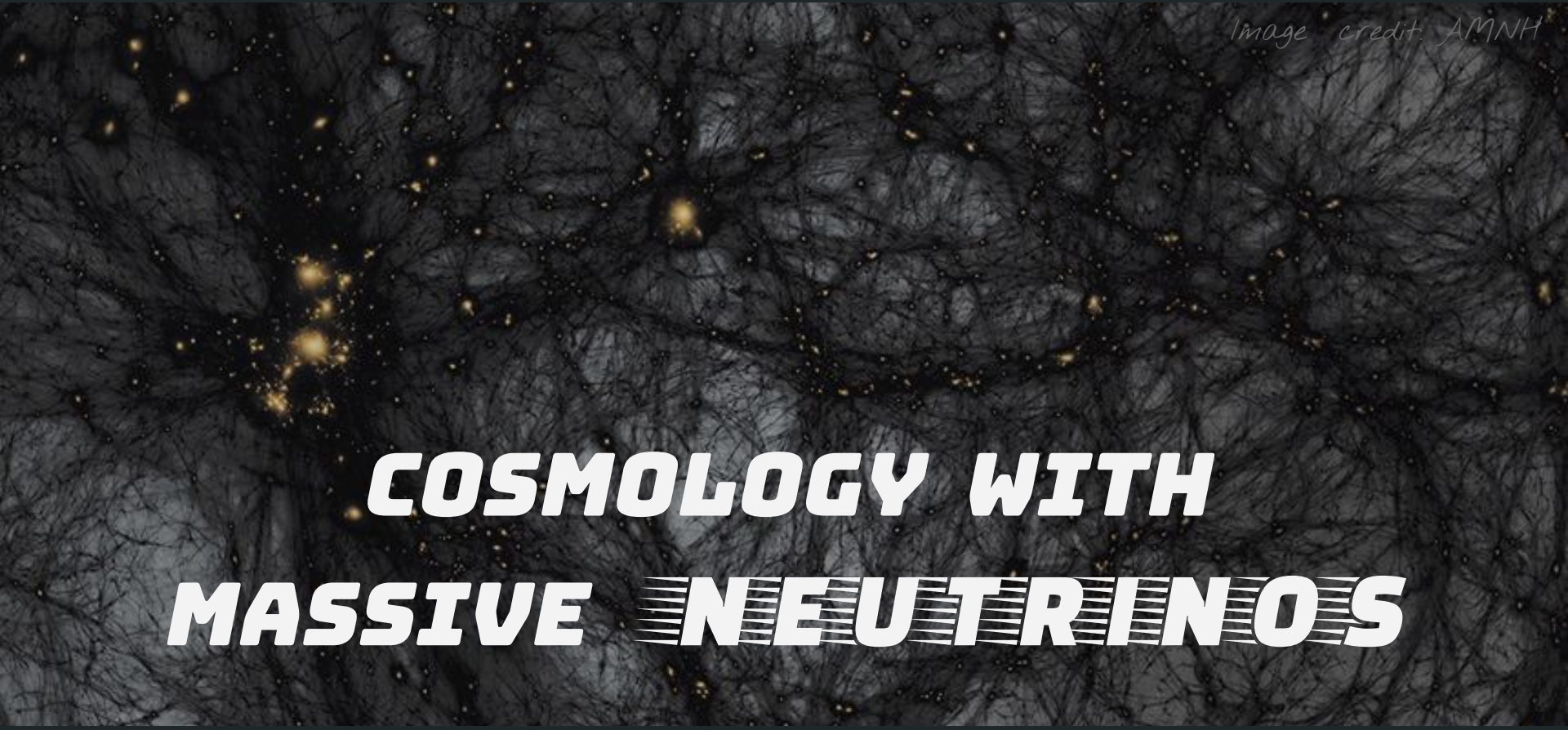


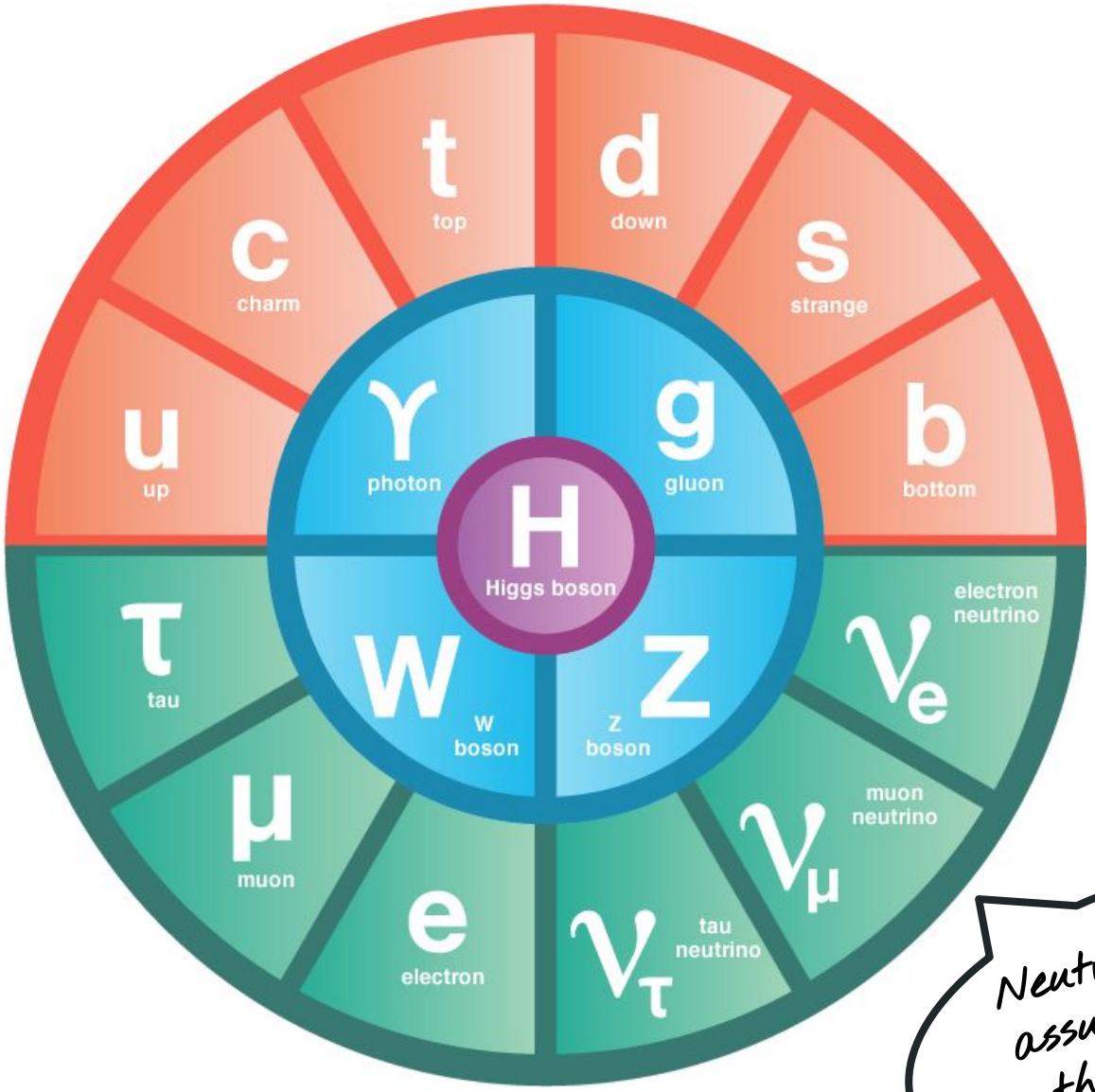
COSMOLOGY WITH MASSIVE NEUTRINOS

INPA, FEBRUARY 22ND 2019

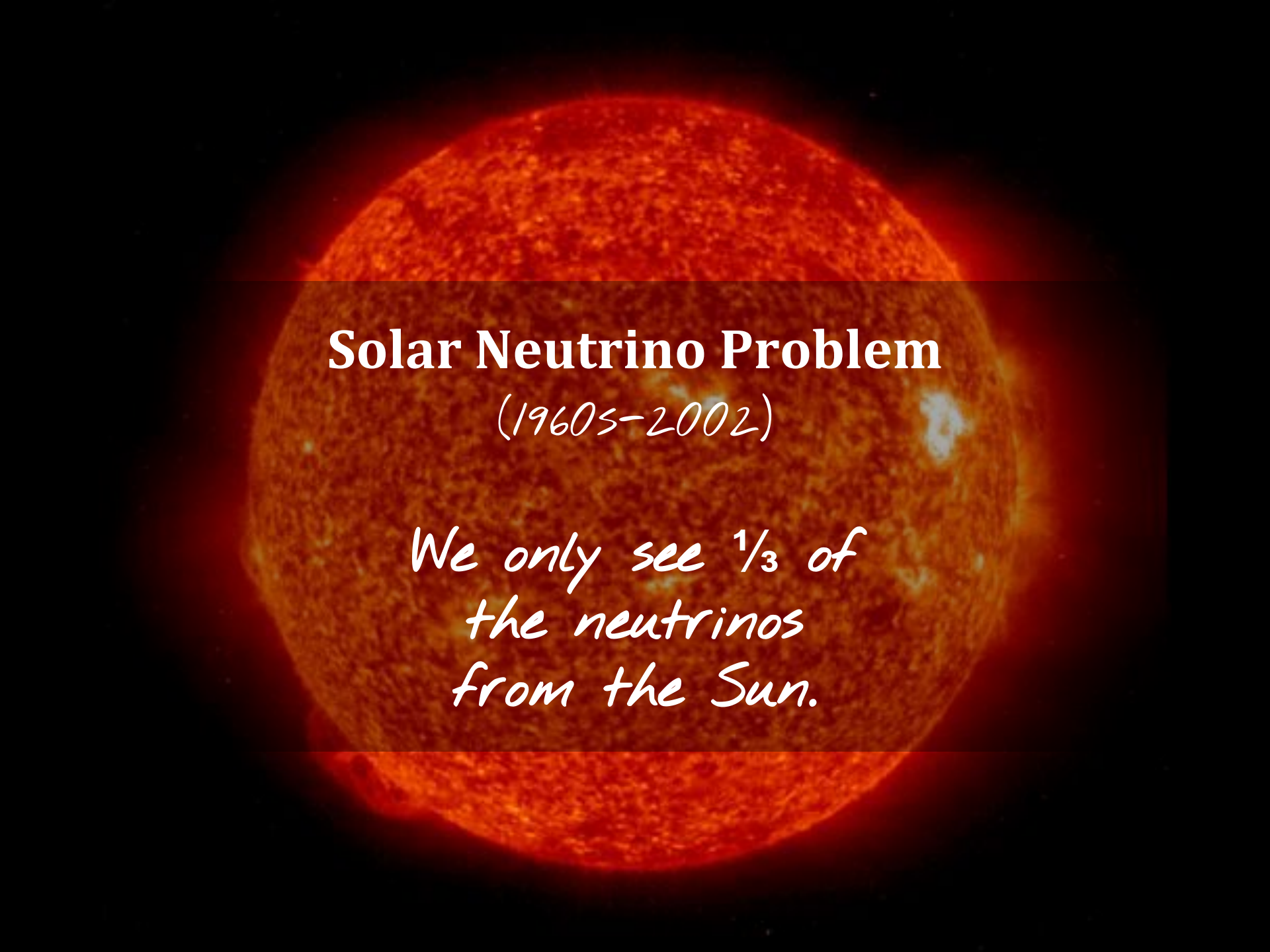
Jia Liu

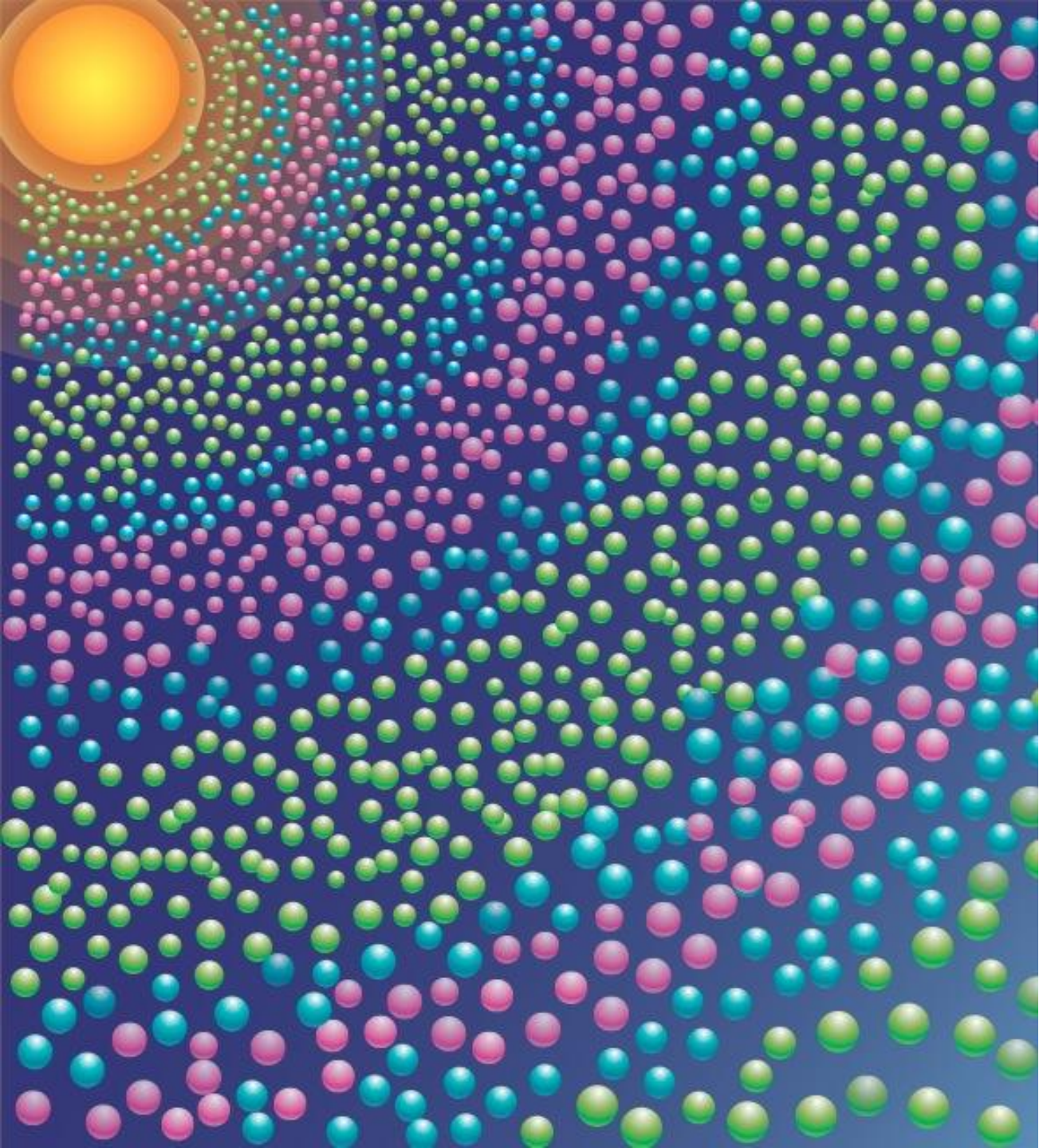
PRINCETON UNIVERSITY

MASSIVE NEUTRINOS



Neutrino masses: assumed zero in the Standard Model


Solar Neutrino Problem
(1960s-2002)
We only see 1/3 of
the neutrinos
from the Sun.

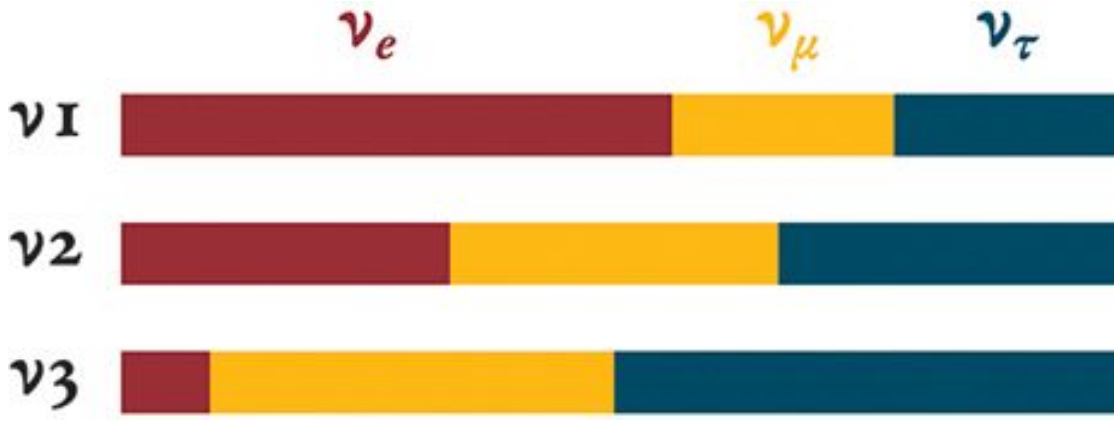


Solution:

Neutrino Oscillation

⅔ of the electron neutrinos turn into other flavors (muon or tau) before reaching the Earth.

Neutrino Oscillation

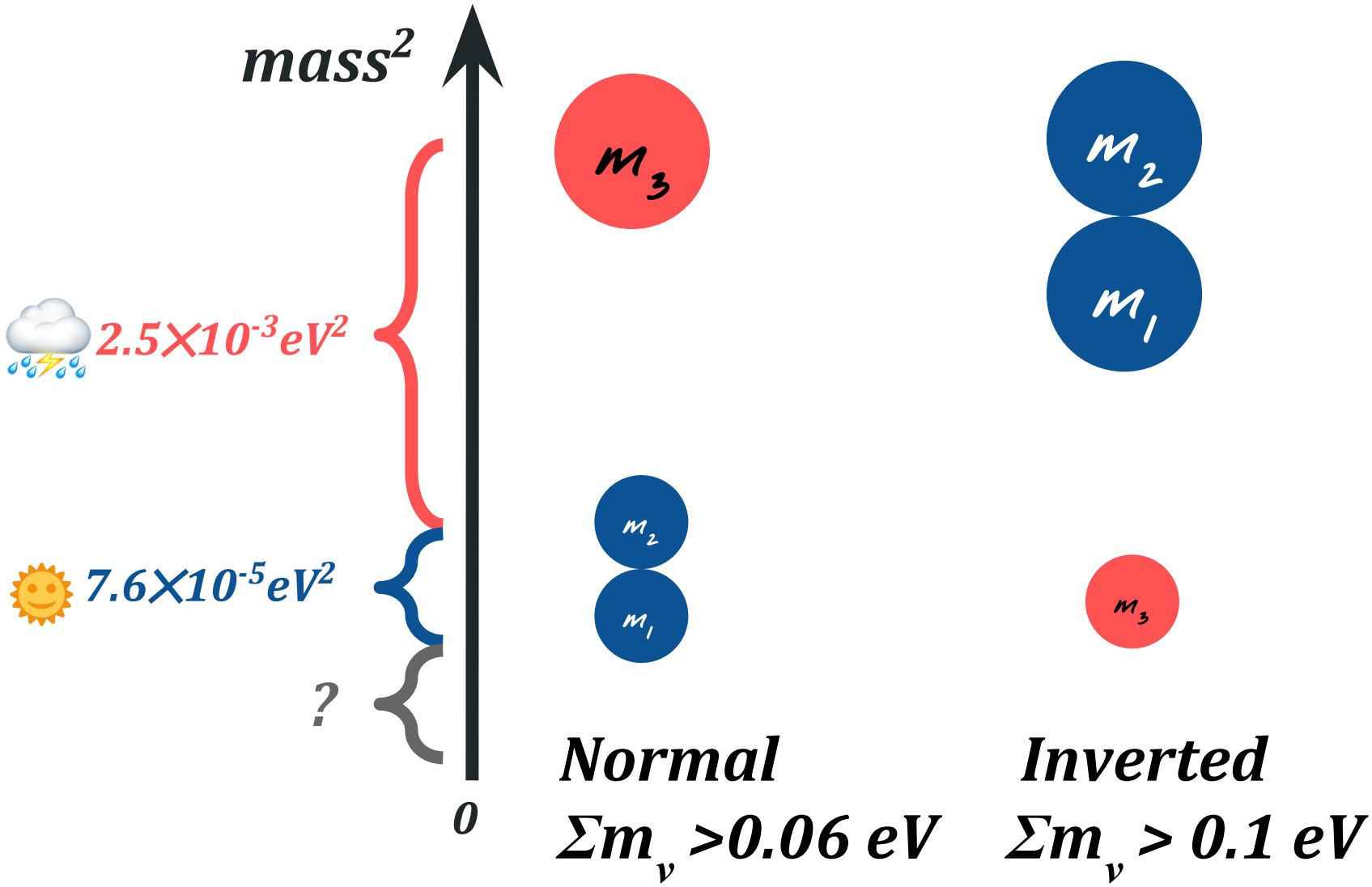


Nobel Physics 2015

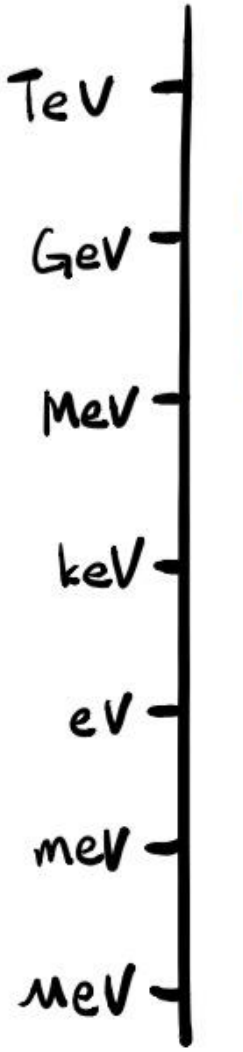
"for the discovery of neutrino oscillations, which shows that

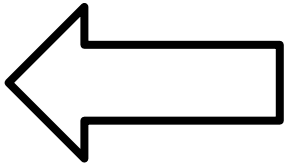
NEUTRINOS HAVE MASS."

Neutrino Mass Hierarchy

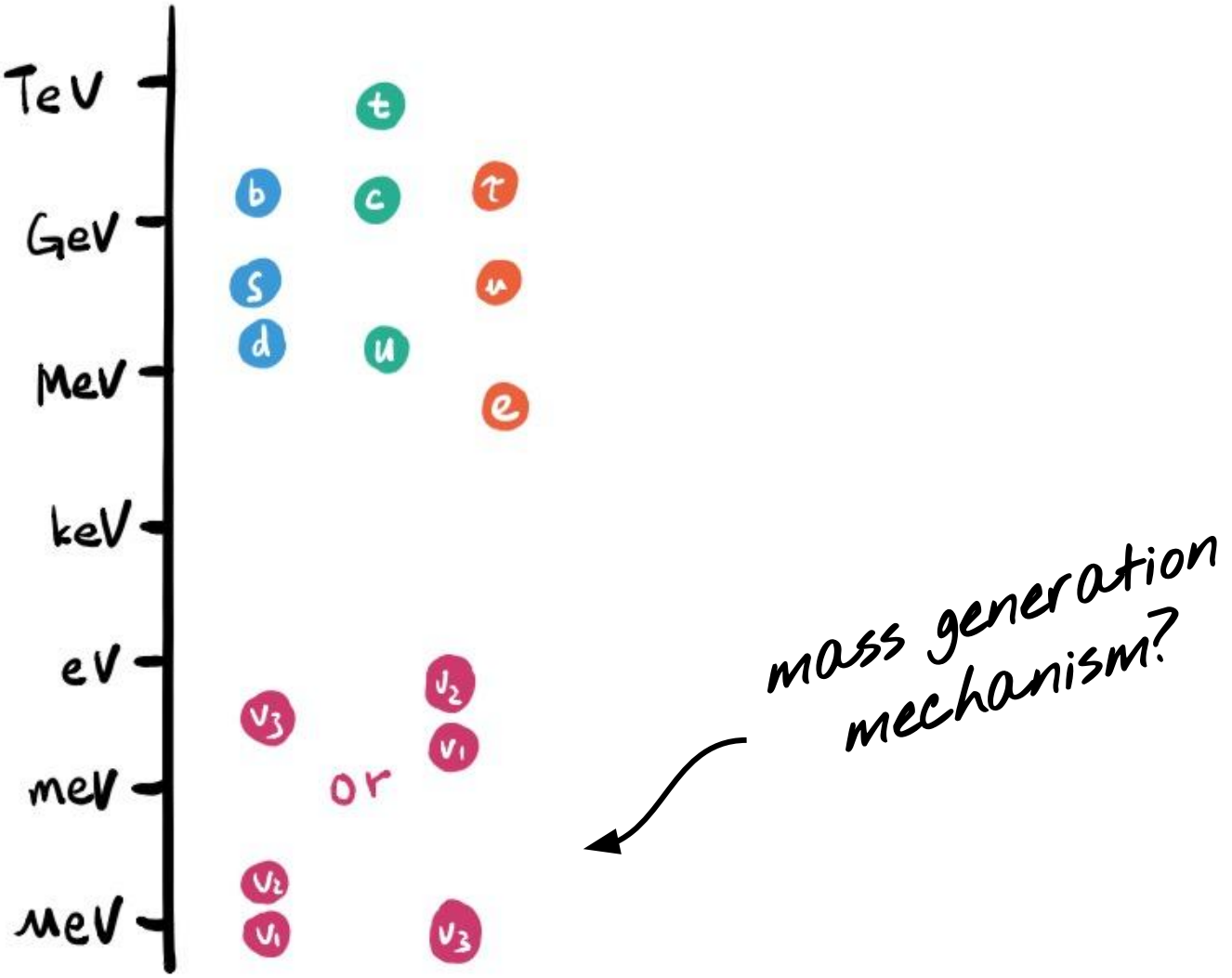


Fermion Masses

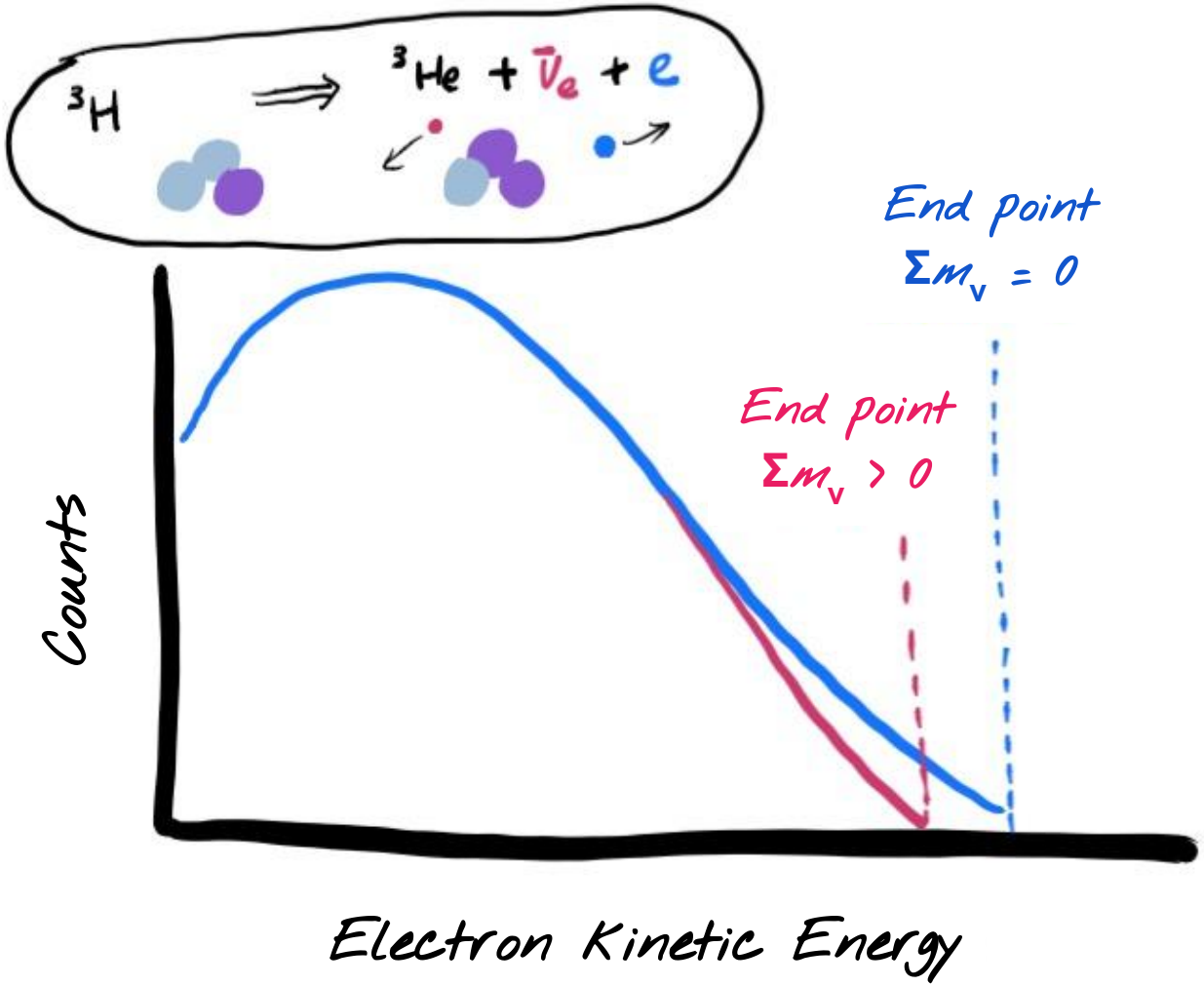




Fermion Masses



Particle Experiments: Tritium beta decay



Current Constraints (95% CL)

Minimum mass: 0.06 eV (Normal), 0.1 eV (Inverted)

Particle experiment

Troitsk beta decay

$$m_{ve}^{eff} < 2 \text{ eV}$$

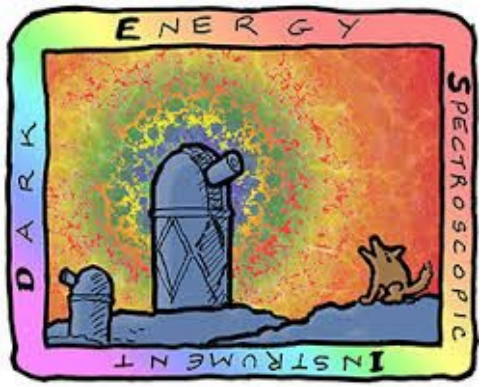
KATRIN projection: **0.2 eV**

Cosmology

Planck CMB, CMB Lensing, BAO

$$\Sigma m_{\nu} < 0.12 \text{ eV}$$

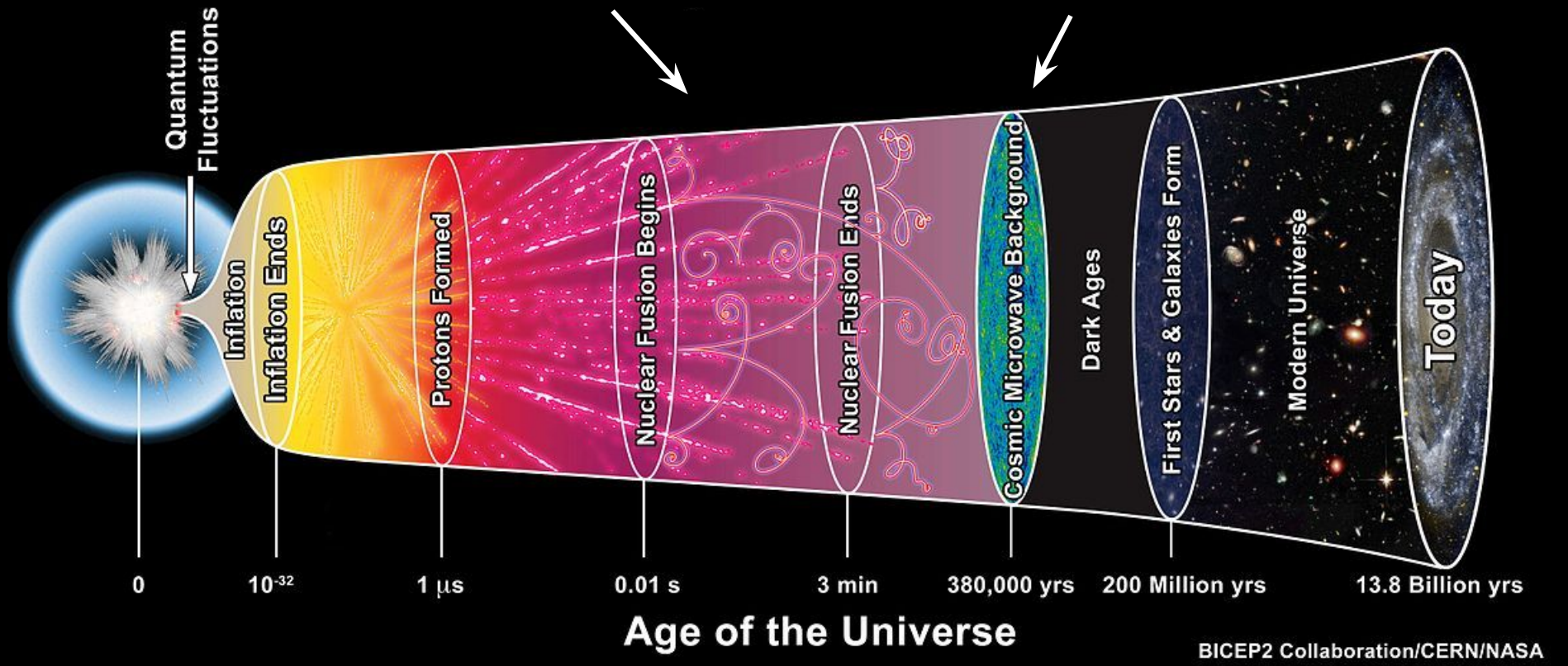
LSST+DESI+CMB-S4 forecast: **0.03 eV**



MASSIVE COSMIC NEUTRINOS

CνB :
One second after the Big Bang

CMB :
380,000 yrs after the Big Bang



CνB :
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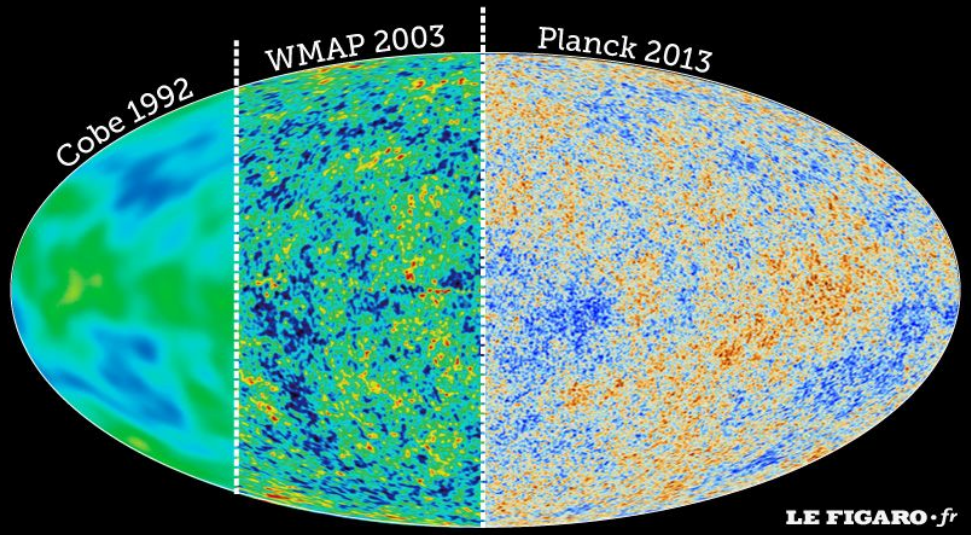
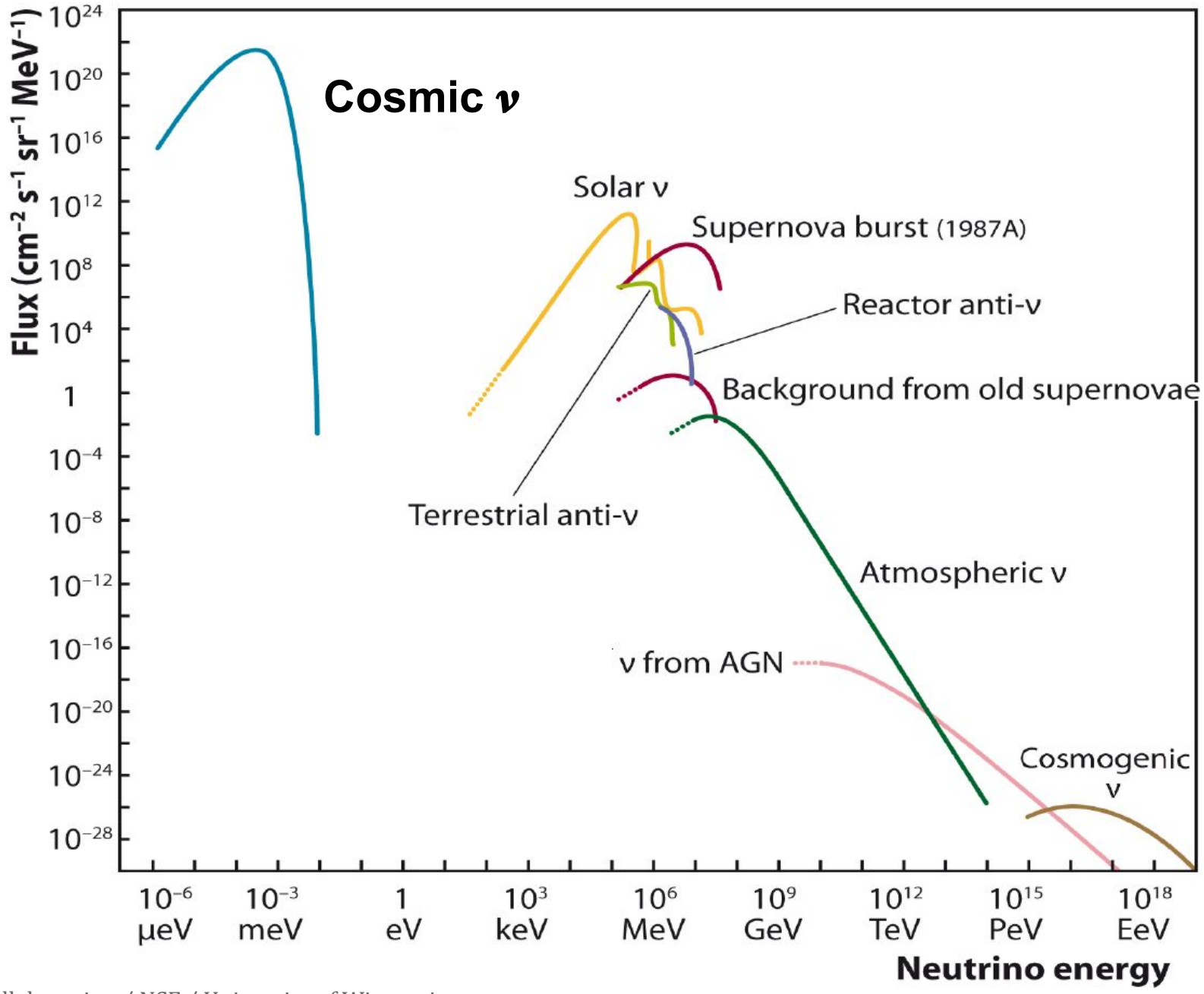
380,000 yrs after the Big Bang

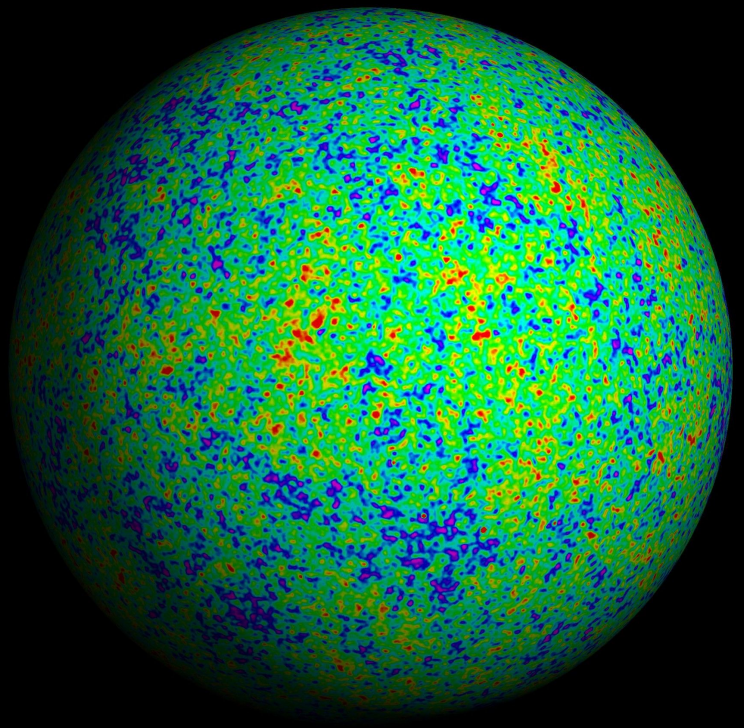
?

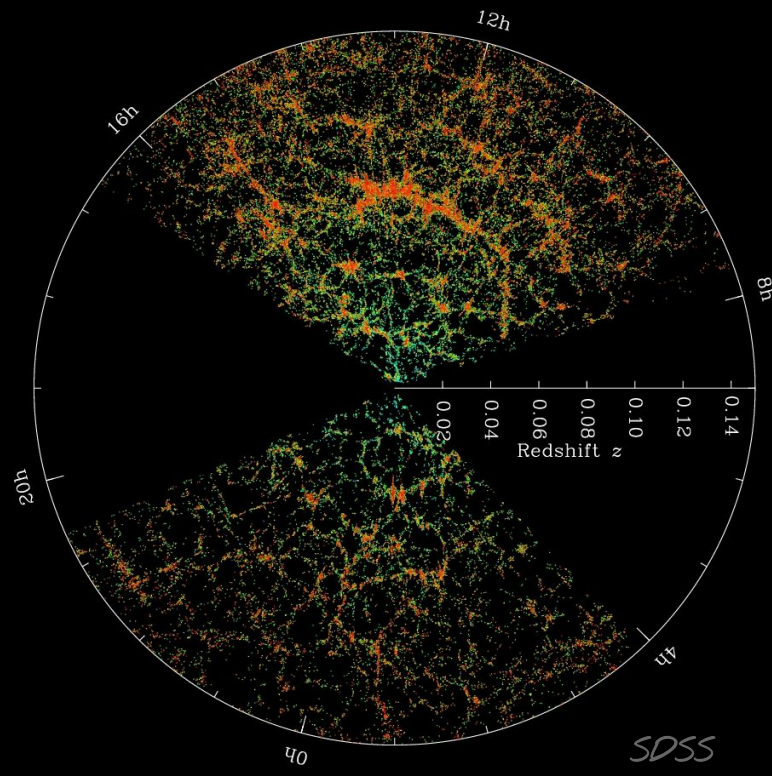




IceCube collaboration / NSF / University of Wisconsin

Structure Formation



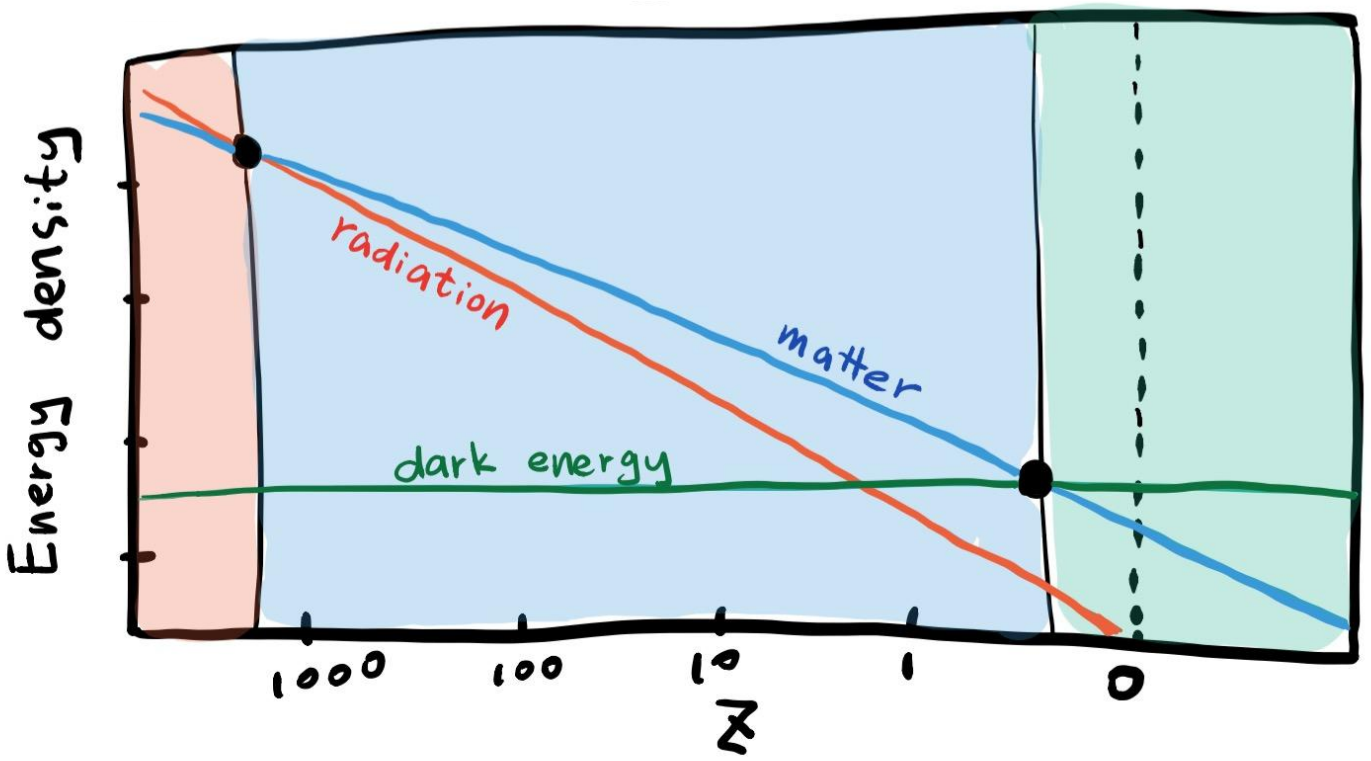


Cosmic Microwave Background:
Extremely **Gaussian** Field

Large Scale Structure Today:
Highly Nonlinear

Massive Cosmic Neutrinos

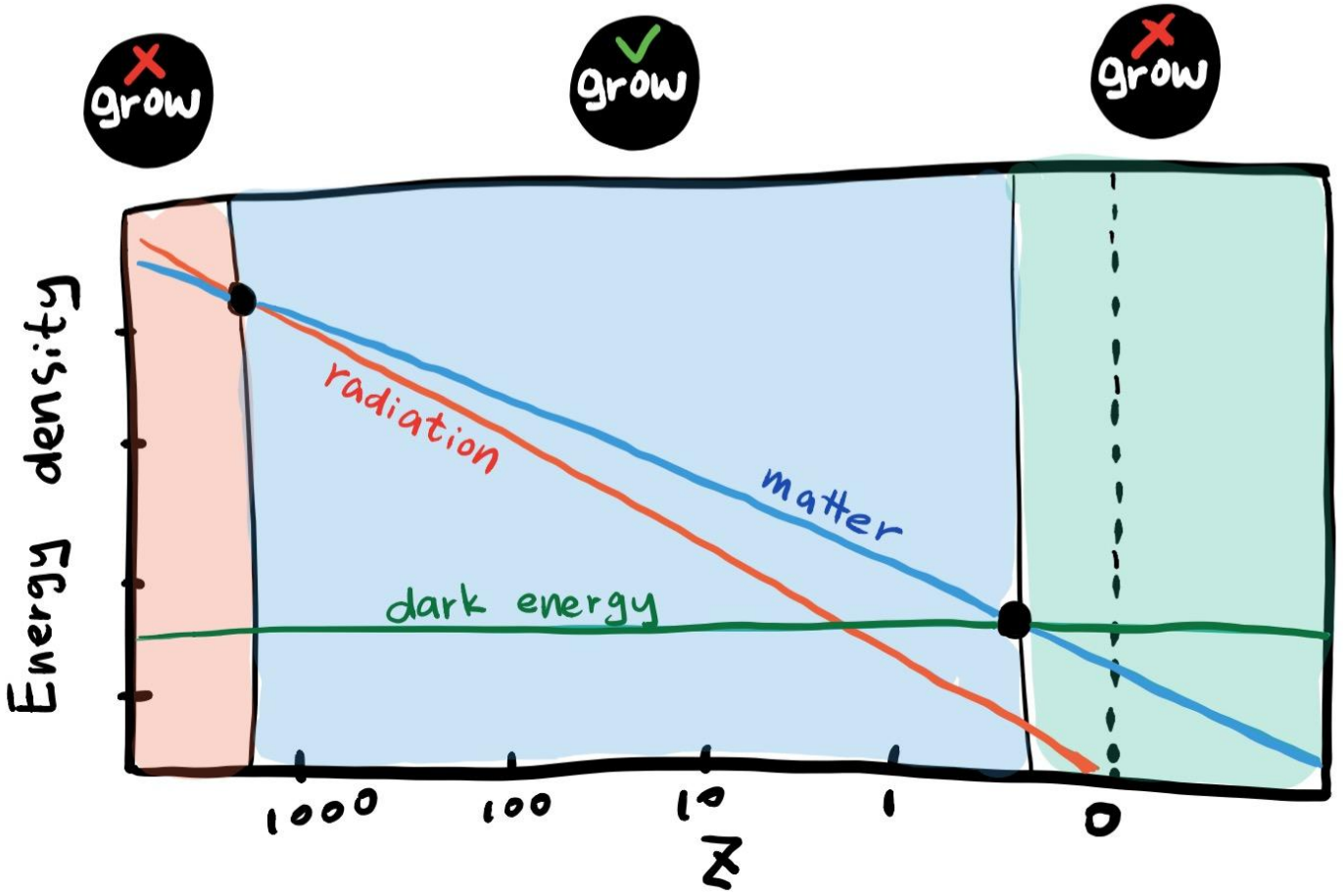
Change Matter-Radiation Equality



Frieman, Turner, Huterer 2008

Massive Cosmic Neutrinos

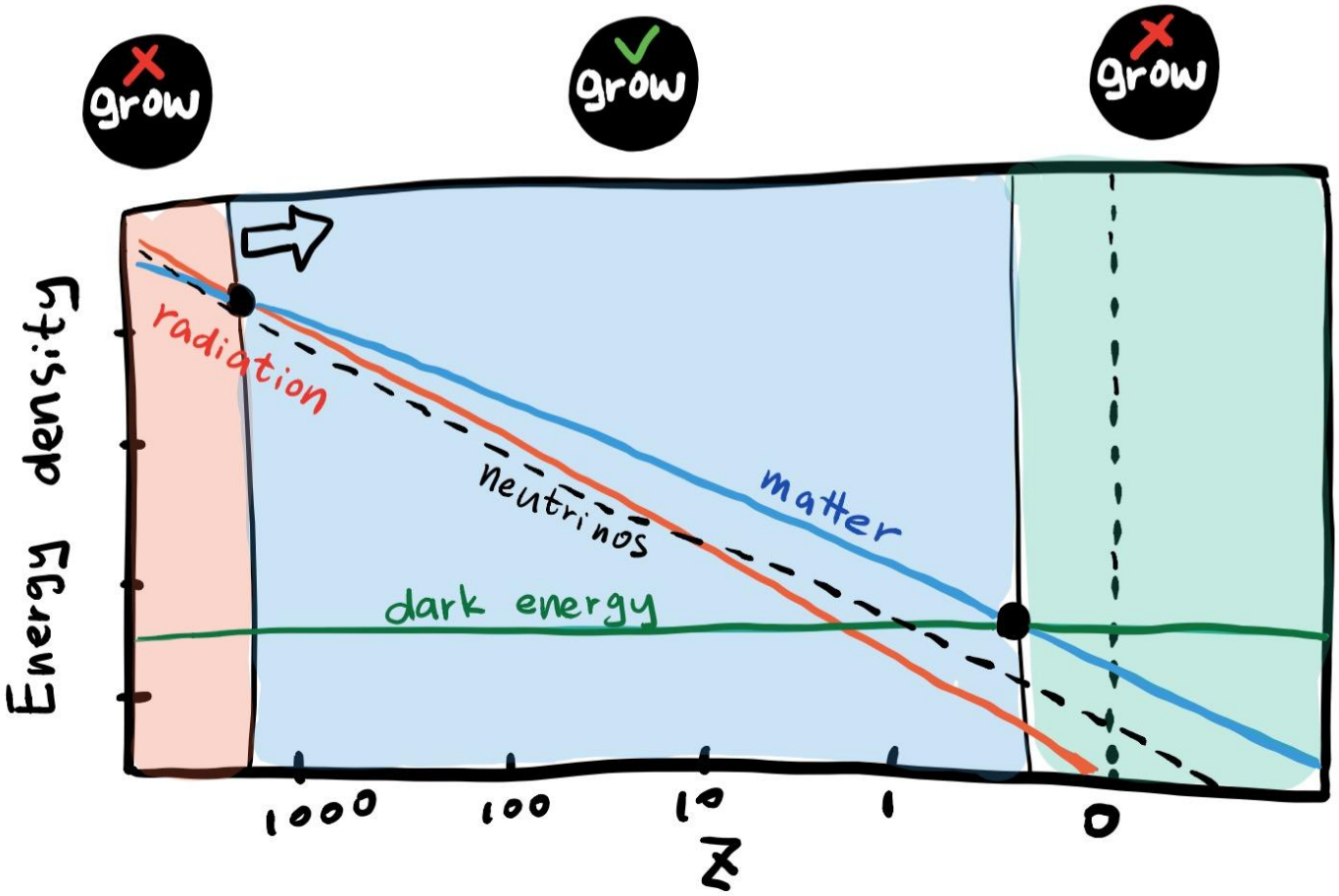
Change Matter-Radiation Equality



Frieman, Turner, Huterer 2008

Massive Cosmic Neutrinos

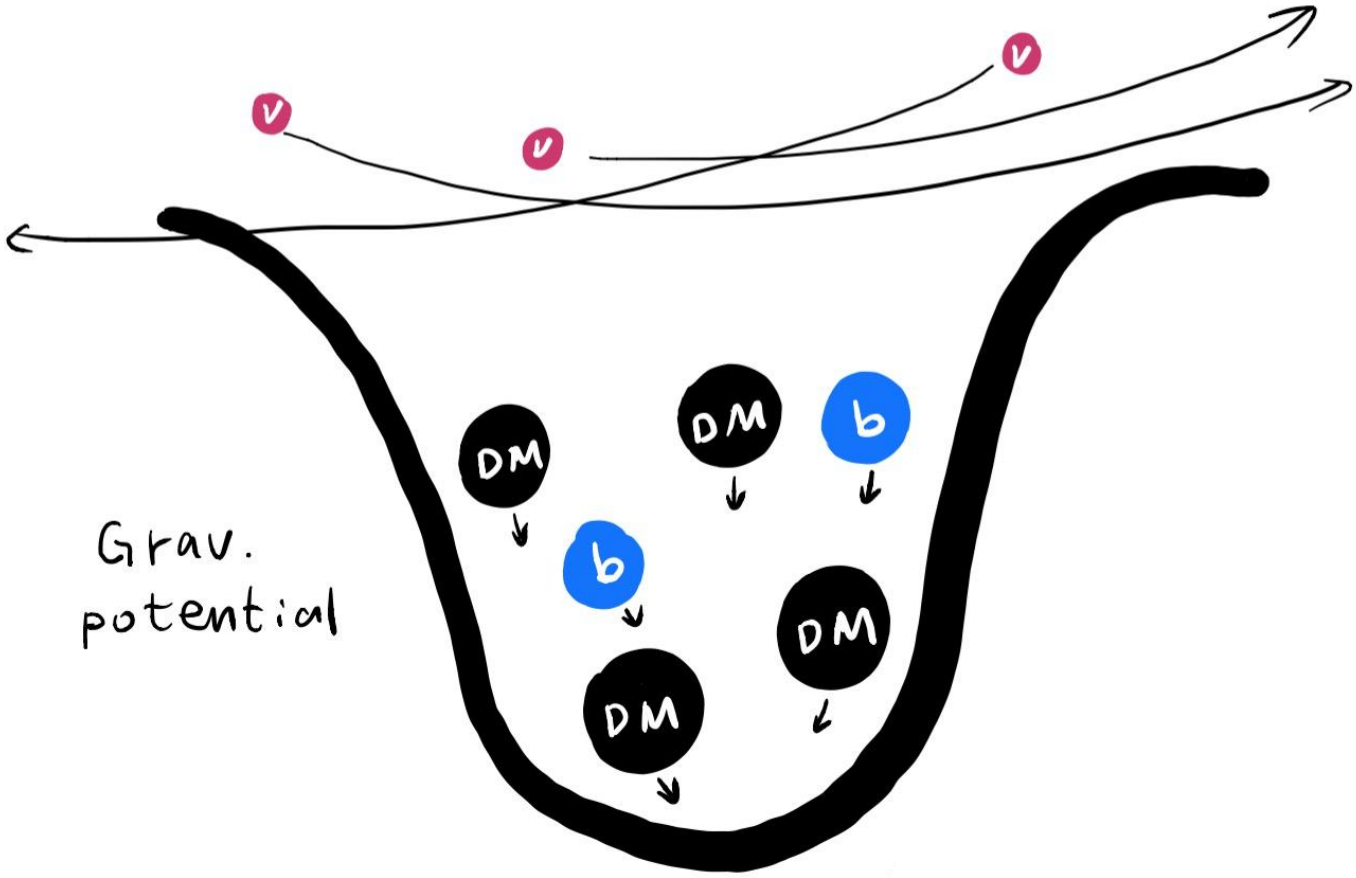
Change Matter-Radiation Equality



Frieman, Turner, Huterer 2008

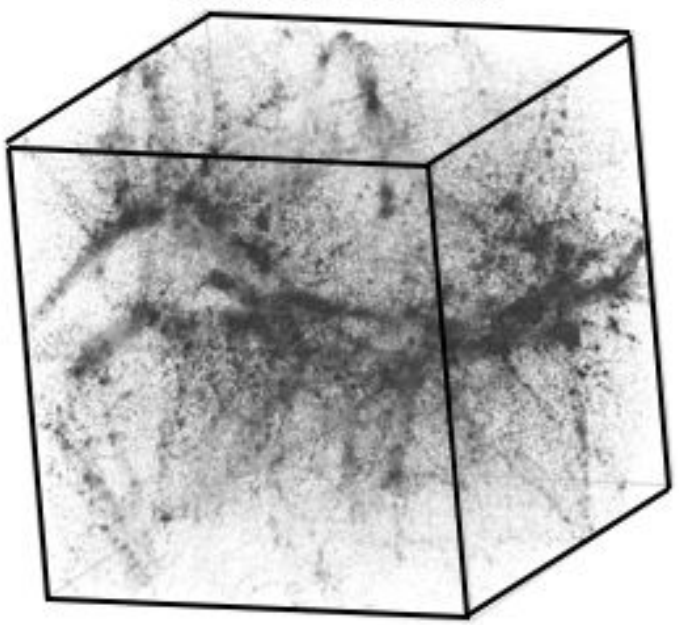
Massive Cosmic Neutrinos

Free stream out of potential wells

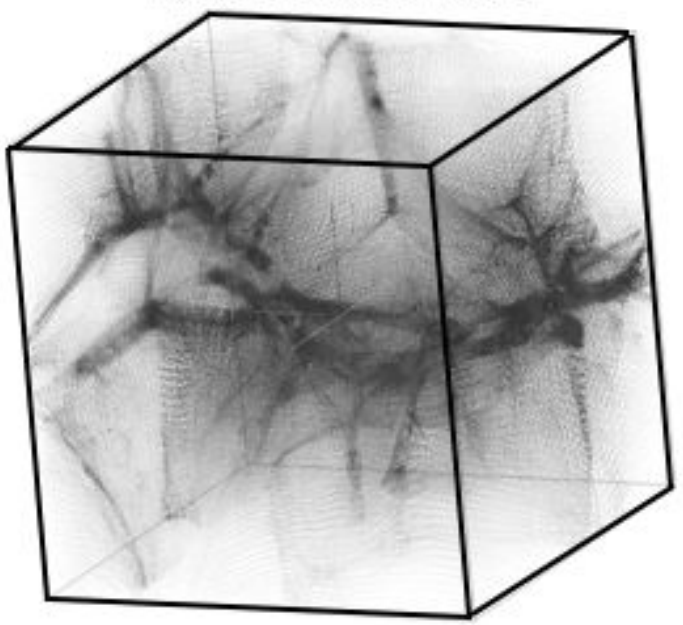


Large Scale Structure

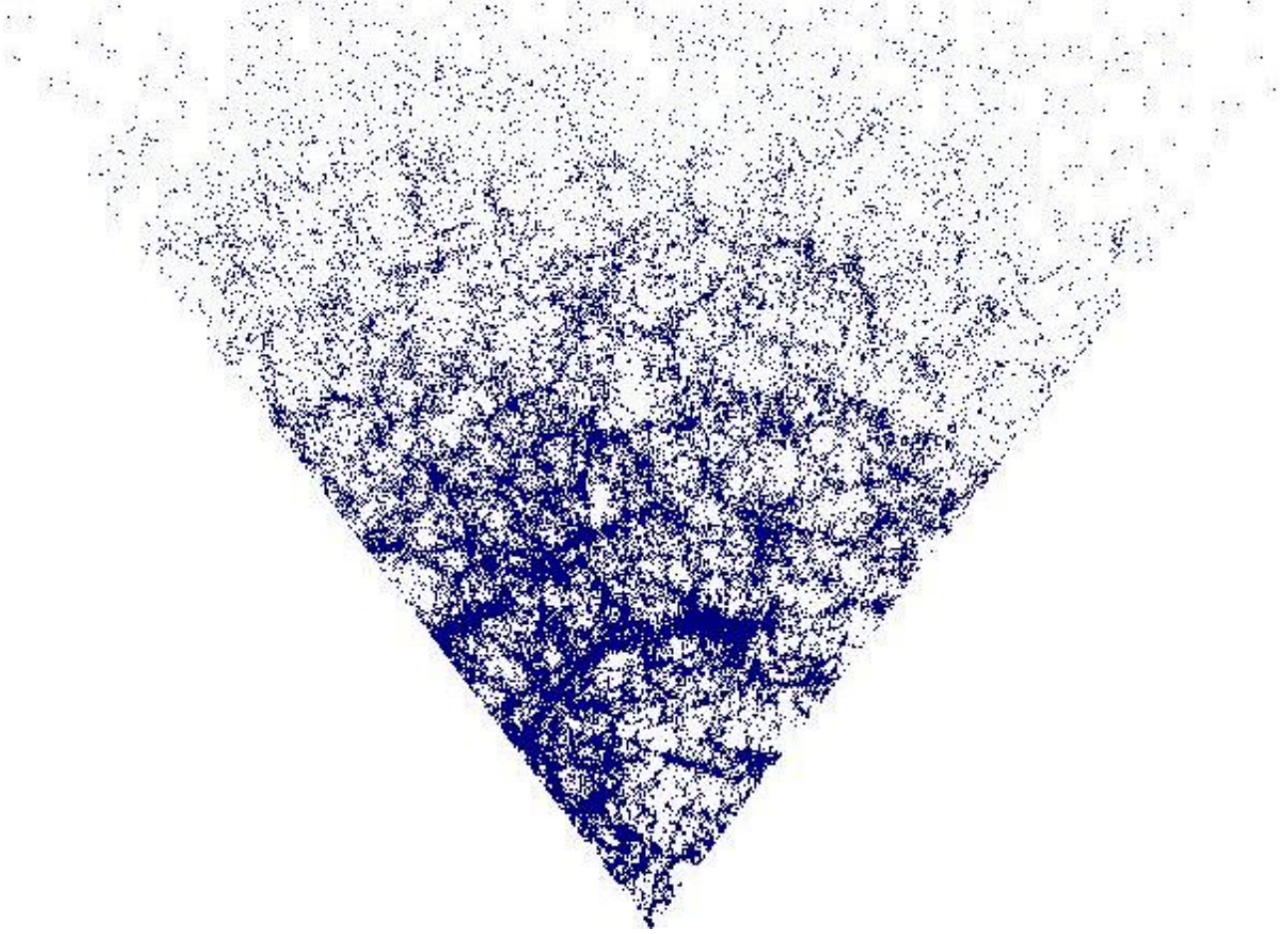
Standard Model of Cosmology



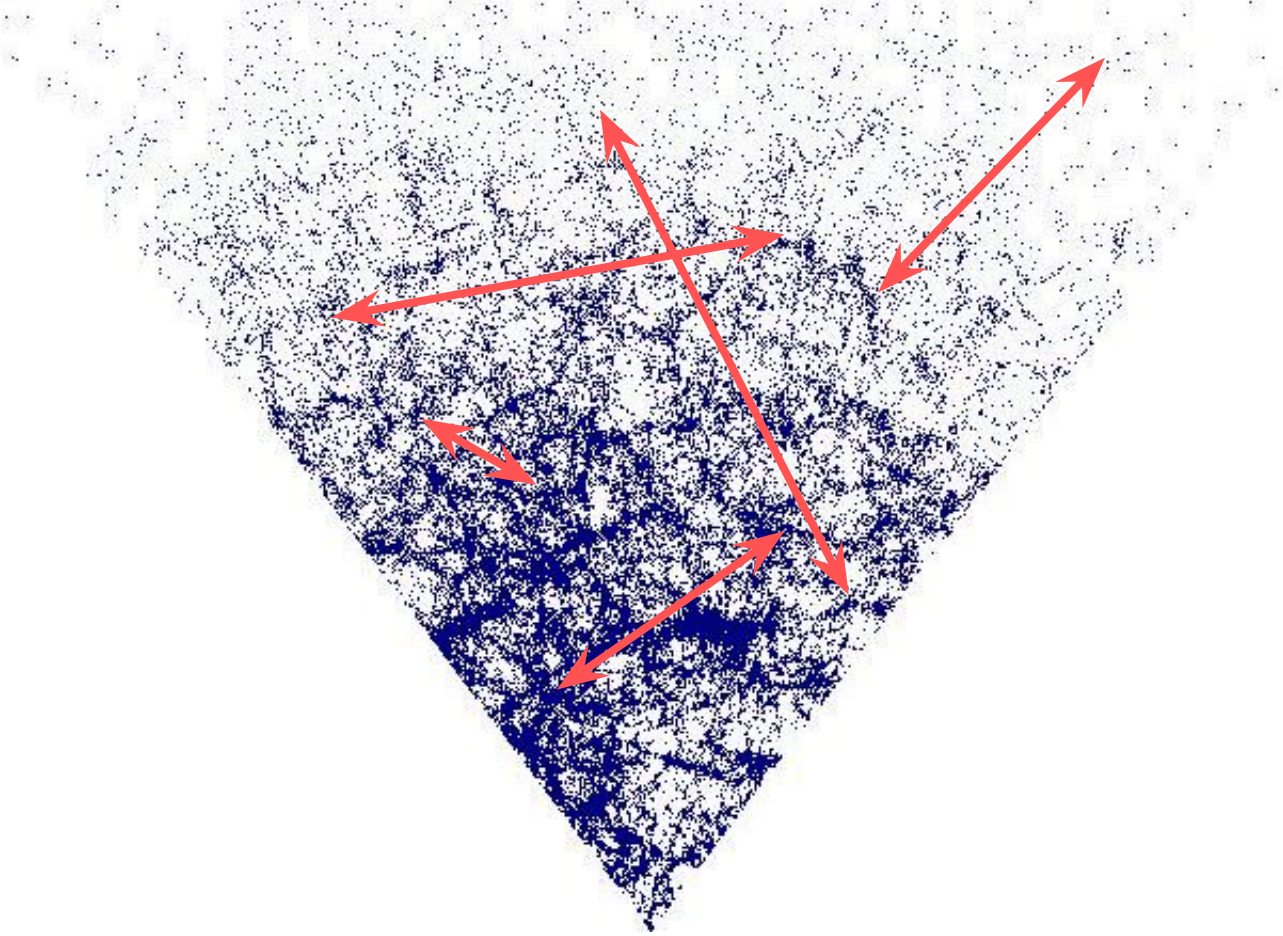
Massive Neutrinos



NONLINEAR COSMOLOGY



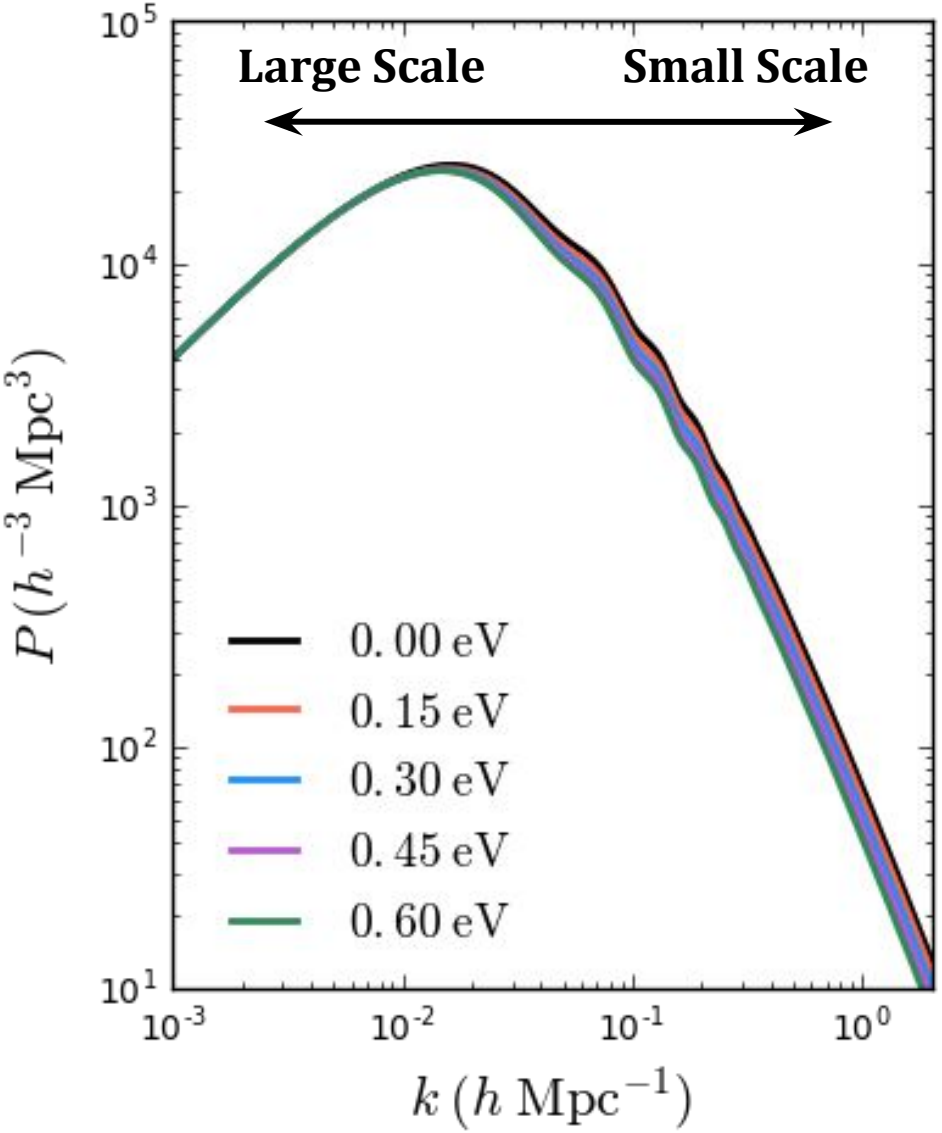
What do we do with all these beautiful Cosmological data ?

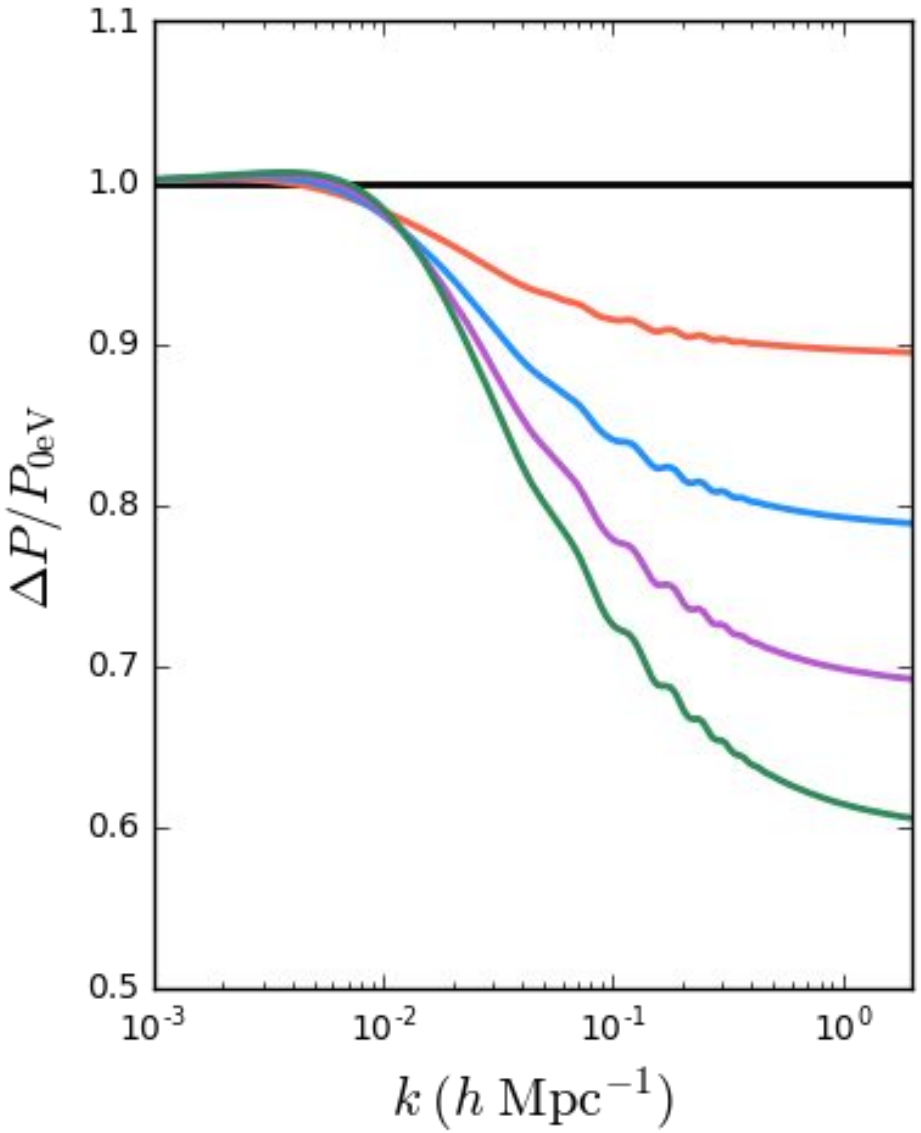


Two Point Correlation Function

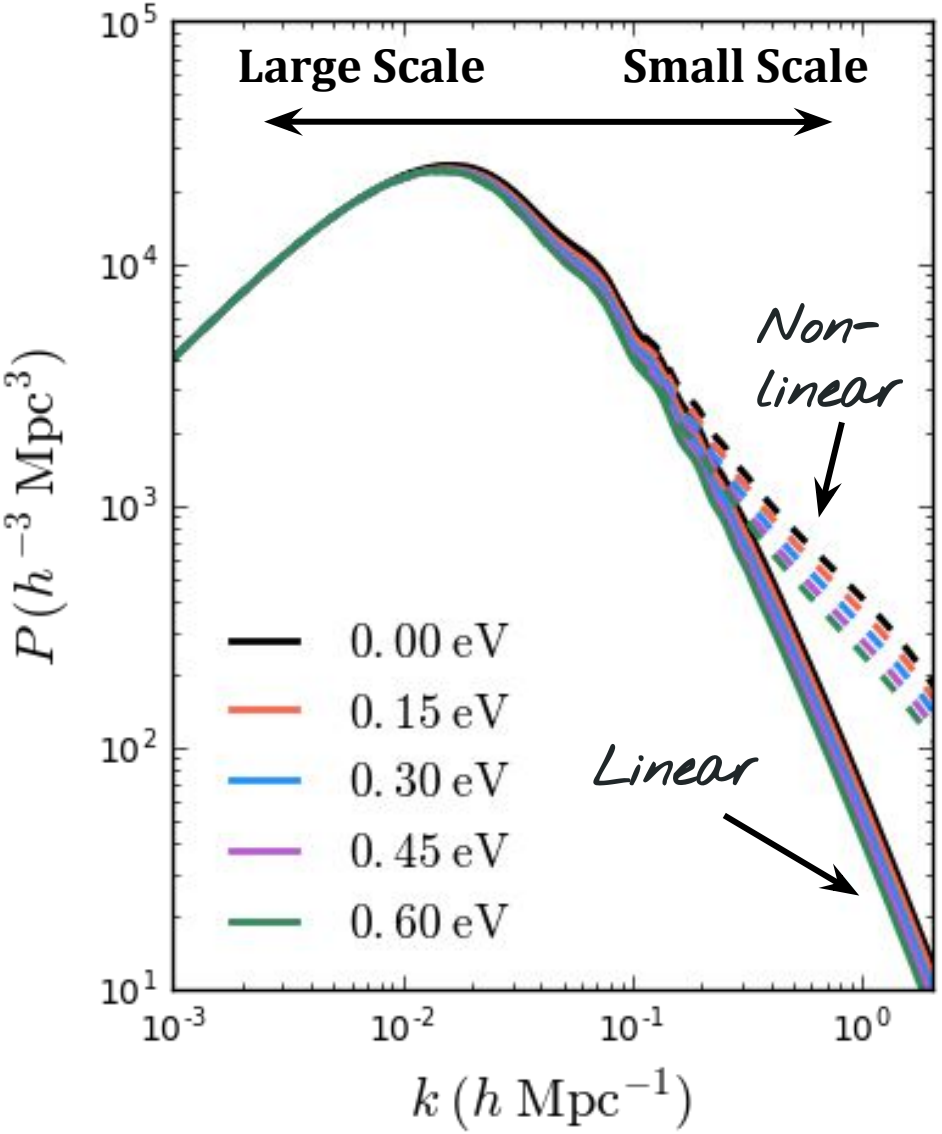
Find one random galaxy and then ask:
"Looking at a position x Mpc away,
how likely is it to find another galaxy?"

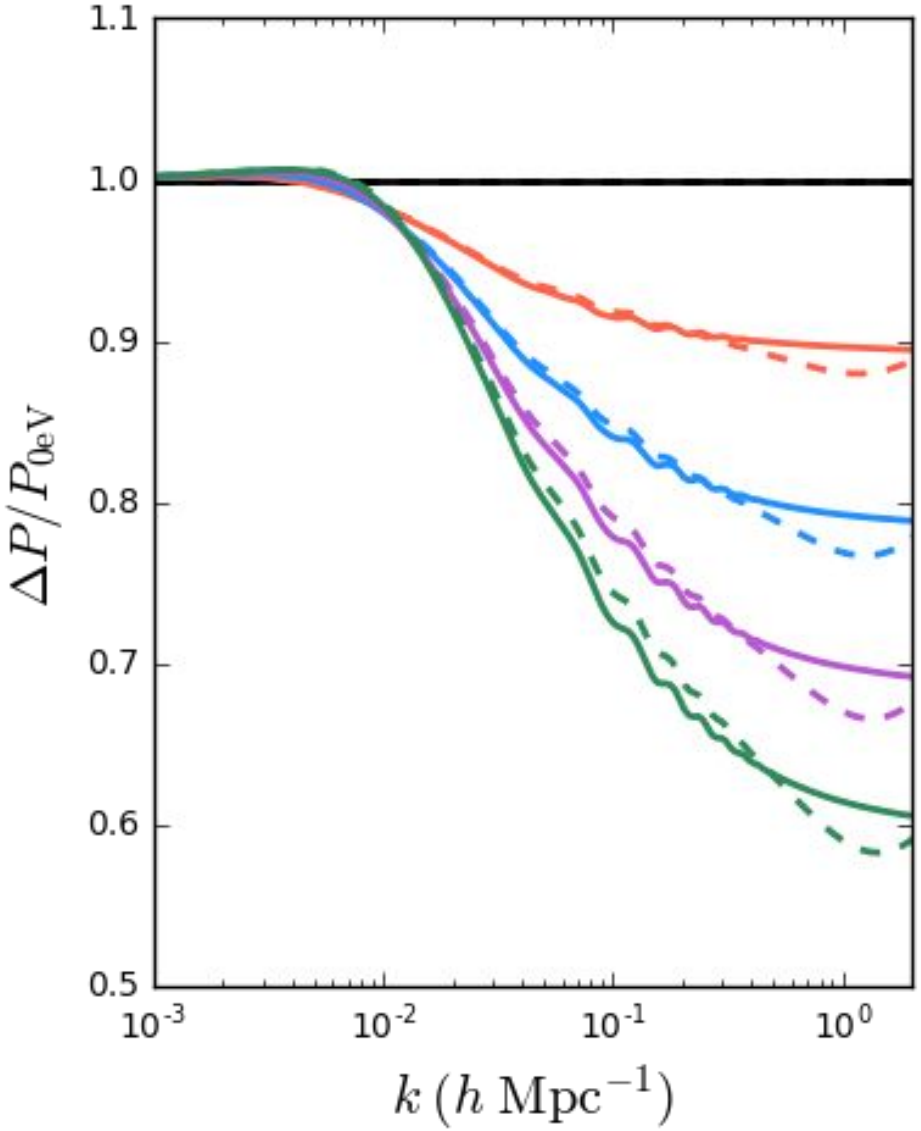
Matter Power Spectrum





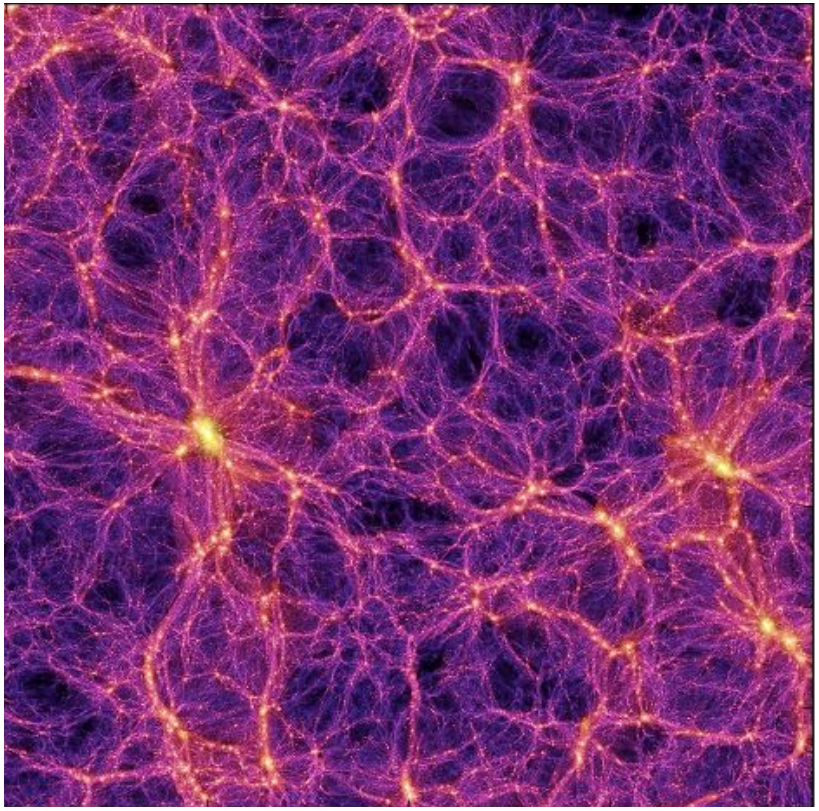
Nonlinear Matter Power Spectrum





Even worse

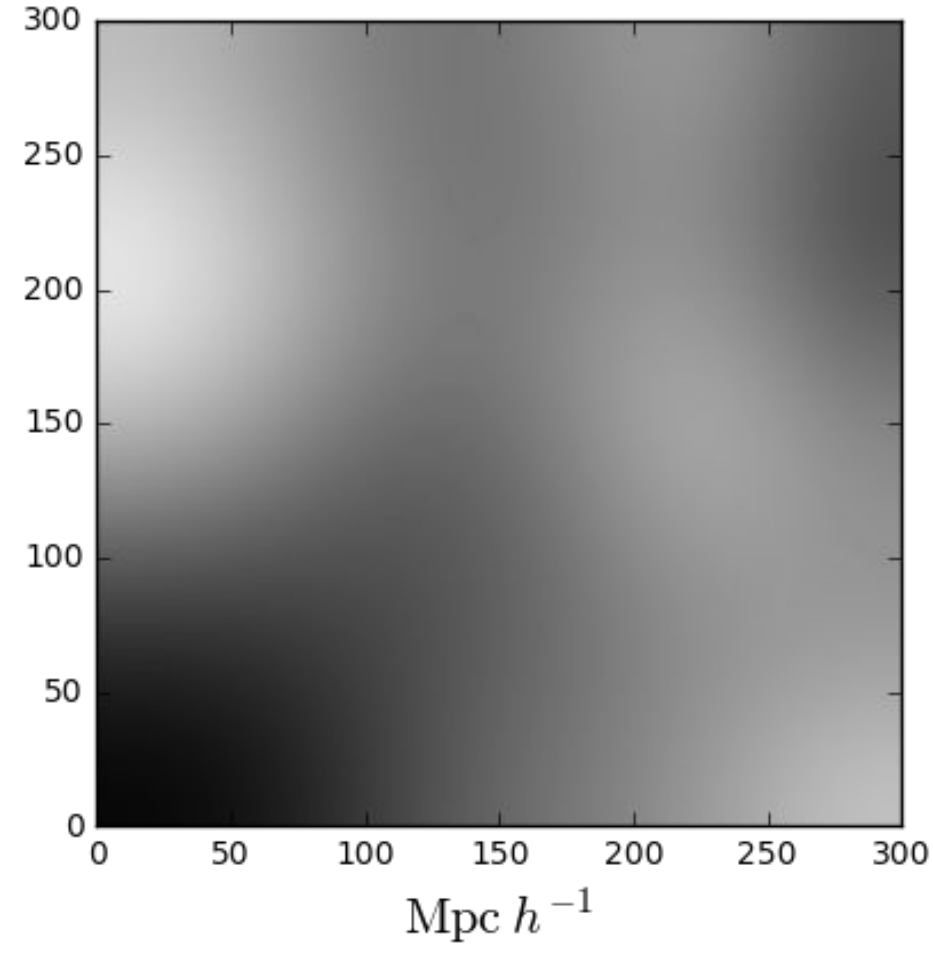
The **nonlinear** power spectrum is still insufficient…

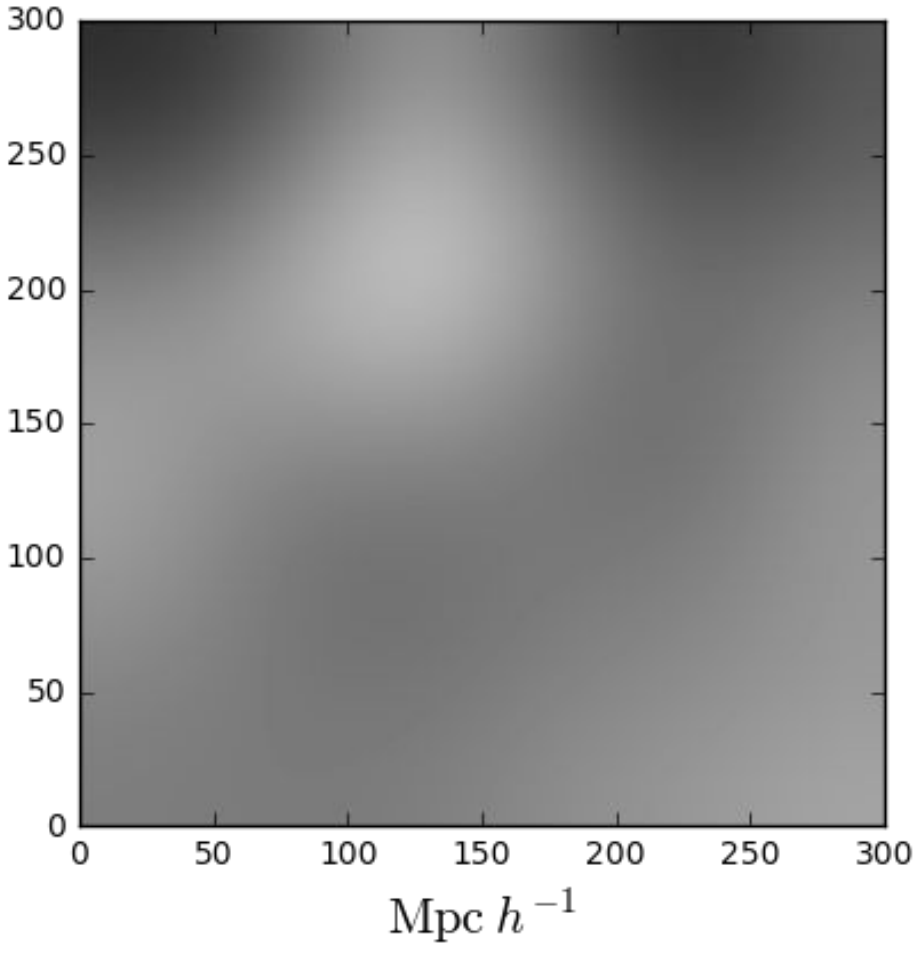


(next, a demonstration with the Millennium simulation)

Smoothing Scale = 50 Mpc

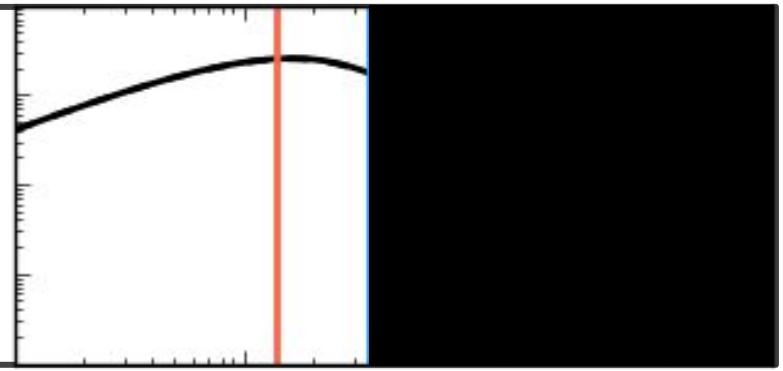
Millennium simulation, Springel et al. 2005

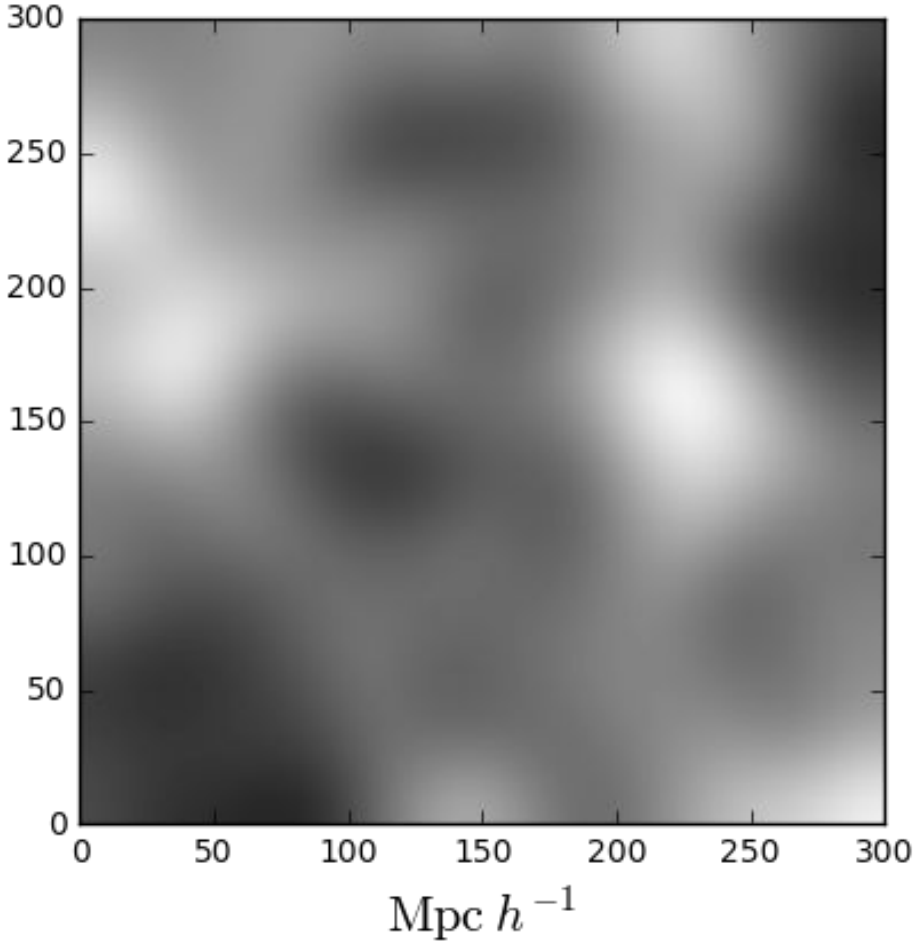


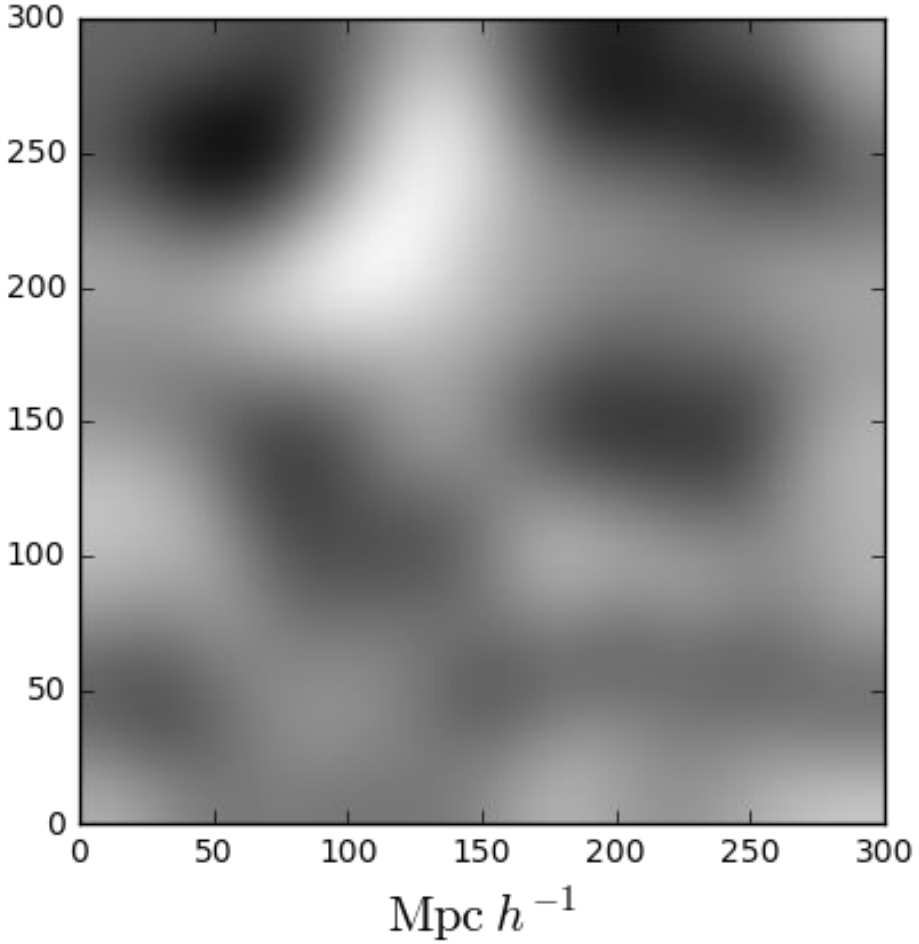


Smoothing Scale = 20 Mpc

Millennium simulation, Springel et al. 2005

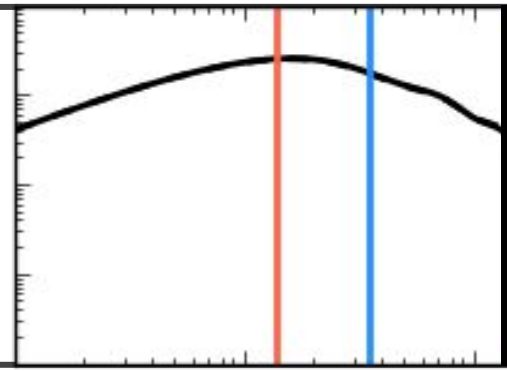


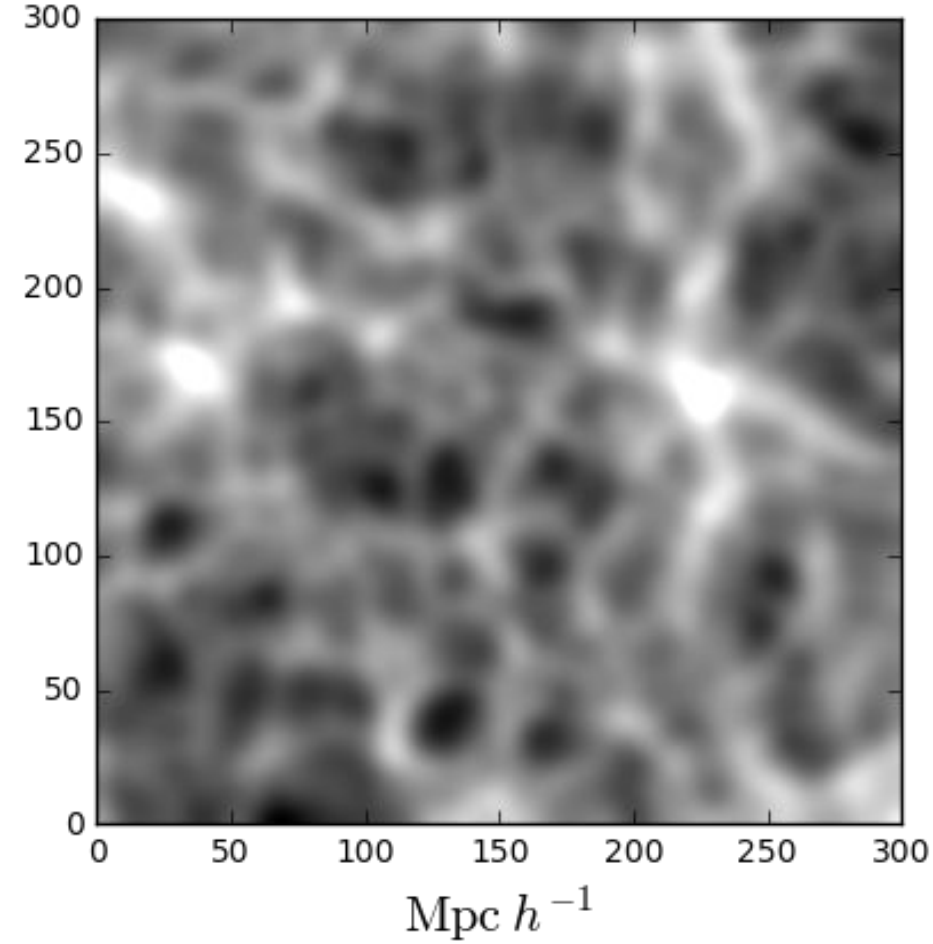


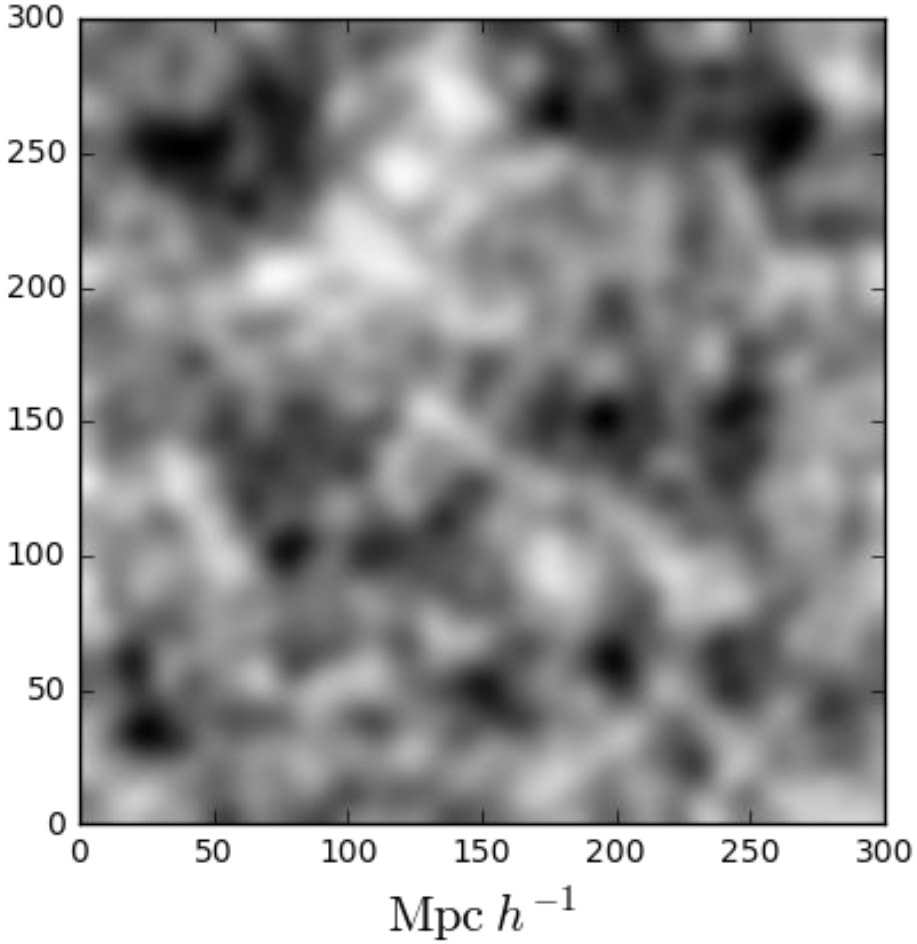


Smoothing Scale $= 5$ Mpc

Millennium simulation, Springel et al. 2005

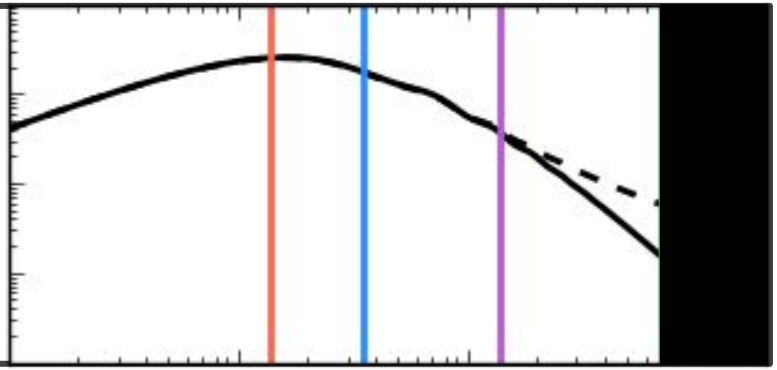


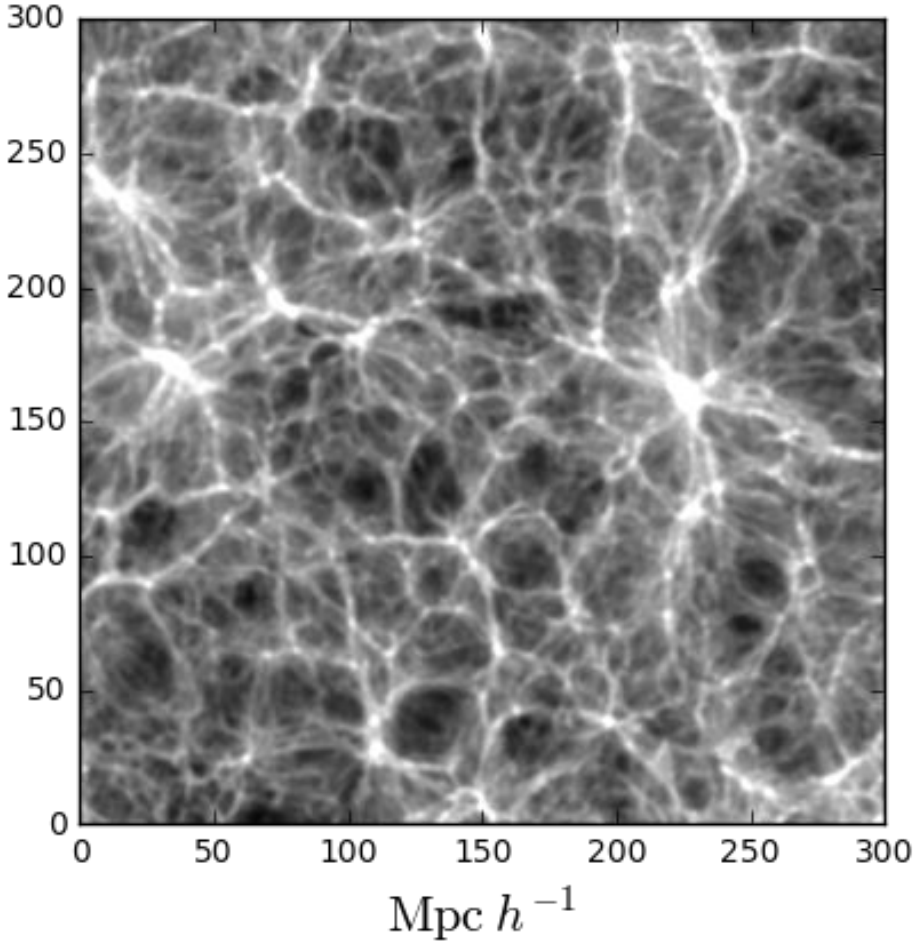


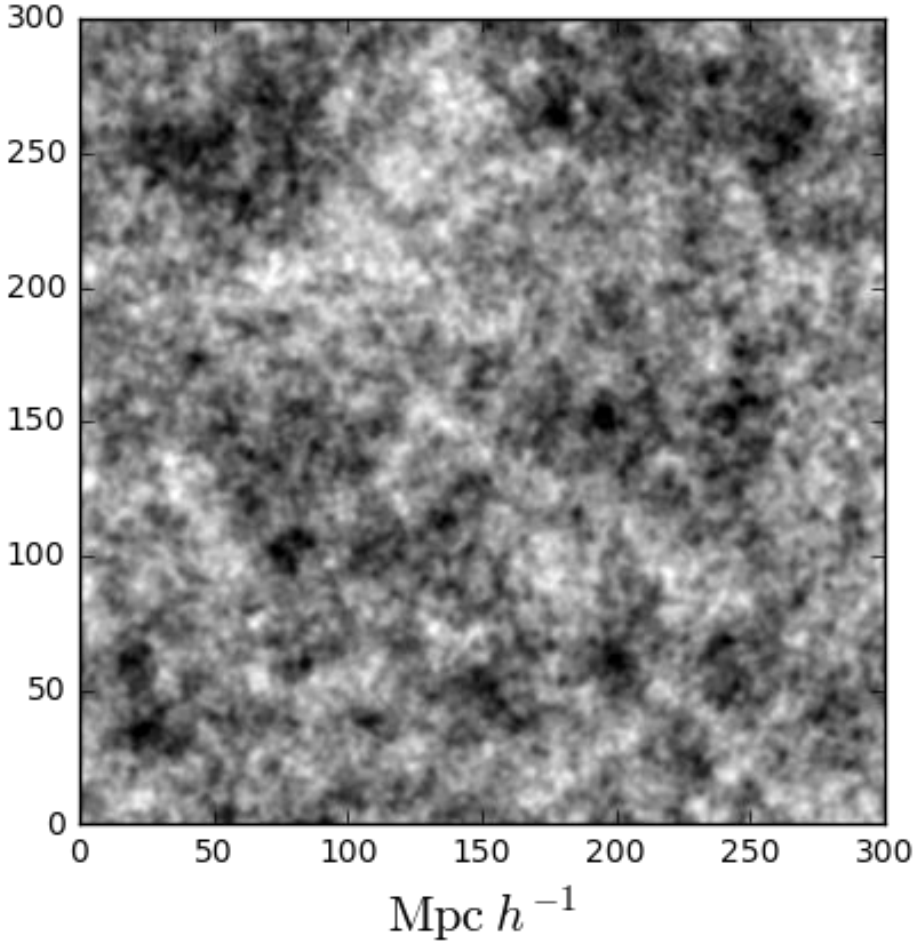


Smoothing Scale $= 1$ Mpc

Millennium simulation, Springel et al. 2005

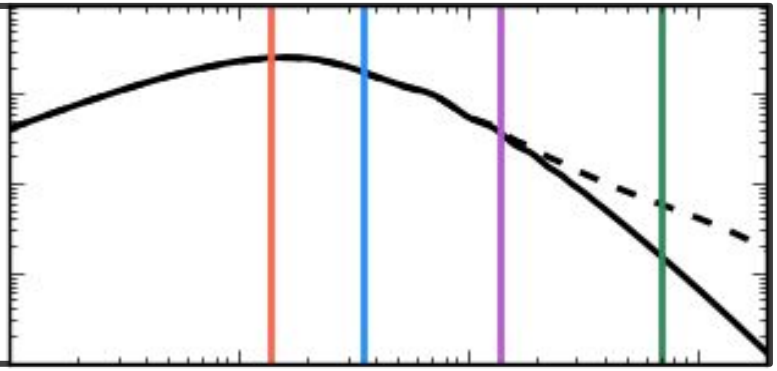


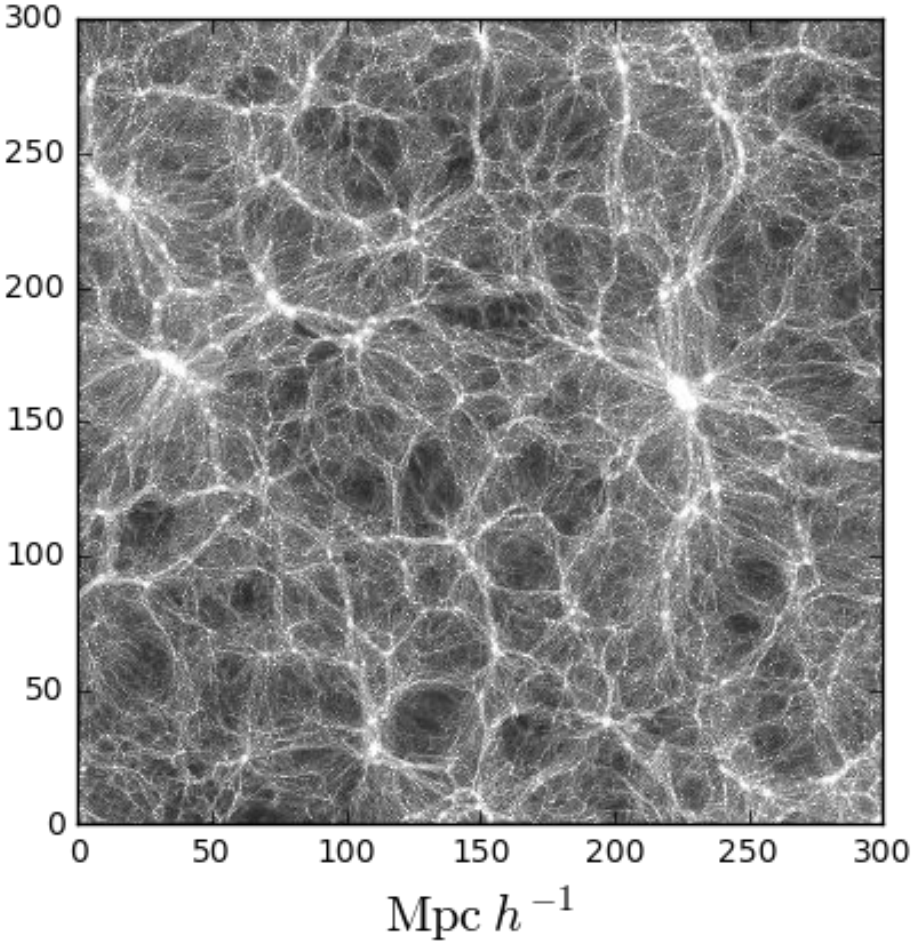


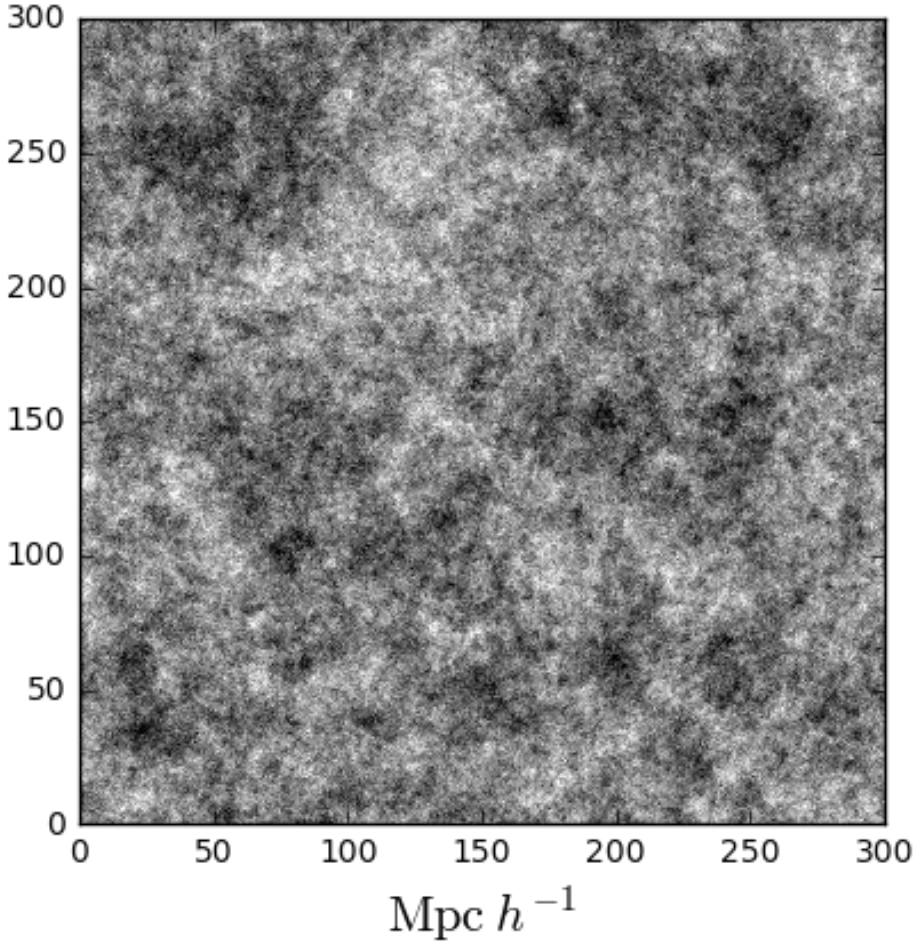


Smoothing Scale $= 0$ Mpc

Millennium simulation, Springel et al. 2005







Origin of non-Gaussianity

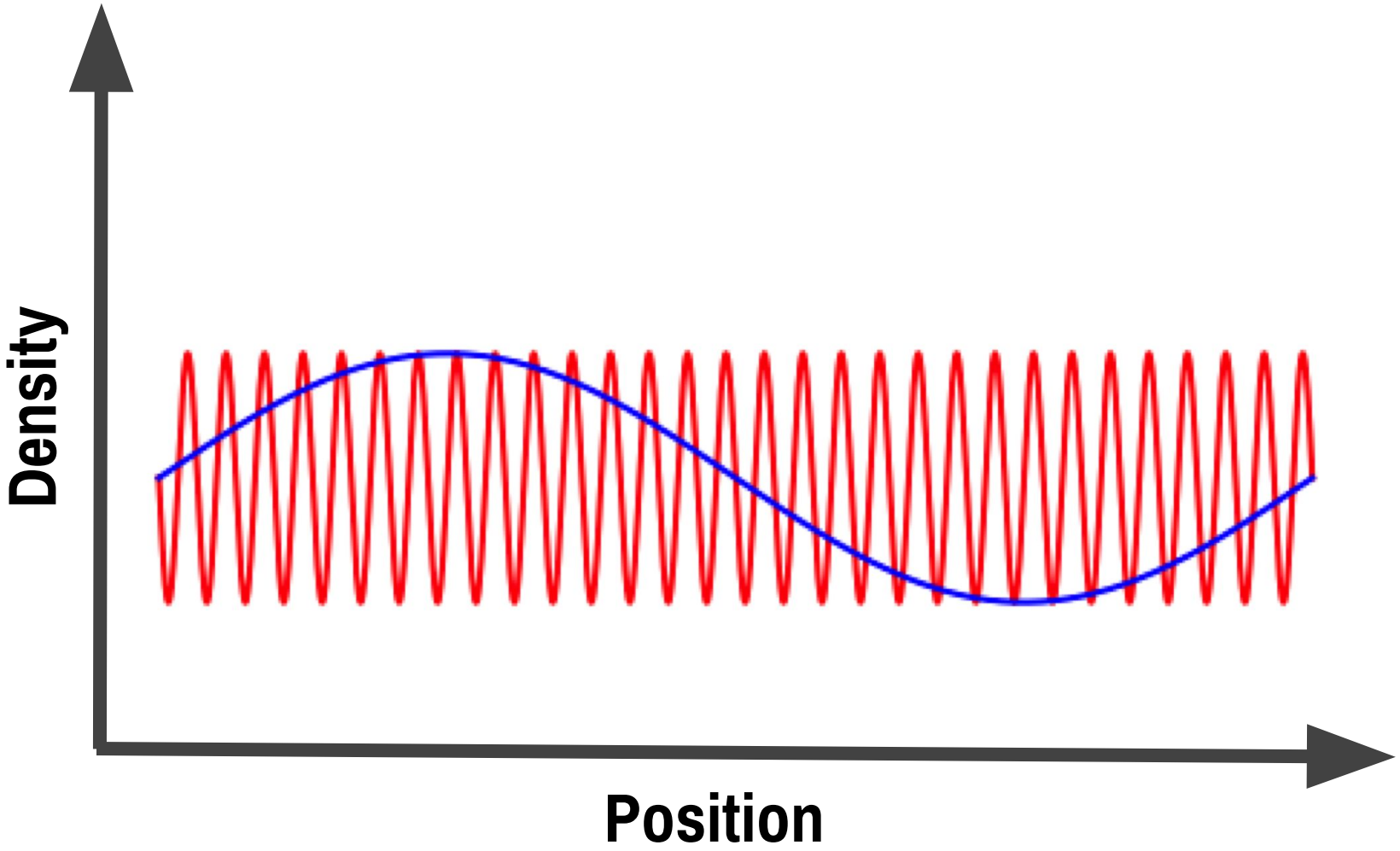


Illustration: Emmanuel Schaan

Origin of non-Gaussianity

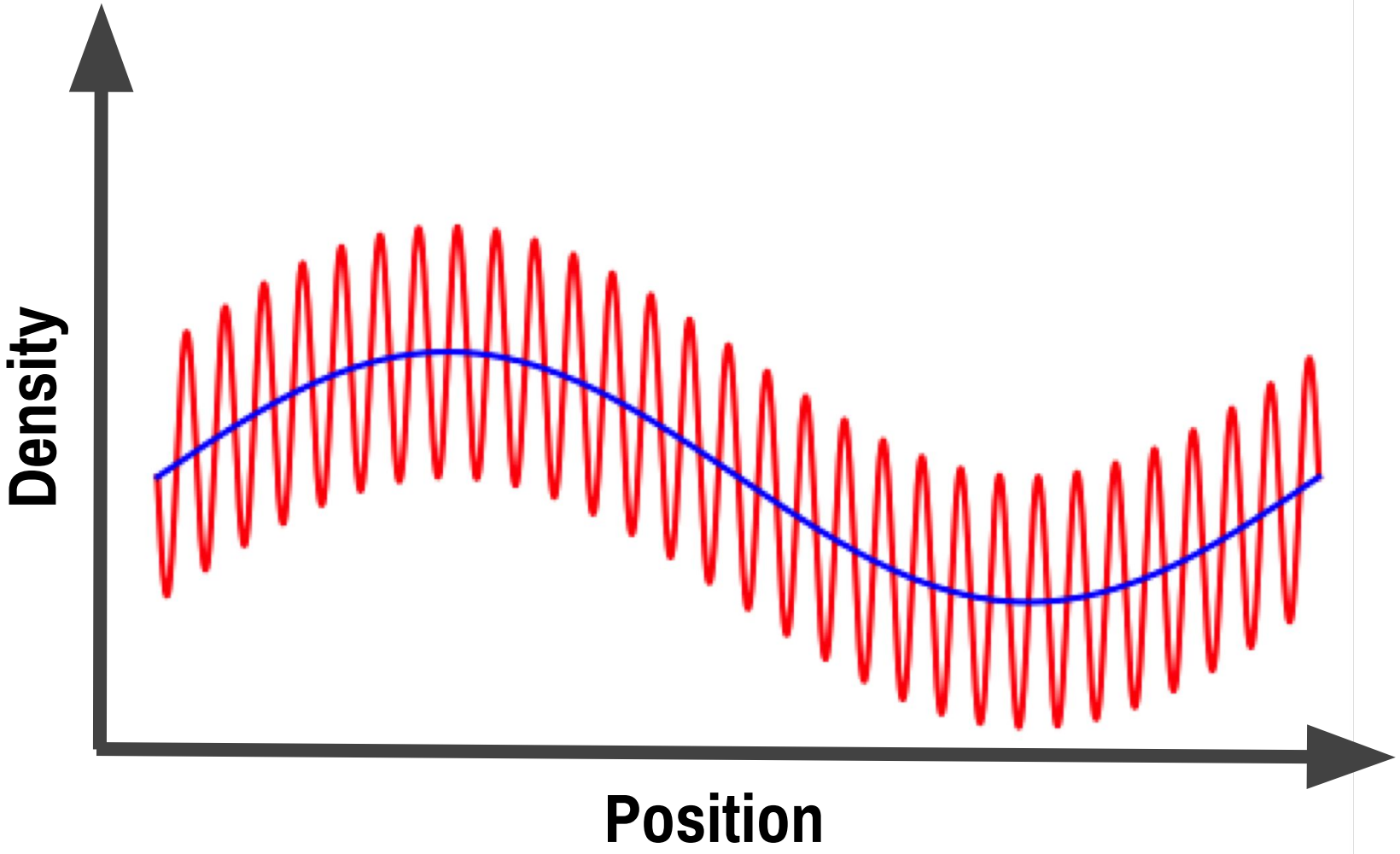


Illustration: Emmanuel Schaan

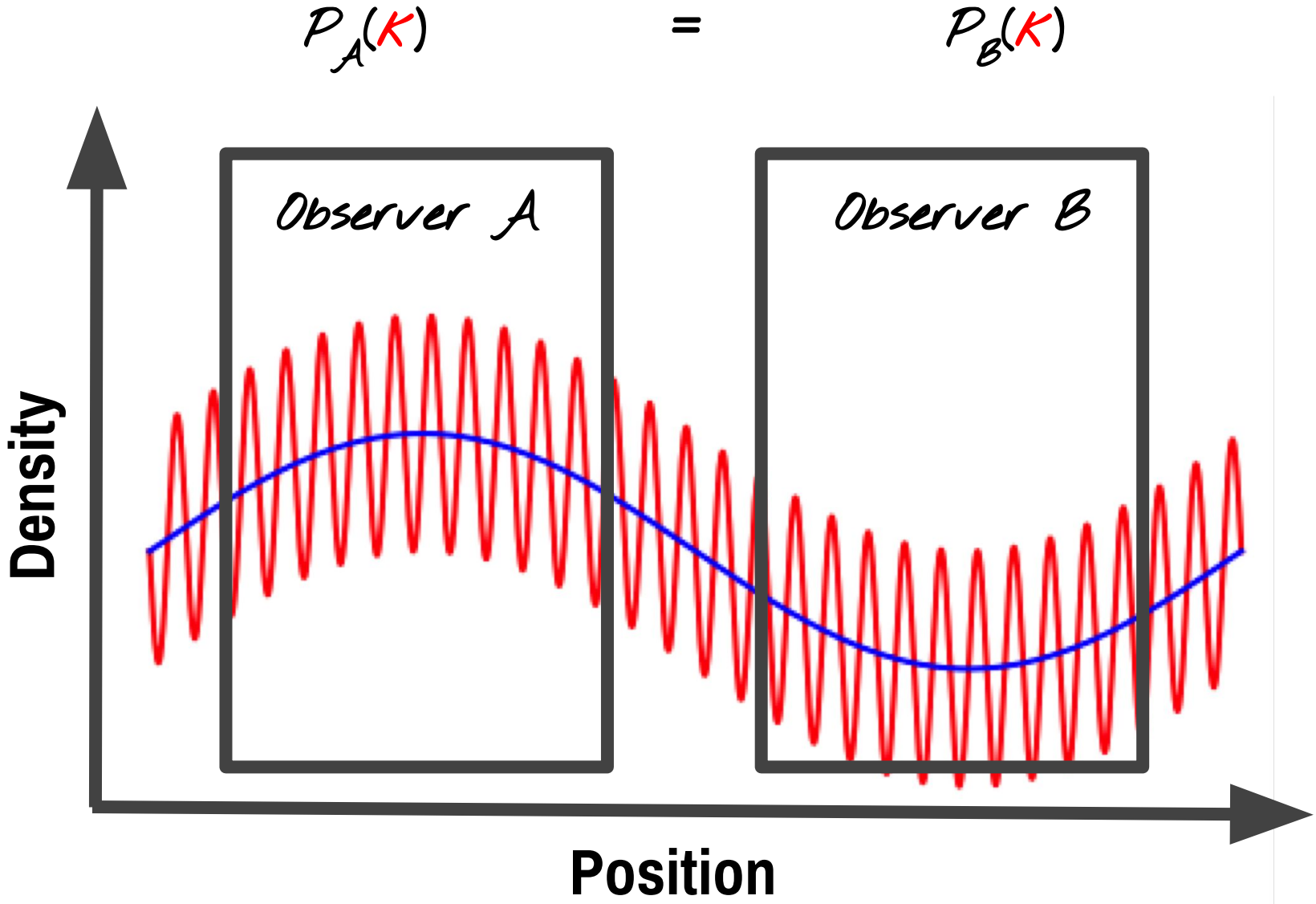


Illustration: Emmanuel Schaan

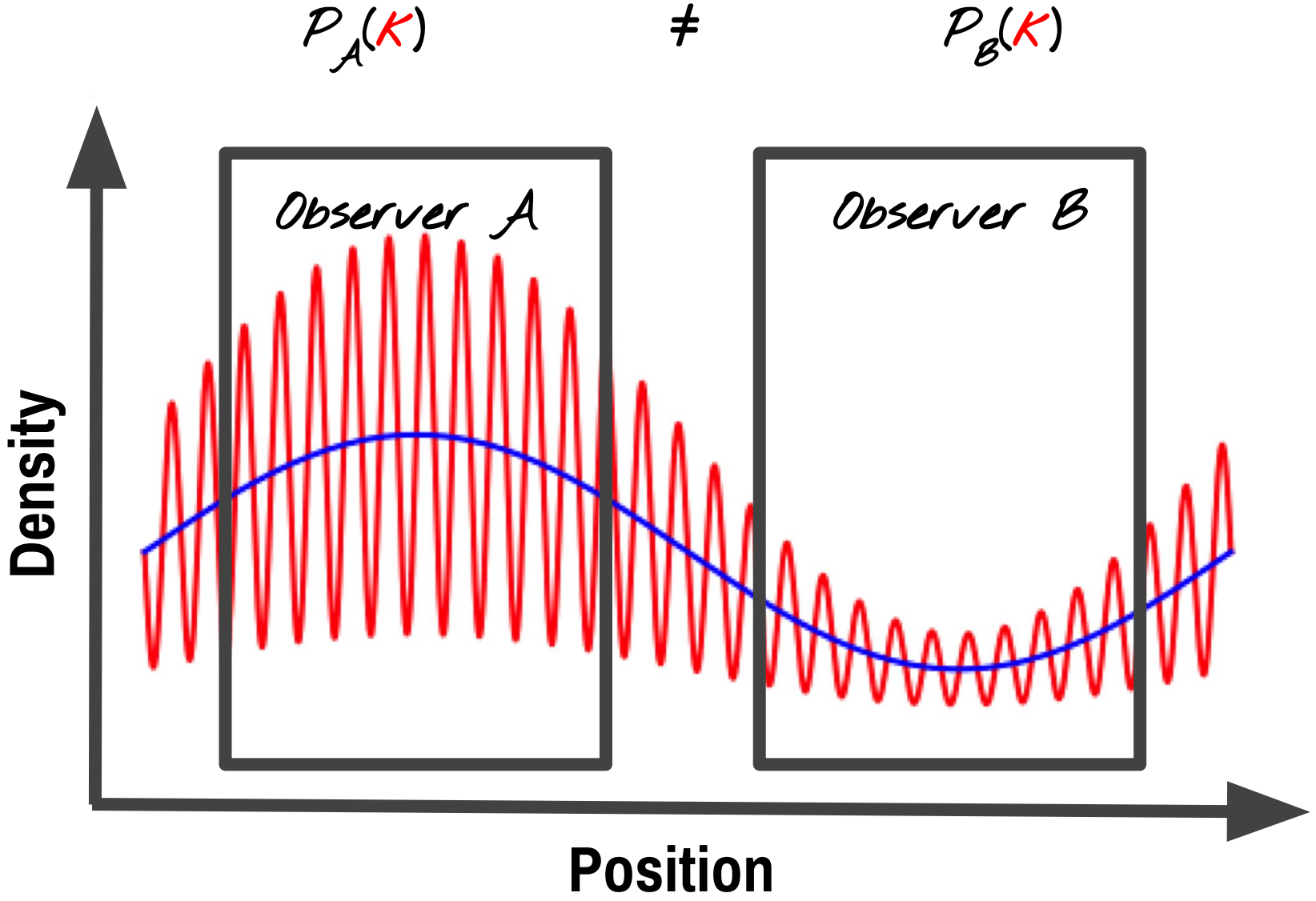


Illustration: Emmanuel Schaan

MASSIVENUS

COSMOLOGICAL MASSIVE NEUTRINO SIMULATIONS

MassiveNuS

JL et al. 2018, 1711.10524

Cosmological Massive Neutrino Simulations

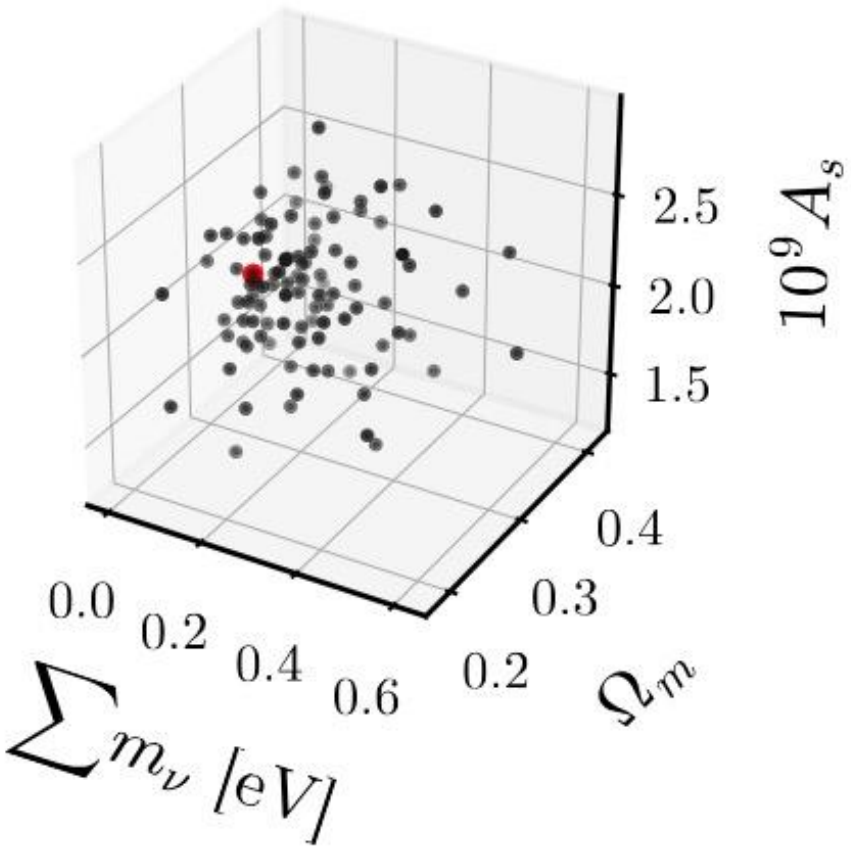
101 cosmological models
capturing the full **nonlinear** evolution
in massive neutrino cosmologies

Data Fully Public

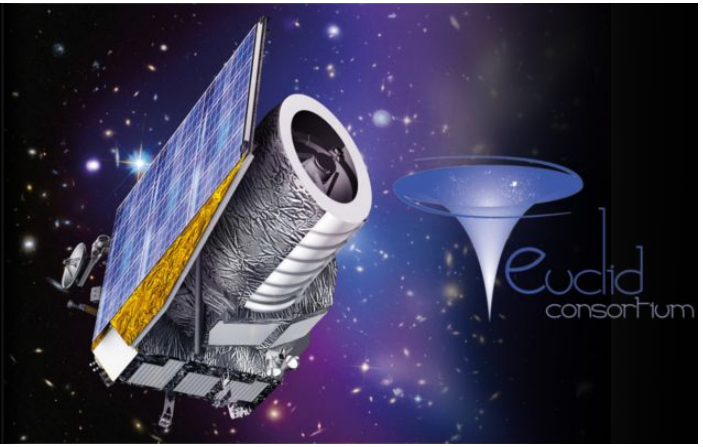
- ➔ CMB & galaxy lensing maps
- ➔ Halo catalogues
- ➔ Merger trees
- ➔ Snapshots

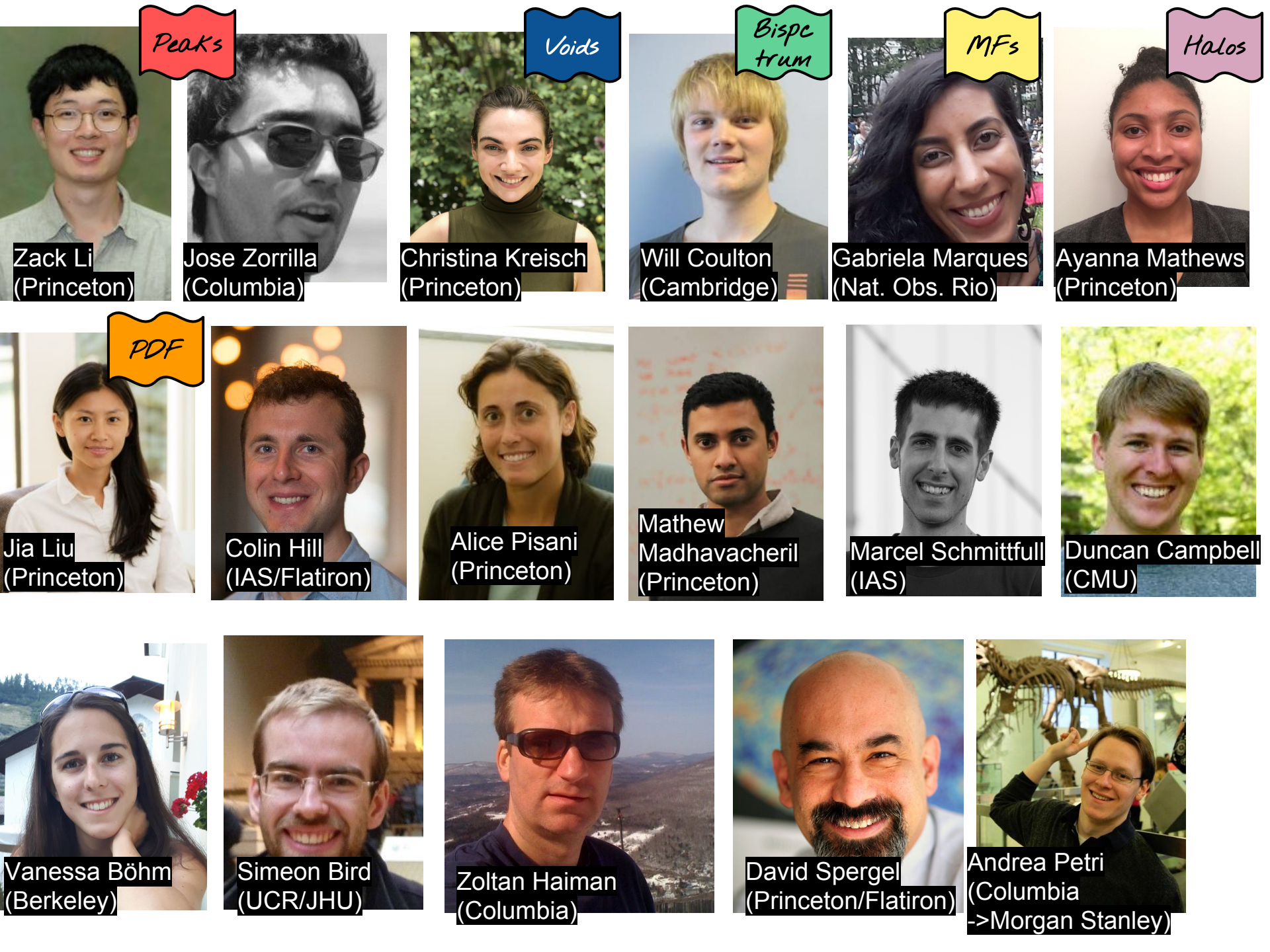
Available @ ColumbiaLensing.org
Hosted @ SkiesAndUniverses.org

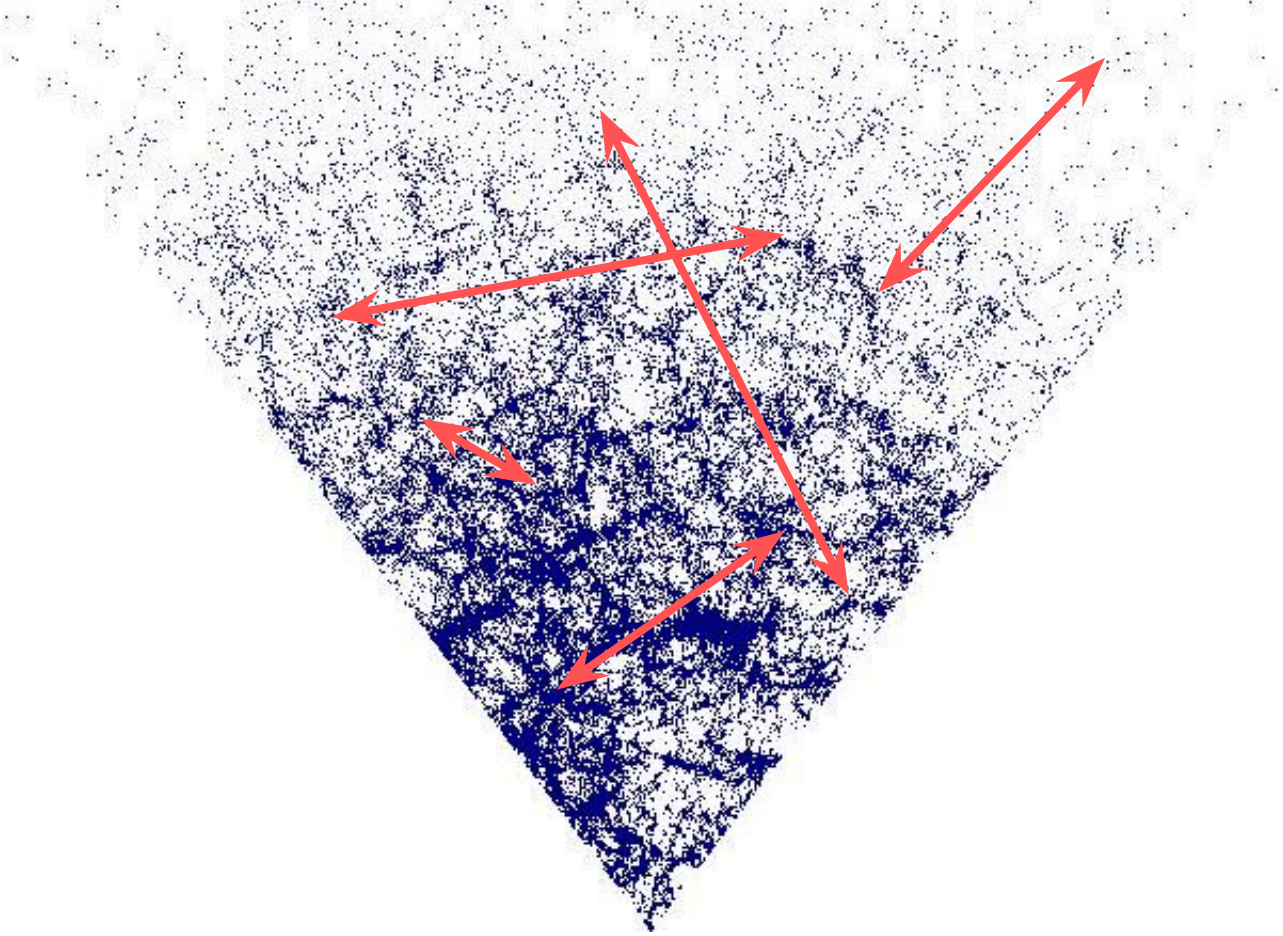
Code:
Gadget-2
1024^3 DM particles
512Mpc/h box
+ **kspace-neutrino**
+ LensTools
+ Rockstar
+ Consistent Tree



Future Surveys

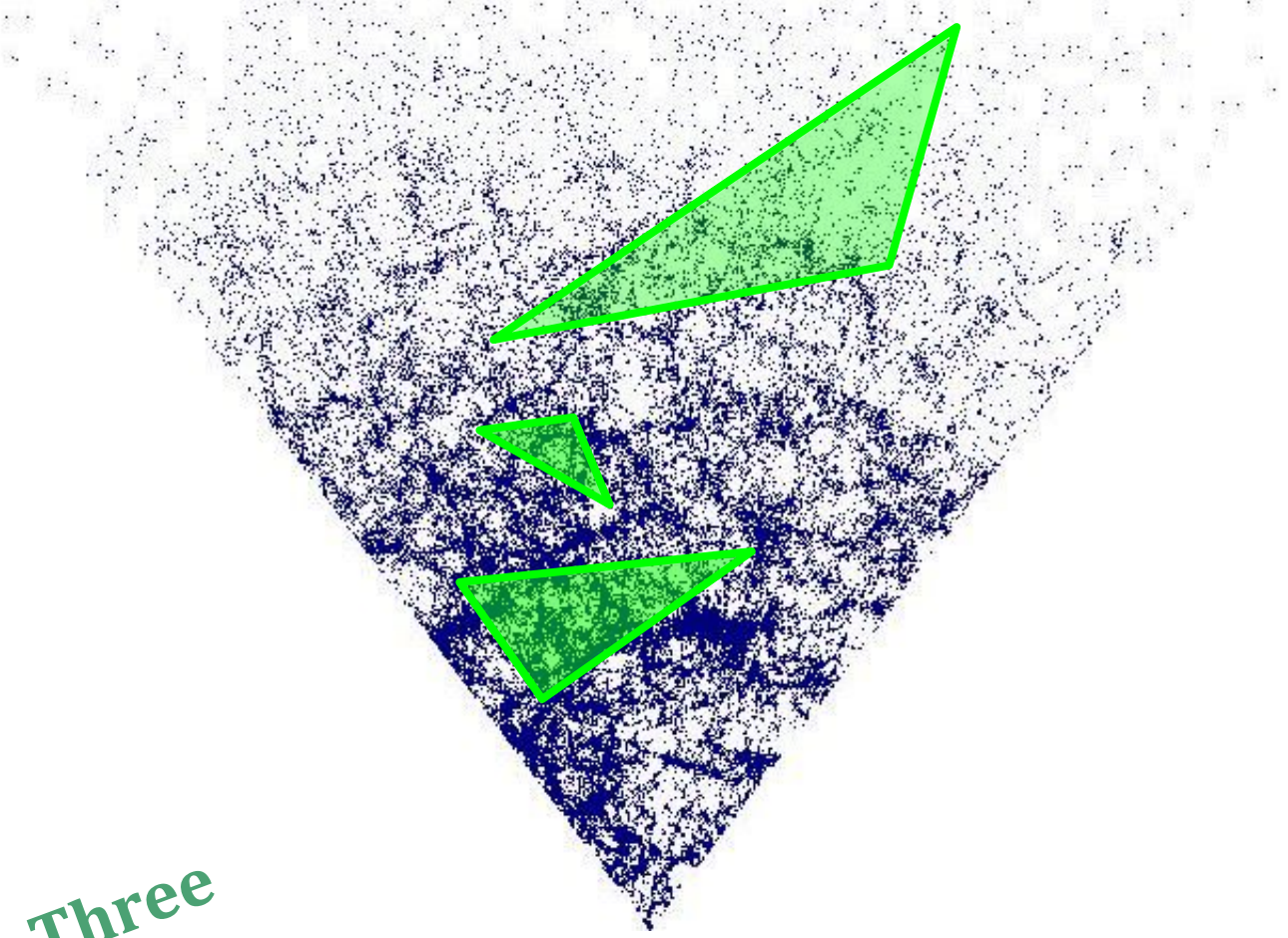



Peaks
Voids
Bispectrum
MFs
Halos
PDF
Zack Li (Princeton)
Jose Zorrilla (Columbia)
Christina Kreisch (Princeton)
Will Coulton (Cambridge)
Gabriela Marques (Nat. Obs. Rio)
Ayanna Mathews (Princeton)
Jia Liu (Princeton)
Colin Hill (IAS/Flatiron)
Alice Pisani (Princeton)
Mathew Madhavacheril (Princeton)
Marcel Schmittfull (IAS)
Duncan Campbell (CMU)
Vanessa Böhm (Berkeley)
Simeon Bird (UCR/JHU)
Zoltan Haiman (Columbia)
David Spergel (Princeton/Flatiron)
Andrea Petri (Columbia ->Morgan Stanley)



Two Point Correlation Function

Find one random galaxy and then ask:
"Looking at a position x Mpc away,
how likely is it to find another galaxy?"



Three

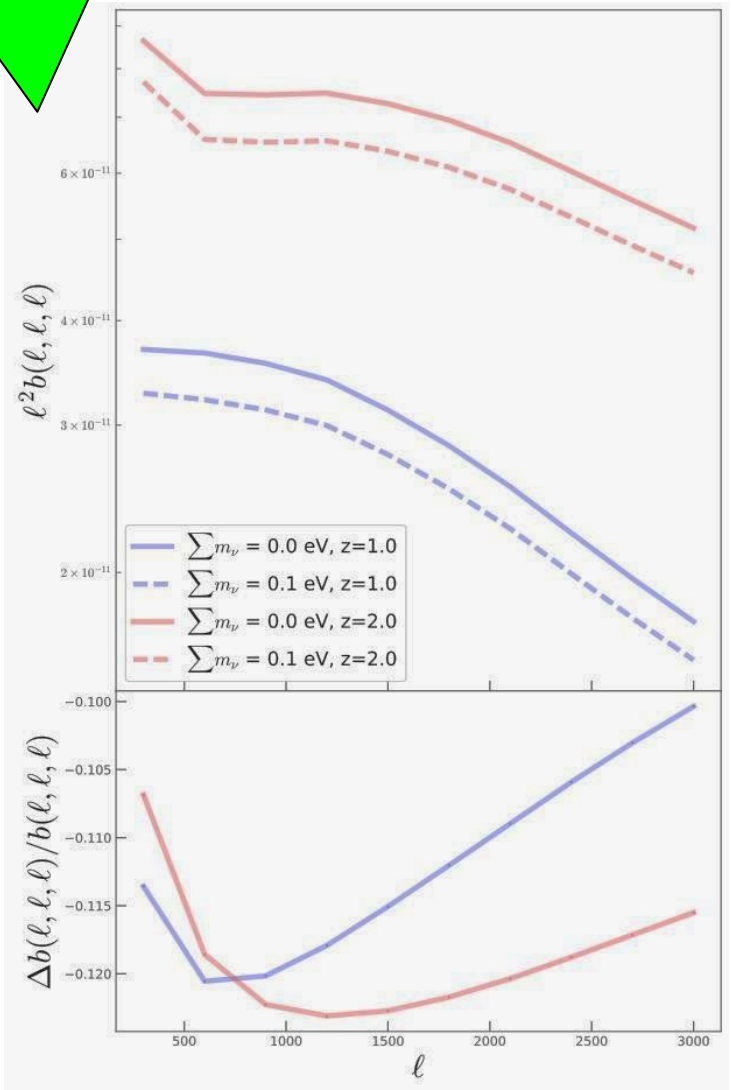
~~Two~~ Point Correlation Function

Find one random galaxy and then ask:
"Looking at a ~~position x Mpc away~~ triangle,
how likely is it to find another galaxy?"

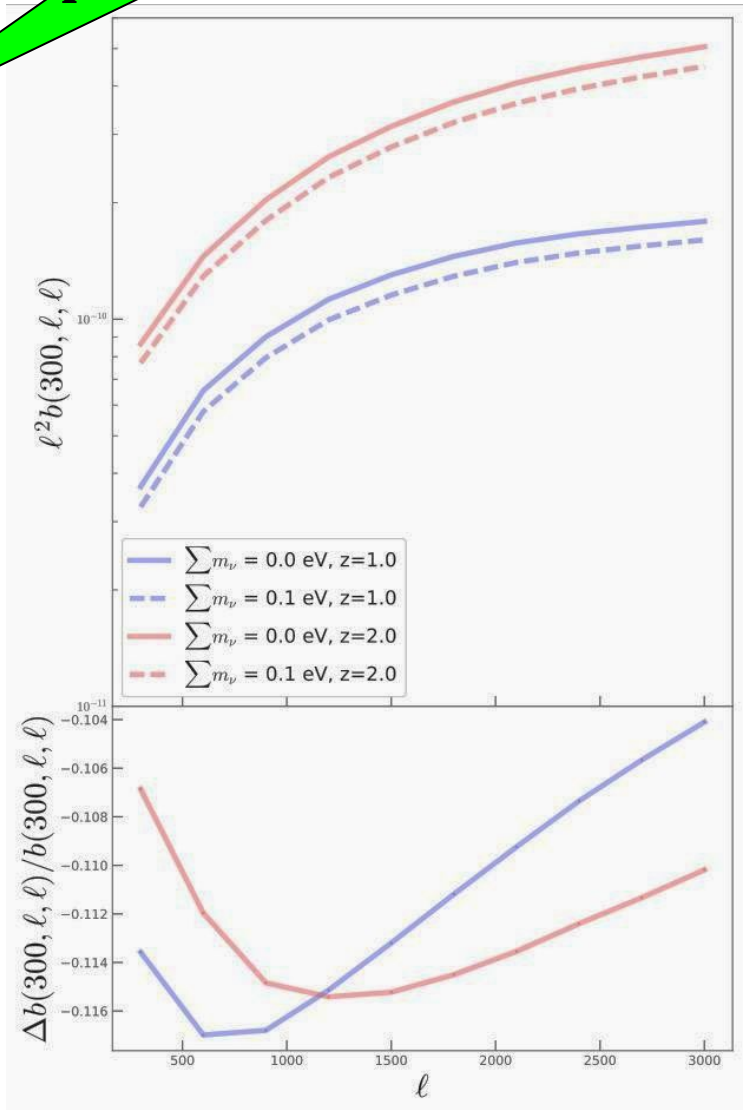
Weak Lensing Bispectrum

Coulton, JL, Madhavacheril, Boehm, Spergel 2018

Equilateral

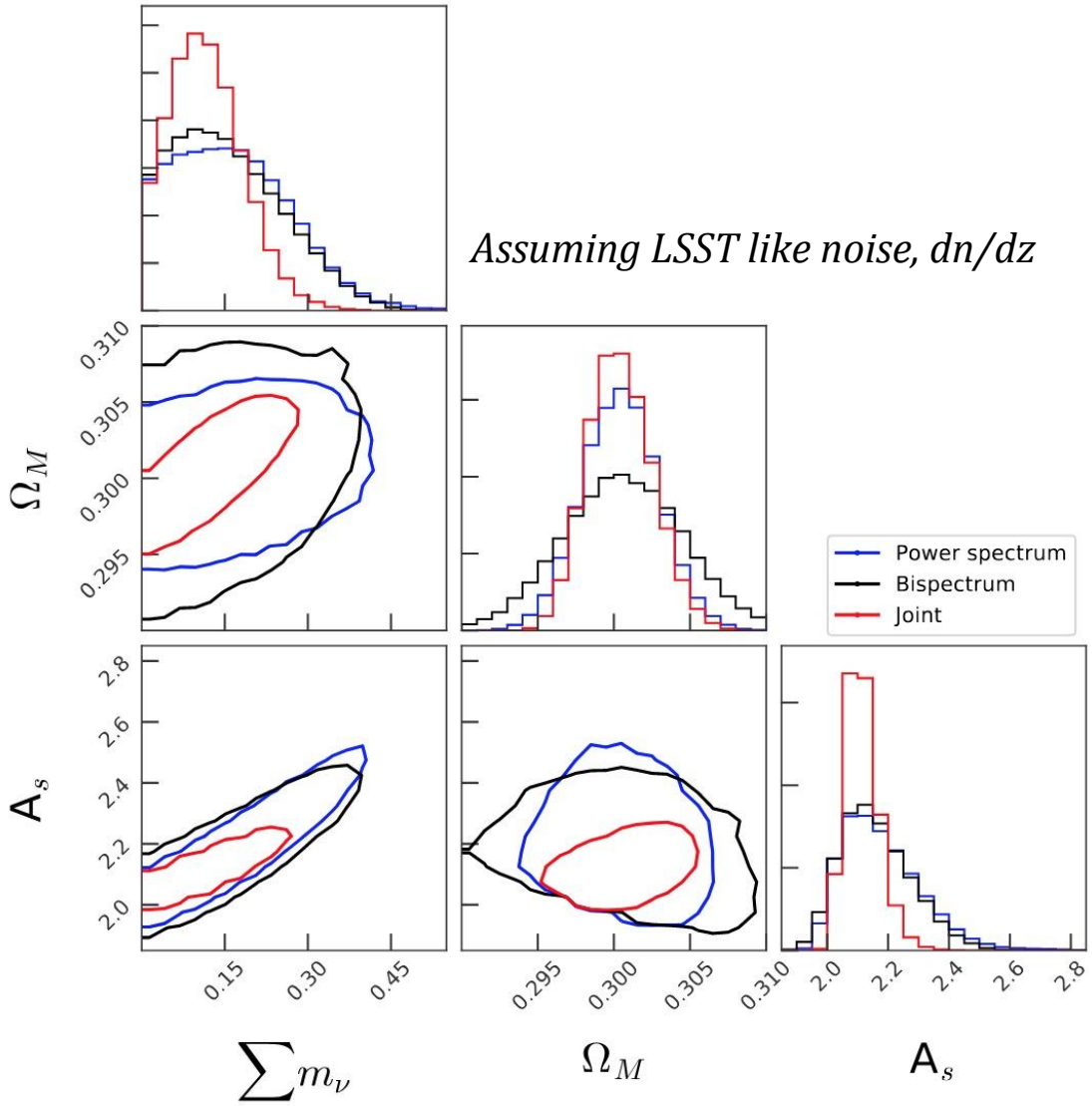


Squeezed limit



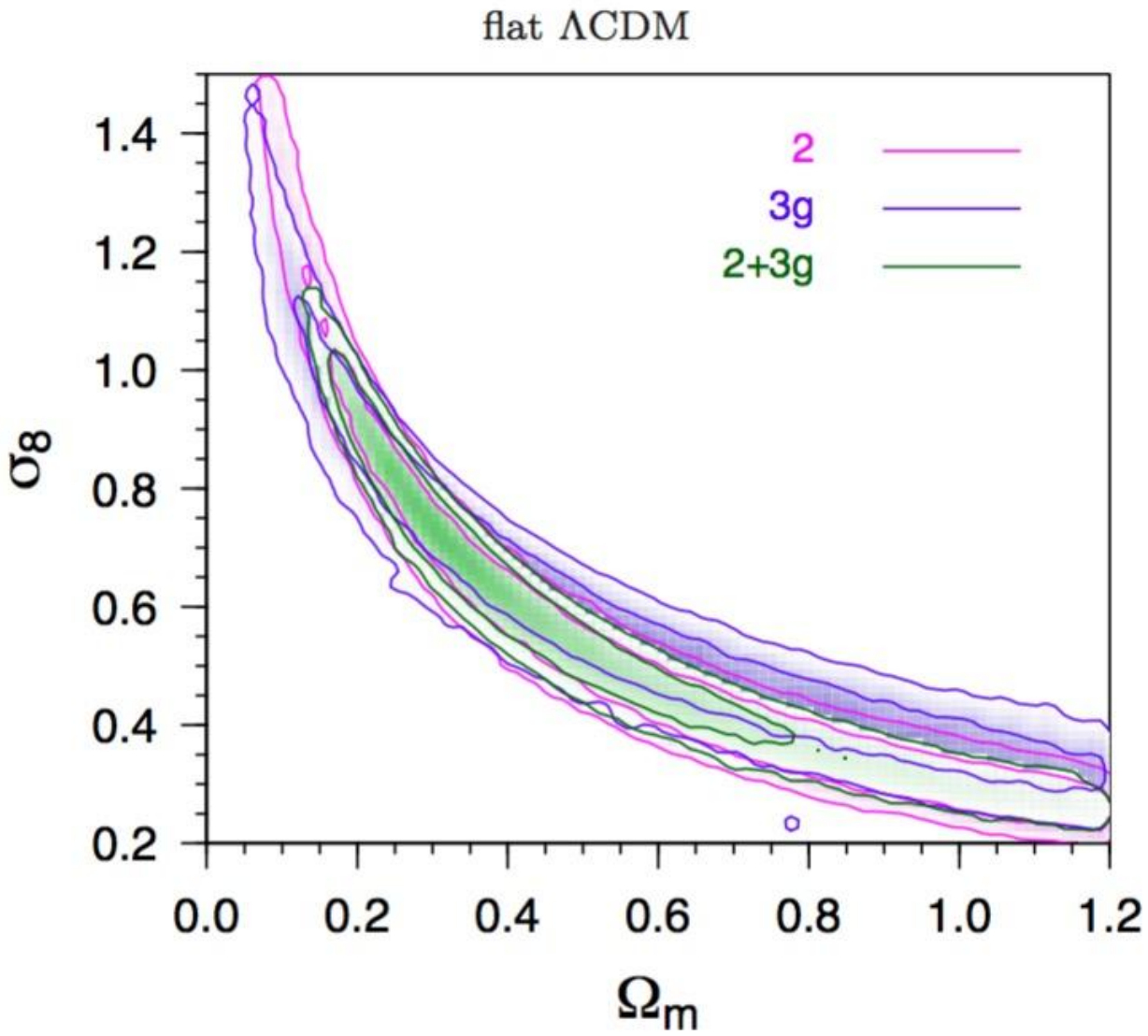
Weak Lensing Bispectrum

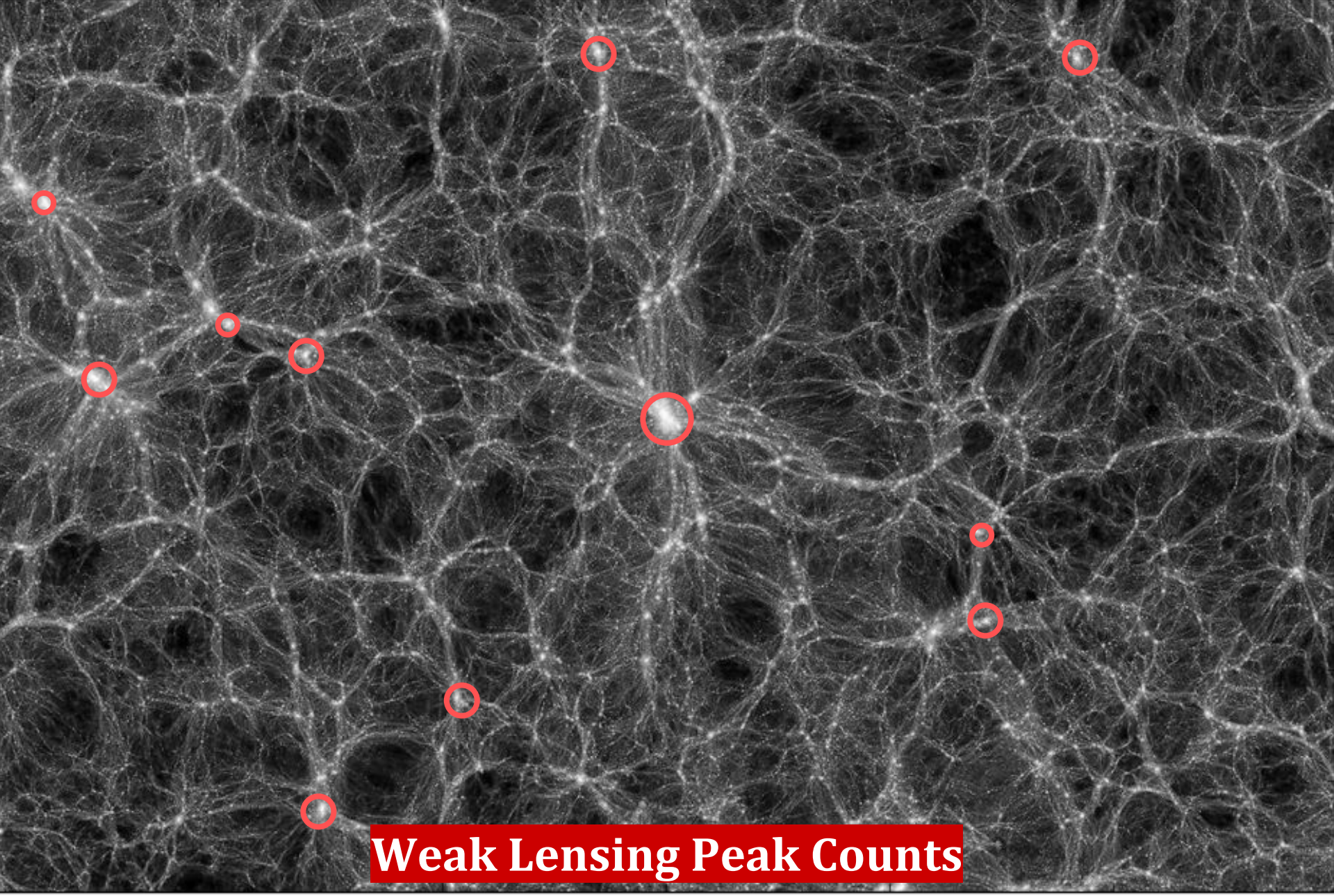
Coulton, JL, Madhavacheril, Boehm, Spergel 2018



Weak Lensing 3pt Function (CFHTLenS)

Fu+2014



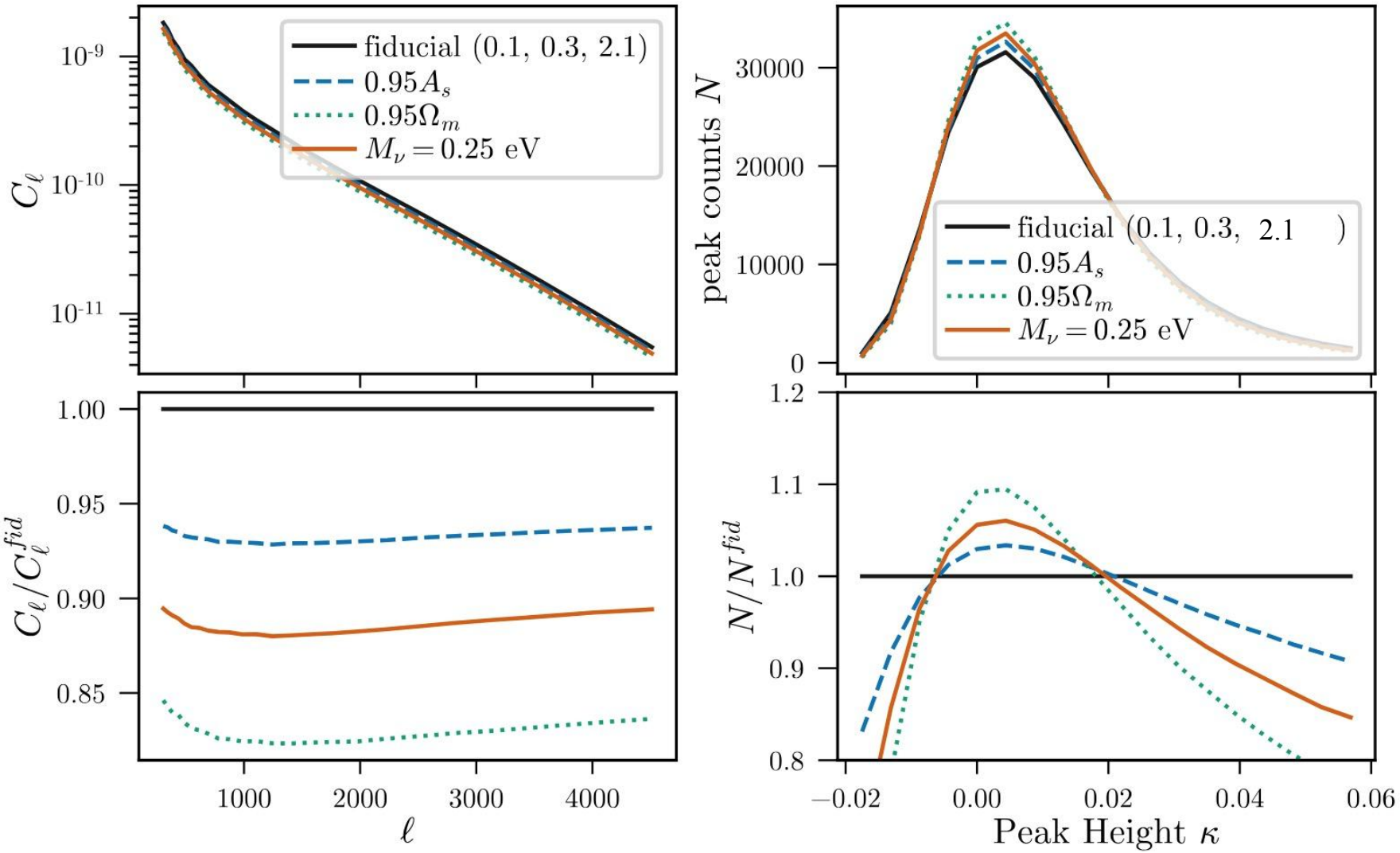


Weak Lensing Peak Counts

Local Maxima in a lensing map
(of galaxies or the CMB)

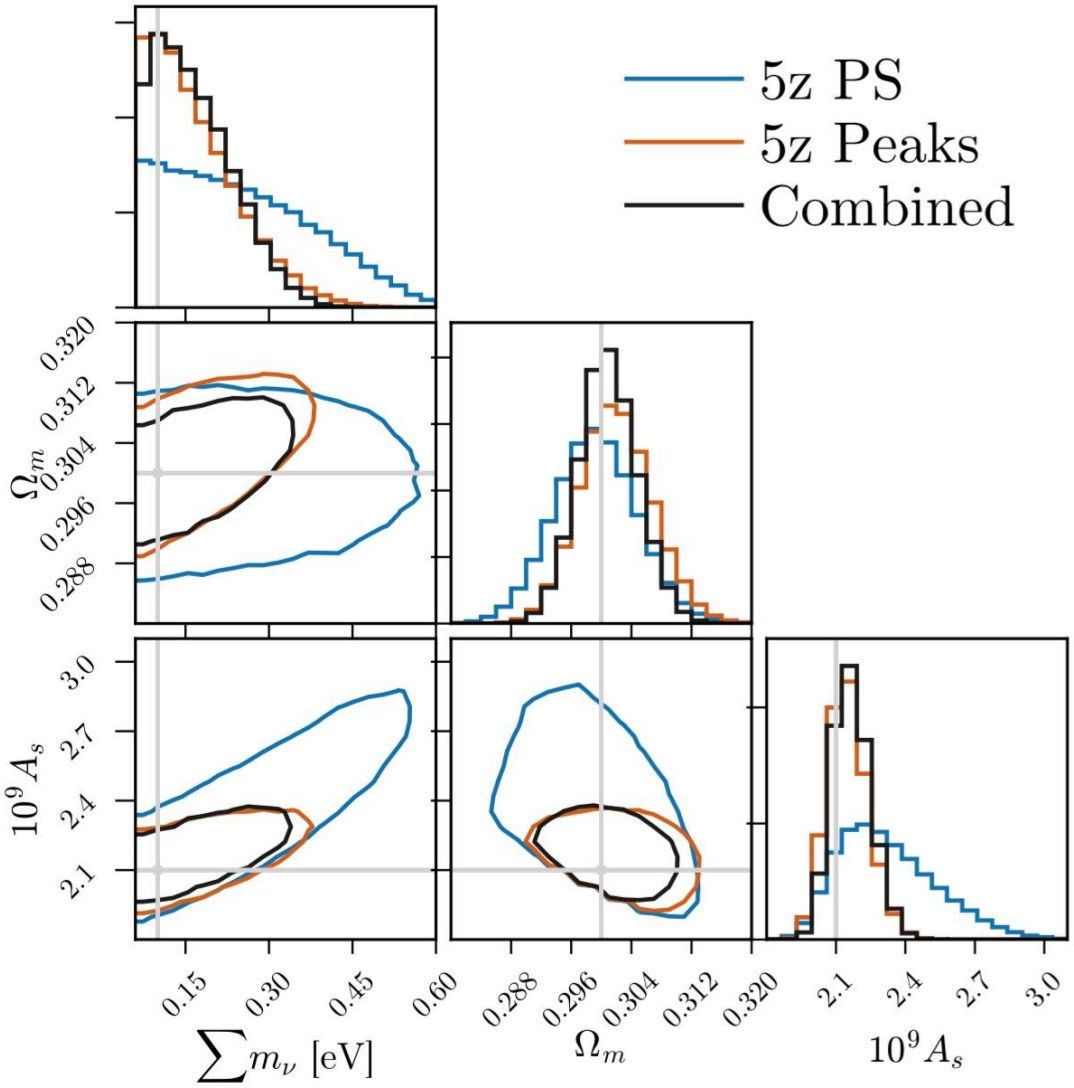
Weak Lensing Peak Counts

Li, JL, Zorrilla, Coulton 2018

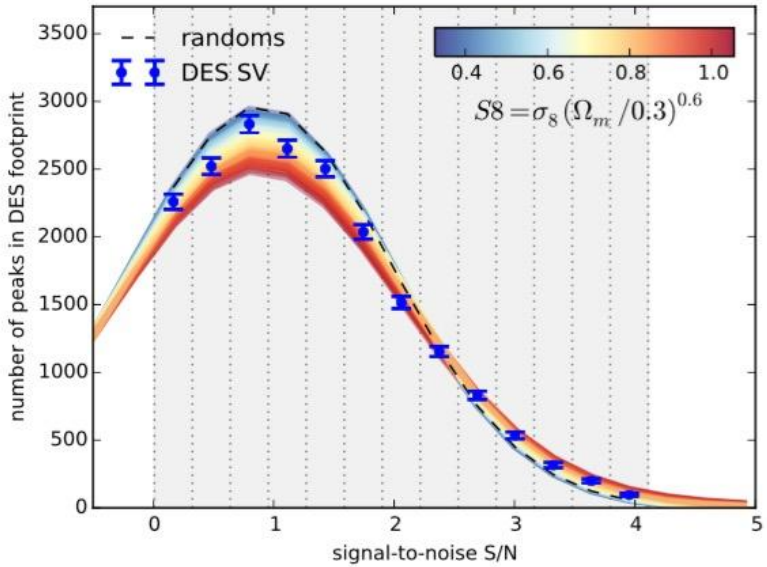


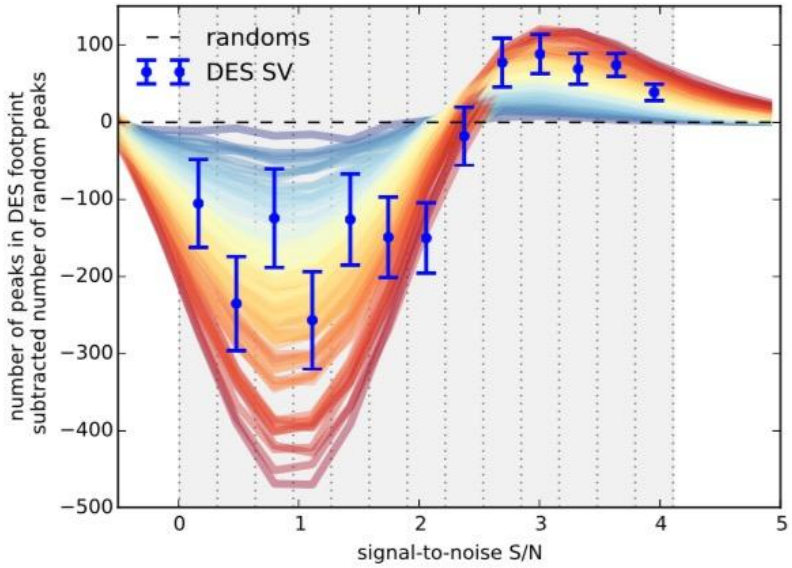
Weak Lensing Peak Counts

Li, JL, Zorrilla, Coulton 2018



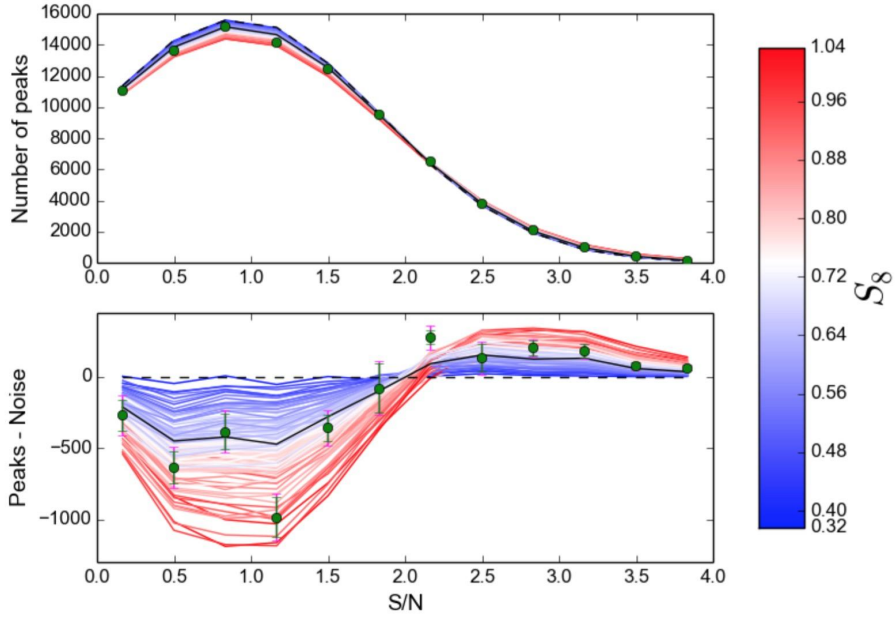
Peak Counts on Data





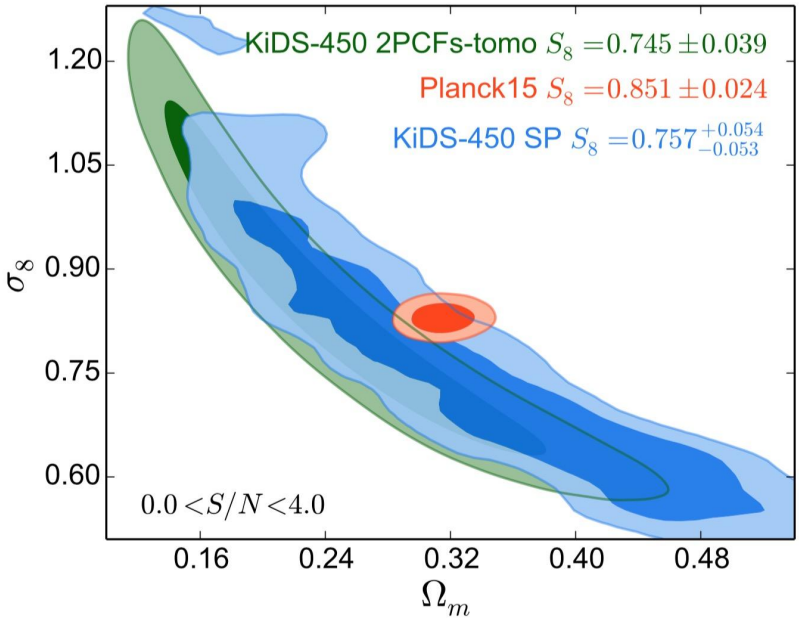
DES (left): Kacprzak+2016
KiDS-450 (bottom): Martinet+2017

Also see:
CFHTLenS: Liu+2015
CS82: Liu X.+2015
KiDS-450: Shan+2017

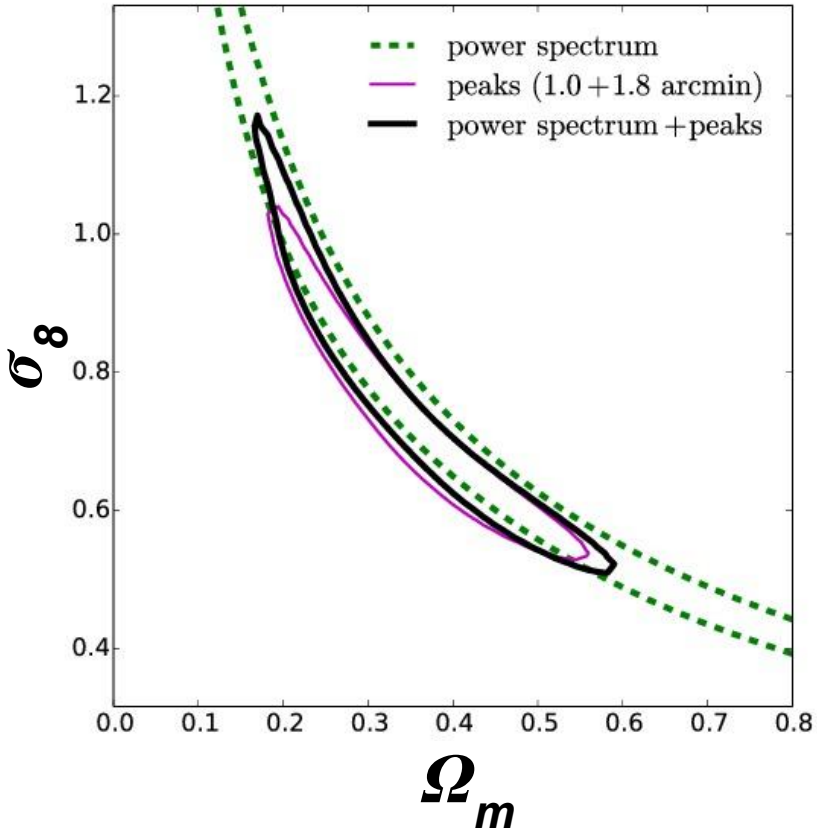


Peak Counts on Data

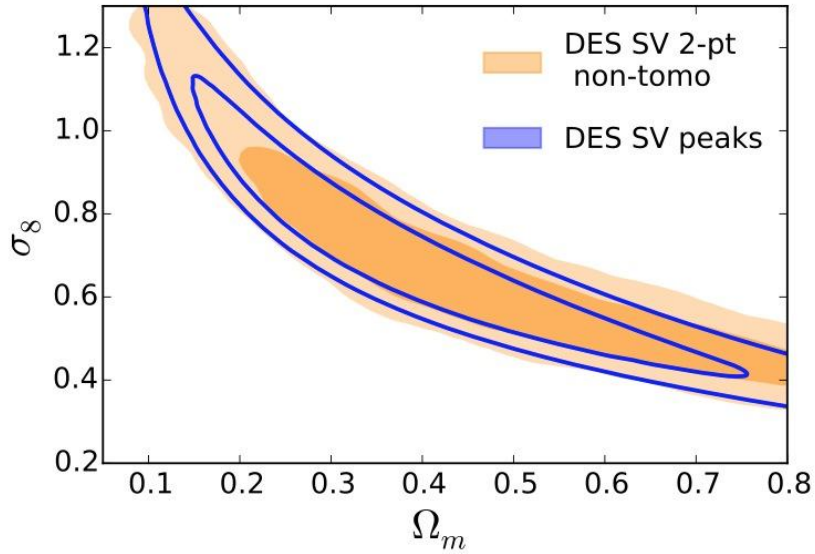
[KiDS] Martinet+ 2017

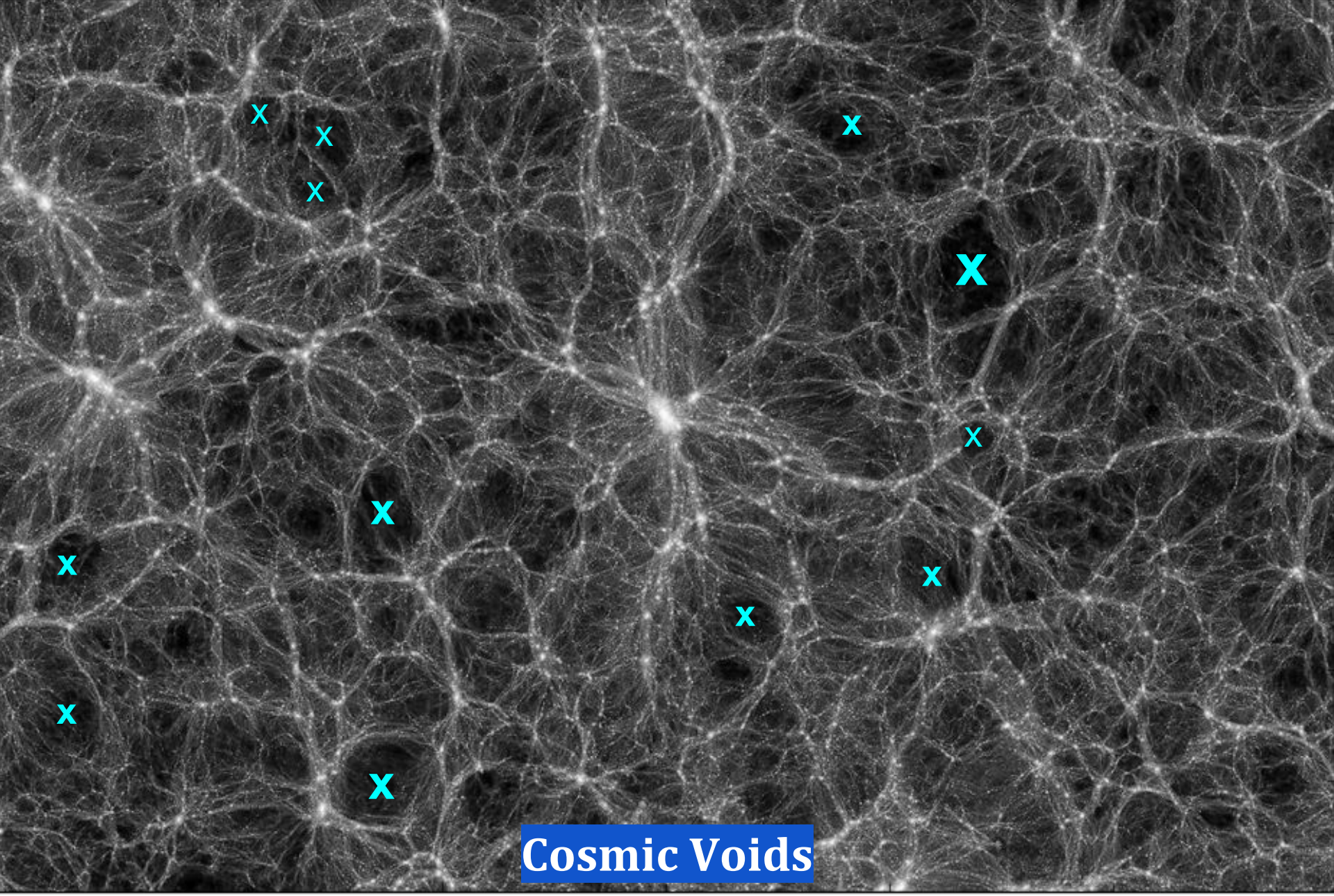


[CFHTLenS] JL+ 2015



[DES] Kacprzak+ 2016

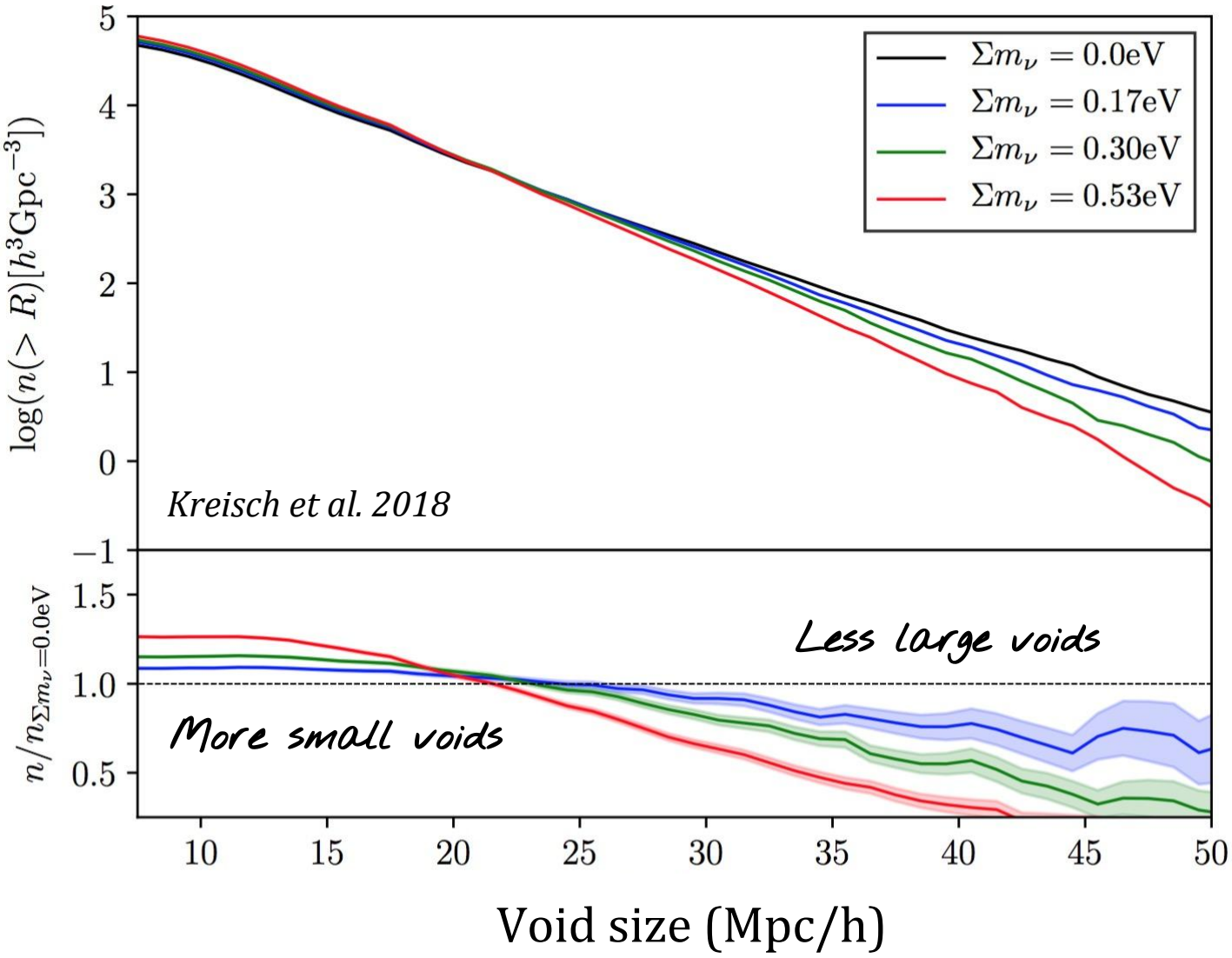




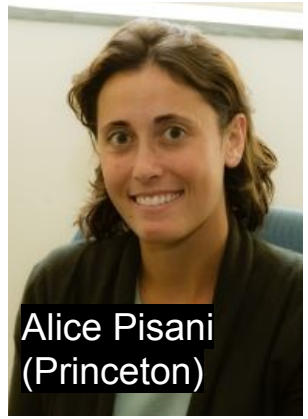
Emptiest places in our Universe
(also less explored in theory...)

Cosmic Voids

Kreisch, Pisani, Carbone, JL+ 2018




Christina Kreisch (Princeton)


Alice Pisani (Princeton)

Summary

One

Massive neutrinos suppress the growth of structure

Two

MassiveNuS: public data from
Cosmological massive neutrino simulations

Three

Rich information in the nonlinear density field:
e.g. bispectrum, peak counts, voids...