Title: Anthropic Origin of the Neutrino Mass from Cooling Failure

Date: Mar 24, 2015 11:00 AM

URL: http://pirsa.org/15030104

Abstract: <p>Given a large landscape of vacua that statistically favors large values of the neutrino mass sum, m_ν, I will present the probability distribution over m_ν obtained by weighting this prior by the amount of galaxies that are produced. Using Boltzmann codes to compute the smoothed density contrast on Mpc scales, we find that large dark matter halos form abundantly for $m_\nu \gtrsim 10$\,eV. However, in this regime structure forms late and is dominated by cluster scales, as in a top-down scenario. I will argue that this change of regime is catastrophic: baryonic gas will cool too slowly to form stars in an abundance comparable to our universe. Upon implementing this cooling boundary, the anthropic prediction for m_ν is consistent at better than 2σ with the entire range of values allowed by current experimental bounds, 58\,meV $\leq m_\nu \lesssim 0.23$\,eV. A degenerate hierarchy is mildly preferred. Without a catastrophic boundary at or below 10\,eV, the theoretical expectation would conflict strongly with the observed mass range. Thus the asserted cooling failure can be regarded as a prediction of the anthropic solution to the neutrino mass problem.</p>

Anthropic Origin of Neutrino Mass from Cooling Failure

Claire Zukowski
U.C. Berkeley and Perimeter Institute

Raphael Bousso, Dan Mainemer Katz, and CZ, to appear soon

PI Cosmology Seminar, March 24, 2015

The problem: neutrino mass

Tegmark, Vilenkin, Pogosian (2005)

$$m_\nu = \sum_{i=1}^{3} m_{\nu,i}$$

$$58 \text{ meV} < m_\nu < 0.23 \text{ eV}$$

neutrino oscillation experiments (lower bound) — cosmological constraints (upper bound)

Question: Why does the neutrino mass sum take this value?

Why is it small compared to the masses of other leptons in the Standard Model?

Why is does it happen to take a value that affects our cosmology "just enough" to observe but not disrupt galaxies, etc.?

Could this have an anthropic explanation?

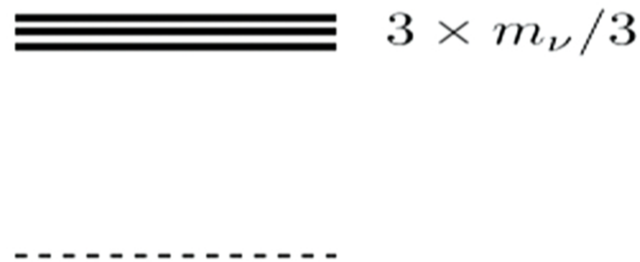
The problem: neutrino mass

$$m_\nu = \sum_{i=1}^{3} m_{\nu,i}$$

$$58 \text{ meV} < m_\nu < 0.23 \text{ eV}$$

Two cases:

Normal hierarchy



Degenerate hierarchy

Outline

- How we compute probabilities
- Structure formation
- The actual calculation: no cutoff
- Cooling catastrophe
  - Review: cooling in our own universe
  - Top-down scenario
- Our results: probability distribution with cooling cutoff
- Conclusions

Bousso and Polchinski (2000)

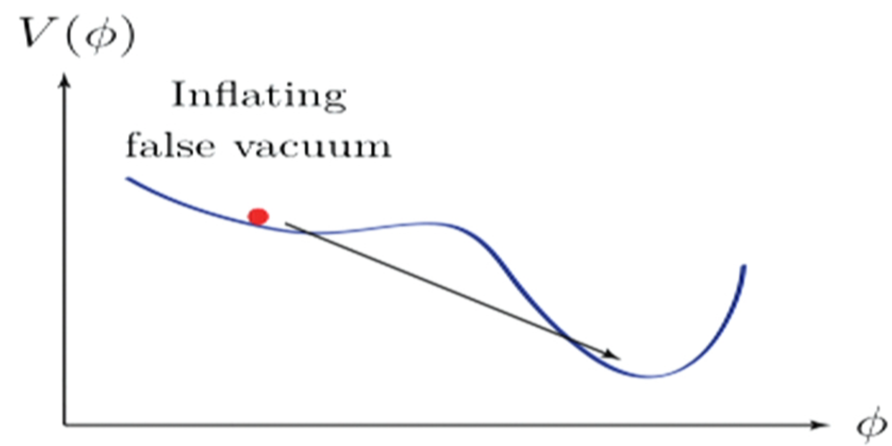
The Landscape

- Consider a large landscape of low-energy vacua e.g. provided by string theory (c.f. the cosmological constant problem)
- "Eternal inflation" will occur if ***at least one*** metastable vacuum is sufficiently long lived: $\Gamma < H$

$\Longrightarrow$ Infinite volume produced by the inflating vacuum

$\Longrightarrow$ All possible realizations occur, e.g. values of m_ν

$\Longrightarrow$ Compute relative probabilities for different possibilities



Probabilities in the Landscape

We condition on the existence of observers who can make a measurement of parameter m_ν

Probability $\propto$ # of observations

$$\frac{d\mathcal{P}}{d\log m_\nu} = f(m_\nu) N_{\rm obs}(m_\nu)$$

+ Regulation by measure (e.g. total volume cutoff, count along a geodesic)

Prior distribution
Distribution of m_ν over the metastable vacua of the landscape

Number of observers in a vacuum where m_ν takes this specific value

The prior

$$\frac{d\mathcal{P}}{d\log m_\nu} = \underbrace{f(m_\nu)}_{\frac{dN_{\rm vac}}{d\log m_\nu}} N_{\rm obs}(m_\nu)$$

- We assume the prior has no special features around the observed range

$$f(m_\nu) \propto m_\nu^n$$

$n = 1 \Rightarrow$ distribution flat over m_ν : $\frac{dN_{\rm vac}}{dm_\nu} =$ const.

- Our results can be translated into constraints on the prior

- $n \sim \mathcal{O}(1)$ consistent with observed value within $2\sigma \Rightarrow$ anthropic solution for the neutrino mass

The anthropic factor

$$\frac{d\mathcal{P}}{d\log m_\nu} = f(m_\nu) N_{\rm obs}(m_\nu)$$

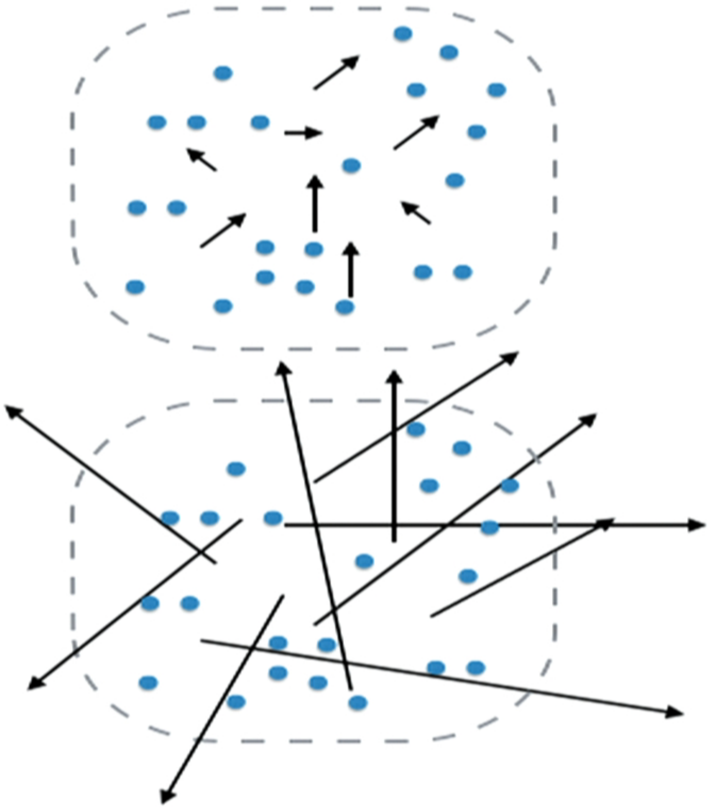
- Need some proxy for observers, such as the number of galaxies $\Rightarrow$ Press-Schechter formalism
- Encodes effect of massive neutrinos on structure formation
- (Should check that the final result is not sensitive to the details of this definition.)

Outline

- How we compute probabilities
- Structure formation
- The actual calculation: no cutoff
- Cooling catastrophe
  - Review: cooling in our own universe
  - Top-down scenario
- Our results: probability distribution with cooling cutoff
- Conclusions

Neutrino free-streaming

The damping of small scale matter perturbations by neutrinos:



$$\lambda \gtrsim \frac{v}{H}$$

$\Rightarrow$

- Neutrinos participate in structure growth as cold dark matter

$$\delta \propto a$$

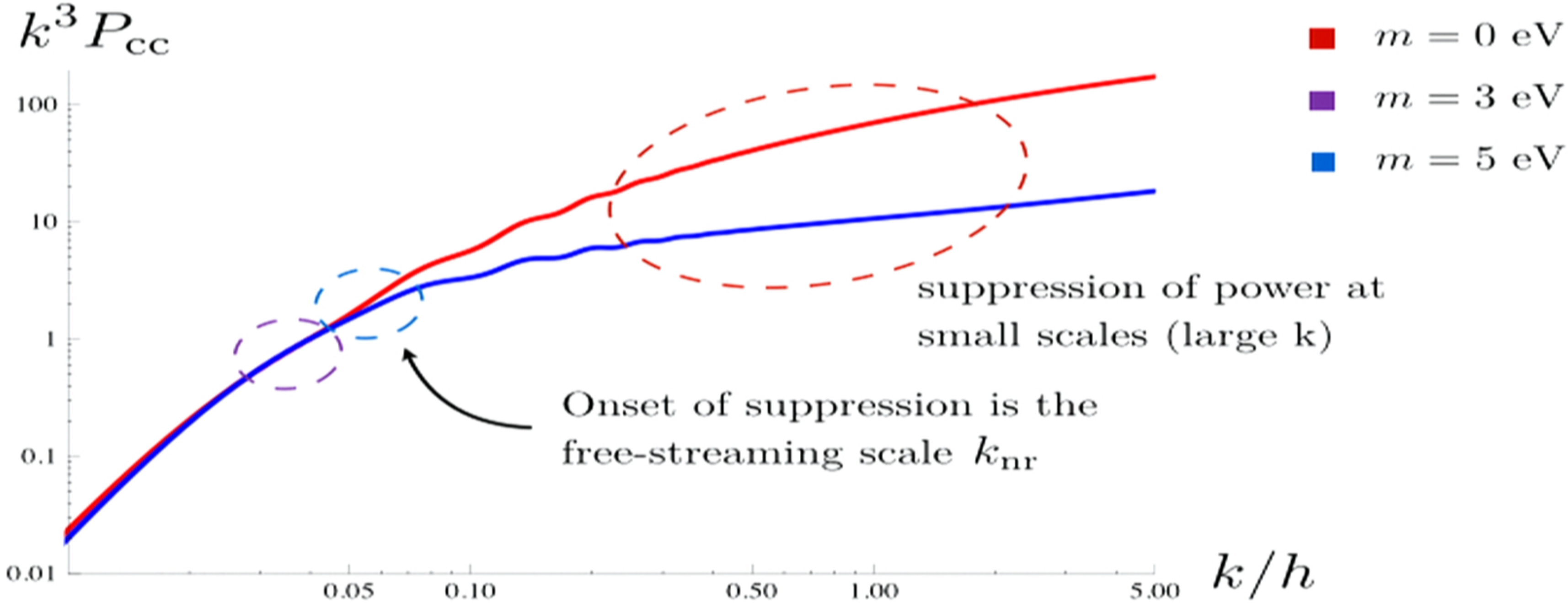
$$\lambda \lesssim \frac{v}{H}$$

$\Rightarrow$

- Neutrinos transfer energy to less dense regions
- Structure is suppressed

$$\delta \propto a^p \quad (p < 1)$$

Neutrinos and the CDM (and matter) power spectrum



Press-Schechter

Press and Schechter (1974)

Gaussian distribution for density contrast $\delta(x,t)$:

$$\mathcal{P}(\delta,t)\,d\delta \sim \exp\left(-\frac{\delta^2}{2\sigma_R^2}\right)d\delta$$

$\sigma_R =$ density contrast smoothed on scale R

distance scale R $\longleftrightarrow$ mass scale $M \sim \rho_{\rm bc} R^3$

$\delta > \delta_* = 1.69$ $\longrightarrow$ collapse

Fraction of mass in halos > mass M:

$$F_R(t) = \int_{\delta_*}^{\infty} \mathcal{P}(\delta,t)d\delta = \mathrm{erfc}\left(\frac{\delta_*}{\sqrt{2}\sigma_R(t)}\right)$$

Press-Schechter

Press and Schechter (1974)

Gaussian distribution for density contrast $\delta(x,t)$:

$$\mathcal{P}(\delta, t)\, d\delta \sim \exp\left(-\frac{\delta^2}{2\sigma_R^2}\right) d\delta$$

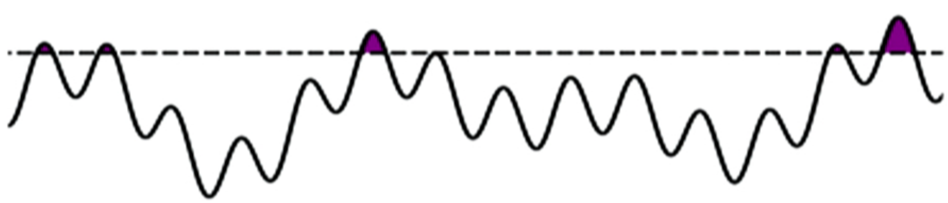
$\sigma_R =$ density contrast smoothed on scale R

distance scale R $\longleftrightarrow$ mass scale $M \sim \rho_{\rm bc} R^3$

$\delta > \delta_* = 1.69$ $\longrightarrow$ collapse

Fraction of mass in halos > mass M:

$$F_R(t) = \int_{\delta_*}^{\infty} \mathcal{P}(\delta, t) d\delta = \text{erfc}\left(\frac{\delta_*}{\sqrt{2}\sigma_R(t)}\right)$$

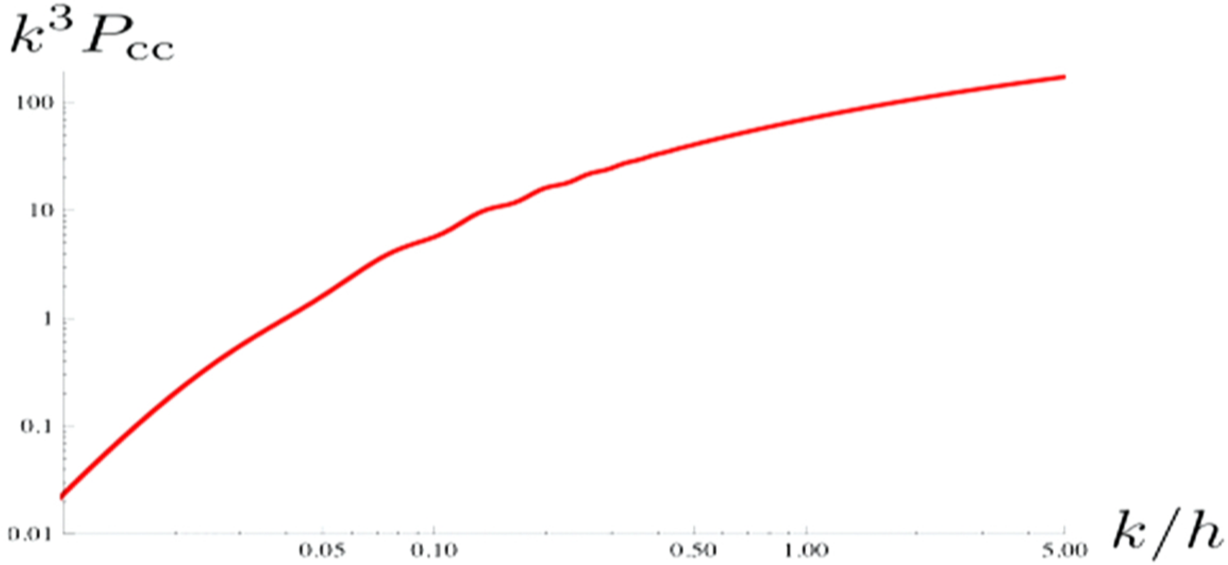


In our case, interested in galaxy-sized halos:

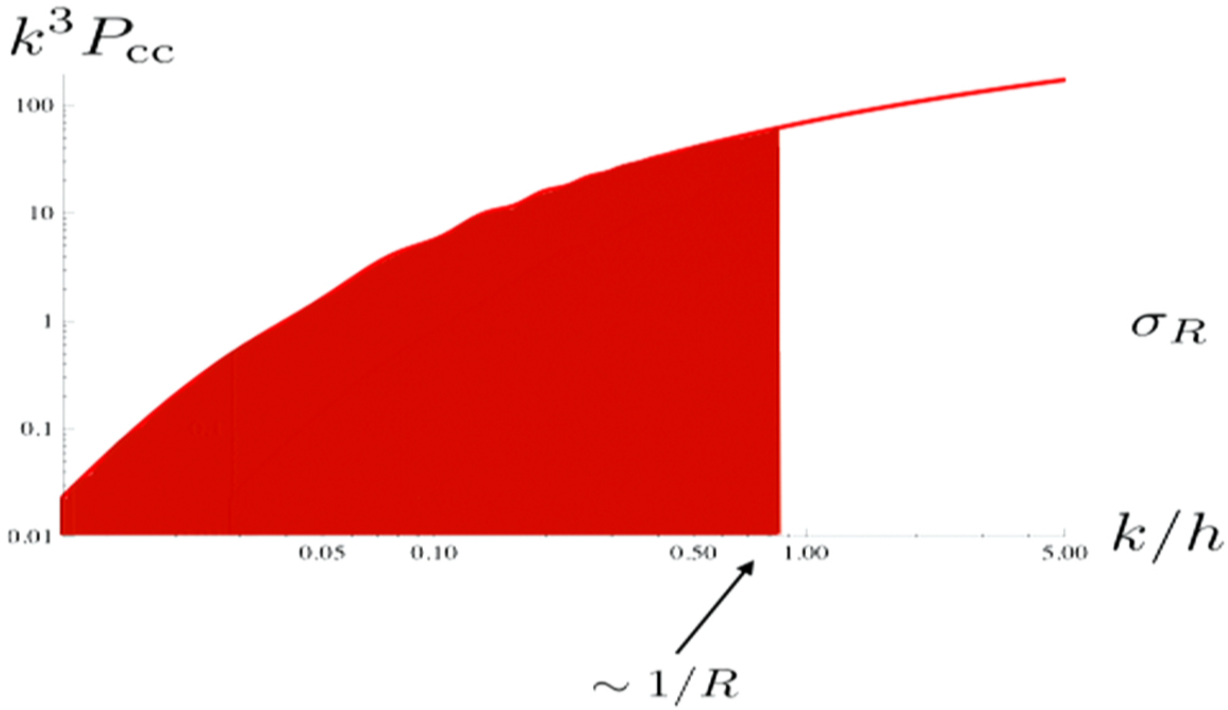
$M = 10^{12} M_\odot$

$R \sim 1.3\, h^{-1}$ Mpc

Press-Schechter mass variance σ_R



Press-Schechter mass variance σ_R



$$\sigma_R \sim \int_0^{1/R} \frac{dk}{k} k^3 P_{cc}(k)$$

Probability distribution recap

$$\frac{d\mathcal{P}}{d\log m_\nu} = f(m_\nu) N_{\rm obs}(m_\nu)$$

+ Regulation by measure (e.g. total volume cutoff, count along a geodesic)

Prior distribution
Distribution of m_ν over the metastable vacua of the landscape

Number of observers in a vacuum where m_ν takes this specific value

$$f(m_\nu) \propto m_\nu^n$$

The causal patch measure

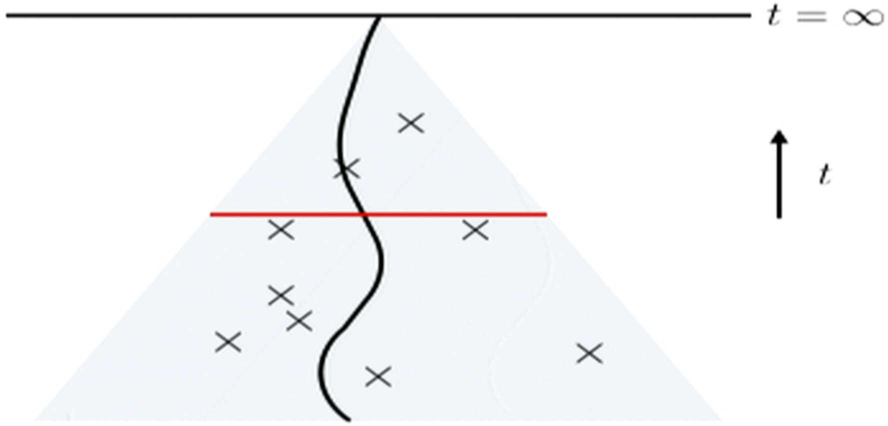
Bousso (2006)

Counts only events within a single causally connected region of a worldline in the eternally inflating spacetime, averaging over possible trajectories

Within a single FRW vacuum, the patch boundary is the cosmological event horizon:

$$r_{\text{patch}} = \int_t^\infty \frac{dt'}{a(t')}$$

(Result appears not strongly sensitive to measure choice.)



The anthropic factor

$$\frac{d\mathcal{P}}{d\log m_\nu} = f(m_\nu) N_{\rm obs}(m_\nu)$$

For definiteness, rate of observation $\propto$ production rate of galaxies:

$$N_{\rm obs} = \int dt\ \dot{M}_{\rm gal}(t) \qquad M_{\rm gal}(t) = \rho_{\rm bc}(t) V_{\rm phys}(t) F_R(t)$$

Physical volume of the causal patch

Suppressed at late times

Press-Schechter factor

σ_R

Small scale suppression of power by massive neutrinos

Our fixing scheme

Keep all fundamental physics other than neutrino mass fixed (i.e. fundamental processes that produced baryons, CDM, etc.)

$$\left.\begin{array}{l} \rho_\Lambda = \Lambda/8\pi \\ \text{flatness} \quad \Omega_\Lambda = 1 - \Omega_m \\ \chi_b \approx 0.6 \text{ eV} \quad \text{mass per photon of baryons} \\ \chi_c \approx 3.0 \text{ eV} \quad \text{mass per photon of CDM} \end{array}\right\} \quad \text{fixed}$$

$$\Rightarrow \quad \Omega_m, \ \rho_m, \ H \quad \text{increase with neutrino mass}$$

$$\rho_b, \ \rho_c \quad \text{fixed}$$

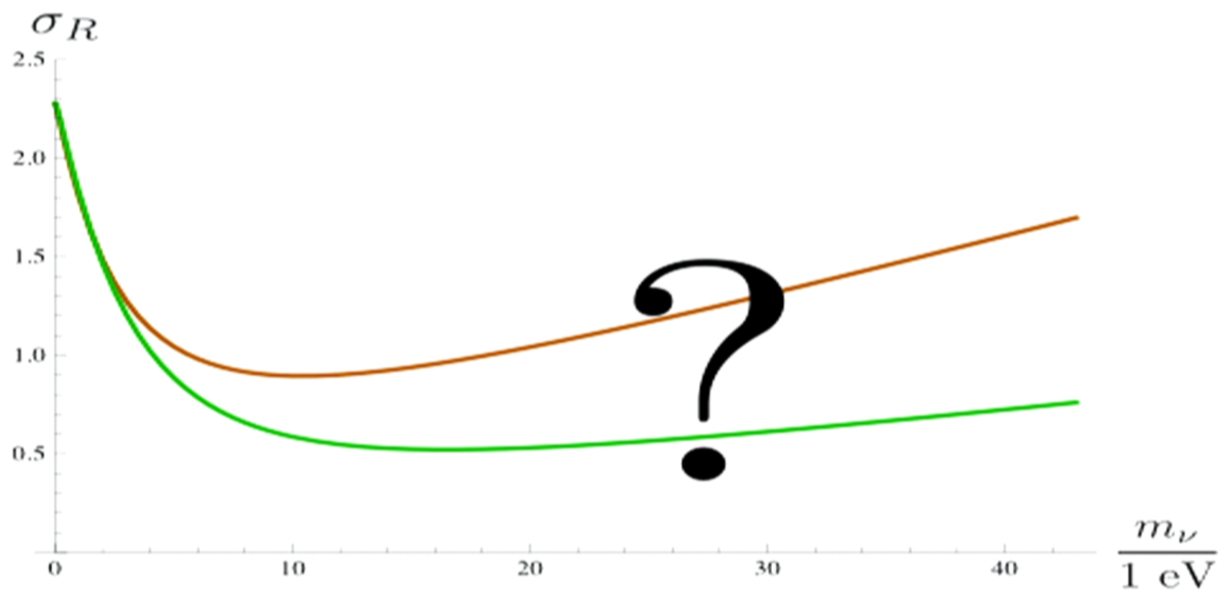
Our fixing scheme

Keep all fundamental physics other than neutrino mass fixed (i.e. fundamental processes that produced baryons, CDM, etc.)

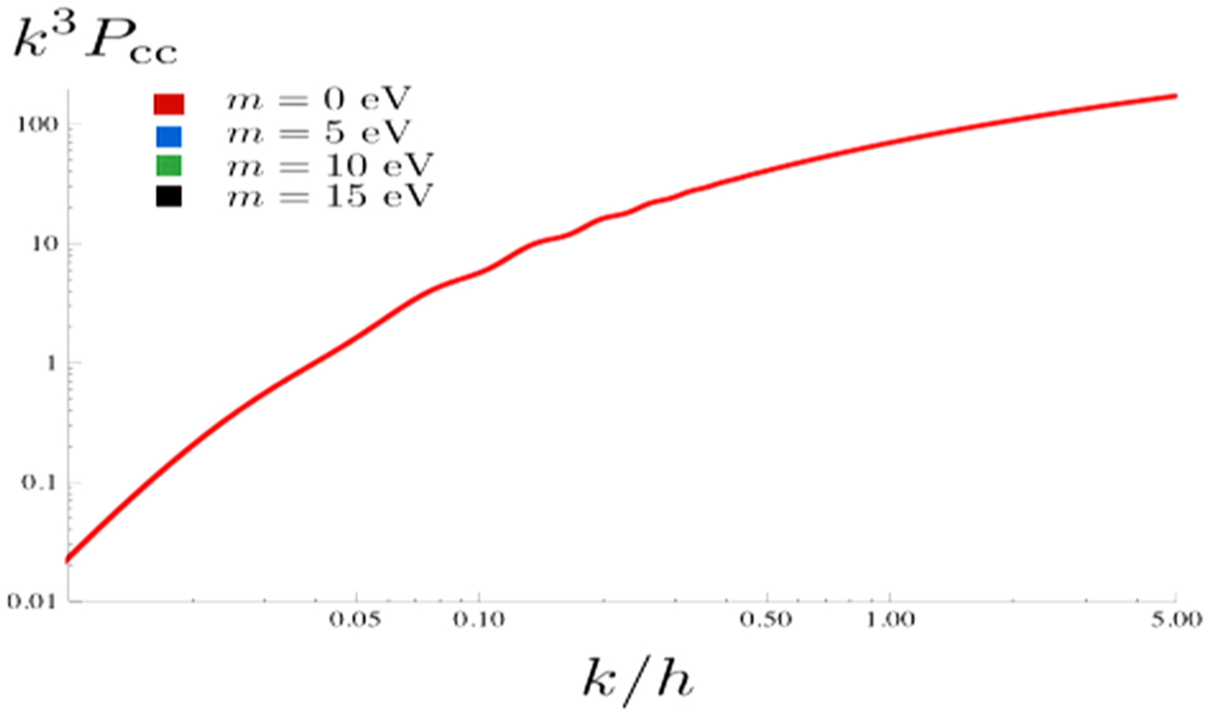
Strategy

- Vary the neutrino mass following our fixing scheme.
- Use Boltzmann codes such as CAMB, CLASS to output the power spectra for these cosmologies
- Integrate to compute the smoothed density contrast up to the galaxy scale, as a function of neutrino mass and for a wide range of redshifts (use a fitting function for negative redshift *only*)
- Integrate against the causal patch volume, weighted by an appropriate prior, to find the probability distribution

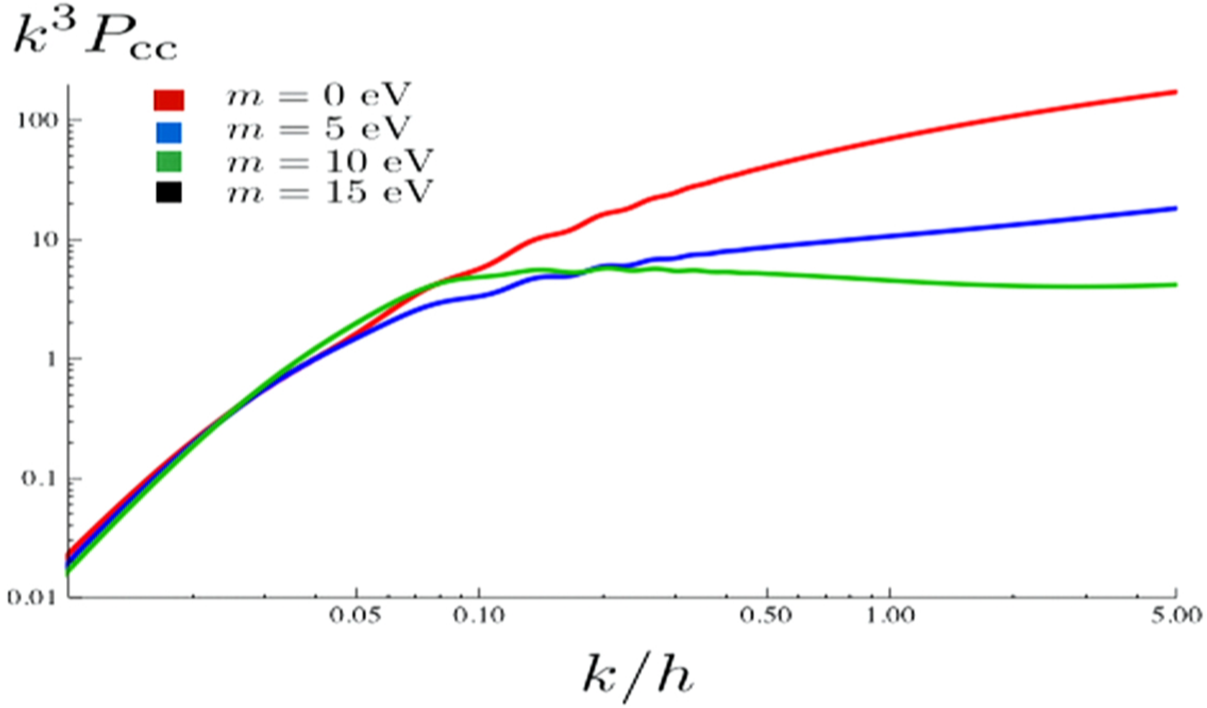
Press-Schechter mass variance σ_R



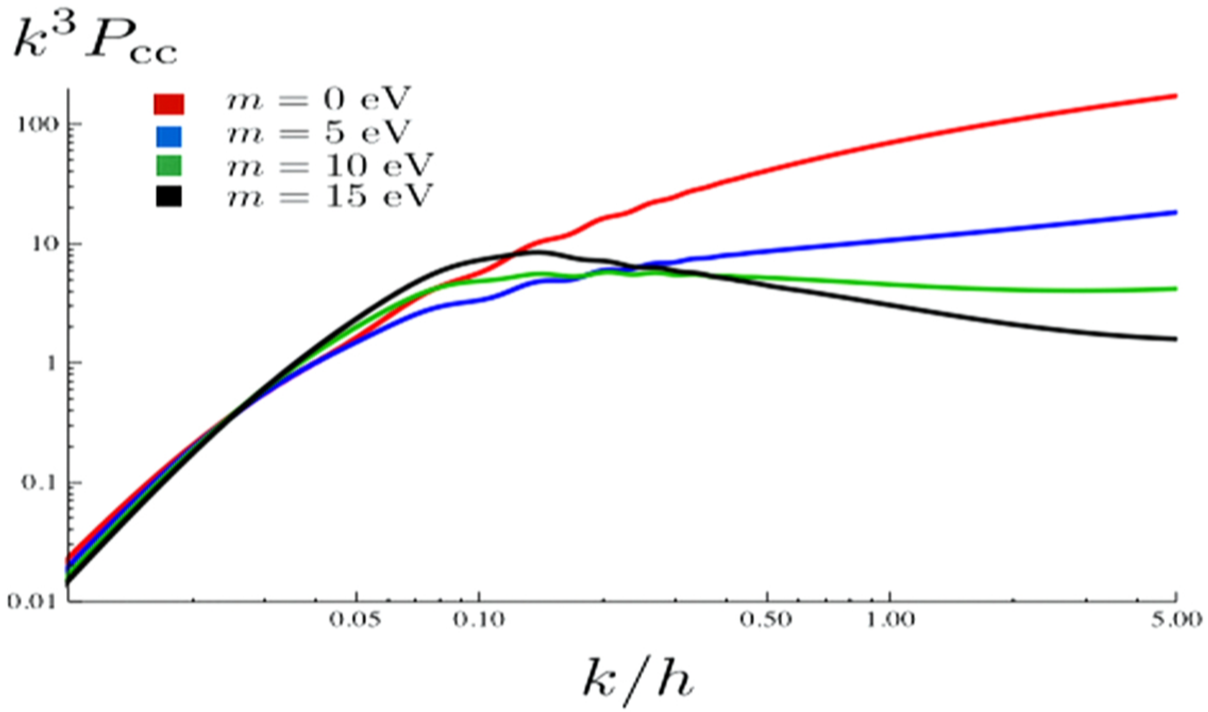
Press-Schechter mass variance σ_R



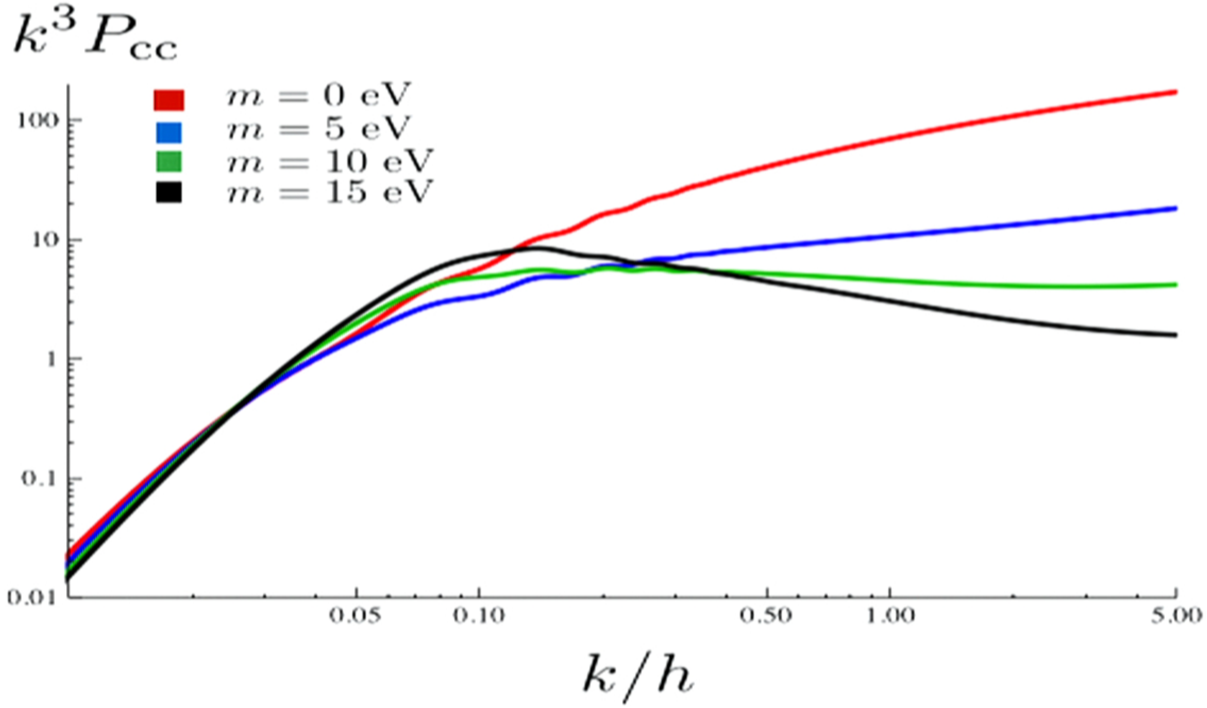
Press-Schechter mass variance σ_R



Press-Schechter mass variance σ_R



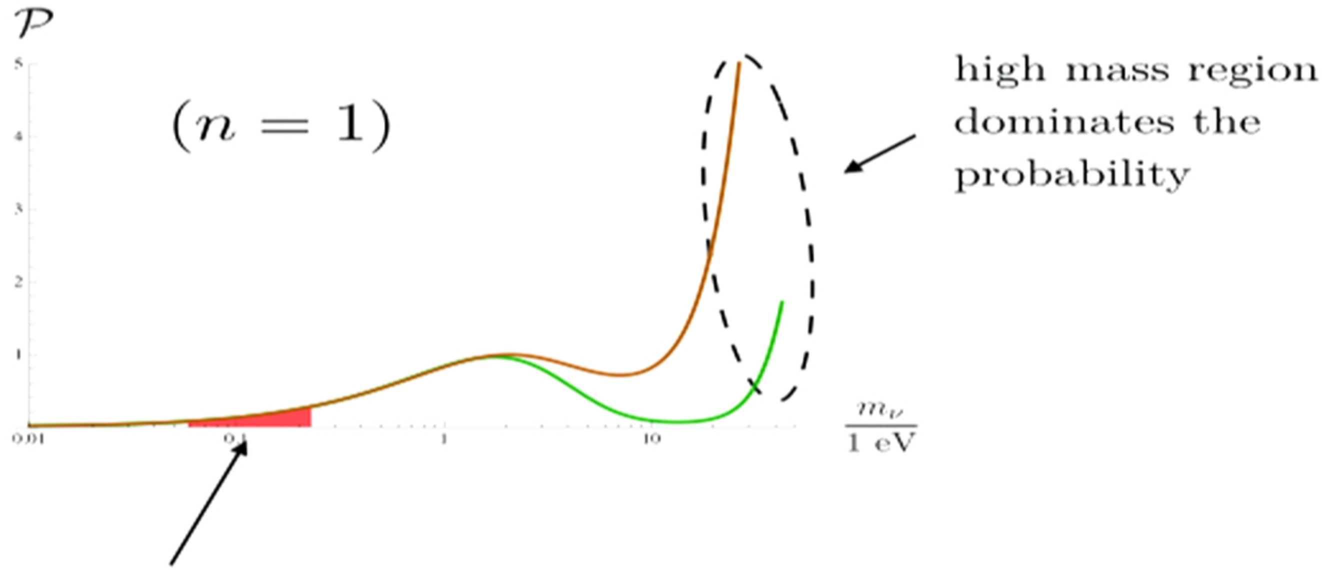
Press-Schechter mass variance σ_R



- Critical mass $m \sim 10$ eV above which $k^3 P$ develops peak near the free-streaming scale $k_{\rm nr}$
- Regime change: integral dominated by peak rather than cutoff
- Peak grows with neutrino mass since $k_{\rm nr}$ increases, length of matter era increases with m

Probability distribution - no cutoff

Predicts more structure above $m \sim 10$ eV!



Observationally viable region

$58 \text{ meV} < m_\nu < 0.23 \text{ eV}$

High mass regime change $m \sim 10$ eV

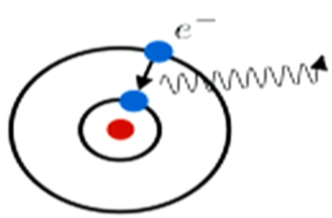
Dimensionless power spectrum goes flat

$\Rightarrow$ Transition away from a traditional bottom-up structure formation scenario, to one where perturbations go nonlinear at all scales simultaneously.

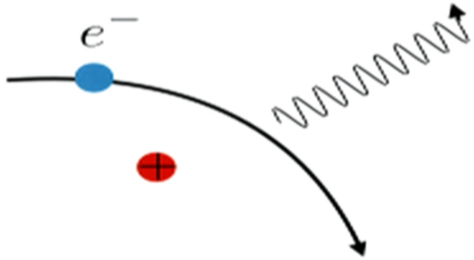
$\Rightarrow$ **Top-down structure formation scenario**

Virialization and cooling

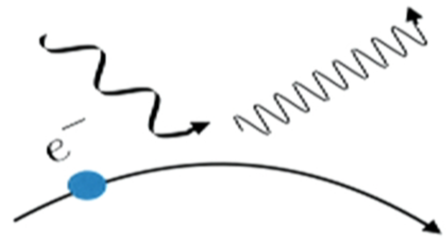
- CDM overdensities exceeding the critical density δ_c will go nonlinear and virialize into halos
- Baryons falling into the gravitational potential of these halos are shock heated to the temperature $T_{\rm vir}$ via the virial theorem
- To collapse further to form stars, these baryons must first cool sufficiently



line cooling



bremsstrahlung



inverse Compton scattering

Cooling criterion

Criterion for efficient cooling: $t_{\rm cool} \lesssim t_{\rm grav}$

$$\left.\begin{array}{l} \dfrac{G_N M_{\rm vir}\mu}{5R_{\rm vir}} = T_{\rm vir} \\ \\ M_{\rm vir} \sim \rho_{\rm vir} R_{\rm vir}^3 \end{array}\right\} \quad \Rightarrow \quad T_{\rm vir} \propto M_{\rm vir}^{2/3}\rho_{\rm vir}^{1/3}$$

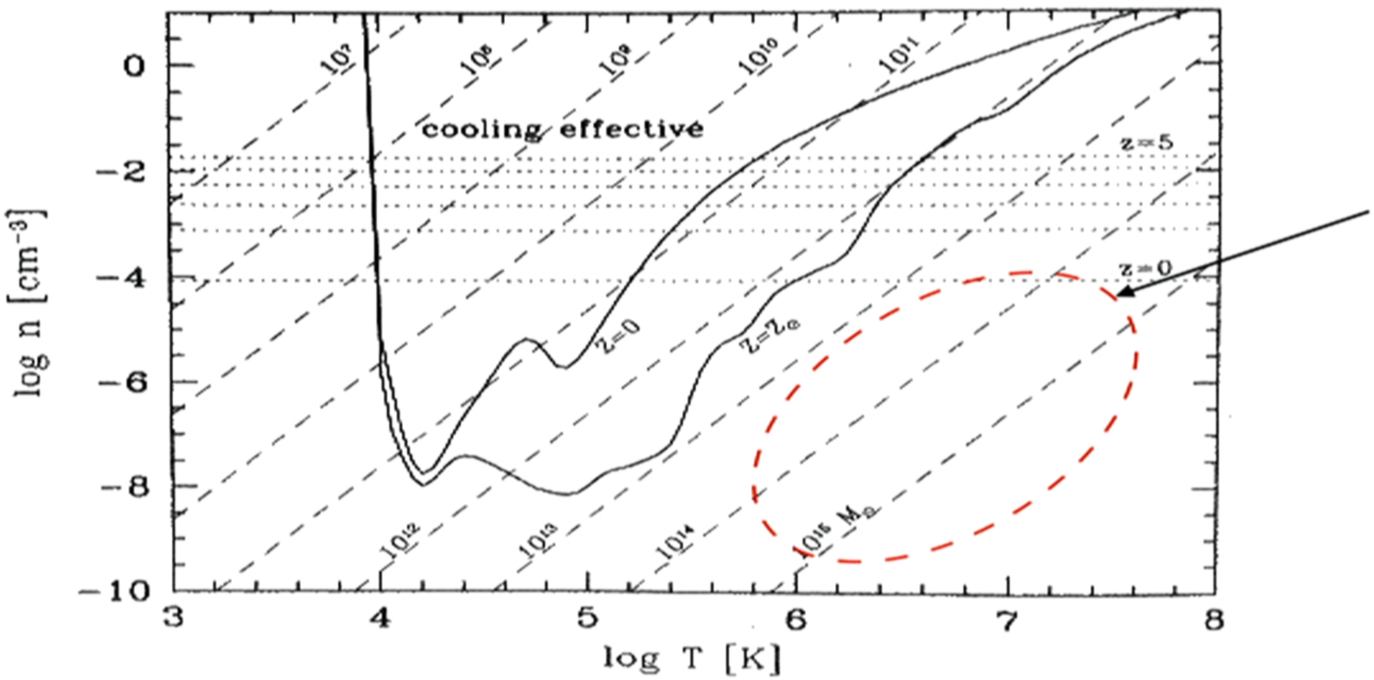
$$t_{\rm brems} \propto \frac{T_{\rm vir}^{1/2}}{\rho_{\rm vir}} \propto \frac{M_{\rm vir}^{1/3}}{\rho_{\rm vir}^{5/6}}$$

$$t_{\rm vir} \propto \rho_{\rm vir}^{-1/2}$$

cooling criterion satisfied $\Rightarrow M_{\rm vir} t_{\rm vir}^2 \lesssim (10^{12} M_\odot)(\mathcal{O}(1)\,{\rm Gyr})^2$

fixed $t_{\rm vir} \gtrsim \mathcal{O}(1)$ Gyr $\Rightarrow$ cooling criterion **violated** by more massive halos

Cooling criterion



Cluster sized halos do not cool efficiently enough to form their own stars

Image Source: Mo, Hougun, van den Bosch, Frank, and White, Simon. *Galaxy Formation and Evolution*. New York: Cambridge University Press, 2010.

Cooling in our universe: bottom-up structure formation scenario

- Smaller, galaxy size halos form first.

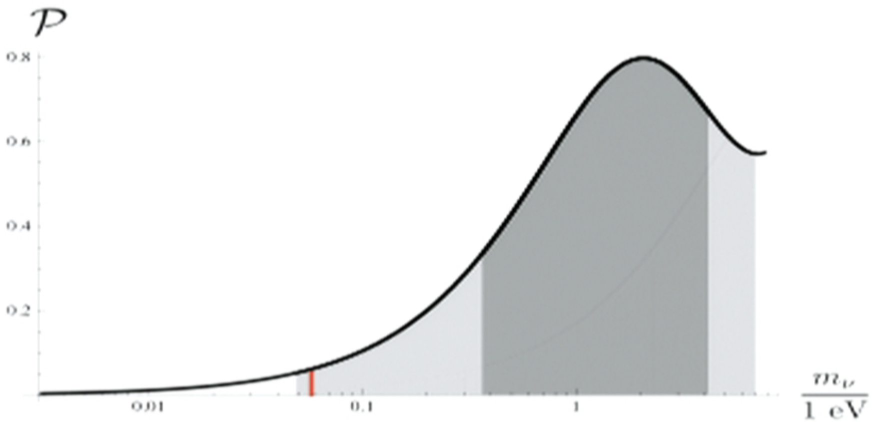
- These halos can cool efficiently, so they produce stars and hence observers.

- Later, larger halos form which may inherit these earlier galaxies. However, these halos cannot cool efficiently themselves, and thus do not produce their own stars significantly.

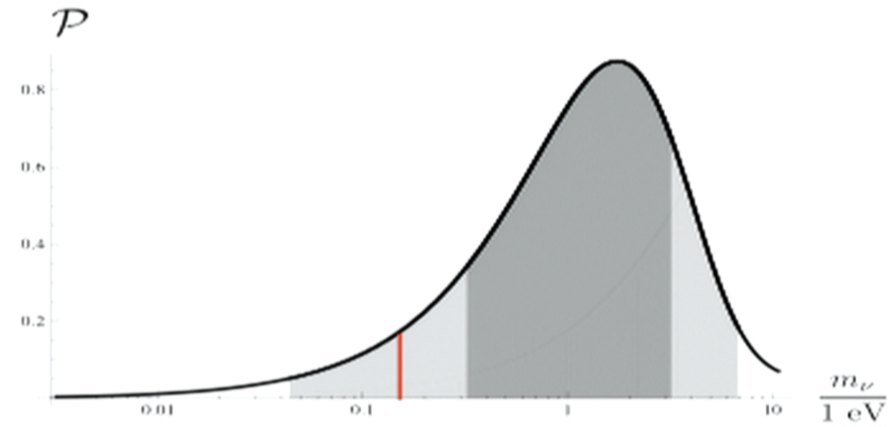
A very different universe: top-down structure formation scenario

- Perturbations go nonlinear roughly simultaneously at all scales (galaxy, halo, etc.)
- These regions virialize together. The scale of the potential (and hence the virial temperature) is set by the largest halo, while smaller substructures are washed out.
- In our own universe, such halos do not form stars in any reasonable abundance, since baryons heated up in these potentials will not be able to cool efficiently. There is no reason to expect more galaxies in universes with large neutrino mass.

Result: Probability distribution with a catastrophic cutoff



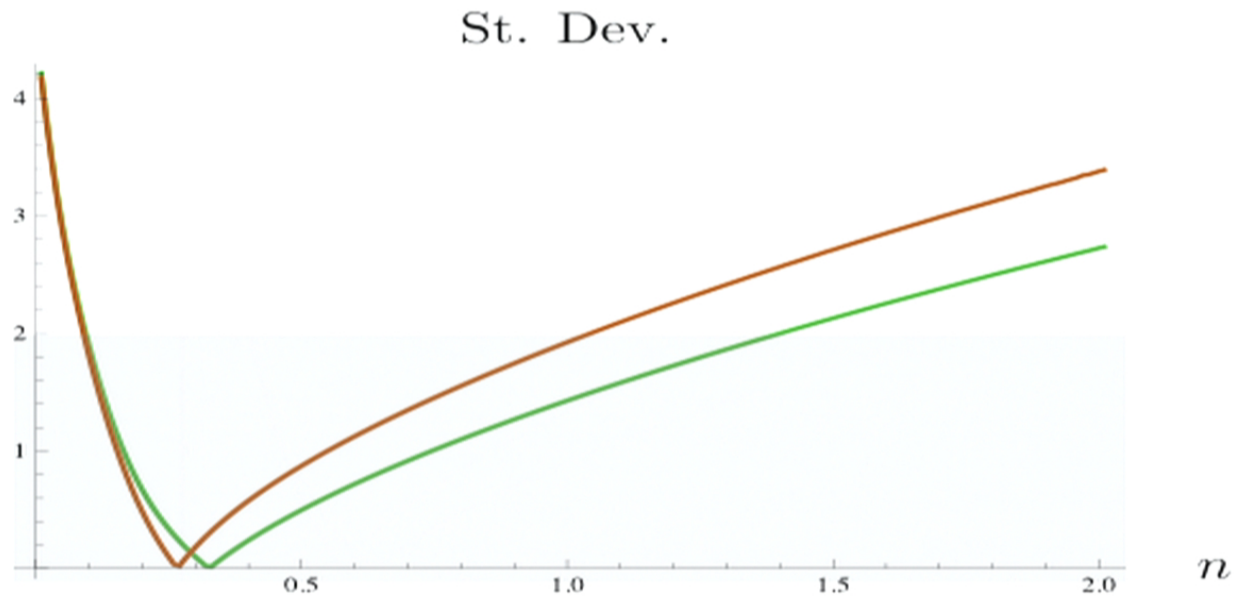
Normal hierarchy



Degenerate hierarchy

Our result: Excluding the high mass region gives a probability distribution (for $n = 1$) that is consistent with the worst case observed value at $> 2\sigma$. A degenerate hierarchy is mildly preferred. This holds for a range of priors $0.09 < n < 1.4$ $(0.09 < n < 1)$ for a degenerate (normal) hierarchy.

Variation of prior



Conclusions

- We constructed a probability distribution for the neutrino mass sum using the causal patch measure.
- Increased neutrino mass suppresses structure. However, ***more*** structure is actually predicted past $m \sim 10$ eV .
- With no anthropic reason to exclude large mass, the resulting probability distribution significantly *disagrees with observation.*
- However, this regime change coincides with a transition to a top-down structure formation scenario, which we argue is catastrophic to observers due to cooling failure.
- Excluding this region gives a prediction for the neutrino mass consistent with observation at $> 2\sigma$. A degenerate hierarchy is mildly preferred. Cooling failure leads to an anthropic explanation for the observed neutrino mass.

Thank you for listening!

"I have done a terrible thing today, something which no theoretical physicist should ever do. I have suggested something that can never be verified experimentally."

- Wolfgang Pauli to a colleague (1930) on his proposal of neutrinos to preserve energy conservation in beta decays.

"Neutrino Cosmology" by Lesgourges, Mangano, Miele, and Pastor