A new vocabulary for textures

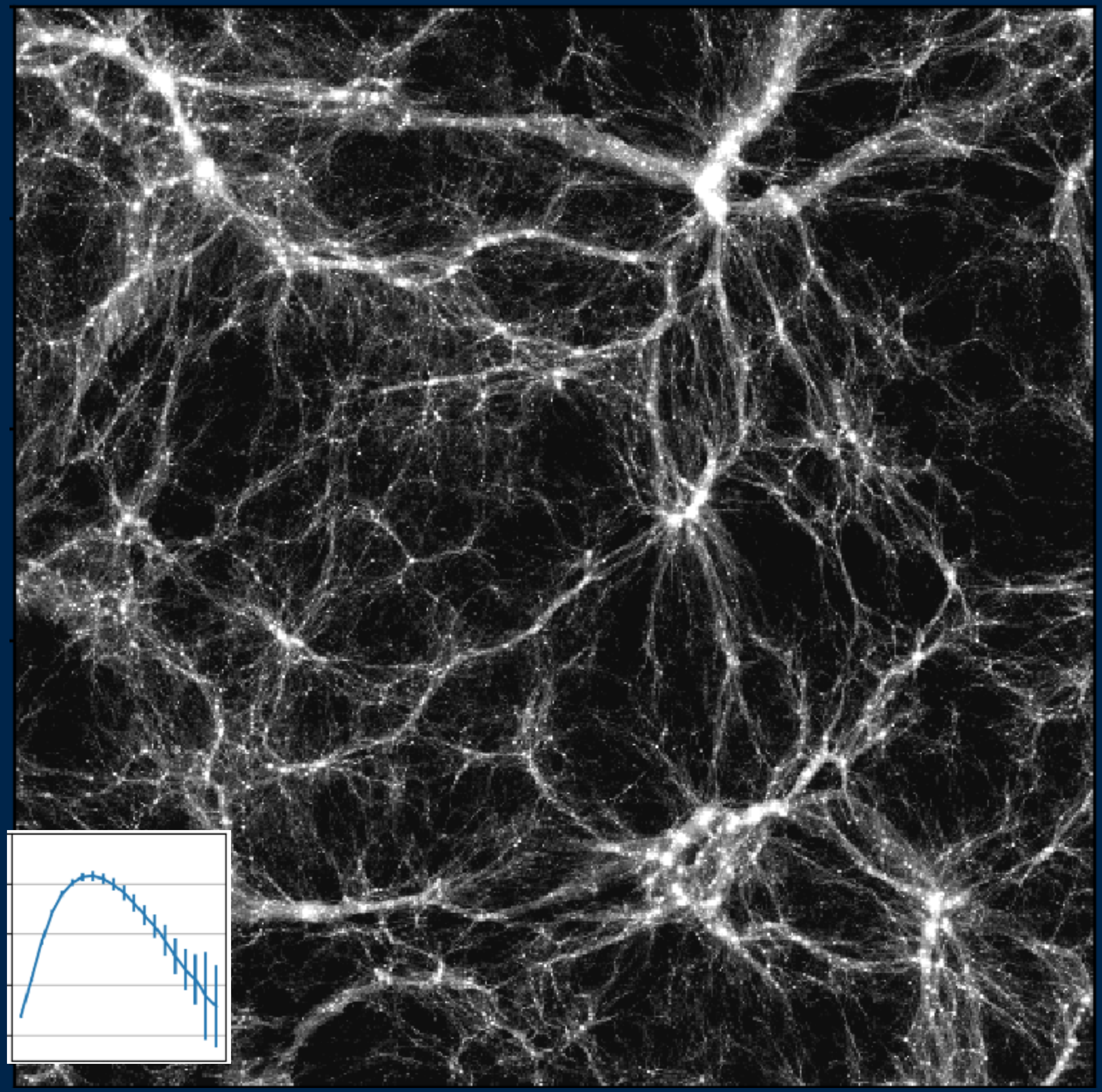
and its cosmological applications

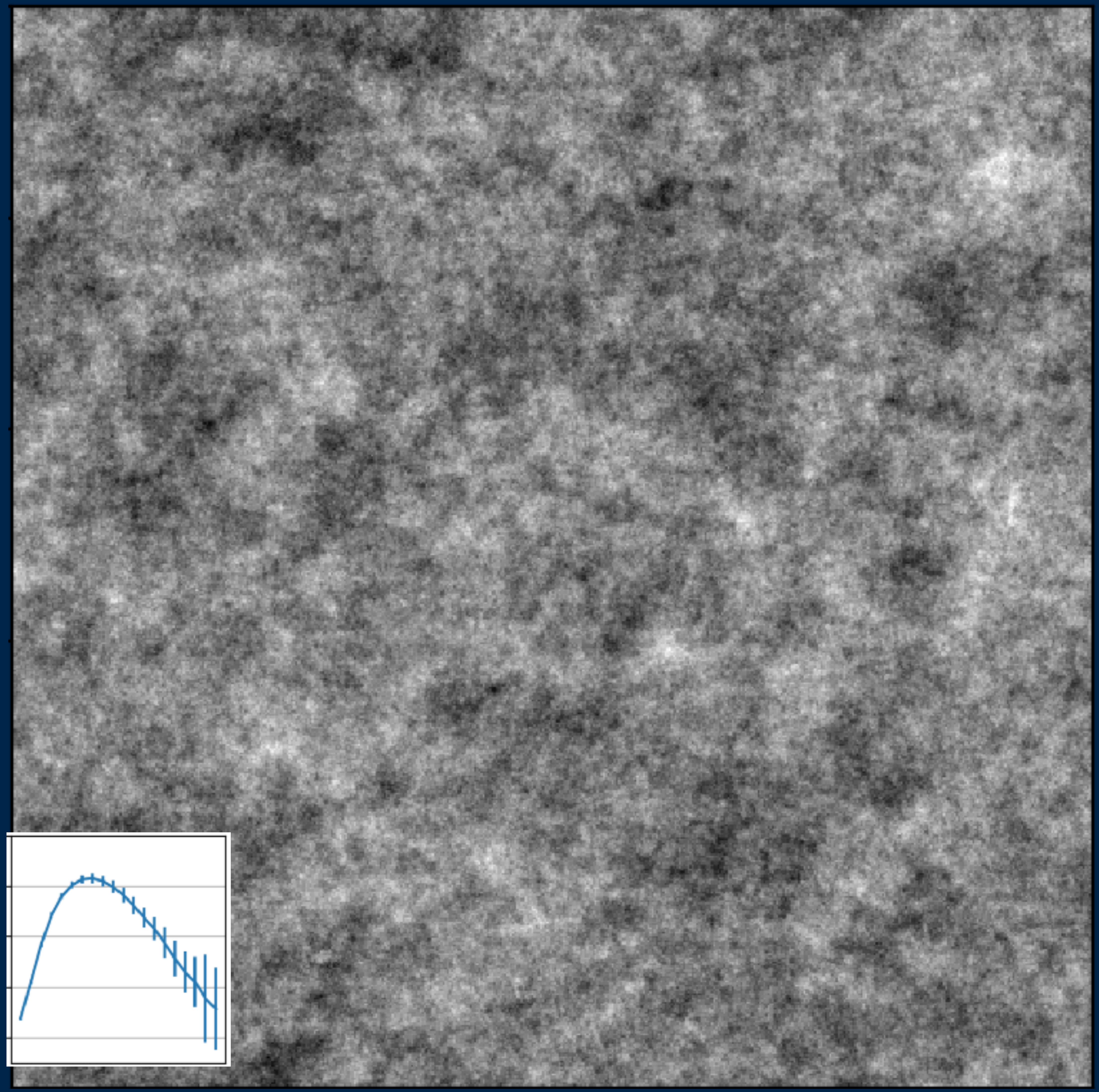
Sihao Cheng (程思浩)
Johns Hopkins University

arXiv: 2006.08561
arXiv: 2103.09247

GCCL seminar
May 21th, 2021

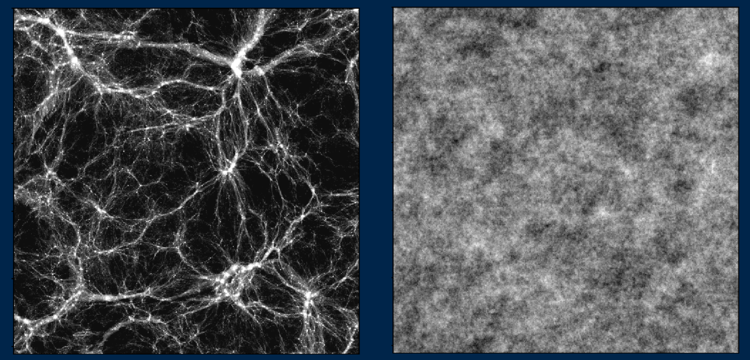
with Brice Ménard, Yuan-Sen Ting, & Joan Bruna





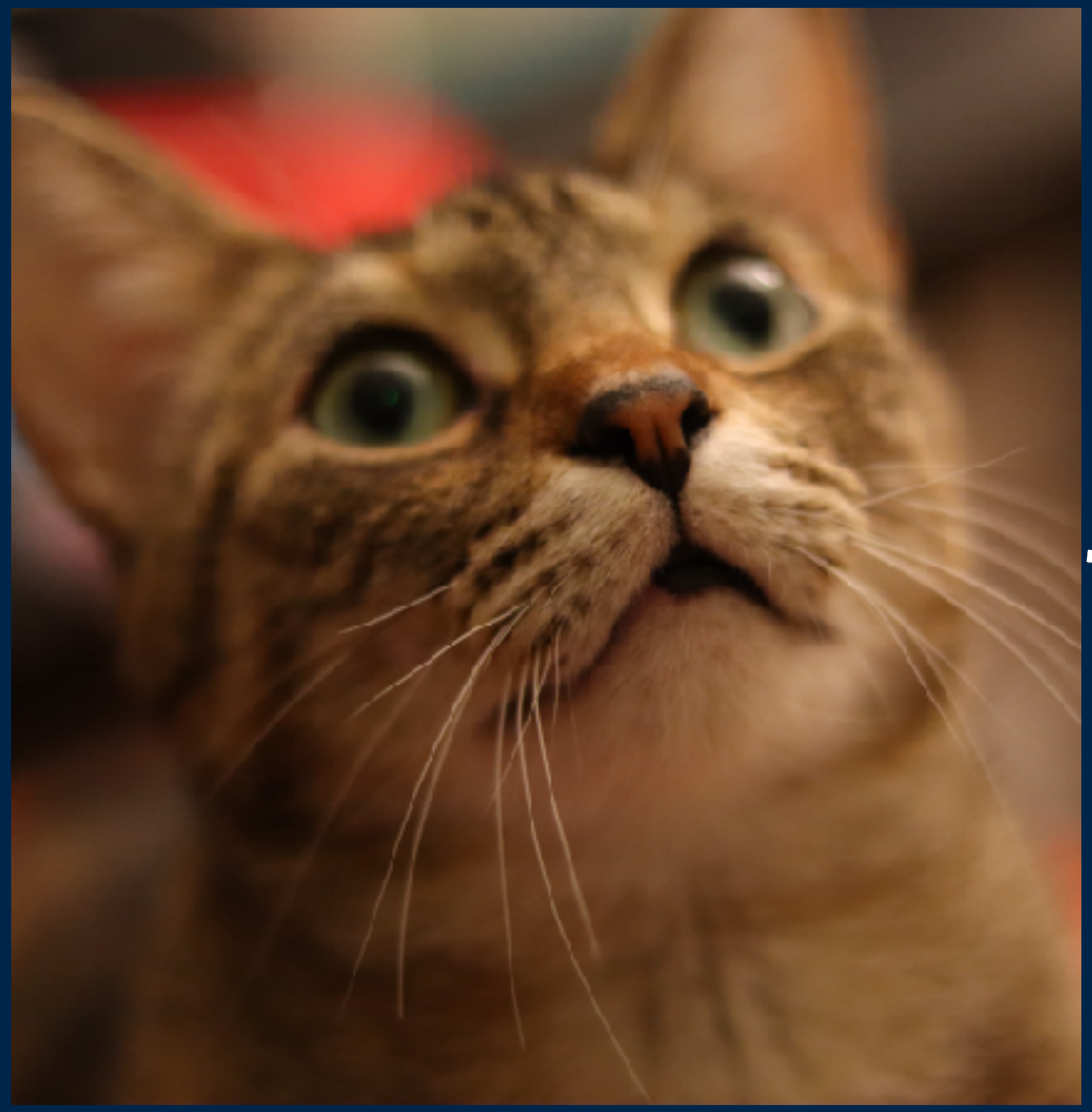
We need to go beyond $P(k)$ to capture non-Gaussianity.

How do we characterize a field?



power spectrum

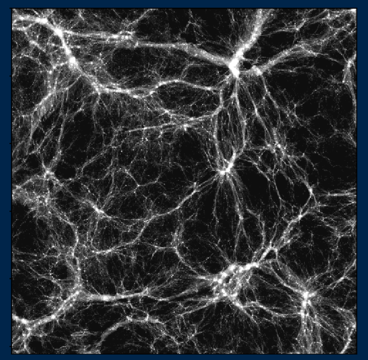
and others

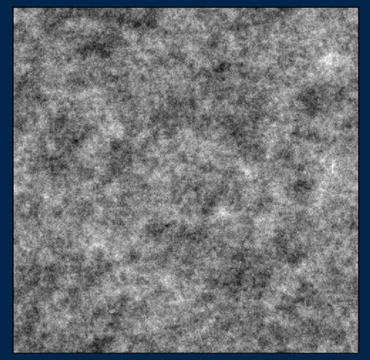


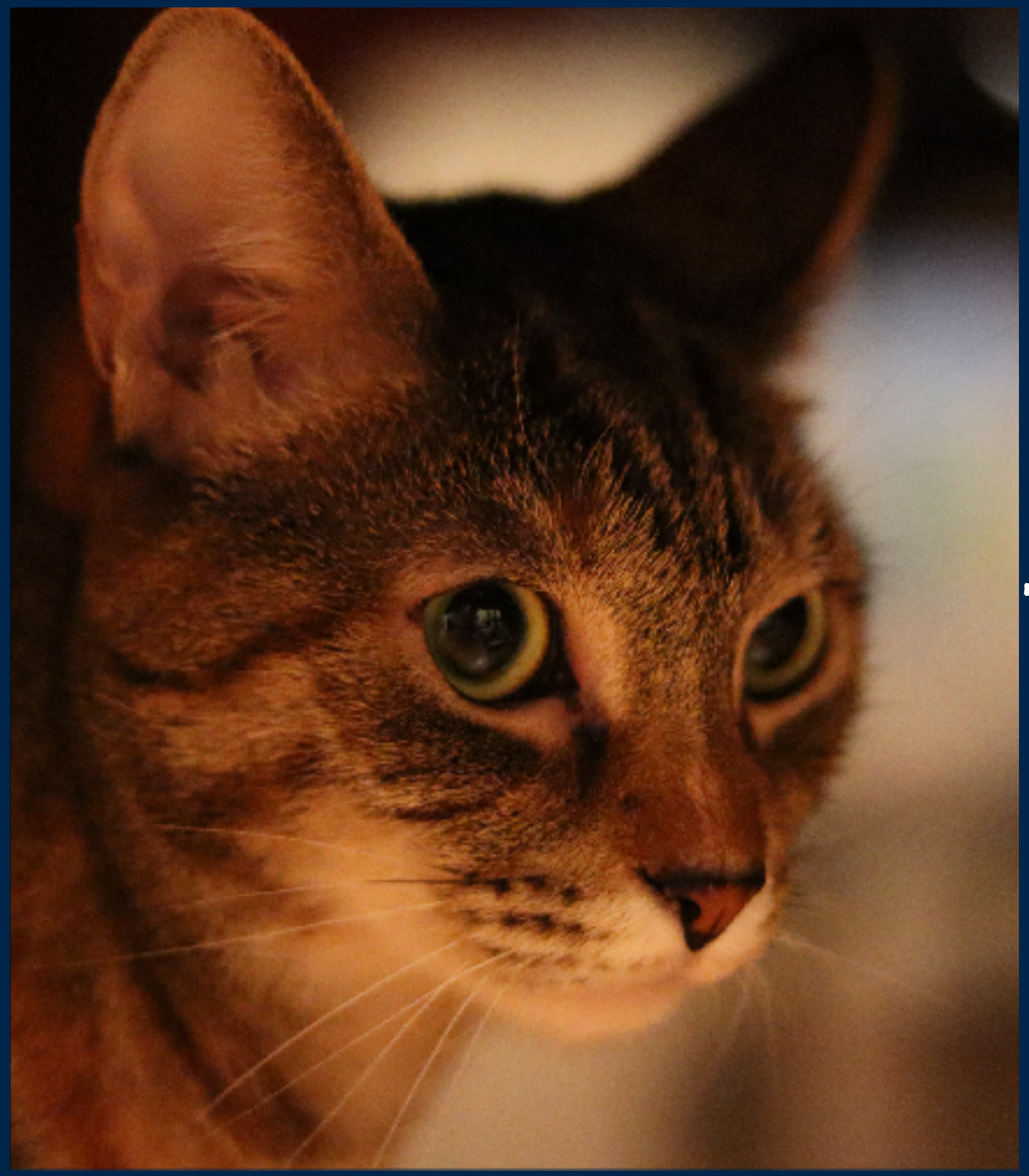
CNN

physical parameters

How do we characterize a field?







power spectrum

and others

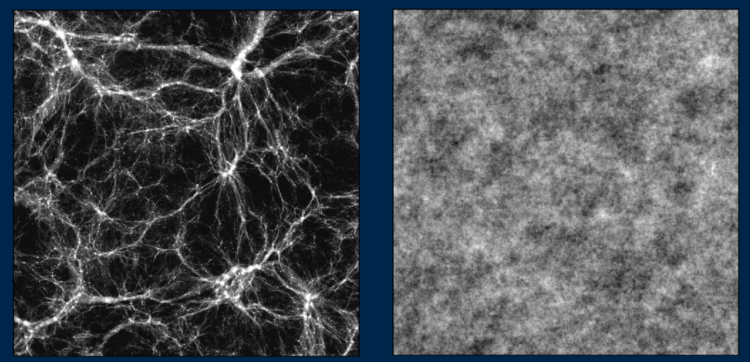
CNN

powerful,

but less interpretable or controllable

physical parameters

How do we characterize a field?



power spectrum

and others

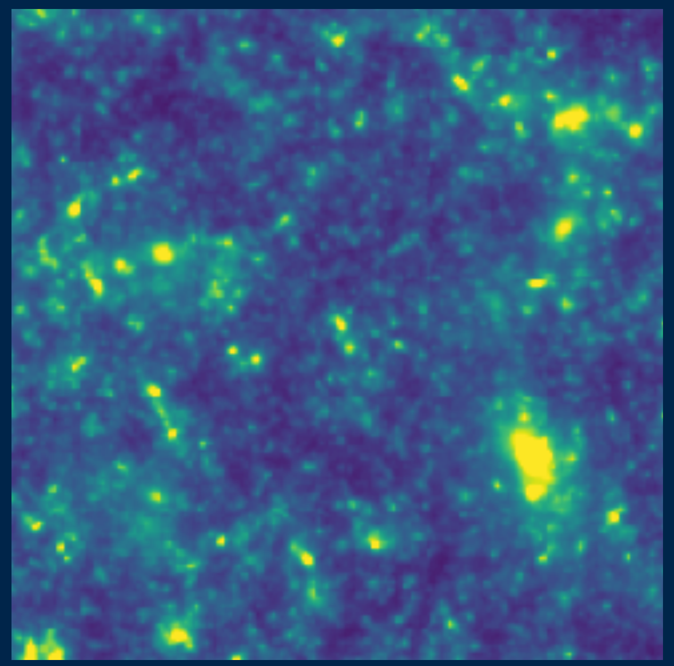
scattering transform

(Mallat 2012)

CNN

powerful,
but less interpretable or controllable

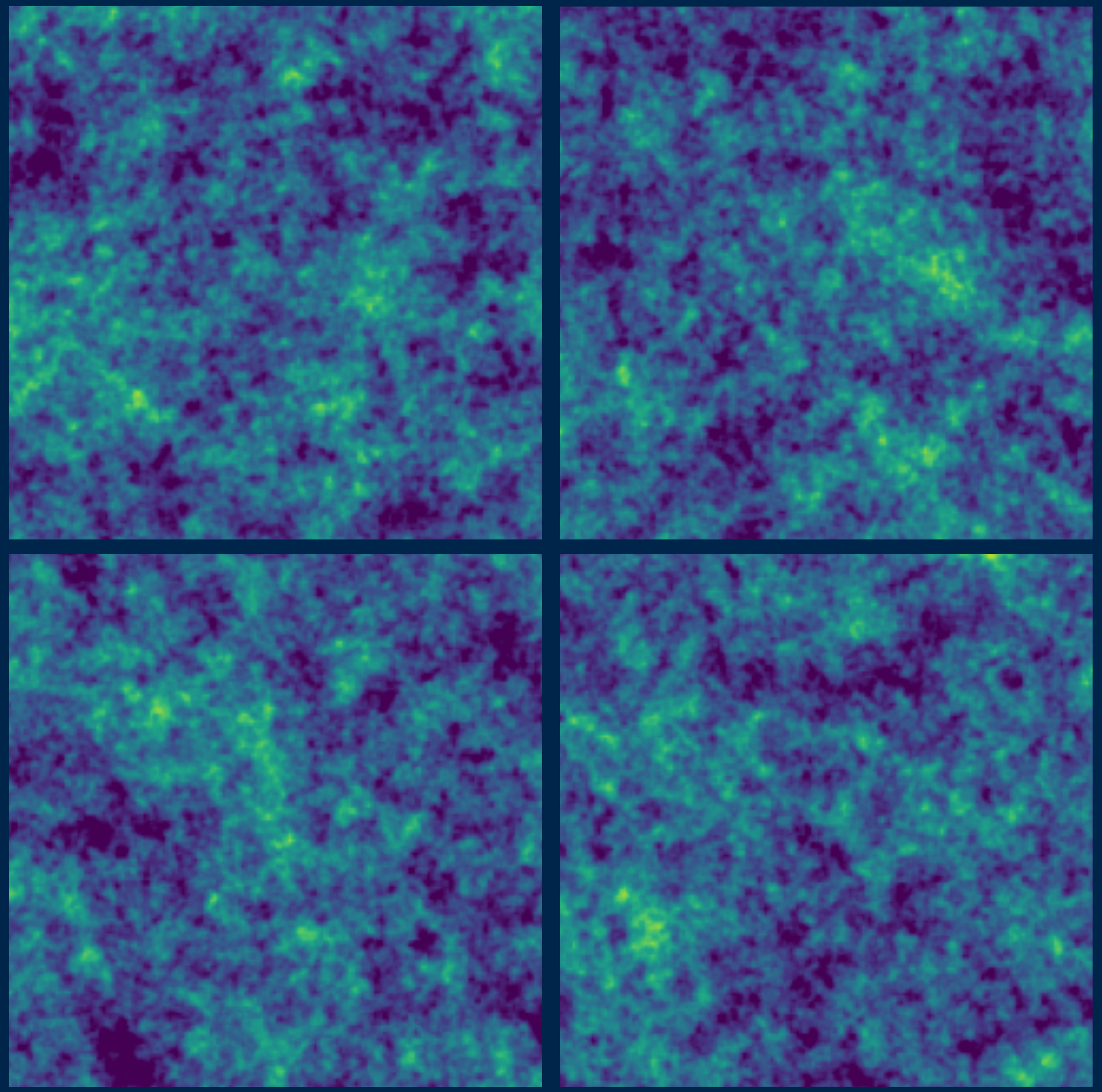
physical parameters



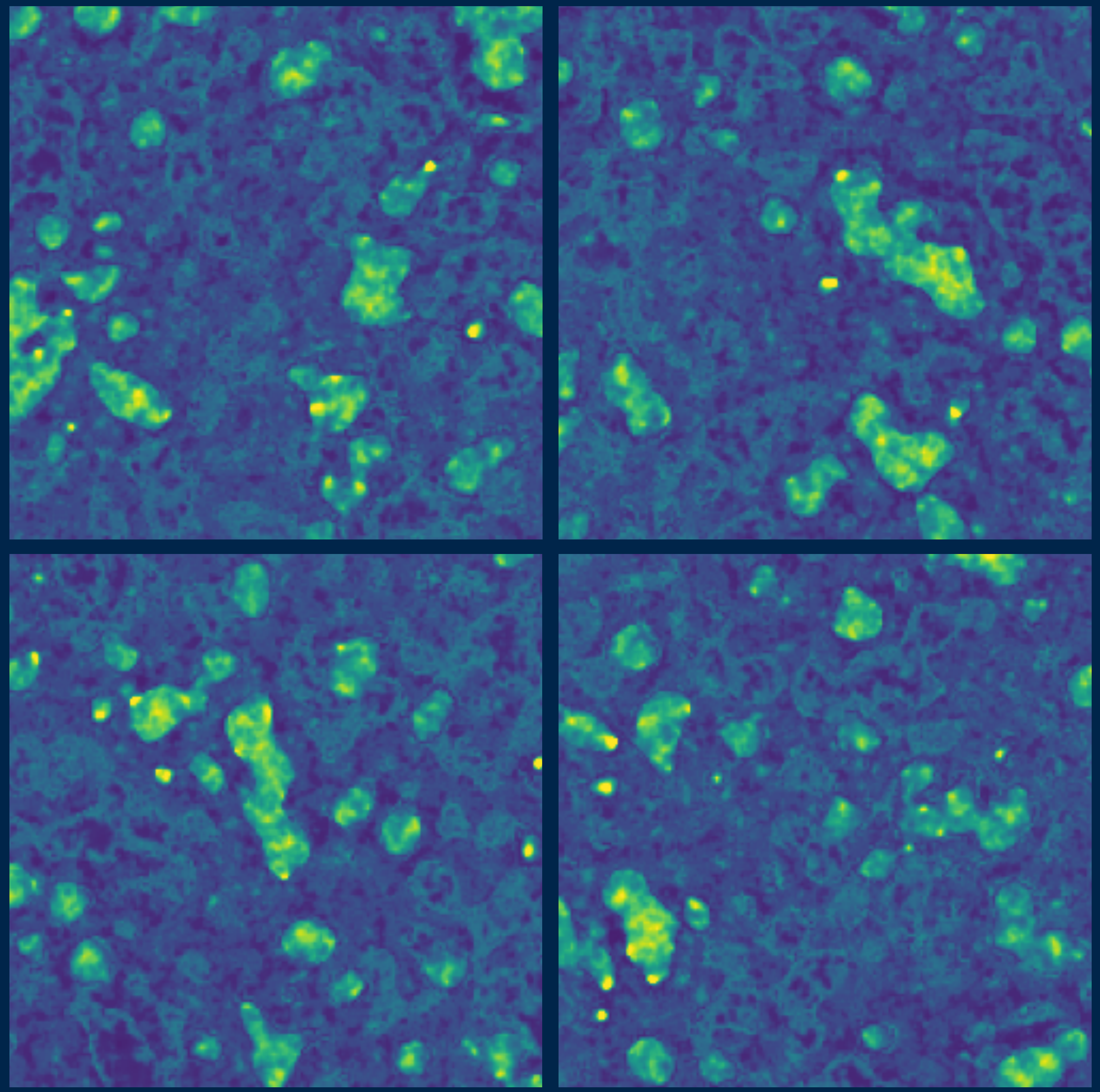
lensing mass map

~ 50 numbers

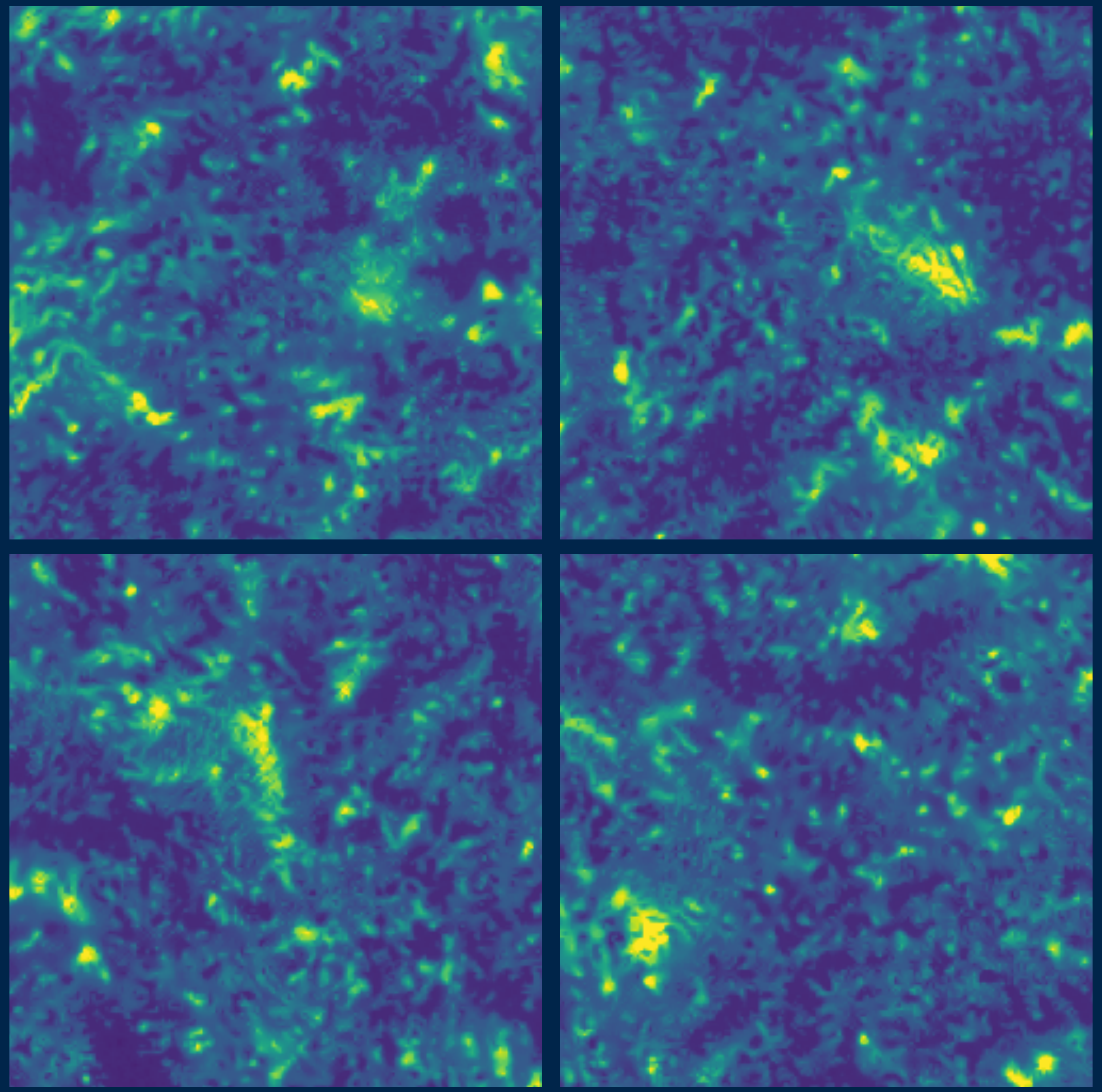
with power spectrum P(l)



with P(l) and bispectrum

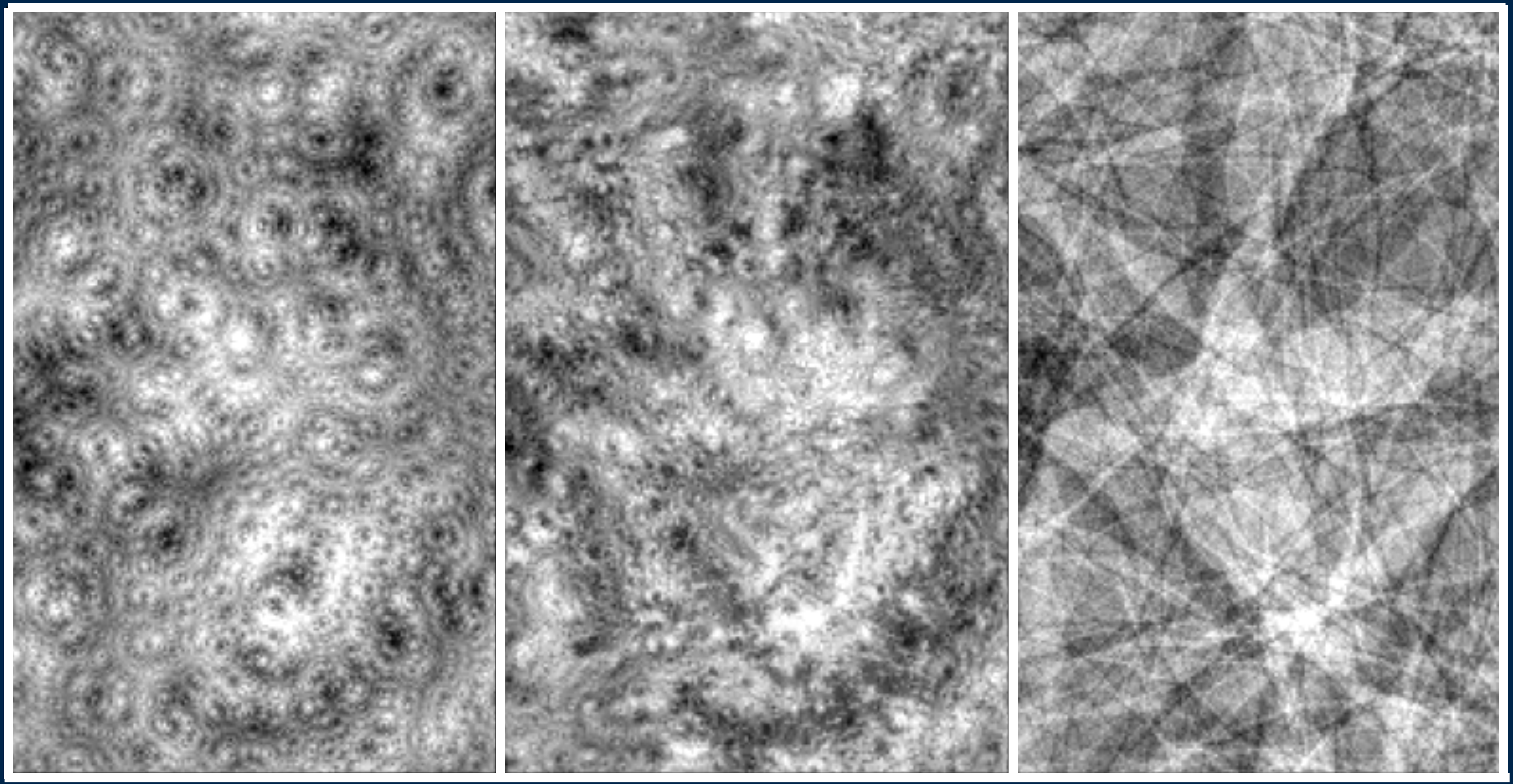


with scattering statistics

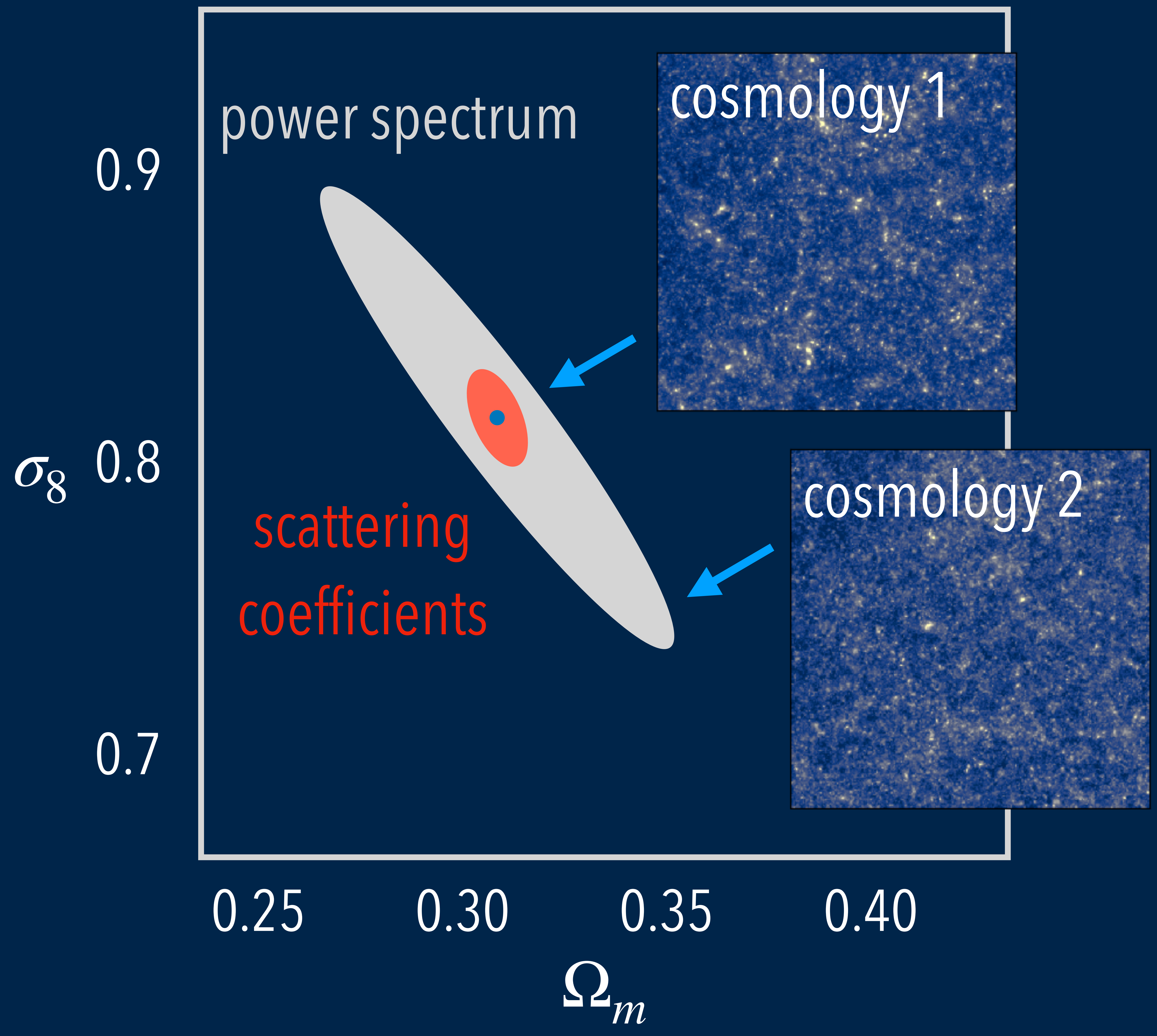


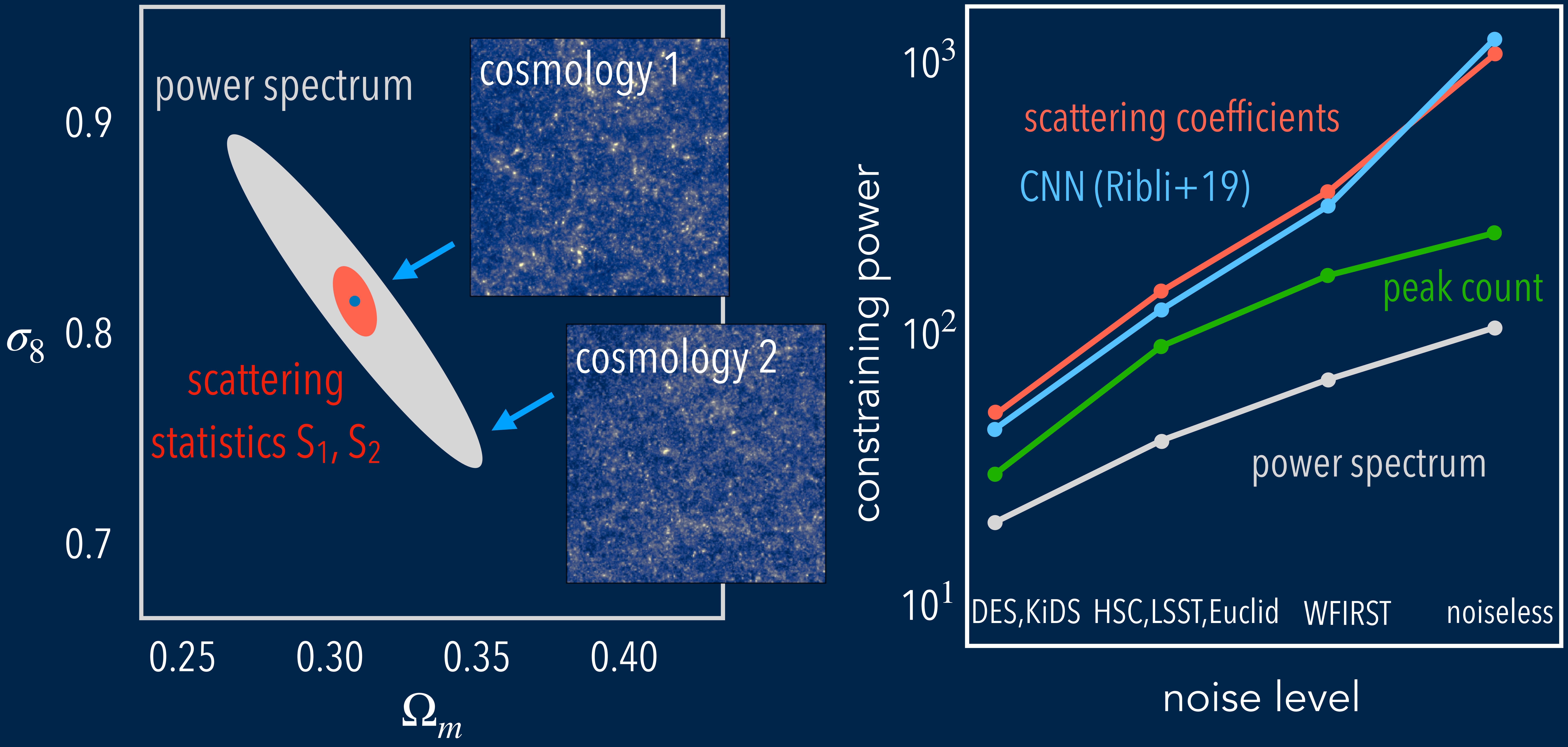

Turing pattern
Ising model
sea temperature
solar UV image
lensing map

Swirls vs. Origami $S_2^{\|}/S_2^{\perp}$

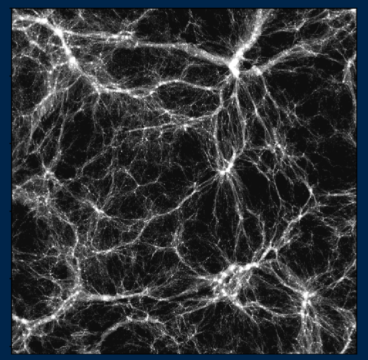
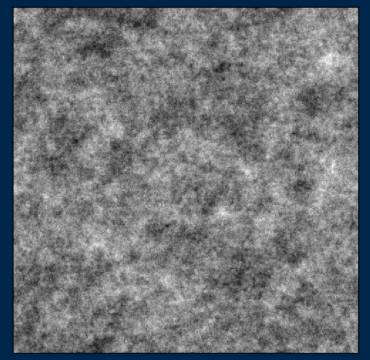


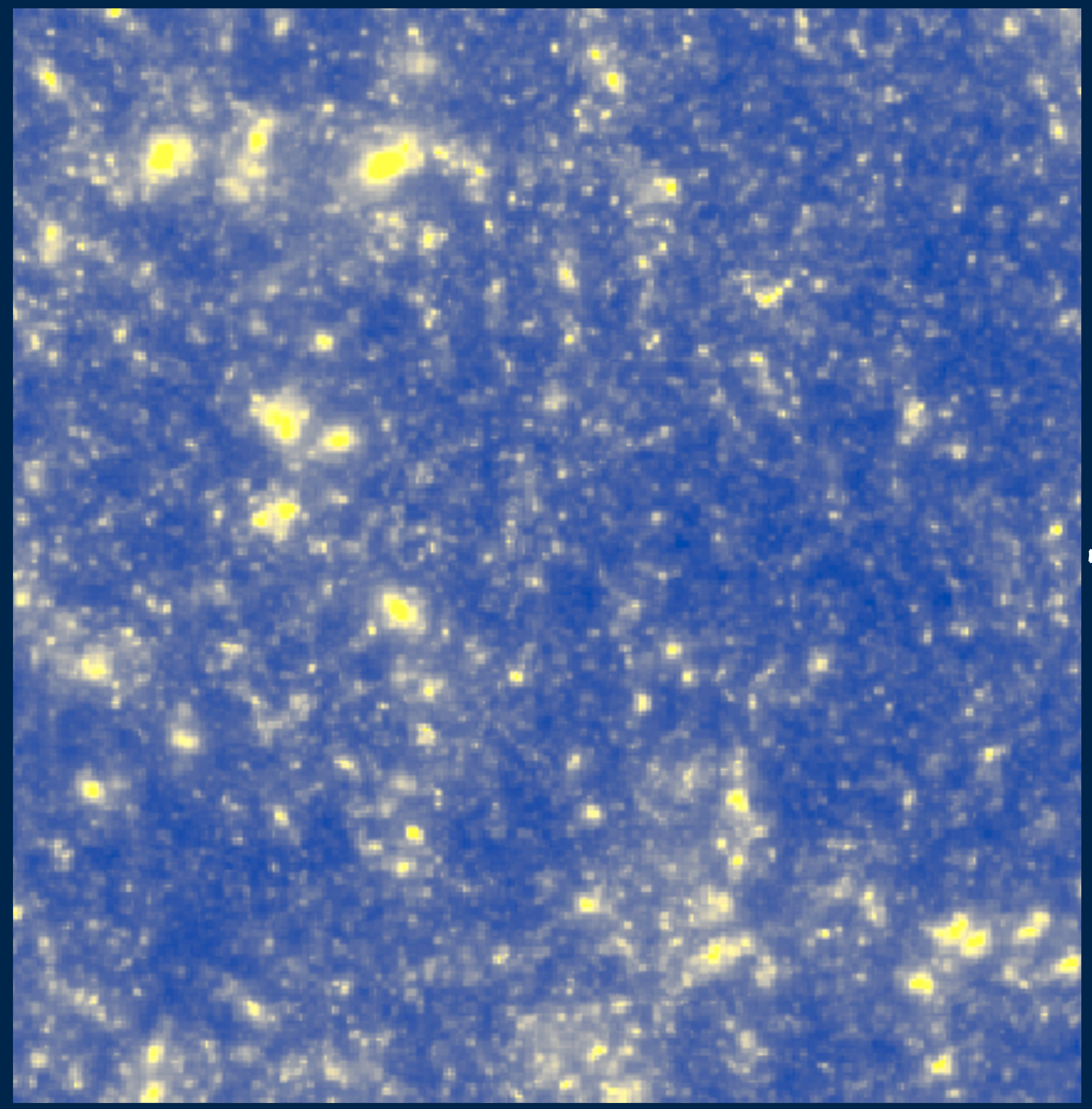
<1 $=1$ >1


power spectrum
cosmology 1
cosmology 2
scattering
coefficients
0.9
0.8
0.7
σ_8
0.25
0.30
0.35
0.40
Ω_m


power spectrum
cosmology 1
cosmology 2
scattering
statistics S1, S2
0.9
0.8
0.7
σ8
0.25
0.30
0.35
0.40
Ωm
scattering coefficients
CNN (Ribli+19)
peak count
power spectrum
constraining power
10^3
10^2
10^1
DES,KiDS
HSC,LSST,Euclid
WFIRST
noiseless
noise level

How do we characterize a field?





power spectrum

and others

scattering transform

(Mallat 2012)

CNN

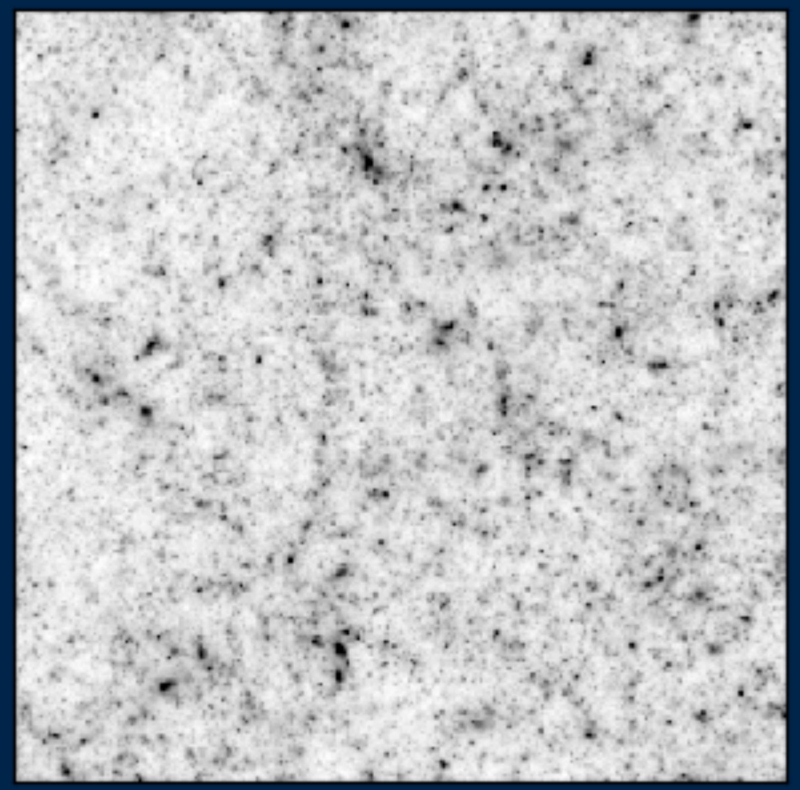
physical parameters

Fourier oscillations

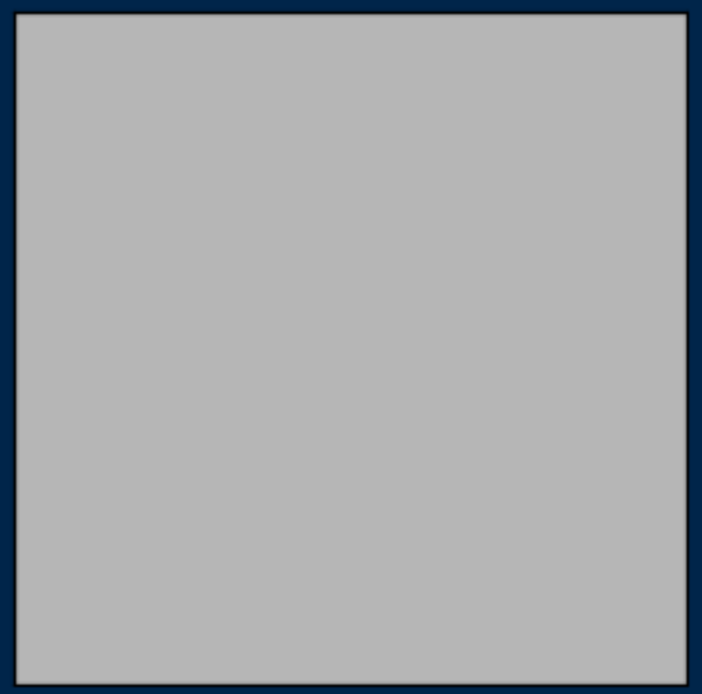
$$P(\overrightarrow{k}) = \langle \left| I \star e^{ik\cdot x} \right|^2 \rangle$$

local kernels (wavelets)

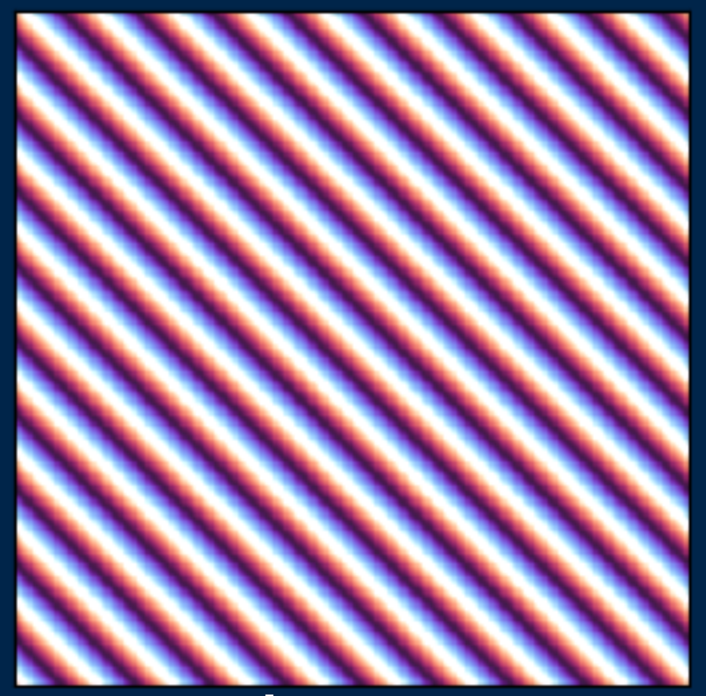
$$S(\overrightarrow{k}) = \langle \left| I \star \psi_k \right| \rangle$$



convolution

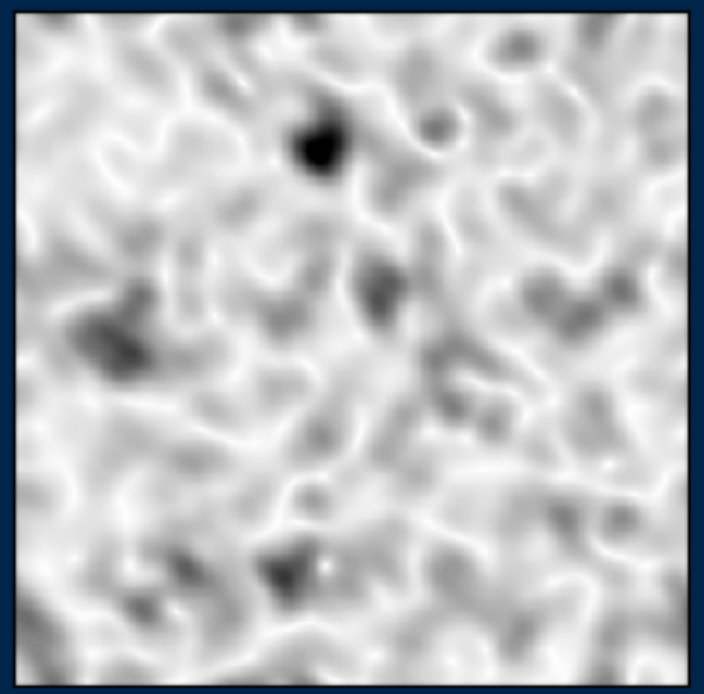


modulus

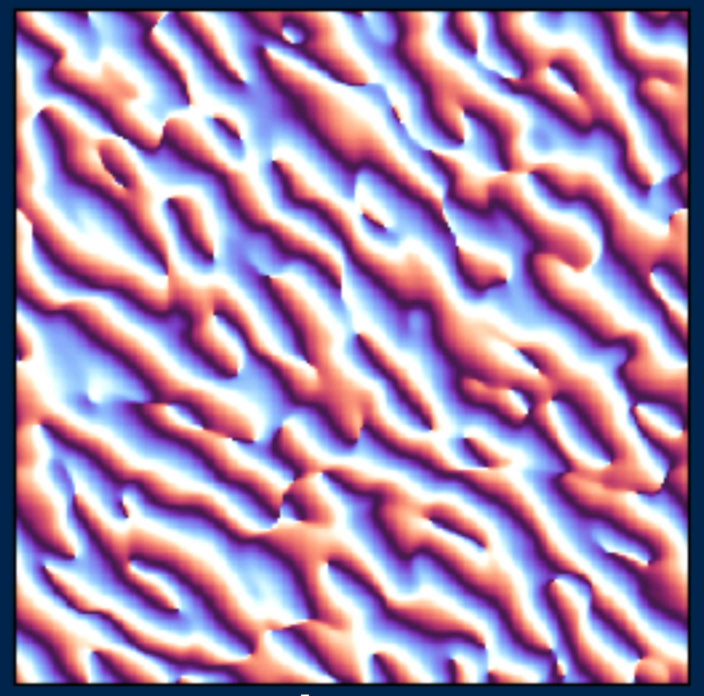


phase

convolution



modulus



phase

Fourier oscillations

$$P(\overrightarrow{k}) = \langle \left| I \star e^{ik\cdot x} \right|^2 \rangle$$

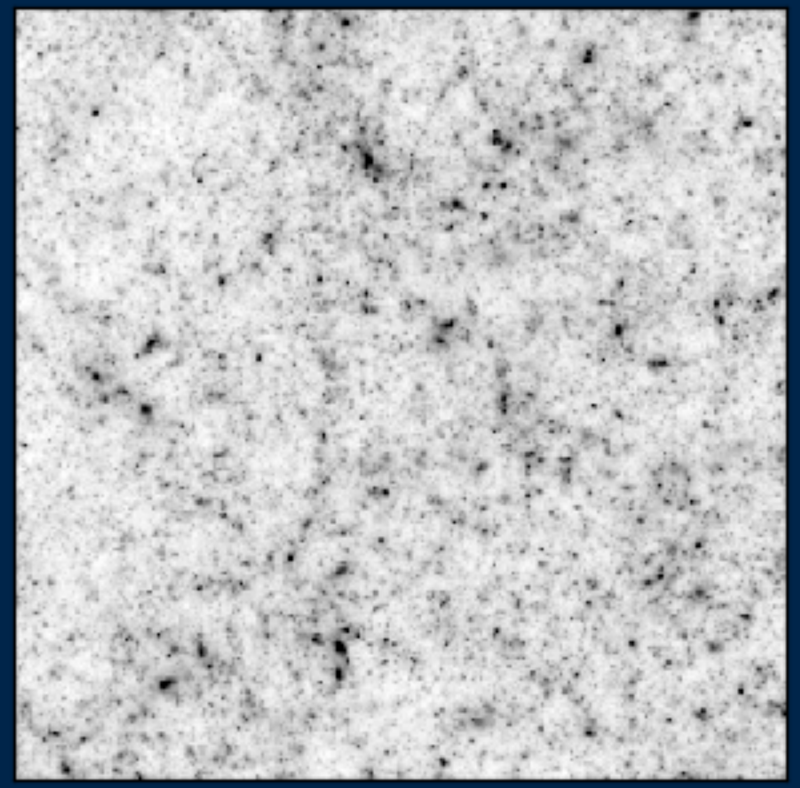
local kernels (wavelets)

$$S_0 = \langle I \rangle$$

$$S_1(\overrightarrow{k}) = \langle \left| I \star \psi_k \right| \rangle$$

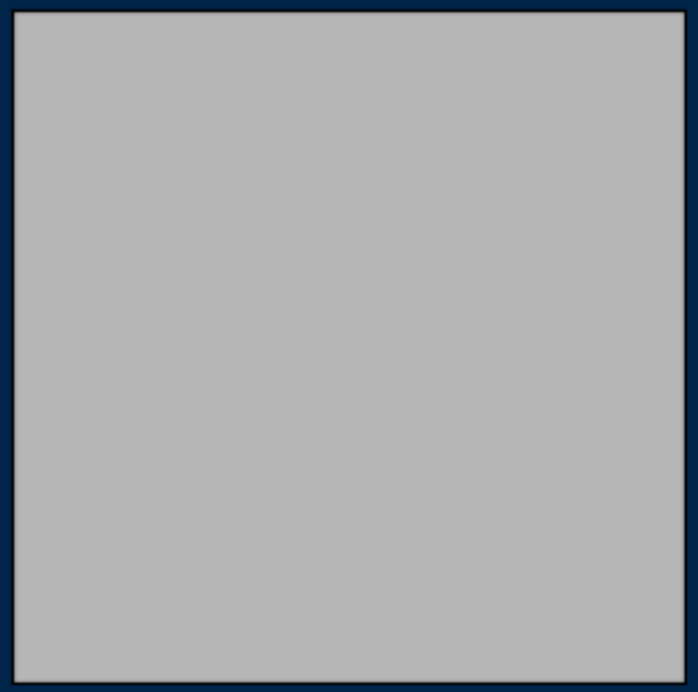
$$S_2(\overrightarrow{k_1}, \overrightarrow{k_2}) = \langle \left| \, |I \star \psi_{k_1}| \star \psi_{k_2} \right| \rangle$$

$$\dots$$

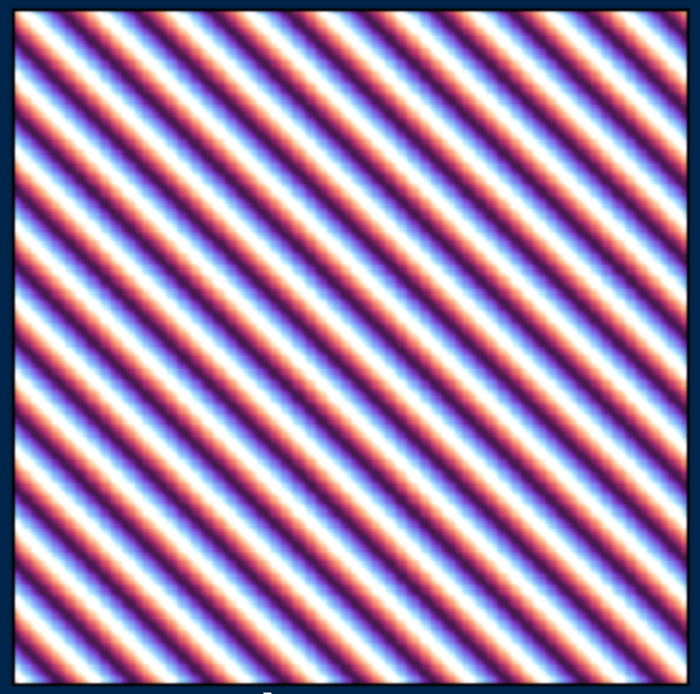


convolution

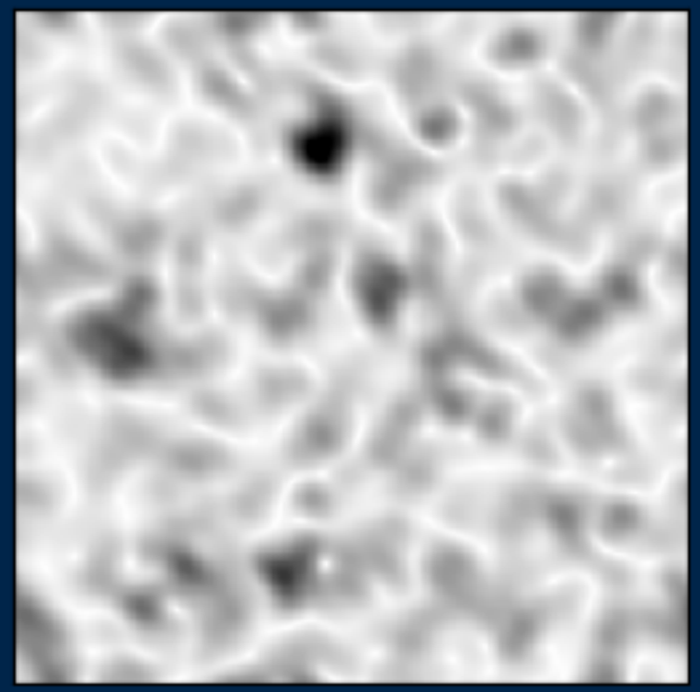
convolution



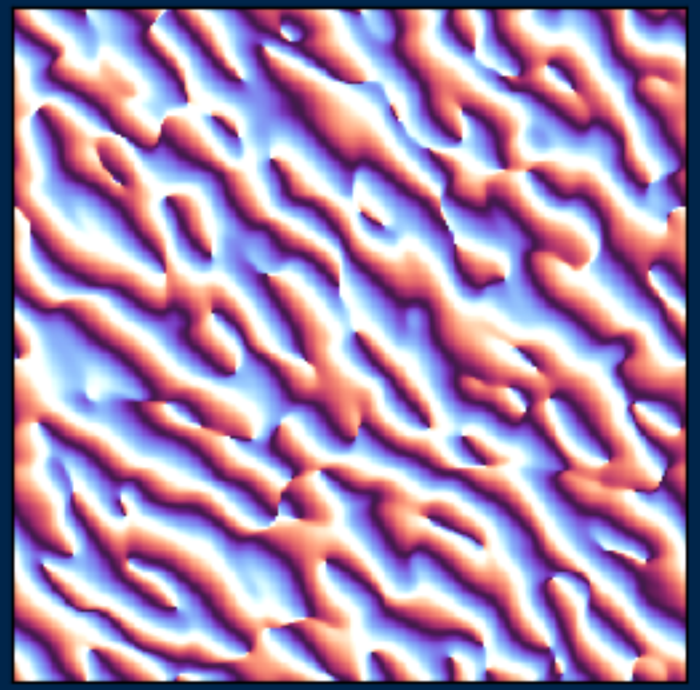
modulus



phase



modulus



phase

local kernels (wavelets)

$$S_0 = \langle I \rangle$$

$$S_1(\vec{k}) = \langle \left| I \star \psi_k \right| \rangle$$

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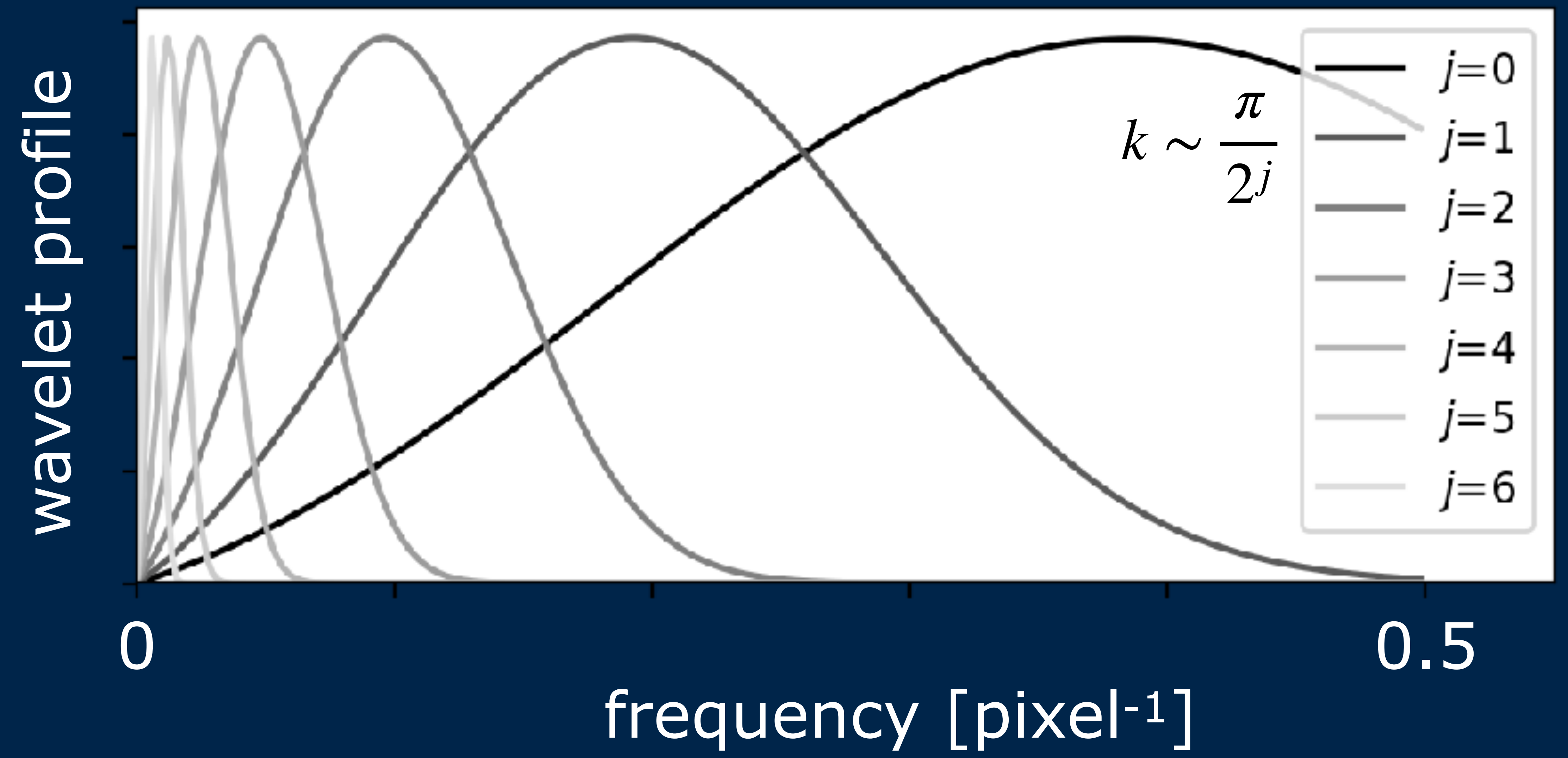
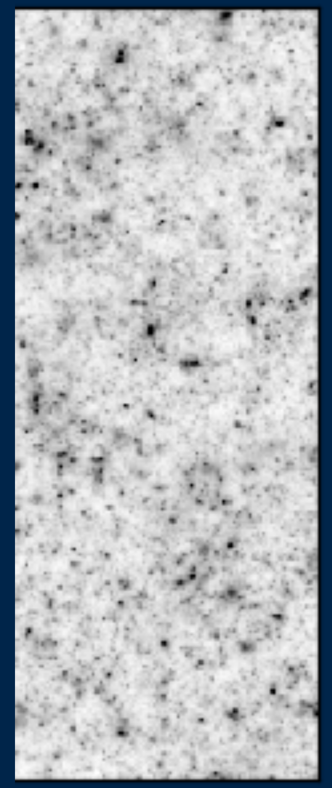
$$\cdots$$

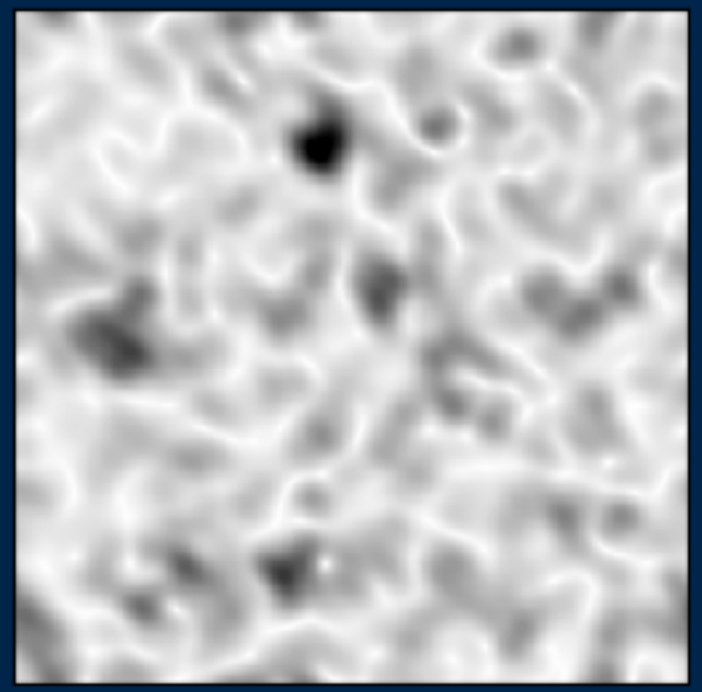
real space

Fourier space

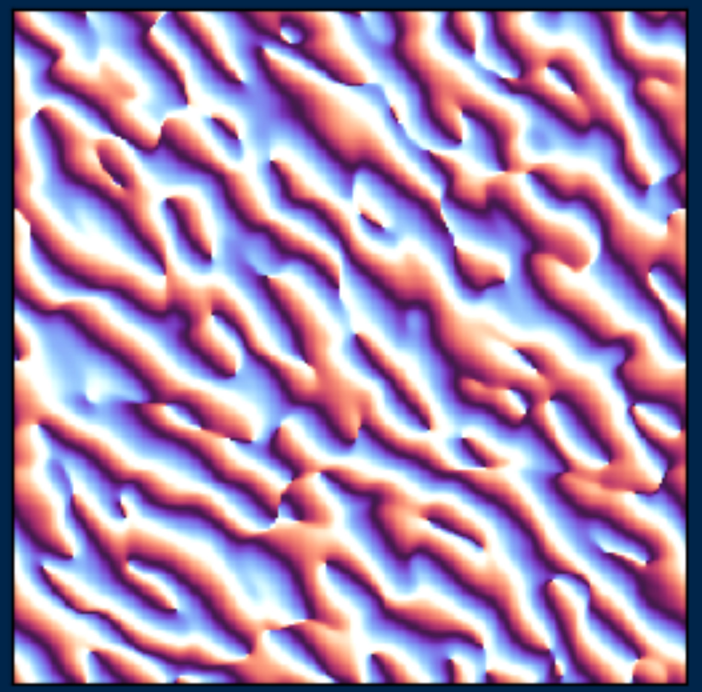




convolution

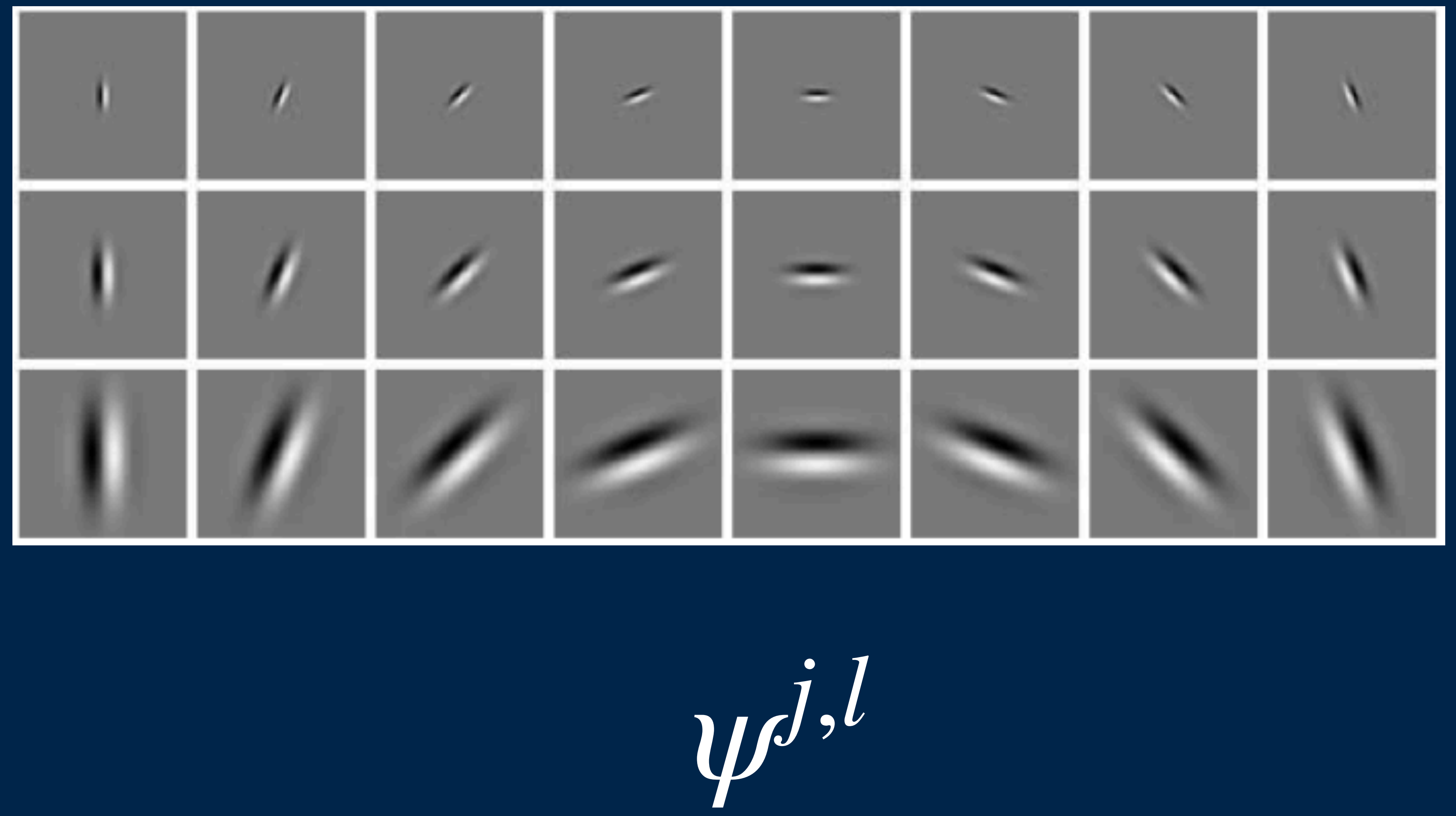


modulus



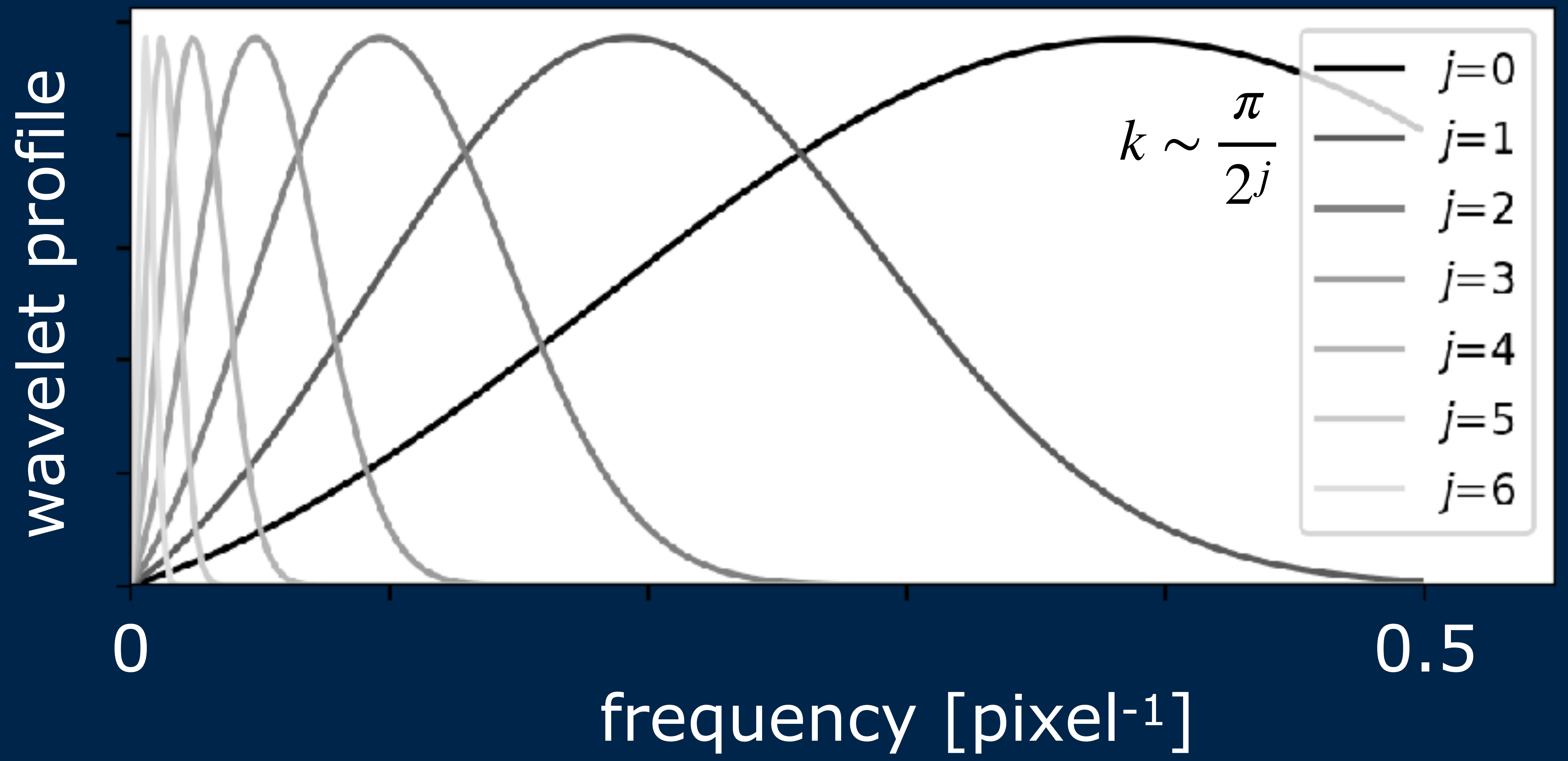
phase

wavelets



j: scales

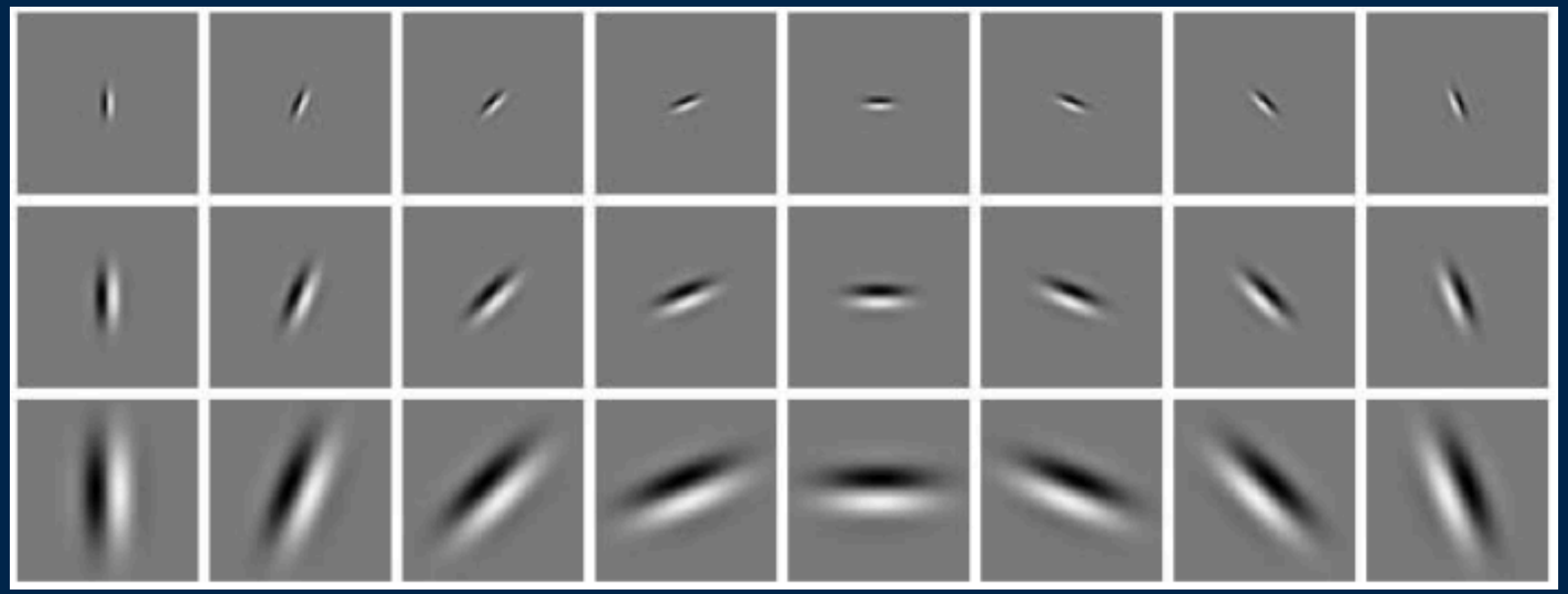
l: directions



close to Gabor wavelets

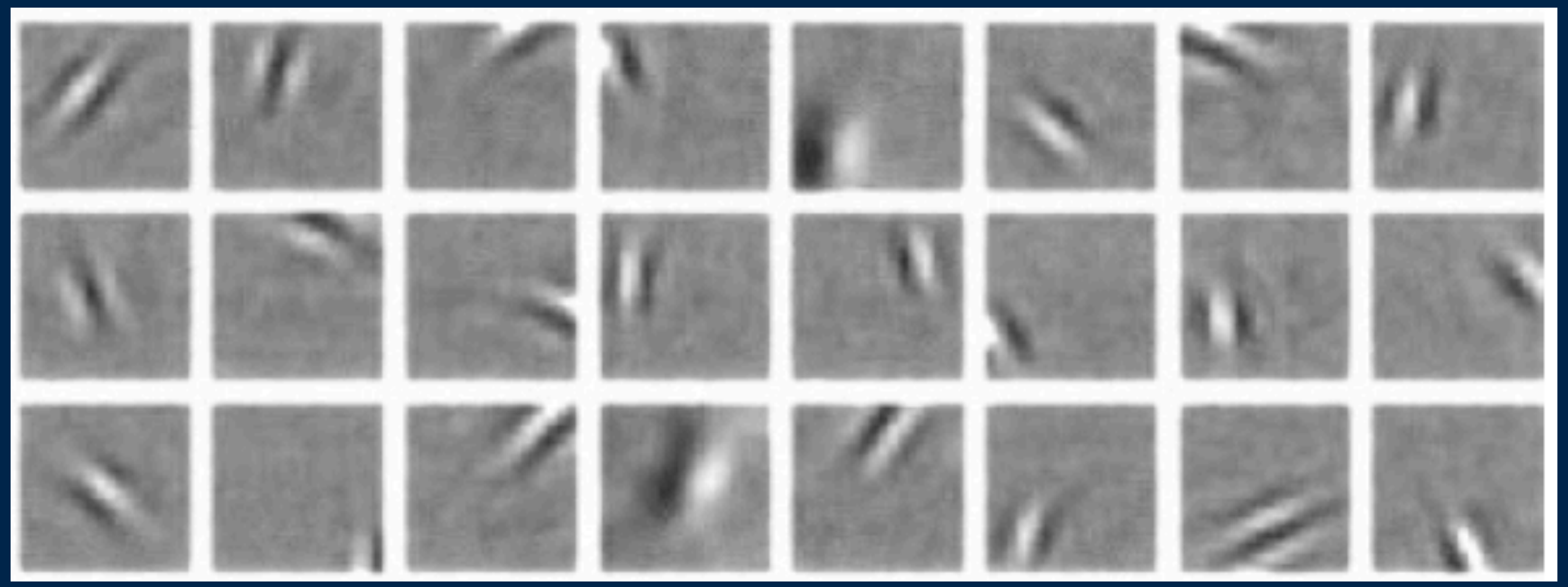
receptive fields of mammal vision

(Hubel & Wiesel 1968)



sparse representation of natural images

(Olshausen & Field 1996)



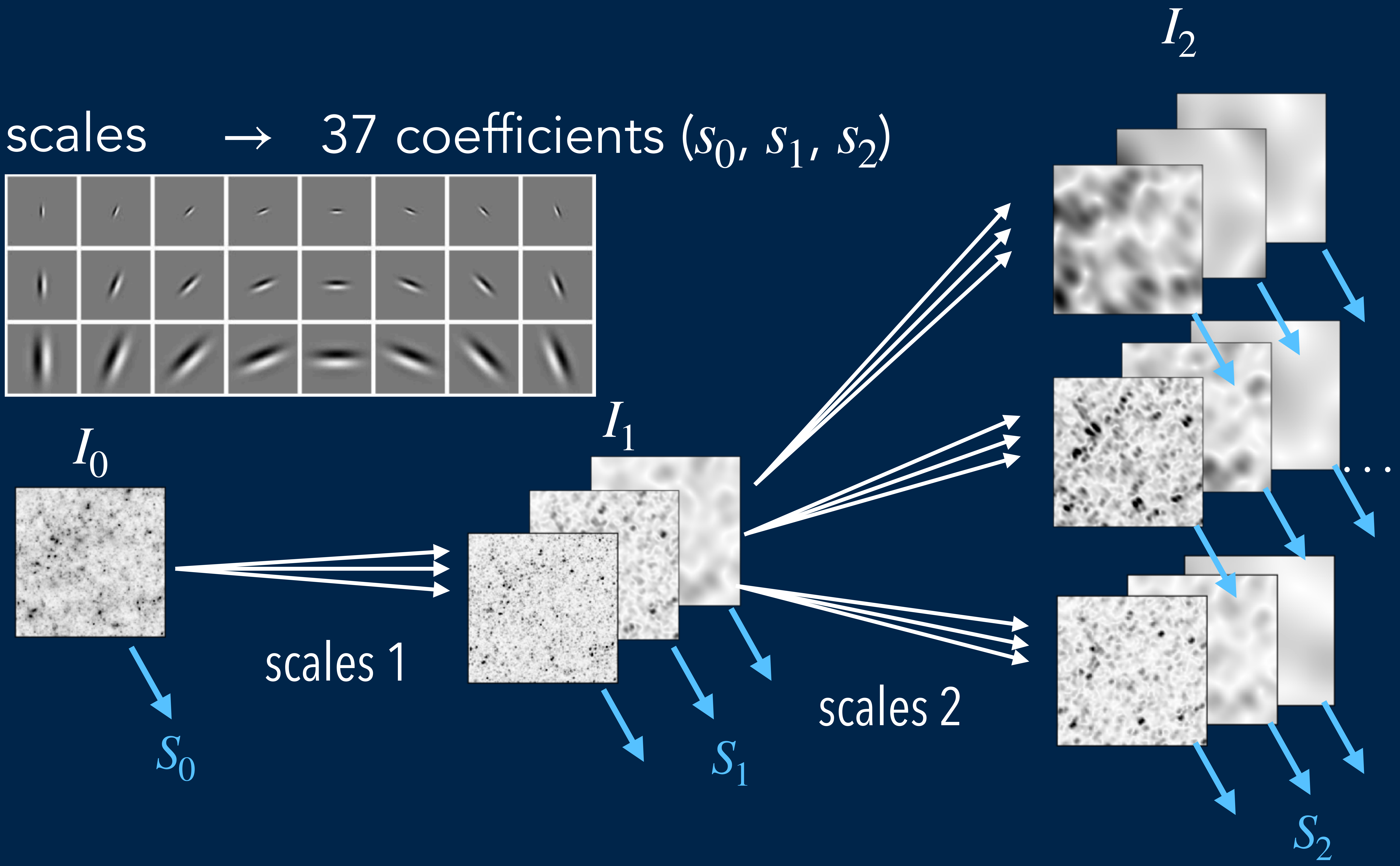
kernels learned in AlexNet

(Krizhevsky, Sutskever, & Hinton 2012)

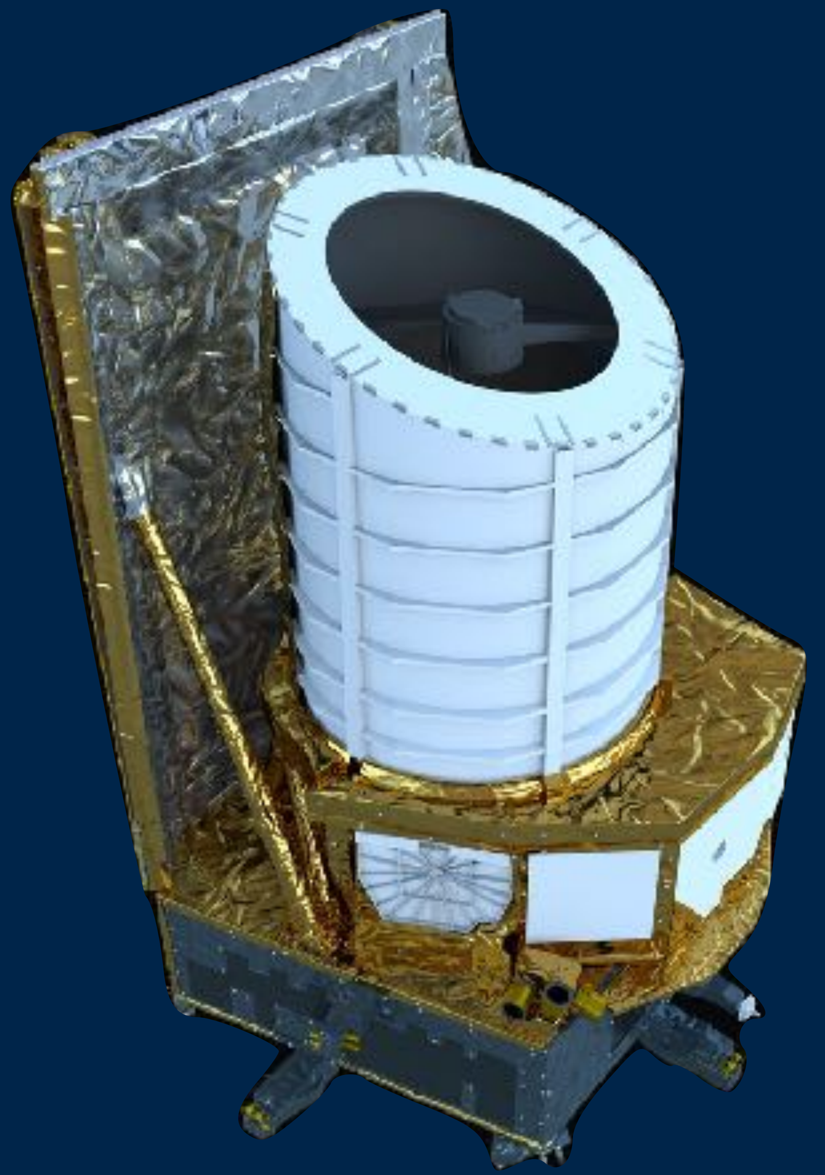
convolutional tree

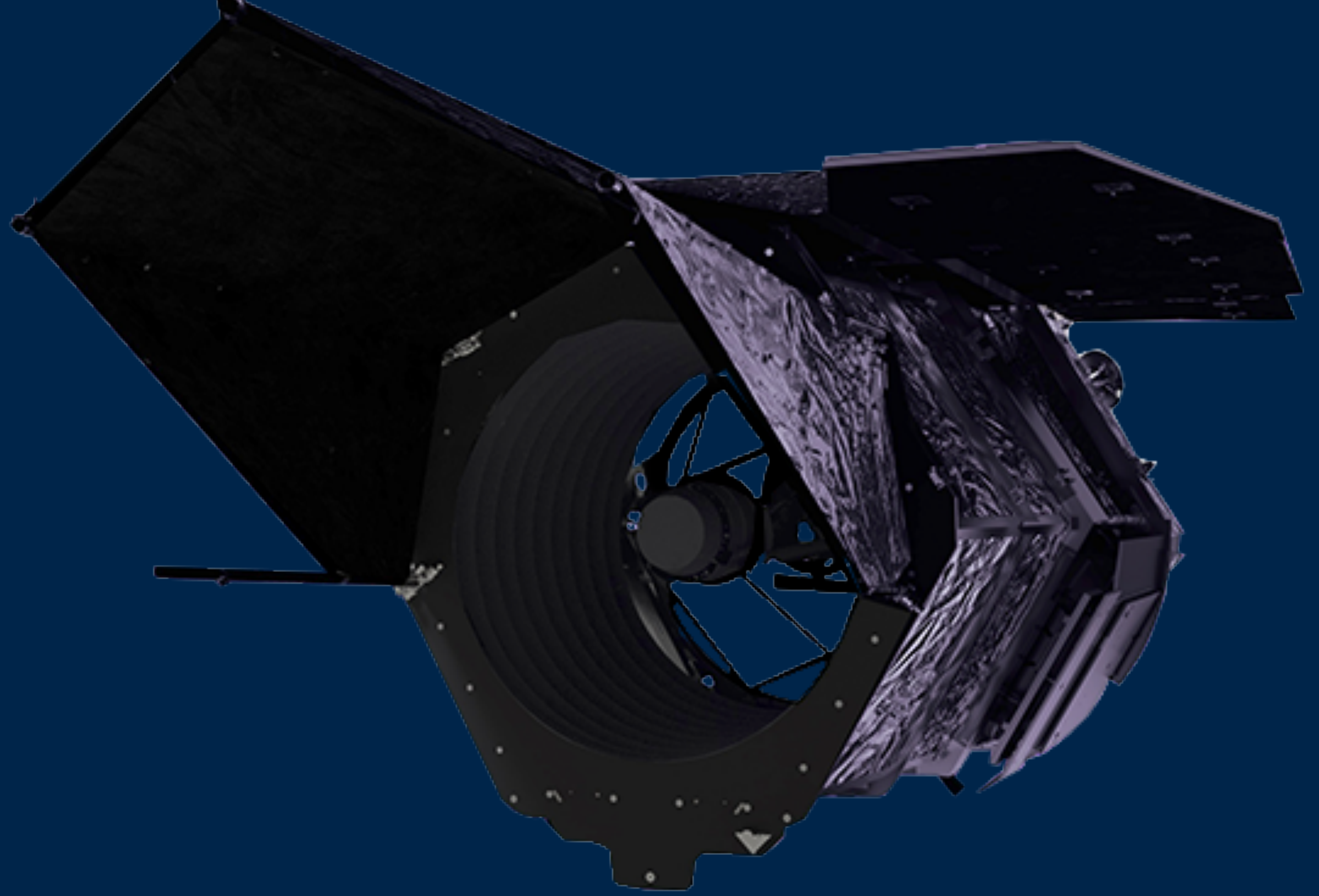
wavelets, modulus, iteration

e.g., 8 scales → 37 coefficients (s_0, s_1, s_2)

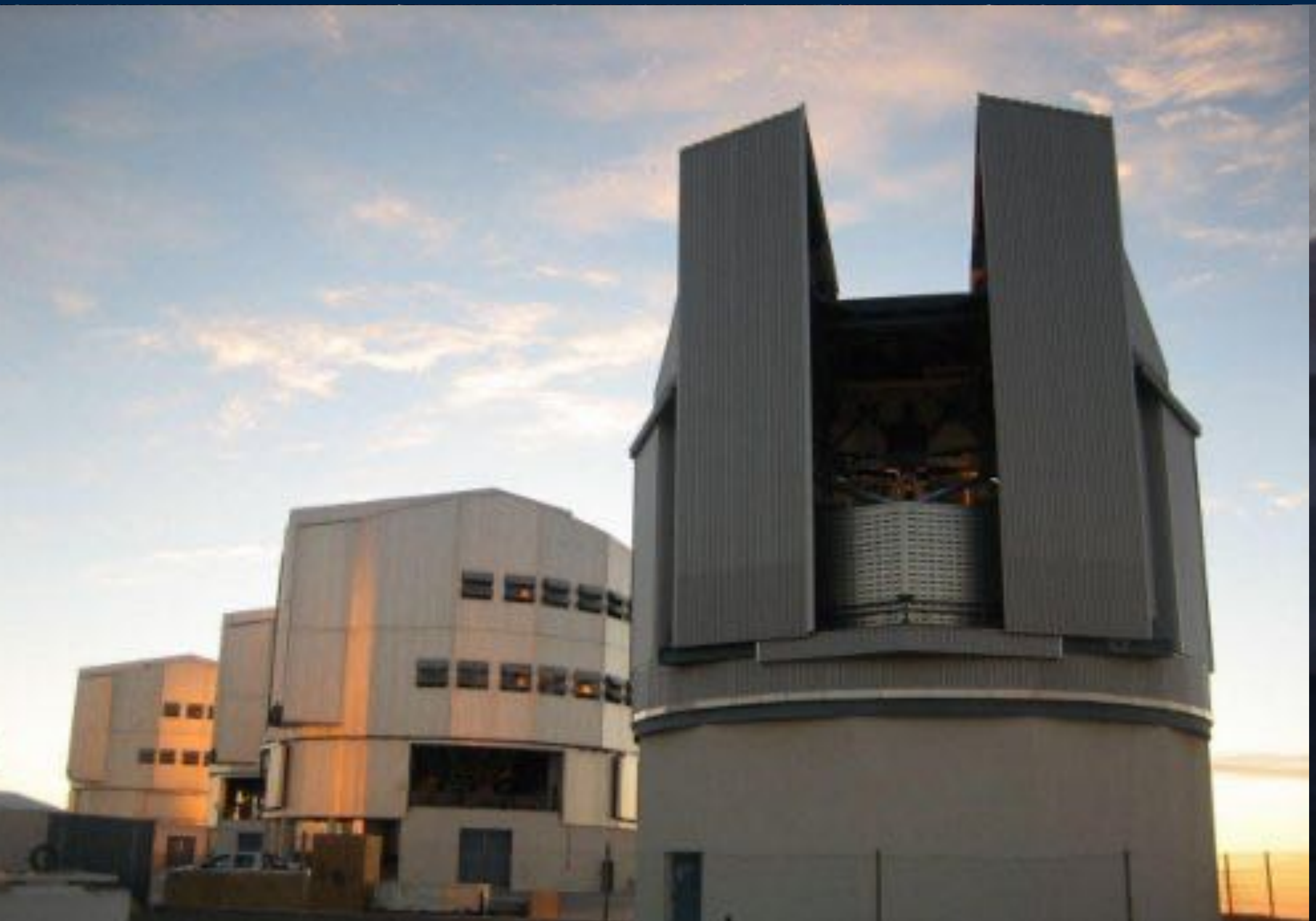


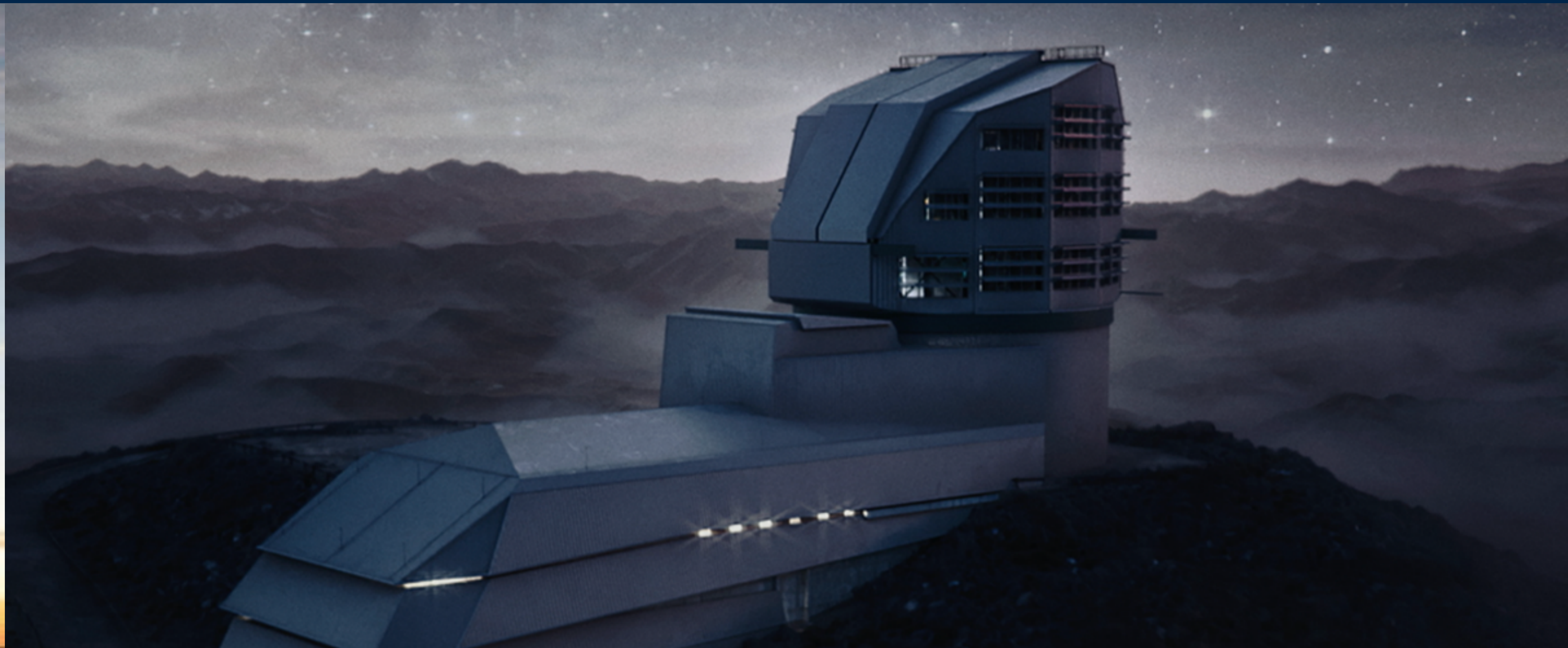
weak lensing cosmology



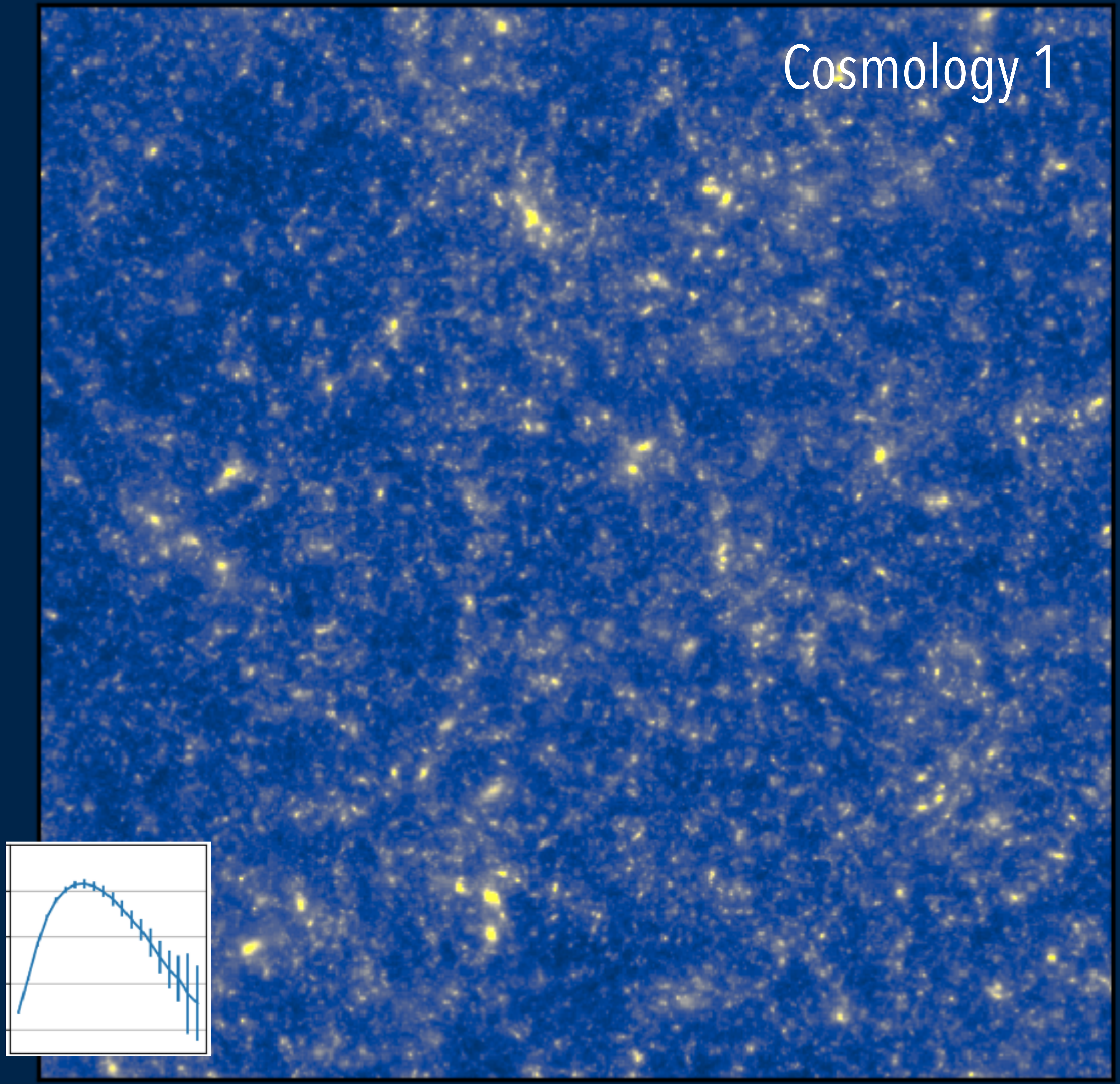


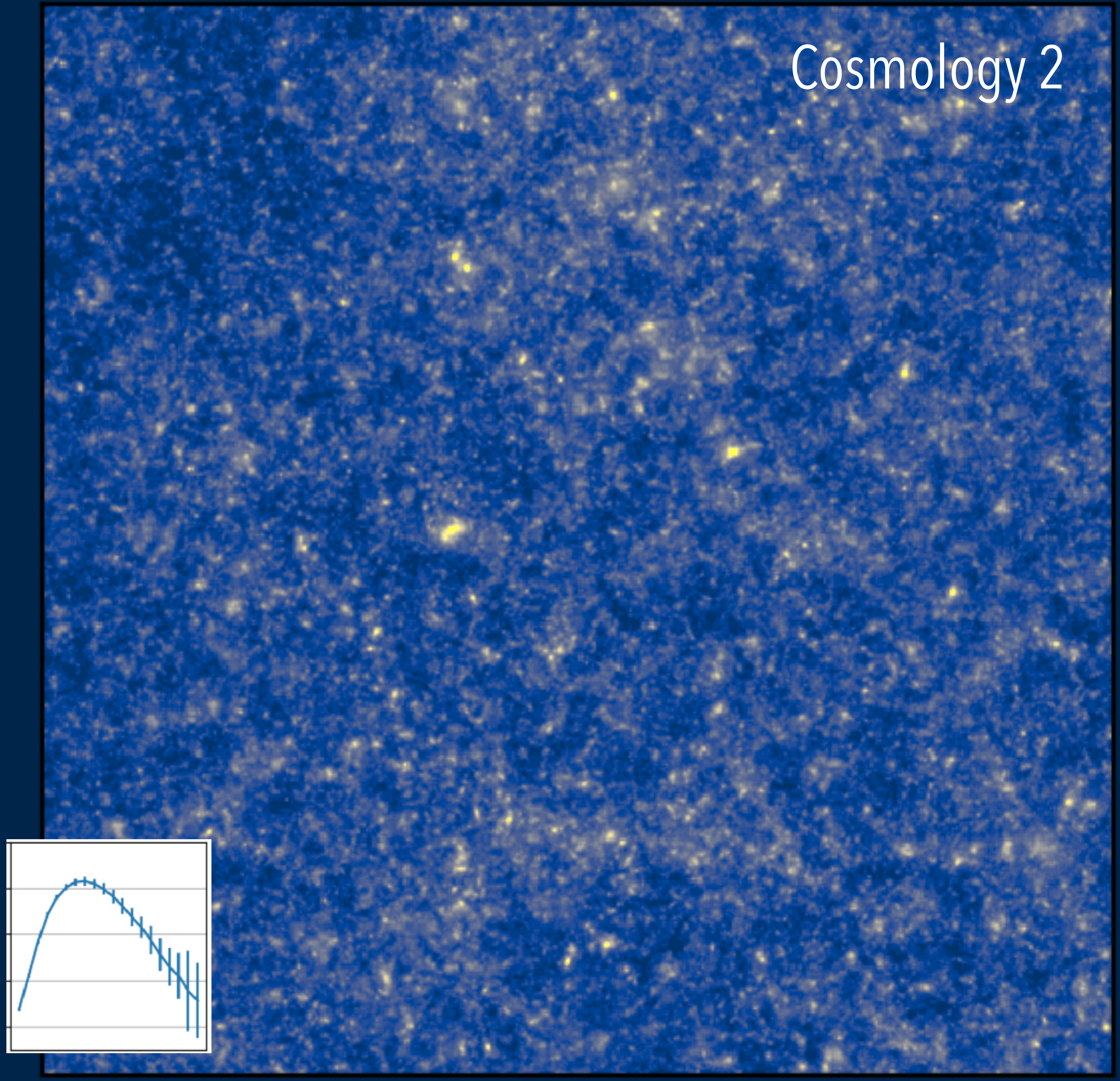
raw data → galaxy catalog → mass map → $\sigma_8, \Omega_m, w, M_\nu$





simulated mass maps (from Columbia lensing group)





Matilla Zorrilla et al. 2016, Gupta et al. 2018

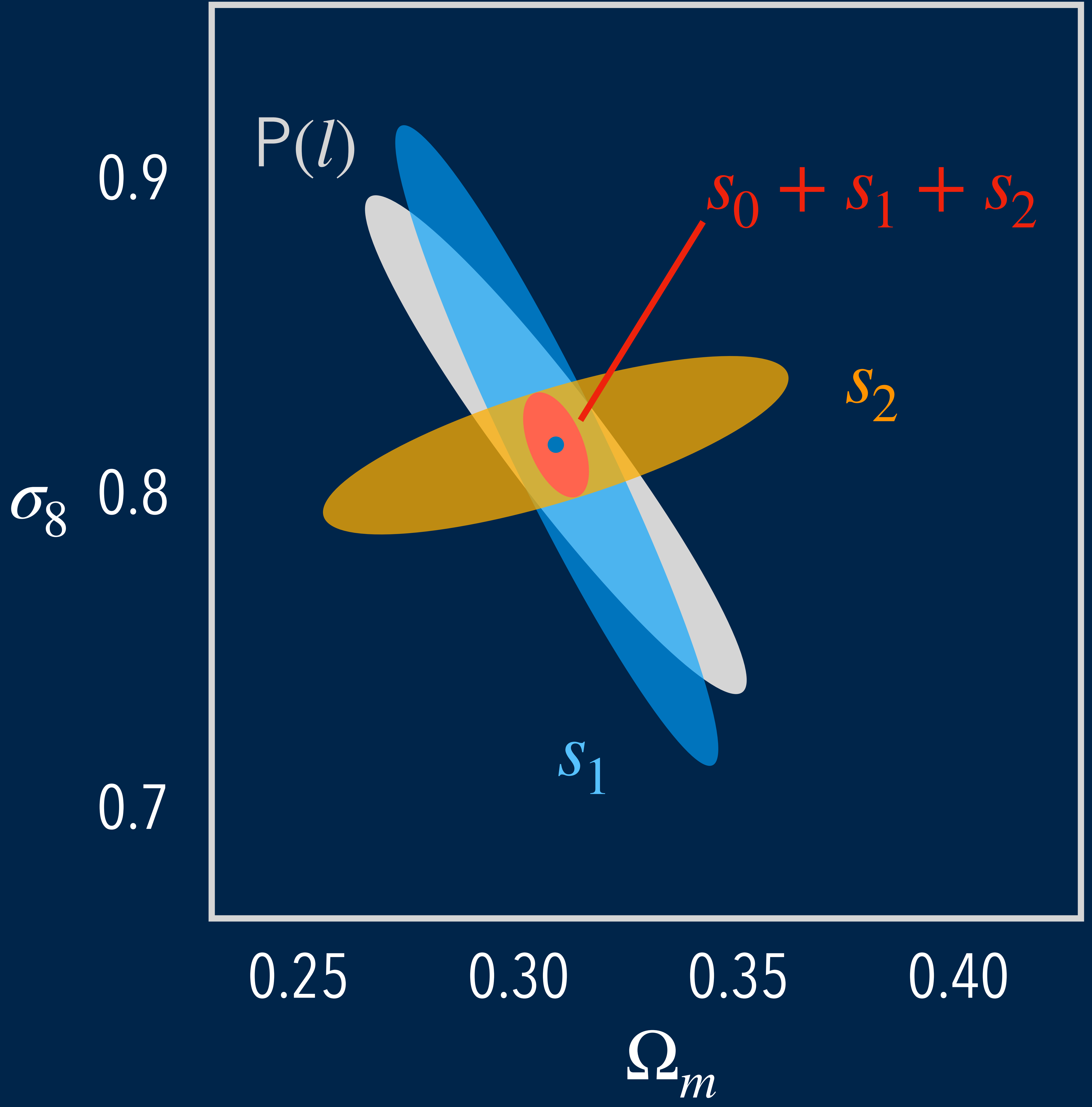
weak lensing cosmology

3.5x3.5 deg² noiseless map
scale range: 1 arcmin to 3.5 deg

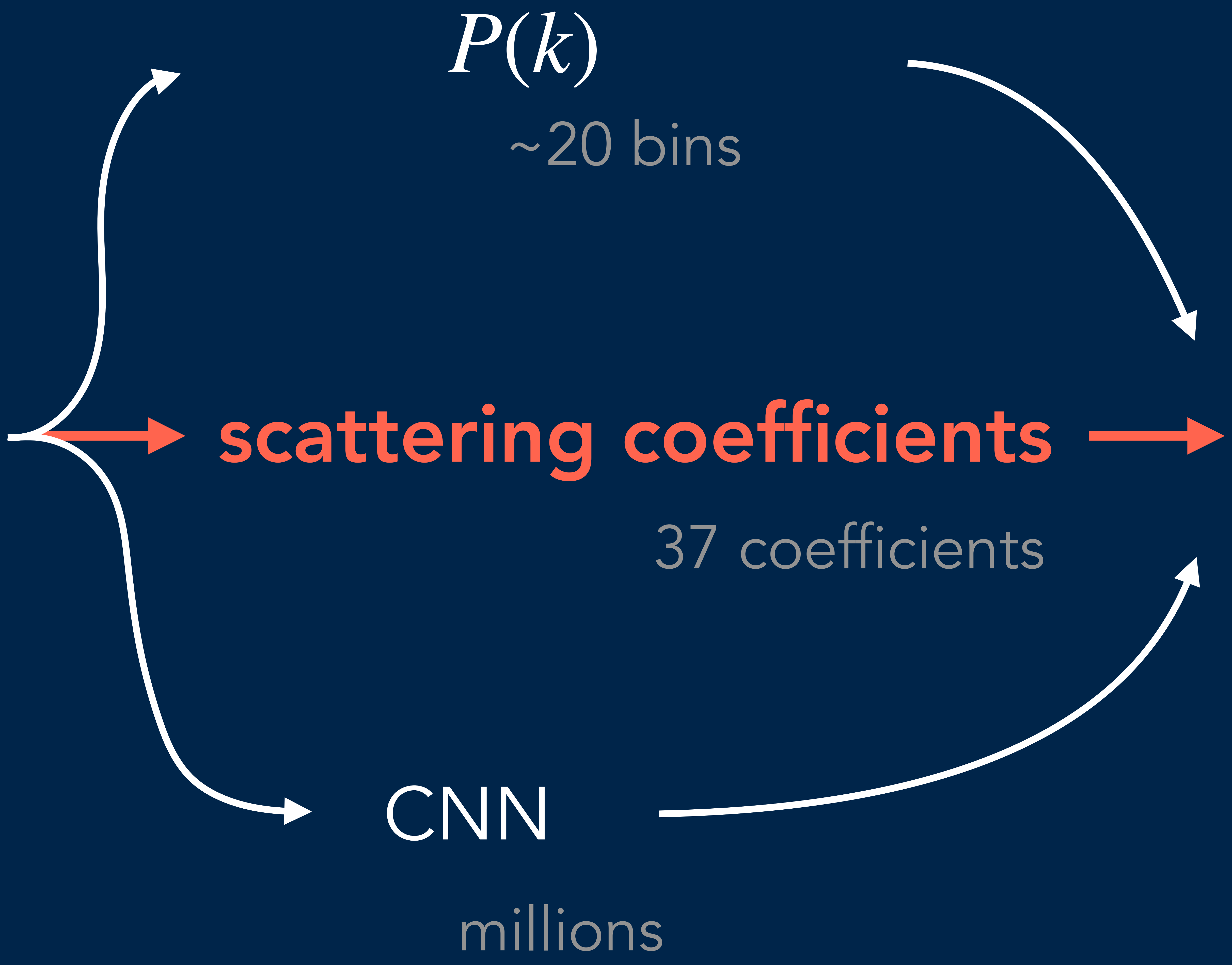
$P(k)$

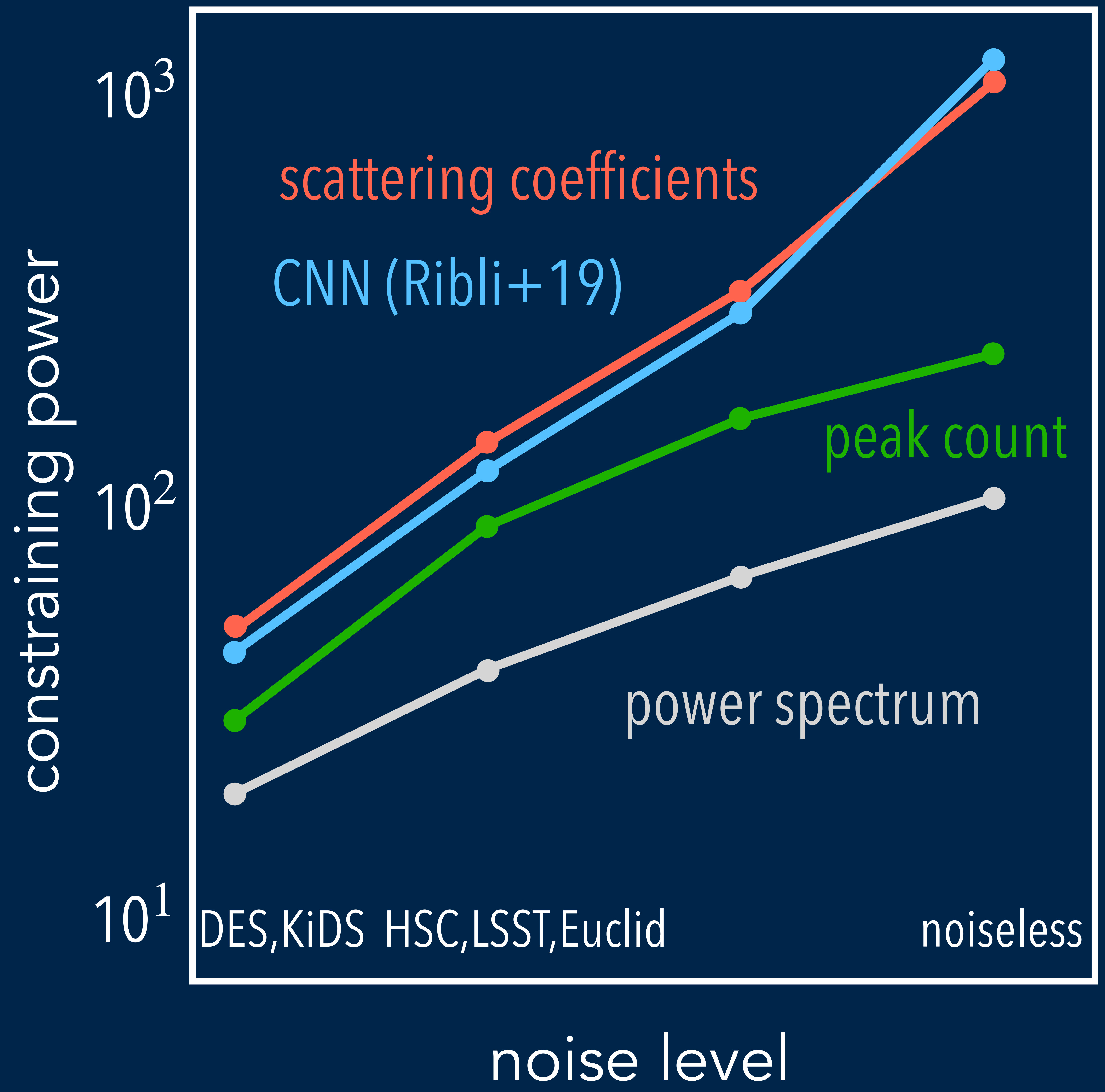
scattering coefficients

CNN

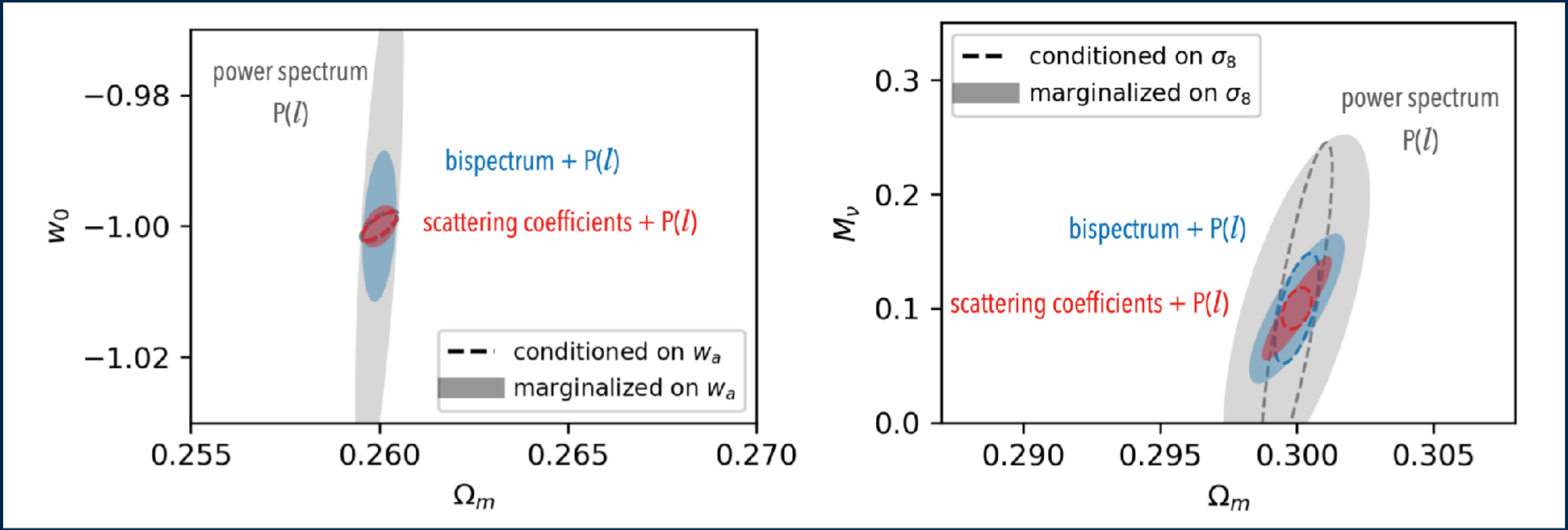


weak lensing cosmology



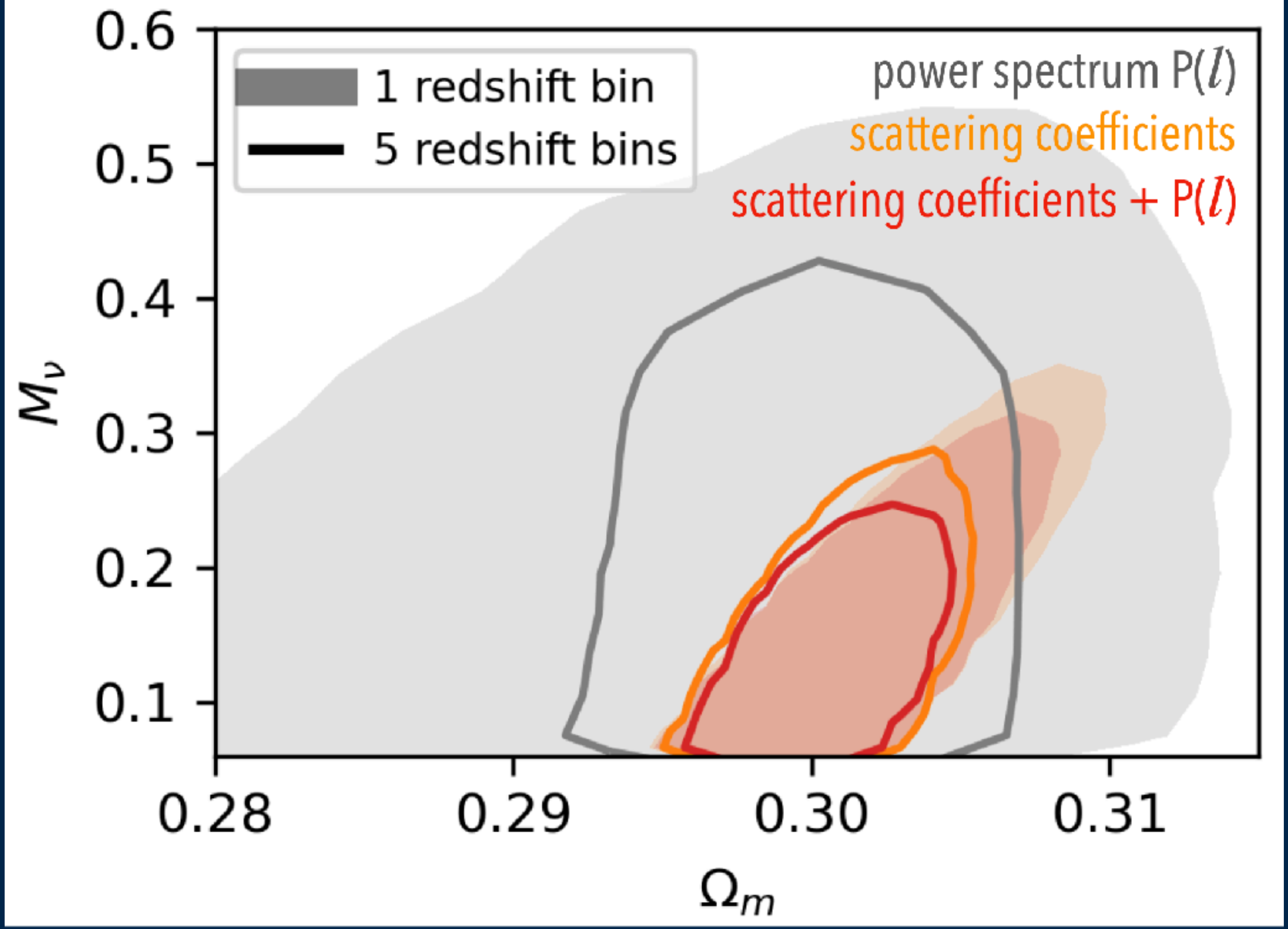


dark energy & neutrino mass sensitivity



neutrino mass sensitivity

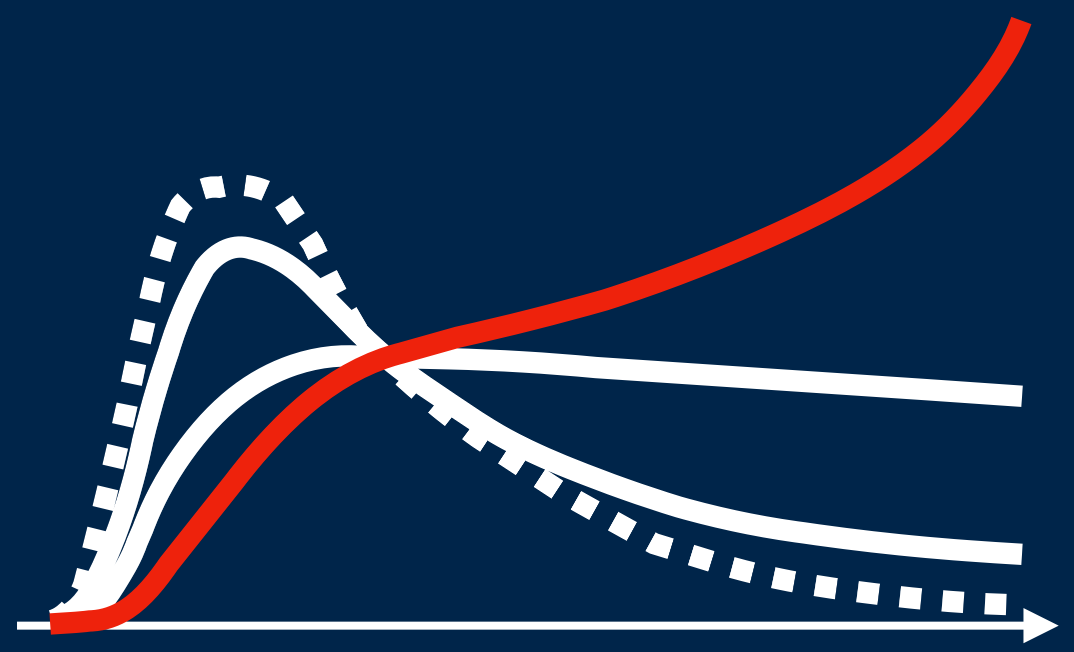
Rubin-like survey



on real data …

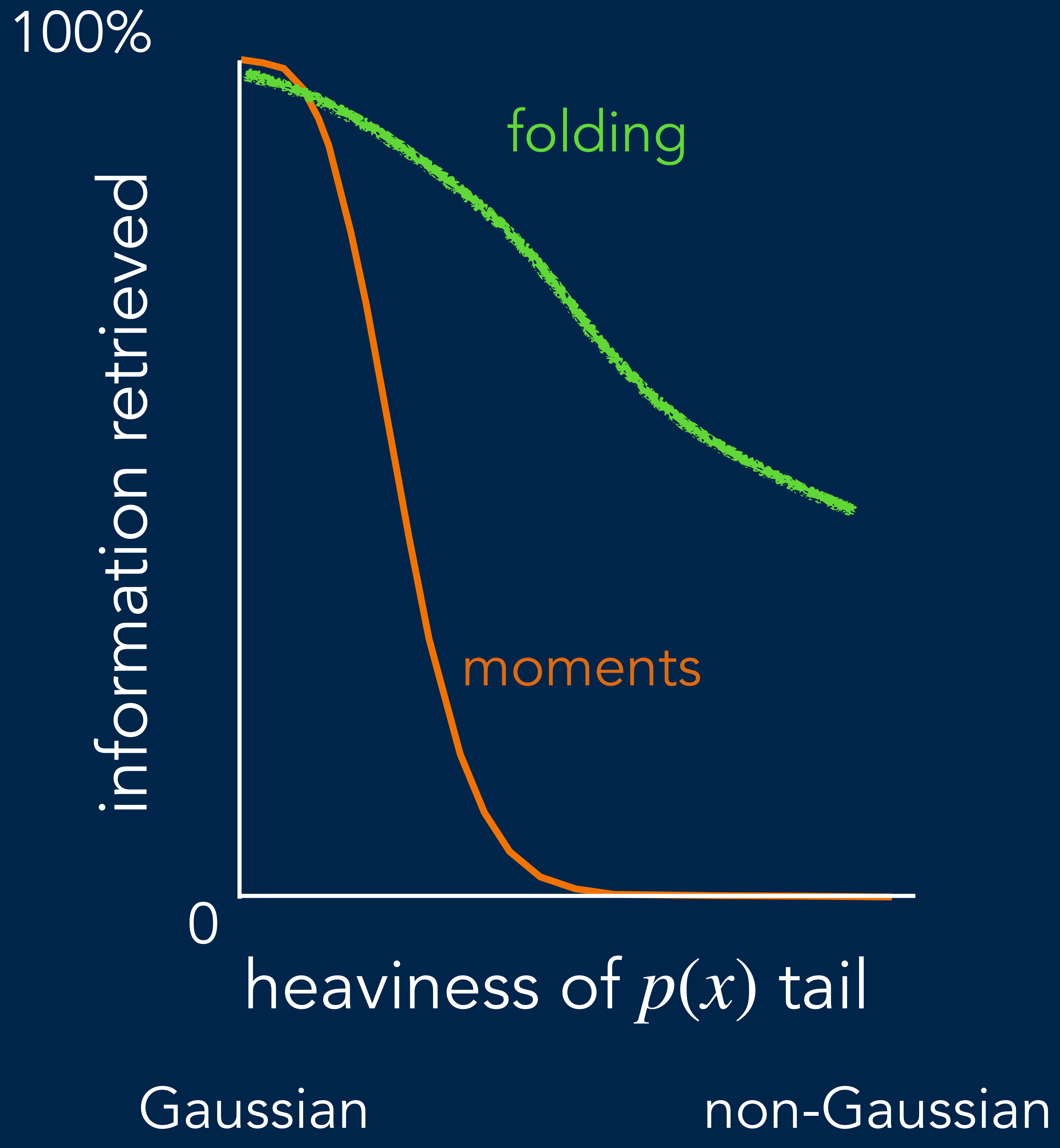
$\langle \delta_1 \delta_2 \ldots \delta_n \rangle$

amplifying the tail

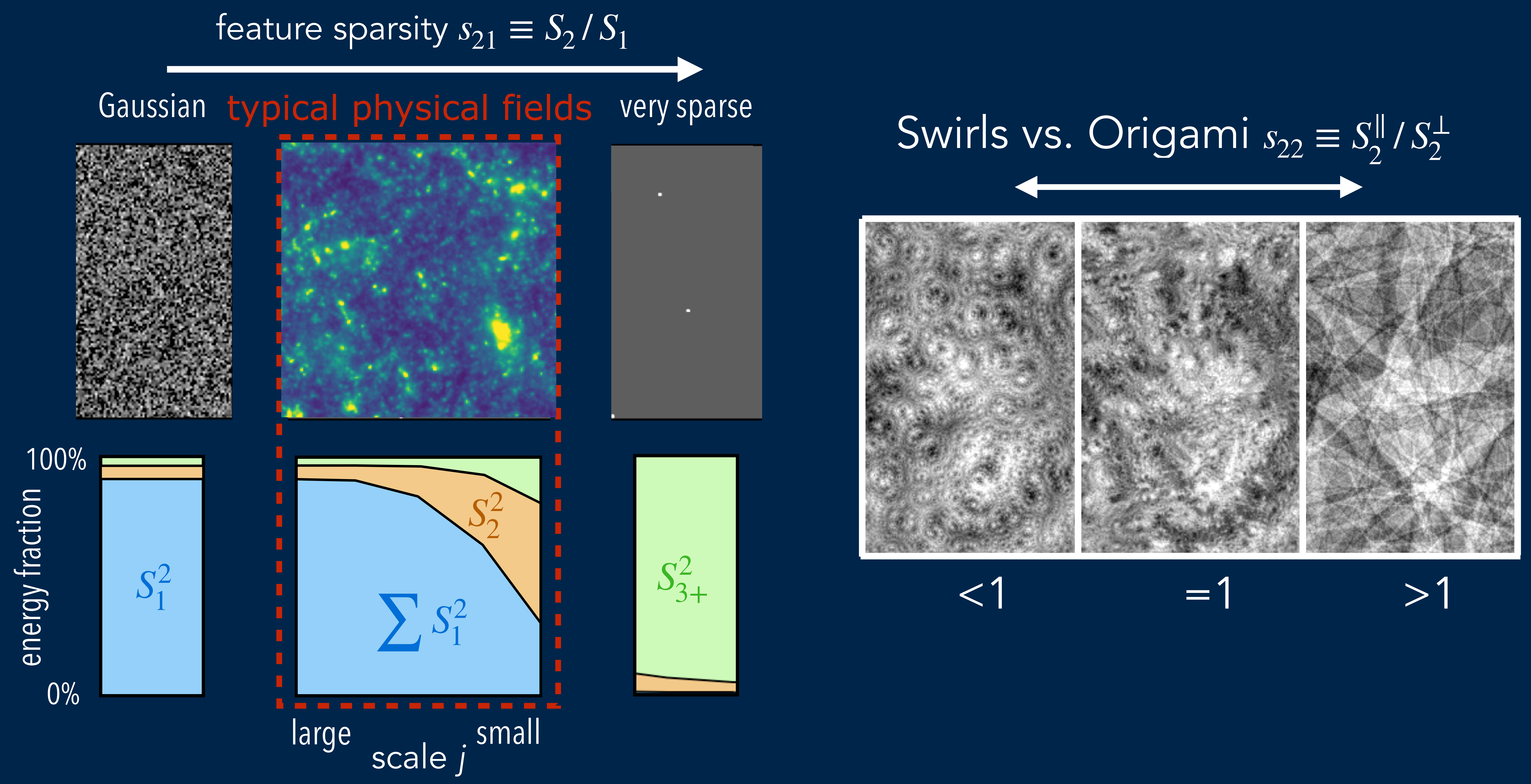


$\langle \, | \, |I \star \psi| \star \psi| \, \rangle$

folding the core

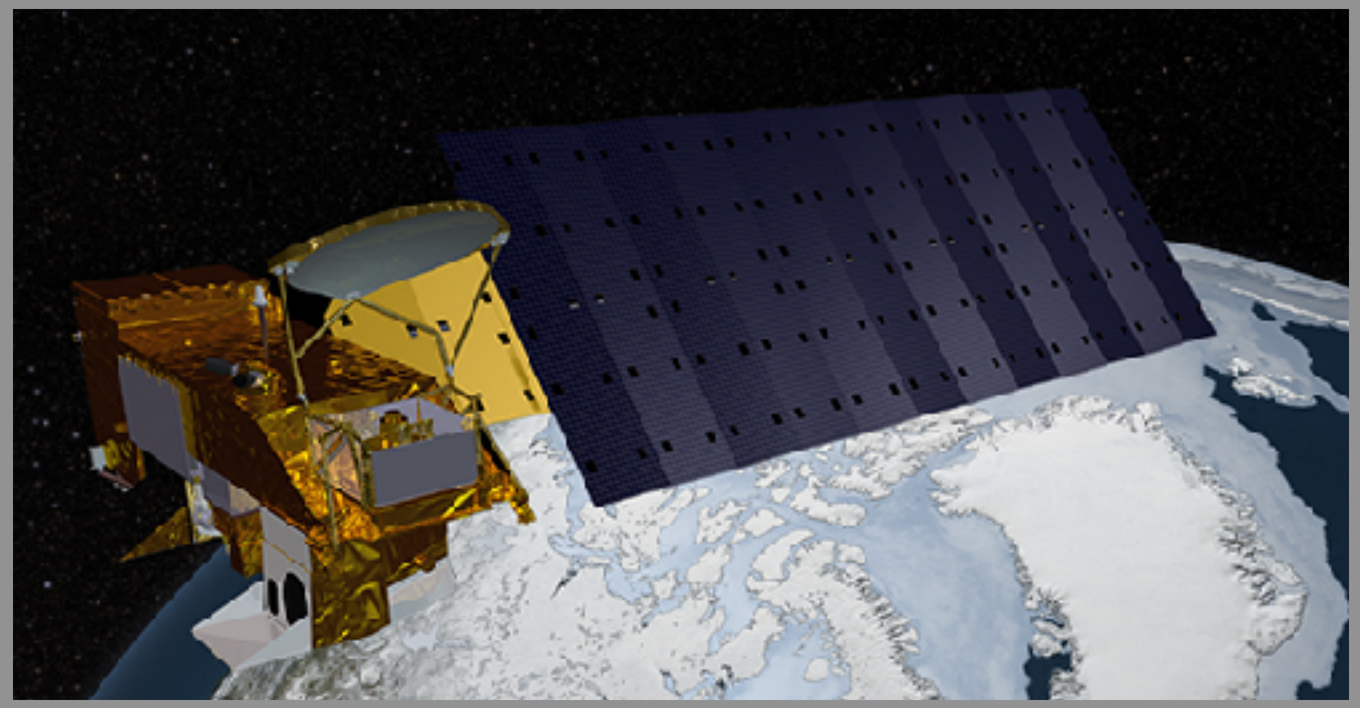


Carron (2011)



feature sparsity $s_{21} \equiv S_2 / S_1$
Gaussian
typical physical fields
very sparse
100%
energy fraction
0%
S_1^2
S_2^2
$\sum S_1^2$
S_{3+}^2
large
small
scale j
Swirls vs. Origami $s_{22} \equiv S_2^{\parallel} / S_2^{\perp}$
<1
=1
>1

Remote sensing application (NASA Aqua Satellite)

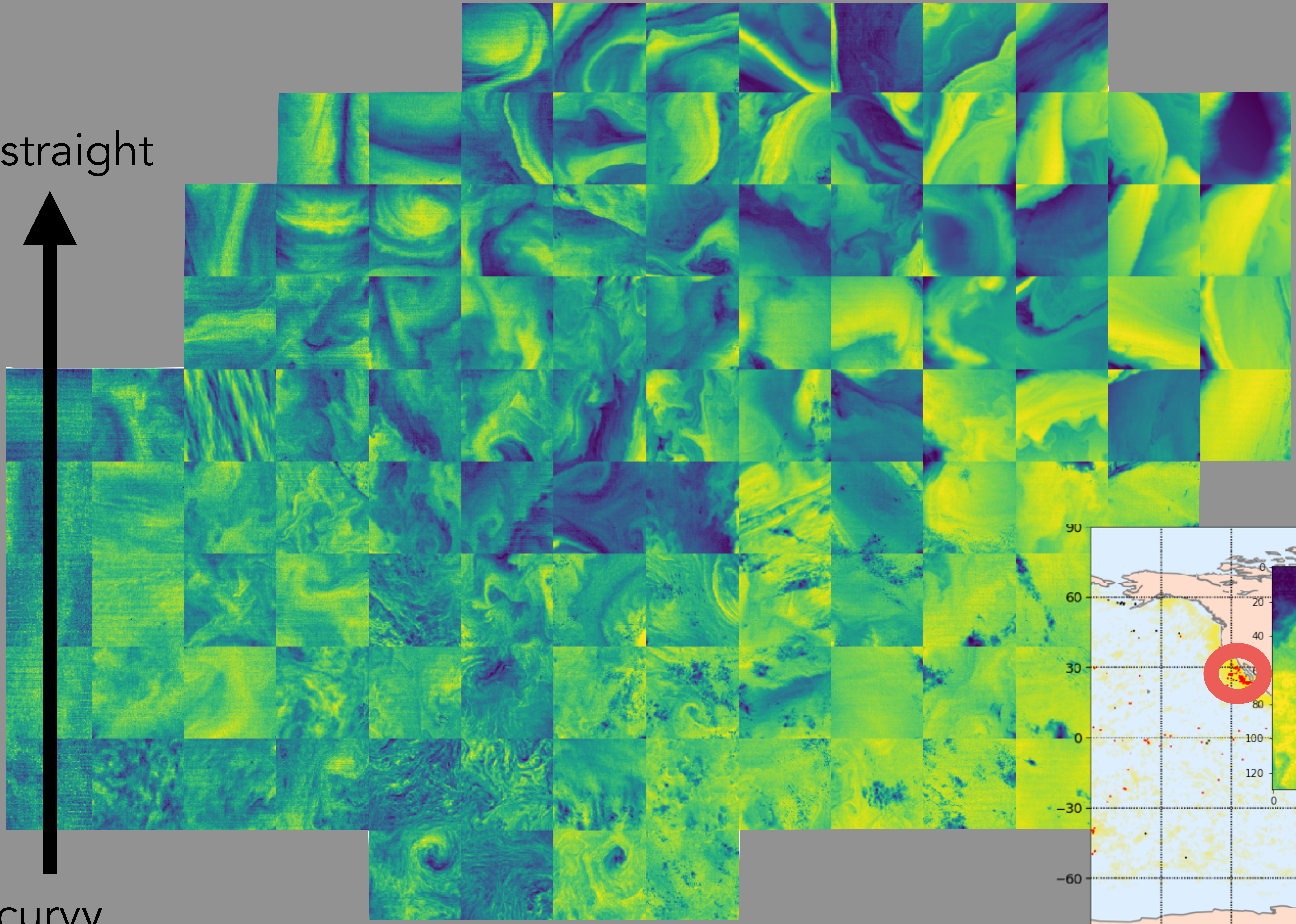


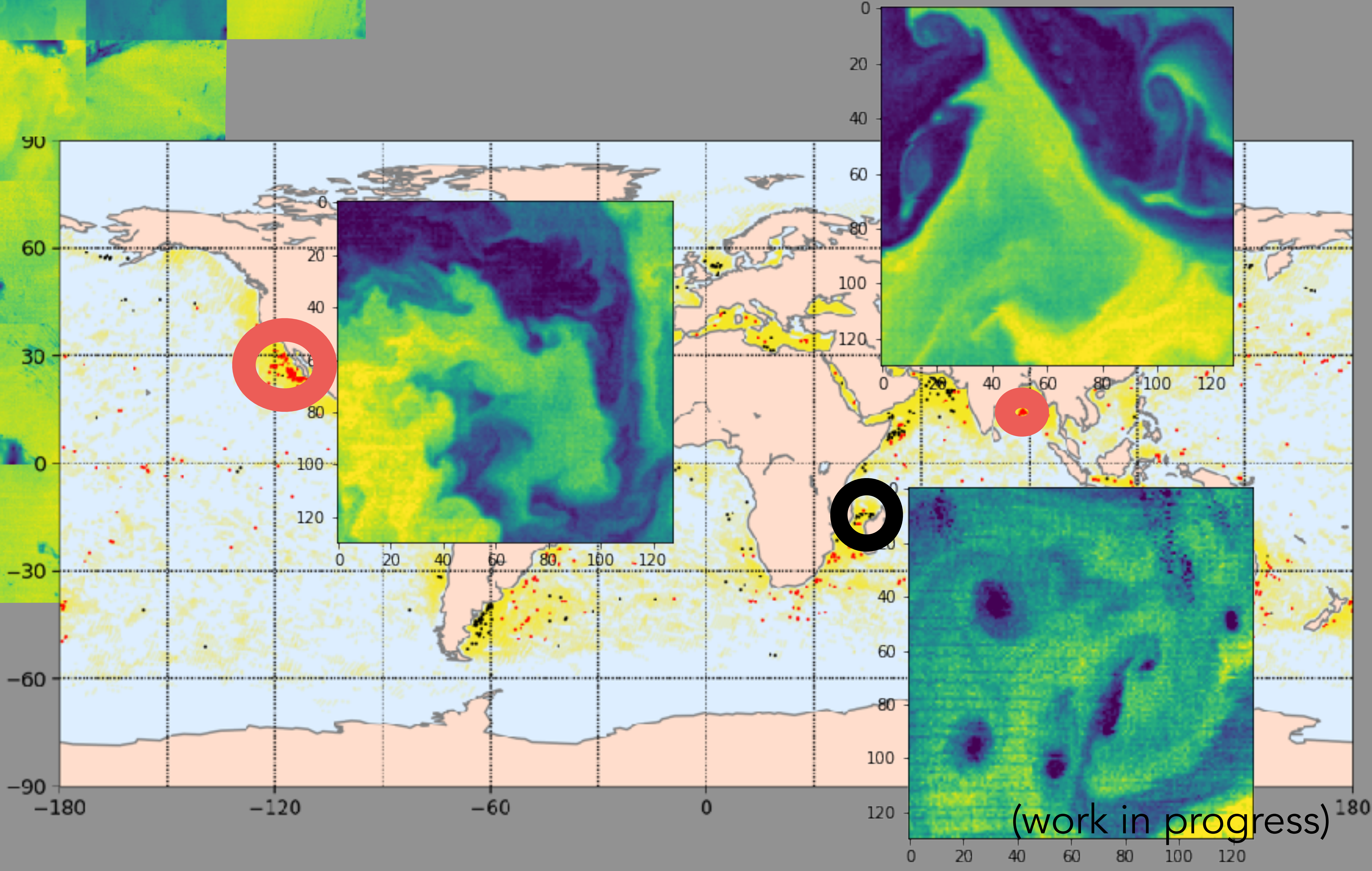
straight

curvy

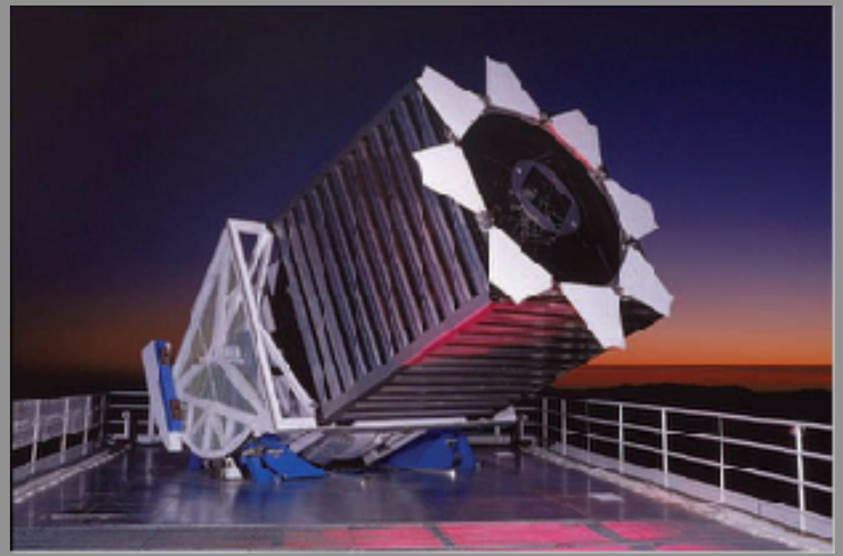
spread

sparse





SDSS galaxies



galaxy images

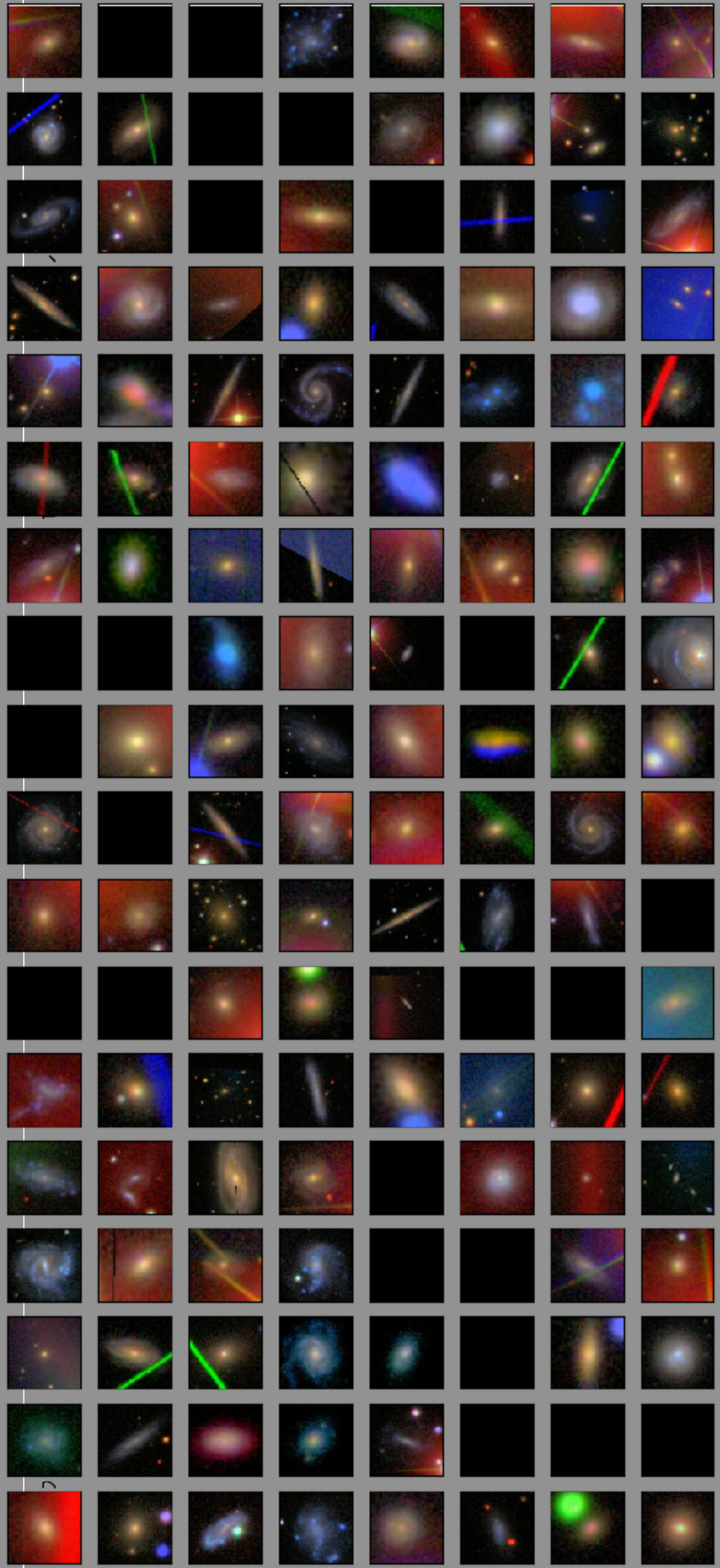
↓

scattering coefficients

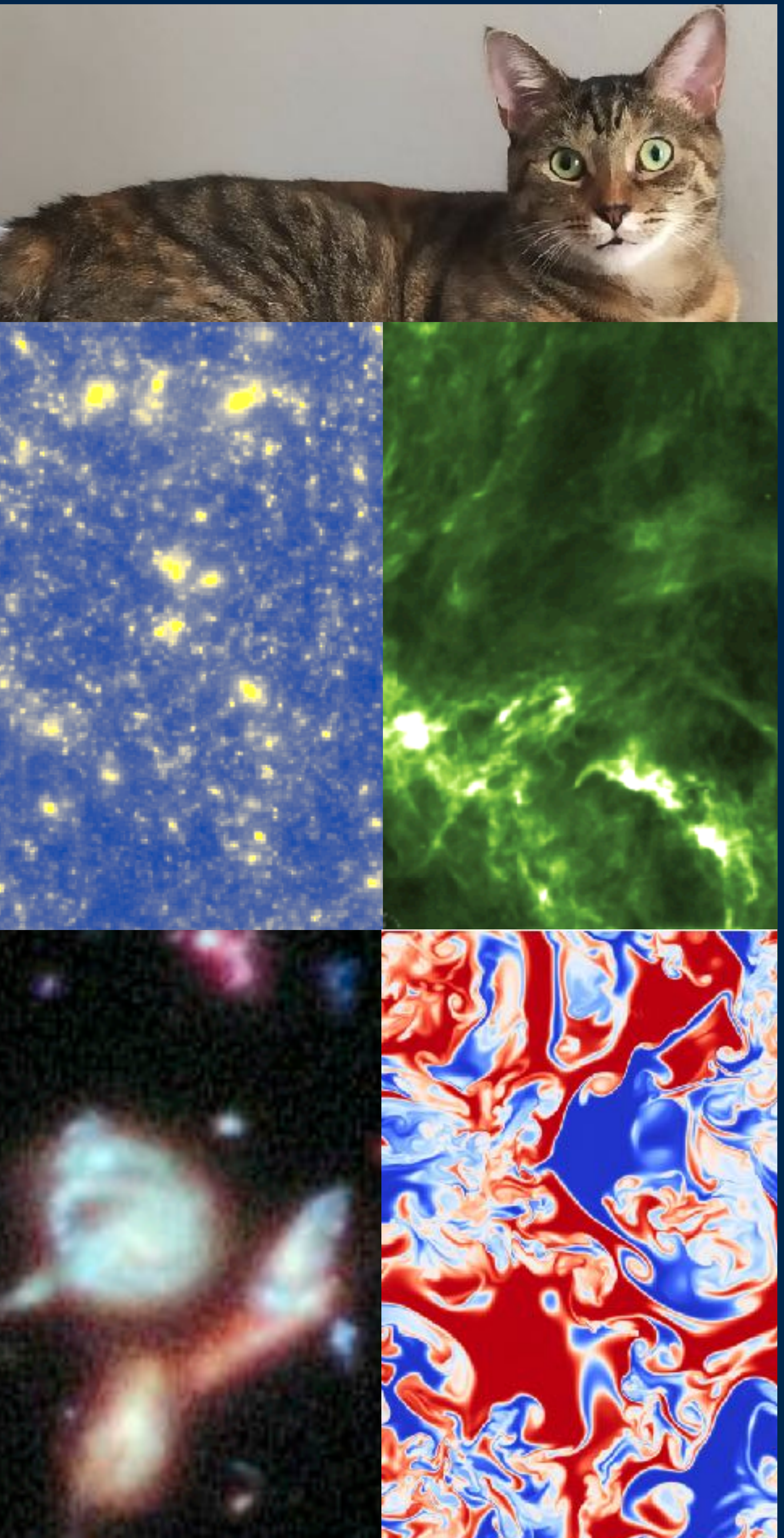
↓

visualization/
outlier detection

(work in progress)



How do we characterize a field?



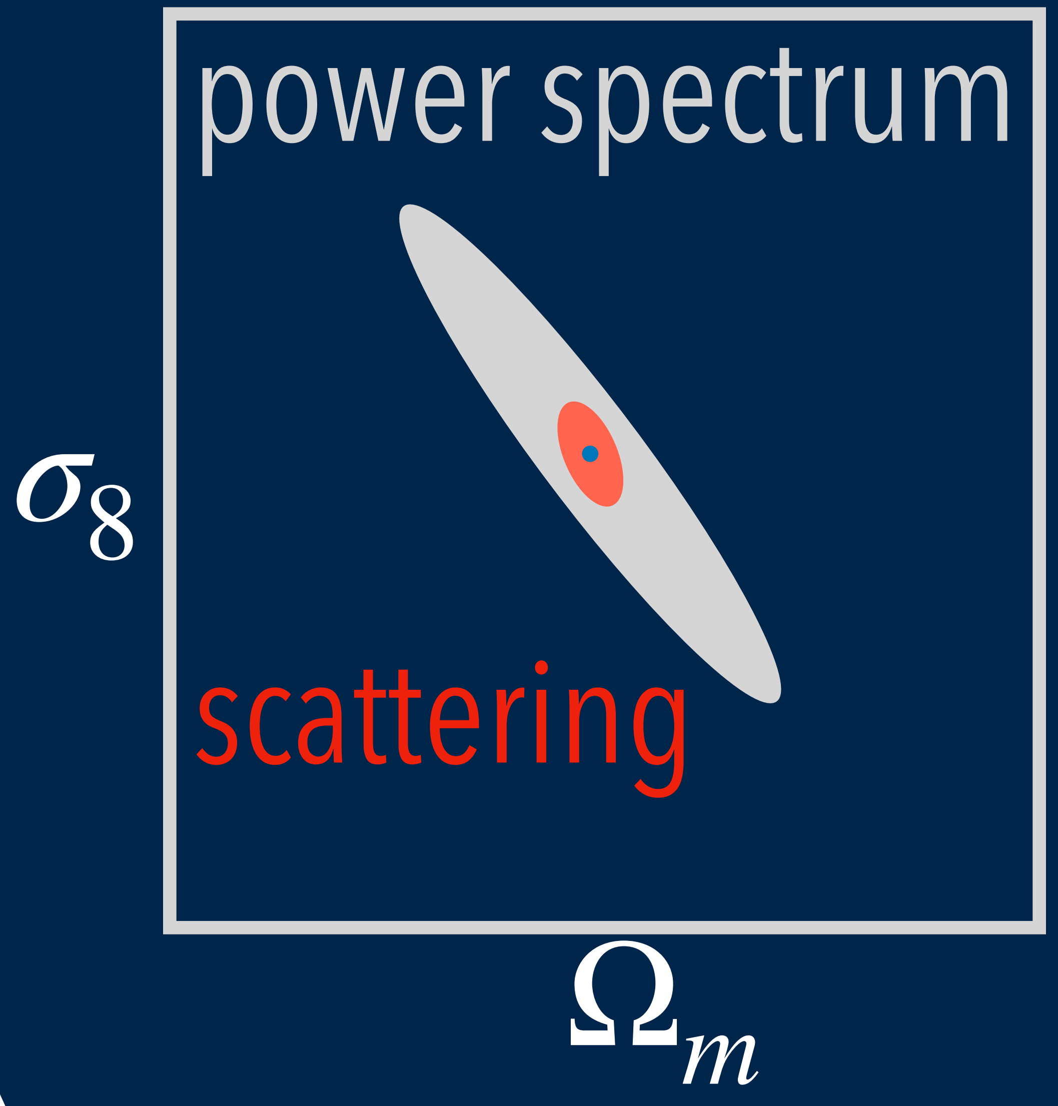
power spectrum

scattering transform

efficient, interpretable, robust

CNN

physical parameters



arXiv: 2006.08561
arXiv: 2103.09247
interpretations (coming soon)