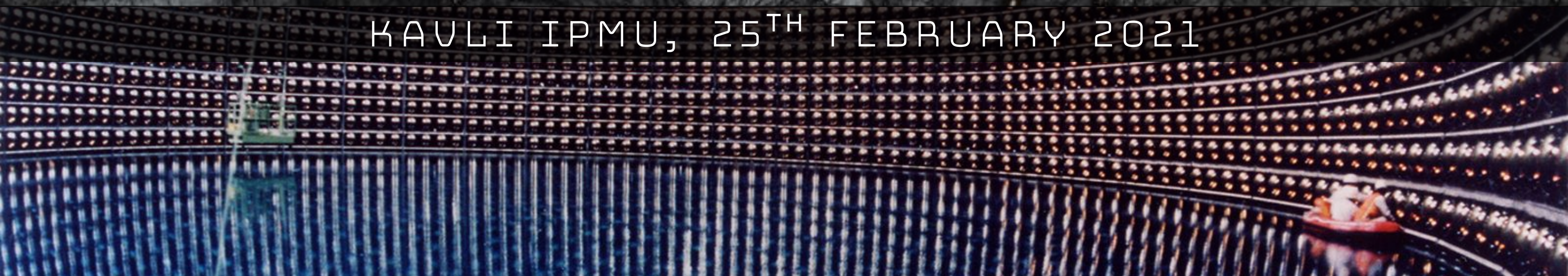
Image credit: (top) Abel & Kaehler; (middle) Kamioka Observatory/ICRR/U. Tokyo

COSMOLOGY WITH MASSIVE NEUTRINOS



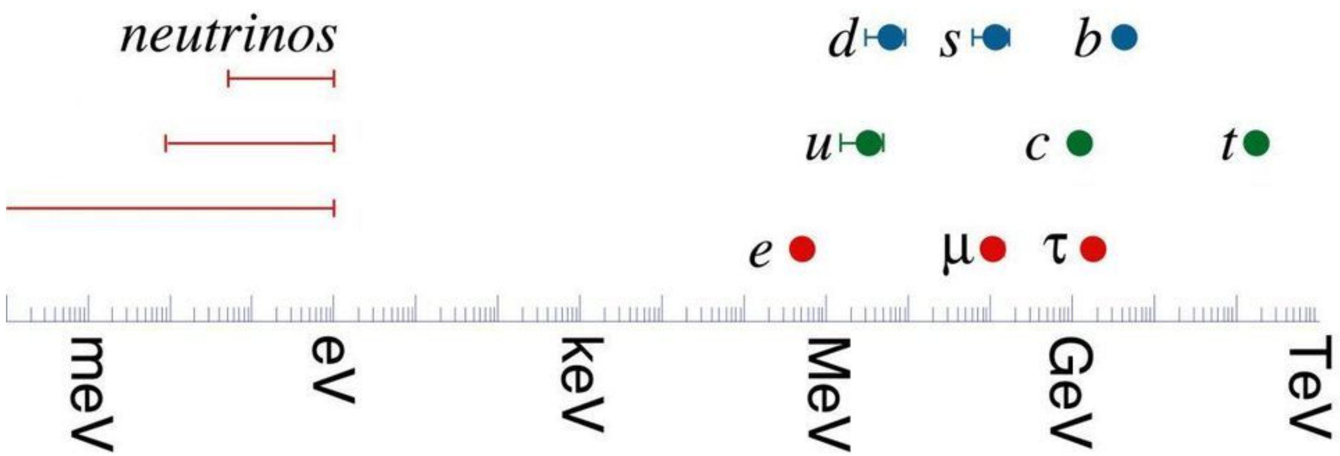
KAVLI IPMU, 25TH FEBRUARY 2021

Jia Liu

University of California, Berkeley

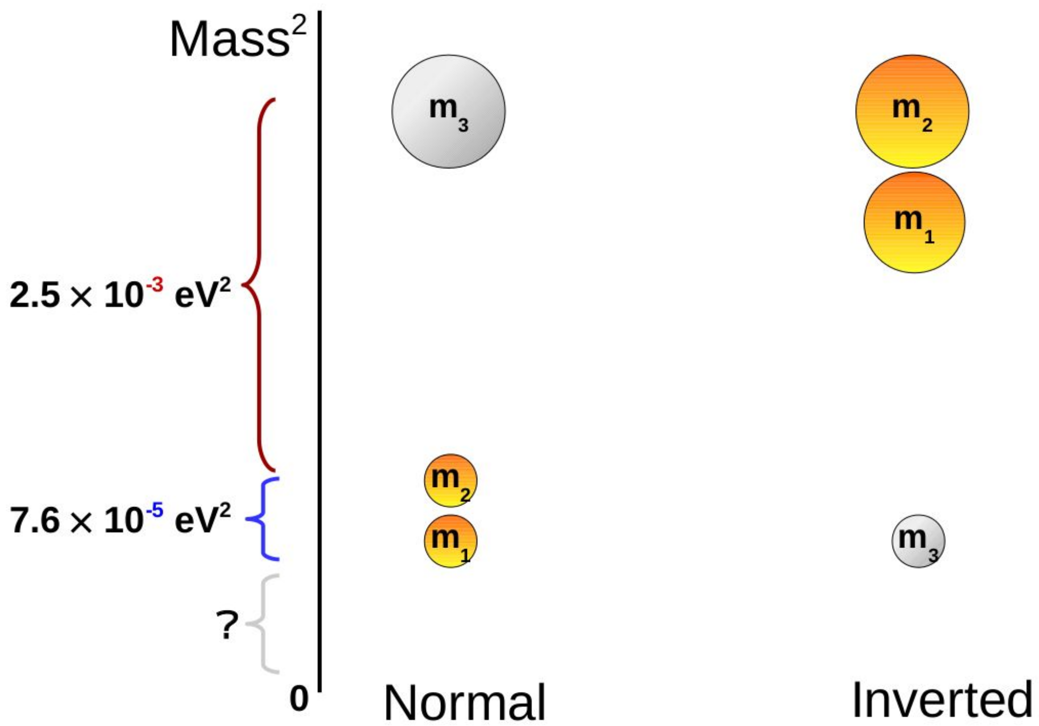
BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Neutrino Masses



What is the mass generation mechanism?

Mass^2 Differences from Neutrino Oscillation



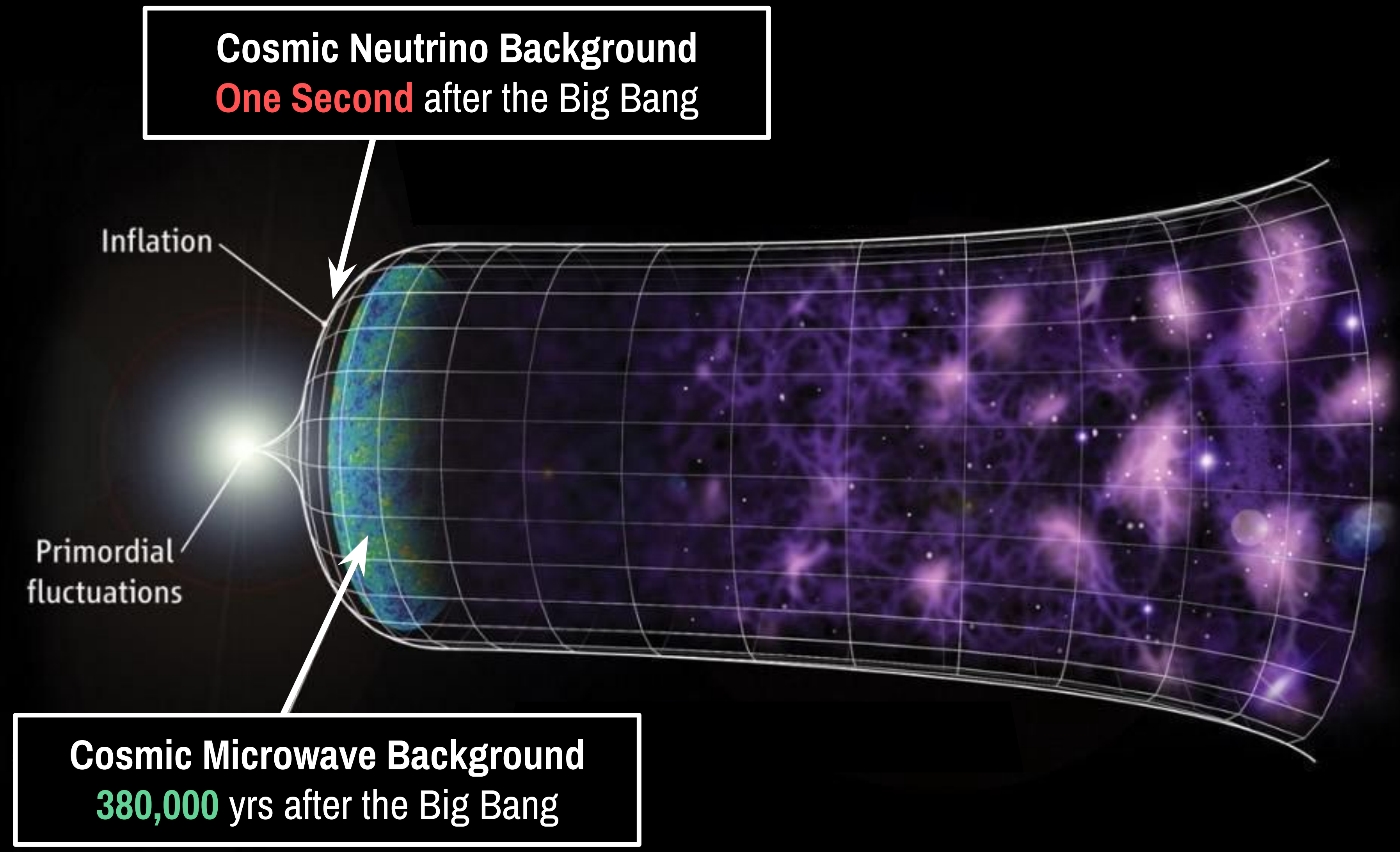
$\Sigma m_\nu > 0.06$ eV $\Sigma m_\nu > 0.1$ eV

Hyper-K Collaboration

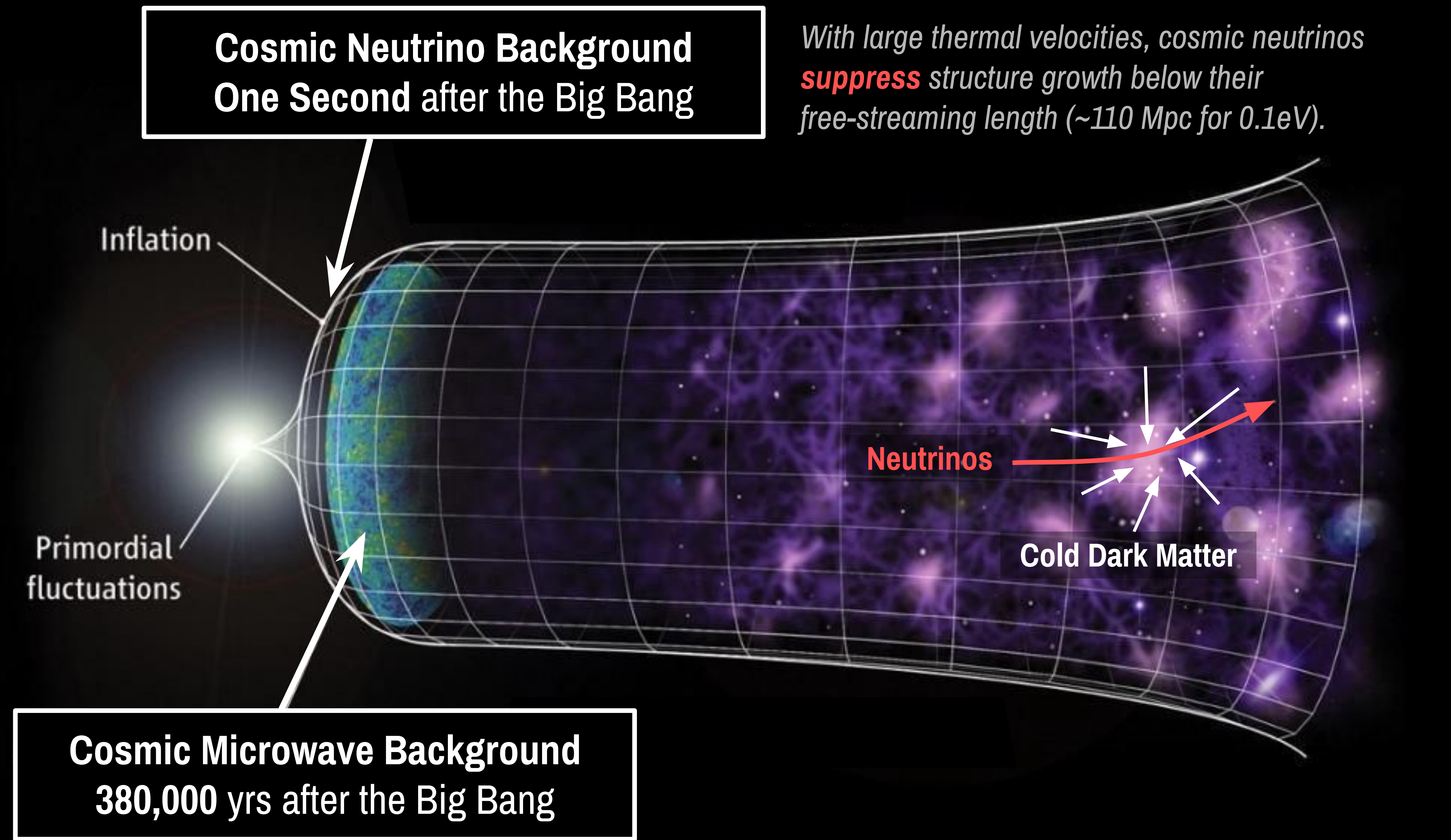
PARTICLE EXPERIMENT	COSMOLOGY
Current $m_{\nu e}^{eff} < 1.1$ eV KATRIN (2019, 90% CL)	**Current** $\Sigma m_\nu < 0.12$ eV Planck (2018, 95% CL)
Future Sensitivity 0.2 eV KATRIN 2023	**Future Sensitivity** ~0.03 eV CMB+LSS

Normal Ordering: $\Sigma m_\nu > 0.06$ eV

Cosmic Neutrinos



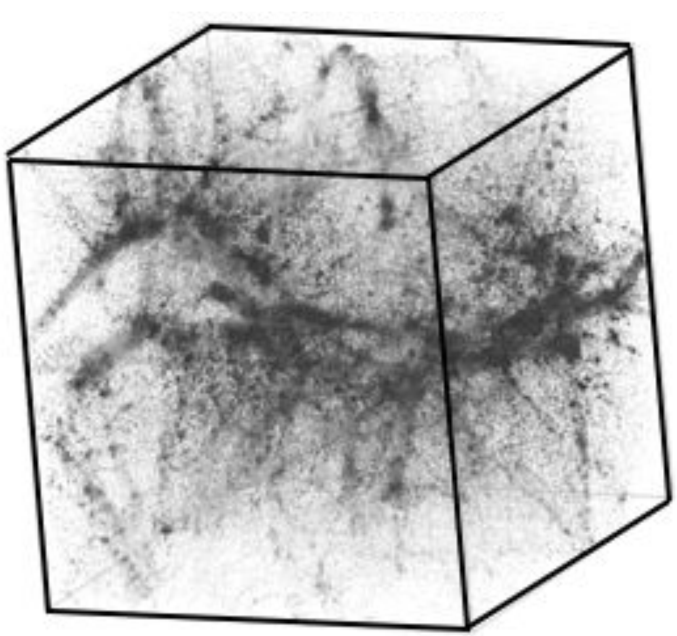
Claude-André, Faucher-Giguère, Adam Lidz, Lars Hernquist



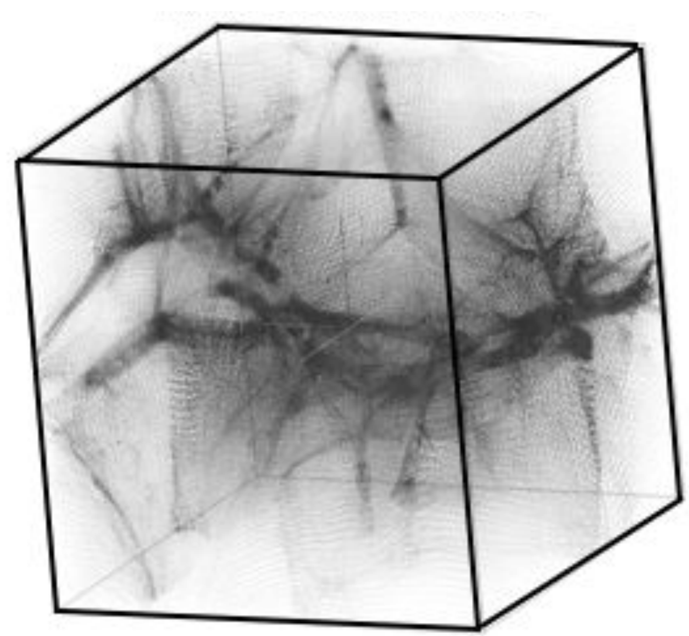
Claude-André, Faucher-Giguère, Adam Lidz, Lars Hernquist

Large Scale Structure (LSS)

Standard Model of Cosmology



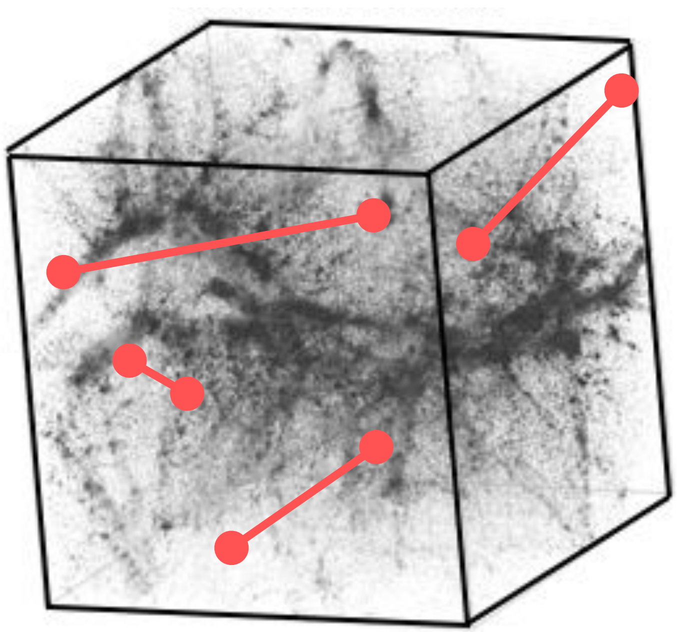
Massive Neutrinos



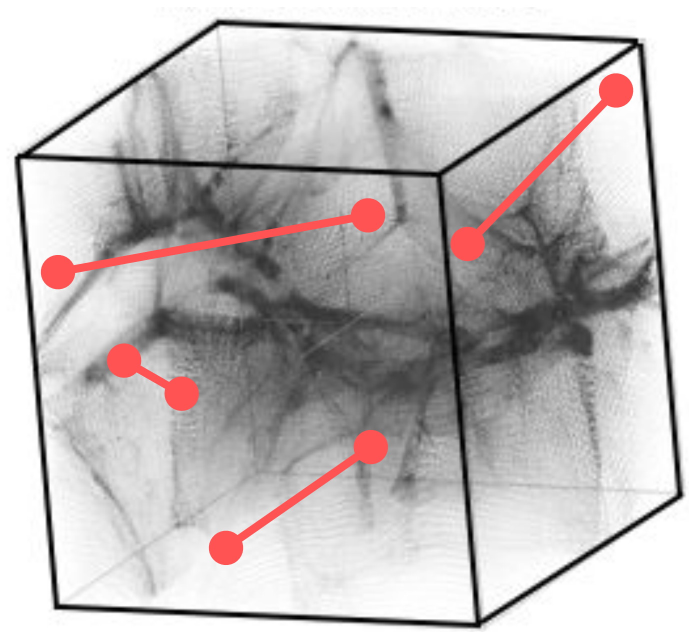
Katrin Heitmann

Measure the Clustering with Power Spectrum

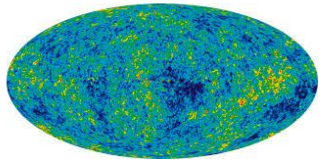
Standard Model of Cosmology

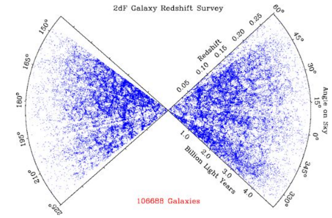


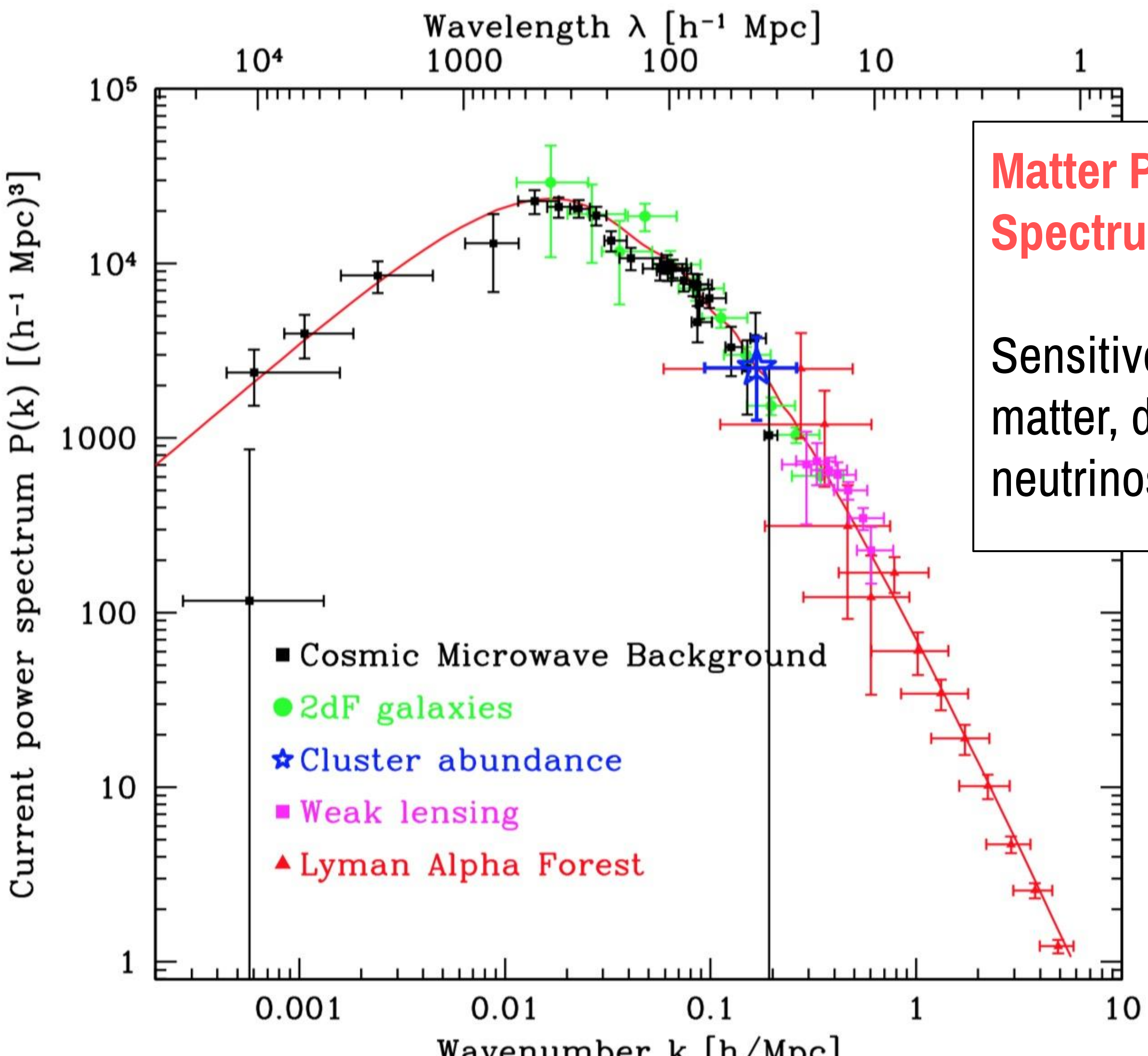
Massive Neutrinos



Katrin Heitmann





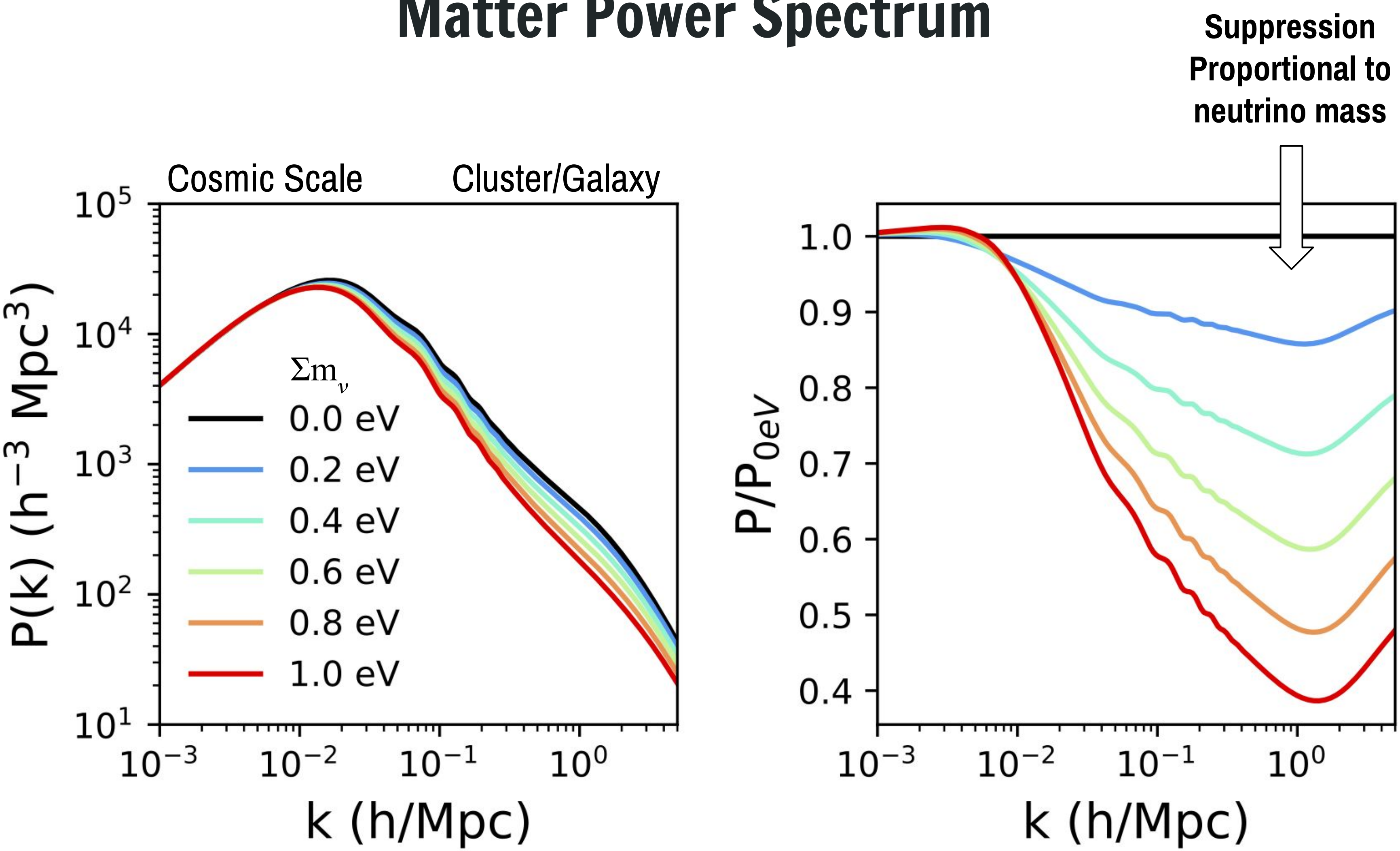


Matter Power Spectrum

Sensitive to: dark matter, dark energy, neutrinos, etc.

Tegmark 2004

Matter Power Spectrum

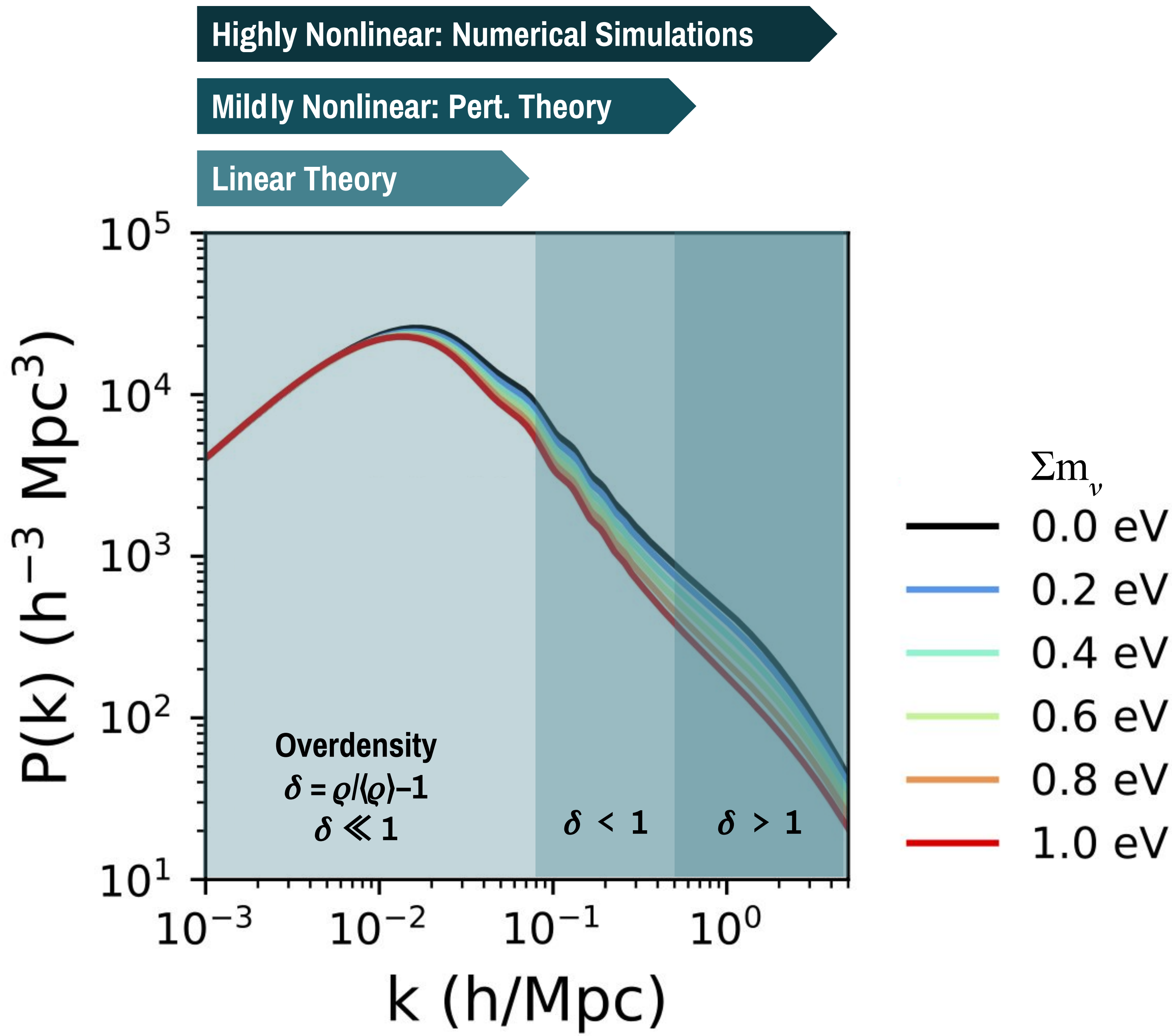


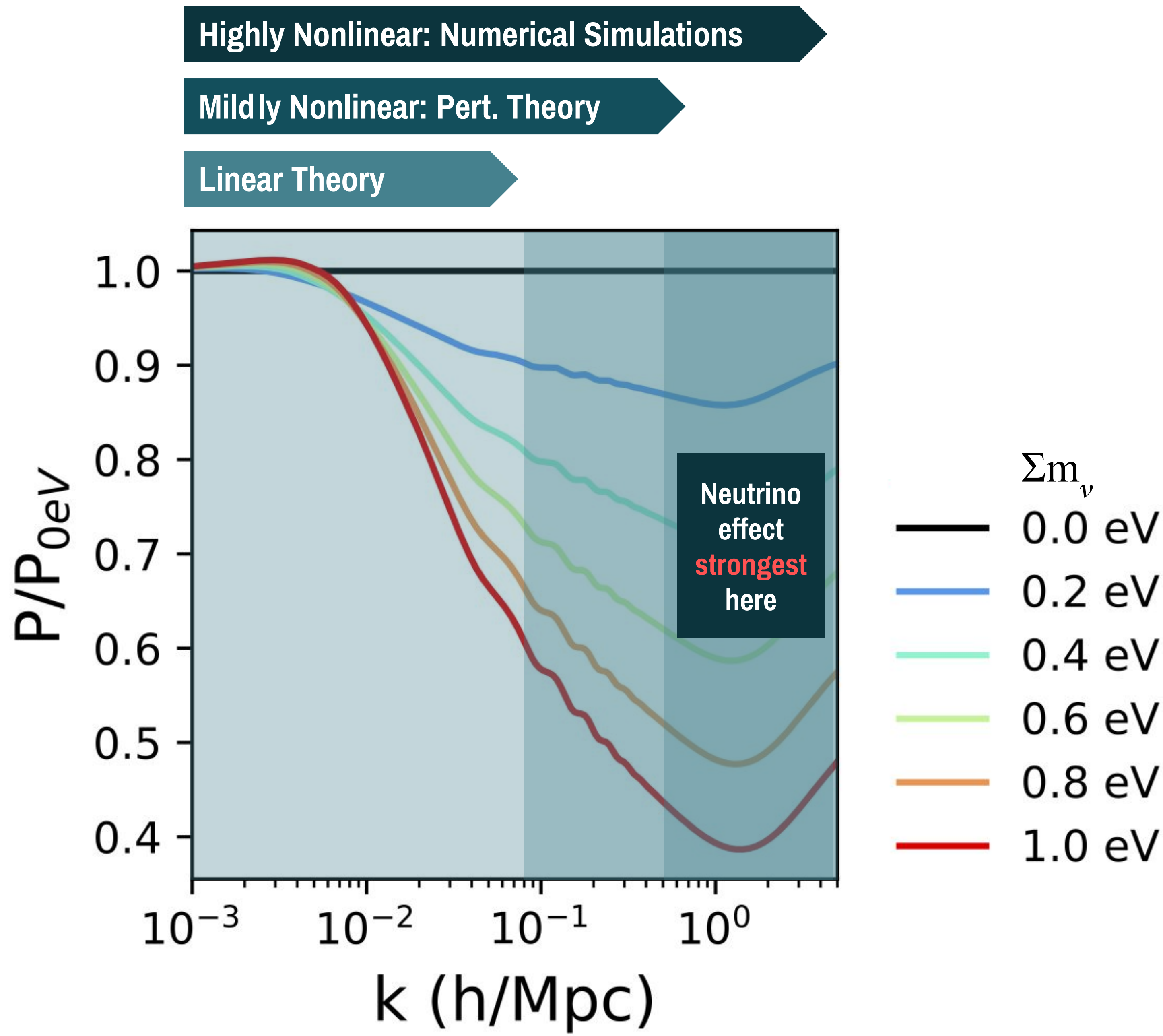
Theoretical Modeling

Fluid Equations for Cosmology

$\partial_t \rho = -\boldsymbol{\nabla}_{\boldsymbol{r}} \cdot (\rho \boldsymbol{u})$	Continuity Equation (Mass Conservation)
$(\partial_t + \boldsymbol{u} \cdot \boldsymbol{\nabla}_{\boldsymbol{r}})\, \boldsymbol{u} = -\frac{\boldsymbol{\nabla}_{\boldsymbol{r}} P}{\rho} - \boldsymbol{\nabla}_{\boldsymbol{r}} \Phi$	Euler Equation (Momentum Conservation)
$\nabla_{\boldsymbol{r}}^2 \Phi = 4\pi G \rho$	Poisson Equation

ϱ: density; Φ: grav. potential; P: pressure; u:velocity


Highly Nonlinear: Numerical Simulations
Mildly Nonlinear: Pert. Theory
Linear Theory
P(k) (h−3 Mpc3)
k (h/Mpc)
Overdensity
δ = ϱ/⟨ϱ⟩−1
δ ≪ 1
δ < 1
δ > 1
Σmν
0.0 eV
0.2 eV
0.4 eV
0.6 eV
0.8 eV
1.0 eV


Highly Nonlinear: Numerical Simulations
Mildly Nonlinear: Pert. Theory
Linear Theory
1.0
0.9
0.8
0.7
0.6
0.5
0.4
P/P$_{0eV}$
10^{-3}
10^{-2}
10^{-1}
10^{0}
k (h/Mpc)
Neutrino effect strongest here
Σm_ν
0.0 eV
0.2 eV
0.4 eV
0.6 eV
0.8 eV
1.0 eV

Theoretical Modeling in the Nonlinear Regime

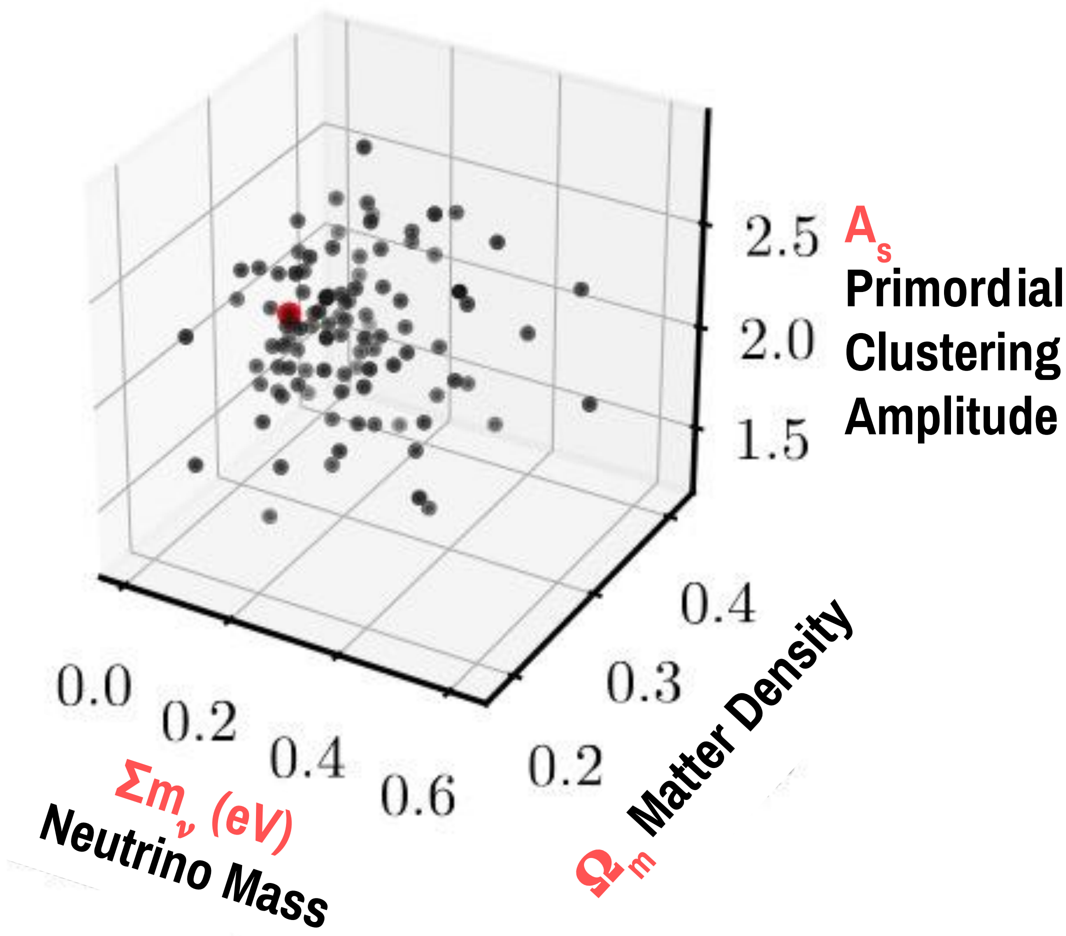
MassiveNuS

Cosmological massive neutrino simulations (JL et al. 2018)

100 high resolution simulations with varying neutrino masses

300TB data (20TB public)
Particles, halo catalogues, merger trees, weak lensing, CMB lensing

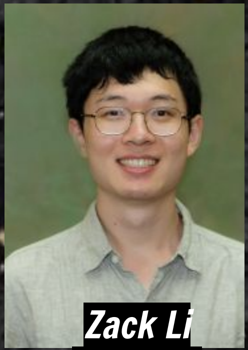
Used by 20+ Research Projects
Including projects related to Euclid, LSST, KiDS, SO, CMB-S4.



Graduate Students


Will Coulton
(Princeton-> Postdoc: IPMU)

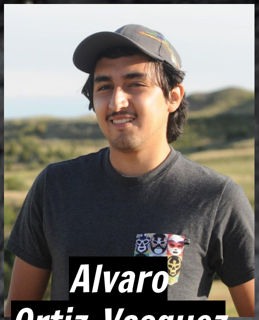

Christina Kreisch
(Princeton)


Zack Li
(Princeton)


Gabriela Marques
(Nat. Obs. Rio -> Postdoc: Florida State)


Adrian Bayer
(Berkeley)

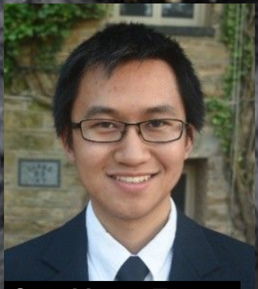
Undergraduate Students

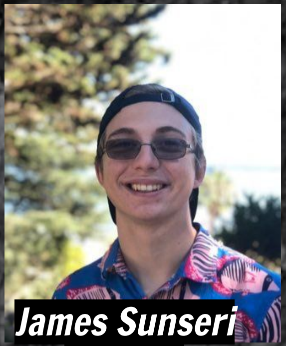

Alvaro Ortiz-Vasquez
(Columbia -> data scientist)


Ryan Golant
(Princeton-> Phd: Columbia)

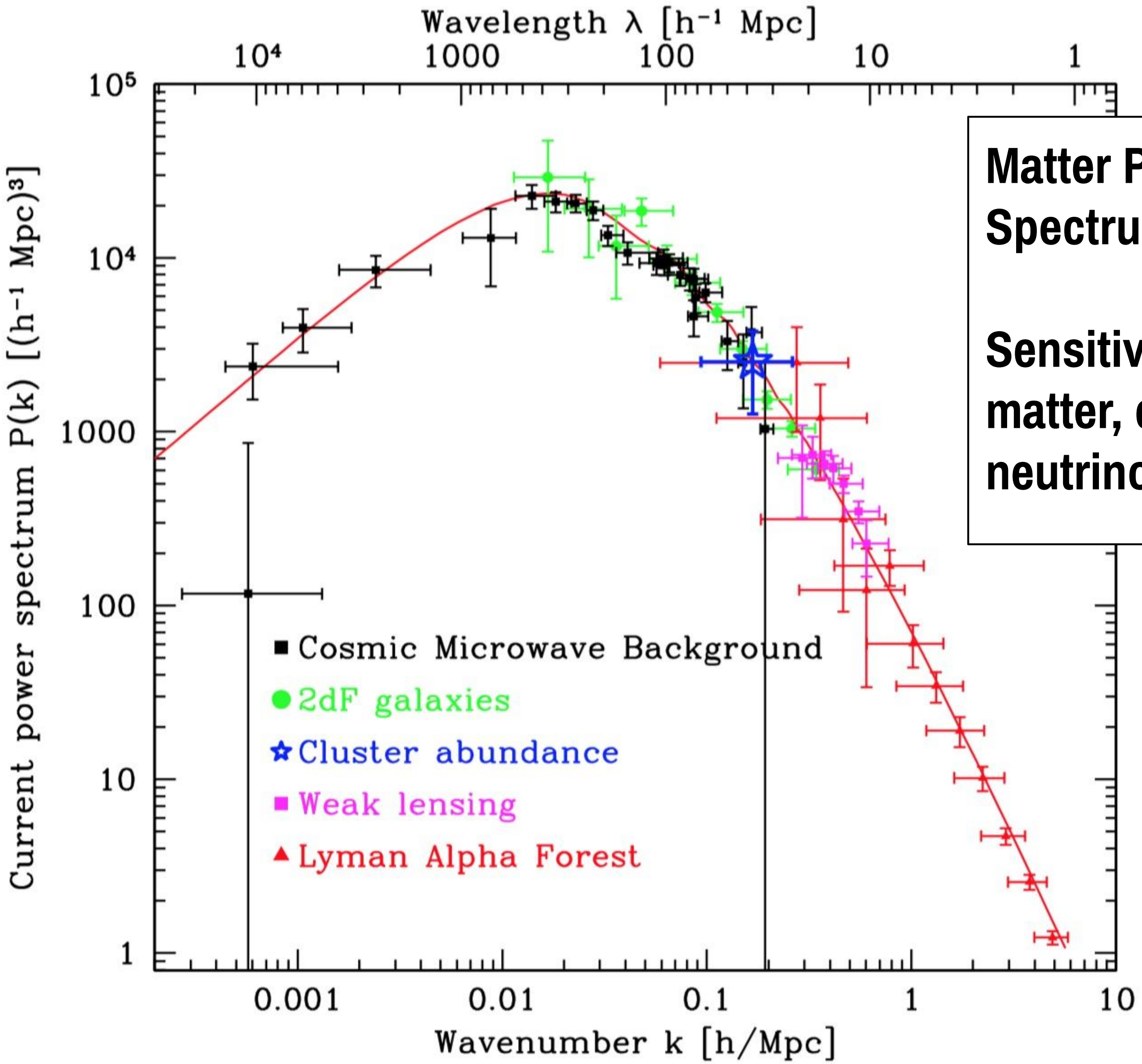

Ayanna Mathews
(Princeton)


Gemma Zhang
(Princeton-> Phd: Harvard)


Geoffrey Zheng
(Princeton-> Phd:Yale)


James Sunseri
(Berkeley)

Power Spectrum: Only Complete for Gaussian Fields



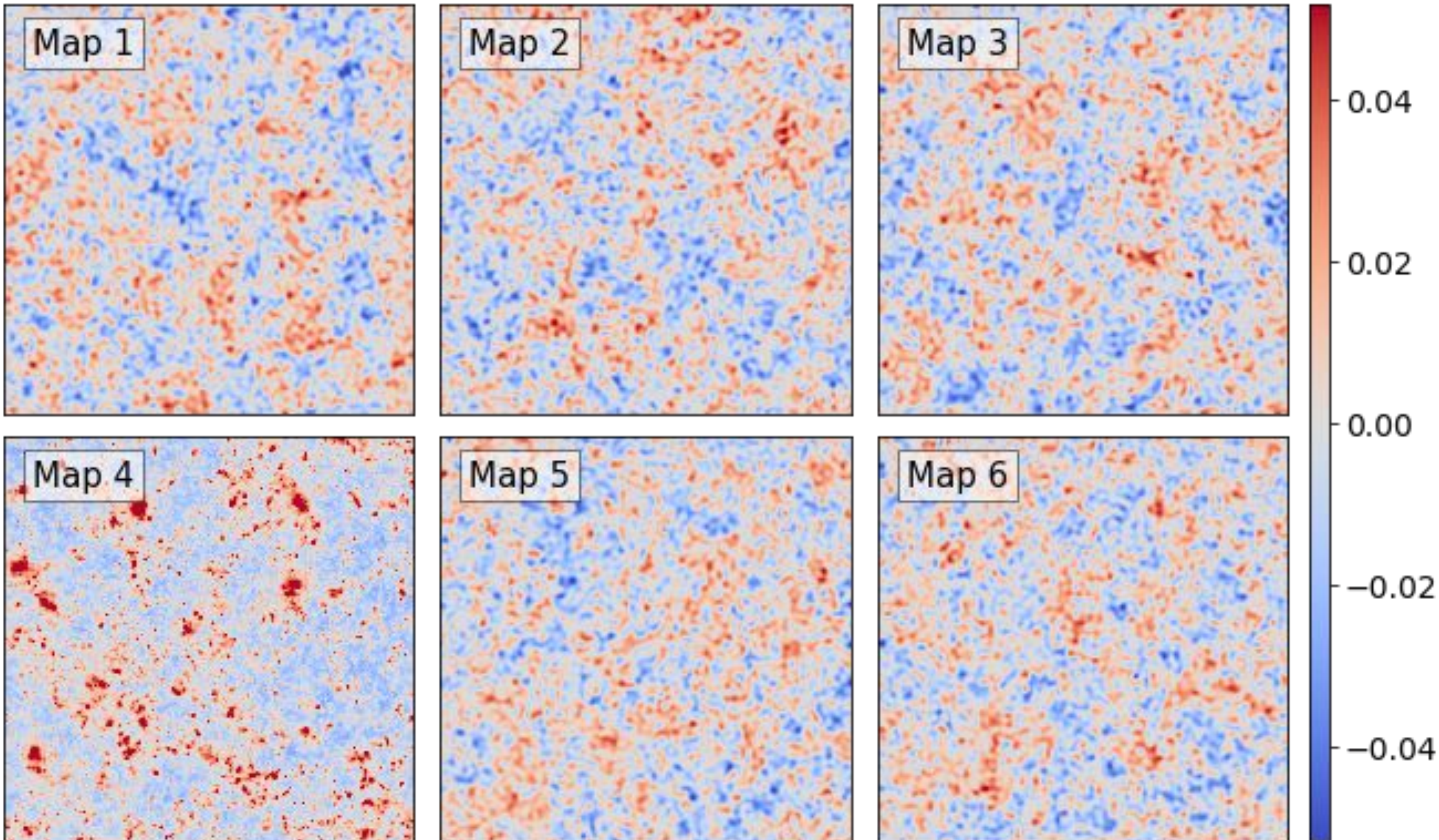
Matter Power Spectrum

Sensitive to: dark matter, dark energy, neutrinos, etc.

Tegmark 2004

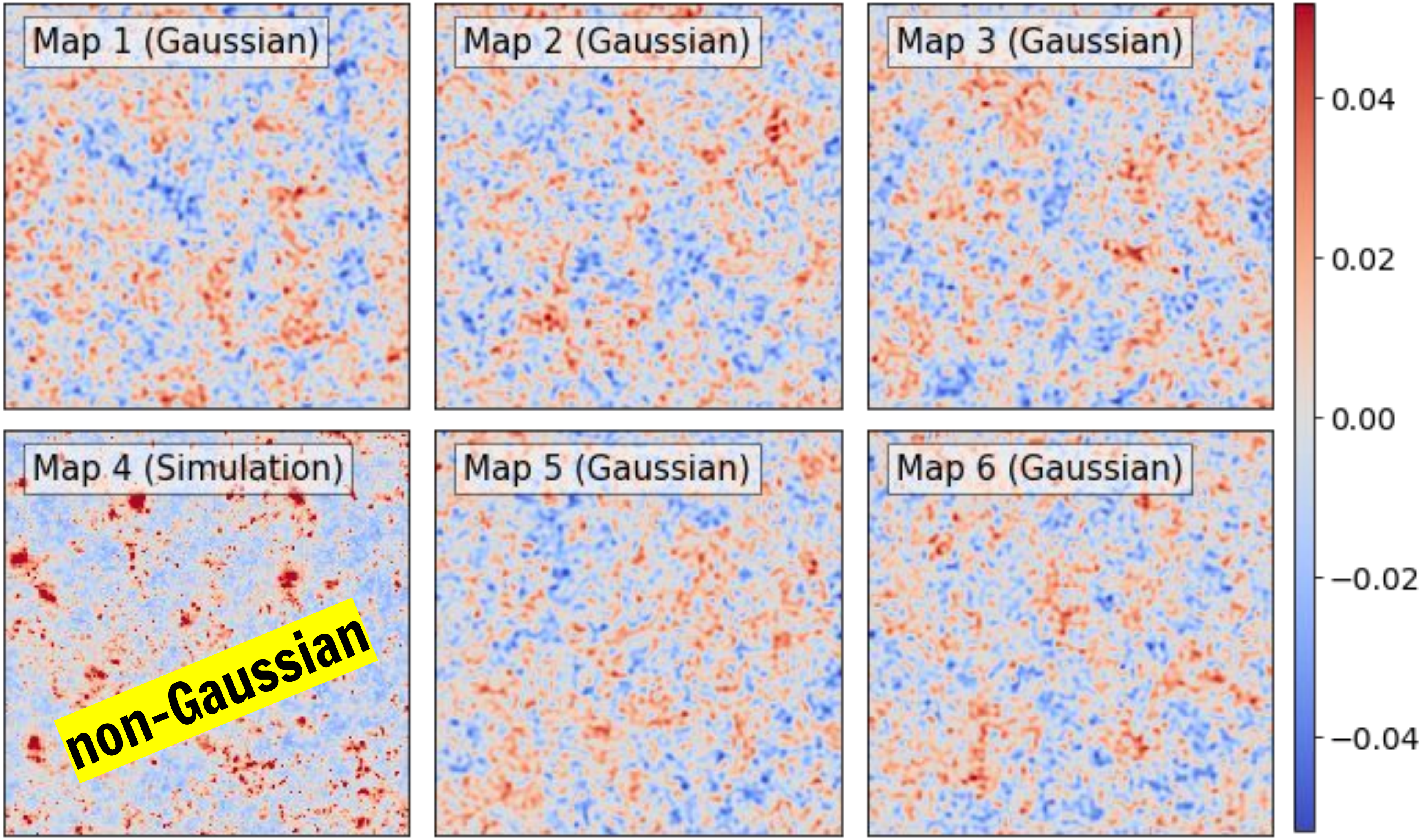
Dark Matter Distribution: Highly Non-Gaussian

color: projected overdensity



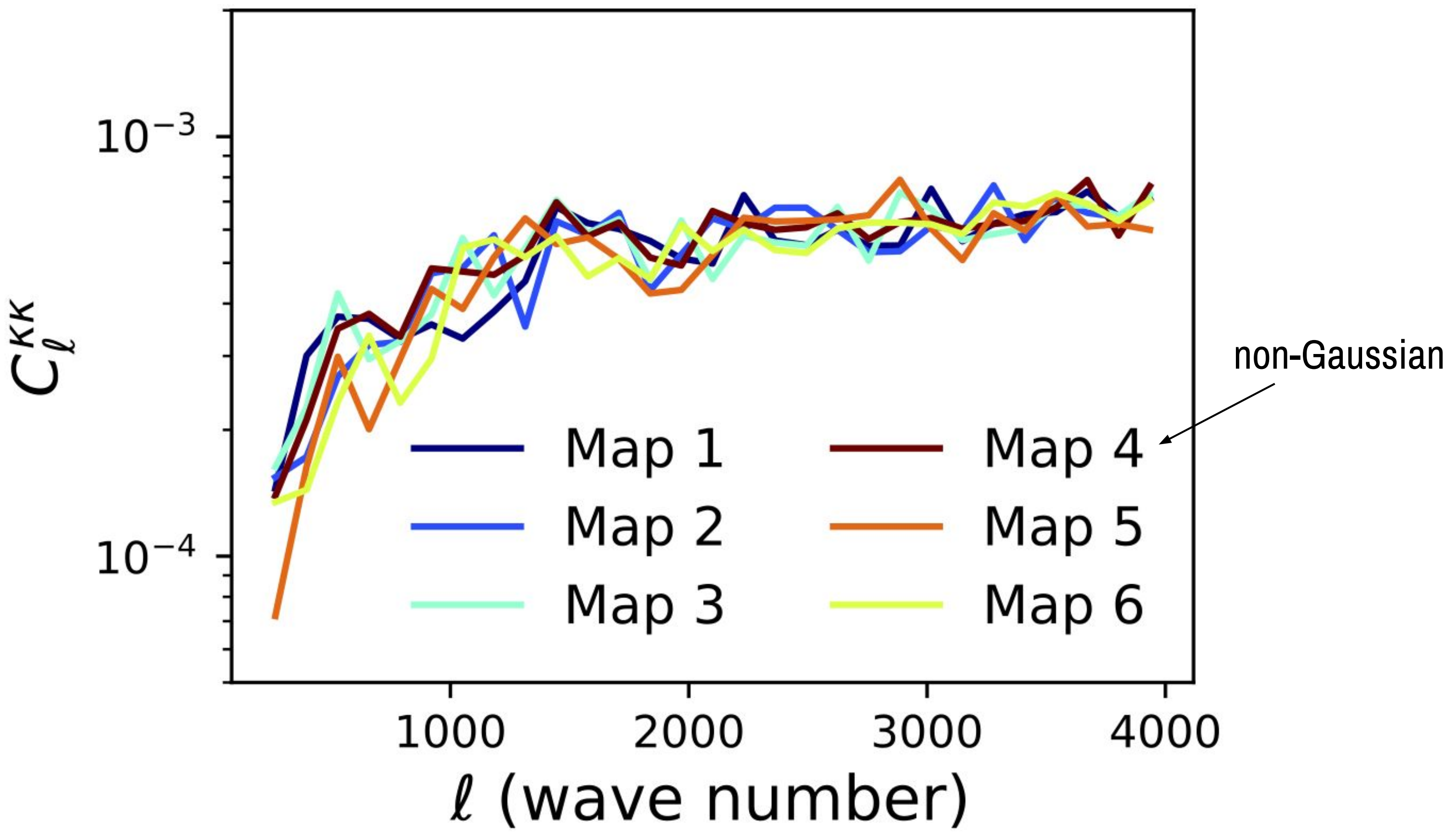
Dark Matter Distribution: Highly Non-Gaussian

color: projected overdensity



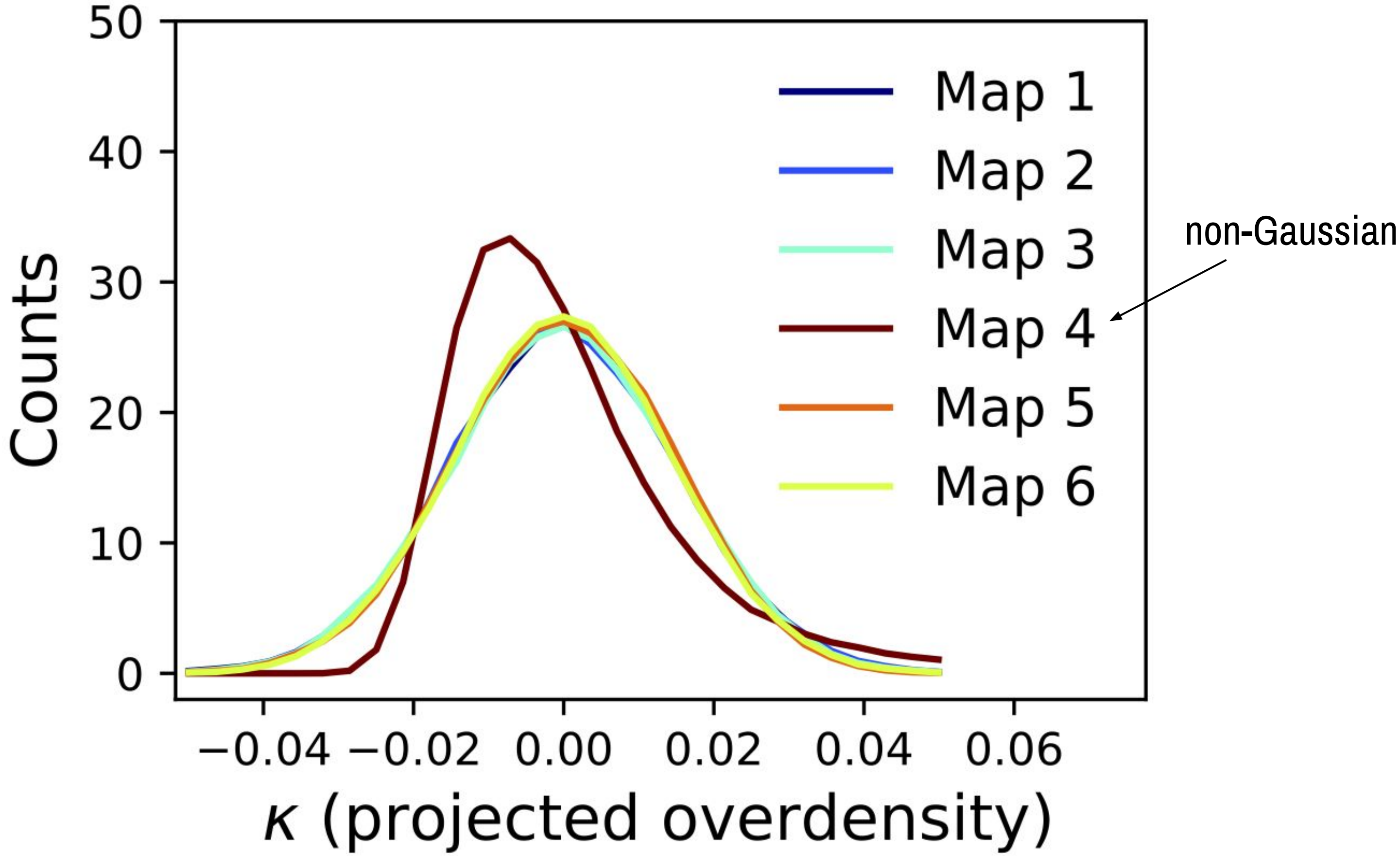
Lensing Power Spectrum

Does not capture non-Gaussian Information

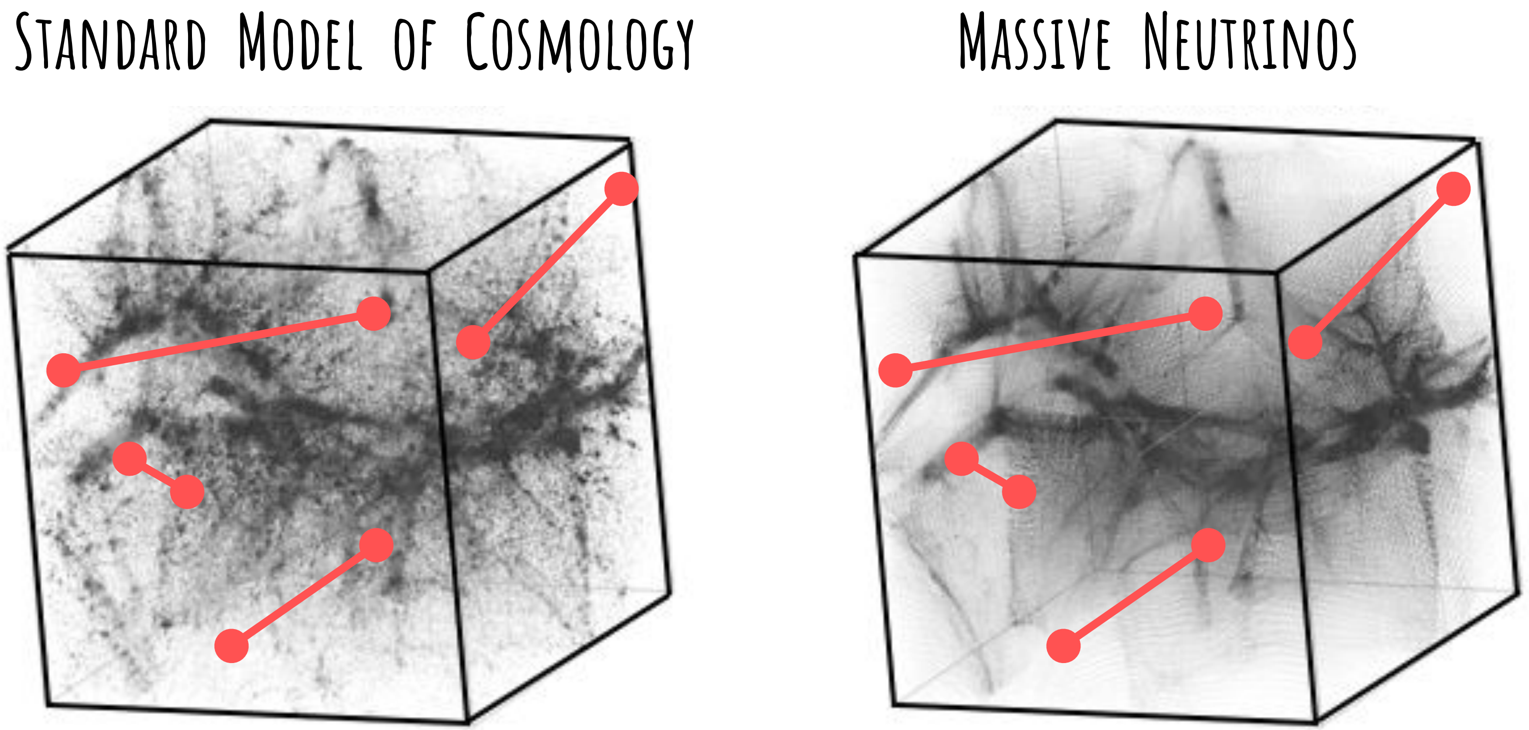


Histogram of All Pixel Values (PDF)

Sensitive to non-Gaussian Information



How do we extract non-Gaussian information?



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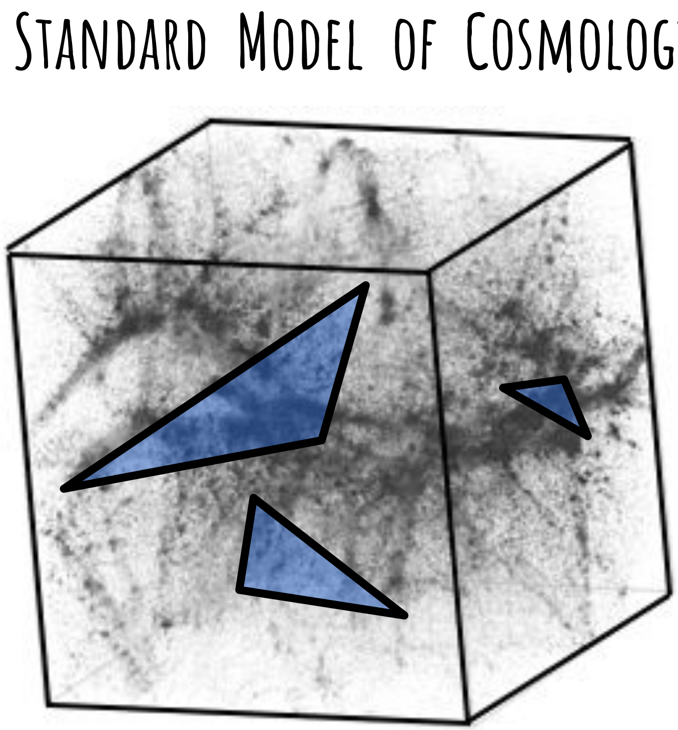
Extracting non-Gaussian information with **Bispectrum**



Bispectrum = zero for a Gaussian field. It is sensitive to **non-Gaussian** information, result of nonlinear growth.

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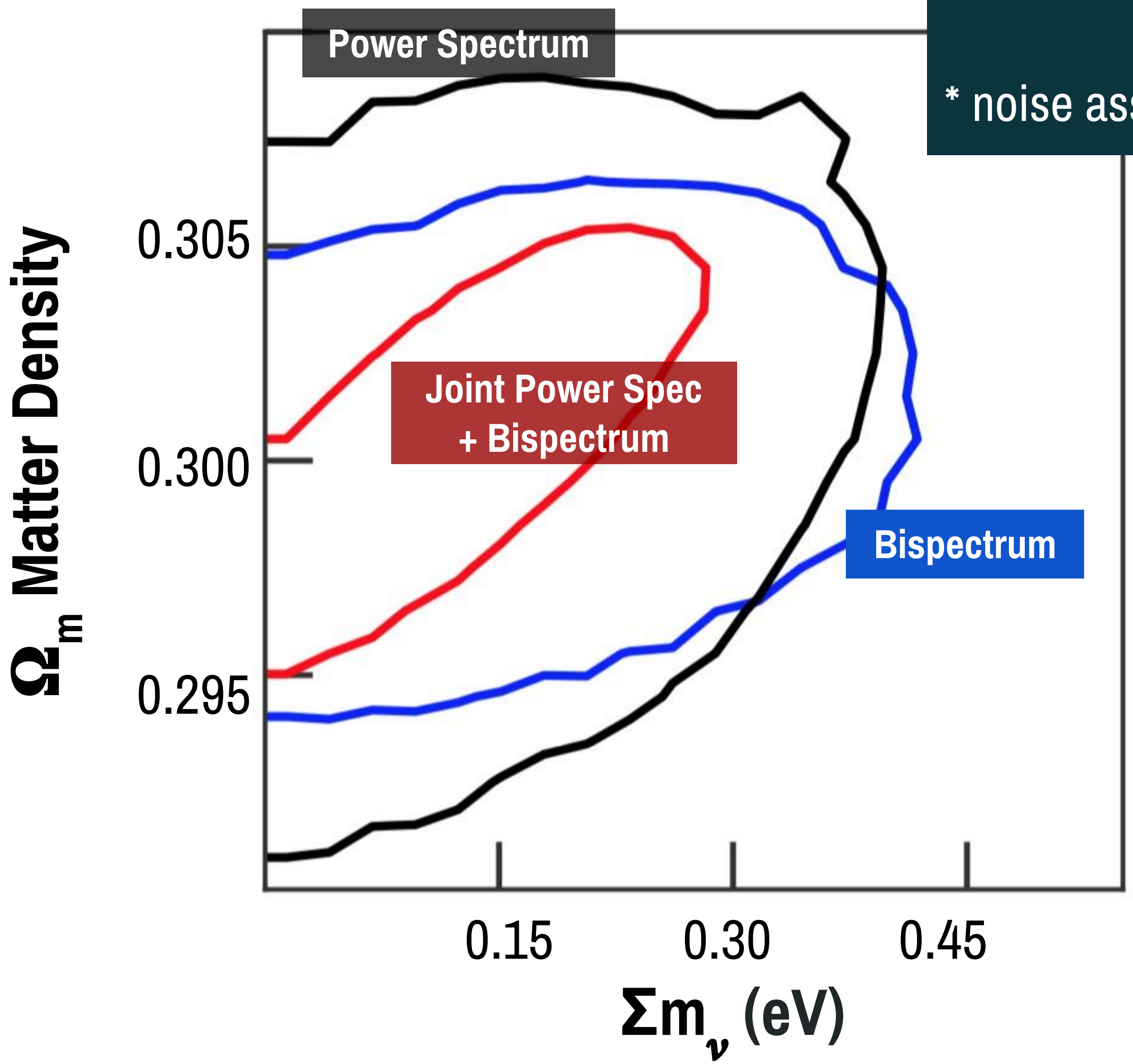
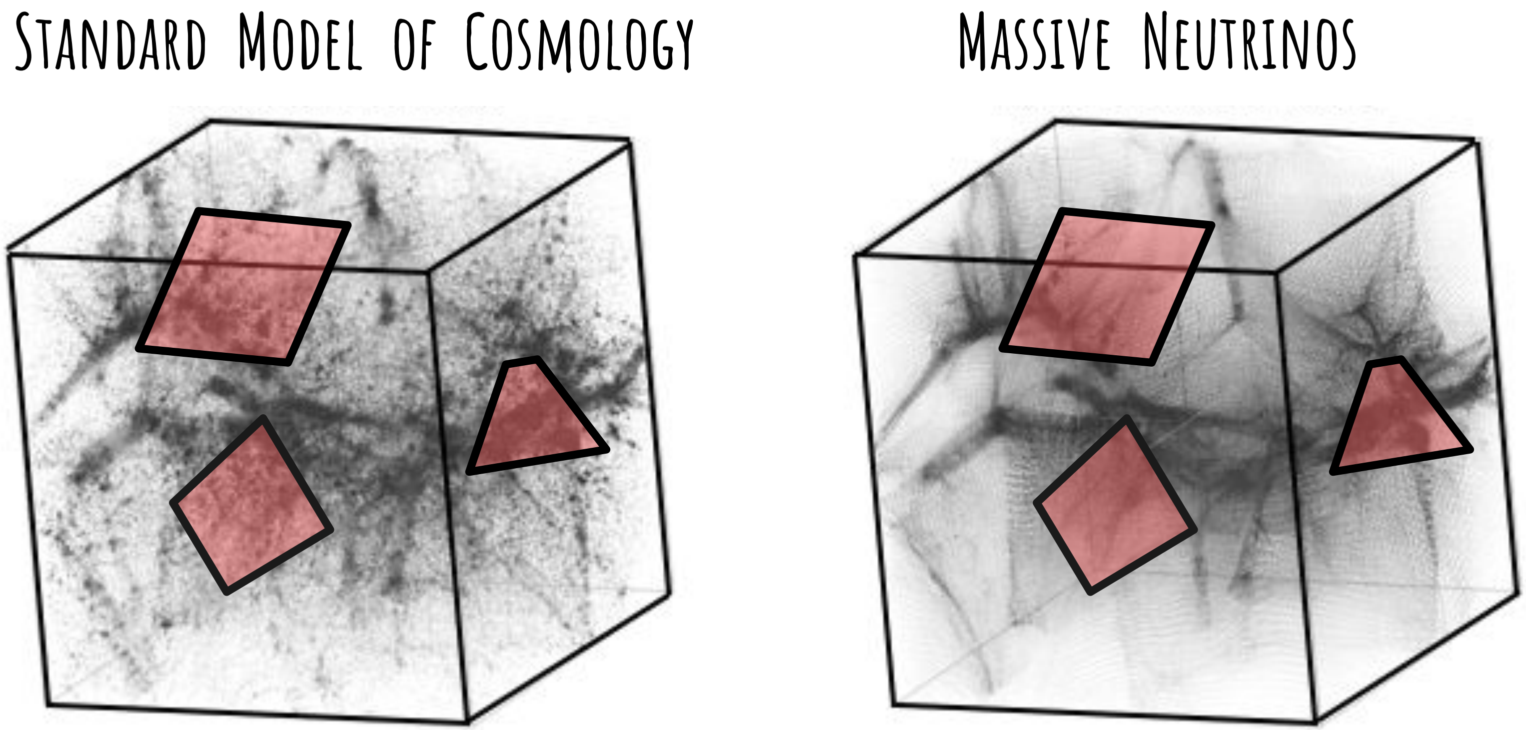
Σm_ν constraint **30% tighter** when lensing bispectrum added.

* noise assumption: LSST



Coulton, JL+2019

Next, Trispectrum?



Not a good idea. Too many possibile shapes.
Computationally prohibitive.

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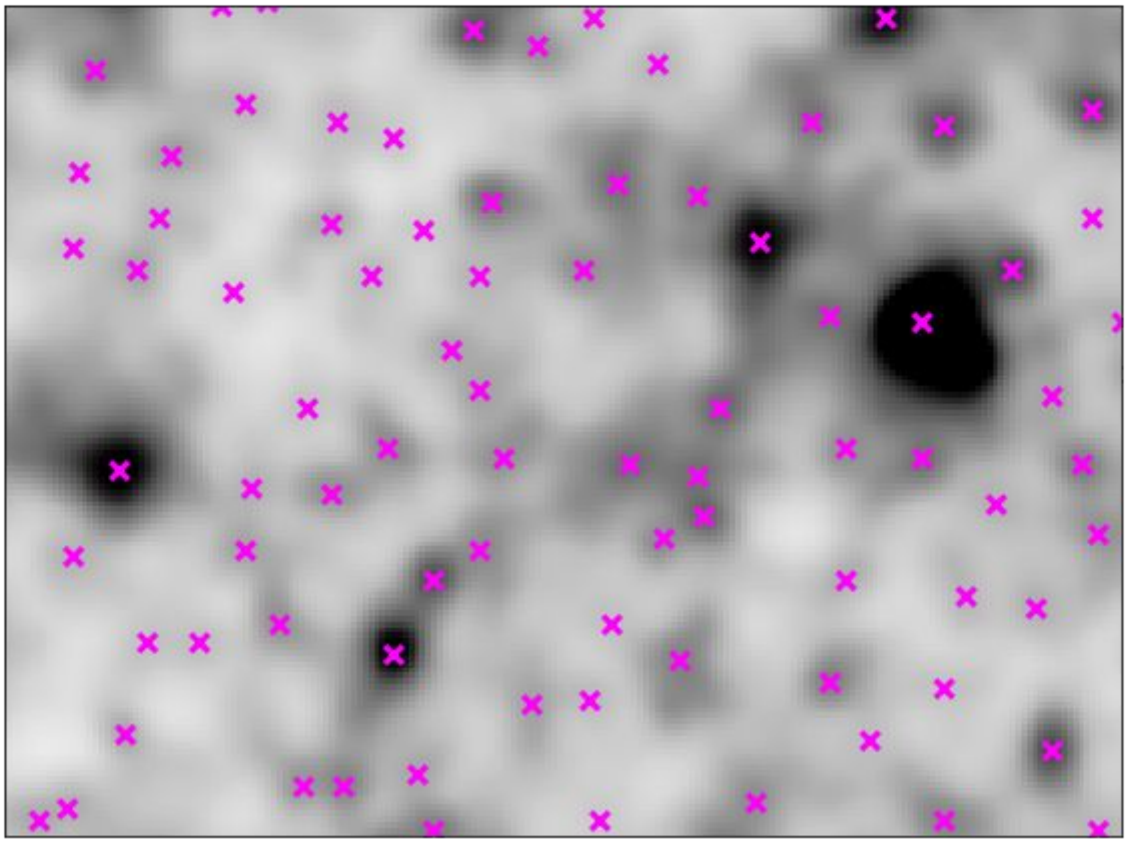
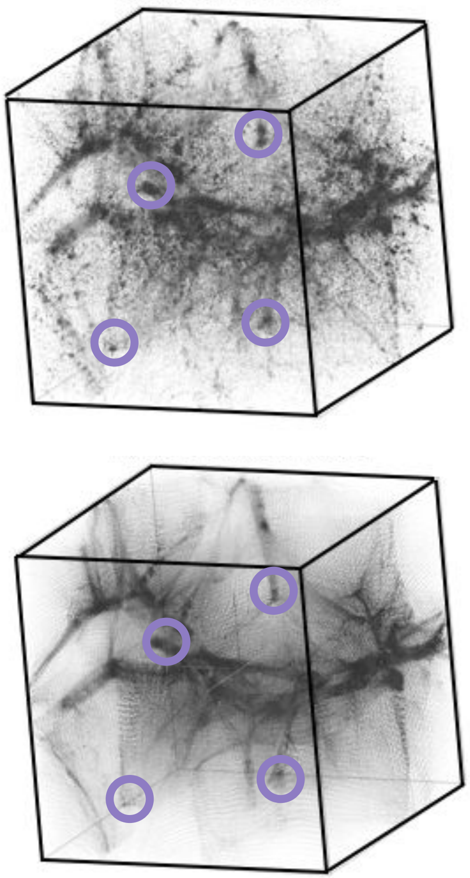
A Promising non-Gaussian Statistic: Peak Counts

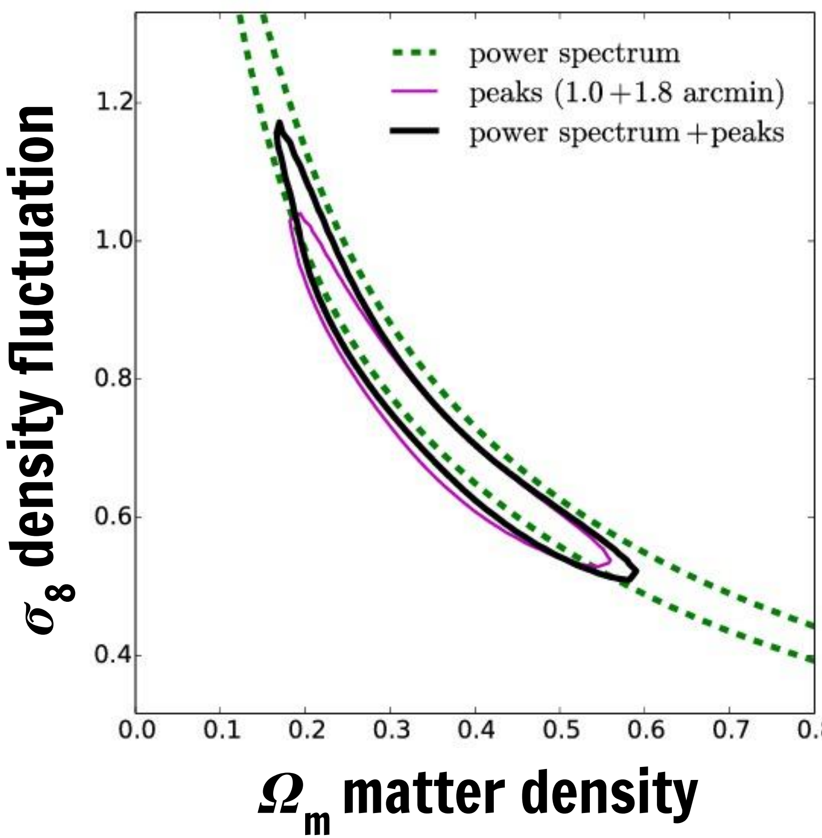




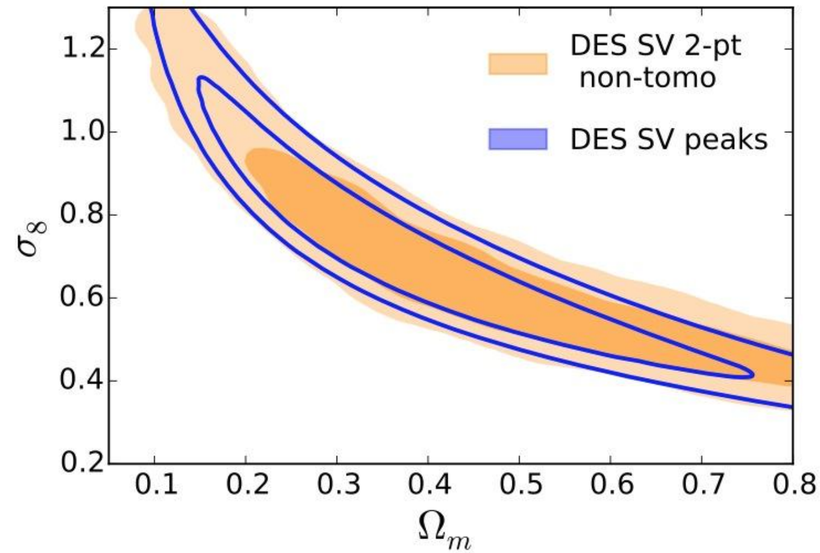
Weak lensing peaks are local maxima that are typically associated with the massive halos in the universe.

Cosmological Constraint with Peak Counts

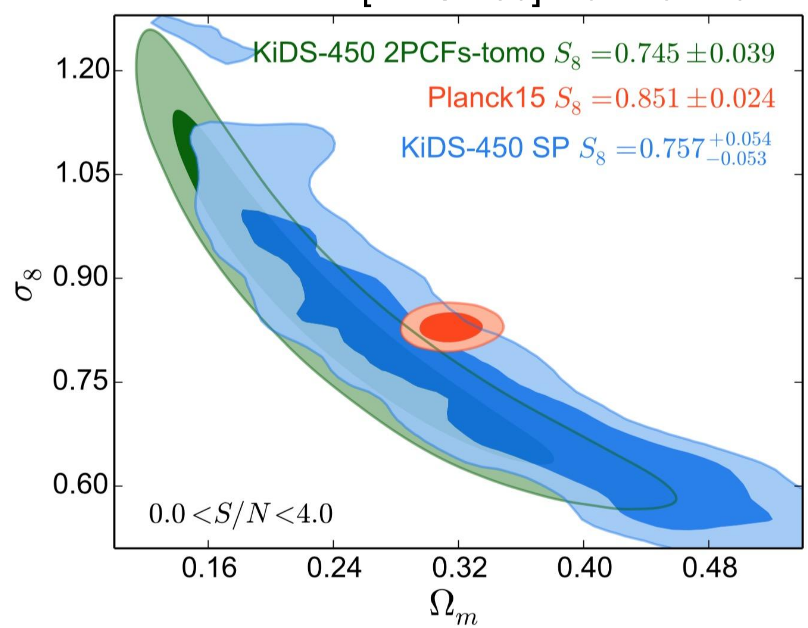
[CFHTLenS] JL+2015



[DES] Kacprzak+2016

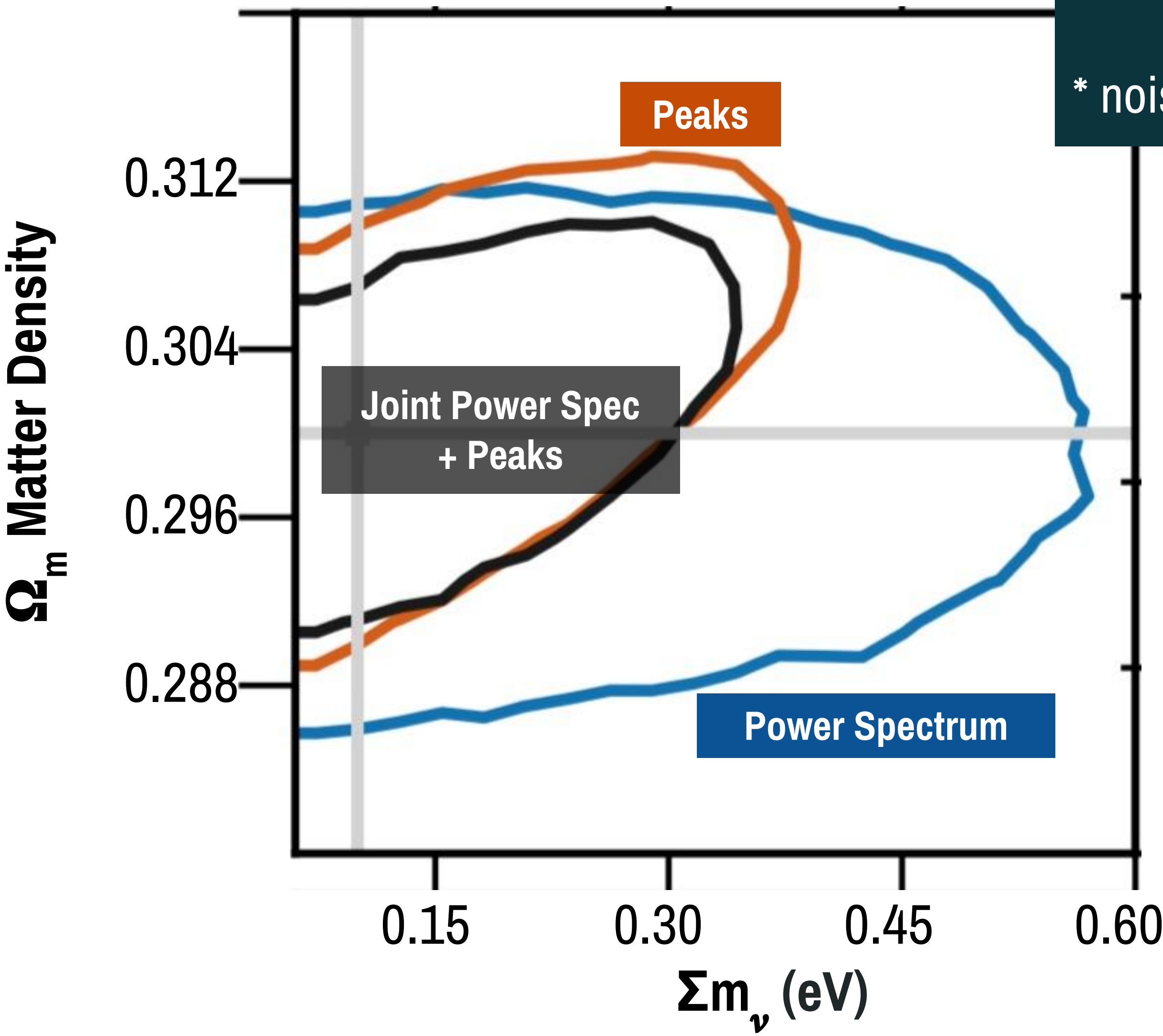


[KiDS-450] Martinet+2017

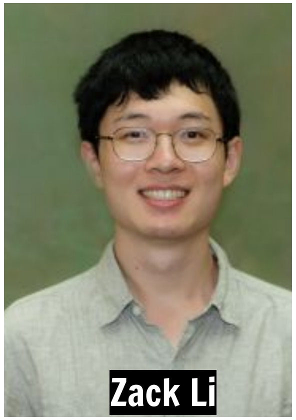


Σm_ν constraint **40% tighter** using lensing peaks alone.

* noise assumption: LSST

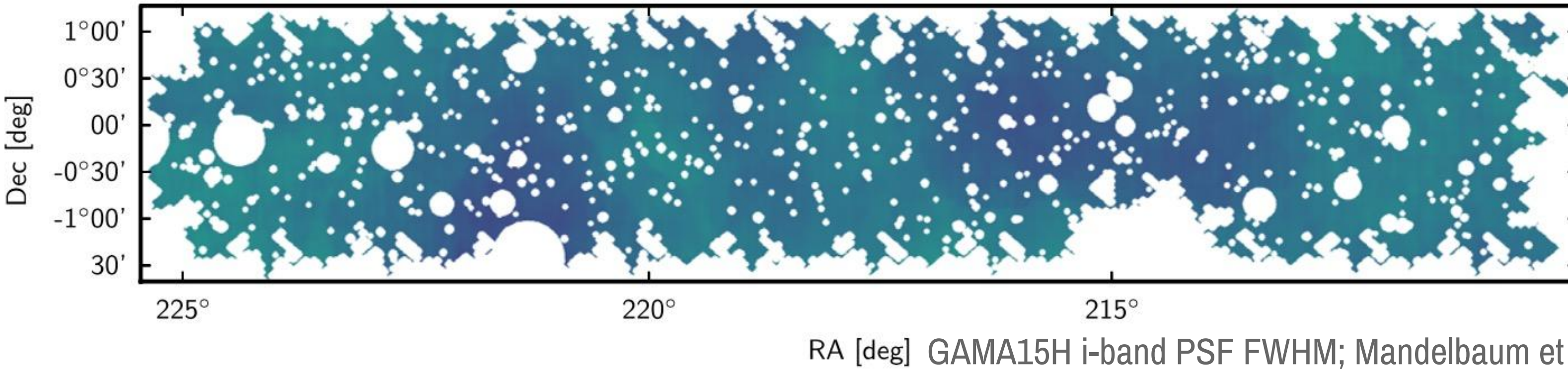


Li, JL+2019



Ongoing: Non-Gaussian Statistics with HSC Y1 Data

Hyper Suprime-Cam: "Path-finder" for Rubin Observatory LSST



GAMA15H i-band PSF FWHM; Mandelbaum et al. (2018)

Gabriela Marques
(peak counts)

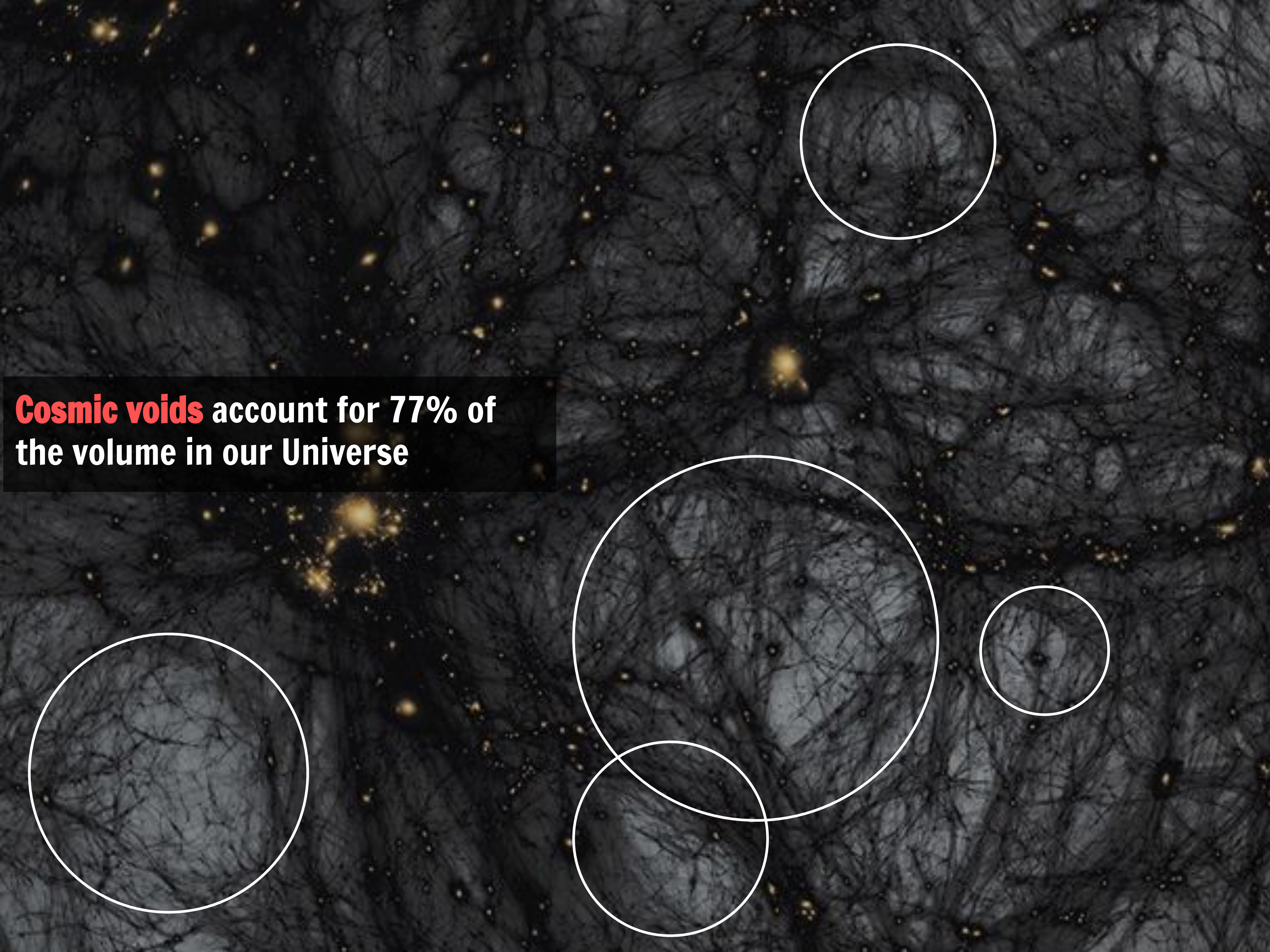
Will Coulton
(bispectrum)

Masato Shirasaki
(simulation)

Sihao Cheng
(scattering transform)

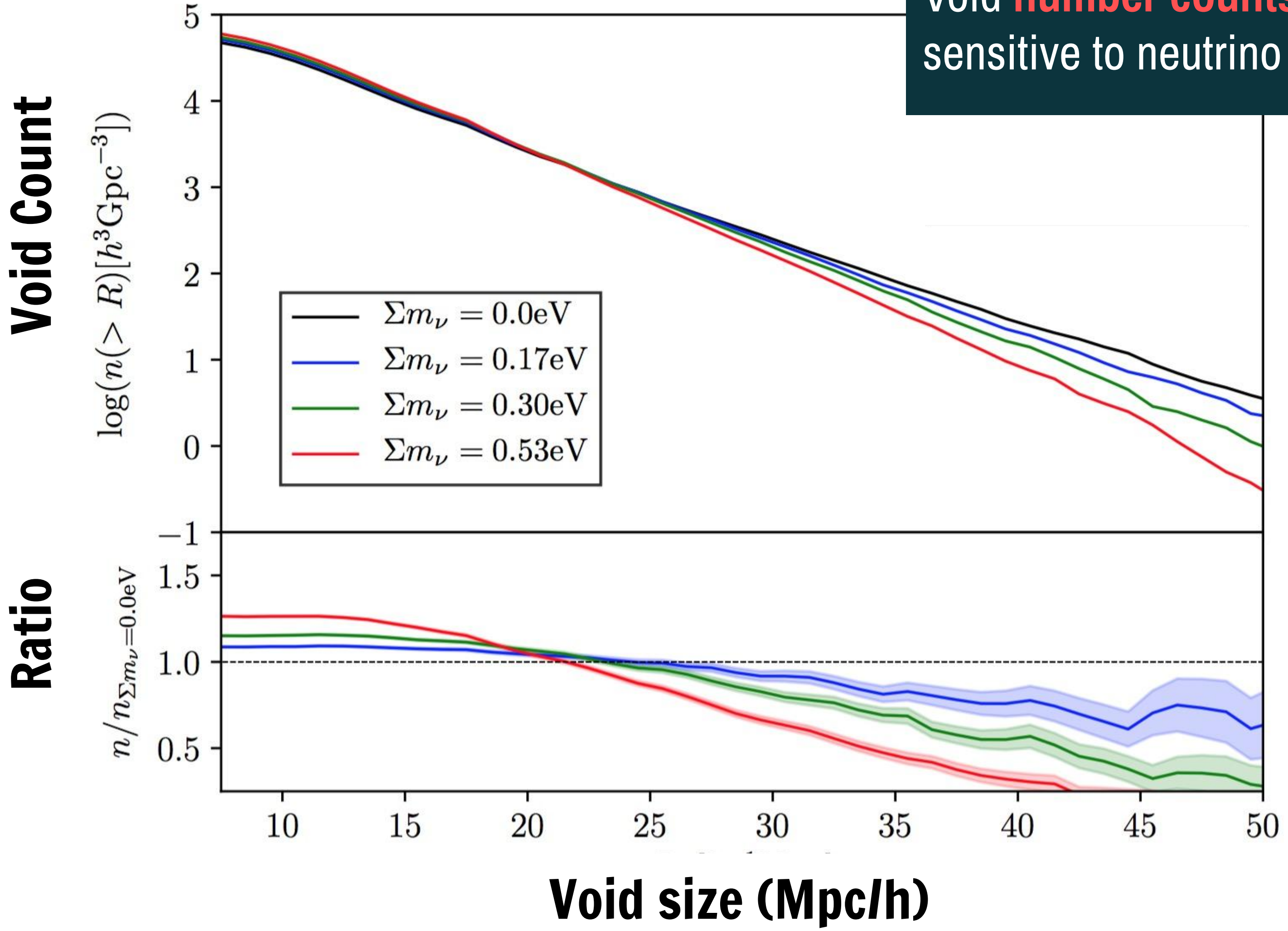
Ken Osato
(baryonic effects)

JL: overall planning; systematic tests design (mask, IA, baryons, photo-z, shear bias); blind analysis design (largely inspired by Hikage+2018 and Hamana+2020).


Cosmic voids account for 77% of the volume in our Universe

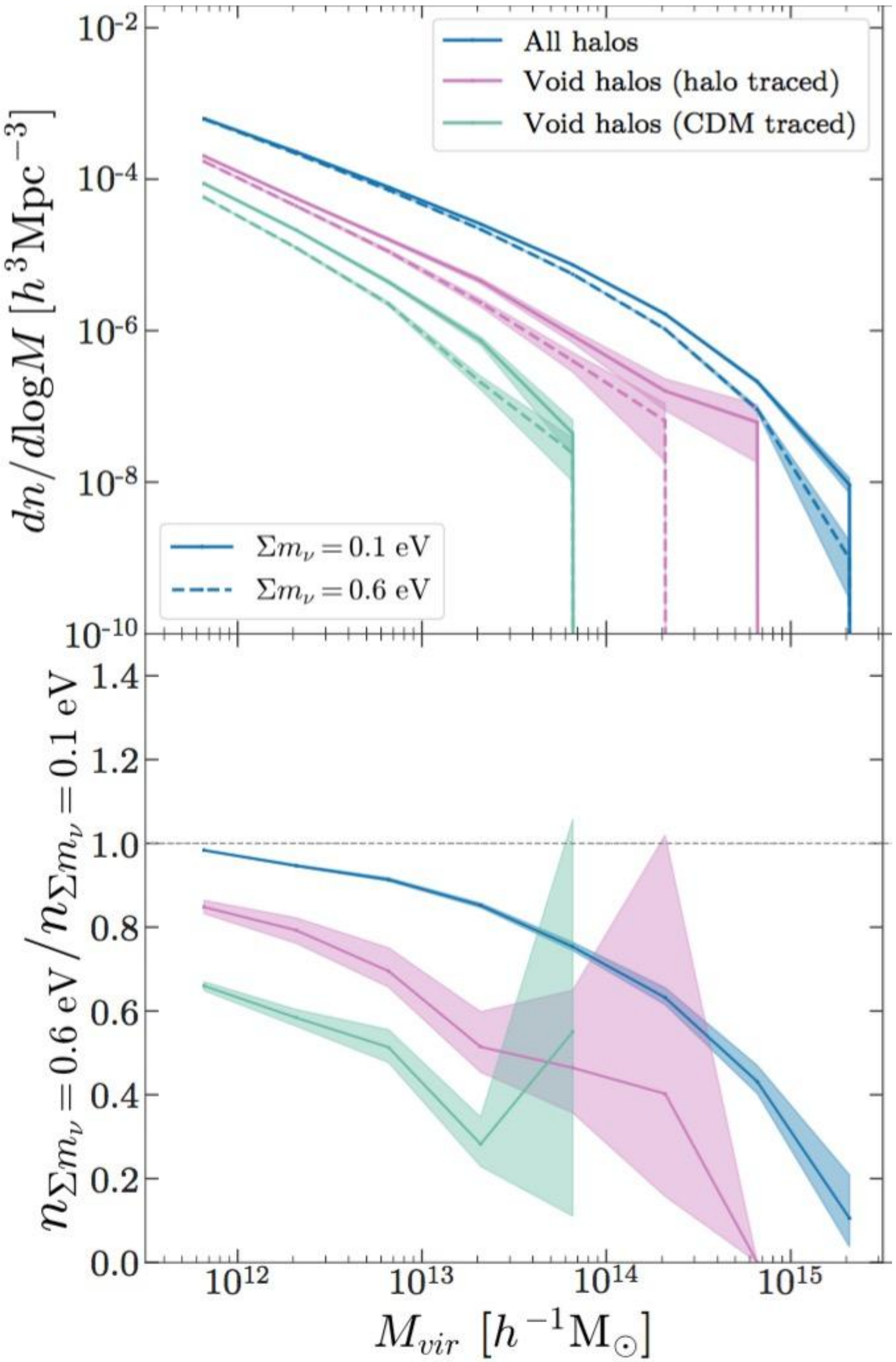
Void **number counts** and **clustering** are sensitive to neutrino mass

Kreisch, Pisani, Carbone, JL+2019



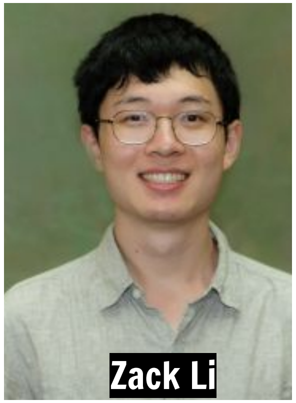
Halo Count

Ratio



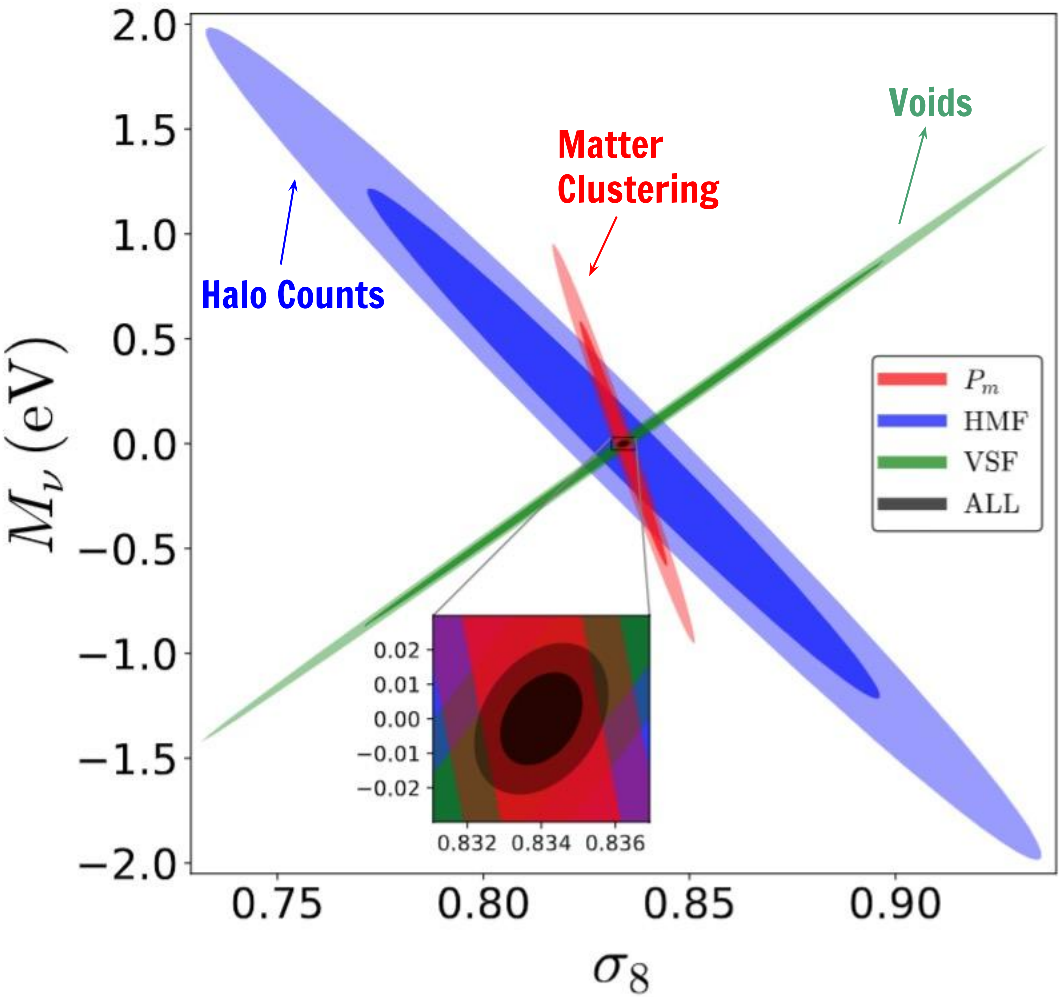
Void halos are more sensitive to neutrino mass than the general halo population

Zhang, Li, JL+2020



Combining the power spectrum with **voids** and **halos** has the potential to significantly improve neutrino mass constraints.

Bayer+(including JL) 2021



Volume =1 (Gpc/h)^3
Based on 23,000 Quijote simulations

Next Decade

Vera C. Rubin Observatory

Data each night: 15TB

Equal to 10 years of Sloan Digital Sky Survey

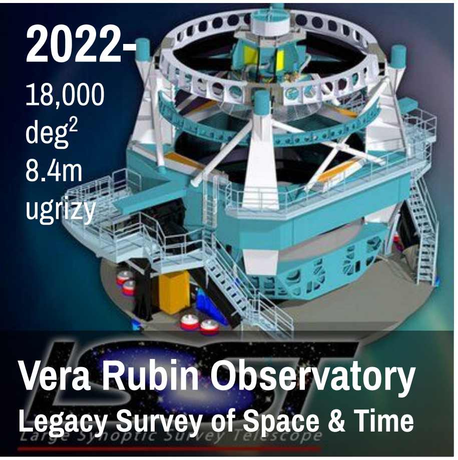
Observe 10^{10} galaxies

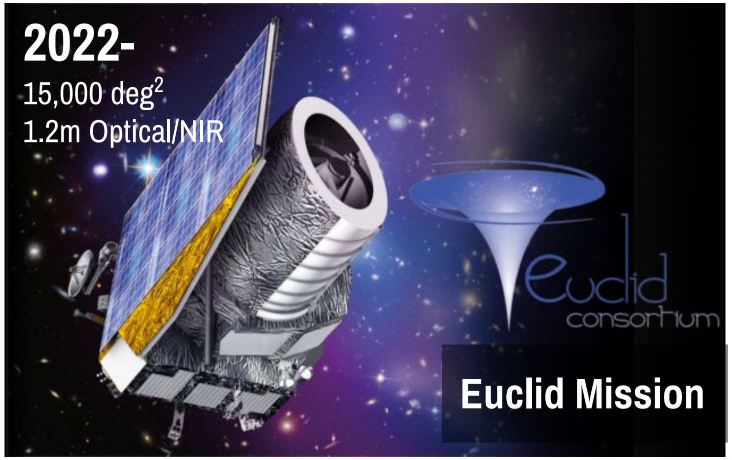
10^7 from Sloan Digital Sky Survey

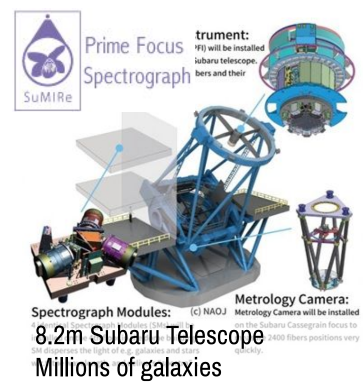
Full Member,
Leader of Weak Lensing
Mass-Mapping WG

Collaborator,
Weak Lensing forecast (arxiv:2001.10993)

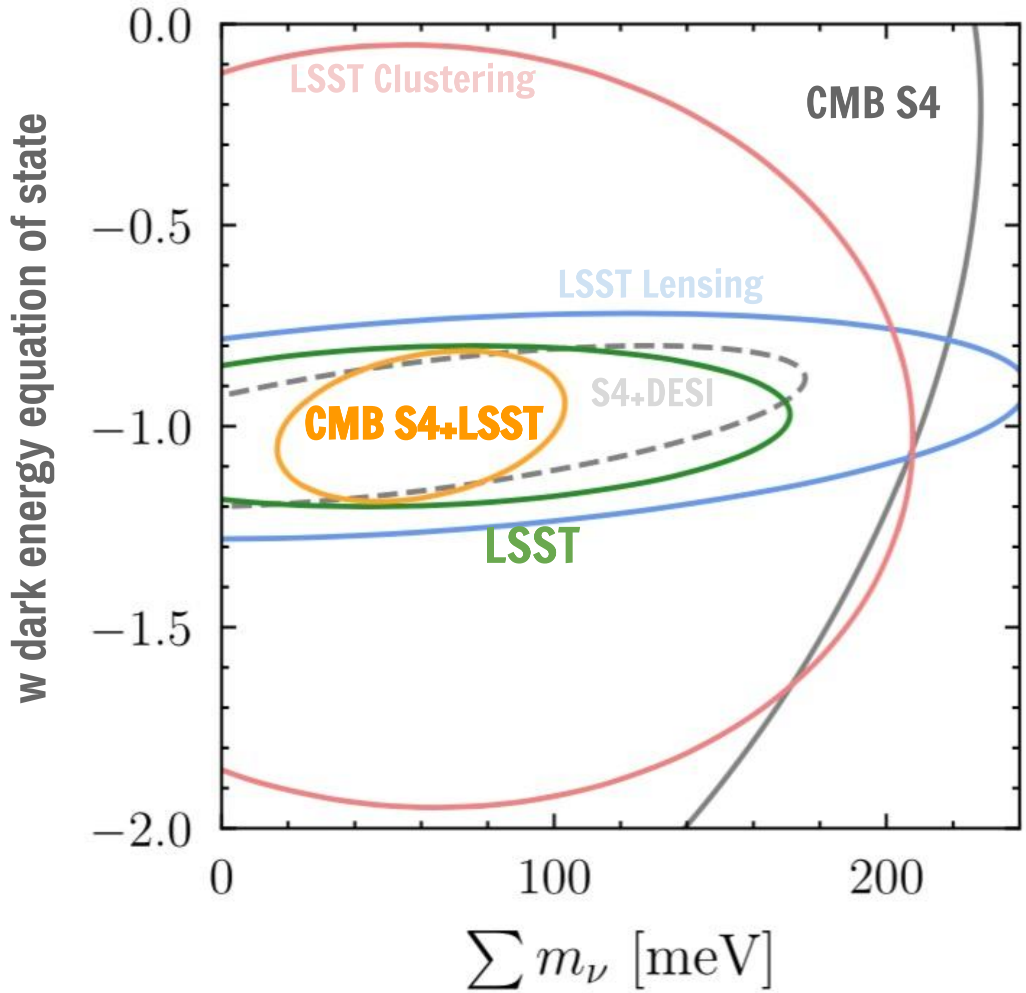
Member,
Leading extragalactic simulations







The Power of Joint Analysis



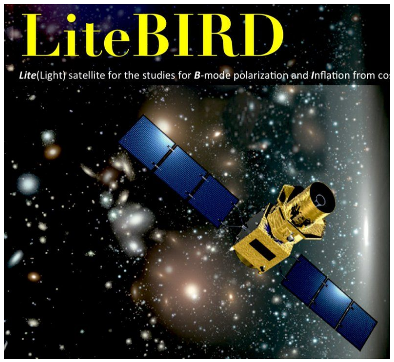
- ➔ Redshift-dependent growth
- ➔ Break parameter degeneracies
- ➔ Calibrate systematics

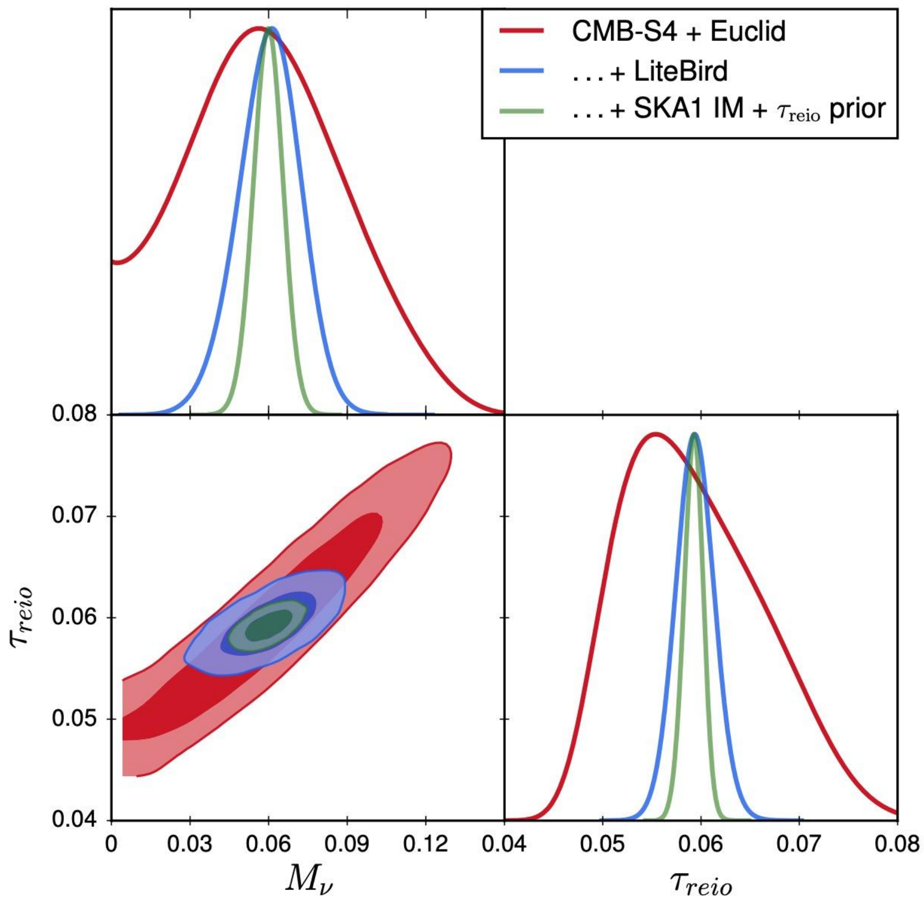
** Related joint analysis work:*
Marquez, JL+2020
Liu & Hill 2016
Liu & Haiman 2016
Liu+2016
Hill+(JL) 2016
Ferraro+(JL) 2016

Mishra-Sharma, Alonso, Dunkley 2018

**dark energy equation of state and spacetime curvature are free parameters.*

Improved τ_{reio} from LiteBIRD will be AMAZING





Brinckmann et al. 2019

* ***τ_{reio}* : reionization optical depth, highly degenerate with neutrino mass**

* *τ_{reio} ~0.007 from Planck; expected to be ~0.002 from LiteBIRD*

* *τ_{reio} prior assumes $\sigma(\tau_{reio})$ = 0.001.*

Planned Work

Novel Probes (Beyond 2pt)

Improve theoretical modeling for lensing non-Gaussian statistics, halo mass function, cosmic voids

Cosmological Simulations

Large grid, high resolution simulations that model: ***massive neutrinos, dark energy, dark matter, baryons.*** *(useful for all other 3 projects)*

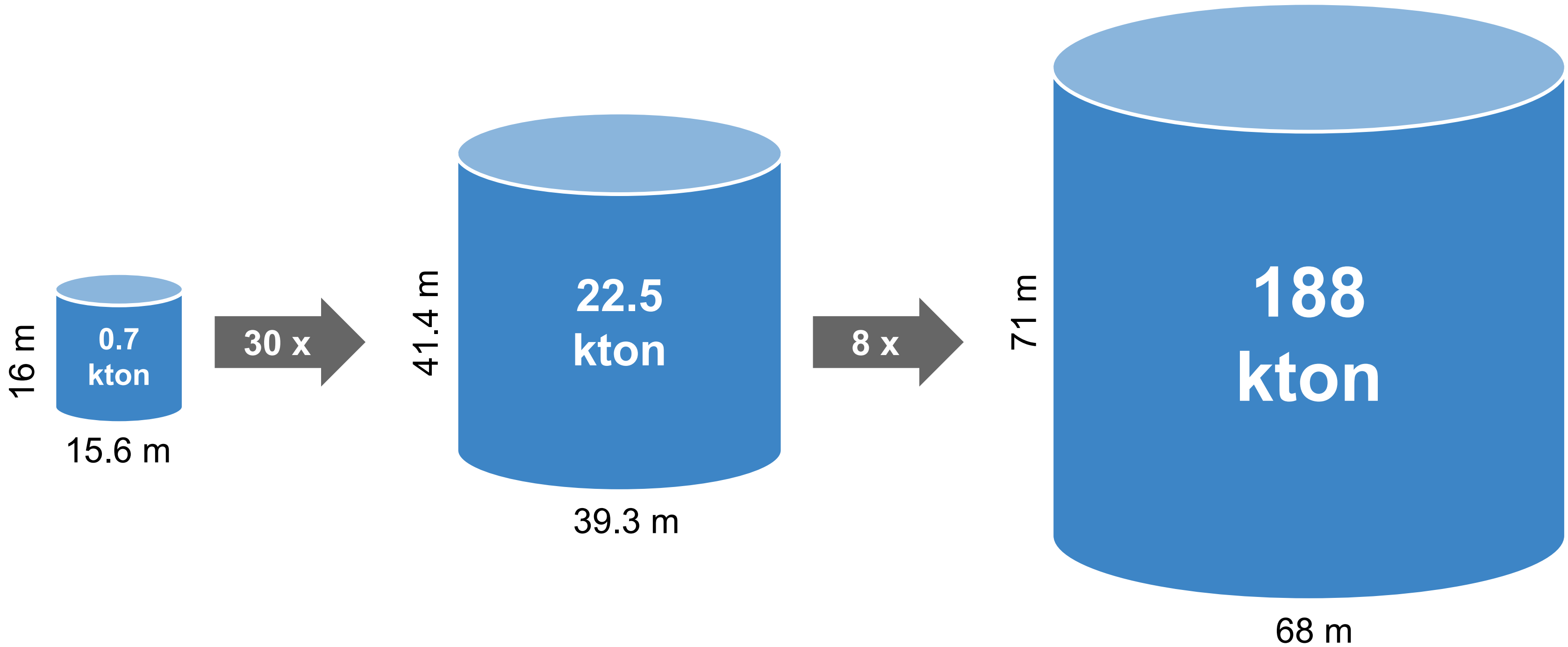
Joint Analysis Galaxy x CMB

Joint analysis of upcoming LSS and CMB data; Correlated simulations; Inter-collaboration coordination.

Machine Learning

How to exhaust all the information from cosmological datasets; model systematics; detect outliers; test ML algorithms

Kamiokande	Super-Kamiokande	Hyper-Kamiokande



1983 — 1996	1996 — present	2027 —
Supernova 1987A  2002 Nobel Physics	Atm. Neutrino Oscillation  2015 Nobel Physics	CPV, proton decay, DM... Multi-messenger astronomy: core-collapse SN, neutron star merger

Summary

Massive Neutrinos

Have high potential to lead to (yet another!)
breakthrough in physics within the next decade

Accurate Modeling of Nonlinear Scales

Is the key for significant improvement from cosmology

Joint Analysis

Is the only way to reach discovery