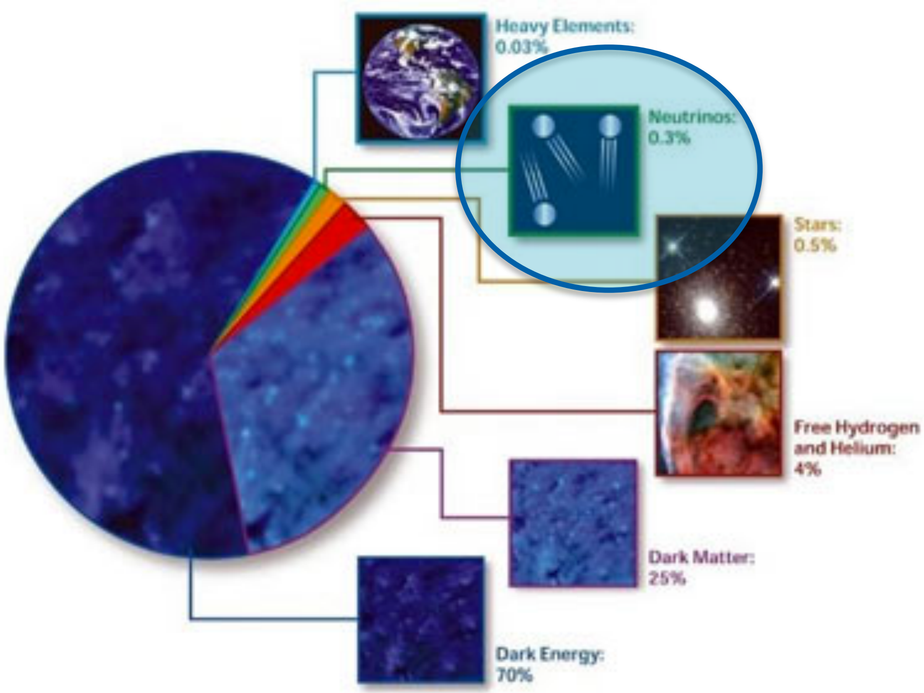
Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

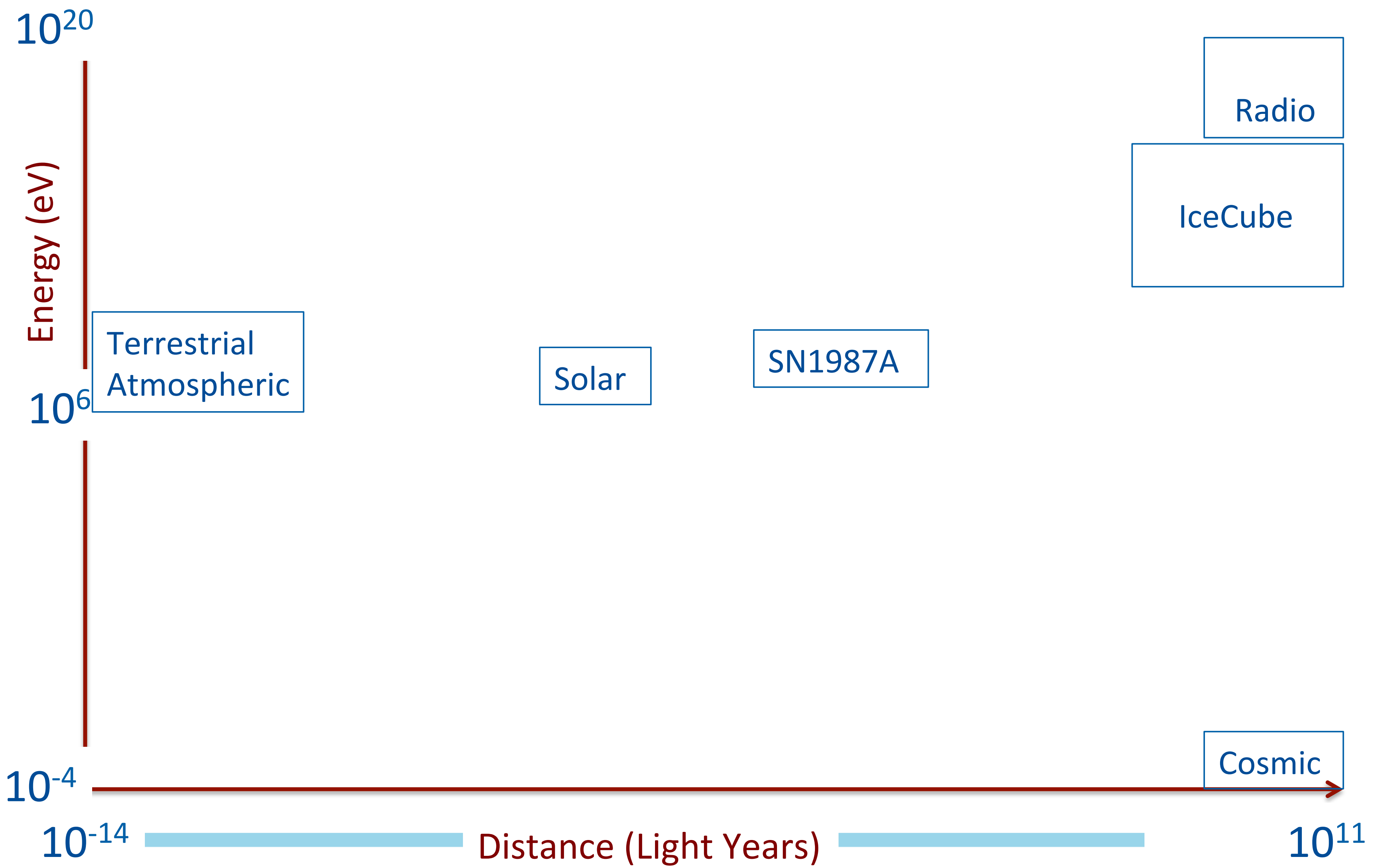


Cosmology Overview

Scott Dodelson

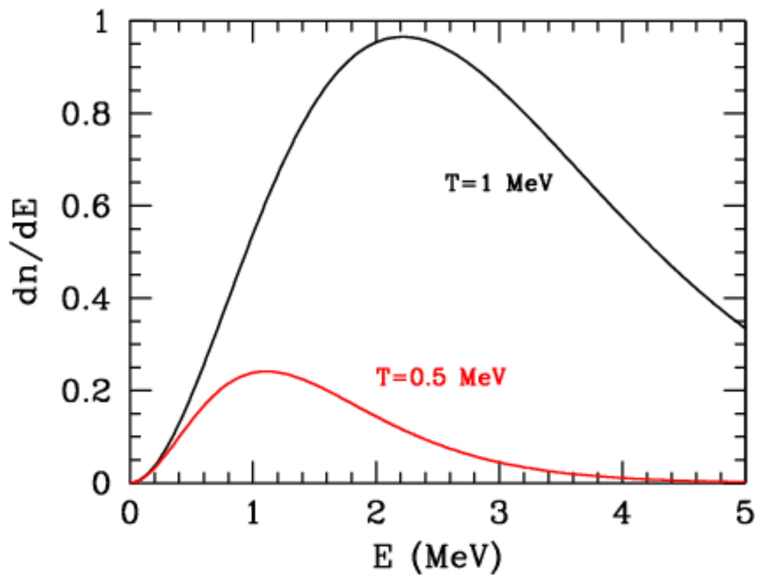
IPA2015

"Area" = (Highest E/Lowest E)X(Largest D/Smallest D) = 10^{50}



At early times, electroweak reactions were frequent enough to keep neutrinos in equilibrium with the rest of the cosmic plasma

Fermi-Dirac distribution with temperature *T* equal to the electron/photon temperature.



After the neutrinos decoupled from the rest of the plasma (kT<MeV), they still maintained Fermi-Dirac distribution with *T* falling as the Universe expanded

Calibrate off the well-known photon temperature

$$n_{\nu\bar{\nu}} = 115 N_{\nu} cm^{-3}$$

Number of species of weakly interacting neutrinos (3)

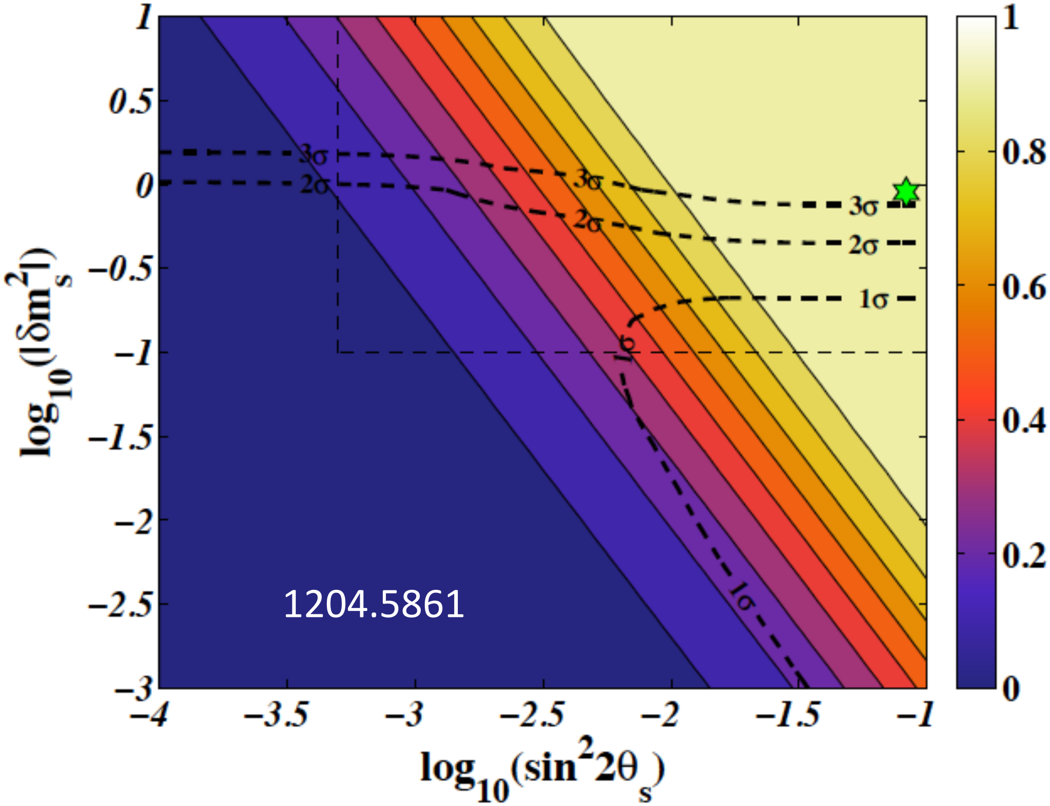
There are ~ a hundred quadrillion cosmic neutrinos (flux of 115x3c = 10^{13} cm^{-2} sec^{-1}) passing through this screen (~10^4 cm^2) every second.

Sterile Neutrinos produced in the early universe via oscillations

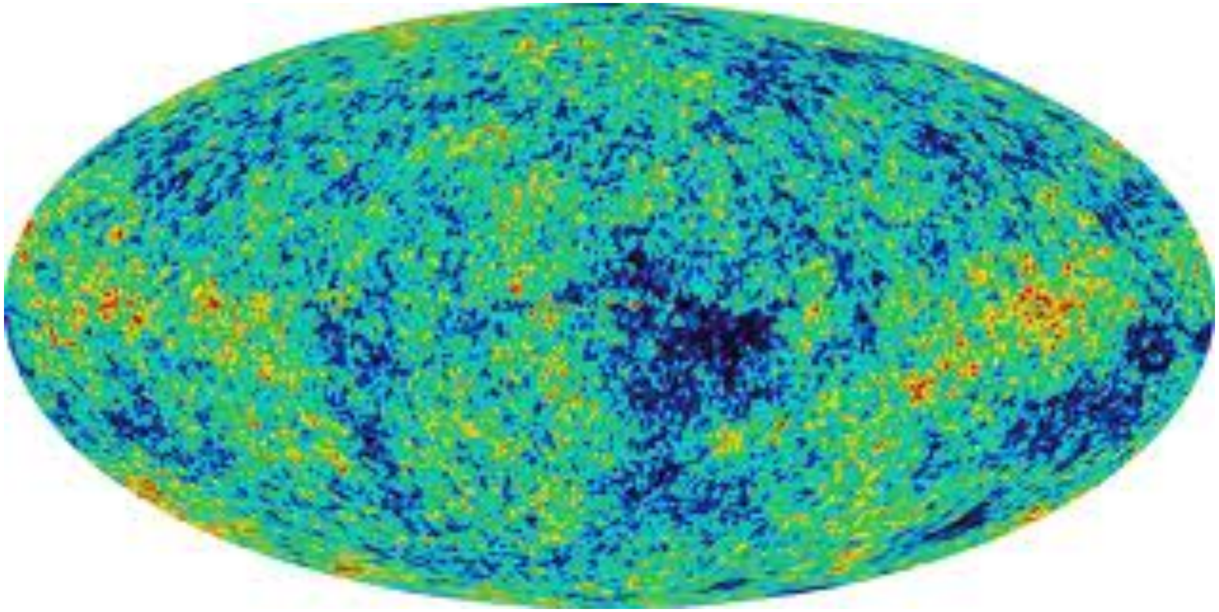
$$Rate = \frac{1}{2}\sin^2(2\overline{\theta}_s)\Gamma_{weak}$$

where the mixing angle needs to be computed in matter

Production peaks at ~100 MeV and can completely thermalize the state so that $N_\nu \rightarrow 4$



Neutrinos leave a subtle imprint on the sky



Cosmic Microwave Background:
Picture of the Universe when it
was 380,000 years old

Acoustic Oscillations

- At these early times, electrons, protons, and photons were tightly coupled, acted as single fluid
- Subject to **restoring force:** over-dense regions become under-dense as photons stream out → **acoustic oscillations**

Acoustic Oscillations and Damping

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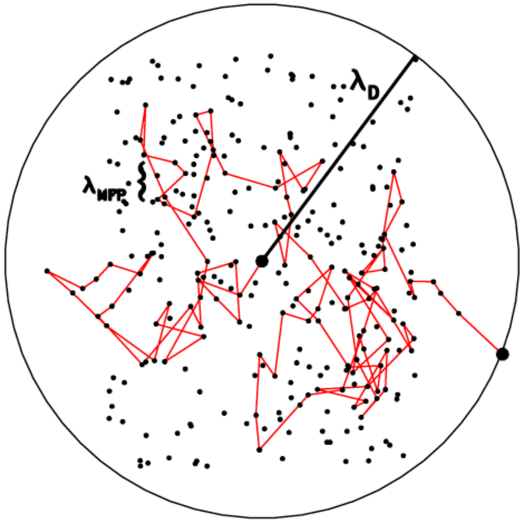

Acoustic Oscillations and Damping

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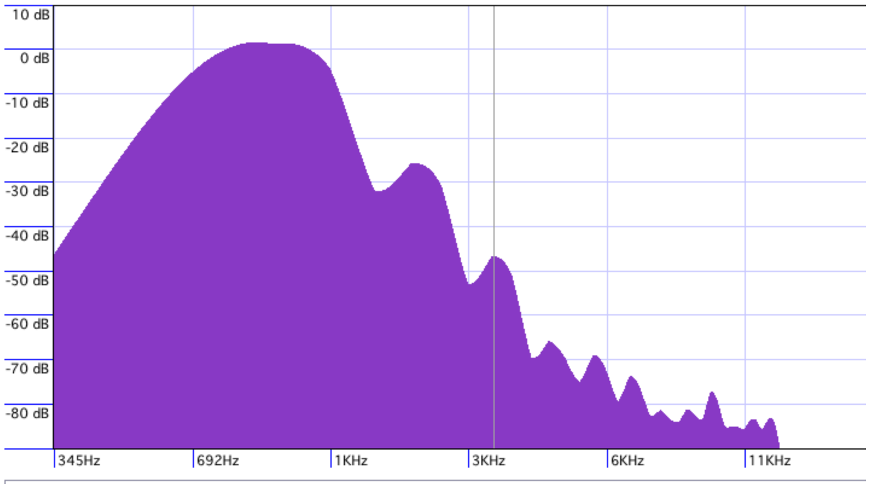
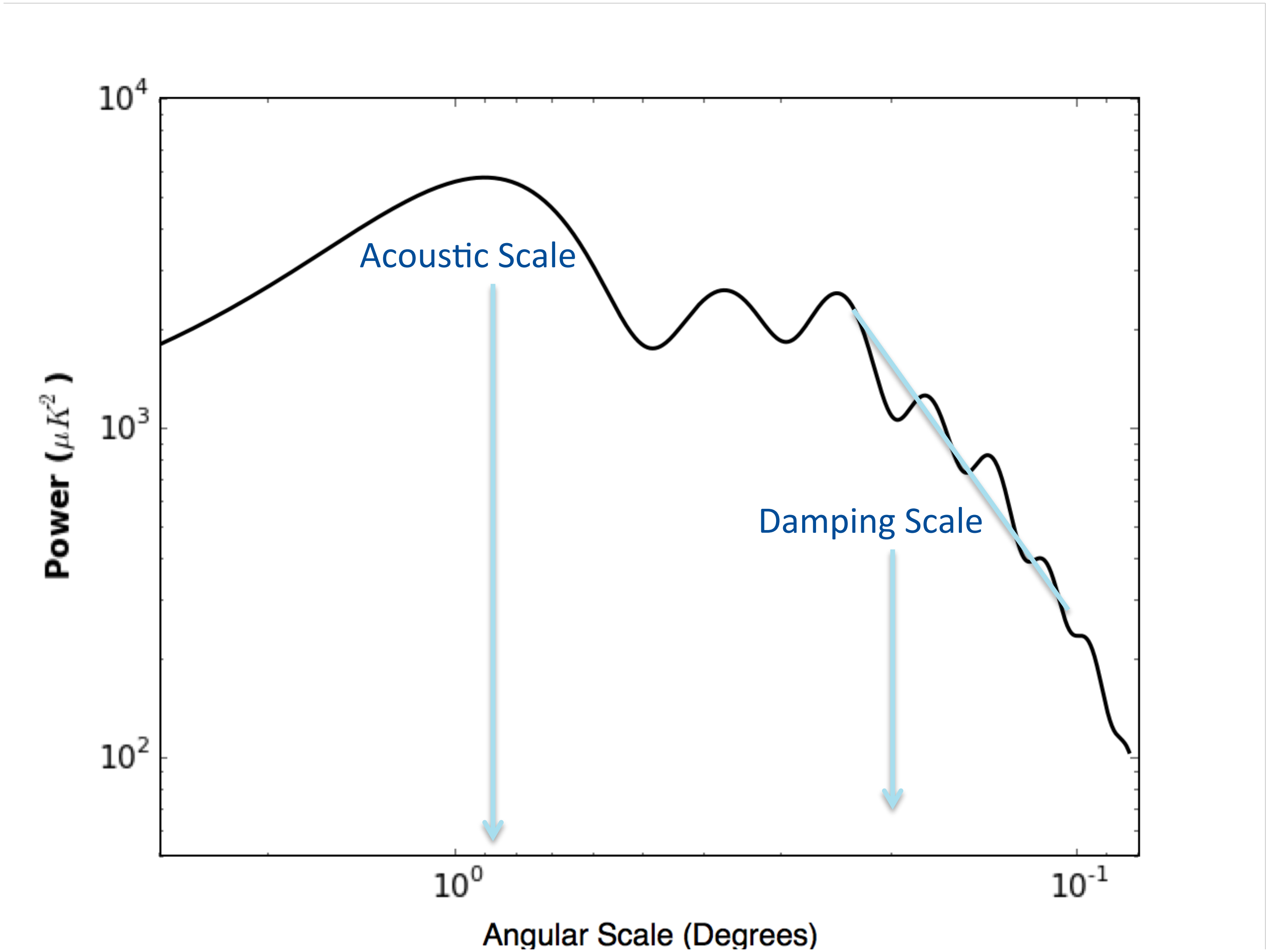
Spectrum of Musical Note



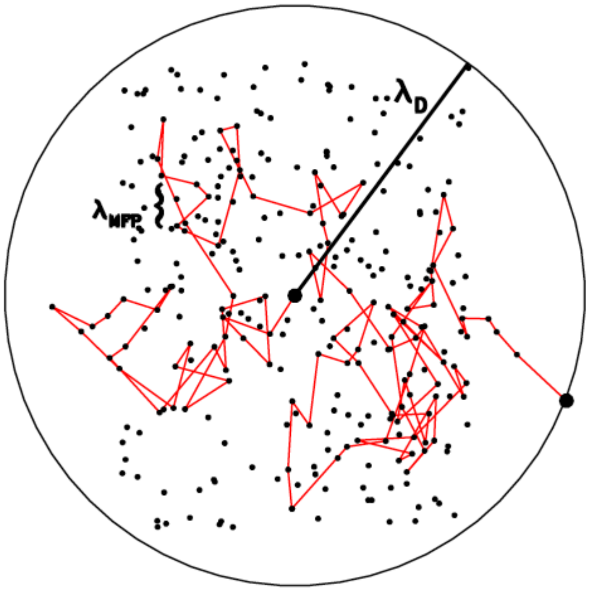
Power Spectrum of CMB: Acoustic Oscillations and Damping



Ratio of Acoustic Scale to Damping scale

$$\lambda_{acoustic} \sim c_{sound} t \propto t$$

$$\lambda_D \sim \lambda_{MFP} \sqrt{N_{scatters}} \sim \lambda_{MFP} \sqrt{\frac{ct}{\lambda_{MFP}}} \propto t^{1/2}$$

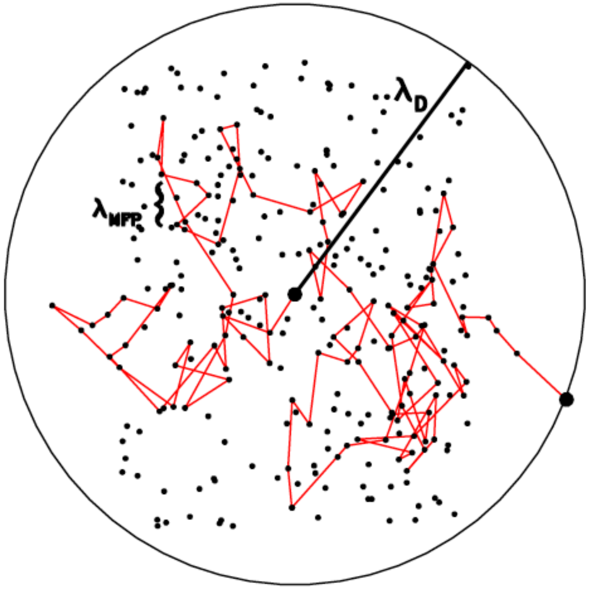


Ratio of Acoustic Scale to Damping scale

$$\lambda_{acoustic} \sim c_{sound} t \propto t$$

The ratio of the damping scale to the acoustic scale:

$$\frac{\lambda_{acoustic}}{\lambda_{damping}} \propto t_{rec}^{1/2}$$

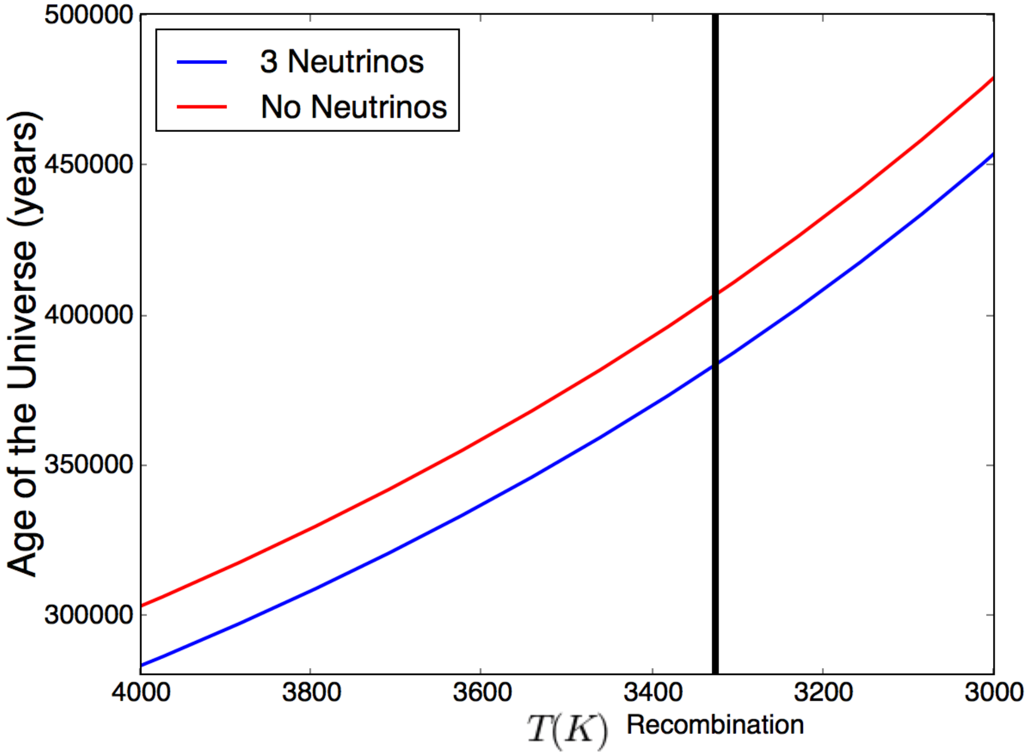


$$\lambda_D \sim \lambda_{MFP}\sqrt{N_{scatters}} \sim \lambda_{MFP}\sqrt{\frac{ct}{\lambda_{MFP}}} \propto t^{1/2}$$

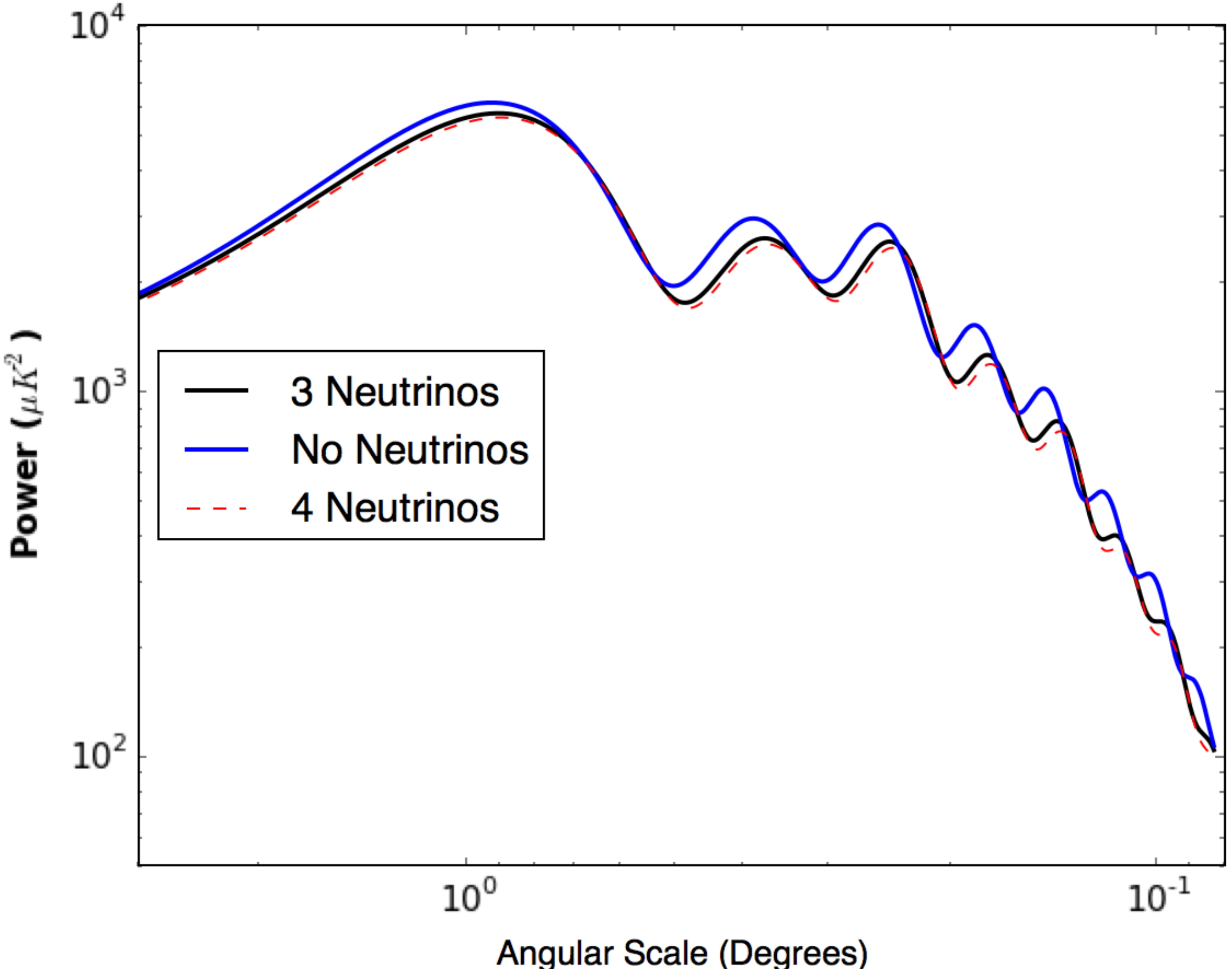
Neutrinos contribute to energy density of the early Universe

$$\frac{\lambda_{acoustic}}{\lambda_{damping}} \propto t_{rec}^{1/2}$$

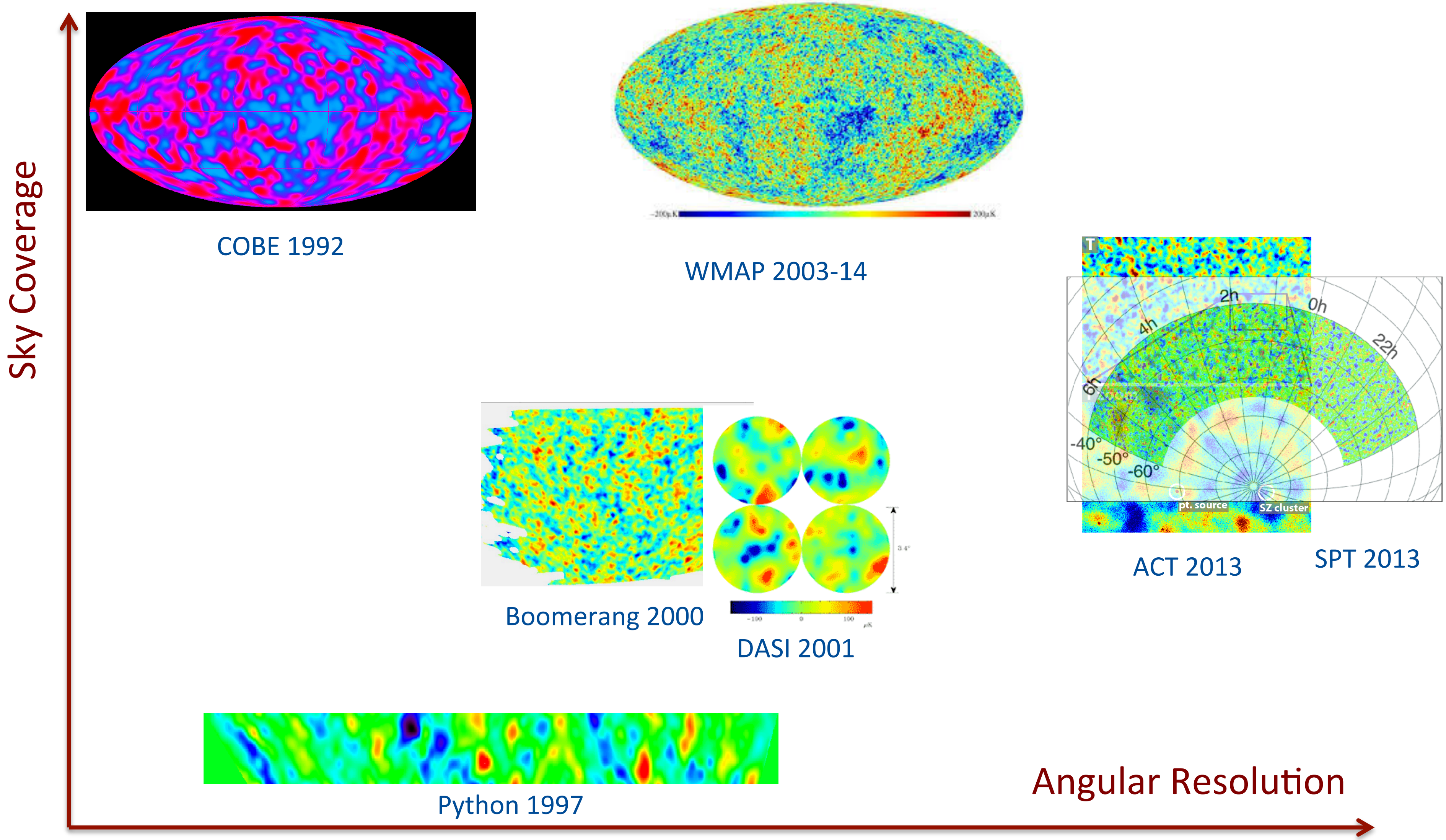
- Einstein's equations → Expansion Rate proportional to energy density
- Age of the universe at given Temperature is higher if expansion rate is slower (e.g., if neutrinos did not contribute to the energy budget)



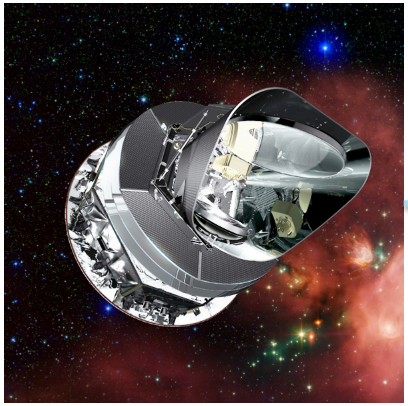
More neutrinos → More Damping
→ Less power on small scales

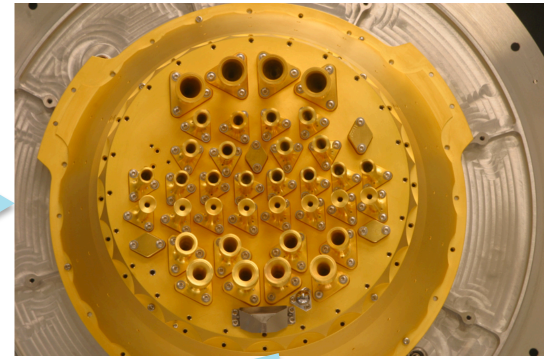


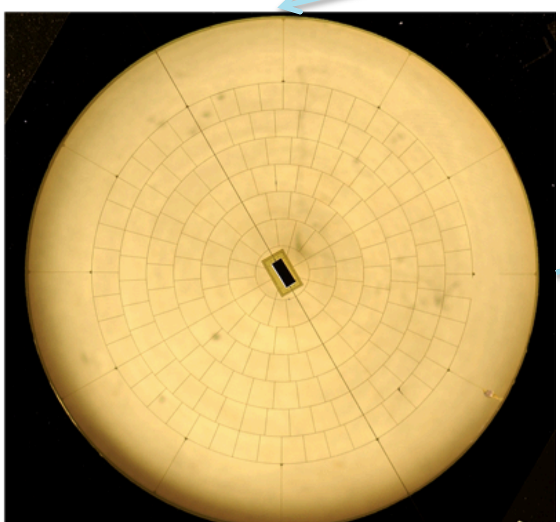
CMB Anisotropies measured for over 20 years

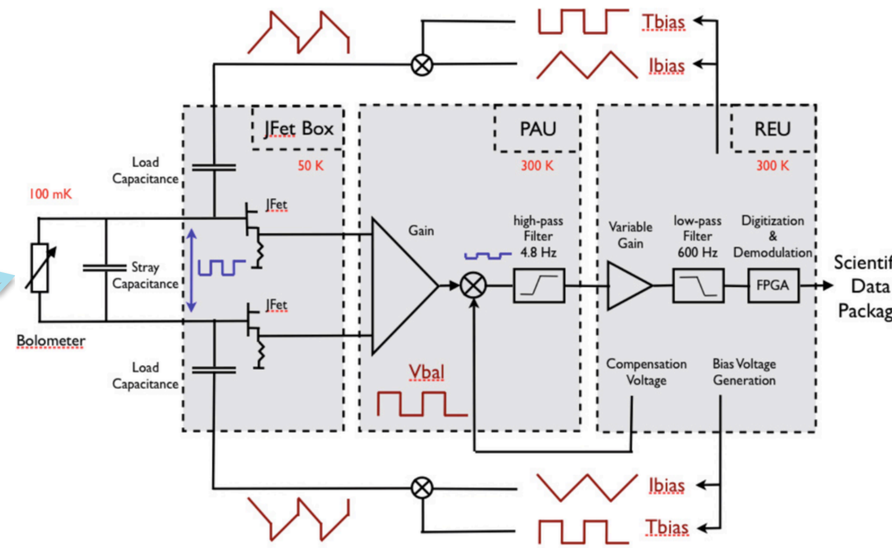


Example: Planck High Frequency Instrument









Map Making

(Simplified) Model for the time-ordered data:

$$d_t = A_{tp} T_p + n_t$$

Pointing matrix

Temperature in pixel *p*

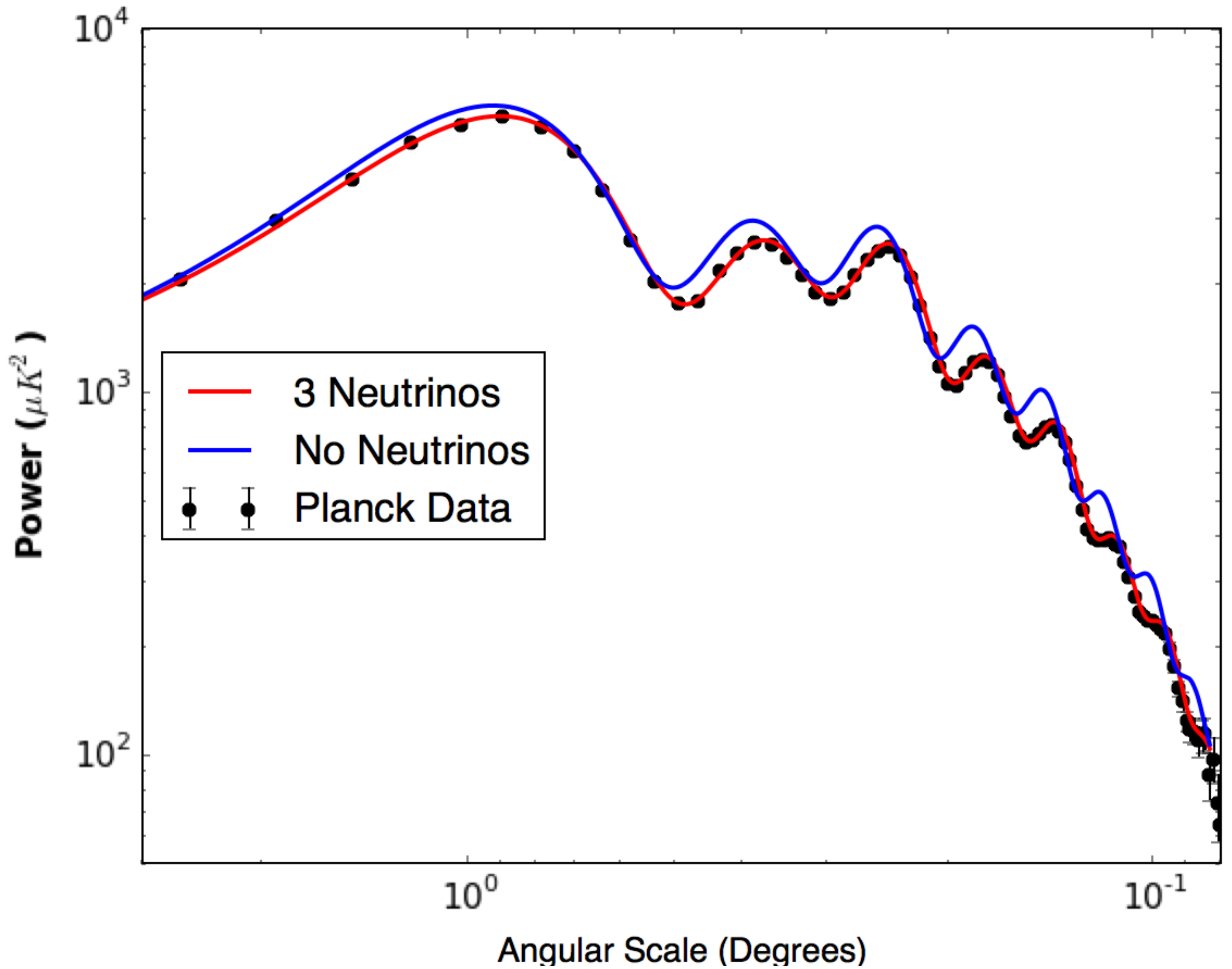
Time-stream noise, with mean zero and variance *N*

Minimum variance estimator for map:

$$\mathbf{T}_p = \left(\mathbf{A}^T \mathbf{N}^{-1} \mathbf{A}\right)^{-1} \mathbf{A}^T \mathbf{N}^{-1} \mathbf{d}$$

(Indirect) Detection of Cosmic Neutrino Background!

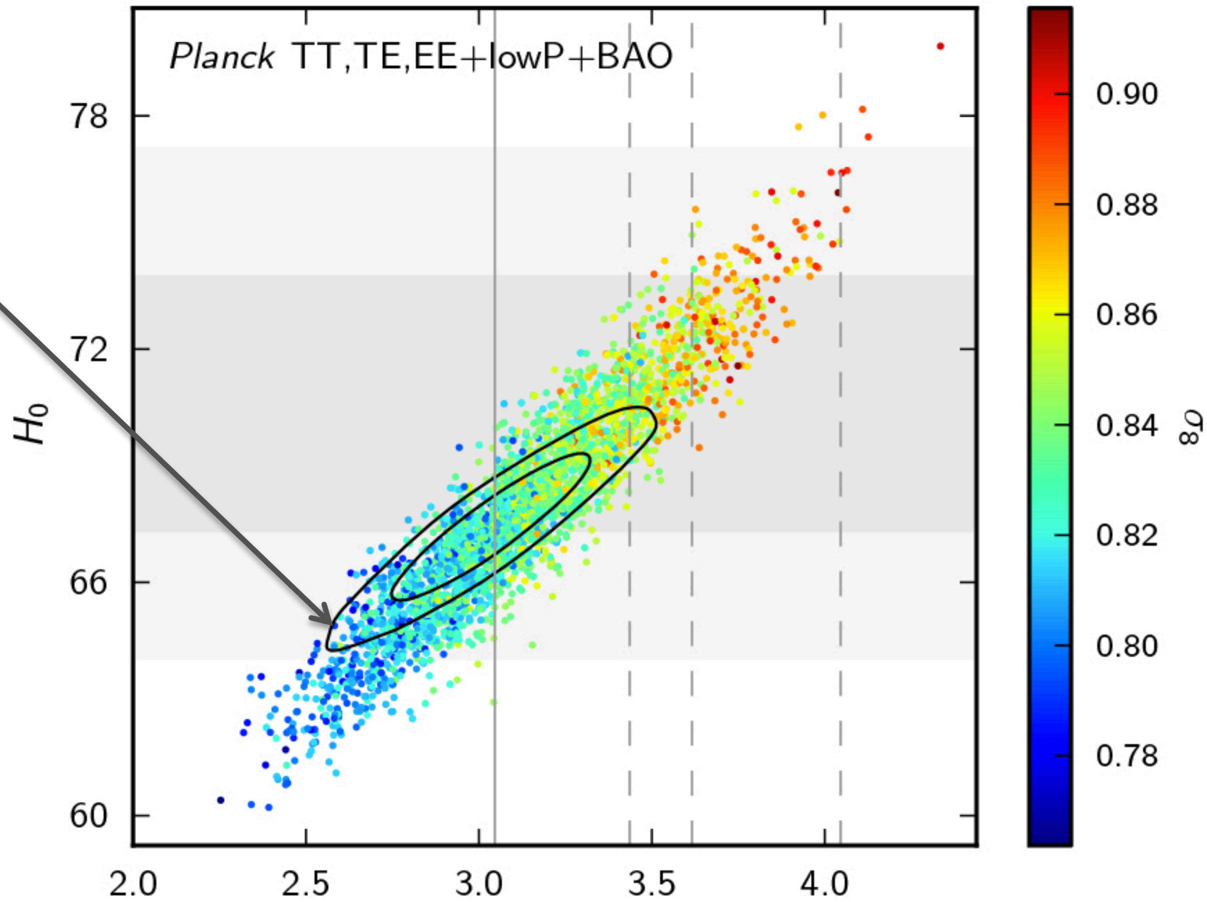
Damping scale in model without neutrinos is too small



Light sterile neutrinos Disfavored

Black contours use more data sets (TT, TE, EE, BAO): N=4 excluded at 5-sigma

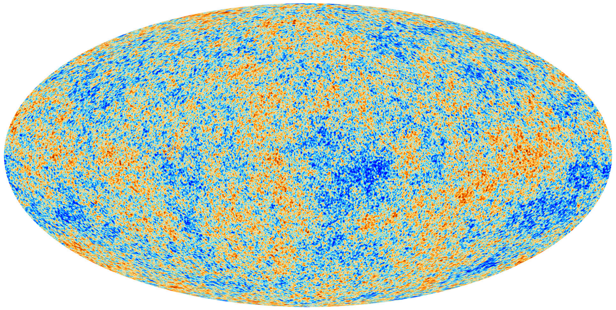
"leads to the robust conclusion that $\Delta N_{eff} < 1$ at over 3-sigma ."



Number of Cosmologically Produced Neutrino Species

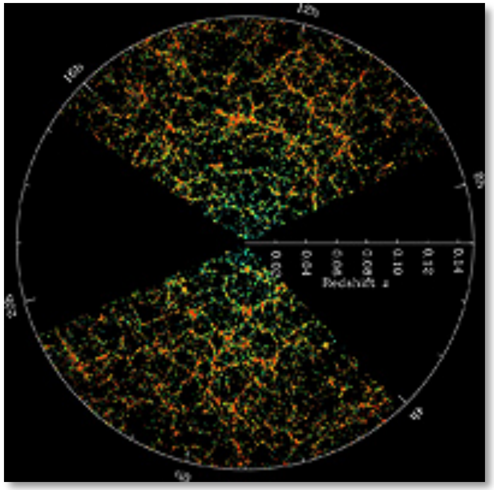
1502.01589

Maps of the Universe at later times inform us about the masses of neutrinos



UNIFORM TO ONE PART IN 10,000

VERY NON-UNIFORM



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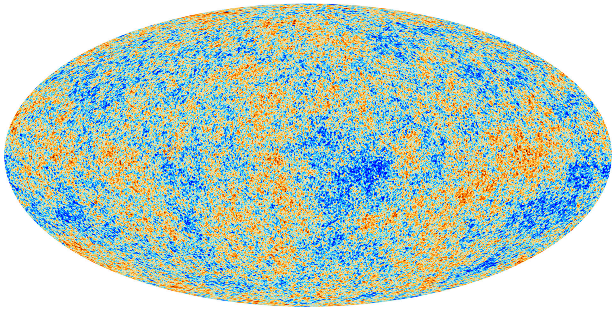
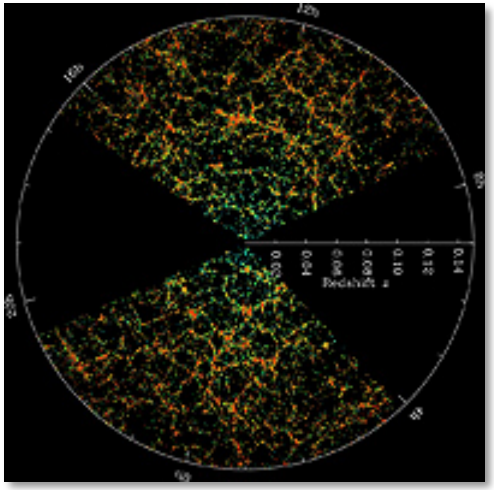


UNIFORM TO ONE PART IN 10,000

This evolution was driven by gravity: over-dense regions became more over-dense, eventually forming galaxies and stars

VERY NON-UNIFORM



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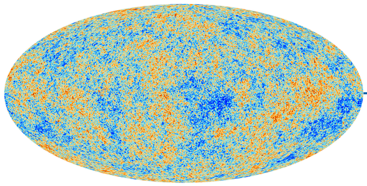

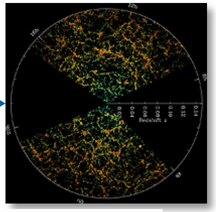

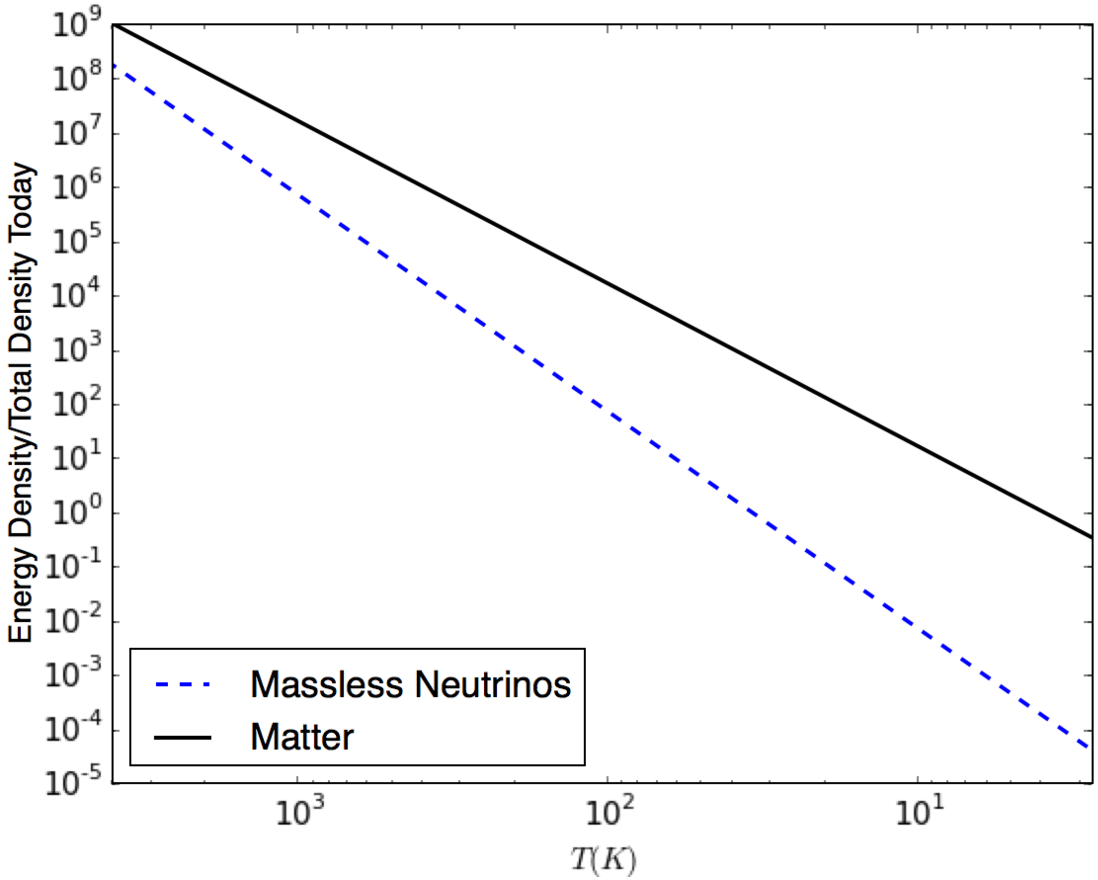

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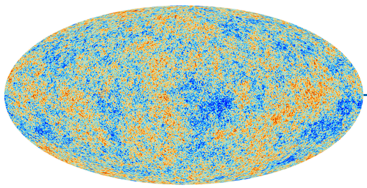
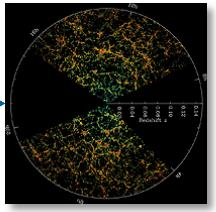
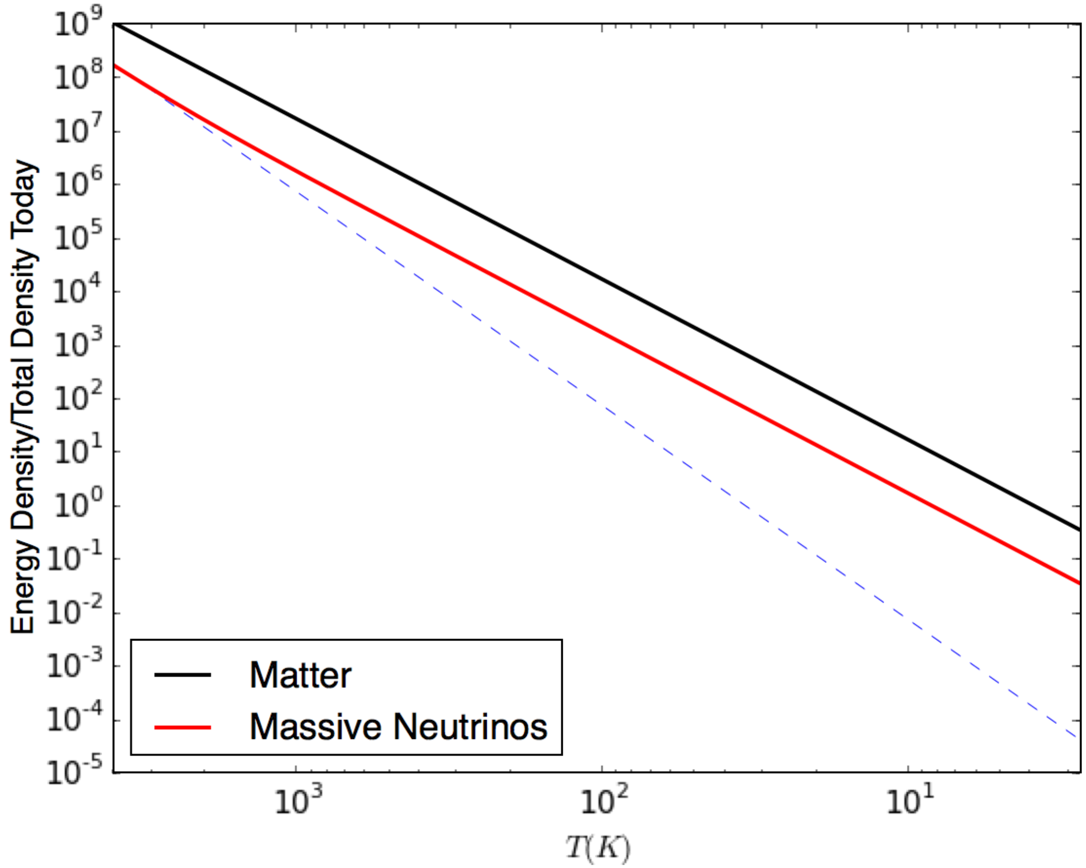




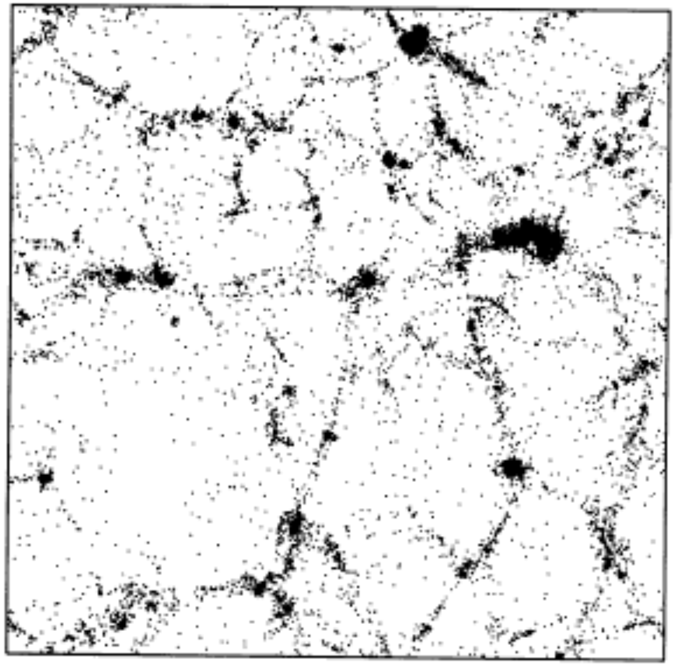


- Massive neutrinos affect the evolution of structure
- Relevant quantity is the neutrino energy density at late times or Σm_ν

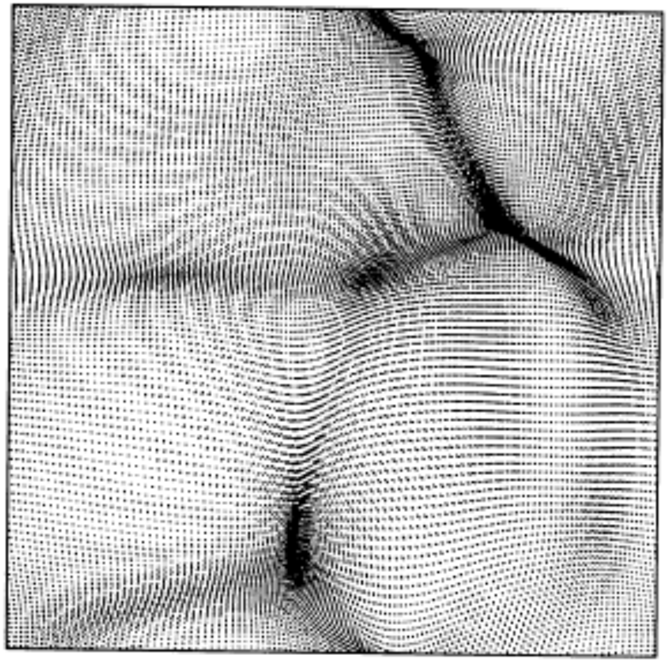
Neutrinos Inhibit Small Scale Structure

Neutrinos have large thermal velocities so do not cluster on small scales. This non-clustering component inhibits the formation of small scale structure.

Massless Neutrinos

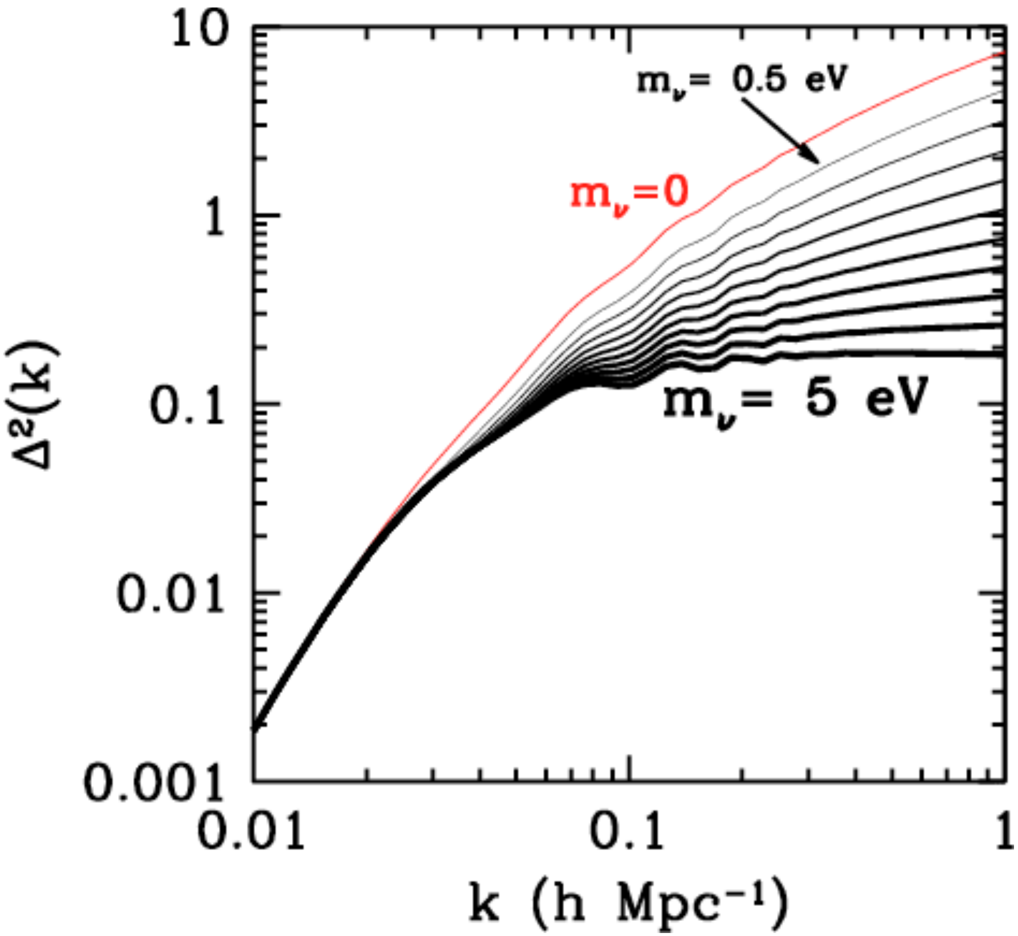


Massive Neutrinos



Neutrinos Inhibit Small Scale Structure

We quantify this with the power spectrum, or the dimensionless $k^3P(k)$.

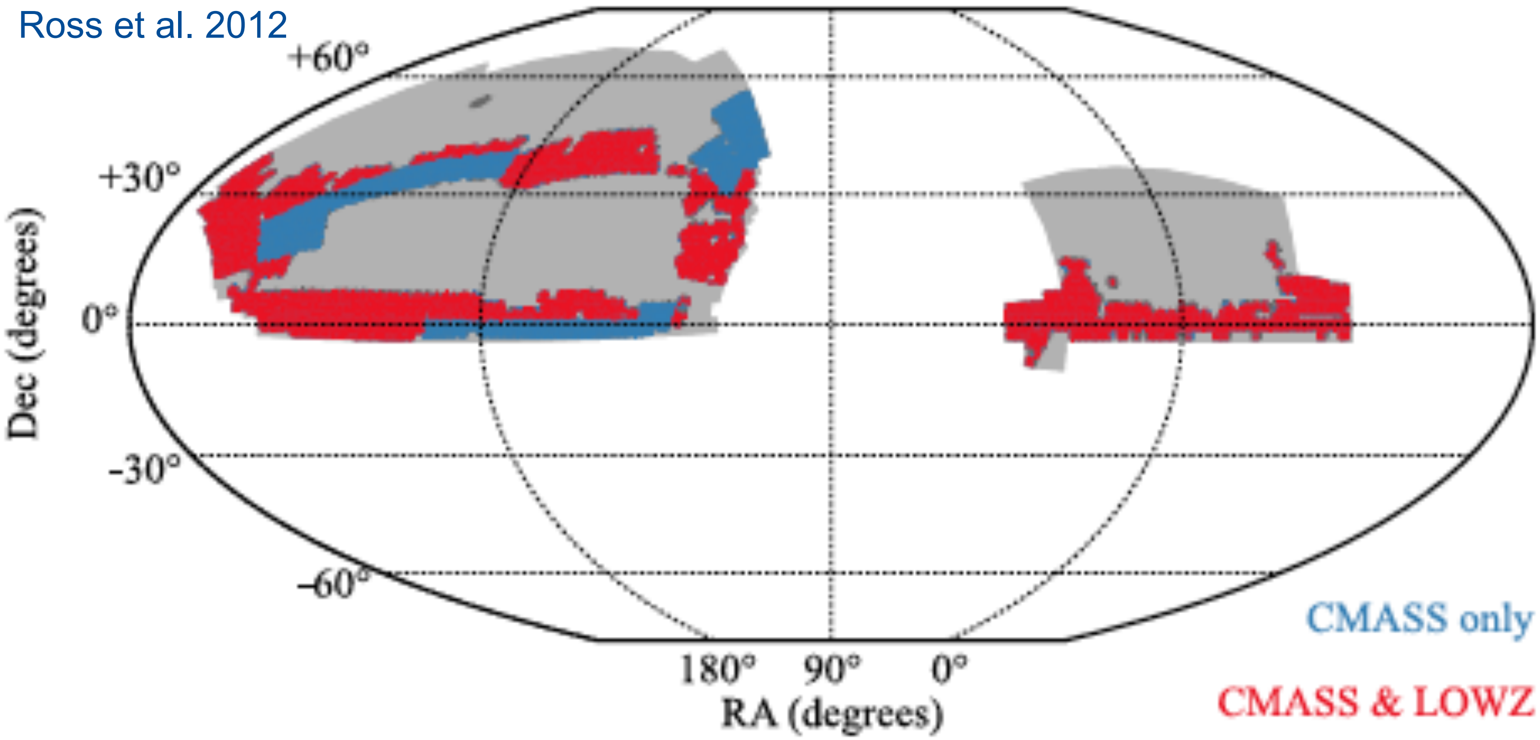


Probes of Structure 1103.5083

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	$0.2 - 0.05$	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	$0.1 - 0.006$	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST

Example: CMASS ("Constant Mass") galaxies from Baryon Acoustic Spectroscopic Survey (BOSS)

Ross et al. 2012



Example: CMASS galaxies from BOSS

- Pixelize the survey and, for each pixel, compute the over-density $\Delta=(n-n^{exp})/n^{exp}$, where n^{exp} is the expected number of galaxies in the pixel

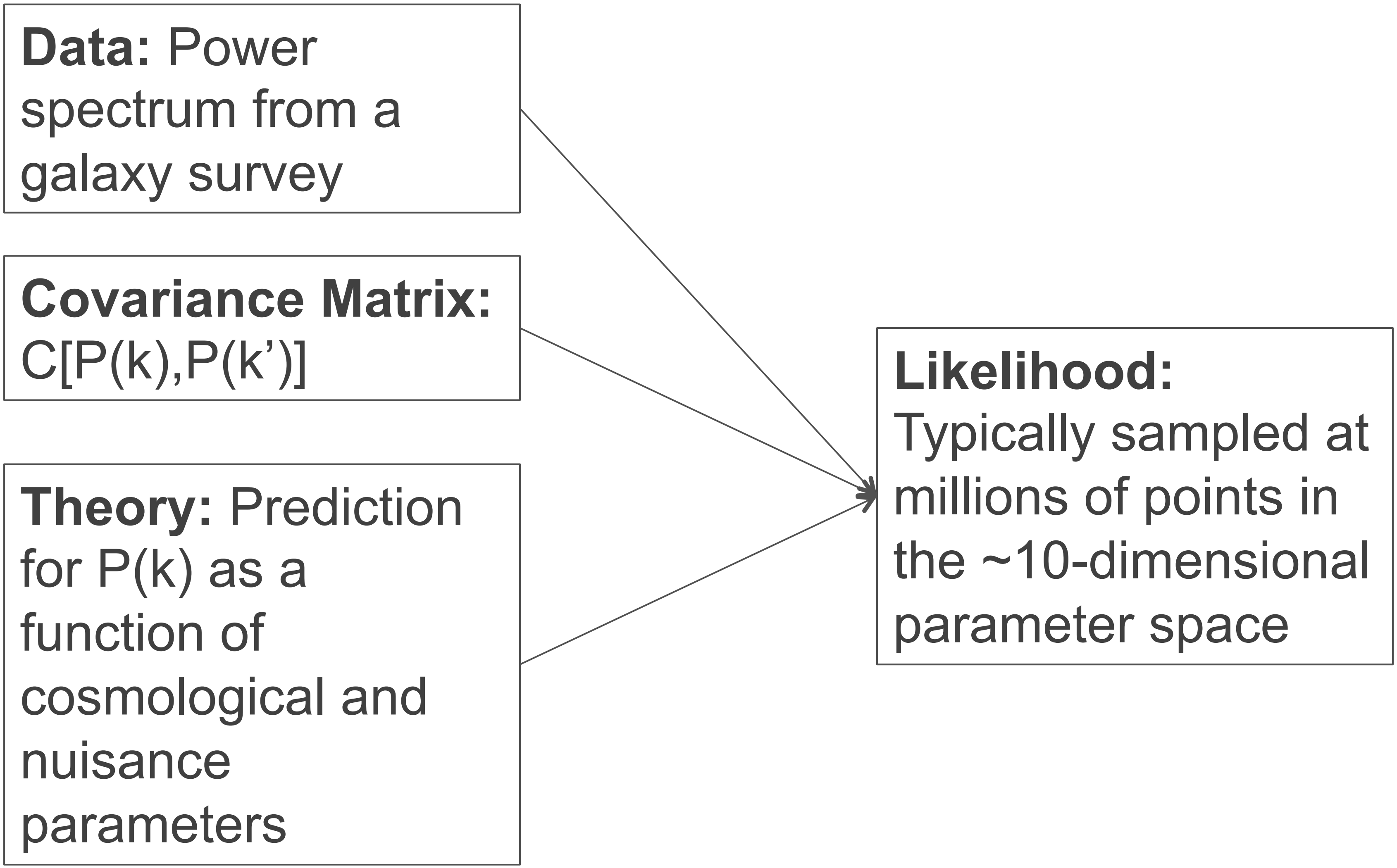
Example: CMASS galaxies from BOSS

- Pixelize the survey and, for each pixel, compute the over-density $\Delta=(n-n^{exp})/n^{exp}$, where n^{exp} is the expected number of galaxies in the pixel
- Form a quadratic estimator

$$\hat{P}(k) = \sum_{ij} \Delta_i \Delta_j M_{ij}(k)$$

A simple guess might be $M_{ij}(k) = e^{i\vec{k}\bullet(\vec{x}_i - \vec{x}_j)}$ but there are many other options, many of which account for masks, edge effects more carefully and have better noise properties

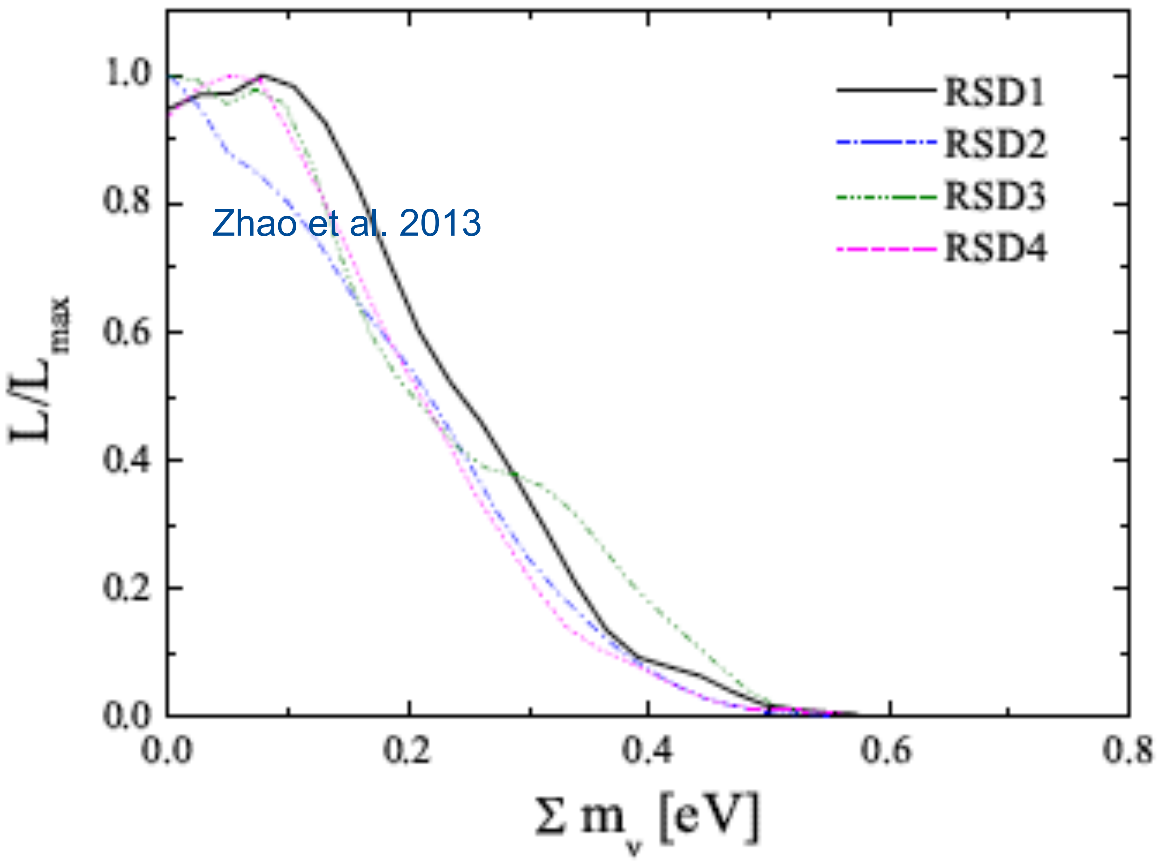
Example: CMASS galaxies from BOSS



Final Constraints insensitive to theory systematics

This analysis (and recent Planck + other experiments) get

$$\sum m_\nu < 0.2\, eV$$



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Galaxy Distribution	0.6	0.1 0.017	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESI (+Planck) DEX [35]
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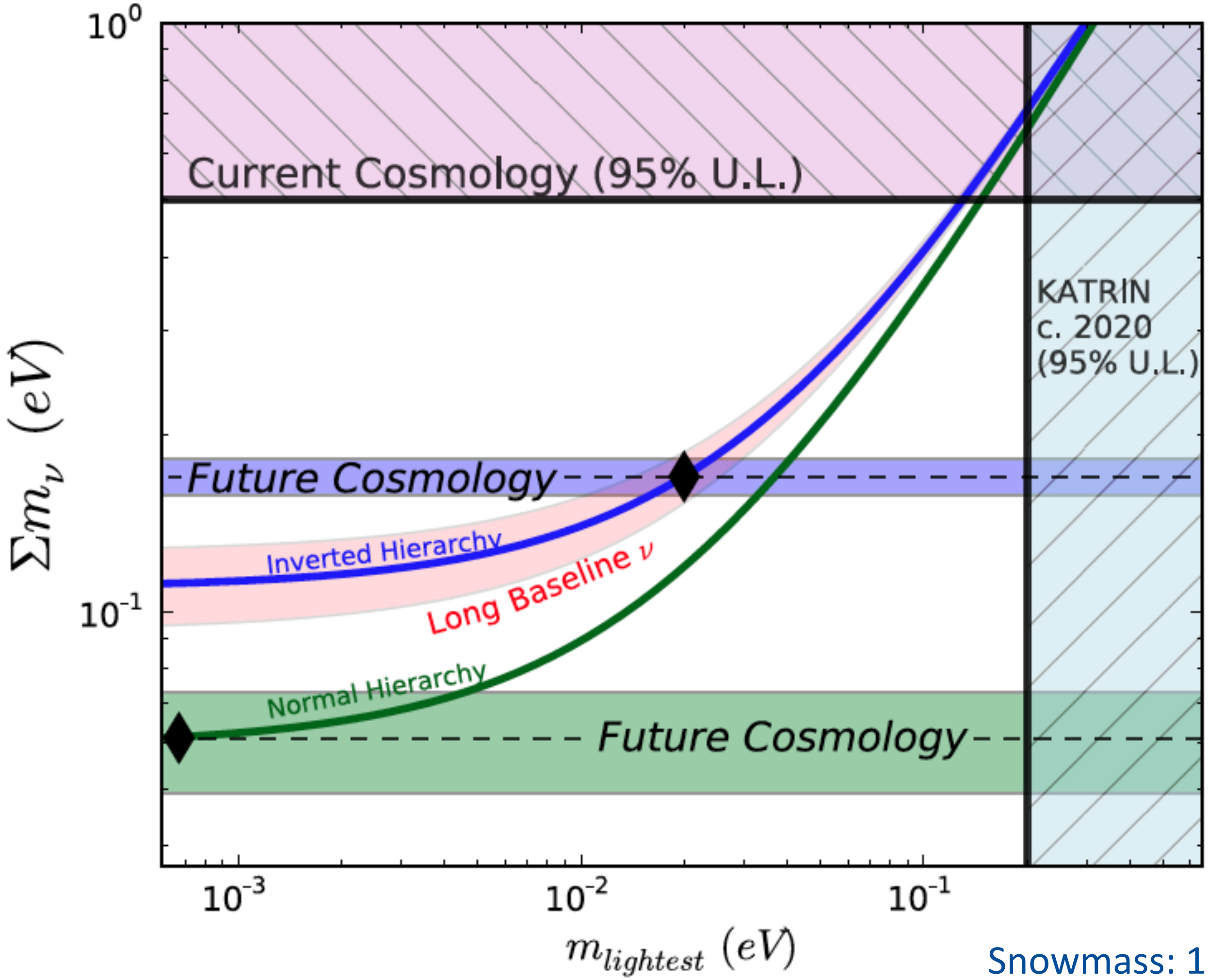
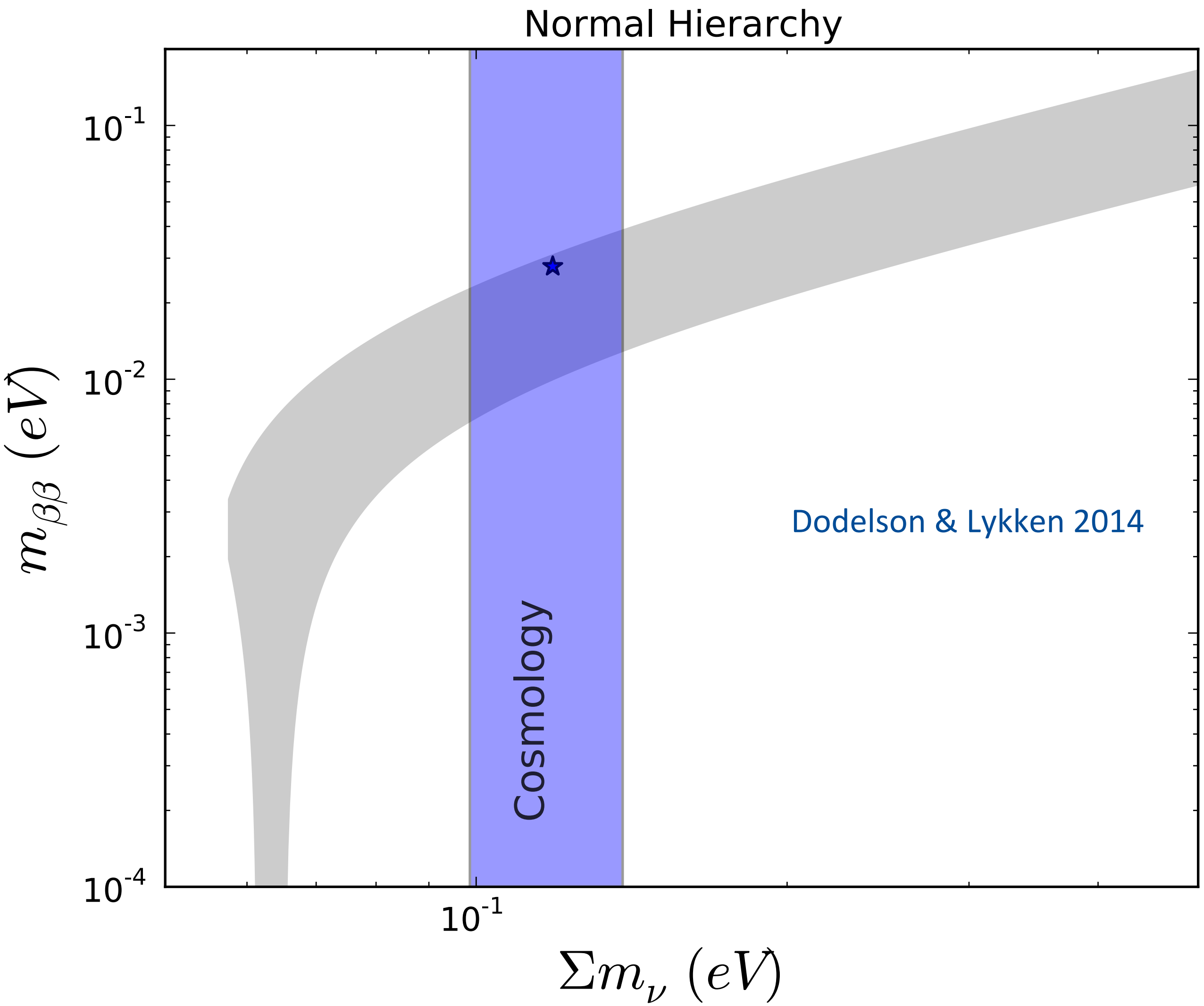
Surveys over the next decade will measure neutrino masses

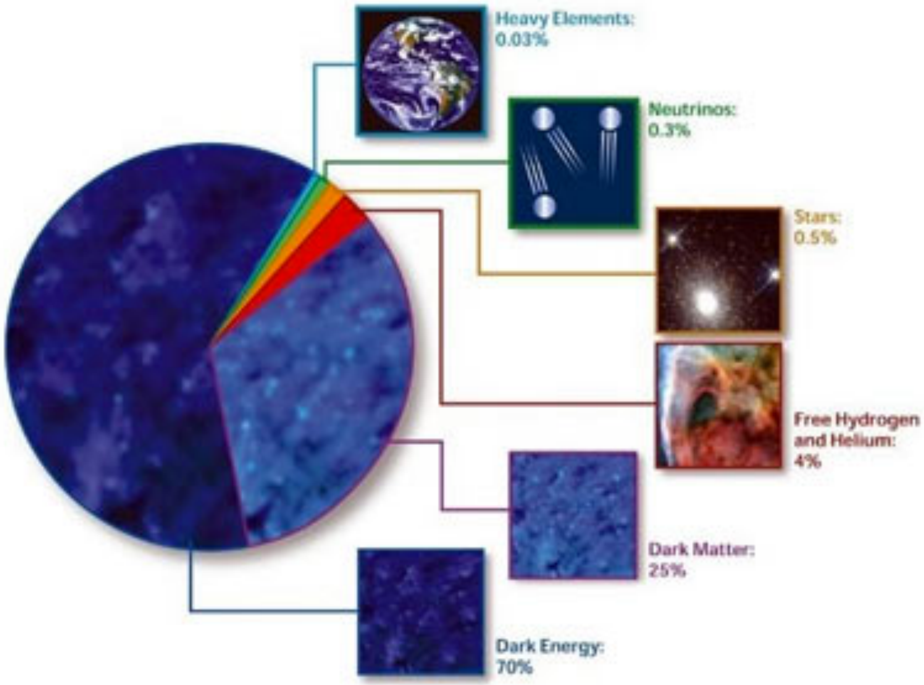


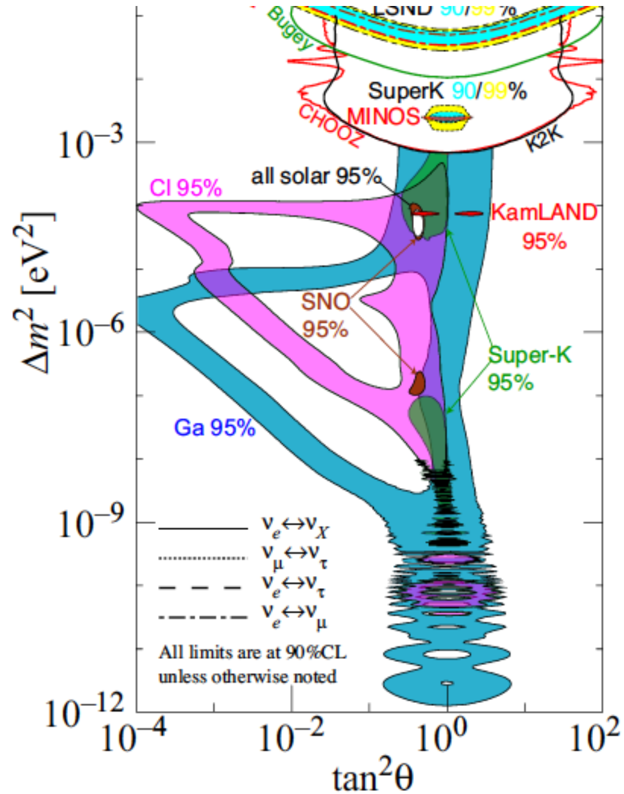
Snowmass: 1309.5383

Complementarity with neutrinoless double beta decay



Conclusion

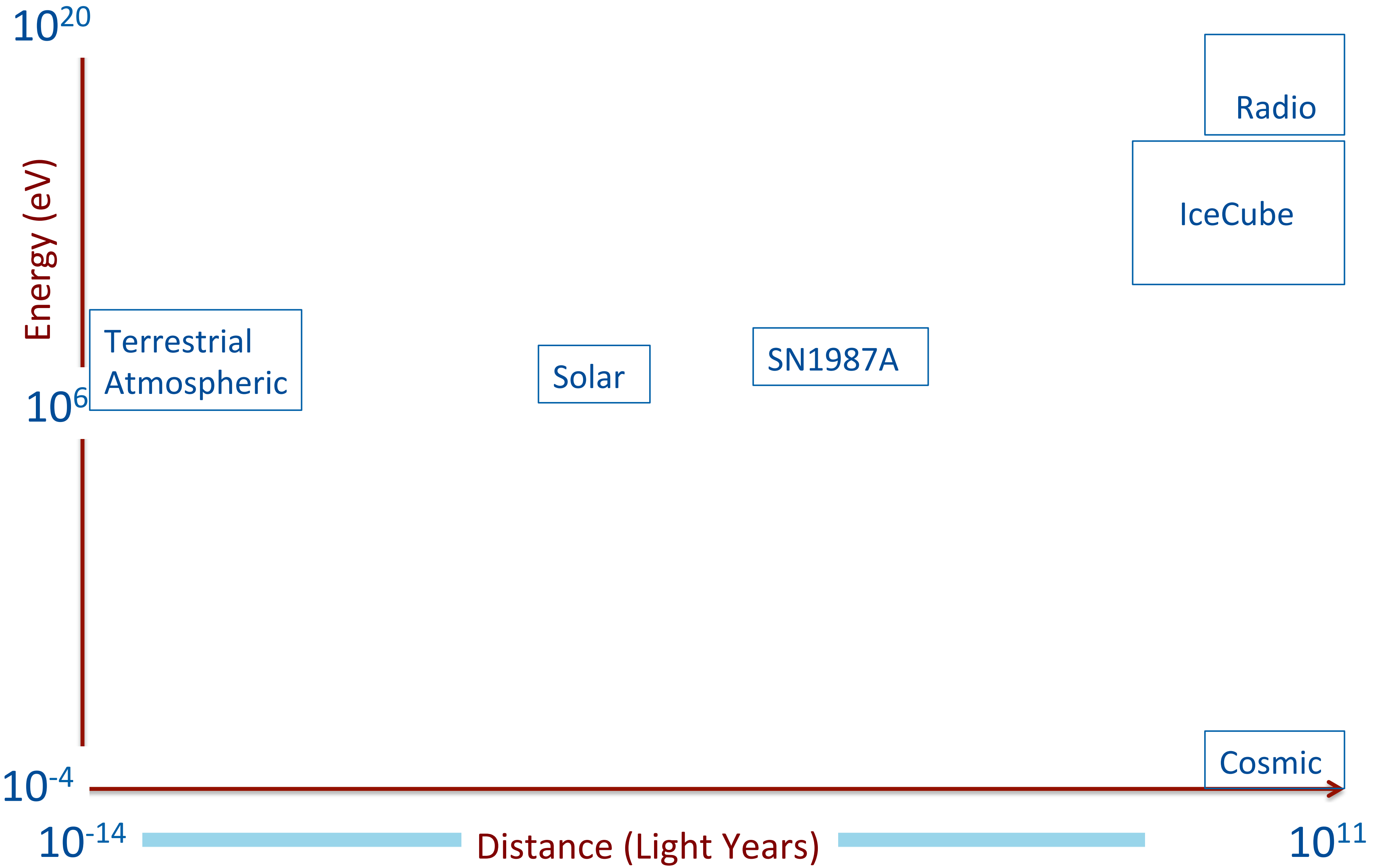




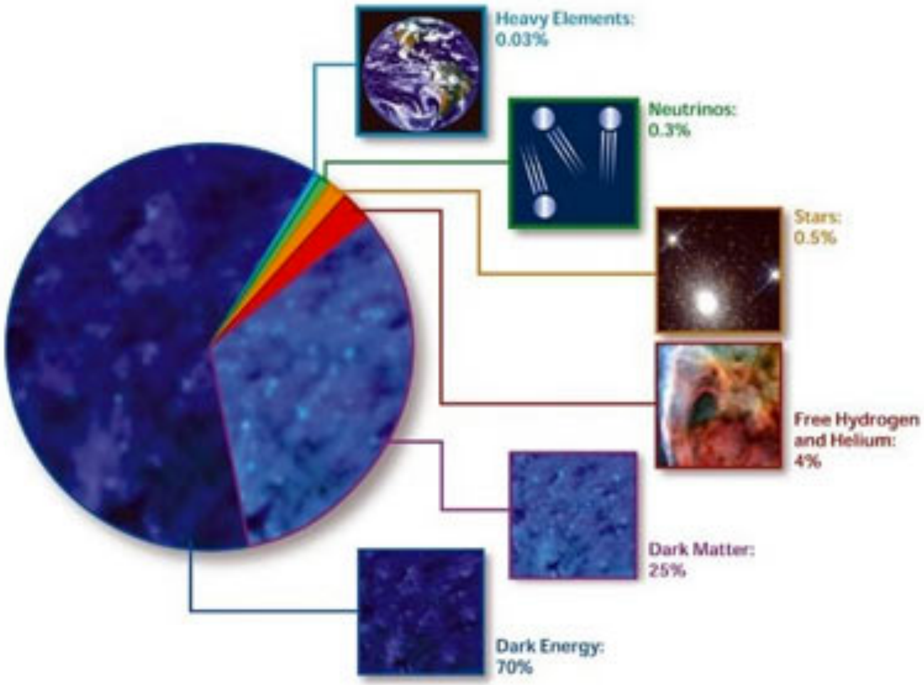
Neutrinos raise doubts about this iconic "set-in-stone" chart

Simple 3-Neutrino Paradigm explains everything, but every time we think we've understood neutrinos, we've been wrong

Exciting "Large Area" Program to test 3-Neutrino Paradigm



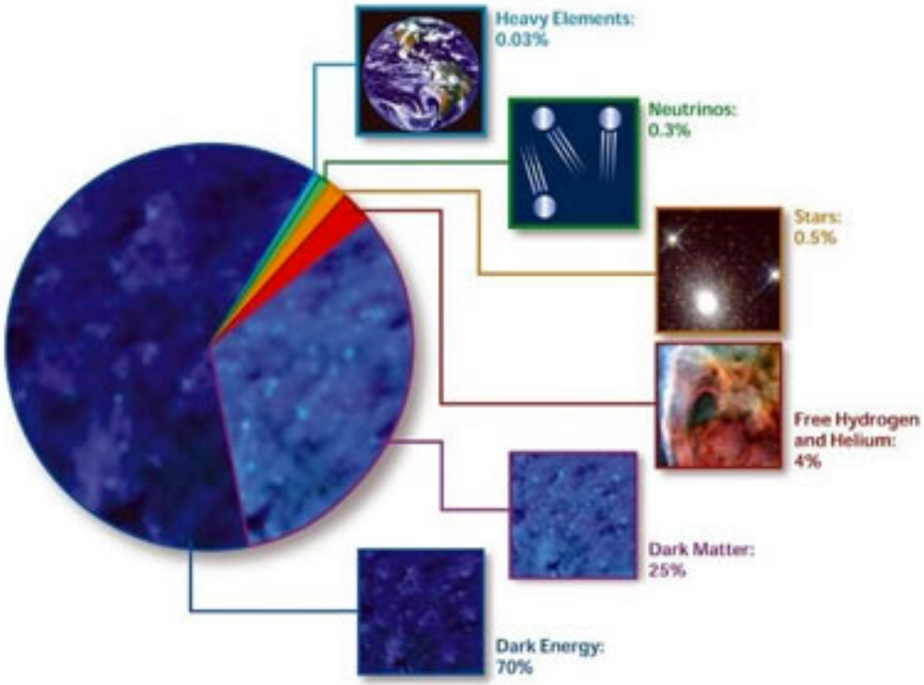
Conclusion



Neutrinos raise doubts about this iconic “set-in-stone” chart

- At the simplest level, keV sterile neutrinos could be the Dark Matter

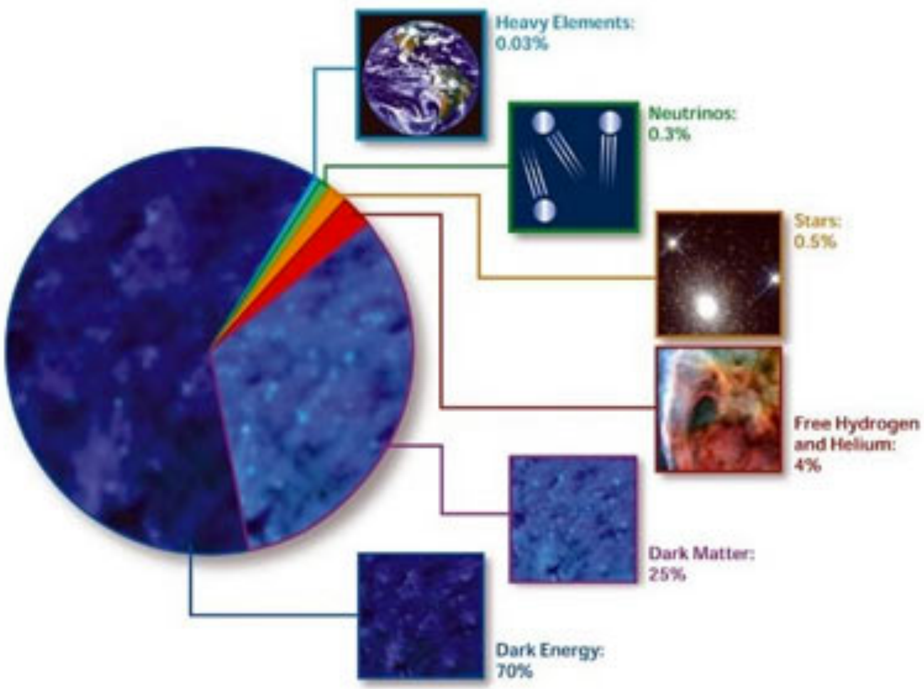
Conclusion



- At the simplest level, keV sterile neutrinos could be the Dark Matter
- More importantly, we have learned from neutrinos that when we think we know everything, we don't

Neutrinos raise doubts about this iconic "set-in-stone" chart

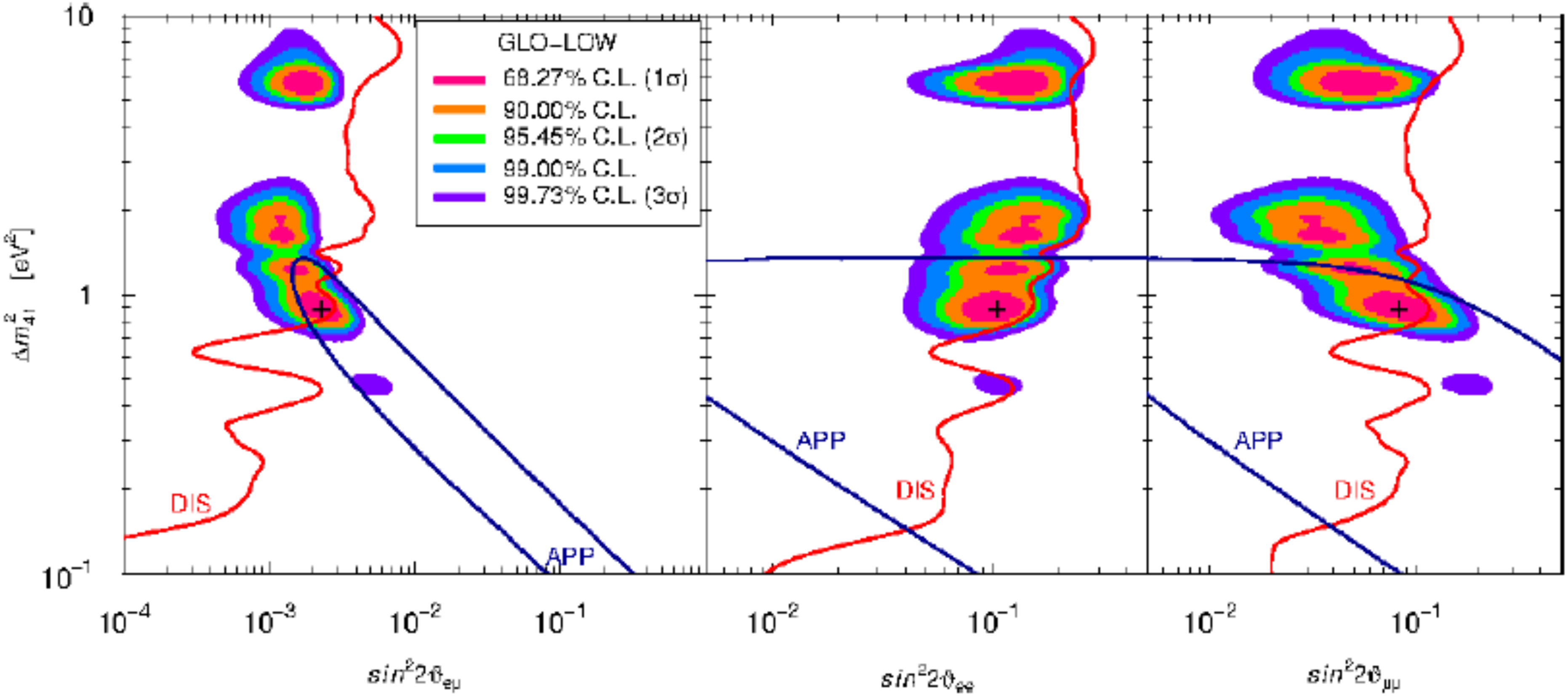
Conclusion



Neutrinos raise doubts about this iconic “set-in-stone” chart

- At the simplest level, keV sterile neutrinos could be the Dark Matter
- More importantly, we have learned from neutrinos that when we think we know everything, we don’t
- We think we have a simple cosmological model that fits everything. Maybe we don’t … and a neutrino discovery will lead the way to a better understanding of the evolution of the universe

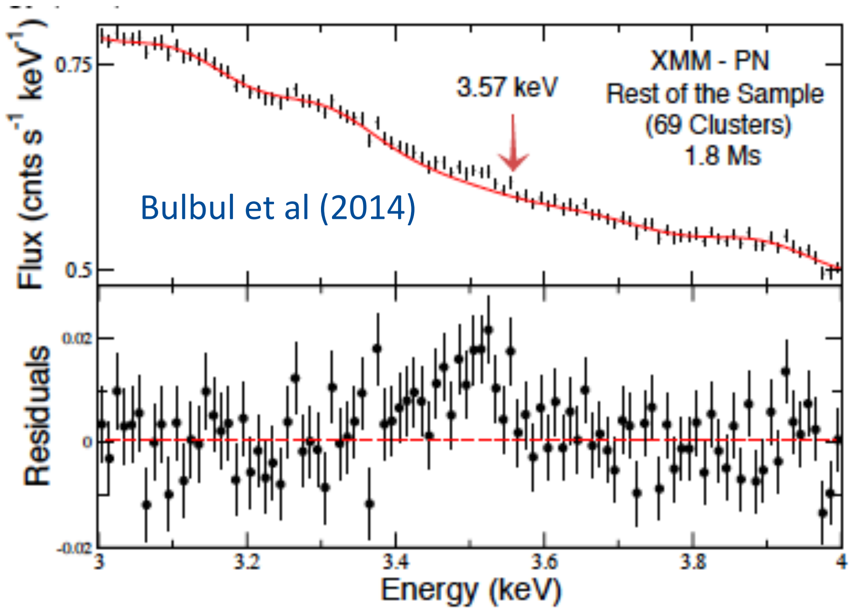
Giunti and Laveder 2012



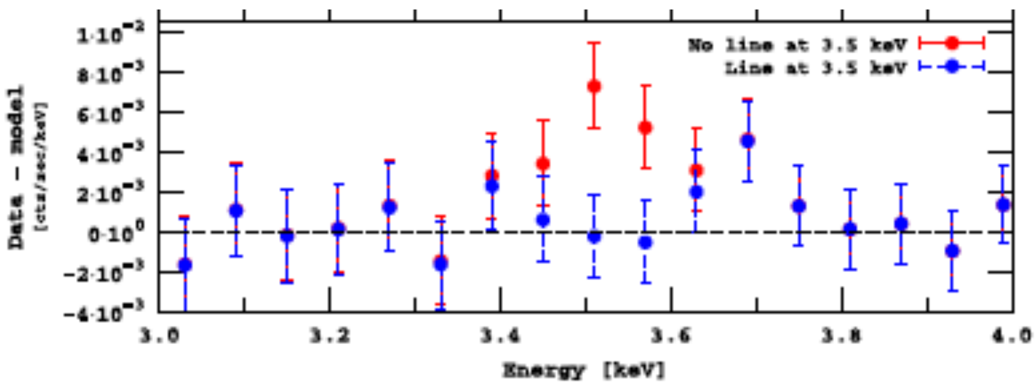
$$\sin^2 2\theta_{ee} = 4|U_{e4}|^2\left(1-|U_{e4}|^2\right)$$

Recent hints for X-ray excess

Stacked signal from many galaxy clusters

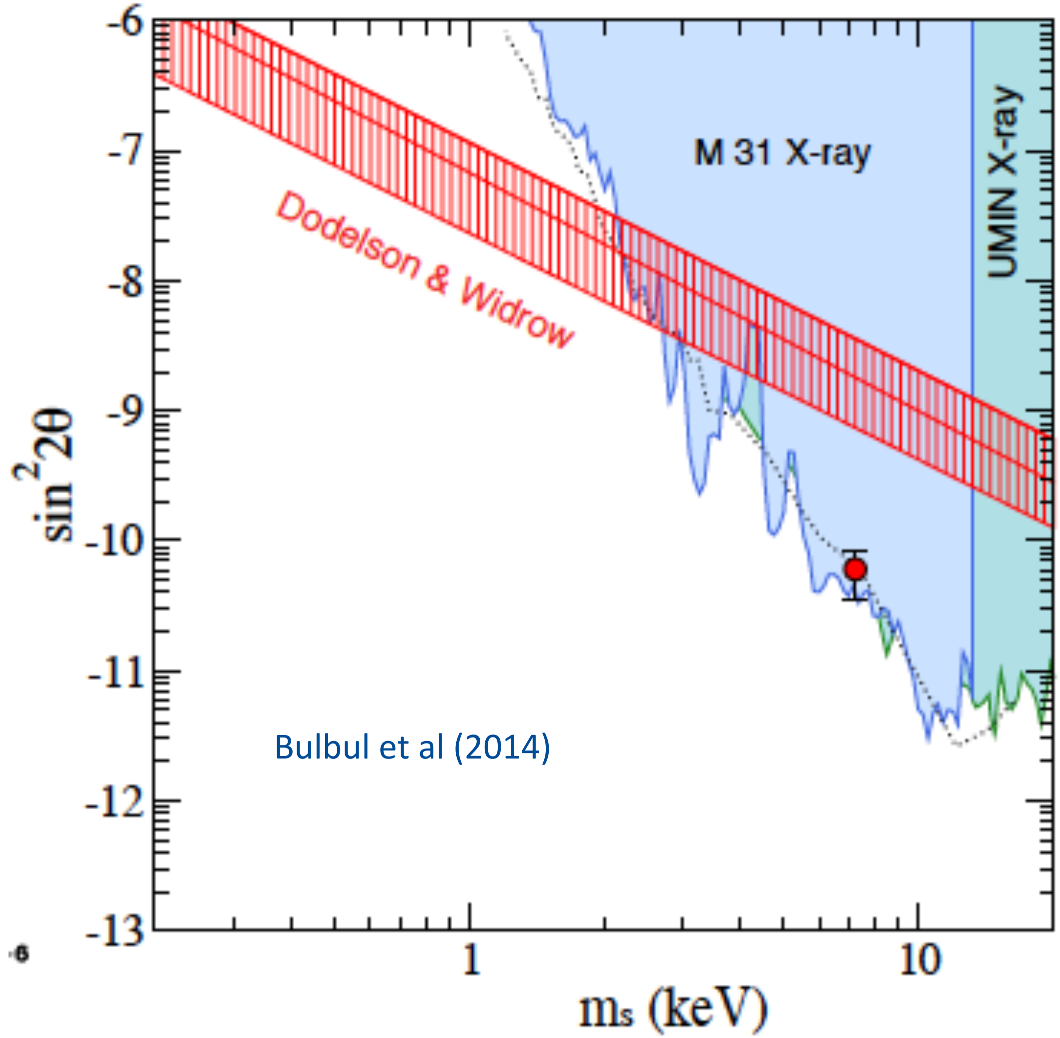


And from Andromeda



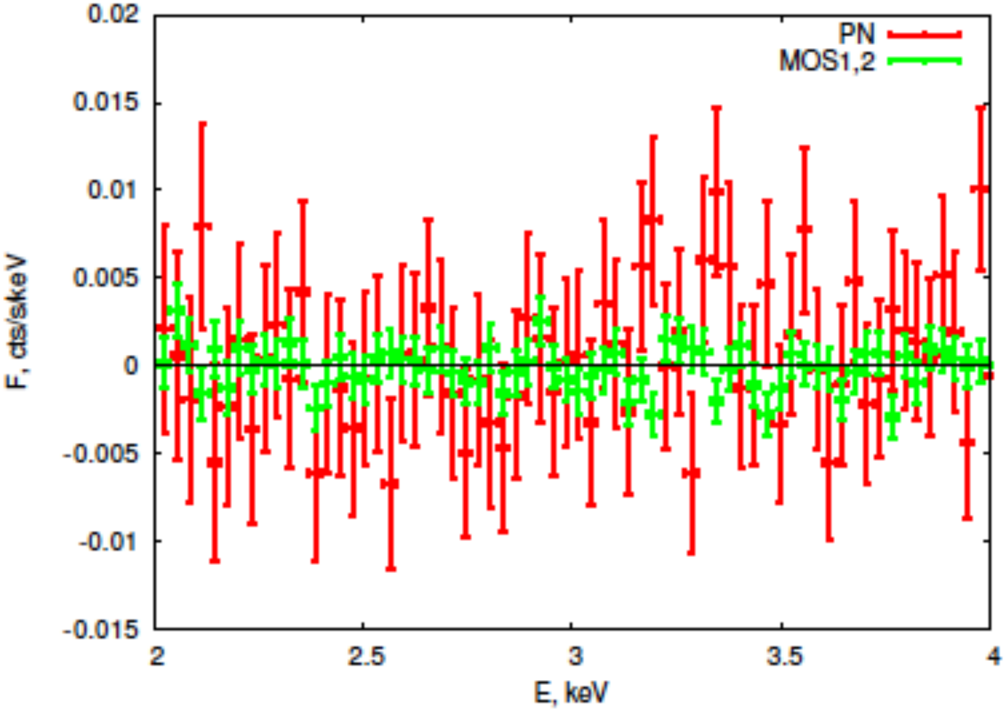
Recent hints for X-ray excess

If interpreted as sterile neutrino decay, mixing angle is too small for them to be produced enough in the early universe in the standard scenario, but alternatives abound: resonances, etc.



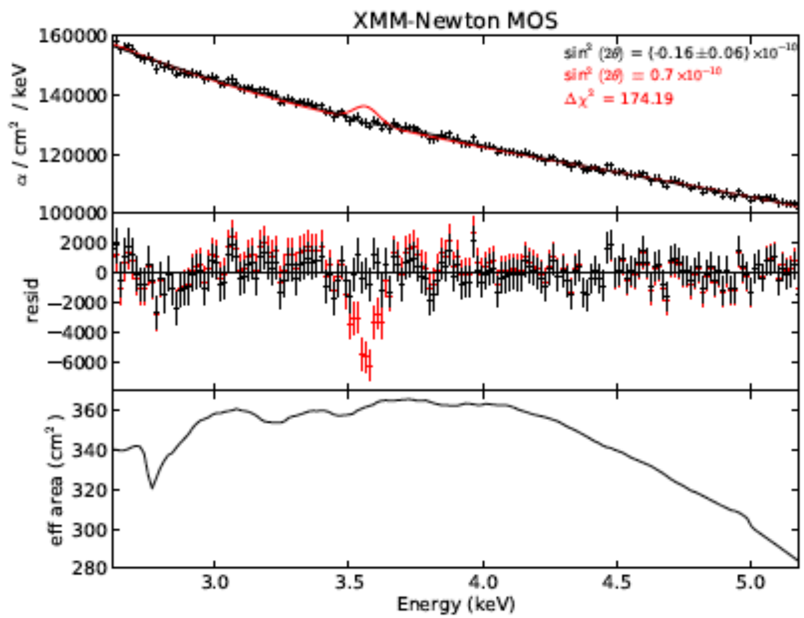
More importantly, no signal seen in other areas

Stacked Dwarf Spheroidals



Malyshev et al (2014)

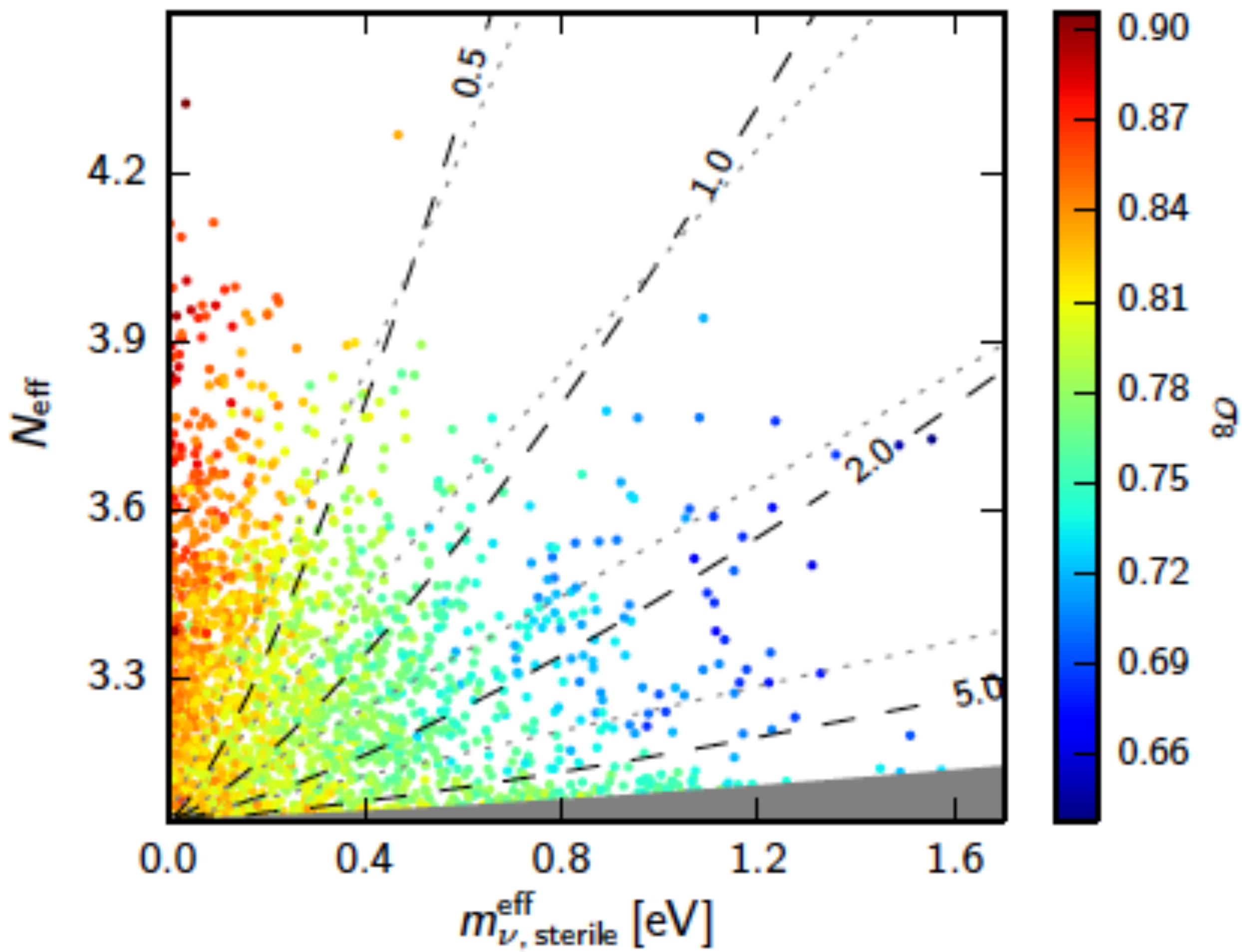
Stacked Galaxies



Anderson et al (2014)

7-keV vs. r=0.1 vs. Galactic Center DM?

Planck constraints on sterile massive neutrinos



Covariance Matrix and Window Function

- Estimate covariance matrix by running 600 mocks

$$C(k,k') = \frac{1}{N_{sim}} \sum_{all\, sims\, i} \left(P_i(k) - \bar{P}(k) \right) \left(P_i(k') - \bar{P}(k') \right)$$

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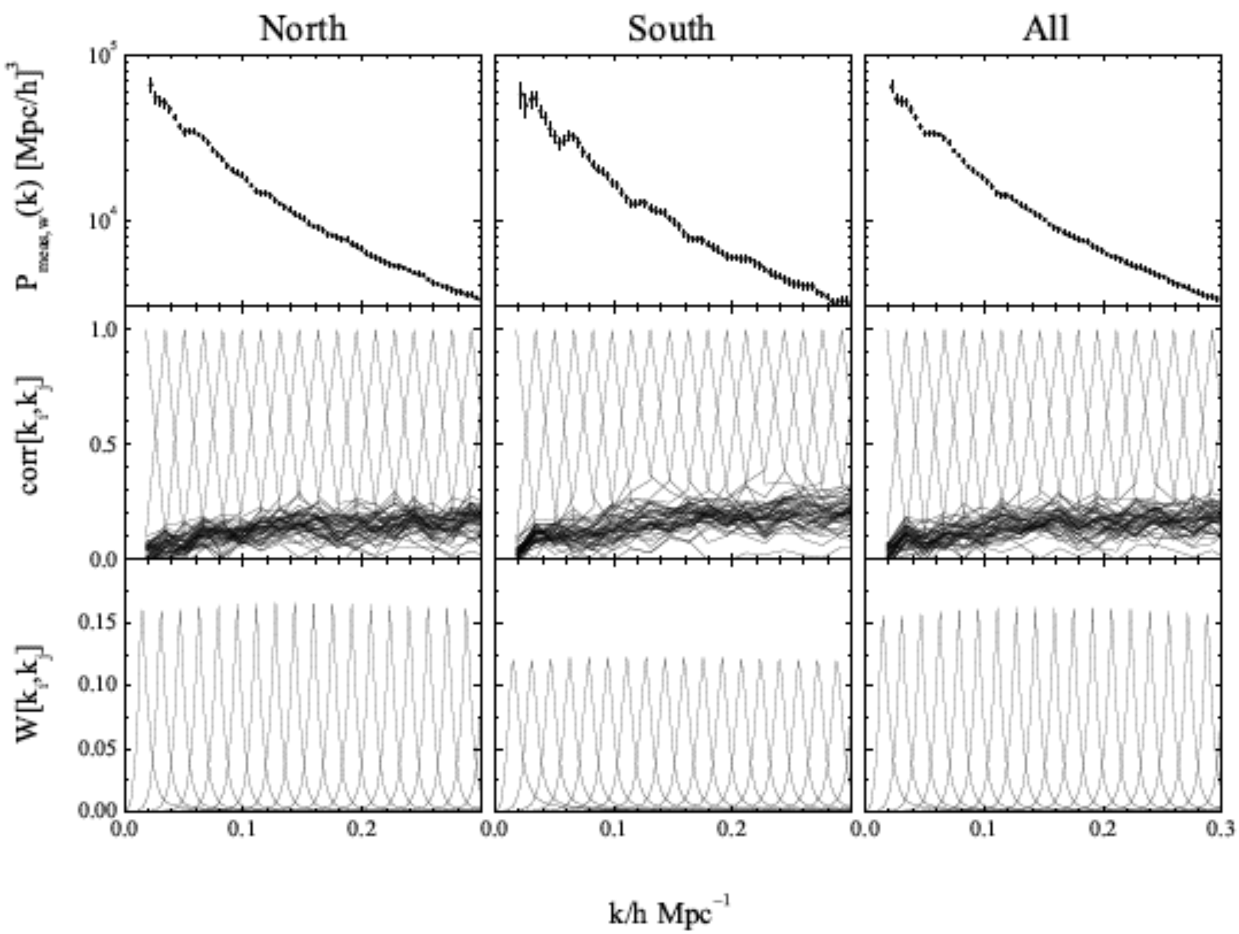
- The power spectrum estimate is sensitive to a range of *P(k); W* follows from *M*

$$\left\langle \hat{P}(k) \right\rangle = \int dk' W(k,k') P(k')$$

Power Spectrum, Covariance Matrix, & Window Function



Zhao et al 2013