

Neutrinos

Neutrinos

Extremely weakly interacting, neutral particles produced in weak force-mediated reactions, e.g. nuclear β decay and its inverse:

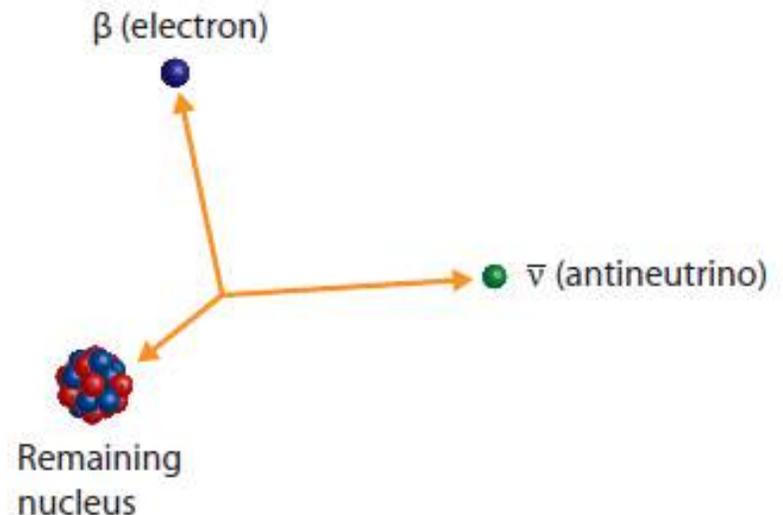
$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

$$p \rightarrow n + e^{+} + \nu_e$$

Three flavors: electron ν_e
muon ν_μ
tau ν_τ

each paired with a lepton

Proposed by Pauli (1930) to “rescue” energy & momentum conservation in β decay (an “invisible” particle to carry away the missing energy and momentum)



Solar neutrinos

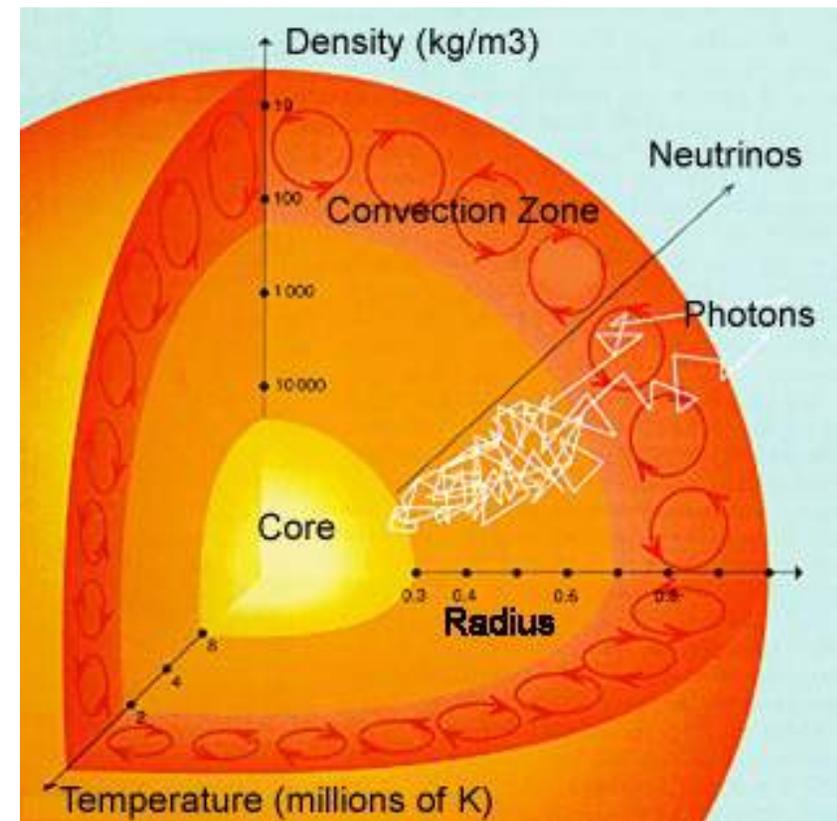
p-p chain reaction in Sun's core produces two ν_e for each 26.3 MeV of energy going into solar radiation

→ expect electron neutrino flux on Earth

$$f_{\nu_e} = \frac{2f_{\odot}}{26.2 \text{ MeV}} = 6.7 \times 10^{10} \text{ s}^{-1} \text{ cm}^{-2}$$

huge number, but hard to detect due to small cross section $\sim 10^{-44} \text{ cm}^2$

→ if can detect, probe deep solar interior!

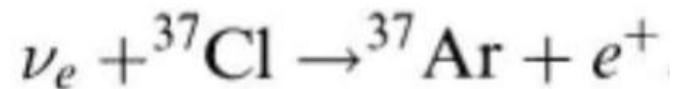


Detecting solar neutrinos

Solar neutrinos first detected by R. Davis in 1968 in a pioneering experiment in the Homestake Gold Mine, South Dakota (mine shields from cosmic rays and other possible contaminants)

610-ton tank of dry-cleaning fluid (C_2Cl_4)

Look for argon-producing



${}^{37}\text{Ar}$ is radioactive so small number of atoms can be counted



The Nobel Prize in Physics 2002



Raymond Davis Jr.

Prize share: 1/4



**Masatoshi
Koshiba**

Prize share: 1/4



Riccardo Giacconi

Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

Solar neutrino problem (1960s-early 2000s)

Davis ran the Homestake experiment for over 30 years

Worked closely with theoretical astrophysicist J. Bahcall, creator of the 'Standard Solar Model'

The Homestake experiment consistently detected only about 1/3 of the predicted electron neutrinos!

Problem with the experiment?
Problem with our understanding of the Sun?



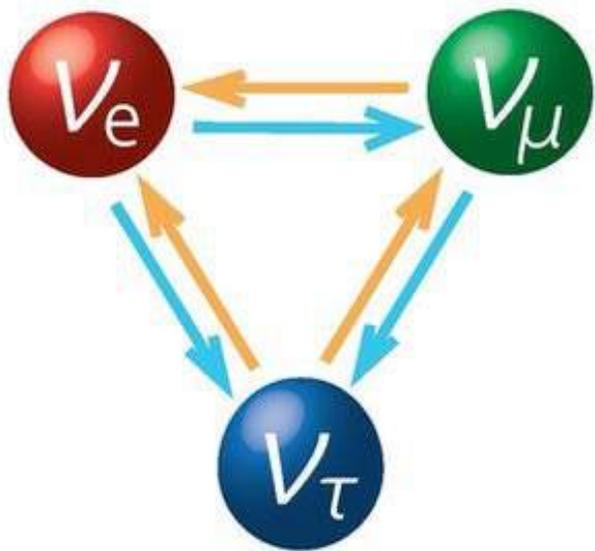
Davis (left) and Bahcall (right),
Homestake 1967

Neutrino oscillations: neutrinos change flavor!

Mikheyev–Smirnov–Wolfenstein (MSW) effect: neutrinos change flavor as they propagate through matter

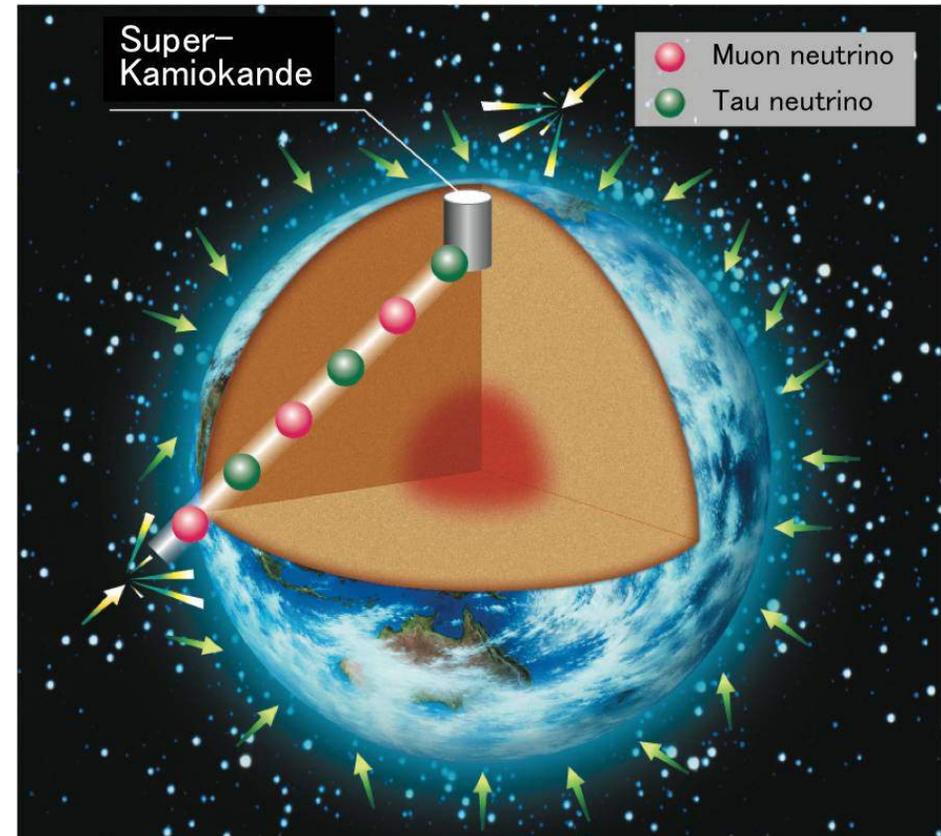
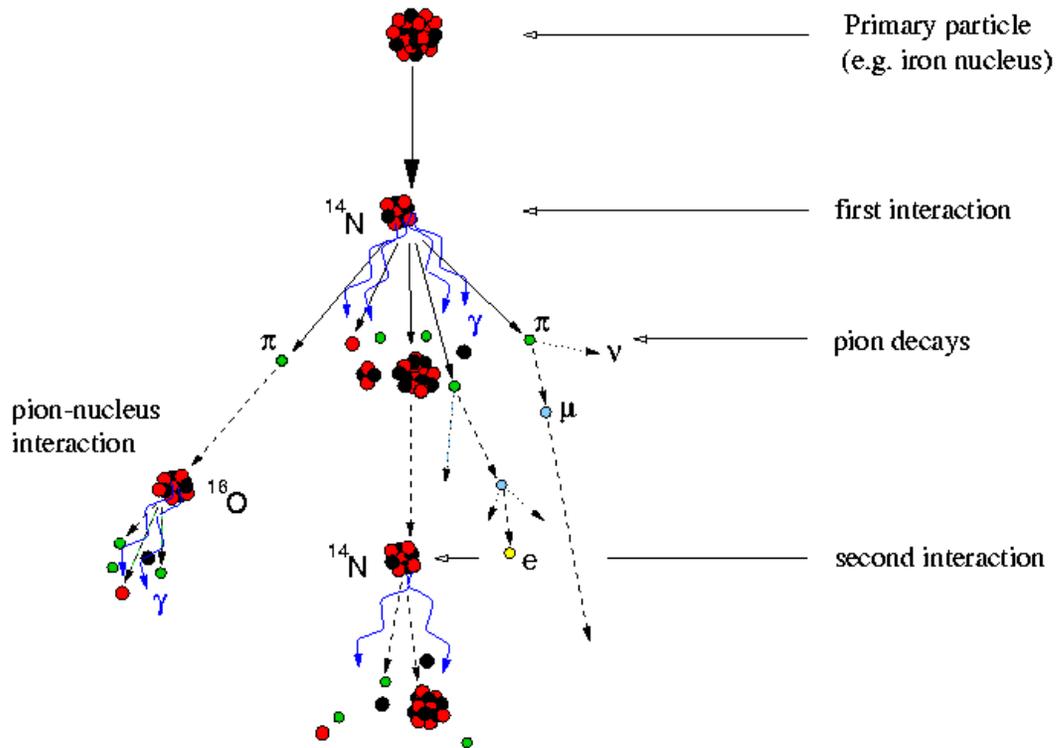
In particle physics models, this requires that neutrinos have mass (previously, they were assumed massless)

Furthermore, the flavor eigenstates differ from the mass eigenstates



Atmospheric neutrinos

Development of cosmic-ray air showers



electron, muon neutrinos are created in CR showers (when CRs interact with the Earth's atmosphere), but very few tau neutrinos are

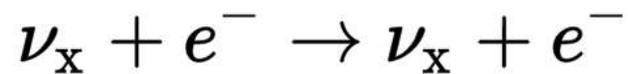
MSW \rightarrow muon neutrinos oscillate into tau neutrinos while propagating through Earth

Super-Kamiokande discovers atmospheric neutrino oscillations (1998)

1,000 m underground, Mozumi Mine, Japan

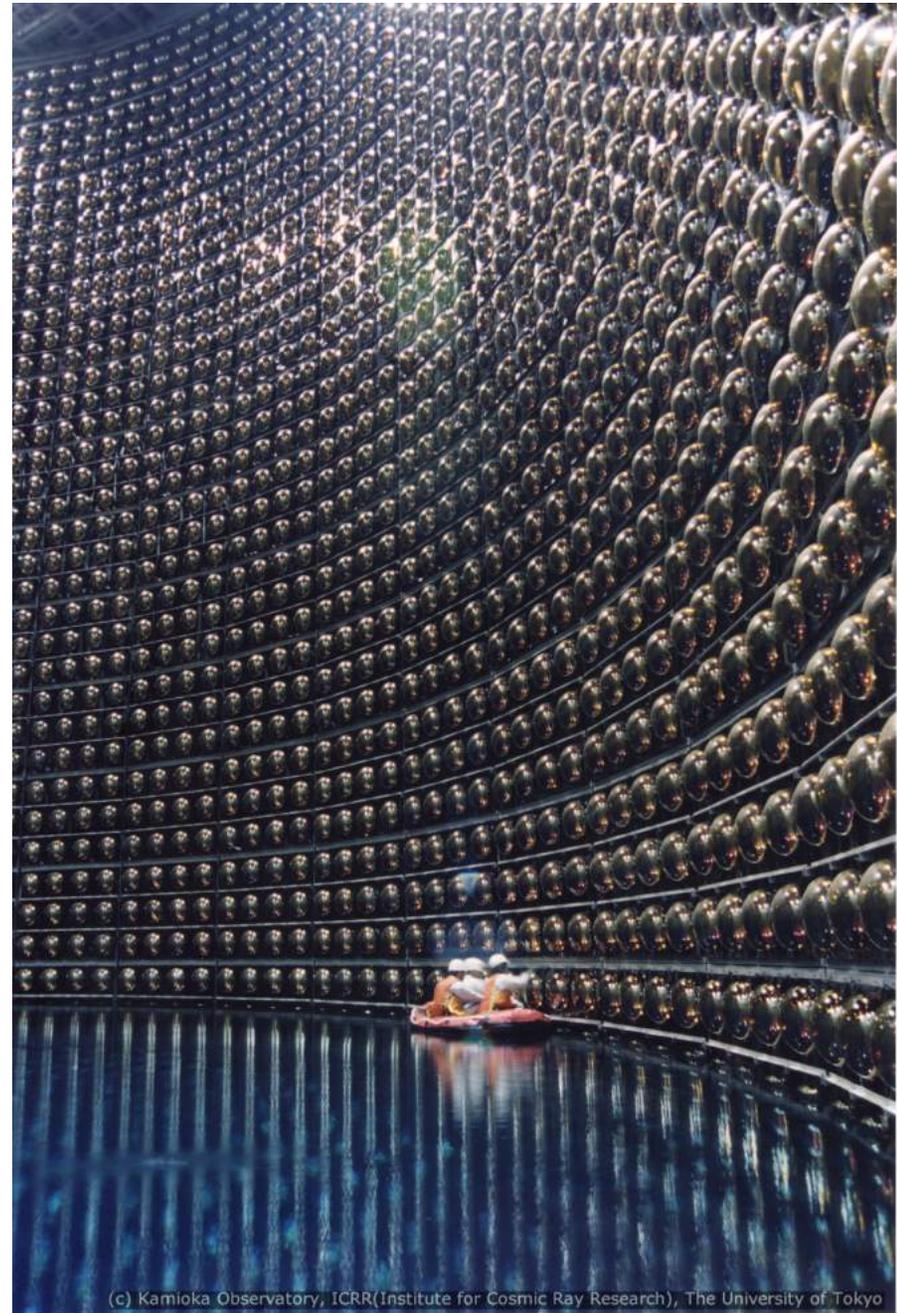
50,000 tons of ultra pure water

Neutrino-electron scattering

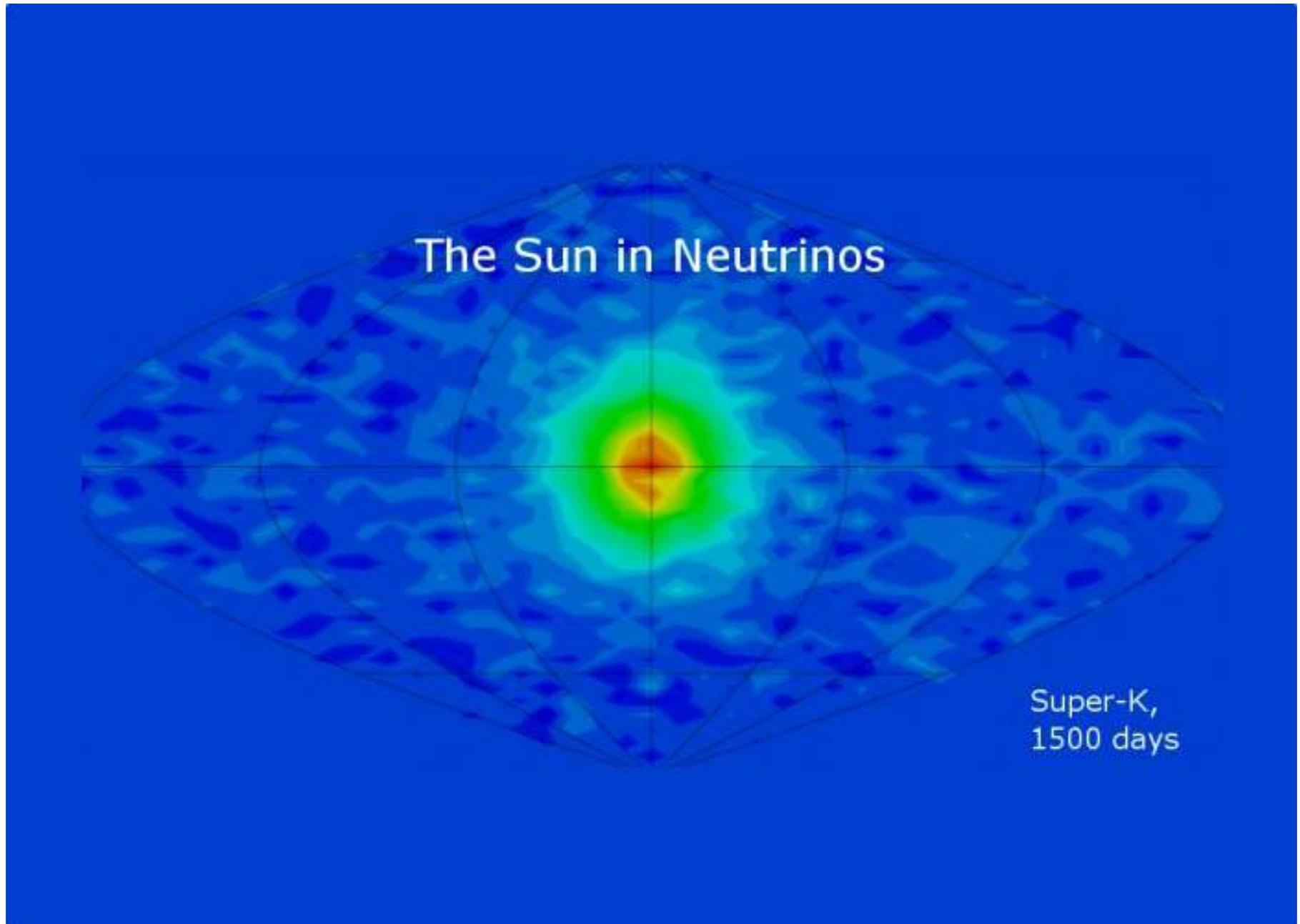


produces Cherenkov radiation
detected by photomultipliers

ν_e/ν_μ ratio depends on whether
looking through Earth or not



Super-Kamiokande's ν_e view of the Sun



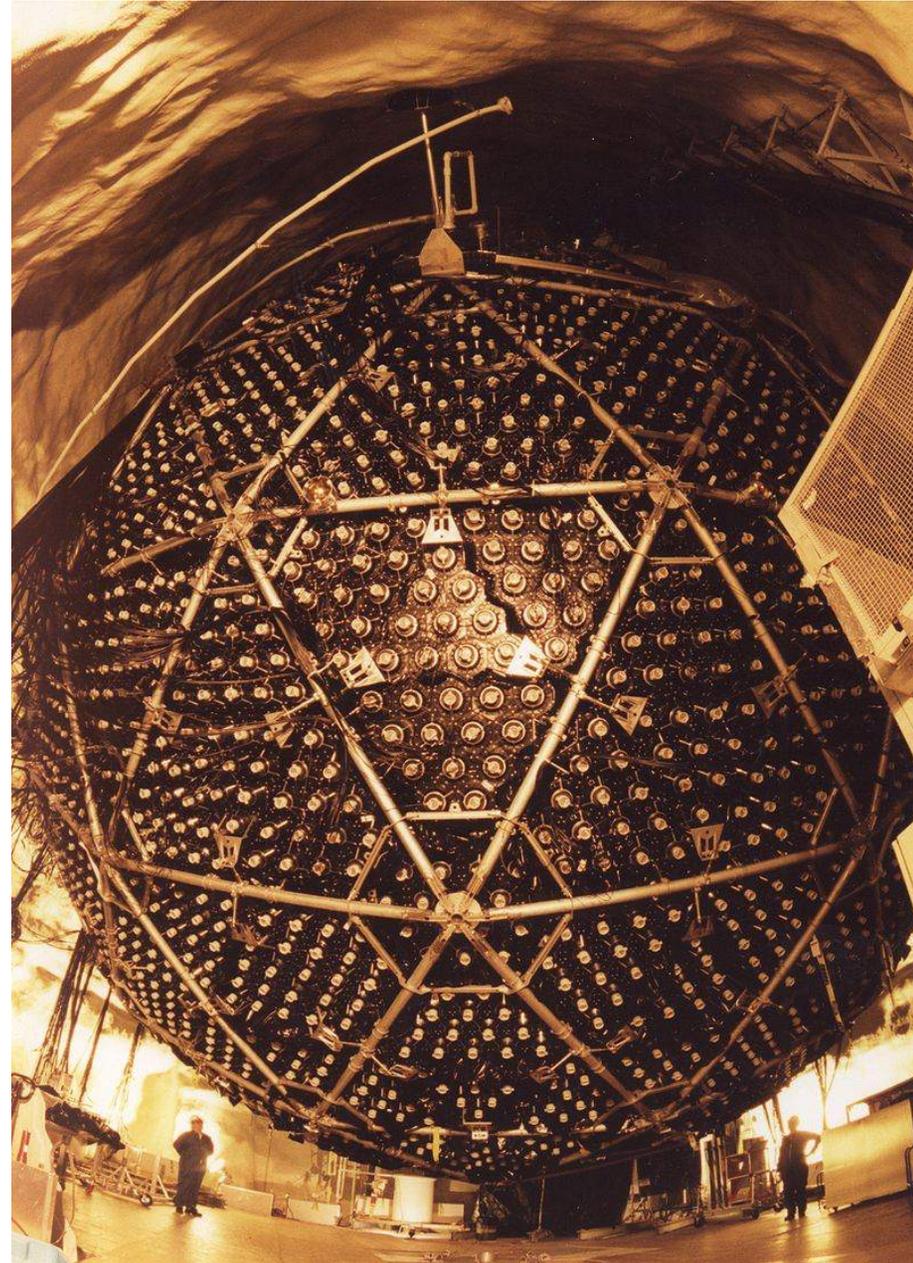
Sudbury Neutrino Observatory (SNO) directly detects solar neutrino oscillations (2001)

2,100 m underground, Creighton Mine, Canada

1,000 tons of heavy water ($^2\text{H}_2\text{O}$)

Neutrino-electron scattering but also other interactions with $^2\text{H}_2$ atoms produce Cherenkov radiation
→ better ability to distinguish between different neutrino flavors

first detected muon, tau neutrinos from the Sun — confirming reason for missing electron neutrinos from Sun is oscillations



The Nobel Prize in Physics 2015



Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2



Photo: A. Mahmoud

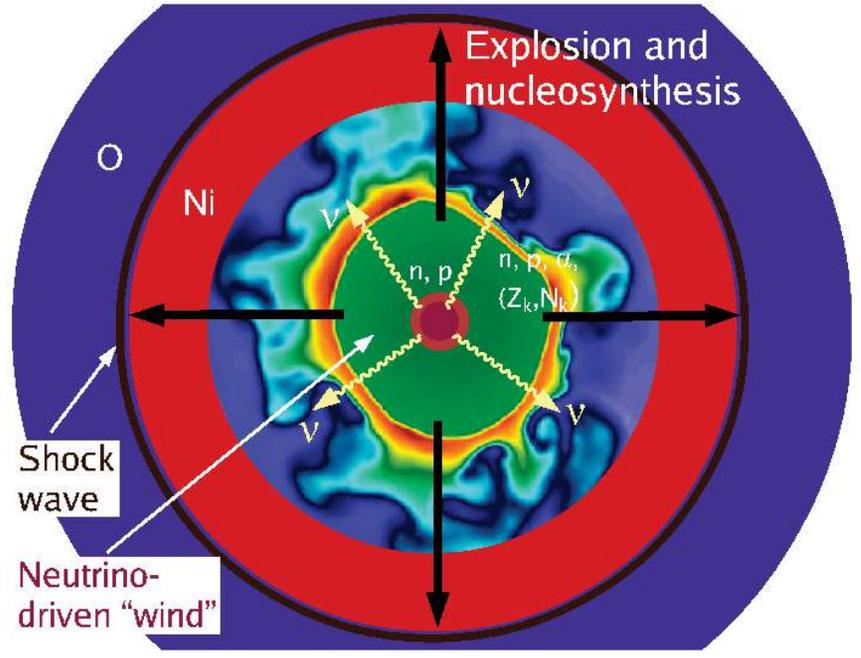
Arthur B. McDonald

Prize share: 1/2

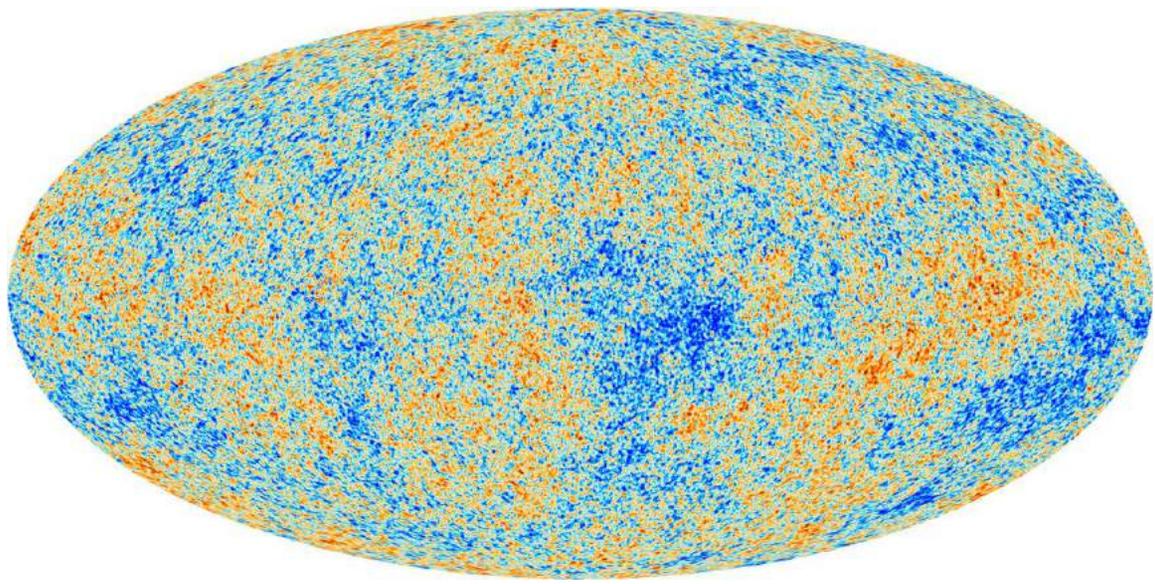
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Other sources of neutrinos

Core collapse supernovae
(during NS formation)



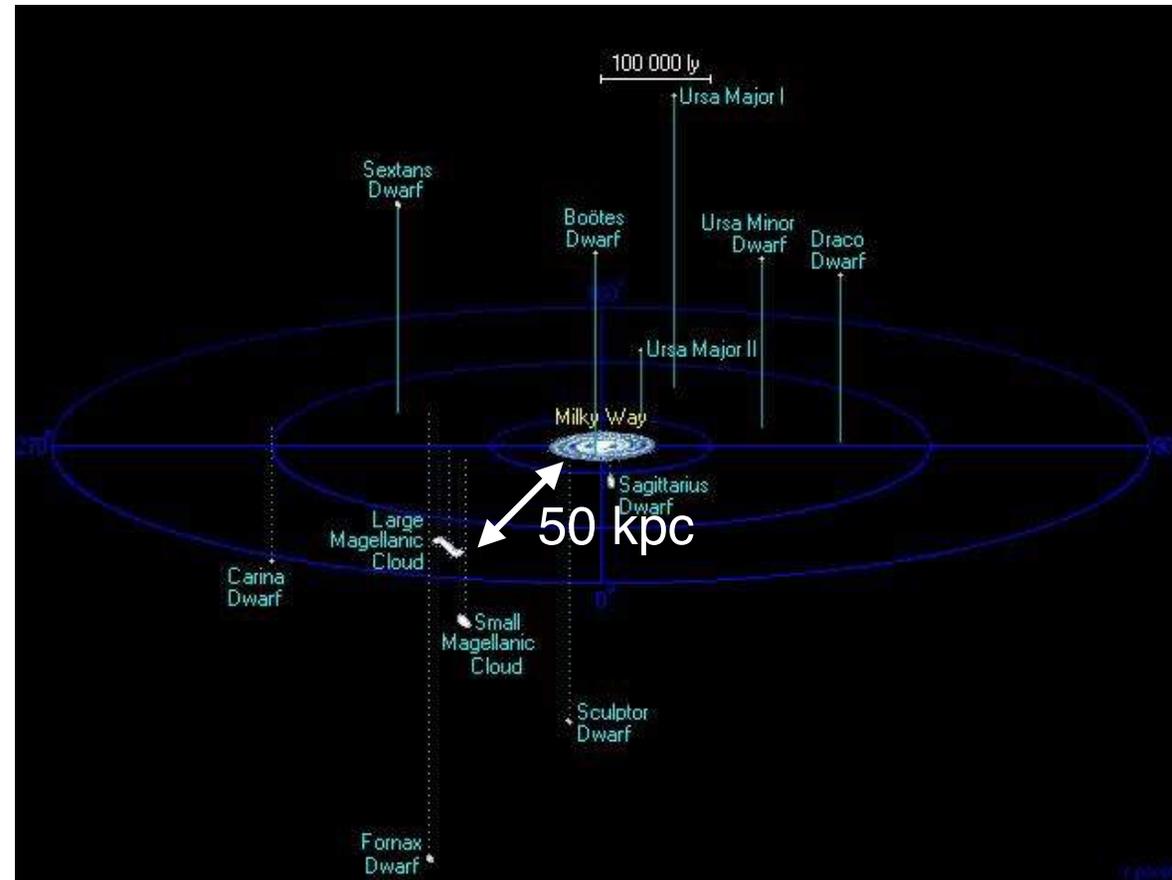
Cosmic neutrino background
(analog of microwave background left over from the Big Bang, shown here)



+ other energetic phenomena, e.g. gamma-ray bursts, and yet-to-be-discovered sources

SN 1987A

First supernova discovered in 1987, originates from the Large Magellanic Cloud, a nearby satellite of the Milky Way galaxy



Rule of thumb: ~ 1 SN per $100 M_{\text{sun}}$ of new stars formed

Milky Way has SFR $\sim 2 M_{\text{sun}}/\text{yr}$, so expect one Galactic SN every ~ 50 yrs

Observation of a Neutrino Burst from the Supernova SN1987A

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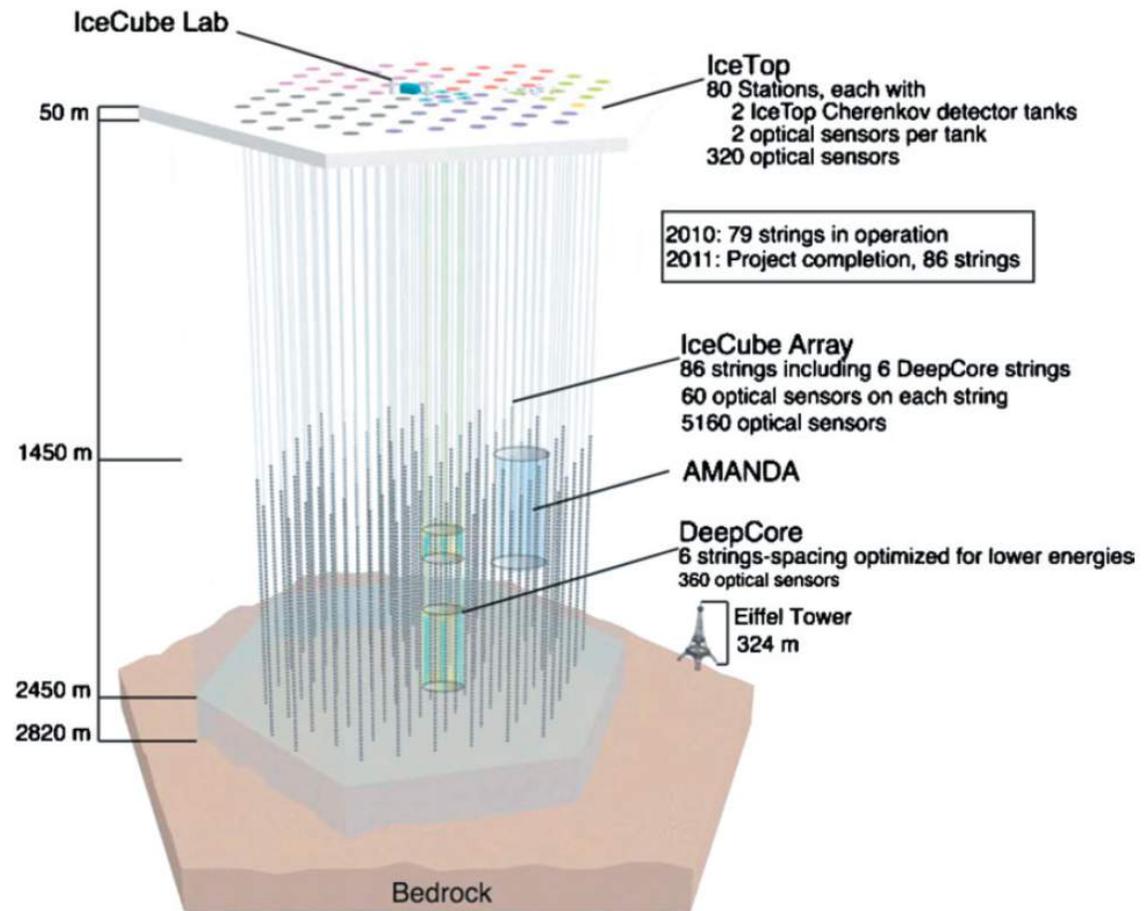
(Received 10 March 1987)

A neutrino burst was observed in the Kamiokande II detector on 23 February 1987, 7:35:35 UT (± 1 min) during a time interval of 13 sec. The signal consisted of eleven electron events of energy 7.5 to 36 MeV, of which the first two point back to the Large Magellanic Cloud with angles $18^\circ \pm 18^\circ$ and $15^\circ \pm 27^\circ$.

IceCube Neutrino Observatory

Thousands of photo-sensors in cubic km under Antarctic ice

Designed to look for neutrinos in TeV energy range to explore highest energy astrophysical processes



Cosmological effects of neutrino mass

Massless particles, like photons, always travel at the speed of light

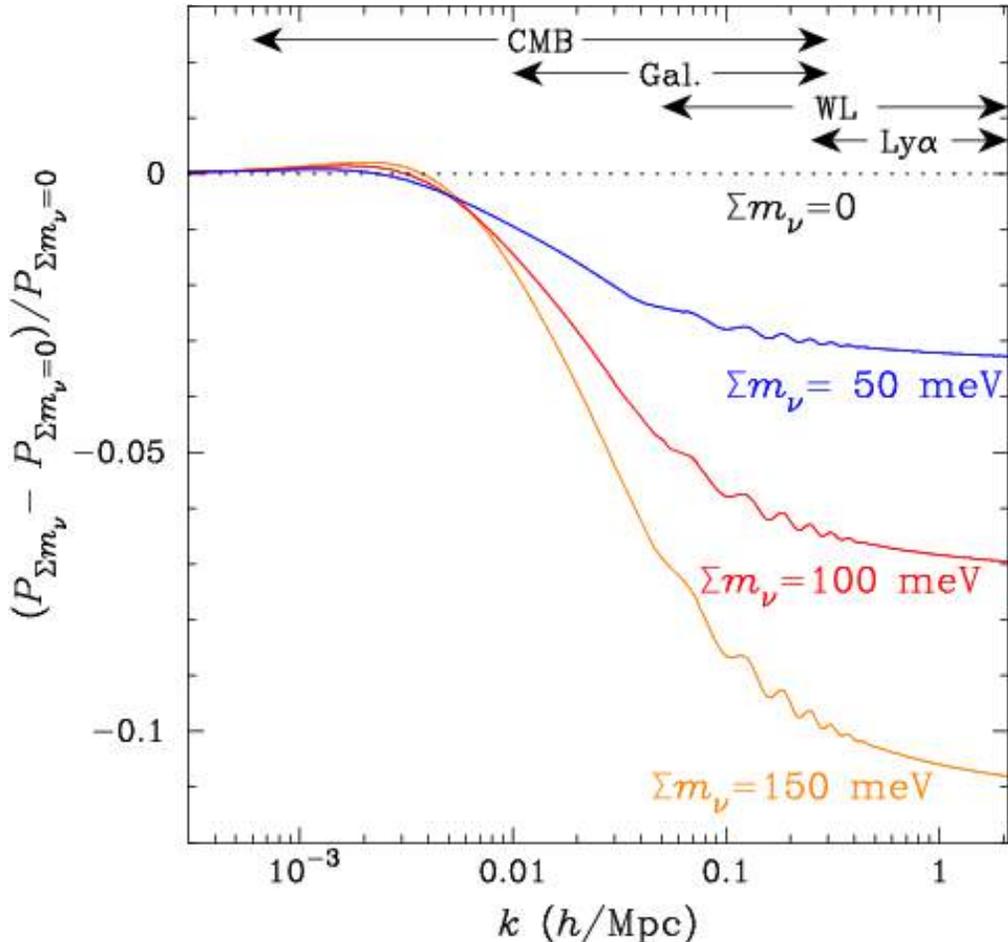
We will see: peculiar velocities of particles with non-zero mass decrease as the universe expands

Even if relativistic in the early universe (e.g., in the cosmic neutrino background), massive neutrinos will eventually become non-relativistic as the universe expands

This affects (gravitationally) development of cosmic structure in a mass-dependent way

Can detect e.g. as gravitational lensing of the CMB by foreground structure, galaxy clustering, or weak lensing of galaxies

Matter power spectrum vs. sum of neutrino masses

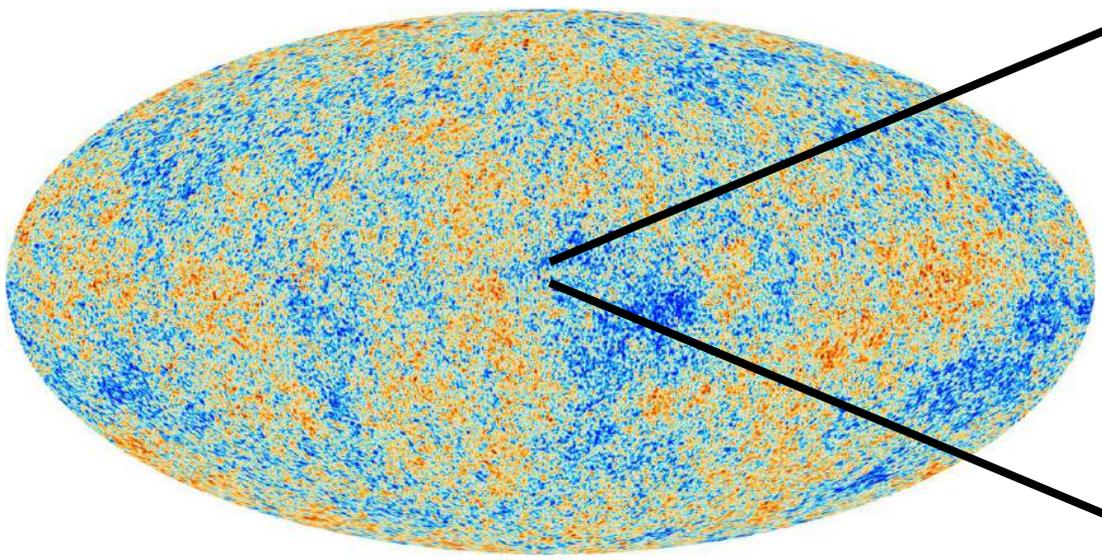


Current bounds on neutrino masses

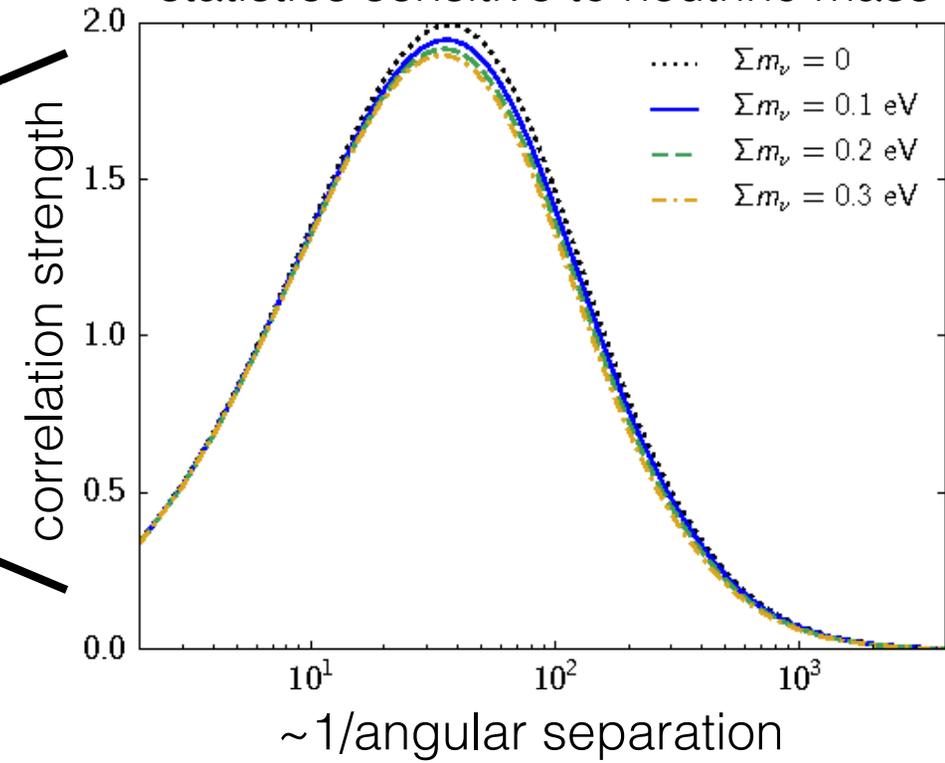
$$0.05 \text{ eV} < \Sigma m_\nu < 0.23 \text{ eV}$$

oscillation experiments

CMB measurements (Planck 2013)



Microwave background correlation statistics sensitive to neutrino mass



Massive neutrinos slightly affect development of cosmic structure via the gravitational forces they exert. Effect should be detectable in next ~5 years.

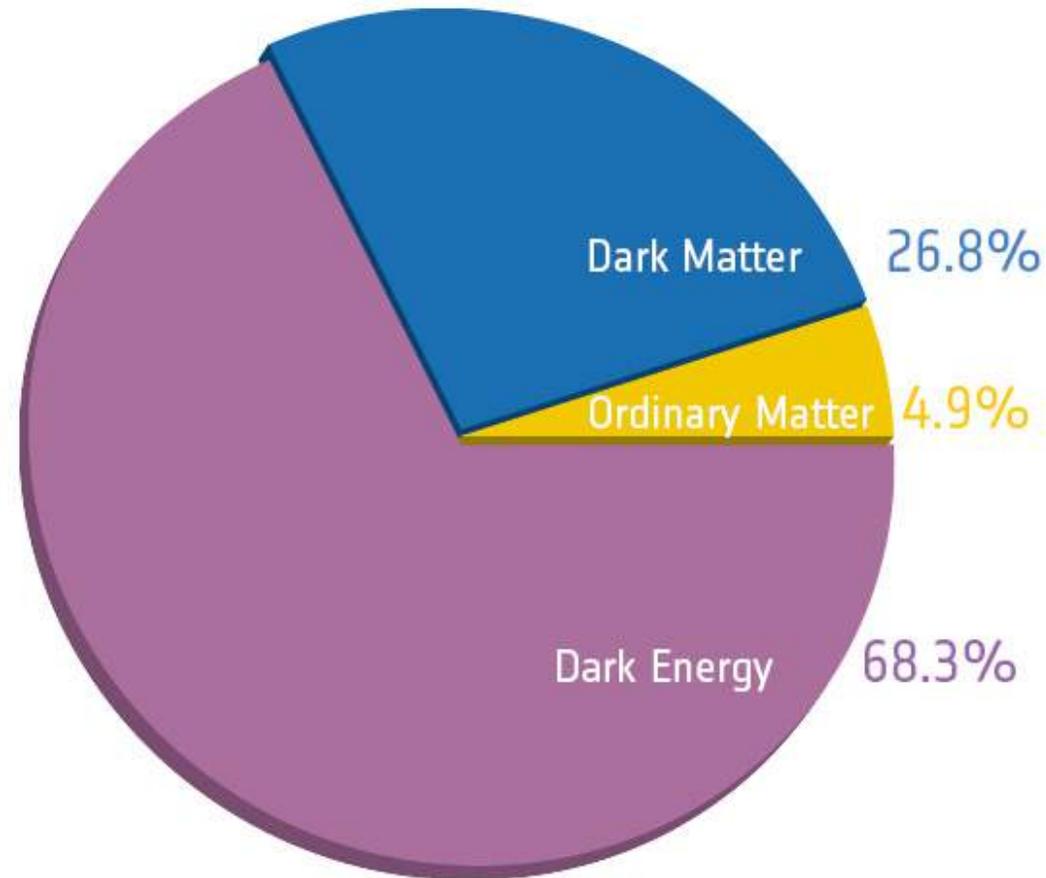
Dark Matter

Non-baryonic dark matter

Dark matter: presence is inferred from gravitational effects but the matter appears invisible

Later, we will discuss in more detail observational evidence that most gravitating mass in the universe is dark and that the majority must be **non-baryonic** (what evidence do you know already?):

- dynamical: galaxy rotation curves, orbits of galaxies in galaxy clusters
- gravitational lensing
- details of CMB anisotropies
- abundances of light elements produced during Big Bang nucleosynthesis (BBN)



Weakly interacting massive particles (WIMPs)

Most popular hypothesis for non-baryonic dark matter

Unknown particles beyond the Standard Model of particle physics (which summarizes the known particles) that interact via gravity and the weak nuclear force, but not E&M

E.g., particles predicted by supersymmetric theories

Do you know other WIMPs?

The neutrino is a known WIMP! But, it was shown in the early 1980s that if massive neutrinos were most of the dark matter, cosmic structures would be washed out too much to explain observations

Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge	Flavor	Approx. Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \cdot 10^{-6}$	0	u up	0.003	2/3
e^- electron	0.000511	-1	d down	0.006	-1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ^- muon	0.106	-1	s strange	0.1	-1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ^- tau	1.7771	-1	b bottom	4.3	-1/3

Spin is the intrinsic angular momentum of particles. Spin s gives in units of \hbar , which is the minimum unit of angular momentum, where $\hbar = 1.05 \cdot 10^{-35} \text{ GeV} \cdot \text{s} = 1.05 \cdot 10^{-34} \text{ J} \cdot \text{s}$.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60 \cdot 10^{-19} \text{ coulombs}$.

The energy unit of particle physics is the electronvolt (eV). The energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$), where $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \cdot 10^{-10} \text{ joules}$. The mass of the proton is $0.938 \text{ GeV}/c^2 = 1.67 \cdot 10^{-27} \text{ kg}$.

BOSONS

Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge
γ photon	0	0	g gluon	0	0
W^-	80.4	-1			
W^+	80.4	+1			
Z^0	91.187	0			

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons. There are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** ($q\bar{q}$) and **baryons** (qqq).

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property	Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Fundamental Strong	Residual Strong
		Mass-Energy	Flavor	Electric Charge	Color Charge	See Residual Strong interaction link
Acts on		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles experiencing		Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Particles mediating						
Strength relative to electromagnetism (in two protons in nucleus)		10^{-42}	10^{-4}	10^{-2}	25	Not applicable to quarks
		10^{-41}	10^{-4}	1	20	
		10^{-36}	10^{-7}	1	20	

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are baryonic hadrons. There are about 140 types of baryons.

Symbol	Quark content	Electric charge	Mass GeV/c ²	Spin
p	uud	1	0.938	1/2
\bar{p}	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	udd	0	0.940	1/2
\bar{n}	$\bar{u}\bar{d}\bar{d}$	0	1.116	1/2
Λ	uds	0	1.116	1/2
$\bar{\Lambda}$	$\bar{s}\bar{s}\bar{s}$	-1	1.872	3/2

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless a \bar{e}^- charge is shown). Particles and antiparticles have identical mass and spin but opposite charge. Some electrically neutral bosons, like Z^0 , γ , and W , are their own antiparticles.

Figures
These diagrams are an artistic conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

The Particle Adventure
Visit the award-winning web feature The Particle Adventure at <http://ParticleAdventures.org>

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