Title: Gravity and the Search for New Physics with Cosmology

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Abstract: Despite its feeble in strength, gravity plays a pivotal role in shaping our Universe and the things in it.

Ever since Newton formulated his universal law of gravitation the recognition that all things gravitate has been nearly sacrosanct. Repeatedly, apparent gravitational anomalies have either foretold the existence of new physics or a misunderstanding of gravity itself, from the existence of nuclear forces to Einstein's general relativity. Eighty years ago gravity betrayed the existence of dark matter, and fifteen

years ago gravity demanded dark energy from reluctant cosmologists. I

will discuss how gravity

enables modern cosmology to explore the echoes of the invisible universe, even if it is impossible or difficult to directly see the invisible universe. In particular, I will show how gravity enables us to put surprisingly severe constraints on the coupling of dark matter to new light particles and search for secret interactions between Fermi's elusive neutrinos. The physics and cosmic history of the invisible universe are writ large across the cosmos itself, and gravity is our tried and trusted messenger.

Gravity and the Search for New Physics with Cosmology

Gravity and the Search for New Physics with Cosmology

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UBC

October 30, 2013

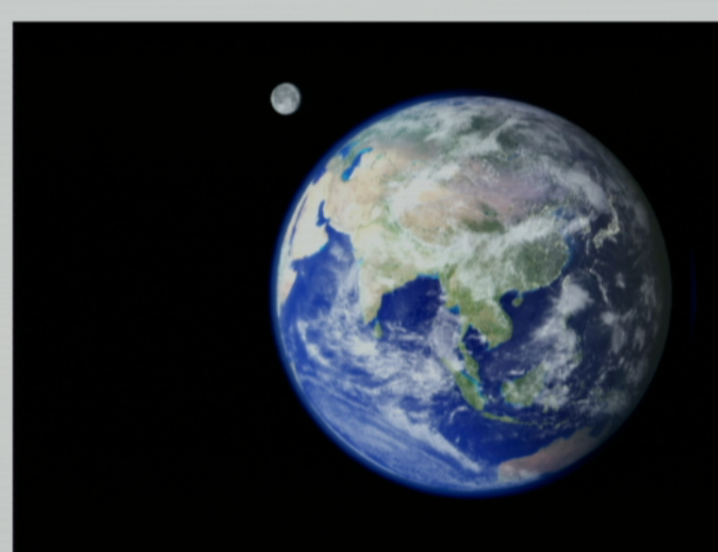
Colloqium

PERIMETER INSTITUTE

In case you forgot....

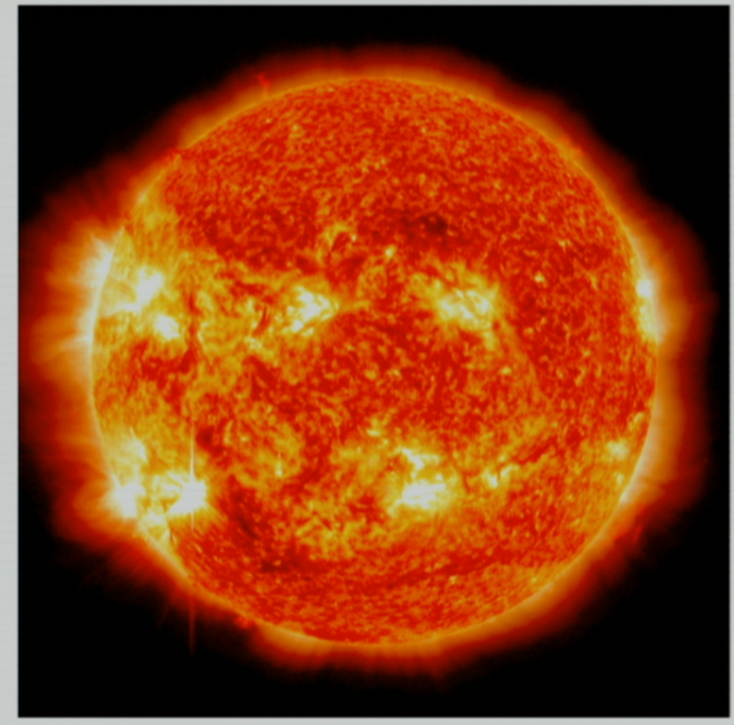
- Gravity plays a pivotal role in shaping our Universe and the things in it.
- This is because it is (usually) attractive and influences things at a long range.

Planets



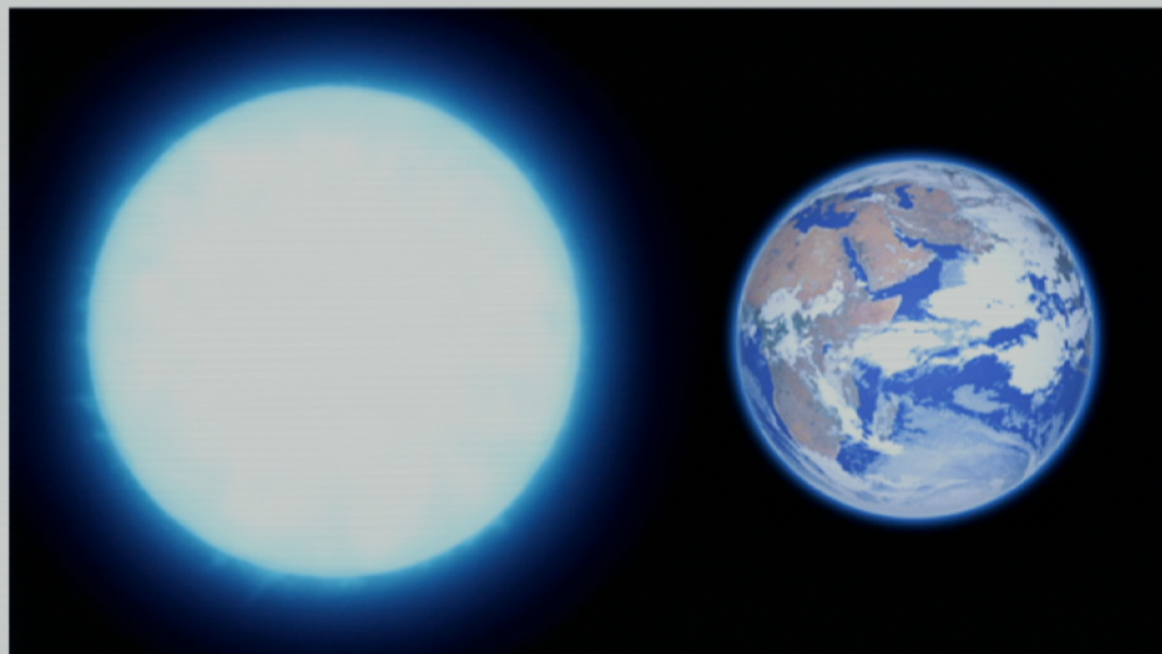
Gravity vs. Material/Fluid/Degeneracy Pressure

Stars



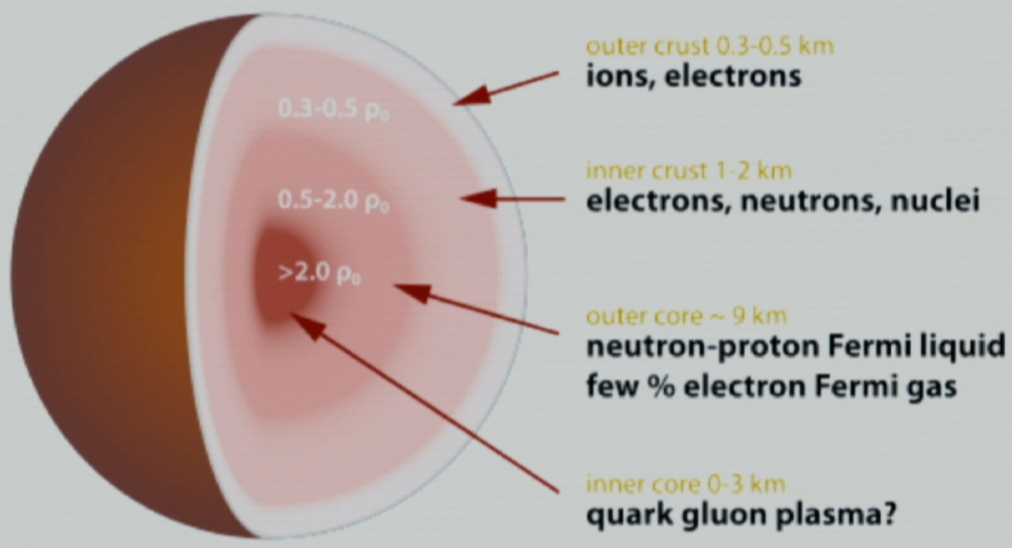
Gravity vs. Nuclear Energy

White Dwarf Stars



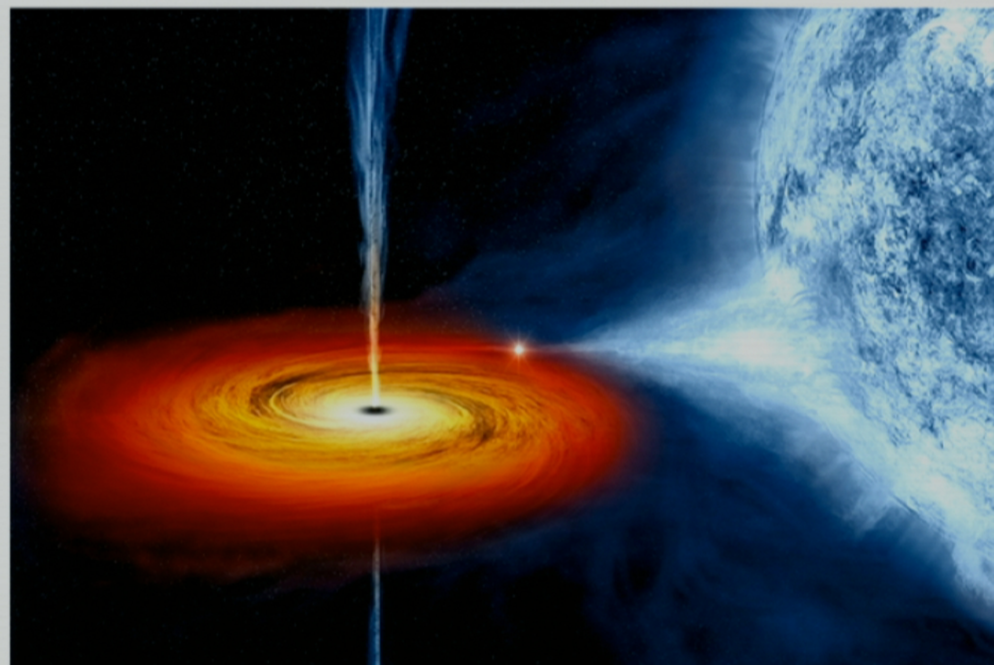
Gravity vs. Electron Degeneracy Pressure

Neutron Stars



Gravity vs. Neutron Degeneracy Pressure

Black Holes



Gravity Wins!

Galaxies

Bound System of Stars / Gas / ?

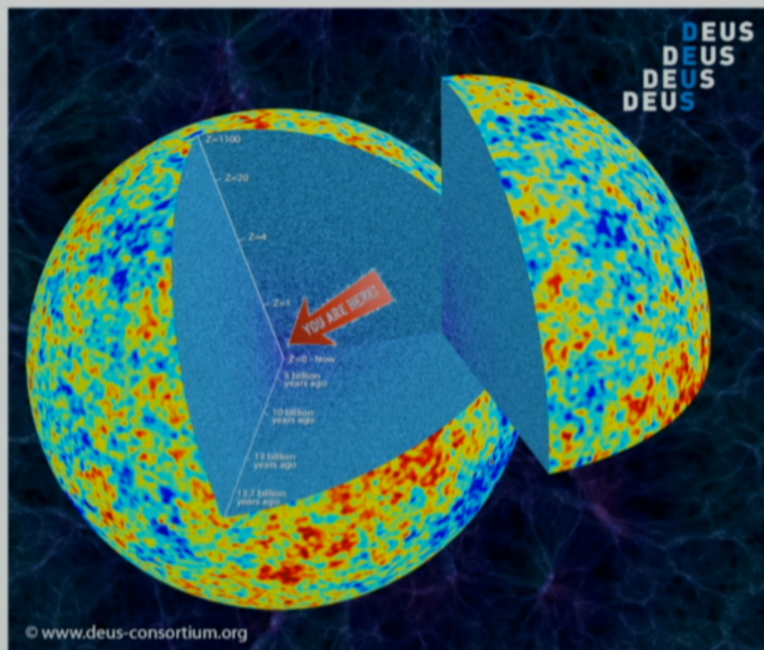
Clusters

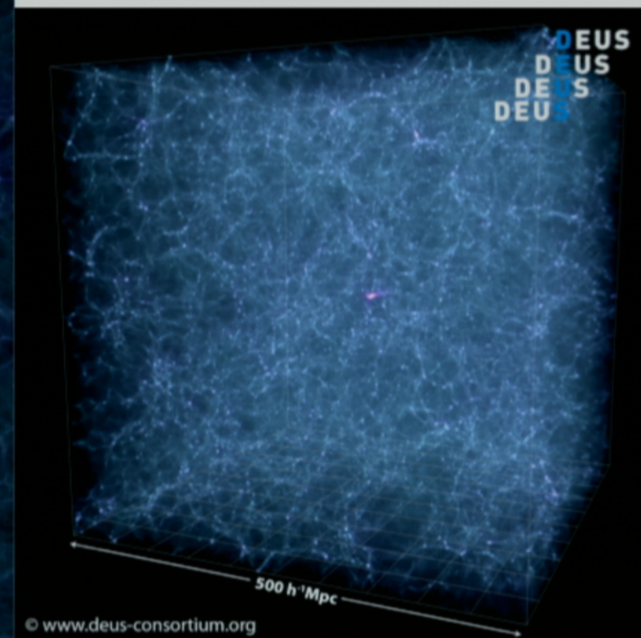
Coma Cluster

Image: Adam Block

Bound System of Galaxies / Gas / ?

Large Scale Structure

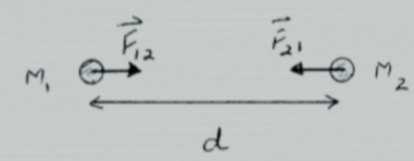




The Gravitational Scaffolding of the Universe

Newton's Universal Gravitation

As far as we know, all things gravitate the same way.



$$|\vec{F}_{12}| = |\vec{F}_{21}| = \frac{G M_1 M_2}{d^2}$$

$$\boxed{U = -\frac{3}{5}\frac{GM^2}{R}}$$

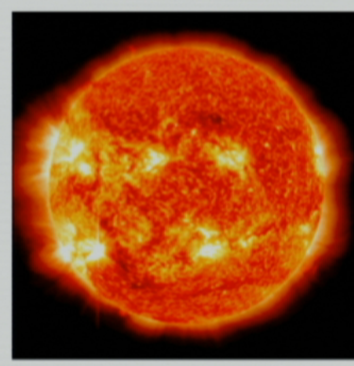
Gravitational Potential Energy
(of uniform sphere)

Size: R Mass: M
Not composition!

Gravity's Wrong or New Physics?
Let's Play!

Gravity's Wrong or New Physics?

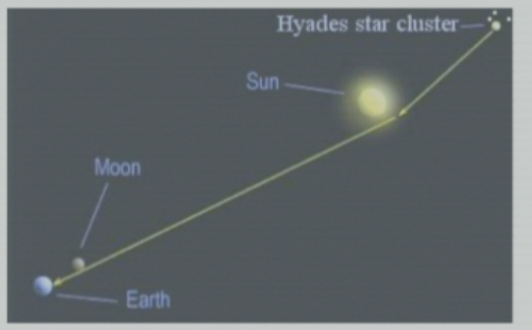
Q:



- 1854: Helmholtz suggests gravitational contraction power's the Sun! $\boxed{U = -\frac{3}{5}\frac{GM^2}{R}}$
- Kelvin-Helmholtz time for Sun is around 20-30 Myr, but geological/biological evidence suggests Earth's age is a Gyr or more. Why?

Gravity's Wrong or New Physics?

Q:



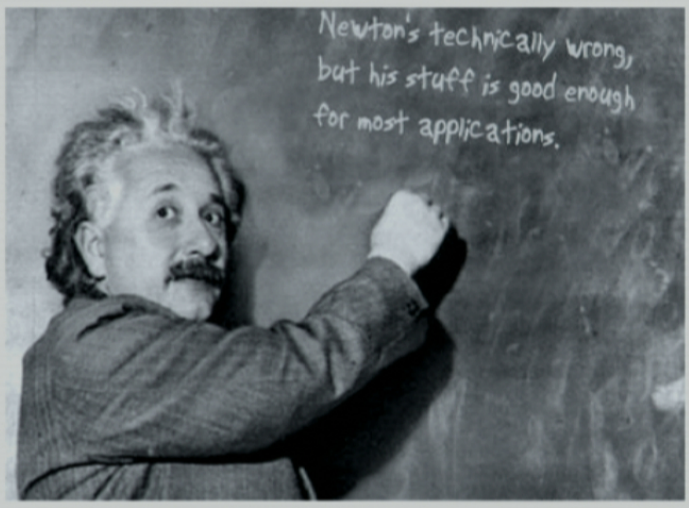
- All things gravitate, even light!
- 1801: Johann Georg von Soldner calculated that, according to Newtonian theory, light should be deflected by 0.875 arcseconds when grazing the surface of the Sun.
- 1919: Eddington measures value of 2*0.875 = 1.75 arcseconds

Gravity's Wrong or New Physics?

A:

- Gravity's Wrong!

(but still Universal)



Need General Relativity for Light Deflection and Cosmology!

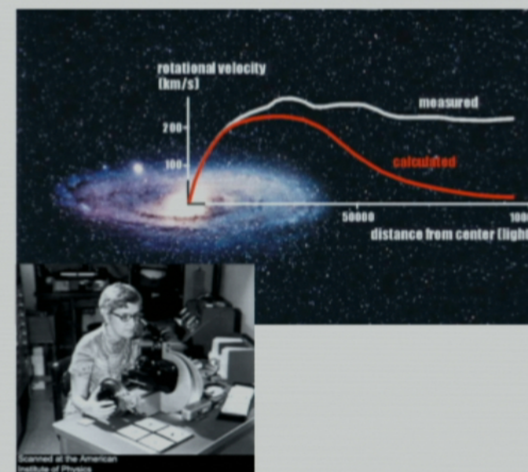
$$G_{\mu\nu} + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space is curved! → Factor of 2

Gravity is sourced not only by mass/energy densit
but also by pressures and stresses!

Gravity's Wrong or New Physics?

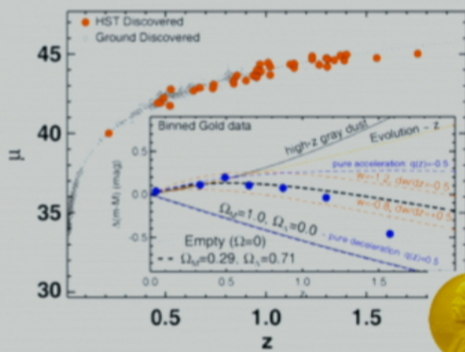
Q:



- 1933: Fritz Zwicky finds galaxies in Coma Cluster move too fast to be bound by their mutual gravity
- 1970's: Vera Rubin finds stars in galaxies are rotating too fast compared to their mass distribution

Gravity's Wrong or New Physics?

Q:



Saul Perlmutter | Brian P. Schmidt | Adam G. Riess

The Nobel Prize in Physics 2011 was awarded *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"* with one half to Saul Perlmutter and the other half jointly to Brian P. Schmidt and Adam G. Riess.

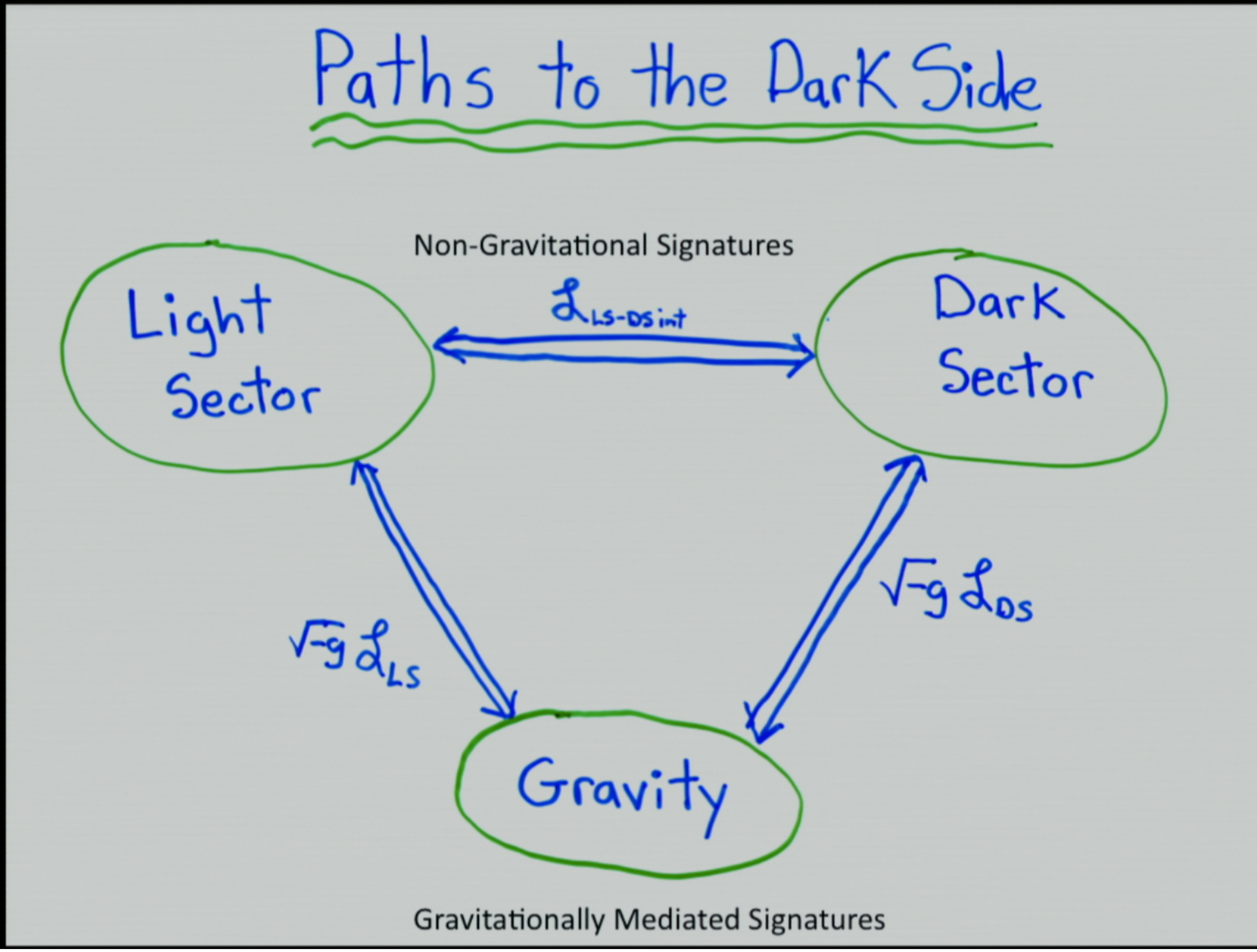
- 1998: Supernova Cosmology Project and High-z Supernova Search Team discover Universe is accelerating!

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

Gravity

Messenger of the Physicists

Universal gravity makes it possible to explore the physics of the invisible universe, even if it is impossible or difficult directly see the invisible universe, because the invisible universe gravitates and modifies the structure of the visible universe.


Paths to the Dark Side
Non-Gravitational Signatures
Light Sector
$\mathcal{L}_{LS\text{-}DS\,int}$
Dark Sector
$\sqrt{-g}\,\mathcal{L}_{LS}$
$\sqrt{-g}\,\mathcal{L}_{DS}$
Gravity
Gravitationally Mediated Signatures

Gravity and the Search for New Physics with Cosmology

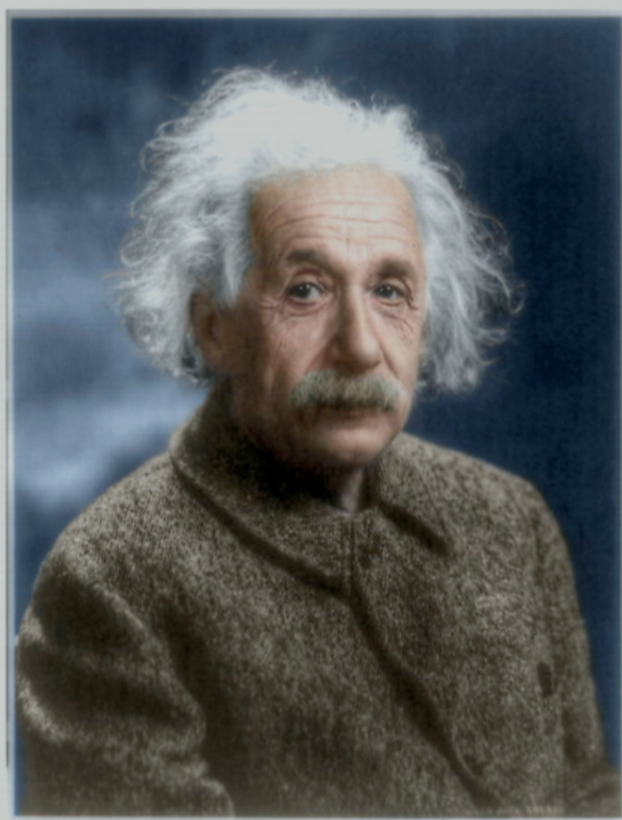
Gravity!!

Cosmological Perturbations.

I) Dark Matter and Dark Acoustic Oscillations (DAO)

II) Shear Stress and Secret Neutrino Interactions (SNI)

General Relativity and Cosmology



Geometry

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu},$$

Matter/Energy/Stre

$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} + \frac{\Lambda}{3},$$

$$\frac{1}{a}\frac{d^2a}{dt^2} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

Cosmological Perturbation Theory

Metric Perturbations about Friedmann-Robertson-Walker

$$ds^2 = a^2(\tau)[-(1+2\Psi)d\tau^2 + \delta_{ij}(1+2\Phi)dx^i dx^j]$$

Generally: Euler/Fluid Equations for Photons, Neutrinos, Baryons, and Dark Matter

For a Radiation Fluid:

$$\dot{\delta}_r + \frac{4}{3}\theta_r + 4\dot{\Phi} = 0 \qquad (\theta_r \equiv \vec{\nabla} \cdot \vec{v}_r)$$

$$\dot{\theta}_r + \nabla^2 \left(\frac{\delta_r}{4} + \Psi \right) = 0 \qquad \delta_r \equiv \frac{\rho_r - \bar{\rho}_r}{\bar{\rho}_r}$$

Plus Einstein Equations for Gravitational Potentials

For a Radiation Fluid: $\Phi = -\Psi$

$$\nabla^2\Phi + 3\frac{\dot{a}}{a}\left(\frac{\dot{a}}{a}\Psi - \dot{\Phi}\right) = -4\pi G a^2 \rho_r \delta_r$$

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Fourier Space

$$\vec{\nabla} \longrightarrow -i\vec{k}$$

Generally: Euler/Fluid Equations for Photons, Neutrinos, Baryons, and Dark Matter

For a Radiation Fluid:

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Plus Einstein Equations for Gravitational Potentials

For a Radiation Fluid: $\Phi = -\Psi$

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Einstein Equations

In detail the evolution is given by (see,e.g., Ma and Bertschinger 1995):

GEOMETRY = MATTER-ENERGY-STRESS

Poisson-like equation

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

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

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

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

Behavior of both invisible and visible
Matter/energy/pressure/stress
Perturbations are encoded by gravity

i-j compone

$$\delta T^0{}_0 = \delta\rho_{\mathrm{visible}} + \delta\rho_{\mathrm{invisible}}$$

$\Delta\psi$ Sourced by shear stresses

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Poisson-like equation

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

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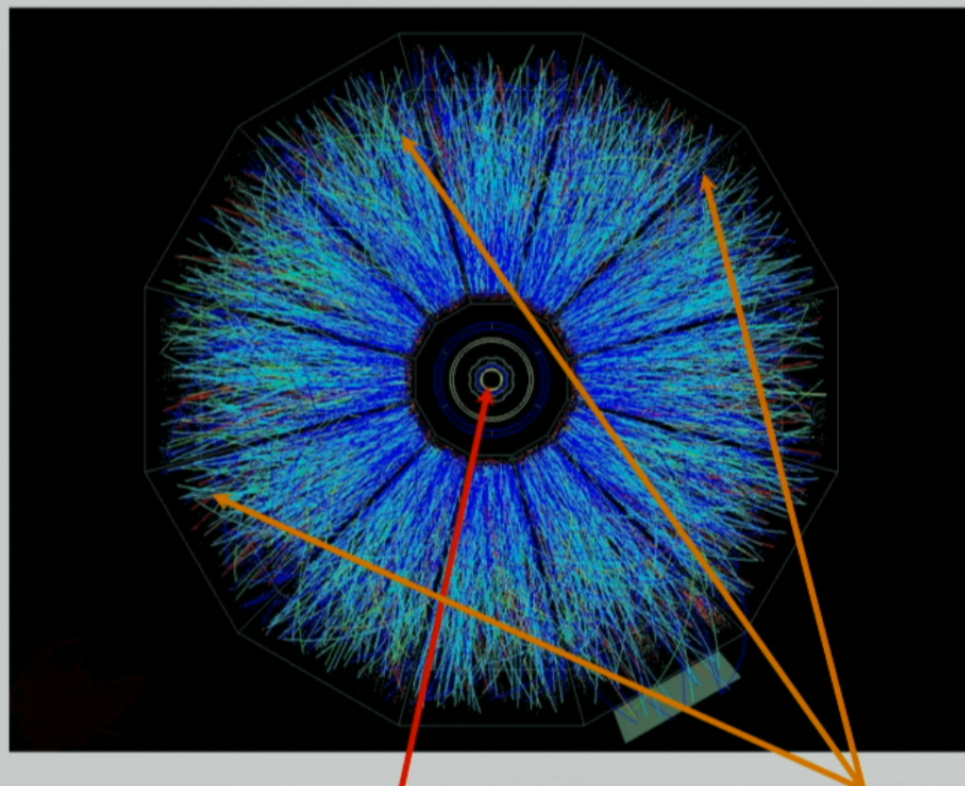
Behavior of both invisible and visible
Matter/energy/pressure/stress
Perturbations are encoded by gravity

$$\delta T^0{}_0 = \delta\rho_{\mathrm{visible}} + \delta\rho_{\mathrm{invisible}}$$

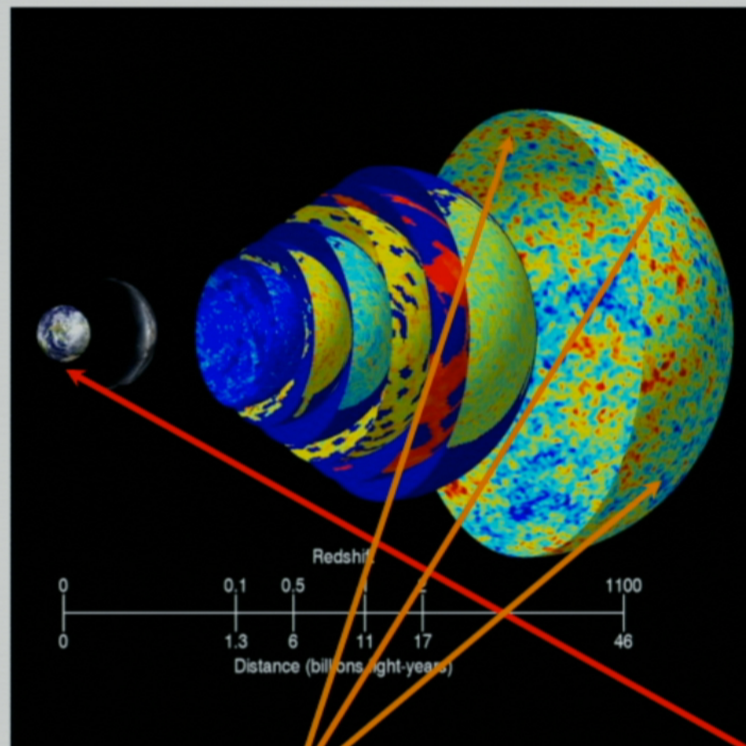
$\Delta\psi$ Sourced by shear stresses

LHC: A Modern Particle Physics Experiment



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

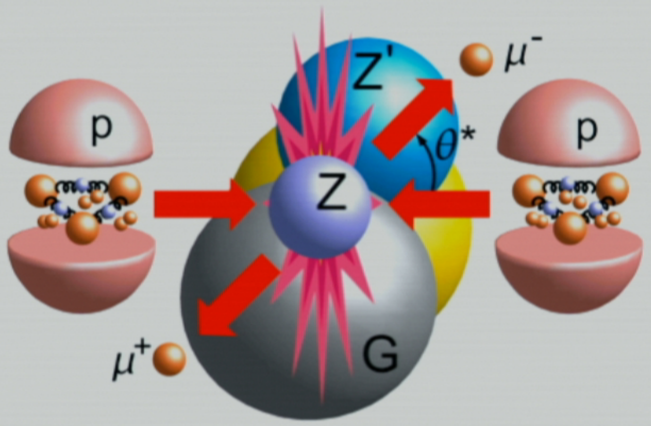
CMB: A Primordial Particle Physics Experiment



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

Carefully Set Up and Run the Experiment: Initial Conditions

LHC:



Carefully Set Up and Run the Experiment: Initial Conditions

CMB:

Adiabatic Initial Conditions

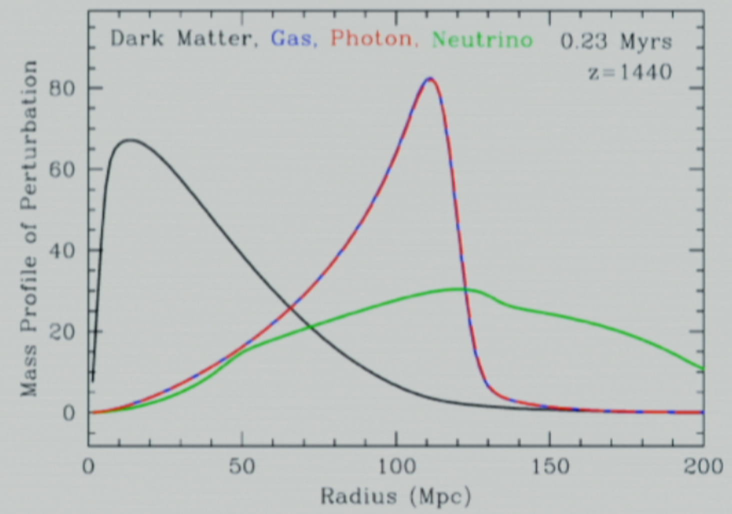


Image: Eisenstein

Evolve According to Linear Perturbation Theory

Carefully Repeat under the Same Conditions:

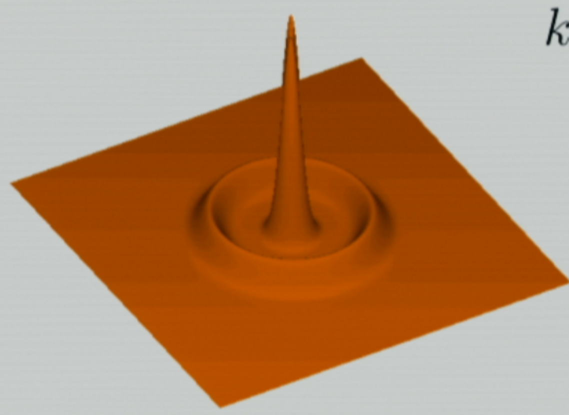
CMB:

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

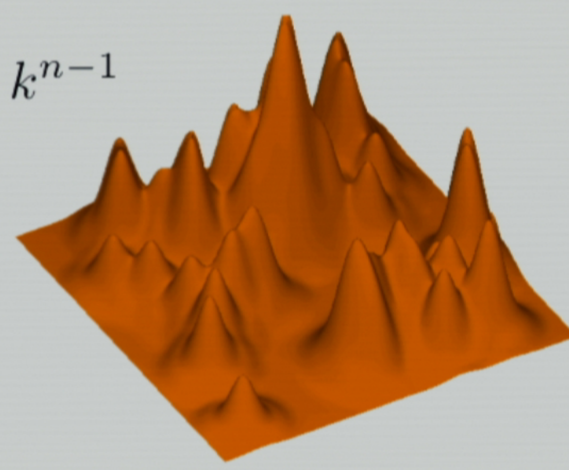
Perform the same experiment everywhere in the Universe with Gaussian random field initial conditions and a nearly scale-invariant power spectrum for the curvature perturbation.

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

$$n \simeq 1$$



Green's Function of Adiabatic Evolution



Convolved with Random Curvature Field

Dark Matter and Dark Acoustic Oscillations

arXiv: 1310.3278, "Constraints on Large-Scale Dark Acoustic Oscillations from Cosmology"
Francis-Yan Cyr-Racine, Roland de Putter,
Alvise Raccanelli and KS.

arXiv: 1209.5752, "The Cosmology of Atomic Dark Matter"
Phys. Rev. D87 103515,
Francis-Yan Cyr-Racine and KS.

Dark Matter and Dark Acoustic Oscillations

- If all or a fraction of Dark Matter couples to Relativistic Particles (Dark Radiation) then the combined system will generically support acoustic oscillations – sound waves!
- Dark Matter gets pushed around for some distance by the Dark Radiation before it decouples.
- This imprints a characteristic scale, the DAO Scale, on the matter distribution that can be detected gravitationally

It might have New Physics!

Baryonic Matter and Baryon Acoustic Oscillations

- If all or a fraction of Baryonic Matter couples to Relativistic Particles (Radiation) then the combined system will generically support acoustic oscillations – sound waves!
- Baryonic Matter gets pushed around for some distance by the Radiation before it decouples.
- This imprints a characteristic scale, the BAO Scale, on the matter distribution that can be detected gravitationally

Compton Coupling

Photon Density $$\dot{\delta}_\gamma = -\frac{4}{3}\theta_\gamma + 4\dot{\phi}\,,$$

Photon Velocity $$\dot{\theta}_\gamma = k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) + k^2 + a n_e \sigma_T(\theta_b - \theta_\gamma)$$

Compton Collision Terms:

Momentum Transfer Tends to Equalize Bulk Velocities of Photon and Baryon Fluid

Baryon Density $$\dot{\delta}_b = -\theta_b + 3\dot{\phi}\,,$$

Baryon Velocity $$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_s^2 k^2 \delta_b + \frac{4\bar{\rho}_\gamma}{3\bar{\rho}_b} a n_e \sigma_T(\theta_\gamma - \theta_b) + k^2\psi$$

Tight-Coupling into a Single Photon-Baryon Fluid When:

$$a n_e \sigma_T \equiv \tau_c^{-1} \gg \dot{a}/a \sim \tau^{-1}$$

Ideal Radiation Fluid

For an Ideal Radiation Fluid:

$$\dot{\delta}_r + \frac{4}{3}\theta_r + 4\dot{\Phi} = 0$$

$$\dot{\theta}_r - k^2\left(\frac{\delta_r}{4} + \Psi\right) = 0$$

$$-k^2\Phi + 3\frac{\dot{a}}{a}\left(\frac{\dot{a}}{a}\Psi - \dot{\Phi}\right) = -4\pi G a^2 \rho_r \delta_r$$

$$\Phi = -\Psi$$

Physics of P/BAO: Harmonic Oscillator Approximation

For a Perfect Radiation Fluid: (ONLY DENSITY AND VELOCITY PERTURBATIONS)

$$\Phi(\chi) = \frac{9\Phi_0}{\chi^3}\left[\sqrt{3}\sin\left(\frac{\chi}{\sqrt{3}}\right) - \chi\cos\left(\frac{\chi}{\sqrt{3}}\right)\right],$$

$$\delta_r(\chi) = \frac{6\Phi_0}{\chi^3}\left[2\sqrt{3}(\chi^2-3)\sin\left(\frac{\chi}{\sqrt{3}}\right) - \chi(\chi^2-6)\cos\left(\frac{\chi}{\sqrt{3}}\right)\right],$$

$$\tilde{\theta}_r(\chi) = -\frac{3\sqrt{3}\tilde{k}\Phi_0}{2\chi^2}\left[2\sqrt{3}\chi\cos\left(\frac{\chi}{\sqrt{3}}\right) + (\chi^2-6)\sin\left(\frac{\chi}{\sqrt{3}}\right)\right],$$

Exact!

$\chi \equiv k\tau$

Physics of P/BAO: Harmonic Oscillator Approximation

For a Perfect Radiation Fluid: (ONLY DENSITY AND VELOCITY PERTURBATIONS)

Potential Tends to Zero

$$\Phi(\chi) = \frac{9\Phi_0}{\chi^3}\left[\sqrt{3}\sin\left(\frac{\chi}{\sqrt{3}}\right) - \chi\cos\left(\frac{\chi}{\sqrt{3}}\right)\right],$$

$$\delta_r(\chi) = \frac{6\Phi_0}{\chi^3}\left[2\sqrt{3}(\chi^2-3)\sin\left(\frac{\chi}{\sqrt{3}}\right) - \chi(\chi^2-6)\cos\left(\frac{\chi}{\sqrt{3}}\right)\right],$$

$$\tilde{\theta}_r(\chi) = -\frac{3\sqrt{3}\tilde{k}\Phi_0}{2\chi^2}\left[2\sqrt{3}\chi\cos\left(\frac{\chi}{\sqrt{3}}\right) + (\chi^2-6)\sin\left(\frac{\chi}{\sqrt{3}}\right)\right],$$

Becomes Cosine Solution for Large $\chi \equiv k\tau$

Physics of P/BAO: Harmonic Oscillator Approximation

$$\dot{\delta}_r + \frac{4}{3}\theta_r + 4\dot{\Phi} = 0$$

$$\dot{\theta}_r - k^2\left(\frac{\delta_r}{4} + \Psi\right) = 0$$

$\xrightarrow{\text{Late Time / Subhorizon}}$

$$\dot{\delta}_r + \frac{4}{3}\theta_r = 0$$

$$\dot{\theta}_r - k^2\frac{\delta_r}{4} = 0$$

$$\ddot{\delta}_r + \frac{1}{3}k^2\delta_r = 0$$

$$\delta_r \propto \cos\left(\frac{1}{\sqrt{3}}k\tau\right)$$

A Harmonic Oscillator When Tightly Coupled

Physics of P/BAO: Forced Harmonic Oscillator

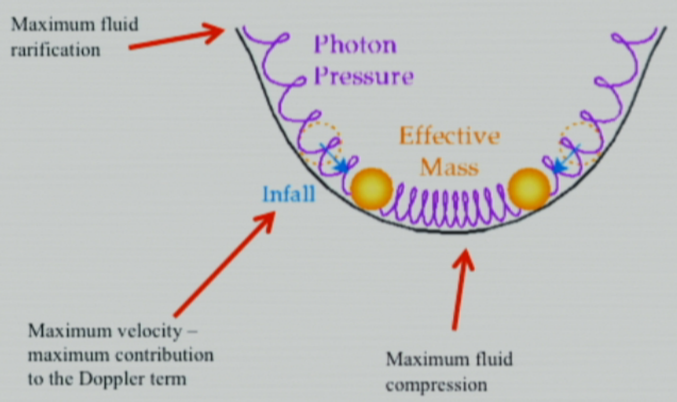


Figure: W. Hu et al.

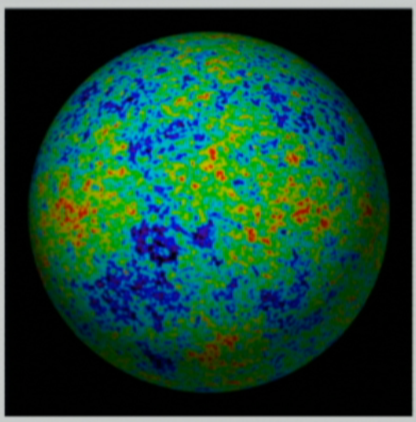
$$\frac{d}{d\tau}\left[m_{\rm eff}\frac{d\delta_b}{d\tau}\right]+\frac{k^2}{3}\delta_b=F[\Psi] \qquad m_{\rm eff}=1+3\rho_b/4\rho_\gamma$$

A Better Description, including non-tight coupling, is a Forced Harmonic Oscillator with a time-dependent "effective-mass"

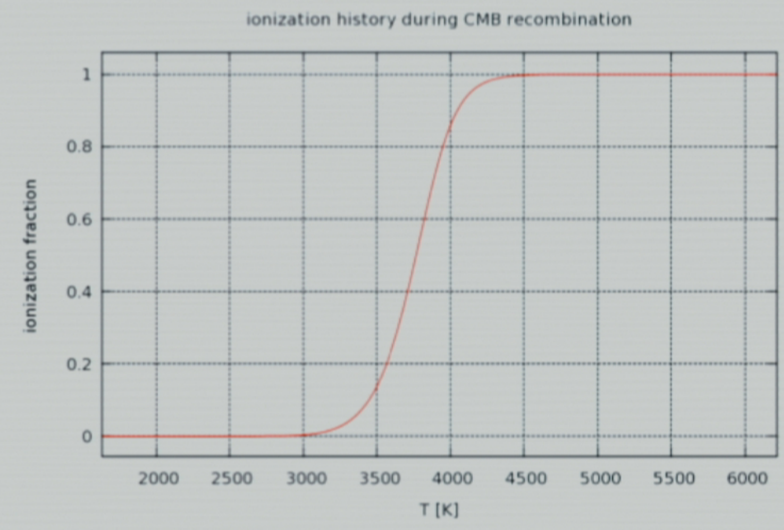
Baryon-Photon Fluid Supports Acoustic Waves!

At least until it ceases to exist as a "single" fluid!

Formation of Atoms: Recombination



Credit: WMAP



Electron Density Plummets!!

Photons and baryons Stop Scattering!!

End of the PBAO Era – Photons Move Ballistically Through the Universe at the Speed of Light

End of the PBAO Era – Baryons Stop Moving; Overdense Regions Gravitationally Collapse

The Sound Horizon:
The BAO Scale

For a Perfect Radiation Fluid:

$$P = \frac{1}{3}\rho \qquad c_s = \sqrt{\frac{dP}{d\rho}} = \frac{1}{\sqrt{3}} \simeq 0.57$$

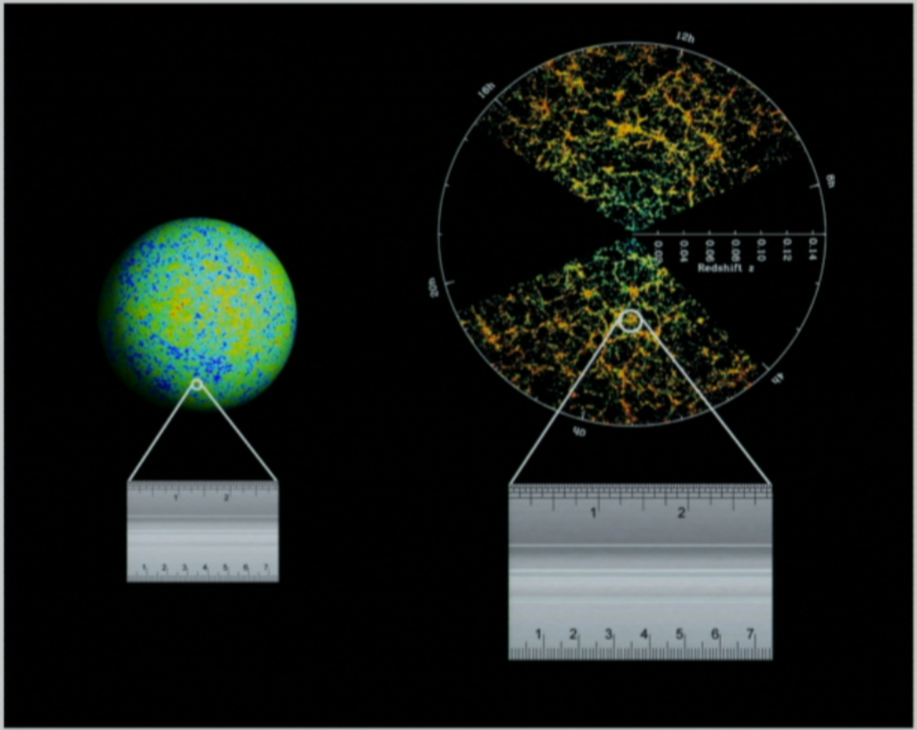
$$s = \frac{1}{\sqrt{3}}\tau_{ls}$$

In the real Universe:

$$s = \int_0^{\tau_{ls}} c_s(\tau) d\tau$$

Calculated from Known Atomic Physics.

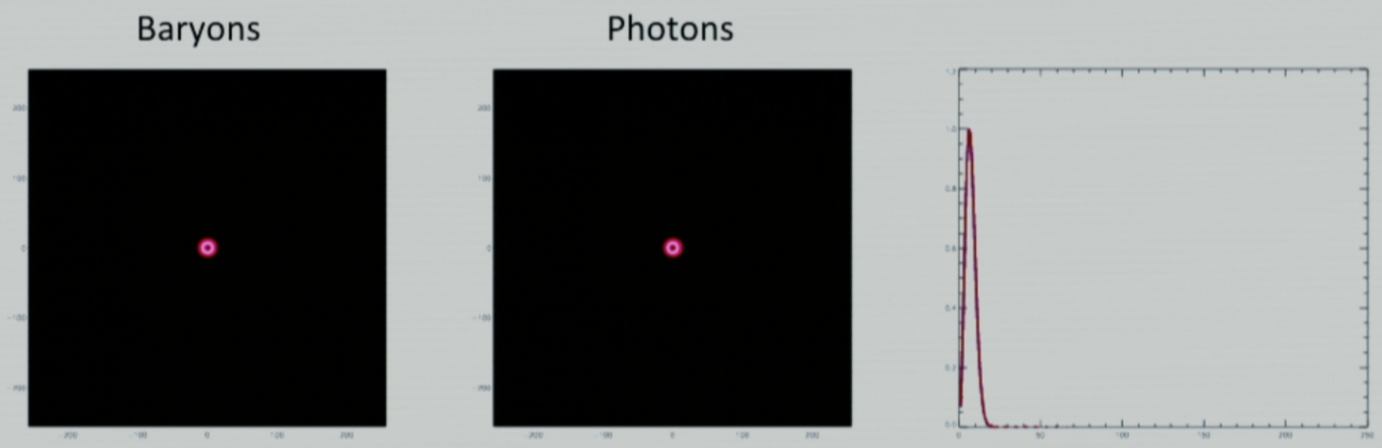
BAO Scale: in the CMB and LSS



$$s = 146.8 \pm 1.8\ \mathrm{Mpc}$$ WMAP 5th yr data

$$= (4.53 \pm 0.06) \times 10^{24}\mathrm{m}$$

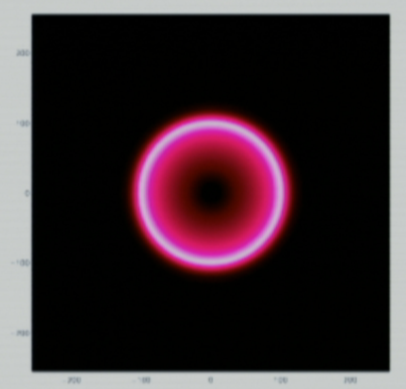
Photon-Baryon Acoustic Oscillations



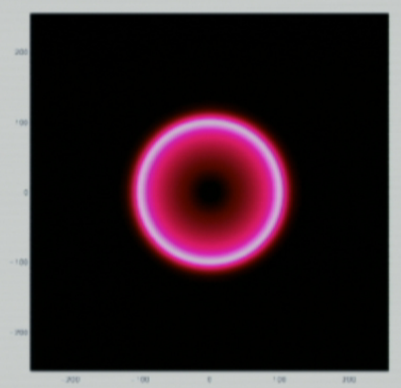
Images: Martin White

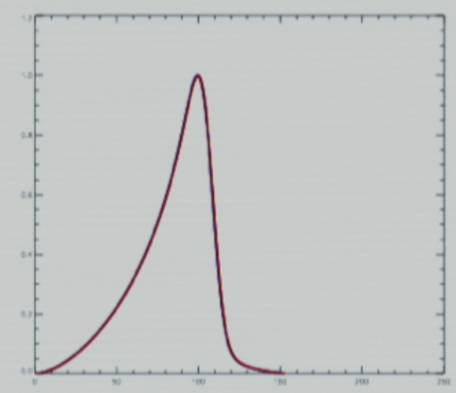
Photon-Baryon Acoustic Oscillations

Baryons



Photons



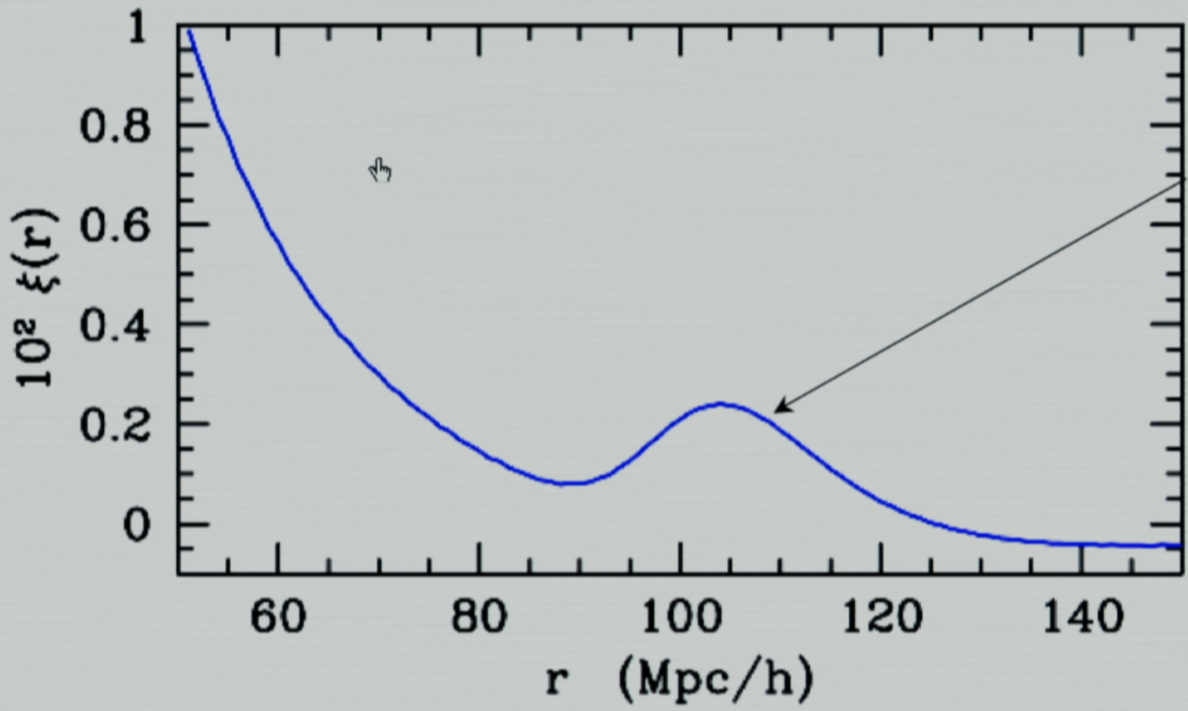


Age of 100,000 years
z ~ 2350

Images: Martin White

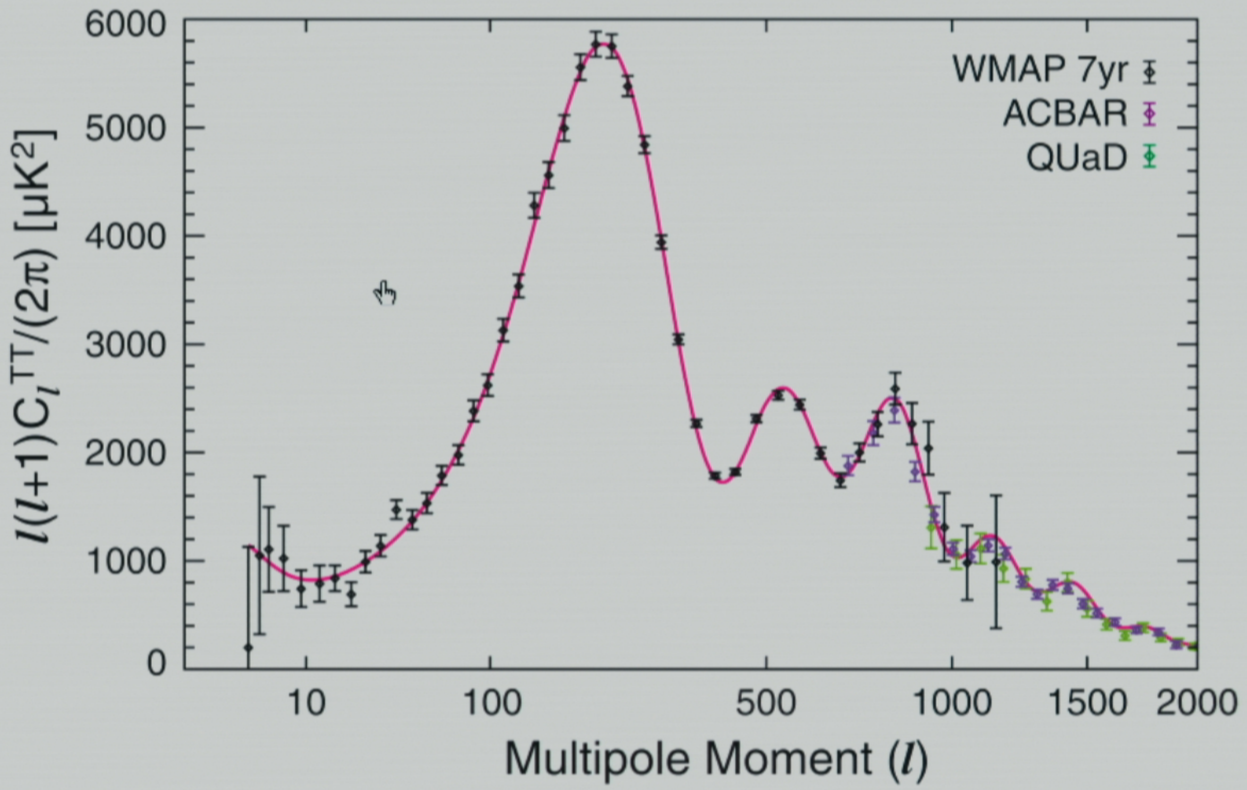
BAO Scale: Real Space

$$\xi(r) = \xi(|\vec{x} - \vec{x}'|) = \langle \delta(\vec{x})\delta(\vec{x}') \rangle$$



Credit: M. White

P/BAO Observed!



Komatsu et al. 2010


DON'T BE AFRAID
OF THE
DARK

Dark Matter and Dark Acoustic Oscillations

Interacting Fraction $f_{\rm int} \equiv \rho_{\rm int}/\rho_{\rm DM}$

Dark Radiation Density $\Delta N_{\rm eff} \leftrightarrow \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\xi^4$ $\quad \xi \equiv (T_D/T_{\rm CMB})|_{z=0}$

DM-DR Interaction Cross Section

$$\left(\frac{\sigma_{\rm DM-DR}(a_D)}{m_D}\right) = 1.9\times 10^{-4}\left(\frac{\xi}{0.5}\right)\left(\frac{\Sigma_{\rm DAO}}{10^{-3}}\right) \times \left(\frac{f_{\rm int}\Omega_{\rm DM}h^2}{0.12}\right)^{-1}\frac{\rm cm^2}{\rm g}.$$

Parameterize with $\Sigma_{\rm DAO}$

Examples: "The Cosmology of Atomic Dark Matter" Francis-Yan Cyr-Racine and KS.
(Dark Copy of Hydrogen)

"Double-Disk Dark Matter" JiJi Fan, Andrey Katz, Lisa Randall, Matthew Reece
(Dark Copy of Hydrogen – a fraction of all dark matter couples relatively strongly)

DAO Scale: Sound Horizon of Dark Matter

$$r_{\mathrm{DAO}} \equiv \int_0^{\eta_D} c_D(\eta)\, d\eta,$$

DM-DR soundspeed
(depends on microphysics)

$$r_{\mathrm{DAO}} = \frac{4\xi^2\sqrt{\Omega_\gamma}}{3H_0\sqrt{f_{\mathrm{int}}\Omega_{\mathrm{DM}}\Omega_{\mathrm{m}}}} \times \ln\left[\frac{\sqrt{\gamma_{\mathrm{int}}}\sqrt{\Omega_{\mathrm{r}}+\Omega_{\mathrm{m}}a_D}+\sqrt{\Omega_{\mathrm{m}}+\gamma_{\mathrm{int}}a_D}}{\sqrt{\gamma_{\mathrm{int}}\Omega_{\mathrm{r}}}+\sqrt{\Omega_{\mathrm{m}}}}\right]$$

$$\gamma_{\mathrm{int}} \equiv \frac{3f_{\mathrm{int}}\Omega_{\mathrm{DM}}}{4\xi^4\Omega_\gamma}$$

Evolution of coupled DM-DR Fluctuations

Dark Matter

$$\dot{\delta}_D + \theta_D - 3\dot{\phi} = 0,$$

$$\dot{\theta}_D + \frac{\dot{a}}{a}\theta_D - c_D^2 k^2 \delta_D - k^2\psi = \frac{R_D}{\tau_D}(\theta_{\tilde{\gamma}} - \theta_D)$$

$$\dot{\delta}_{\tilde{\gamma}} + \frac{4}{3}\theta_{\tilde{\gamma}} - 4\dot{\phi} = 0;$$

Dark Radiation

$$\dot{\theta}_{\tilde{\gamma}} - k^2\left(\frac{1}{4}\delta_{\tilde{\gamma}} - \frac{F_{\tilde{\gamma}2}}{2}\right) - k^2\psi = \frac{1}{\tau_D}(\theta_D - \theta_{\tilde{\gamma}});$$

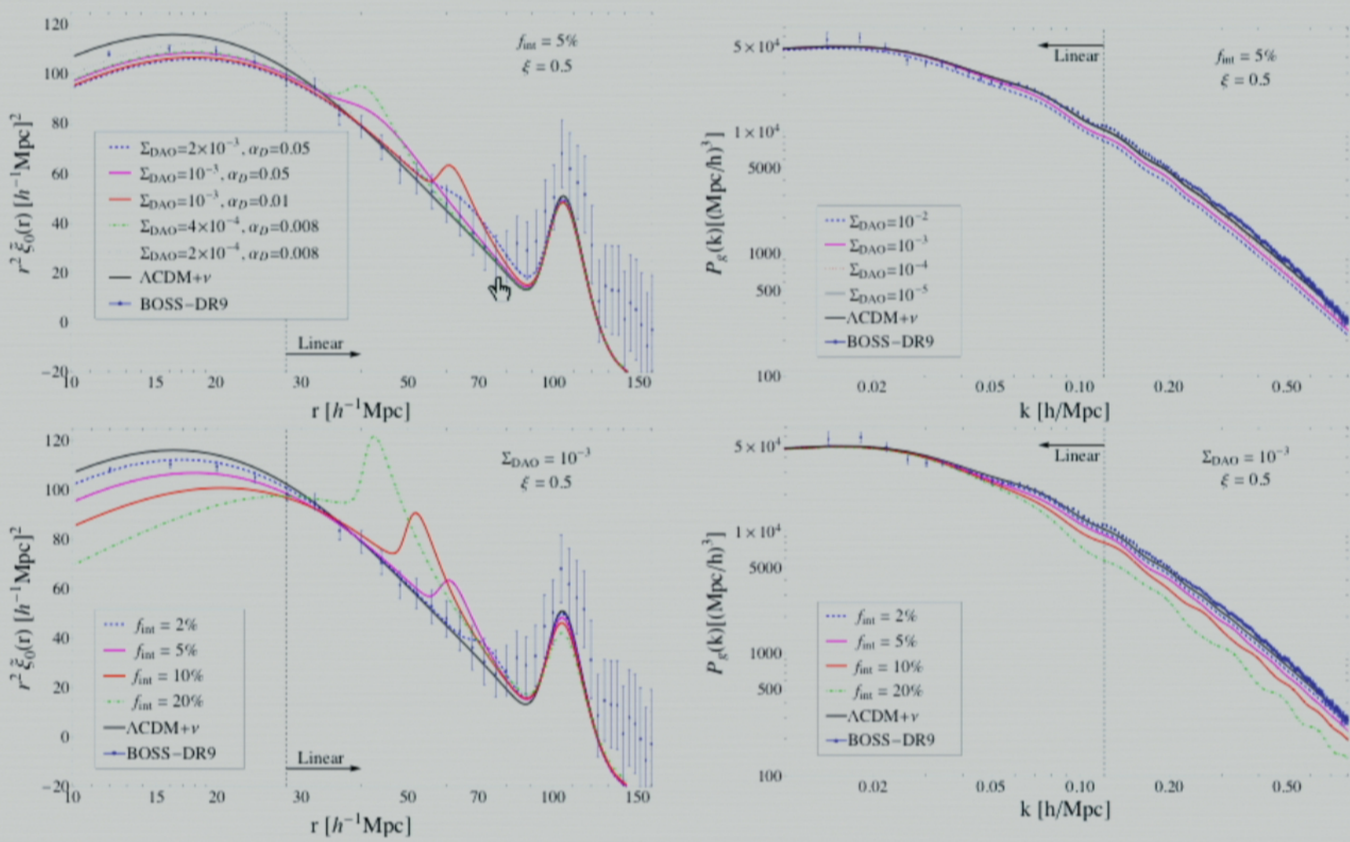
Dark Radiation Scattering Time

τ_D

$$\dot{F}_{\tilde{\gamma}2} = \frac{8}{15}\theta_{\tilde{\gamma}} - \frac{3}{5}kF_{\tilde{\gamma}3} - \frac{9}{10\tau_D}F_{\tilde{\gamma}2};$$

$$\dot{F}_{\tilde{\gamma}l} = \frac{k}{2l+1}\left[lF_{\tilde{\gamma}(l-1)} - (l+1)F_{\tilde{\gamma}(l+1)}\right] - \frac{1}{\tau_D}F_{\tilde{\gamma}l}.$$

DAO in the Matter Correlation Function and Power Spectrum



CMB Lensing

Lensing of the CMB by the Matter Distribution is sensitive to DM physics!

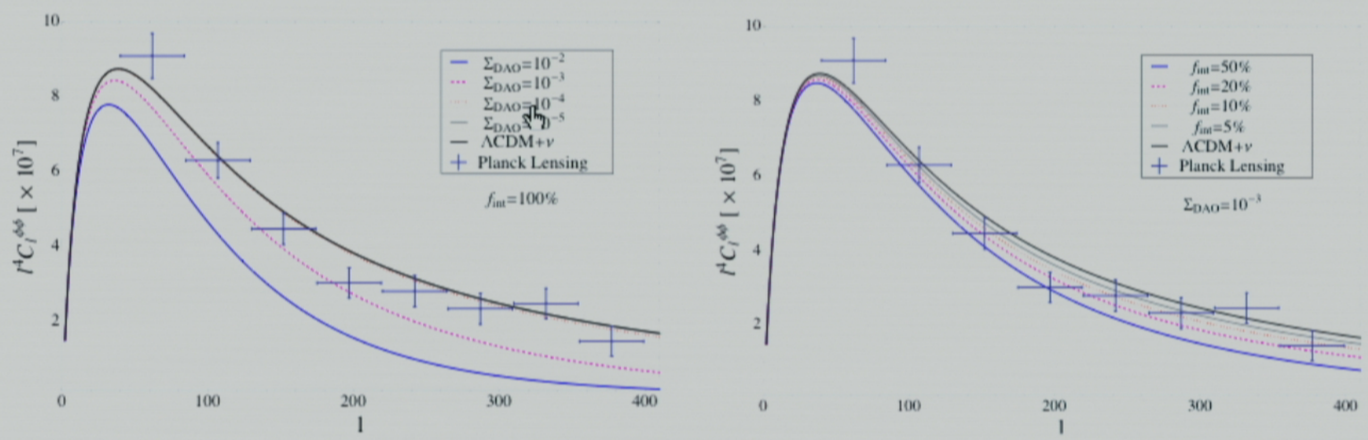
$$\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_*} d\chi\, \psi(\chi\hat{\mathbf{n}};\eta_0-\chi)\frac{\chi_*-\chi}{\chi\chi_*},$$

$$C_l^{\phi\phi} = 16\pi\int \frac{dk}{k}P_{\mathcal{R}}(k)|\Delta_\psi(k)|^2,$$

$$\Delta_\psi(k) = \int_0^{\chi_*} d\chi T_\psi(k;\eta_0-\chi))j_l(k\chi)\frac{\chi_*-\chi}{\chi\chi_*},$$

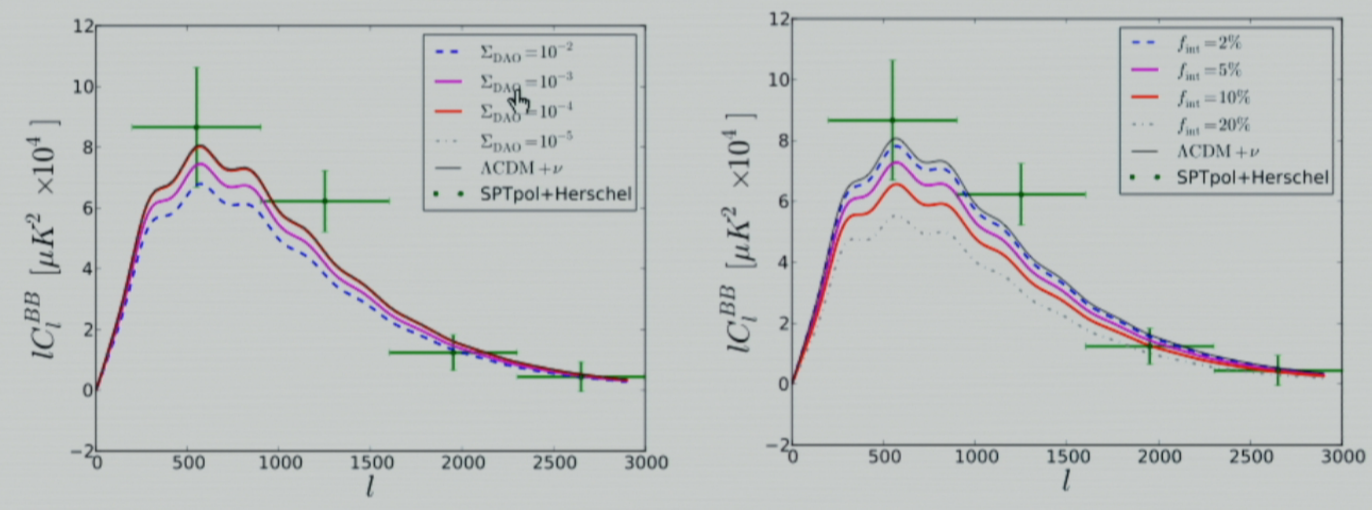
$$\psi(k,\eta) \;=\; T_\psi(k,\eta)\mathcal{R}(k),$$

Planck Projected Potential Constraints



$$C_l^{\phi\phi} = 16\pi \int \frac{dk}{k} P_{\mathcal{R}}(k) |\Delta_\psi(k)|^2,$$

CMB Lensing B-modes



DAO Constraints

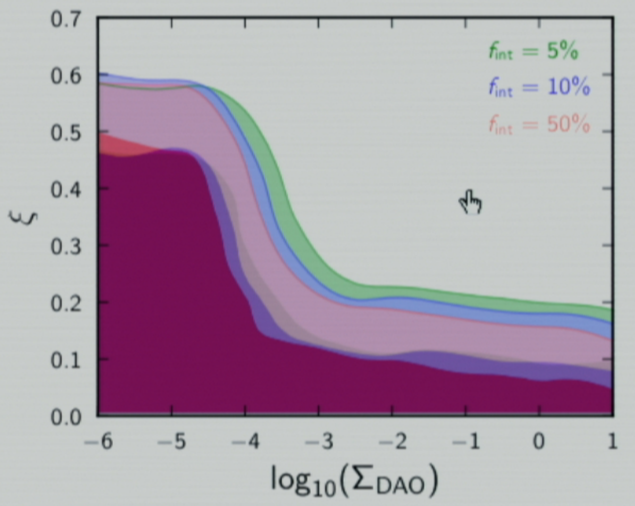


FIG. 11: Marginalized constraints on ξ and $\Sigma_{\rm DAO}$ for three fixed values of $f_{\rm int}$. We display the 68% and 95% confidence regions for the dataset "Planck+WP+High-l+BAO+Lens".

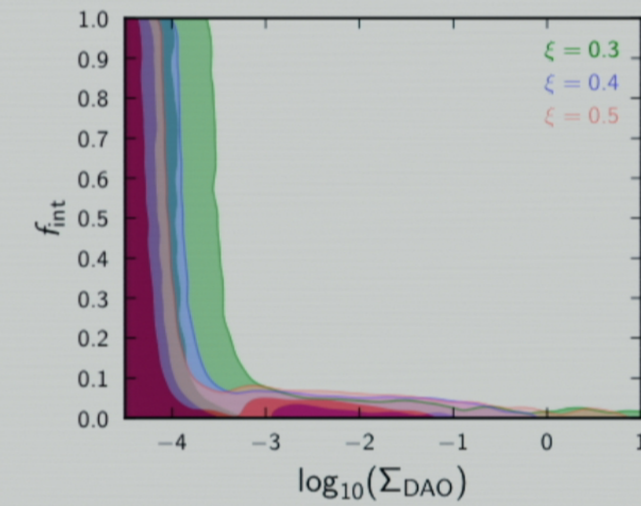


FIG. 13: Marginalized constraints on $f_{\rm int}$ and $\Sigma_{\rm DAO}$ for three values of ξ. Here, we have fixed $\alpha_D = 0.05$ and $m_D = 10$ GeV. We display the 68% and 95% confidence regions for the dataset "Planck+WP+High-l+BAO+Lens".

Limits on the Interacting Fraction

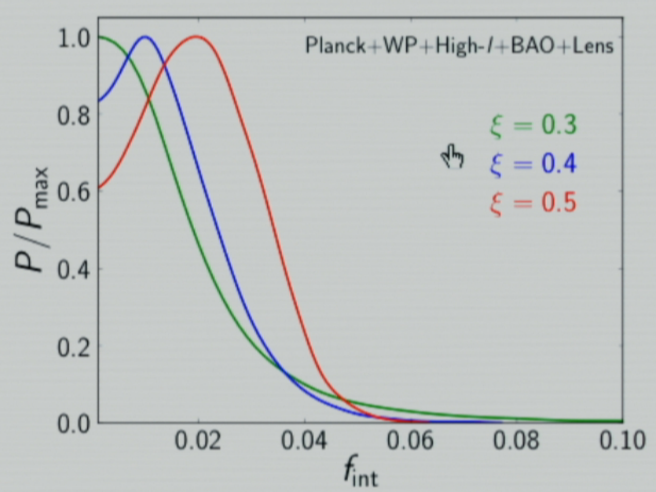
ξ	CMB+DR9	CMB+BAO
0.3	< 0.085	< 0.049
0.4	< 0.018	< 0.035
0.5	0.02 ± 0.016	< 0.038

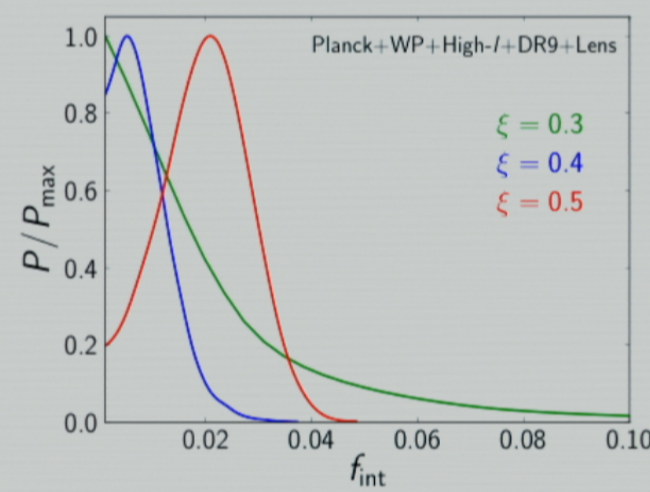
$\xi = 0.3$ corresponds to $\Delta N_{\rm eff} \simeq 0.036$

Key Result:

Less than 5% of all Dark Matter can interact strongly with Dark Radiation!

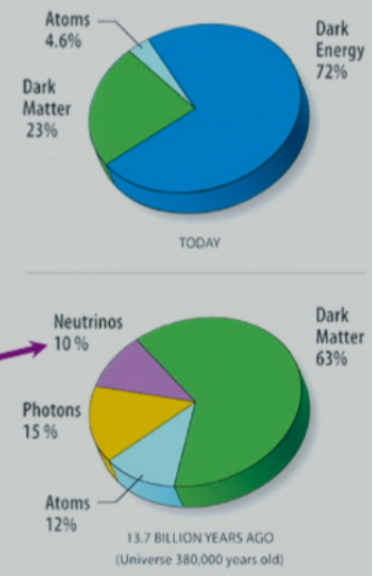
Limits on the Interacting Fraction





Shear Stress and Secret Neutrino Interactions

arXiv: 1306.1536, "Limits on Neutrino-Neutrino Scattering in the Early Universe"
Francis-Yan Cyr-Racine and KS.



The Early Universe: A Natural Source of Particles of All Sorts:
Photons, Electrons, Protons, Helium
"Dark Matter Particle", Neutrinos

CMB: A "Metricometer"

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

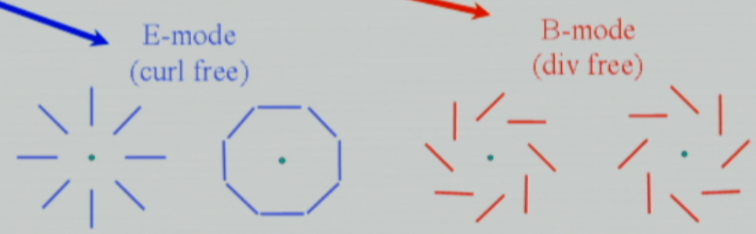
$$\begin{aligned} g_{00} &= -a^2(\tau)\,\{1 + 2\psi(\vec{x},\tau)\}\ , \\ g_{0i} &= a^2(\tau)\,w_i(\vec{x},\tau)\,, \\ g_{ij} &= a^2(\tau)\,\{[1 - 2\phi(\vec{x},\tau)]\delta_{ij} + \chi_{ij}(\vec{x},\tau)\}\ , \qquad \chi_{ii} = 0 \end{aligned}$$

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

Scalar Potentials

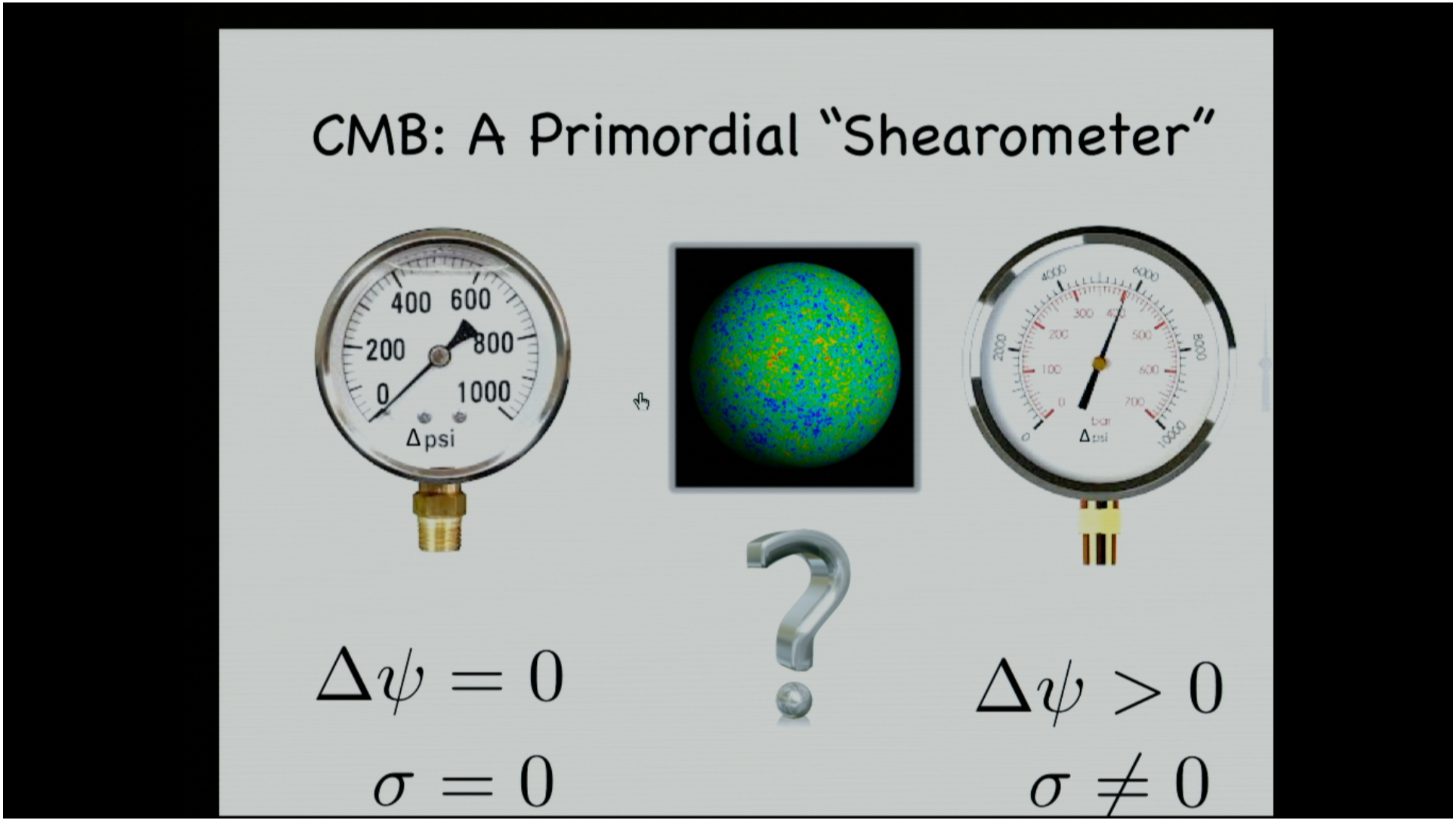
In contrast to Newtonian gravity, scalar perturbations in GR are described by two gravitational potentials rather than one (gravity is a spin-2 field not spin-0)

$$\psi = \Psi$$ Gravitational Potential in the Newtonian Limit

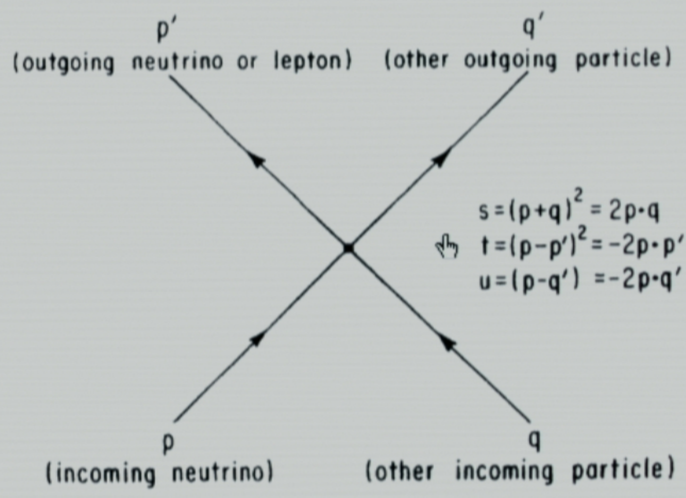
$$\phi = -\Phi$$ Curvature Perturbation

$$\Delta\psi = \psi - \phi$$ Difference Sourced by Shear Stresses

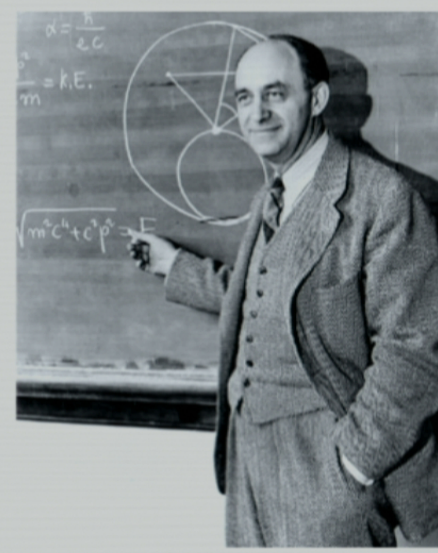
$$\sigma$$


CMB: A Primordial "Shearometer"
400 600
200 800
0 1000
Δpsi
$\Delta\psi = 0$
$\sigma = 0$
$\Delta\psi > 0$
$\sigma \neq 0$

Low Energy ν−ν Scattering



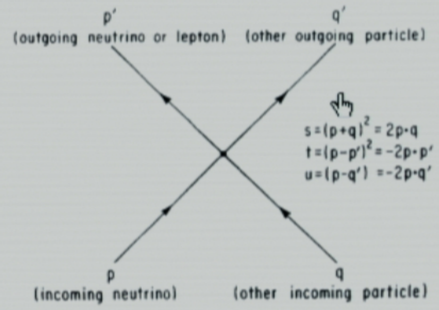
4 Fermion Interaction

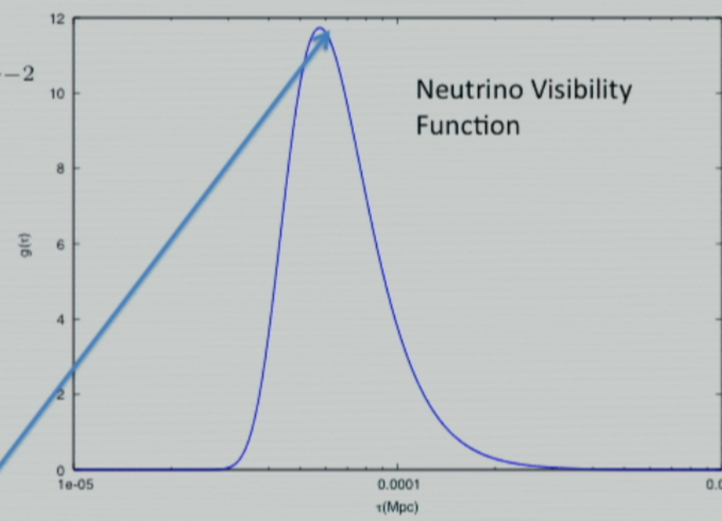


Prof. Fermi

Weak Neutrino Decoupling

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





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

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

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)

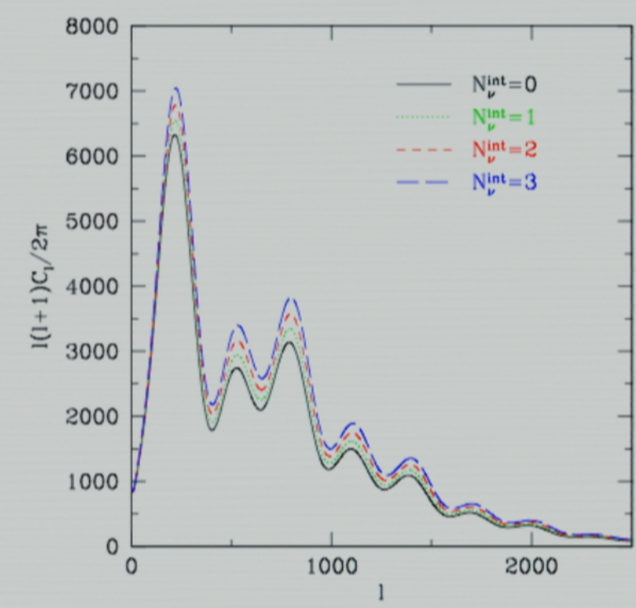
$$d_\gamma(\tau, k) = 3\zeta_{\rm in}(1+\Delta_\gamma)\cos(\varphi_s + \delta\varphi) + O(\varphi_s^{-1}),$$

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

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

Francis-Yan Cyr-Racine

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

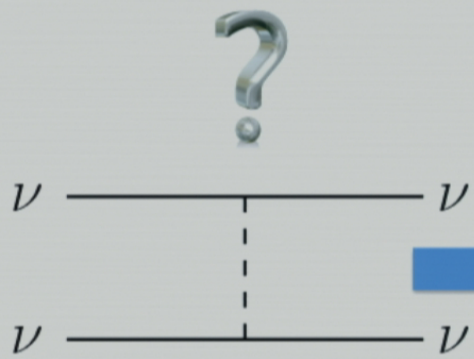
Kris Sigurdson

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

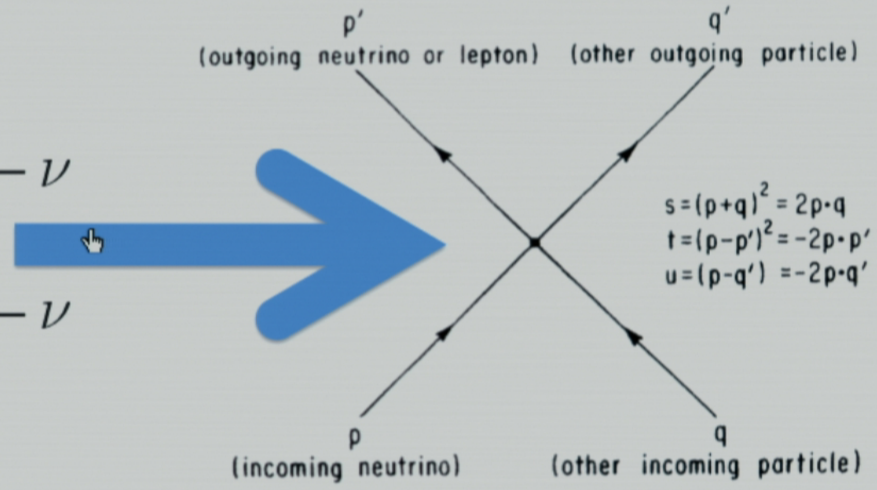
(Dated: June 10, 2013)

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 use observations of the CMB to constrain the strength of neutrino self-interactions $G_{\rm eff}$ and put limits on new physics in the neutrino sector from the early Universe. Recent 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 ΛCDM parameters cosmological data are compatible with $G_{\rm eff} \lesssim 1/(56\,{\rm MeV})^2$ 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 $z \sim 10^4$ with a preferred interaction strength in a narrow region around $G_{\rm eff} \simeq 1/(10\,{\rm MeV})^2$. This distinct self-interacting neutrino cosmology is characterized by somewhat lower values of both the scalar spectral index and the amplitude of primordial fluctuations. While we phrase our discussion here in terms of a specific scenario in which a late onset of neutrino free-streaming could occur, our constraints on the neutrino visibility function are very general.

Self-Interacting Neutrinos



New Unknown
Contact Interaction



4 Fermion Interaction

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

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

General Neutrino Decoupling

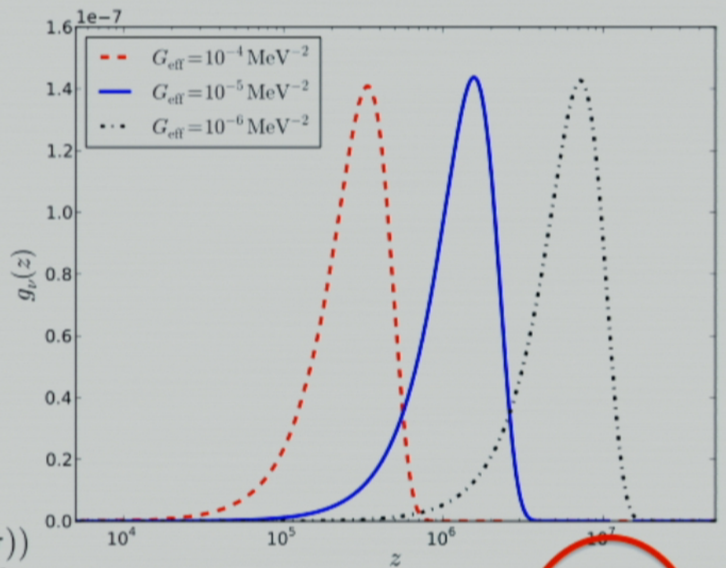
Thermalized Cross Section

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

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

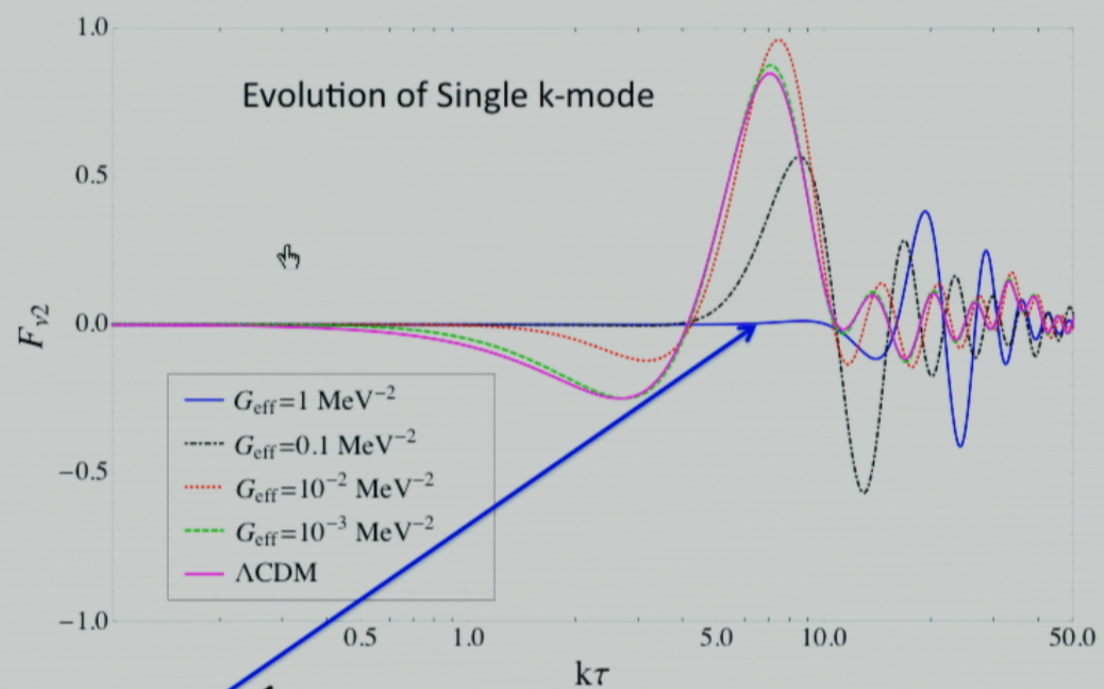
$$\dot{F}_{\nu 2} = \frac{8}{15}\theta_\nu + \frac{8}{15}k\sigma - \frac{3}{5}kF_{\nu 3} + \frac{9}{10}\alpha_2 \dot{\tau}_\nu F_{\nu 2},$$

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

Extra Neutrino Interactions → Delayed Neutrino free streaming!

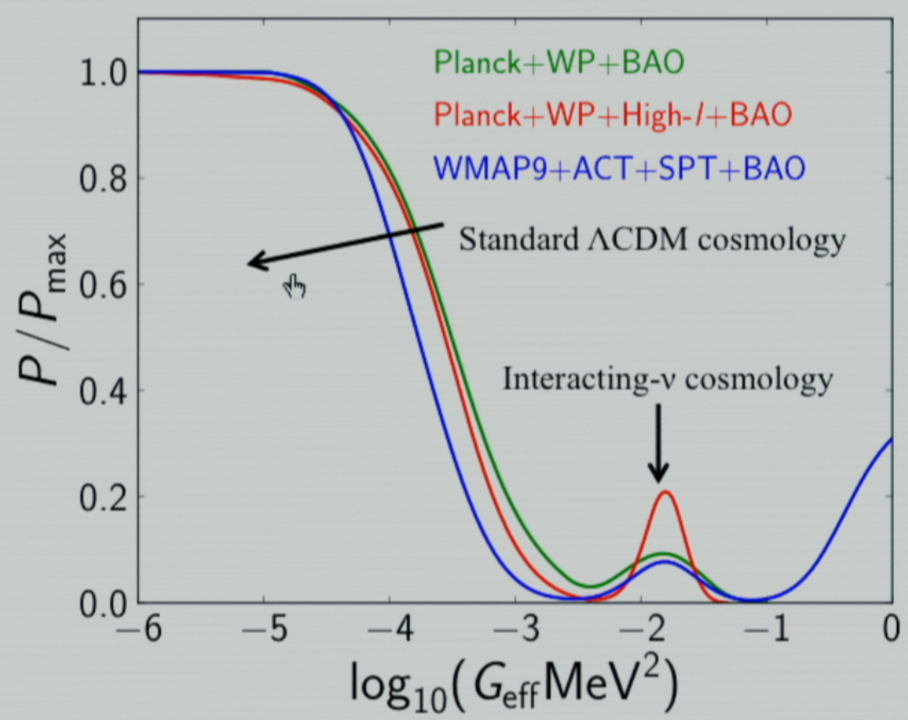
General Neutrino Decoupling

σ



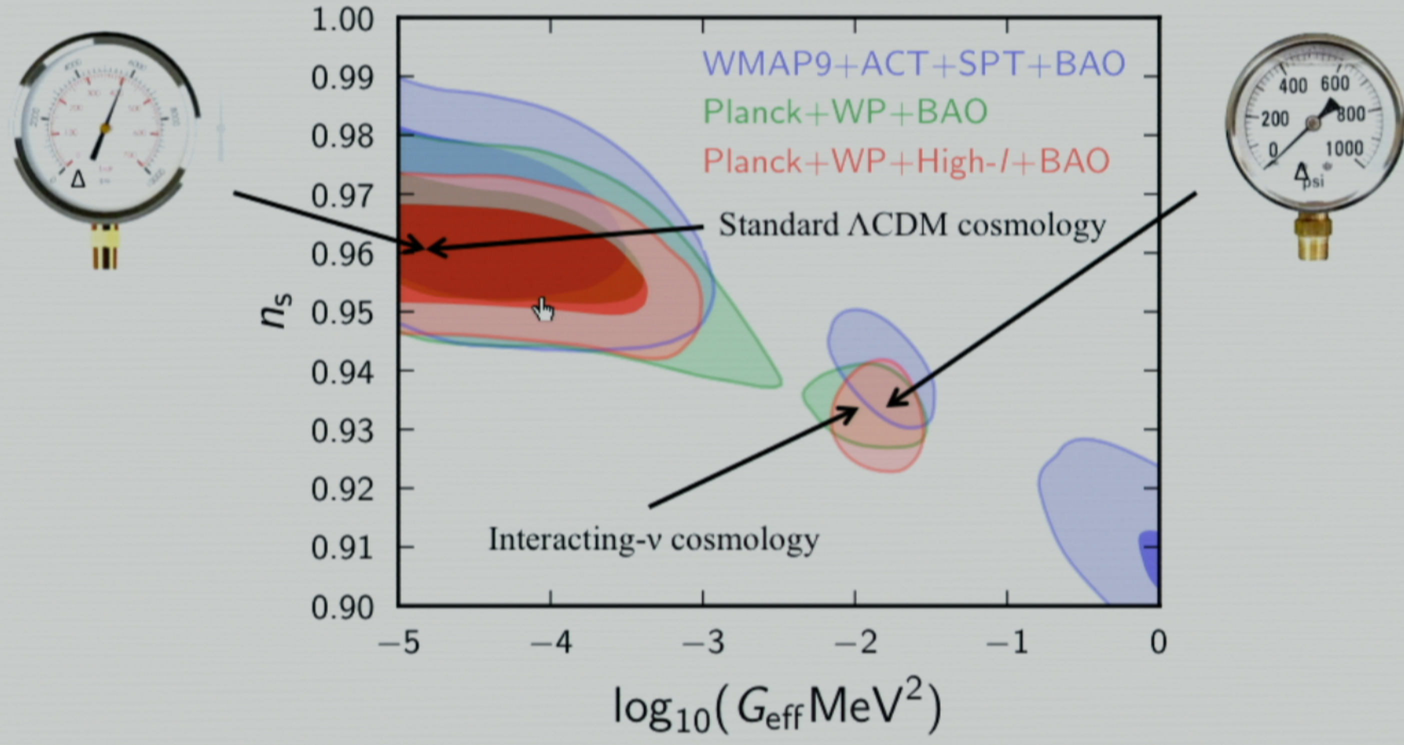
$\cancel{\sigma}$ Missing Shear Stress!

Constraints on G_{eff} from the CMB

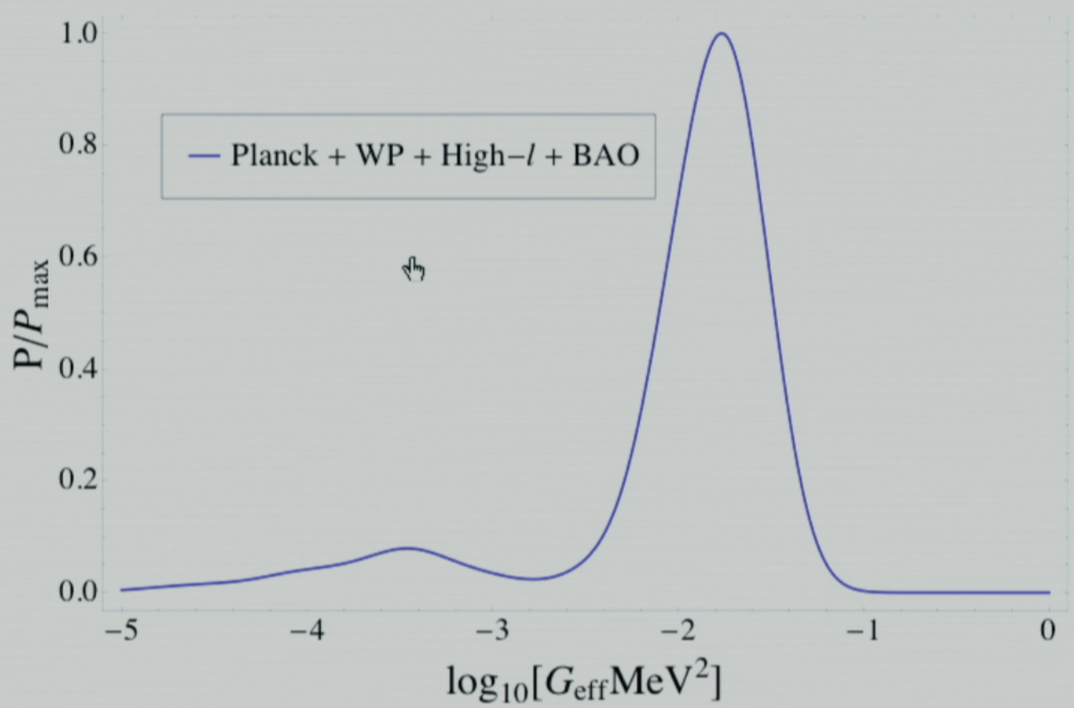


$$\frac{G_{\mathrm{F}}}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_{\mathrm{W}}^2} = 1.16637(1) \times 10^{-11}\,\mathrm{MeV}^{-2}$$

Constraints on G_{eff} from the CMB



Interacting Neutrinos?



Shear Stress and Secret Neutrino Interactions

- 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
$\Omega_{\rm b} h^2$	0.0221 ± 0.0002	0.0222 ± 0.0003
$\Omega_{\rm c} h^2$	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
$n_{\rm s}$	0.959 ± 0.006	0.932 ± 0.006
$10^9 A_{\rm s}$	2.19 ± 0.02	2.07 ± 0.02
$\log$ [illegible] $\mathrm{MeV}^2)$	$<$ [illegible]3.5 (95% C.L.)	[illegible]

Gravity

Messenger of the Physicists

Universal gravity makes it possible to explore the physics of the invisible universe, even if it is impossible or difficult directly see the invisible universe, because the invisible universe gravitates and modifies the structure of the visible universe.

Gravity attracts Hollywood