Summary of Observational Cosmology

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Physics 330

May 7, 2020

The Four Pillars of Big Bang Cosmology

- Expansion
- Cosmic Microwave Background (CMB)
- Nucleosynthesis (BBN)
- Structure Formation

Questions

- Dark Matter
- Dark Energy
- Baryogenisis

Olber's paradox

If the universe is static, infinitely large and with an infinite number of stars distributed uniformly, then the night sky should be bright.

The Hubble constant

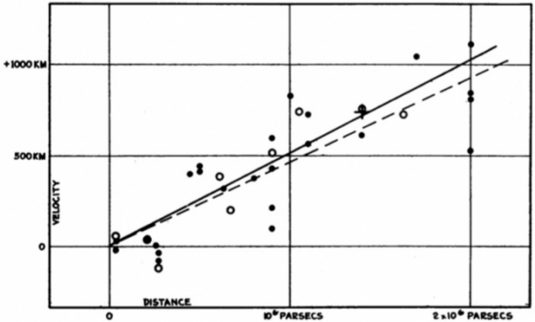
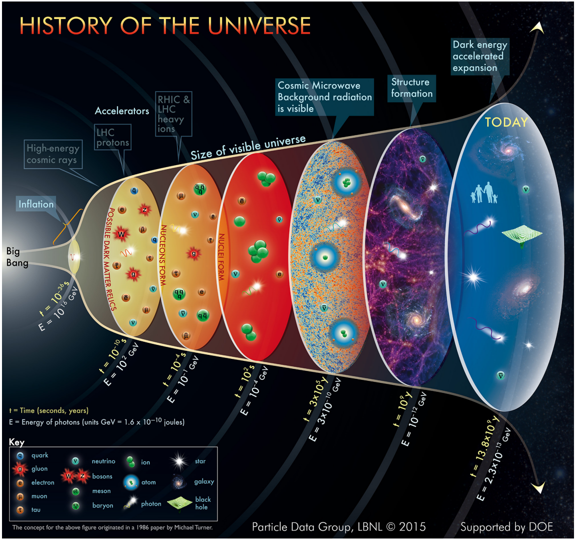


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

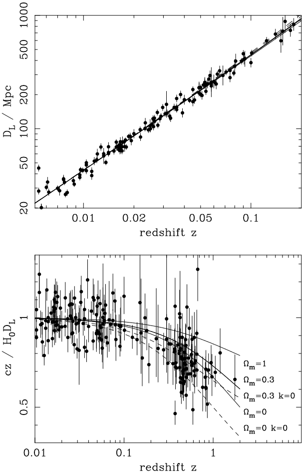
Expansion rate given by Hubble constant $v = H_0 r$, with value $\mathrm{H}_0 \approx 70\mathrm{km/s/Mpc}$

1 parsec (pc) = 3.3 light-years. The milky way is 16 Kpc in diameter.

Big Bang Cosmology



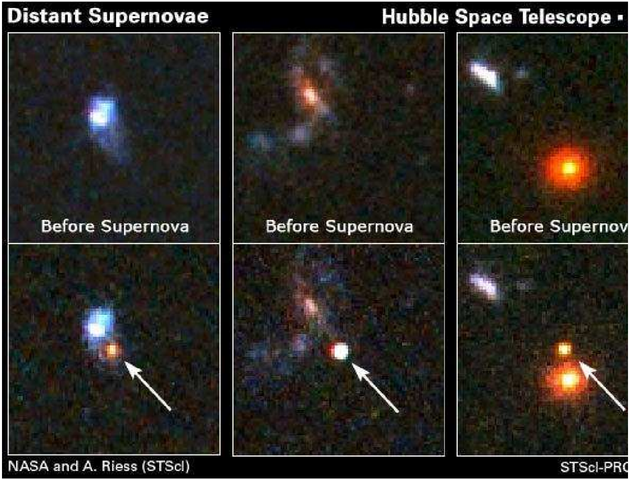
1) Expansion



Top shows that for small $Z << 1$, expansion is linear. Bottom: Linear expansion divided out, showing that the Hubble law becomes non-linear for large Z. Results strongly favor flat (k=0) universe with $\Omega_{Vac} \approx 0.7$.

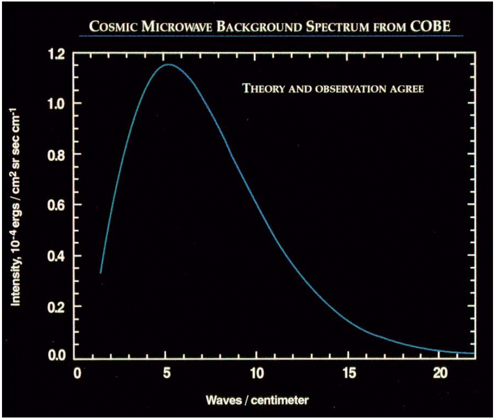
Type 1A Supernovae

Supernovae examples from Hubble.



Type 1A identified by light "curve" (intensity vs time) and used as standard candles.

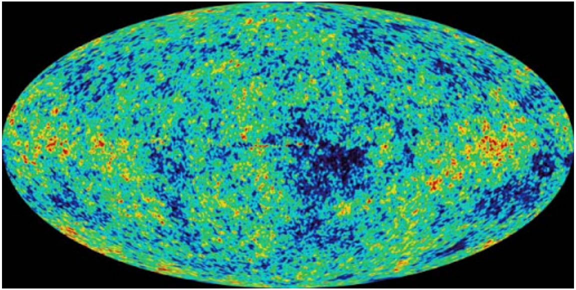
2) Cosmic Microwave Background (CMB)



photon decoupling: Universe becomes transparent to CMB photons at T=10^4K (1eV) at time 380,000 y. Red shift $Z \approx 1000$ where

$$Z = \frac{\lambda_{obs}}{\lambda_{emit}} - 1 \,, \ \Omega_\gamma \approx 10^{-5}$$

“Face of God”

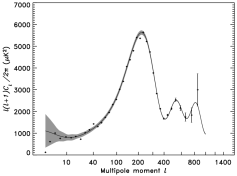


Temperature fluctuations in the CMB after removing Doppler shift and background from the galactic plane.

$$\delta T_0 \approx 60\mu K$$

$$\delta T_0 / T_0 = 2 \times 10^{-5}$$

Temperature fluctuations



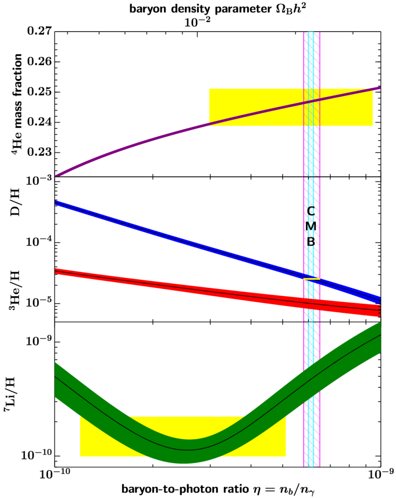
Temperature fluctuations result from density fluctuations whose size can be calculated (acoustic waves in plasma), and therefore act as "standard rulers" on the surface of last scattering.
Correlation function,

$$C(\theta) =< \frac{\delta T(\hat{n})}{T}\frac{\delta T(\hat{n}')}{T} >,$$

averaged over $\hat{n}\cdot\hat{n}' = \cos(\theta)$

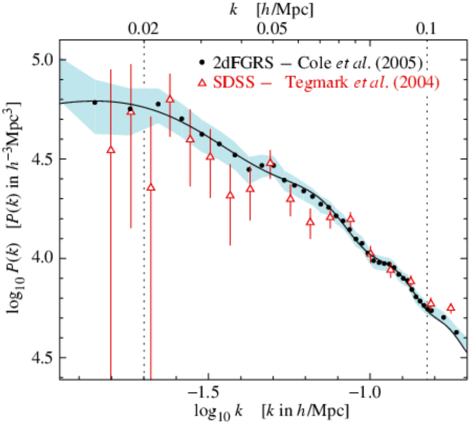
$$\Omega_{vac} \approx 0.7$$

3) Nucleosynthesis (BBN)



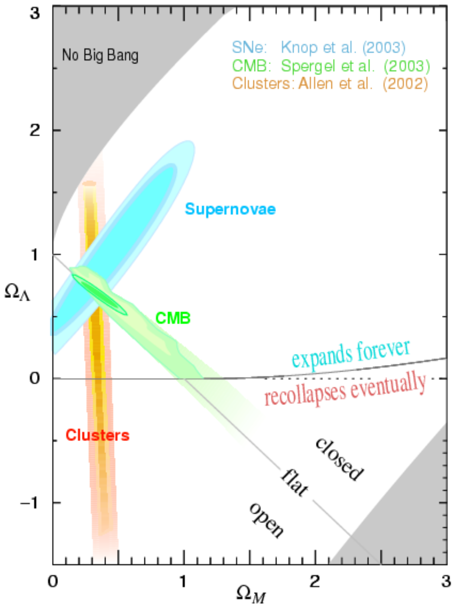
The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by Big-Bang nucleosynthesis as a function of the baryon-to-photon ratio η. The bands show the 95% CL range. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of η.

4) Structure Formation



$$\Omega_{\text{matter}} = 0.168 \text{ with } \Omega_{\text{baryonic}}/\Omega_{\text{matter}} = 0.17$$

Global best Fit



$\Omega_{tot} = 1.02 \pm 0.02$, consistent with $\Omega = 1$ (flat) universe

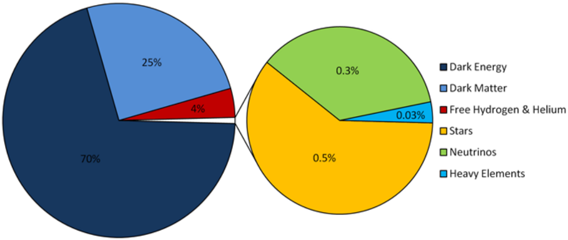
$\Omega_{vac} = 0.73 \pm .04$

$\Omega_b = .044 \pm .004$

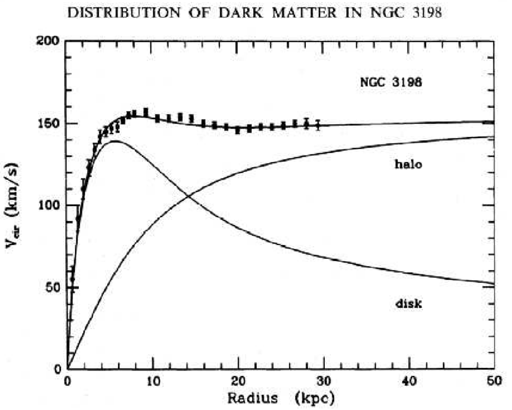
$\Omega_{matter} = \Omega_{dark} + \Omega_b = 0.27 \pm .04$

$t_{bigbang} = 13.7 \pm 0.2$ Gyr

What the Universe is made of?



70% Dark Energy–what is it?
25% Dark Matter– what is it?

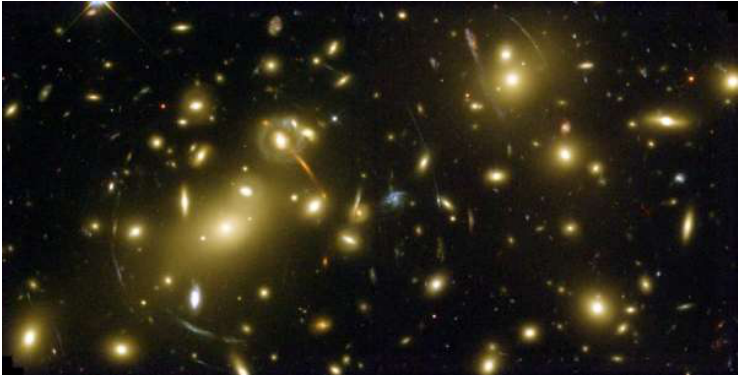


Typical galactic rotation curve.

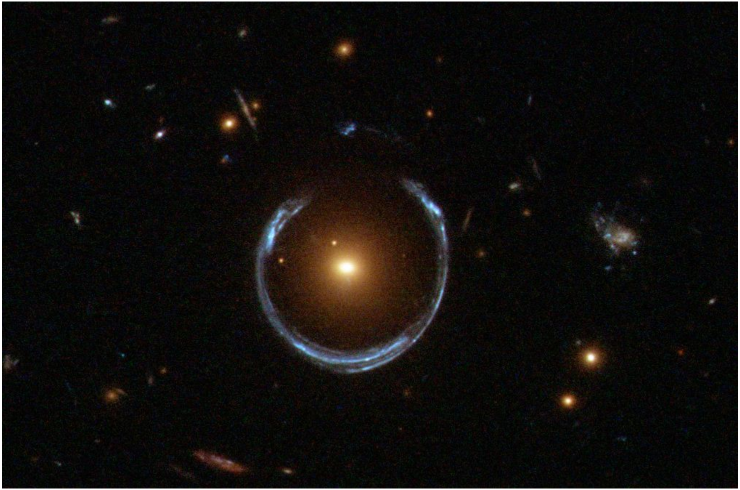
$$\rho_{Dark} \approx 0.3 \mathrm{GeV}/\mathrm{cm}^3$$

interaction rate of < 1 event/kg/day

Strong Lensing

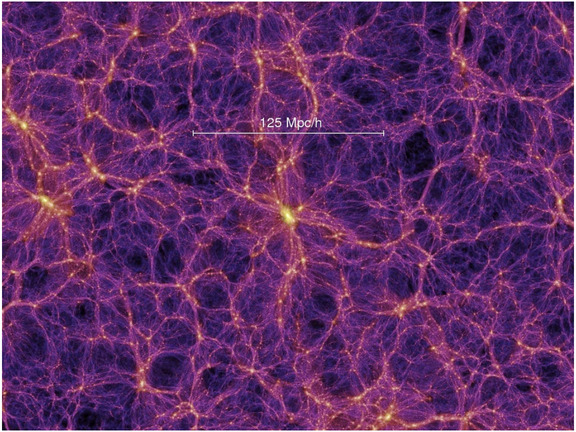


Einstein Ring

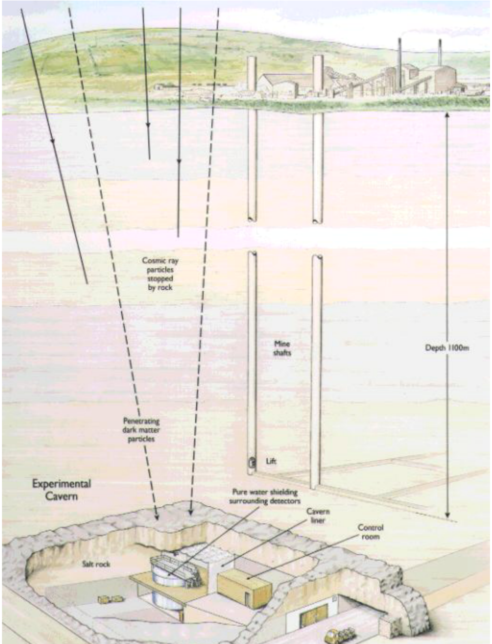


Large Scale Structure

Need dark matter to form large filamentary structure, galaxy clusters and galaxies. This is a computation of the large scale structure based on GR with only dark matter.



WIMP Dark Matter: Direct Detection Experiments



Weakly Interacting Dark Matter: There is no known particle ("Standard Model") with the necessary properties: stable, heavy $M > 10 GeV$, weakly interacting. A new particle like the supersymmetric photon, the "photino"?

WIMP Dark Matter Principle

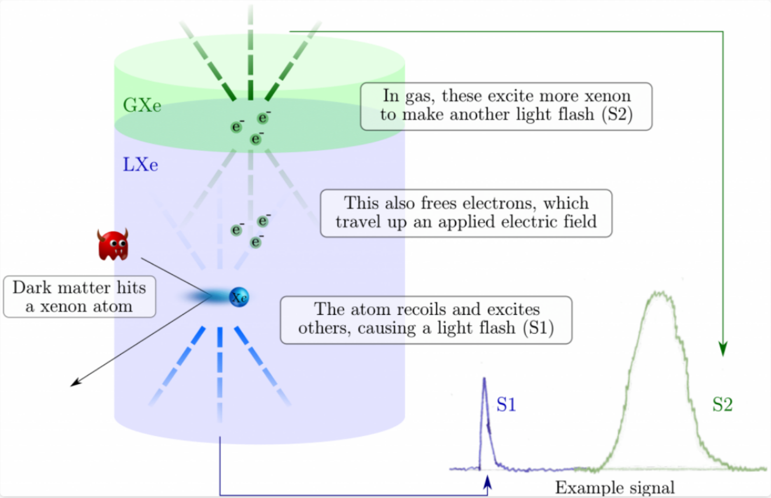


Figure: How dark matter would make S1 and S2 signals in the XENON1T detector.

WIMP Dark Matter Limits

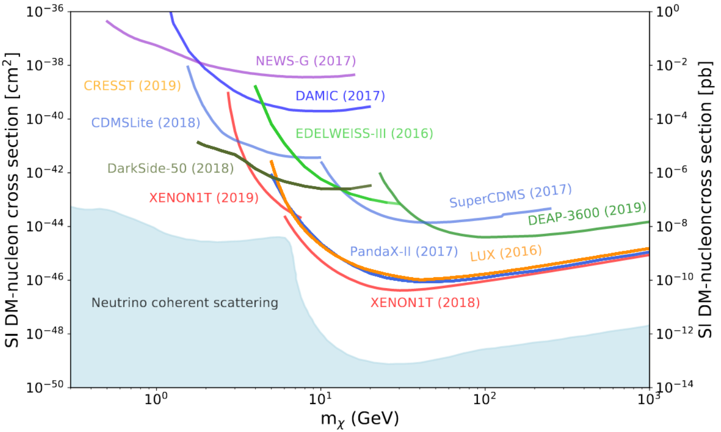
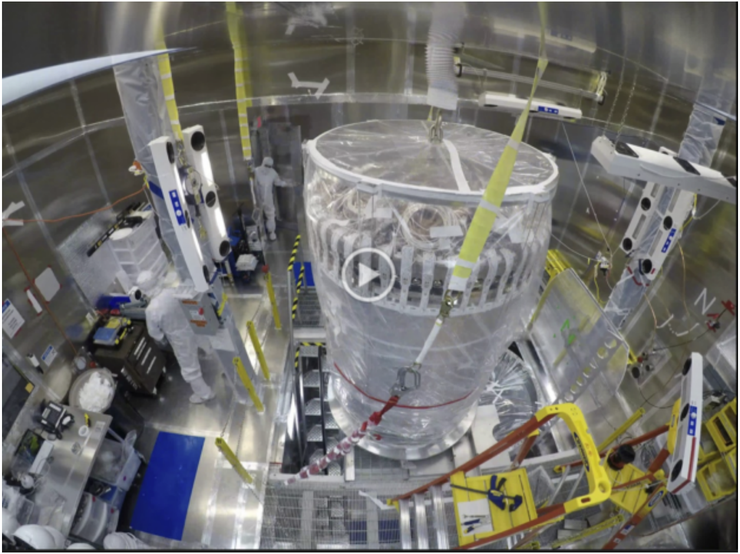


Figure 26.1: Upper limits on the SI DM-nucleon cross section as a function of DM mass.

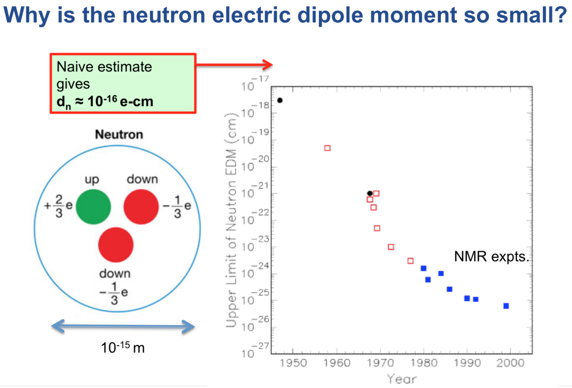
XENON 1T 3.3 T LUX 370 kg

WIMP Dark Matter Next Generation



next generation: LZ 10 Ton , XENONnT 8.3 Ton shown is LZ TPC in SURF, South Dakota

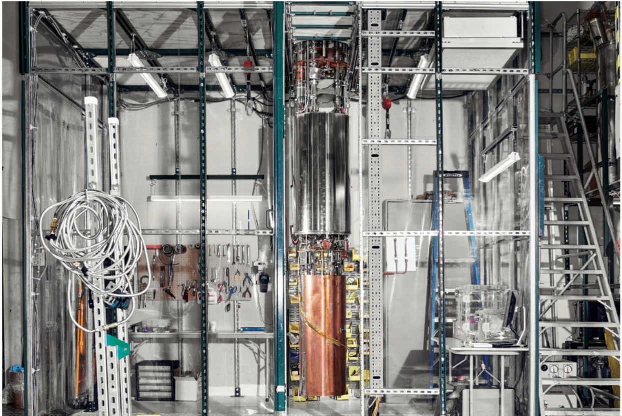
Neutron Electric Dipole Moment (EDM)



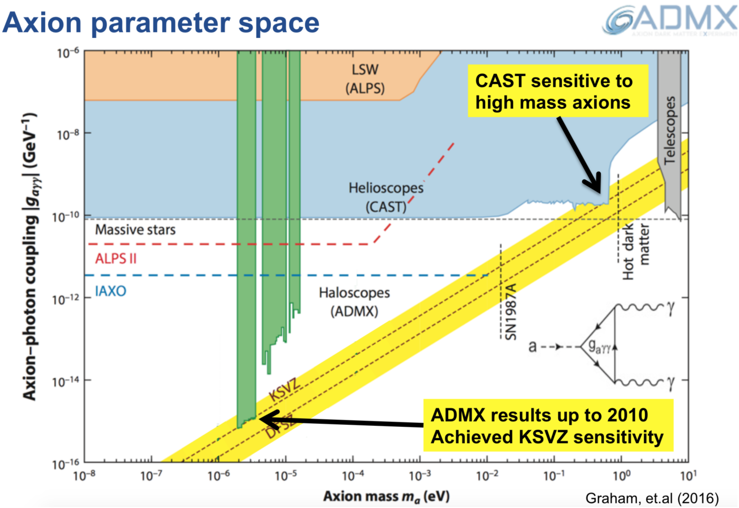
EDM would violate CP. Why violation is so small is called the "strong CP" problem. New U(1) symmetry, new extremely light ($\sim 10\mu eV$) boson, the axion Dark Matter axions can convert to two photons (resonant microwave cavity) in magnetic field.

The ADMX G2 Experiment

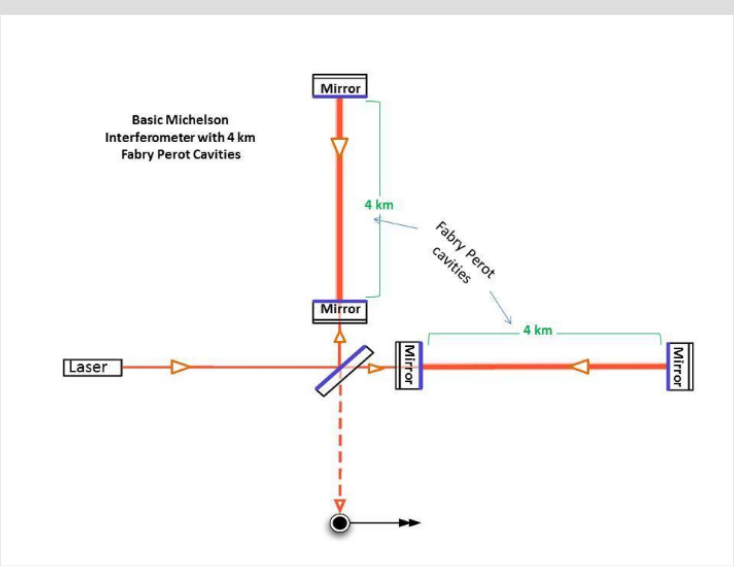
ADMX is an axion haloscope, which uses a strong magnetic field to convert dark matter axions to detectable to microwave photons. The ADMX G2 experiment is one of the US Department of Energy's flagship dark matter searches, and the only one looking for axions. The experiment consists of a large magnet, a microwave cavity, and ultra-sensitive low-noise quantum electronics.



Axion Dark Matter Limits



Graviational Waves



Basic Michelson interferometer with Fabry

Graviational Waves

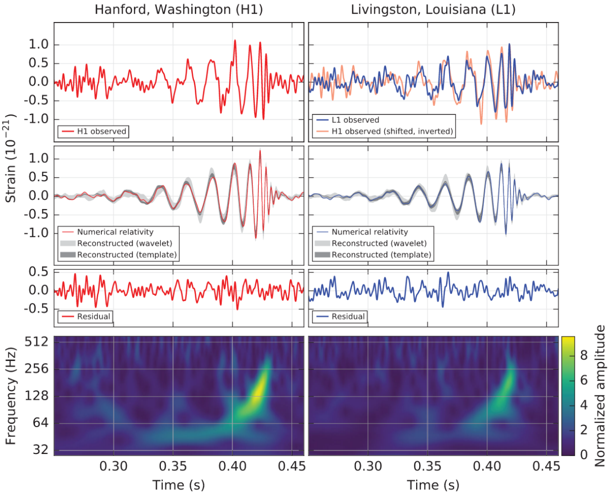
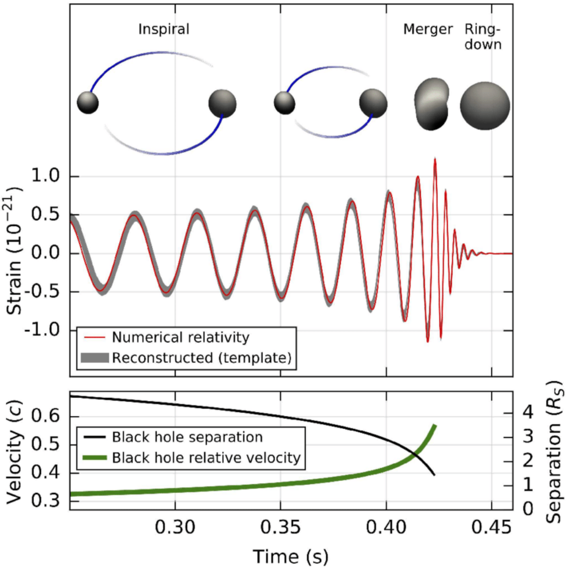


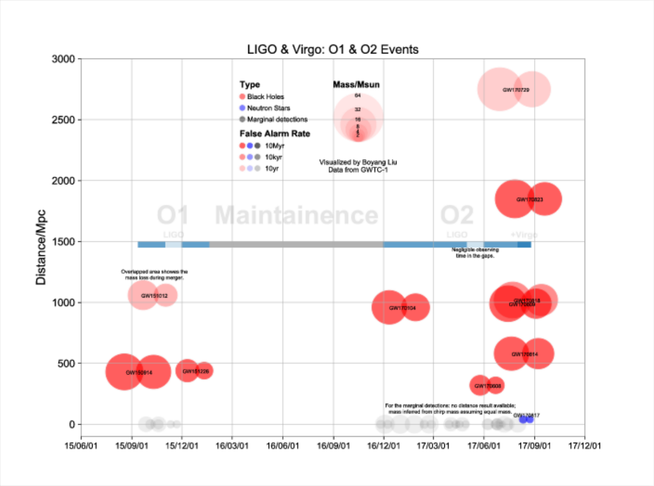
FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. *Top row, left:* H1 strain. *Top row, right:* L1 strain. GW150914 arrived first at L1 and $6.9^{+0.5}_{-0.4}$ ms later at H1; for a visual comparison, the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors' relative orientations). *Second row:* Gravitational-wave strain projected onto each detector in the 35–350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914 [37,38] confirmed to 99.9% by an independent calculation based on [15]. Shaded areas show 90% credible regions for two independent waveform reconstructions. One (dark gray) models the signal using binary black hole template waveforms [39]. The other (light gray) does not use an astrophysical model, but instead calculates the strain signal as a linear combination of

Graviational Waves



Graviational Waves

https://upload.wikimedia.org/wikipedia/commons/5/50/O1&O2.svg



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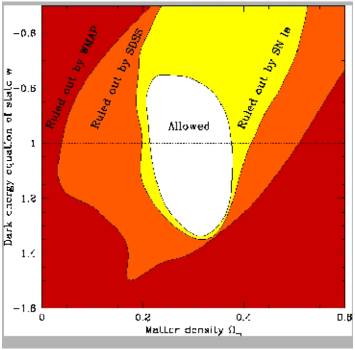
Nature of the Dark Energy

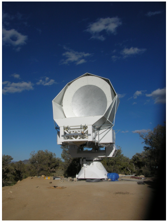


$w = 1$ means a Cosmological constant;
"quitessence", a time varying vacuum energy? Or does General Relativity need to be modified at large distances?
Various Dark Energy measurements planned.

- Horizon Problem: patches of sky separated by $> 2^\circ$ were causally disconnected at time of (CMB) decoupling, yet spectrum is perfect black body implying equilibrium.
- Homogeniety and Isotropy problem: Expect quantum fluctuations in early universe to create inhomogeneities.
- Flatness problem: Why an almost perfectly flat geometry.

Proposed solution: Inflation (Guth)– An exponential expansion of the universe at times 10^{-34}s due to a vacuum phase transition, releasing enormous vacuum energy, due to some (unknown) "inflaton" field. This theory predicted flat ($\Omega = 1$) universe!

CMB polarization



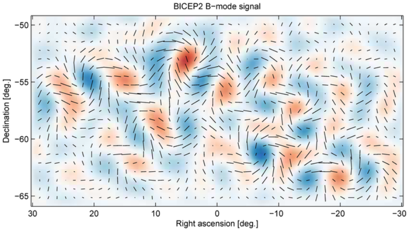


Figure: located in northern Chile @17,100 ft. Other experiments at the south pole.

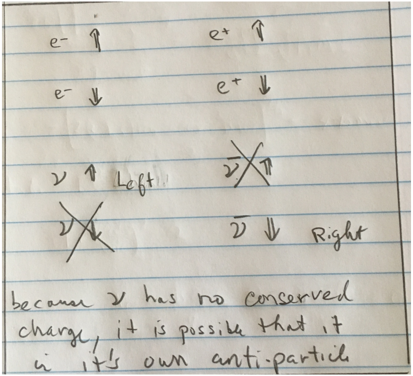
Inflationary theories predict that the early Universe underwent a phase of exponential expansion during which a background of gravitational waves was produced. Those gravitational waves will then produce a primordial B-mode signal at the time of recombination.

baryogenisis

Particle physics has an almost perfect matter-antimatter symmetry. Most of the matter-antimatter in the early universe annihilated to radiation leaving $N_p/N_\gamma \approx 6 \times 10^{-9}$ Yet there are almost no antiprotons in the universe! Particle physics has all the ingredients to produce the matter-antimatter asymmetry, but not enough.
There must be new particle physics to explain this!

Majorana Neutrino

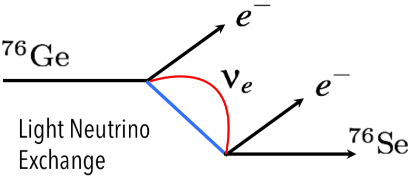
lepto-genesis – theories that explain matter-antimatter asymmetry of barons as resulting from lepton number violation from Majorana neutrino



The electron is really four separate fields. The neutrino might be only two. It might be its own anti-particle.

Neutrino-less Double Beta

A hypothetical nuclear decay that can only happen if the neutrino is its own anti-particle. Measured $^{76}\mathrm{Ge}$ $\beta\beta$ with 2ν is $T(1/2) = (1.84 + 0.14 - 0.10)10^{21}$ yr.



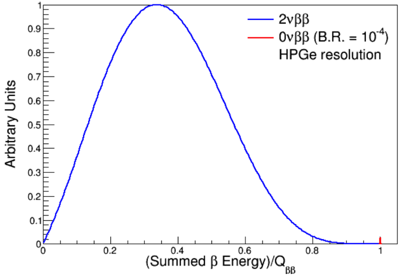
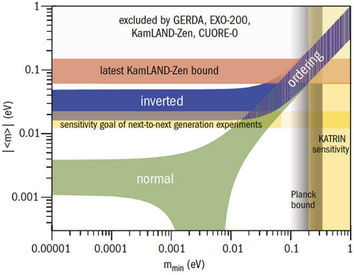


Figure: Tiny red blip at endpoint greatly exaggerated. Looking for $\tau \sim 10^{28}$ yr

LEGEND Experiment



Ge detectors emersed in liquid argon veto. Because we have only measured neutrino squared-mass differences, we don't know the mass ordering. "Normal" has state which is mostly electron-neutrino as the lightest.

Liquid Argon Veto

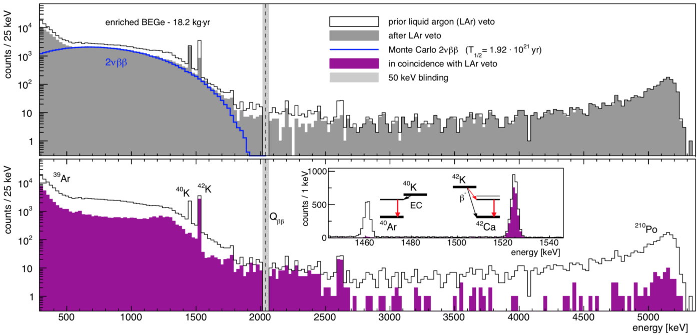


FIG. 8. Background energy spectra of BEGe detectors obtained during GERDA Phase II data taking. The spectra for events after LAr veto rejection and events with scintillation light coincidence are displayed separately. The overlay of the $2\nu\beta\beta$ contribution from Monte Carlo simulations in the spectrum after LAr veto highlights the suppression of the background dominated by Compton scattered γ's at these energies.

Cosmology and Particle Physics