Title: Cosmological Limits on Neutrino-Neutrino Scattering and Particle Physics in the Early Universe

Date: Jul 09, 2013 09:00 AM

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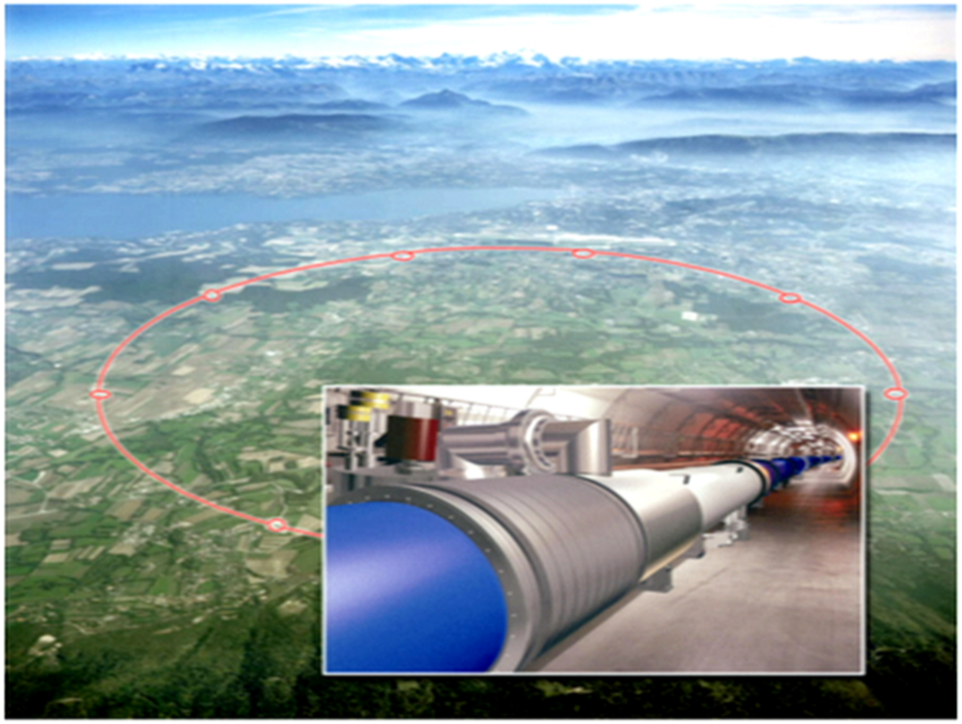
Abstract: In the standard model neutrinos are assumed to have streamed across the Universe since they last scattered at the weak decoupling epoch when the temperature of the standard-model plasma was ~MeV. The shear stress of free-streaming neutrinos imprints itself gravitationally on the Cosmic Microwave Background (CMB) and makes the CMB a sensitive probe of neutrino scattering. Yet, the presence of nonstandard physics in the neutrino sector may alter this standard chronology and delay neutrino free-streaming until a much later epoch. We will discuss how observations of the CMB can be used to constrain the strength of neutrino self-interactions G_eff and put limits on new physics in the neutrino sector from the early Universe. Key measurements of the CMB at large multipoles made by the Planck satellite and high-l experiments are critical for probing this physics. Within the context of conventional LambdaCDM parameters cosmological data are compatible with G_eff < 1/(56 MeV)^2 and neutrino free-streaming might be delayed until their temperature has cooled to as low as ~25 eV. Intriguingly, we also find an alternative cosmology compatible with cosmological data in which neutrinos scatter off each other until z~10^4 with a preferred interaction strength in a narrow region around G_eff = 1/(10 MeV)^2. This distinct self-interacting neutrino cosmology is characterized by somewhat lower values of both the scalar spectral index and the amplitude of primordial fluctuations. We phrase our discussion in terms of a specific scenario in which a late onset of neutrino free-streaming could occur, but in fact our constraints on the neutrino visibility function are very general.

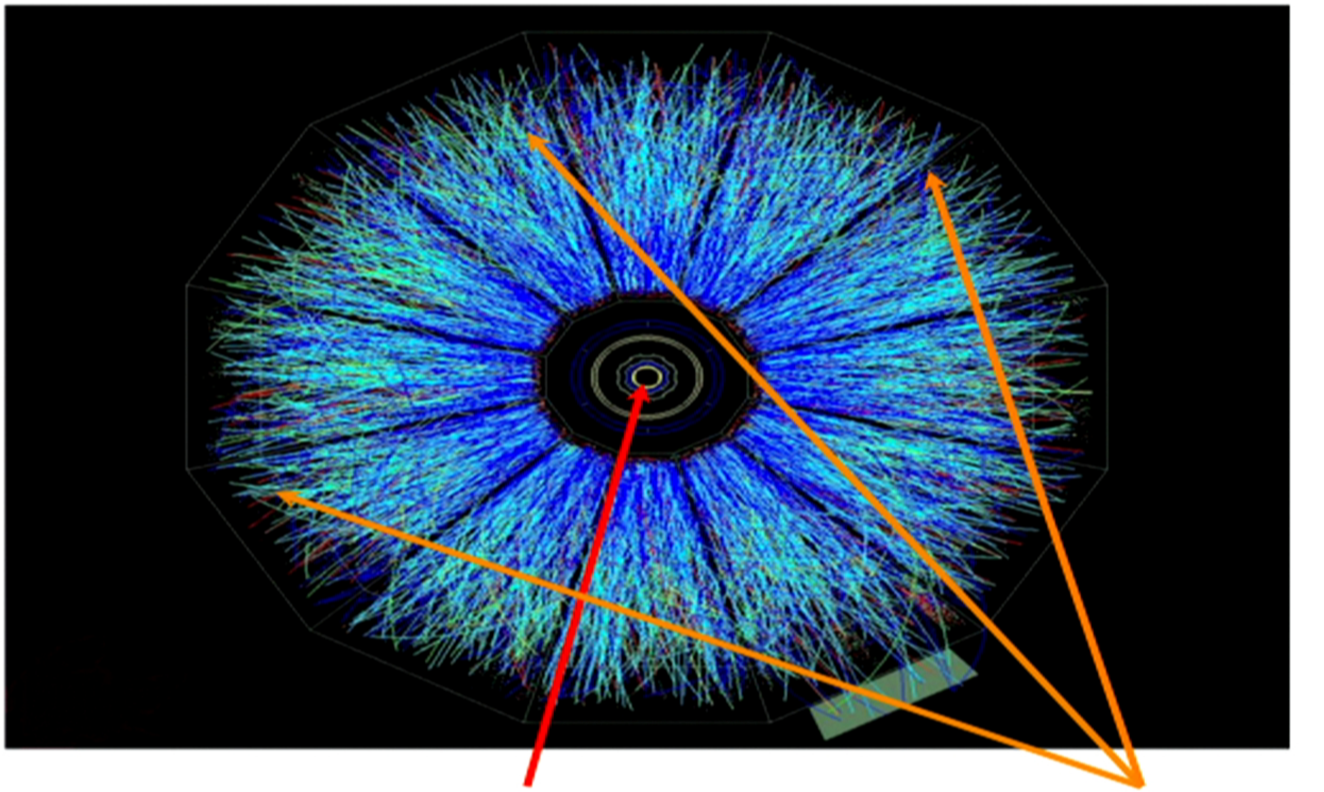

PERIMETER
INSTITUTE
FOR THEORETICAL PHYSICS

LHC: A Modern Particle Physics Experiment



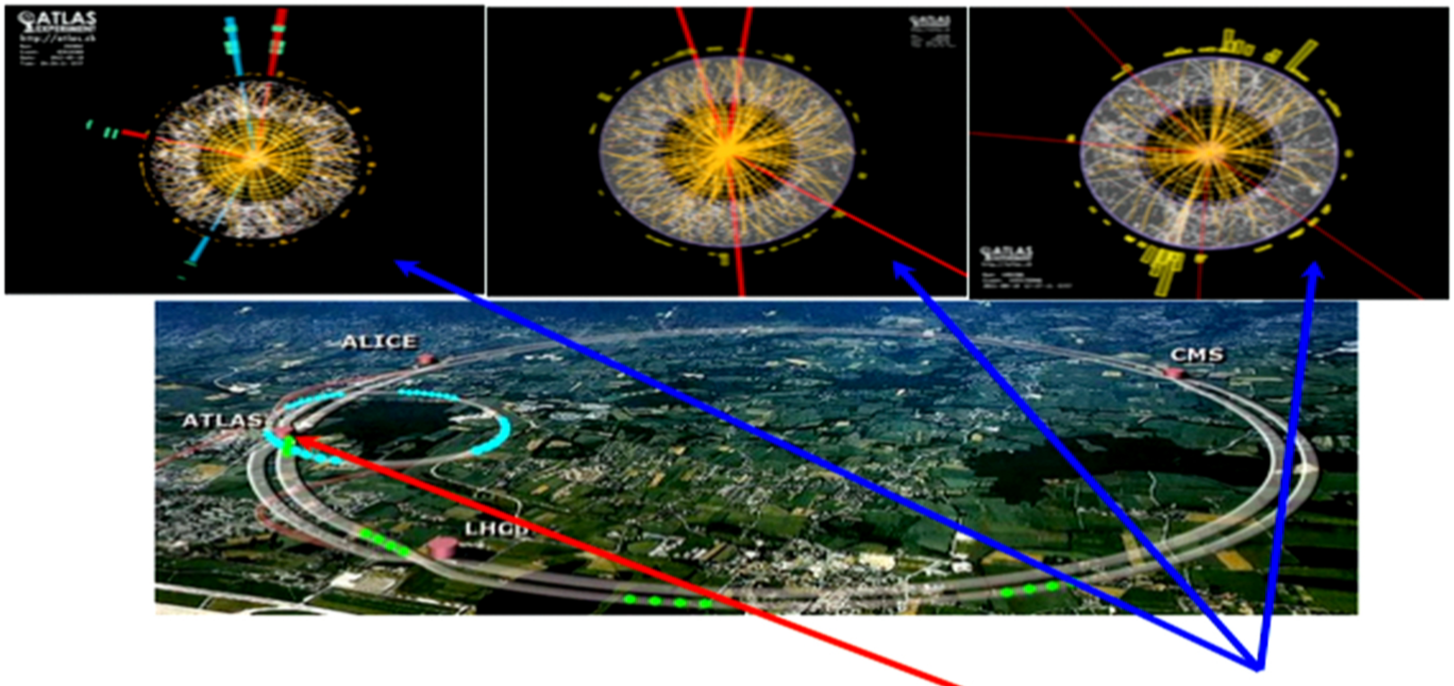
Geneva: A Wonderful Place for Particle Physics!

LHC: A Modern Particle Physics Experiment



Collide particles it at the centre, see what comes OUT at a distance

LHC: A Modern Particle Physics Experiment



Run the same scattering experiment, at the same place, many times.

LHC: A Modern Particle Physics Experiment

1. Find a Place to Run an Experiment:

   Geneva: A Wonderful Place for Particle Physics!

2. Carefully Set Up and Run the Experiment:

   Collide particles it at the centre, see what comes OUT at a distance

3. Carefully Repeat under the Same Conditions:

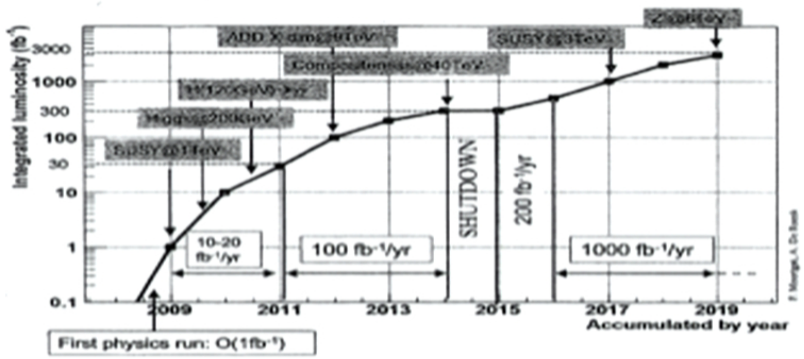
   Run the same scattering experiment, at the same place, many times.

4. Get constraints on Physics!!

LHC: A Modern Particle Physics Experiment

Run the same scattering experiment, at the same place, many times.

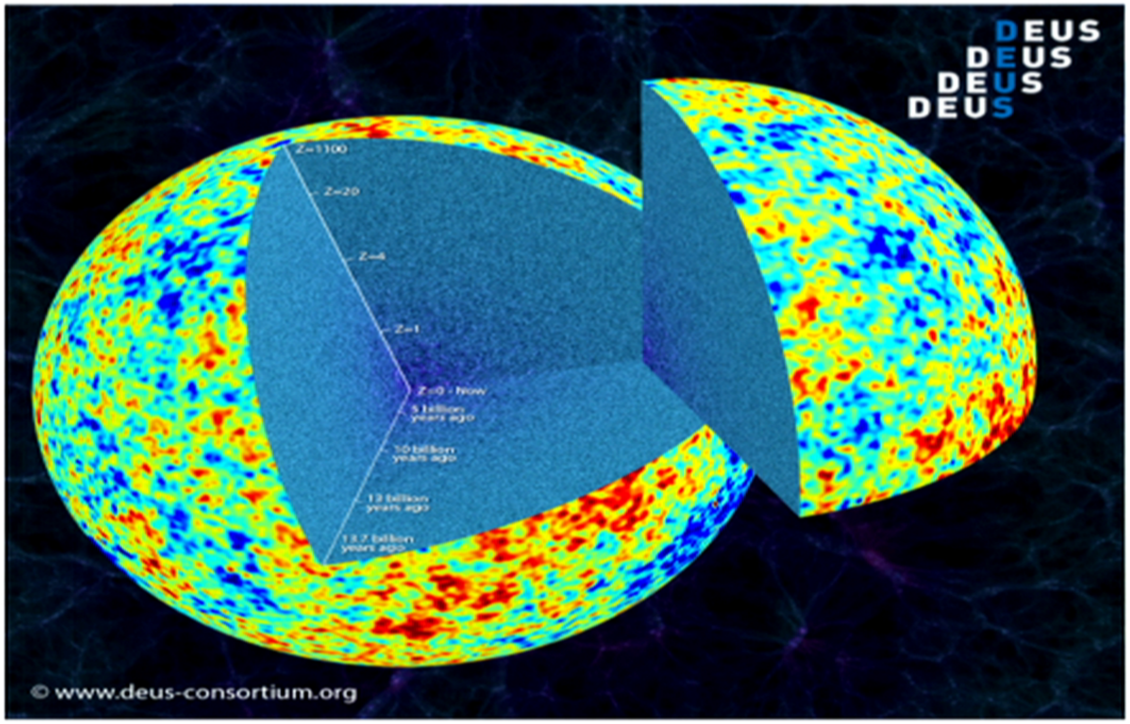
LHC Physics Evolution



But… why do we have both ATLAS and CMS?
Surely if not for lacking of funding impatient physicists would:

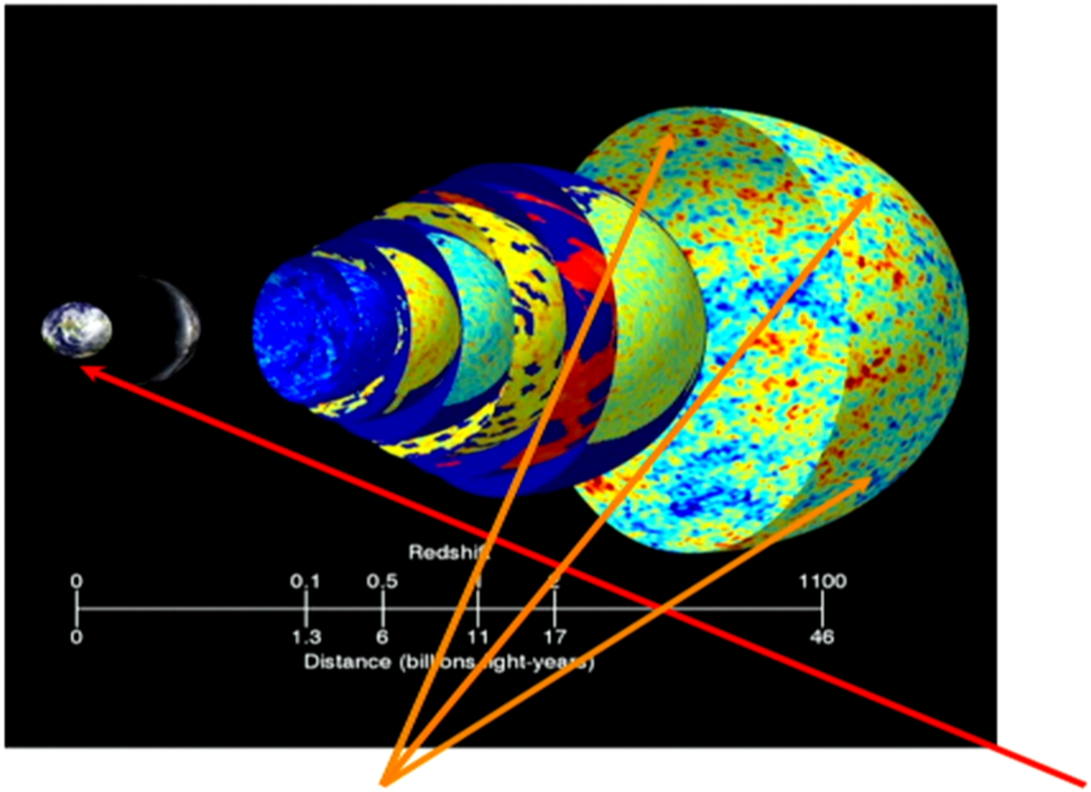
Run the same scattering experiment, at many places, at the same time.

CMB: A Primordial Particle Physics Experiment



The Universe: A Wonderful Place for Particle Physics!

CMB: A Primordial Particle Physics Experiment



Collide particles it at a distance, see what comes IN to the centre

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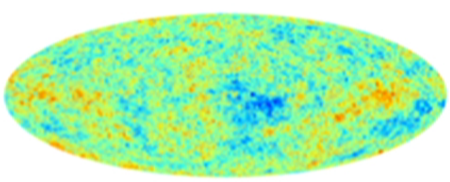

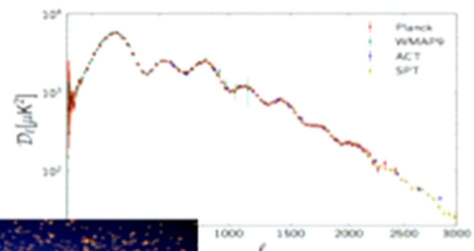

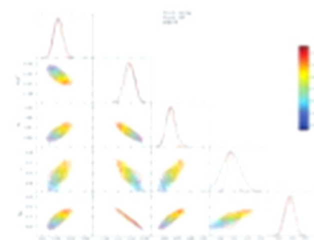

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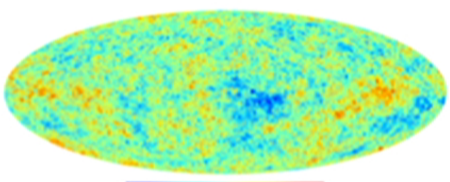
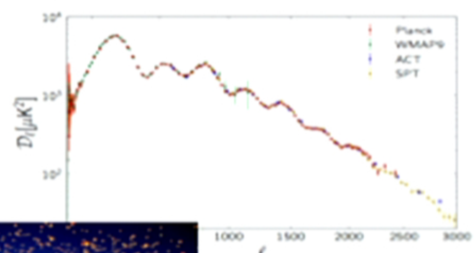
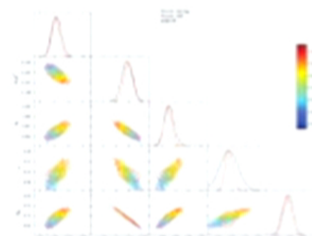







RESERVED
RESERVED

1. Find a Place to Run the Experiment

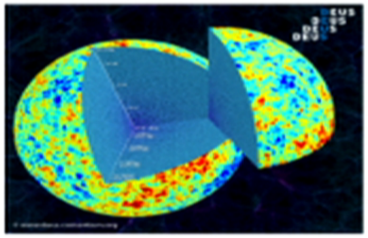
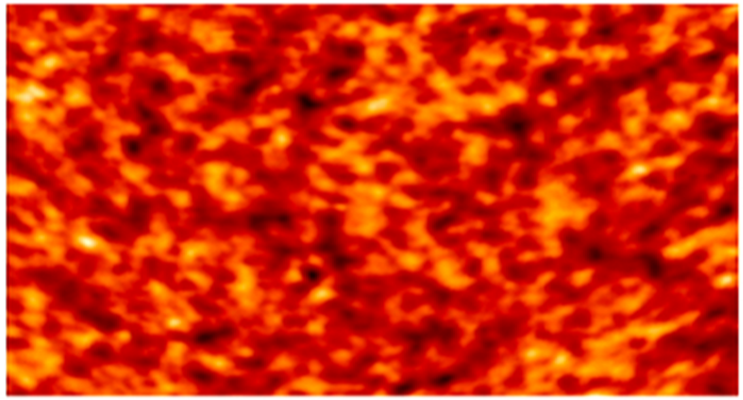
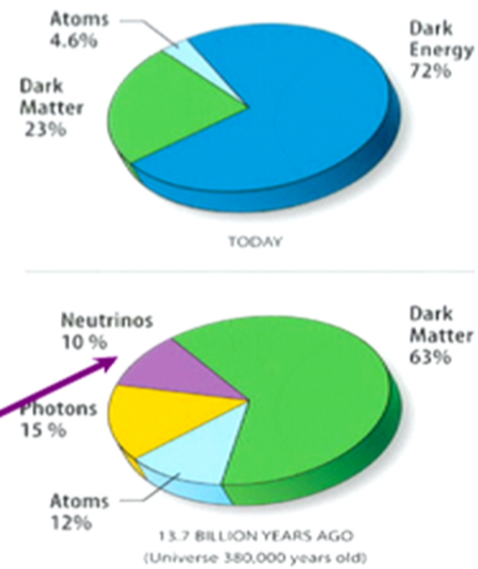


Image: Boomerang





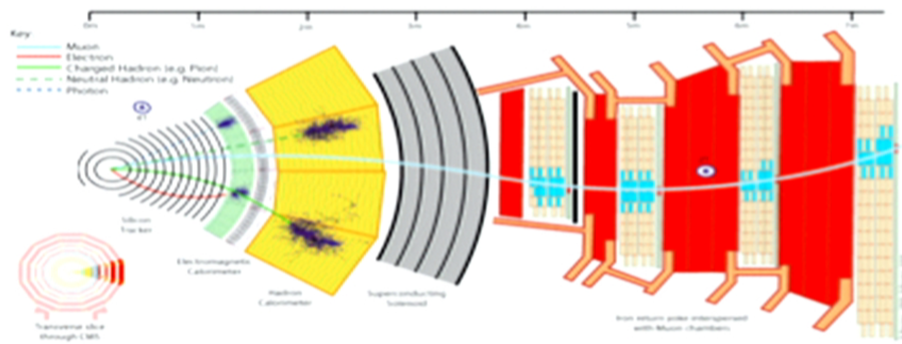
The Early Universe: A Natural Source of Particles of All Sorts:

Photons, Electrons, Protons, Helium

"Dark Matter Particle", Neutrinos

2. Carefully Set Up and Run the Experiment: Detectors

A Section of the CMS Experiment



High Energy:
Photons,
Electrons,
Muons, Pions,
Nucleons

LHC:

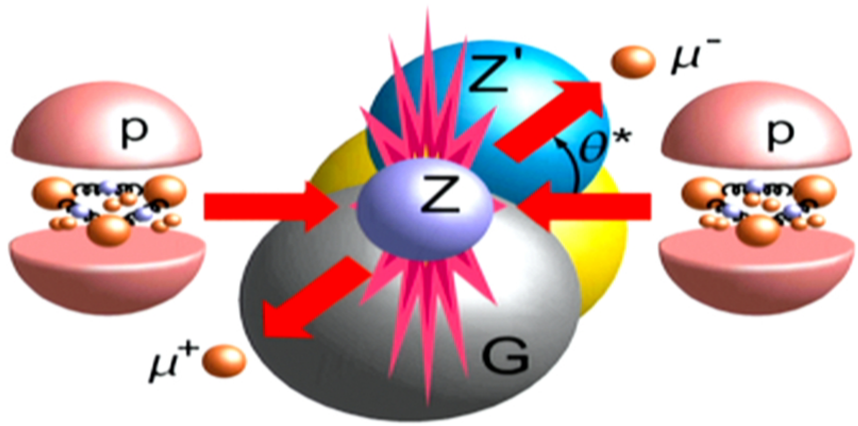
Microwave:
Photons

CMB:

Build detectors that can determine the properties of certain "messenger particles" that interact strongly enough to tell us something about the fundamental physics we are interested in

2. Carefully Set Up and Run the Experiment: Initial Conditions

LHC:



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CMB:

Adiabatic Initial Conditions

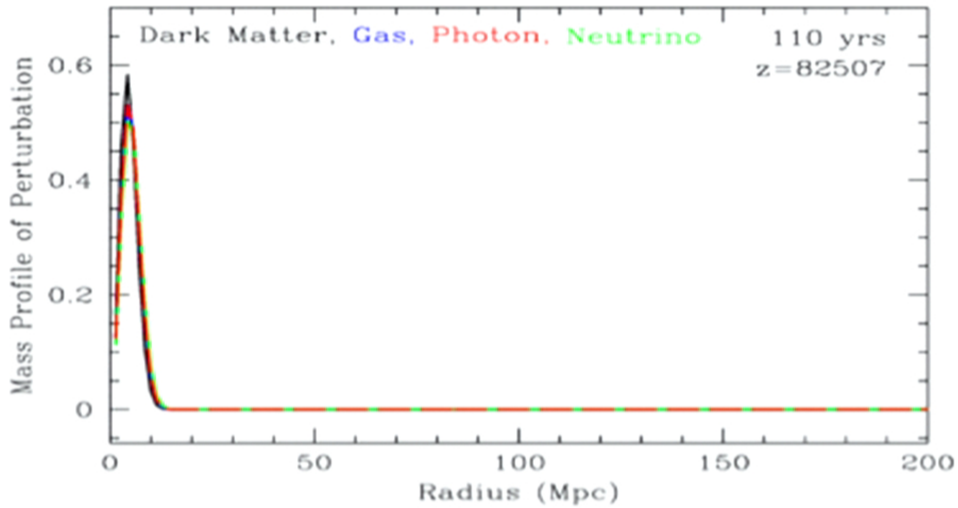


Image: Eisenstein

Initially Correlated Over or Underdensities of All types of Particles!

2. Carefully Set Up and Run the Experiment: Initial Conditions

CMB:

Adiabatic Initial Conditions

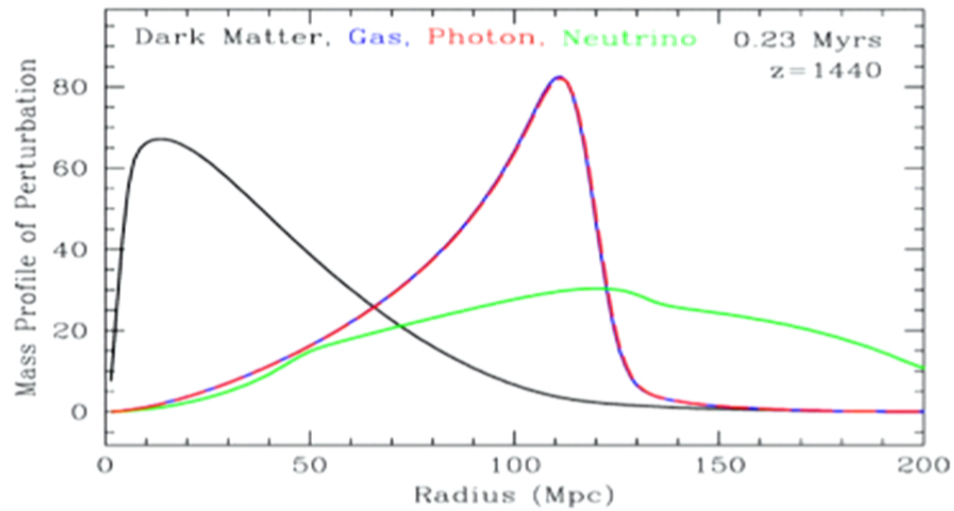
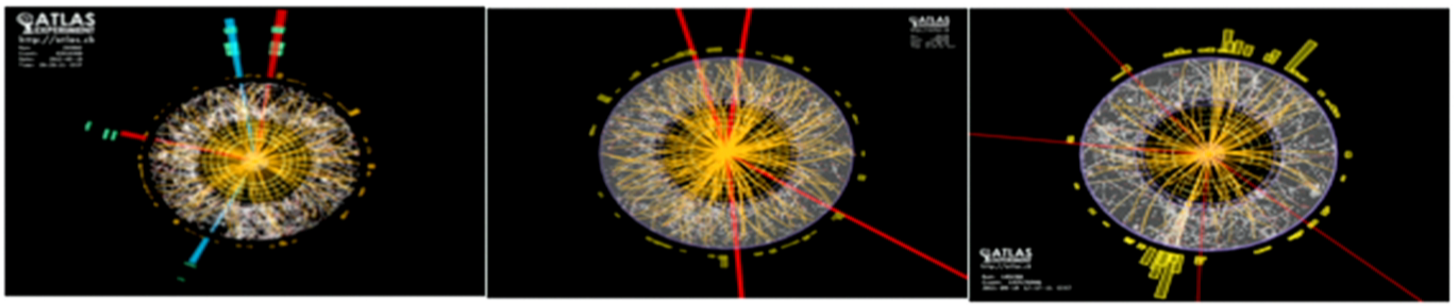


Image: Eisenstein

Evolve According to Linear Perturbation Theory

3. Carefully Repeat under the Same Conditions:

LHC:



Run Many Times and Record Different Outcomes

3. Carefully Repeat under the Same Conditions:

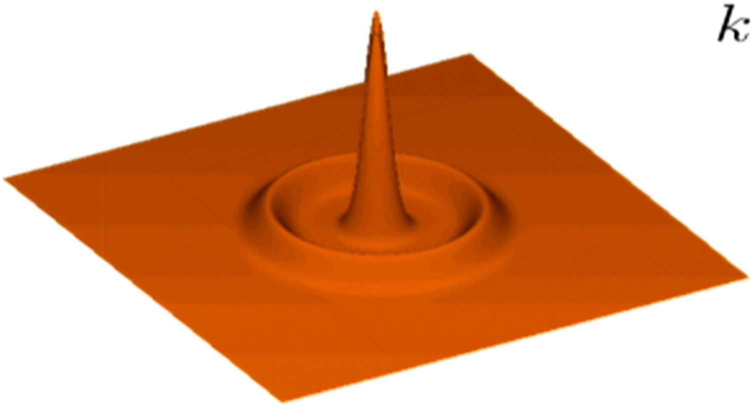
CMB:

$$\zeta(\mathbf{x}) = \int d^3\mathbf{k}\, e^{i\mathbf{k}\cdot\mathbf{x}}\zeta(\mathbf{k})$$

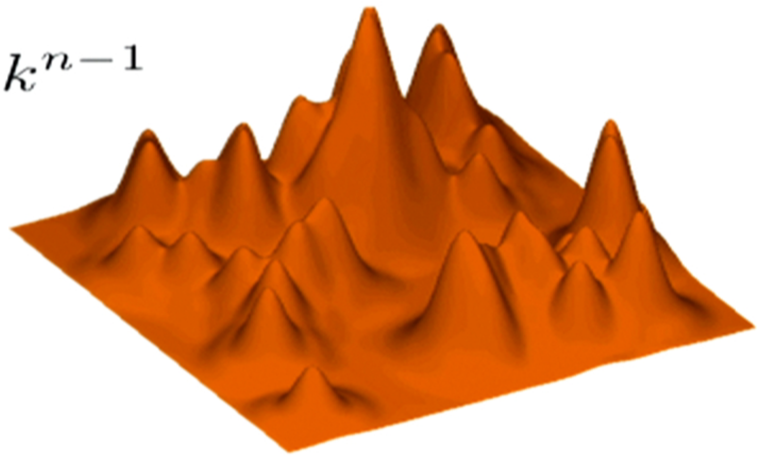
Perform the same experiment everywhere in the Universe with Gaussian random field initial conditions and a nearly scale-invariant power spectrum for the curvature perturbation.

$$k^3 P_{\zeta\zeta}(k) \propto k^{n-1}$$

$$n \simeq 1$$



Green's Function of Adiabatic Evolution



Convolved with Random Curvature Field

CMB: A "Metricometer"

In linear GR about an FRW background we can decompose the metric into the form:

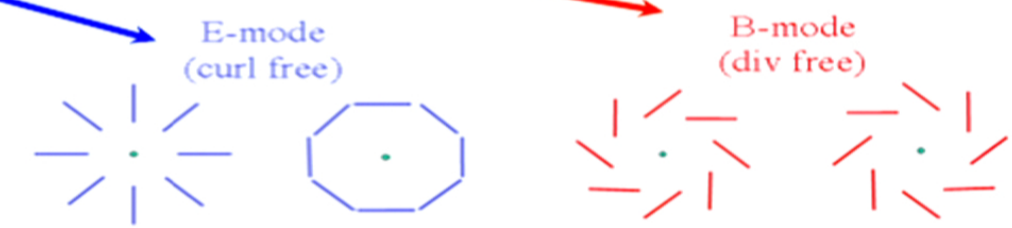
$$\begin{aligned} g_{00} &= -a^2(\tau)\ \{1 + 2\psi(\vec{x},\tau)\}\ , \\ g_{0i} &= a^2(\tau)\, w_i(\vec{x},\tau)\ , \\ g_{ij} &= a^2(\tau)\ \{[1 - 2\phi(\vec{x},\tau)]\delta_{ij} + \chi_{ij}(\vec{x},\tau)\}\ , \qquad \chi_{ii} = 0 \end{aligned}$$

As CMB photons travel through the Universe their evolution is sensitive to the Form of the Scalar, Vector, and Tensor perturbations of the metric.

e.g.

$$\frac{\Delta T}{T} = \frac{1}{3}\psi$$

Sachs-Wolfe Effect



CMB Polarization

CMB: Scalar Potentials

In contrast to Newtonian gravity, scalar perturbations in GR are described by two gravitational potentials:

ψ Gravitational Potential in the Newtonian Limit

ϕ Curvature Perturbation

$$\Delta\psi = \psi - \phi$$

Difference Sourced by Shear Stresses σ

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$$\Delta\psi = \psi - \phi$$

Difference Sourced by Shear Stresses σ

CMB: Scalar Potentials

In detail the evolution is given by (e.g. Ma and Bertschinger):

GEOMETRY = MATTER-ENERGY-STRESS

Poisson-like equation

$$k^2\phi + 3\frac{\dot{a}}{a}\left(\dot{\phi} + \frac{\dot{a}}{a}\psi\right) = 4\pi G a^2 \delta T^0{}_0(\mathrm{Con}) \,,$$

$$k^2\left(\dot{\phi} + \frac{\dot{a}}{a}\psi\right) = 4\pi G a^2 (\bar{\rho} + \bar{P})\theta(\mathrm{Con}) \,,$$

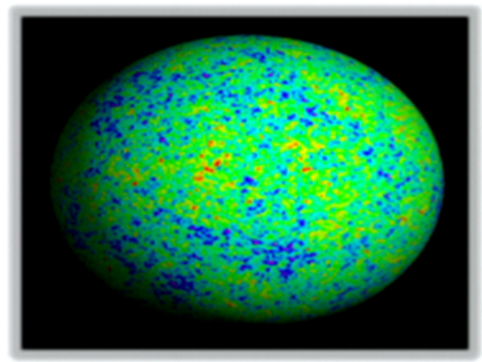
$$\ddot{\phi} + \frac{\dot{a}}{a}(\dot{\psi} + 2\dot{\phi}) + \left(2\frac{\ddot{a}}{a} - \frac{\dot{a}^2}{a^2}\right)\psi + \frac{k^2}{3}(\phi - \psi) = \frac{4\pi}{3} G a^2 \delta T^i{}_i(\mathrm{Con}) \,,$$

$$k^2(\phi - \psi) = 12\pi G a^2 (\bar{\rho} + \bar{P})\sigma(\mathrm{Con}) \,,$$

i-j component

$\Delta\psi$ Sourced by shear stresses

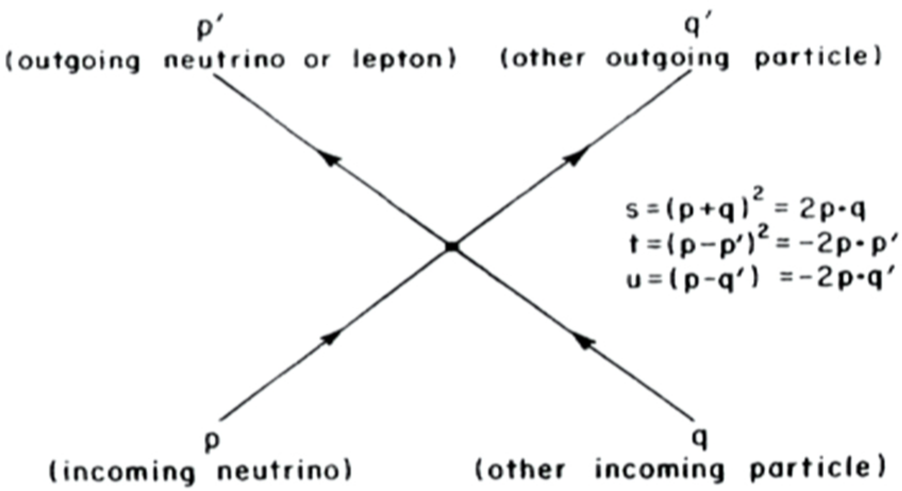
CMB: A Primordial "Shearometer"



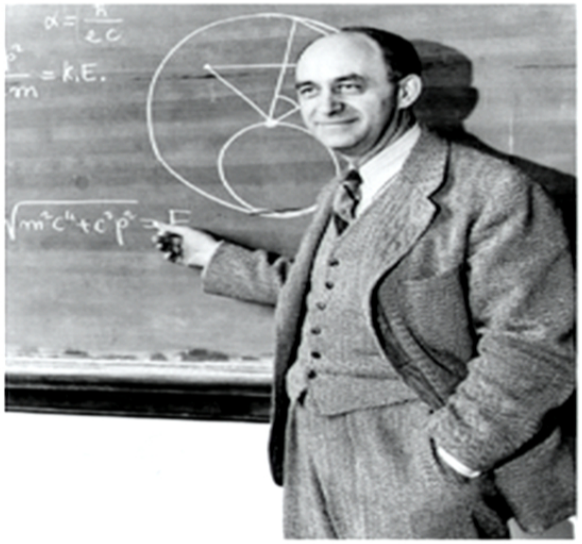
$$\Delta\psi = 0$$
$$\sigma = 0$$

$$\Delta\psi > 0$$
$$\sigma \neq 0$$

Low Energy ν–ν Scattering

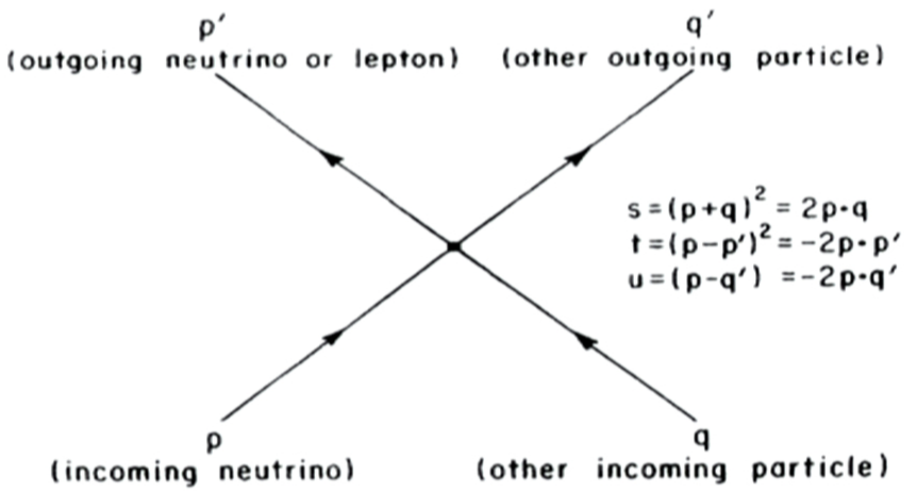


4 Fermion Interaction



Prof. Fermi

SM ν–ν Scattering



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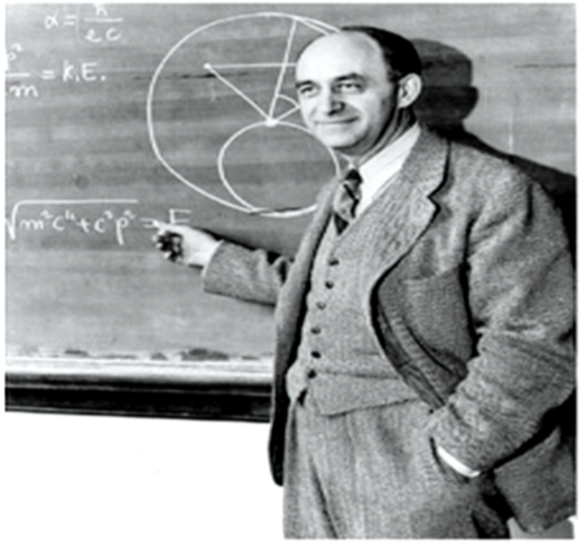
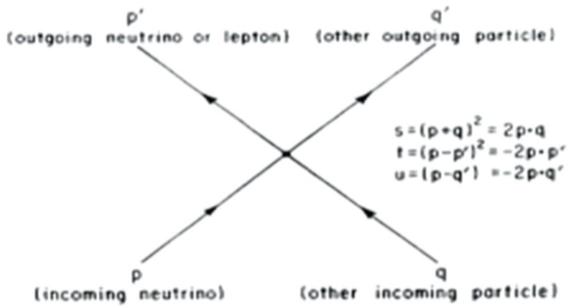


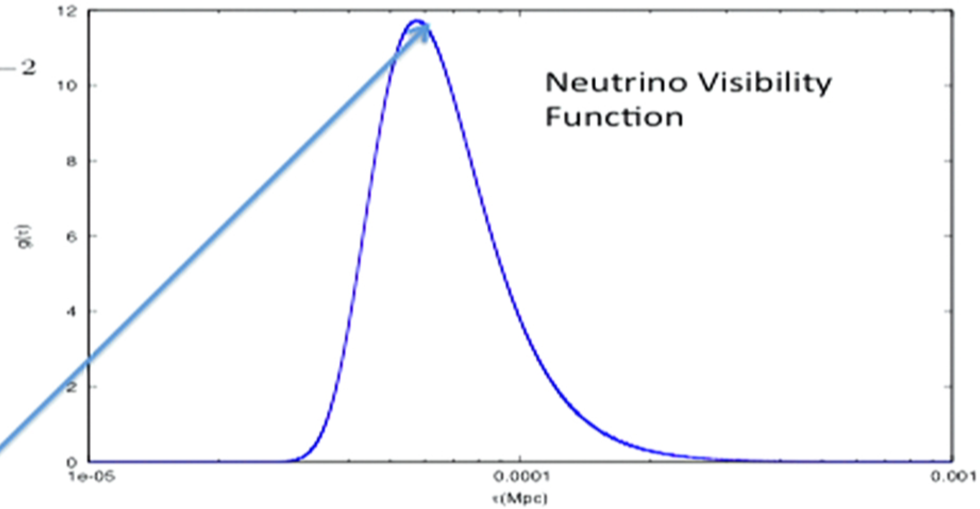
Prof. Fermi

$$\frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2} = 1.16637(1) \times 10^{-11}\,\mathrm{MeV}^{-2}$$

Weak Neutrino Decoupling

$$\frac{G_{\mathrm{F}}}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_{\mathrm{W}}^2} = 1.16637(1) \times 10^{-11}\,\mathrm{MeV}^{-2}$$





$$T_{\nu,\mathrm{dec}} = 1.48\,\mathrm{MeV}$$

$$\Gamma_{\mathrm{W}} \propto n_\nu G_{\mathrm{F}}^2 T_\nu^2 \propto G_{\mathrm{F}}^2 T_\nu^5$$

Only SM Interactions →Neutrinos free stream after 1.48 MeV!

$$\sigma \neq 0$$

Free-streaming relativistic particles generate shear stress!

Neutrinos and the CMB

S. Bashinsky and U. Seljak (2004)

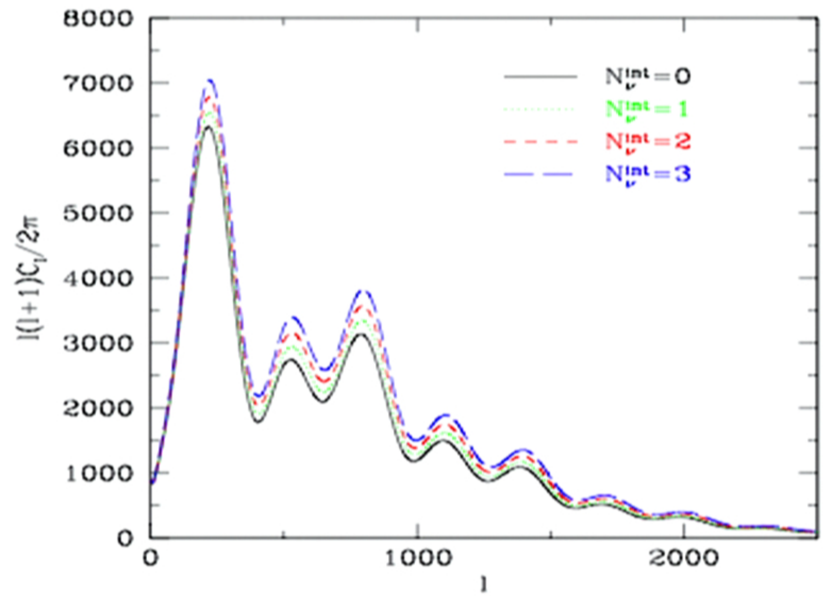
$$d_\gamma(\tau,k) = 3\zeta_{\rm in}(1+\Delta_\gamma)\cos(\varphi_s+\delta\varphi) + O(\varphi_s^{-1}),$$

where

$$\Delta_\gamma \simeq -0.2683 R_\nu + O(R_\nu^2),$$
$$\delta\varphi \simeq 0.1912\,\pi R_\nu + O(R_\nu^2).$$

$$R_\nu = \frac{\rho_\nu}{\rho_\gamma+\rho_\nu} \simeq 0.403 \quad \text{for} \quad N_{\rm eff} \simeq 3.046$$

Free-streaming Neutrinos→
Amplitude Suppression
Phase Shift in k or l space



N. Bell, E. Pierpaoli, and KS (2006)

Used by, e.g., Trotta and Melchorri (2005) to find evidence for Free-Streaming Neutrinos within a c_{vis} paramatrization

Neutrinos and the CMB

We can use the CMB to conduct a ν-ν Scattering Experiment!

Look for non-standard self-interactions!

Neutrinos and the CMB

Francis-Yan Cyr-Racine and KS, arXiv:1306.1536

Limits on Neutrino-Neutrino Scattering in the Early Universe

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NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA and California Institute of Technology, Pasadena, CA 91125, USA

Kris Sigurdson
Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, V6T 1Z1, Canada

(Dated: June 10, 2013)

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PACS numbers: 98.80.-k,14.60.St,98.70.Vc

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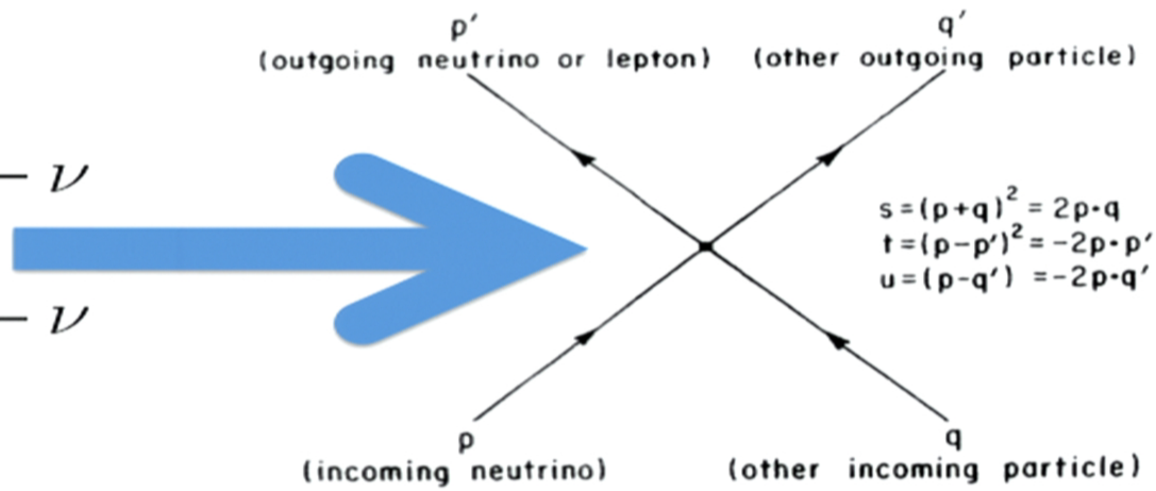
Self-Interacting Neutrinos

New Unknown
Contact Interaction

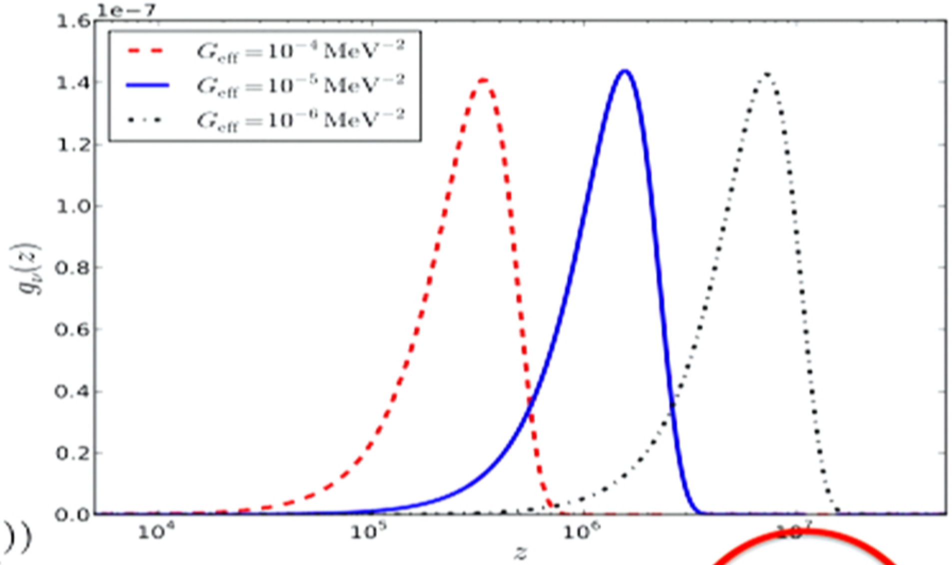


4 Fermion Interaction

$$G_\nu \propto g_\nu^2/M_X^2$$

$$G_\nu > G_{\rm F}$$

General Neutrino Decoupling



Thermalized Cross Section

$$\langle \sigma_\nu \rangle_{T_\nu} \equiv G_{\rm eff}^2 T_\nu^2$$

Neutrino Opacity

$$\dot{\tau}_\nu = a n_\nu \langle \sigma_\nu \rangle_{T_\nu}$$

$$c_{\rm vis}^2 = (1/3)(1 - (27/16)\dot{\tau}_\nu \alpha_2 F_{\nu 2}/(\theta_\nu + k\sigma))$$

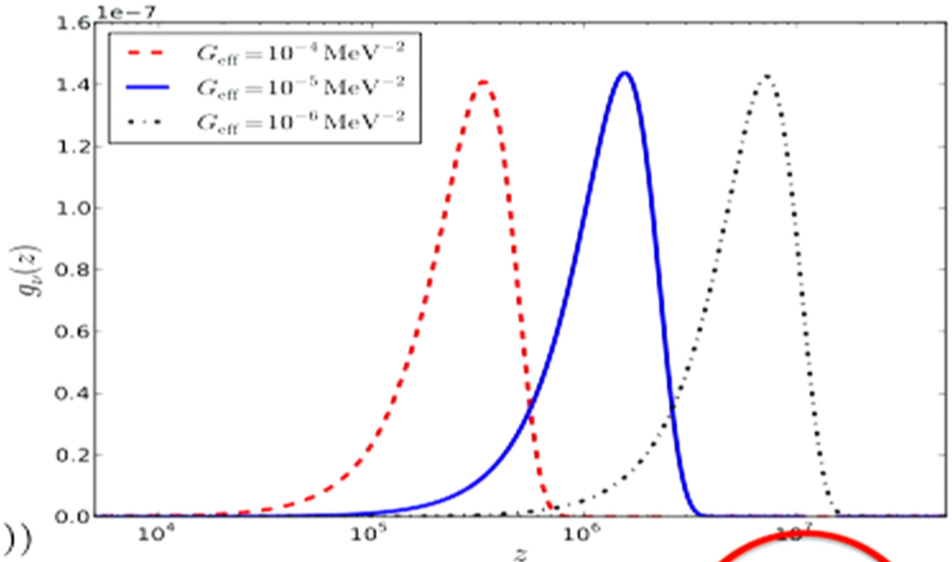
Modified Boltzmann Hierarchy

$$\dot{F}_{\nu 2} = \frac{8}{15}\theta_\nu + \frac{8}{15}k\sigma - \frac{3}{5}kF_{\nu 3} + \frac{9}{10}\alpha_2 \dot{\tau}_\nu F_{\nu 2},$$

$$\dot{F}_{\nu l} = \frac{k}{2l+1}\left[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right] + \alpha_l \dot{\tau}_\nu F_{\nu l},$$

Extra Neutrino Interactions → Delayed Neutrino free streaming!

General Neutrino Decoupling



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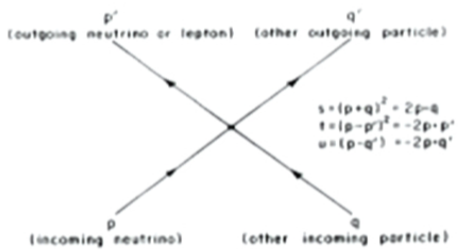
General Neutrino Decoupling

Extra Neutrino Interactions → Delayed Neutrino free streaming!

Shear Perturbations Damped.

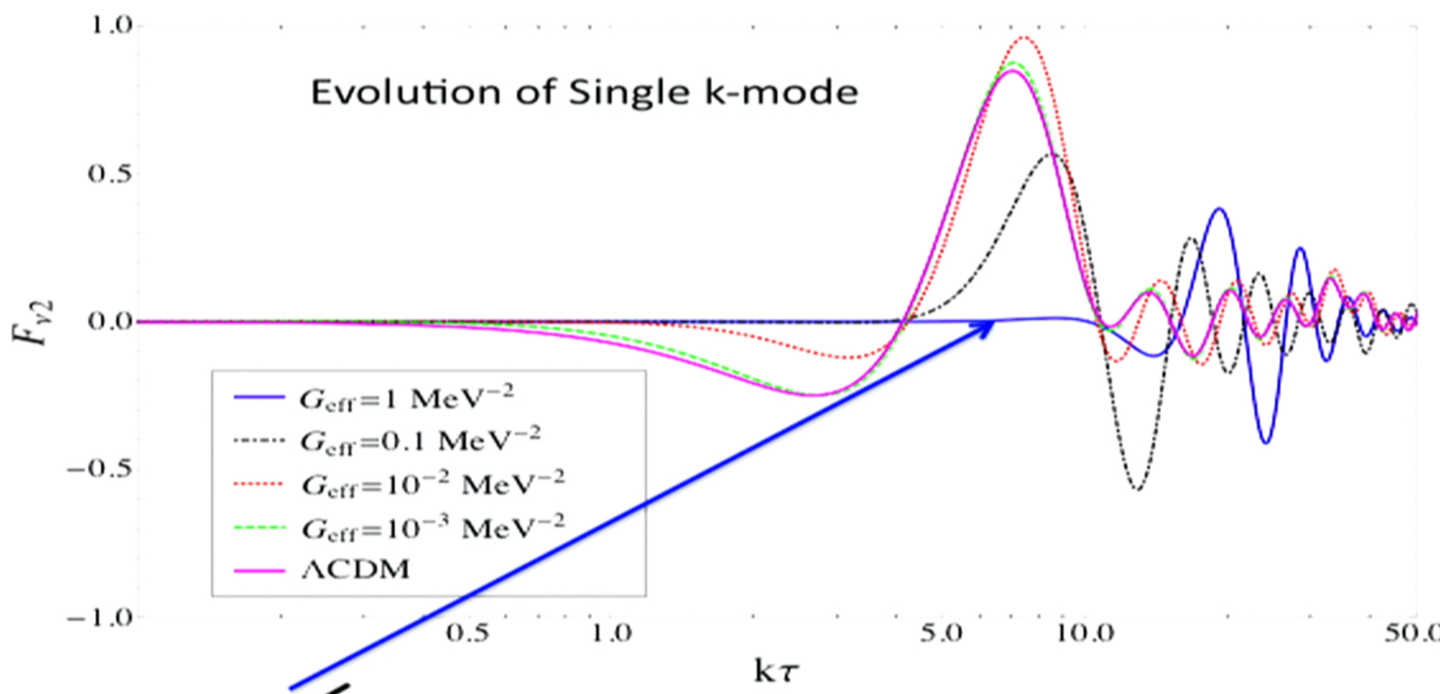


$$G_\nu > G_{\mathrm{F}}$$

Missing Shear Stress!
Modified CMB.

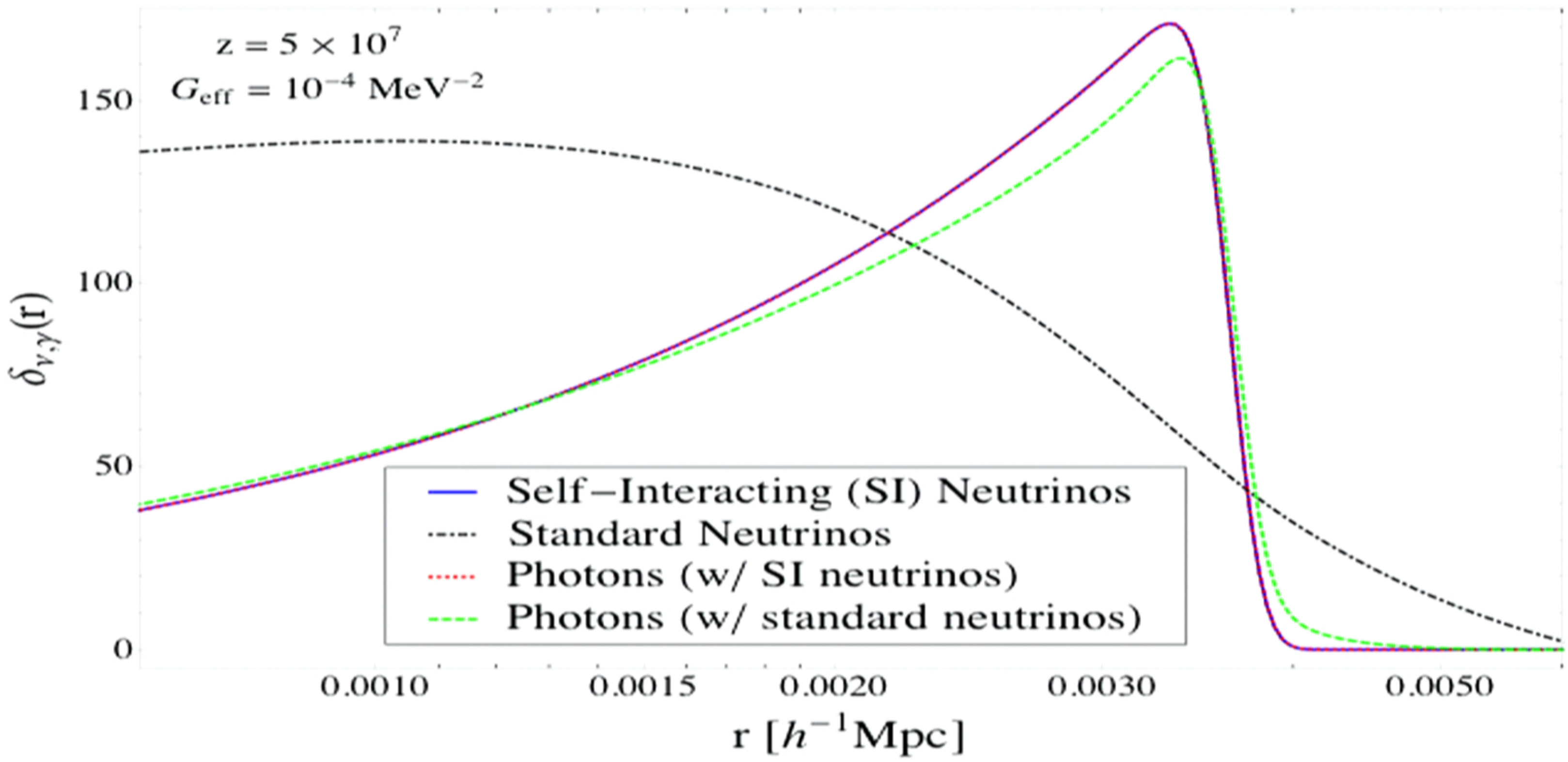
General Neutrino Decoupling

σ

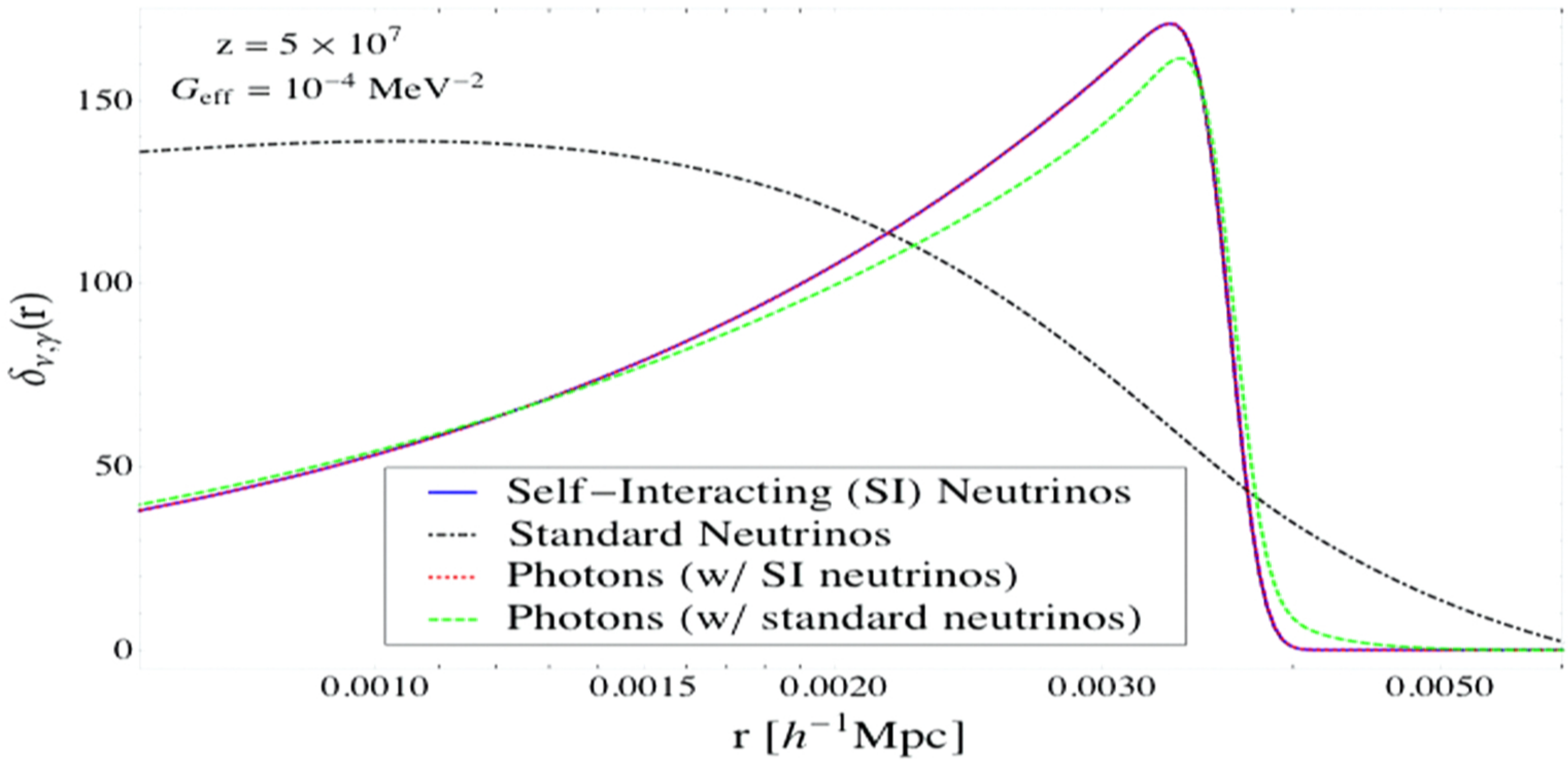


$\not\sigma$ Missing Shear Stress!

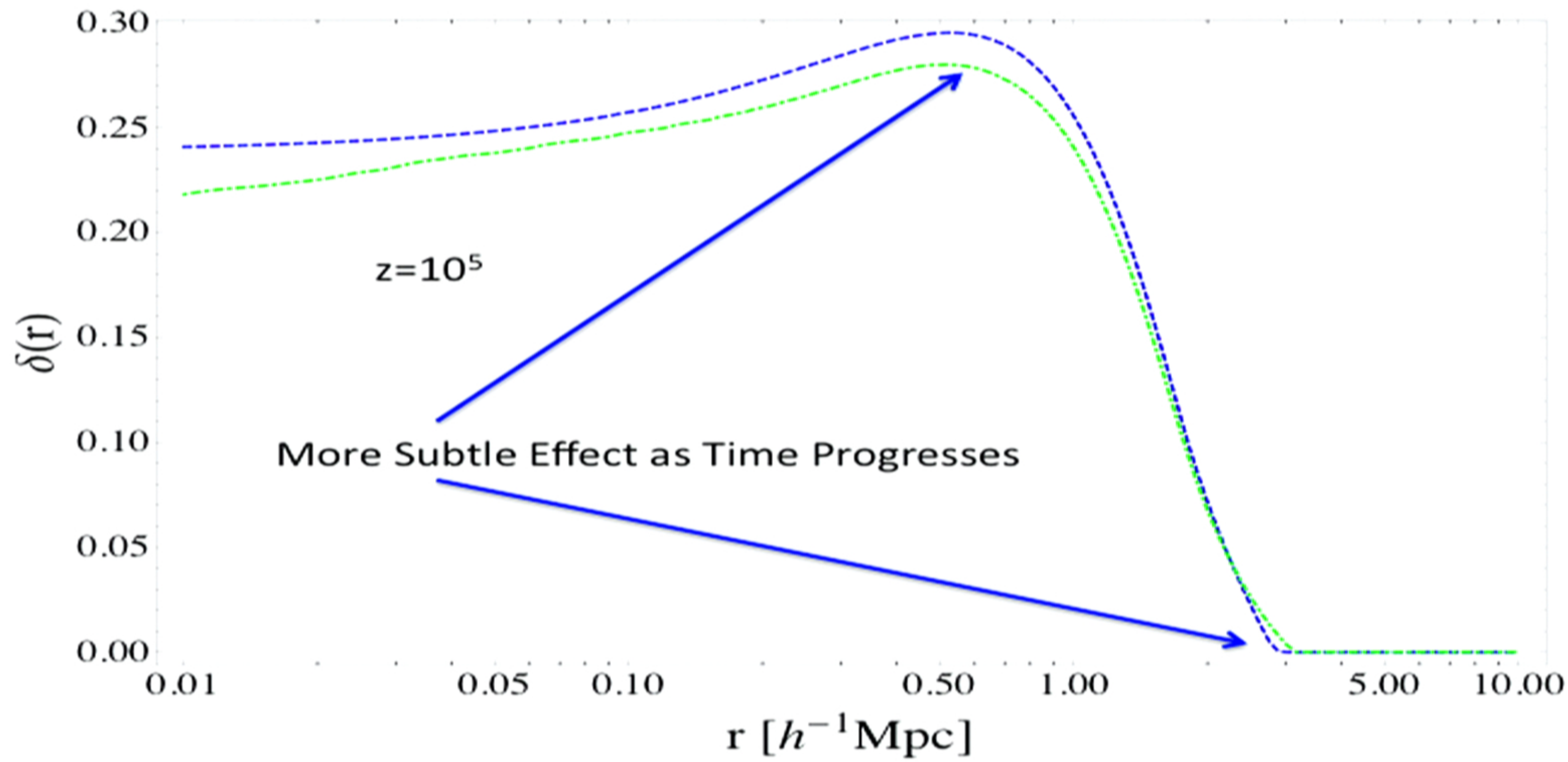
Delayed Neutrino Free-Streaming



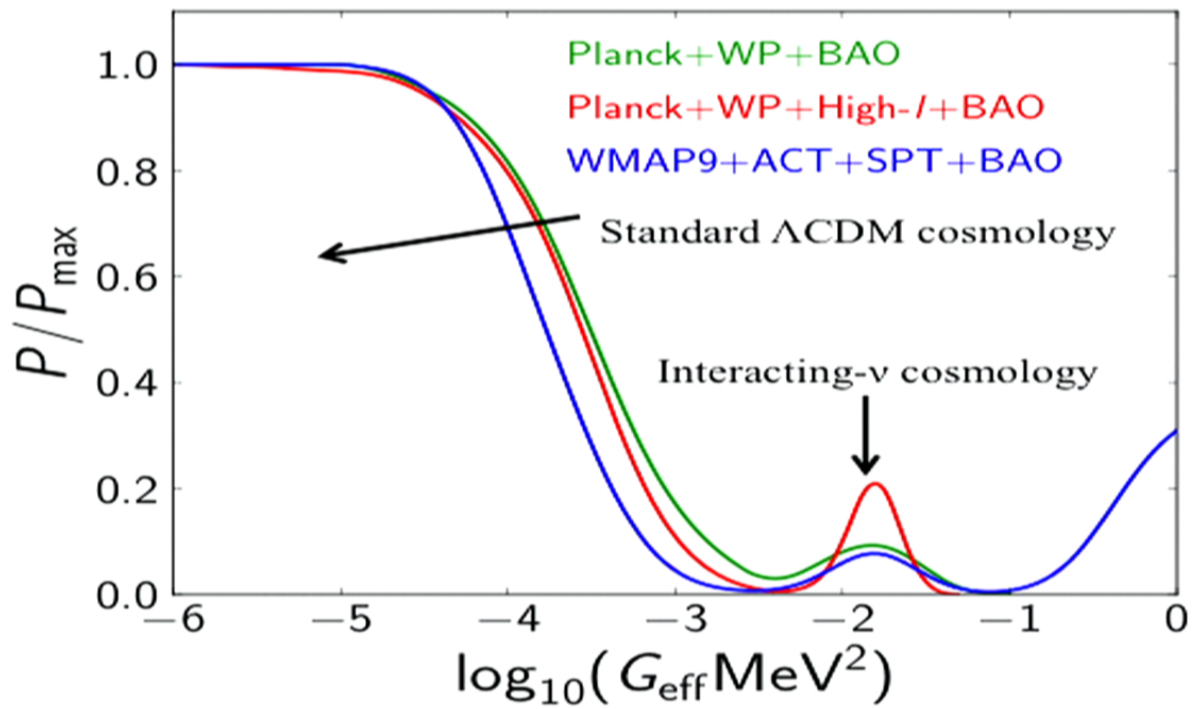
Delayed Neutrino Free-Streaming



Delayed Neutrino Free-Streaming

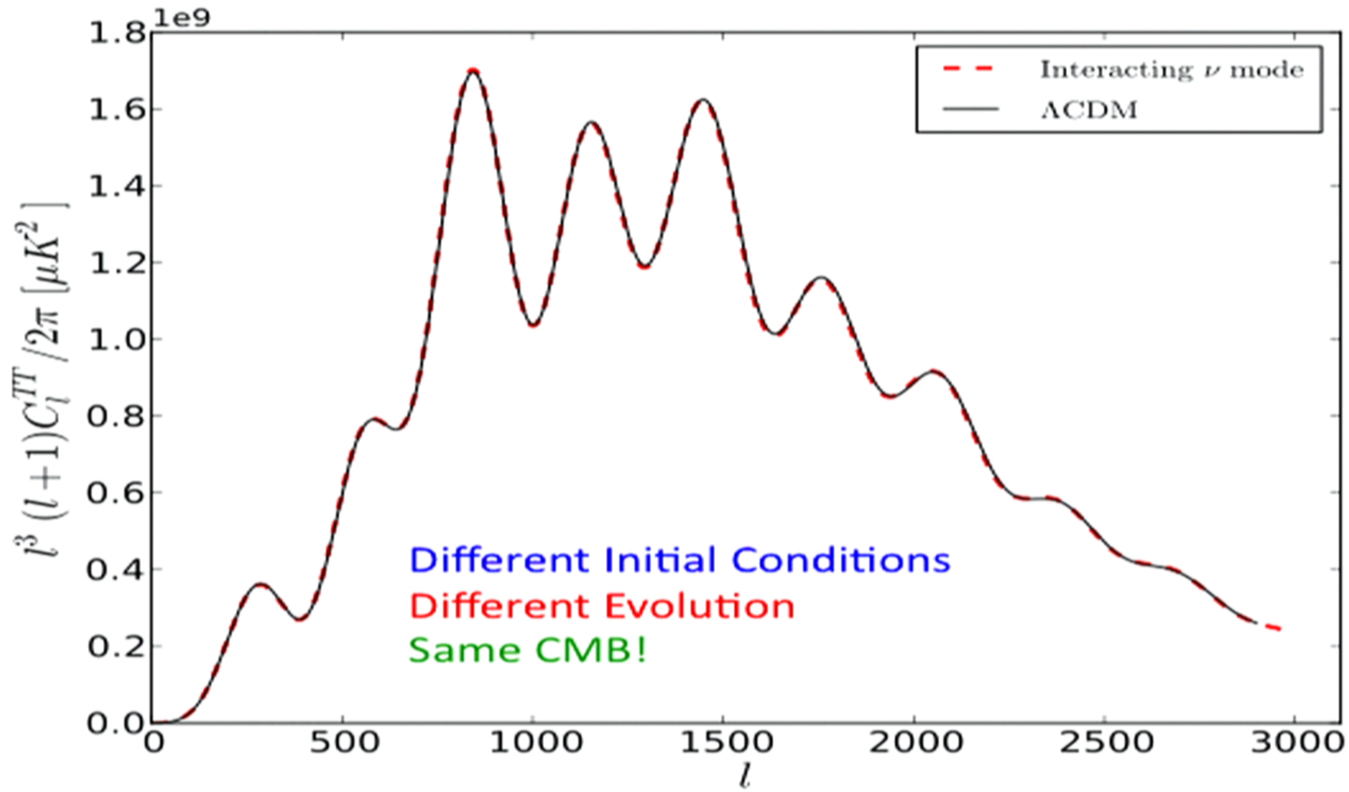


Constraints on $G_{\rm eff}$ from the CMB

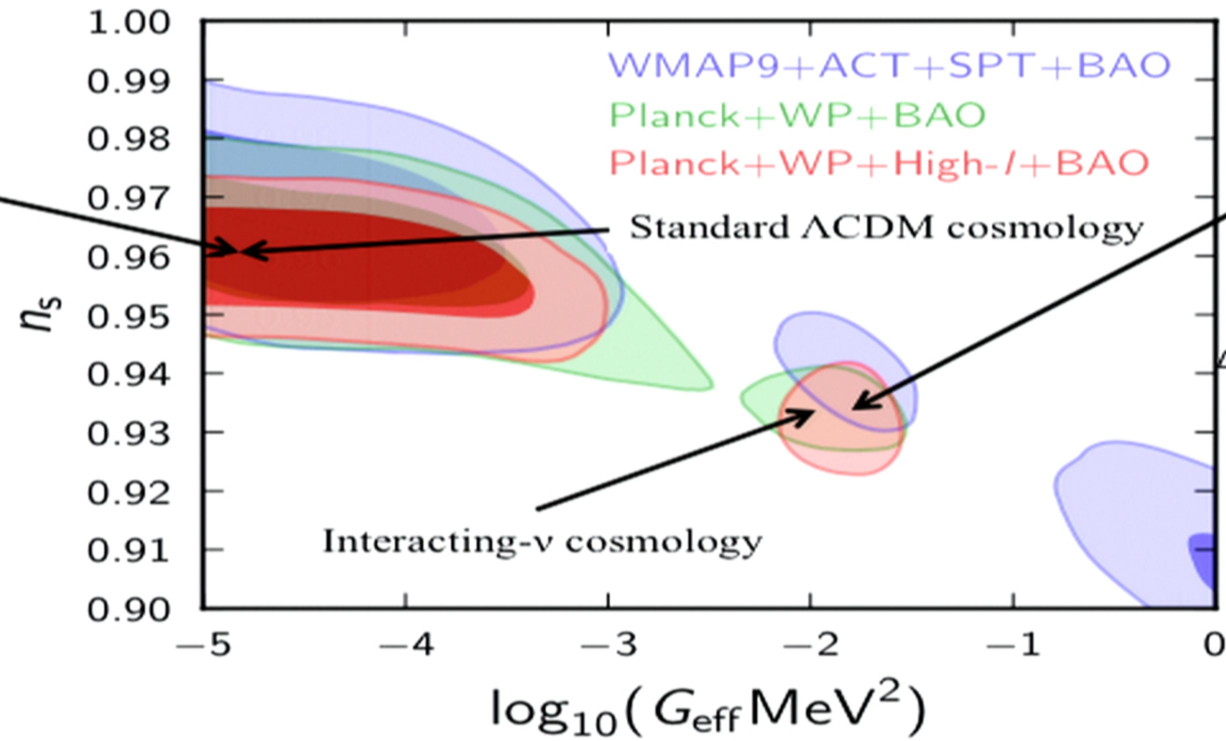


$$\frac{G_{\rm F}}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_{\rm W}^2} = 1.16637(1) \times 10^{-11}\,{\rm MeV}^{-2}$$

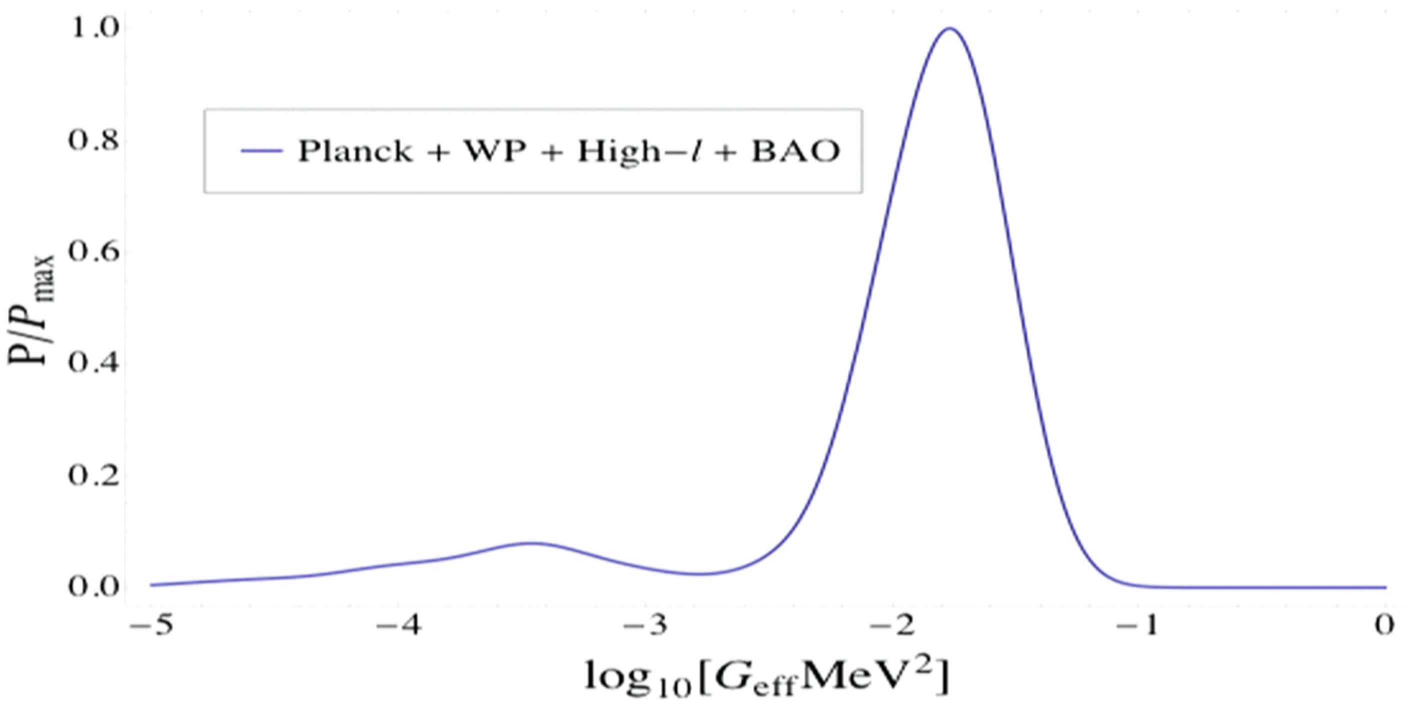
An Interacting Neutrino Cosmology?



Constraints on $G_{\rm eff}$ from the CMB



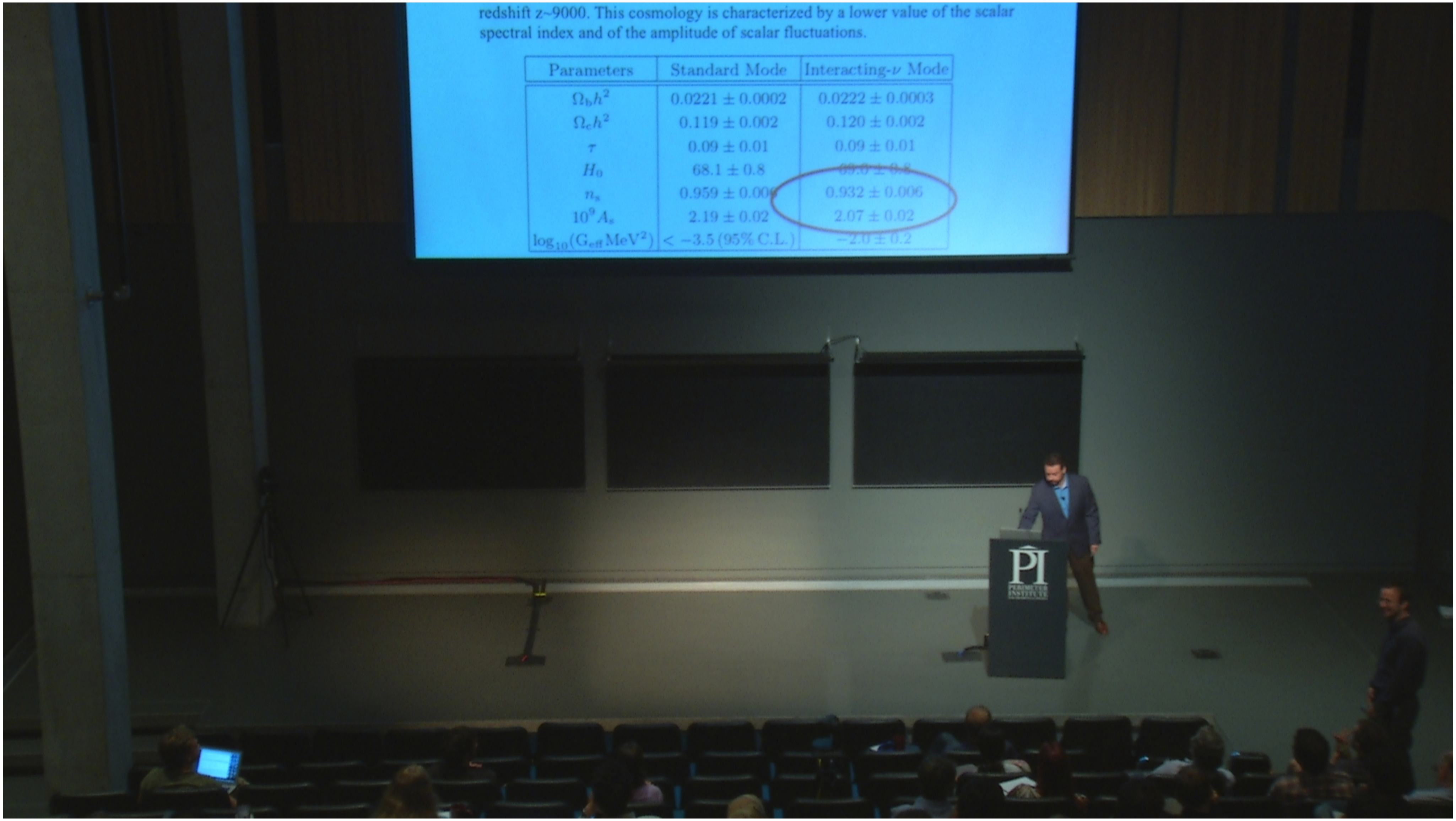
Interacting Neutrinos?



Conclusions

- We can use the CMB to conduct an ν-ν scattering experiment to look for missing shear stress.
- Within the standard cosmological paradigm, neutrino free-streaming could be delayed until the Universe has cooled to a temperature close to 35 eV, almost 5 order of magnitude below the value predicted by the Standard Model of particle physics.
- We have found a new cosmology in which neutrinos are tightly-coupled until redshift z~9000. This cosmology is characterized by a lower value of the scalar spectral index and of the amplitude of scalar fluctuations.

Parameters	Standard Mode	Interacting-ν Mode
$\Omega_b h^2$	0.0221 ± 0.0002	0.0222 ± 0.0003
$\Omega_c h^2$	0.119 ± 0.002	0.120 ± 0.002
τ	0.09 ± 0.01	0.09 ± 0.01
H_0	68.1 ± 0.8	69.0 ± 0.8
n_s	0.959 ± 0.006	0.932 ± 0.006
$10^9 A_s$	2.19 ± 0.02	2.07 ± 0.02
$\log_{10}(G_{eff} MeV^2)$	< -3.5 (95% C.L.)	-2.0 ± 0.2



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RESERVED
RESERVED

Constraints on G_{eff} from the CMB