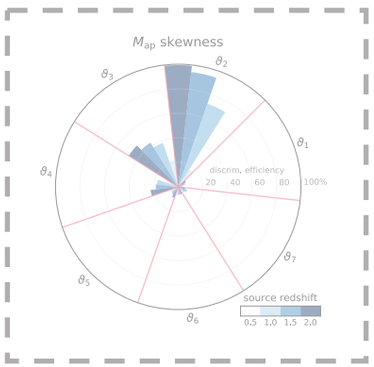

M_{ap} kurtosis
ϑ_1
ϑ_2
ϑ_3
ϑ_4
ϑ_5
ϑ_6
ϑ_7
discrim. efficiency
20 40 60 80 100%
source redshift
0.5 1.0 1.5 2.0

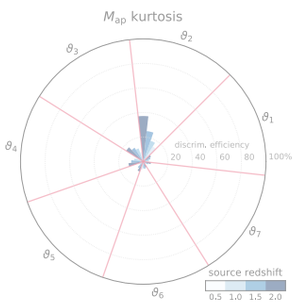

M_{ap} peak count($> 3\sigma$)
ϑ_1
ϑ_2
ϑ_3
ϑ_4
ϑ_5
ϑ_6
ϑ_7
discrim. efficiency
20 40 60 80 100%
source redshift
0.5 1.0 1.5 2.0

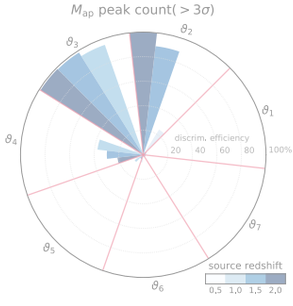
$f_5(R)$ $[m_\nu = 0$ eV$]$


M_{ap} variance
LESS degenerate with ΛCDM case
ϑ_1
ϑ_2
ϑ_3
ϑ_4
ϑ_5
ϑ_6
ϑ_7
discrim. efficiency
20 40 60 80 100%
source redshift
0.5 1.0 1.5 2.0





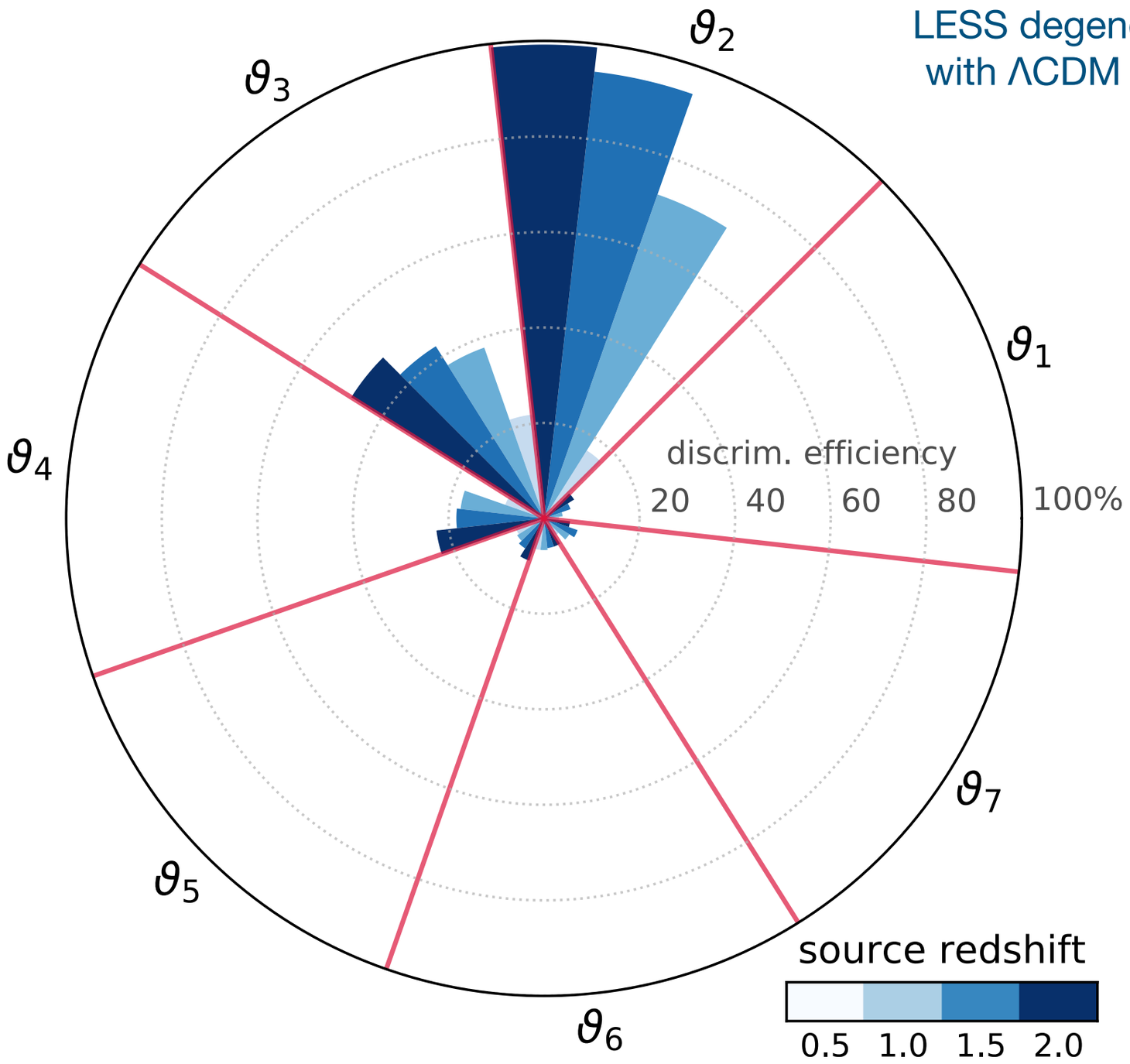


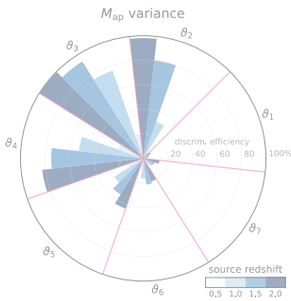


$f_5(R)$ $[m_\nu = 0$ eV$]$

$M_{\rm ap}$ **skewness**

LESS degenerate with ΛCDM case

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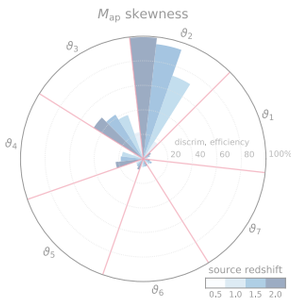
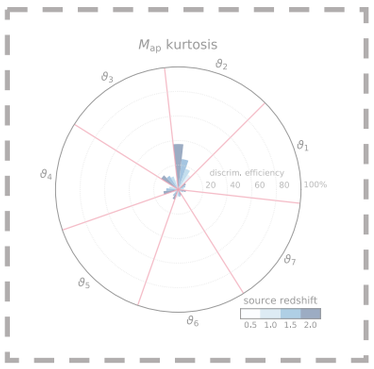
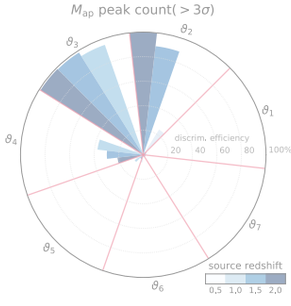
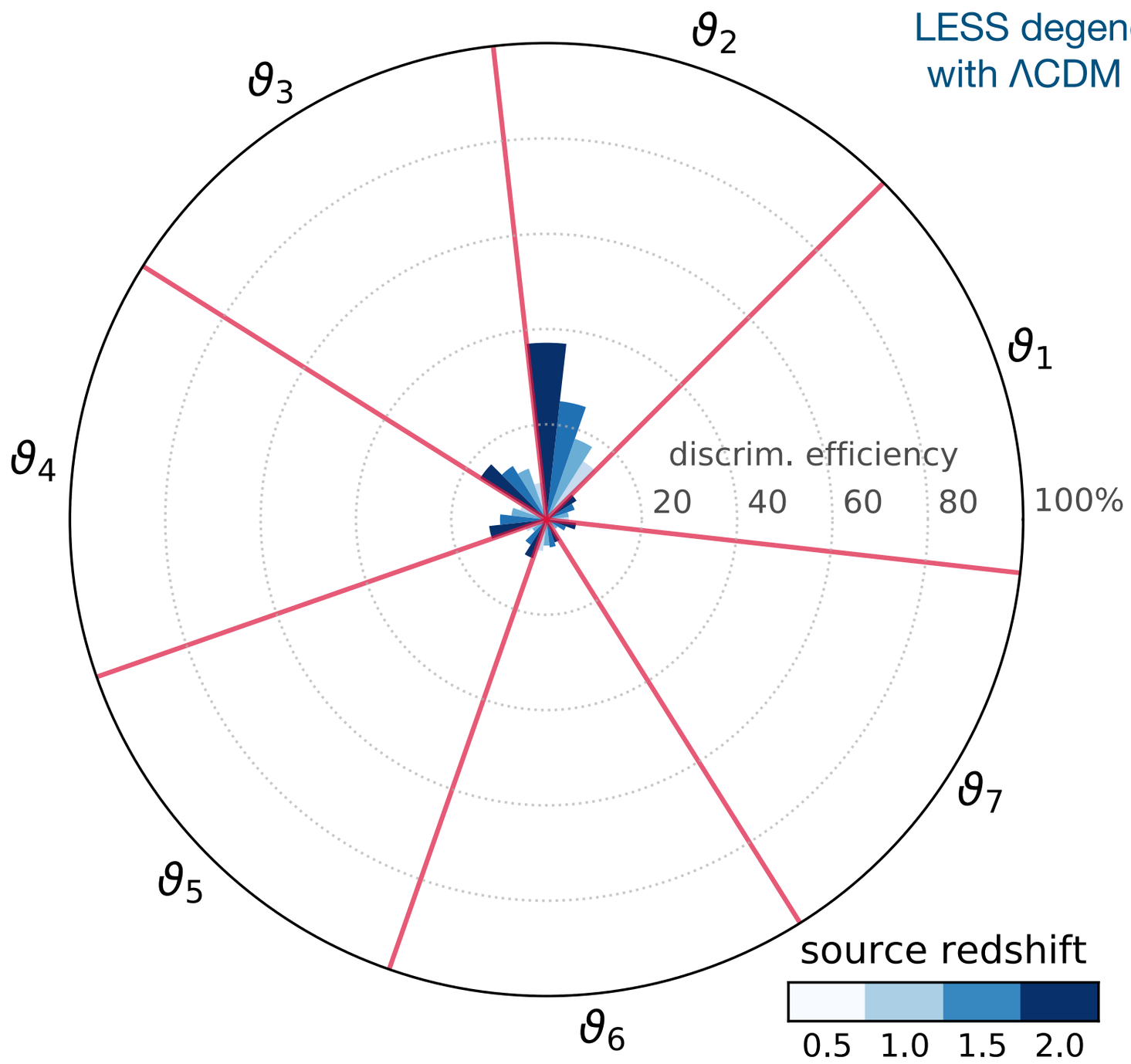
source redshift
0.5 1.0 1.5 2.0

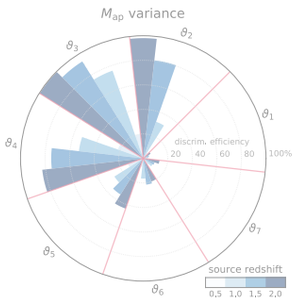

M_{ap} skewness
ϑ_1
ϑ_2
ϑ_3
ϑ_4
ϑ_5
ϑ_6
ϑ_7
discrim. efficiency
20 40 60 80 100%
source redshift
0.5 1.0 1.5 2.0

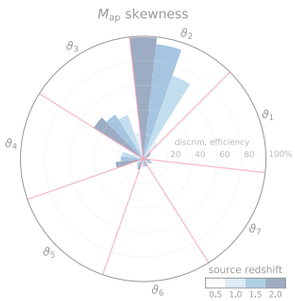

M_{ap} kurtosis
ϑ_1
ϑ_2
ϑ_3
ϑ_4
ϑ_5
ϑ_6
ϑ_7
discrim. efficiency
20 40 60 80 100%
source redshift
0.5 1.0 1.5 2.0

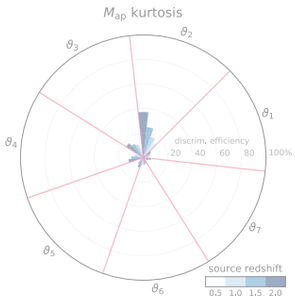

M_{ap} peak count($> 3\sigma$)
ϑ_1
ϑ_2
ϑ_3
ϑ_4
ϑ_5
ϑ_6
ϑ_7
discrim. efficiency
20 40 60 80 100%
source redshift
0.5 1.0 1.5 2.0

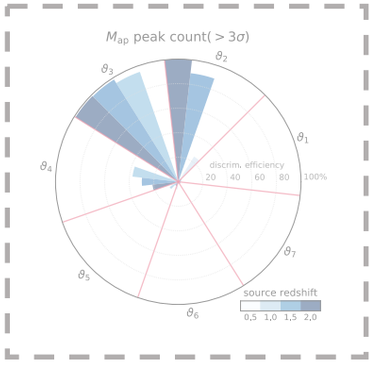
$f_5(R)$ $[m_\nu = 0$ eV$]$


M_{ap} kurtosis
LESS degenerate with ΛCDM case
ϑ_1
ϑ_2
ϑ_3
ϑ_4
ϑ_5
ϑ_6
ϑ_7
discrim. efficiency
20 40 60 80 100%
source redshift
0.5 1.0 1.5 2.0

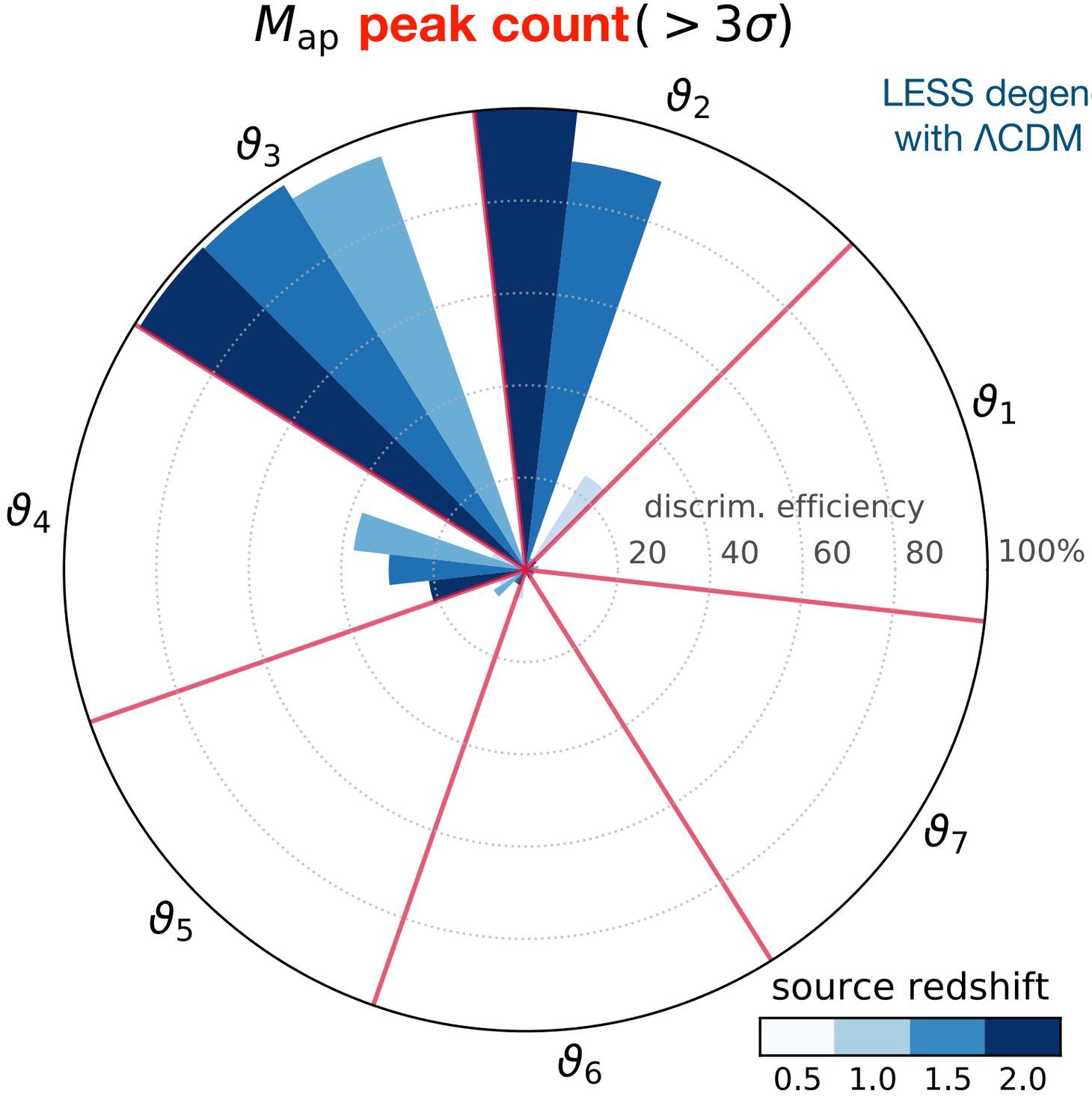


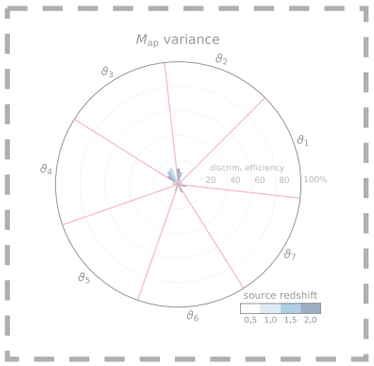


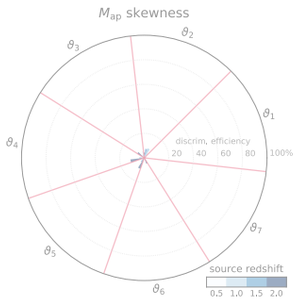


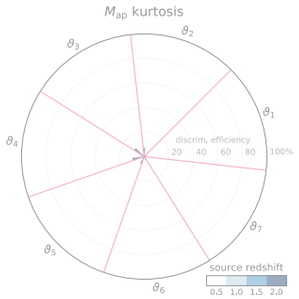


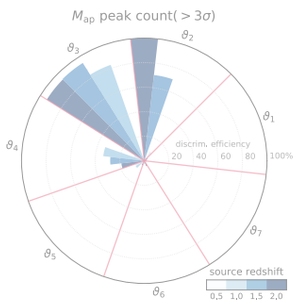
$f_5(R)$ $[m_\nu = 0\ \mathrm{eV}]$



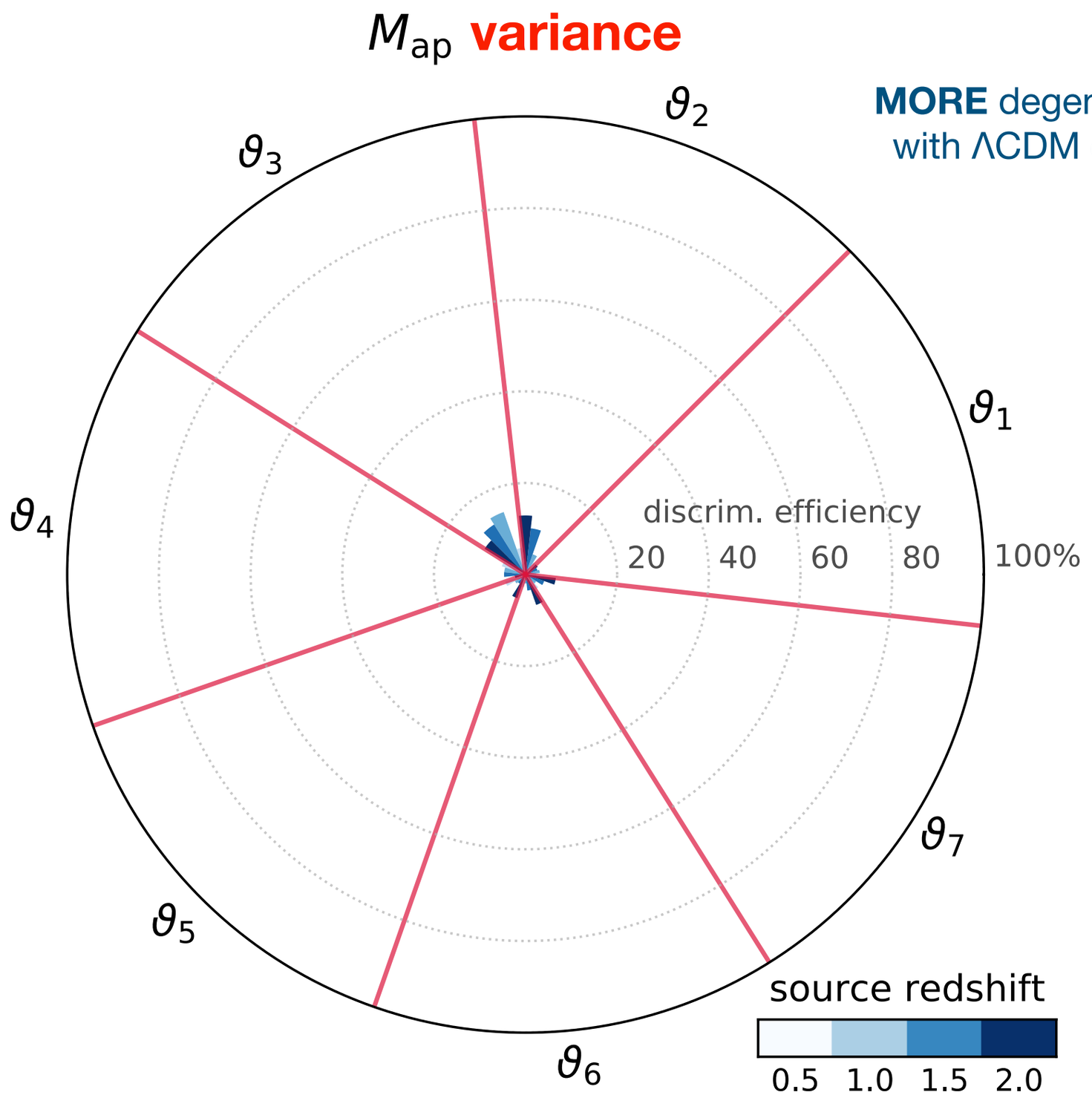




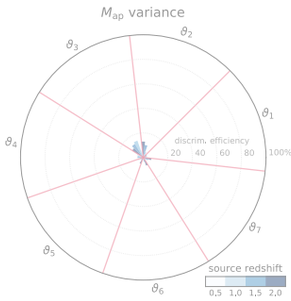


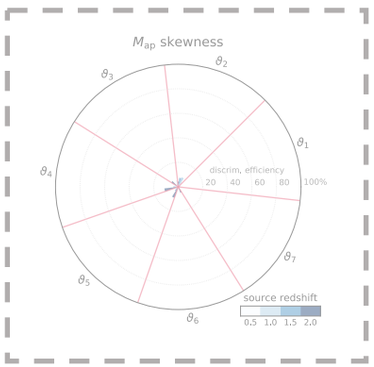


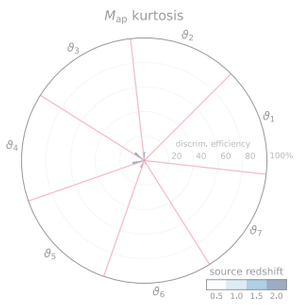
$f_5(R)$ $[m_\nu = 0.15\ \mathrm{eV}]$

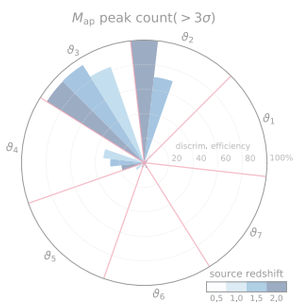


MORE degenerate with ΛCDM case





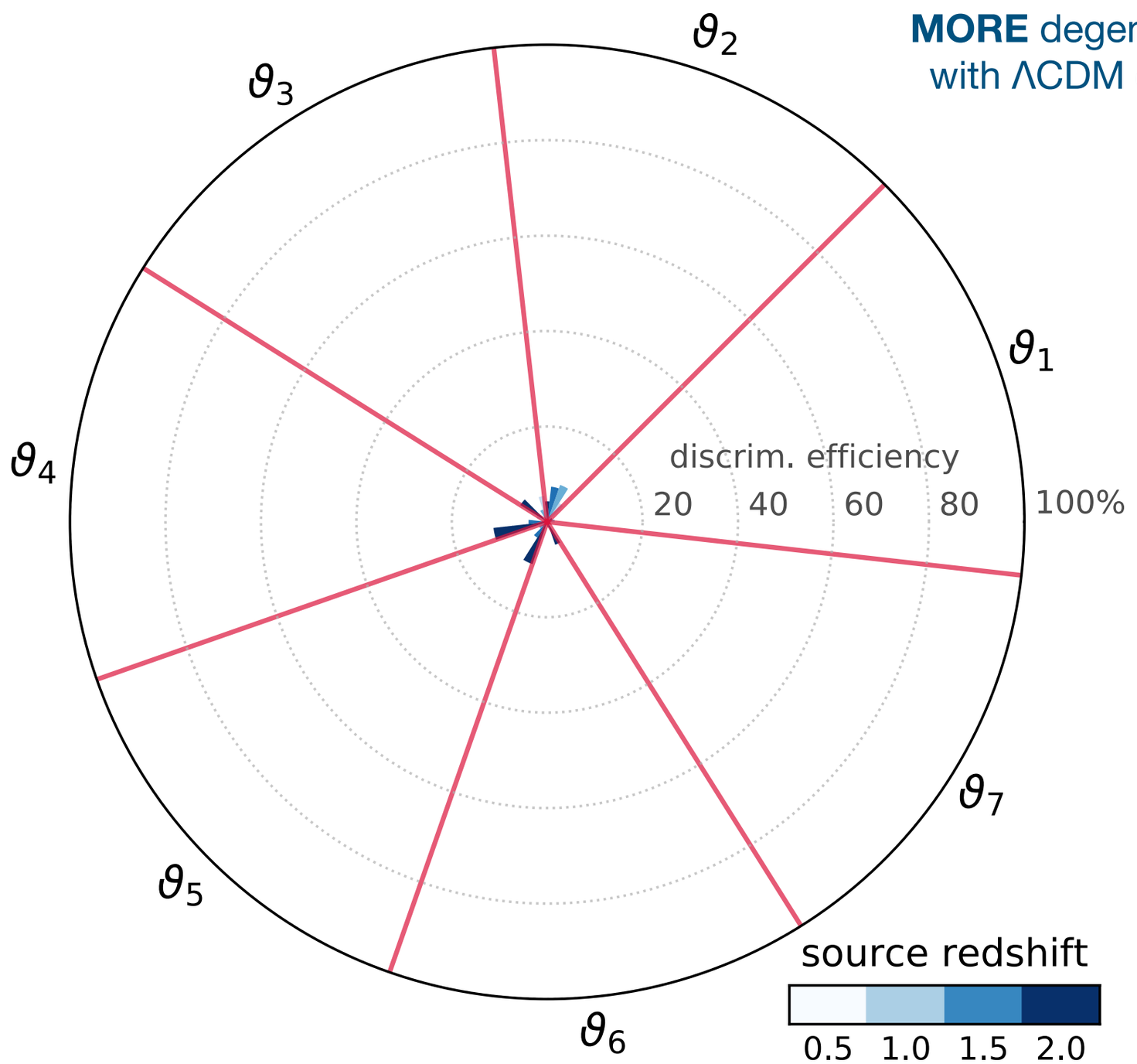


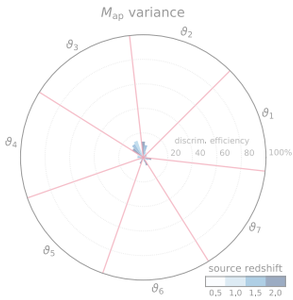


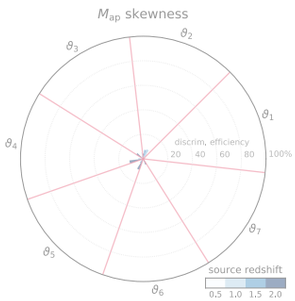
$f_5(R)$ $[m_\nu = 0.15\ \mathrm{eV}]$

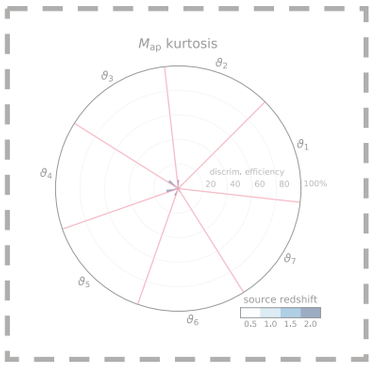
M_{ap} skewness

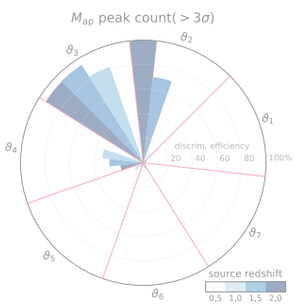
MORE degenerate with ΛCDM case







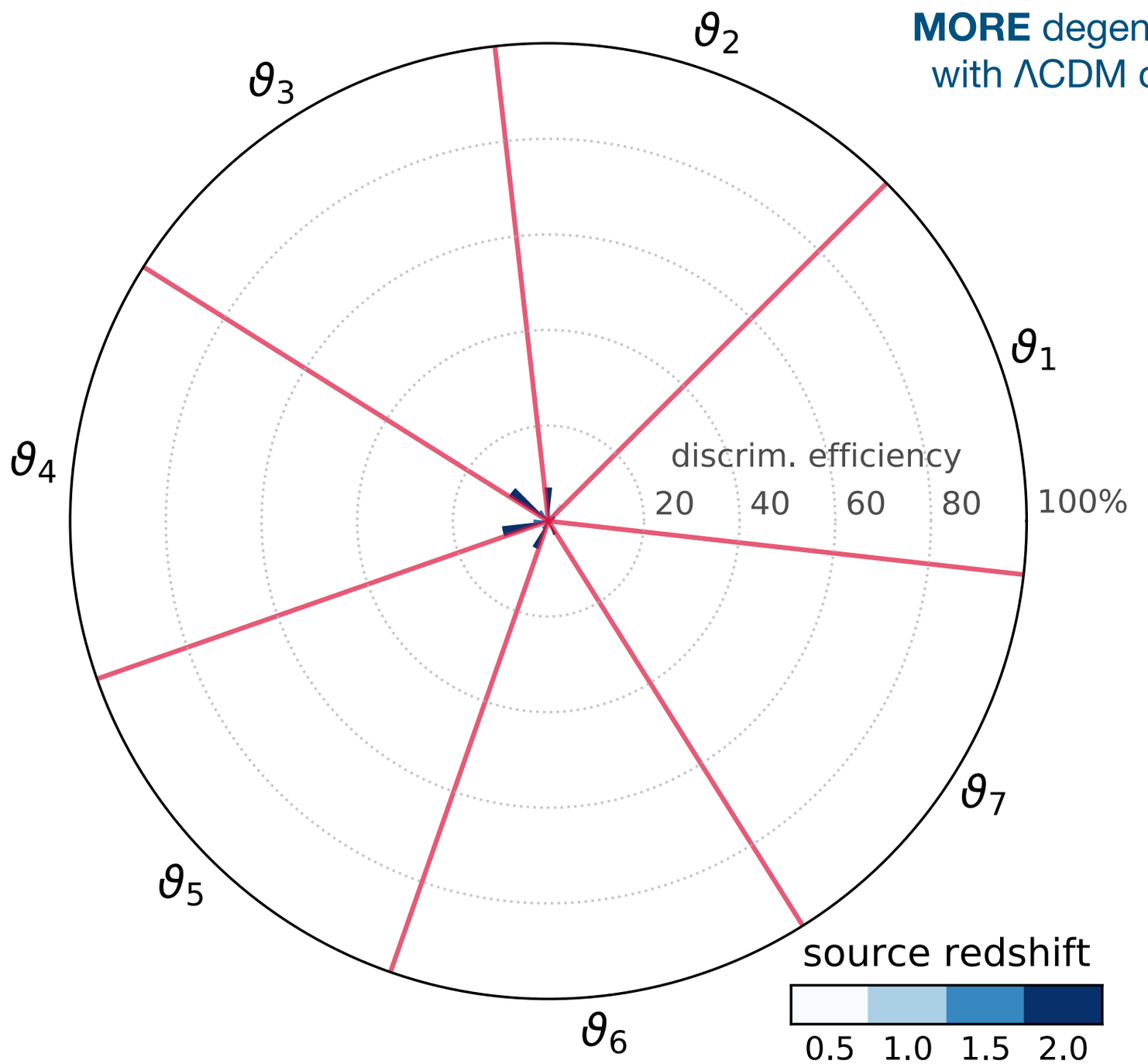


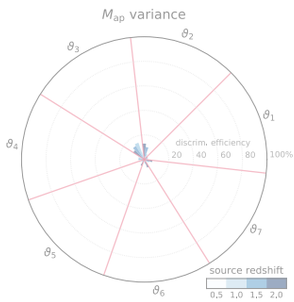


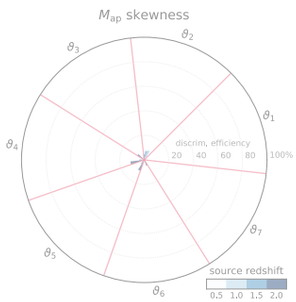
$f_5(R)$ $[m_\nu = 0.15\ \mathrm{eV}]$

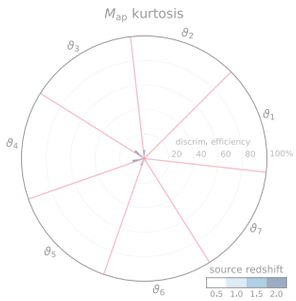
M_{ap} **kurtosis**

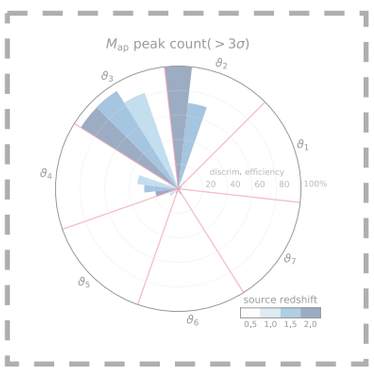
MORE degenerate with ΛCDM case







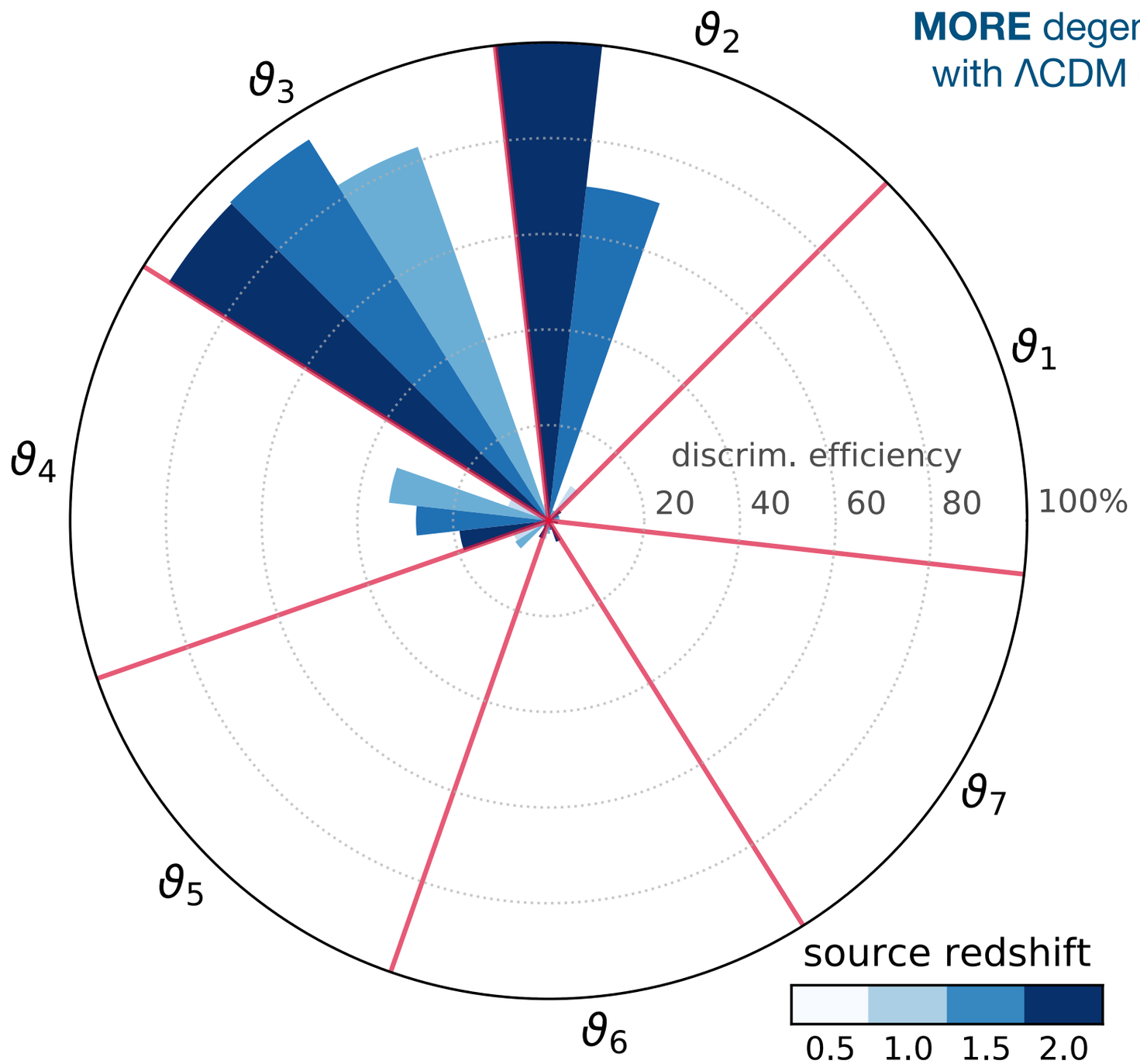




$f_5(R)$ $[m_\nu = 0.15\ \mathrm{eV}]$

M_{ap} **peak count**$(> 3\sigma)$

MORE degenerate with ΛCDM case

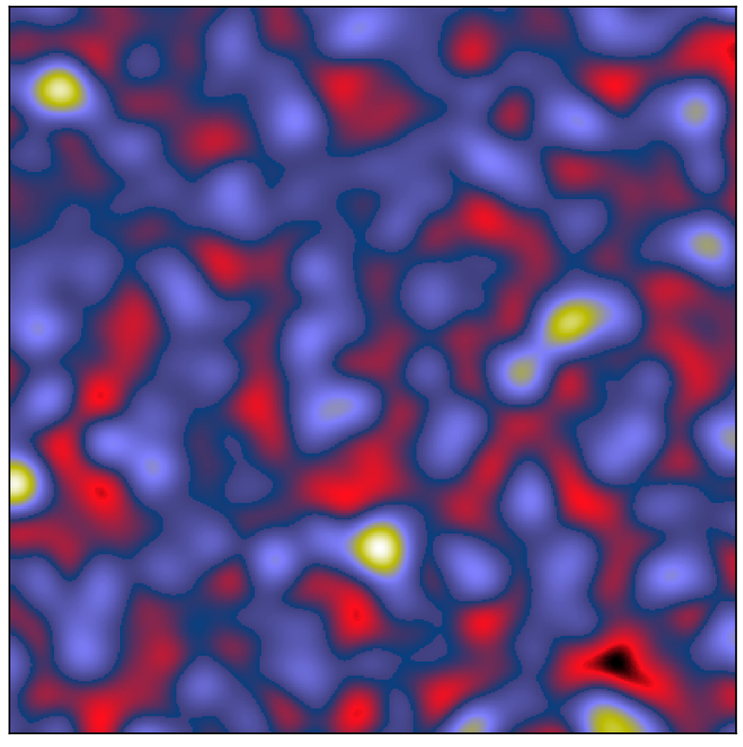


Outline

1. Modifying gravity
2. Simulations
3. Aperture mass statistics
4. Model discrimination
5. **Summary**

Summary

- The nature of late-time **cosmic acceleration** is still unknown
- Modified gravity (MG) models can **mimic ΛCDM** at background and linear level—non-zero neutrino mass helps produce this
- Weak lensing observations accessing **non-Gaussian information** can be used to break degeneracies
- In particular, **peak counts** generally outperform higher (than second) order moments of the aperture mass



Collaborators

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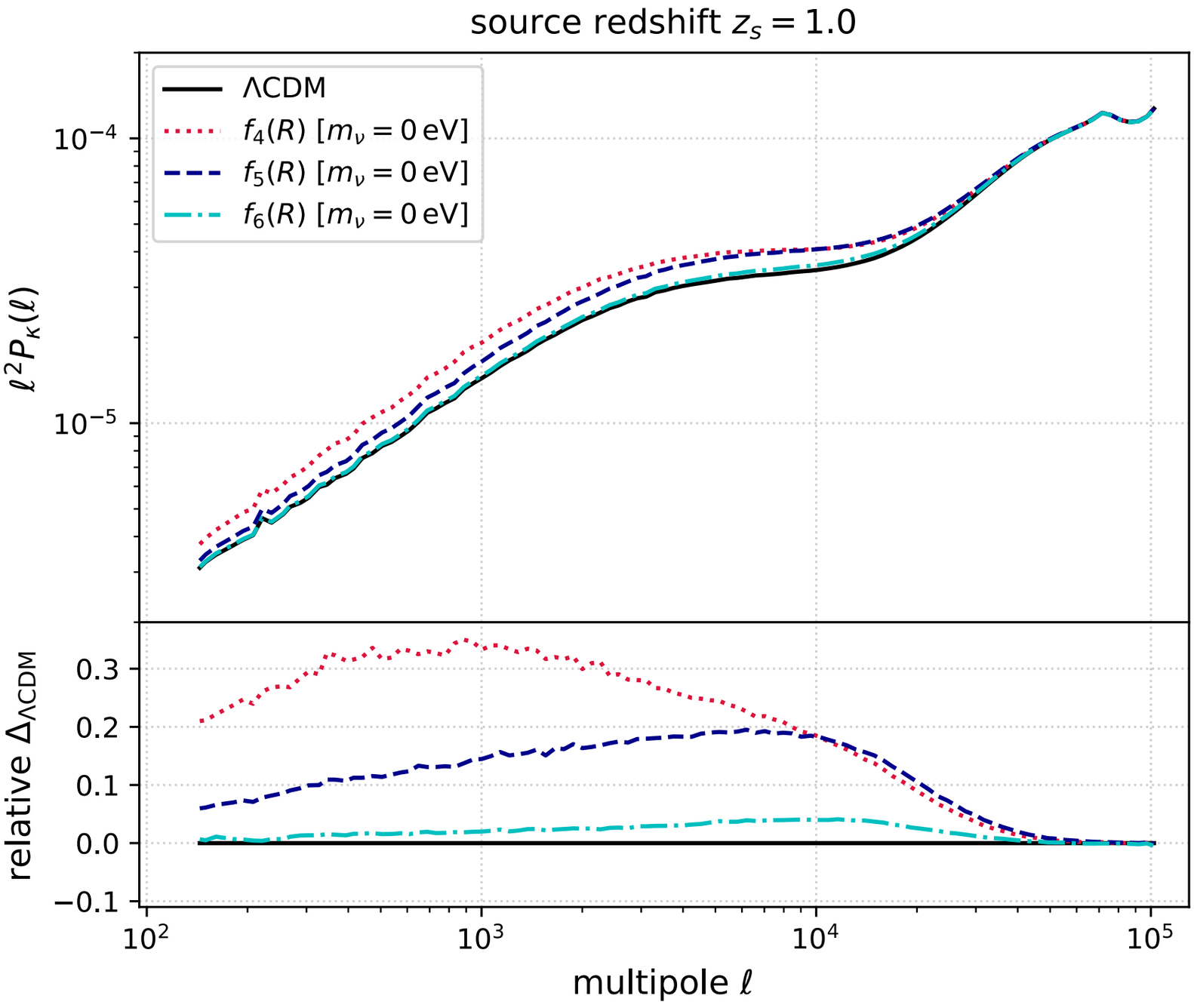
Jean-Luc Starck – CosmoStat / CEA Saclay
Marco Baldi – DIFA Università di Bologna

Reference

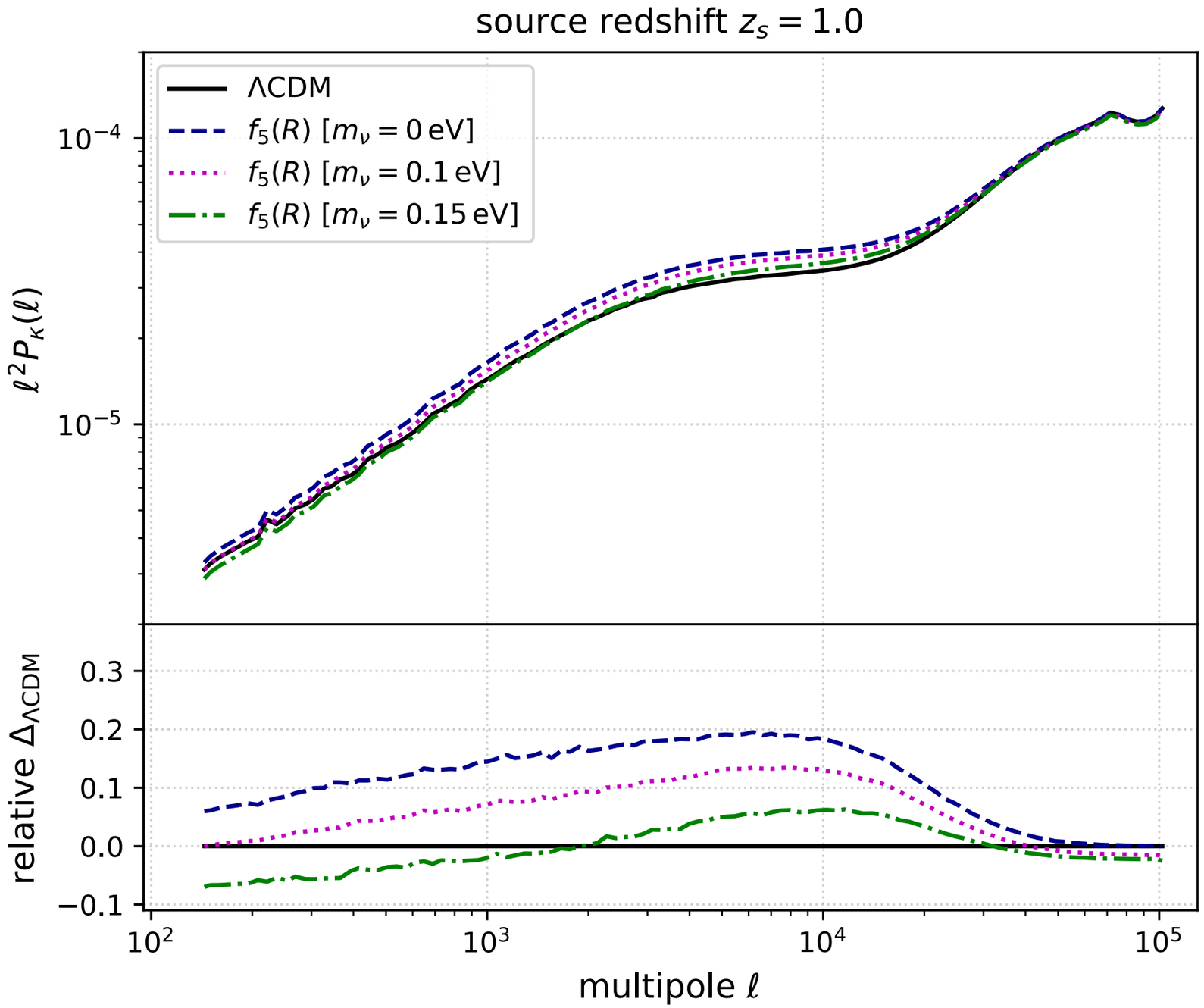
A. Peel et al., submitted to A&A (2018) [arXiv:1805.05146]

Extras

Weak-lensing convergence power spectra (varying f_{R0})



Weak-lensing convergence power spectra (varying m_ν)

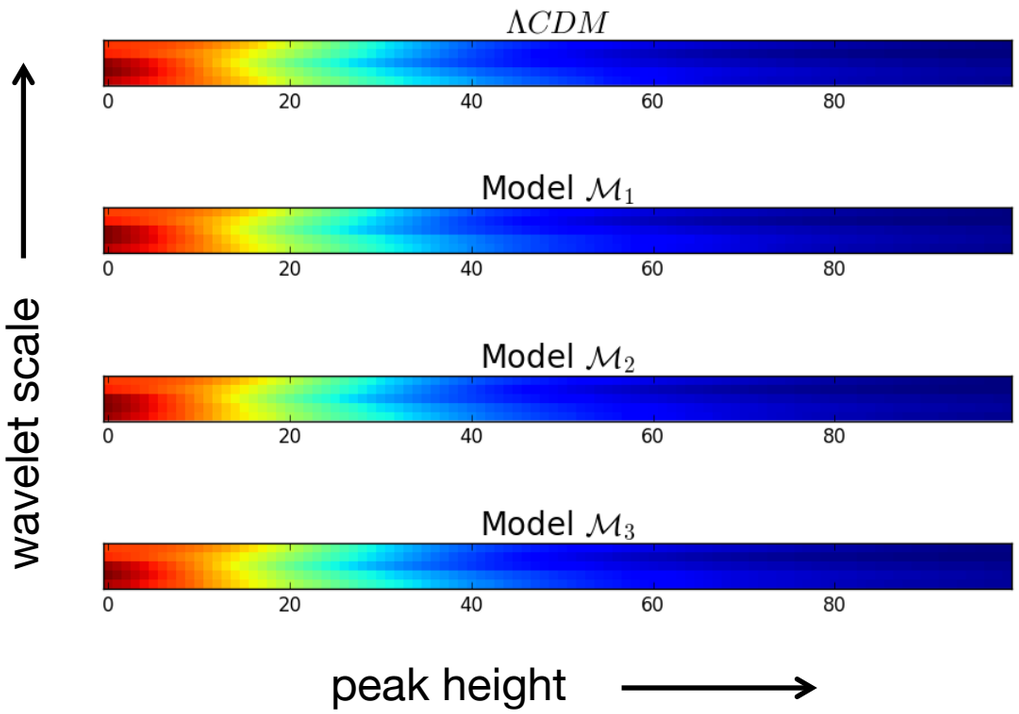


An alternative approach : Machine Learning

PRELIMINARY

(results of Florian Lalande)

New (combined) data representation



Higher source redshifts yield greater model discrimination power.

Model prediction

Truth

	ΛCDM	MG_1	MG_2	MG_3
ΛCDM	0.999	0.000	0.000	0.001
MG_1	0.000	0.695	0.279	0.026
MG_2	0.000	0.324	0.510	0.166
MG_3	0.004	0.012	0.179	0.805

$z_s = 1.0$

Truth

	ΛCDM	MG_1	MG_2	MG_3
ΛCDM	0.999	0.000	0.000	0.001
MG_1	0.000	0.780	0.215	0.005
MG_2	0.000	0.317	0.581	0.102
MG_3	0.002	0.004	0.095	0.899

$z_s = 2.0$

Comparison for $z_s = 2.0$

PRELIMINARY

(results of Florian Lalande)

Machine Learning

Truth	ΛCDM	MG_1	MG_2	MG_3
ΛCDM	0.999	0.000	0.000	0.001
MG_1	0.000	0.780	0.215	0.005
MG_2	0.000	0.317	0.581	0.102
MG_3	0.002	0.004	0.095	0.899

VS

False Discovery Rate (best case)

Truth	ΛCDM	MG_1	MG_2	MG_3
ΛCDM	1.000	0.000	0.000	0.000
MG_1	0.000	0.487	0.418	0.094
MG_2	0.000	0.341	0.436	0.223
MG_3	0.000	0.088	0.249	0.662

combined $z_s = (0.5, 1.0, 1.5, 2.0)$

Machine Learning

Truth	ΛCDM	MG_1	MG_2	MG_3
ΛCDM	0.999	0.000	0.000	0.001
MG_1	0.000	0.757	0.241	0.001
MG_2	0.000	0.215	0.696	0.089
MG_3	0.000	0.000	0.074	0.925

Using 3D information by combining redshifts performs even better.

Distinguishing MG from GR using WL