Title: No nus is good news

Speakers: Daniel Green

Collection/Series: Colloquium

Subject: Other

Date: November 20, 2024 - 2:00 PM

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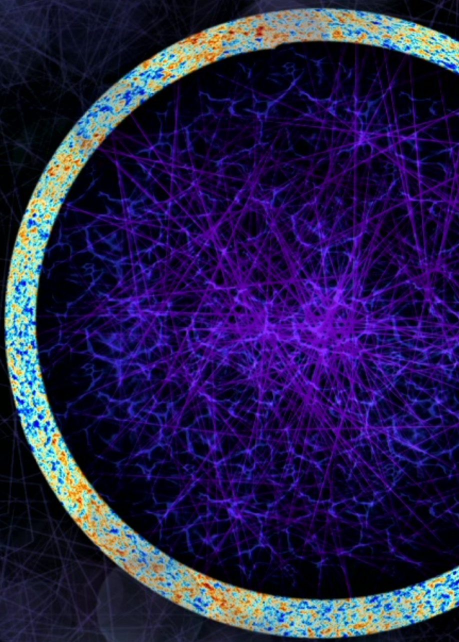
Abstract:

Cosmic surveys offer a unique window into fundamental physics, particularly the physics of light particles such as neutrinos. As a striking example, the recent results from the Dark Energy Spectroscopic Instrument (DESI) have placed surprisingly stringent constraints on the sum of neutrino masses, nearly excluding the entire range of masses consistent with neutrino oscillation measurements. In this colloquium, I will review what we have learned about cosmic neutrinos from maps of the universe. I will then discuss this confusing situation, the status possible explanations for the current data, and the implications for Beyond the Standard Model physics.

No νs is Good News

Daniel Green
UC San Diego

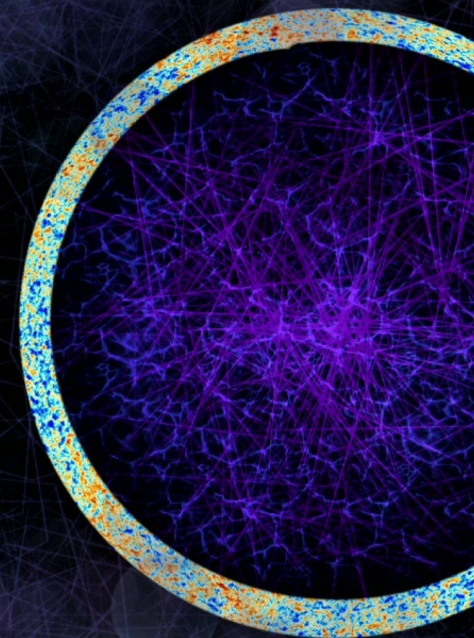


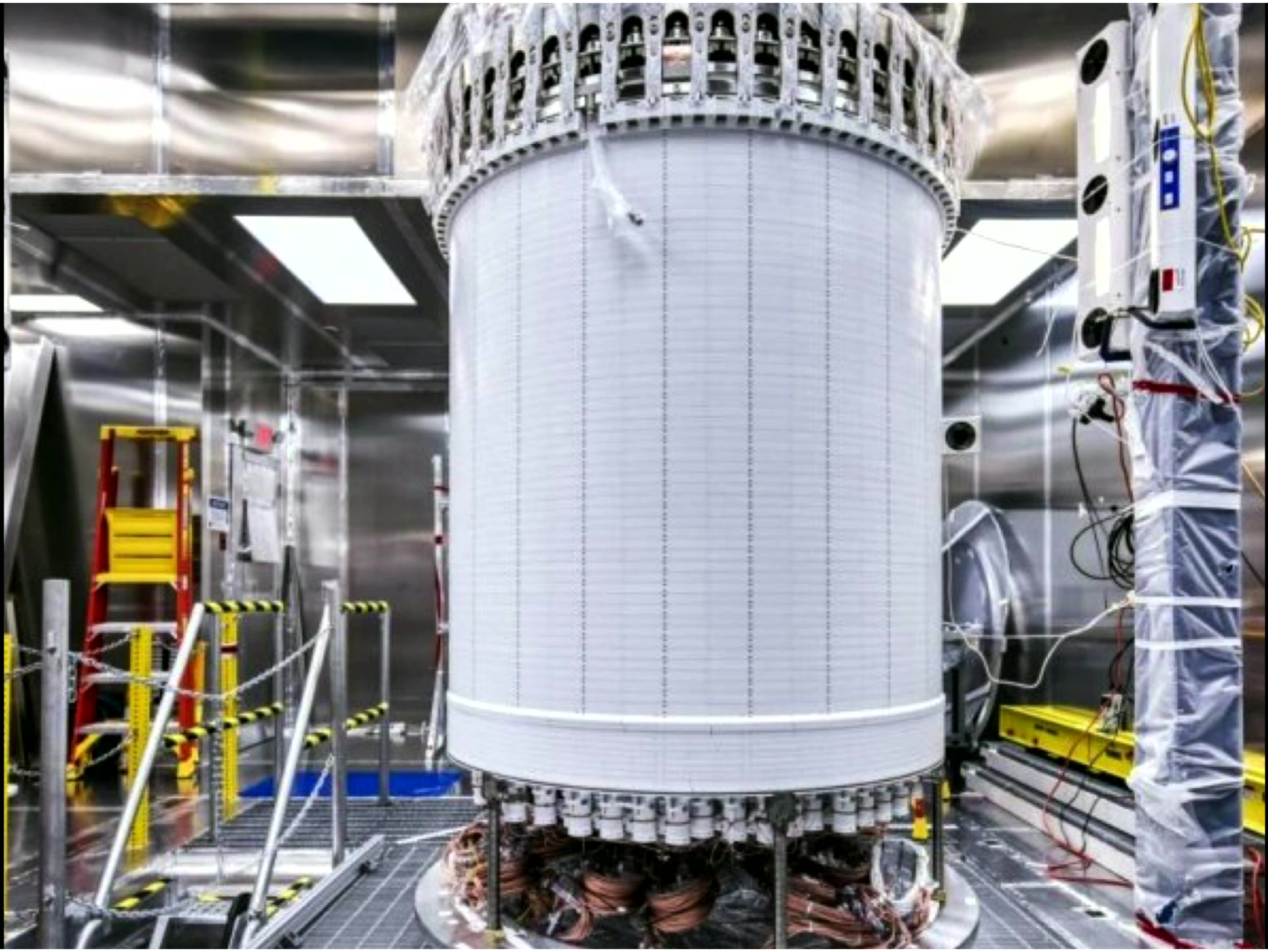
Cosmology & New Physics

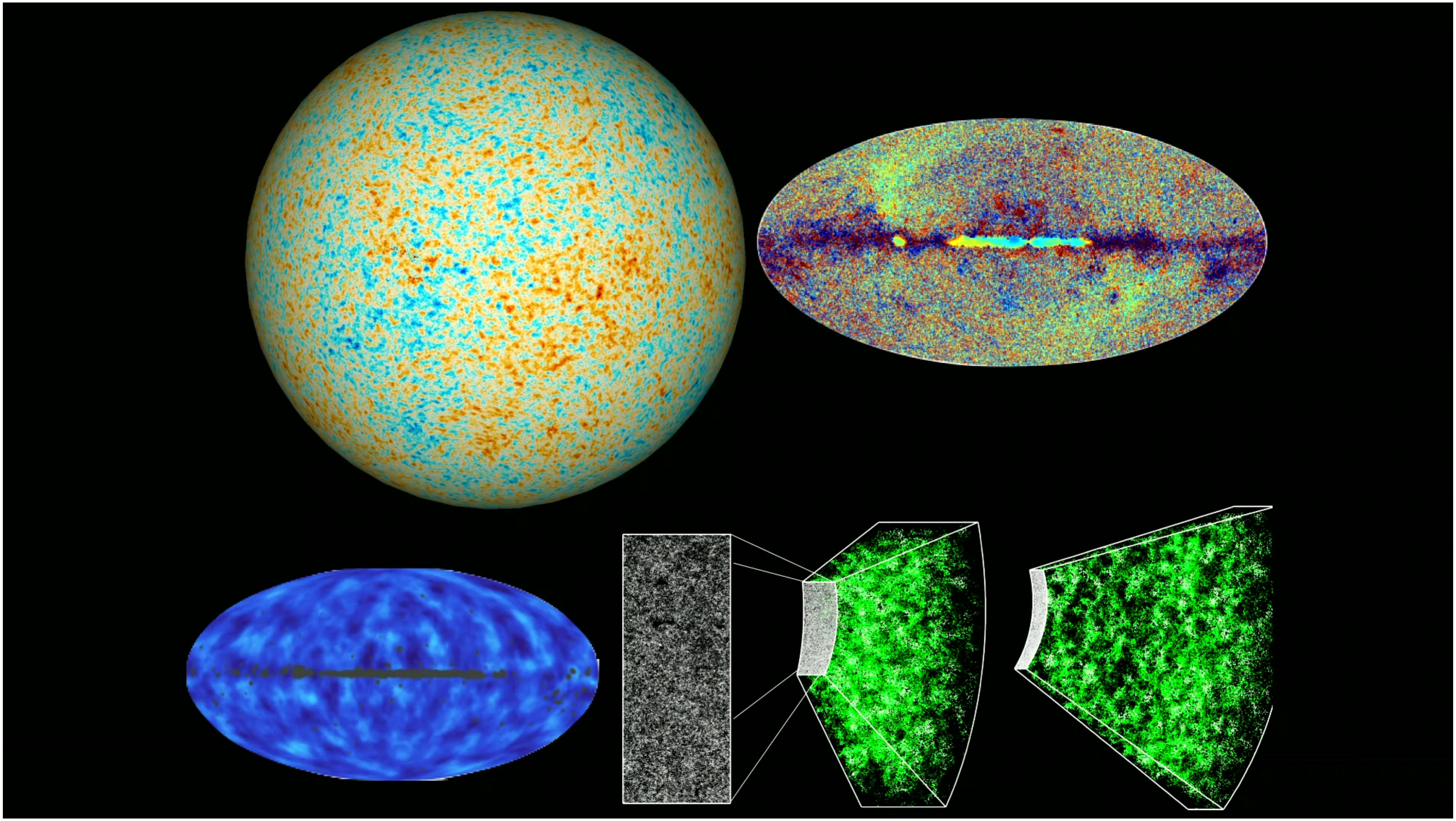
Cosmic Neutrinos

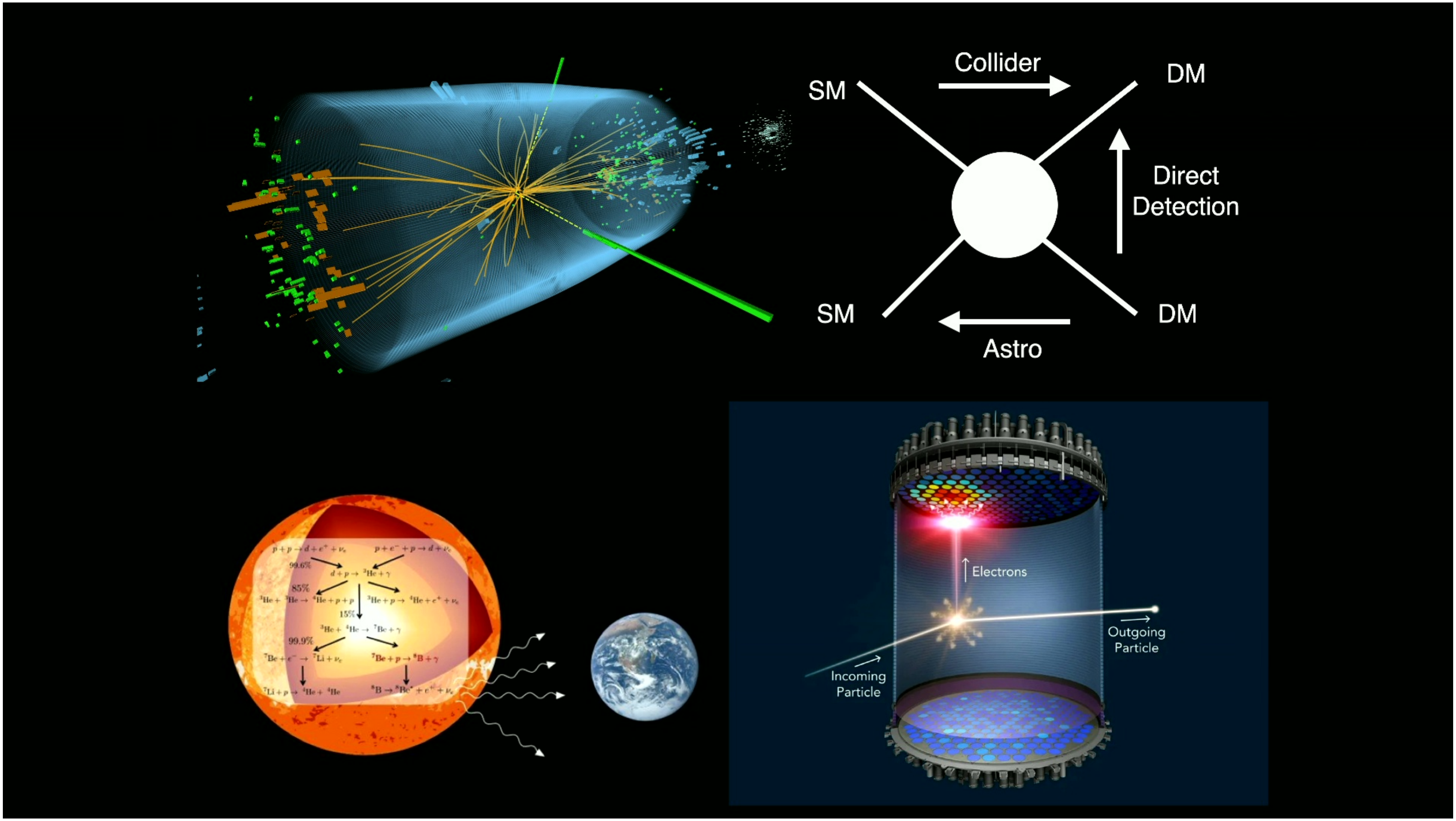
Neutrino Mass & Cosmology

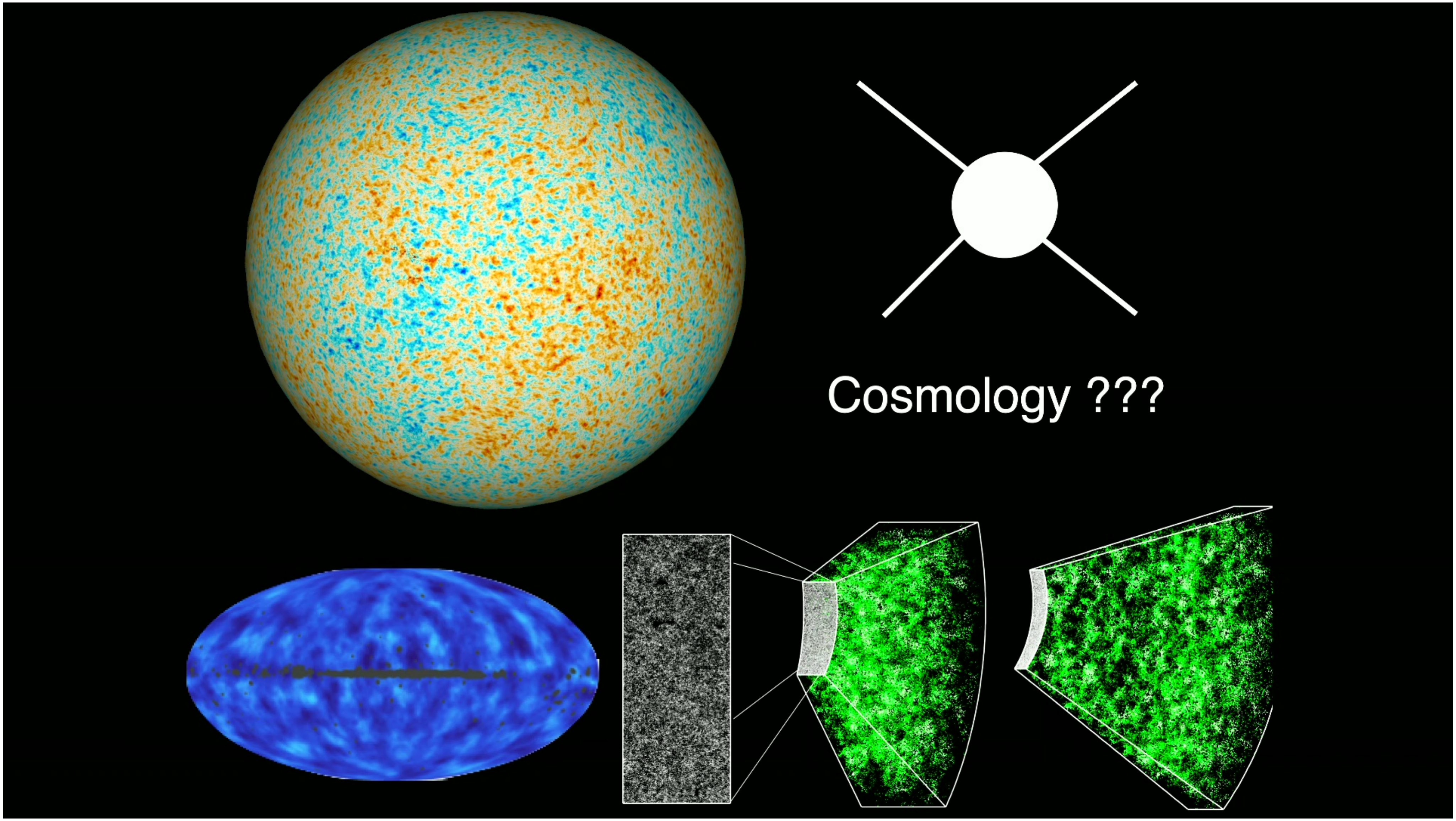
No νs is Good News







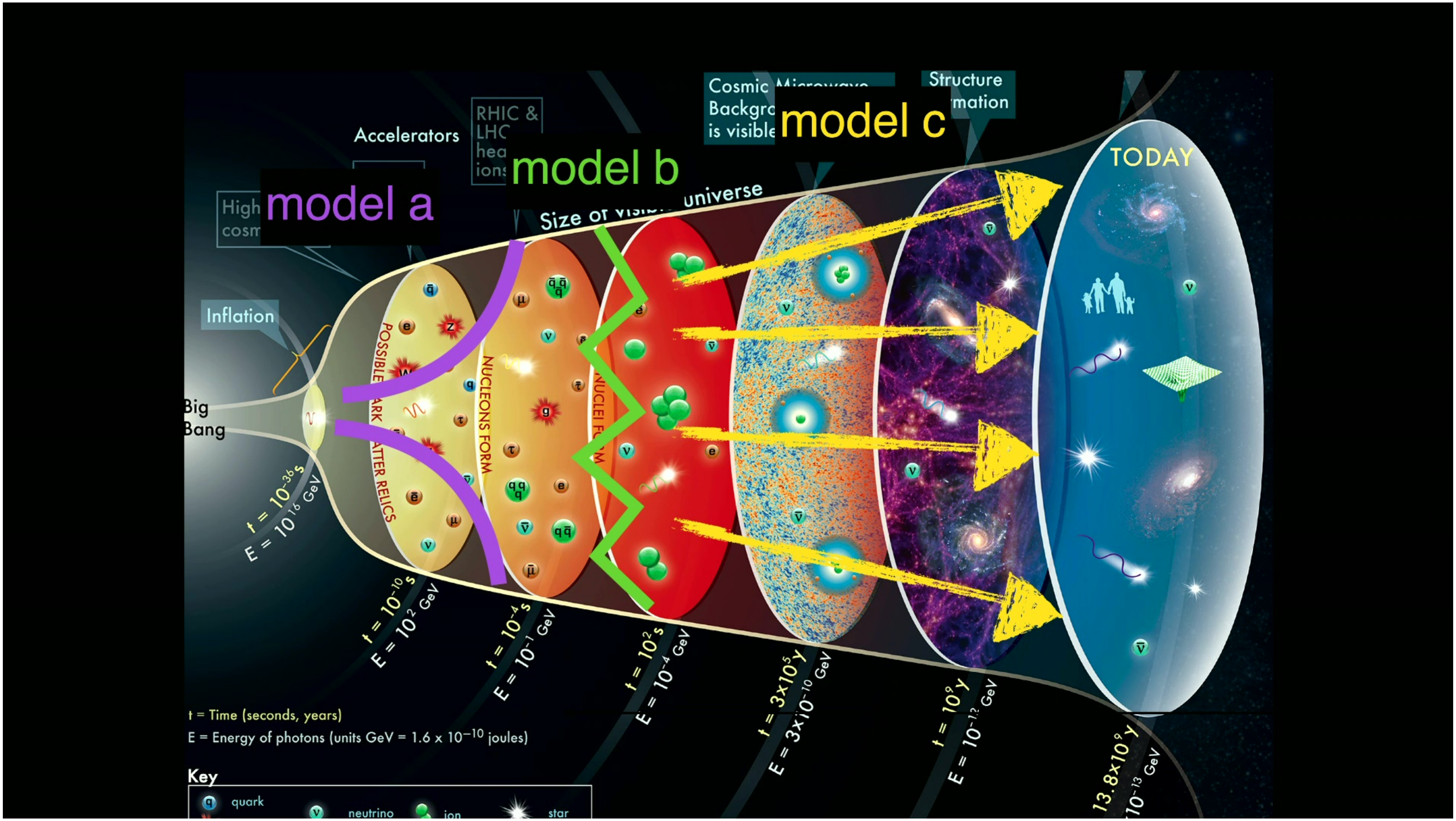

SM
Collider
DM
Direct
Detection
SM
Astro
DM
Electrons
Incoming
Particle
Outgoing
Particle


Cosmology ???

New Physics & Cosmology

Cosmology fundamentally tied to model building

- Cosmological Constant
- Dark Matter / Dark Sectors
- Solution to strong CP problem (axion)
- Cosmological solutions to Hierarchy Problem
- Relics from new symmetries (e.g. gravitino)
- Origin of structure, baryogenesis, B-fields, ...



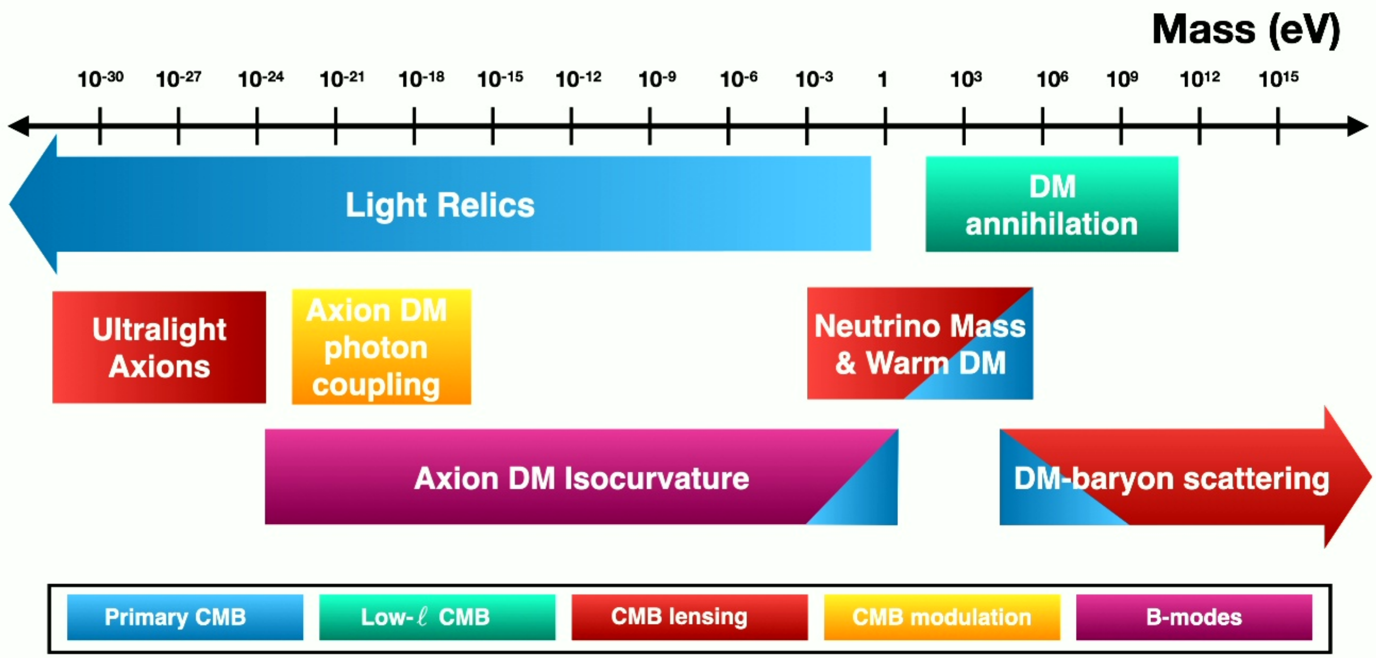
model a
model b
model c
Accelerators
Inflation
Big Bang
TODAY
Structure
Size of visible universe
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10−10 joules)
Key
quark
neutrino
ion
star

New Physics & Cosmology

Observations are relevant to:

- Cosmological Constant
- Dark Matter / Dark Sectors ✓
- Solution to strong CP problem (axion) ✓
- Cosmological solutions to Hierarchy Problem ✓
- Relics from new symmetries (e.g gravitino) ✓
- Origin of structure, baryogenesis, B-fields, ... ✓

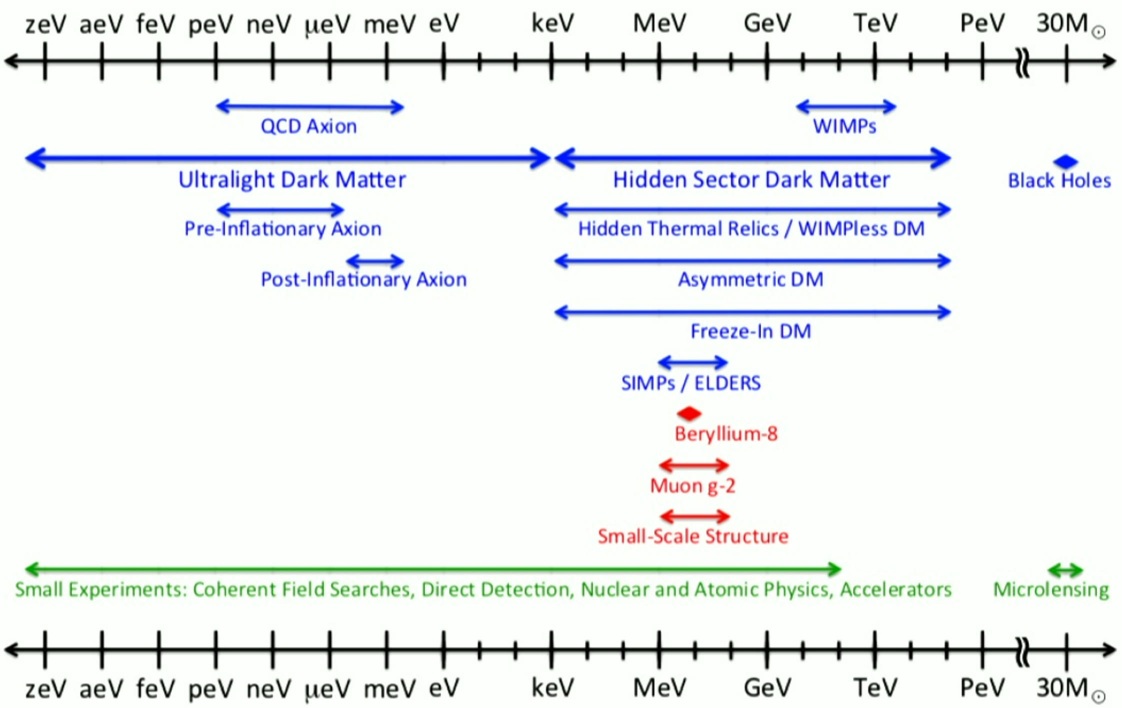
New Physics & Cosmology



arXiv: 1907.04473

New Physics & Cosmology

Dark Sector Candidates, Anomalies, and Search Techniques



arXiv: 1707.04591

New Physics & Cosmology

Cosmology competes head to head with the lab

- Detect dark matter at 120σ
- Detect cosmic neutrino background at 30σ

Neither has been seen in the lab

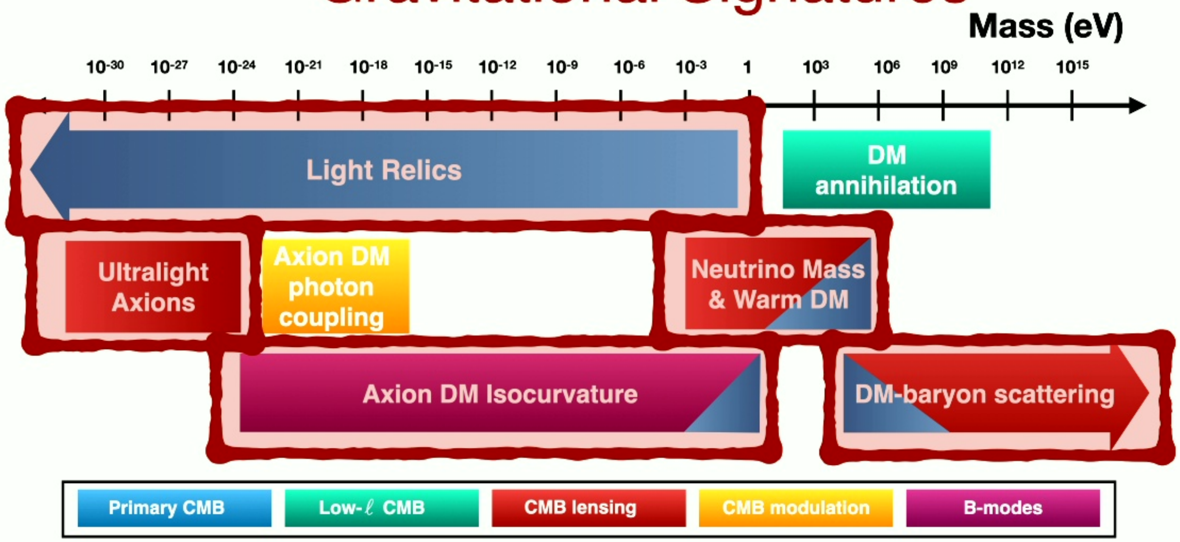
Superior sensitivity arises because of

(1) high T / number density in early universe

(2) large gravitational influence at recombination

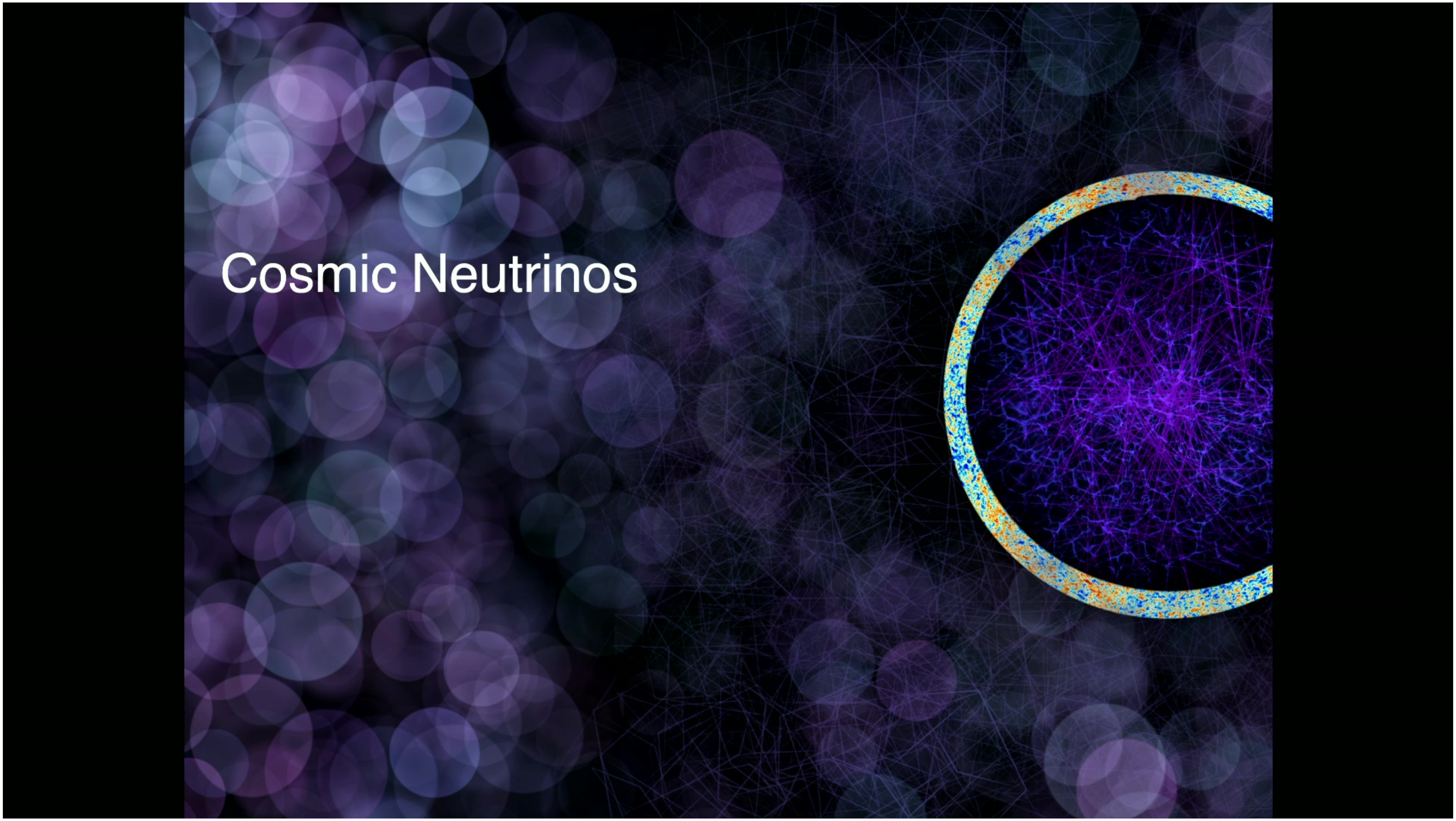
Dark Sectors

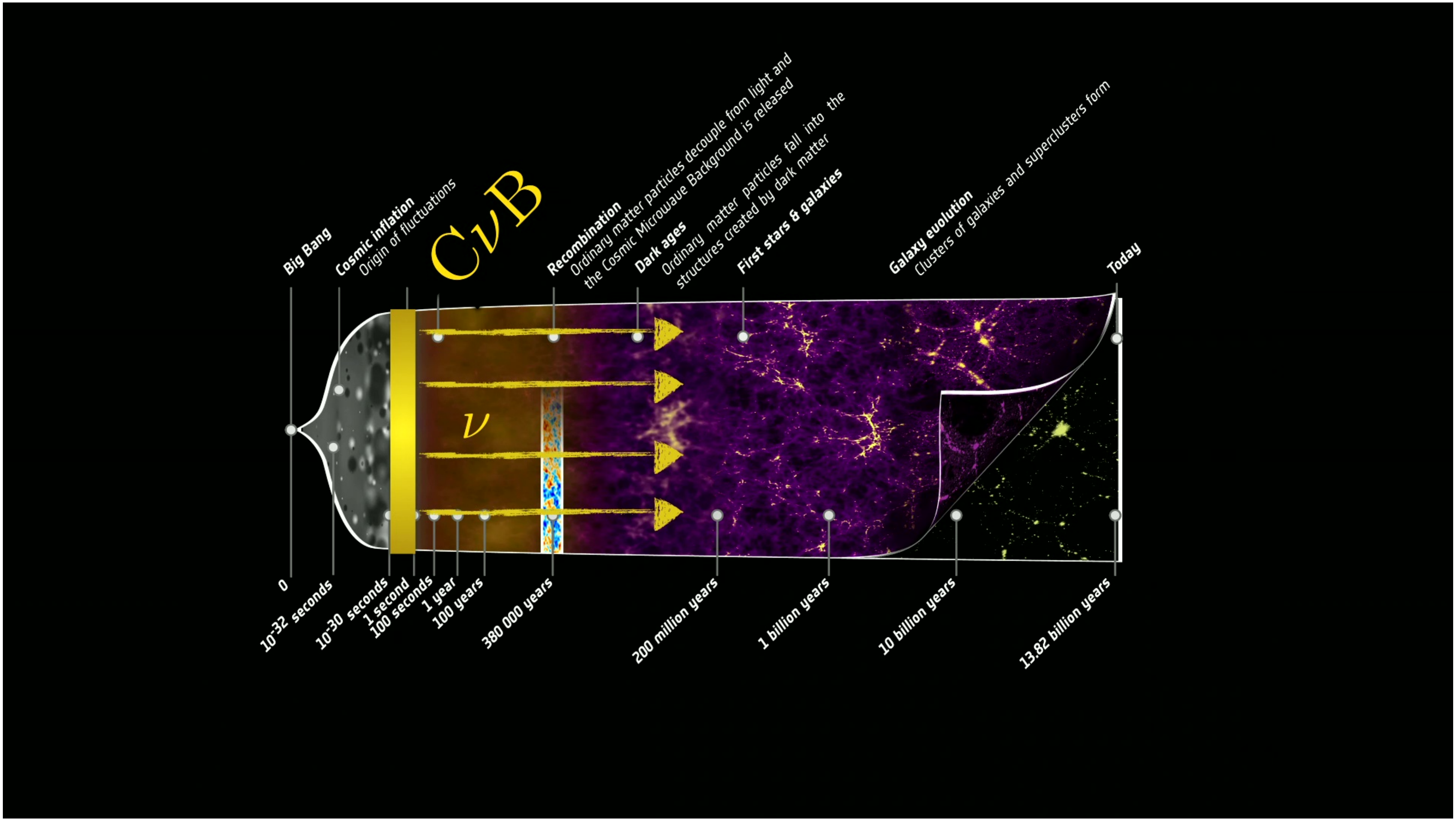
Gravitational Signatures



We see these dark sectors through gravity

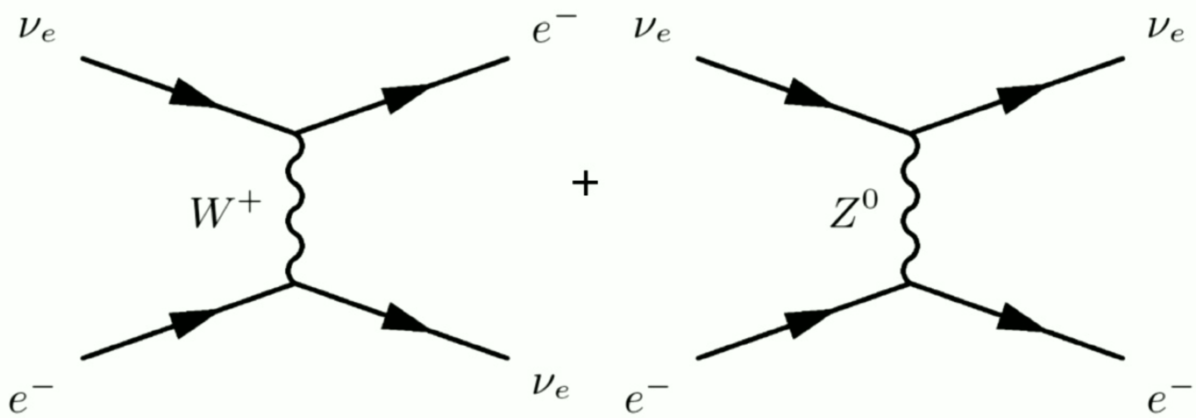
Can't hide the signature by changing the coupling


Cosmic Neutrinos



Big Bang
Cosmic inflation
Origin of fluctuations
CνB
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
ν
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

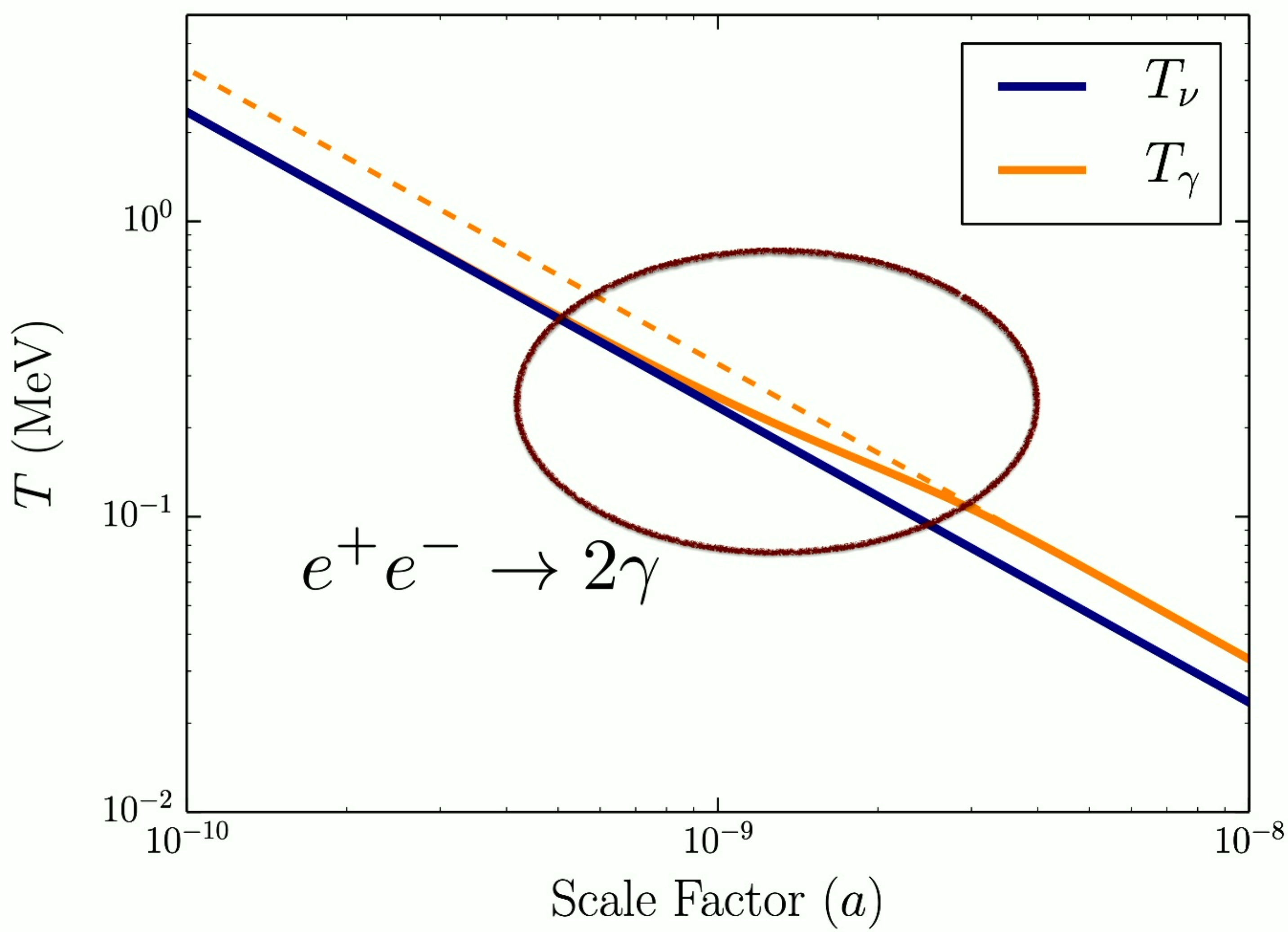
Cosmic Neutrino Background



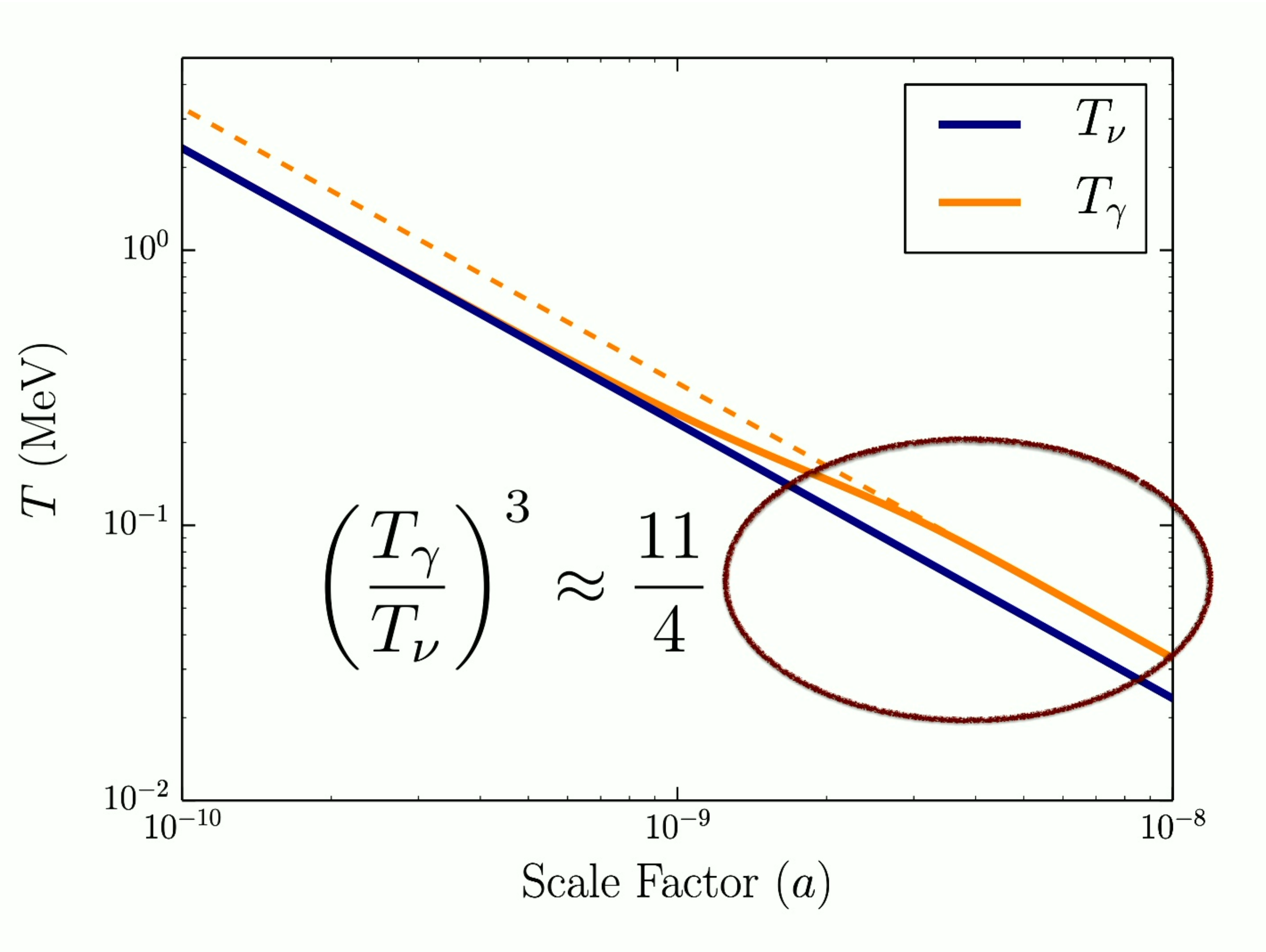
Equilibrium :

$$\Gamma \sim G_F^2 T^5 > H \sim \frac{T^2}{M_{\rm pl}}$$

Decoupling: $T^3 \sim G_{\rm F}^{-2}/M_{\rm pl} = \mathcal{O}(1\,{\rm MeV})$



T_ν
T_γ
10^0
10^{-1}
10^{-2}
T (MeV)
$e^+e^- \rightarrow 2\gamma$
10^{-10}
10^{-9}
10^{-8}
Scale Factor (a)



T_ν
T_γ
10^0
10^{-1}
10^{-2}
T (MeV)
10^{-10}
10^{-9}
10^{-8}
Scale Factor (a)
$\left(\frac{T_\gamma}{T_\nu}\right)^3 \approx \frac{11}{4}$

Cosmic Neutrino Background

Cosmology sensitive to the neutrino energy density

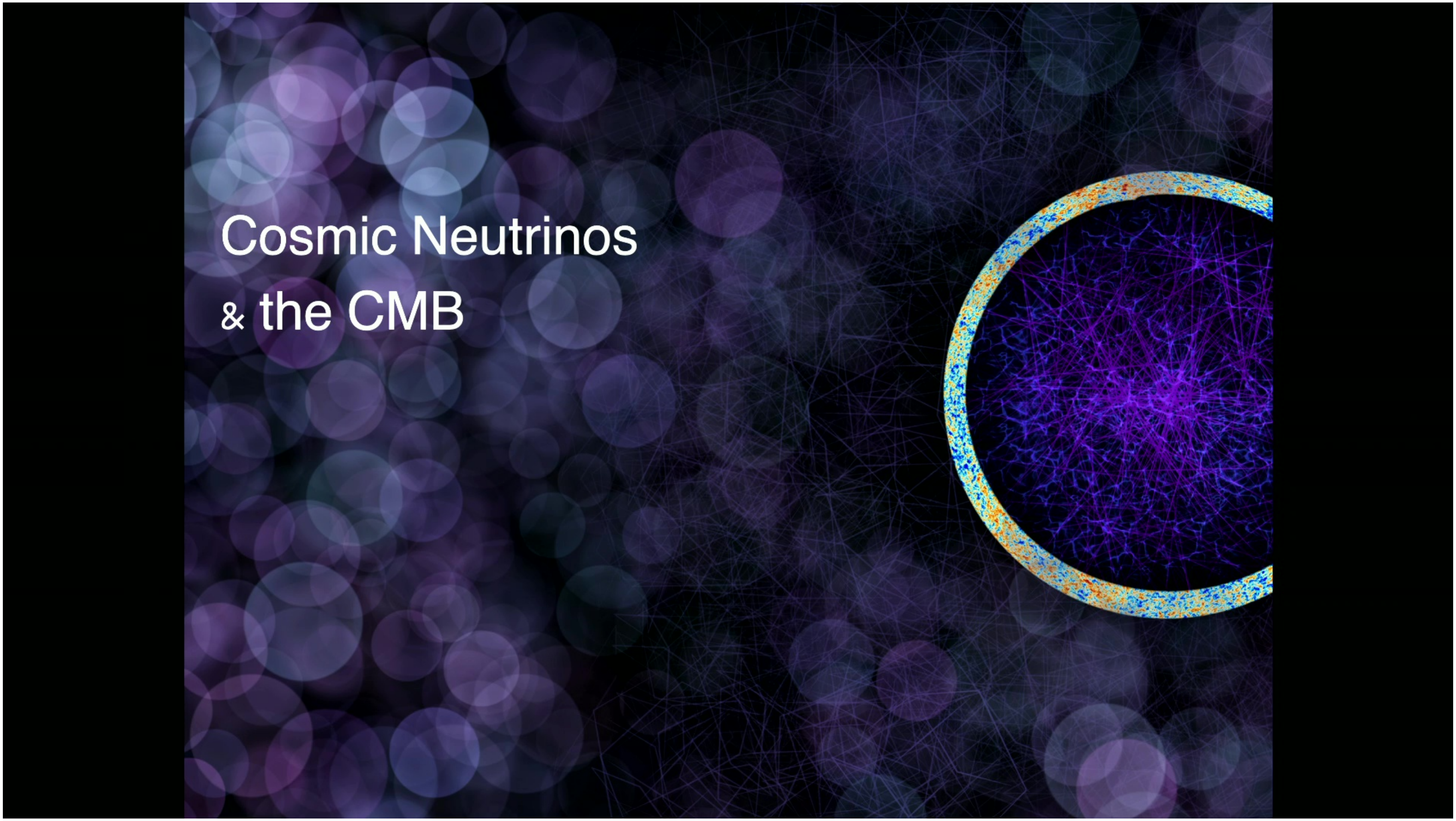
Conventional to define

$$N_{\text{eff}} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_\nu}{\rho_\gamma}$$

Perfect decoupling : $N_{\text{eff}} = 3.$

Imperfect decoupling + QED : $N_{\text{eff}} = 3.0440 \pm 0.0002$

Bennett et al. (2020)


Cosmic Neutrinos
& the CMB

Cosmic Microwave Background (CMB)

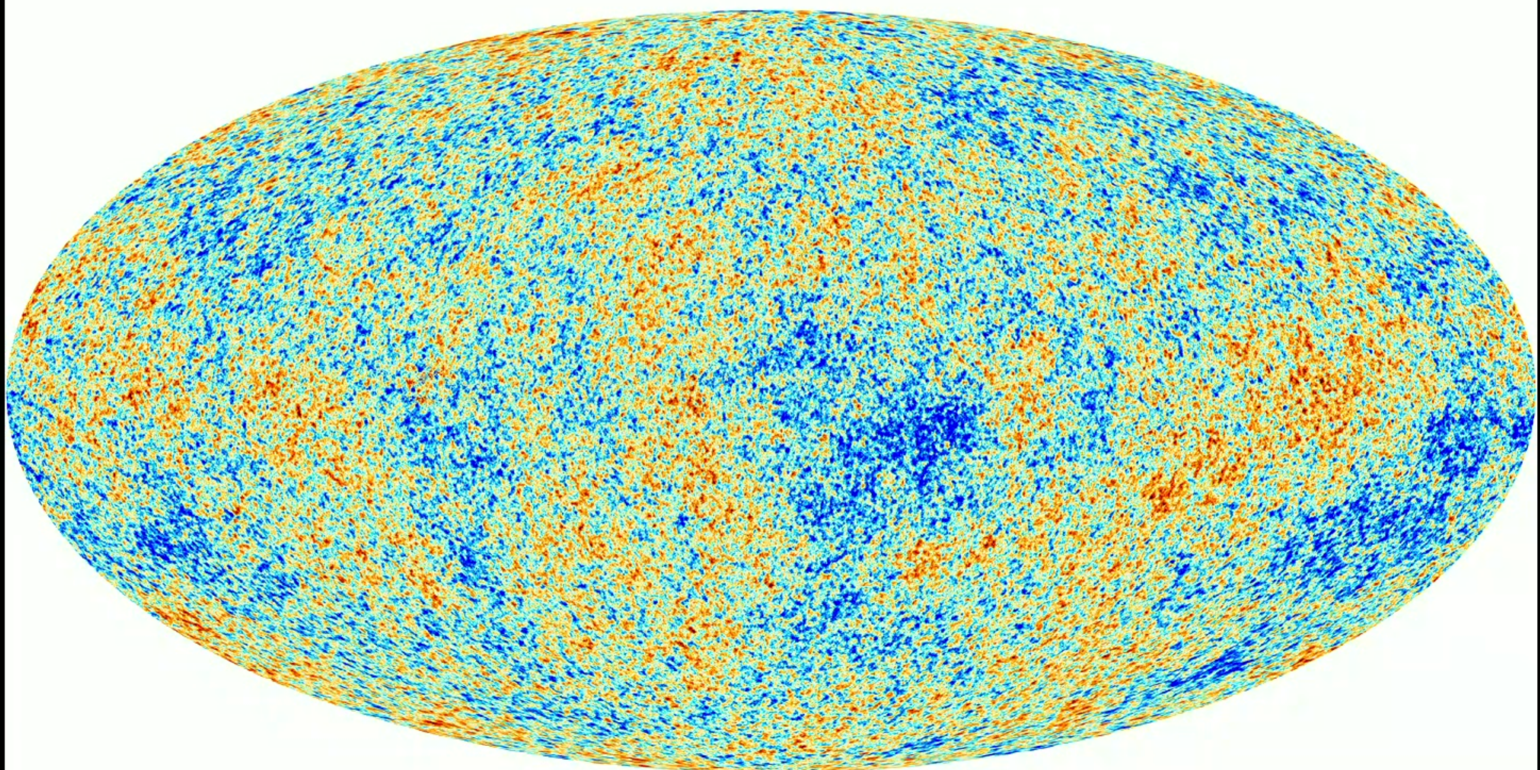


Image from Planck

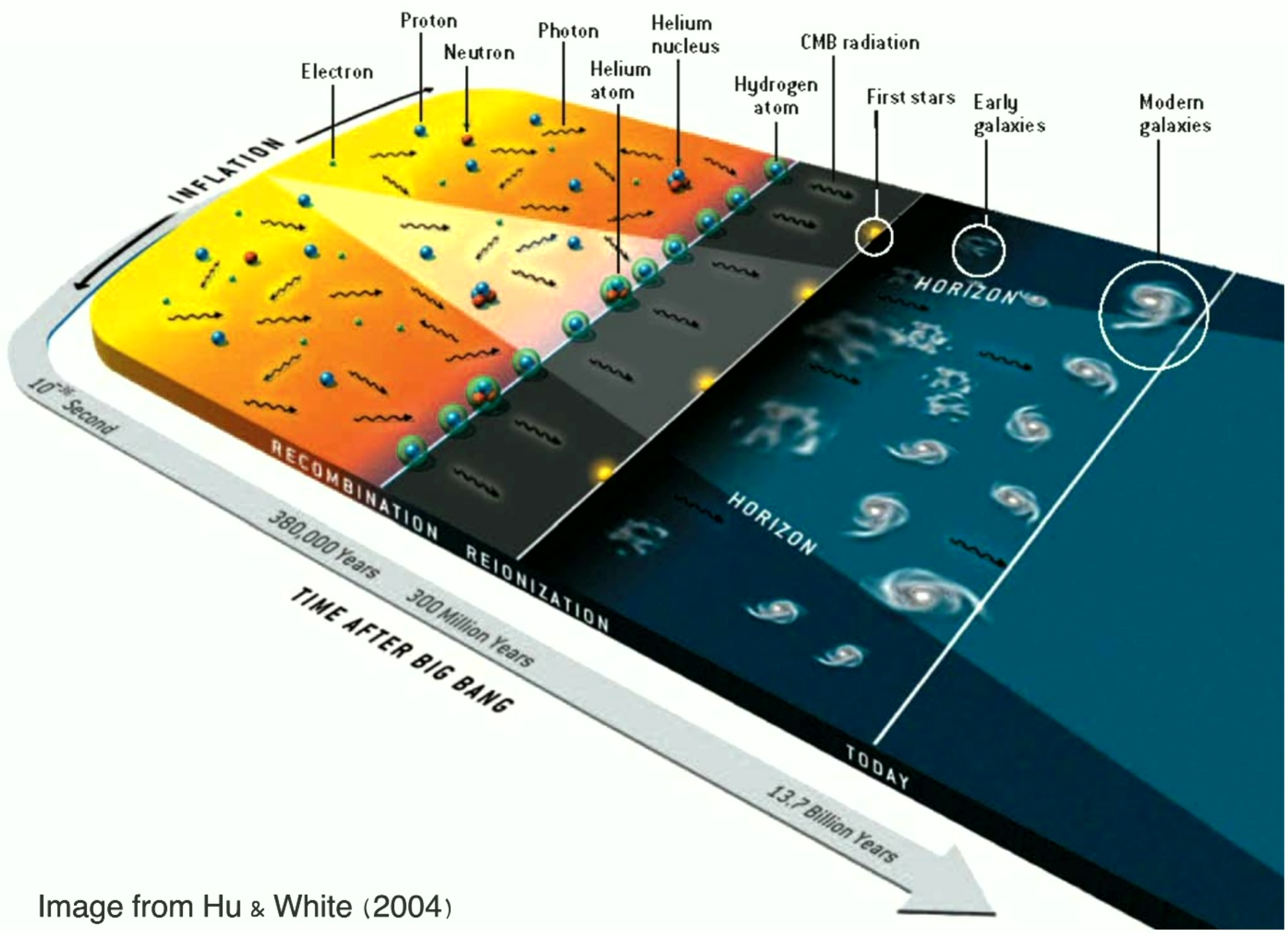
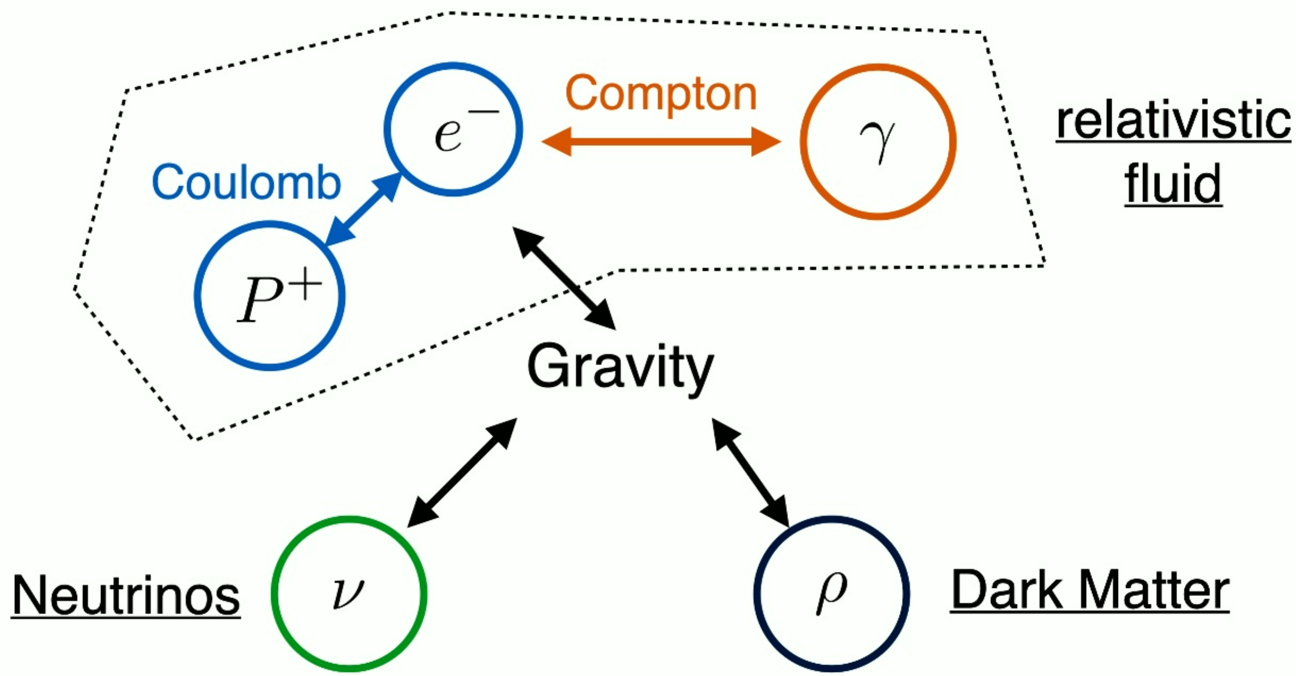
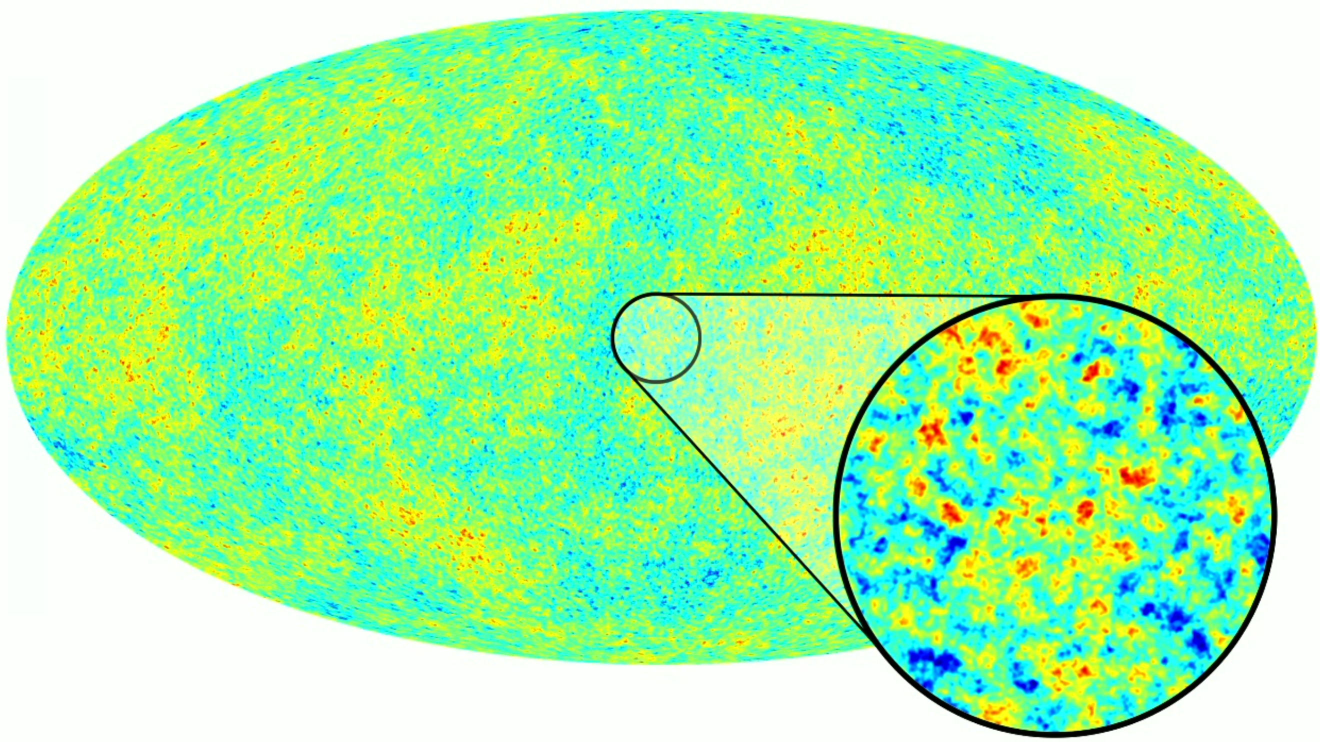
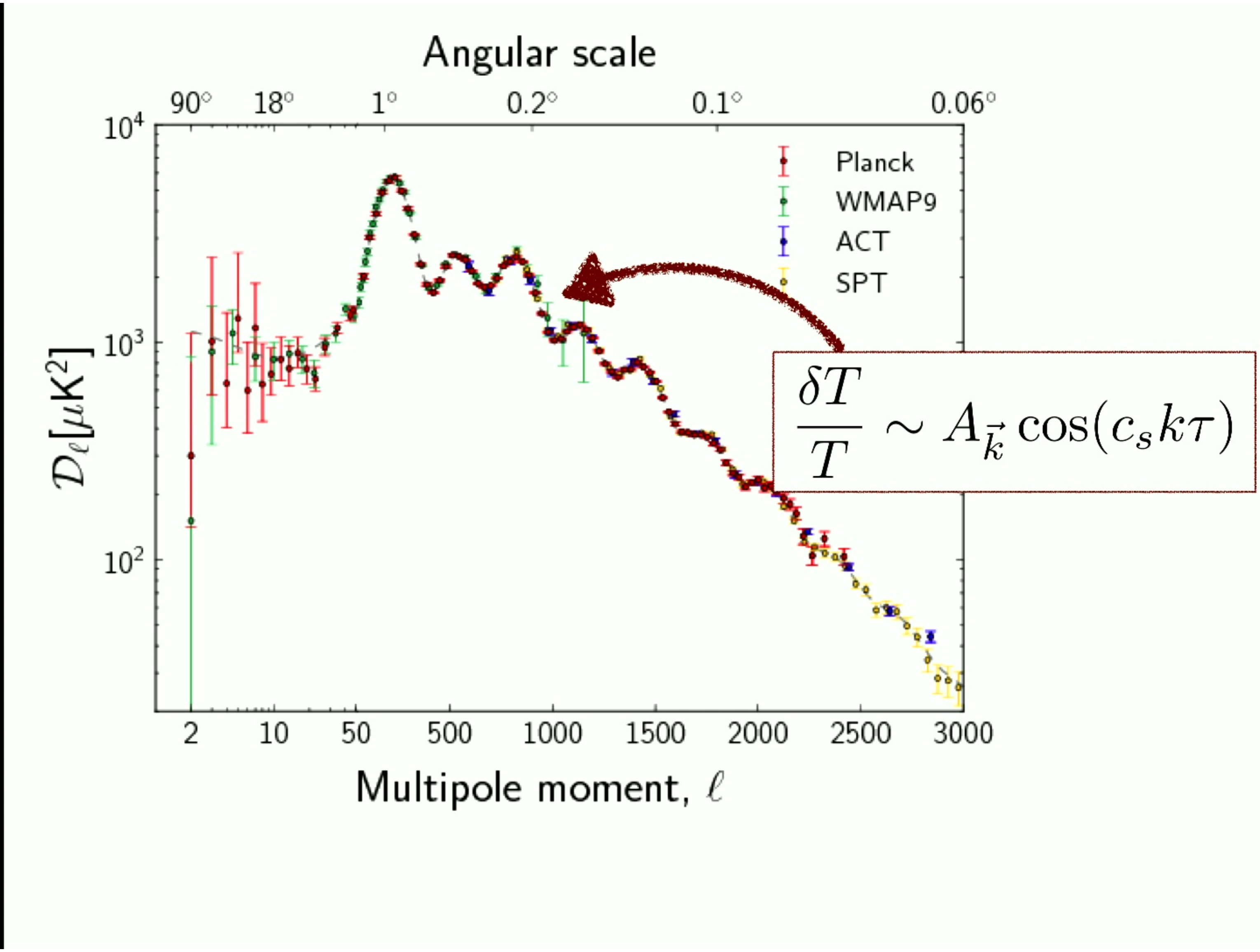


Image from Hu & White (2004)



Compton
e^-
γ
Coulomb
P^+
relativistic fluid
Gravity
Neutrinos
ν
ρ
Dark Matter





Angular scale
90° 18° 1° 0.2° 0.1° 0.06°
10^4
10^3
10^2
$\mathcal{D}_\ell[\mu K^2]$
Planck
WMAP9
ACT
SPT
2 10 50 500 1000 1500 2000 2500 3000
Multipole moment, ℓ
$\frac{\delta T}{T} \sim A_{\vec{k}} \cos(c_s k \tau)$

Cosmic Sound

$$\ddot{d}_\gamma - c_s^2 \nabla^2 d_\gamma \approx \nabla^2 \Phi$$

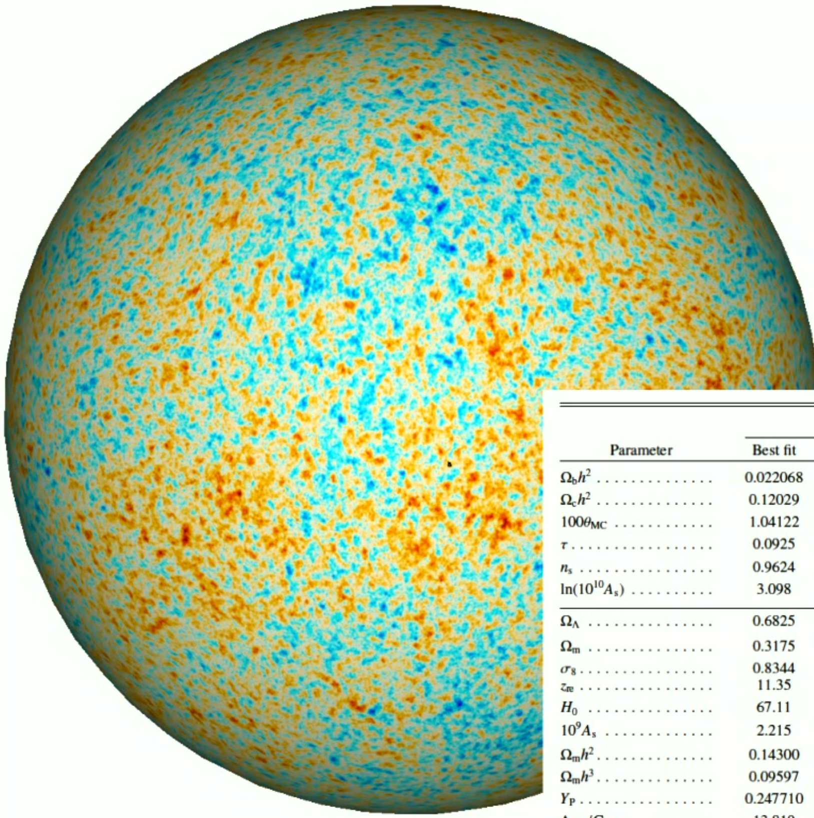
$$d_\gamma \approx A_{\vec{k}} \cos c_s k\tau + B_{\vec{k}} \sin c_s k\tau$$

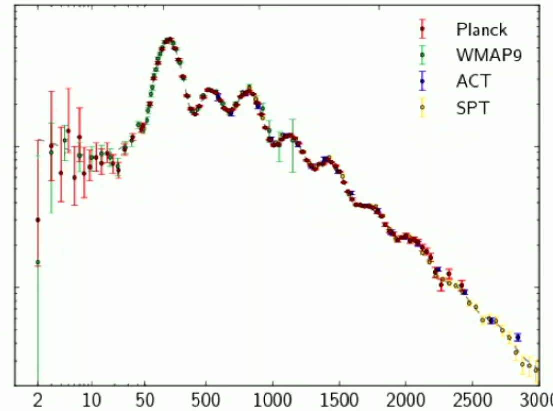
Absence of sine term comes from producing fluctuations long before recombination

$$\frac{\delta T}{T} \sim A_{\vec{k}} \cos(c_s k \tau)$$

"Inflation": statistical initial conditions

Sound waves at recombination:

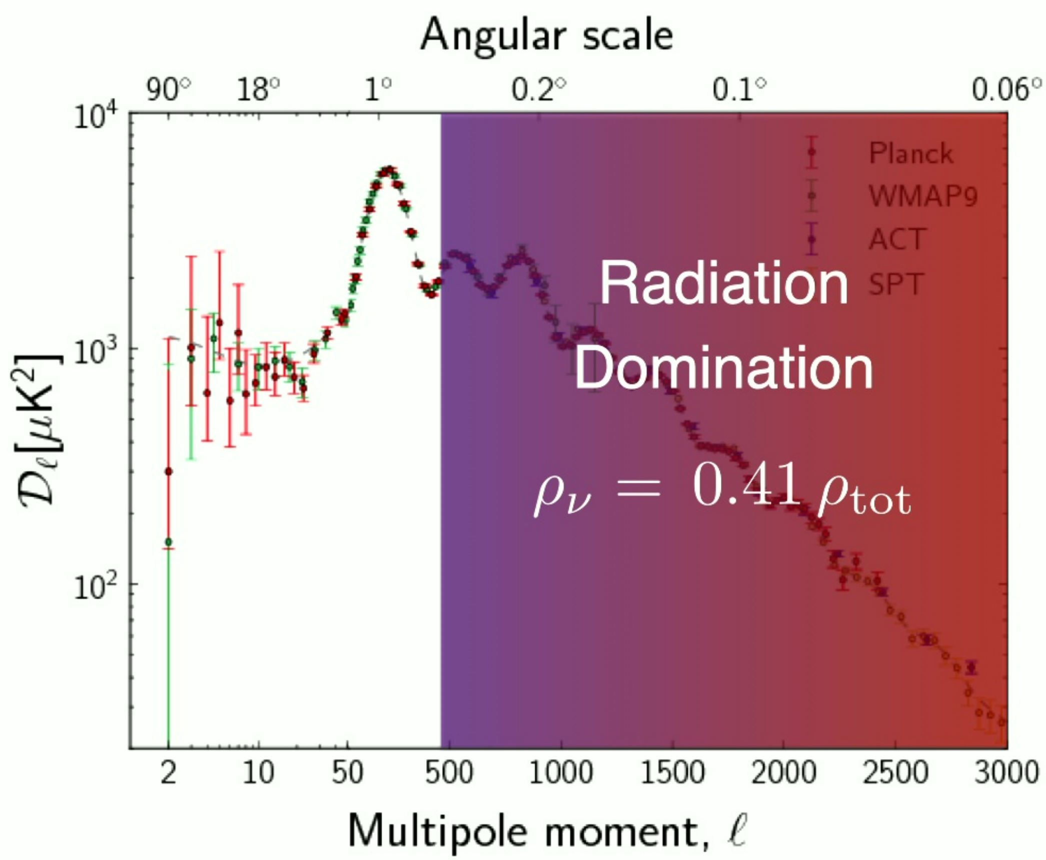




Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

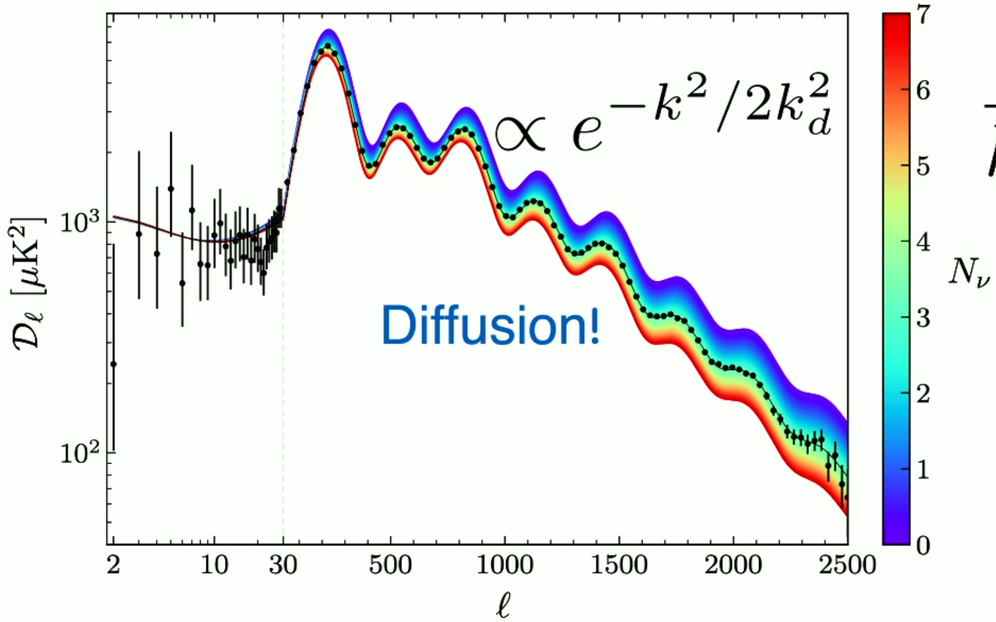
Courtesy of thecmb.org

Cosmic Microwave Background



Cosmic Microwave Background

$$3M_{\rm pl}^2 H^2 = \rho_\gamma + \rho_\nu$$



$$\frac{1}{k_d^2} \sim \langle \Delta x^2 \rangle \propto t$$

$$t \propto \frac{1}{H}$$

Cosmic Microwave Background

Damping drives the constraints for $\Lambda\text{CDM} + N_{\text{eff}}$

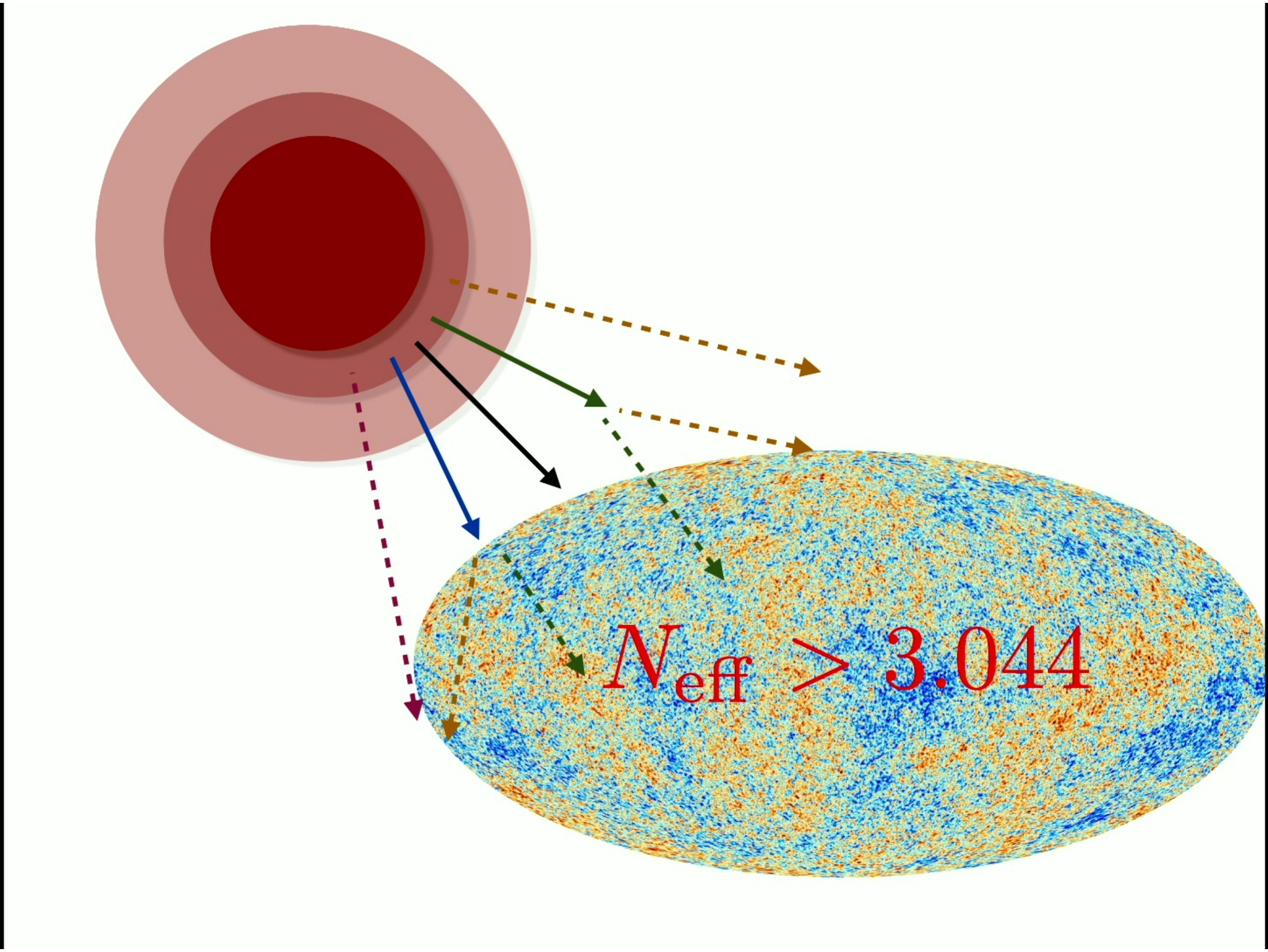
$$N_{\text{eff}} = 2.99 \pm 0.17 \, (\text{TTTEEE} + \text{BAO} + \kappa\kappa)$$

Planck 2018

What is the meaning of this measurement?

Measurement is interesting (my definition)

A different result can arise from plausible BSM physics without contradicting other measurements / experiments


$N_{\rm eff} > 3.044$

Light Relics

Any light thermalized particle looks like a neutrino

If a light particle decouples at temperature T_F

Only diluted by annihilation after decoupling

$$\Delta N_{\rm eff} = N_{\rm eff} - 3.045 = g_s \frac{4}{7} \left(\frac{43}{4 g_\star(T_F)} \right)^{4/3}$$

Light relics degrees of freedom

Standard Model degrees of freedom

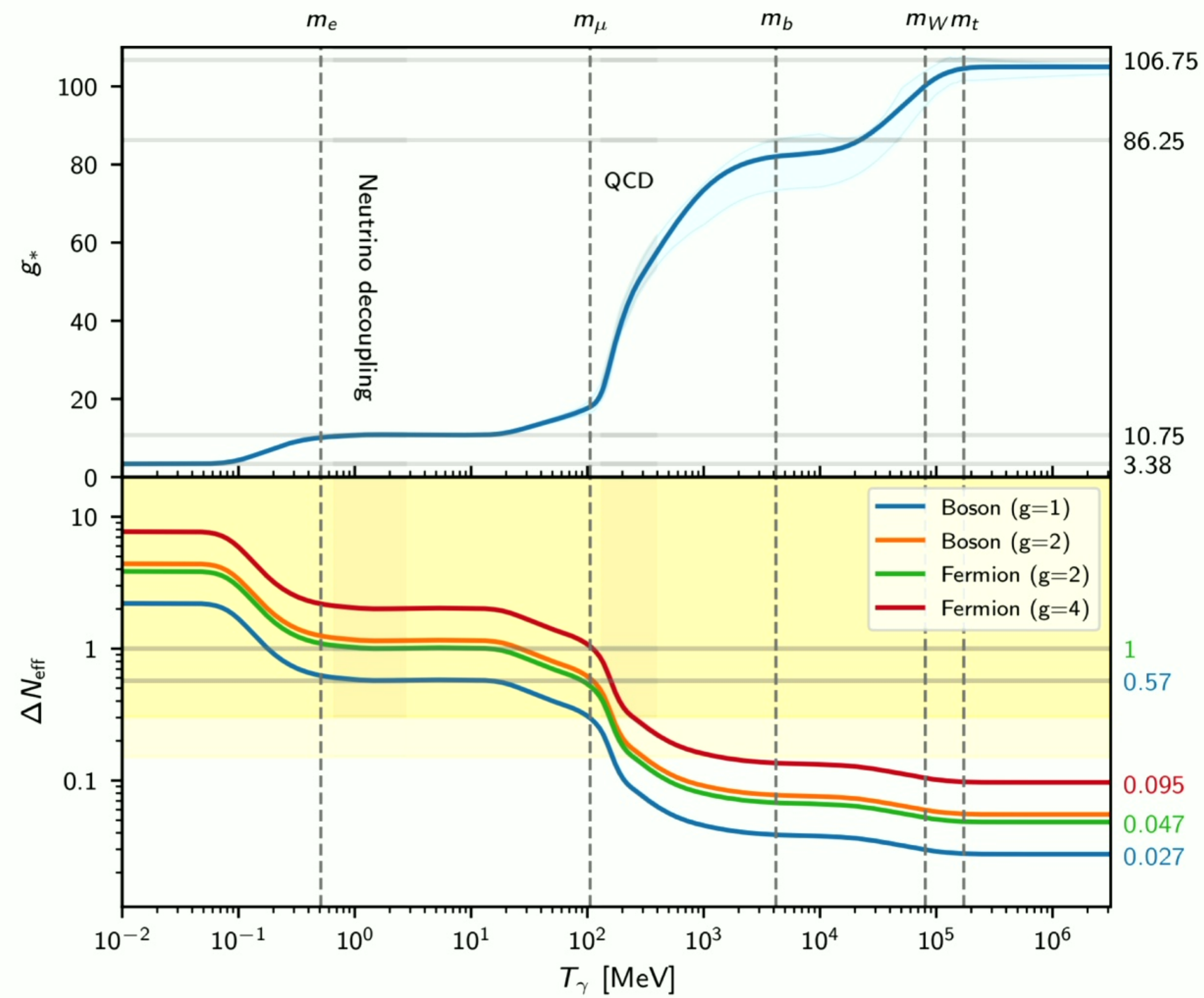
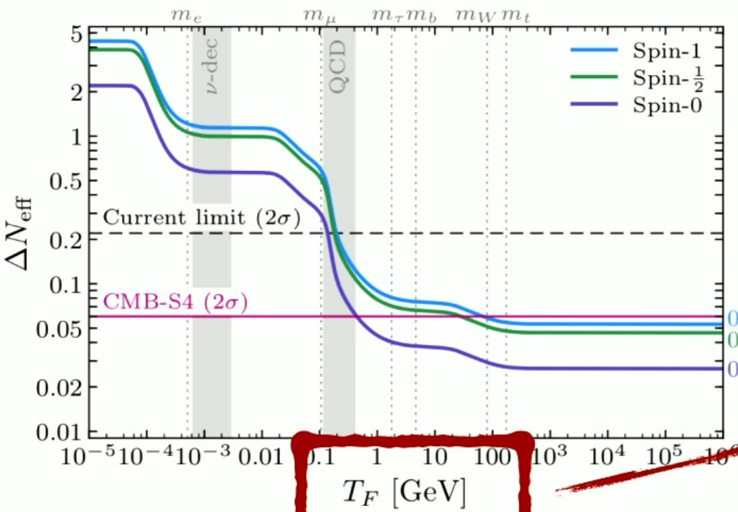


Image from Planck 2018

Light Relics



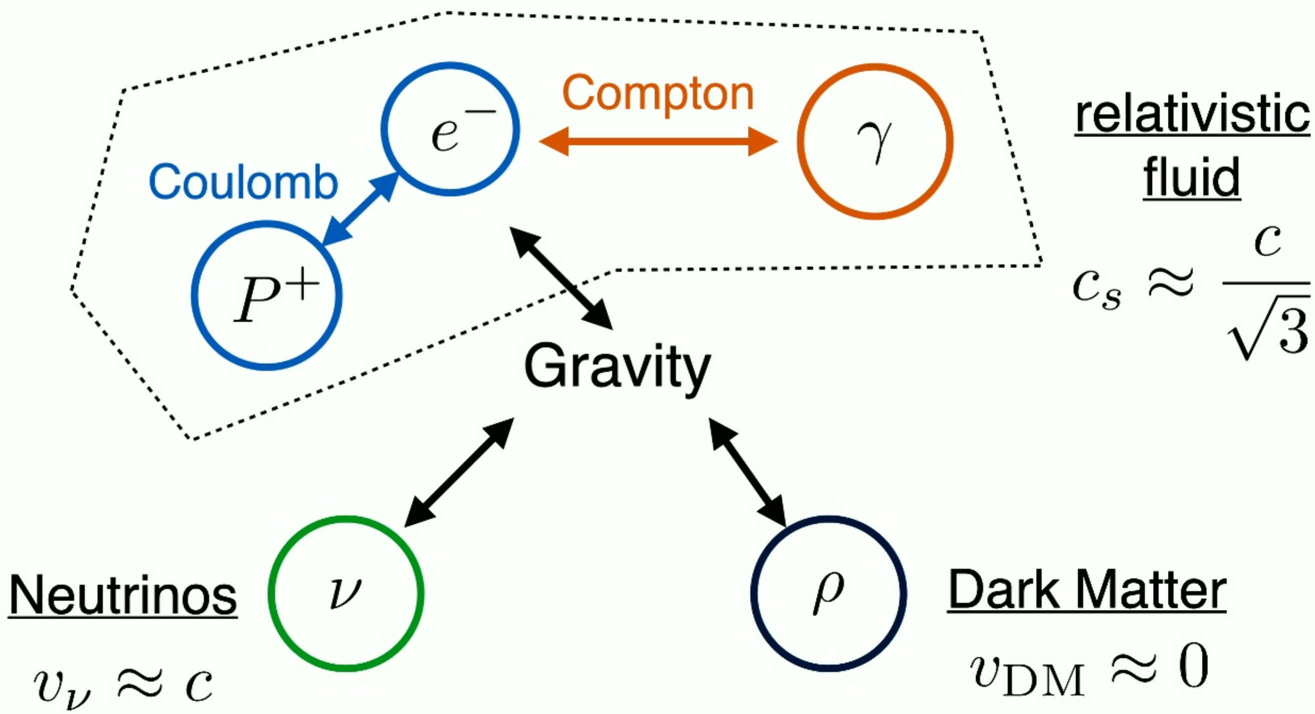
	Current Constraints		Future CMB Constraints		
Coupling	Bound [GeV]	Origin	Freeze-Out [GeV]	Freeze-In [GeV]	$\Delta\tilde{N}_{\rm eff}$
Λ_{ee}	1.2×10^{10}	White dwarfs	6.0×10^{7}	2.7×10^{6}	1.3
$\Lambda_{\mu\mu}$	2.0×10^{6}	Stellar cooling	1.2×10^{10}	3.4×10^{7}	0.5
$\Lambda_{\tau\tau}$	2.5×10^{4}	Stellar cooling	2.1×10^{11}	9.5×10^{7}	0.05
Λ_{bb}	6.1×10^{5}	Stellar cooling	9.5×10^{11}	–	0.04
Λ_{tt}	1.2×10^{9}	Stellar cooling	3.5×10^{13}	–	0.03
$\Lambda^V_{\mu e}$	5.5×10^{9}	$\mu^+ \to e^+ \phi$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\mu e}$	3.1×10^{9}	$\mu^+ \to e^+ \phi \gamma$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\tau e}$	4.4×10^{6}	$\tau^- \to e^- \phi$	1.0×10^{11}	1.3×10^{8}	0.05
$\Lambda_{\tau\mu}$	3.2×10^{6}	$\tau^- \to \mu^- \phi$	1.0×10^{11}	1.3×10^{8}	0.05
Λ^A_{cu}	6.9×10^{5}	D^0-$\bar{D}^0$	1.3×10^{11}	2.0×10^{8}	0.05
Λ^A_{bd}	6.4×10^{5}	B^0-B^0	4.8×10^{11}	3.7×10^{8}	0.04
Λ_{bs}	$6.1 \times 10^{[illegible]}$	$b \to s\phi$	4.8×10^{11}	3.7×10^{8}	0.04
[illegible]	6.6×10^{9}	Mixing	1.8×10^{13}	2.1×10^{9}	0.03
Λ_{tc}	2.2×10^{9}	Mixing	1.8×10^{13}	2.1×10^{9}	0.03

E.g. T_F is sensitive to any standard model coupling

$N_{\rm eff}$ constrains many couplings simultaneously

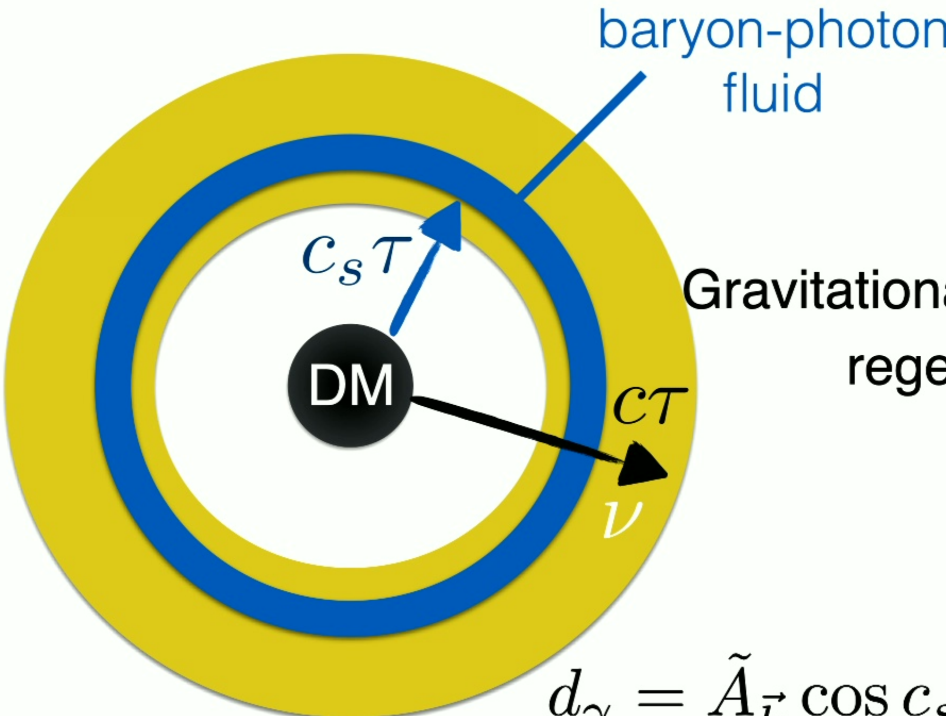
Phase Shift

Neutrinos fluctuations move faster than sound



Phase Shift

Information propagates ahead of the sound horizon



Gravitational force of neutrinos regenerates sine

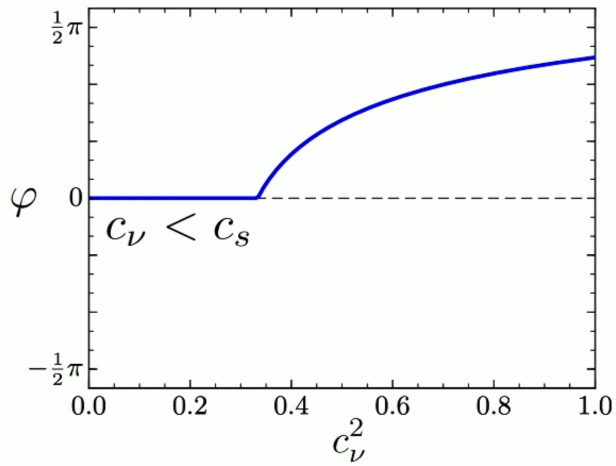
$$d_\gamma = \tilde{A}_{\vec{k}} \cos c_s k\tau + B_{\vec{k}} \sin c_s k\tau$$

Phase Shift

Supersonic signal is equivalent to a phase shift

$$\cos(kr_s) \to \cos(kr_s + \varphi) \qquad \varphi \sim B/\tilde{A}$$

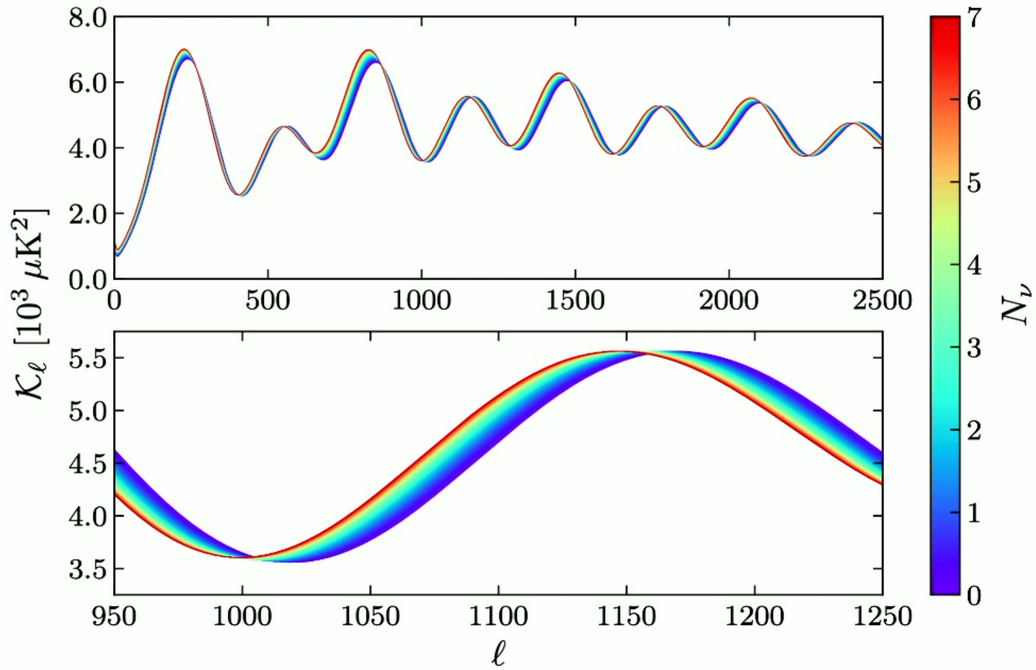
Cannot be produced by other components of the universe



Bashinsky & Seljak (2003); Baumann, DG, Meyers, Wallisch (2015)

Phase Shift

Neutrinos produce a unique shift in the CMB



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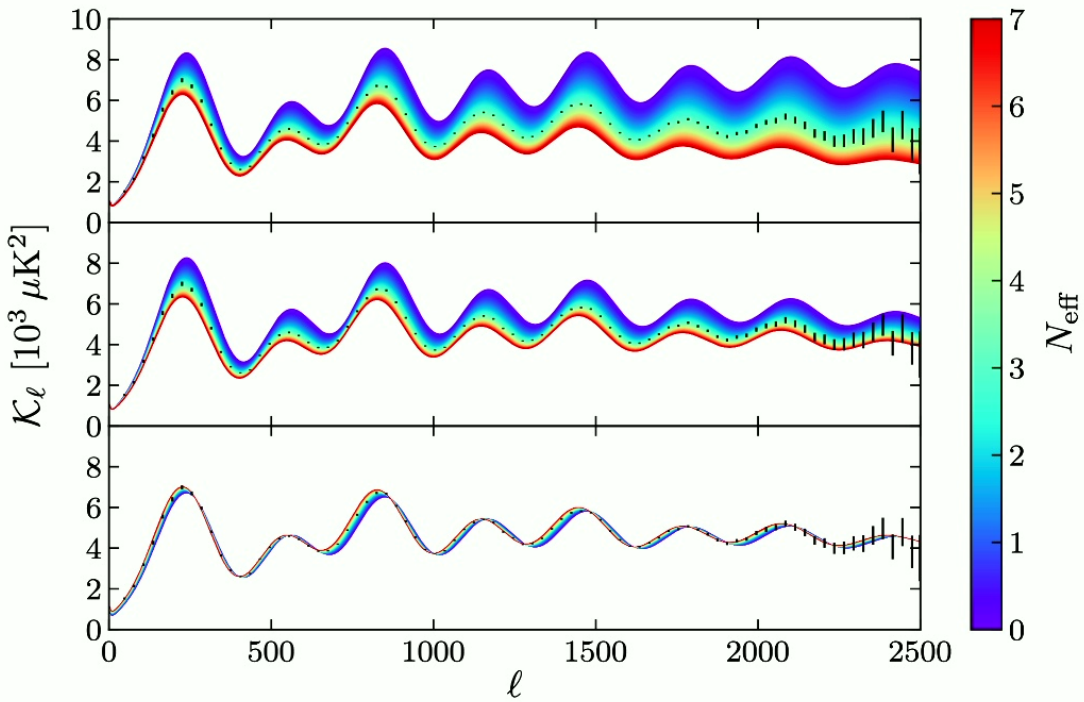

Phase Shift

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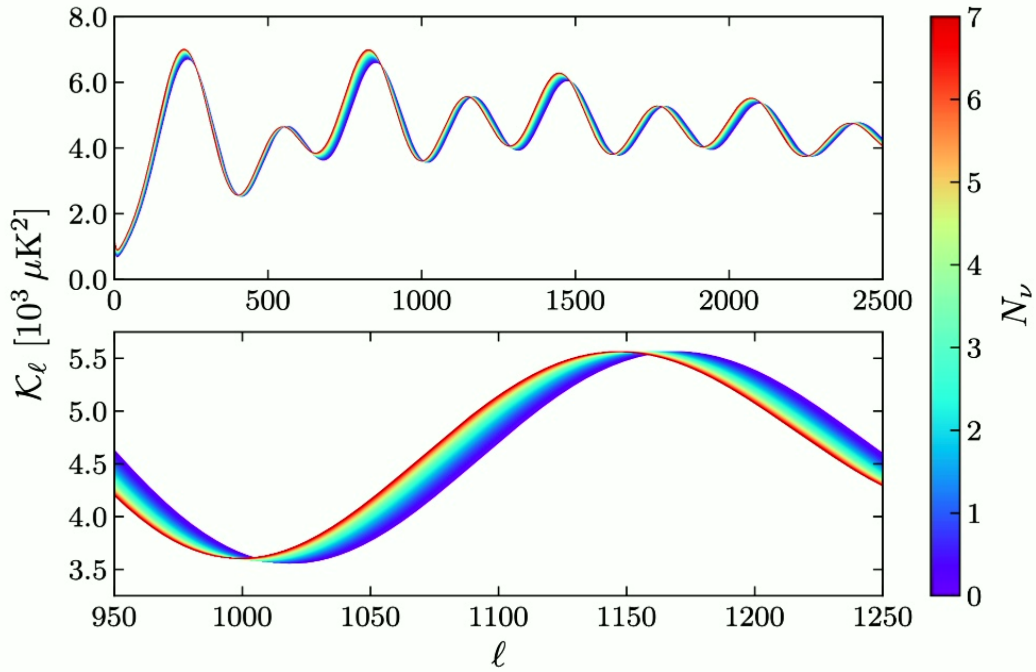
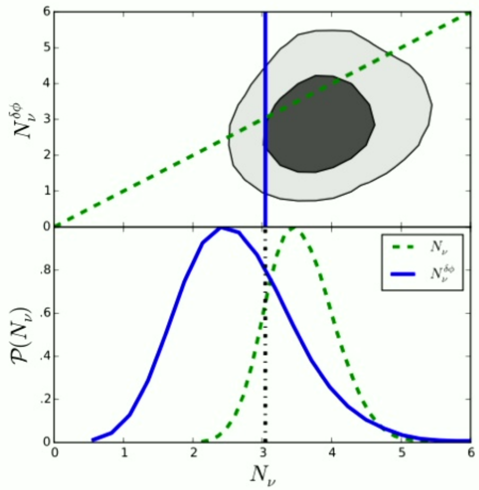
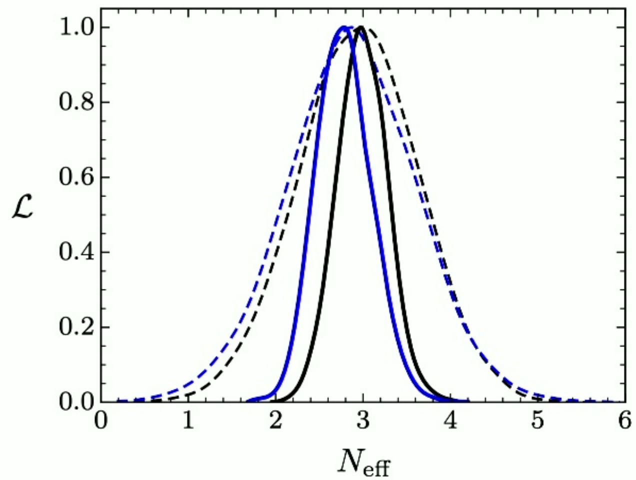


Phase Shift

This phase shift is detected in the CMB





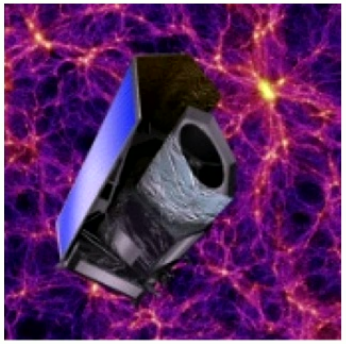
$$N_{\rm eff}^{\rm phase} = 2.3^{+1.1}_{-0.4}$$

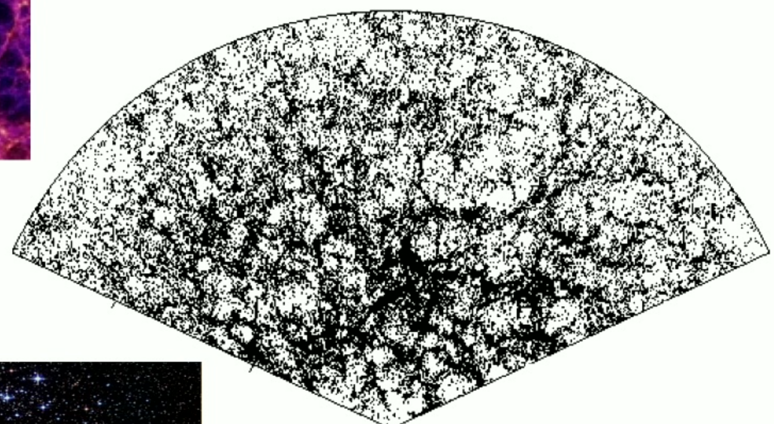
Follin et al. (2015)

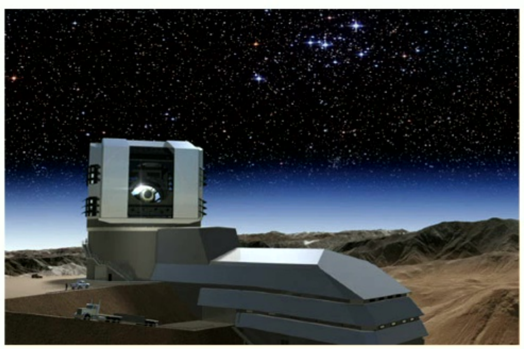
$$N_{\rm eff}^{\rm phase} = 2.68^{+0.29}_{-0.33}$$

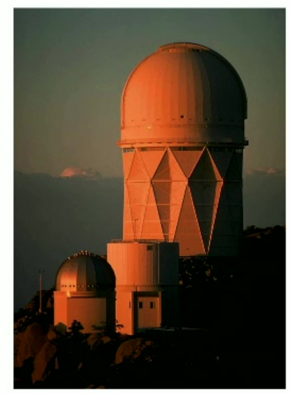
Baumann, DG, Meyers, Wallisch (2015); Brust, Cui, Sigurdson (2017)

Galaxy Surveys







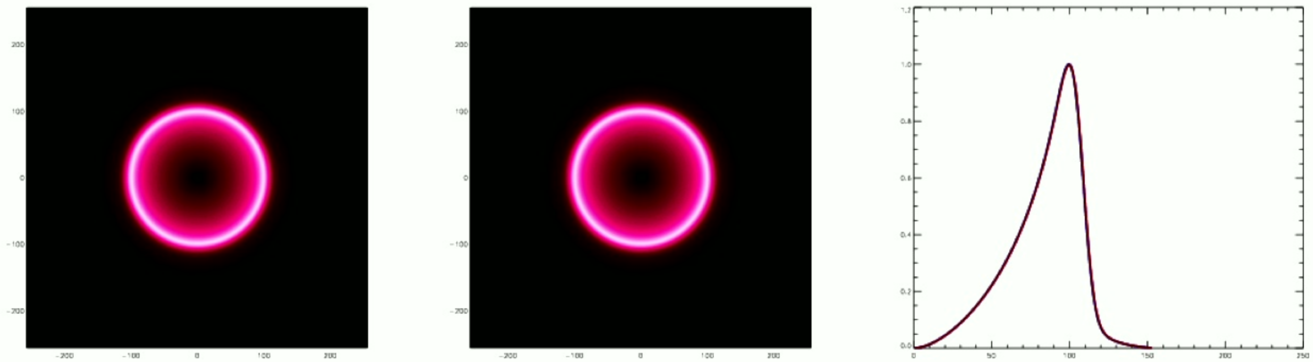


Baryon Acoustic Oscillations (BAO)

Most surveys are driven by dark energy science

Goal: map the BAO peak over cosmic time

“Baryons” photons



Courtesy of Martin White

Pre-CMB - Photons support sound wave

Baryon Acoustic Oscillations (BAO)

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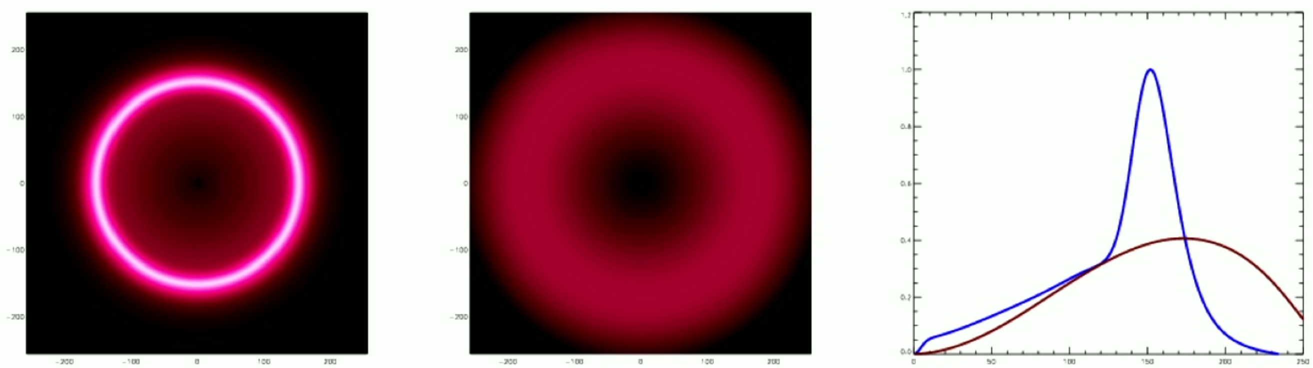
Goal: map the BAO peak over cosmic time

“Baryons” photons

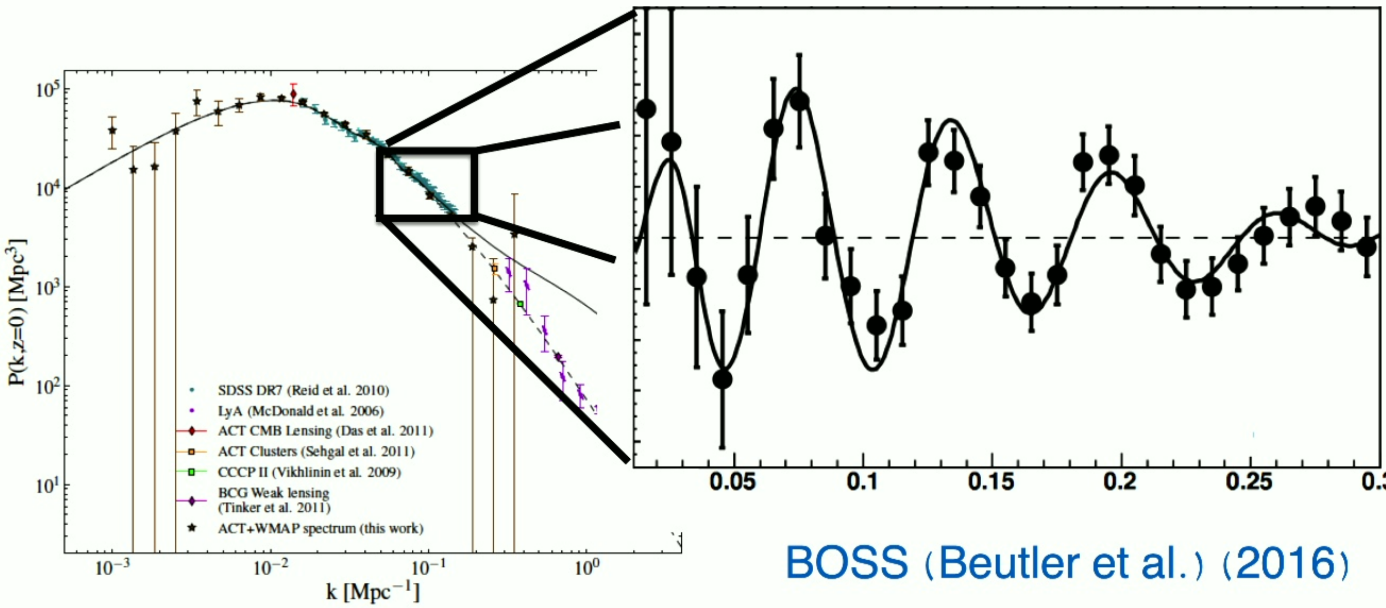


Courtesy of Martin White

Post-CMB - Photons free-stream

Baryon Acoustic Oscillations（BAO）

Signal is frozen in distribution of galaxies / matter

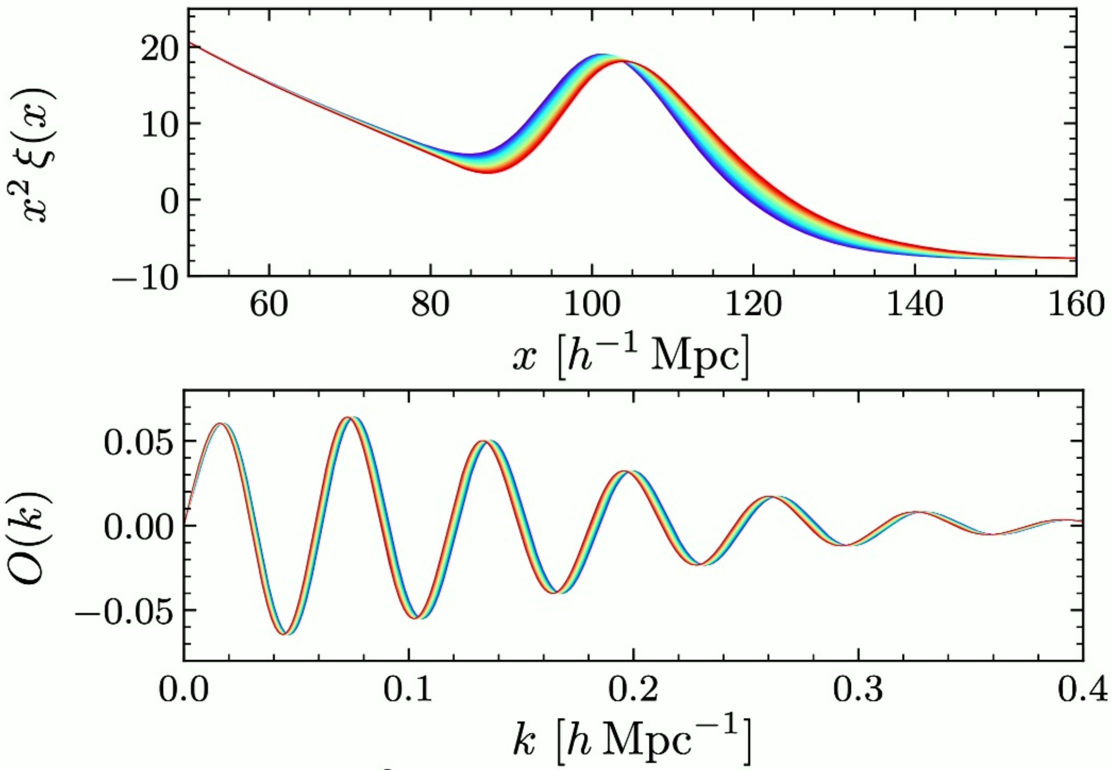


BOSS（Beutler et al.）（2016）

Figure from Hlozek et al.

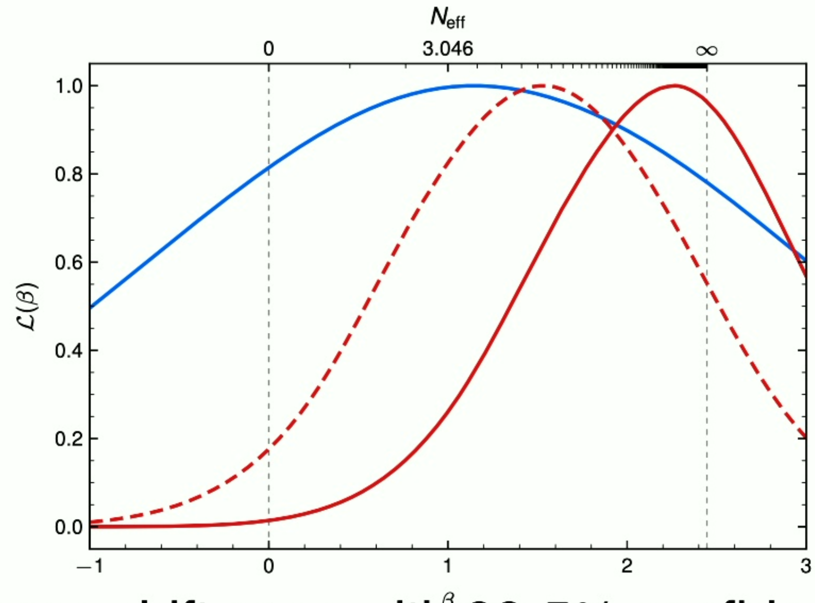
BAO Phase Shift

Phase shift appears in BAO



BAO Phase Shift

Applying same idea to BOSS data



Positive phase shift seen with 99.5% confidence

Baumann et al. (2018)

Summary

We have very strong evidence for cosmic neutrinos

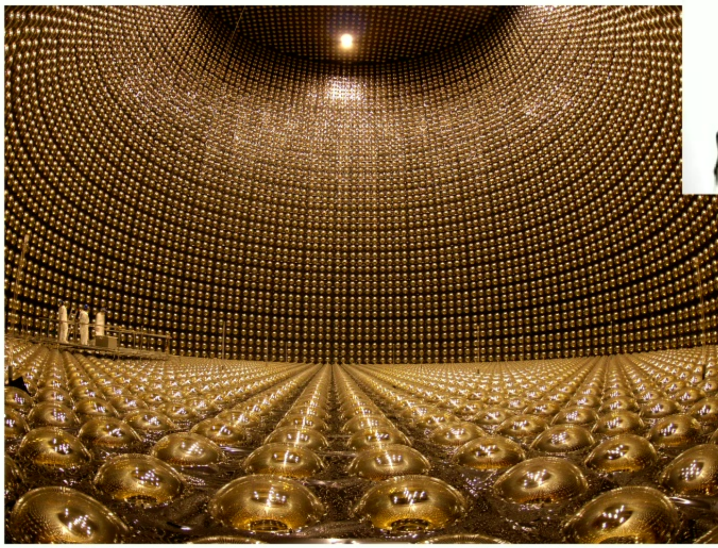
- Detect cosmic neutrino background in CMB at 20σ
- CMB + BBN at 30σ
- Phase shift in CMB measured at 10σ
- Phase shift seen in BAO at 3σ

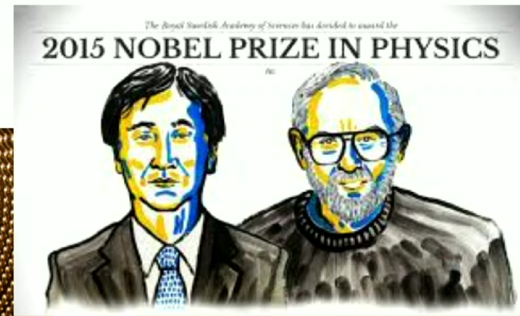
The phase shift is unique to neutrinos

Not mimicked by other components or nonlinear physics

Neutrino Mass

Neutrinos have mass





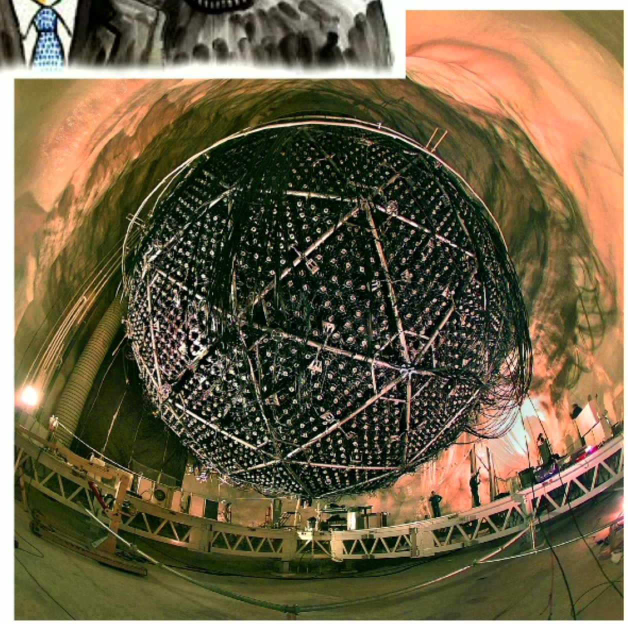
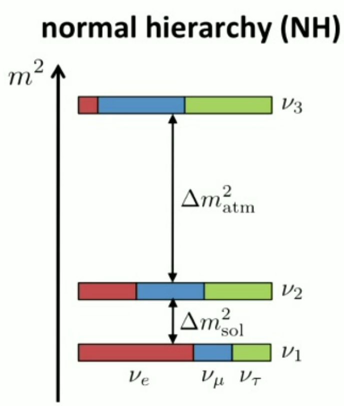


Image from Super-K ; SNO

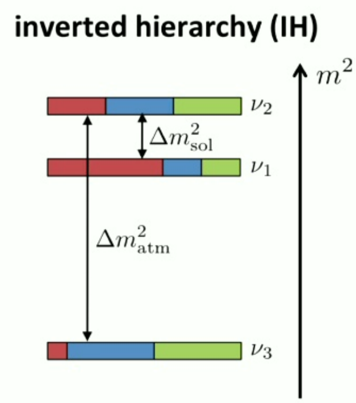
Neutrino Mass

Cosmology mostly cares about the sum of mass

$$\Omega_\nu h^2 \approx g_\star T_\nu^3 \sum m_\nu$$



$$\sum m_\nu \geq 58\,\mathrm{meV}$$



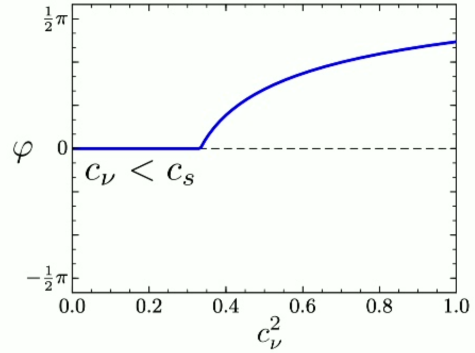
$$\sum m_\nu \geq 100\,\mathrm{meV}$$

Image via Fermilab

Neutrino Mass

We know neutrinos were relativistic at recombination

If they weren't, $c_\nu \approx \dfrac{3T_\nu}{m_\nu} \ll 1$



Phase shift doesn't arise when non-relativistic

$$T_{\rm CMB}(z_{\rm recomb.}) \approx 0.25\,{\rm eV}$$

$$\sum m_\nu < 0.26\,{\rm eV}\ (95\%)$$

Planck TTTEEE (2018)

We can still improve by going to lower redshift

Neutrino Mass

NR neutrinos are a small component of matter

$$\Omega_m = \Omega_{\rm cdm} + \Omega_{\rm b} + \Omega_\nu$$

$$f_\nu = \frac{\Omega_\nu}{\Omega_m} = 4 \times 10^{-3} \frac{\sum m_\nu}{58\,\mathrm{meV}}$$

Most observables, the neutrinos contribute $f_\nu \times \mathcal{O}(1)$

Few observables will be sensitive to the minimum sum

Neutrino Mass

Massive neutrinos free stream / suppress growth

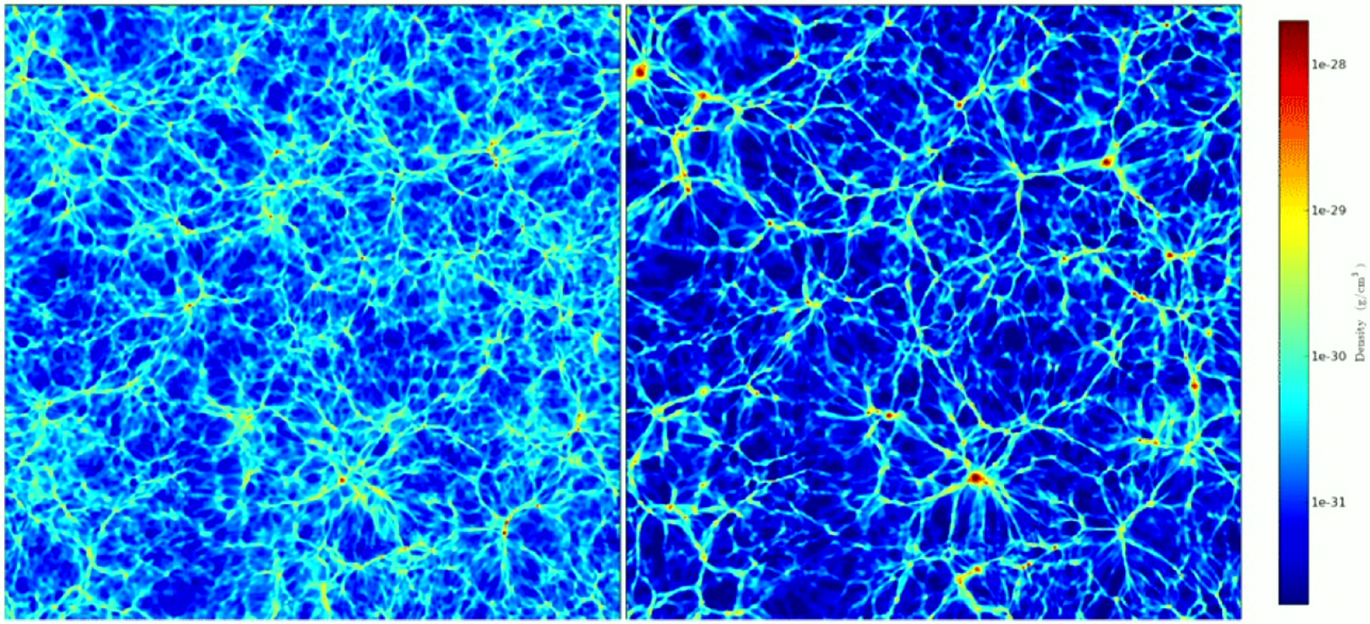
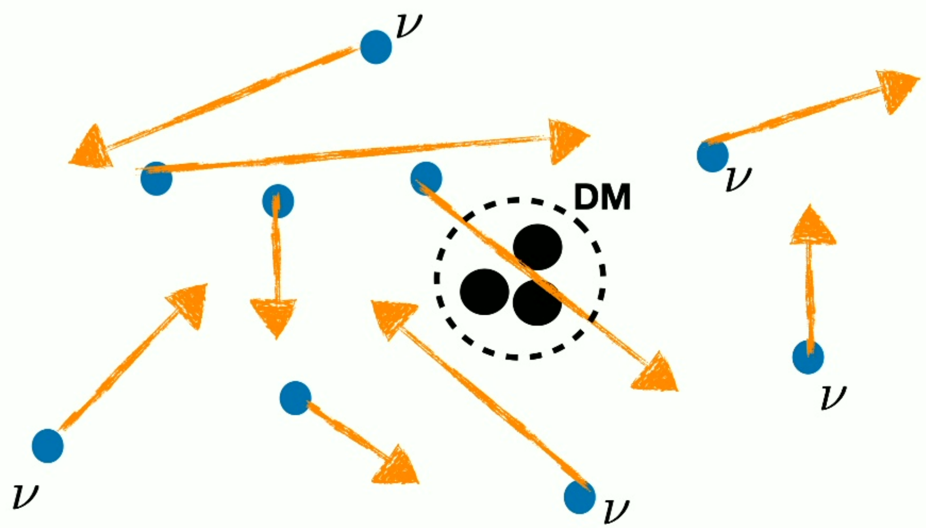


Image from Agarwal & Feldman (2010)

Neutrino Mass

Massive neutrinos free stream / suppress growth

$$c_\nu \approx 8.7 \times 10^{-3} c \, \frac{1}{1+z} \left(\frac{58\,\mathrm{meV}}{\sum m_\nu} \right) \qquad c_{\mathrm{dm}} \approx 0$$



Neutrino Mass

Gives a free streaming scale $k_{\rm fs} = \dfrac{2a^2}{3c_\nu^2 t^2}$

Linear solution one small scales $k \gg k_s$

$$\boxed{\delta_\nu = 0} \qquad \delta_{\rm cb} = t^\gamma \to \gamma = \frac{2}{3} - \frac{2}{5} f_\nu + \mathcal{O}(f_\nu^2)$$

1. Neutrinos redshift like matter but don't cluster

$$P_m[m_\nu \neq 0] \approx (1 - 2f_\nu) P_m[m_\nu \neq 0]$$

Neutrino Mass

Gives a free streaming scale $k_{\rm fs} = \frac{2a^2}{3c_\nu^2 t^2}$

Linear solution one small scales $k \gg k_s$

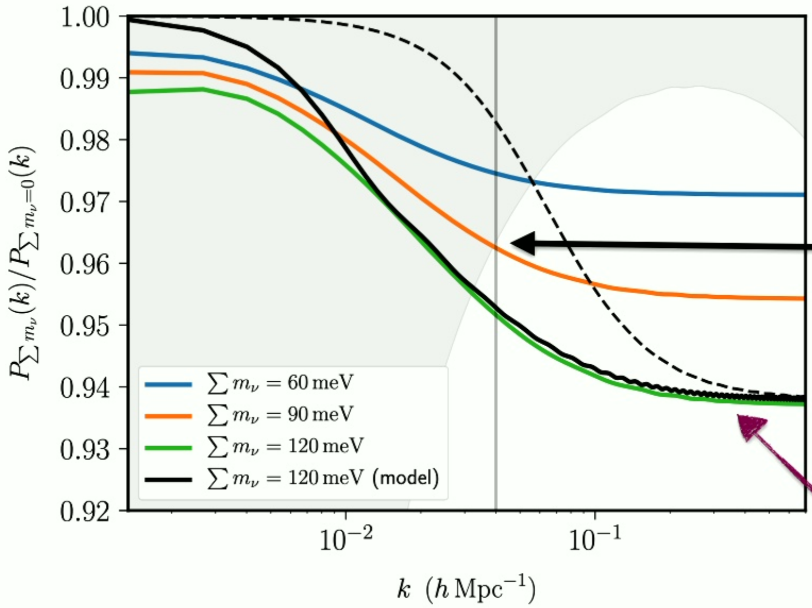
$$\delta_\nu = 0 \qquad \boxed{\delta_{\rm cb} = t^\gamma \to \gamma = \frac{2}{3} - \frac{2}{5} f_\nu + \mathcal{O}(f_\nu^2)}$$

2. Dark matter clusters more slowly (log enhanced!)

$$P_m[m_\nu \neq 0] \approx (1 - \frac{3}{5} f_\nu \log \frac{1+z_{\rm NR}}{1+z}) P_m[m_\nu \neq 0]$$

Neutrino Mass

Massive neutrinos free stream / suppress growth



$$k_{\rm fs} \approx 0.04 \frac{h}{\rm Mpc} \left(\frac{m_\nu}{50\,\rm meV}\right)$$

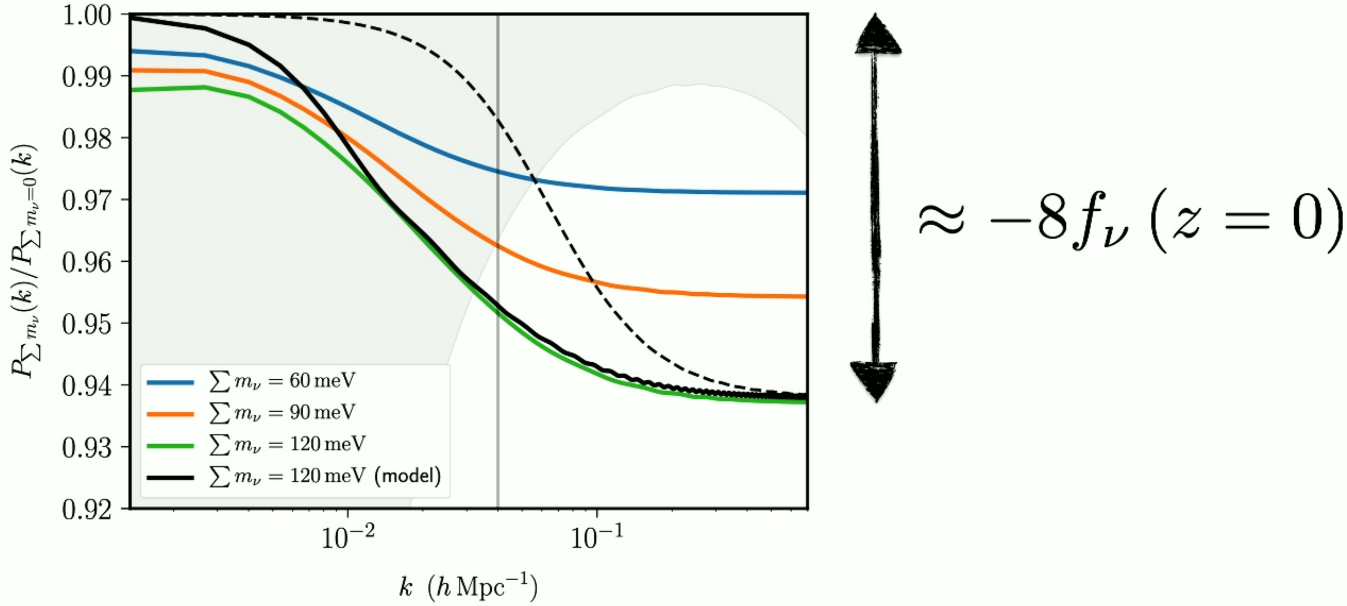
CLASS code

Numeric solution to linear equations

DG & Meyers (2022)

Neutrino Mass

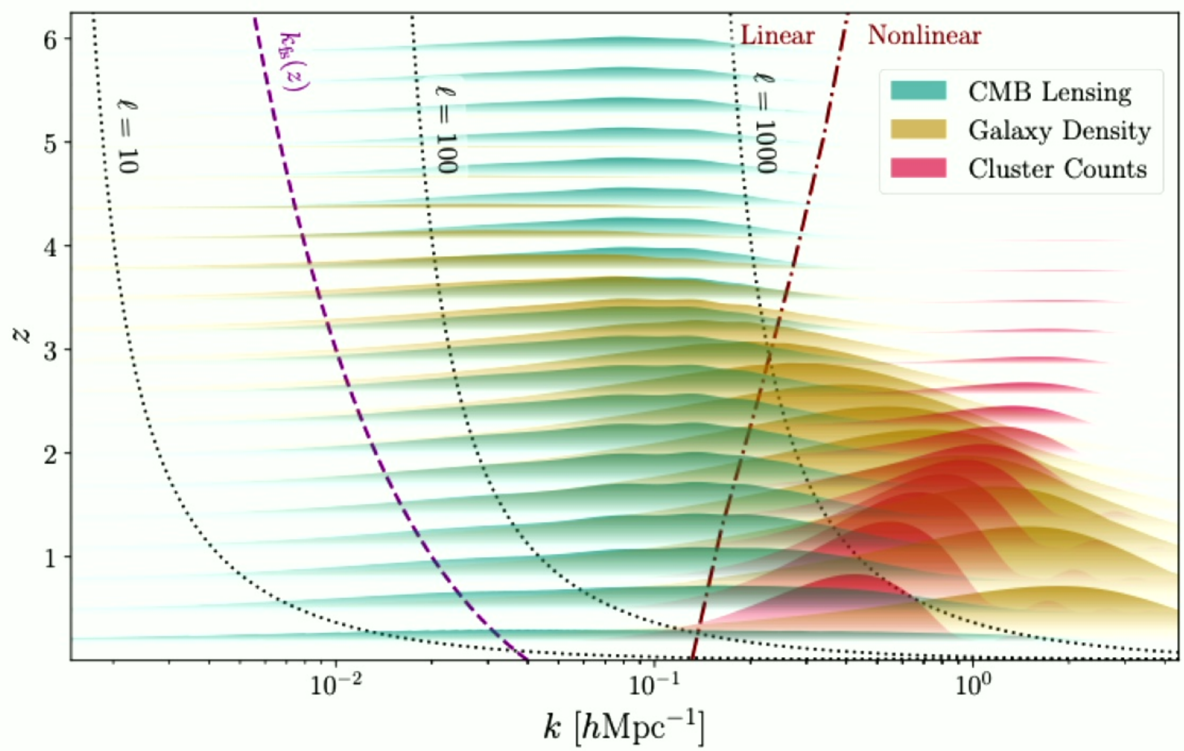
Leads to a large suppression of power on small scales



Factor of ~10 makes detecting minimum mass possible

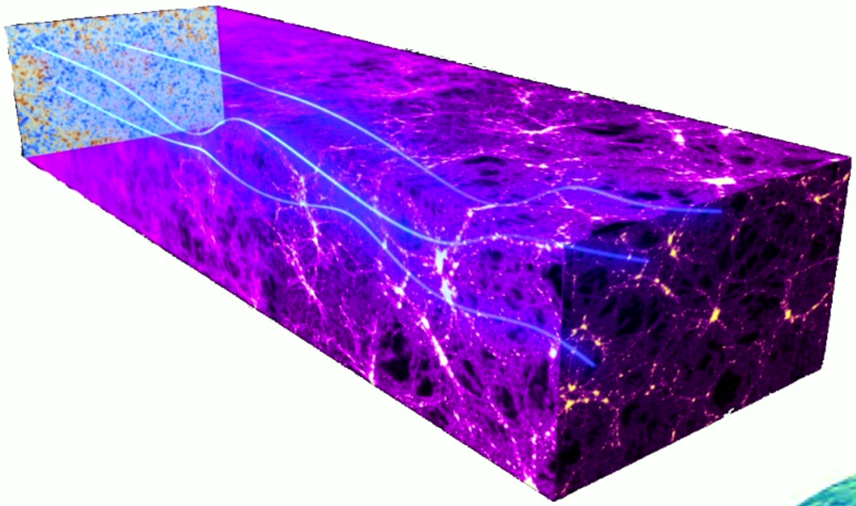
DG & Meyers (2022)

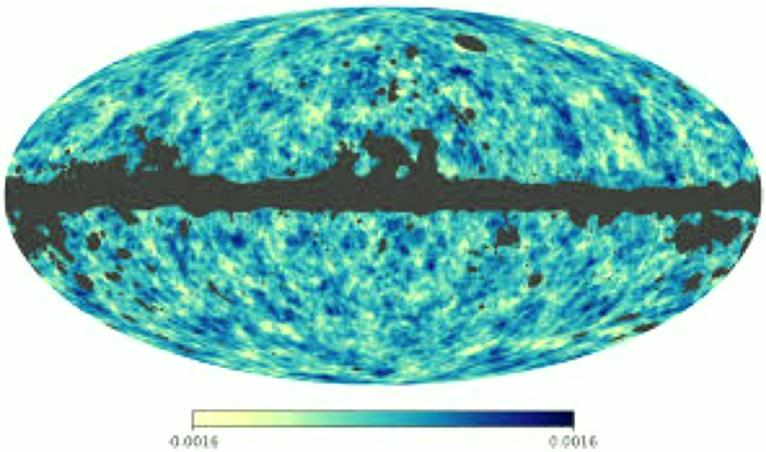
Cosmological Observables



DG & Meyers (2022)

Cosmological Observables

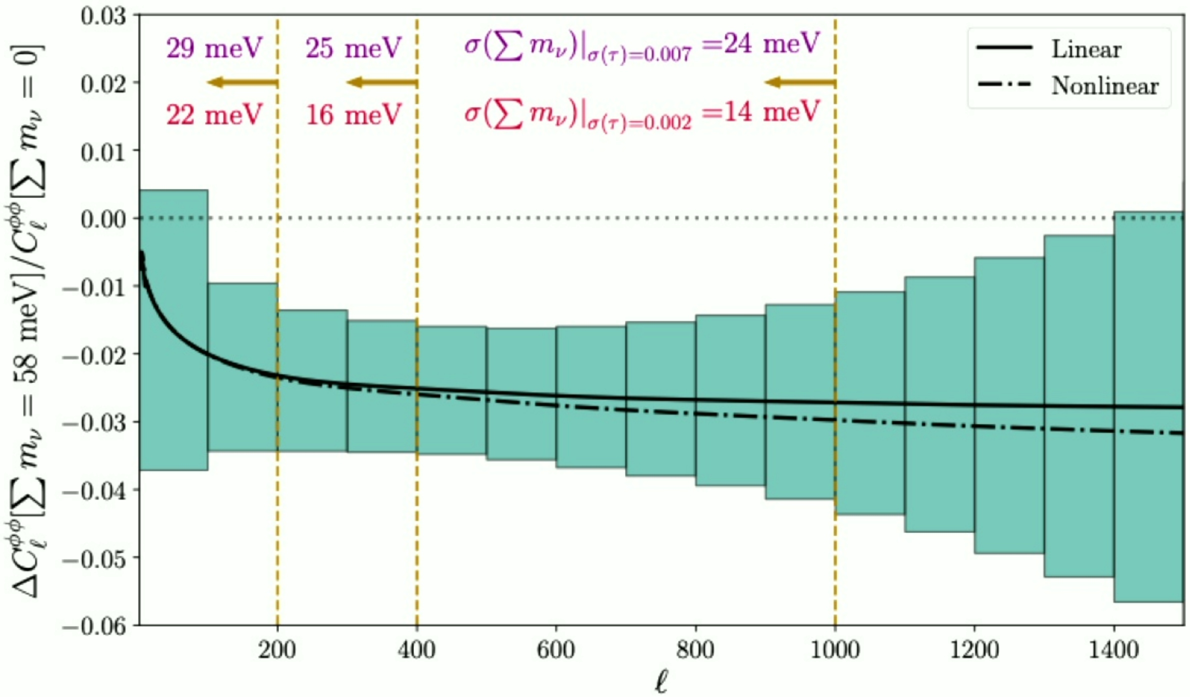




Images from ESA

Cosmological Observables

Hard because we don't measure $k_{\rm fs}$



DG & Meyers (2022)

Cosmological Observables

To determine f_ν, we need to measure 3 numbers:

(1) Matter power spectrum – via CMB lensing

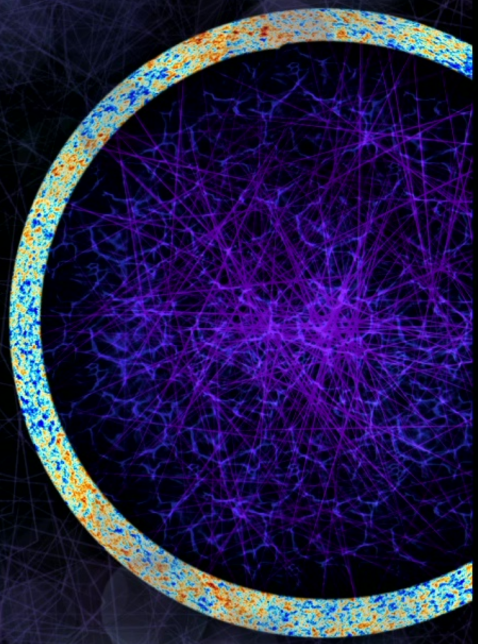
$$P_{\text{lensing}} \propto (\Omega_m h^2)^2 \times A_s(1-5f_\nu)$$

(2) Ω_m : High accuracy matter abundance – BAO

(3) A_s : Primordial Amplitude of Fluctuations – CMB

With planned observations: 1–3 are easiest–hardest

No νs is Good News



arXiv: 2405.00836 w. N. Craig, J. Meyers, S. Rajendran
arXiv: 2407.07878 w. J. Meyers

Cosmological Observables

To determine f_ν, we need to measure 3 numbers:

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(2) Ω_m : High accuracy matter abundance - BAO

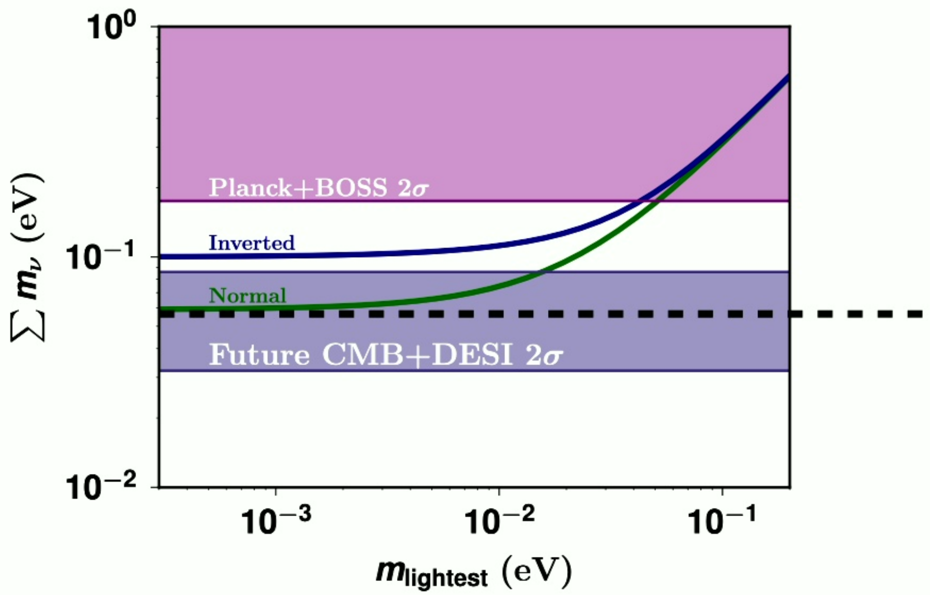
(3) A_s : Primordial Amplitude of Fluctuations - CMB

With planned observations: 1-3 are easiest-hardest

DESI

DESI was supposed to be the final piece of the puzzle:

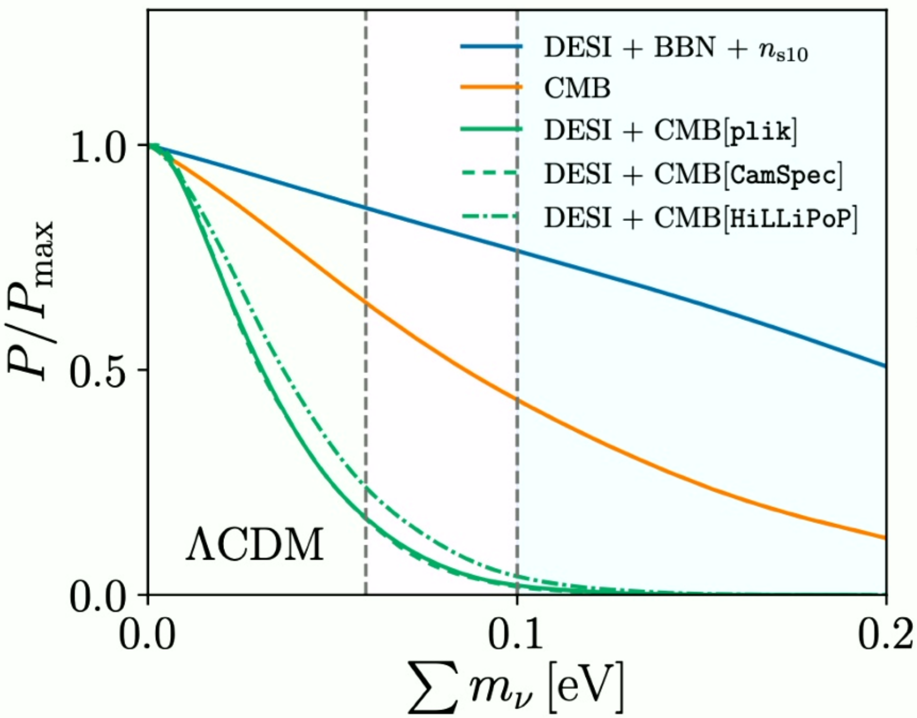
E.g. This kinds of figures are everywhere



$$\sum m_\nu \geq 58\,\mathrm{meV}$$

DESI

DESI is here, and there is no sign of neutrino mass

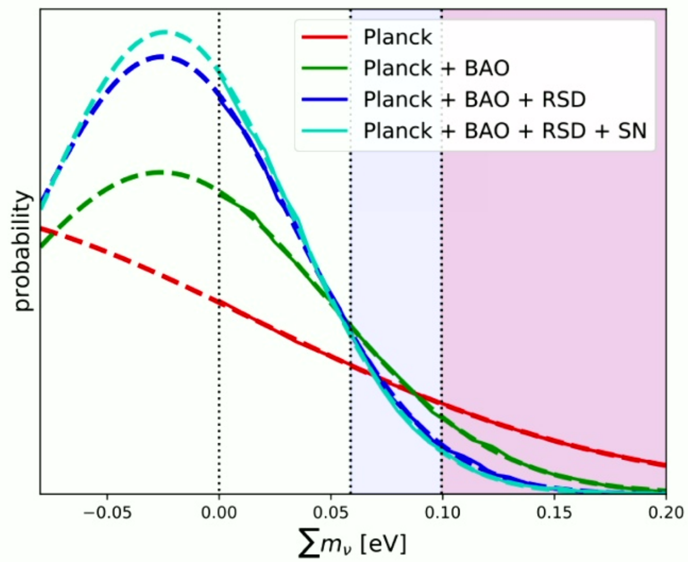


$$\sum m_\nu < 0.071\,\mathrm{eV}\;(95\%)$$

DESI (2024)

eBOSS

Hints of the same issue were present in eBOSS



$$\sum m_\nu < 134\,\mathrm{meV}\ (95\%)$$

Here negative mass is inferred from Gaussian fit

eBOSS (2020)

Negative Mass Analysis

Extend analysis to negative "neutrino mass": $\sum \tilde{m}_\nu$

Defined only as a change to the lensing power spectrum

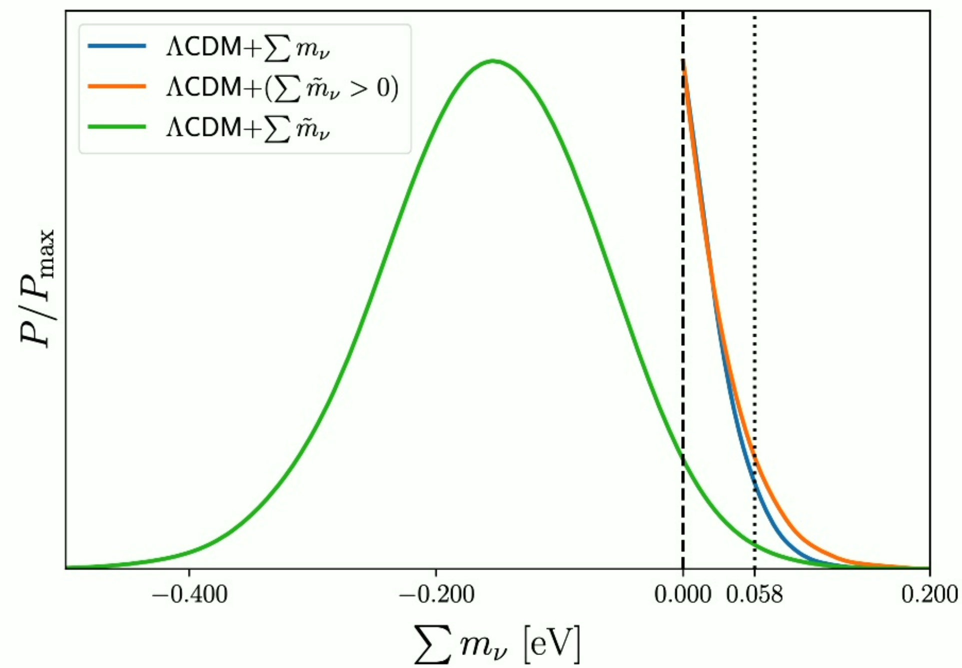
$$C_\ell^{\phi\phi} \approx (1 - \sum \tilde{m}_\nu \times F(k; \sum \tilde{m}_\nu))C_\ell^{\phi\phi,(m_\nu=0)}$$

The shape is defined to be symmetric

$$F(k; \sum \tilde{m}_\nu) = F(k; -\sum \tilde{m}_\nu)$$

Not defined for average density $\Omega_m = \Omega_{\rm cdm} + \Omega_{\rm b}$

Negative Mass Analysis



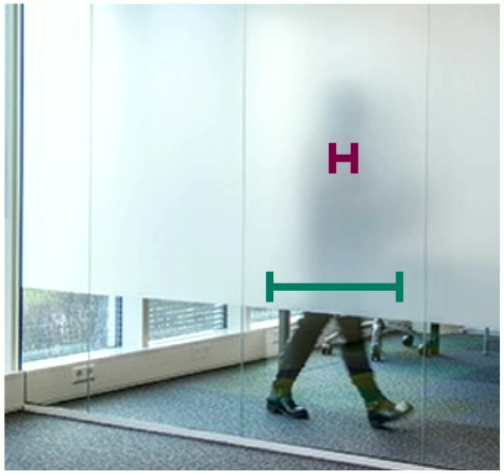
$$\sum \tilde{m}_\nu < -156^{+95}_{-85}\,\text{meV}$$

What could be going wrong

To measure f_ν , we need Ω_m, A_s

Most obvious concern is the primordial amplitude

Reionization scatters photons like frosted glass

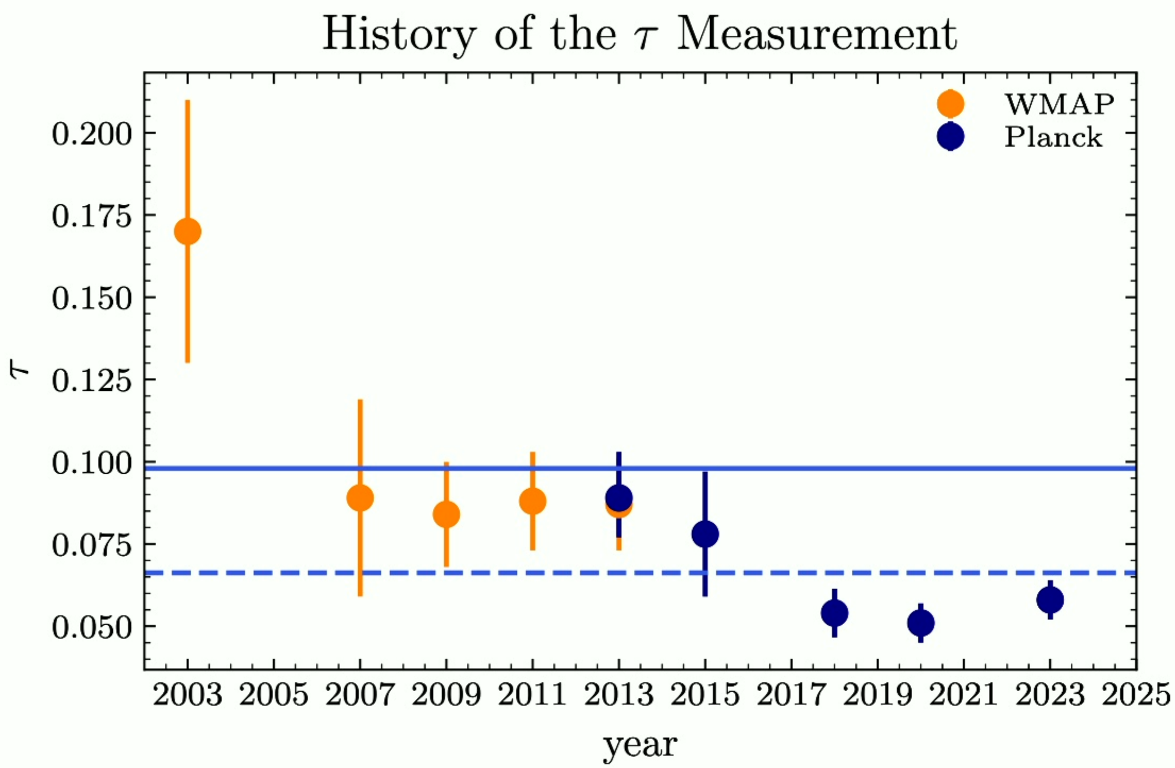


On small scales $A_s e^{-2\tau}$

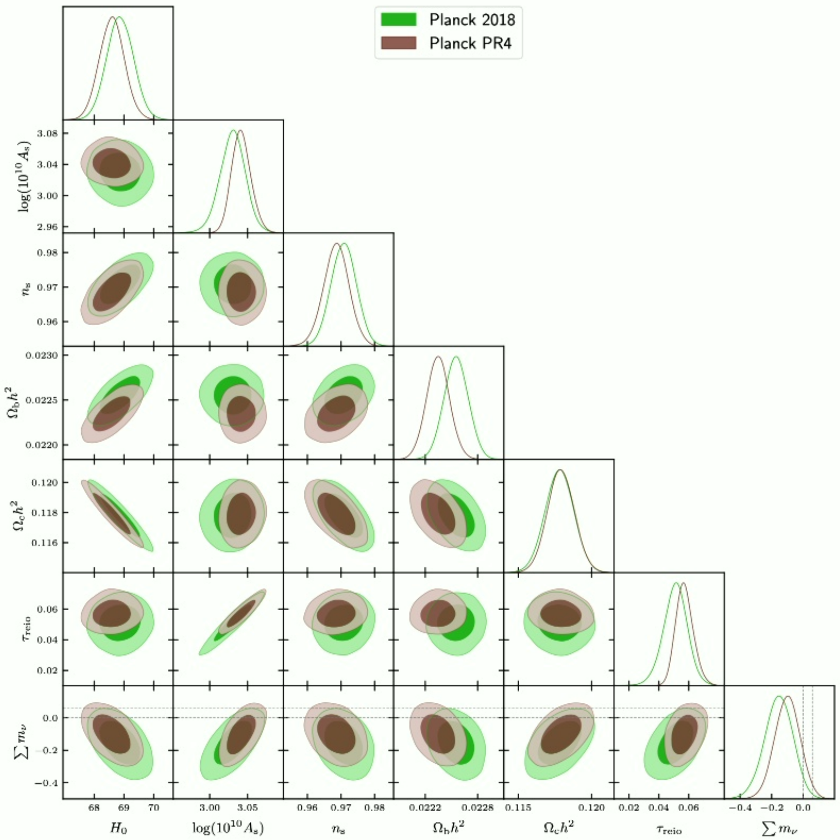
On large scales A_s

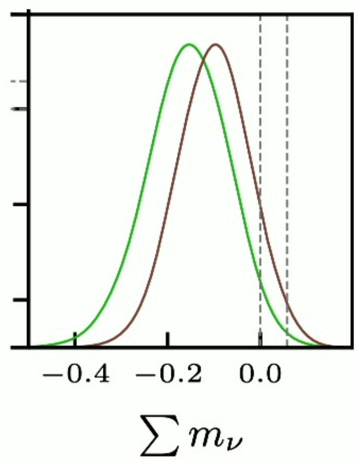
Same as measuring optical depth

Optical Depth

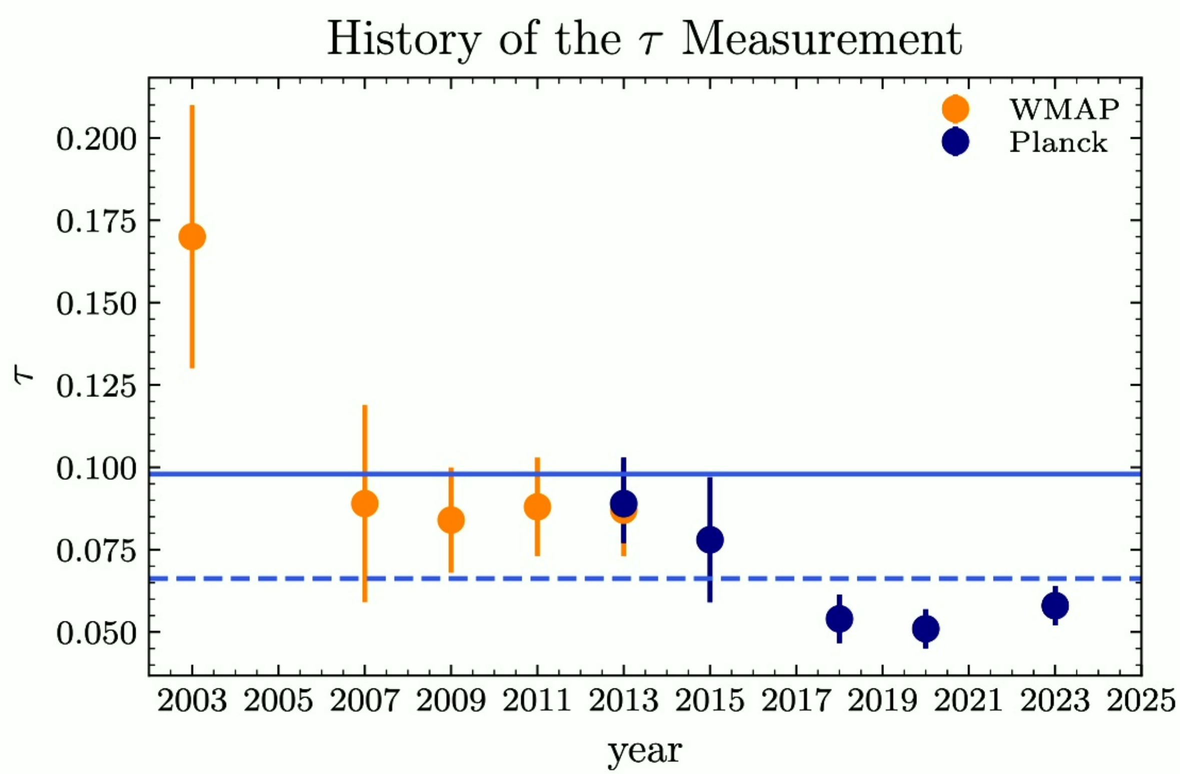


Optical Depth

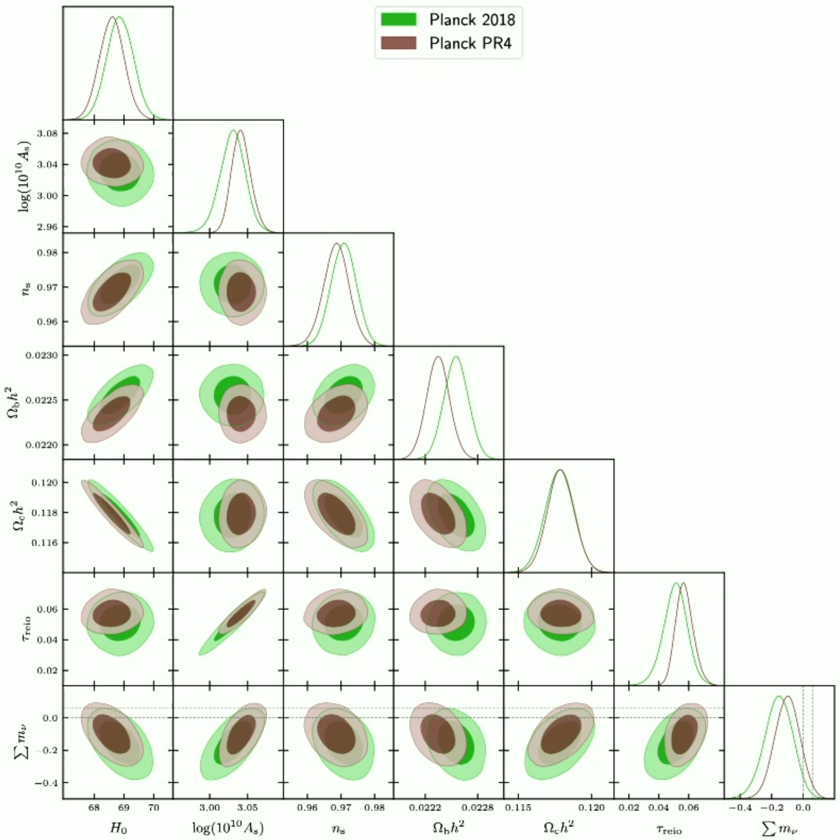


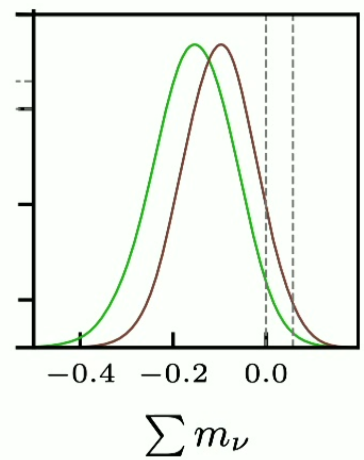


Optical Depth



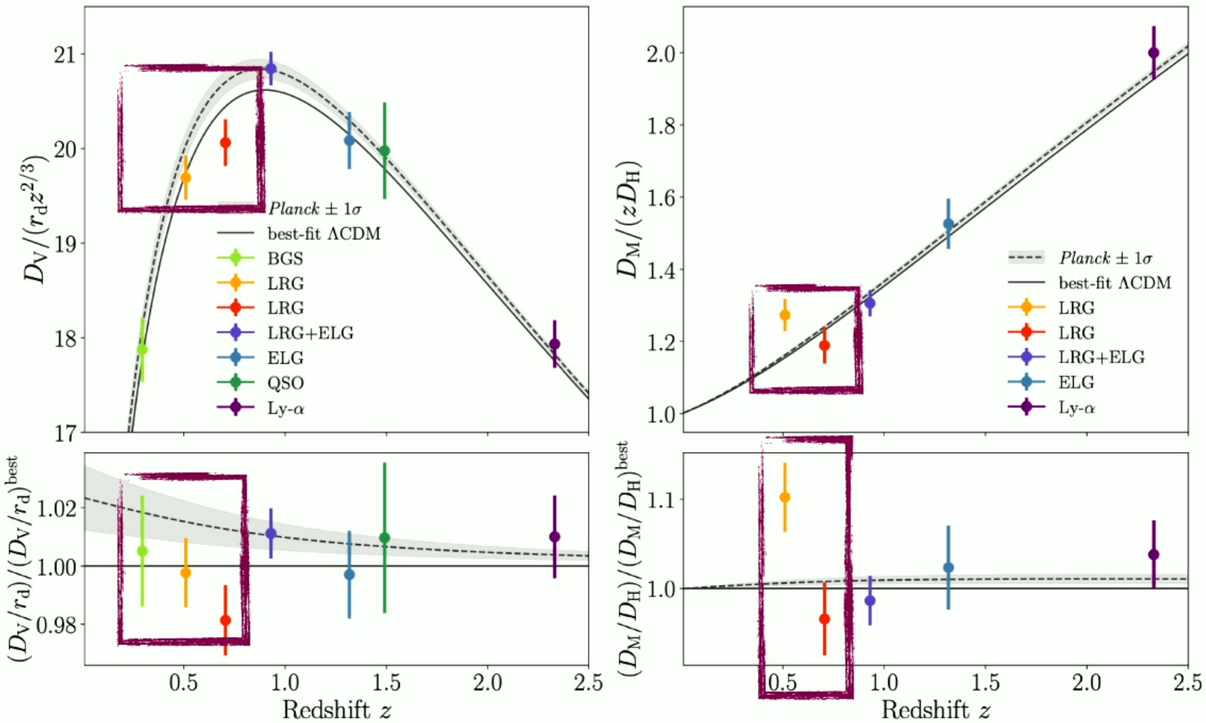
Optical Depth





BAO

Maybe it's just a couple bad points?

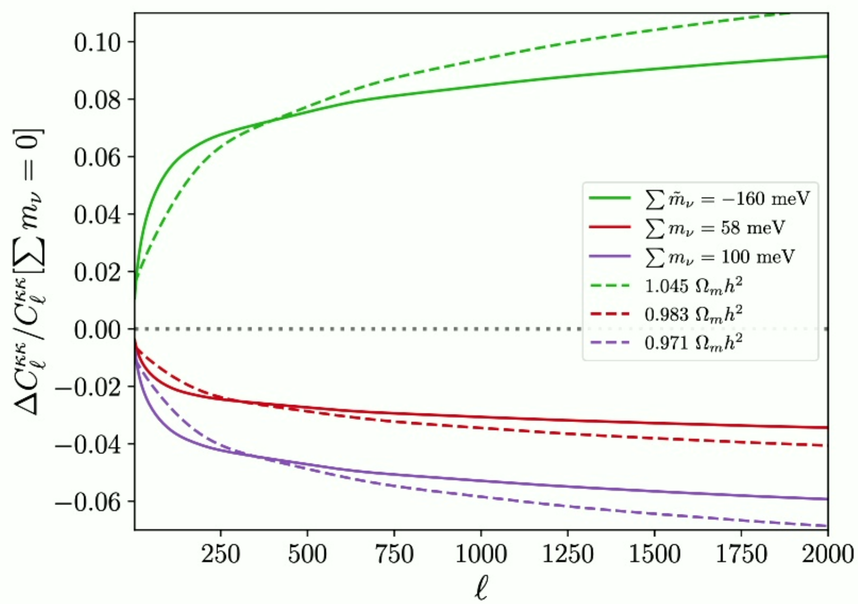


DESI (2024)

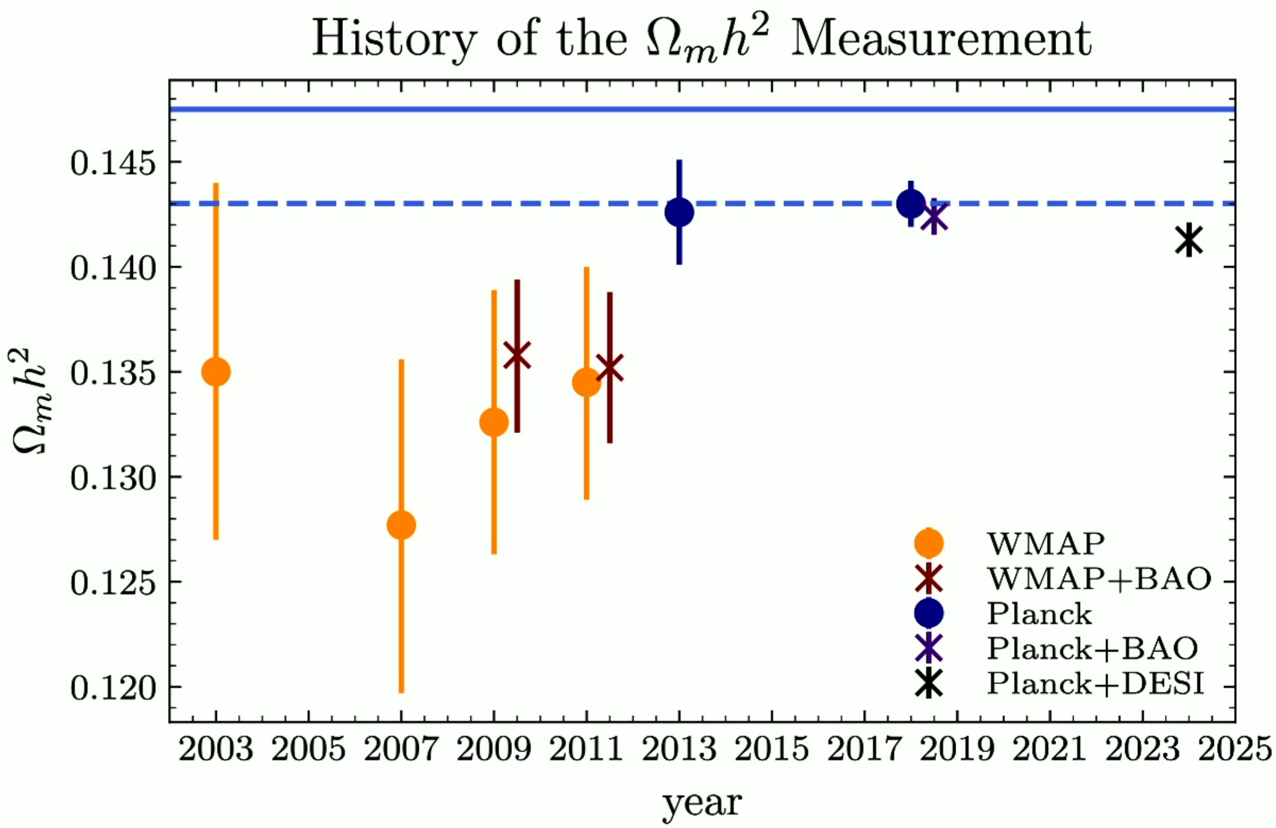
Omega Matter

To measure f_ν , we need Ω_m, A_s

In principle, it could be due to BAO data

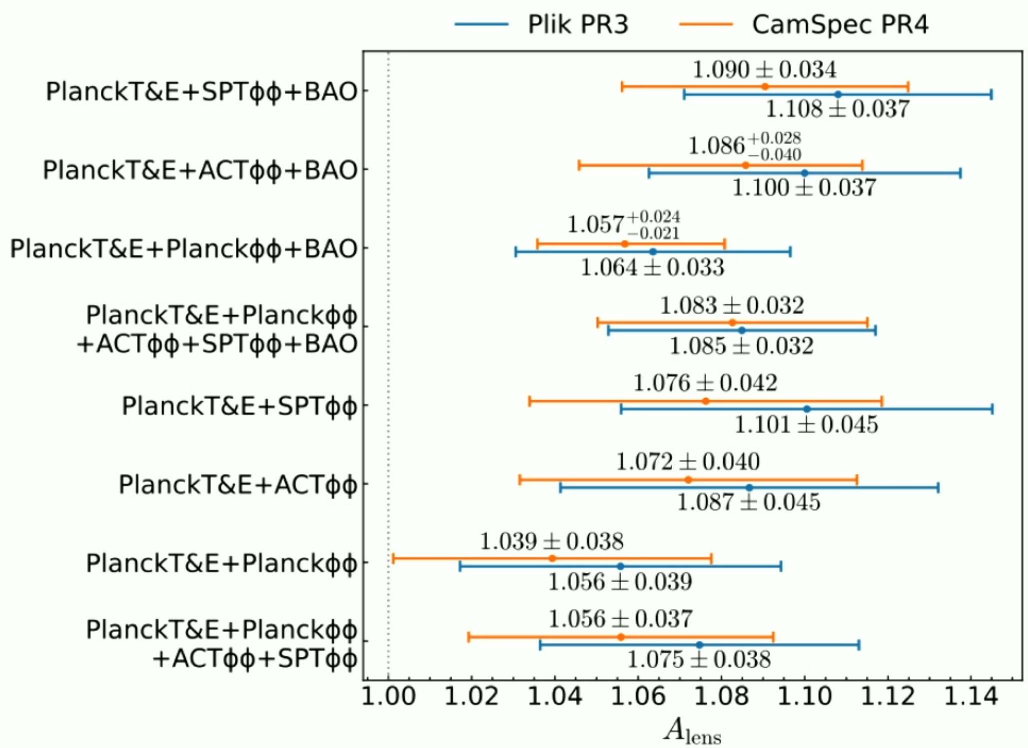


Omega Matter



Lensing

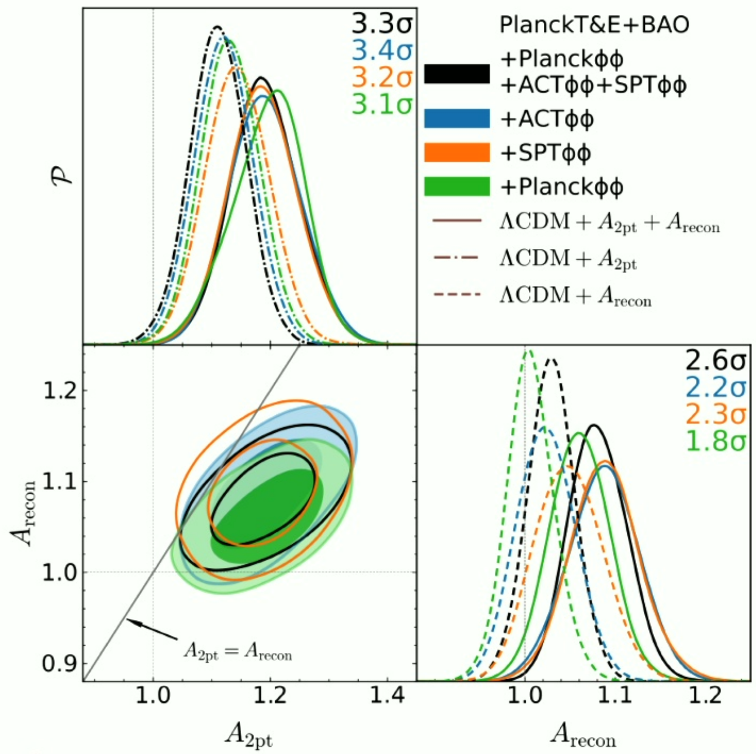
Access lensing seen in all surveys



STP [arXiv:2411.0600]

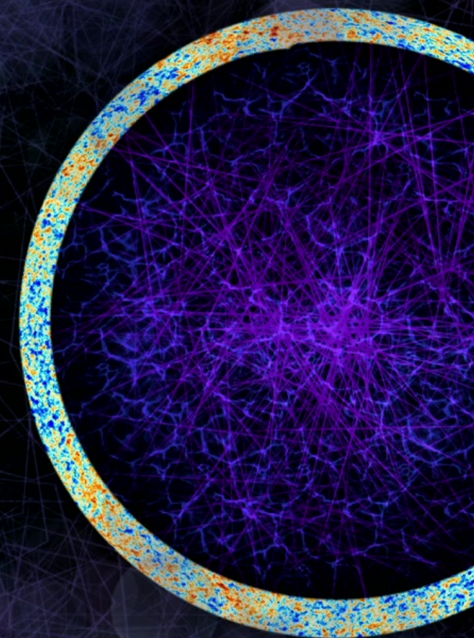
Lensing

Access lensing seen in all surveys



STP [arXiv:2411.0600]

BSM Implications



Future Data

The current situation is unlikely to change for a long time

- Optical depth won't be measured until LITEbird [2032]
- DESI/Euclid unlikely to help
- Wait for Simons / CMB-S4 lensing for E-B maps

What does this mean in practice?

(1) It very very likely to be consistent with $\sum m_\nu = 0$

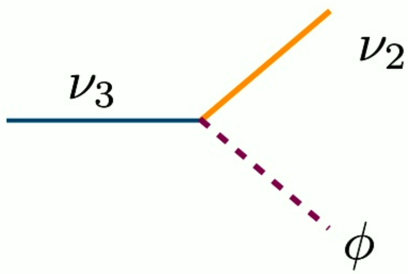
(2) It is likely that $\sum \tilde{m}_\nu < 0$

Neutrino Decay

Most of the mass is in the heaviest neutrino

We can get ride of this via decay

$$\mathcal{L}_\phi \supset \frac{\lambda_{ij}}{2}\bar{\nu}_i \nu_j \phi + \frac{\tilde{\lambda}_{ij}}{2}\bar{\nu}_i \gamma_5 \nu_j \phi + \text{ h.c.}$$



$$\tau \simeq 7 \times 10^{17} \text{ s} \times \left(\frac{0.05\text{eV}}{m_{\nu_i}}\right)\left(\frac{10^{-15}}{\tilde{\lambda}_{ij}^2}\right)^2$$

$$\sum_{j=1}^{3} m_{\nu_j} \to m_1 + m_2$$

The heaviest neutrino(s) aren't cosmologically relevant

Neutrino Decay

Coupling has to be large enough to decay by $z \sim 100$

But, needs to be free streaming at $1100 < z < 10000$

$$4 \times 10^{-15} \lesssim \lambda, \tilde{\lambda} \lesssim 4 \times 10^{-10}$$

Large window of viable parameter space

Most stringent constraint is from CMB phase shift

Similar story for annihilation (diagonal couplings)

Neutrino Cooling

The signal is due to free streaming

Cooling would move signals to smaller scales

$$k_{\rm fs}(z) = 0.04h\mathrm{Mpc}^{-1}\left(\frac{\sum m_\nu}{58\mathrm{meV}}\right) \times \left(\frac{1.95\ \mathrm{K}}{T_\nu(z=0)}\frac{1}{1+z}\right)$$

Neutrino Cooling

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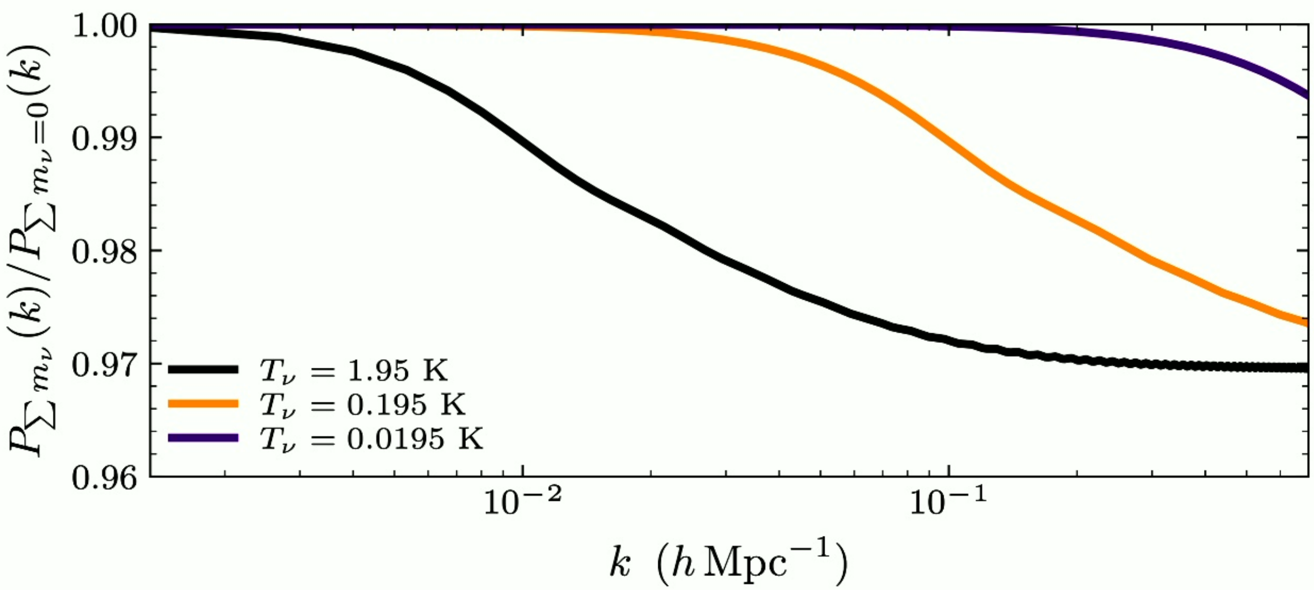


Neutrino Cooling

Cooling doesn't change number density $\rho_\nu \approx m_\nu n_\nu$

Need a heat sink: dark matter is a good candidate

$$\mathcal{L} \supset g_N \phi NN + g_\chi \phi \chi\chi + m^2\phi^2 + m_N NN + \lambda hLN + m_\chi \chi\chi$$

Coupling to right-handed neutrinos is weakly constrained

Requires scattering to be inelastic:

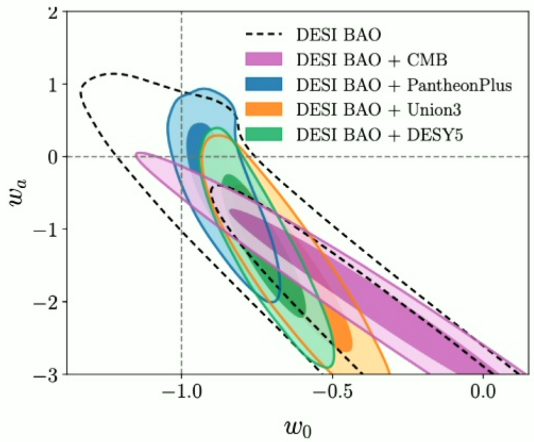
- Include dark matter - dark radiation coupling
- Dark matter either degenerate internal states

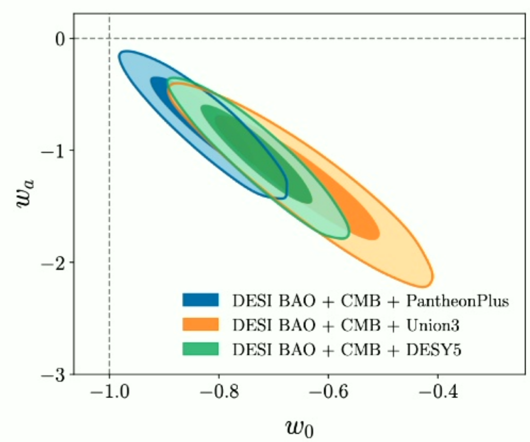
Dark Energy

Dark energy is known to relax neutrino mass constraints

- We need BAO to measure Ω_m
- Degenerate with dynamical dark energy

DESI sees some preference for DDE





Dark Energy

Dark energy can also give enhanced growth function

$$D(a) = \frac{5\Omega_m}{2}\frac{H(a)}{H_0}\int_0^a \frac{da'}{\left(a'H\left(a'\right)/H_0\right)^3}$$

Increasing clustering requires

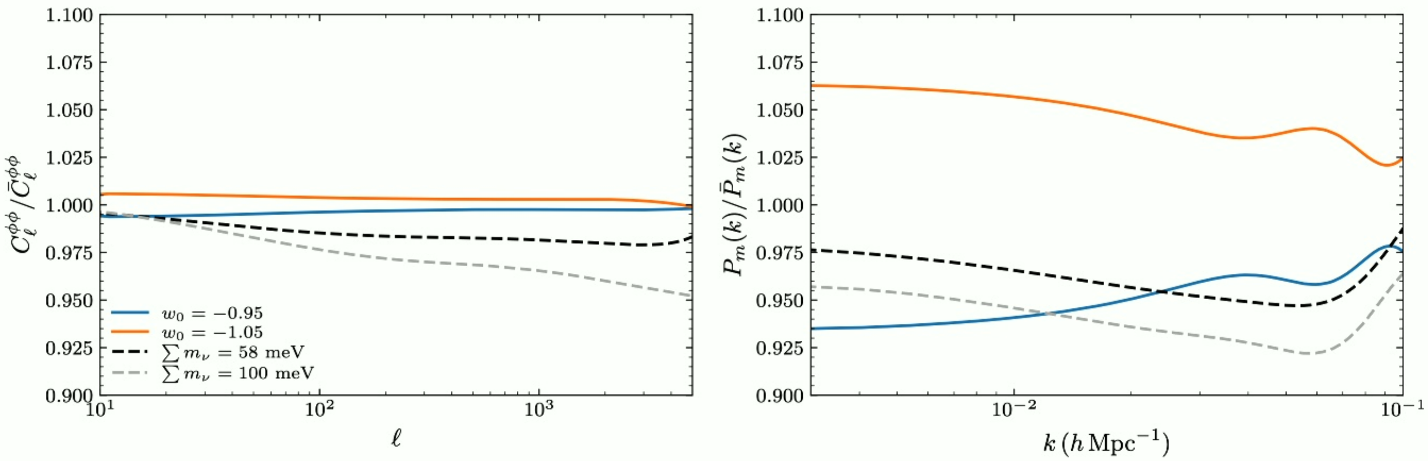
$$H(a<1) < H_{\Lambda\mathrm{CDM}}(a<1)$$

Most of the time this means violating the NEC

But, for w0 and wa, expect regions with extra growth

Dark Energy

Problem: CMB lensing dominated by high redshifts

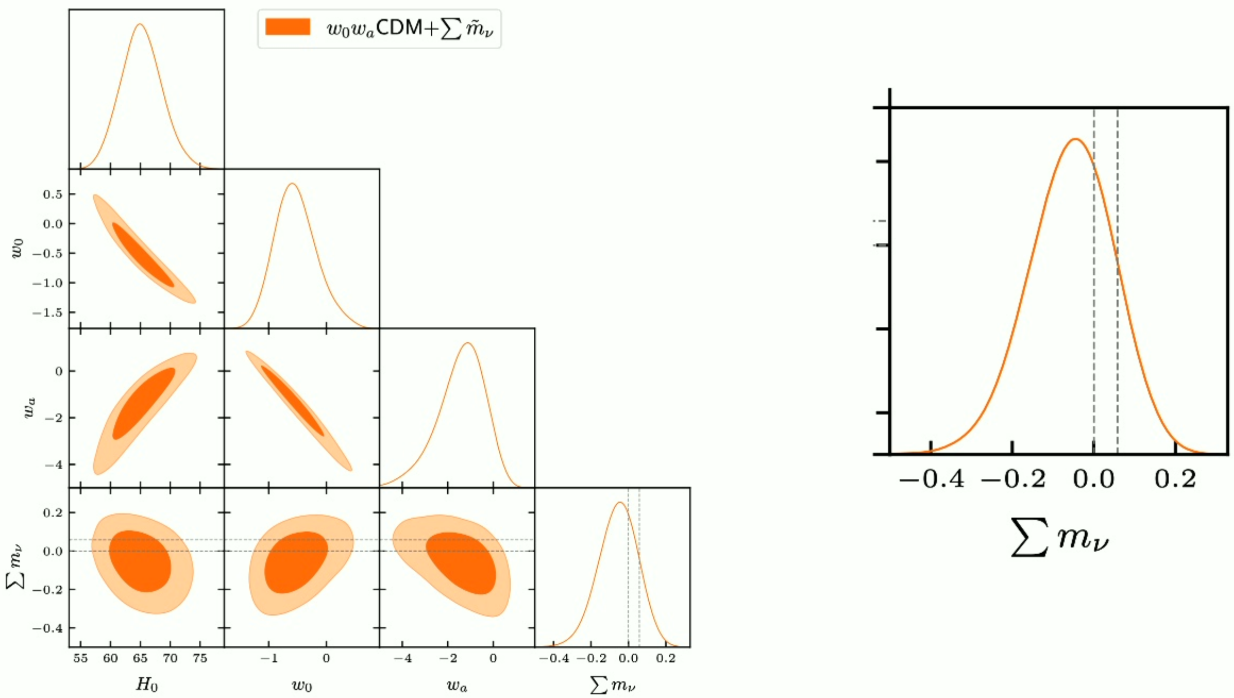


Dark energy can have a large affect on growth at z=0

Leaves little imprint in CMB lensing

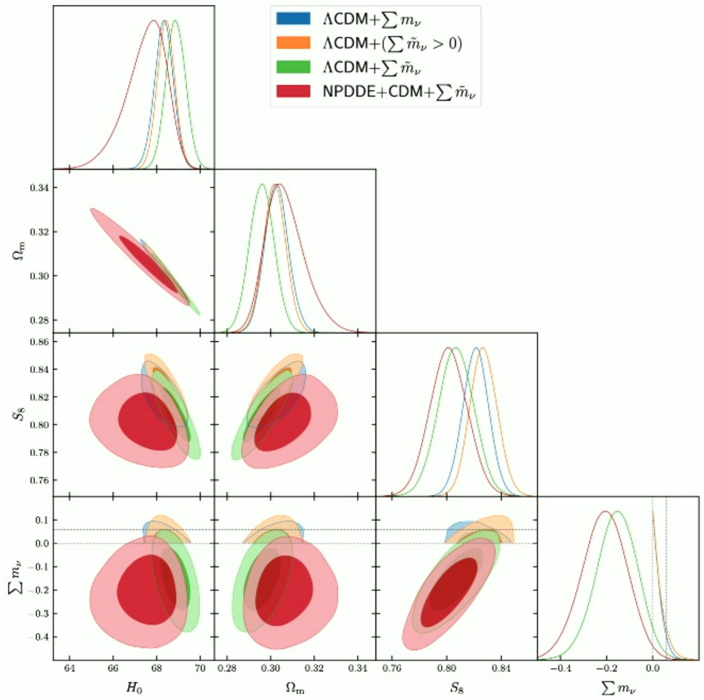
Dark Energy

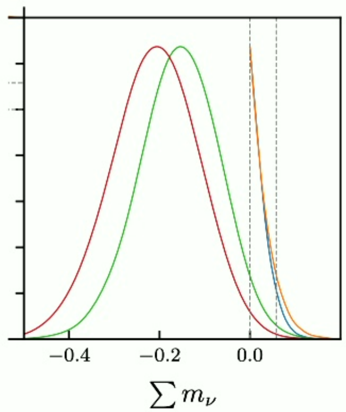
Adding DE increases error / leaves preference $\sum \tilde{m}_\nu < 0$



Dark Energy

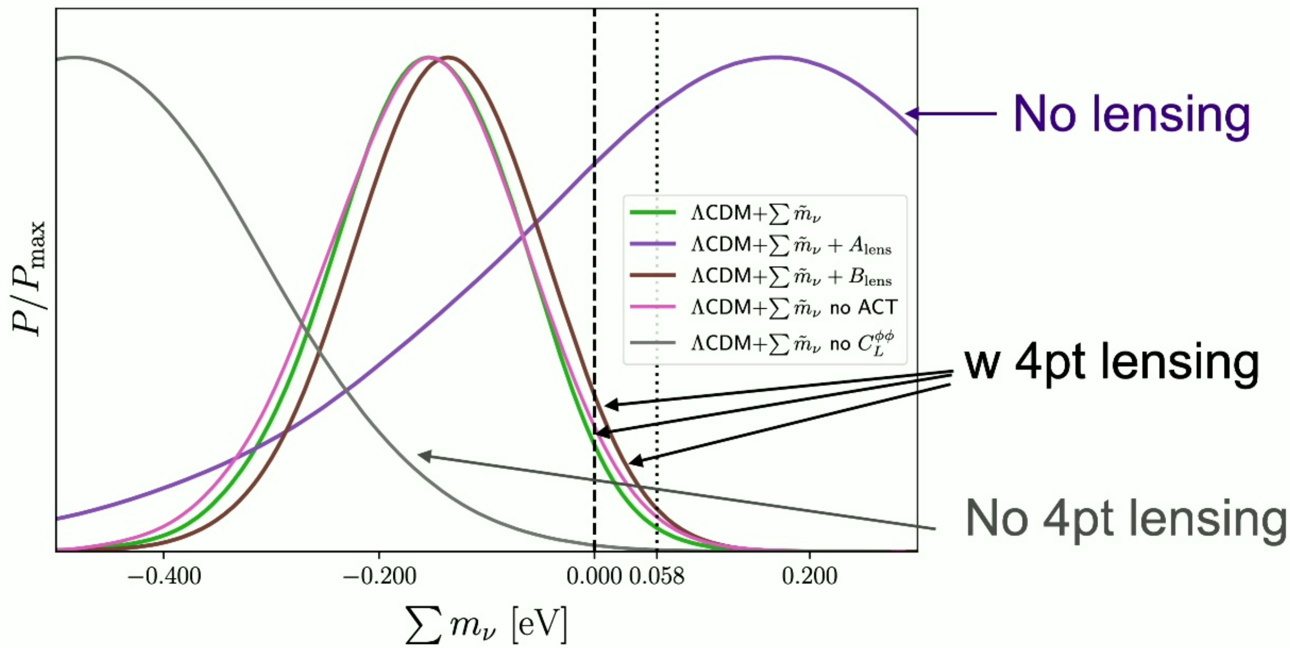
More negative with the NEC (non-phantom DDE)





Trispectrum

The key observable is the CMB lensing power spectrum



Preference dominated by 4pt lensing information

Trispectrum

Increase the apparent lensing with primordial trispectrum

$$\zeta(\vec{x}) = \zeta_{\rm G}(\vec{x}) + \sqrt{\tau_{\rm NL}^{\sigma}}\zeta_{\rm G}(\vec{x})\sigma(\vec{x})$$

$$\left\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\zeta_{\vec{k}_4}\right\rangle' = \tau_{\rm NL}^{\sigma} P_{\zeta}\left(k_1\right) P_{\zeta}\left(k_3\right) P_{\sigma}\left(\left|\vec{k}_1 + \vec{k}_2\right|\right) + \text{ permutations}$$

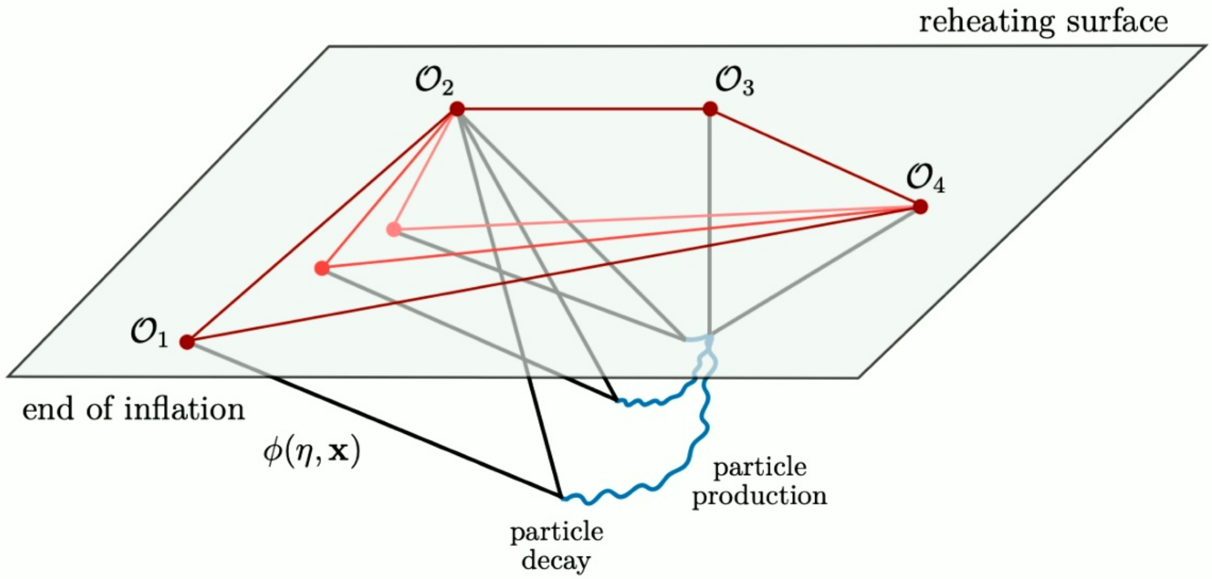
Need a power spectrum $P_\sigma(k) \sim P_m(k)$

General trispectra are weakly constrained by CMB

Model does not need to be tuned to avoid constraints

Trispectrum

Lots of ways to generate such trispectra



Baumann et al. (2022)

Summary

CMB + BAO shows a preference for $\sum m_\nu \leq 0$

- Due to apparent access in 4pt lensing signal
- Not easily explained by known systematics
- Present in the data for a long time
- Very likely to persist with more DESI data

Summary

Cosmology is more sensitive than lab to comic neutrinos

- Many BSM ideas could explain this signal
- Vanishing mass $\sum m_\nu = 0$ points to neutrino sector
- Decays/annihilation/cooling are viable
- Negative mass requires non-neutrino enhancement
- Primordial non-Gaussianity is one easy possibility


Thank you